IRPL RADIO PROPAGATION HANDBOOK

PART I

ISSUED 15 NOVEMBER, 1943

JOINT COMMUNICATIONS BOARD
INTERSERVICE RADIO PROPAGATION LABORATORY
at National Bureau of Standards
Washington, D.C.

CRPL
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ERRATA:

IRPL RADIO PROPAGATION HANDBOOK

p. 17: The equation of paragraph 3 should read

$$\mu = \sqrt{1 - \frac{81N}{f^2}}$$

p. 52: In the example, third paragraph, the longitude given in line 5 should be "28°W". In the same paragraph, line 7 should read "1100 GMT, lie at about 0730 and 0910 local time, respectively".

p. 53: Second paragraph, last sentence: The report referred to is IRPL-R4.

p. 90: Line 2 should read: "only about 1/7", etc.

p. 97: Equation, next to last line, should read:

$$F = F_0 - S_0 \overrightarrow{K} d + P$$

Fig. 9: The values of the gyro-frequency given are roughly 0.06 Mc too low, and should accordingly be raised when calculations are made.

Fig. 105: Values of $\overline{K}\ S_0$ shown as curve parameters should be divided by 10.

Figs. 121 through 125: Second sentence of legends should read: "For CW reception, field intensities required are 0.14 as great, i.e., decrease logarithm by 0.85."

Figs. 126 through 128: Values given as 0.5, 5, 50, 500 kw on auxiliary power-distance scale should be 0.4, 4, 40, 400 kw, respectively.

IRPL RADIO PROPAGATION HANDBOOK, PART 1.

Note.- It is expected that this Part 1 will be followed by other Parts later. Present tentative plans for these are given in the Appendix on page 98. The suggestions of readers for the revision of Part 1 and the preparation of future Parts are invited by the Interservice Radio Propagation Laboratory. It is expected that the entire Handbook will eventually be issued as a printed book.

Sections I and II hereof give a general explanation of radio propagation with principal emphasis on the sky wave, which makes long-distance transmission possible. While it is helpful to the user to have this background, he can skip this and proceed directly to pages 47-52, 79-88, 91-95, and 95-97, to learn how to calculate maximum usable frequencies, field intensity produced by a transmitter, required field intensity, and lowest useful high frequencies together with distance ranges, respectively.

The IRPL acknowledges valuable assistance in the preparation of this book from material received from the Inter-Services Ionosphere Bureau and National Physical Laboratory of England, the Australian Radio Propagation Committee, the Canadian Naval Service, the Carnegie Institution of Washington, and the National Bureau of Standards.

Contents

SECTION I. INTRODUCTION

1. Purpose of the Handbook

The purpose of this Handbook is to provide a radio operator or a radio communications officer with a working knowledge of the principles underlying the propagation of radio waves from a transmitting antenna to a receiving antenna. This Handbook explains how the radio waves travel from the transmitting antenna to the receiving antenna, and how they can be effectively utilized in spite of varying conditions that occur in their travel. The purpose is also to give an outline of methods for calculating the field intensity to be expected, at any place in the world, produced by a transmitter in any other part of the world, and for evaluating the results in terms of whether the received intensity is great enough to be useful.

In general, radio wave propagation varies with time of day, season, phase of the sunspot cycle, and geographical location of the transmitter and receiver. On some frequencies, propagation is less variable than on others, and data may be given which are valid, within limits, for a long period of time. On other frequencies, however, propagation may vary widely with time, and so for these frequencies only the general principles of calculation can be given here, quantitative data being included in monthly supplements of predictions of radio transmission conditions.

A basic knowledge of the fundamentals of radio is assumed. Thus it is presumed that the reader has some idea of what a radio wave is and how it is generated, and that he is familiar with such terms as frequency, wavelength, power, field intensity, and polarization of the wave.

2. Modes of Radio Propagation

Section I of Part 1 is devoted to a general description of radio wave propagation. There are two principal ways in which the waves travel from transmitter to receiver: by means of the ground wave, which travels directly from transmitter to receiver, and by means of the "sky wave", which travels up to the "ionosphere", the electrically conducting layers in the earth's upper atmosphere, and is reflected by them back to earth. Long-distance transmission on frequencies greater than about 300 kc takes place principally by means of the sky wave; short-distance transmission and transmission on ultra-high frequencies takes place mainly by means of the ground wave; transmission on frequencies below about 300 kc has somewhat the nature of a "guided wave" being propagated between two conductors, the earth and the ionosphere.

This section is an introduction to radio sky-wave calculations, and explains in detail what the ionosphere is, and how it affects high-frequency radio transmission.

3. Ground-Wave Propagation

In Section I of Part 3 of this Handbook is described the mechanism of ground-wave propagation. There are three general classes into which ground-wave propagation falls.

(a) Transmission at medium and high frequencies, where the heights of the antennas above ground are usually small in comparison to a wavelength. The "surface wave" is the predominant component of the ground wave at these frequencies. The electrical properties of the ground are the most important factors here.

(b) Transmission at very high, ultra-high, and super-high frequencies, where the antennas are usually a number of wavelengths above the earth. The "direct wave", "ground-reflected wave", and "tropospheric wave" are the predominant components of the ground wave at these frequencies. Local meteorological conditions are more important in these ranges than are the electrical properties of the ground.

(c) Transmission above about 3 megacycles where one or both of the antennas are elevated a great number of wavelengths above the ground (as for plane-to-plane or plane-to-ground communication). The direct- and ground-reflected wave components are of principal importance here, and meteorological conditions play an important role at the higher frequencies.

In this section graphs, nomograms, and methods are given for calculating ground-wave field intensities and distance ranges for frequencies up to about 30 megacycles.

4. Low-Frequency Propagation

In Section II of Part 3 is described the mechanism of propagation of frequencies from 15 to about 300 kc between the concentric conducting surfaces of the ionosphere and the earth. The wavelengths involved at these frequencies are large compared with distances in the ionosphere, and so the ionosphere is relatively smooth and stable. Consequently transmission conditions vary only slowly with time, and "phase-interference" patterns, consisting of regions where the intensity is very small compared with intensities a few miles away, are very pronounced at short distances (1000 miles or so).

Graphs, nomograms, and methods are given for calculating low-frequency field intensities, and descriptions are given of diurnal and seasonal variations and the effects of ionosphere abnormalities, such as ionosphere storms and sudden ionosphere disturbances.

5. Sky-Wave Propagation at High Frequencies

Sky-wave transmission over a fixed distance is confined between two limits of frequency, the "maximum usable frequency" (m.u.f.) and the "lowest useful high frequency" (l.u.h.f.). Similarly, at a fixed frequency, sky-wave transmission is confined between two limits of distance, the "skip distance" and the "distance range". The limits of frequency and distance within which sky-wave transmission is possible depend upon time of day, season, and sunspot cycle, as well as other factors.

The skip distance and the maximum usable frequency are nearly independent of transmitter power, and are limited by the reflecting properties of the ionosphere, which decrease abruptly for frequencies above the maximum usable. The distance range and the lowest useful high frequency, on the other hand, depend on transmitter power, radio noise level of the receiver, antenna characteristics, and operator's skill, as well as upon ionospheric properties.

Sections III and IV of Part 1 give the principles of calculation of m.u.f. and of sky-wave field intensities, together with some general rough information on radio noise levels in different parts of the world. Graphs, nomograms, and methods are given for calculating sky-wave propagation calculations from basic data, samples of which are attached. Because of the great variation of basic data with time, it is necessary to use up-to-date predicted material. This material is issued monthly by the Interservice Radio Propagation Laboratory at the National Bureau of Standards in the form of supplements to this Handbook.

Sky-wave field intensities are in general greater, the higher the frequency. It is therefore an advantage to use as high a frequency as possible, compatible with the m.u.f. The m.u.f., however, is not constant at the same hour from day to day, but varies within limits of up to ± 20 percent from the monthly average. The best or "optimum" frequency to use is thus somewhat below the average m.u.f. Since a factor of safety is thus introduced, it is permissible to make certain simplifications in the world-wide picture for certain applications. Such procedures are outlined in Part 2 of this Handbook, and short-cut methods of calculation are given for various types of problem. One such general problem, for example, is that of frequency allocation, discussed in Section III of Part 2.

6. The Transmission Path

The length, direction, and geographic location of the transmission path are of fundamental importance in radio propagation calculations. This is especially true for long-distance sky-wave calculations, since the condition of the ionosphere at any time varies widely over the world. Although transmission is usually by way of the great-circle path joining the transmitter and receiver, it may on occasion take place by paths which deviate somewhat from the great circle.

The basic problem is that of determining the great-circle path between transmitter and receiver, and of locating the places along the path where the ionosphere controls the transmission. For transmission paths less than 2500 miles in length the m.u.f. is determined by ionospheric conditions at the midpoint of the path, and so the latitude and local time of this midpoint are the most important information. For transmission paths greater than 2500 miles in length the m.u.f. is determined by the condition of the ionosphere at two "control points" 1250 miles from each end of the transmission path, and so the location and local time of these points are of importance for such transmission paths. Methods for these and other path calculations are given in Sections I to IV of Part 4.

7. Angles of Arrival and Departure

In designing equipment for specific communication purposes, it is necessary to know how best to direct the waves emitted from the transmitting antenna so that they will be as intense as possible on arrival at the receiving antenna. For sky-wave communication over great distances this involves knowing the vertical angle or the probable range of vertical angles which will cover the desired transmission distance, by reflection from regular ionosphere layers. For ultra-high-frequency communication, it involves knowing how to allow for tropospheric reflection or refraction, and the proper combination of direct- and ground-reflected wave components.

Furthermore, transmission over long distances does not always take place via the great-circle path, but there may be appreciable and indeed great deviations therefrom, especially over paths in certain parts of the world. Both for the design of directional antennas for point-to-point communication, and in practical operational use of direction finders, it is necessary to know about horizontal angles of arrival and departure of the waves.

In Part 7 of this Handbook are given data and methods for evaluation of vertical and horizontal angles of departure and arrival, and discussion of the deviations and variations from the normal. Applications to special problems, like distance estimation and off-path transmission at frequencies greater than the m.u.f. along the great-circle path, are mentioned.

8. Required Field Intensities

In order to interpret calculated received field intensities in terms of their usefulness for communication, it is necessary to know the minimum value of field intensity required for reception. This is a function primarily of the radio noise level at the receiving location, although the factors of antenna directivity and operator's skill also enter in. The type of service desired (phone, CW, direction finding, etc.) also must be considered.

At frequencies generally used for sky-wave communication, and in some parts of the world at still higher frequencies, the radio noise level at a good receiving location (one free from man-made noise) is due primarily to atmospheric electrical disturbances, propagated from their sources (mostly thunderstorms) to the receiver just as radio waves are propagated. If the number, intensity, and location of thunderstorms everywhere in the world are known at any given time, then the radio noise level anywhere in the world should be calculable. Practically there is but a handful of principal noise centers in the world. This simplifies the picture somewhat.

Since the calculation of radio noise levels, on this basis, is itself a radio propagation problem, the methods outlined in the rest of the Handbook for radio waves can be applied to the propagation of the noise emanating from the disturbance centers. In Sections V and VI of Part 4 are given data and methods for performing these calculations and for deriving therefrom required field intensities for various types of service.

A discussion is also given of radio set noise and man-made electrical interference, both of which play important roles in certain locations (big cities, etc.), and for certain types of service (mobile communication on u.h.f., etc.

9. Transmission above 40 Mc

Above 40 Mc, transmission is mostly by means of the ground wave, except for irregular periods of sporadic-E transmission and for short periods of F_2-layer transmission in the middle of the day at sunspot maximum. Ground-wave transmission at these frequencies is markedly different in characteristics from that at lower frequencies because:

(a) The surface wave gives only a minor contribution to the received field intensity.

(b) The antennas are usually elevated at least several wavelengths above the earth.

(c) Reflection and refraction in the lower atmosphere (up to a few thousand feet) is extremely important, becoming more so as the frequency is raised.

(d) Line-of-sight transmission is often, but not always, the most reliable kind.

The restricted distance range of the ground wave makes these frequencies useful where it is desired to cover a limited area and not be intercepted at great distances. Frequencies up to 100 Mc or so must be used cautiously, however, if it is desired to avoid interception, because there is danger, great at times, of sporadic transmission over great distances.

In Part 5 graphs and nomograms are given for optical-path transmission, and for surface-wave coverage, and atmospheric reflection and refraction is discussed. Special consideration is given to noise levels at these high frequencies, and to transmission over sea water and different types of ground.

10. Radiation from Antennas

The field intensity produced by a transmitter over a given transmission path at a given time is proportional to the square root of the radiated power (transmitter-output power times antenna efficiency). Furthermore the field intensity over a given path, for a given power output and frequency, may vary enormously depending upon the directional properties of the transmitting antenna. It is therefore important to know the amount and direction of the power radiated from the antenna in order to calculate the field intensity at a distance.

Close to any antenna there is an "induction field", superposed on the "radiation field", so that any object (such as a parasitic reflector), placed close to the antenna, responds to the induction as well as to the radiation field. Also the effective vertical directional pattern of an antenna is different for distances involved for sky-wave transmission than it is near the antenna, because the surface wave decreases more rapidly with distance than does the space wave.

Part 7 gives the principles underlying radiation from antennas and gives methods for estimating the surface and space waves at various distances from the antennas and in various directions. An elementary discussion of directional arrays is also given.

11. Services of the Interservice Radio Propagation Laboratory

The Interservice Radio Propagation Laboratory, at the National Bureau of Standards, Washington, D.C., has been set up for the specific purpose of centralizing radio wave propagation data and of disseminating such information to the armed forces. The facilities of the IRPL are available, upon direct request through authorized channels, for the solution of any type of radio wave propagation problem, on either a special or regular basis. Examples of special problems of this type would be:

(a) Selection of locations and frequencies for new communications services, point-to-point or in specific areas.

(b) Recommendations of best frequencies for operations in specific areas at specific times in the near future.

(c) Survey of frequencies allocated for specific services, with recommendations for improvements.

(d) Estimates of distance ranges of communication equipment in specific parts of the world.

(e) Specific opinions on various phases of radio wave propagation, both theoretical and empirical.

(f) Assistance in setting up schedules for broadcasts or communication.

(g) Estimates of the grade or quality of radio transmission on specific days, including forecasts or warnings of radio disturbance a day or more in advance.

(h) Recommendations of types of equipment (frequency range and power) for specific communications needs.

(i) Any problem requiring knowledge of ionospheric data in various parts of the world, e.g., a distance-range estimation problem, or one involving vertical angles of arrival.

Examples of regular services of a specific nature are:

(a) Monthly predictions of best frequencies or best of assigned frequencies for point-to-point services, for each hour of the day.

(b) Regular predictions of m.u.f. for various distances in specific areas.

(c) Regular reports of up-to-the-minute ionospheric data to serve as corrections to previous predictions.

(d) Regular warnings or forecasts of radio disturbances.

(e) Regular predictions of frequencies to be monitored for intercept work (monthly average for each hour of the day).

(f) Regular predictions of best frequencies for mobile unit-base communication in any area (monthly average for each hour of the day).

(g) Regular predictions of frequencies for use on regular shipping or air lanes for communication with post or base.

(h) Any problem involving regular reports on best frequencies, field intensities or distance ranges for specific services.

The predictions are available in graphical, tabular, and nomographic form. It is suggested that those desiring regular reports for specific paths or areas consult with the IRPL to determine the best form for their individual use.

The IRPL issues regularly at present several series of pamphlets covering both general and specific problems.

(a) IRPL series A, "Tables of recommended frequency bands for use by ships or aircraft for communication with bases in the Atlantic and Pacific." Issued every three months for three months ahead.

(b) IRPL series B, "Tables of recommended frequency bands for use by submarines for communication with bases in the Pacific." Issued every three months for three months ahead.

(c) IRPL series H, "Frequency guide for operating personnel." Issued every six months for six months ahead.

(d) IRPL series K, "Tables of best frequencies for use by ground stations for communication with aircraft or other ground stations in the Atlantic." Issued every three months for three months ahead.

(e) "Radio propagation conditions". Monthly supplement to this Handbook.

(f) "Radio propagation forecast". Issued each week.

12. Obtaining Information from the IRPL

The authorized channels for submission of problems to the IRPL are:

(a) For the Army:
Office of the Chief Signal Officer,
Communications Liaison Branch,
Room 3D243, Pentagon Bldg.,
Washington, D.C.

(b) For the Navy:
Chief, Radio Section,
Bureau of Aeronautics,
Navy Department,
Washington, D.C.

(c) For all others:
Chairman, Wave Propagation Committee,
Combined Communications Board,
Washington, D.C.,

or

Chief, Interservice Radio Propagation Laboratory,
National Bureau of Standards,
Washington, D.C.

SECTION II. RADIO WAVE PROPAGATION

1. General

The radio waves which are emitted from a transmitting antenna are both electric and magnetic in nature, and are therefore called electromagnetic waves. The alternating electric field produces a similarly alternating magnetic field, and this alternating magnetic field gives rise to an alternating electric field, and the whole structure propagates itself through space at the speed of light. (Light, in fact, consists of electromagnetic waves of extremely high frequencies). In this Handbook the electric field alone will usually be dealt with, so that when field intensity is mentioned, for example, the electric field intensity is meant. It must be remembered, however, that both electric and magnetic fields exist together and that neither the electric nor the magnetic field of a radio wave can exist alone.

Practical limitations on the size of a radio antenna result in very little power being radiated at frequencies less than 15,000 cycles per second, so only frequencies greater than that are used in radio communication. The frequencies used in radio communication are classified as follows:

Frequency Range	Nature of Range	Abbreviation
Below 30 kc	Very low frequencies	VLF
30-300 kc	Low frequencies	LF
300-3000 kc	Medium frequencies	MF
3000-30 000 kc	High frequencies	HF
30-300 Mc	Very high frequencies	VHF
300-3000 Mc	Ultra high frequencies	UHF
3000-30 000 Mc	Super high frequencies	SHF

This is the official classification of radio waves, as approved by the Combined Communications Board.

2. Modes of Propagation

There are two principal ways in which radio waves travel from transmitter to receiver; by means of the "ground wave", which travels directly from transmitter to receiver, and by means of the "sky wave", which travels up to the electrically conducting layers in the earth's upper atmosphere, called the "ionosphere", and is reflected by them back to earth. Long-distance radio transmission takes place mainly by means of the sky waves; short-distance transmission and ultra-high frequency transmission take place mainly by means of the ground wave. The propagation of the ground wave is determined principally by the electric characteristics of the ground (soil or sea);it is different in different places, but remains practically constant with time. Sky-wave propagation, on the other hand, is very variable, since the state of the upper atmosphere is always changing. Transmission by means of sky waves varies with time, place, and direction of transmission.

The electric intensity of a received radio wave varies as the square root of the power radiated. The intensity of a direct wave in free space varies inversely as the distance from the source. The ground-wave intensity is less, the greater the distance, the poorer the conductivity of the ground, and the higher the frequency. Except very near the transmitting antenna, it is much less than the intensity which would be due to the direct wave in free space at the same distance from the same transmitting antenna. The sky wave has to travel all the way up to the ionosphere and down again, and so is reduced in intensity at least as much as a direct wave would be which traveled an equivalent distance. There is frequently, however, relatively little energy absorption in the ionosphere, so sky-wave intensities are commonly strong enough for communication at great distances.

Most radio waves are long enough to be propagated around small obstacles and gentle curves, such as that of the earth's surface, with little obstruction. At very high frequencies, however, the wavelength is short and the effect of obstacles in producing a "shadow" is pronounced.

3. The Ground Wave

The waves radiated from an antenna spread out into the atmosphere, along the earth, and also into the earth. Because of the conducting properties of the earth some of the energy is reflected from the earth's surface, and the part which enters the earth is rapidly dissipated in the form of heat. The waves which spread out along the earth and into the atmosphere travel to the receiver and provide radio communication.

The wave which is received in the absence of a "sky wave" is generally known as the "ground wave". The field intensity of the ground wave depends in a complex manner upon the geometry of the transmission path and of the transmitting and receiving antennas, upon the diffraction of the waves around the earth, upon the electrical characteristics (conductivity and dielectric constant) of the local terrain, upon the frequency of the waves, and also upon local meteorological conditions, such as the distribution of the water-vapor content of the atmosphere along the path. Most of the received ground-wave field intensity can usually be accounted for in terms of one or more of the above-listed factors. Where the ground wave can be considered as due predominantly to one or more of the factors separately, it may receive a special name such as "direct wave", "ground-reflected wave", "surface or diffracted wave", and "tropospheric wave".

The direct-wave component is the wave which travels most directly from the transmitting antenna to the receiving antenna. In the case of communication between airplanes, say, at heights of several thousand feet and over distances of a few miles, this is the principal mode of transmission. The electric field intensity in a direct wave varies inversely as the distance of transmission; this is called the "inverse-distance" attenuation, and is caused by the spreading out of the waves, whereby the energy in a unit volume of space is less, the farther away the volume is from the source. The direct-wave component is not affected by the ground, or the earth's surface, but it is subject to refraction in the atmosphere between the transmitter and the receiver. This refraction is particularly important at very high frequencies.

The ground-reflected wave component, as its name implies, is the wave which reaches the receiver after being reflected from the ground. For communication between planes lower than a few thousand feet and separated by several miles the ground-reflected wave takes on an importance comparable to the direct wave for communication. The phase of the wave is altered upon reflection from the ground. The combination of the direct with the ground-reflected wave is affected by their relative phase, as well as their amplitude.

The so-called "surface" or diffracted wave is the wave which is affected primarily by the conductivity and dielectric constant of the earth, and is able to follow the earth's curvature. When both transmitting and receiving antennas are on or close to the ground, the direct and ground-reflected waves cancel out, and the entire field intensity is that of the surface wave. The surface wave is, however, not confined to the earth's surface, but extends up to considerable heights, diminishing with increasing height. Energy is constantly fed into the earth from the surface wave, to supply the energy dissipated in the ground. When the transmission distance is appreciably greater than line-of-sight transmission, the surface wave, in the absence of a troposphere wave, constitutes the entire field. The effect of ordinary refraction in the layers of the atmosphere close to the earth's surface contributes to this wave also. This refraction is caused by the normal vertical change of atmospheric density and moisture content.

The troposphere wave component is the wave which is refracted or reflected primarily from relatively steep gradients in atmospheric humidity and possibly also from steep gradients in atmospheric density and temperature. Its phase is more or less random with respect to the other components of the ground wave, and it is responsible for (1) fading of the ground wave beyond the optical horizon, and (2) abnormal, and sometimes great increases in ground-wave field intensity at distances far beyond the normal ground-wave range. This effect is similar to a mirage, which is similarly caused by refraction of light from atmospheric gradients.

The electrical properties of the underlying terrain which determine the loss of ground-wave field intensity vary but little with time, so that "ground-wave" transmission has relatively stable characteristics. An exception to this may be found in localities where there are distinct "wet" and "dry" seasons, and where the ground characteristics may thus be markedly different in different seasons.

In general, waves of low frequencies are transmitted by the ground wave with less energy loss than are high frequencies. At low and medium frequencies, the conductivity of the underlying terrain is more important than the dielectric constant; the decrease of field intensity is less over soil of high conductivity. The conductivity of sea water is approximately 5000 times as great as that for dry soil. Hence ground-wave transmission over sea water is far superior to that over land. If the path between transmitter and receiver lies principally over water, it is advantageous to have the transmitting station located as close to the water's edge as practicable; the loss in field intensity caused by removal of the transmitter from such a location to a distance as little as a mile inland is quite appreciable.

At high frequencies (above 3000 kc) the dielectric constant plays a greater role in the decrease of ground-wave field intensity with distance, and becomes the chief factor at very high frequencies.

For frequencies higher than about 30,000 kc the transmitting antenna is usually several wavelengths above the ground, and the decrease of field intensity with distance is much more rapid than for lower frequencies. The field intensity varies roughly inversely as the square of the distance. The combination of direct and ground-reflected waves, from antennas at heights of a wavelength or more above the earth's surface, is responsible in part for this.

As will be mentioned later, frequencies above about 40 Mc are in general unsuitable for communication over great distances, and on these frequencies only ground-wave transmission is reliable. The surface wave component becomes less and less important as the frequency is raised, and the direct and ground-reflected wave components assume the predominant role. It should be noted that whereas the distance range of the ground wave at low frequencies can be effectively increased by increasing the radiated power, the distance range at frequencies of about 30 Mc and higher can be effectively increased only by increasing the heights of the transmitting and receiving antennas.

The ground wave is essentially vertically polarized at appreciable distances from the antenna. This is caused by the cancellation of direct with ground-reflected wave components at low angles for horizontally polarized waves, and also by the relatively greater attenuation of a horizontally polarized surface wave component as compared with that of a vertically polarized surface wave component.

4. Propagation in the Atmosphere

The atmosphere has, in general, less conductivity than the earth, but its conductivity is far from negligible. Conductivity of the atmosphere is due to the presence of electrically charged particles of matter, called ions. These particles are produced chiefly by solar radiation, which separates such electrically charged particles from the atoms of matter comprising the atmosphere. At very great heights there are only a few such ions per unit of volume, since the atmosphere there is very thin and there is little matter present to absorb the radiation and become ionized. At low levels, below about 30 miles above the earth, there is a great amount of air present, but the powerful ultraviolet solar radiation has been mostly absorbed, and there are few ions because there is not much radiation left to produce them. At heights between 60 and 200 miles above the earth's surface, there occur regions where the density of ionization is great. This is because (1) these regions have enough matter to produce sufficient ions, (2) the concentration and degree of ionization of the oxygen and nitrogen in the earth's atmosphere there are such as to absorb the ionizing radiation particularly well, and (3) the solar radiation has suffered little absorption before reaching such levels.

Ions may be positive or negative in electrical charge, and of different sizes; the small negatively charged particles called electrons are the most important in affecting the behavior of radio waves, because of their small mass and the corresponding ease with which they can be set in motion.

When an electromagnetic wave encounters an electron, some of the energy of the wave is absorbed by the electron, and the electron is set into mechanical vibration by the wave. Part of the energy thus absorbed is dissipated when the electron hits nearby air particles, but the rest is reradiated by the electron. The slight loss of time involved in this process tends to slow down the speed of propagation of electromagnetic energy traveling in matter. Actually, however, the wave itself is speeded up and is traveling faster than in free space. The reason for this is that the electron possesses a certain amount of inertia, and therefore does not reradiate the wave in phase with the wave incident upon it, but rather advances it part of a cycle. The velocity with which the wave itself is propagated is called the "phase velocity". The velocity with which the energy is propagated is called the "group velocity". The envelope of modulation of a radio wave travels with the group velocity; the propagation of the individual waves, however, determines where the group is to go. The waves may be considered as merely constituting a guide, and telling the energy, which travels at a different velocity, where to go.

The effect of increase in speed of the waves is to change the direction in which they travel as they pass through the ionized region. The manner in which this occurs is illustrated in Fig. 1. Each point along a wave front may be regarded as an individual source of electromagnetic waves (Huygens' principle). If we consider a wave sufficiently distant from its original source so that the wave front may be regarded as plane, and the direction of travel as perpendicular to that plane, as in Fig. 1A, the individual point sources, a, b, c, etc., may be regarded as sending out individual waves. These are represented by the small semicircles, which indicate positions having the same stage of the alternation (equal "phase"). At the sides of these individual waves, l, m, n, o, etc., where they encounter each other, one will cancel the effect of the other, if they are equal in strength, since they are moving oppositely. The total effect is the propagation of the wave forward, where there is no such interference.

If, however, some of these individual waves were advanced part of an alternation over the others, there would not be total cancellation of their effects in the same places, and the wave front would change direction. This is shown in Fig. 1B. The constant advancement of wave form as the waves enter the ionized region is effectively the same as if they moved at greater speed, as far as their interference with other waves is concerned. The individual wave fronts, which, combined, make up the total wave front, are thus seen to lie so as to cause the resultant wave front to move in a direction away from the perpendicular to the surface separating the ionized medium from the non-ionized space. A wave front bent in this manner is said to be refracted.

The ratio of the sine of the angle of incidence to the sine of the angle of refraction depends upon the number of electrons per unit volume in the ionized medium and upon the frequency of the electromagnetic waves. This ratio is equal to the refractive index of the ionized medium (Snell's Law). If N is the number of electrons per cubic centimeter, f the frequency of alternation in kc, and μ the refractive index, it may be easily shown that

$$\mu = 1 - \frac{81N}{f^2}$$

This neglects the effect of the earth's magnetic field; if this field is considered, the expression for μ is much more complex.

The earth's magnetic field, in combination with the electromagnetic alternations of the radio wave, has a very interesting effect on the reradiation of the wave by an electron. Instead of simply vibrating back and forth with the applied force of the wave, the electron is pulled out of line by the earth's magnetic field, proportionally to the speed it possesses while vibrating. This is because the moving electrical charge of the electron is equivalent to an electrical current; the current is proportional to the rate of motion of the charge. The speed being greatest at the center of its path of vibration, the electron is caused to move in a small elliptical path.

At high frequencies the electron has not enough time in which to attain great speed, so that the effect of the earth's magnetic field is only slight. As the frequency is lowered, the speed increases and the electron's elliptical path becomes larger. The field reradiated from the electron, therefore, is affected by the electron's behavior in the earth's magnetic field, and this effect is greater the lower the frequency.

Actually, a plane polarized wave incident upon the ionosphere is split into two oppositely rotating elliptically polarized components, the one rotating to the left being known as the ordinary wave, and the one rotating to the right as the extraordinary wave. The physical explanation of this is that the electron in its complicated motion, radiates a wave which can be regarded as made up of two waves, one of which travels faster than the other, and has a different but a definite state of polarization. The refractive indexes of the ionized medium for the two kinds of waves are different and so their propagation characteristics are different, both as to velocity and absorption. When the two component waves emerge from the ionized medium again, they combine, no longer as a plane polarized wave but as a single elliptically polarized wave of characteristic amplitude, phase, and orientation of axes.

Due to a resonance effect, the extraordinary wave is absorbed to a great extent if the frequency is near the so-called "gyro-frequency" which has the nature of a frequency of precession for electrons in the earth's magnetic field. This frequency is about 1.4 Mc. Near this frequency the direction of the electron which is driven by the radio wave changes just as the direction of the electrical force in the wave acting on it reverses, and the path of the electron becomes a spiral in which the electron's speed builds up indefinitely, so that a great deal of energy is taken from the incident radio wave, and very little of it reradiated.

5. Reflection from the Ionosphere

So far in this discussion a sharply defined boundary has been assumed between the ionized and the non-ionized regions. This is, however, not the case in the ionosphere, for the number of electrons per unit volume increases gradually with distance of penetration. According to Snell's law, mentioned above, the sine of the angle of incidence (ϕ_0) of the waves upon the ionosphere is always equal to the product of the refractive index (μ) and the sine of the angle of refraction ϕ at any point. Expressed mathematically,

$$\mu \sin \phi = \sin \phi_0 .$$

As the waves penetrate farther and farther into the ionosphere N becomes greater and therefore μ becomes smaller. Since ϕ_0 is constant this means that ϕ must become greater, i.e., the waves are bent farther and farther from the vertical, until finally, at a critical value of μ equal to $\sin \phi_0$, the waves are traveling horizontally.

At this instant the portion of the wave front which is traveling in the region of greater density (the higher region) is traveling faster than that part which is traveling in the lower region, of lower electron density. The wave is therefore bent downward and eventually is deflected back again into the non-ionized medium.

The smallest value of μ encountered by the wave is the value $\mu = \sin \phi_o$. The electron density corresponding to this value is

$$N = \frac{f^2}{81} \cos^2 \phi_o .$$

The frequency f, at angle of incidence ϕ_o, is thus reflected from a region of electron density $N = 0.0124 f^2 \cos^2 \phi_o$.

If a wave is sent into the ionosphere at normal incidence (perpendicular to the ionosphere), $\phi_o = 0$, and the wave is reflected from a level where the electron density is $N = 0.0124 f^2$, where f is in kilocycles and N is the number of electrons per cubic centimeter. It follows that a wave of frequency $f \sec \phi_o$ does not need, for reflection at an angle of incidence ϕ_o, any greater electron density than does a wave of frequency f at normal incidence. If there is a maximum value of N reached somewhere in the ionosphere, then higher frequency waves will be reflected at oblique incidence than at normal incidence.

The two components of the wave present when the earth's magnetic field is considered require somewhat different electron densities for reflection. At normal incidence the electron density required for reflection of the ordinary wave is independent of the earth's magnetic field, but this is not the case for the extraordinary wave, nor for the ordinary wave at other angles of incidence. If f_x is the frequency of the extraordinary wave, and f_o that of the ordinary wave, reflected at a level where the electron density is N, and if $f_H = eH/2\pi mc$, the "gyro-frequency", where H is the intensity of the earth's magnetic field in gauss and c is the velocity of light, then at normal incidence:

$$f^o_2 = f^x(f^x \pm f_H).$$

6. Sky-Wave Transmission

For ordinary values of power radiated from an antenna, transmission of a signal over very great distances is only practicable by the sky wave refracted back to earth from the conducting layers in the upper atmosphere. This is because the loss in field intensity is far less for this method of transmission than for a direct path to the receiving station, and so this wave generally predominates for all except short distances, for frequencies between about 300 kc and an upper limit which varies at different times from 2000 kc to as much as 100,000 kc. Because of the wide variations in the sky wave caused by the ionosphere, it is necessary to know the ionization characteristics of the earth's atmosphere in order to explain or predict long-distance radio transmission characteristics.

At frequencies of 100 kc and below, and especially between 15 and 50 kc, radio transmission over long distances takes place by a combination of sky wave and ground wave. At such low frequencies the two components are not readily distinguishable, as they are at the higher frequencies, between 1000 and 50,000 kc, say. Propagation at low frequencies has the nature of a wave guided between two conductors, the earth and the conducting layers in the atmosphere, rather than the combination of two separate waves, the ground wave and the sky wave. Propagation at frequencies of about 100 to 300 kc or so is not easy to describe, since these frequencies mark the transition between guided-wave propagation, where the distance between ground and conducting atmospheric layer is but a few wavelengths, and sky-ground-wave propagation, where the distance is greater than several hundred wavelengths.

The sky wave, which travels outward toward the upper atmosphere, suffers comparatively little loss or deviation from a straight line until it reaches the conducting layers, where there are many free electrons. These layers lie at heights of from 60 to 200 miles above the earth's surface. If there is sufficient ionization (a great enough number of free electrons) at these heights, and if too much of the wave's energy has not been absorbed at the levels immediately below, due to collisions of electrons with molecules of air, the wave is refracted or bent around so as to return to earth again, perhaps at great distances from the emitting antenna.

The distance at which the wave returns to the earth depends upon the height of the ionized layer and the amount of bending of the path while traversing the layer, the latter depending on the frequency of the wave. Upon return to the earth's surface, part of the energy enters the earth, to be rapidly dissipated, but part is reflected back into the atmosphere again, where it may travel upward to the ionized layers, as before, and be refracted downward again at a still greater distance from the transmitter. This mode of travel in hops, by alternate reflections from the ionosphere and from the earth's surface, may continue indefinitely, and may enable messages to be received at enormous distances from the transmitter. Figs. 2 and 3 illustrate this mode of travel for paths involving one and two reflections from the ionosphere (single-and double-hop transmission).

The paths shown here illustrate three of the many possible paths of radio waves from a transmitter to a receiver as transmitted by reflection from the electrically conducting layers in the atmosphere. This picture, simple as it is, does in fact represent the basic mechanism of long-distance high-frequency radio transmission. When the variations of ionization and heights of the layers with time and the effects of the ionization upon the field intensity and the limits of useful frequency at a particular time are taken into consideration, the picture loses its simplicity. Almost all long-distance high-frequency radio transmission is, however, explainable and predictable in terms of the behavior of the conducting layers of the earth's upper atmosphere.

In general, radio waves are radiated at all vertical angles from the transmitting antenna. For a frequency above a certain limit (about 5 to 10 Mc by day, 2 to 5 Mc by night) there is a certain critical angle, above which the waves pass all the way through the ionosphere and are not reflected back to earth. The distance corresponding to this critical angle and a given layer height is the minimum distance from the transmitter at which the sky wave of the given frequency will return to earth. This distance is called the "skip distance" for the given frequency, since the sky wave skips over all points closer to the transmitter. Correspondingly, the given frequency is the "maximum usable frequency", abbreviated m.u.f., for the distance, because waves of higher frequencies will not be returned to earth at that distance. The relation between m.u.f. and skip distance is therefore that:

The m.u.f. for a given distance is the frequency for which that distance is the skip distance.

When the skip distance is zero, the sky wave will return to earth near the transmitting location, and both the sky wave and the ground wave may have nearly the same field intensity, but a random relative phase. When this occurs, the field of the sky wave successively reinforces and cancels that of the ground wave, causing severe "fading" of the signal. When the skip distance is great enough so that the ground-wave field intensity is too small to detect at that distance, there is a region, between the limiting range for the ground wave and the skip distance, within which no signal can be heard. This region is known as the "skip zone". The limits of the skip zone depend on frequency, since both the skip distance and the rate of weakening of the ground wave with distance depend on frequency.

Beyond a certain distance from a given transmitter on a given frequency, the waves are too weak for reliable communication. This is a result of the weakening of the waves with distance, due both to the spreading out of the waves and to the absorption of the waves' energy as they travel along. This limiting distance is known as the "distance range" for the given frequency and transmitter power. The absorption of radio waves in the ionosphere is greater, the lower the frequency, and so sky waves of frequencies lower than the given frequency will not be strong enough to detect at the distance mentioned. The given frequency is therefore called the "lowest useful high frequency" for the distance and power (abbreviated l.u.h.f.). The relation between the l.u.h.f. and the distance range is:

The l.u.h.f. for a given distance and transmitter power is the frequency at which that distance is the distance range for the given power.

The path which the radio waves normally traverse in traveling from the transmitter to the receiver lies in the plane passing through the center of the earth and the transmitting and receiving points. The intersection of this plane with the surface of the earth is the "great-circle" path between transmitting and receiving points. Radio-wave transmission paths which lie in this plane are generally, for brevity, also called great-circle paths. Frequently, however, waves do not follow paths confined to this plane, and this is called "off-path transmission".

The geographical part of the ionosphere which controls sky-wave propagation is the portion of the ionosphere traversed by the waves in traveling from transmitter to receiver. For single-hop transmission, this portion is a region centered about the midpoint of the great-circle path; for multihop transmission that part of the ionosphere lying between the first and last reflection points on the transmission path affects the propagation of the waves.

Waves can follow either the major arc or the minor arc of the great-circle path between transmitter and receiver. The two types of transmission are called "long-path" and "short-path" transmission, respectively.

7. Summary: Overall Picture of Radio Transmission

The overall picture of radio transmission on frequencies greater than about 1000 kc is this: There is a ground wave extending to short distances about the transmitting antenna; the higher the frequency and the poorer the ground, the shorter the distance. Beyond this range and on frequencies greater than a certain limit (the maximum usable frequency), there is a zone of silence where no signal can be heard. At the skip distance, the signal suddenly comes in very strongly; as the distance is still further increased the intensity falls off until beyond the "distance range" it can no longer be used for communication. The sky wave is weaker, the lower the frequency, the longer the distance of transmission, and the more sunlight there is over the path. The maximum usable frequency is greater, the longer the distance (up to 2500 miles), and the more sunlight there is over the path. Thus the best frequency to use for communication over more than a few hundred miles is greater during the day than at night, and greater the longer the distance.

For any distance beyond the ground-wave distance range, there is a band of useful frequencies, bounded on the one hand by the lowest useful high frequency (l.u.h.f.) and on the other by the maximum usable frequency (m.u.f.). The l.u.h.f. is limited by the absorption, and the m.u.f. is limited by the ionization. Correspondingly, for any frequency for which the skip distance is not zero there is a range of useful distances bounded on the one hand by the skip distance and on the other hand by the distance range. The distance range is limited by the absorption, and the skip distance by the ionization.

At frequencies below 2000 kc there is generally no skip distance. At some distances, however, the sky wave may be equal in strength to the ground wave, and the interference of the two causes continual variation of the signal strength, or "fading".

As the frequency is lowered below about 1000 kc, the ground wave extends farther and farther out, and the sky wave becomes more intense. At the lower frequencies the waves are guided between the earth and the ionosphere, acting as conductors, and radio transmission is more stable and reliable.

8. The Ionosphere

The sky wave is reflected from electrically conducting layers in the high atmosphere of the earth, from 60 to 200 miles above the earth's surface. The air at these levels is rendered electrically conducting by the ultraviolet radiation from the sun, and also by charged particles shot off by the sun. This upper region of the atmosphere is called the "ionosphere"; the conducting property of the layers is called "ionization"; the term "ion" is used to designate the extremely small electrified particles of the air.

Solar radiation at such high altitudes is far more intense than at the earth's surface, since it has been but little absorbed by the atmosphere. In fact, the ultraviolet radiation from the sun is so intense at such heights that it would prove fatal to human beings. Fortunately most of this radiation is absorbed by the atmosphere at high levels, thereby enabling the earth's inhabitants both to live, and enjoy good radio transmission.

The ultraviolet light absorbed by the atmosphere is sufficiently intense to disrupt the atoms of the air, separating charged particles from them. Two parts of atoms so disrupted are oppositely charged electrically, and are attracted to each other, tending eventually to rejoin. Distances between atoms at such heights, however, are very great, and once ionization occurs, recombination may not take place for a considerable time. The probability of recombination is greater, the greater the atmospheric density (i.e. the lower the height above the surface of the earth).

The ionization in the ionosphere is not uniformly distributed with height, but is stratified, and there are certain definite layers where the ionization density is sufficient to absorb or reflect radio waves. If one were able to ascend to somewhat more than twice the highest altitude ever reached by man, one would encounter, between heights of about 30 to 55 miles (50 to 90 km), the first region of pronounced ionization, known as the D layer or D region. In comparison to conditions in the layers existing at greater heights, the amount of ionization here is not very great, and has little effect in bending the paths of high-frequency radio waves. The chief effects of the ionization in this region are (1) to cause a weakening of the field intensity of high-frequency radio waves as the transmission path crosses this layer, and (2) to cause complete reflection of low- and medium-frequency radio waves. The D layer is only found to exist during daylight hours, since its level is sufficiently low so that rapid recombination of ions takes place. It is chiefly responsible for the fact that the intensity of sky waves is lower when the transmission path lies in sunlit regions than when it lies in darkness.

At heights between 55 and 90 miles (90 and 140 km) lies another region of ionization, called the E region, in which there appears a well defined layer of much more intense ionization at a height of about 70 miles (110 km). This is known as the E layer. This layer is also ordinarily observed only during daylight hours, since its level is low enough for fairly rapid recombination of ions to take place. The ionization in it is a maximum at about local noon. The number of electrons per unit volume in this layer may be great enough regularly to refract radio waves of frequencies as high as 20 Mc, at times, back to earth. The E layer is of great importance to radio transmission for distances below about 1500 miles. For greater distances than this, transmission by E layer is rather poor because of the low vertical angle of departure from the ground. Better transmission will take place by the F, F_1, or F_2 layers, for these distances.

At heights of between 90 and 250 miles above the earth's surface is another region of ionization known as the F region. In this region at night, there exists a layer of ionization called the F layer, the lower edge of which is at about 170 miles (270 km) in height. The atmosphere at these heights is so rare that recombination of ions takes place very slowly, and sufficient ions remain here all during the night to refract radio waves of some frequencies back to earth.

During the daylight hours, especially when the sun is high, as in tropical latitudes and during summer months, there are two layers in the F region; the F_1 layer, with a lower edge at a height of about 100 miles (140 km), and the F_2 layer, with a lower edge at a height of about 160 to 220 miles, depending on season and time of day.

Besides these regions of ionization which appear regularly, and undergo variations in height and ionization diurnally, seasonally, and from year to year, other layers occasionally appear, particularly at heights near that of the E layer, much as clouds appear in the sky. Frequently their appearance is in sufficient amounts to enable good radio transmission to take place by means of reflection from them. At other times, especially during disturbed conditions in polar regions, diffuse ionization may occur over a fairly large range of heights, and may be detrimental to radio transmission, because of the excessive absorption it produces.

The relative heights, thicknesses and degree of ionization of the regular ionosphere layers are illustrated in Fig. 2, which is for a typical summer daytime condition, the E, F_1, and F_2 layers all being present. This diagram is drawn to scale, so the angles of reflection of radio waves from the layers may be estimated correctly. The three layers are shown as thin lines, for simplicity. The layers have in fact a certain thickness, and the density of ionization varies somewhat in this thickness. At the right of the diagram is a rough illustration of a possible distribution of ionization density with height.

9. Measurement of Ionosphere Characteristics

The principal ionosphere characteristics which control long-distance radio transmission are the height and the ionization density of each of the ionosphere layers.

It is necessary to define the sense in which the term, height, is used, since each layer has a certain thickness. When radio waves are reflected by a layer, the train of waves is slowed down as soon as it starts to penetrate into the layer. The process of reflection goes on from the place at which the waves enter the layer until they have been fully bent back around and leave the layer. This is true whether the waves travel vertically or obliquely to the ionosphere. It is illustrated for the oblique case in Fig. 4. The waves follow a curved path in the layer until they emerge at a vertical angle equal to that at which they entered. The time of transmission along the actual path BCD in the ionized layer is, for the simple case, the same as would be required for transmission along the path BED if there were no ionized particles present. (This is known as "Breit and Tuve's theorem".) The height h' from the ground to E, the intersection of the two projected straight parts of the path, is called the "virtual height" of the layer. This is an important quantity in all measurements and applications.

Knowledge of the height and degree of ionization of the different ionosphere layers, and how they vary with geographical position and with time, is obtained by sending radio waves of various frequencies up to the ionosphere and measuring the time which elapses before they are received after being reflected by the ionosphere. Referring to Fig. 4, the virtual height of a layer is measured by transmitting a radio signal from A, and receiving at F both the signal transmitted along the ground and the echo, or signal reflected by the ionosphere, and measuring the difference in time of arrival of the two. Since the time differences are mere thousandths of a second, the signal is a very short pulse, in order that the ground-wave and reflection may be separated in an oscillograph. The difference between the distance (AE + EF) and AF is found by multiplying the measured time difference by the velocity of light. From this and the known distance AF, the virtual height is calculated. In practice, measuring equipment is calibrated directly in kilometers of virtual height rather than time differences. It is usual to make AF zero, i.e., to transmit the signal vertically upward and receive it at the same place (and it is for this case that the term "virtual height" rigorously applies). In general, the virtual height varies with frequency of the radio waves used in the measurement. The virtual height for such vertical-incidence measurements is called h' and a curve showing the variation of h' with the frequency f is called an "h'-f curve".

The effectiveness of the ionosphere in reflecting the waves back to earth depends on the number of electrons present in a unit of volume, i.e., the ionization density. The higher the frequency, the greater is the density of ionization required to reflect the waves back to earth. It has been shown that a wave of frequency f incident vertically upon the layer will penetrate the ionosphere until it reaches a level where the ionization density N is equal to $0.0124 f^2$ (f in kc, N in electrons per cubic centimeter). This relation is for the "ordinary wave" referred to in Section II, 4. If N represents the maximum value of ionization density in the layer, then the corresponding frequency f is the highest frequency which will be returned to earth by the layer. This value of f is called the "critical frequency" of the layer. For vertical transmission, waves of all frequencies higher than this pass on through the ionized layer and are not reflected back to earth, while waves of all lower frequencies are reflected. If the frequency is too low, however, the waves may be absorbed so much as to be too weak to observe on their return to earth (see discussion of absorption below). Measurement of the critical frequency is, with the equation just given, a means of measuring the maximum ionization density in an ionized layer. (Waves of frequencies higher than the critical are sometimes reflected by another mechanism - see discussion of "Sporadic E", below).

The procedure generally followed in measuring the critical frequency is to measure the virtual height, h', by the method described above, at successively increasing frequencies, until the waves are no longer received back from the layer. Typical results of such measurements are illustrated in the h'-f curves of Figs. 5, 6, and 7, observed at Washington, D.C., for different times of year, day and night. The sharp increases in virtual height, in certain frequency ranges, indicate the critical frequencies. These sharp increases in virtual height occur because waves of frequencies near the critical are excessively retarded in the ionized layer.

For example, in Fig. 5, starting at a frequency below 2000 kc (2 Mc), the virtual height is found, in this example, to be about 110 kilometers, and remains at about this height until about 3.3 Mc. The critical frequency of the E layer at the time of this measurement is thus 3.3 Mc, i.e., this is the highest frequency at which vertically incident waves are reflected back to earth from this layer; all vertically incident waves of higher frequency pass on through the E layer and go on up to the next higher layer, the F_1. At about 4.6 Mc the waves pass on through the F_1 layer and go on up to the F_2 layer. The F_2 layer has a greater ionization density and so it reflects back waves of frequency greater than 4.6 Mc. It is not until frequencies greater than 11.6 Mc are used that the F_2 layer fails to reflect them, in the case illustrated. Near the critical frequency of any layer the virtual height increases sharply with increasing frequency, until the wave is no longer reflected by the layer; with further increase of frequency, reflection is only obtained from a layer of a higher critical frequency at a higher level. If there is no such level, the waves go on into space and are lost.

At the right of each curve appear two critical frequencies for the F or F_2 layer. This is an indication of the splitting of the wave into two components due to the earth's magnetic field, mentioned above, -- Section II, 4 . The ordinary wave and the extraordinary wave are designated by the symbols o and x, respectively. The critical frequency of a layer n is represented by the symbol f_n, and to such symbol the o or x is added as a superscript. Thus the critical frequencies of the F_2 layer for the ordinary and extraordinary waves are indicated by the respective symbols, $f^o_{F_2}$ and $f^x_{F_2}$.

In the case of the E layer, the ordinary wave usually predominates and the extraordinary wave is so weak it does not affect radio reception. The extraordinary wave must however be considered in F, F_1 or F_2-layer transmission. At Washington the critical frequency for the extraordinary wave is about 750 kc higher than for the ordinary wave, for frequencies of 4000 kc or higher. The difference in frequency is proportional to the intensity of the earth's magnetic field at the place of reflection, and is therefore different at different places on the earth, and at different heights in the ionosphere. It also varies with the magnitude of the critical frequency. The difference is given by the relation

$$f^x - f^o = \sqrt{\left(f^o - \frac{f_H}{2}\right)^2 + f^o f_H} - \left(f^o - \frac{f_H}{2}\right),$$

where f_H is the gyro frequency, and f^o and f^x are the critical frequencies for the ordinary and extraordinary waves, respectively. The map of Fig. 9 gives the gyro frequency for the F, F_2 layer, at any place on the earth. In reporting results of measurements of critical frequencies it is customary to give the values for the ordinary wave.

Besides the virtual heights and critical frequencies, the absorption of the energy of radio waves by the ionosphere is an important factor in limiting radio transmission. This absorption exists because the electrons set in motion by the radio waves collide with air molecules and dissipate the energy they have taken from the radio waves. The energy thus absorbed from the radio waves is greater, the greater the distance of penetration of the waves into the ionized layer and the greater the density of ions and air molecules in the layer, i.e., the greater the number of collisions between electrons and air molecules. Absorption is especially great in the daytime, and it occurs chiefly in the D region, because of the relatively great atmospheric density in this region. It also occurs in the high ionosphere, near critical frequencies. The D-region absorption is usually of greater significance in radio communication than is absorption near the critical frequencies. Most of the D-region absorption disappears with the decrease of ionization of this region at night. Higher frequencies are less affected by absorption than are lower frequencies, for waves passing through the same ionized layers.

10. Normal Variation of Ionosphere Characteristics

Regular variations in ionosphere characteristics are of three types: diurnal, seasonal, and from year to year with the sunspot cycle.

Most fundamental is a gradual, long-period variation with solar activity, like that manifested by the solar sunspot cycle. Sunspots are whirlpools in the outer layers of the sun, which are visible as dark spots on the sun's disc and which indicate local variations of the sun's temperature. The number and activity of sunspots are a general indication of the relative intensity of the radiations from the sun. The intensity of solar radiation varies in approximately an eleven-year cycle, called the "sunspot cycle". There is a corresponding variation of radio transmission characteristics. The period of time near the year 1937, for example, was a period of maximum solar activity, as manifested by the number of sunspots observed. The ionization of the ionosphere and consequently the critical frequencies of all ionosphere layers were at a maximum at this time. A period of minimum solar activity occurred in 1933, and will probably repeat in the latter part of 1944 or in 1945. The next period of maximum will probably occur about 1949 or 1950, but the times and relative degrees of sunspot maxima and minima can not be predicted accurately.

From the sunspot minimum in 1933 to the sunspot maximum in 1937 the F,F_2-layer critical frequencies doubled, for most hours of the day, and the E-layer critical frequencies became 1.25 times as great. Consequently the best radio frequencies for long-distance transmission were approximately twice as great in 1937 as in 1933 (except for summer daytime, when they were about 1.5 times as great). In about 1944 or 1945 they are expected to return to minimum values, and reach maximum values again about 1949 or 1950.

Ionosphere characteristics vary regularly with season and time of day, since the amount of sunlight received at any place on earth depends on the season of the year and the time of day.

The diurnal and seasonal variations of the critical frequencies of the normal E layer are particularly regular. The critical frequencies vary with the altitude of the sun, being highest when the sun is most nearly overhead. Thus the diurnal maximum of the E-layer critical frequency is at local noon, and the seasonal maximum is at the summer solstice. At night this layer usually does not regularly reflect at vertical incidence waves of frequencies higher than about one megacycle.

The diurnal and seasonal variations of the critical frequencies of the F,F_2 layer are quite different from those of the E layer. The daytime F,F_2-layer critical frequencies are in general greater in winter than in summer. They are higher in the tropics than elsewhere in the world. They have generally a broad diurnal maximum, centering about 1300 or 1400 local time, except that in the northern hemisphere in summer, the maximum occurs about sunset. The night F-layer critical frequencies are lower in winter than in summer, and reach a minimum just before sunrise. More details of the diurnal and seasonal variations may be seen from the critical frequency maps of Figs. 47 through 49.

The F_2 virtual heights are much lower during a winter day than during a summer day. The F virtual heights at night are about the same in winter as in summer.

The seasonal effects in the ionosphere synchronize with the sun's seasonal position, not lagging a month or two as do the seasons of weather. Winter conditions in the F_2 layer obtain during a period of several months from about the fall equinox to the spring equinox, and summer conditions for a period of several months from about May to August, inclusive. On the summer side of the equinoxes, there is a transition period of about a month in which the change occurs between winter and summer conditions.

Fig. 8 shows the typical variations of ionospheric critical frequencies and virtual heights during the day for both summer and winter at Washington, D.C., and for periods of maximum and minimum solar activity.

The critical frequencies and virtual heights of the ionosphere layers are not the same from day to day, at the same hour, but are apt to vary, within limits. This is discussed in detail in Sec. III below. It is sufficient to say here that the F,F_2-layer critical frequencies will in general nearly always fall within ± 15% of the average, on quiet days, i.e., days when there is no ionosphere storm (see below). The E- and F_1-layer critical frequencies show much less day-to-day variation.

For a given local time, the condition of the ionosphere varies considerably with geographical latitude, and also somewhat with geographical longitude. To a first approximation, a world-wide picture may be given, as in Figs. 10 through 25 of this Handbook, in terms of latitude and local time, neglecting the above mentioned longitude variations. This simplified picture will lead to some discrepancies when it is attempted to apply the world ionosphere charts to longitudes other than those for which the charts are constructed.

An example of the longitude differences may be seen on comparing Fig. 14, which gives the June, 1943, ionosphere characteristics for Washington, D.C. (39.0°N) with Fig. 15, which gives the June, 1943, ionosphere characteristics for Stanford University, Calif. (37.4°N). The dashed curves in each Fig. are from the predicted world chart which was made weighting the Washington observations more than the Stanford observations. The Washington observations are seen to fit the predictions more closely than do the Stanford observations.

A more striking example of the longitude difference is seen in Figs. 25 and 24, which compare predictions and observations for July, 1943, for Baton Rouge, La. (30.5°N) and Delhi, India (28.6°N). Both predictions were made without the benefit of observations from either place, but the locations considered in making the predictions (i.e., Washington and Puerto Rico) were much closer to the longitude of Baton Rouge (91.2°W) than to the longitude of Delhi (77.2°E).

It seems possible that longitude variations may be connected with geomagnetic latitude, the critical frequencies being lower, the higher the magnetic latitude, for a given geographic latitude. It may be seen from the map of Fig. 43 that the auroral zone is farthest south at about longitude 70°W, and this may be related to the fact that the F,F_2-layer critical frequencies appear to be lower at Washington than at 39°N latitude at any other place in the world. The statement about F,F_2-layer critical frequencies is based both on critical-frequency observations and on actual radio communication data over different paths.

Diurnal curves of critical frequencies and virtual heights are given, in Figs. 10 through 22, for thirteen observing stations scattered throughout the world, for June, 1943. These represent typical conditions in June near the sunspot minimum, and constitute a sample of the type of data available for making predictions and constructing world charts similar to those of Figs. 47 through 58. Worthy of note is the similarity of the curves for Watheroo, Mt. Stromlo, Brisbane, and the Kermadec Is., all fairly close in geographical location. In each of the Figs. 10 through 25, the solid-line graphs show the averages of the observed values; the dashed-line graphs show the IRPL predictions made five months before. The predictions shown are not those for the stations themselves but are for the latitudes of the stations, taken from the predicted smoothed world chart.

11. Abnormal Variations in Ionosphere Characteristics

While the normal behavior of ionospheric ionization is such that its characteristics may be predicted with fair success for comparatively long periods of the future, there are occasional large deviations from this behavior which are important in their effect upon radio transmission.

a. Sporadic E.- The presence of occasional scattered irregular clouds or patches of ionization in the atmosphere has already been mentioned. Most prevalent is the appearance of such clouds at about the height of the E layer, where they may often be so intensely ionized and so continuous in occurrence that excellent radio communication at high frequencies is possible by means of reflections from them. In temperate latitudes this so-called "sporadic-E" ionization is most prevalent in the summer. It is a maximum in the auroral zones during disturbed periods (see below). It increases with decreasing sunspot number, which is very fortunate, since it sometimes enables better radio transmission to be achieved during pre-sunrise hours than might otherwise be obtained due to the very low ionization densities which occur during such times.

Sporadic-E reflections occur from E-layer heights but at frequencies considerably in excess of the regular m.u.f. for the E layer. Thus in the example shown in Fig. 6 waves of frequencies up to about 12 Mc would be reflected, at vertical incidence, at E-layer heights, although this would not regularly occur for frequencies above 3.9 Mc, as shown. Some of these reflections are probably produced by "partial reflection" at a sharp boundary of stratified ionization; this may, but need not necessarily, involve great ionization densities. Radio transmission may take place to points within the normal skip zone, by such sporadic-E reflections. The existence of these sporadic reflections necessitates a redefinition of the term "critical frequency", previously defined as the highest frequency at which waves sent vertically upward are received back from the layer. When sporadic-E reflections occur they may often be received simultaneously with reflections from higher layers; thus, in the case referred to above, vertical-incidence reflections might be received at 7 Mc from both the E and the F_2 layers. The E-layer critical frequency, more precisely defined, is the value (3.9 Mc in the example shown in Fig. 6) at which the observed virtual height shows a sudden rise to large values as the frequency is increased. Except when sporadic-E reflections occur, all waves of higher frequency pass through the E layer and are not reflected by it.

Sporadic E leads to interesting results in long-distance radio transmission. As stated, it produces transmission within the normal skip zone of the regular layers, and it accounts for long-distance transmission up to higher frequencies than by any other means. Strong vertical-incidence reflections by sporadic E sometimes occur at frequencies up to above 16 Mc. By reason of the large angles of incidence possible with the E layer, this makes occasional long-distance communication possible on frequencies as high as 80 Mc. Such communication is generally for only a short time and for restricted localities. Sporadic E is patchy in both time and space.

b. Scattered Reflections.- An irregular type of reflection from the ionosphere occurs at all seasons and is prevalent both day and night. These reflections are observable within the skip zone of the regular layers, and at frequencies higher than those well receivable from the regular layers. They are complex, consisting of a large number of reflections of slightly different retardation. They may cause signal distortion and so-called "flutter fading". Either they arrive from all directions, or, if the transmitter operates with a highly directional antenna, they may appear to come from the direction in which the antenna is pointed. Many of these scattered reflections are believed to be produced in the E layer. The mechanism of scattering by the E layer may be envisaged by the following analogy, in terms of visible light:

Let the radio transmitter be replaced by a small light bulb, or if it is used with a highly directional antenna, by a focussed searchlight. Now consider the F layer to be a mirror (for the moment ignoring the phenomenon of "skip"). If the frequency is high enough, the normal E layer will always be penetrated; it can be represented in this analogy as a tenuous layer of smoke. If the focussed searchlight is directed upward toward the mirror (F layer) for reflection downward to the reception point (a single-hop transmission), the beam will pass through the smoke region (E layer) both going up to and returning from the mirror. The regions in the smoke layer (E layer) will be illuminated and become visible, e.g., will scatter some of the radiation. This scattering can be thought of as the irregular reflection of the radiation from a very large number of very small reflectors.

If the scattering region were absent, no radiation would illuminate the ground except that in the reflected beam. With the scattering layer present a relatively weak illumination will fall over a considerable area below the places where the E layer or scattering region is illuminated by the direct radiation.

There are several important features of this E-layer scattering. The radiation scattered from the portion of the E layer illuminated by a transmitter is in general very weak and is only easily detected if the original transmitter is very powerful, and if no regularly reflected radiation is present, i.e., the particular observation point must be within the skip zone for regular transmission. Insofar as vertical-incidence pulse measurements of virtual heights are concerned, scattered reflections coming from directions other than the vertical will, from the time delay involved on the path, appear to come from heights between or above the regular layers. At one time observations of this sort were thought to indicate higher layers.

Since scattered reflections are usually observable within the normal skip zone, it follows that bearings taken on such reflections coming from an area of the E region illuminated by a narrow beam of radiation, may be in error by as much as 180°; indeed such bearings will have no meaning whatsoever as far as locating the transmitting station is concerned.

Another type of very complex reflections, sometimes called "spread echoes", is often observed at night and during ionosphere storms. These are of intensities as great as, or greater than the intensity of the normal F-layer reflections, and their apparent virtual heights may cover a range of several hundred kilometers, beginning with a height of about that of the normal F layer. These reflections are usually observed most strongly near (below, as well as above) the F-layer critical frequency, and may make the determination of the critical frequency quite difficult. Little is known about the mechanism of production of this type of scattered reflections, or about their effect on radio transmission. It seems likely, however, that transmission is possible by way of these reflections at frequencies in excess of the regular m.u.f.

c. <u>Sudden Ionosphere Disturbances (Dellinger Effect).-</u> The most startling of all the irregularities of the ionosphere and of radio wave transmission is the sudden type of disturbance manifested by a "radio fadeout". This phenomenon is the result of a burst of ionizing radiation from a bright eruption on the sun, causing a sudden abnormal increase in the ionization of the D layer, frequently with resultant disturbances in terrestrial magnetism and earth currents as well as in radio transmission. The radio effect is the sudden cessation of radio sky-wave transmission on frequencies usually above 1000 kc, caused by absorption in the D region. This effect has occasionally been observed on somewhat lower frequencies. At the very low frequencies the effect of the sudden ionosphere disturbance is a strengthening of the sky wave, because of the increase in the conductivity of the D layer.

The drop of the radio signals to zero usually occurs within a minute. The effects occur simultaneously throughout the hemisphere illuminated by the sun, and do not occur at night. The effects last from about ten minutes to an hour or more, the occurrences of greater intensity in general producing effects of longer duration. The effects are more intense, and last longer, the lower the frequency in the high-frequency range (i.e., from about 1000 kc up). It is consequently sometimes possible to continue communication during a radio fadeout by raising the working frequency.

The radio and magnetic effects are markedly different from other types of changes in these quantities. The effects are most intense in that region of the earth where the sun's radiation is perpendicular, i.e., greater at noon than at other times of day and greater in equatorial than in higher latitudes.

Taking due account of the relations between the occurrences of these disturbances, the frequency and the distance, varying effects in differing directions can be explained. Thus, reception in the United States from stations in the southern hemisphere usually exhibits greater effects than reception from other directions (because of passing the equatorial regions). Similarly, when the disturbance occurs at a time when it is morning at the receiving point the effects are usually greater in reception from the east than from the west, and vice versa for the afternoon (because of passing the region where it is noon). A radio fadeout sometimes occurs when it is night at the receiving point, but only when the path of the waves is somewhere in daylight.

This effect should not be confused with the "radio blackout" associated with ionosphere storms in polar latitudes (see below).

d. Prolonged Periods of Low-Layer Absorption.- This phenomenon is similar to the sudden ionosphere disturbance in its radio effects and characteristics except that its beginning as well as recovery is gradual and it has a longer time duration, commonly several hours. The intensity diminution is in general not as severe as in the more intense fadeouts, but sometimes the intensities fall to zero.

The low-layer absorption effect appears to be due to increased ionization in the D region (below the E layer), exactly as for the sudden ionosphere disturbances. The increased ionization is caused by an abnormally great outpouring of ultraviolet light from the sun, but in this case it is not so sudden as in the eruptions which cause the sudden ionosphere disturbances. The variation of the effects with frequency, and other characteristics, are the same as for the sudden ionosphere disturbances.

Both phenomena occur at all seasons, but the prolonged periods of low-layer absorption have been found to occur irregularly in groups of high sunspot activity, the groups being separated by more or less quiet periods of several months. They frequently but not always occur during periods when sudden ionosphere disturbances are numerous.

e. Ionosphere Storms.- An ionosphere storm is a period of disturbance in the ionosphere during which there are great anomalies of critical frequencies, virtual heights, and absorption. High-frequency radio sky-wave transmission above about 1500 kc is of low intensity and subject to flutter fading caused by complex reflections from an unstable ionosphere. The flutter fading is especially marked at night and may then be present over high-latitude paths for even minor storms. At frequencies below about 1500 kc the sky wave is considerably weakened at night. At the very low frequencies the daytime sky wave increases in intensity while at broadcast frequencies it sometimes increases and sometimes decreases in intensity. The high-frequency effects usually last for one or two days while the low-frequency effects persist for several days or sometimes weeks. An ionosphere storm is usually accompanied by a magnetic storm (i.e., a period of unusual fluctuation of terrestrial magnetic intensity). During the first few hours of very severe ionosphere storms the ionosphere is turbulent, stratification is destroyed, and radio wave propagation erratic. During the latter stages of very severe storms and during the whole of more moderate storms, the upper part of the ionosphere, principally the F_2 layer, is expanded and diffused. The critical frequencies are much lower than normal and the virtual heights much greater, and therefore the maximum usable frequencies are much lower than normal. It is often necessary to lower the working frequency in order to maintain communication during one of these storms. There is also increased absorption of radio waves during an ionosphere storm. Ionosphere storms are most severe in auroral latitudes and decrease in intensity as the equator is approached. Ionosphere storms occur approximately simultaneously over wide geographical areas. The condition of the ionosphere is much less uniform from point to point than on undisturbed days.

An ionosphere storm usually develops during a period of a few minutes to several hours. The effects are noticed first in the F,F_2 layer and move progressively downward. Recovery to normal conditions usually takes several days, depending on geographical latitude and the severity of the storm. Ionosphere storms are probably caused by bursts of electrified particles from the sun. They are prone to occur during bursts of high solar activity, and to recur at about 27-day intervals, the period of solar rotation. The latter effect may be caused by the reappearance of an active area on the part of the sun which faces the earth.

12. Fading

When radio transmission takes place by way of sky waves or troposphere waves, the intensity is not constant, but varies with time, because of fluctuations in the atmosphere or in the ionosphere. The alternate increase and decrease in field intensity of the received waves is called "fading". In general fading is more rapid on high than on low frequencies.

There are many types of fading, which fall into four principal classes: (1) interference fading, (2) polarization fading, (3) absorption fading, and (4) skip fading. Most of the rapid fading usually observed when listening to a signal is a combination of the first two types.

a. Interference Fading.- Interference fading is caused by phase interference of two or more waves from the same source arriving at the receiver over slightly different paths. If the paths are of different lengths, and their relative lengths vary, because, say, of fluctuations in the height of the ionosphere layers, the relative phases of the waves arriving over the various paths vary with time also, causing alternate reinforcement and cancellation of the field intensity. Because of irregularities in the ionosphere, a single arriving sky wave is really the summation of a great number of waves of small intensity and of random relative phases. The resultant field intensity can vary over wide limits, the maximum value being the value which would be observed were all the components in phase, i.e., for a "homogeneous" wave. This maximum value occurs only rarely.

The most convenient value of this fluctuating field intensity to talk about is the "median" value, or the value which is exceeded fifty percent of the time by the instantaneous field intensity. The distribution of the resultant value of a large number of waves of random phases and of nearly the same amplitude has been studied, and gives the following relation:

$$T = \epsilon^{-0.693\left(\frac{F}{F_o}\right)^2},$$

where T is the fraction of the time the instantaneous field intensity exceeds the value F, and F_o is the median value of the field intensity. This is called the "Rayleigh" distribution.

Very bad interference fading is experienced in cases where the sky wave returns to earth at a distance from the transmitter such that the ground wave is of comparable amplitude. The combination of a randomly fluctuating sky wave with the steady ground wave produces much more severe fading than is commonly experienced with the sky wave alone.

The "flutter" fading, or very rapid fluctuations of intensity, associated usually with ionospheric disturbances on paths passing in or near the auroral zone, is another type of interference fading. It is caused by the combination of a large number of wave components which have traversed paths differing appreciably (possibly several wavelengths) in length. This type of fading is also associated with transmission by scattered reflections, for the scattering centers, themselves, are fairly widely separated, and the waves travel different distances in going to and from the scattering centers.

Another type of interference fading is experienced primarily at low frequencies, where radio transmission is relatively stable. Near sunrise and sunset the heights of the ionosphere layers change rather rapidly, and the sky wave arrives alternately in and out of phase with the ground waves, producing interference fading with a relatively long period.

b. <u>Polarization Fading.</u>- Polarization fading is caused by variations in the state of polarization of the wave relative to the orientation of the receiving antenna. When the polarization is such that the electric force in the wave has a large component in the direction of the receiving antenna, the resultant voltage induced in the antenna is large; when that component is small, the induced voltage is also small.

In general, the state of polarization of the downcoming sky wave is constantly changing. This is due mainly to the combination, with random amplitudes and phases, of the two oppositely polarized magneto-ionic components, the ordinary wave and the extraordinary wave (see Section II, 4). The state of polarization of the downcoming sky wave is in general elliptical, with either direction of rotation, and with random and constantly changing values of the dimensions and orientation of the ellipse with respect to the receiving antenna. The state of polarization of sky waves varies more rapidly the higher the frequency, which accounts in part for more rapid fading on the higher frequencies.

Near the critical frequency for the ordinary wave, the retardation of the ordinary wave becomes great and erratic compared with that of the extraordinary wave, and the place of reflection of the ordinary wave is not very definite. In this case the polarization and interference fading due to the combination of the two components of the sky wave is particularly severe.

c. Absorption Fading.- Absorption fading is caused by short-time variations in the amount of energy lost from the wave because of absorption in the ionosphere. In general the period of this type of fading is much longer than for the other two types, since the ionospheric absorption usually changes only slowly. The sudden ionosphere disturbance is an extreme case of this type of fading, although it is usually classified as an anomaly rather than as fading.

Somewhat analogous to this type of fading, although the cause is not in the ionosphere but in reflections and absorption in objects close to the receiver, is the type of fading experienced in receiving a signal while moving along in an automobile. The fading out of a signal when the receiver is passing under a bridge or near a steel structure is caused by absorption of the wave's energy by the structure. Effects of this sort are involved in so-called "dead spots" or places where radio reception is especially difficult. Also, reradiation from wires, fences, and steel structures can cause an interference pattern which is relatively fixed in space, and can be noticed on moving the receiving equipment around. Where there are nearby structures which can cause these effects, care must be exercised in selecting a receiving site.

d. Skip Fading.- Skip fading is observed at places near the skip distance, and is caused by the waves alternately skipping and returning to earth. Near sunrise and sunset, when the ionization density of the ionosphere is changing, it may happen that the m.u.f. for a given transmission path oscillates about the actual frequency. When the skip distance moves out past the receiving station (sometimes called "going into the skip") the received intensity abruptly drops by a factor of 100 or more, and just as abruptly increases again when the skip distance moves in again. This may take place many times before steady conditions of transmission or skip are established.

Besides variations of field intensity, fading also causes distortion of radio telephone signals. This is because at any instant the fading is different on different frequencies, and therefore affects differently the sidebands and carrier wave. This is called "selective fading" because the fading is thought of as "selecting" some frequencies rather than others.

Fading may be reduced by a number of different methods, such as automatic volume control, suppressed carrier transmission, and diversity reception. Discussion of these methods is not within the scope of this Handbook.

13. Availability of Ionospheric Data

Ionosphere observations are made continuously at a number of observatories throughout the world. The data thus obtained are centralized, summarized, interpreted, and disseminated by three principal laboratories:

(1) The Interservice Radio Propagation Laboratory at the National Bureau of Standards, (IRPL), Washington, D.C., U.S.A.
(2) The Inter-Services Ionosphere Bureau (ISIB), London, England.
(3) The Australian Radio Propagation Committee (ARPC), Sydney, Australia.

All of these laboratories issue regular ionospheric and radio transmission data, and offer special services in the solution of specific problems.

In particular, long-range forecasts of maximum usable frequencies, optimum working frequencies, lowest useful high frequencies and distance ranges for all times of day and all latitudes are presented in various IRPL publications in the form of contour charts, nomograms, and tables, together with predictions of sporadic-E occurrence and short-time transmission forecasts. Information in reply to special authorized requests concerning transmission problems related to particular paths or equipment is also disseminated by the IRPL. Also, monthly average values of ionospheric data for each station are available at the IRPL shortly after the end of each month. Predicted monthly average values are available at the IRPL some months in advance - both values for the individual observing stations and world-map summaries made up by interpolation between stations for latitude and local time.

The world maps and contour charts issued by the IRPL, of which samples are presented in this Handbook, are all plotted on a modified cylindrical projection coordinate system. This projection is similar to, but not the same as, the familiar Mercator projection of the world. The world maps and great-circle charts, Figs. 43 through 46, 92, 119, 120, are plotted in conventional latitude and longitude; the contour charts of m.u.f., etc., e.g. Figs. 47 through 58, 64 through 66, and 80 through 91, are plotted in terms of latitude and local time, expressing thus the idea that the ionosphere "moves with the sun" and is the same, on the average, at any latitude, at the same local time. (This may not be strictly true - see discussion of longitude effect in Sec. III below).

SECTION III. MAXIMUM USABLE FREQUENCIES

1. General

The maximum usable frequency, abbreviated m.u.f., for radio sky-wave transmission over a given distance depends on two quantities:

(1) the maximum ionization density of the layer which reflects the waves, which is measured by the critical frequency (f_c),

(2) the angle of incidence at which the waves meet the layer; this depends on the height of the layer, expressed in terms of the "virtual height" (h'). The m.u.f. is a function only of the ionospheric conditions and the distance of transmission; it has nothing to do with the radiated power or the radio noise level at the receiving location.

A knowledge of the heights and critical frequencies of the ionosphere layers is therefore sufficient to enable the m.u.f. to be determined. For very precise determination, it is necessary to know the virtual heights of reflection for all frequencies, since the height, and therefore also the angle of incidence, varies with frequency.

If f_c is the critical frequency, f' the maximum usable frequency for a distance d, and h' the virtual height and ϕ the angle of incidence of the waves upon the layer (see Fig. 3), then to a first approximation $f' = f_c \sec \phi$. For relatively short transmission paths,

$$f' = f_c \frac{\sqrt{h'^2 + (\frac{d}{2})^2}}{h'}, \text{ approximately.} \qquad (1)$$

More precisely, for a curved earth,

$$f' = f_c \frac{\sqrt{2R(R + h')(1-\cos \frac{d}{2R}) + h'^2}}{h' + R(1-\cos \frac{d}{2R})}, \qquad (2)$$

where R is the radius of the earth. This reduces to the simpler expression when $\frac{d}{R}$ and $\frac{h'}{R}$ are $<< 1$, i.e., for short distances and low layer heights.

Since the virtual height h' of reflection varies with frequency, the height of reflection of radio waves traveling from a transmitter to a distant receiver varies both with frequency and angle of incidence. In any actual radio transmission, therefore, the frequency and the angle of incidence of the waves upon the layer must be such that they will be reflected at the proper height to reach the receiver when they are reflected at the given angle. The frequency f' and the height h' must satisfy simultaneously both the geometrical relation (2) above and the observed h'-f curve.

The solution is most conveniently done graphically, by plotting on the same coordinate scale both the observed h'-f curve and the relation between h' and f in the equation:

$$f' = f \sec \phi \qquad (3)$$

for the given frequency f' and distance d. The intersection of the two curves gives the height h' of reflection of the waves and the angle of incidence ϕ implicitly from the relation sec ϕ = f'/f. If the curves do not intersect, the waves will skip over the given distance; if they are just tangent to each other, the frequency f' is the m.u.f. for the given distance.

The calculation is simplified by plotting both the h'-f curve and the f'= f sec ϕ curve (called the "transmission curve") on logarithmic or semi-logarithmic scales. The m.u.f. can be determined by sliding the two curves along the frequency scale, with the height scales coinciding, until the transmission curve for a given distance is just tangent to the observed h'-f curve. The index (sec ϕ = 1) on the transmission curve then indicates the m.u.f.

Figs. 26 through 28 show sets of transmission curves plotted on semi-logarithmic scales for various distances in ordinary (statute) miles, nautical miles, and kilometers, respectively. (Note that 1 nautical mile = 1.1516 ordinary miles and = 1.8532 kilometers).

For more accurate determination of maximum usable frequency, allowance must be made for the curvature of the ionosphere, and for the effect of the earth's magnetic field. The ionosphere curvature correction, for F,F_2-layer transmission, has been included in the transmission curves of Figs. 26, 27, and 28. The correction for the earth's magnetic field is too complex a subject to be treated in detail in this Handbook; it is of importance only at short distances, and consists of adding a small amount (usually less than 0.8 Mc) to the ordinary-wave m.u.f. to obtain the extraordinary-wave m.u.f. The procedure outlined below for calculating m.u.f. includes an average value of this correction.

2. Maximum Usable Frequency Factors for Transmission Via the Regular Layers

Other methods besides the above have been devised for calculating the m.u.f. for various distances from the vertical-incidence h'-f curve. The results of all of them can be readily summarized into an array of factors by which the critical frequency of a given layer may be multiplied to obtain the m.u.f. for radio transmission via that layer over various distances. These factors, called the "m.u.f. factors", depend principally on the transmission distances and the heights of the layers, but also take into account the refraction of the waves in the lower ionosphere layers.

The m.u.f. factor is roughly proportional to the secant of the angle of incidence of the waves upon the layer. At short distances the secant of this angle is nearly unity and varies but slowly; at the longer distances it approaches a limiting maximum value corresponding to the wave's leaving the transmitting antenna horizontally and grazing the earth. The factor thus varies between unity and a limiting value of approximately $\sqrt{R/2h'}$ where R is the radius of the earth and h' is the virtual height of reflection; it attains its maximum value for a distance equal to the maximum distance of transmission for a single hop, which is roughly $\sqrt{8h'R}$. This latter expression, giving the limitation of transmission distance imposed by the earth's curvature, comes from the following consideration: For antennas close to the ground the waves cannot take off at an angle below the horizontal; in fact little energy will be radiated at angles of less than about 3^{o} above the horizontal, over ordinary ground.

It has been found that the F,F_2-layer m.u.f. factor at any distance can be expressed as a fraction of the m.u.f. factor at a standard distance, say 2500 miles, to a degree of approximation sufficient for most applications. This distance is a convenient one to use, since the F,F_2-layer m.u.f. for 2500 miles is also the m.u.f. for longer distances, for the same condition of the ionosphere. For more precise calculations, especially for transmission distances of less than about 1000 miles, there is some advantage in expressing the m.u.f. factor as a percentage of the vertical-incidence m.u.f. factor (the vertical-incidence m.u.f. factor is the ratio of the extraordinary-wave critical frequency to that for the ordinary-wave). The F,F_2-layer m.u.f. factor can be determined more precisely yet for all distances up to 2500 miles by taking measured values of it for three distances, such as 0, 1000 miles, and 2500 miles, plotting these values on a sheet of the graph paper shown in Figs. 29 or 30, and drawing a smooth curve through the points. The IRPL has on hand a stock of such graph paper, and will supply some on request to those who wish to use this method in their operations.

Tables 1, 2, and 3 give average values of factors for calculating m.u.f. from ionospheric or radio prediction data furnished by the IRPL. These factors are also presented in nomogram form in Figs. 31 through 42, for direct use in multiplying critical frequencies by factors to get m.u.f. for various distances. The factors given in the tables and Figs. referred to are averages only; in the case of F,F_2-layer transmission the factors may vary somewhat with time of day, latitude, and season, but the factors for E- and F_1-layer transmission are substantially constant for any given distance.

Table 1 gives average values of factors by which the 2500-mile F,F_2-layer m.u.f. and the 1000-mile E-layer m.u.f. may be multiplied to obtain the m.u.f. by F,F_2-layer transmission and by E- or F_1-layer transmission, respectively, for any distance up to 2500 miles. The F,F_2-layer factors are more accurate for distances of between 1000 and 2500 miles than for shorter distances; they are subject to an error of up to perhaps ± 10% if used for distances of 100 or 200 miles.

A single set of factors is given in Table 1 taking care of both E- and F_1-layer transmission. Distances of 1500 to 2000 miles are too great for single-hop E-layer transmission, but not for single-hop F_1-layer transmission. It has been found that the F_1-layer m.u.f. are roughly proportional to the E-layer critical frequencies during the day. Therefore the F_1-layer m.u.f. can be obtained by multiplying the E-layer critical frequency by appropriate factors, for the range of distances where the F_1 layer rather than the E layer may control the m.u.f. The E- or F_1-layer factors shown in Table 1 are a simplified approximation to the actual case. The m.u.f. does not appear to decrease abruptly for distances greater than the maximum for single-hop E-layer transmission, possibly because effects such as extraordinary-wave transmission, sporadic E, and scattering, come in to bridge over the gap where the actual F_1-layer m.u.f. is lower. A detailed analysis and discussion of this point is outside the scope of this Handbook.

For distances of up to 1000 miles by F, F_2-layer transmission it is better to use the factors given in Table 2. This table gives the factors by which the vertical-incidence critical frequency of the F, F_2-layer, extraordinary wave, may be multiplied to give the m.u.f. at any distance up to 1000 miles. Table 2 also gives factors by which the E-layer critical frequency, ordinary wave, may be multiplied to give the m.u.f. for distances up to 1400 miles.

For completeness, Table 3 is given to show the factors by which the 1000-mile E-layer m.u.f. and the 2000-mile F_1-layer m.u.f. may be multiplied to obtain the E-layer and F_1-layer m.u.f. for distances up to 1400 miles and 2000 miles, respectively.

Table 1

Distance Factors for Maximum Usable Frequency

Maximum usable frequency for a given distance is the greater of the two values obtained by multiplying the 1000-mile E m.u.f. and the 2500-mile F, F_2 m.u.f. by the factors in this table for the given distance.

Distance in miles	For E- or F_1-layer transmission	For F,F_2-layer transmission
0	0.22	0.35
100	0.25	0.35
200	0.33	0.36
300	0.43	0.37
400	0.54	0.39
500	0.65	0.42
600	0.74	0.45
700	0.82	0.49
800	0.89	0.54
900	0.95	0.59
1000	1.00	0.64
1100	1.03	0.68
1200	1.05	0.72
1300	1.06	0.76
1400	1.07	0.80
1500	1.08	0.83
1600	1.08	0.86
1700	1.08	0.89
1800	1.08	0.91
1900	1.07	0.93
2000	1.07	0.95
2100	1.06	0.97
2200	1.05	0.98
2300	1.03	0.99
2400	1.00	1.00
2500	0.95	1.00

Table 2

Average Maximum Usable Frequency Factors (up to 1000 miles)

Maximum usable frequency for a given distance is the greater of the two values obtained by multiplying the zero-distance m.u.f. (or f^x) for the E or F, F_2 layers by the appropriate factors for the distance under consideration.

Distance in miles	For E-layer transmission	For F, F_2-layer transmission
0	1.00	1.00
100	1.13	1.01
200	1.47	1.03
300	1.93	1.07
400	2.43	1.13
500	2.90	1.21
600	3.32	1.30
700	3.69	1.41
800	4.01	1.54
900	4.28	1.65
1000	4.50	1.83

Table 3

Distance Factors for Maximum Usable Frequency

Maximum usable frequency for a given distance is the greatest of the three values obtained by multiplying the 1000-mile E m.u.f. and the 2000-mile F_1 m.u.f. by the factors in this table for the given distance and by multiplying the 2500-mile F,F_2 m.u.f. by the corresponding factors for that distance given in Table 1.

Distance in miles	For E-layer transmission	For F_1-layer transmission
0	0.22	0.30
100	0.25	0.31
200	0.33	0.33
300	0.43	0.35
400	0.54	0.40
500	0.65	0.46
600	0.74	0.52
700	0.82	0.58
800	0.89	0.64
900	0.95	0.70
1000	1.00	0.75
1100	1.03	0.79
1200	1.05	0.82
1300	1.06	0.85
1400	1.07	0.88
1500		0.91
1600		0.94
1700		0.96
1800		0.97
1900		0.99
2000		1.00

3. The Calculation of Maximum Usable Frequencies for Single-Hop Transmission

The method of calculating m.u.f. is different for short distances from that for long distances. The dividing line is roughly at 2500 miles, the maximum distance for single-hop F,F_2 transmission. The method of calculation presented in this section is for transmission distances up to 2500 miles. These m.u.f. are for transmission via the regular ionosphere layers over the great-circle path from transmitter to receiver; scattering in the ionosphere, sporadic-E reflections and off-path transmission may modify the m.u.f. considerably at times.

The first step is to determine the E- and F,F_2-layer critical frequencies, or, alternatively, the 1000-mile E-layer m.u.f. and the 2500-mile F,F_2-layer m.u.f. at the midpoint of the transmission path. The basic data from which these can be determined are scaled regularly from records at the various ionospheric observing stations over the world, and are available in detail at the IRPL. They are summarized and predictions are issued regularly by the IRPL. Sample world contour charts for the months of June, September, and December, giving critical frequencies and m.u.f., are presented in Figs. 47 through 58 herewith. Table 4 (page 48) is a sample, for 20°S at sunspot minimum, of a set of tables presented every six months in the Supplement to this Handbook, giving predicted 2500-mile F,F_2-layer m.u.f. and 1000-mile E-layer m.u.f. for each 20° of latitude, for 12 months in advance. Daily values of noon, midnight, and pre-sunrise minimum critical frequencies and maximum usable frequencies for certain stations are received daily at the IRPL and can be furnished upon request, where prompt information is desired.

The method of calculating the m.u.f. for any path up to 2500 miles in length is as follows:

1. Determine the latitude and longitude of the midpoint of the transmission path. Methods for such determination are given in Part 4 of this Handbook.

2. From the longitude of the midpoint of the path, determine the local time at the midpoint corresponding to the time for which the calculation is to be made. Time is earlier to the west, later to the east, at the rate of four minutes per degree of longitude.

3. From the available data for the month or day in question, determine the E-layer and F,F_2-layer critical frequencies or the 1000-mile E m.u.f. and the 2500-mile F m.u.f. for the latitude and local time desired.

4. Convert these values to the m.u.f. for the desired distance by multiplying them by the appropriate factors from Tables 1 and 2,

Table 4. Sample of Predicted Maximum Usable Frequencies, in Megacycles. Average for Quiet Days. Midpoint of Transmission Path at Latitude 20°S.

Local time of day	July	Aug.	Sept.	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June
	For F, F_2-layer transmission, 2500 miles											
Midnight	12.0	11.2	16.2	21.1	15.2	13.8	13.6	17.5	20.2	22.0	16.8	12.6
4 A.M.	11.8	9.6	11.9	10.0	10.0	9.6	7.8	11.1	11.7	11.0	11.0	10.9
8 A.M.	18.3	18.1	23.0	22.0	24.0	18.0	21.9	21.0	24.5	25.8	20.2	17.6
Noon	16.9	18.3	21.4	21.2	25.1	22.0	20.2	20.0	23.1	23.8	19.5	17.3
4 P.M.	20.2	19.2	21.7	22.7	25.5	26.4	23.5	22.2	26.3	27.0	21.2	18.9
8 P.M.	17.5	13.6	20.0	23.0	21.1	21.0	20.9	20.1	22.7	22.8	13.5	13.5
	For E-layer transmission, 1000 miles											
8 A.M.		11.8				12.7						
Noon	14.9	15.8	15.6	16.0	15.9	16.0	16.6	15.8	16.2	15.4	14.0	13.9
4 P.M.		12.2										

or by using the nomograms of Figs.31 through 36. The greater of the two values thus obtained, for E- and F-layer transmission, is the m.u.f. for the path.

5. If no E-layer values are shown on the maps or in the tables, or if they are shown dotted on the E-layer maps, as is the case for some parts of the world, the E-layer calculation can be omitted.

6. Skip distances can be obtained from m.u.f. values by noting the fact that the m.u.f. for a given distance is the frequency for which that distance is the skip distance.

7. Repeat steps 1 through 6 for each time for which the m.u.f. is desired.

Note that tables such as Table 4 and charts like those of Figs. 50 through 52 and 56 through 58 give explicitly the maximum usable frequency by way of the F,F_2 layer over a distance of 2500 miles, and for transmission by way of the E layer over a distance of 1000 miles. The times and latitudes given are those of the midpoints of the paths, in each case.

As an example of the use of tables like Table 4, suppose it is desired to know the m.u.f. for 1200 miles in December, for a path whose midpoint is at latitude 20°S and at 1200 local time at the midpoint. From Table 4 the 2500-mile F,F_2-layer m.u.f. is 22.0 Mc and the 1000-mile E-layer m.u.f. is 16.0 Mc. For 1200 miles the distance factors given in Table 1 are 1.05 for E- and 0.72 for F,F_2-layer transmission. 1.05 x 16.0 Mc = 16.8 Mc for E-layer transmission; 0.72 x 22.0 Mc = 15.8 Mc for F,F_2-layer transmission. The m.u.f. for the path is thus 16.8 Mc, and conversely the skip distance for 16.8 Mc at the time and latitude indicated is 1200 miles.

As an example of the use of the world charts for short-distance analysis, suppose the m.u.f. is required for a transmission path between New York and Havana, during December, at 0800 local time at New York. The transmission path is 1370 miles long, with the midpoint at latitude 32.5°N and longitude 80°W. Local time of 0800 at New York corresponds to a local time of 0740 at the midpoint of the path.

The F,F_2-layer m.u.f. for a latitude of 32.5°N and local time of 0740 for a 2500-mile transmission path, as given by the chart of Fig. 52, is 18.2 Mc. The 1000-mile E-layer m.u.f. for the same latitude and local time is given by the chart of Fig. 58 as 9.1. This occurs in the region, indicated by dotted lines, where the E layer never controls the transmission, so E-layer values need no longer be considered for this problem.

By interpolation between the values of the factors given in Table 1, the factor by which the 2500-mile m.u.f. should be multiplied in order to give the m.u.f. for 1367 miles is 0.79. By multiplying 18.2 Mc by 0.79, or by use of the nomogram of Fig. 31, the m.u.f. for transmission between New York and Havana for the time under consideration is 14.4 Mc.

4. The Calculation of Maximum Usable Frequencies for Multi-hop Transmission

There is no practical way of simplifying the picture of radio transmission over distances of 2500 miles or more. No single series of graphs, nomograms or tables can possibly represent all the variations of the factors involved in m.u.f. determination, especially since the geographical variation of critical frequencies obeys no simple law and enters into the determination of m.u.f. in a very complex manner.

For transmission over distances involving more than one hop, or reflection from the ionosphere, the paths must be individually analyzed. The phenomena of reflection in these cases are no longer simple and able to be approximated by a geometrical ray theory. The ionosphere, as well as the earth (land or sea), is rough to a radio wave, (ocean waves at times are higher than a wavelength of a high-frequency radio wave), and hence there is considerable scattering of the radiation at each reflection from the ionosphere and from the earth. This results in transmission over a multiplicity of paths, each of which can show different transmission characteristics. Furthermore, the probability of off-path transmission from ion banks or clouds of sporadic-E layer is greater. For these and other reasons, transmission over paths longer than 2500 miles can not be in general considered as a simple extension of single-hop transmission to multiple hops. In some respects, such as vertical angles of departure ("angles of fire") and arrival, the simplified picture may give results consistent with experiment; in respect to the calculation of maximum usable frequencies, it certainly does not.

After long detailed study of the relations between ionospheric data and long-distance radio transmission, during which it has been attempted to exclude scattered transmission, sporadic E, and similar effects, a relatively simple operational procedure for long-path calculation has been developed.

The basic materials needed for the calculations are the following:

(1) 2500-mile F m.u.f. charts of the world, showing average values for the months for which calculations are to be made. Figs. 50 through 52 are samples included for illustration only. Predicted charts are issued regularly as a supplement to this Handbook.

(2) A great-circle chart of the world, centered on the equator, showing great-circle paths marked off with equal intervals of distance along the paths. Figs. 44 through 46 in this Handbook are such charts, with the distance intervals expressed in miles, nautical miles, and kilometers respectively.

(3) A world map showing oceans and land masses and the auroral zones, which are the zones of maximum ionospheric storminess. This is for assisting in locating the transmitter and receiver on the great-circle chart. Fig. 43 in this Handbook is such a map.

(4) A supply of blank transparent paper for superposing over the maps and charts.

The procedure for using the maps is as follows:

1. Rule horizontal lines on the transparent paper corresponding to latitudes 90°N, 0°, 90°S for aid in orienting the paper properly on the several charts.

2. Place the paper over the world map of Fig. 43, so that the latitude scales coincide and mark the locations of the terminal points of the path to be investigated.

3. Mark the meridian whose local times are to be used as the times for the calculation.

4. Place the paper over the desired one of the great-circle charts of Figs. 44 through 46 so that the latitude scales coincide.

5. Move the paper horizontally until the terminal points marked on it either fall on the same great-circle curve, or fall the same proportional distance between adjacent great-circle curves.

6. Sketch in the great-circle curve between the terminal points, and plot points 1250 miles (1100 nautical miles, 2000 kilometers, or 18 degrees of arc) from each end along the curve. Use the distance marks on the great circles of the chart as guides in locating these points. These are the "control points", or the points at which the ionosphere determines the m.u.f. over the path.

7. Place the transparent paper over the 2500-mile F,F_2-layer m.u.f. map for the desired month, so that the latitude scales coincide. (It is not necessary to consider E-layer values).

8. Slide the paper horizontally until the meridian which was marked in step 3 falls on the local time for which the m.u.f. is desired.

9. Read the value of the m.u.f. at each control point. The lower of the two values is the m.u.f. for the path. The ionosphere between the control points need not be considered, nor the number nor length of the hops.

10. Repeat steps 8 and 9 for each time for which the m.u.f. is desired.

As an example let it be desired to calculate the m.u.f. for the path between New York and London, at 1100 GMT, in December as shown on the sample map of Fig. 52. The control point at the New York end of the path is at about latitude 49°N, longitude 53°W; the control point at the London end is at about latitude 53°N, longitude 30°W. Following the procedure outlined above, the control points, at 1100 GMT, lie at about 0730 and 0905 local time, respectively. The 2500-mile F,F_2-layer m.u.f. at the New York control point is 10.0 Mc, and at the London control point is 16.5 Mc. The m.u.f. for the path is thus 10.0 Mc at 0800 GMT.

The idea given here, of waves taking off horizontally and always making the first and last hops of maximum length 2500 miles should not be taken as denoting that this is the actual mechanism of transmission. It is merely a usable picture for m.u.f. calculation, which takes into account some of the complexities which occur in multipath, multihop transmission. These complexities - scattered reflections, lateral deviations from the great-circle path, asymmetry of the transmission path, laterally and longitudinally, scattering from the earth and ionosphere, even upon normal reflection, the coexistence of several modes of transmission - all serve to increase the m.u.f. above what it would be according to the geometrical ray theory.

It should be noted further that all calculations described here are for average conditions on ionospherically quiet days, i.e., days when there are no ionosphere storms. They are also for transmission via the regular layers. The actual m.u.f. may often exceed the values calculated as above because of reflections from clouds of sporadic-E layer, or because of scattered reflections (described below).

5. The Prediction of Critical Frequencies and Maximum Usable Frequencies.

In order to predict maximum usable frequencies for the construction of the world charts shown in Figs. 50 through 58, it is first necessary to predict the critical frequencies of the E, F_1, and F,F_2 layers and to construct the F,F_2-layer critical frequency charts of Figs. 47 through 49. Furthermore, the complete story of maximum usable frequencies is not told until information is also given on the day-to-day deviations of critical frequencies and m.u.f. from the average.

The average variation of the critical frequencies of the various ionosphere layers diurnally, seasonally, from year to year with the sunspot cycle, and with geographical latitude are sufficiently regular to permit long-range predictions to be made for average conditions on ionospherically quiet days (days without ionosphere disturbances).

The method of prediction of critical frequencies used by the IRPL consists of analyzing the data supplied by each of its various cooperating laboratories for sunspot cycle, seasonal, and diurnal trends, extrapolating these trends to the time for which prediction is to be made and properly combining the resulting predicted values. Coordination of such predictions for various observation stations over the earth affords the means of making world-wide predictions of critical frequency for any time. The prediction method is described in detail in report IRPL-S1, available upon request to the IRPL.

The extrapolated trends are then combined to obtain predicted monthly average values of the critical frequency at each time of day. A graph of diurnal variation of the critical frequency, for the month considered, is then drawn through the predicted points, with due regard to the observed diurnal curves for the same month in previous years. The result gives values of the predicted critical frequencies for the month in question.

The same procedure is followed with respect to the F,F_2-layer m.u.f. factors for the standard distance of 3500 kilometers (2175 miles). This distance was adopted several years ago for the regular scaling of m.u.f. factors from vertical incidence h'-f records. The resultant predicted factors, converted into factors for 2500-mile paths, are multiplied by the predicted F,F_2-layer critical frequencies to obtain predicted 2500-mile F,F_2-layer m.u.f. Predicted values of the 1000-mile E-layer m.u.f. are obtained by multiplying the predicted E-layer critical frequencies by a factor of 4.5, which is assumed constant with time of day and sunspot cycle. The experimental evidence to date is not sufficient to indicate any systematic deviations from this value of the factor. Similarly, predicted values of the 2000-mile F_1-layer m.u.f. are obtained by multiplying the predicted F_1-layer critical frequencies by a constant factor of 3.87.

The predicted F,F_2-layer critical frequencies, 2500-mile F,F_2-layer m.u.f. and 1000-mile E-layer m.u.f. for each station are plotted on the modified cylindrical projection base chart form, which is used for all the world maps and contour charts in this Handbook. Contours are then drawn through the predicted points to obtain the predicted world charts of F,F_2-layer critical frequencies, of which samples are shown in Figs. 47 through 49, and the predicted world maps of m.u.f., of which samples are shown in Figs. 50 through 58.

6. Deviations from the Predicted Values

The contour maps and tables plotted from the data predicted as described above show monthly average values, for quiet or undisturbed days only, for transmission via the regular ionosphere layers. Quiet days are those when there is less than a certain minimum of ionospheric storminess (see Sec. II-11e above). It is necessary to present average values like these, rather than detailed data, for the sake of simplifying a comprehensive picture of them.

Maximum usable frequencies are not exactly the same day after day, for the same time of day, but are distributed about the monthly average. Furthermore, the monthly averages themselves do not fall on a smooth seasonal curve, since the solar radiation varies irregularly, and thus far nearly unpredictably, about a mean value. For both reasons the actual daily and hourly values of the m.u.f. during a given month show a deviation, even on quiet days, from the predicted mean. The following discussion indicates the nature, source, and approximate magnitude of deviations from the predicted averages.

Deviations from predicted average values for a particular time and place fall into six general classes: (1) errors in extrapolating established ionosphere trends; (2) day-to-day variations about the average, random in nature; (3) irregular month-to-month variation from the smooth trend, caused probably by variations in solar activity; (4) latitude interpolation errors, due to insufficient number of observing stations from which basic data are obtained; (5) the errors in the assumption that the only longitude variation of ionosphere characteristics is due to difference in local time, and (6) large deviations from the average due to ionospheric disturbances.

The errors of class (1) due to incorrect estimation of ionosphere trends are likely to be relatively minor, since the trends are well established for most of the observing stations. Those due to latitude interpolation errors can, in general, be estimated only upon the acquisition of more data from a greater number of observation stations.

It has only recently become possible to estimate the errors incurred in the assumption that longitude differences in ionospheric characteristics are the equivalents of those caused by differences in local time. At present, three pairs of observatories for ionospheric data are located so as to have considerable longitude differences in comparison with the latitude differences between them. There are notable differences in the critical frequencies reported for Ottawa (Lat. 45.4°N, Long. 75.7°W) in comparison with those for Great Baddow (51.7°N, 0.5°E), for Stanford (37.4°N, 122.2°W) in comparison with those for Washington (39.0°N, 76.8°W), those for Watheroo (30.3°S, 115.9°E) in comparison with those for Mt.

Stromlo (35.3°S, 149.0°E), and those for Delhi, India (28.6°N, 77.2°E) in comparison with those for Baton Rouge, La. (30.5°N, 91.2°W). These differences may possibly be caused by variation in geomagnetic latitude, or by geographical effects upon the ionosphere, due perhaps to the influence of land masses upon atmospheric convection currents. This is the subject of investigation now going on.

In using the data for the above pairs of stations, the present practice is to compromise between two sets of values, giving greater weight to the values of that station for which the trends are best established. This helps to guard against possibility of the discrepancy's being due to random ionospheric variations.

The approximate magnitude of the day-to-day deviation in E-, F_1- and F,F_2-layer critical frequencies, at the present phase of the sunspot cycle, together with their seasonal and diurnal variations, is shown in Fig. 59. The number of cases where the critical frequency falls between band limits of every 0.5 Mc, is given for Washington for the winter, summer, and equinoctial months of January, June, and April, in comparison with the monthly averages for these quantities.

The E-layer critical frequency varies much less from day to day than does the F,F_2-layer critical frequency. Deviations of F,F_2-layer critical frequency from the monthly averages are generally greatest during the spring equinoctial period, due to the prevalence of ionospheric storms during this period. They are also greater for the steeply sloped portions of the diurnal curve in the morning and evening, than for the level portions at night, noon, and the presunrise minimum periods. The day-to-day variations of the m.u.f. are somewhat greater than those of the critical frequencies, because m.u.f. variations depend not only upon variations of critical frequency, but also upon variations of virtual height.

The diurnal variation of the average deviations in the F,F_2-layer critical frequencies, and approximately also of m.u.f. at Washington, expressed in percentages of the average value, is shown in Fig. 60. These values are averages of the day-to-day deviations taken without regard to sign. Corresponding average deviations read on the chart of Fig. 61 indicate that at this latitude the use of a frequency equal to or lower than 80% of the monthly average m.u.f. for summer months, 85% of the monthly average for winter days, and 75% of the monthly average for winter nights insures practically continuous transmission, except insofar as it is limited by absorption.

An indication of the variation of the normal day-to-day deviations with latitude is given by Table 5. This table presents briefly the results of a statistical survey of five-hour averages of the F,F_2-layer critical frequency taken for the hours 23-03 inclusive, and 11-15 inclusive, local time, at four stations. It will be seen that the relative dispersion of the values (relative dispersion = standard deviation divided by the mean) is generally greater at night than during the day. The particularly large night values for the Huancayo data are doubtless partially due to the fact that the diurnal variation of critical frequency is unusually rapid at this station during these hours. High values of relative dispersion are also exhibited by the data from College, Alaska, for both night and day. This station is in the auroral zone and the F, F_2-layer critical frequencies are therefore subject to very great deviations from normal during periods of ionospheric storminess. The critical frequencies observed in north temperate regions show a greater relative dispersion during the spring equinoctial period, as previously noted, than during other seasons. This is probably caused in part by great deviations from normal during ionosphere storms, which are particularly prevalent in the spring.

Table 5

Statistical analysis of 5-hour averages of f^o_{F,F_2} for typical night (23-03h) and midday (11-15h) conditions, at four observation stations

Station	Midday				Night			
	Winter	Spring	Summer	Autumn	Winter	Spring	Summer	Autumn
	Mean f^o_{F,F_2}							
College, Alaska	5.92	5.36	4.97	5.36	2.29	3.34	3.69	2.69
Washington, D.C.	7.99	7.41	5.60	8.89	2.98	3.60	3.60	3.16
Huancayo	9.96	8.64	7.21	8.41	6.26	6.17	4.93	6.24
Watheroo	8.05	8.62	7.66	8.84	5.30	4.04	3.54	4.51
	Standard Deviation							
College, Alaska	0.846	0.871	0.505	0.937	0.598	0.941	0.656	0.749
Washington, D.C.	0.789	1.212	0.651	0.698	0.488	0.803	0.409	0.314
Huancayo	1.396	1.061	0.881	1.370	1.451	1.309	1.089	1.115
Watheroo	1.392	1.045	0.823	1.063	0.719	0.543	0.581	0.653
	Relative Dispersion							
College, Alaska	0.143	0.162	0.102	0.175	0.261	0.282	0.178	0.278
Washington, D.C.	0.099	0.164	0.116	0.078	0.164	0.223	0.114	0.099
Huancayo	0.140	0.123	0.122	0.163	0.232	0.212	0.221	0.179
Watheroo	0.173	0.121	0.107	0.120	0.136	0.134	0.164	0.145

Further analysis of the random day-to-day deviations from average has indicated that the distribution about the model (most probable) value is, in general, fairly symmetrical, although slightly flatter than for an ideal "normal" random distribution.

In general, operating frequencies should be kept slightly under the maximum usable frequency calculated, if continuous transmission is to be insured, to allow for day-to-day variations in critical frequency and virtual height. The frequency used should be, where practicable, about 15% below the maximum for F,F_2-layer tranmission, and about 3% below the maximum for E-layer transmission, since the latter is less variable. The "optimum working frequency", abbreviated o.w.f., is as near the maximum usable frequency as can be used, after the above allowances have been made for probable day-to-day variations in the m.u.f. This is because the loss of field intensity by absorption at medium and higher frequencies is greater, the lower the frequency.

7. Sporadic-E Reflections

Besides the regular predictable sky-wave radio transmission that is characterized by the m.u.f. shown in the sample graphs and charts of this Handbook, there occurs at irregular and unpredictable times very strong radio transmission, at frequencies much greater than the normal maximum usable frequency, caused by reflections from E-layer heights. Such transmission is called sporadic-E transmission, and often results in excellent reception within the normal skip zone, and over long distances on frequencies which are considerably higher than any which normally are propagated by sky waves. This type of transmission is not usually widespread or of long duration. Sporadic-E reflections are described in Sec. II-11a above.

Sporadic E (abbreviated E_s, and sometimes called "abnormal E", since reflections occur at frequencies higher than those transmitted by the normal E layer) appears to be of two classes, which may be called the "reflecting" type (type R) and the "blanketing" type (type B) from their observed characteristics.

The R-type of sporadic E may cause either total or partial reflection of radio waves. In general it produces a very steady strong reflection at the lower of the frequencies for which it is observed at a given time. Its reflection coefficient is very high at these frequencies, and it reflects all or nearly all of the energy incident upon it, so that no higher level reflections are seen through it. This type of sporadic E becomes, however, increasingly transparent as the frequency of the waves is increased, and a larger and larger fraction of the incident energy penetrates the layer and is reflected by higher layers. It is the R-type of sporadic E which is most prevalent in temperate latitudes in the summer. It seems to correlate inversely with ionospheric storminess, being a minimum in the spring and fall, when ionospheric storminess is most likely, and occurring at higher frequencies and much more regularly at the minimum than at the maximum of sunspot activity. Very little sporadic E has been reported from equatorial latitudes, but instead there is present all the time a relatively weak sharp-boundary E reflection which may produce usable radio transmissions over long distances. This type of sporadic E does not necessarily involve great ionization densities, but rather very steep gradients of ionization density.

The blanketing type of sporadic E (type B) is so named because it is completely opaque to radio waves at all frequencies at which it is observed. It is this type of sporadic E which appears to be correlated with auroras in polar latitudes, and in temperate latitudes during the onset of severe ionosphere storms. It is most prevalent and the frequencies at which it is observed are highest during ionosphere storms; it is most likely to occur during the spring and fall, when ionospheric storminess is most prevalent. It is most likely to occur during the hours of darkness; it appears possible that this type of ionization may produce absorption during the daylight hours, and sporadic-E reflections at night, both associated with ionospheric storminess. This type of sporadic E probably involves great ionization densities.

Sporadic-E reflections, in view of their great prevalence at certain seasons and hours of the day, are very important in their effect upon radio transmission. Because E_s reflects fairly high frequencies at low heights it can produce transmission within the normal skip zone of the regular layers, and it also accounts for long-distance transmission up to higher frequencies than by any other means. Strong vertical-incidence reflections by sporadic E sometimes occur at frequencies up to above 12 Mc. By reason of the large angles of incidence possible with the E layer, this makes long-distance communication possible on frequencies higher than 60 Mc. Communication at such high frequencies is generally for only a short time and for restricted localities. Sporadic E is patchy or sporadic in both geographic distribution and time. At lower frequencies, however, it can sometimes produce nearly continuous transmission at frequencies above the m.u.f. calculated for F,F_2-layer data.

There is evidence that the probability of sporadic-E transmission over an oblique path on a given frequency is greater than the probability of getting reflections at vertical incidence on a frequency equal to the oblique-incidence frequency divided by the secant of the angle of incidence (or by the factor 5 assumed for long-distance transmission). This is accounted for by the "patchiness" of the layer, permitting off-path transmission from patches to the side of the great-circle path, thereby greatly increasing the number of possible modes of transmission.

Sporadic-E reflection data are relatively few, except from a few observing stations, so that predictions of its occurrence are considerably less precise than those of critical frequencies for the regular layers of the ionosphere.

Vertical-incidence reflections from sporadic E do not ordinarily exhibit the variation of virtual height with frequency characteristic of the regular layers. Frequencies through an indefinitely established range are continuously reflected from a relatively constant height, followed by the cessation of reflection without any pronounced retardation of the wave (increase of virtual height) such as characterizes a critical frequency.

Sporadic-E ionization may be described by indicating the relative frequency of occurrence of vertical-incidence E_s reflections at a station for various transmission frequencies. The curves of Fig. 62 show the relative occurrence of sporadic-E reflections for three months, typical of summer, spring equinox, and winter conditions, at several observatories, for maximum reflected frequencies equal to or greater than 3 Mc, 5 Mc, and 7 Mc, respectively. Sporadic-E reflections are seen to be most prevalent in the auroral zone during morning and evening. Relatively little sporadic E is observed in equatorial regions (except the sharp-boundary E reflection mentioned above).

Fig. 63 illustrates the apparent increase in sporadic-E occurrence with decreasing sunspot number. This increase is fortunate in that it somewhat compensates for the general decrease in the critical frequencies of the regular layers with decreasing sunspot number; it is, especially in and near the auroral zones, of marked aid to radio transmission. The value of sporadic-E reflection to transmission may be seen from Table 6. Here is shown, for each hour, the percentage of time that transmission over a 2500-mile distance was possible at 15 Mc, due to F,F_2-layer reflection, and to sporadic-E reflection, separately, and in combination during typical winter, summer, and equinox months in 1943. These tables are for the stations at Washington, D.C. and at College, Alaska. The sample contour charts of Figs. 64 through 66 show the relative frequency of occurrence of long-distance sporadic-E transmission at 15 Mc for the typical months June, September, and December. These charts are based on the available information from such ionospheric stations as reported sporadic-E occurrence during these months. On these charts, the relative frequencies of occurrence, expressed as percentages of total time, are shown as contour lines, similar to those of the critical frequency and m.u.f. charts. These, together with the regular m.u.f. charts, give a much more complete concept of radio transmission conditions likely to prevail during a given period. The sporadic-E charts are also issued regularly as predictions by the IRPL. They should be considered in making any analysis of sky-wave radio transmission over a given path.

Table 6

Percentage of total time that m.u.f. is in excess of 15 Mc, for transmission distance of 2500 miles, due to F,F_2-layer reflection, sporadic-E reflection, and the combination of both.

Washington, D.C.

	January, 1943			April, 1943			June, 1943		
Hour	F,F_2	Sp.E	F,F_2 & Sp.E	F,F_2	Sp.E	F,F_2 & Sp.E	F,F_2	Sp.E	F,F_2 & Sp.E
00	0.0	29.0	29.0	3.3	20.0	22.7	0.0	70.0	70.0
01	0.0	38.7	38.7	0.0	16.7	16.7	0.0	50.0	50.0
02	0.0	29.0	29.0	0.0	20.0	20.0	0.0	63.3	63.3
03	0.0	41.9	41.9	0.0	26.7	26.7	0.0	60.0	60.0
04	0.0	48.4	48.4	0.0	20.0	20.0	0.0	60.0	60.0
05	0.0	48.4	48.4	0.0	13.3	13.3	0.0	66.7	66.7
06	0.0	35.5	35.5	26.9	16.7	39.1	18.2	80.0	83.6
07	0.0	38.7	38.7	53.6	20.0	62.9	47.1	70.0	84.1
08	89.7	32.3	93.0	66.7	36.7	78.9	41.2	76.7	86.3
09	92.0	19.4	93.6	87.5	23.3	90.4	35.3	73.3	82.7
10	100.0	25.8	100.0	57.1	16.7	64.3	76.9	66.7	92.3
11	100.0	29.0	100.0	80.0	13.3	82.7	80.0	53.3	90.7
12	100.0	32.3	100.0	76.9	10.0	79.2	92.3	56.7	96.7
13	100.0	29.0	100.0	82.4	6.7	83.5	45.4	60.0	78.2
14	100.0	29.0	100.0	82.6	13.3	84.9	63.2	53.3	82.8
15	100.0	12.7	100.0	91.3	20.0	93.0	53.8	70.0	86.2
16	100.0	22.6	100.0	88.5	26.7	91.5	69.2	86.7	95.9
17	100.0	32.3	100.0	92.6	26.7	94.6	84.0	86.7	97.9
18	57.1	38.7	73.7	88.9	26.7	91.8	96.0	73.3	98.9
19	11.1	32.3	39.8	85.2	23.3	88.6	100.0	60.0	100.0
20	0.0	32.3	32.3	73.1	13.3	76.7	92.0	73.3	97.9
21	0.0	25.8	25.8	52.0	23.3	63.2	61.9	63.3	86.0
22	0.0	19.4	19.4	7.1	23.3	28.8	16.0	73.3	77.6
23	0.0	25.8	25.8	7.1	20.0	25.7	3.8	60.0	61.5

Table 6 - (continued)

Percentage of total time that m.u.f. is in excess of 15 Mc, for transmission distance of 2500 miles, due to F,F_2-layer reflection, sporadic-E reflection, and the combination of both.

College, Alaska

	January, 1943			April, 1943			June, 1943		
Hour	F,F_2	Sp.E	F,F_2 & Sp.E	F,F_2	Sp.E	F,F_2 & Sp.E	F,F_2	Sp.E	F,F_2 & Sp.E
00	0.0	68.5	68.5	0.0	53.3	53.3	50.0	42.5	71.2
01	0.0	74.2	74.2	0.0	59.2	59.2	0.0	45.0	45.0
02	0.0	76.6	76.6	0.0	56.7	56.7	0.0	52.5	52.5
03	0.0	70.1	70.1	0.0	55.0	55.0	0.0	49.2	49.2
04	0.0	65.3	65.3	0.0	41.7	41.7	0.0	45.0	45.0
05	0.0	49.2	49.2	0.0	22.5	22.5	70.0	32.5	79.8
06	0.0	48.4	48.4	0.0	12.5	12.5	80.0	18.3	83.7
07	0.0	33.0	33.0	0.0	8.3	8.3	0.0	10.8	10.8
08	0.0	21.0	21.0	0.0	4.2	4.2	83.3	11.7	85.3
09	0.0	4.8	4.8	0.0	4.2	4.2	0.0	2.5	2.5
10	15.4	0.8	15.3	0.0	0.0	0.0	90.0	1.7	90.2
11	44.0	2.4	45.3	4.5	0.0	4.5	83.3	5.0	84.2
12	75.0	4.0	76.0	8.0	0.0	0.0	90.0	4.2	90.4
13	76.0	0.0	76.0	12.5	1.7	12.1	83.3	4.2	84.0
14	67.9	0.0	67.9	11.5	0.0	11.5	80.0	1.7	80.3
15	42.3	0.0	42.3	12.5	3.3	11.7	0.0	0.0	0.0
16	24.0	4.8	27.3	8.3	10.0	17.5	80.0	3.3	80.6
17	0.0	11.3	11.3	13.0	7.5	19.6	86.7	12.5	88.3
18	0.0	18.5	18.5	12.5	15.0	25.6	90.0	10.0	91.0
19	0.0	41.9	41.9	12.5	20.8	30.7	80.0	10.8	82.2
20	0.0	58.0	58.0	0.0	34.2	34.2	90.0	15.0	91.5
21	0.0	68.5	68.5	6.2	50.0	53.1	76.7	30.0	83.7
22	0.0	71.7	71.7	0.0	48.3	48.3	63.3	35.8	76.5
23	0.0	66.1	66.1	0.0	48.3	48.3	66.7	34.2	78.1

8. Sky-Wave Transmission by Scattered Reflections

Thus far sky-wave radio transmission has been described in terms of simple regular reflections from the normal ionosphere layers, exhibiting, except in the case of the sporadic-E layer, well defined and calculable absorption and m.u.f. characteristics. The presence of scattering centers in the E layer, as described in Sec. II above, requires that this simple picture be somewhat modified.

In general, radio waves of frequencies high enough to pass through the E layer are scattered in all directions by the patches in the layer. Most of the energy travels forward in the general direction which the waves had before they entered the layer, but appreciable amounts of energy may be scattered at large angles to this direction, and even backward toward the transmitter, as described in Sec. II. For short-distance single-hop transmission (less than about 1000 miles) these scattered reflections cause transmission within the skip zone of the regular layers, or at frequencies higher than the m.u.f. of the regular layers. In this case the reflections are complex and jumpy thus causing signal distortion and flutter fading, and are almost useless for radiotelephone communication. They are, however, useful for radiotelegraph communication, especially for manual operation.

In general, radio transmission by scattered reflections can be divided into two categories:

(a) "Short scatter" - the first reflection to reach the receiver, coming directly off the lower edge of the scattering patches or clouds.

(b) "Long scatter" - the reflections returned to the receiver from the upper surface of the scattering patches or clouds, via the F,F_2 layer, after having reached the scattering patches via the F,F_2 layer.

Long scatter is the most common cause for reception in the skip zone (reception on frequencies above the m.u.f.) and is often responsible for the condition wherein no sharp bearing or a spurious bearing is obtained. Short scatter, coming from relatively widely separated and short-lived patches, usually gives rise to signals of poor quality, whereas waves received by long scatter often arrive with fair quality and can be used for automatic telegraphy up to moderate speeds.

The effect of scattering must be taken into consideration in determining transmission conditions over long paths. Measurements have indicated that much of the energy received from a transmitter a long distance away sometimes comes from directions considerably off the great-circle path. This is especially true for paths which are subject to ionosphere storms, such as the North Atlantic path. Thus, in addition to the great-circle path calculation of the m.u.f. as outlined above, it is necessary to consider to what extent scattered reflections from regions off the great-circle path may affect the transmission.

The manner in which long scatter can affect long-distance radio transmission can be visualized as follows. A radio transmitter in general radiates energy in all directions, and a receiving set can receive from all directions, if antenna directivity be neglected. At frequencies lower than the m.u.f. the attenuation suffered by the waves is, in general, less over the shortest possible path between transmitter and receiver (i.e., the minor arc of the great circle upon which they both lie). Consequently the preponderant portion of the received signal strength arrives along this path. The total field intensity is the sum of that due to propagation along this path, and that arriving from all other directions, due to scatter.

In Sec. III, 4, it was stated that for long paths the m.u.f. can be obtained by consideration of ionosphere conditions at only two points, the so-called control points 1250 mi. from each end of the transmission path. Transmission and reception of radio waves at the working frequency are possible in all the directions for which the m.u.f. at the respective control points is as high as or higher than the working frequency. Thus, at some times of day long-distance transmission or reception is possible from all directions on a given high frequency, neglecting absorption, since at no point on the circle 1250 mi. in radius around the station does the m.u.f. drop below the working frequency. If the frequency is high enough, however, a time comes when the m.u.f. at one of the control points on a given path drops below the operating frequency. For low- and medium-powered stations communication generally deteriorates rapidly in quality at this time, and a change to a lower frequency has to be made if it is desired to continue communication.

When this happens there are nearly always directions - usually toward the equator- over which signals can still be transmitted and in which directions the upper surface of the scattering region may be"illuminated" by the downcoming waves from the F,F_2 layer on the first hop. If the power is sufficiently great, waves scattered from these illuminated areas will continue to be received above the noise level at the receiving station, but the bearing, or horizontal direction of arrival of the waves, will deviate from the great-circle path toward the equator. The signals would be expected to be received by this process until, for all points on the circle of 1250 mi. radius about either the transmitting or the receiving station, the m.u.f. is below the operating frequency. Any further received signals would be expected to be weak and of poor quality, propagated perhaps by a mechanism involving short scatter. There is some experimental evidence in support of the above picture, e.g., in the case of reception in England of transmissions from Japan, where bearing indications point to a transmitter in the direction of the Indian Ocean near the time of failure of communication caused by decreasing m.u.f.

Inasmuch as the received waves always arrive predominantly by the path offering the least overall attenuation, the mechanism of transmission by long scatter just described is of considerable importance. It is especially important in intercept work, both with regard to the possibilities of interception of intelligence on working frequencies of an order believed to be above the m.u.f. for enemy stations, and with regard to the false bearing indications which will be obtained. The effect of lateral deviation from great-circle paths appears to be most pronounced on long paths passing through high latitudes, for in such cases ionosphere storms may often block direct great-circle communication and leave only the scattered transmission arriving by paths closer to the equator.

Thus, although scattered reflections alone may not suffice to explain transmission over long paths at frequencies in excess of the calculated m.u.f., they may well provide a means whereby radiation can reach portions of the ionosphere where the ionization is sufficient to support transmission in the regular manner over most of the path. This is especially applicable where the transmission is limited theoretically by a lack of ionization on one end of the path, and scattering may provide transmission over this difficult condition.

It is also worthy of note that the longer the path, the less abrupt is the beginning or end of transmission as determined by the m.u.f. For paths of 1000 miles or less in length a change in field intensity of 100 to 1 may take place within a minute at these times, whereas for paths of 3000 miles or longer the change may require several hours. This probably indicates the greater relative importance of scattered reflections over long paths.

Field-intensity records of radio transmission over a North Atlantic path show definite changes in transmission at the times when the calculated great-circle path m.u.f. falls below the frequency used. Transmission is, however, often observed to persist several hours after this change is observed. This effect may be explained, and taken account of in describing or predicting radio transmission over long paths, by considering scattered reflections.

It is possible that short scatter may play some role in long-distance transmission. While normally not considered as important as long scatter, it might account for prolongation of communication on long east-west paths, when highly directional antennas are used both for transmitting and receiving. If the m.u.f. at one control point is too law, it is possible that the effect of short scatter may be to send some of the energy back to earth at a point about

1500 mi. away, (as if the first reflection had taken place from the E layer). From this ground-reflection point the waves may travel to a point in the F,F_2 layer, perhaps as much as 2750 mi. from the station, where normal reflection can take place. Such an outward extension of the control point may permit continued weak signals to be received for several hours after failure of strong transmission. The mechanism just described may also be extended to non-great-circle scatter communication as suggested previously. That is, possibly the F,F_2-layer m.u.f. on a circle of 2750 mi. radius around each end of the transmission path is of importance for this type of scatter.

The above discussion has been in terms of omni-directional aerials. This condition is not necessary, however, for any practical directional antenna has many lesser radiation lobes besides its principal one. There can thus be considerable amounts of energy radiated in nearly all directions even from a good directional antenna.

The general characteristics of the scattering patches which have so far been principally discussed are:

(a) Their apparent coincidence in height with the E layer.
(b) Their frequent occurrence and short life, giving the effect of a rapidly fluctuating layer.
(c) The fact that the intensity of radiation scattered from these patches decreases with increasing frequency.

The type of complex reflections referred to in Sec. II, 11b above as "spread echoes" appears at frequencies near to and above the F,F_2-layer critical frequency, and at about F,F_2-layer heights. These reflections are very intense and complex, usually appearing only at night. It is uncertain as to exactly what relation they have to long-distance radio communication, but measurements indicate that they are somewhat effective in increasing the m.u.f., albeit the signals transmitted thus are rapidly fading and fluttery. The scattering centers responsible for these reflections may possibly be patches or clouds above the main body of the F layer, which return waves which have passed through the layer.

A third kind of complex reflection appears during ionosphere storms, and probably indicates a turbulent condition of the ionosphere, in which the normal stratification is broken up into eddies and patches. This type of scattering is especially prevalent in and near the auroral zone, but may appear elsewhere during severe ionosphere storms. They may be caused by the influx of heterogeneous groups of charged particles into the ionosphere, in the act of producing an ionosphere storm. This "auroral zone" scattering is known to produce off-path radio transmission on very high frequencies at times, and may be one of the principal sources of discrepancies in paths which pass near the auroral zone (see below, for description of auroral zone).

A fourth kind of complex reflection is especially prevalent at night in equatorial latitudes. It shows up, on vertical-incidence measurements, on a large number of nights, shortly after sunset, and may persist throughout most of the night. The regular-layer reflections are entirely obscured by strong complex reflections with equivalent paths anywhere from less than normal F-layer heights to many times the normal F-layer heights. They occur over a wide range of frequencies and often occur on frequencies greatly in excess of the normal F-layer critical frequency. They seem to have little or no relation to the critical frequency, being in this respect different from the second type of scattered reflections described above. They show no correlation with ionosphere storms or other disturbances. The extent to which they affect night-time radio transmission in the tropics is unknown, but it seems likely that they can cause radio transmission to take place at frequencies far above the usual m.u.f. for tropical latitudes at night.

9. Ionosphere Storm Effects

a. Ionosphere Storm

As described in Sec. II above, an ionosphere storm is a period of disturbance in the ionosphere characterized by great anomalies in critical frequencies, virtual heights, and absorption. It is probably caused by bursts of electrified particles from the sun. This causes radio transmission conditions to be abnormal, with a decrease of maximum usable frequencies, increase of skip distances, raising of layer heights, and lowering of received radio intensities. Usually also abnormal magnetic fluctuations occur. High-frequency radio transmission above 200 kilocycles is of low intensity and subject to flutter fading caused by complex reflections from a patchy and unstable ionosphere. Night sky waves below 2000 kilocycles are greatly weakened, both during the storm and for several days after the effects on the higher frequencies have disappeared. All effects are greater in radio transmission paths passing through the polar regions.

During the first few hours of severe ionosphere storms, and in high latitudes even for small storms, the ionosphere is very turbulent and radio transmission is weak and erratic. During the later stages of the storms the maximum usable frequencies are lowered and the lowest useful high frequencies are raised, so that the bands of useful frequencies are narrowed and sometimes completely disappear. This results in the condition often referred to as "radio blackout", which is often experienced in Greenland, Iceland, Alaska, and Antarctica. Very low frequencies are little disturbed, and communication may be carried on at frequencies below 100 kilocycles when all high-frequency communication is impossible. Ionosphere storms are most severe in auroral-zone latitudes and decrease in intensity toward the equator.

An ionosphere storm usually develops during a period of a few minutes to an hour or more. The effects are noticed in the F, F_2 layer first and move progressively downward. Recovery to normal conditions usually takes several days, depending on the severity of the storm and the geographical latitude.

b. Auroral Zone Effects

When a radio transmission path passes through latitudes higher than about 50° it may pass through regions where the ionosphere is unstable and there is abnormally high absorption of the radio wave energy even when no ionosphere storm is in progress. Such paths are characterized by lower received intensity, and more fluctuation in field intensity, than other paths. This poor radio transmission is caused by conditions in the "auroral zones", or the regions where visible aurora is most prevalent. In these zones there are nearly continuous magnetic and radio disturbances, and the disturbances are much more severe than in surrounding regions, either closer to or more remote from the magnetic poles of the earth. The auroral zones are roughly circular, with centers about 78°N, 65°W, and about 78°S, 111°E. The center line of each auroral zone has a radius of roughly 20° of arc on the earth's surface. The maximum of radio disturbance occurs in a band several degrees wide and centered approximately at the center of the auroral zone. The radius of the auroral zone is greater during severe ionosphere storms than during mild or moderate storms. During the development of a storm the radius increases to an ultimate extent determined by the severity of the storm. This increase often takes several hours and the effect can be used to anticipate poor radio conditions over paths passing not too far from the normal auroral zone. During severe storms the disturbance at a given place within the auroral zone may actually be less than during less severe disturbances because of the expansion of the radius of the zone.

Transmissions over paths which lie, even in part, in or near the auroral zones, are subject to a greater degree of irregular and erratic performance, and poor radio transmission conditions than are transmissions over other paths. Severe and prolonged ionosphere storms with associated radio blackouts occur frequently, often developing suddenly in the course of a few minutes. Over such paths, it is not unusual for long-distance radio transmission to be difficult or impossible on all high frequencies for a day or more at a time, and to be erratic and only partially recovered on a small portion of the frequency spectrum for as much as a week. There have been instances of ionospheric storminess lasting almost continuously for a month.

Frequently, also, in auroral zones during ionosphere storms, there appear strong, widespread, and continuous intense sporadic-E reflections lasting for many hours. These may considerably improve radio reception in certain directions and over some paths while the sporadic E lasts, but there is no way of predicting this.

For transmission paths which do not pass through the auroral regions, radio transmission may generally be had during an ionosphere storm of moderate severity by using frequencies somewhat lower than usual. Such transmission, however, is probably weaker than normal, and the change to lower frequencies should always be made with caution, because absorption is liable to increase during ionosphere storms, even for paths somewhat outside the auroral zones. However, when an ionosphere storm of severe intensity occurs over such a path, or when even a relatively mild storm occurs over a path which lies even partly in the auroral zone, there is usually nothing that can be done to obtain better weak sporadic radio transmission on any high frequency over a path of greater than a hundred miles or so in length. Transmission over auroral-zone paths during ionosphere storms can be insured only by the use of the ground wave or by using low frequencies (below 300 kc). Transmissions on frequencies below 100 kc are actually improved during severe ionosphere storms; this is because the D layer becomes more heavily ionized at these times and therefore a better conductor, and better able to reflect waves of wavelengths great compared with the thickness of the layer, although it may completely absorb waves of wavelengths short enough to penetrate through it.

For reference, the auroral zones, or zones of maximum auroral frequency, are shown on the map of Fig. 43. The dotted line shows the approximate lower latitude limit of ionosphere storminess, for mild and moderate storms. Severer storms start in the auroral zones and spread out from them.

SECTION IV. LOWEST USEFUL HIGH FREQUENCIES

1. General

The lowest useful high frequency (l.u.h.f.) for radio sky-wave transmission over a given distance depends chiefly on:

1. The power radiated by the transmitting antenna (not the power output of the transmitter but the actual power radiated).

2. The energy lost by the radio wave due to absorption in the ionosphere.

3. The vertical and horizontal directional properties of the transmitting and receiving antennas.

4. The radio noise level at the receiving location (local noise as well as atmospheric noise propagated from a distance).

5. The skill of the radio receiving operator.

6. The type of service (A3, A1 printing, A1 aural, direction finding, etc.).

It is possible to calculate the amount of absorption of the sky wave in the ionosphere under specified conditions of season, time of day, and direction and length of the transmission path. If the radiated power and the transmitting antenna are also specified, it is possible to determine the expected field intensity of the received radio wave, in microvolts per meter.

The question as to whether this intensity will be great enough to use depends on the other factors listed. These factors may, to a rough approximation, be considered together and specified as a "required field intensity" for a given service. In general, the required field intensity for any specified service is variable with time and with geographical location, and often it is chiefly determined by the magnitude of the radio noise at the receiving location.

The process of determining the sky-wave distance range for a given frequency, or the l.u.h.f. for a given distance, is really two problems:

(1) The calculation of the actual sky-wave field intensity at the receiver.

(2) The determination of the required field intensity.

If the actual field intensity is equal to or greater than the field intensity required, the communication can be carried on - otherwise not.

The matter of required field intensities will be treated in detail in Sections V and VI of Part 4 of this Handbook. The present discussion is concerned chiefly with the calculation of sky-wave field intensity, and only rough indications of estimated required field intensities are given for use as a guide until Part 4 is issued.

2. Sky-Wave Radiation

In traversing a non-ionized region of the atmosphere, practically no energy is lost from the wave, and the only decrease in field intensity is that due to the spreading out of the wave front, the "inverse-distance attenuation". The field intensity along a path encountering no obstacles (neither large masses nor ions) and no interfering wave trains, varies inversely as the distance from the emitting source; the energy density in the waves, which is proportional to the square of the field intensity, varies inversely as the square of the distance (the familiar "inverse square law").

If a short dipole (less than, say, 1/10 wavelength long) is radiating P kilowatts of power in free space, the electric field intensity E of the direct wave at a distance d in a direction making an angle Θ with the axis of the dipole is given by

$$E = 131{,}700 \frac{\sqrt{P}}{d} \sin \Theta,$$

where E is in microvolts per meter,
P is in kilowatts radiated,
d is in miles.

Note that P is the actual power radiated from the antenna (current squared times radiation resistance) and not the power output P_o from the transmitting set. (The ratio P/P_o is the "radiation efficiency" of the antenna). The field intensity produced by other antennas is similar in magnitude, but different in detail as to directional pattern, etc. For example, the field intensity at one mile, due to a short vertical wire one end of which is on the ground, is given by

$$E = 186{,}300 \sqrt{P} \sin \Theta$$

for perfectly conducting ground. E is somewhat less than this for average ground. Part of this field intensity near the ground (near $\Theta = 90^\circ$) is due to the surface wave, which is negligible when the wave reaches the ionosphere. Consequently the vertical directional pattern of an antenna, for sky-wave calculations, is considerably different from the pattern as measured within a mile or so of the antenna.

To a first approximation, the sky-wave field intensity produced by an antenna can be considered as the field intensity produced by a similar antenna over a perfect earth, multiplied by the quantity $\frac{1-R}{2}$ where R is the plane-wave reflection coefficient of the ground for waves incident at an angle equal to the vertical angle ψ of departure of the waves. This reflection coefficient has a phase angle as well as a magnitude, and is:

$$R = \frac{u\sqrt{1-u^2\cos^2\psi} - \sin\psi}{u\sqrt{1-u^2\cos^2\psi} + \sin\psi}$$ for vertically polarized waves, and

$$R = \frac{u\sin\psi - \sqrt{1-u^2\cos^2\psi}}{u\sin\psi + \sqrt{1-u^2\cos^2\psi}}$$ for horizontally polarized waves, where

$$u = \frac{1}{\sqrt{\epsilon - jx}},$$

ϵ = dielectric constant of ground,

$$x = \frac{18,000\ \sigma}{f},$$

σ = conductivity of ground in m.k.s. units,

f = frequency in Mc,

$j = \sqrt{-1}$.

The value of R is given here for reference only; further discussion of it is outside the scope of this Handbook.

A more complete description of radiation patterns from various antennas is also outside the scope of this section of this Handbook. The calculations outlined in the remainder of this section are based on the following antenna characteristics:

1. A short vertical wire is assumed radiating 1 kilowatt, for transmission distances beyond about 500 miles (for vertical angles of radiation of about 40° or less above the horizontal).

2. A half-wave dipole, one quarter wavelength above the earth, is assumed radiating 1 kilowatt for distances of about 100 miles or less (for vertical angles of radiation of about 60° or greater above the horizontal).

3. The field intensity at vertical angles between about 40° and 60° is interpolated between these two cases.

The median value of the field intensity is the value used in most sky-wave calculations. Sometimes it is useful to consider also the "quasi-maximum" value of the field intensity, or the value which is exceeded only 5% of the time by the instantaneous field intensity. The quasi-maximum is about 1.5 times the median value of field intensity, for a normally fading wave.

3. The Unabsorbed Field Intensity

The unabsorbed field intensity of a sky wave is defined as the field intensity which is received at a given distance from a transmitter of given power and antenna system in the absence of ionospheric absorption. For standardization, the unabsorbed field intensity is usually referred to 1 kw radiated from the antennas described above.

When no absorption is introduced by the ionosphere a radio wave decreases in strength with distance because of:

(1) the "inverse distance" attenuation (spreading of waves),
(2) the breaking up of the "homogeneous" wave into components which combine with random intensities and phases to produce a fading wave whose median field intensity is less than that of the homogeneous wave;
(3) loss of energy upon reflection at the ground between hops.

These effects, together with the assumed directional patterns of the transmitting antennas, have all been considered together in formulating curves of "unabsorbed field intensity" given in Figs. 74 through 76 and described for use below. For the convenience of users, most of the graphs and nomograms in this Section are given in terms of three distance units, - miles, nautical miles, and kilometers. One mile (sometimes called statute mile) = 1.6092 km, and one nautical mile (abbreviated n.mi.) = 1.8532 km.

4. Sky-Wave Absorption

The slower and more regular variations of intensity which the sky-wave field undergoes are the result of absorption in the ionosphere. In general these variations are predictable, since they are due to diurnal, seasonal, and year-to-year variations in the ionosphere. The mechanism of absorption is essentially as follows:

When the radio wave encounters a free electron in the ionosphere, some of the energy in the wave is given up to the electron, causing it to vibrate. Some of this energy is reradiated at the frequency of the incident wave, and some is lost in the form of heat as the electron collides with neighboring air molecules. The loss of energy by collision becomes greater with increasing chance of collision, and therefore is greater at higher atmospheric pressures, or lower atmospheric heights. The energy loss is also greater, the greater the amplitude of vibration of the electron. For this reason, the loss is greater, the lower the frequency.

The loss of energy through absorption per unit distance of travel of a wave of frequency f, in a region of the ionosphere where the density of electrons is N and the collisional frequency of electrons with air molecules (due to ordinary thermal agitation) is ν, is given by:

$$k = \frac{e^2}{cm} \cdot \frac{N \nu}{\mu f^2}$$

where e and m are the charge and mass of the electron, c is the velocity of light, and μ is the refractive index of the medium for the frequency f. This is on the basis of the simple theory, not considering the effect of the earth's magnetic field.

The presence of the earth's magnetic field complicates the picture greatly. In general, the extraordinary wave is absorbed more than the ordinary wave, especially near the gyro-frequency (about 1.4 Mc at Washington, - different at other places). Near the ordinary-wave critical frequency, however, the ordinary wave is absorbed more than the extraordinary wave. The inverse-frequency-squared variation of absorption is also modified, especially at the lower frequencies; the variation with frequency is not quite so rapid, for the ordinary wave, when the earth's field is considered. A more detailed discussion of this point is not at present in the scope of this Handbook.

As the sky wave leaves the transmitter, no loss, except that due to spreading of the wave front, is suffered until the wave encounters the lowest height at which there is appreciable ionization. Here the absorption loss depends, as described above, upon the number of electrons per unit volume, the density of the atmosphere, and the length of time during which the wave remains in the ionized region.

During the night hours, when the F layer is the only layer of pronounced ionization present, ionospheric absorption is, for most frequencies, negligible on frequencies above 2 or 3 Mc, for quiet conditions outside the auroral zone. This is because at F-layer heights there are relatively few encounters between ions and gas molecules. There is some absorption for frequencies near the maximum usable frequency, because waves of such frequencies are abnormally retarded in passing through the ionized region and there is sufficient time for appreciable energy loss to take place. This is called "deviative absorption" since it occurs with the bending of the wave path in the ionosphere. Since the critical frequencies for ordinary and extraordinary waves are slightly different, the maximum deviative absorption for each component occurs at slightly different frequencies; thus, while in general the extraordinary wave is more susceptible to absorption, this situation is reversed at frequencies very near the critical or maximum usable frequency for the ordinary ray.

During daylight hours, there is also appreciable sky-wave energy loss due to deviative absorption for frequencies near the m.u.f. for each layer. However, the principal daytime energy loss occurs in the D region, which lies just below the E layer. In the D region the atmosphere is relatively dense, and the frequency of collisions between electrons and air molecules is far greater here than at the heights of the other layers. This type of energy loss is called "non-deviative absorption", since it takes place in a region where there is little or no bending of the waves.

Ionization in the D region is principally caused by ultraviolet radiation from the sun, and the height of the region is low enough for rapid recombination to occur, so that the density of electrons in this region varies practically in step with the amount of sunlight incident upon it. The electron density is thus greatest at noon, at latitudes directly under the sun.

5. The Measurement of Ionospheric Absorption

In the measurement of ionospheric absorption, the quantity actually measured is the "reflection coefficient" of the ionosphere, the ratio of the field intensity of the reflected sky-wave to the intensity of the incident wave at the ionosphere. The negative of the logarithm of this number is called the "absorption coefficient". The absorption coefficient varies regularly diurnally, seasonally, and from year to year with the sunspot cycle and ionospheric storminess. It is different for different frequencies, distances, geographical locations, and angles of incidence of the sky waves upon the ionosphere.

Two principal methods are now used to measure the ionosphere reflection coefficient. One consists of using pulses, and of comparing the relative amplitudes of successive reflected pulses at a given frequency at vertical incidence. The amplitudes differ because of the absorption in the ionosphere, and also because of the extra distances that must be traversed by different pulses (i.e., a pulse received after two reflections will have suffered twice the absorption of a pulse received after one reflection). The distance traversed is known from ionospheric height measurements; therefore the absorption can be evaluated.

The other method is more widely applicable and does not need special equipment like that needed for the use of pulses. It consists of making continuous automatic records of the field intensities produced by radio transmitters, both at vertical incidence and for transmission from a distance. These records can be interpreted in terms of known ionospheric data, so that the modes of transmission are known. The field intensity as measured is the sum of the intensities of a definite number of waves, whose relative amplitudes can be deduced. By this means a great mass of data can be obtained automatically for a wide range of frequencies and angles of incidence, and the results combined into curves of absorption coefficient against frequency.

The results indicate that the absorption coefficient of the ionosphere for vertical incidence increases with frequency to a maximum at a frequency in the neighborhood of one megacycle, then decreases steadily with frequency, except for small ranges of frequency in the neighborhood of the critical frequencies of the regular ionospheric layers. Fig. 67 shows a typical curve of absorption coefficient as a function of frequency for noon conditions at Washington in January, 1942, as obtained from data of the National Bureau of Standards. The absorption coefficient is given as the logarithm, to the base ϵ , of the ratio of the incident to the reflected sky-wave field intensity.

It is convenient to deal with absorption in terms of the logarithms of the field intensity ratios, because the relation between actual field intensity and "unabsorbed" field intensity over a given path is

$$E = E_0 \epsilon^{-\bar{k}d}$$

where E is the actual field intensity, E_0 is the unabsorbed field intensity, or the intensity which would have been observed in the absence of absorption, $\bar{k}$ is the average, over the path, of the absorption coefficient, and d is the length of the path of the wave in the ionosphere.

6. Summary of Absorption Phenomena

Fig. 68 shows the results of automatic field intensity measurements for an actual station. Were no ionospheric absorption present, the field intensity would be practically constant over the day; actually the intensity is much less during the daylight hours than during the night hours, principally because of the absorption in the D region during the daytime. Analysis of many records such as this have led to the following conclusions regarding absorption.

(1) The absorption over a given path can be represented by the relation

$$E = E_0 \text{ x } 10^{-\frac{1}{2}S}$$

where E is the median value of field intensity, E_0 is the median value of unabsorbed field intensity, which is negligibly different from the night value of E, for frequencies of 4 Mc and above, and S is the "absorption constant", which depends on frequency, length of path, and the amount of sunlight over the path.

(2) In general the absorption constant S can be considered to be made up of the product of three factors, the length of the transmission path, d; the "absorption index", K; and the "subsolar absorption constant", S_o. The absorption index K depends on the elevation of the sun above the horizon; it is a maximum at noon for a given latitude and season, it is unity at the subsolar point, and it decreases with increasing altitude of the sun, reaching zero when the sun is about 9° or 10° below the horizon. There is appreciable absorption at ground sunrise and sunset, because of ionization of the D region at these times due to diffusion, and other effects whose description is outside the scope of this Handbook. The subsolar absorption constant S_o is twice the logarithm to the base 10 of the ratio of the incident to the reflected sky-wave field intensity for a wave traversing a unit distance (say 1000 miles) at and near the subsolar point. It is a function of frequency and of ionospheric conditions. The distance d is expressed in the same units as those for S_o - in this case, thousands of miles. We can write, then,

$$S = S_o K \, d.$$

This is only valid for paths of lengths in excess of about 500 miles; for shorter paths the distance d is not the length of the transmission path on the earth's surface, but is proportional to, but not equal to the distance the wave travels in the D region.

(3) If the field intensity is expressed as the logarithm to the base 10 of the microvolts per meter, the field intensity may be readily calculated as

$$F = F_o - \tfrac{1}{2} S_o \, K \, d,$$

where F and F_o are the logarithms to the base 10 of the actual and unabsorbed field intensities, respectively, and S_o, K, and d are as described above. It is convenient to use logarithms in field intensity work, because the response of most communications apparatus is on a percentage basis.

(4) The variation of the absorption index with the elevation of the sun, except in the auroral zone, may be fairly well expressed by the empirical relation

$$K = 0.142 + 0.858 \cos\psi \qquad \cos\psi \geqslant -0.165 \; (\psi \leqslant 99.5°)$$
$$\text{and} \quad K = 0 \qquad \cos\psi \leqslant -0.165 \; (\psi \geqslant 99.5°)$$

Here K is the ratio of the absorption of a particular frequency at any latitude and local time, to that directly under the sun, and ψ is the zenith angle of the sun for the latitude and local time under consideration.

Fig. 69 shows typical variations of field intensity measured throughout the day for three different transmission paths on two different frequencies. The graphs shown are averages for all the days of the month. They illustrate the effect of D-region absorption, as well as the effect of "skipping".

For the lower of the two frequencies shown, i.e., 5000 kc, night reception is comparatively good over the path from Washington to Baton Rouge, for which path 5000 kc is well below the maximum usable frequency. This transmission suffers little ionospheric absorption. During midday there is pronounced D-region absorption of 5000 kc over both paths, and, consequently, low values of field intensity.

On the more northern transmission path from Washington to Boston, for 5000 kc, the frequency is above the maximum usable frequency, between about 2300 and 0530 (75°W time), so that relatively small field intensities are recorded between these hours. Just following this period, at about sunrise, the average intensity increases, following the curve of probability that this frequency will be reflected, and not skip. In a short time following sunrise, this probability becomes a certainty, but little increase of field intensity is now exhibited, since here the D-region ionization has become sufficiently great to cause appreciable absorption. In the evening, the field intensity rises again as the D-region absorption disappears, and then falls because of the fact that the transmission begins to skip on some days of the month. As the time gets later in the evening the transmission skips on more and more days until a time is reached when it skips every day, and at this time the average field intensity becomes relatively small, since only scattered reflections are received (see Section III, 8).

Field intensities measured on the higher of the two frequencies, i.e., 13,525 kc, manifest characteristics similar to those shown on 5000 kc over the northern path during the night, early morning, and evening hours. (The break in the curve between 0150 and 0330 (45°W time) indicates absence of record at this time). During midday, however, recorded field intensities are higher at this frequency than at 5000 kc, since D-region absorption is less, the higher the frequency.

7. Abnormal Ionospheric Absorption

In addition to such absorption effects, believed to be caused by ultraviolet light normally radiated from the sun, there are the effects, previously mentioned in Section II of this Handbook, due to sudden outbursts of solar activity and to solar particle emanation. They include the absorption effects manifested during ionosphere storms and sudden ionosphere disturbances, and the absorption continually present in the auroral zone.

As mentioned in Section II, there are irregularities in the eleven-year sunspot cycle, resulting in abnormal variation of sunspot number. During such periods of abnormally increased solar activity, D-layer ionization, and consequently ionospheric absorption, is increased. These periods may last for several weeks, and appear at intervals of a few months apart.

During periods of ionospheric storminess, which are often heralded by the appearance of large sunspots or groups of spots, ionization becomes diffuse, and sometimes the normal stratification of the ionosphere into layers disappears. At these times far more ionization exists at low levels than ordinarily, especially at night, and absorption is abnormally high, and irregular in nature.

Fig. 70 shows, for comparison, the records of field intensities, measured on the same frequency, for an ionospherically quiet day, and during days of moderate and severe storms. Fig. 71 presents field-intensity measurements showing the effects of a severe ionosphere storm on transmission at three different frequencies.

Coincident with the appearance of solar flares, or bright eruptions on the sun, there often occur periods of abnormally high D-layer ionization, lasting from a few minutes to an hour or more, and occurring only during daylight hours. These sudden ionosphere disturbances are caused by sudden intense bursts of ultraviolet light emanating from the solar flares. The intense ultraviolet light reaches our atmosphere, penetrating to the lower regions where it produces sufficiently intense ionization to cause cessation of all, or all but the higher, high-frequency radio transmission.

This increase in D-layer ionization makes it a better conductor, and so waves of frequencies which normally are reflected from this layer (frequencies below 500 kc or so) are actually increased in strength, while the waves which normally penetrate the D layer, as in the medium-frequency broadcast band, may be strongly reflected from the D layer during this time.

Fig. 72 shows field-intensity records of signals received at widely separated stations over quite different paths during a day on which one of these sudden disturbances occurred. It will be seen that the striking sudden drop in field intensity to practically zero occurs simultaneously.

Streams of particles from regions outside the earth's atmosphere arrive continually near the earth's magnetic poles, being deflected into the lower atmospheric regions there by the earth's magnetic field. They also cause pronounced ionization at low atmospheric heights, and are considered to be the primary cause of auroral displays, which are also ionization phenomena.

Although auroras are frequently seen at lower latitudes, they are observed most frequently at places located roughly on circles centered above the earth's axis magnetic poles, at 78°N, 69°W and 78°S, 111°E in relatively narrow bands whose centers are about 20 degrees of arc away from these poles. Fig. 43 shows the locations of these regions of maximum auroral frequency.

Ionization in the auroral zones is intense at low levels, with a generally diffuse and erratic distribution, so that there is pronounced absorption at nearly all times, enhancing the effect of ordinary daytime absorption and that appearing during ionospheric storms. Auroral absorption reaches a maximum in the regions of maximum auroral frequency shown in Fig. 43, in general, although erratic variation in absorption occurs over many different paths traversing this region.

Fig. 73 presents field-intensity records taken on two days, one being approximately normal, the other coincident with an auroral display. Here the sudden decrease of field intensity with onset of the auroral display is marked.

8. The Calculation of Sky-Wave Field Intensities

The distance range of radio waves is defined as the maximum distance at a given time and over a given transmission path at which a transmitter of a given power can produce a field intensity great enough to be useful. The lowest useful high frequency (abbreviated l.u.h.f.) is the lowest frequency in the range of frequencies from about 2 Mc up which will produce a field intensity great enough to be useful over a given transmission path at a given time.

The first step in the calculation of distance ranges or l.u.h.f. is to calculate the field intensity that will be produced by a given transmitter at a given distance over a path whose location and local times are specified.

At distances greater than about 500 miles from the emitting source, the field intensity received at a station may be expressed by the following relation:

$$F = F_o - \tfrac{1}{2}(S_o \overline{K} d) + \tfrac{1}{2} \log P ,$$

where F = $\log_{10}$ of the field intensity, in microvolts per meter, received at the location under consideration.

F_o = $\log_{10}$ of the "unabsorbed field intensity", in microvolts per meter, produced at the distance d by a transmitter radiating 1 kw of power.

S_o = subsolar absorption constant, twice the $\log_{10}$ of the ratio of incident to reflected sky-wave field intensity for a wave traveling 1000 miles at or near the subsolar point.

$\overline{K}$ = average value of the absorption index K over the path.

d = length of the transmission path, in thousands of miles.

P = radiated power, in kilowatts.

(S_o and d can also be expressed in terms of thousands of kilometers, or thousands of nautical miles, if convenient).

To aid in evaluating the received field intensity, the following are presented in this Handbook:

Figs. 74 through 76, F_o, the $\log_{10}$ of the unabsorbed field intensity for 1-kw radiated power, and its variation with both distance and frequency (distances expressed in mi., n.mi., and km).

Figs. 77 through 79. The variation with frequency of S_o, the subsolar absorption constant, for calculations in terms of mi., n.mi., and km.

Figs. 80 through 91. A set of absorption index charts showing the variation of K with latitude and local time, for each month of the year.

Fig. 92. An absorption map for the auroral zone.

Miscellaneous graphs and nomograms facilitating rapid computation of quantities in the above equation.

To compute the received field intensity, it is necessary to know the power radiated, the frequency of the signal, the location of both ends of the transmission path, and the time.

It is first necessary to calculate $\overline{K}$, the average value of the absorption index over the path, or $\overline{K}$ d, the average absorption index times the distance, over the given path. If the distance of transmission is not known, but is to be calculated, it is necessary to evaluate $\overline{K}$ or $\overline{K}$ d for various distances of transmission along the path.

For paths which do not pass through the auroral zones the following method is convenient for this calculation:

(1) Plot the terminal points of the transmission path on a sheet of transparent paper placed over the world map of Fig. 43, just as in the procedure for calculating the m.u.f. described in Section III above.

(2) Mark the meridian whose local times are to be used as the times for the calculations.

(3) Superpose the transparent paper on the great-circle chart of Figs. 44, 45, or 46, depending upon the choice of mi., n.mi., or km

as distance units, so that the latitude scales coincide.

(4) Slide the paper horizontally until the terminal points fall on the same great-circle curve, or the same proportional distance between great-circle curves.

(5) Sketch in the great-circle curve between the terminal points and mark distance intervals of 500 miles on it for reference, using as guides the small circles on the chart placed 500 miles apart. Note the total length of path d.

(6) Place the transparent paper over the absorption-index map for the month desired. Align the meridian marked in step 2 with the local time for which the calculation is to be made.

(7) Read K_1 and K_2, the values of the absorption index at the terminal points of the path. If one or both of the terminal points lie in the region bounded by the K = 0 contour, enter 0 for these values.

(8) Read the length of the path, in thousands of miles (or n.mi. or km), which lies in the region where K is <u>not</u> equal to zero. Call this length D'.

(9) Repeat steps 6, 7, and 8 for each time for which the calculation is to be made.

(10) The quantity $\overline{K}$, the average value of K over the path, can now be calculated by using the formula

$$\overline{K} = \left[0.142 + \frac{\tan \frac{1}{2}D'}{D'} (K_1 + K_2 - 0.284)\right] \frac{D'}{d} ,$$

where d is the total length of the path. Table 7 gives the values of the function $\tan \frac{1}{2}D'/D'$ for each 100 miles.

(11) The quantity $\overline{K}$ d can be calculated by using the formula

$$\overline{K}\, d = 0.142D' + \tan \tfrac{1}{2}D' \; (K_1 + K_2 - 0.284).$$

(12) Alternatively, the quantities $\overline{K}$ and $\overline{K}$ d may be obtained by entering the values of $K_1 + K_2$ and D' in the nomograms of Figs. 93 through 95, and 96 through 101, respectively,

(13) For other paths, or for the same path at other months repeat steps 1 through 12.

Table 7

Values of $\frac{\tan \frac{D'}{2}}{D'}$

Miles	0	100	200	300	400	500	600	700	800	900
0	0.500	0.500	0.500	0.500	0.500	0.501	0.501	0.501	0.502	0.502
1,000	0.503	0.503	0.504	0.504	0.505	0.506	0.507	0.508	0.509	0.510
2,000	0.511	0.512	0.513	0.514	0.516	0.517	0.519	0.520	0.522	0.524
3,000	0.525	0.527	0.529	0.531	0.533	0.535	0.538	0.540	0.542	0.545
4,000	0.547	0.550	0.553	0.556	0.559	0.562	0.565	0.568	0.572	0.576
5,000	0.579	0.583	0.587	0.591	0.595	0.600	0.605	0.609	0.614	0.619
6,000	0.624	0.630	0.636	0.642	0.648	0.654	0.661	0.668	0.675	0.682
7,000	0.690	0.698	0.707	0.715	0.725	0.734	0.744	0.755	0.766	0.777
8,000	0.789	0.802	0.815	0.829	0.844	0.859	0.875	0.892	0.911	0.930
9,000	0.950	0.972	0.994	1.019	1.045	1.073	1.103	1.135	1.170	1.207
10,000	1.247	1.292	1.340	1.393	1.450	1.514	1.585	1.664	1.754	1.854
11,000	1.968	2.101	2.253	2.436	2.651	2.911	3.240	3.652	4.204	4.954
12,000	6.049	7.835	11.124	19.605	83.101	-36.272	-14.626	-9.150	-6.604	-5.163
13,000	-4.225	-3.560	-3.074	-2.695	-2.398	-2.156	-1.954	-1.785	-1.639	-1.515
14,000	-1.407	-1.310	-1.225	-1.149	-1.081	-1.020	-0.964	-0.913	-0.866	-0.823
15,000	-0.783	-0.747	-0.713	-0.682	-0.652	-0.625	-0.599	-0.575	-0.552	-0.531
16,000	-0.510	-0.491	-0.473	-0.456	-0.440	-0.424	-0.410	-0.396	-0.382	-0.370
17,000	-0.357	-0.346	-0.334	-0.324	-0.313	-0.303	-0.294	-0.284	-0.276	-0.267
18,000	-0.259	-0.251	-0.243	-0.236	-0.229	-0.222	-0.215	-0.209	-0.202	-0.196
19,000	-0.190	-0.185	-0.179	-0.174	-0.168	-0.163	-0.158	-0.153	-0.149	-0.144
20,000	-0.140	-0.135	-0.131	-0.127	-0.123	-0.119	-0.115	-0.111	-0.107	-0.104
21,000	-0.100	-0.096	-0.093	-0.090	-0.086	-0.083	-0.080	-0.077	-0.074	-0.071
22,000	-0.068	-0.065	-0.062	-0.060	-0.057	-0.054	-0.051	-0.049	-0.046	-0.044
23,000	-0.041	-0.039	-0.036	-0.034	-0.032	-0.029	-0.027	-0.025	-0.022	-0.020
24,000	-0.018	-0.016	-0.014	-0.012	-0.010	-0.007	-0.005	-0.003	-0.001	0.001
25,000	0.003									

9. The Field-Intensity Factor A

For many calculations, it simplifies the procedure to use a quantity called the "field-intensity factor" (A) instead of working the problems through in terms of radiated power and logarithmic field intensity. The factor A combines these two quantities in a way such that after calculations have been made for a given path any desired values of radiated power and required field intensity can be used. The field-intensity factor A is characteristic of a given path at a given time.

The field-intensity factor A is defined as

$$A = 4 + \log_{10} \frac{E^2}{P} = 4 + 2F - \log_{10} P,$$

where E is the field intensity in microvolts per meter, F is the $\log_{10}$ of the field intensity in microvolts per meter, and P is the radiated power (not the power output of the transmitter) in kilowatts. A nomogram showing this relation is given in Fig.102. Table 8 gives approximate values of A for certain noise conditions and types of receiving set.

Table 8

Estimated Values of Field-Intensity Factor A

Power		Good receiving set			Average receiving set			Poor receiving set		
		Quiet	Mod. noise	Bad noise	Quiet	Mod. noise	Bad noise	Quiet	Mod. noise	Bad noise
Phone	(low	6	9	12	8	11	14	10	12	14
	(medium	4	7	10	6	9	12	8	10	12
	(high	2	5	8	4	7	10	6	8	10
CW	(low	4	7	10	6	9	12	8	10	12
	(medium	2	5	8	4	7	10	6	8	10
	(high	0	3	6	2	5	8	4	6	8

The radiated power is based on radiation from the standard antenna described above. For other types of antenna, an "effective" radiated power should be used, taking into account the relation between the horizontal and vertical radiation patterns of the antenna as compared with those of a short vertical antenna.

Examples of the use of the field-intensity factor are given below.

10. The Calculation of A over a Given Path

When the average value of K over the path is known ($\overline{K}$), the field-intensity factor for high frequencies (above 3 Mc) may readily be calculated for any value of S_o by the relation

$$A = A_o - S_o \overline{K} d,$$

where A_o is the unabsorbed field-intensity factor, defined as the value of A when E is replaced by E_o, the unabsorbed field intensity (or F replaced by F_o, the $\log_{10}$ of the unabsorbed field intensity), and P is made unity.

Typical values of S_o for different frequencies and seasons are given in Figs. 77 through 79. The values of A corresponding to the above formula can be read off the graphs of Figs. 103 through 105. These graphs show A as a function of distance d and of the quantity $\overline{K} S_o$. Given any two of these quantities, the third may be determined; for example, if the value of A is fixed by a known radiated power and required field intensity, a given distance corresponds to a definite value of $\overline{K} S_o$. Knowing what the $\overline{K}$ is for a given time of day, the S_o can be calculated, and thus the frequency, through the relation between S_o and frequency. Alternatively, the relation between A, d, and $\overline{K} S_o$ may be determined from the nomograms of Figs. 106 through 114, which express the same relation as the graphs of Figs. 103 through 105.

The relation between A, $\overline{K}$, S_o, and d can be represented graphically in a number of different ways, each of which has its own particular convenience for a particular operational use. For example, if it is desired to calculate regularly the l.u.h.f. over a given path, it is convenient to draw curves of $\overline{K}$ against frequency for that length of path, for various values of A. For any time of day, then, it is merely necessary to look up the value of f corresponding to the $\overline{K}$ for the path at the given time of day, corresponding to an assumed value of A based on an assumed required field intensity. If the required field intensity corresponding to the frequency so determined is not that assumed, it requires little effort to adjust the required field intensity assumed until it does agree with that for the frequency determined from the graphs.

A set of such graphs is given for a path 4000 km long in Fig. 115. An example of their use is given later.

11. Direct Calculations of Field Intensities

If desired, the logarithm of the field intensity can be calculated without reference to the field intensity factor. Figs. 116 through 118 give a graph of F_o', the $\log_{10}$ of the unabsorbed field intensity, as a function of the distance d for various values of radiated power in kilowatts. For a given frequency S_o can be read off Figs. 77, 78, or 79, and $\bar{K}$ d determined as above. Then, by using the formula,

$$F = F_o' - \tfrac{1}{2}S_o \bar{K} d,$$

F, the $\log_{10}$ of the field intensity in microvolts per meter can be obtained.

12. Paths Passing through the Auroral Zone

When a radio transmission path passes through latitudes higher than about 50°, it may include regions where there is abnormally high absorption of the radio wave energy. Such paths are characterized by lower received intensity, and more fluctuation, than other paths.

Such poor reception is caused by conditions in the "auroral zones", the regions where visible aurora is most prevalent. In these zones there are nearly continuous magnetic and radio disturbances, and the disturbances are much more severe than in surrounding regions.

Since the absorption of the energy of radio waves is particularly severe in the auroral zones, and is thus not symmetrical about the geographic poles of the earth, the variation of absorption in polar regions is not directly a function of local time, as is the normal D-region absorption represented by the absorption charts of Figs. 80 through 91. An extra amount of absorption, in addition to that shown in the charts, is undergone by radio waves traversing polar regions, and this absorption is a function of geographic longitude, and not of local time. The following considerations must therefore be allowed for, in determining radio transmission characteristics over any path which lies even partly in polar regions:

(1) Transmissions over paths which lie, even in part, in the auroral zones, are subject to a greater degree of irregularity and erratic performance than are transmissions over other paths.

(2) The absorption is very great, especially during daylight conditions in polar regions. As an example, stations operating at less than 6000 kilocycles can not be heard during daylight hours over any great distance in these regions.

(3) Severe and prolonged ionosphere storms occur frequently, often developing suddenly in the course of a few minutes. They are manifested by greatly increased absorption, which raises the lowest useful high frequency, and by a drop in the ionization of the higher

layers of the ionosphere, which lowers the maximum usable frequency. The result is the narrowing or complete disappearance of the bands of useful frequencies. It is not unusual for long-distance transmission to be impossible on all high frequencies for a day or more at a time, and to be erratic and only partially recovered on a small portion of the frequency spectrum for as much as a week. There have been instances of ionospheric storminess lasting almost continuously for a month.

(4) Frequently also, in auroral zones during ionosphere storms, there appears strong, widespread, and continuous intense sporadic-E transmission lasting for many hours. This may considerably improve radio reception in certain directions and over some paths while it lasts, but there is no way of predicting it.

(5) During the polar winter night conditions (except during ionosphere storms) good radio transmission is often experienced on frequencies up to near the maximum usable frequency.

(6) Some paths which are similar except for direction seem to display different propagation characteristics. For example, from parts of Greenland, the European high-frequency stations on about 9 to 15 megacycles are heard much better than United States stations at similar distances and frequencies. Also, while transmission across the auroral zone between the United States and Greenland is unfavorable for the broadcast frequencies, 550 to 1500 kilocycles, United States stations on these frequencies are received well in northern Canada and Greenland, during the winter night. Not enough is yet known about the auroral zone to explain such effects fully.

(7) Observations seem to indicate that the northern band of severe radio wave absorption is a relatively sharp one, centered slightly to the south of the northern line of maximum auroral frequency. Transmissions outside of this band are affected to a much smaller extent by the auroral absorption. Transmissions over paths which lie mostly within the band are not possible on frequencies less than about 6000 kc, over appreciable distances (1500 miles or more).

In the auroral zone, it is not possible to express at all accurately the variation of absorption for several reasons:

1. Insufficient data exist for these regions to give more than the roughest of estimates of absorption.

2. From available data, variation of absorption in the auroral zone is highly erratic.

3. The location of the maximum region of auroral absorption being at a definite longitude, rather than at a definite local time, pre-

vents accurate expression of the longitude variation of auroral absorption on a chart showing local time. For these reasons, calculation of absorption cannot be made in the manner described above.

The following procedure is offered to assist in estimating the normal performance of radio transmission paths which lie in or near the auroral zone. The map of Fig. 92 has been constructed, on which contours have been drawn following the observed zones of maximum auroral frequency. These contours are marked with numbers, which represent the amount K' to be added to the quantity $\overline{K}$ d for paths which pass through those regions. The method of use is as follows:

(1) Sketch in the great-circle path in the manner described above for the calculation of $\overline{K}$.

(2) Analyze the path into possible modes of transmission, one-hop, two-hop, etc. Determine the length of hop for each mode; call this D_n, say, for n-hop transmission.

(3) Locate the ground reflection points for each of the component hops. Locate points approximately one-sixth of D_n on each side of each ground reflection point. These are the D-layer points.

(4) For each mode of transmission, add together the values of K' for all the D-layer points.

(5) The minimum of the values so obtained for different modes, multiplied by the factor given in Table 9 for the various values of D_n, is the amount (K") to be added to the $\overline{K}$ d for the path, as given in miles. If $\overline{K}$ d is given in kilometers, these factors should be multiplied by 1.609; if in nautical miles, by 0.868.

For such paths, then, the value of $\overline{K}$ d calculated as described above for the normal daytime absorption is to be increased by the amount K" before the remainder of the field-intensity calculation can be made. This part of the calculation is for undisturbed days. When an ionosphere storm takes place in the auroral zone, which may happen, during certain periods, about 50% of the time, the absorption is greatly increased, and no high-frequency radio communication of any kind may be possible. It must be noted that this is only a first approximation to the calculation of auroral-zone absorption. It is included so that the user may have some kind of rough guide as to the amount of absorption introduced by passage through the auroral zone. This is based on information at present available, which is rather scanty. As more information becomes available, the auroral-zone map will be revised and better values of K' given.

For paths which pass through the auroral zones it is usually advisable to choose the highest frequency that can be used for sky-wave transmission, i.e., the m.u.f. During times of disturbances, the use of frequencies in excess of the normal m.u.f. may be tried, since the presence of sporadic-E layer may permit transmission when the F-layer m.u.f. is so low that the absorption accompanying the disturbance would be too great to permit transmission on a frequency low enough so as not to skip by F,F_2-layer transmission.

Table 9

Absorption Factors for Auroral-Zone Paths

Miles	0	100	200	300	400	500	600	700	800	900
0	0.11	0.11	0.12	0.14	0.16	0.19	0.22	0.25	0.28	0.31
1000	0.35	0.38	0.41	0.44	0.47	0.50	0.53	0.55	0.57	0.59
2000	0.60	0.61	0.62	0.62	0.62	0.62	-	-	-	-

13. Distance Ranges and Lowest Useful High Frequencies

As radio waves decrease in intensity on spreading out from the transmitter, and as they lose energy by absorption in either the ground or the ionosphere, they finally become so weak that they can not be heard above the level of radio noise at the receiving station. This radio noise may be either "static" or man-made electrical disturbance. The minimum radio field intensity needed to allow an intelligible signal to be heard above the noise at the receiving station is called the required field intensity, and the distance from the transmitter to any point beyond which the radio field intensity is less than the required field intensity is the distance range.

The required field intensity is subject to wide variation. It depends on the receiving antenna, the type and adjustments of the receiving set, the local electrical noise, "static", and the type of modulation of the radio wave. It varies, with the noise, according to the time of day and season.

The distance range depends in addition on the transmitting station power and antenna and on the energy loss by absorption in the ground or ionosphere. The determination of distance ranges is a very complex problem, although effects of many of the factors, such as radiated power, antenna design, and absorption of the wave energy can be calculated with fair precision.

In general, for a given path of transmission and time of day, waves of higher frequencies undergo less energy absorption than do waves of lower frequencies. Thus waves of lower frequencies arrive at the receiving point with less energy than waves of higher frequencies, if the radiated power of the transmitter is the same on high and low frequencies. There is consequently usually some frequency, for a given distance and radiated power of the transmitter, below which the field intensity of the waves at the receiver is too weak to use. This is called the lowest useful high frequency, for the given distance, radiated power, and state of the ionosphere. (It is not called the lowest useful frequency, because there is useful ground-wave transmission at very much lower frequencies).

In contrast to the maximum usable frequency, which does not depend on radiated power, the lowest useful high frequency depends on all the factors which were given above as affecting the distance range. The maximum usable frequency depends almost entirely on the state of the ionosphere; the lowest useful high frequency depends in addition on the equipment and on local receiving conditions, and is not nearly as well-defined or clear-cut as is the maximum usable frequency. Note that the lowest useful high frequency has the same relation to the distance range as has the maximum usable frequency to the skip distance. The distance range and the skip distance are the limits of the range of useful distances; the maximum usable frequency and the lowest useful high frequency are the limits of the band of useful frequencies.

It is possible to calculate with fair accuracy, from vertical-incidence measurements, the total median sky-wave field intensity as a function of distance for any radiated power and any specified type of antenna. The field intensities required for reception depend on many factors, and much more detailed data are needed before these requirements can be stated to an accuracy compatible with that of the field intensity.

14. Field Intensities Required for Reception

In order to determine whether or not a signal will be successfully received, the field intensity at the point of reception must equal or exceed a certain value, called the "required field intensity", determined by the sensitivity or the receiving apparatus and degree of masking of the signal by radio noise, which includes receiving-set noise, man-made noise at and near the receiving station, and atmospheric noise, both from nearby electrical or thunder storms, and from distant noise centers, propagated along the transmission path like the radio wave itself.

The minimum field intensity required for a given service also depends on the type of service. Measurements have shown, for example, that the field intensity required for a given reliability of radiotelegraph (CW) communication is only about 1/8 of that required for a radiotelephone (phone) service of the same reliability. Table 10 gives an indication of the relative field intensities required for a reliable service, based on the value for commercial phone service.

Table 10

Correction Factors for Various Types of Service

(Ratio of required field intensity for type of service under consideration to that for barely satisfactory commercial telephony).

Type of Service	Ratio		$\log_{10}$ of Ratio	
	Barely satisfactory	Entirely good	Barely satisfactory	Entirely good
Commercial telephony	1.0	6.0	0.0	0.8
Broadcasting	1.6	13.0	0.2	1.1
Telegraphy (aural)	0.2	0.5	-0.7	-0.3
Telegraphy (automatic)	1.0	2.5	0.0	0.4
Telegraphy (printing)	1.5	4.5	0.2	0.6
Direction finding (small loop)	13.0	40.0	1.1	1.6
Direction finding (modern)	2.0	6.0	0.3	0.7
Facsimile	1.0	2.5	0.0	0.4

Aside from considerations of receiving set quality and operator's ability, both of which are highly important, the ratio of field intensity to the radio noise level is the most important factor in determining the reliability of a given service. The type of noise must be considered in this respect, - whether the noise consists of high peaks and a relatively low background level, or of relatively low peaks and a high average background noise level. The degree of directivity of the receiving antenna, together with the predominant direction of arrival, if any, of the atmospheric noise plays an important role also.

15. Atmospheric Radio Noise*

The first step in determining required fields consists of an analysis of the causes of atmospheric noise level in different parts of the world. Most of the atmospheric noise in the world originates in thunderstorms. At a given location the noise level is made up of noise from nearby centers of noise, such as local thunderstorms whose distance from the receiving set may vary from a few miles to hundreds of miles, plus noise which has been propagated to the receiving location from one or more of the principal centers of noise generation, such as the active thunderstorm areas in equatorial

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*Much of the information in this Section is based on data from or originally collected by I.S.I.B.

Africa, Central America, and the East Indies. The location and activity of the various noise centers vary with time of day and season, but probably not much with the sunspot cycle.

The determination of the diurnal variation of noise at any location is thus a series of radio propagation problems, in which the noise originating in each center of storm activity produces a definite field intensity at the location being studied. The problem is to calculate the relative field intensity contributed on each frequency and at each time of day by each noise center, and then to combine them, with due regard to the direction of arrival and the directivity of the receiving antenna. To this must be added the noise due to local thunderstorm activity, if any, and the result is a picture of the diurnal variation of the noise quality and level at the given receiving location. The noise variation thus theoretically calculable can then be referred to average required field-intensity data, for some frequencies and times of day, and curves can then be drawn of required field intensities on all frequencies at all times of day.

The above is the line of investigation to be followed in the study of the required field-intensity problem. As a temporary expedient, until the more exhaustive study can begin producing results, the following information on required field intensities is presented.

Figs. 119 and 120 are maps of the world divided roughly into noise zones. They are based on the well-known thunderstorm charts of Dr. C. E. P. Brooks, but contain revisions based on more recent data and include the tropical ocean areas of bad weather, known as the doldrums. The areas of the world in which thunderstorms are most frequent, and in which local thunderstorms may be of almost daily or daily occurrence, are indicated as zones 4 and 5. The areas most remote from the principal thunderstorm areas, and in which but little atmospheric radio noise may be expected, even by way of long-distance sky-wave propagation on high frequencies, are indicated as zone 1. The other zones are intermediate in radio noise expectation.

Corresponding to these noise zones are the required field-intensity graphs of Figs. 121 through 125. These data are for about the middle of each zone; for locations near the boundaries between zones the values should be found by interpolation. The required field intensities given are those for a reasonably good radiotelephone service; they are not adequate for a broadcast quality service, nor are they so low that much difficulty and repetition would be required in order to get a message through. The values for other types of service may be obtained from the values on these curves by multiplying them by the ratios given in Table 10.

The atmospheric noise (often called atmospherics, or static) which governs the required field intensities for radiotelephony, shown in the graphs, has all been assumed to originate in lightning discharges somewhere on the surface of the earth. Man-made noise, electrical or otherwise, and precipitation static (rain, snow) or static due to dust or sandstorms, have not been included in the graphs, although they may at times, depending upon local considerations at particular receiving sites, be dominating factors. Lightning discharges which cause atmospheric radio noise are believed to occur, at some time or other, at practically every place on the earth's surface except in the polar regions. However, most lightning discharges occur within certain rather well-defined areas. These areas, while primarily in the tropics, extend well into temperate regions in the respective summers and autumns of each hemisphere (i.e., June, July, and August for the northern hemisphere; December, January, and February for the southern hemisphere).

Over tropical land masses, such as central Africa, northern South America, the West Indies, the East Indies, and Northern Australia, the maximum incidence of thunderstorms occurs at about 1600 local time, with a minimum at about 0400 local time. Even at the minimum, however, there may be considerable storm activity. Over tropical ocean areas, i.e., the central doldrum area and the adjoining regions of the trade wind belt, thunderstorms rarely occur by day but are likely to be frequent at night, and tend to a peak of activity jurt before sunrise. In some regions of the East and West Indies, where the ocean (doldrum) mechanism acts with the land mechanism of thunderstorm production, there may be two peaks of thunderstorm activity; one about 1600-2000 local time and the other about 0600 local time. In all tropical regions there is a minimum of local atmospherics around 0800-1100 local time.

A given lightning discharge produces a radio noise intensity at a nearby receiver which depends, for a given receiver band width, principally upon frequency. The noise intensity is greatest on low frequencies, and appears in general to vary inversely as the first or 3/2 power of the frequency. This frequency characteristic, or so-called "spectral" law is roughly taken account of in the graphs.

In general, the areas marked 5 and, to a lesser degree, those marked 4, are regions where one or more local thunderstorms occur nearly every day, in the vicinity of any given point in the zone. The radio noise observed in these zones does not show any conspicuous change in intensity from day to night. This is shown in Figs. 124 and 125. The noise is least in these zones in mid-morning, and from about 0800 to 1100 local time is the best time for radio reception. It is to be noted that a signal that cannot be used for communication at this time is likely to be useless at any other time of day in these zones.

For calculation of noise, regions 4 and 5 may be regarded as generating centers for the noise. The effects diminish with increasing distance from these centers. A fair approximation to the noise level can be obtained by making calculations of the propagation from areas 4 and 5, bearing in mind the diurnal variation in intensity. The noise generated in areas 4 and 5 is roughly proportional to the areas of the zones; the activity is greater in zone 5, so that a given area of zone 5 is equivalent to a considerably larger area of zone 4. The noise intensity produced by any one land center, exclusive of propagation effects, may be considered to vary within a ratio of about 5 to 1 during the day, having a maximum at 1600 and a minimum at 0400 local time.

Areas marked 3 are those in which there are occasional local thunderstorms in most parts of the area. The local noise produced by these storms is similar in intensity to that produced by the storms of areas 4 and 5, but the general noise level is greater in areas 4 and 5 because of the greater prevalence of storms. For frequencies of 2 to 10 Mc there is a substantial contribution to the noise level by ground- and sky-wave propagation of noise from these relatively local thunderstorms, the remainder of the noise being caused by longer distance propagation of noise from areas 4 and 5. For frequencies of 12 to 20 Mc by day, and 8 to 15 Mc by night the local noise skips over the receiver, and the remaining radio noise is caused by long-distance propagation primarily from areas 4 and 5.

Areas marked 3 and 4 over tropical ocean areas are the source of sudden intense night thunderstorms on some nights. These are especially likely to occur around 2000 and 0600 local time, although they may occur at any time during the night. When a period of nights occurs without any storms, these areas are as quiet as any other ocean area; when the night storms are prevalent, the areas may be very noisy. Since these ocean areas are noise centers by night only, the regular diurnal variation of noise does not apply to them. Consequently they are to be regarded as having their assigned grade (3 or 4) at night, but a lower grade by day. It is suggested that this lowering of grade be accomplished, for calculation, by splitting the difference between the assigned grade and grade 2. That is, if a location corresponds to grade 3.4, say, the daytime grade will be 2.7.

Areas marked 1 and 2 are remote from the centers of noise generation, and the atmospheric noise is determined almost entirely by propagation from the centers of areas 4 and 5. In area 2 there may be an occasional local storm; hardly ever will there be one in area 1.

The diurnal characteristics of noise are most marked in areas 1 and 2, and to a lesser degree in 3. See Figs. 121-123. In these zones daytime noise is fairly low at frequencies from 0.5 Mc up to perhaps 10 or 12 Mc. Above and below this frequency range, long-distance propagation of atmospherics from the noise-generating centers in areas 4 and 5 becomes important, and causes the noise level to increase. Above about 20 Mc at sunspot minimum, and 30-40 Mc at sunspot maximum, the long-distance noise will not be received because of skip. The graphs of Figs. 121 through 125 show this effect as a dropping-off of the required field intensity at the higher frequencies.

In the daytime the atmospheric noise at frequencies between 0.5 Mc and 12 Mc is greater in areas marked 3 than in those marked 1 and 2 because of the increased number of thunderstorms occurring within a radius of 100 to 1000 miles of the receiving site. The effects of truly local storms (those occurring within about 20 miles of the receiving site) can not be represented on the charts because of the enormous and varying noise intensities they produce. Much of the radio noise from such local storms, particularly on the lower frequencies, is due to induction in the receiving antenna, rather than to radiation of the noise energy.

At night in zones 1 and 2, and in zone 3 to a lesser degree (because of some local noise production), the required field intensity decreases with increasing frequency roughly according to the spectral law mentioned above. Above the m.u.f. for long-distance propagation (about 10 Mc at sunspot minimum, and perhaps 15-20 Mc at sunspot maximum) even the most oblique reflections cannot be propagated, and the noise decreases very rapidly with increasing frequency.

When considering noise on directional receiving antennas, it should be noted that the principal generating centers, indicated by areas 4 and 5, will have little effect on reception if the antennas point away from them. On the other hand, a transmission path across one of the centers, like the path from London to Capetown, gains nothing by having directional receiving antennas except to exclude a little noise arriving from the side. This is because the antennas point directly at the noise source. Considerations such as these have in the past been responsible for supposed "non-reciprocity" in high-frequency radio communication. For example, in transmission between New York and Berlin the New York station always received Berlin quite easily whereas at times the Berlin station, with essentially the same equipment, could hardly hear New York. The reason for this is that Berlin's directive receiving antennas point also toward the summer noise sources in Florida, Mexico, and Central America.

In using the required field-intensity graphs of Figs. 121 through 125 it is to be noted that the edges of the zones do not represent sudden changes in noise. For example, a location in zone 2 near the boundary between 2 and 1 will have a noise level part way between those shown on the graphs for grade 2 and those shown on the graphs for grade 1. For purposes of interpolation, the boundaries between zones may be taken as half-grades. For example, the boundary between zones 2 and 3 is to be taken as grade 2.5, and the center of zone 3 is to be taken as grade 3. It is believed that a useful indication of the required field intensity for radio communication on most days and nights will be obtained by the use of the graphs and maps of Figs. 121 through 125, bearing carefully in mind all the time the discussion above. The required field intensity will in general vary from day to day; the graphs represent average conditions. The values given on the graphs are not valid during periods of purely local thunderstorms; during these periods the required field intensities may sometimes be very high.

It is to be noted that the information as given in Figs. 121 through 125 is intended to apply to non-directional receiving antennas only. The use of a directional antenna pointed away from a "static" source will discriminate against the noise and permit the use of a smaller field intensity for communication than would be needed were the antenna non-directional.

16. The Calculation of Lowest Useful High Frequencies

The lowest useful high frequency is the lowest frequency, in the range from 2 Mc on up, by the use of which a transmitter of a given power will produce at least the minimum required field intensity for a given service at a given time of day and over a given path. It is obtained by calculating the field intensity actually produced by the transmitter, and comparing it with the required field intensity, on various frequencies. The frequency at which the two are equal is the l.u.h.f.

In making this comparison, the following variables have to be considered; the radiated power of the transmitter, the frequency or frequencies to be used, the absorption index over the path, the required field intensity for the desired service, the times when communication is desired, and the directivity, if any, of the transmitting and receiving antennas. Depending on the type of problem, some of these variables are arbitrarily fixed, and it is desired to calculate others. The methods to be followed for rapid operational use of ionospheric data for this purpose need to be devised or revised for each particular class of problem.

In Figs. 126 through 128 are given "master field-intensity nomograms" with provision on them for plotting any arbitrary variation of required field intensity with frequency. By the use of a number of these for a given receiving location, one for each time of day, values of the l.u.h.f. can be scaled off very rapidly, after having calculated the values of $\bar{K}$ d for the paths to be investigated.

These nomograms, like the other methods of field-intensity calculation given in this Handbook, are based on the equation:

$$F = F_o - \tfrac{1}{2}S_o \bar{K} d .$$

The left-hand scale of the nomogram, marked "equivalent distance" needs special mention. The distances labeled thereon are accurate for 1-kilowatt radiated power. For other values of power the scale must be displaced vertically-upward for increased power, downward for decreased power - by a linear amount proportional to the logarithm to the base 10 of the radiated power. For convenience, an auxiliary distance scale has been printed alongside the nomogram, indicating how the scale should be lined up for various powers. The value of power P on the scale should be aligned with the arrow on the nomogram.

A straight line connecting the equivalent distance with the $\bar{K}$ d value and crossing the frequency-field intensity grid determines the variation of field intensity with frequency for given values of power, distance, and $\bar{K}$ d. If on the same grid a curve of required field intensity against frequency be drawn, the intersection of this curve with the straight line gives the l.u.h.f. For this purpose the nomograms can be simplified by omitting the field-intensity lines and drawing only the vertical (frequency) lines on a piece of transparent paper and the required field-intensity curve.

For greater facility in estimating distance ranges or lowest useful high frequencies under normal receiving conditions, where the midpoint of the transmission path lies between 30°N and 50°N, resource may be had to nomograms of the type regularly presented in the monthly report on radio propagation conditions, supplementary to this Handbook, a sample of which is given, for December, in Fig. 129. Here is presented the co-variation of the distance range, power, time of day, and frequency, so that any one of these quantities, may be determined if the other three are known. The lowest useful high frequency for a given distance is the frequency for which that distance is the distance range.

Fig. 130 similarly presents more comprehensive although somewhat less precisely known information on distance ranges and lowest useful high frequencies for transmission paths whose midpoints may be at any latitude between 60°S and 60°N. (In this nomogram, northern latitudes are represented as positive, southern as negative values).

Although the method of use of this last nomogram is, as in other cases, illustrated by an example thereon, special instructions may not be amiss, since nomograms of this type are rather complex.

A perpendicular is drawn from the time point on the latitude line corresponding to the midpoint of the path to the reference line C. A line is drawn from the latitude point corresponding to the midpoint of the path at the base of the power cone to its vertex. The intersection of this line with the line indicating the radiated power, when connected to the frequency used, is projected to the reference line B. A line from the point determined on reference line C, through the point determined on reference line B, is projected to reference line A. From its intersection with A, a perpendicular drawn to the latitude line corresponding to the midpoint of the path indicates the distance range.

If the foregoing process is reversed to the extent that the desired distance range is previously known, the frequency indicated will be the lowest useful high frequency for the transmission path.

17. Note on Units

Because of the logarithmic response of the human ear and much radio equipment, and because absorption in the ionosphere is logarithmic, it has been convenient for calculation to adopt the $\log_{10}$ of the field intensity in microvolts per meter, rather than the field intensity in microvolts per meter itself, as the unit of field intensity. For the benefit of radio and communication engineers who are familiar with the decibel as a unit of ratio, it is to be noted that the field intensity in decibels above 1 microvolt per meter is 20 times the $\log_{10}$ of the field intensity in microvolts per meter. The power radiated from an antenna in decibels above 1 kw is 10 times the $\log_{10}$ of the radiated power in kw. Since the field intensity is proportional to the square root of the radiated power, it is evident that a 10-db change in radiated power also produces a 10-db change in the field intensity. If a directional transmitting antenna has a gain of 15 db, the field intensity at a given point will be 15 db higher than if a non-directional antenna were used. The absorption constant S_o in db is 10 times the value given in Figs. 77-79. The field-intensity factor A as used in this book, may be expressed in db by multiplying the values on the graphs and nomograms by 10.

The field intensity formula given on page 79 may be rewritten

$$F = F_o \; S_o \; \bar{K} \; d + P$$

if F, F_o, S_o, and P are all given in db.

Appendix A. Plan for Future Parts of Handbook

(The order of Parts is chronological, i.e., the approximate order in which the issuance of the multilithed versions is planned. In the eventual printed version of the Handbook a more logical order will be used).

Part 2. Optimum Frequencies

- I. Definition
- II. Calculations
  - 1. Short paths
  - 2. Long paths, good conditions
  - 3. Long paths, poor conditions
- III. Use of optimum frequencies
  - 1. Frequency allocation
  - 2. Choice of frequency from those allocated
  - 3. Guide to compromise
- IV. Rapid estimation of optimum frequencies and field intensities

Part 3. Ground-Wave and Low-Frequency Propagation

- I. Ground wave
  - 1. Description
  - 2. Ground-wave distance ranges
  - 3. Methods of calculation
- II. Low frequencies
  - 1. Description
  - 2. Diurnal variations
  - 3. Method of calculation
    - a. Radiated power
    - b. Intensities

Part 4. Factors Determining Propagation Conditions

- I. Dependence of transmission conditions on the path.
  - 1. Latitude and local time
- II. Great-circle path.
  - 1. The direct path
  - 2. The long path
  - 3. Lateral deviations
- III. Calculation for great-circle paths
  - 1. Distance
  - 2. Bearing
  - 3. Latitude and local times of midpoint of path.
- IV. World maps
  - 1. Rectangular projection
  - 2. Method of determining great-circle paths
- V. World radio conditions
  - 1. Noise maps
  - 2. Auroral zone maps

- VI. Required field intensities
  - 1. Noise level
  - 2. Type of receiver and operator
  - 3. Type of operation
  - 4. Antenna directivity
  - 5. Frequency
  - 6. Time of day and season
  - 7. Variations
  - 8. Atmospheric noise propagation
  - 9. Graphs and tabular values
  - 10. Radiated power
    - a. Power input to antenna
    - b. Antenna efficiency
    - c. Radiated power
    - d. Directional effects
    - e. Effective radiated power
  - 11. The field-intensity factor "A"
    - a. Definitions
    - b. Measure of conditions over a path
    - c. Use in radio transmission calculations

Part 5. Propagation above 40 Mc

- I. General description
- II. Components of the wave at frequencies above 40 Mc
  - 1. Surface wave
  - 2. Direct wave
  - 3. Ground-reflected wave
  - 4. Troposphere wave
- III. Propagation effects
  - 1. Refraction and reflection in the atmosphere
  - 2. Effect of antenna height
  - 3. Effect of ground conductivity
  - 4. Calculation of field intensity and distance ranges
  - 5. Anomalous propagation effects
- IV. Factors affecting distance range
  - 1. Antenna directivity
  - 2. Radio noise at high frequencies.

Part 6. Angles of Arrival and Departure

- I. Vertical angles
  - 1. Relation to ionospheric heights
  - 2. Methods of calculation for:
    - a. Single-hop transmission
    - b. Long-path transmission
  - 3. Variations of vertical angles caused by:
    - a. Normal ionospheric variations
    - b. Fading of various components
    - c. Ionospheric irregularities
  - 4. Applications to special problems

- II. Horizontal angles
    - 1. Great-circle and off-path transmission
    - 2. Causes of lateral deviation
    - 3. Relation to m.u.f. and modes of propagation
    - 4. Geographical considerations
    - 5. Relation to ionosphere irregularities
    - 6. Methods of calculation
- III. Retardation times
    - 1. Relation to sky-wave propagation
    - 2. Velocity of propagation
    - 3. Methods of calculation
    - 4. Applications to special problems

Part 7. Antenna Radiation and Reception

- I. The mechanism of radiation
    - 1. Principles of radiation
    - 2. The electromagnetic field from antenna
        - a. Induction field
        - b. Radiation field
    - 3. Polarization
- II. Directional effects
    - 1. Directional patterns of the simple antenna
        - a. Ground wave
        - b. Sky wave
    - 2. Directional patterns of long-wire antennas
    - 3. Directional arrays
- III. Antenna design and efficiency
    - 1. Effect of propagation data on the design of antennas
        - a. Vertical and horizontal angles of departure
        - b. Location of sites
    - 2. Radiated power
        - a. Antenna losses
        - b. Directional radiation
- IV. Antennas for special purposes
    - 1. High- and low-angle antennas
    - 2. Antennas for direction finding

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Mrs.
Payne

CAUTION

Figs. 43-58, 66, 80-92, 119, 120 should all be to same scale (length 9 in.) if transparency is used.

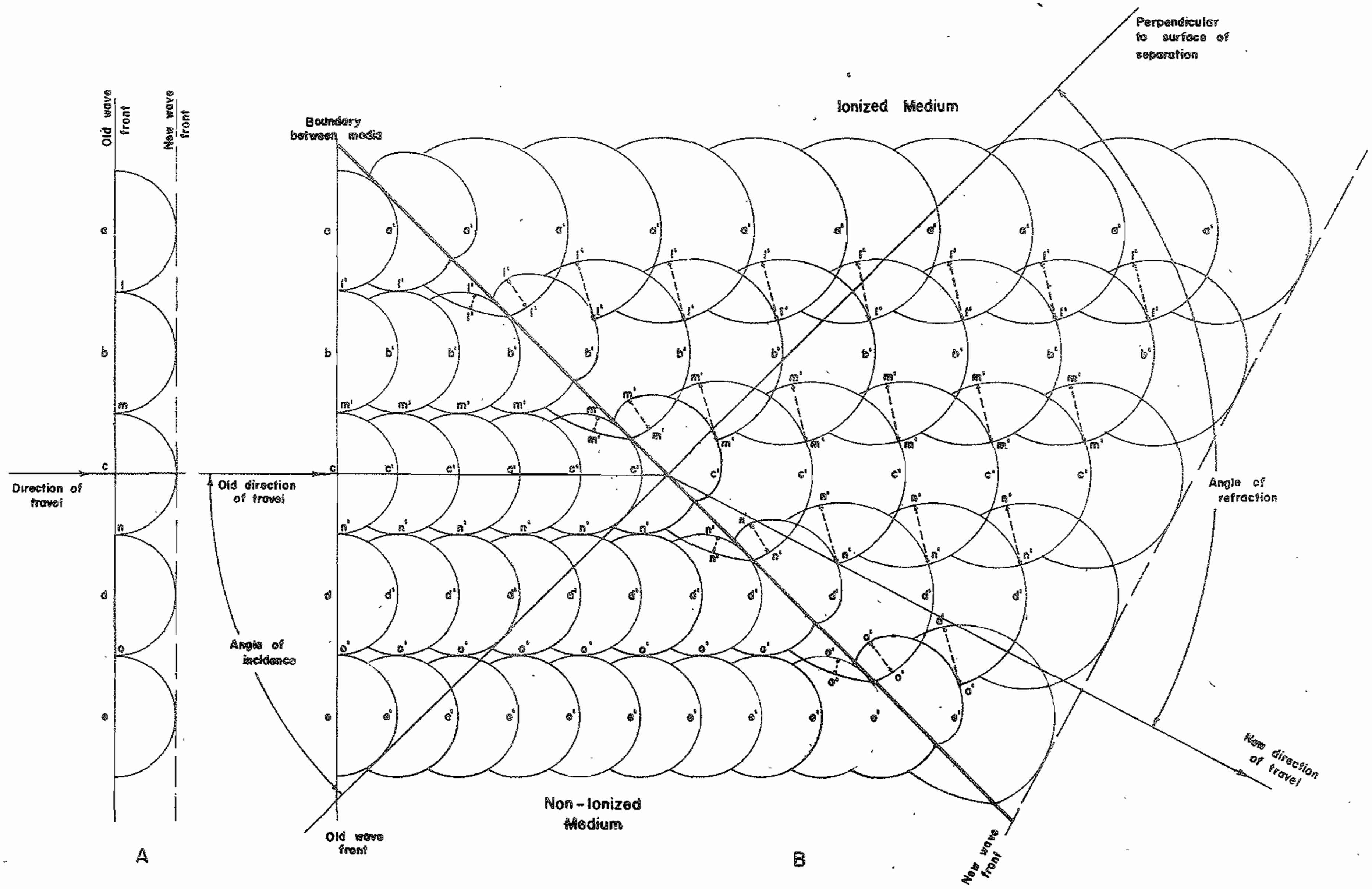


Fig. 1. A. Propagation of wave front in a uniform medium.
B. Propagation of wave front on passing into a medium in which the wave phase is continually being advanced.

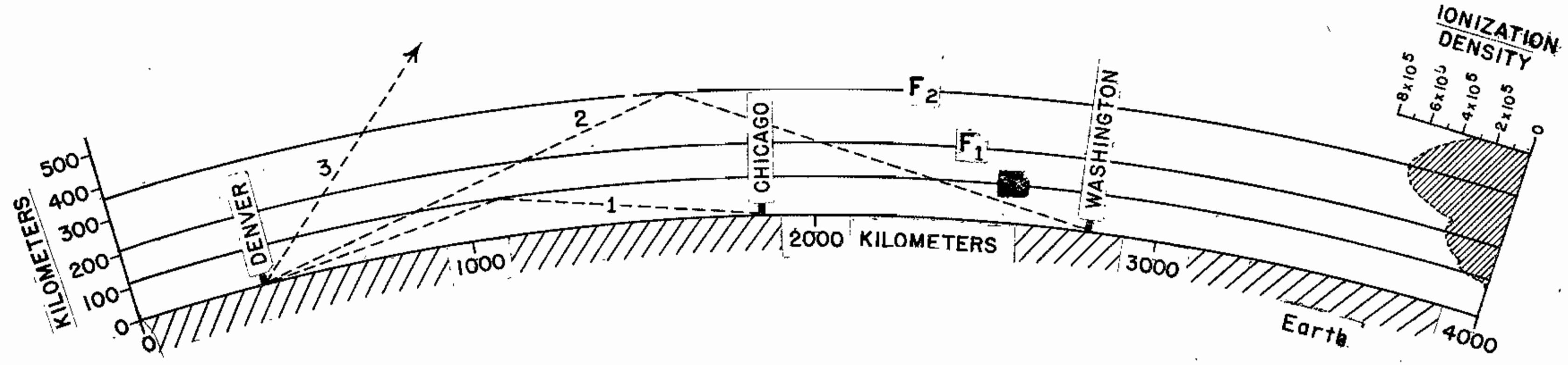


Fig. 2. Structure of the ionosphere, summer daytime condition. Dashed lines 1 and 2 indicate two of many possible paths of radio waves reflected by the ionosphere.

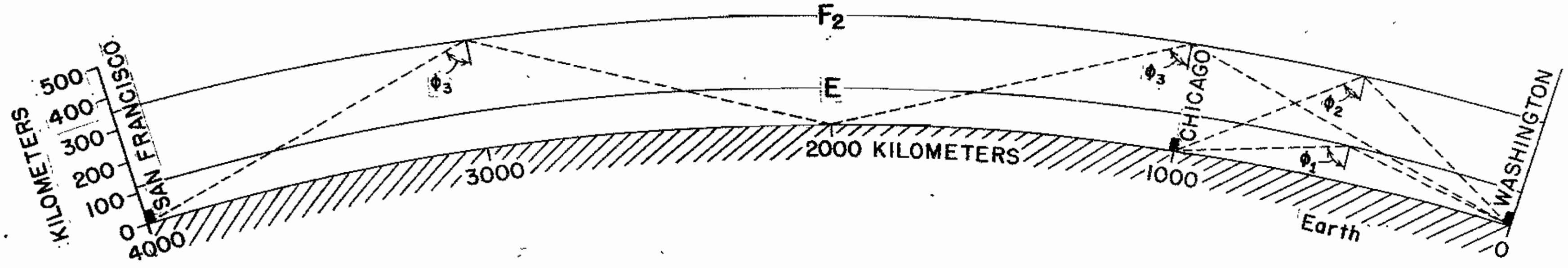


Fig. 3. Single- and multiple-hop transmission by reflection from regular ionosphere layers, night (or winter daytime) conditions.

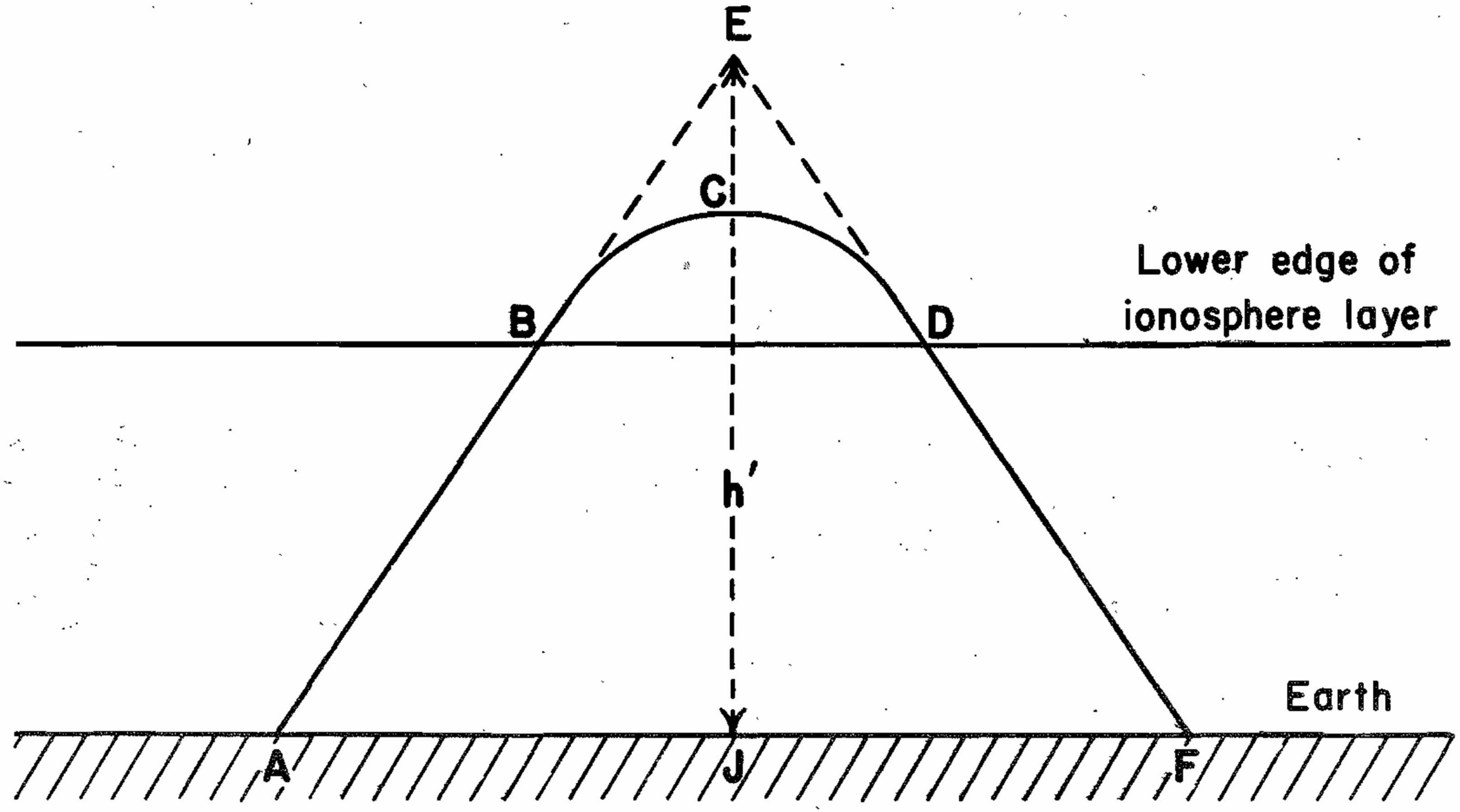


Fig. 4. Transmission path of a radio wave refracted by an ionosphere layer (ABCDF). Virtual height is indicated by JE.

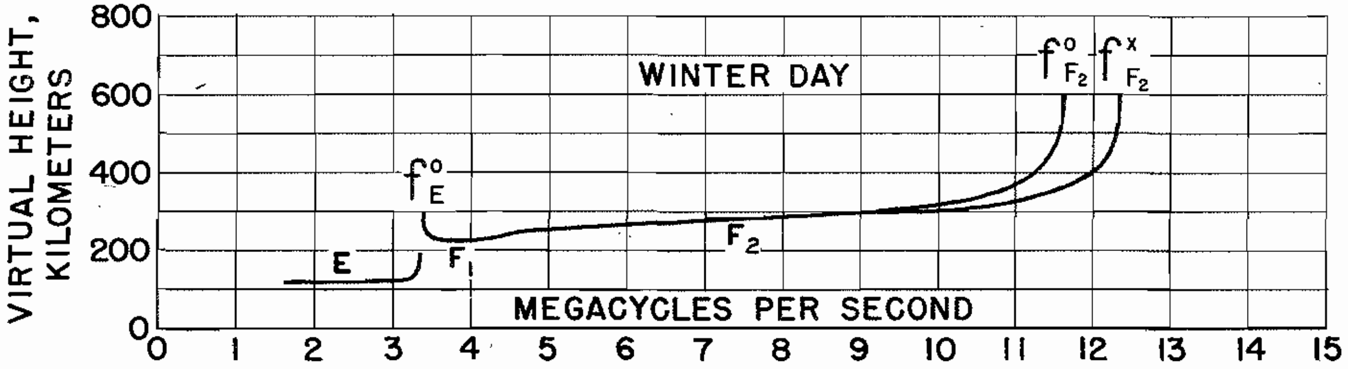


FIG. 5

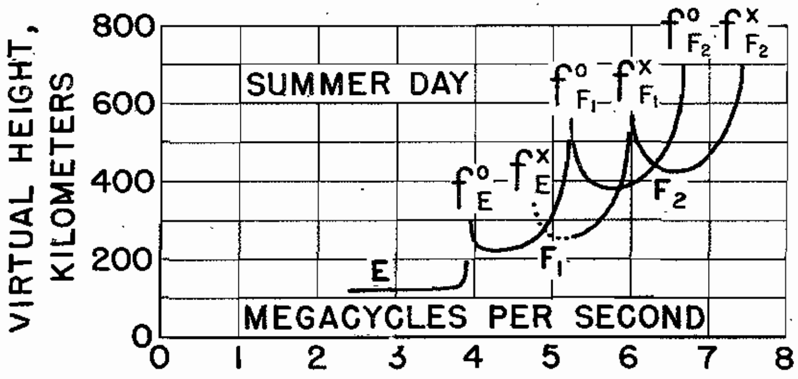


FIG. 6

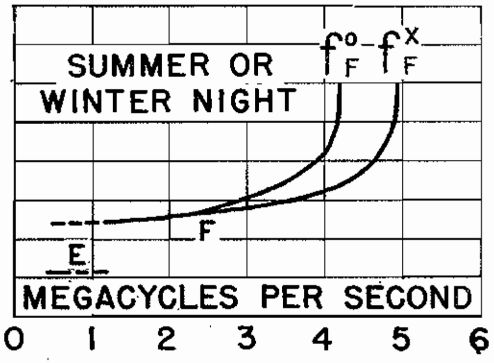


FIG. 7

Figs. 5, 6, 7. Typical virtual height-frequency sweeps (h'-f curves).

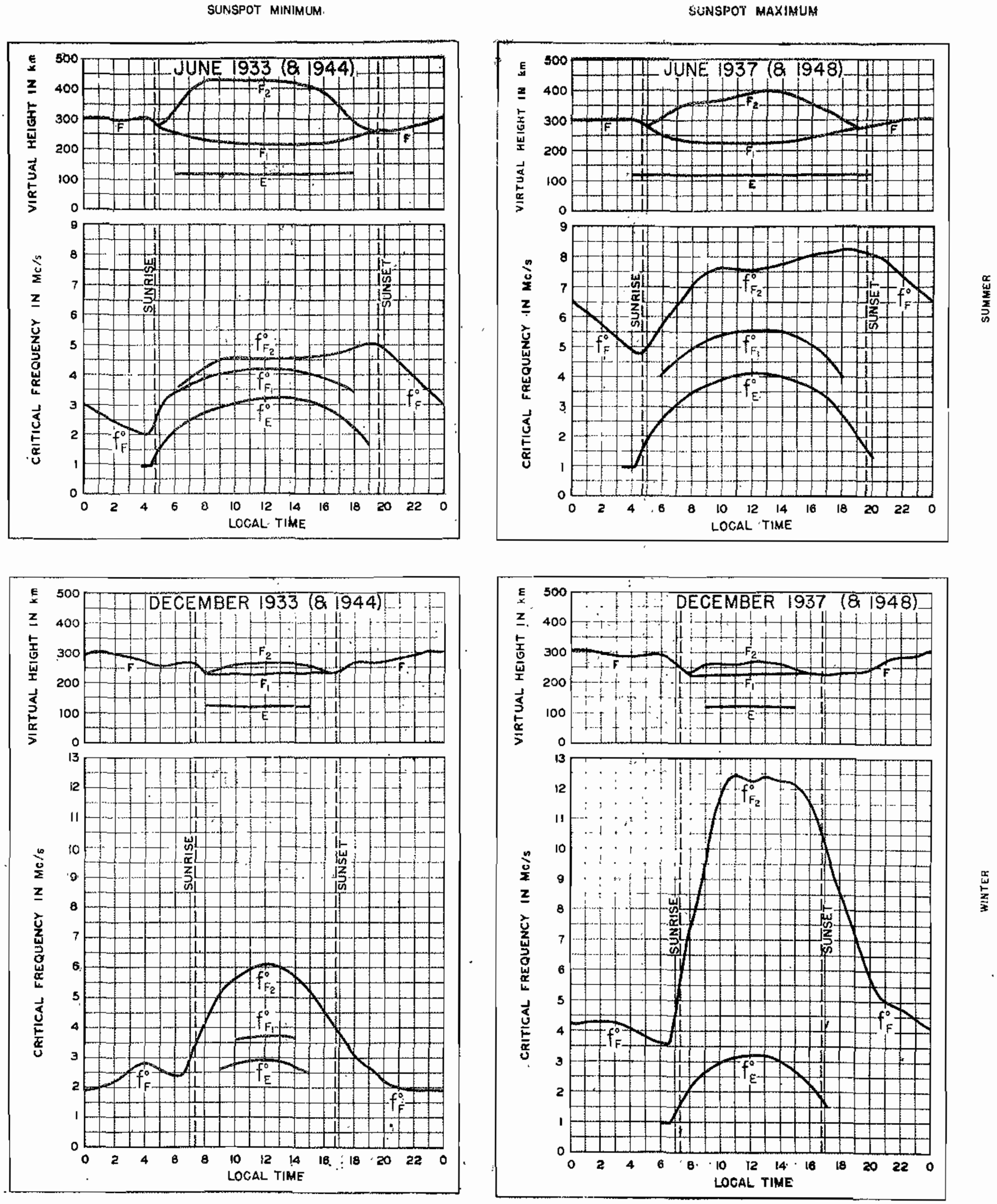


Fig. 8. Typical diurnal variation of critical frequency and virtual height of the regular ionosphere layers for summer and winter conditions, at periods of sunspot minimum and maximum.

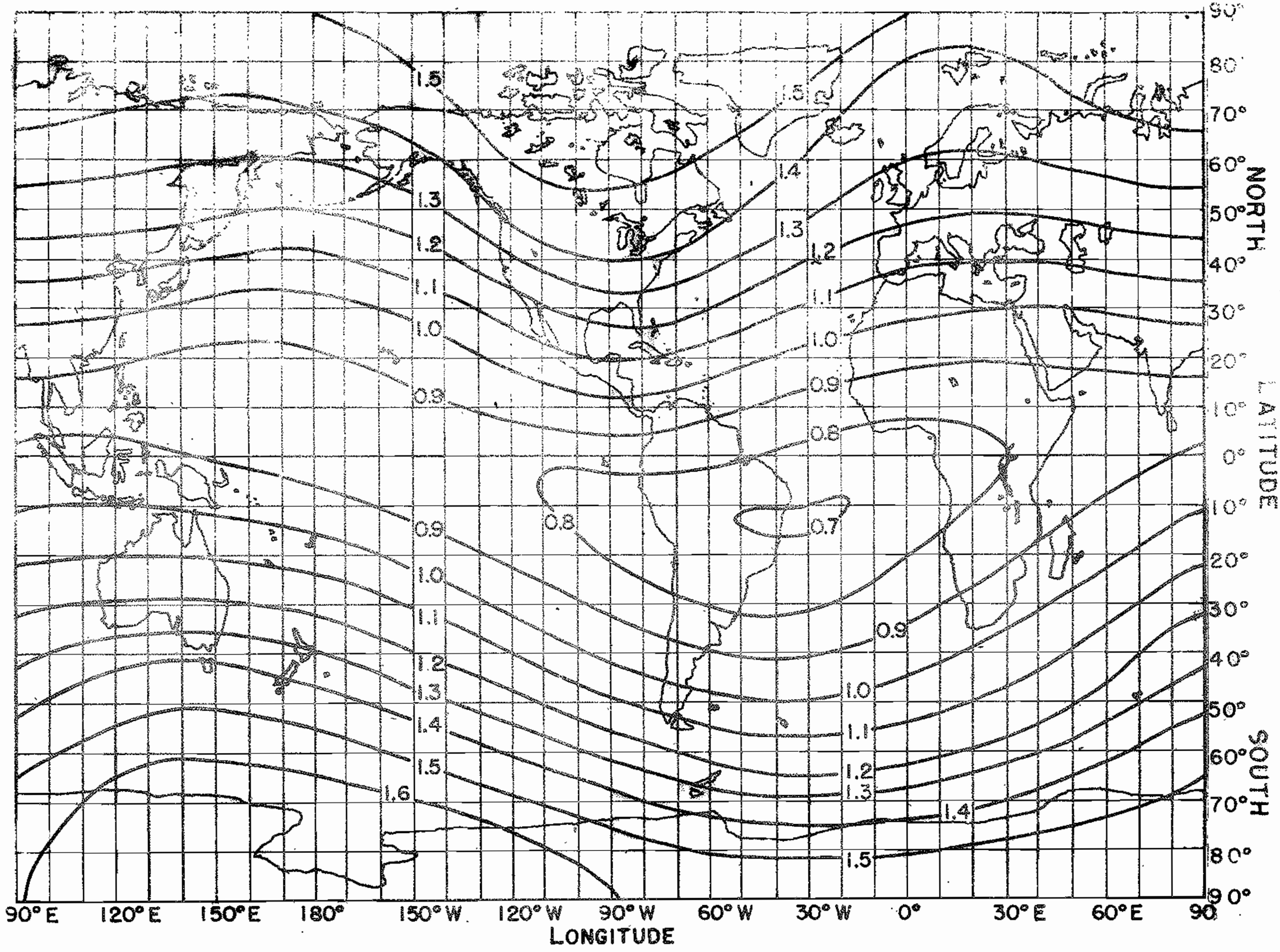


Fig. 9. Gyro-frequency map of the world. Numbers on contours are gyro-frequencies in Mc.

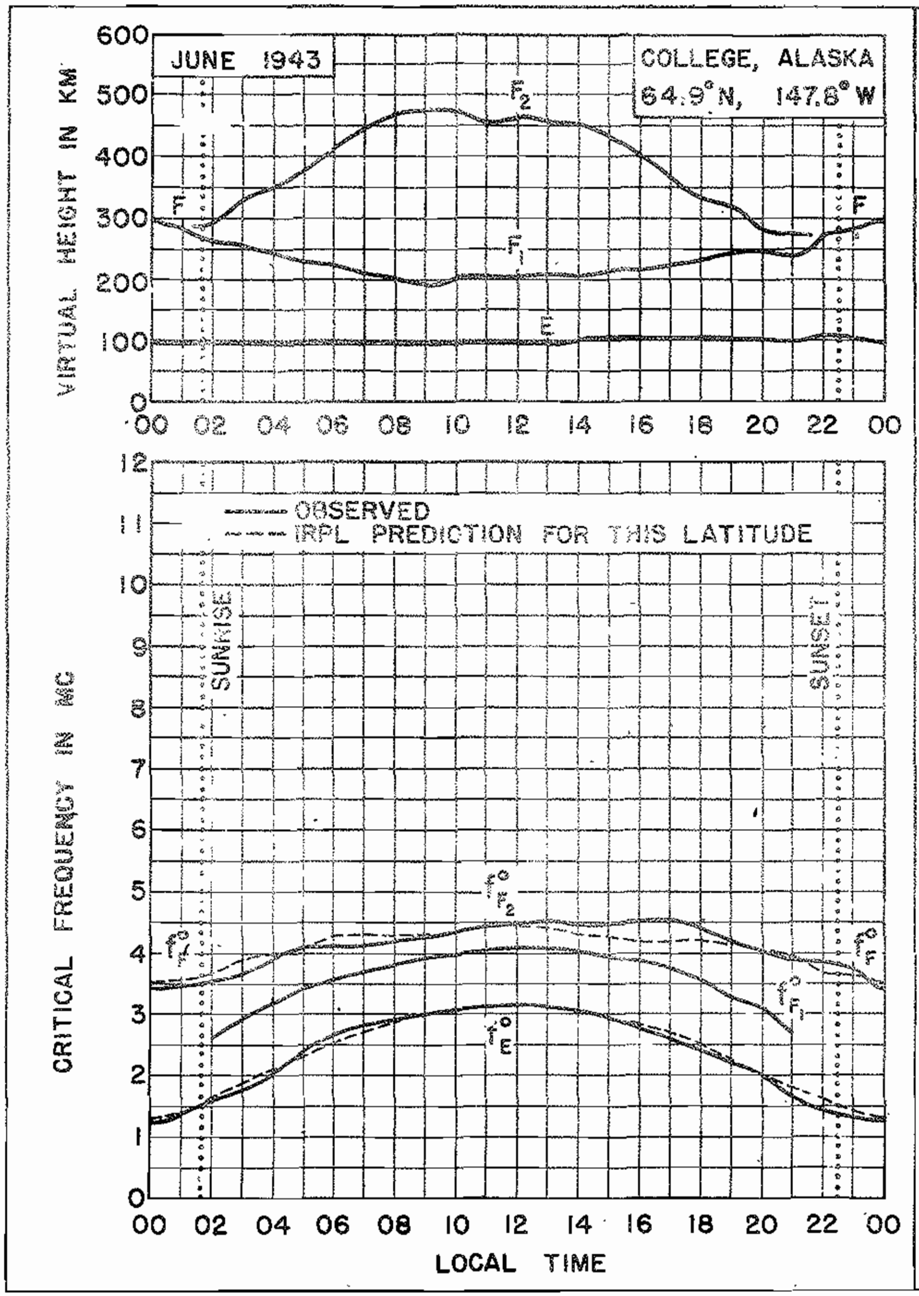

JUNE 1943
COLLEGE, ALASKA
64.9°N, 147.8°W
VIRTUAL HEIGHT IN KM
600
500
400
300
200
100
0
F
F
F_2
F_1
E
00 02 04 06 08 10 12 14 16 18 20 22 00
OBSERVED
IRPL PREDICTION FOR THIS LATITUDE
SUNRISE
SUNSET
CRITICAL FREQUENCY IN MC
12 11 10 9 8 7 6 5 4 3 2 1 0
f^o_F
$f^o_{F_2}$
$f^o_{F_1}$
f^o_E
f^o_F
LOCAL TIME

Fig. 10

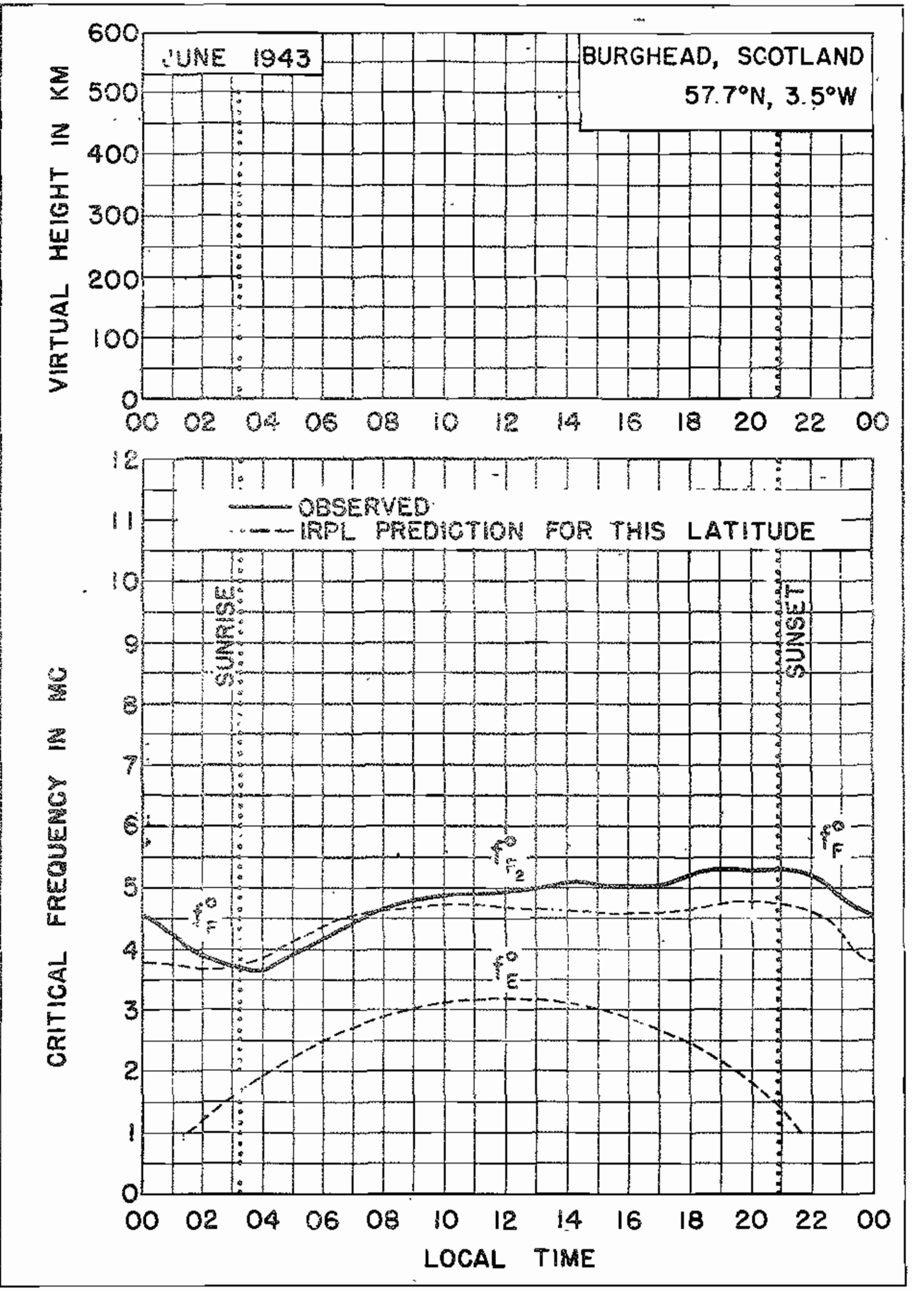

JUNE 1943
BURGHEAD, SCOTLAND
57.7°N, 3.5°W
VIRTUAL HEIGHT IN KM
600
500
400
300
200
100
0
00 02 04 06 08 10 12 14 16 18 20 22 00
OBSERVED
IRPL PREDICTION FOR THIS LATITUDE
SUNRISE
SUNSET
CRITICAL FREQUENCY IN MC
12 11 10 9 8 7 6 5 4 3 2 1 0
f^o_F
$f^o_{F_2}$
f^o_E
f^o_F
LOCAL TIME

Fig. 11

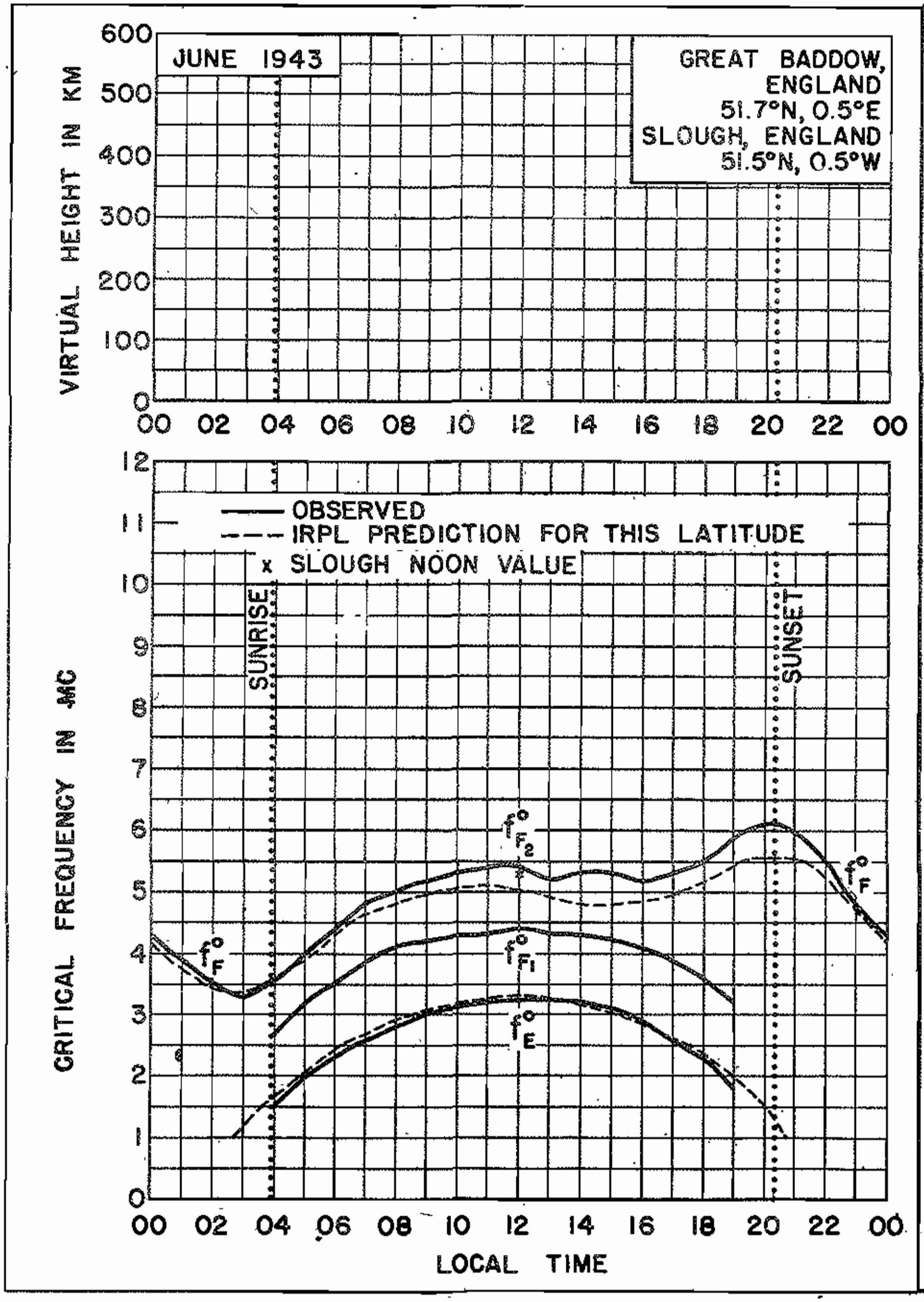

JUNE 1943
GREAT BADDOW, ENGLAND
51.7°N, 0.5°E
SLOUGH, ENGLAND
51.5°N, 0.5°W
VIRTUAL HEIGHT IN KM
600
500
400
300
200
100
0
00 02 04 06 08 10 12 14 16 18 20 22 00
OBSERVED
IRPL PREDICTION FOR THIS LATITUDE
x SLOUGH NOON VALUE
SUNRISE
SUNSET
$f^o_{F_2}$
f^o_F
$f^o_{F_1}$
f^o_E
CRITICAL FREQUENCY IN MC
12
11
10
9
8
7
6
5
4
3
2
1
0
00 02 04 06 08 10 12 14 16 18 20 22 00
LOCAL TIME

Fig. 12

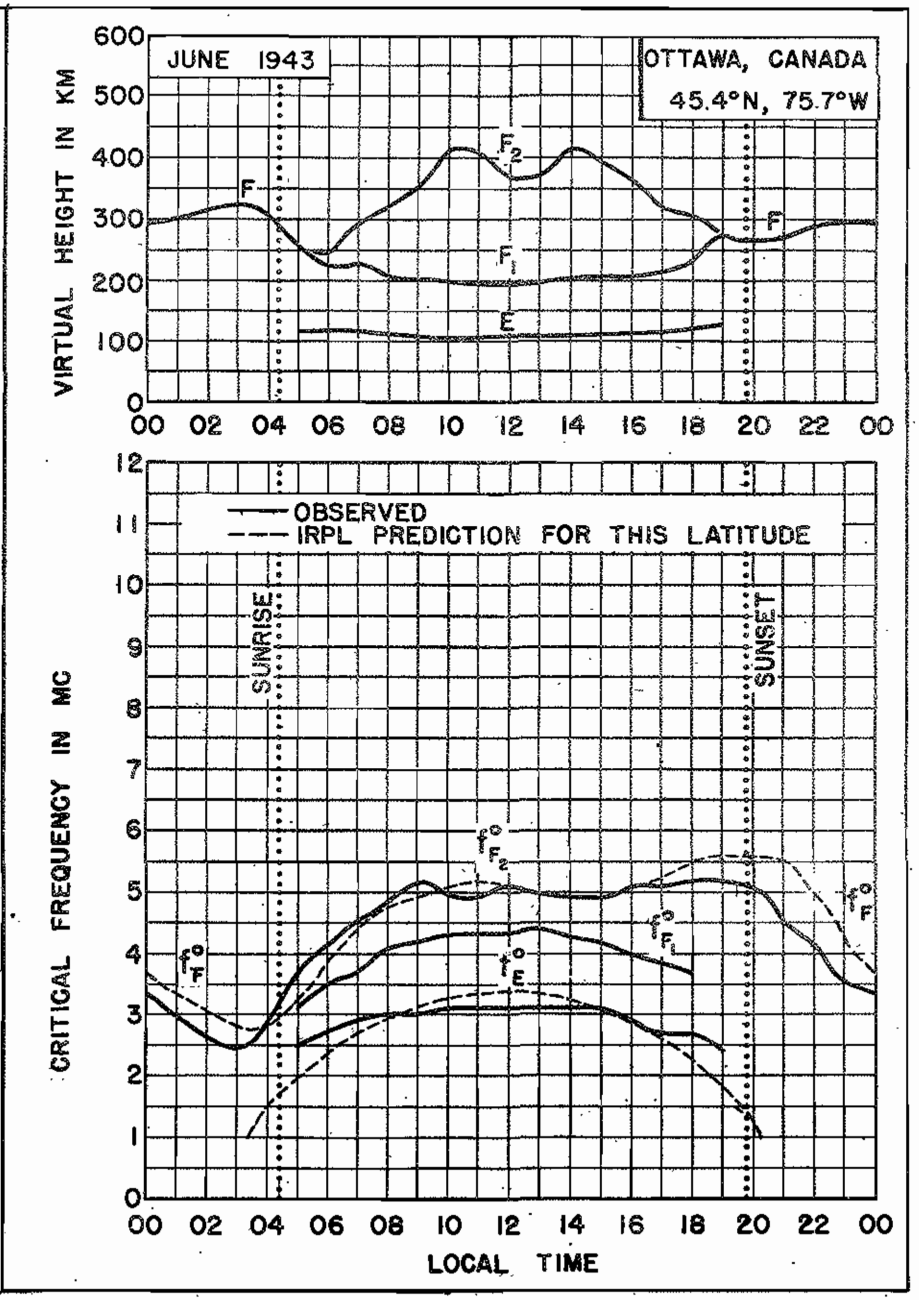

JUNE 1943
OTTAWA, CANADA
45.4°N, 75.7°W
VIRTUAL HEIGHT IN KM
600
500
400
300
200
100
0
F
F_2
F_1
E
F
00 02 04 06 08 10 12 14 16 18 20 22 00
OBSERVED
IRPL PREDICTION FOR THIS LATITUDE
SUNRISE
SUNSET
$f^o_{F_2}$
f^o_F
$f^o_{F_1}$
f^o_E
f^o_F
CRITICAL FREQUENCY IN MC
12
11
10
9
8
7
6
5
4
3
2
1
0
00 02 04 06 08 10 12 14 16 18 20 22 00
LOCAL TIME

Fig. 13

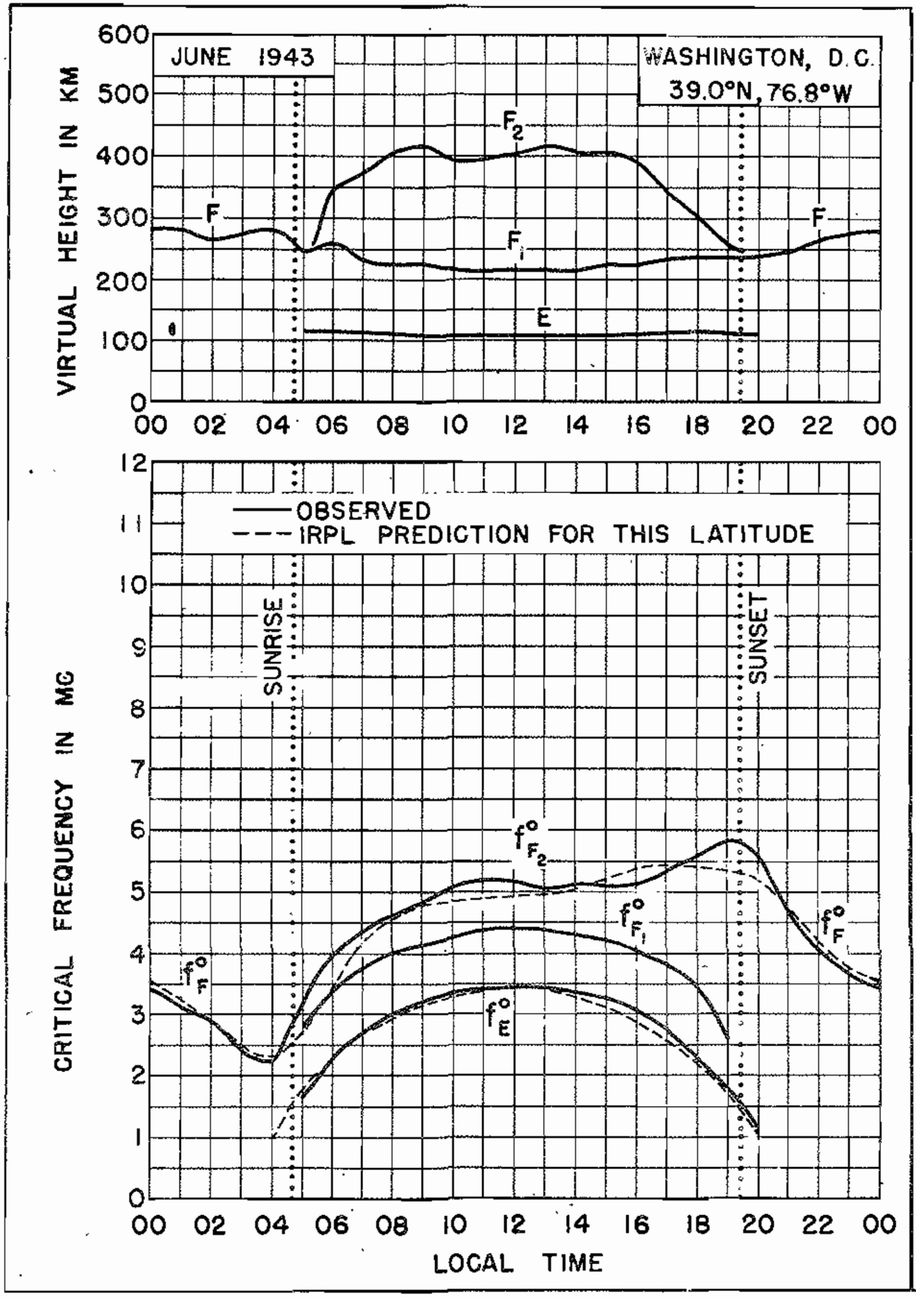

JUNE 1943
WASHINGTON, D.C.
39.0°N, 76.8°W
VIRTUAL HEIGHT IN KM
600
500
400
300
200
100
0
F
F2
F1
E
F
00 02 04 06 08 10 12 14 16 18 20 22 00
12 11 10 9 8 7 6 5 4 3 2 1 0
OBSERVED
IRPL PREDICTION FOR THIS LATITUDE
SUNRISE
SUNSET
CRITICAL FREQUENCY IN MC
f°F2
f°F1
f°F
f°F
f°E
LOCAL TIME

Fig. 14

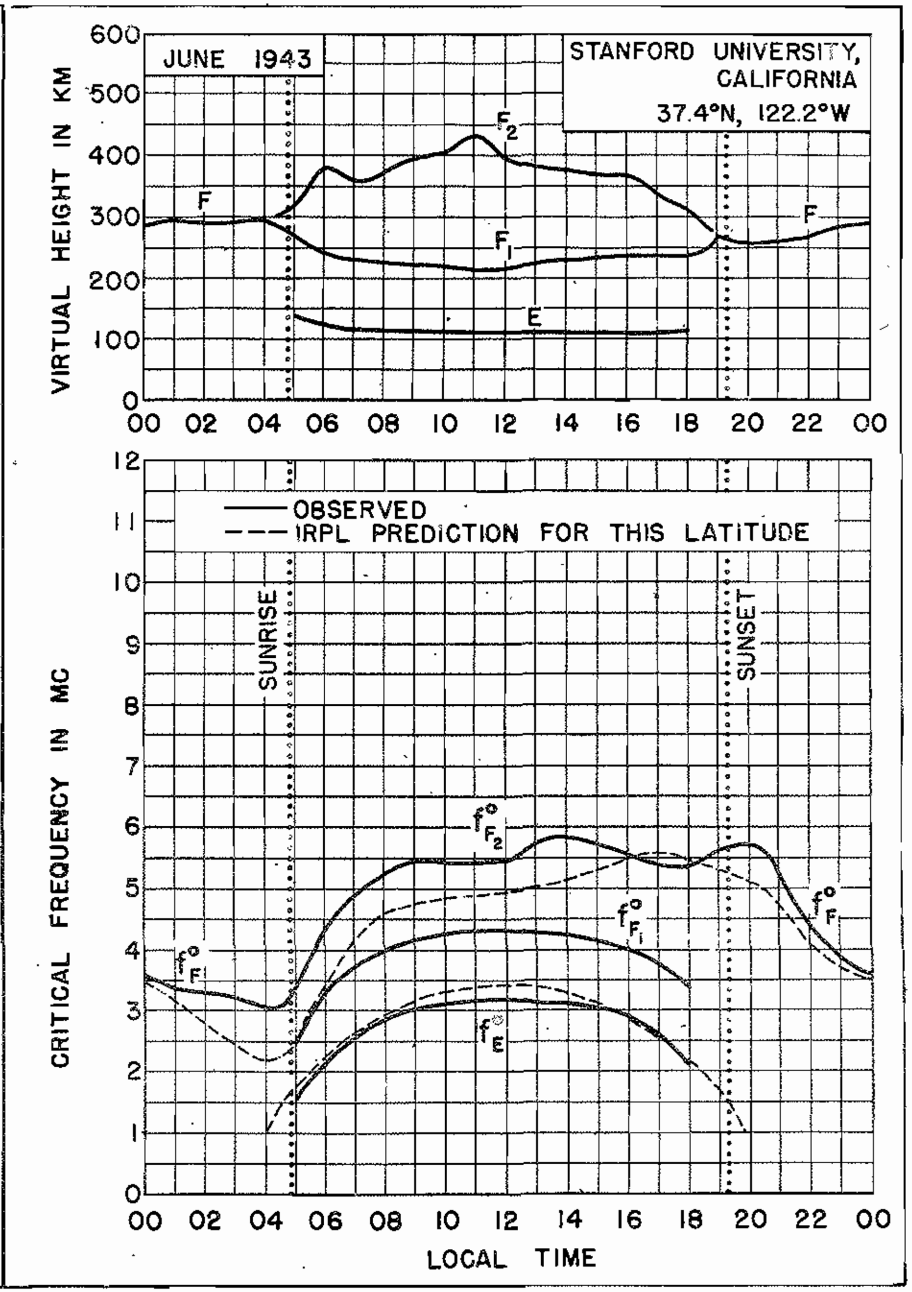

JUNE 1943
STANFORD UNIVERSITY, CALIFORNIA
37.4°N, 122.2°W
VIRTUAL HEIGHT IN KM
600
500
400
300
200
100
0
F
F2
F1
E
F
00 02 04 06 08 10 12 14 16 18 20 22 00
12 11 10 9 8 7 6 5 4 3 2 1 0
OBSERVED
IRPL PREDICTION FOR THIS LATITUDE
SUNRISE
SUNSET
CRITICAL FREQUENCY IN MC
f°F2
f°F1
f°F1
f°F
f°E
LOCAL TIME

Fig. 15

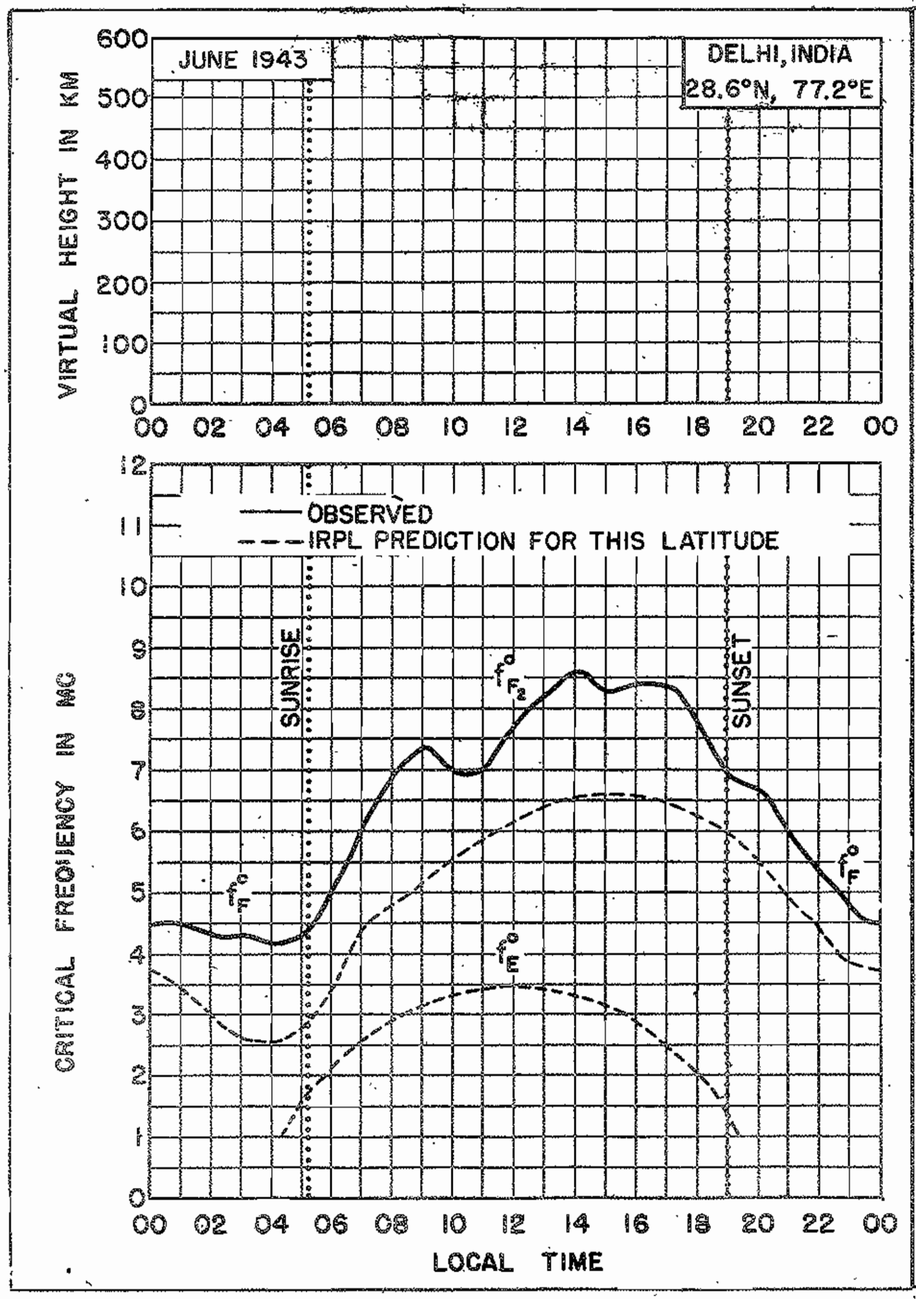


Fig. 16 (See note in text)

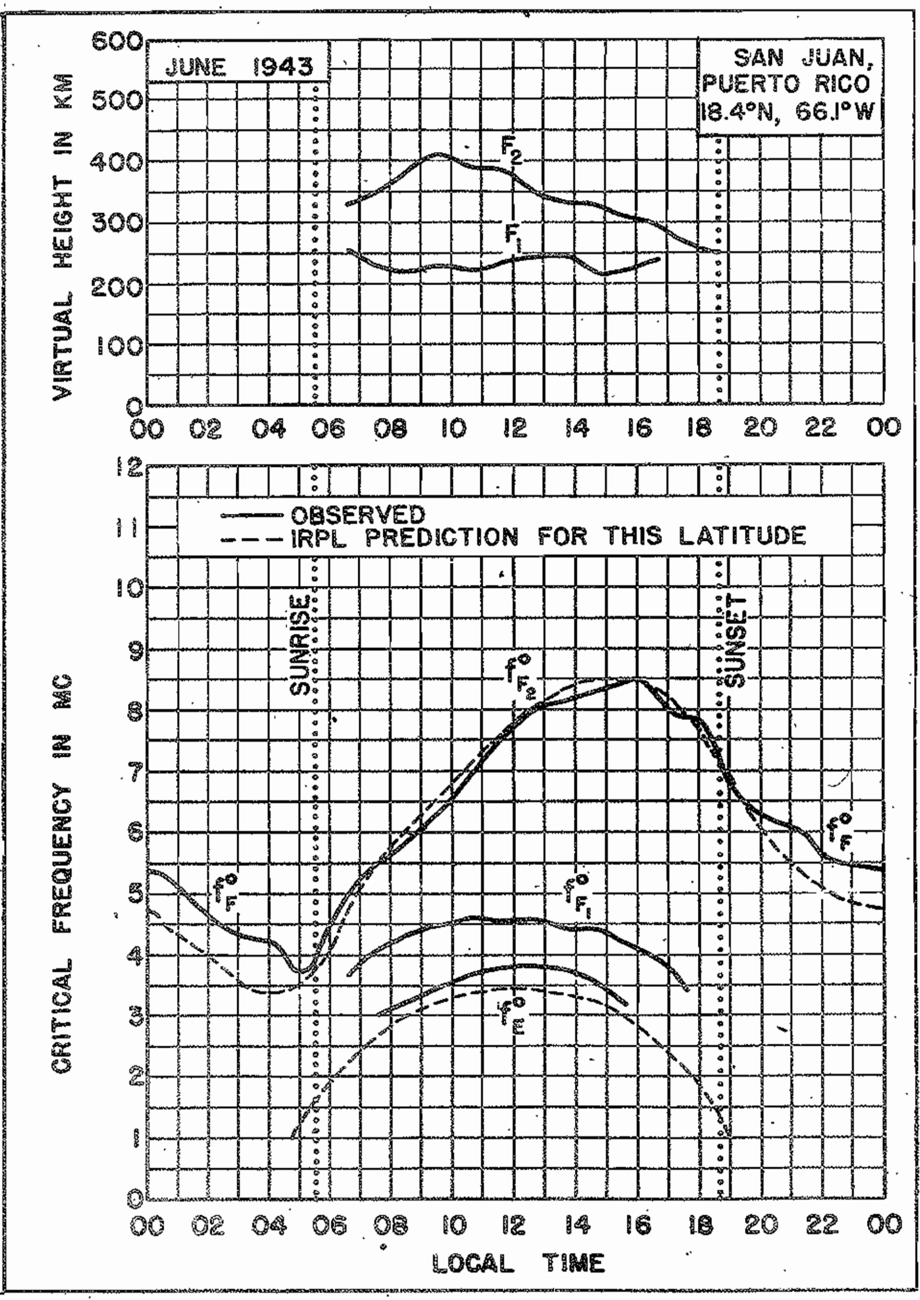


Fig. 17

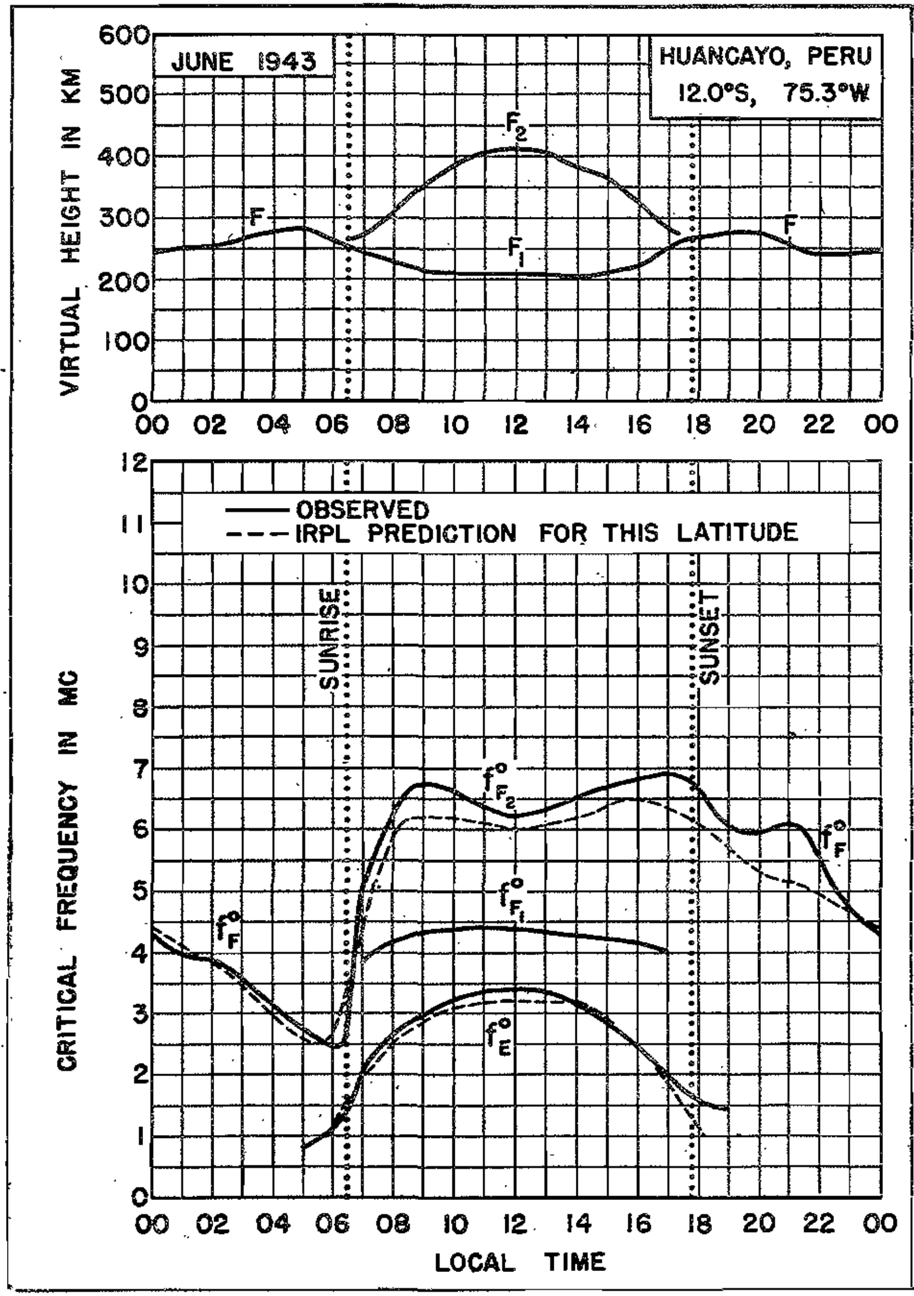

JUNE 1943
HUANCAYO, PERU
12.0°S, 75.3°W
VIRTUAL HEIGHT IN KM
600
500
400
300
200
100
0
F
F2
F1
F
00 02 04 06 08 10 12 14 16 18 20 22 00
12
11
10
9
8
7
6
5
4
3
2
1
0
OBSERVED
IRPL PREDICTION FOR THIS LATITUDE
SUNRISE
SUNSET
CRITICAL FREQUENCY IN MC
f^o_F
$f^o_{F_2}$
$f^o_{F_1}$
f^o_E
f^o_F
00 02 04 06 08 10 12 14 16 18 20 22 00
LOCAL TIME

Fig. 18

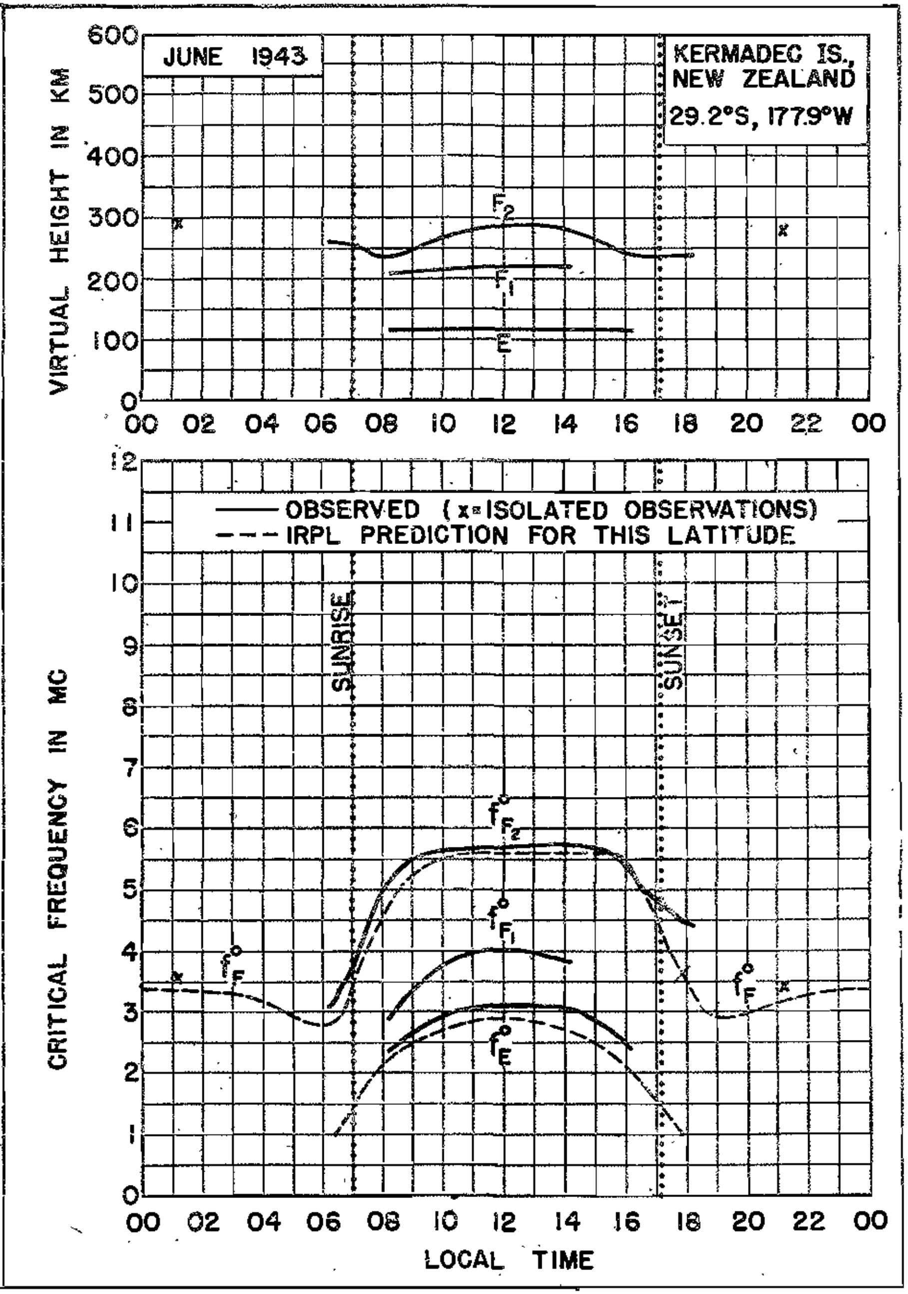

JUNE 1943
KERMADEC IS., NEW ZEALAND
29.2°S, 177.9°W
VIRTUAL HEIGHT IN KM
600
500
400
300
200
100
0
x
F2
F1
E
x
00 02 04 06 08 10 12 14 16 18 20 22 00
12
11
10
9
8
7
6
5
4
3
2
1
0
OBSERVED (x=ISOLATED OBSERVATIONS)
IRPL PREDICTION FOR THIS LATITUDE
SUNRISE
SUNSET
CRITICAL FREQUENCY IN MC
x
f^o_F
$f^o_{F_2}$
$f^o_{F_1}$
f^o_E
f^o_F
x
00 02 04 06 08 10 12 14 16 18 20 22 00
LOCAL TIME

Fig. 19

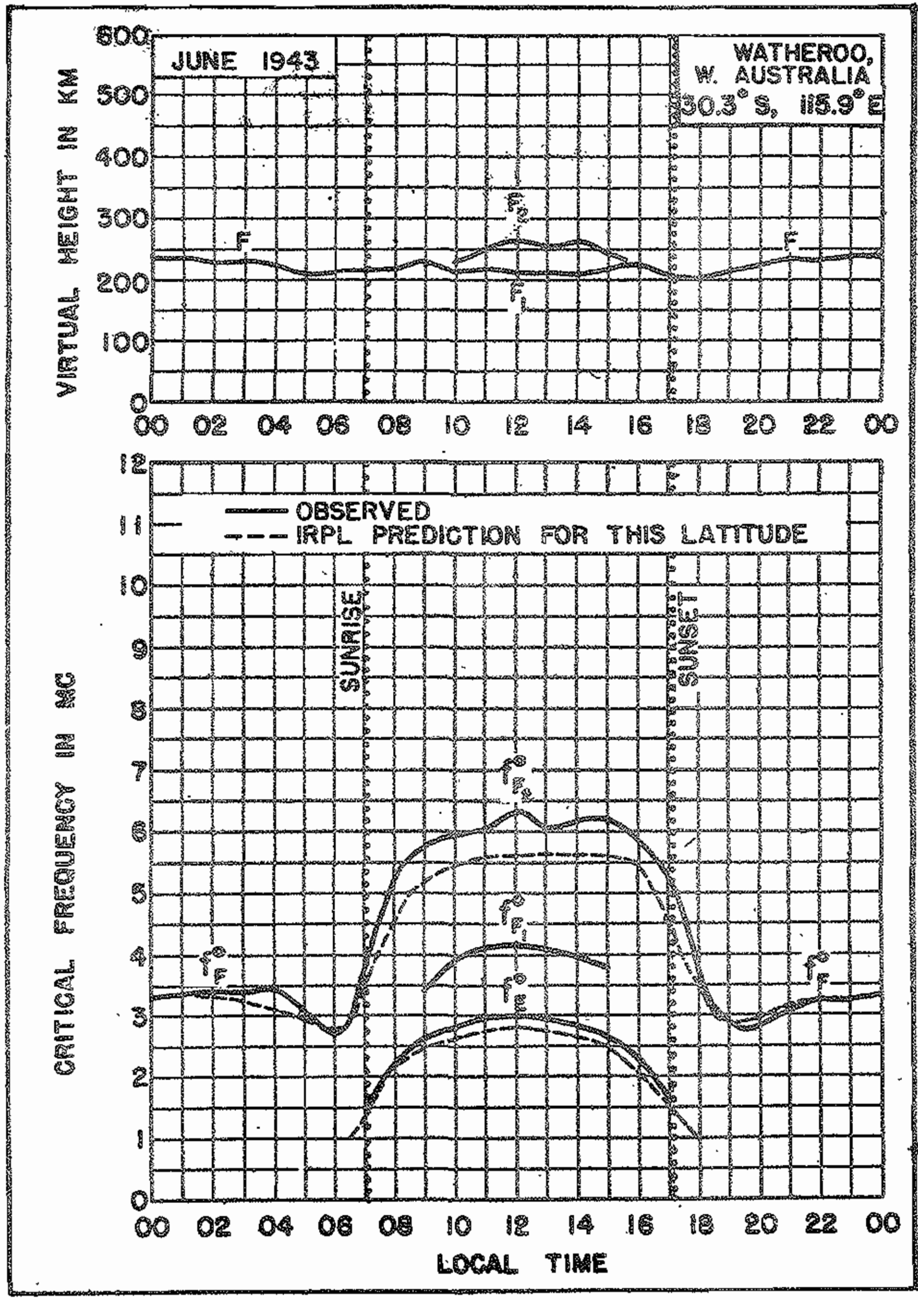

JUNE 1943
WATHEROO, W. AUSTRALIA 30.3° S, 115.9° E
VIRTUAL HEIGHT IN KM
600
500
400
300
200
100
0
F
F_2
F_1
F
00 02 04 06 08 10 12 14 16 18 20 22 00
OBSERVED
IRPL PREDICTION FOR THIS LATITUDE
SUNRISE
SUNSET
CRITICAL FREQUENCY IN MC
12 11 10 9 8 7 6 5 4 3 2 1 0
$f^o_{F_2}$
$f^o_{F_1}$
f^o_E
f^o_F
f^o_F
00 02 04 06 08 10 12 14 16 18 20 22 00
LOCAL TIME

Fig. 20

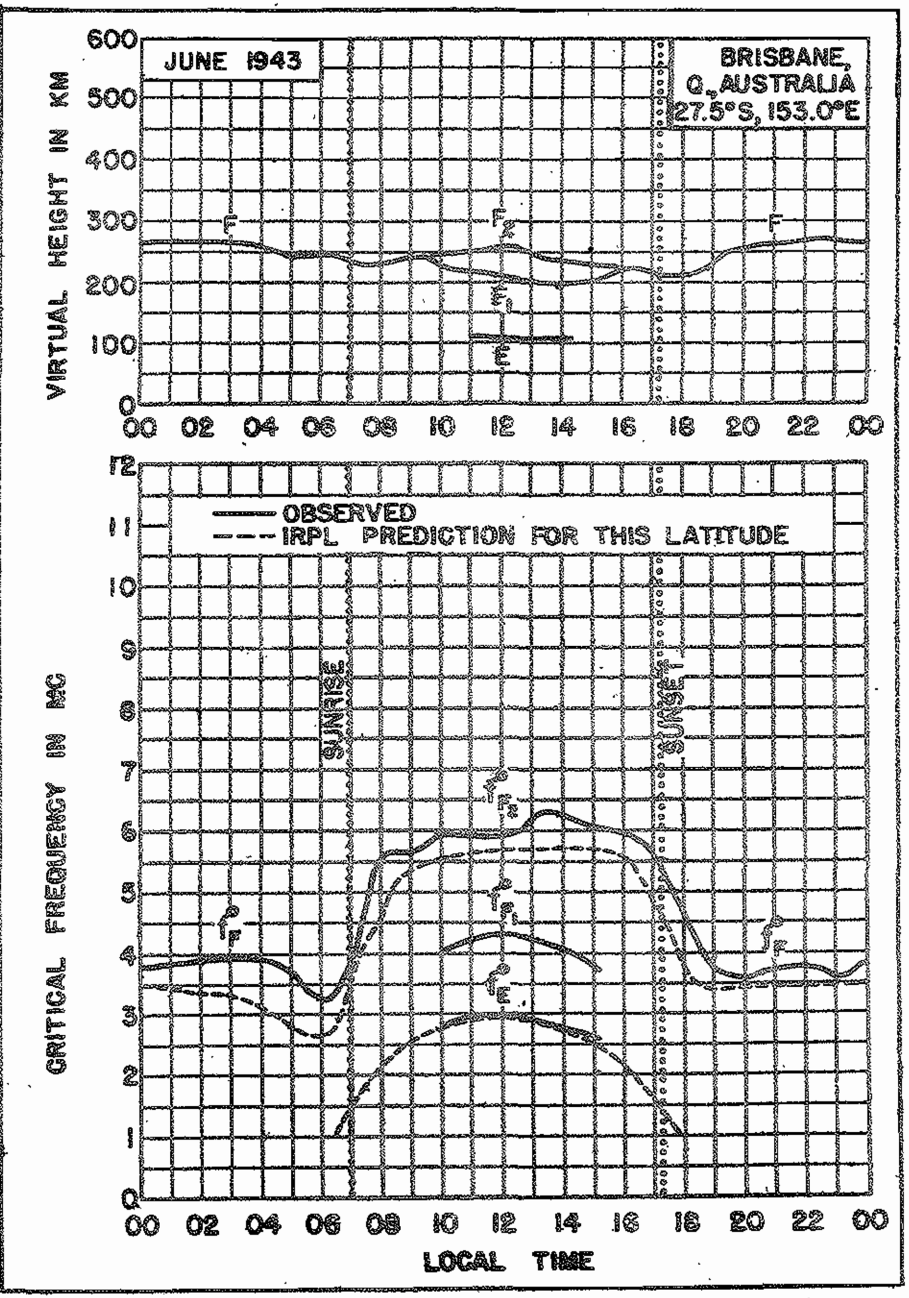

JUNE 1943
BRISBANE, Q., AUSTRALIA 27.5°S, 153.0°E
VIRTUAL HEIGHT IN KM
600
500
400
300
200
100
0
F
F_2
F_1
E
F
00 02 04 06 08 10 12 14 16 18 20 22 00
OBSERVED
IRPL PREDICTION FOR THIS LATITUDE
SUNRISE
SUNSET
CRITICAL FREQUENCY IN MC
12 11 10 9 8 7 6 5 4 3 2 1 0
f^o_F
$f^o_{F_2}$
$f^o_{F_1}$
f^o_E
f^o_F
00 02 04 06 08 10 12 14 16 18 20 22 00
LOCAL TIME

Fig. 21

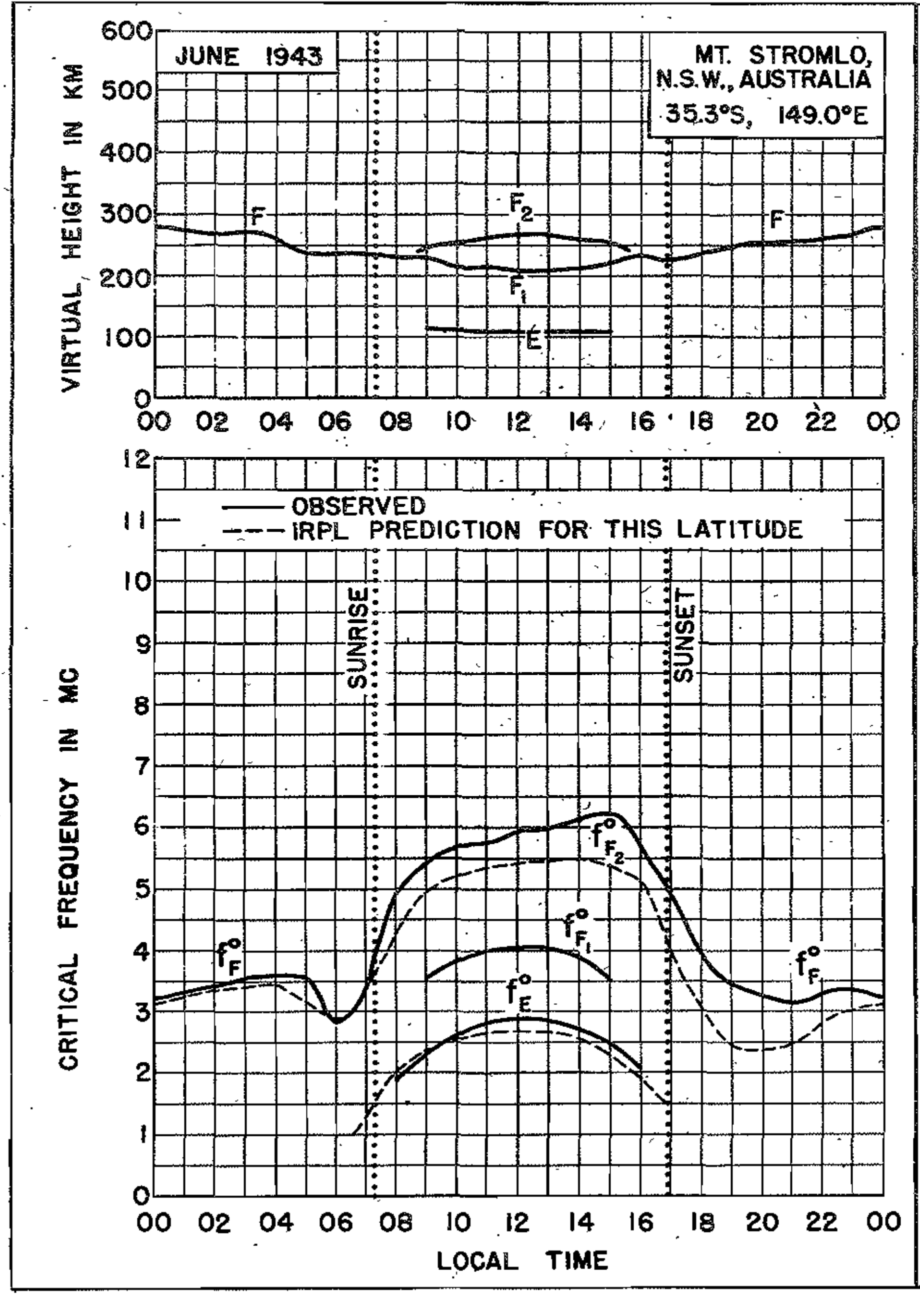

JUNE 1943
MT. STROMLO, N.S.W., AUSTRALIA 35.3°S, 149.0°E
VIRTUAL HEIGHT IN KM
600
500
400
300
200
100
0
F
F2
F
F1
E
00 02 04 06 08 10 12 14 16 18 20 22 00
CRITICAL FREQUENCY IN MC
12 11 10 9 8 7 6 5 4 3 2 1 0
OBSERVED
IRPL PREDICTION FOR THIS LATITUDE
SUNRISE
SUNSET
$f^o_{F_2}$
$f^o_{F_1}$
f^o_E
f^o_F
f^o_F
00 02 04 06 08 10 12 14 16 18 20 22 00
LOCAL TIME

Fig. 22

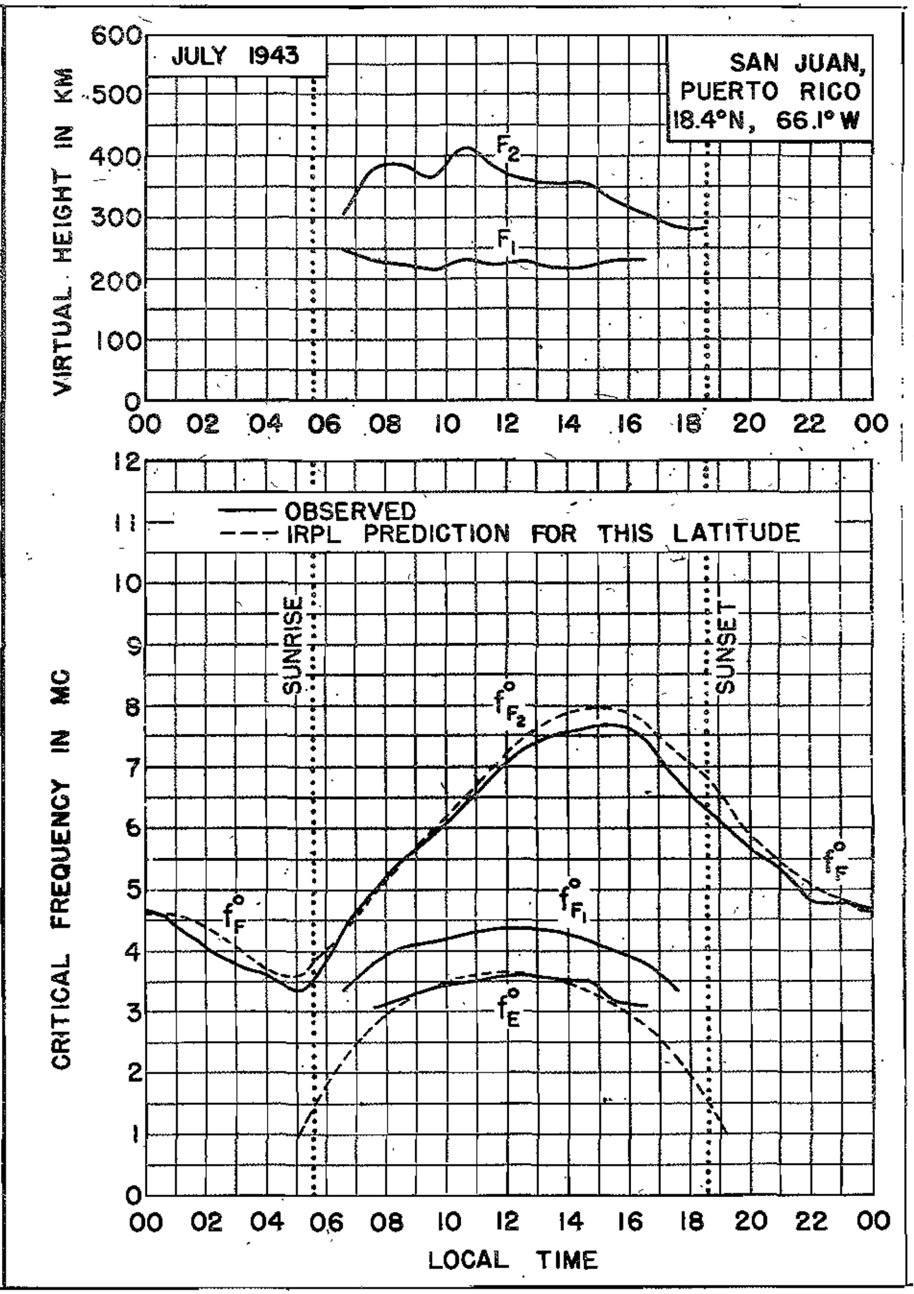

JULY 1943
SAN JUAN, PUERTO RICO 18.4°N, 66.1°W
VIRTUAL HEIGHT IN KM
600
500
400
300
200
100
0
F2
F1
00 02 04 06 08 10 12 14 16 18 20 22 00
CRITICAL FREQUENCY IN MC
12 11 10 9 8 7 6 5 4 3 2 1 0
OBSERVED
IRPL PREDICTION FOR THIS LATITUDE
SUNRISE
SUNSET
$f^o_{F_2}$
f^o_F
$f^o_{F_1}$
f^o_E
f^o_F
00 02 04 06 08 10 12 14 16 18 20 22 00
LOCAL TIME

Fig. 23

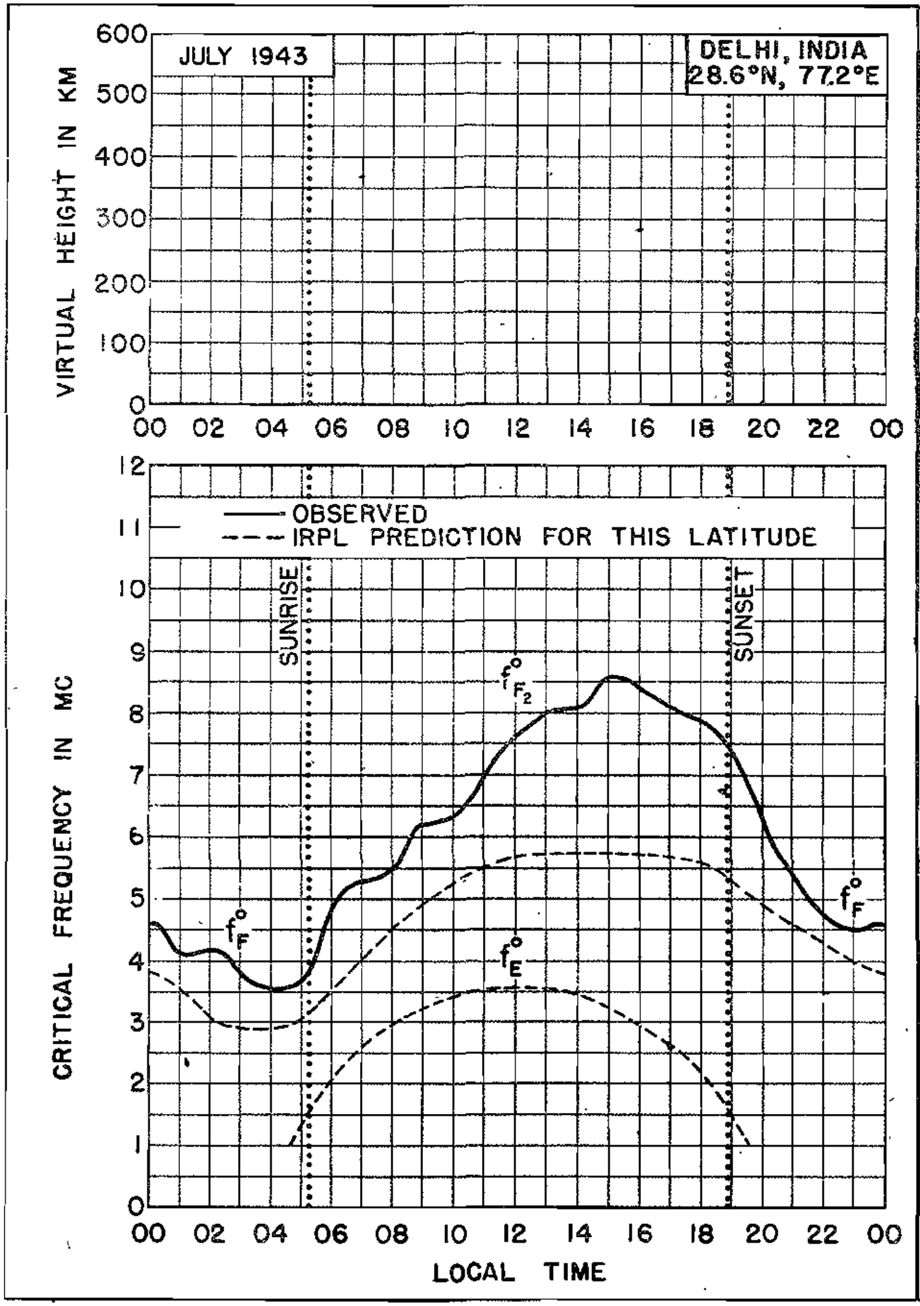


Fig. 24 (See note in text)

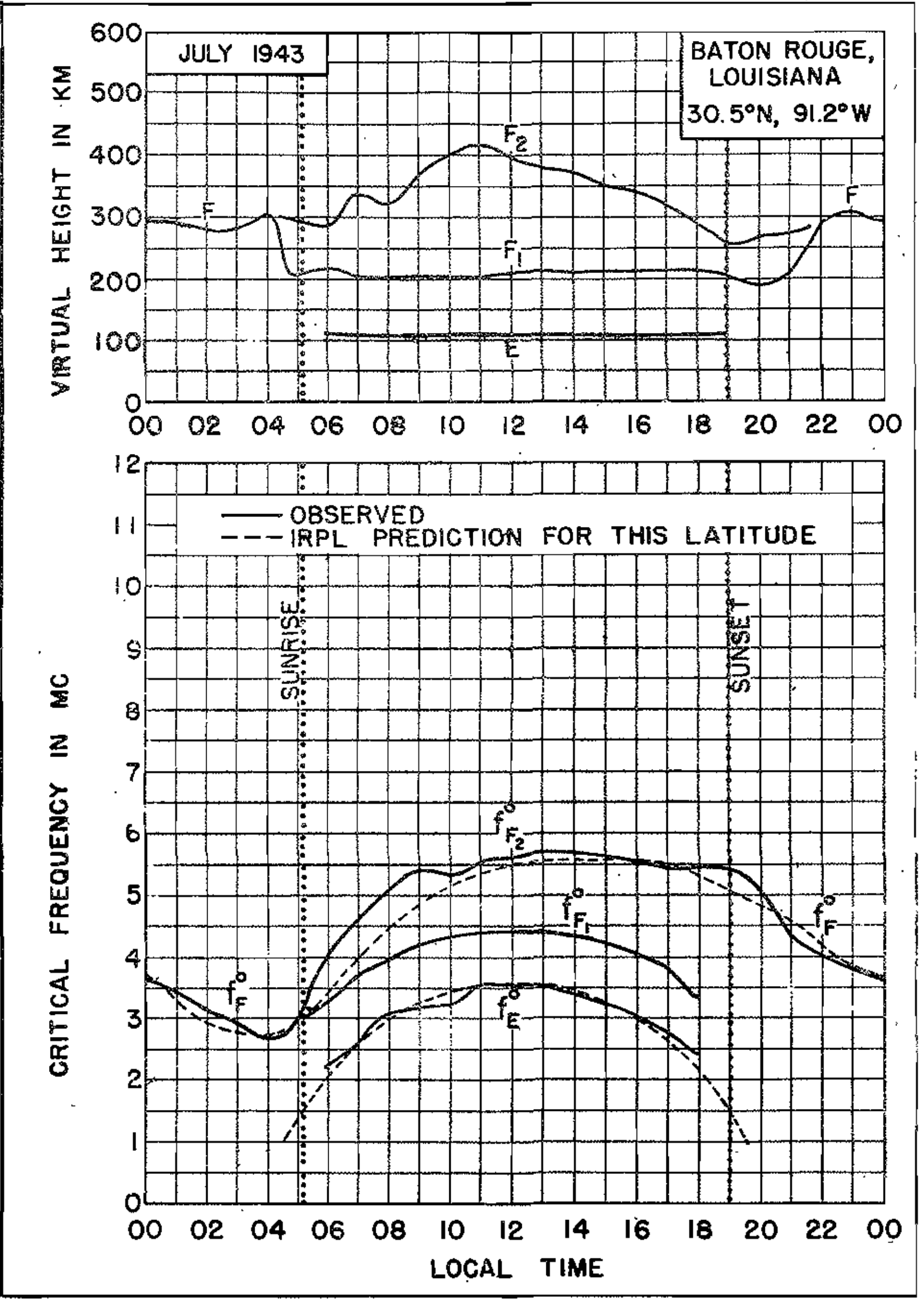


Fig. 25

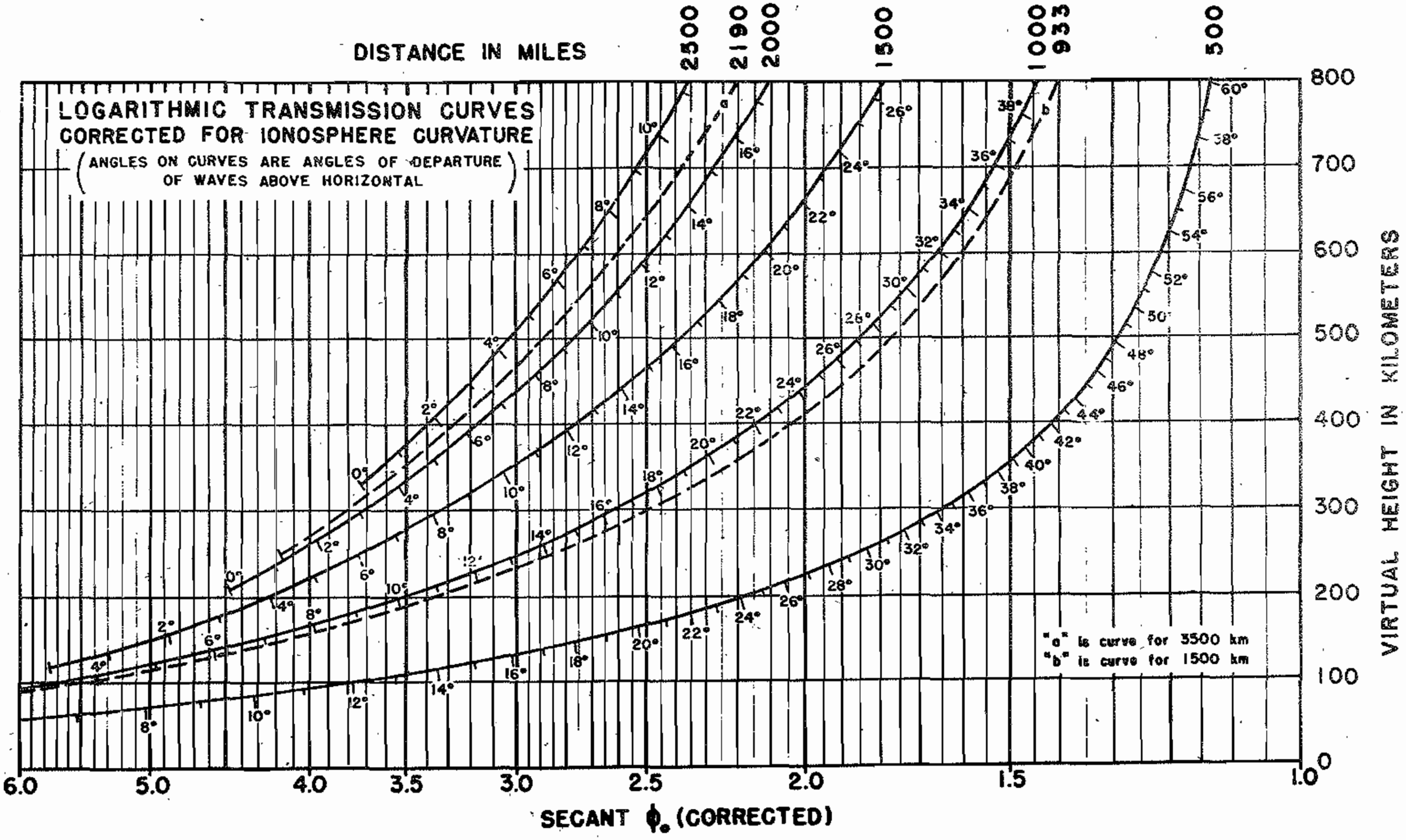

LOGARITHMIC TRANSMISSION CURVES
CORRECTED FOR IONOSPHERE CURVATURE
(ANGLES ON CURVES ARE ANGLES OF DEPARTURE OF WAVES ABOVE HORIZONTAL)
DISTANCE IN MILES
2500
2190
2000
1500
1000
933
500
VIRTUAL HEIGHT IN KILOMETERS
800
700
600
500
400
300
200
100
0
SECANT φ₀ (CORRECTED)
6.0
5.0
4.0
3.5
3.0
2.5
2.0
1.5
1.0
a
b
"a" is curve for 3500 km
"b" is curve for 1500 km

Fig. 26

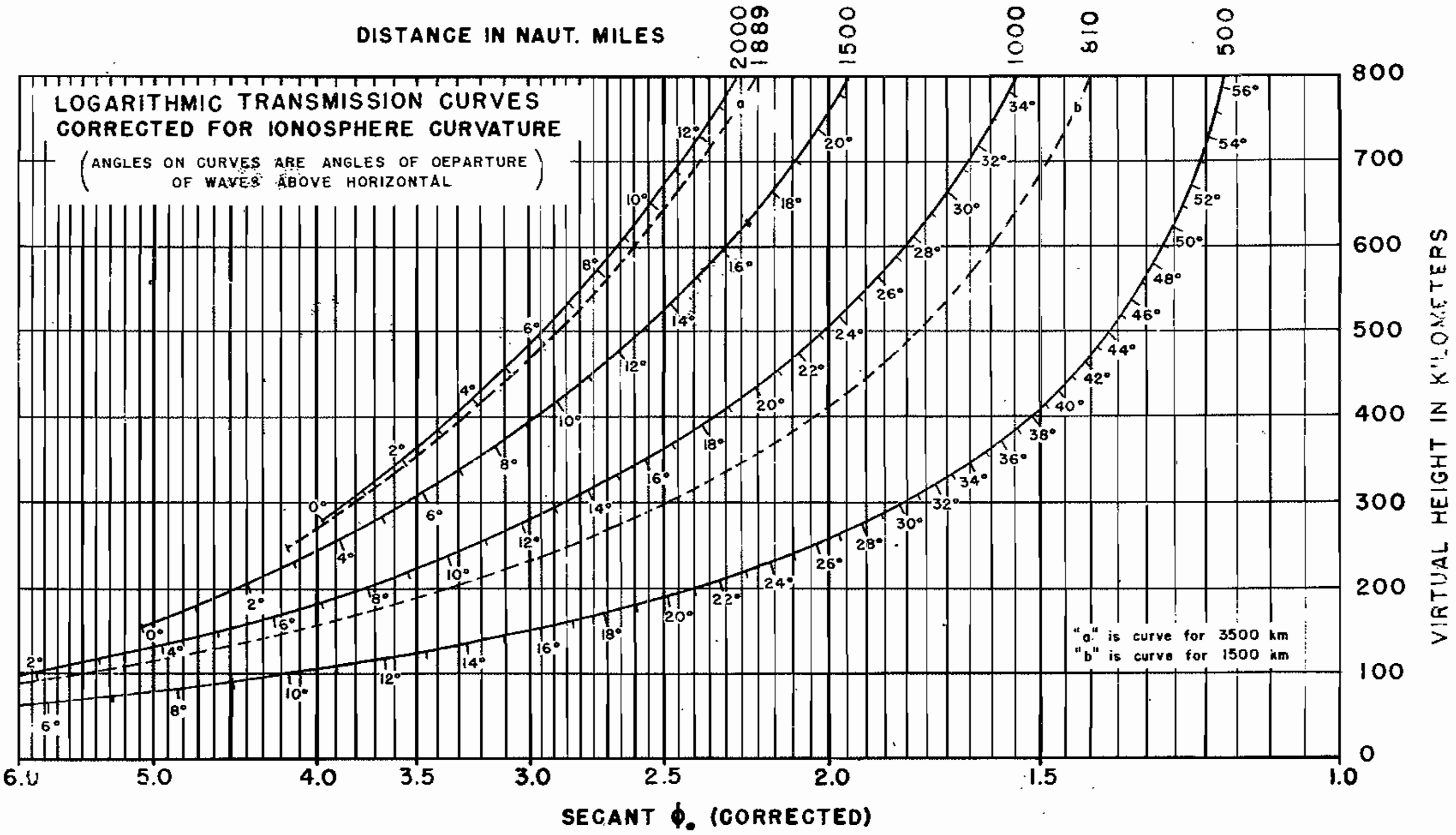

LOGARITHMIC TRANSMISSION CURVES
CORRECTED FOR IONOSPHERE CURVATURE
(ANGLES ON CURVES ARE ANGLES OF DEPARTURE OF WAVES ABOVE HORIZONTAL)
DISTANCE IN NAUT. MILES
2000
1889
1500
1000
810
500
VIRTUAL HEIGHT IN KILOMETERS
800
700
600
500
400
300
200
100
0
SECANT ϕ₀ (CORRECTED)
6.0
5.0
4.0
3.5
3.0
2.5
2.0
1.5
1.0
"a" is curve for 3500 km
"b" is curve for 1500 km
a
b

Fig 27

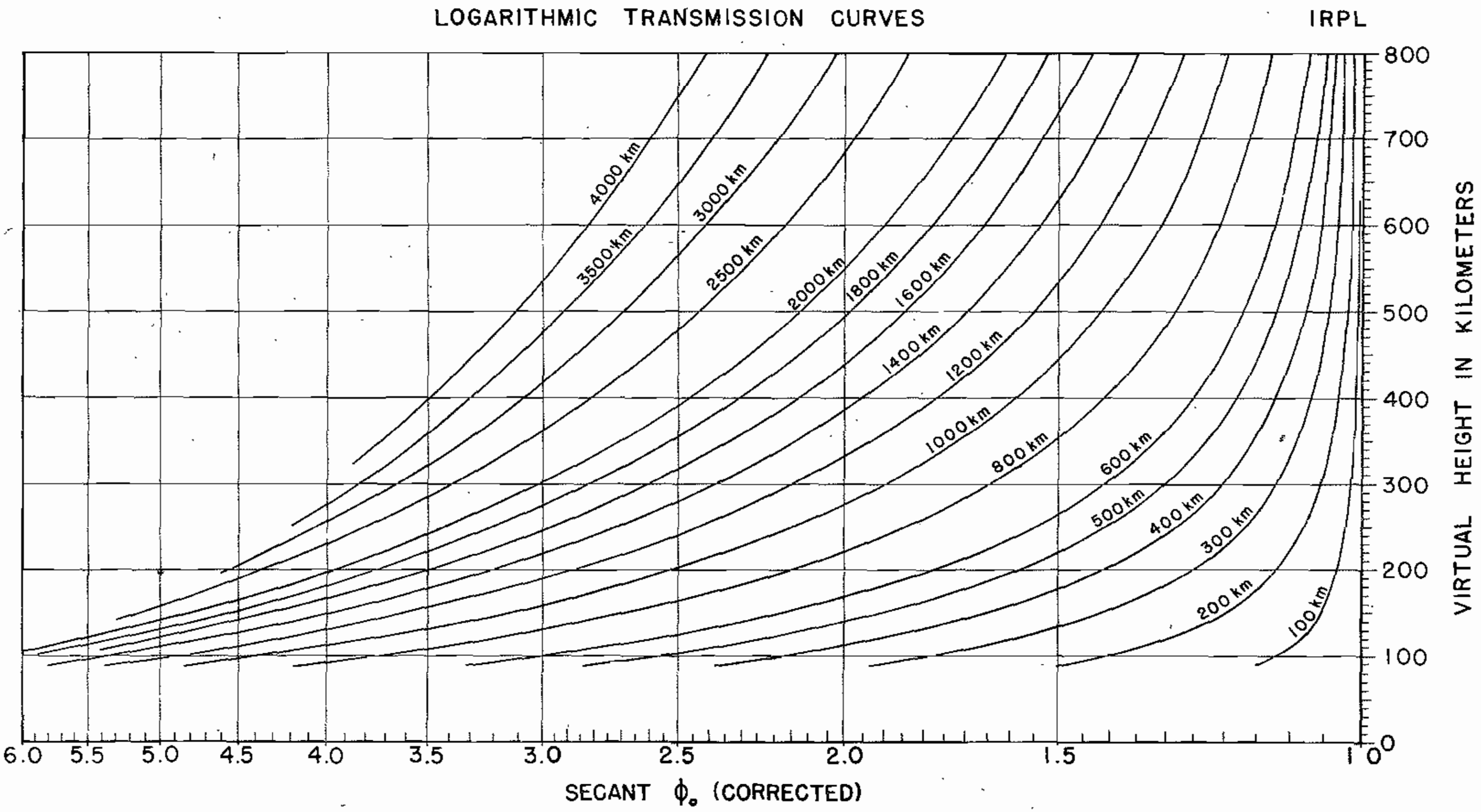

LOGARITHMIC TRANSMISSION CURVES
IRPL
VIRTUAL HEIGHT IN KILOMETERS
800
700
600
500
400
300
200
100
0
SECANT ϕ_o (CORRECTED)
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
4000 km
3500 km
3000 km
2500 km
2000 km
1800 km
1600 km
1400 km
1200 km
1000 km
800 km
600 km
500 km
400 km
300 km
200 km
100 km

Fig. 28

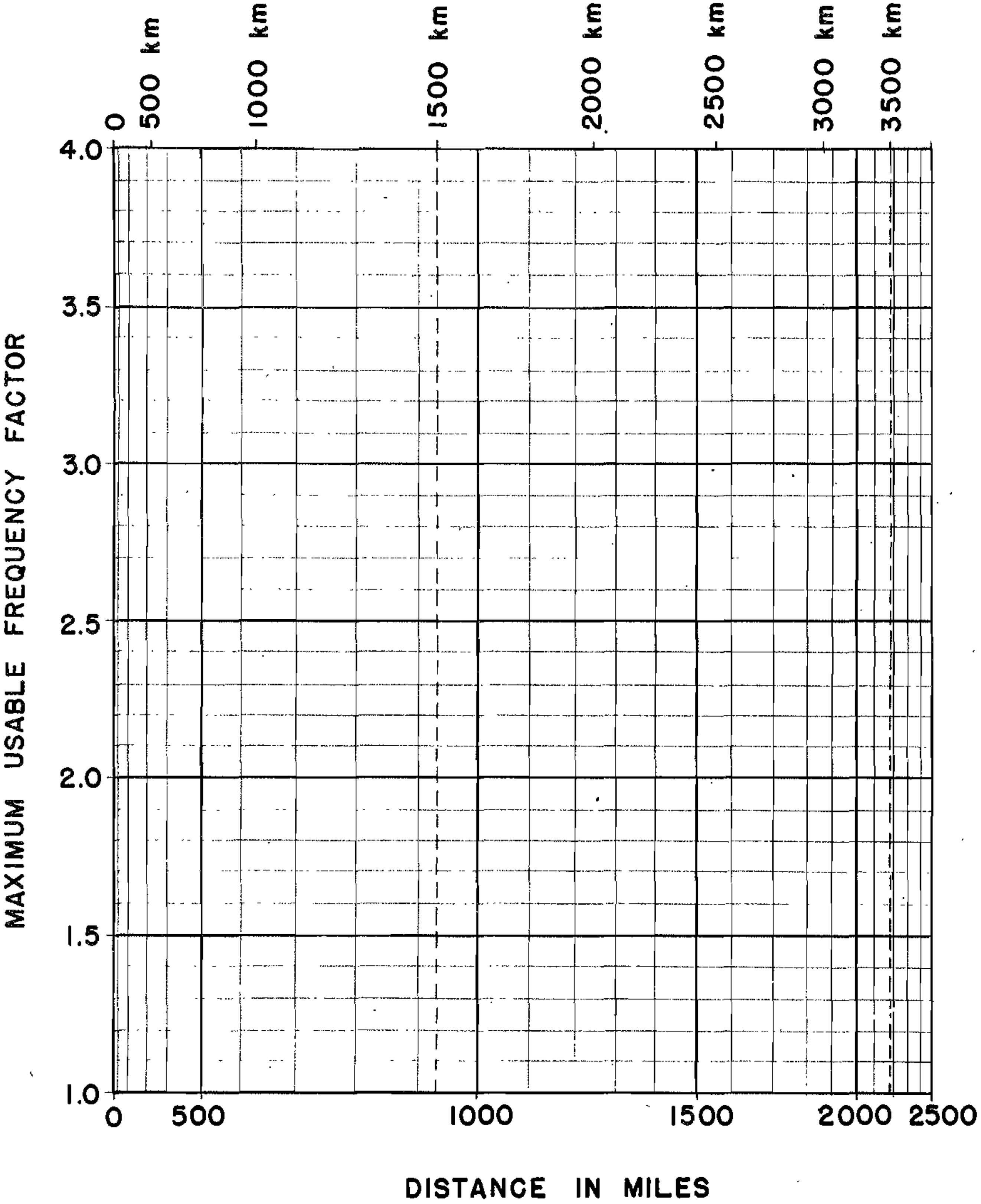


Fig. 29. Graph paper for rapid determination of maximum usable frequency factor for transmission distance up to 2500 miles. (Distances indicated in miles and kilometers).

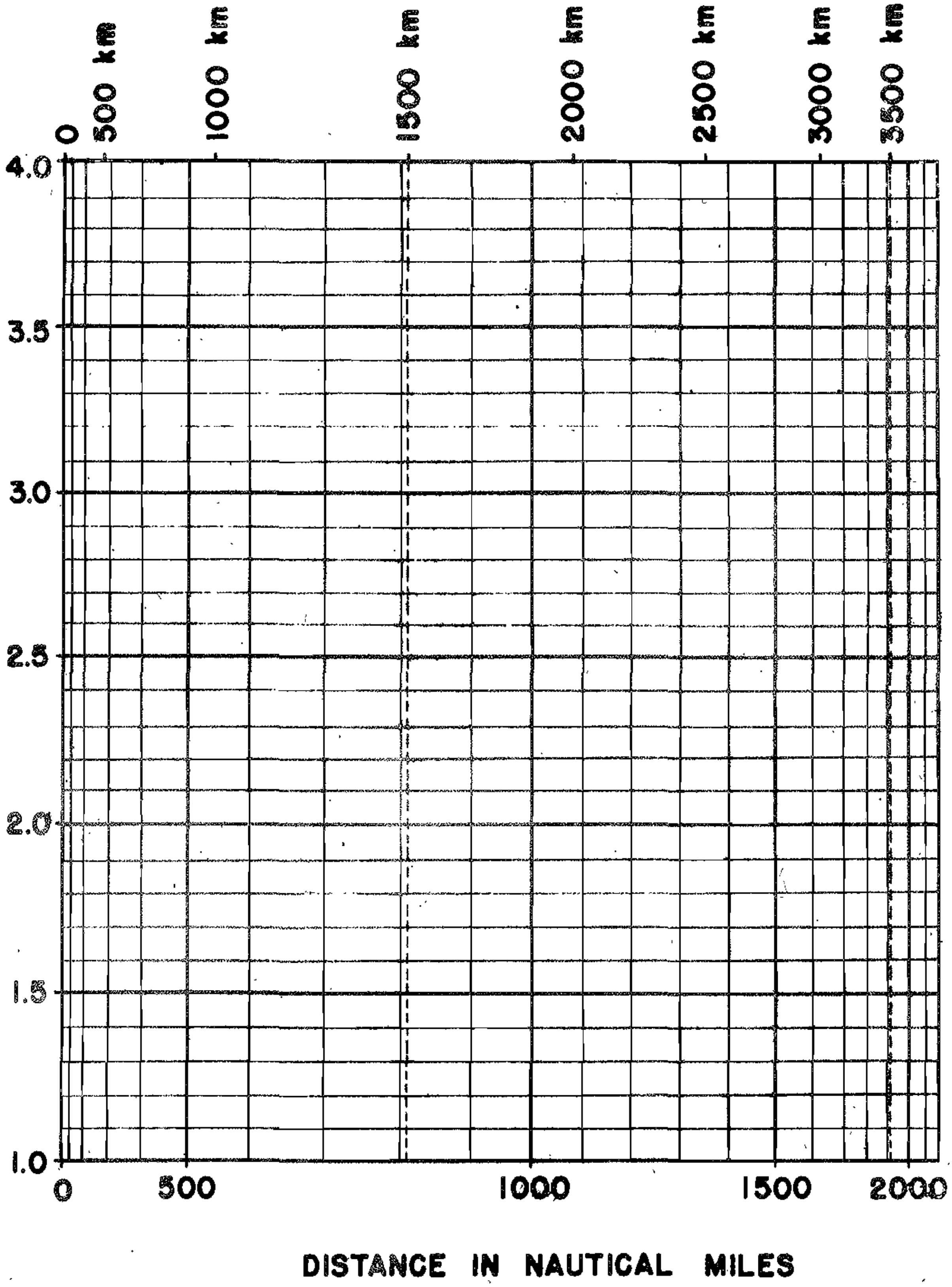
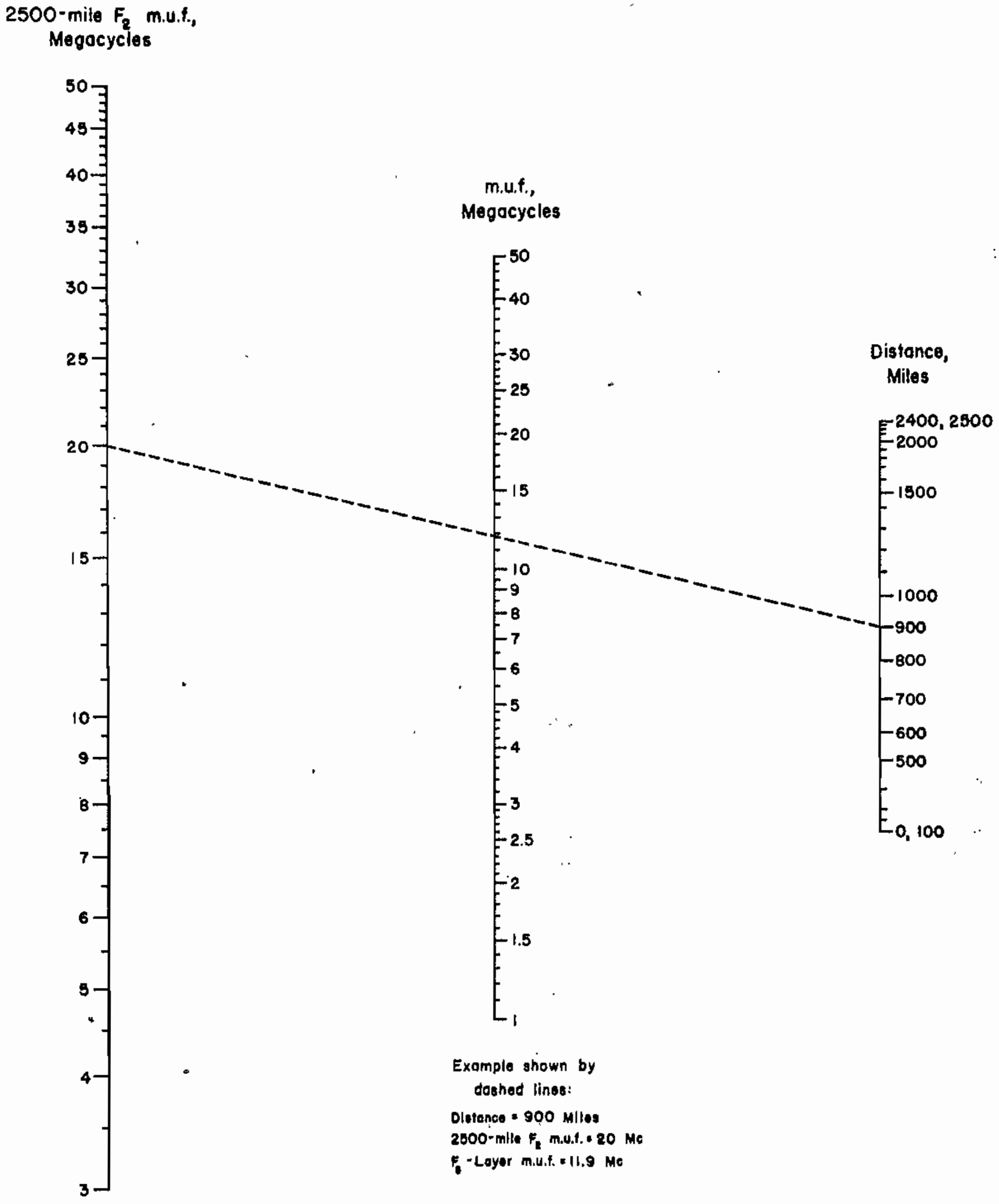


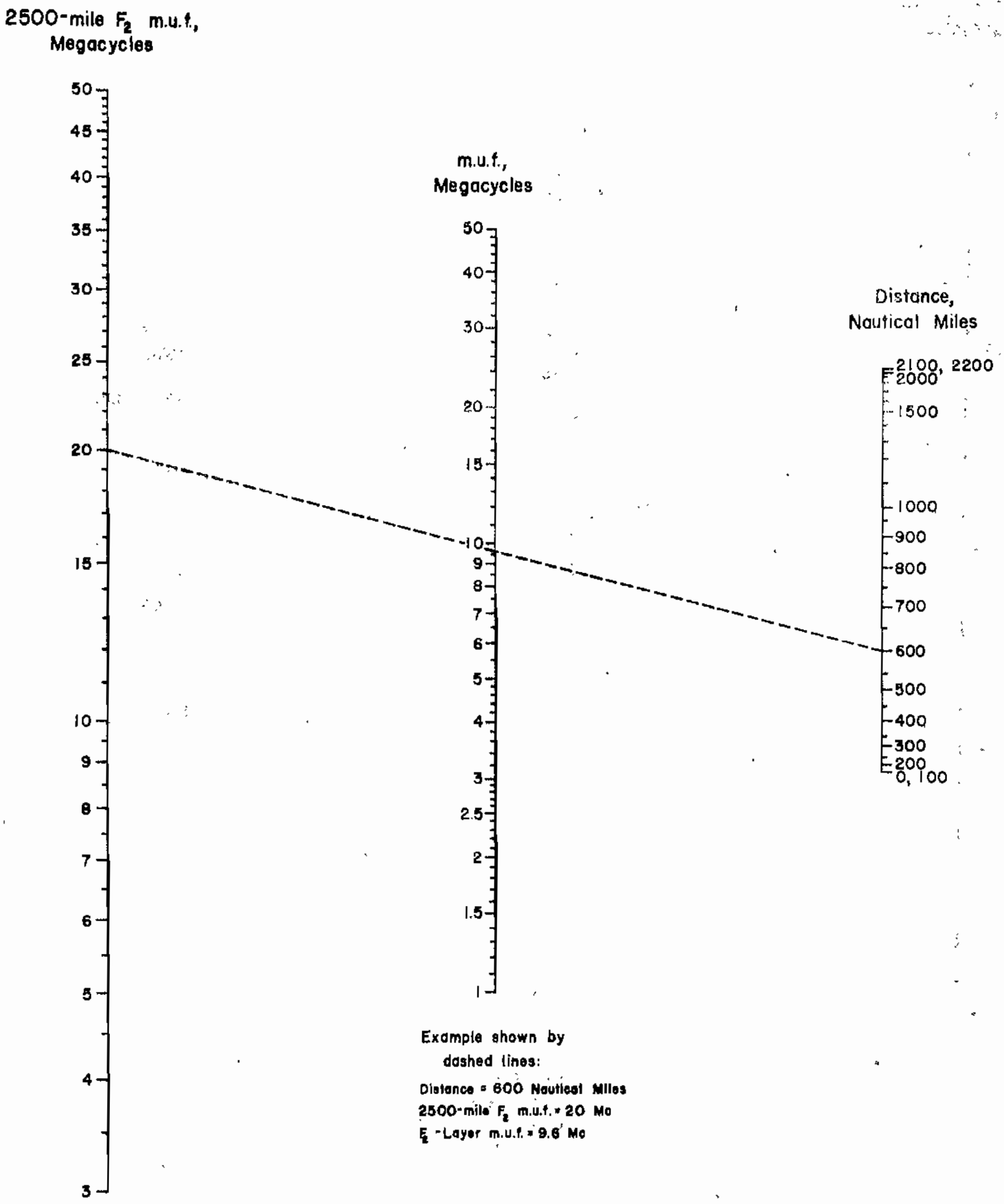
Fig. 30. Graph paper for rapid determination of maximum usable frequency factor for transmission distances up to 2200 nautical miles. (Distances indicated in nautical miles and kilometers).



Example shown by dashed lines:

Distance = 900 Miles
2500-mile F_2 m.u.f. = 20 Mc
F_2-Layer m.u.f. = 11.9 Mc

Fig. 31. Nomogram for transforming F- or F_2-layer maximum usable frequencies at 2500 miles to equivalent values at lower transmission distances. (Distances in miles).



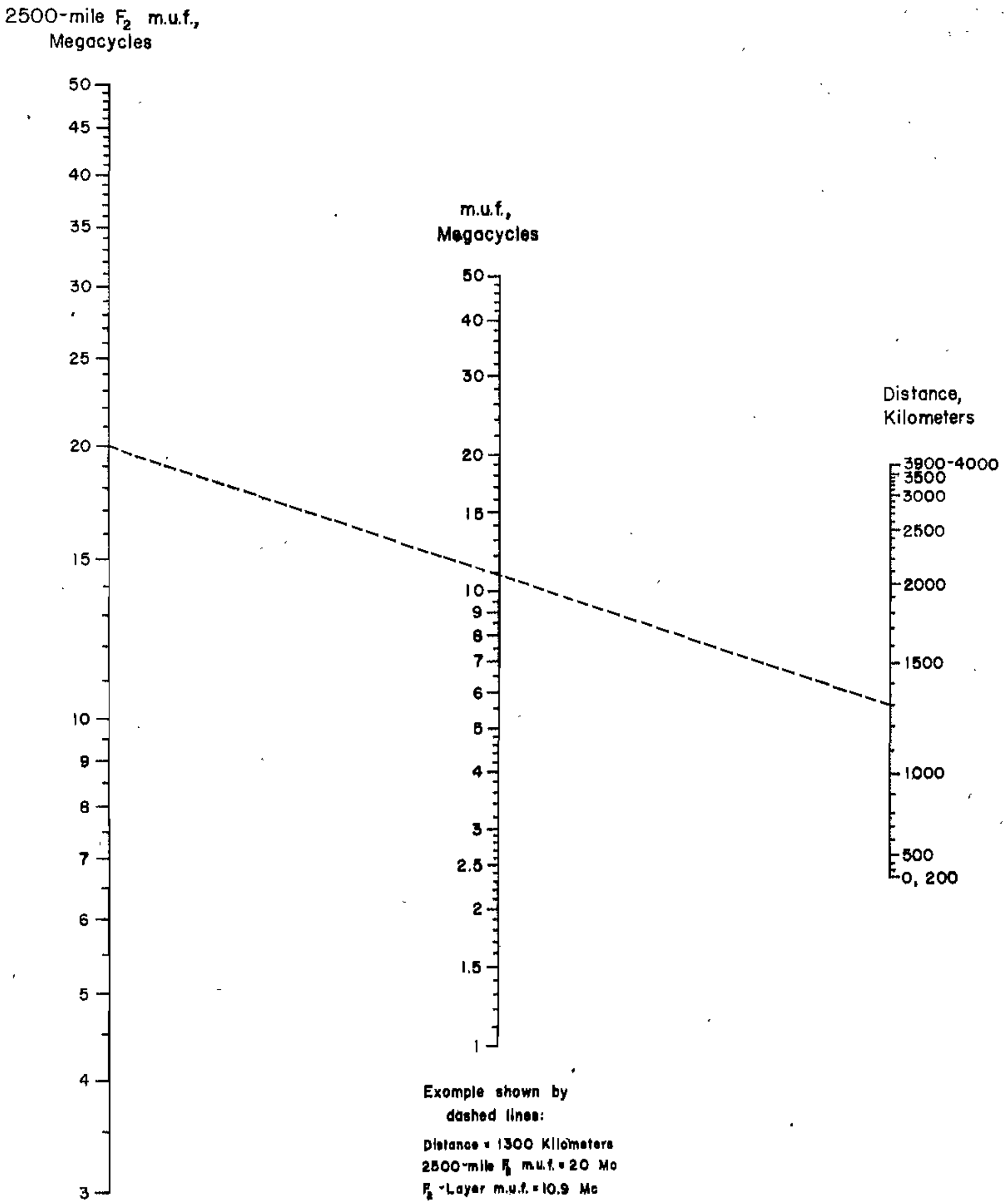
Example shown by dashed lines:

Distance = 600 Nautical Miles

2500-mile F_2 m.u.f. = 20 Mc

F_2 -Layer m.u.f. = 9.6 Mc

Fig. 32. Nomogram for transforming F- or F_2-layer maximum usable frequencies at 2500 miles to equivalent values at lower transmission distances. (Distances in nautical miles).



Example shown by dashed lines:

Distance = 1300 Kilometers
2500-mile F_2 m.u.f. = 20 Mc
F_2-Layer m.u.f. = 10.9 Mc

Fig. 33. **Nomogram for transforming F- or F_2-layer maximum usable frequencies at 2500 miles to equivalent values at lower transmission distances. (Distances in kilometers).**

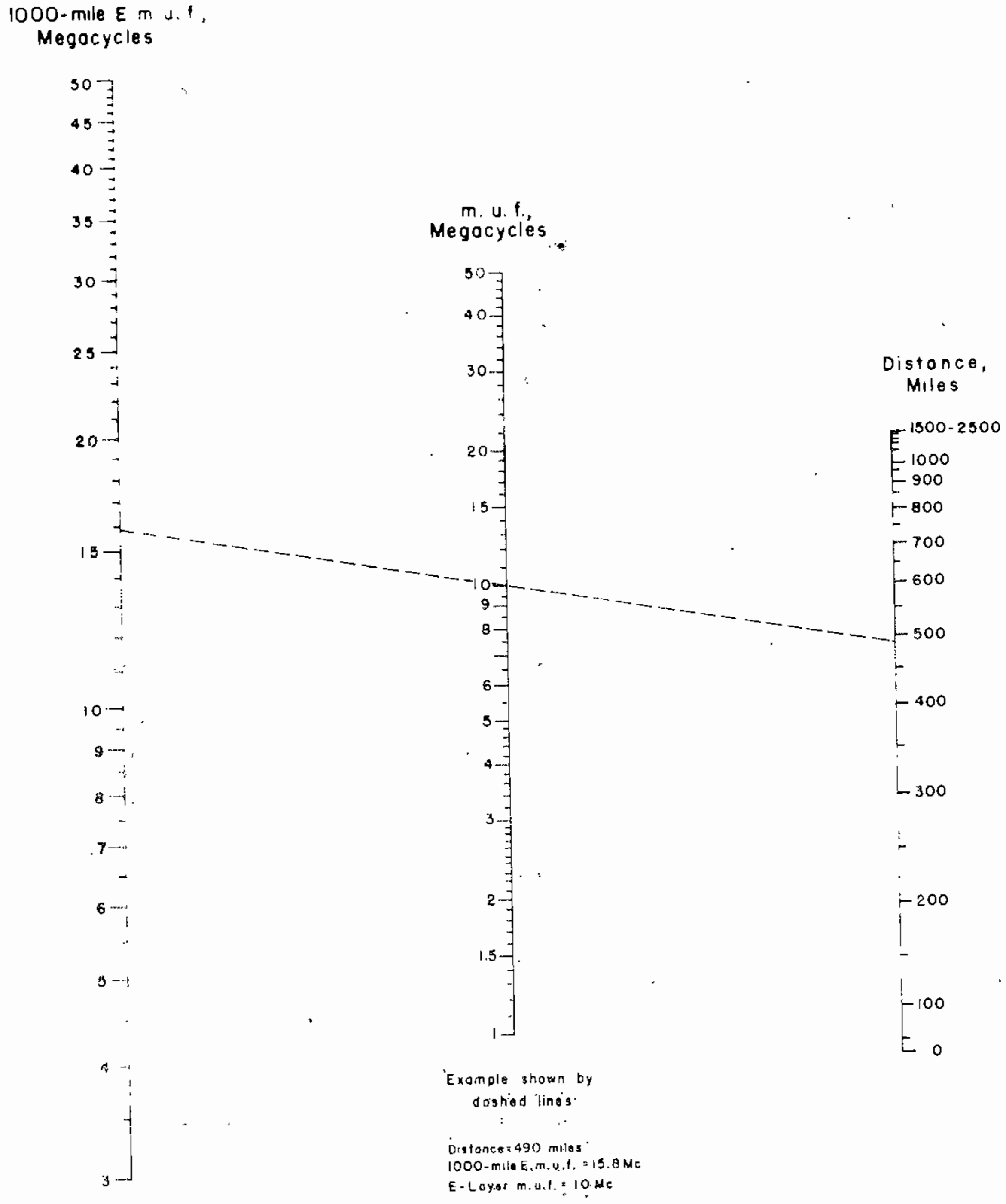
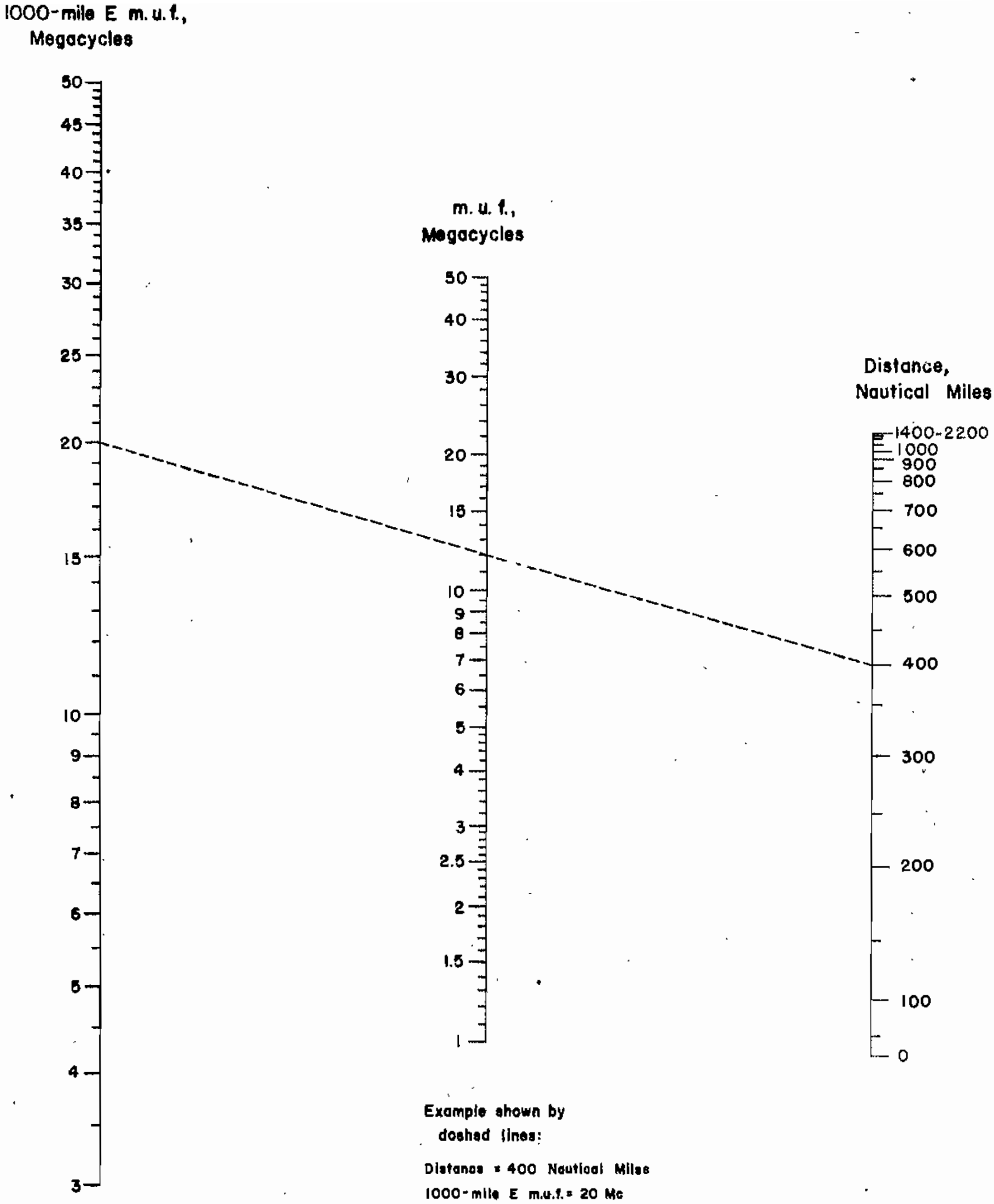


Fig. 34. Nomogram for transforming E-layer maximum usable frequencies at 1000 miles to equivalent values of maximum usable frequency due to combined effect of E-layer and F_1-layer at other transmission distances up to 2500 miles.



Example shown by dashed lines:

Distance = 400 Nautical Miles

1000-mile E m.u.f.= 20 Mc

Combined E-and F_1-Layer m. u. f. = 12 Mc

Fig. 35. Nomogram for transforming E-layer maximum usable frequencies at 1000 miles to equivalent values of maximum usable frequency due to combined effect of E-layer and F_1-layer at other transmission distances up to 2200 nautical miles.

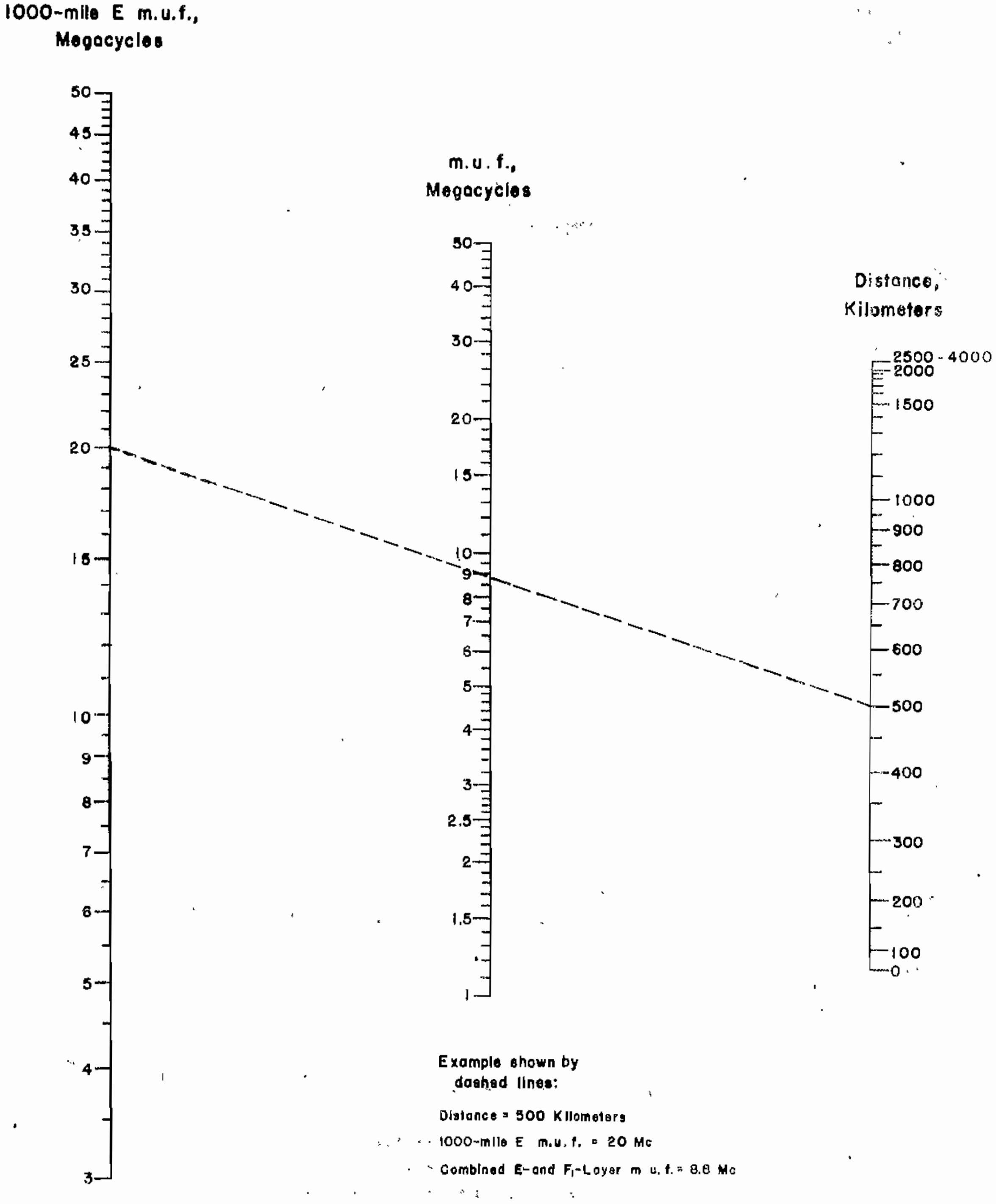
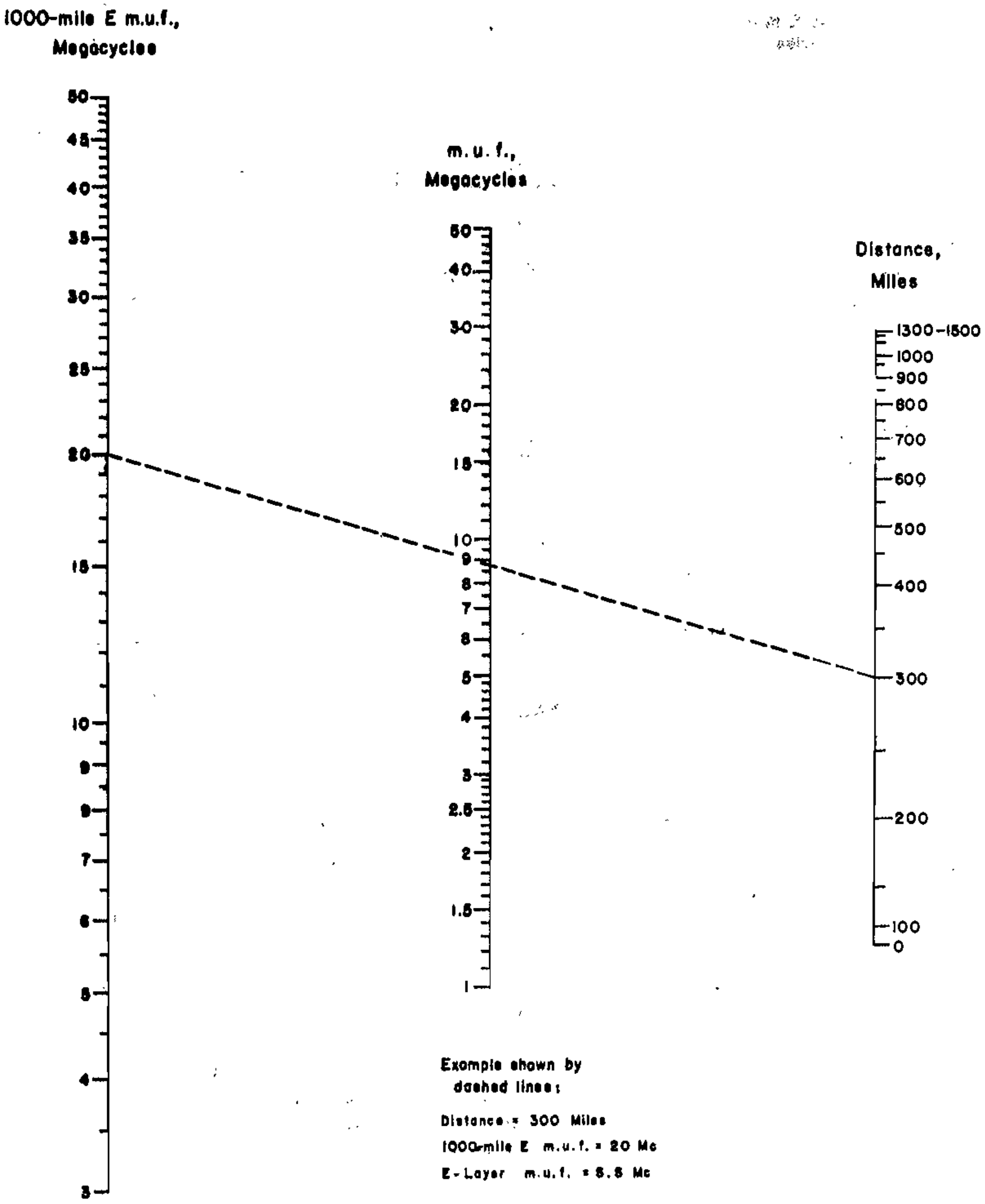


Fig. 36. Nomogram for transforming E-layer maximum usable frequencies at 1000 miles to equivalent values of maximum usable frequency due to combined effect of E-layer and F_1-layer at other transmission distances up to 4000 kilometers.



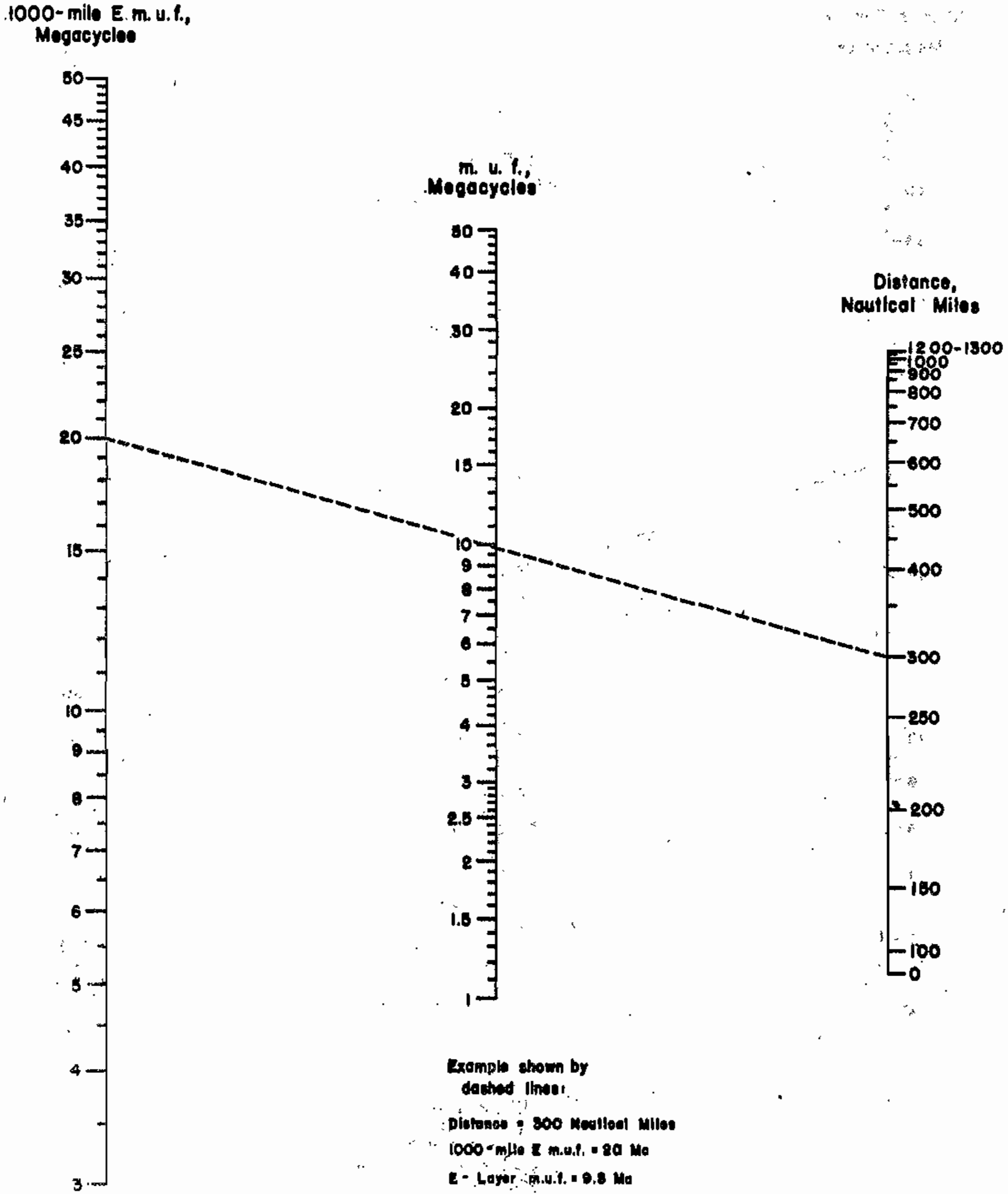
Example shown by dashed lines:

Distance = 300 Miles

1000-mile E m.u.f. = 20 Mc

E-Layer m.u.f. = 8.8 Mc

Fig. 37. Nomogram for transforming E-layer maximum usable frequencies at 1000 miles to equivalent values at other transmission distances up to 1500 miles.



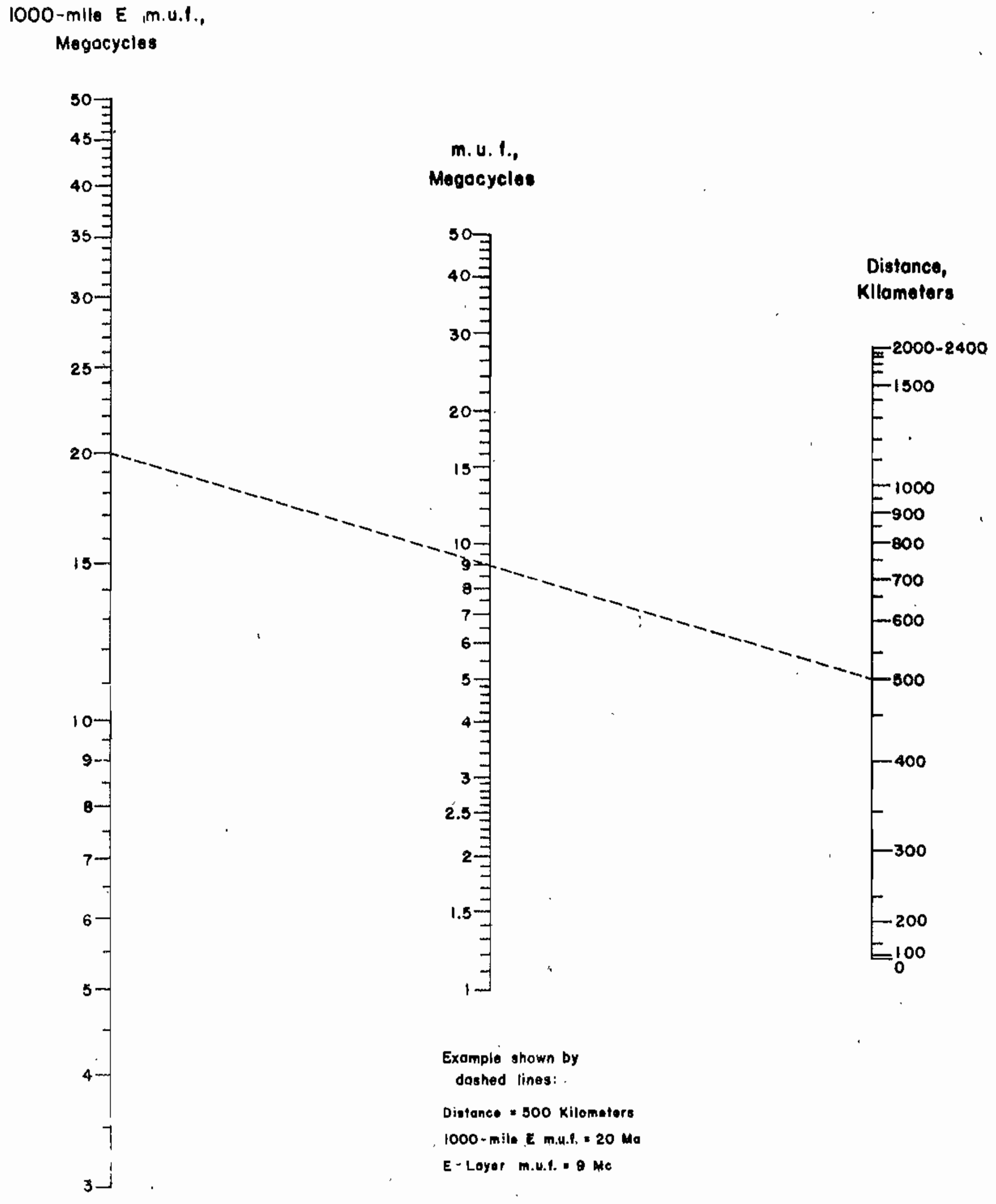
Example shown by dashed lines:

Distance = 300 Nautical Miles

1000-mile E m.u.f. = 20 Mc

E-Layer m.u.f. = 9.8 Mc

Fig. 38. Nomogram for transforming E-layer maximum usable frequencies at 1000 miles to equivalent values at other transmission distances up to 1300 nautical miles.



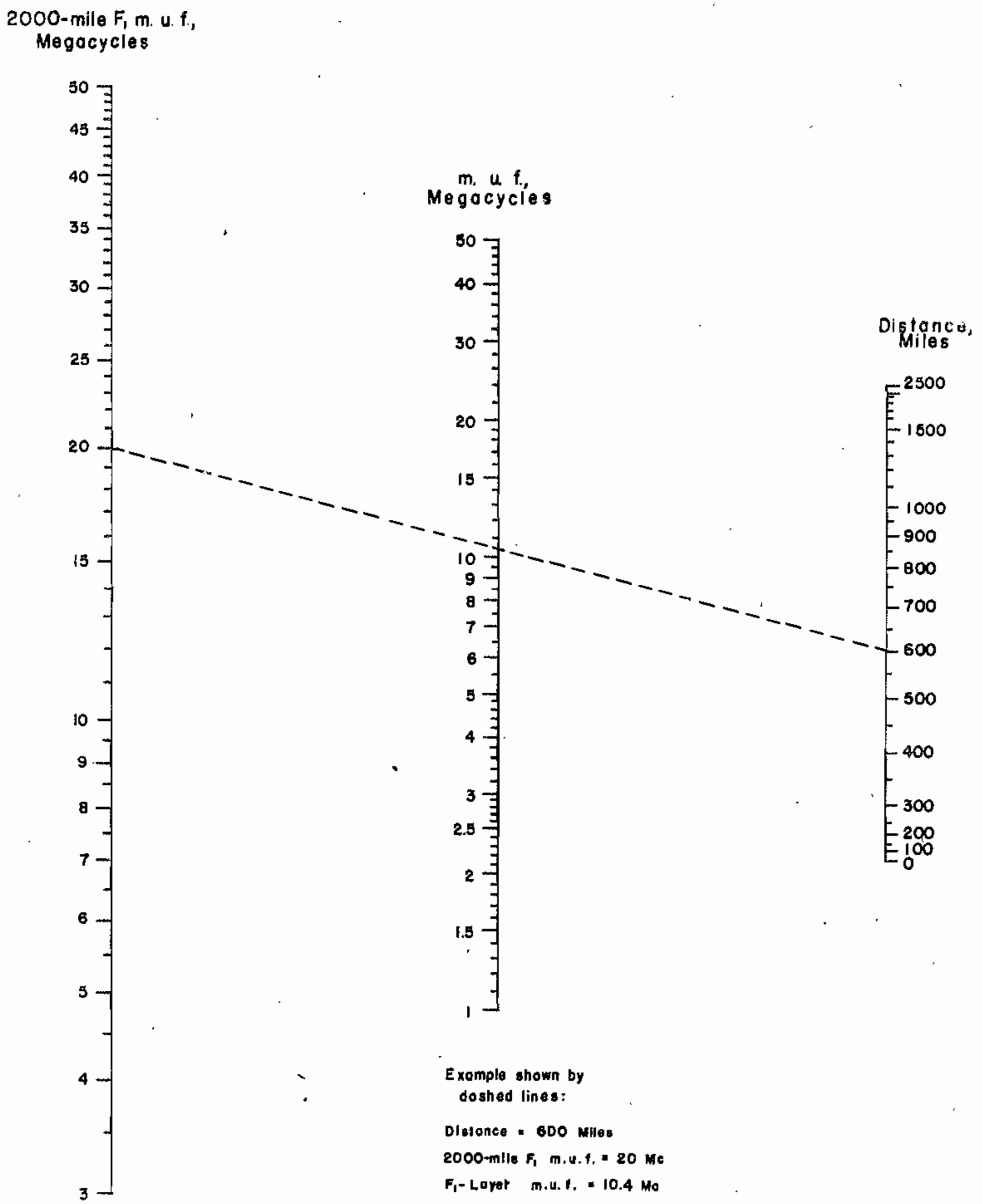
Example shown by dashed lines:

Distance = 500 Kilometers

1000-mile E m.u.f. = 20 Mc

E-Layer m.u.f. = 9 Mc

Fig. 39. Nomogram for transforming E-layer maximum usable frequencies at 1000 miles to equivalent values at other transmission distances up to 2000 kilometers.



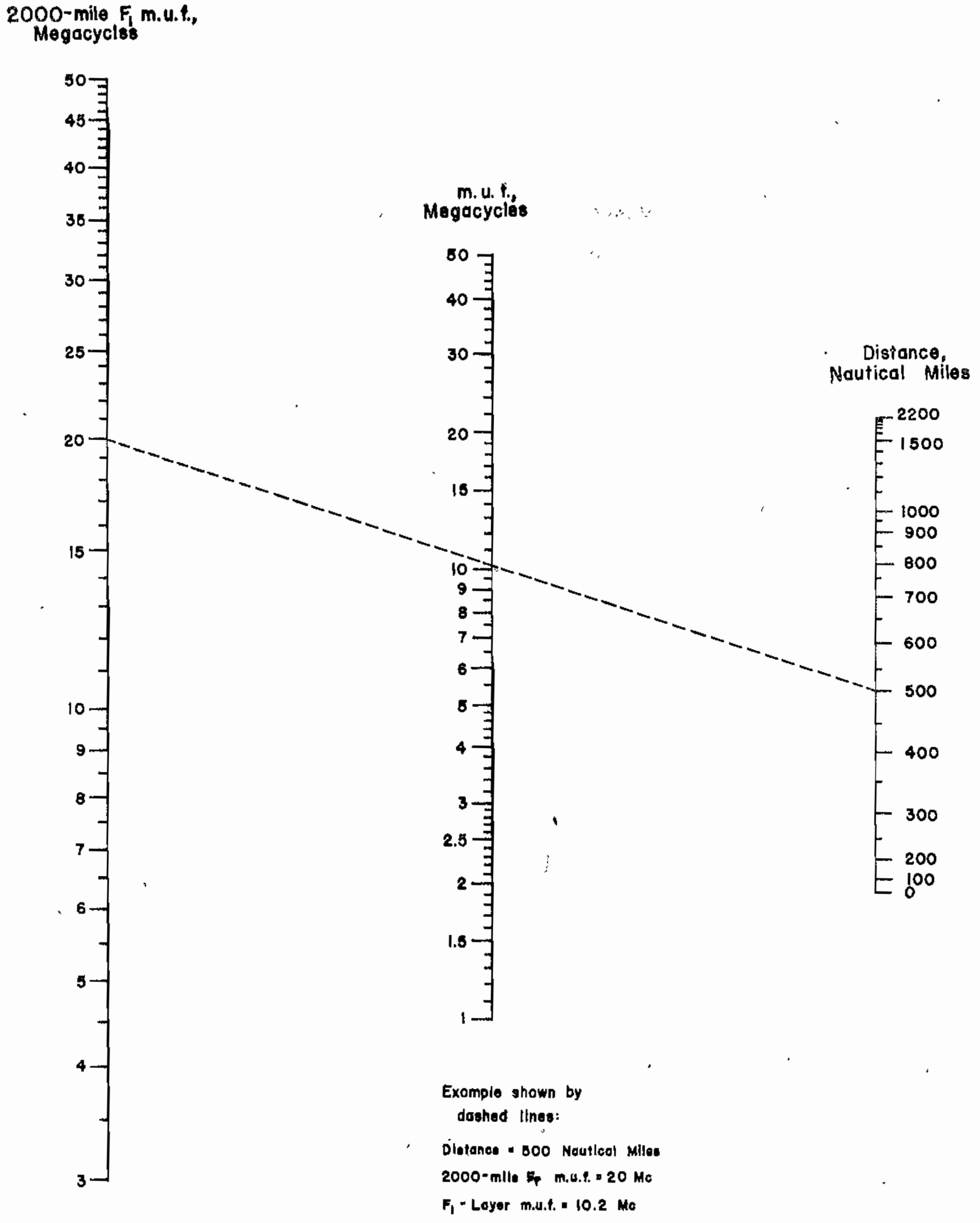
Example shown by dashed lines:

Distance = 600 Miles

2000-mile F_1 m.u.f. = 20 Mc

F_1-Layer m.u.f. = 10.4 Mc

Fig. 40. Nomogram for transforming F_1-layer maximum usable frequencies at 2000 miles to equivalent values at other transmission distances up to 2500 miles.



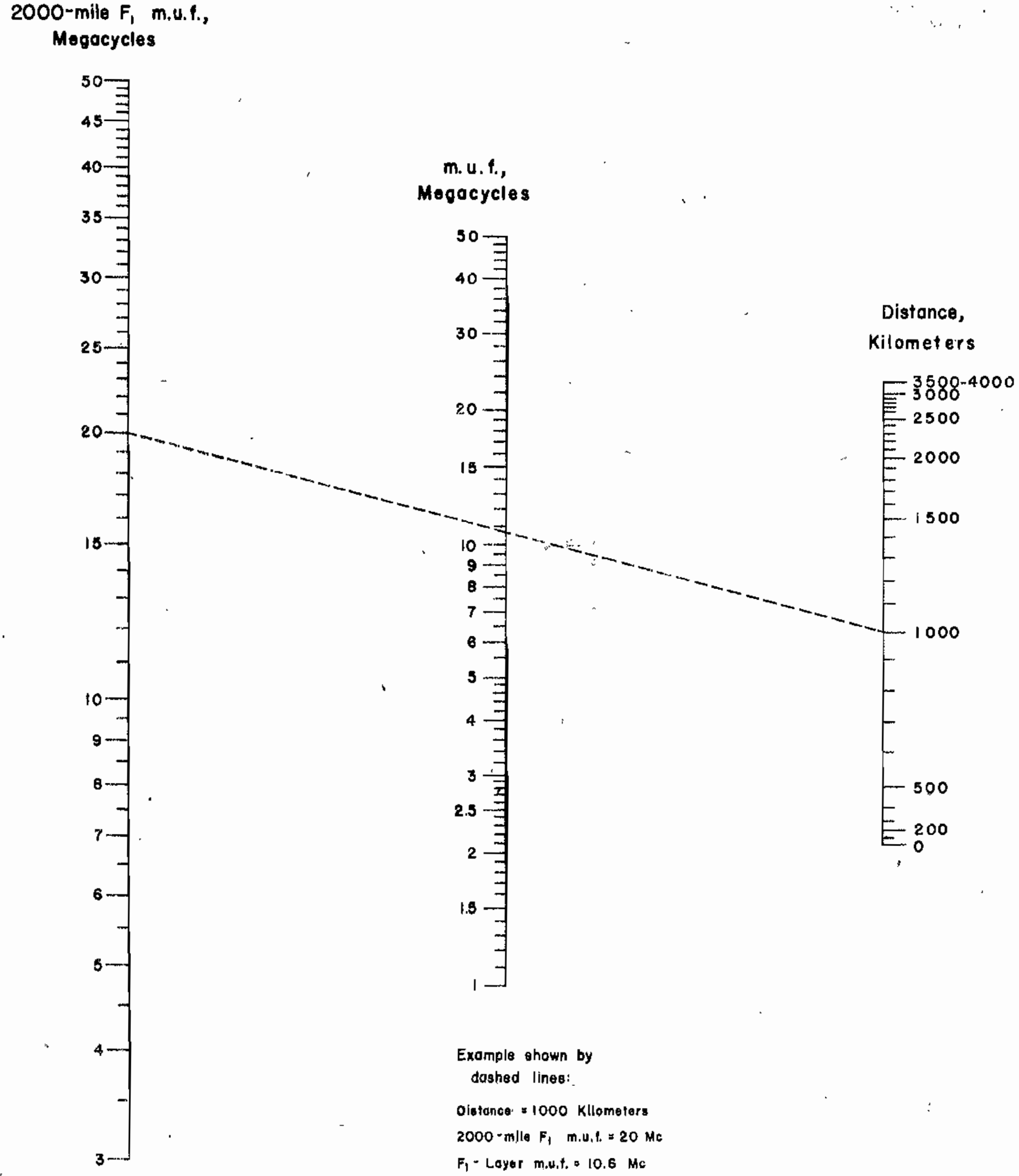
Example shown by dashed lines:

Distance = 500 Nautical Miles

2000-mile F_1 m.u.f. = 20 Mc

F_1 - Layer m.u.f. = 10.2 Mc

Fig. 41. Nomogram for transforming F_1-layer maximum usable frequencies at 2000 miles to equivalent values at other transmission distances up to 2200 nautical miles.



Example shown by dashed lines:

Distance = 1000 Kilometers

2000-mile F_1 m.u.f. = 20 Mc

F_1 - Layer m.u.f. = 10.6 Mc

Fig. 42. Nomogram for transforming F_1-layer maximum usable frequencies at 2000 miles to equivalent values at other transmission distances up to 4000 kilometers.

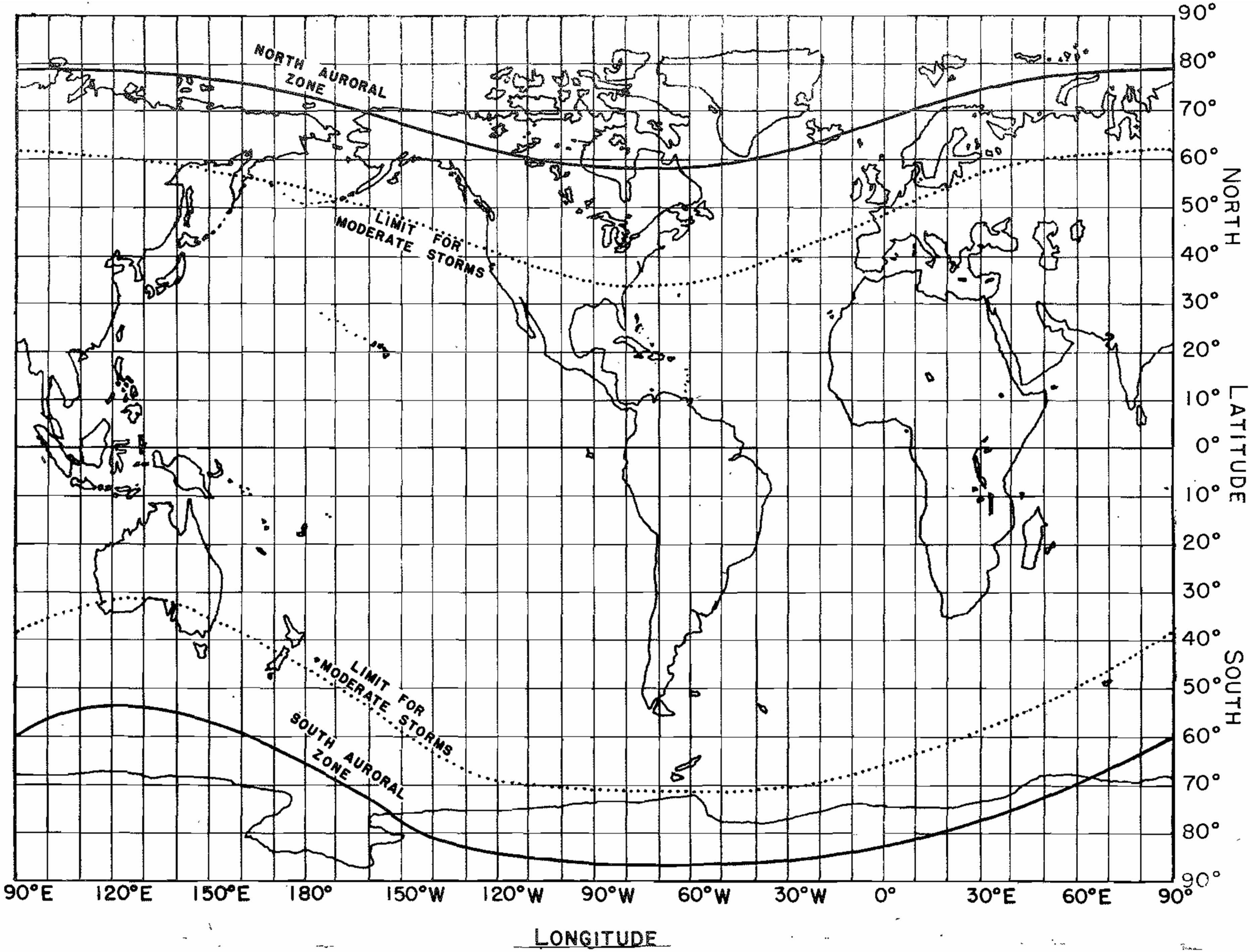


Fig. 43. World map, showing auroral zones.

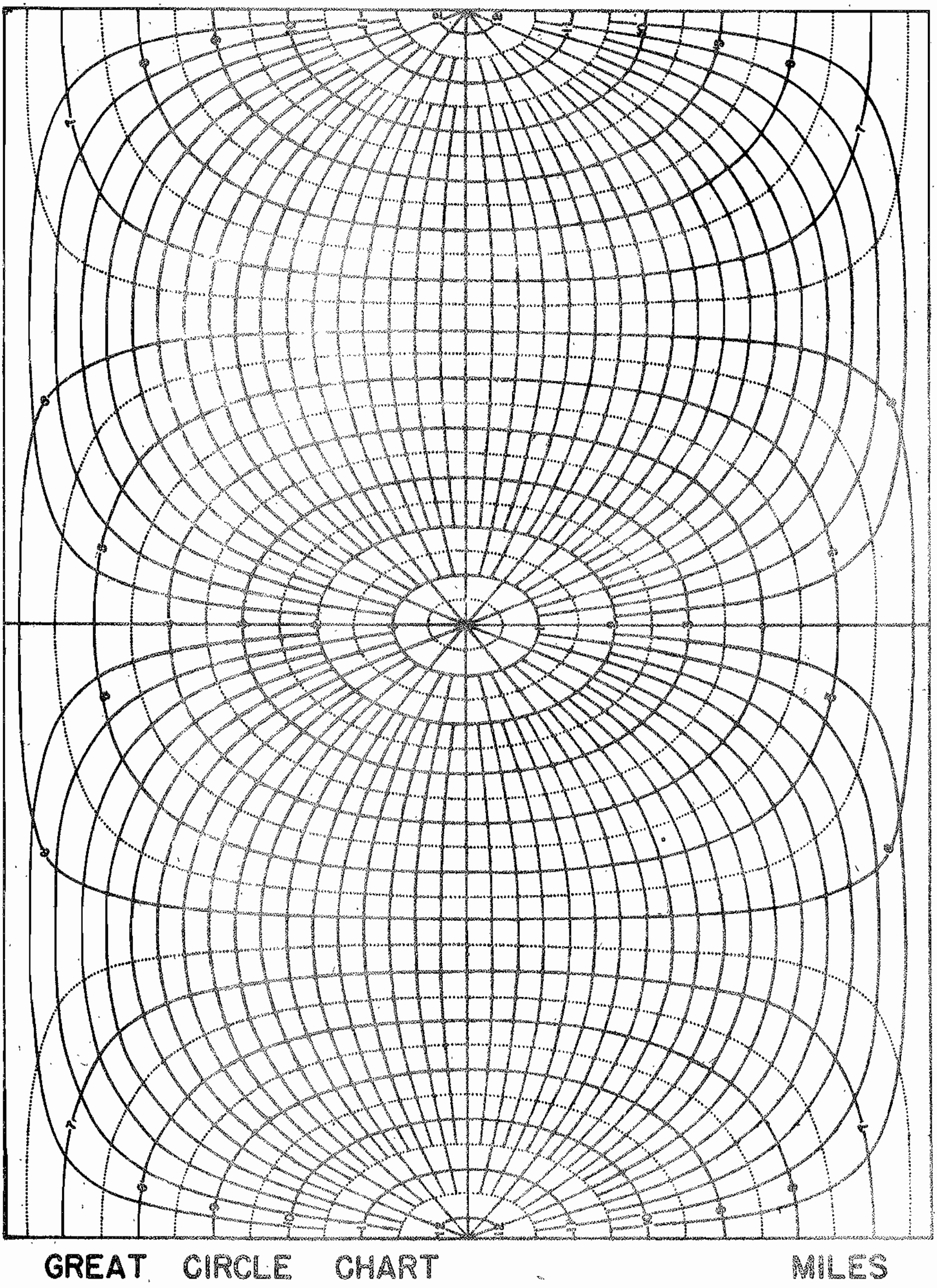


Fig. 44. Great circle chart, centered on equator. Small circles indicate distances, in thousands of miles.

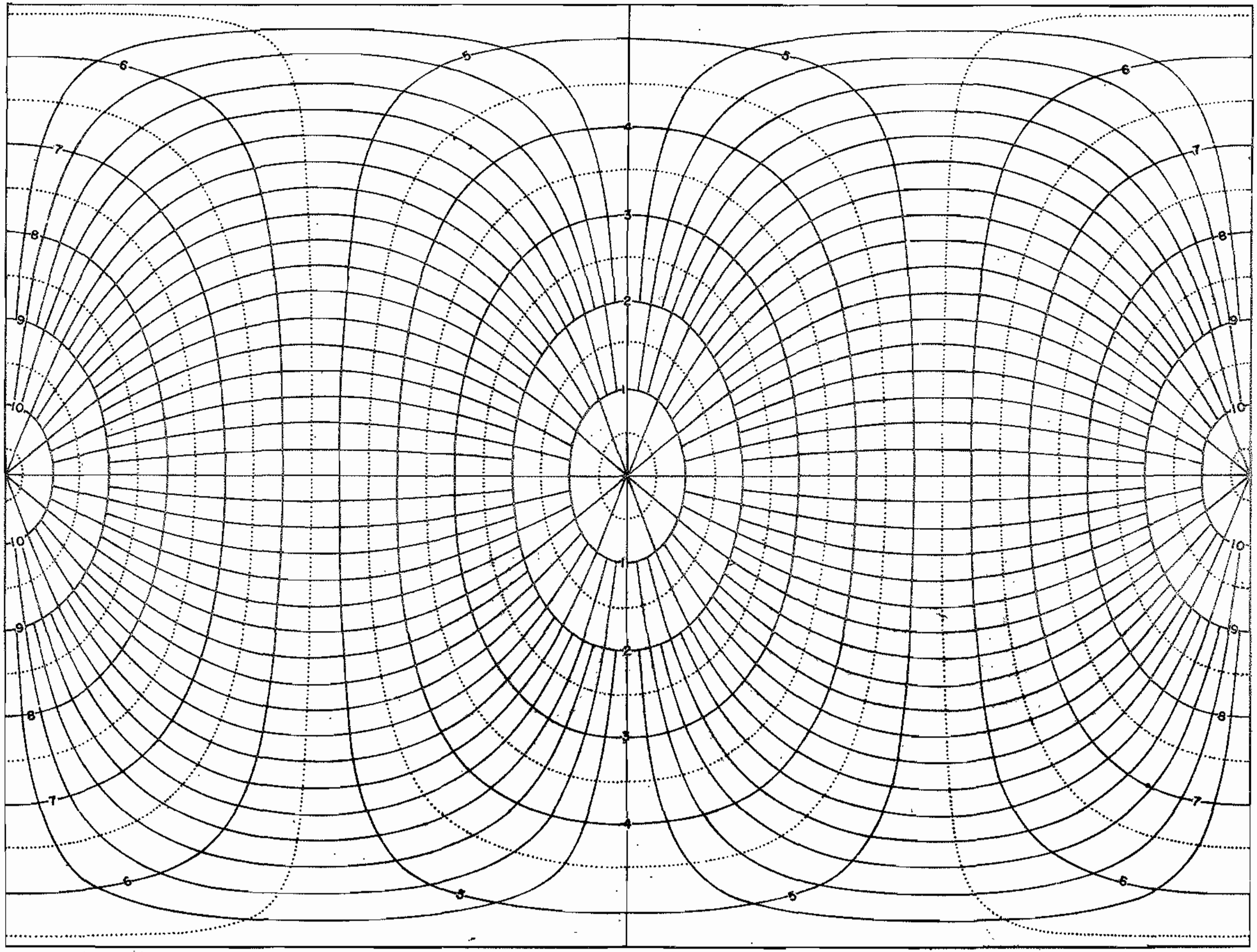


Fig. 45. Great circle chart, centered on equator. Small circles indicate distances, in thousands of nautical miles.

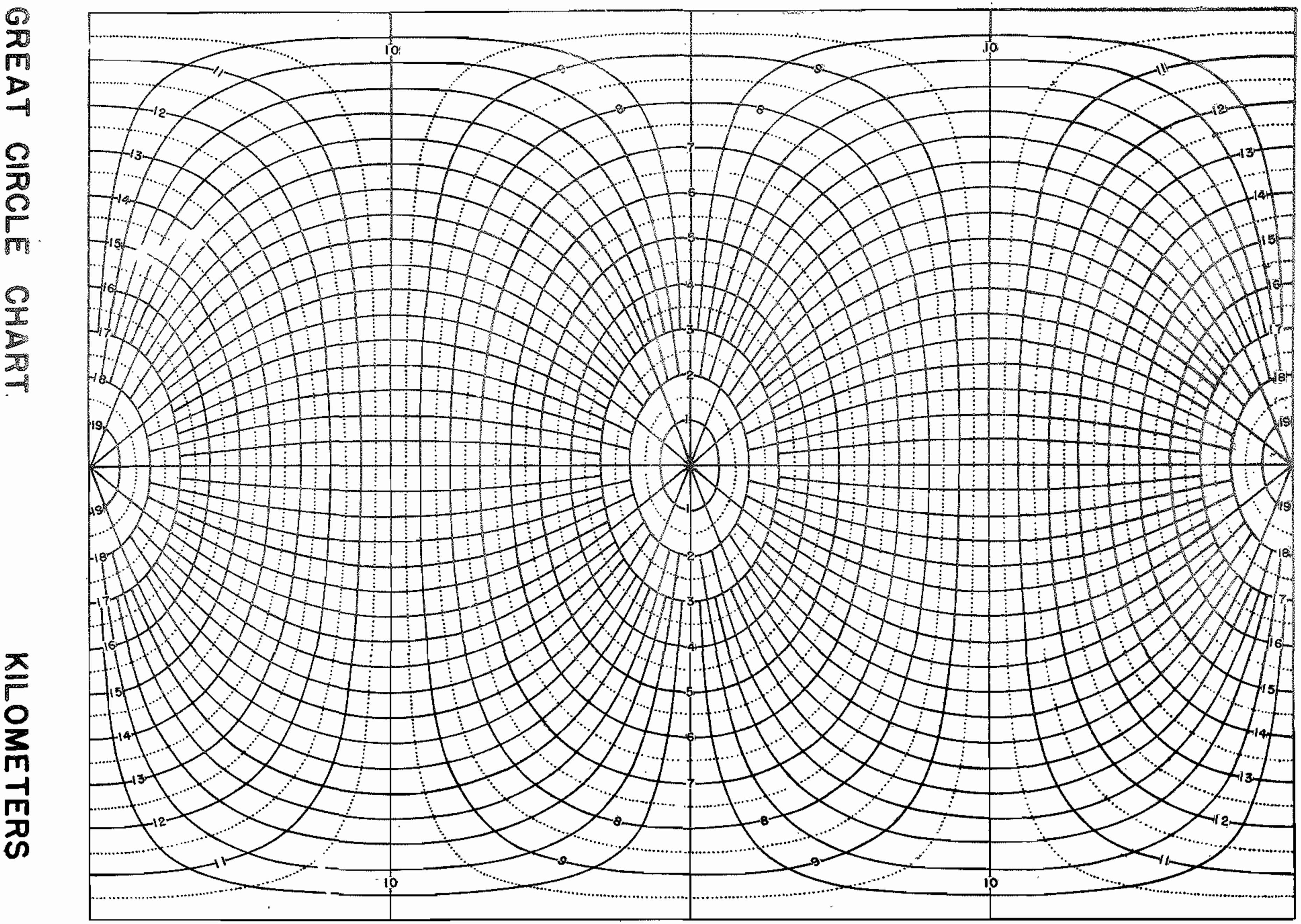


Fig. 46. Great circle chart, centered on equator. Small circles indicate distances, in thousands of kilometers.

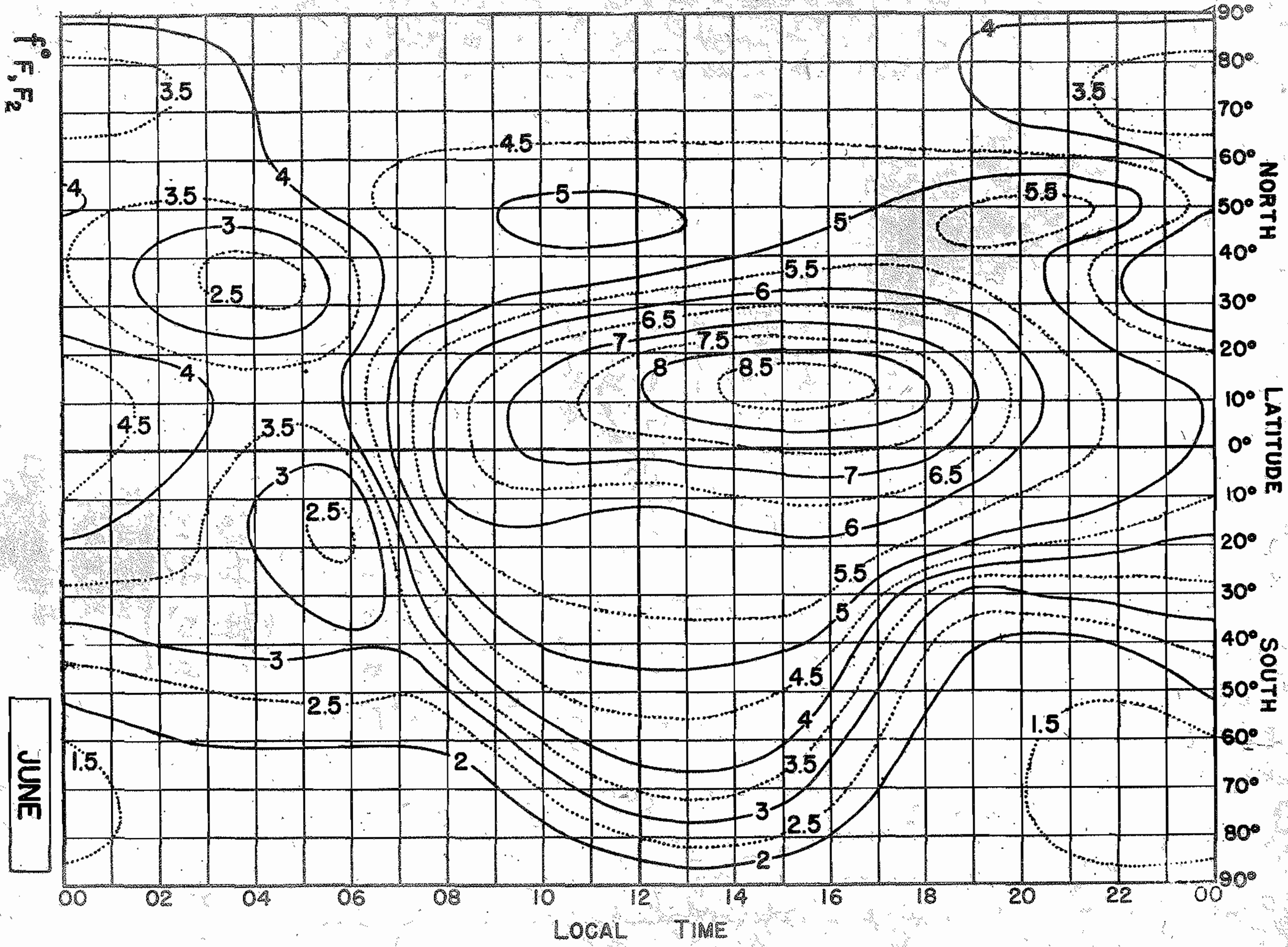


Fig. 47. F- and F_2-layer critical frequencies, (predicted average for quiet days), June. Numbers on curves are f^oF in Mc.

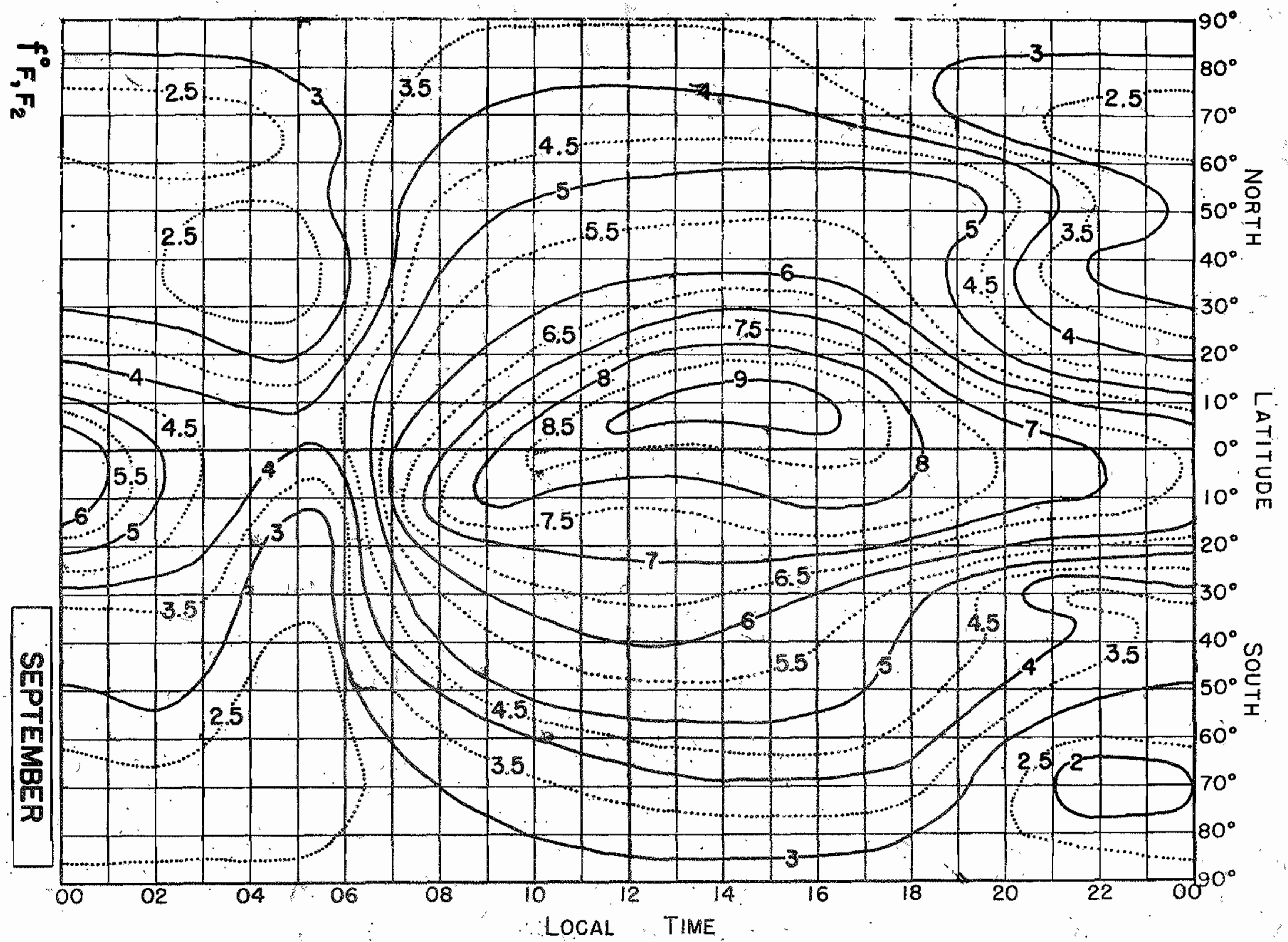


Fig. 48. F- and F_2-layer critical frequencies, (predicted average for quiet days), September. Numbers on curves are f^{0}_{F} in Mc.

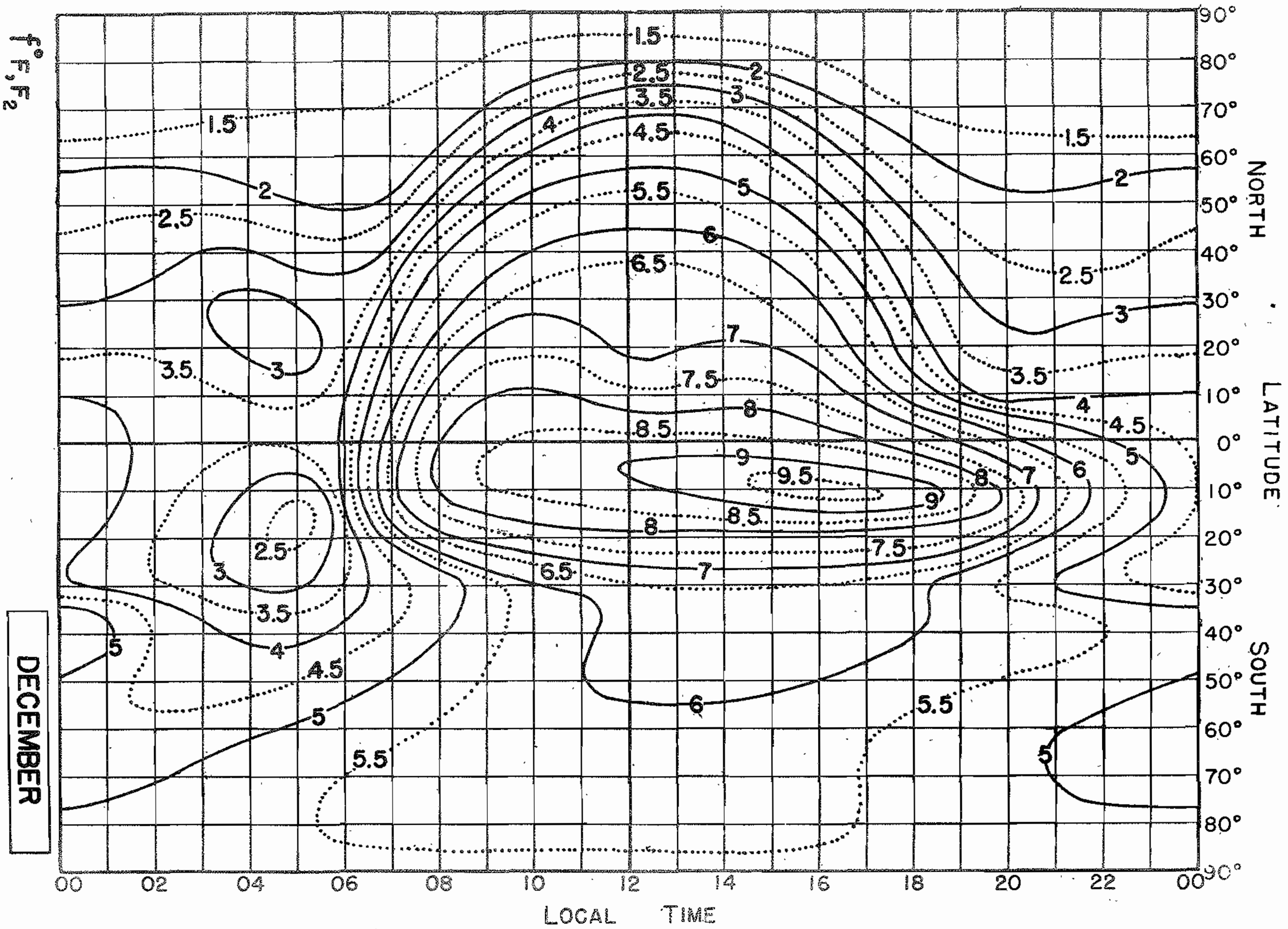


Fig. 49. F- and F_2-layer critical frequencies, (predicted average for quiet days), December. Numbers on curves are f^oF in Mc.

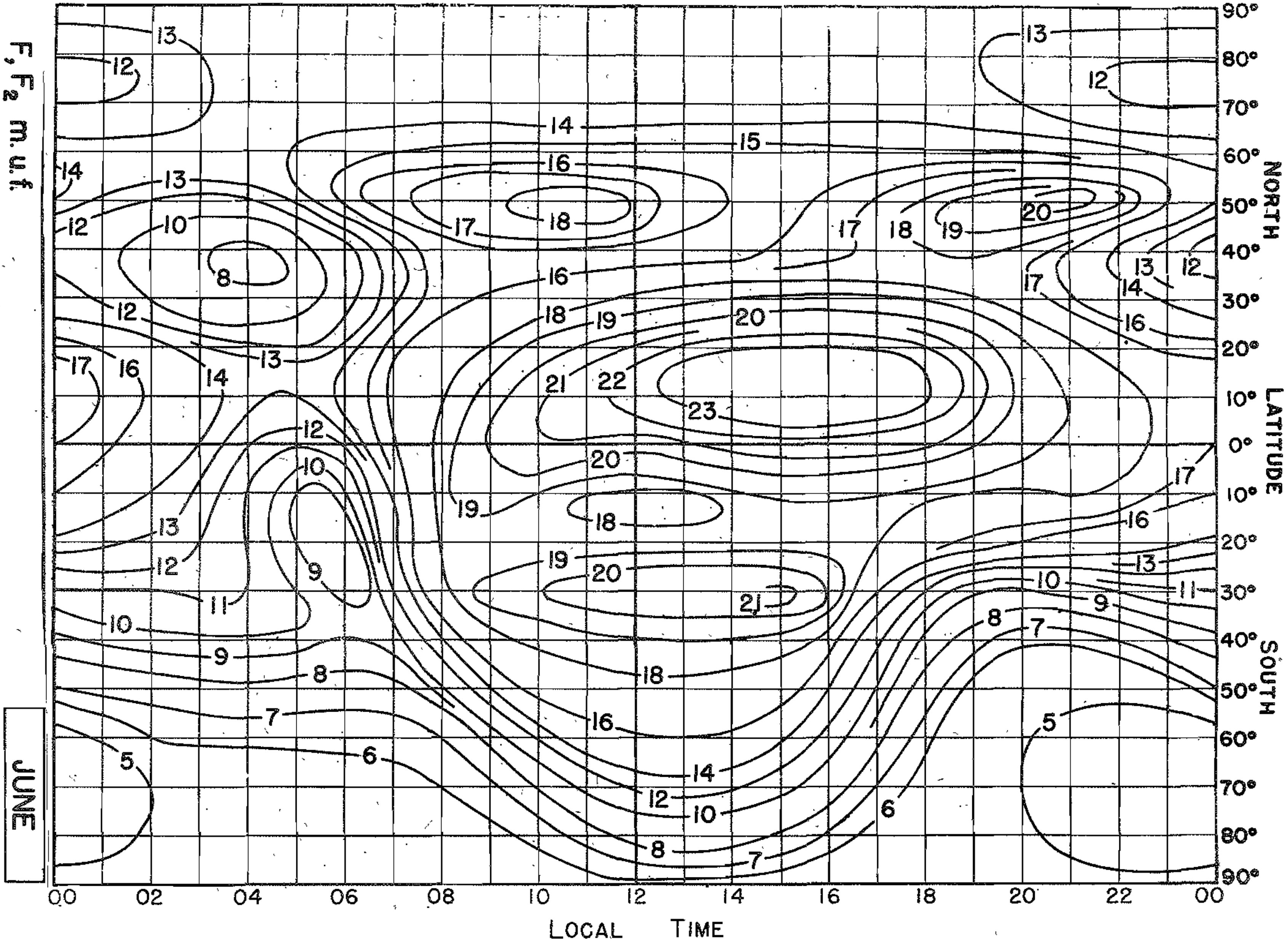


FIG. 50 F-, F_2-layer frequencies, (predicted average for quiet days), June. Numbers on curves are F- and F_2-layer m. u. f. in Mc for transmission distance of 2500 miles.

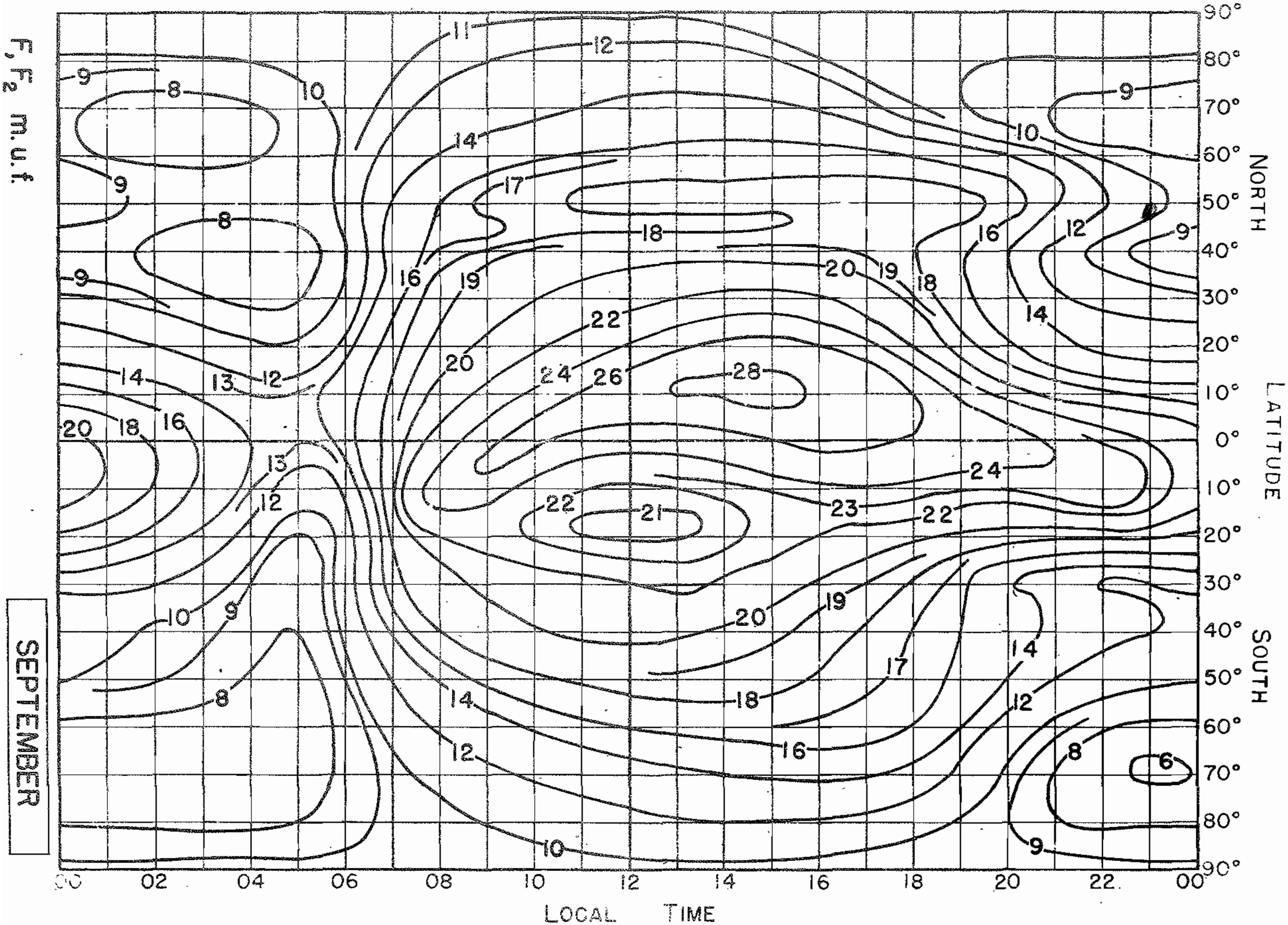


Fig. 51. F-, F_2-layer frequencies, (predicted average for quiet days), September. Numbers on curves are F- and F_2-layer m.u.f. in Mc for transmission distance of 2500 miles.

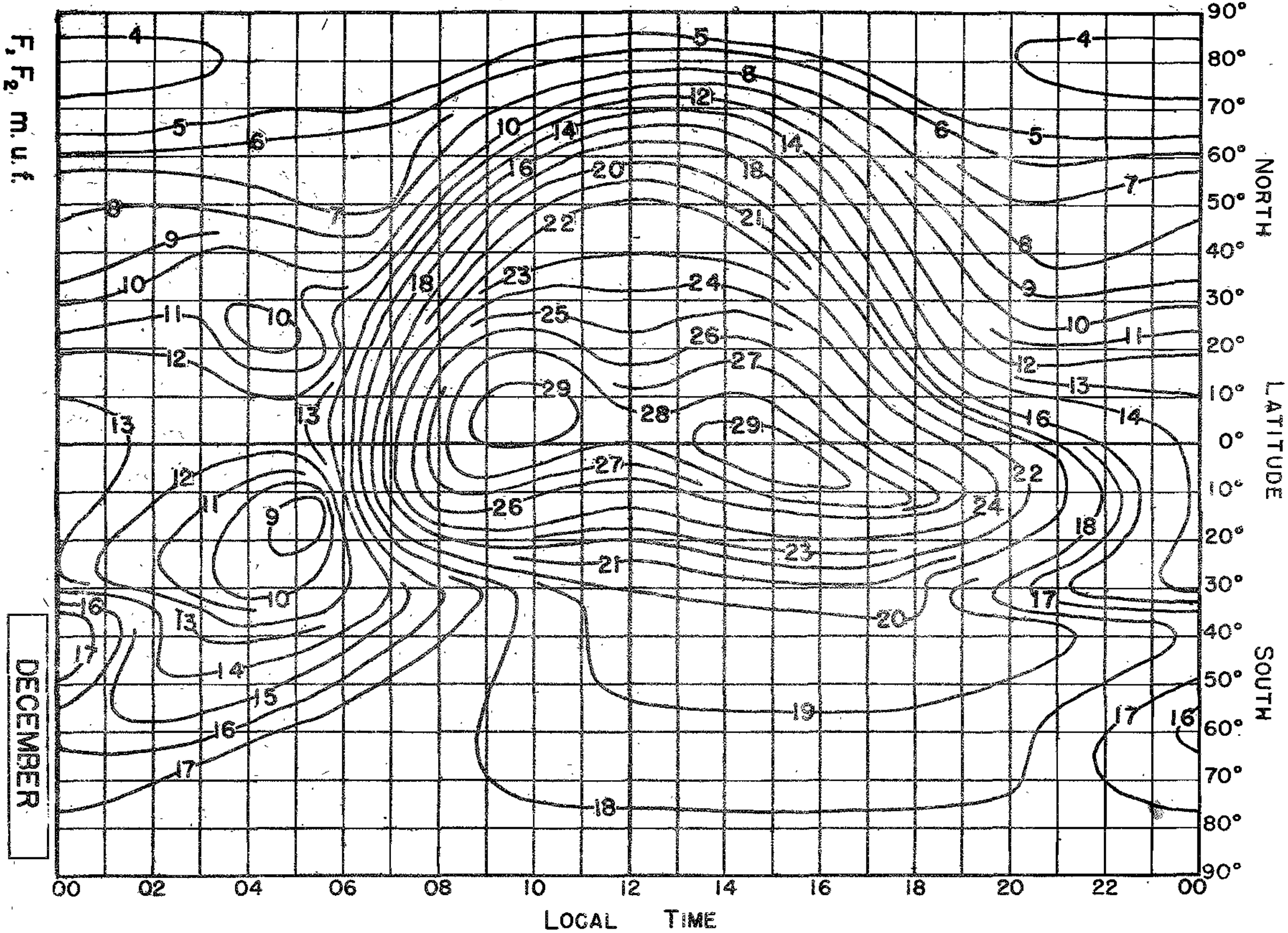


Fig. 52. F-, F_2-layer frequencies, (predicted average for quiet days), December. Numbers on curves are F- and F_2-layer m. u. f. in Mc for transmission distance of 2500 miles.

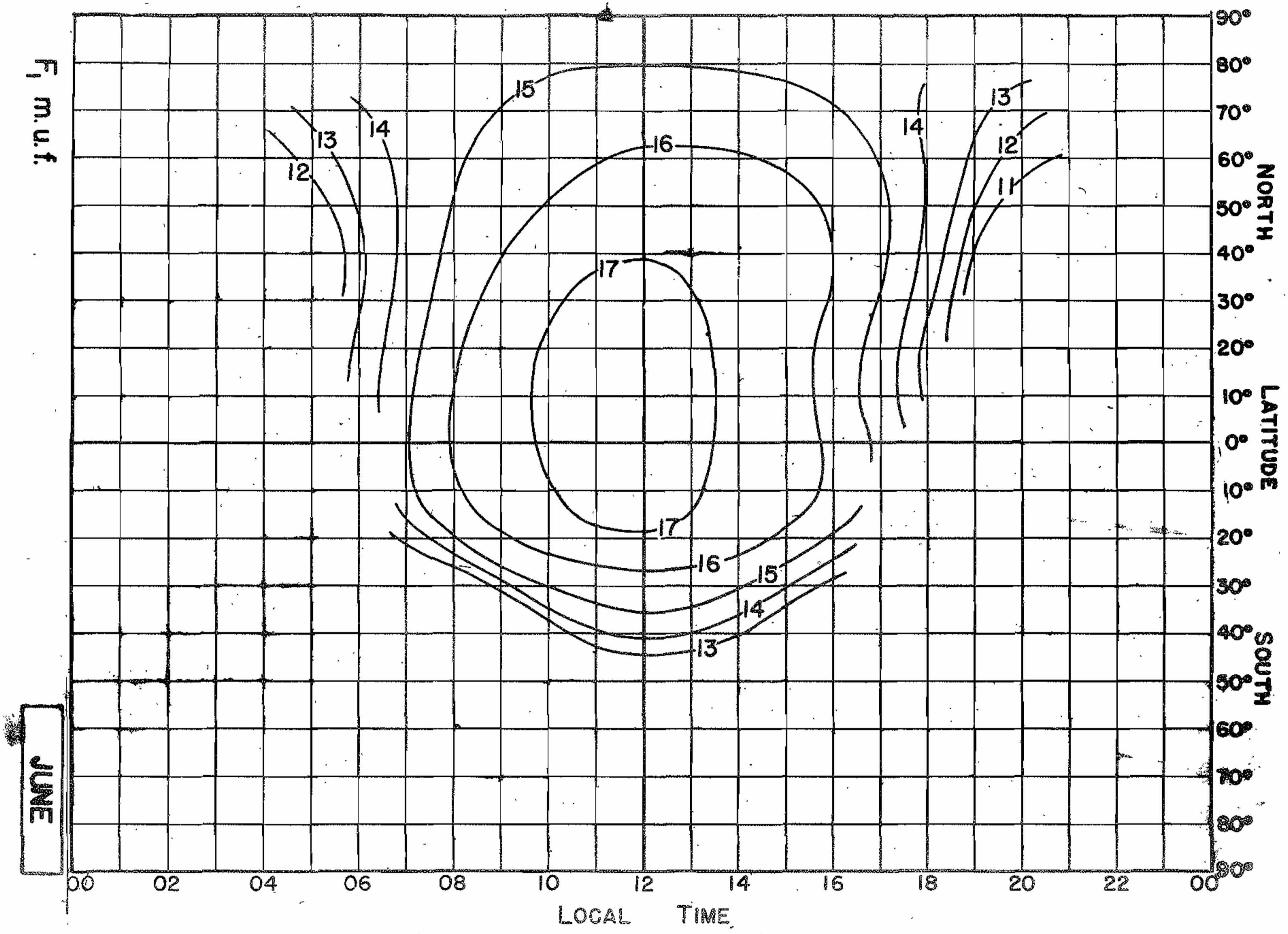


Fig. 53. F_1-layer frequencies, (predicted average for quiet days), June. Numbers on curves are F_1-layer m.u.f. in Mc for transmission distance of 2000 miles.

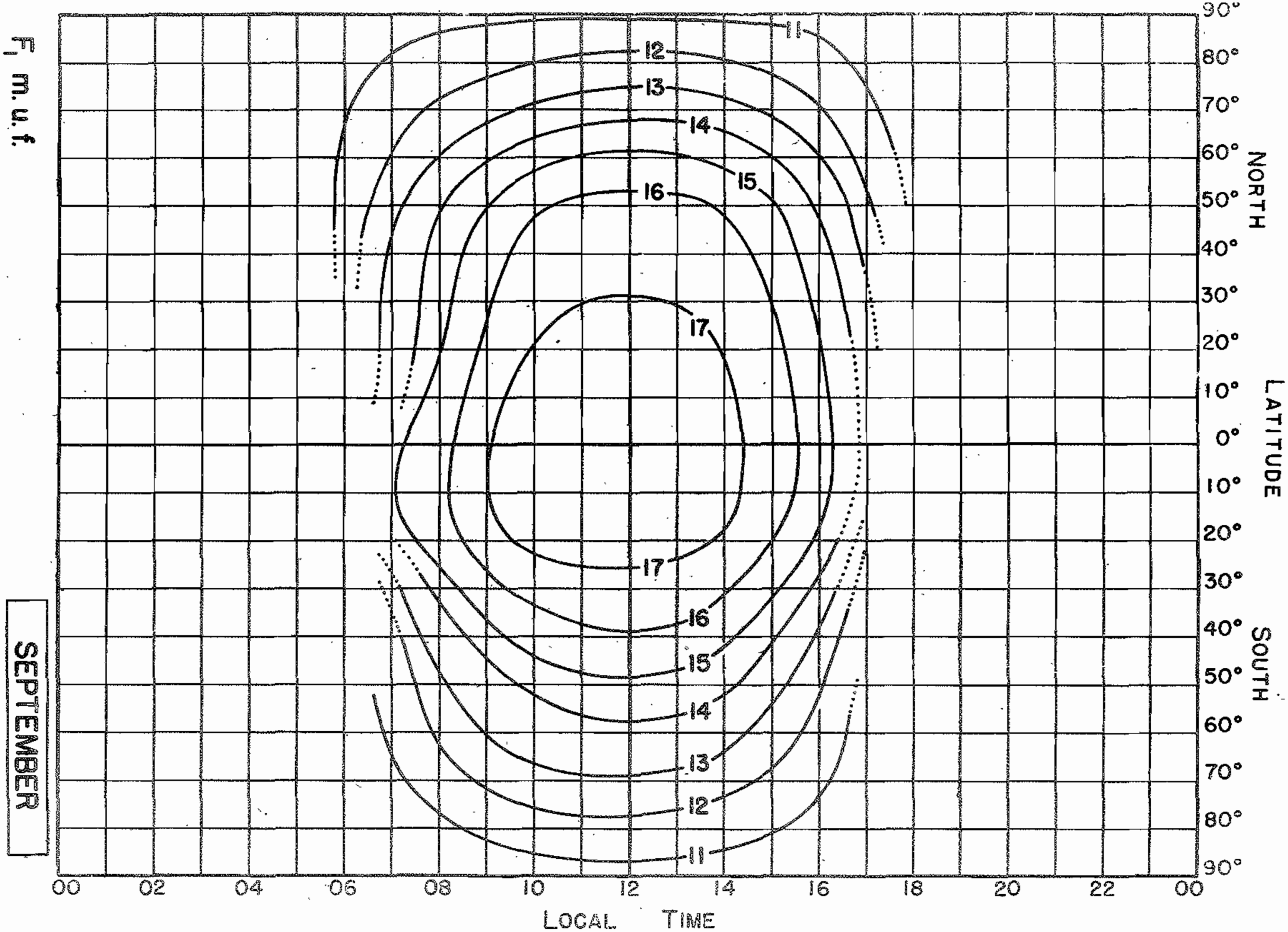


Fig. 54. F_1-layer frequencies, (predicted average for quiet days), September. Numbers on curves are F_1-layer m. u. f. in Mc for transmission distance of 2000 miles.

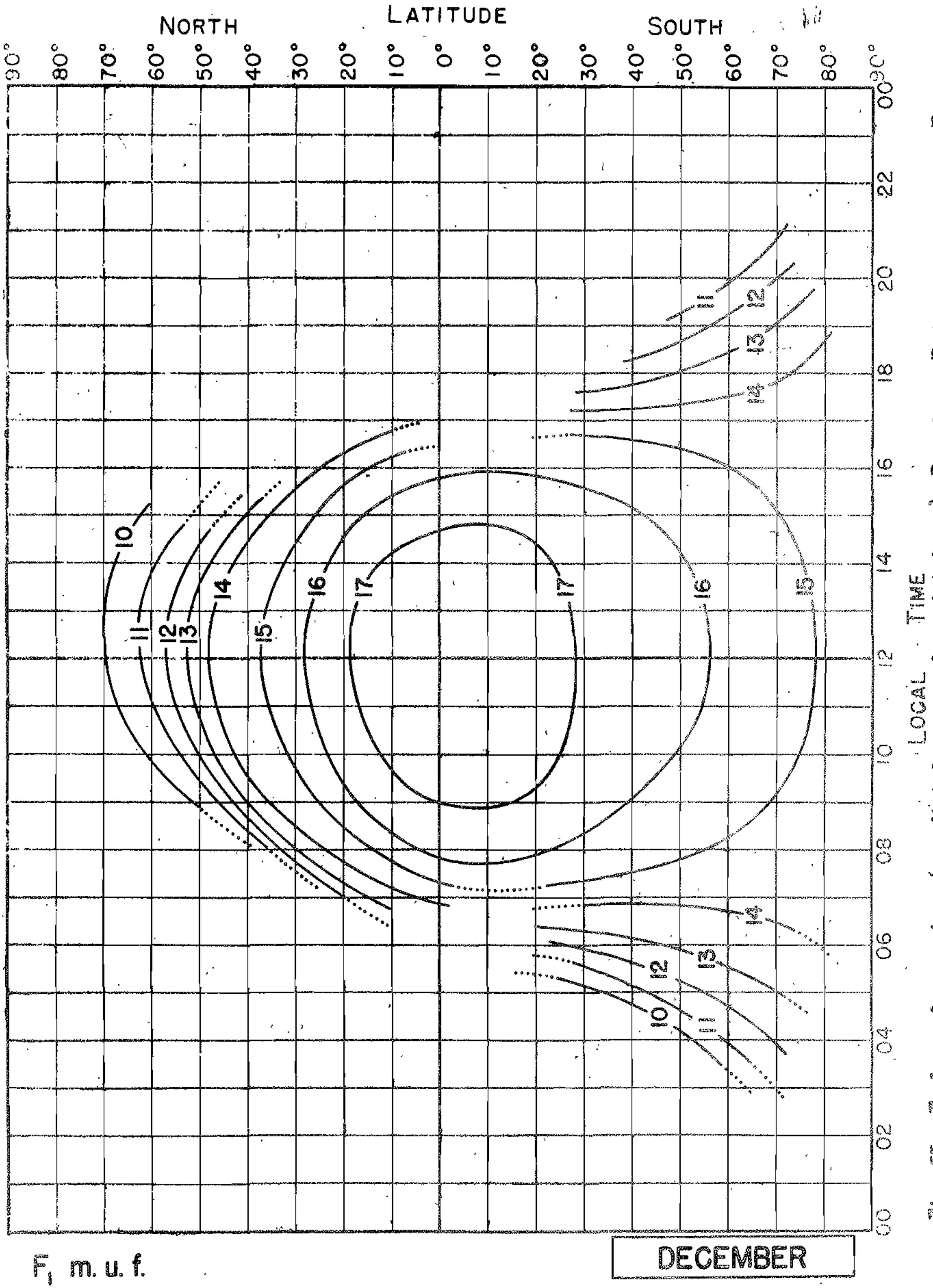


Fig. 55. F_1-layer frequencies, (predicted average for quiet days), December. Numbers on curves are F_1-layer m. u. f. in Mc for transmission distance of 2000 miles.

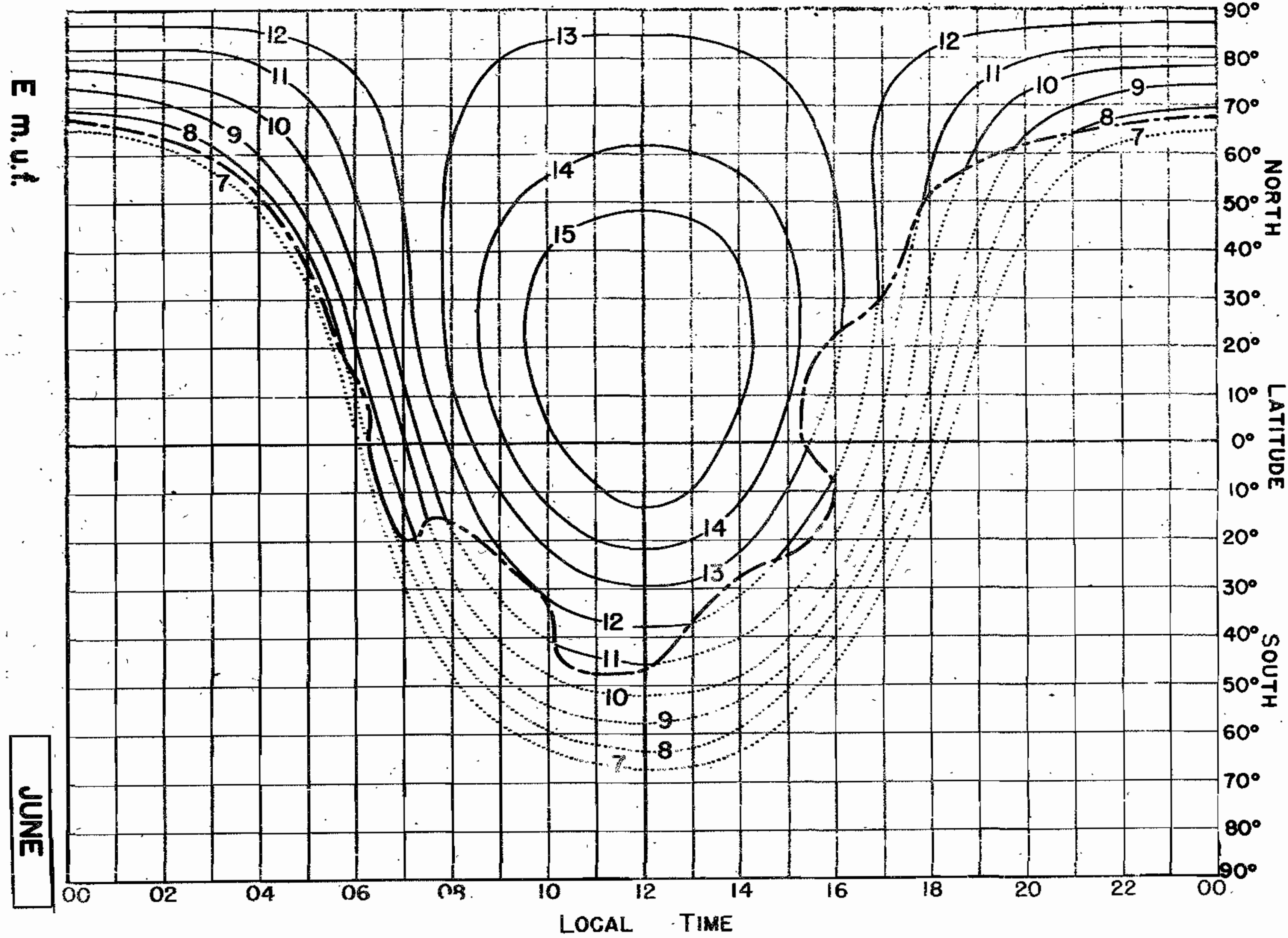


Fig. 56. E-layer frequencies, (predicted average for quiet days), June. Numbers on curves are E-layer m.u.f. in Mc for transmission distance of 1000 miles.

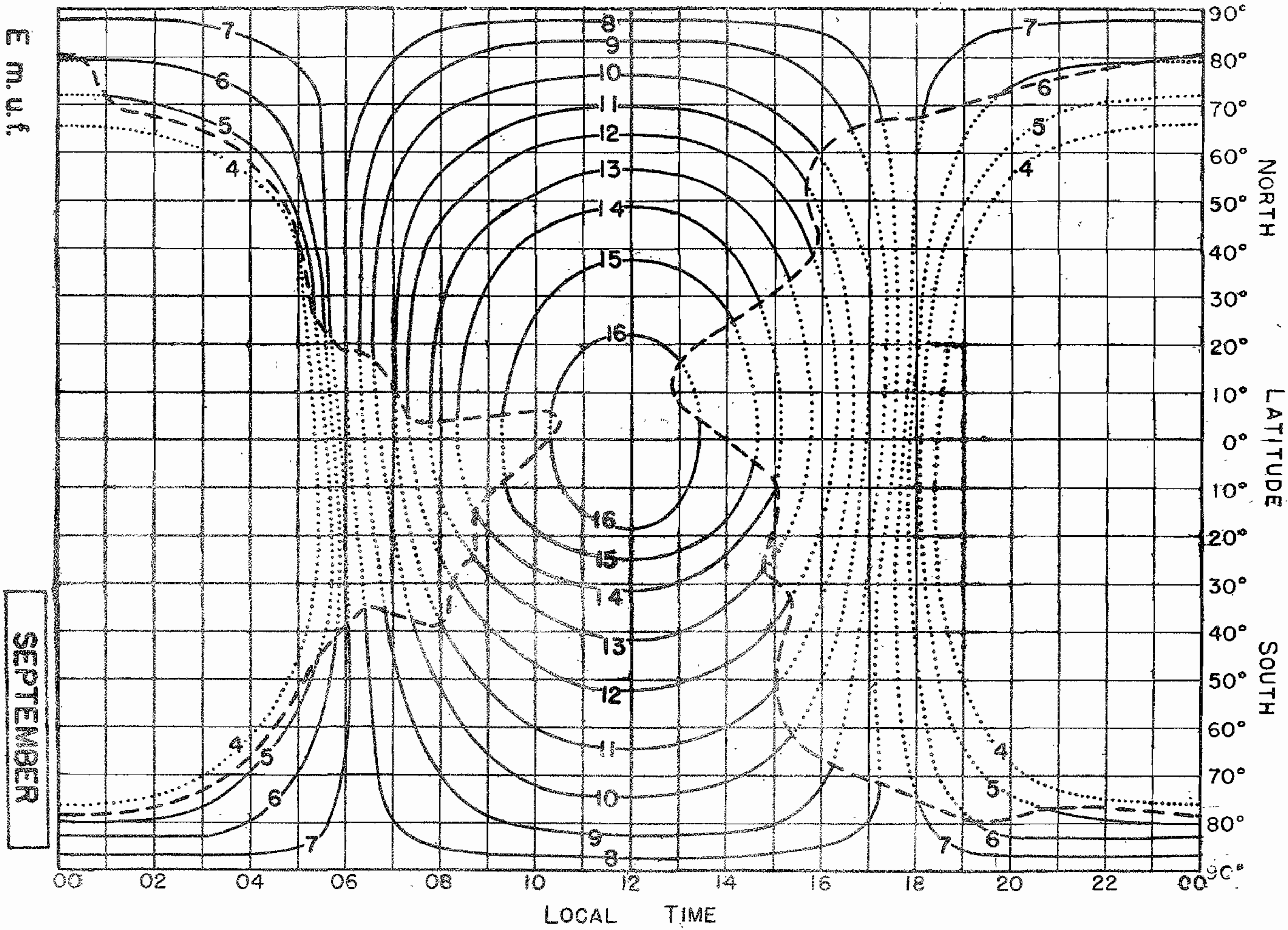


Fig. 57. E-layer frequencies, (predicted average for quiet days), September. Numbers on curves are E-layer m. u. f. in Mc for transmission distance of 1000 miles.

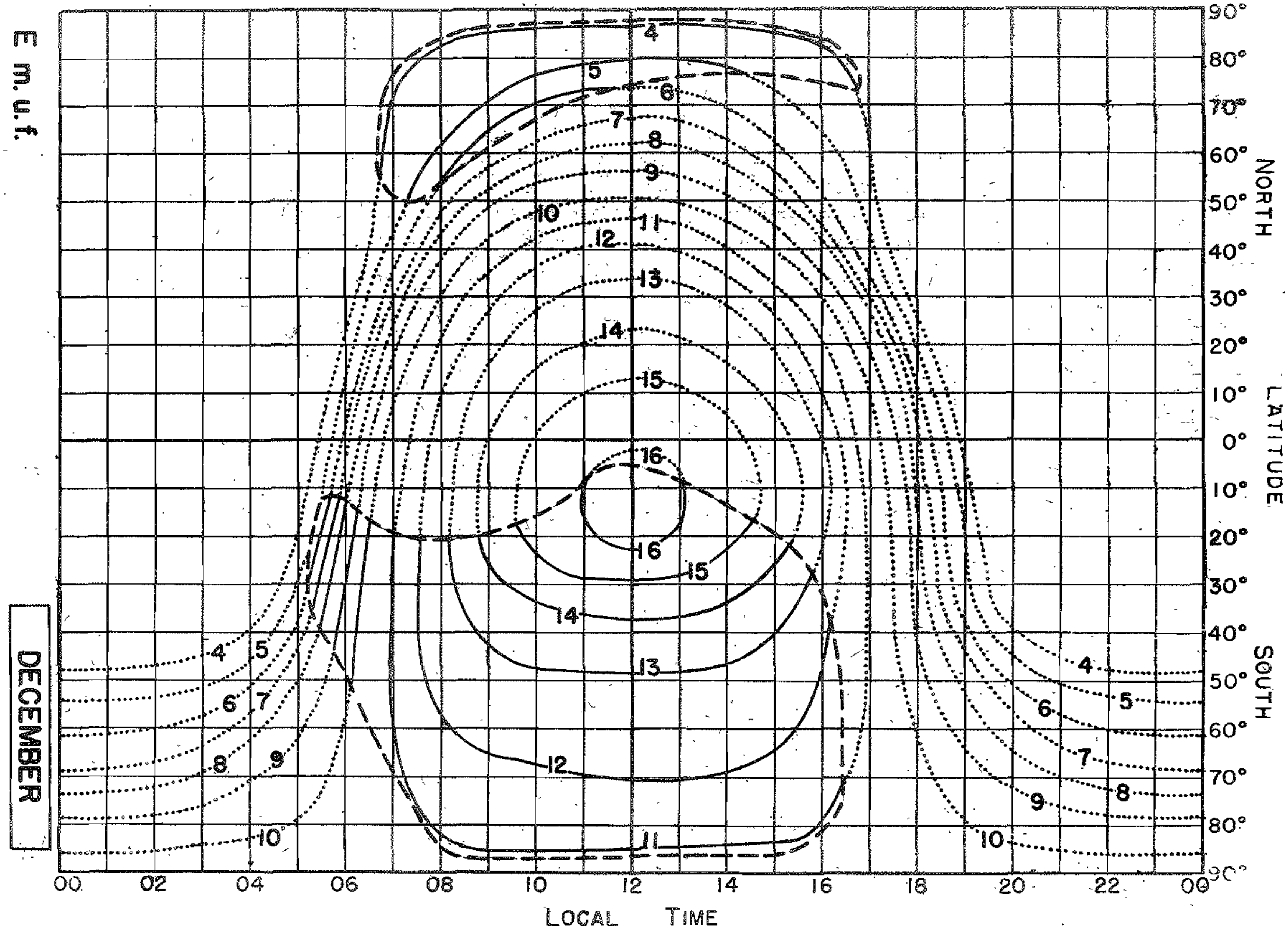


Fig. 58. E-layer frequencies, (predicted average for quiet days), December. Numbers on curves are E-layer m.u.f. in Mc for transmission distance of 1000 miles.

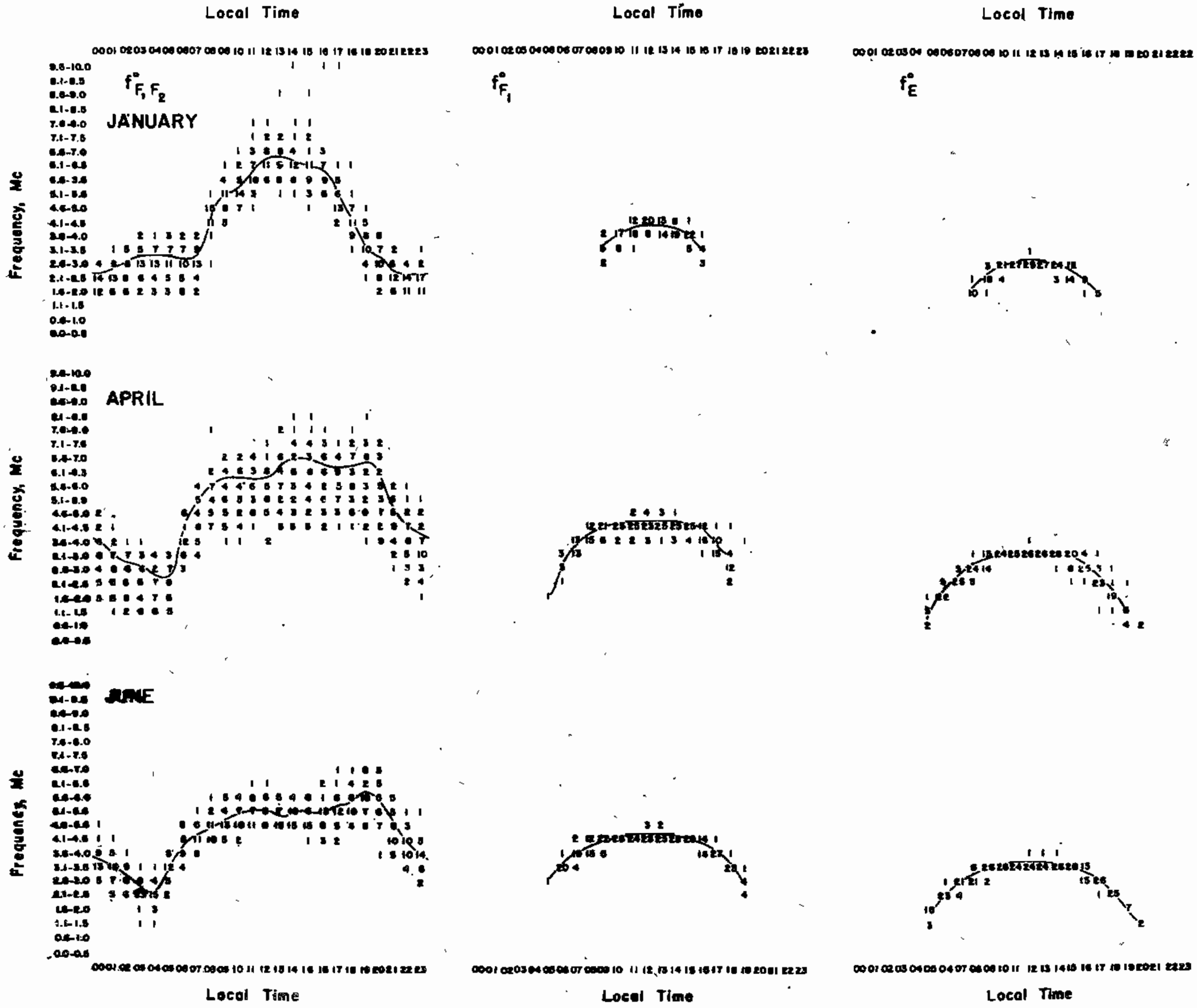


Fig. 59. Distribution of critical frequencies during the months of January, April, and June, 1943. Numbers refer to number of cases lying between indicated band limits. Curve drawn through this table indicates monthly average values.

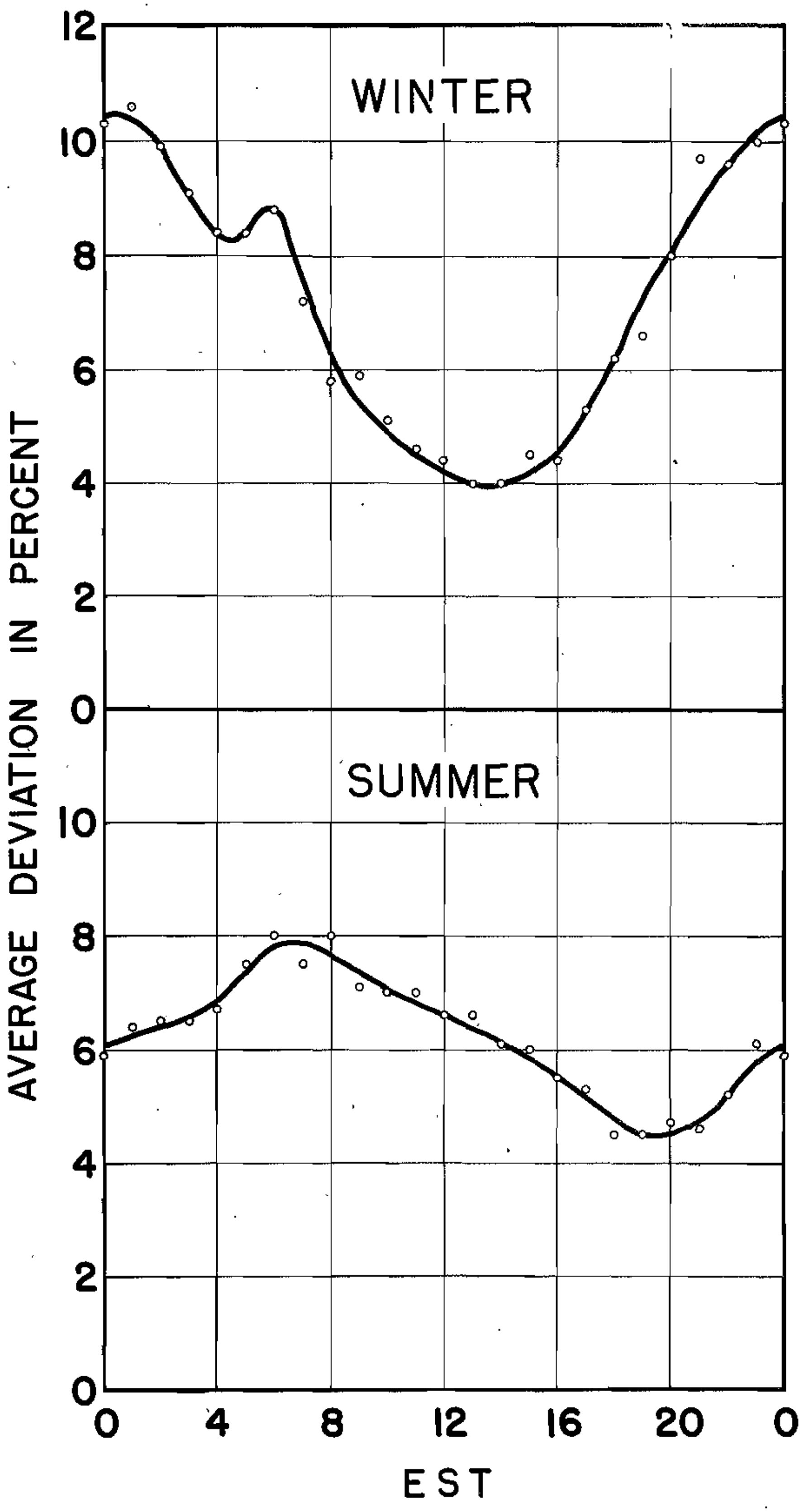


Fig. 60. Idealized winter and summer curves of diurnal variation of average deviations of F- and F_2-layer critical frequencies, and approximately also of muf for transmission by these layers.

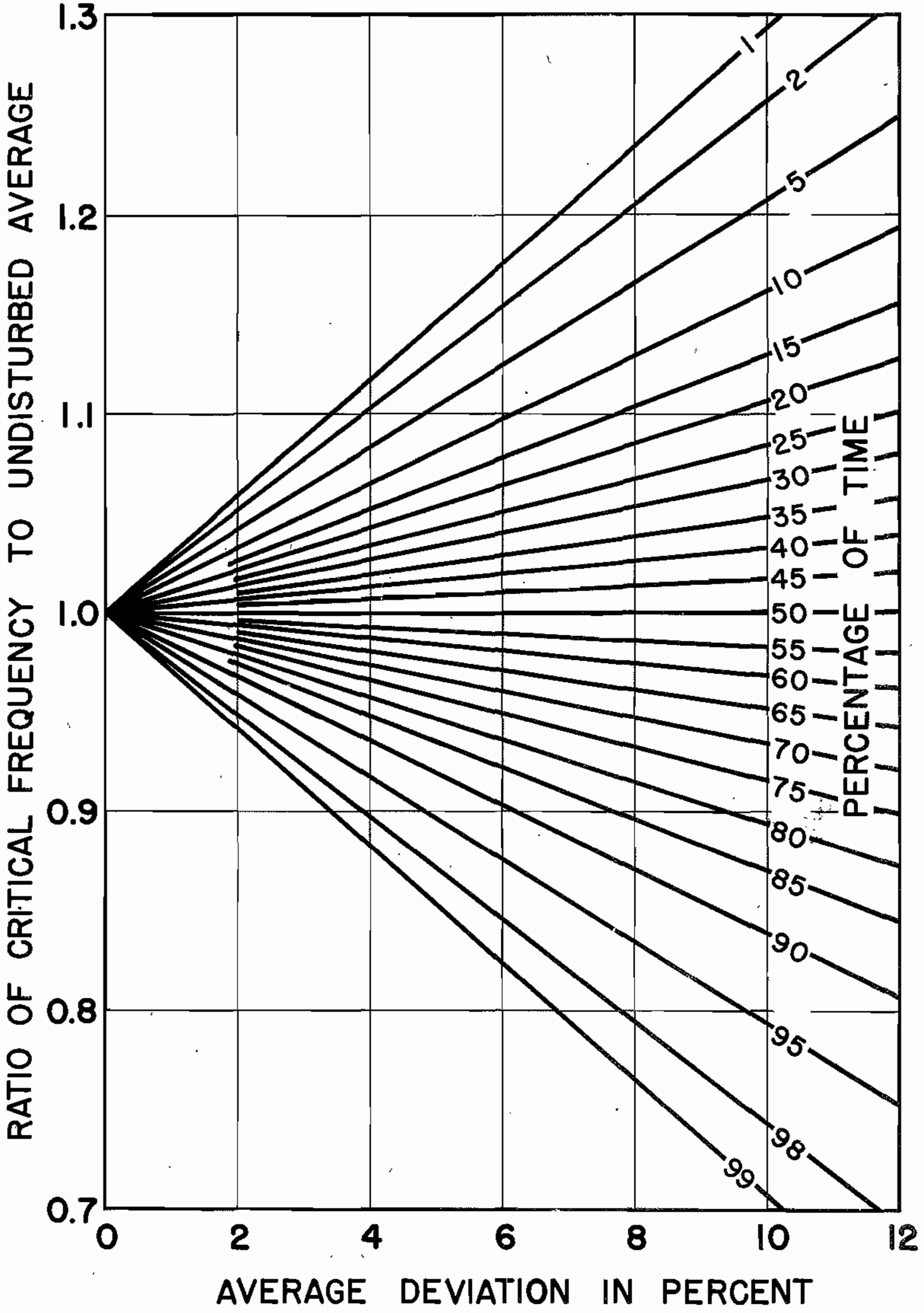


Fig. 51. Curves showing the relation between average deviations, ratio of operating frequency to the average muf for a given distance, and percentage of time for which the operating frequency will not skip over the given distance. These curves are based on ideal random distributions.

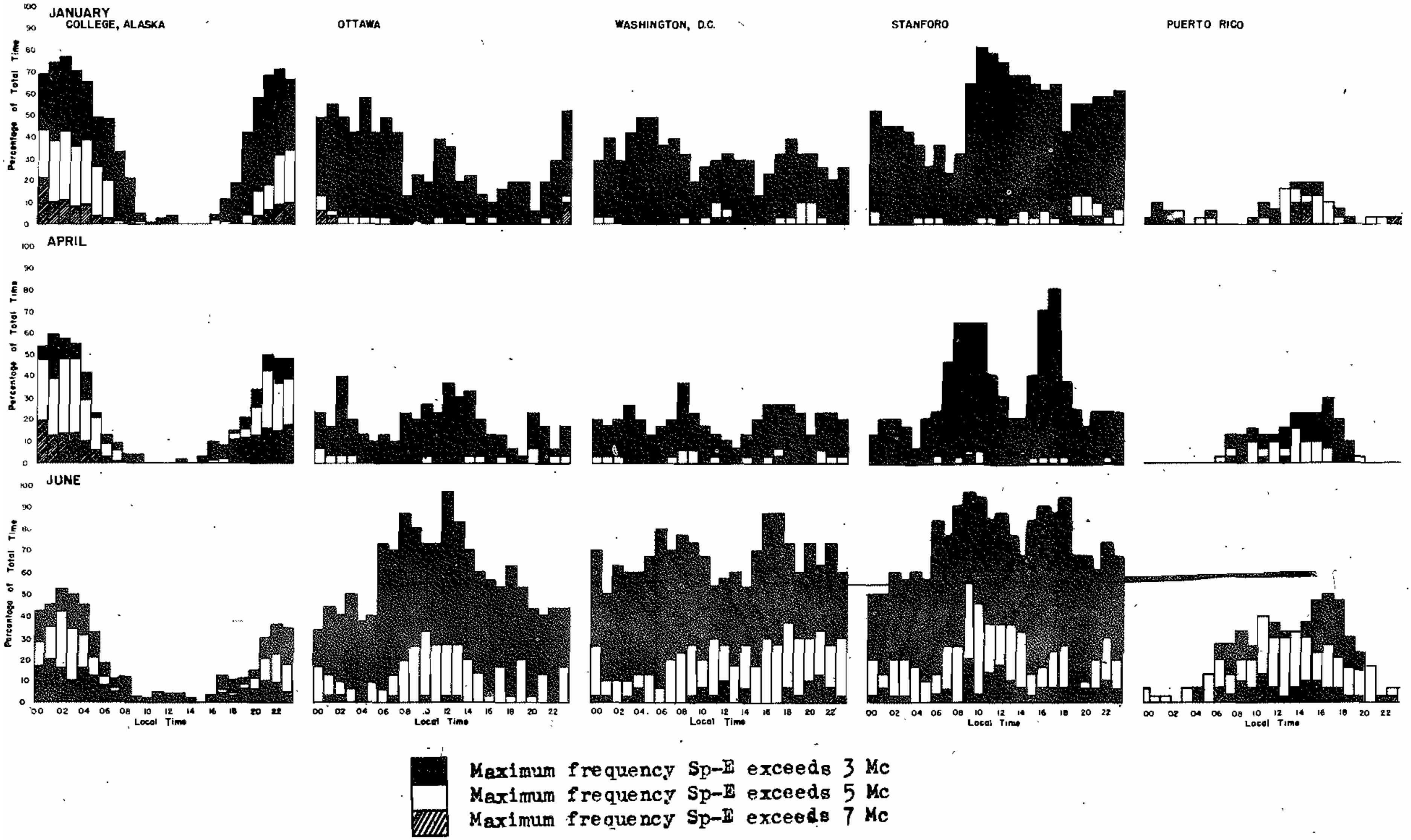


Fig. 62. Relative occurrence of sporadic-E vertical reflections, in percent of total time, for several observatories, during the months of January, April, June, 1943, at frequencies equal to or greater than 3 Mc, 5 Mc, and 7 Mc.

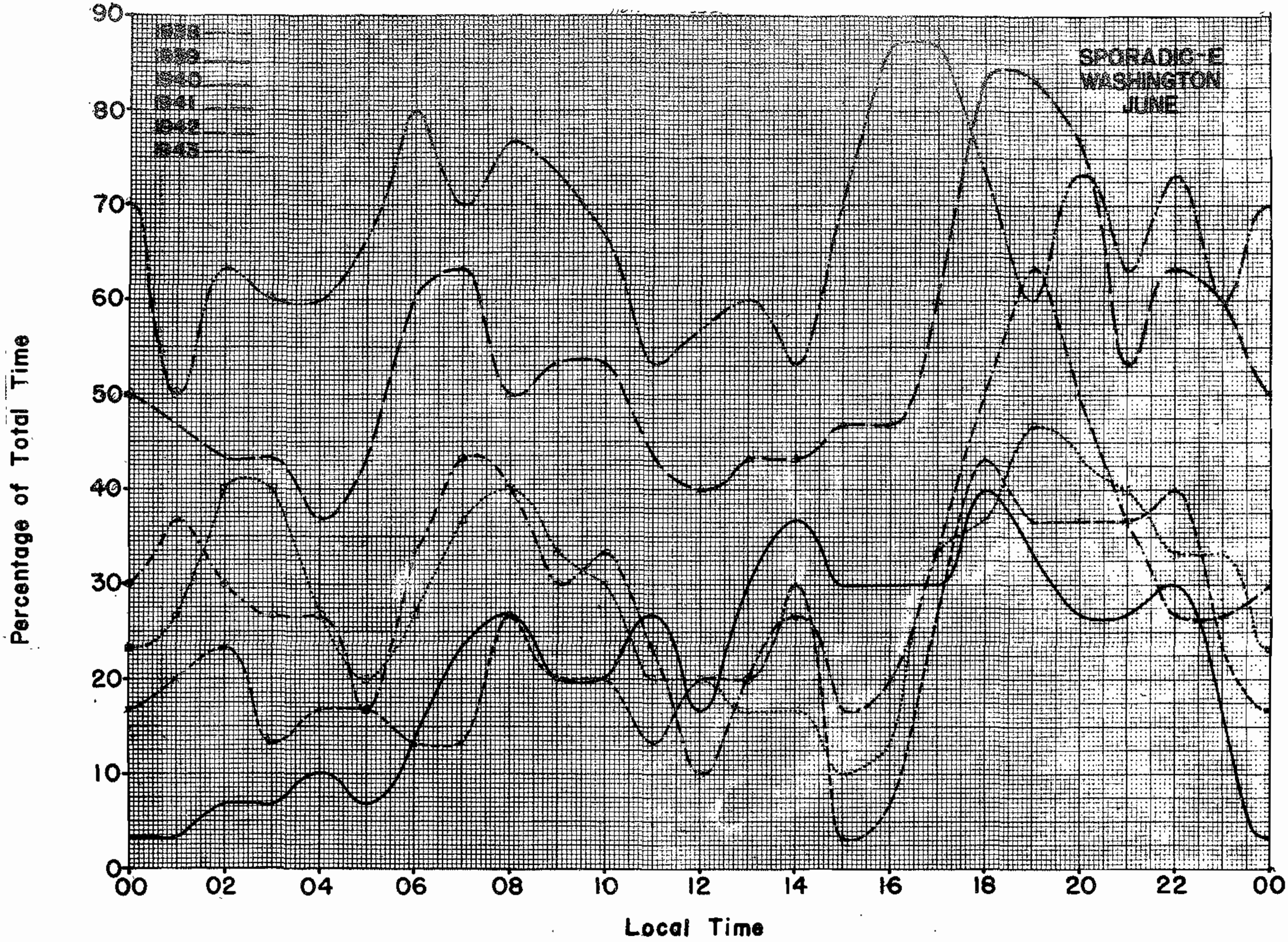


Fig. 63. Year-to-year change of sporadic-E vertical reflections, in percentage of total time, for frequencies equal to or in excess of 3 Mc, June, Washington, D. C.

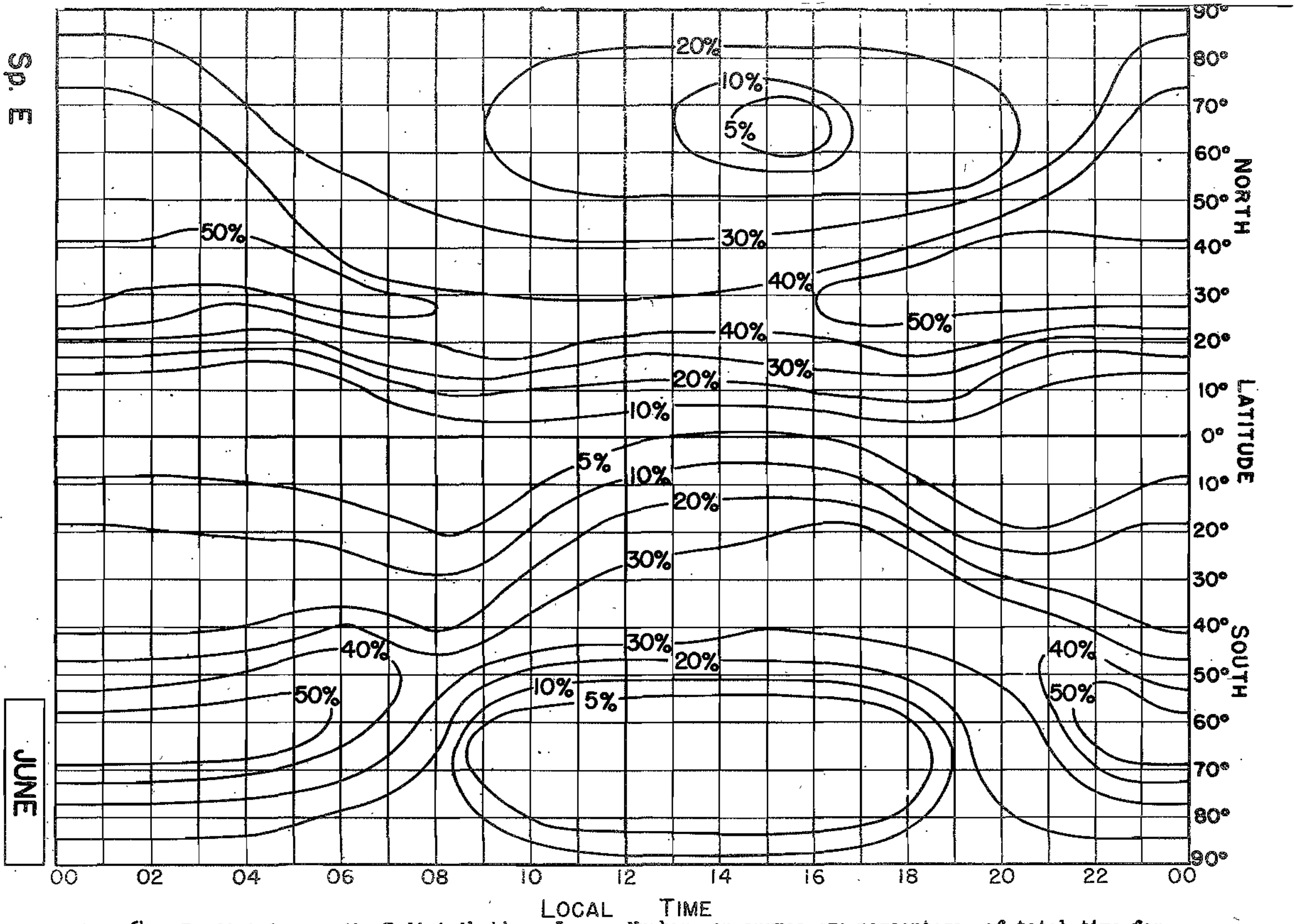


Fig. 64. Predicted sporadic-E distribution, June. Numbers on curves are percentages of total time for sporadic-E maximum usable frequency in excess of 15 Mc.

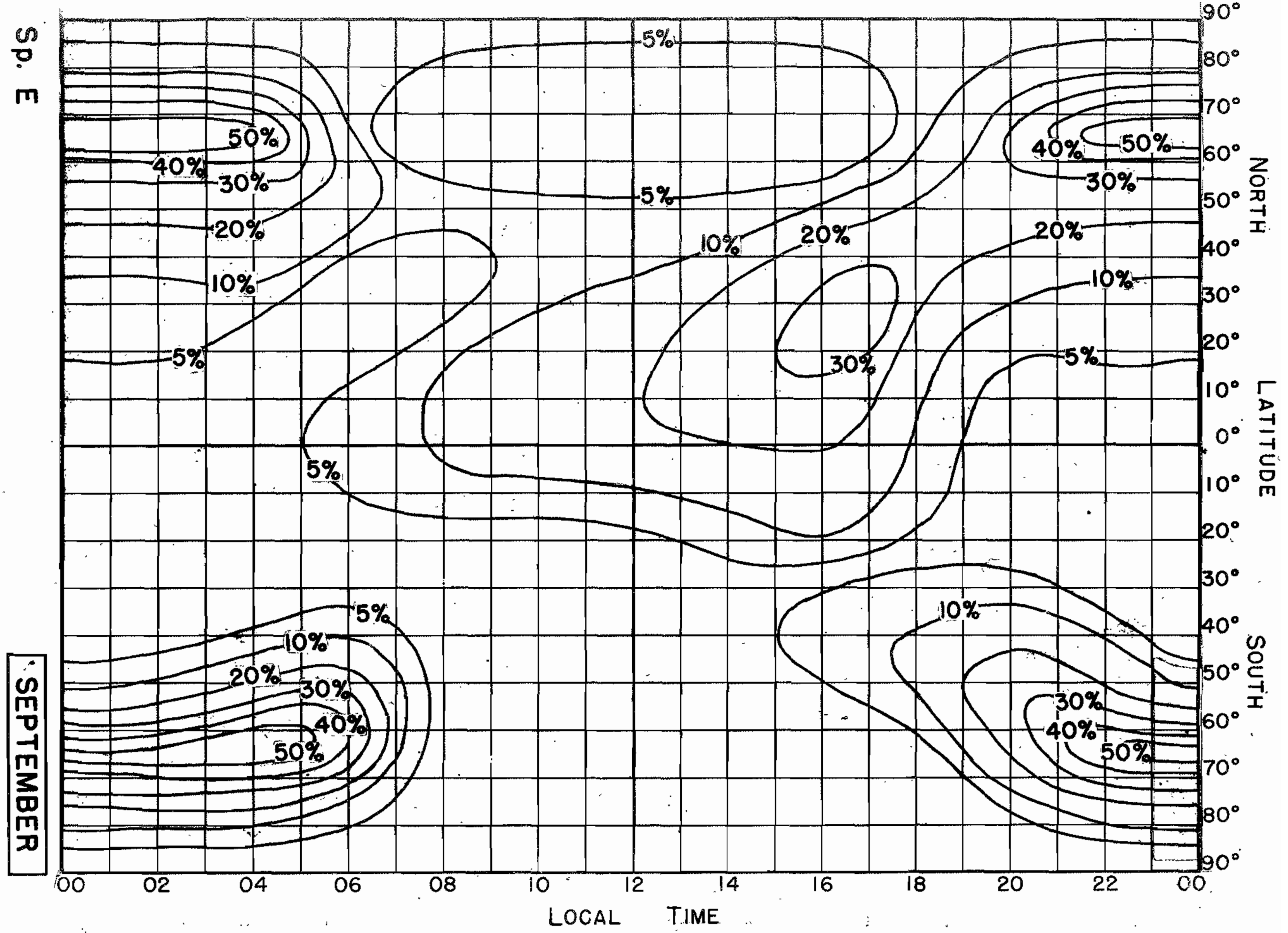


Fig. 65. Predicted sporadic-E distribution, September. Numbers on curves are percentages of total time for sporadic-E maximum usable frequency in excess of 15 Mc.

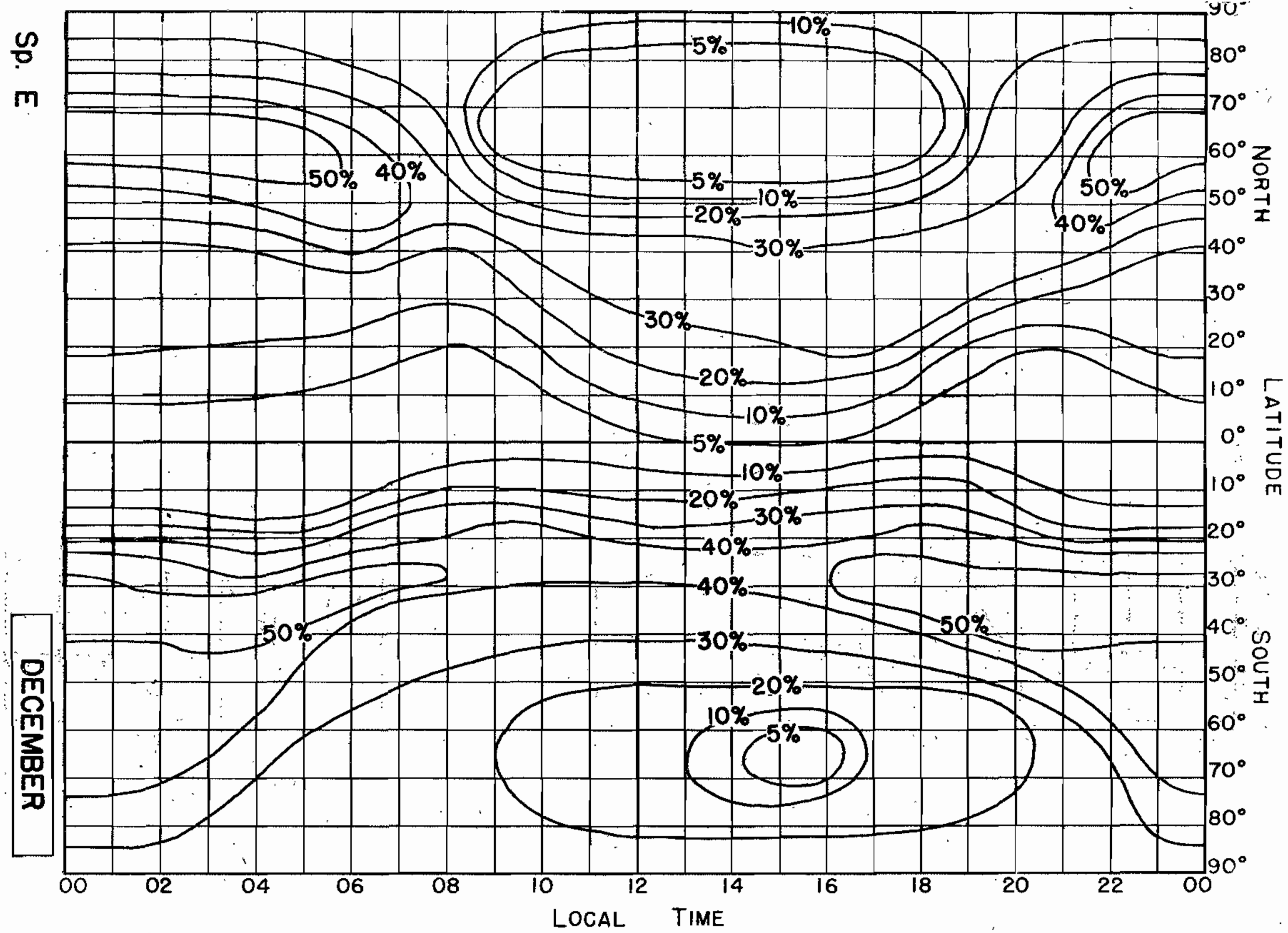


Fig. 66. Predicted sporadic-E distribution, December. Numbers on curves are percentages of total time for sporadic-E maximum usable frequency in excess of 15 Mc.

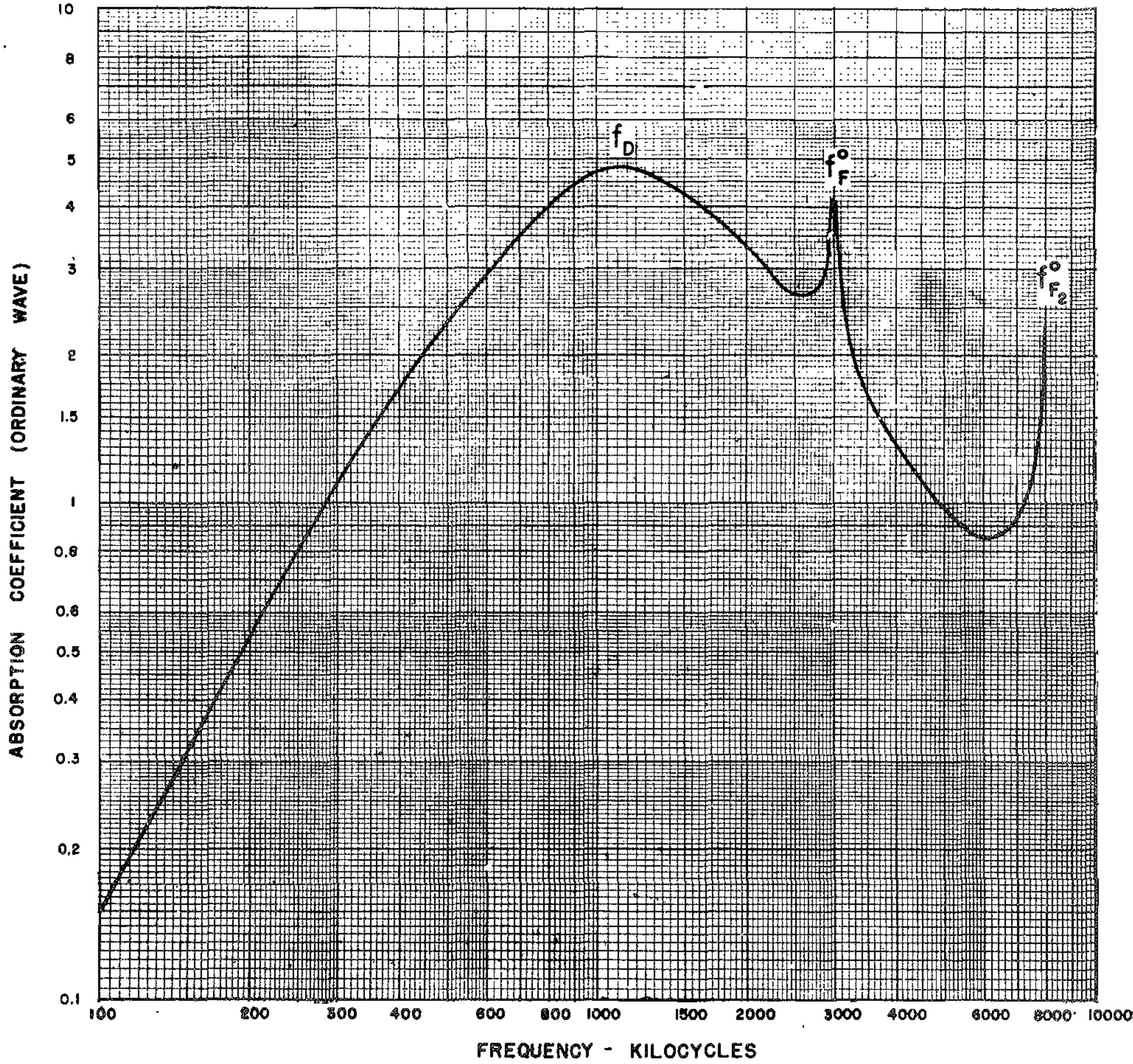


Fig. 67. Variation of absorption coefficient with frequency, noon, January, 1942, at Washington, D.C. (Absorption coefficient given as $\log_e$ [Incident field intensity/reflected field intensity]). Cusps on curve correspond to indicated critical frequencies. f_D indicates frequency of maximum vertical-incidence absorption; this shows a close approach to a condition of critical frequency for the D layer.

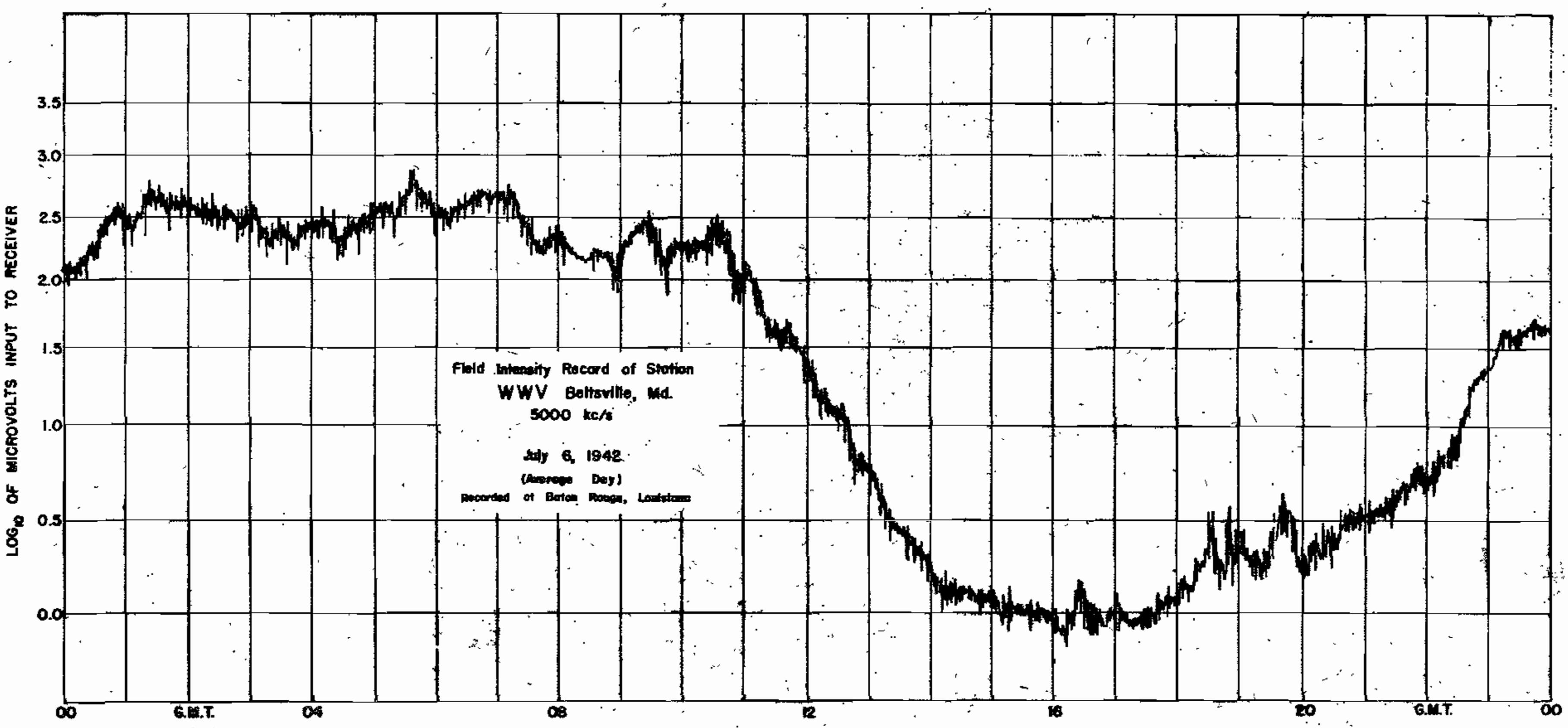


Fig. 68. Record of field intensity measured at Baton Rouge, La., normal day.

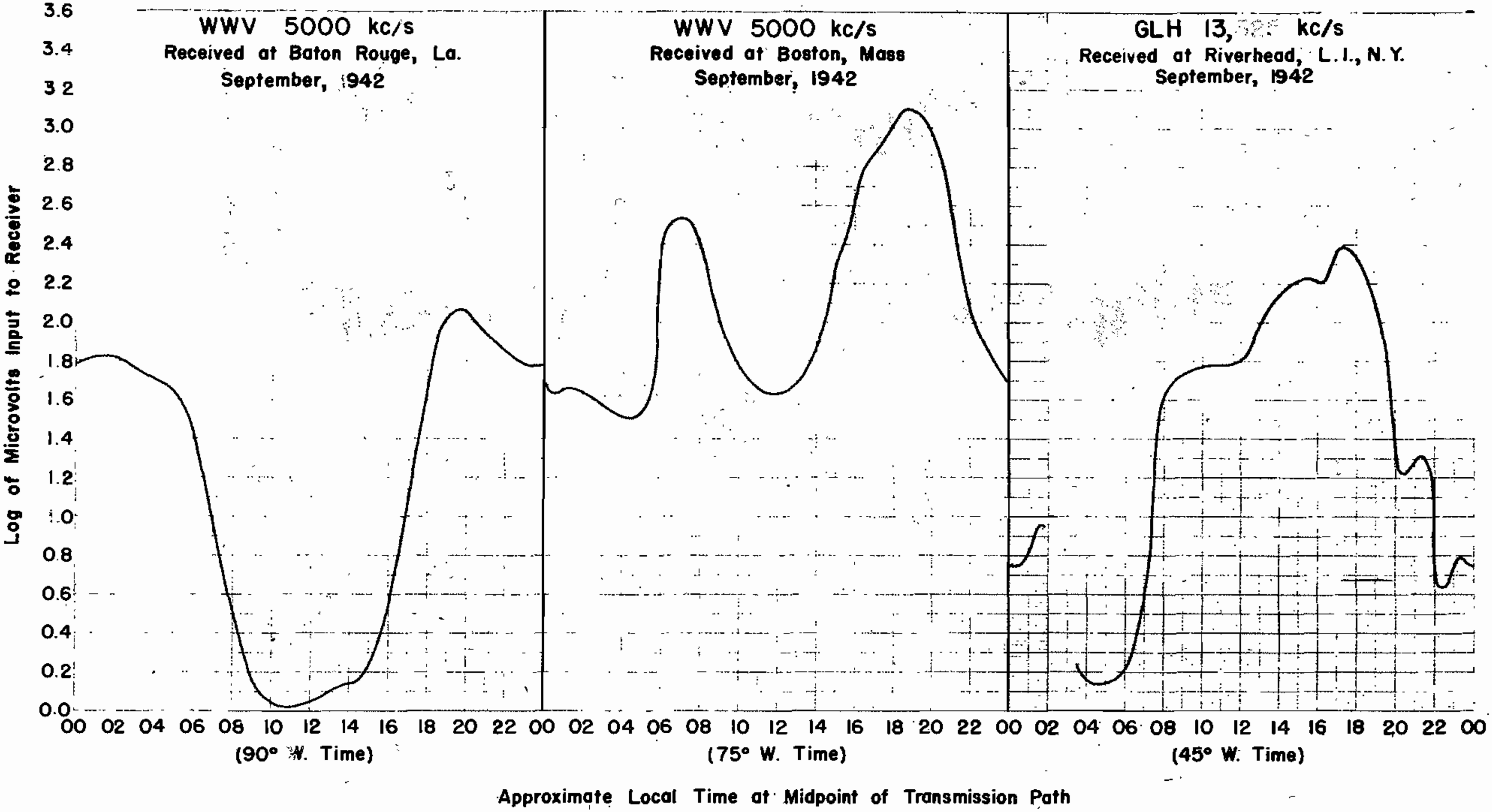


Fig. 69. Typical variation of radio field intensity for normal ionospheric conditions for various frequencies and distances.

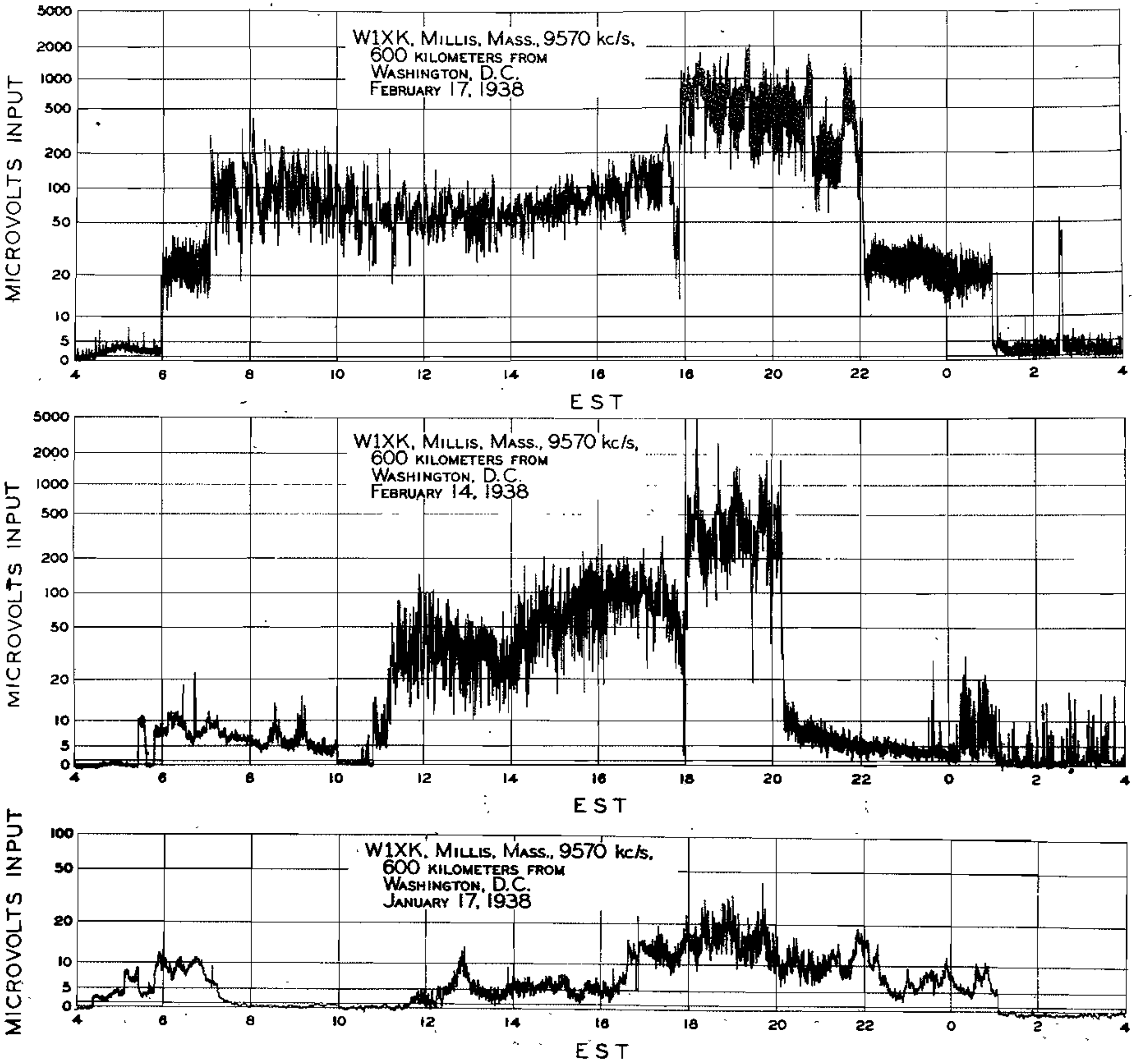


Fig. 70. **Field-intensity measured over the same path, on the same frequency, for a quiet day (February 17, 1938), a day of moderate storm (February 14, 1938), and a day of severe storm (January 17, 1938).**

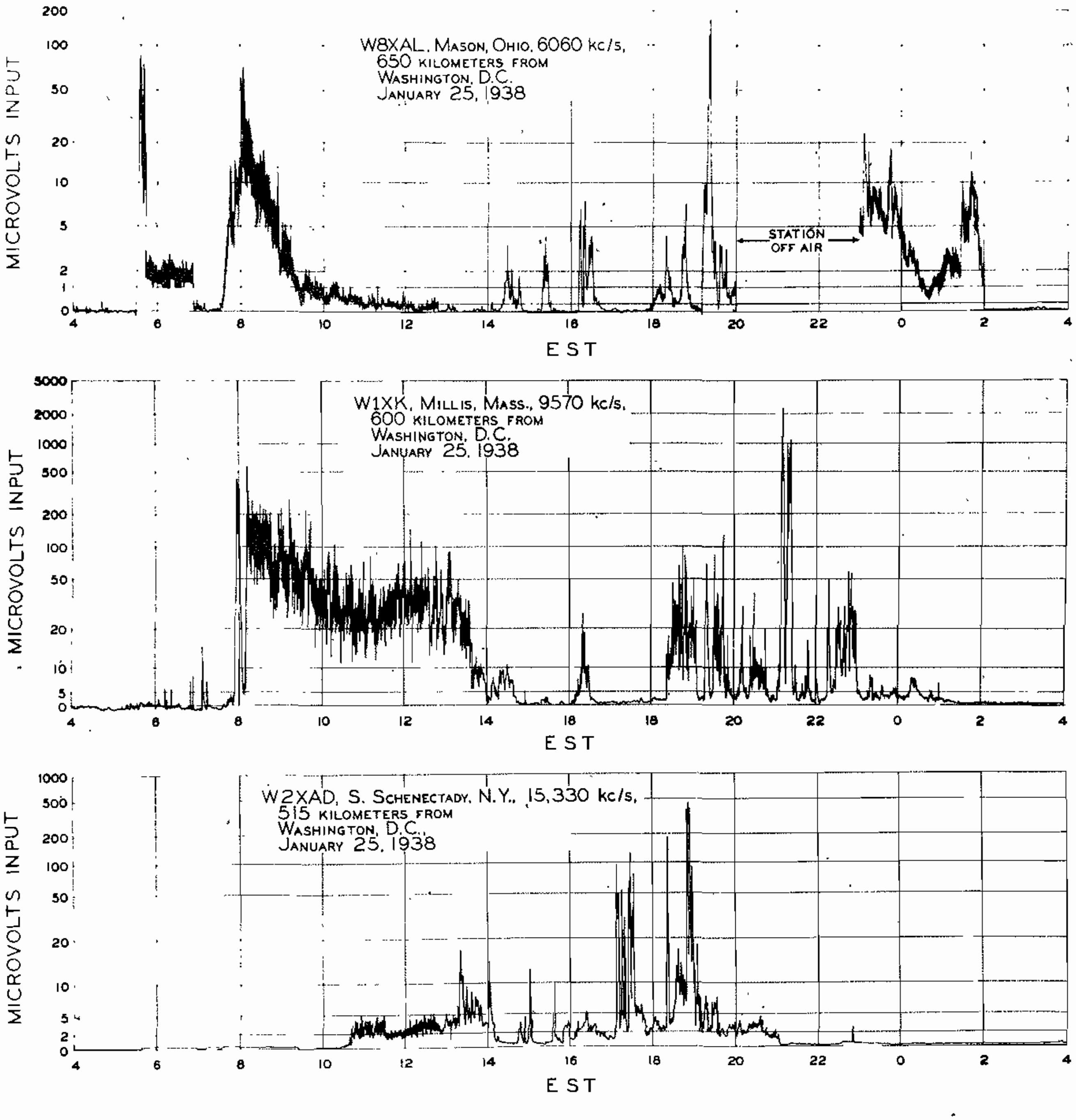
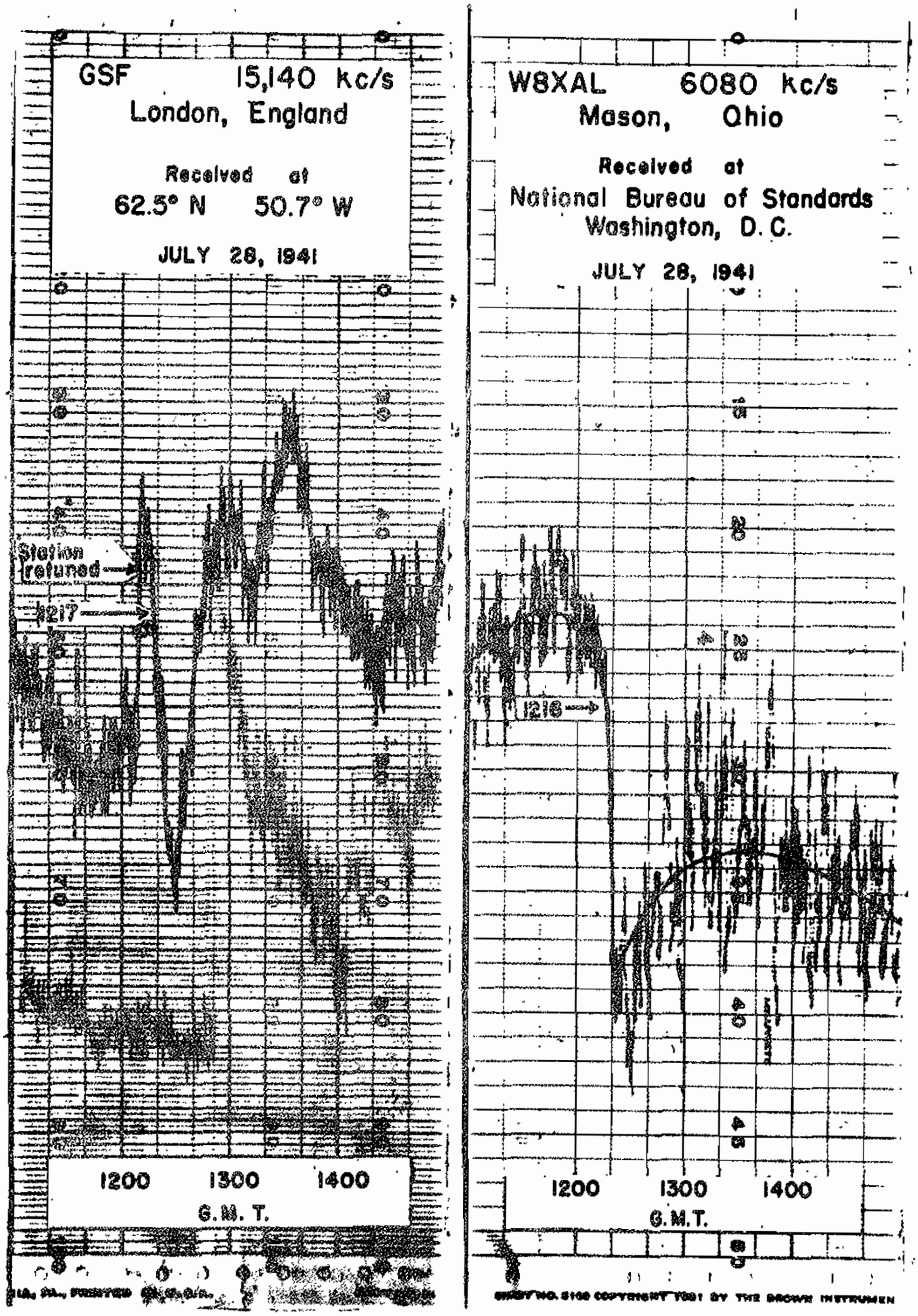


Fig. 71. Effect of severe ionosphere storm on radio field-intensity measurements on three different frequencies.



72. Field-intensity records showing simultaneous effects of sudden ionosphere disturbance for widely separated transmission paths.

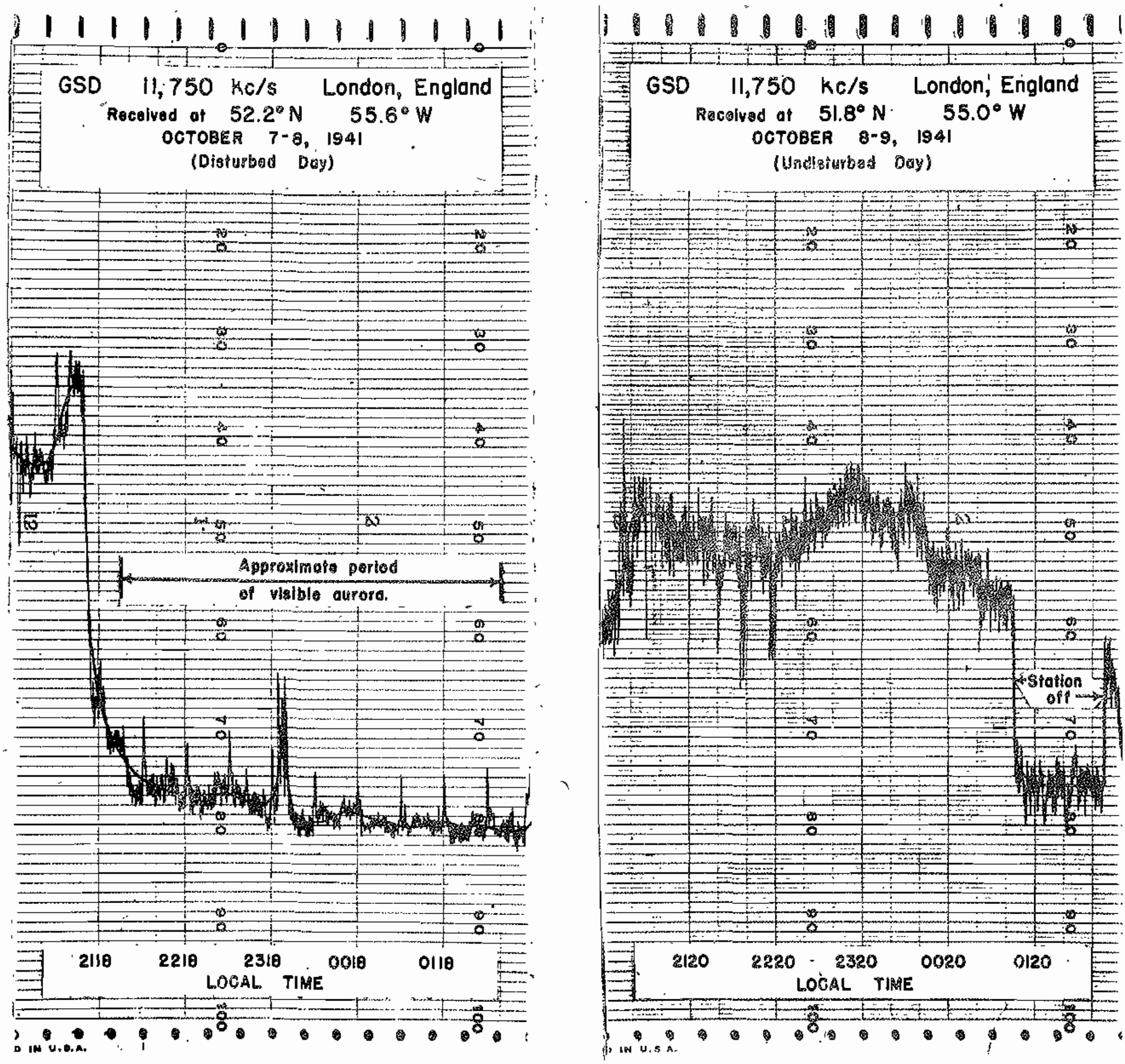


Fig. 73. Field-intensity variation during and after visible aurora of October 7-8, 1941. Note depression of field intensity as compared with following day.

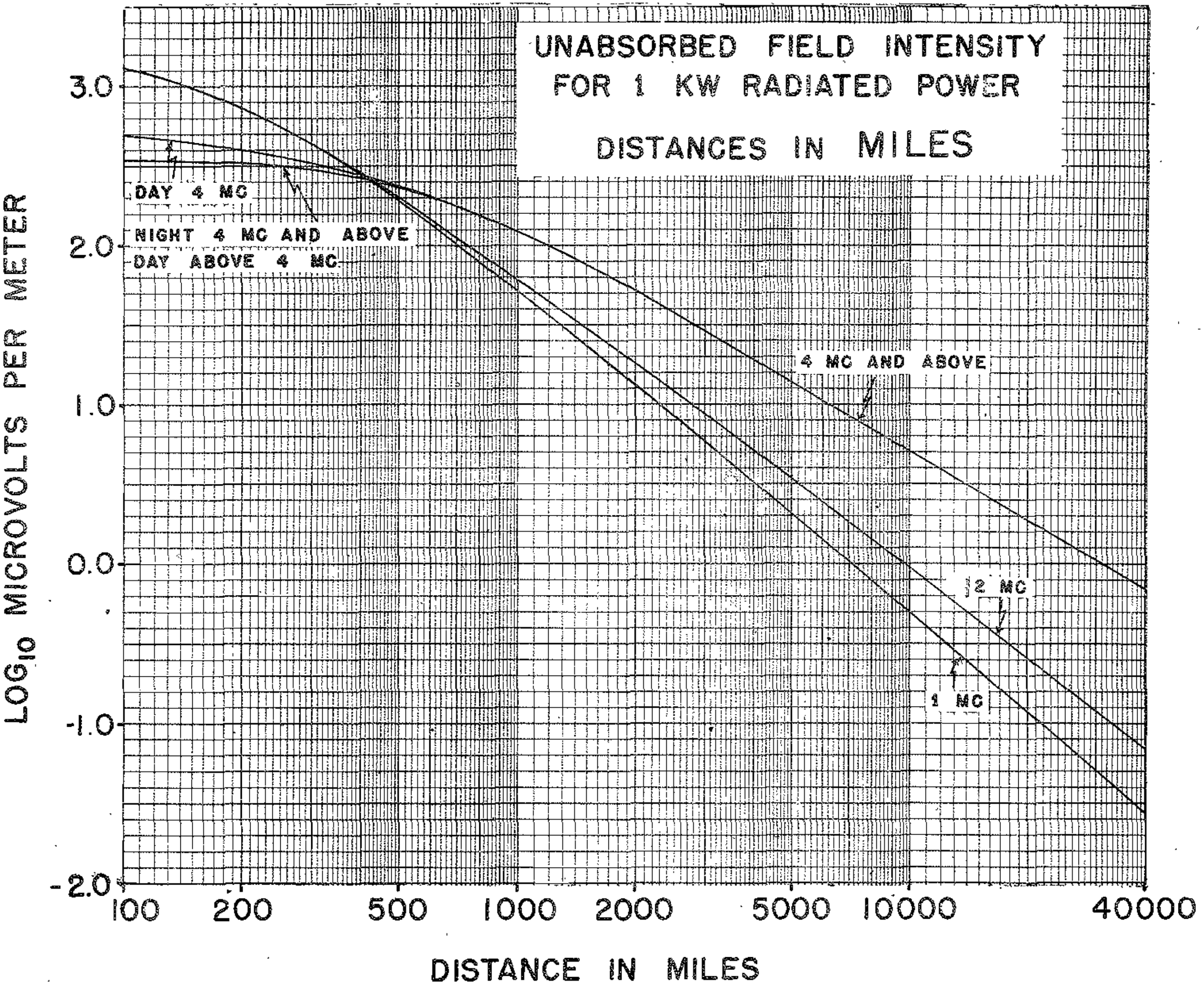


Fig. 74. Logarithm of unabsorbed field intensity, F_o, for 1-kilowatt radiated power. as a function of distance. (Distance in miles.)

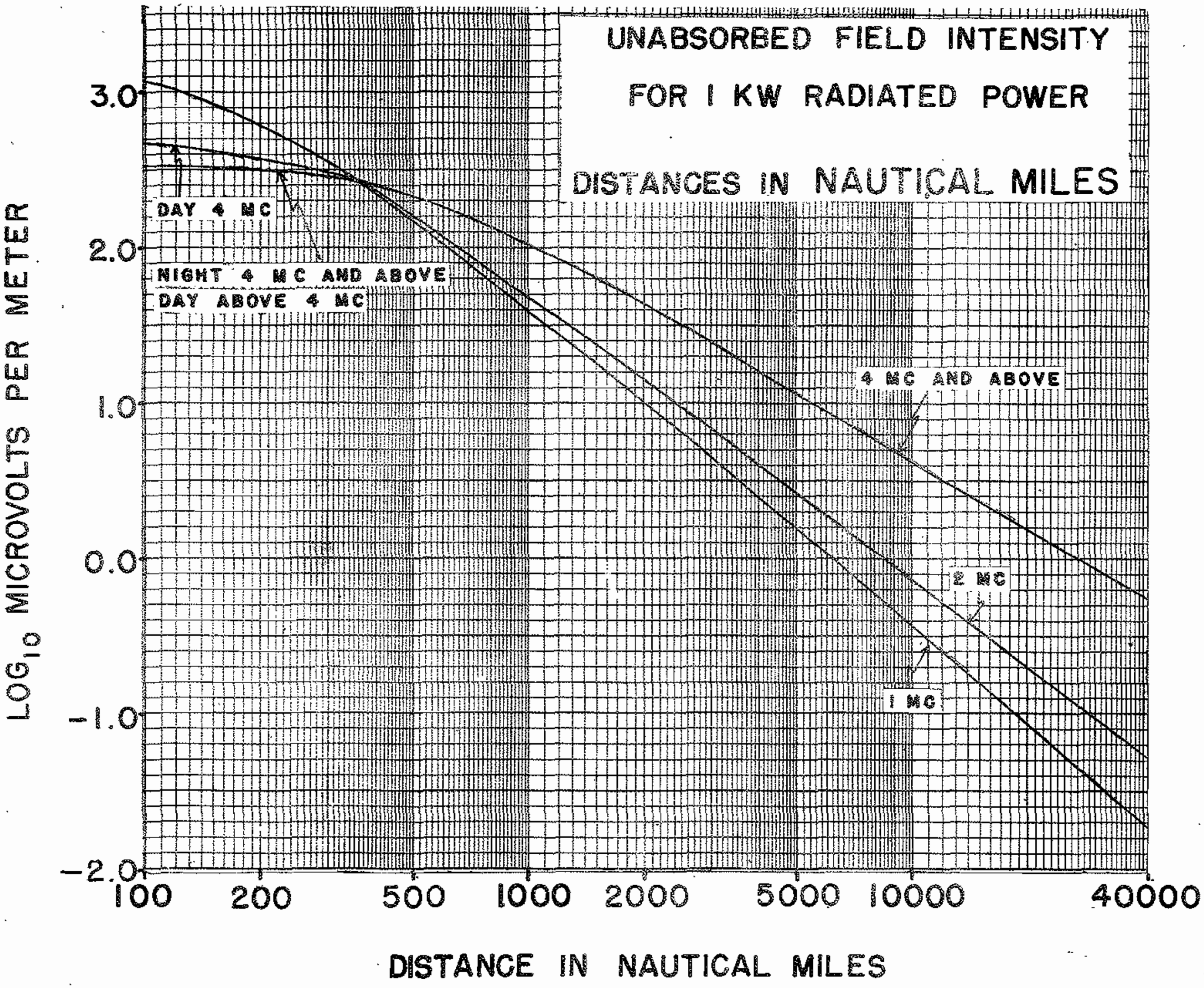


Fig. 75. Logarithm of unabsorbed field intensity, F_o, for 1-kilowatt radiated power, as a function of distance. (Distance in nautical miles.)

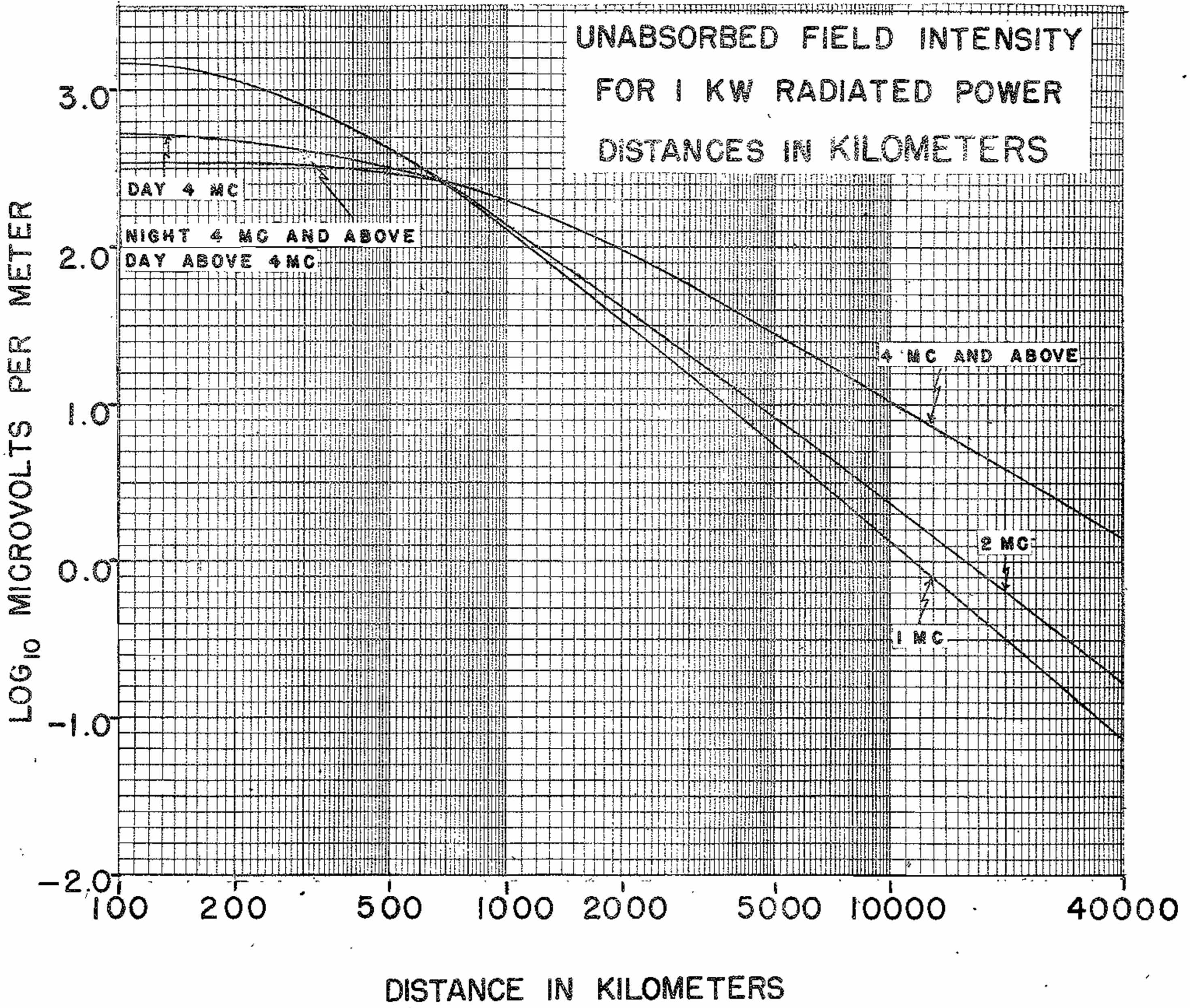


Fig. 76. Logarithm of unabsorbed field intensity, F_0, for 1-kilowatt radiated power, as a function of distance. (Distance in kilometers.)

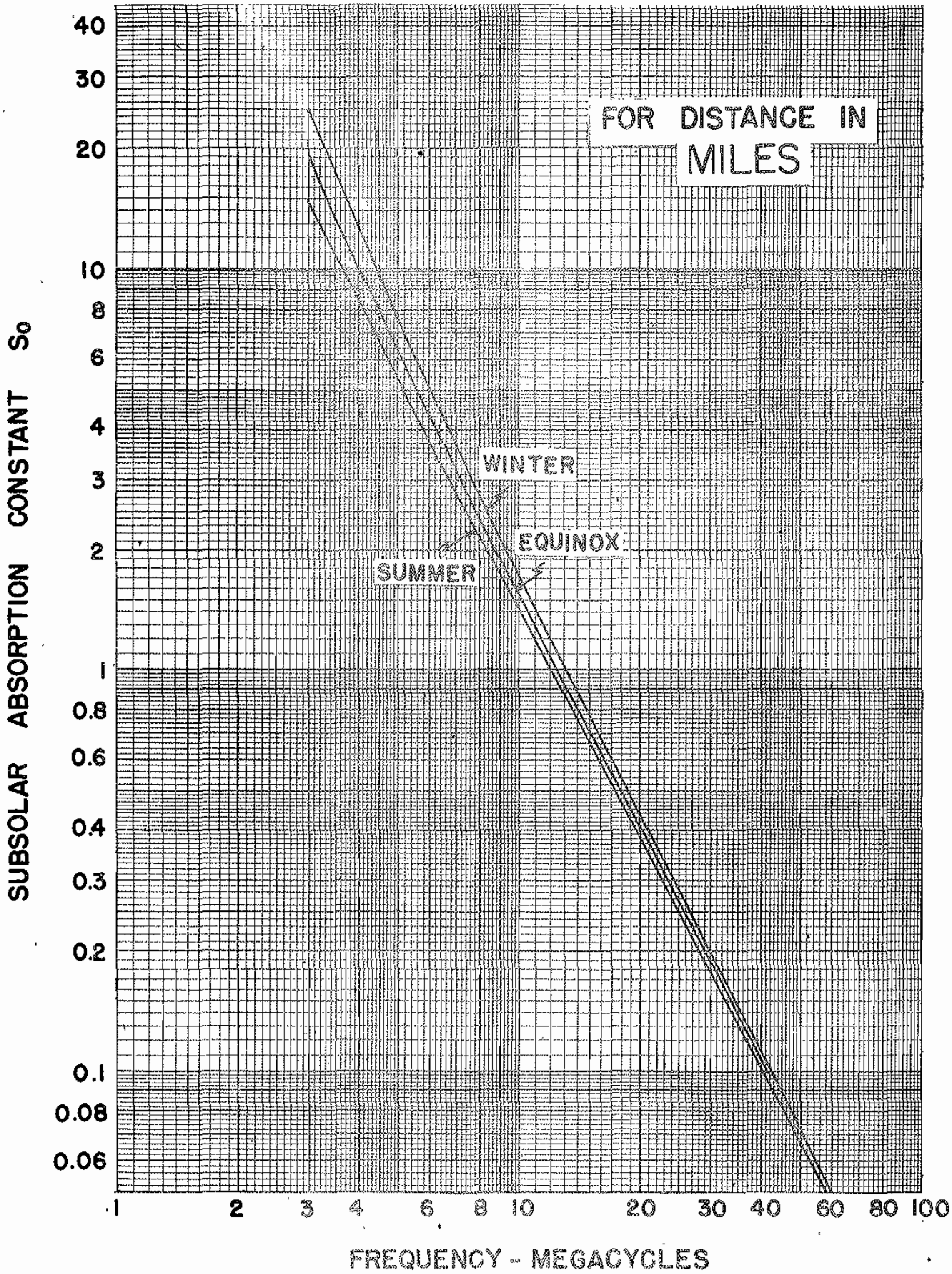


Fig. 77. Variation of subsolar absorption constant, S_0, with frequency, for summer, equinoctial and winter seasons. (S_0 for distance units of 1000 miles.)

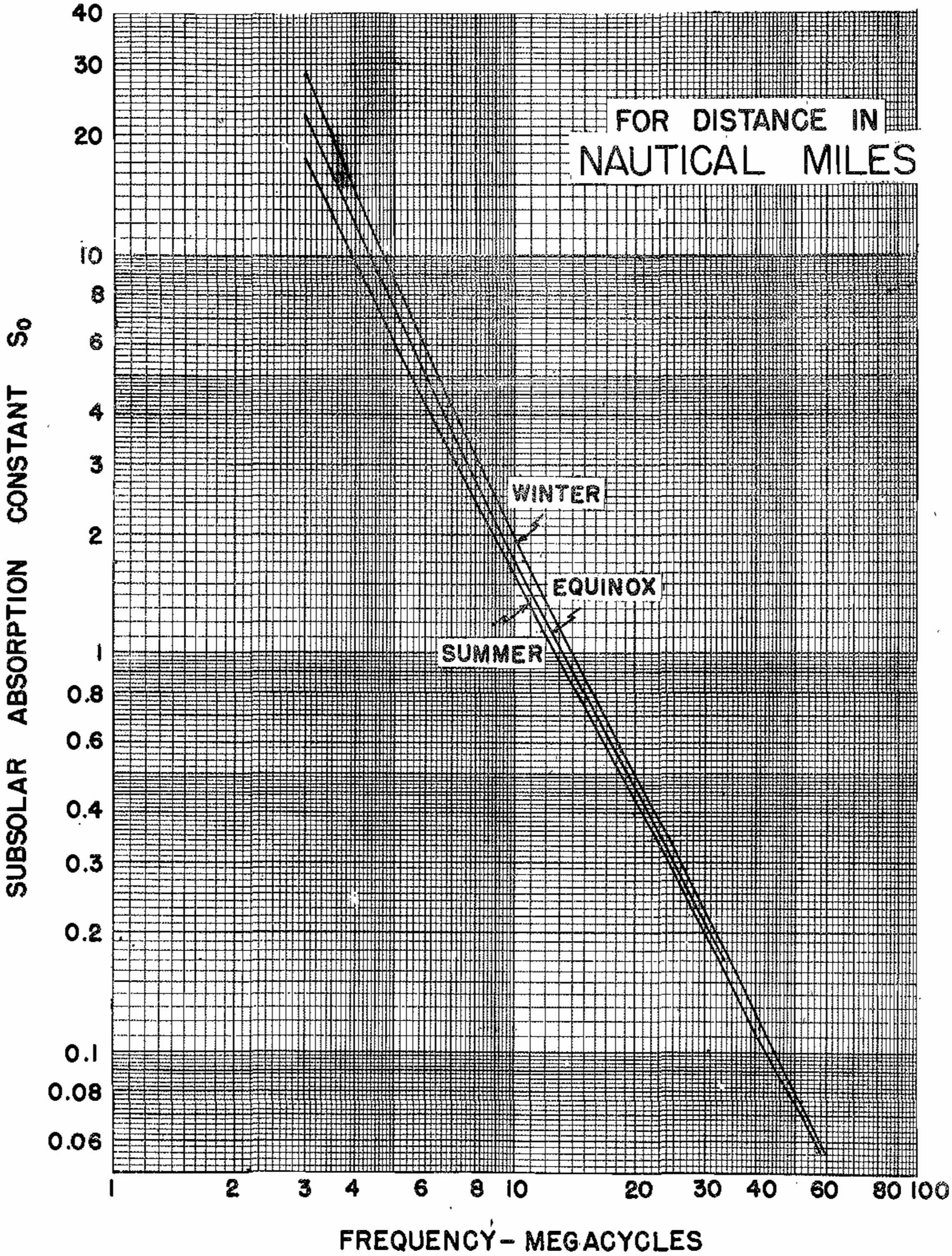


Fig. 78. Variation of subsolar absorption constant, S_o, with frequency, for summer, equinoctial and winter seasons. (S_o for distance units of 1000 nautical miles.)

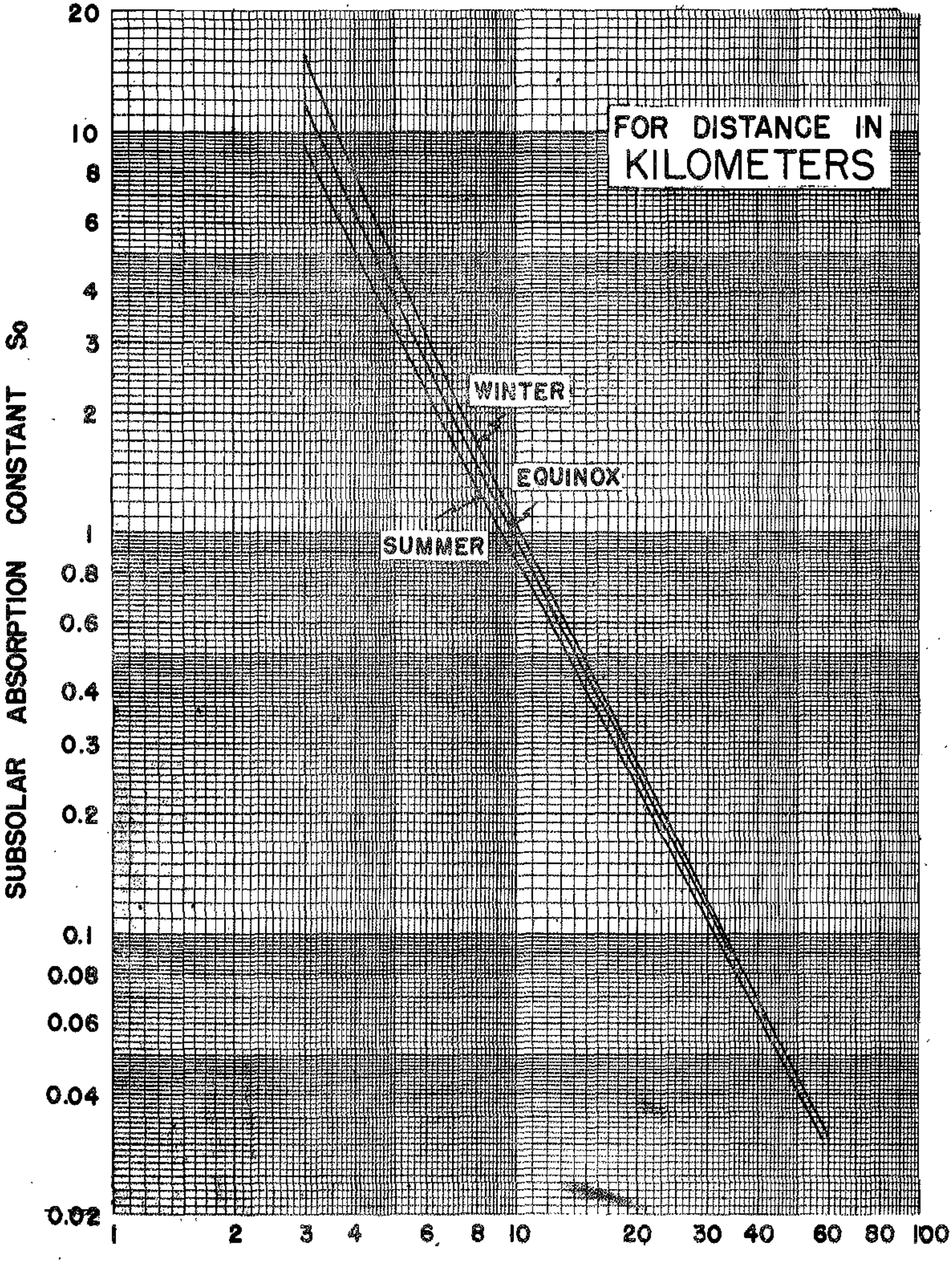


Fig. 79. Variation of subsolar absorption constant, S_0, with frequency, for summer, equinoctial and winter seasons. (S_0 for distance units of 1000 kilometers.)

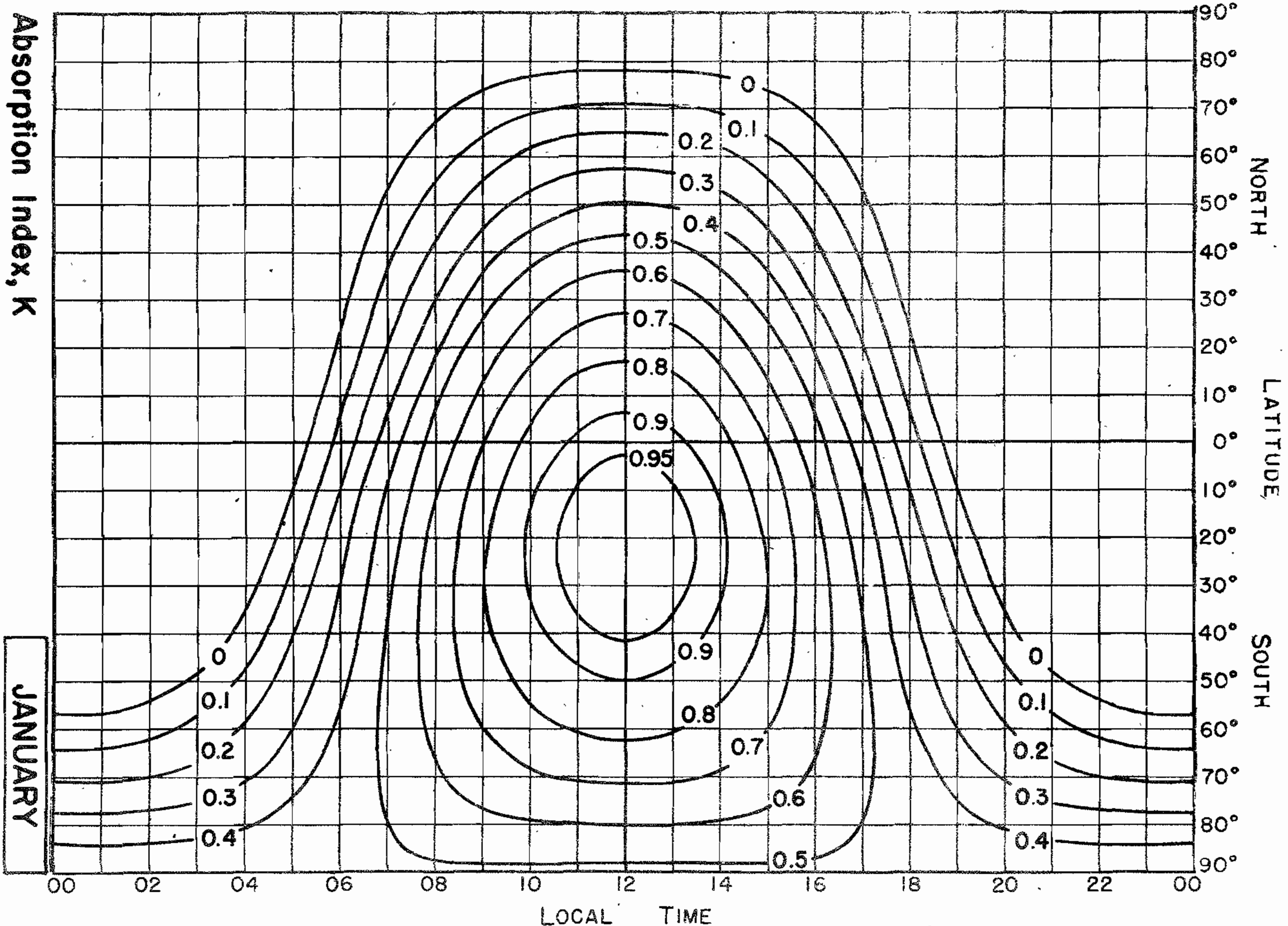


Fig. 80. Absorption index chart, January (excluding auroral-zone absorption.) Numbers on curves are absorption indexes, K.

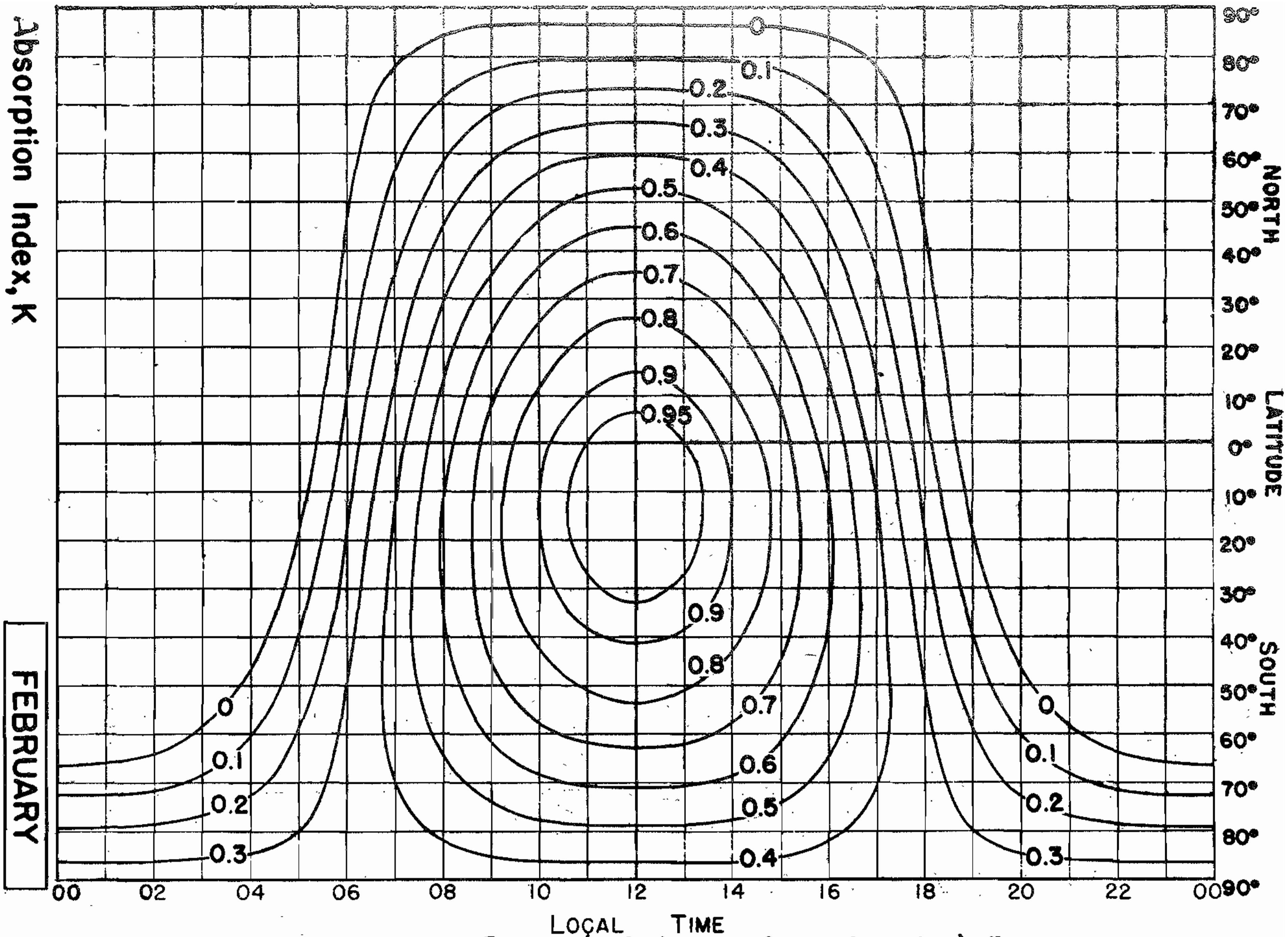
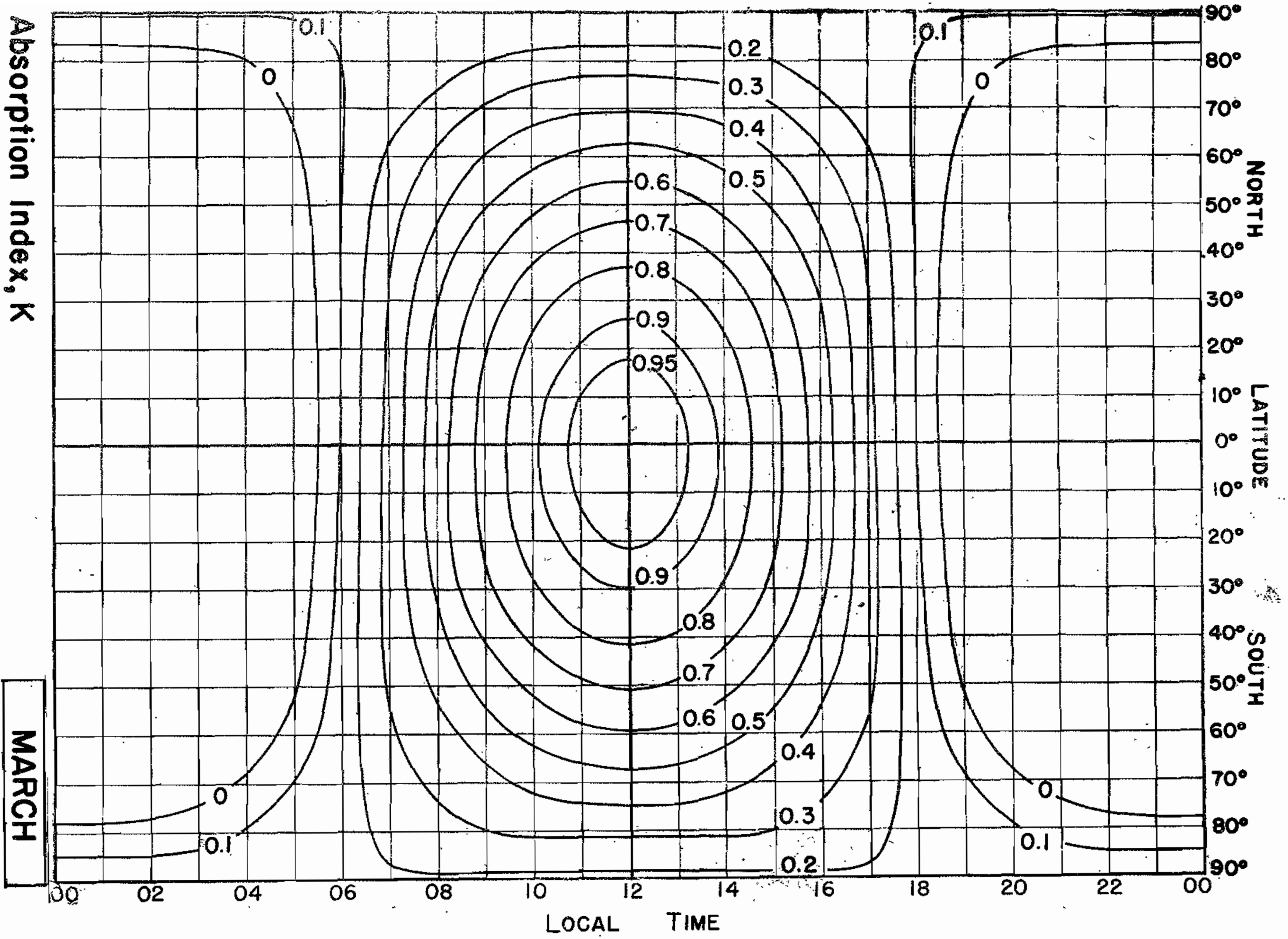


Fig. 81. Absorption index chart, February (excluding auroral-zone absorption.) Numbers on curves are absorption indexes, K.



lg. 82. Absorption index chart, March (excluding auroral-zone absorption.) Numbers on curves are absorption indexes, K.

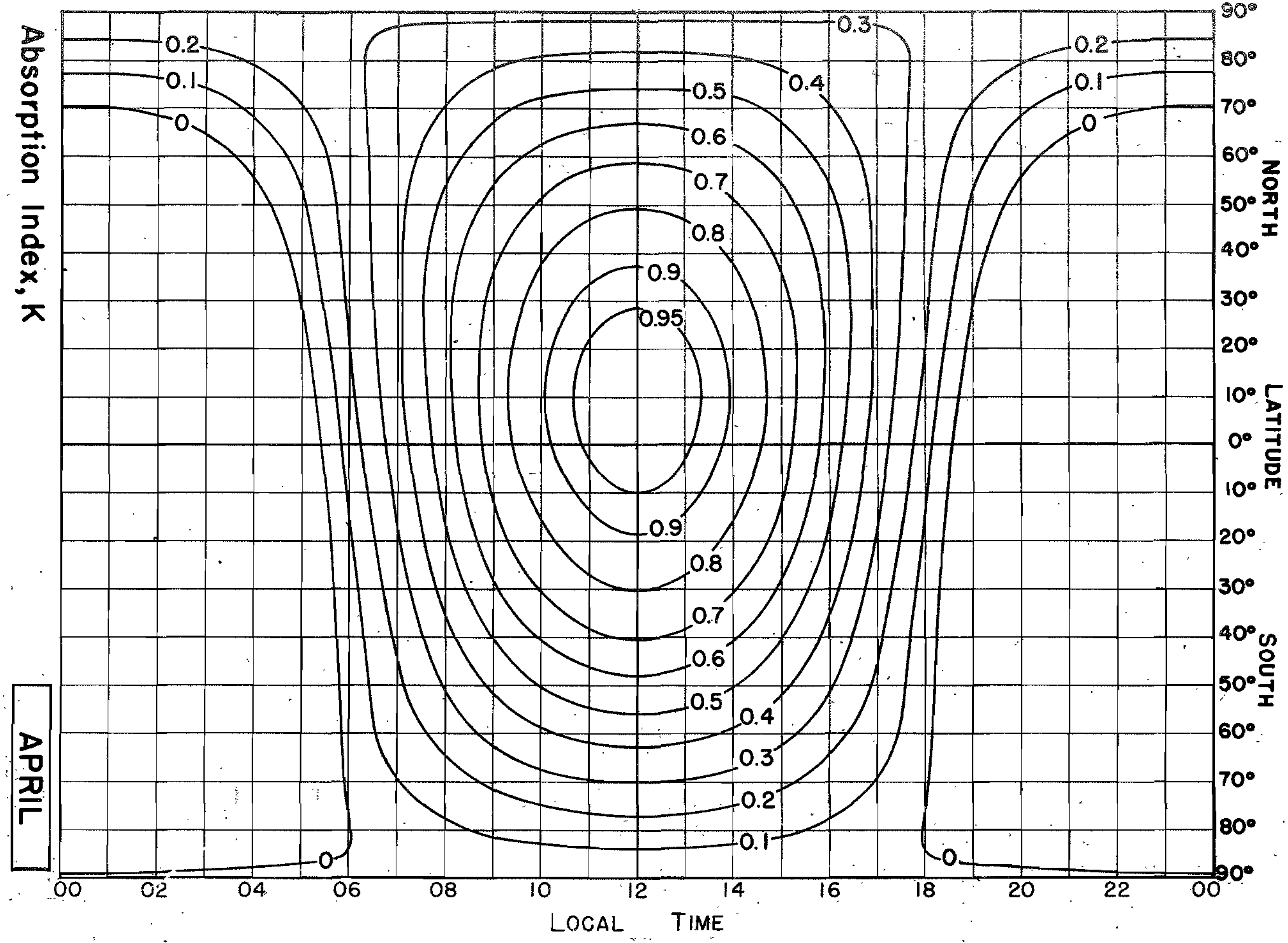


Fig. 83. Absorption index chart, April (excluding auroral-zone absorption.) Numbers on curves are absorption indexes, K.

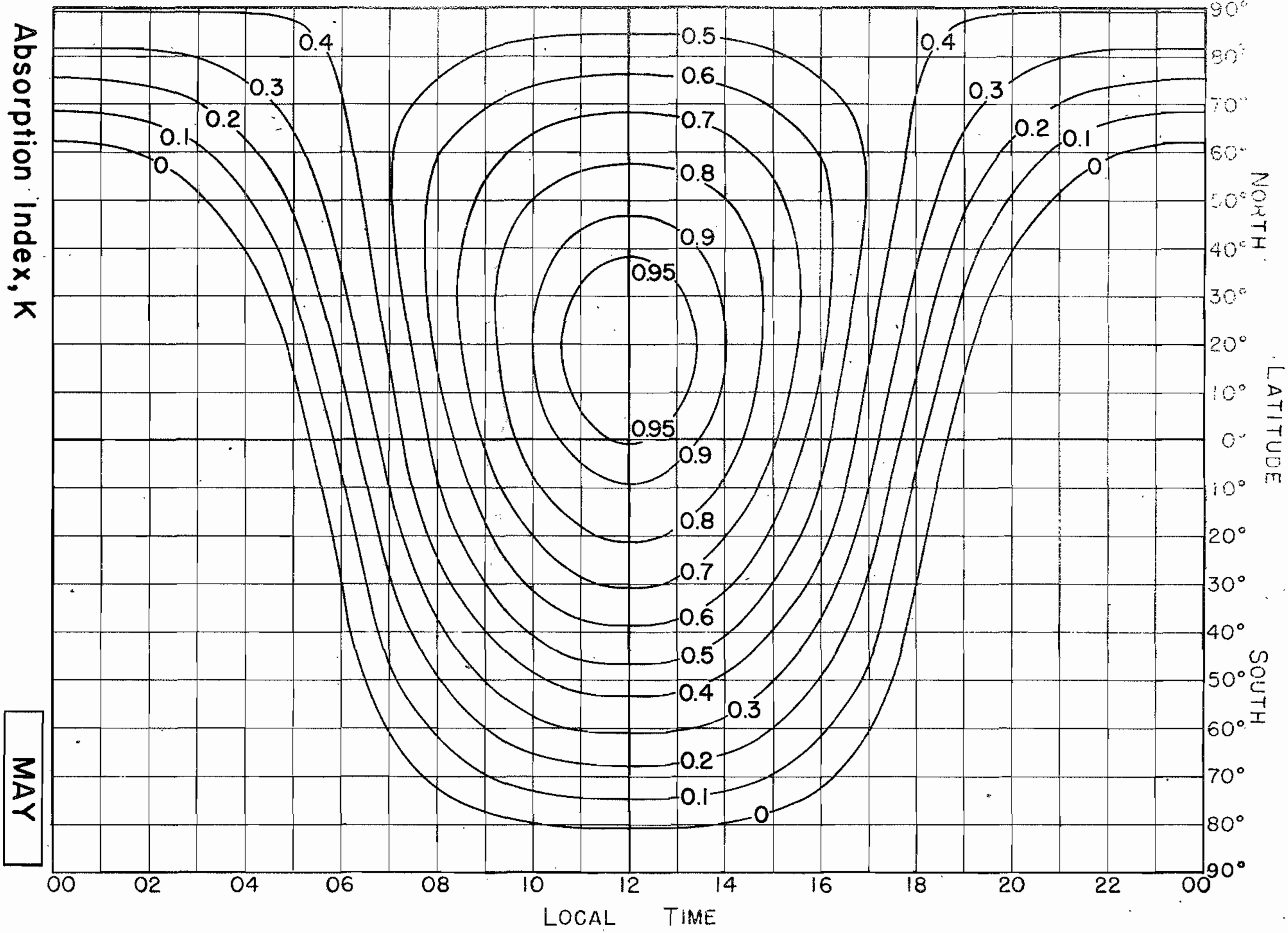


Fig. 84. Absorption index chart, May (excluding auroral-zone absorption.) Numbers on curves are absorption indexes, K.

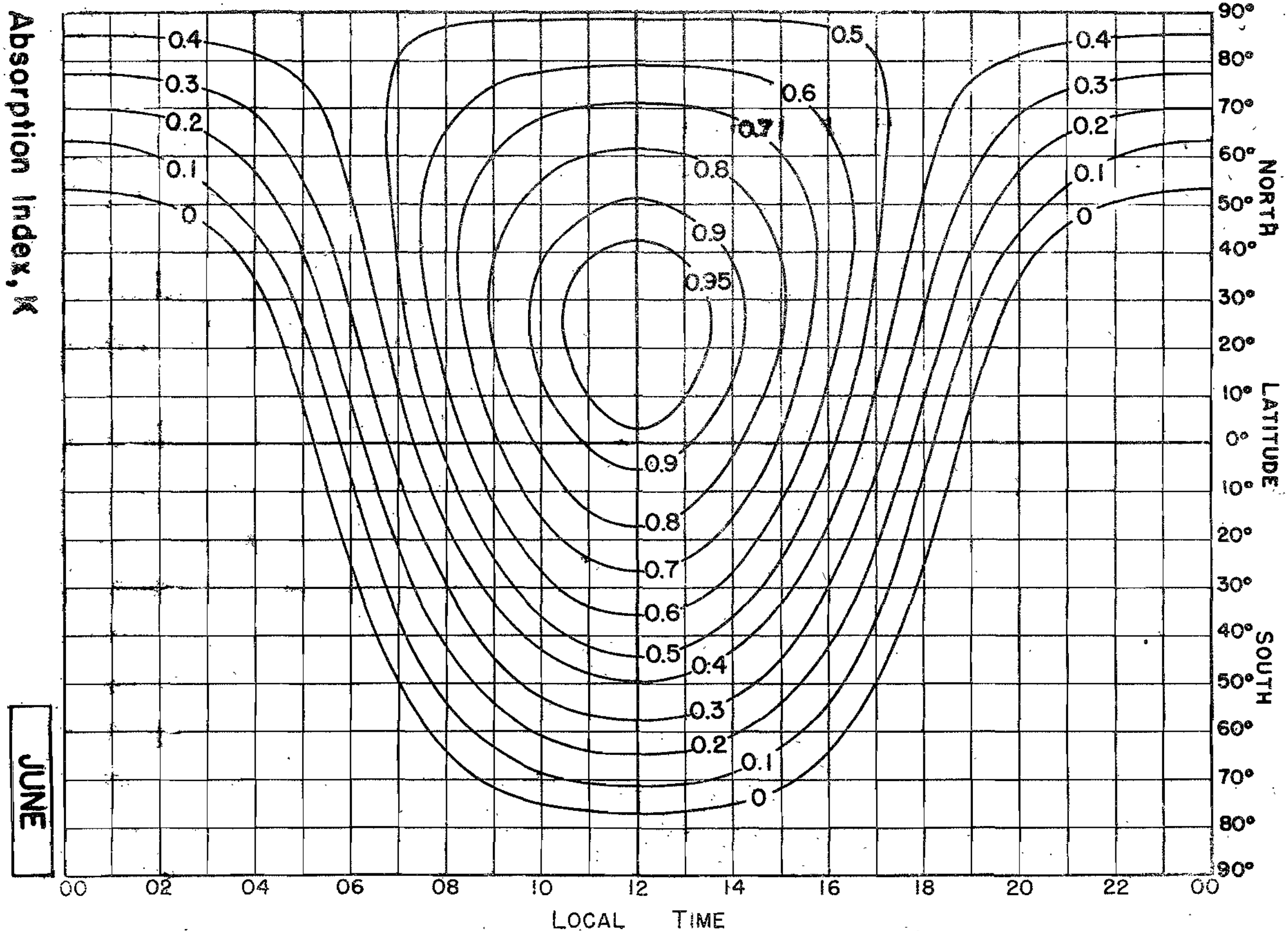


Fig. 85. Absorption index chart, June (excluding auroral-zone absorption.) Numbers on curves are absorption indexes, K.

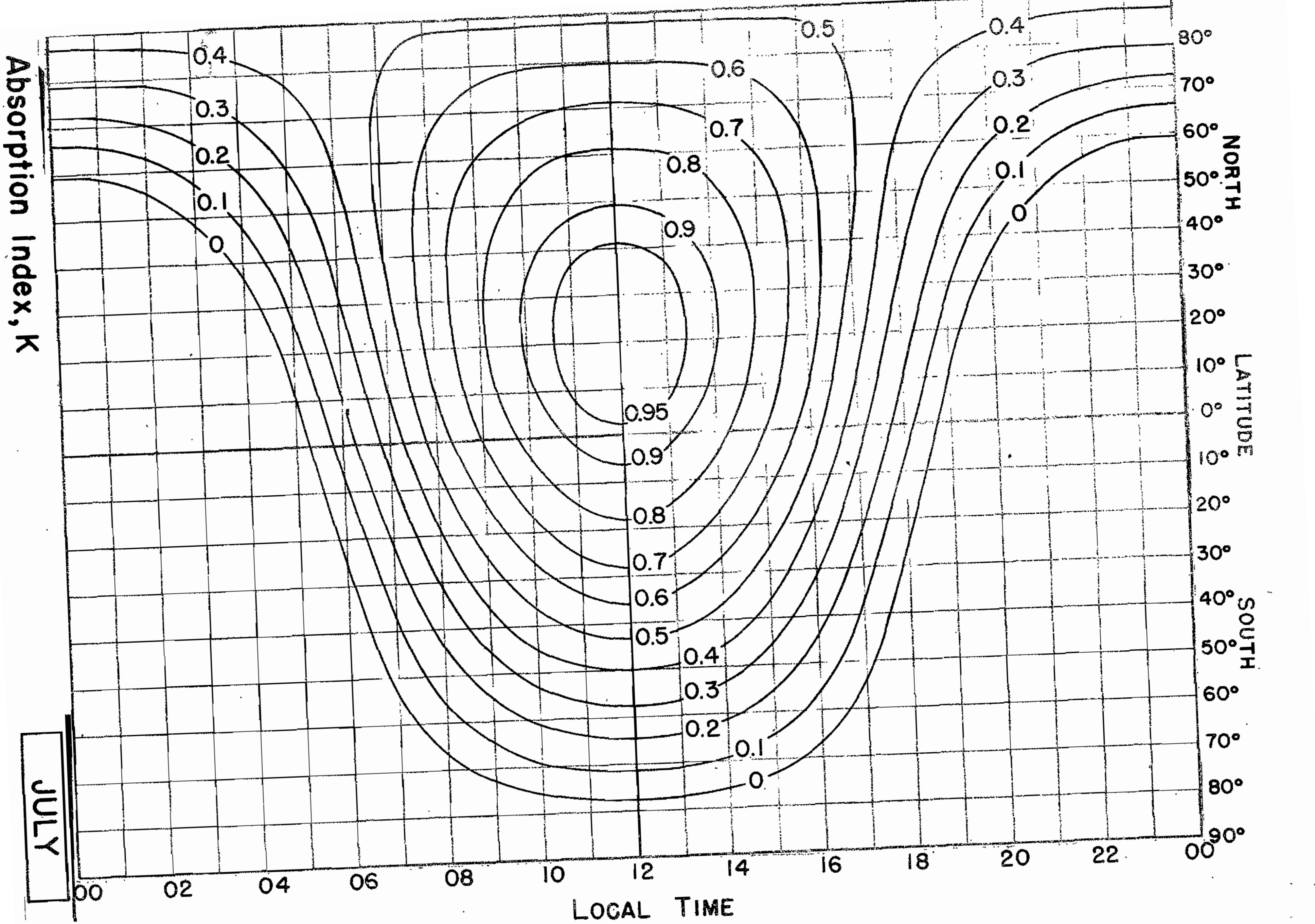


Fig. 86. Absorption index chart, July (excluding auroral-zone absorption.) Numbers on curves are absorption indexes, K.

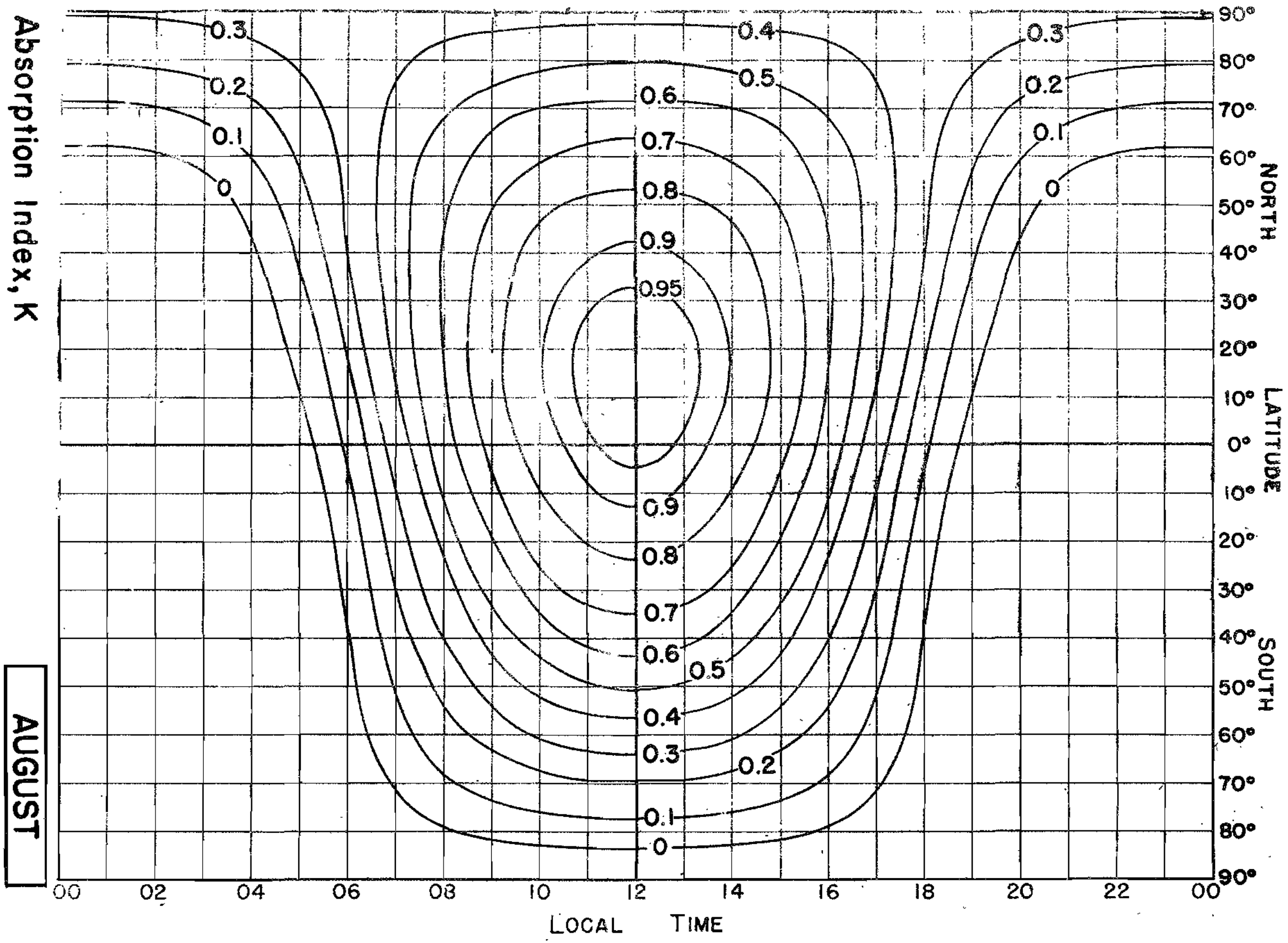


Fig. 87. Absorption index chart, August (excluding auroral-zone absorption.) Numbers on curves are absorption indexes, K.

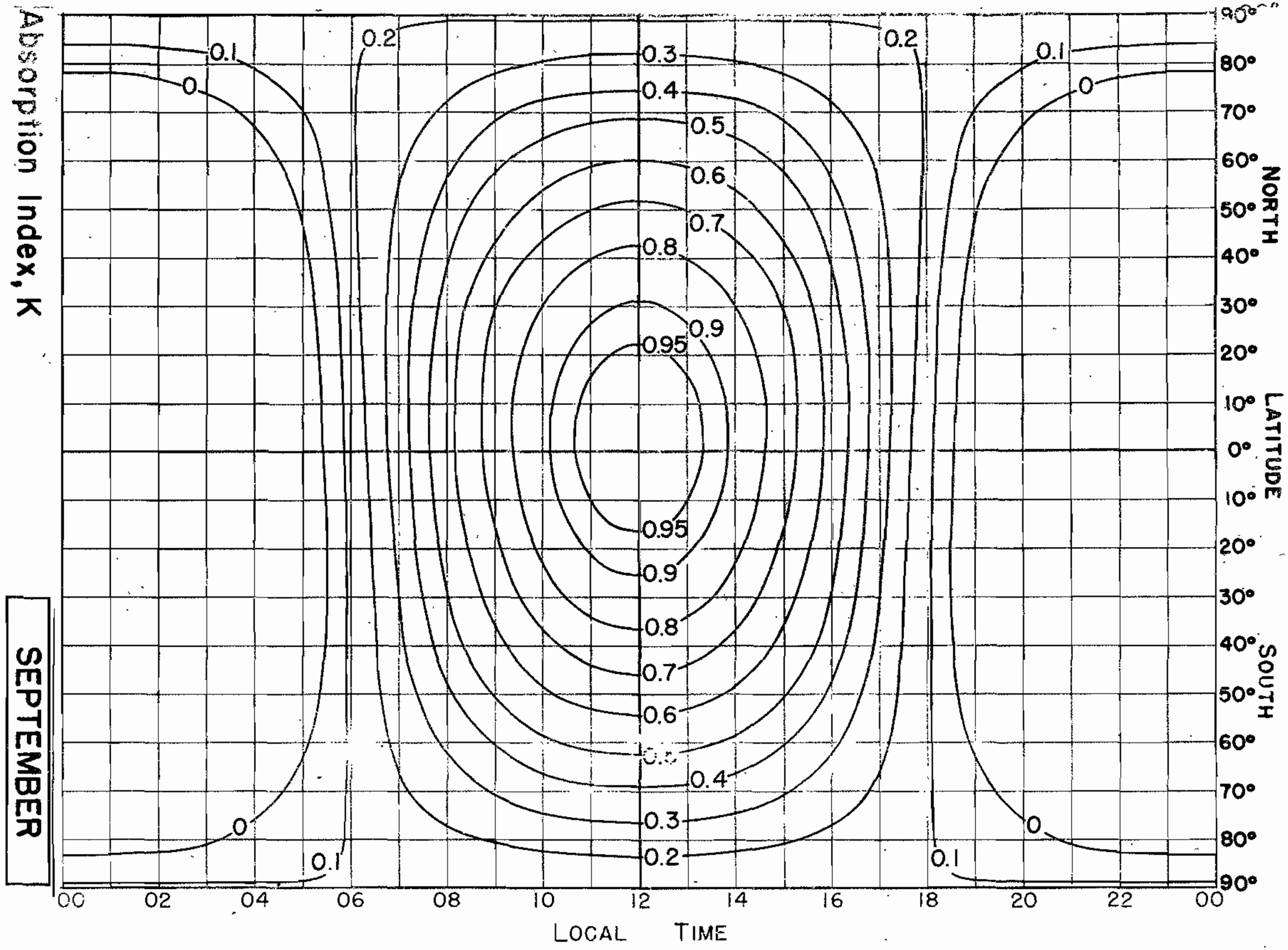


Fig. 88. Absorption index chart, September (excluding auroral-zone absorption.) Numbers on curves are absorption indexes, K.

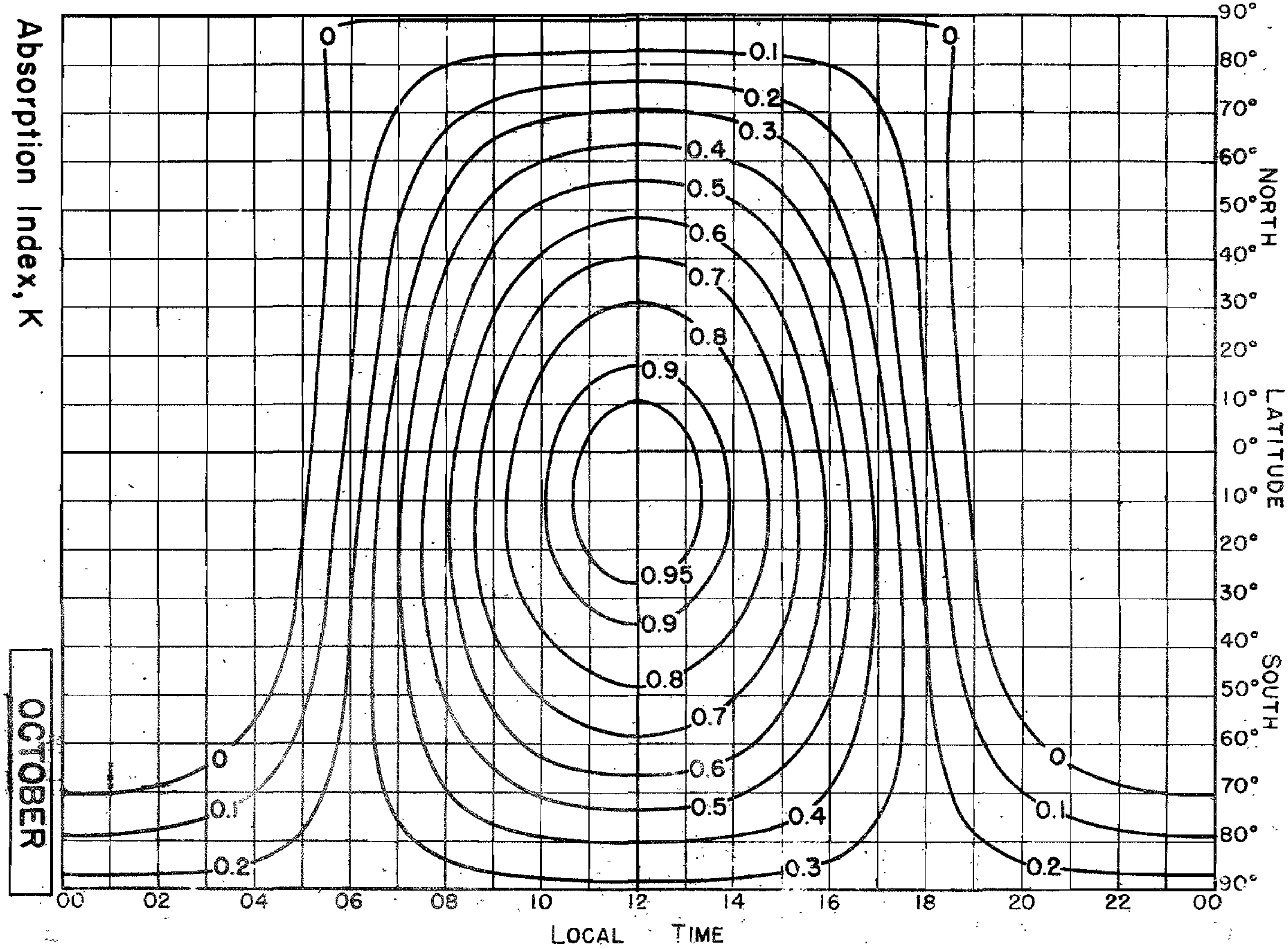


Fig. 89. Absorption index chart, October (excluding auroral zone absorption). Numbers on curves are absorption indexes, K.

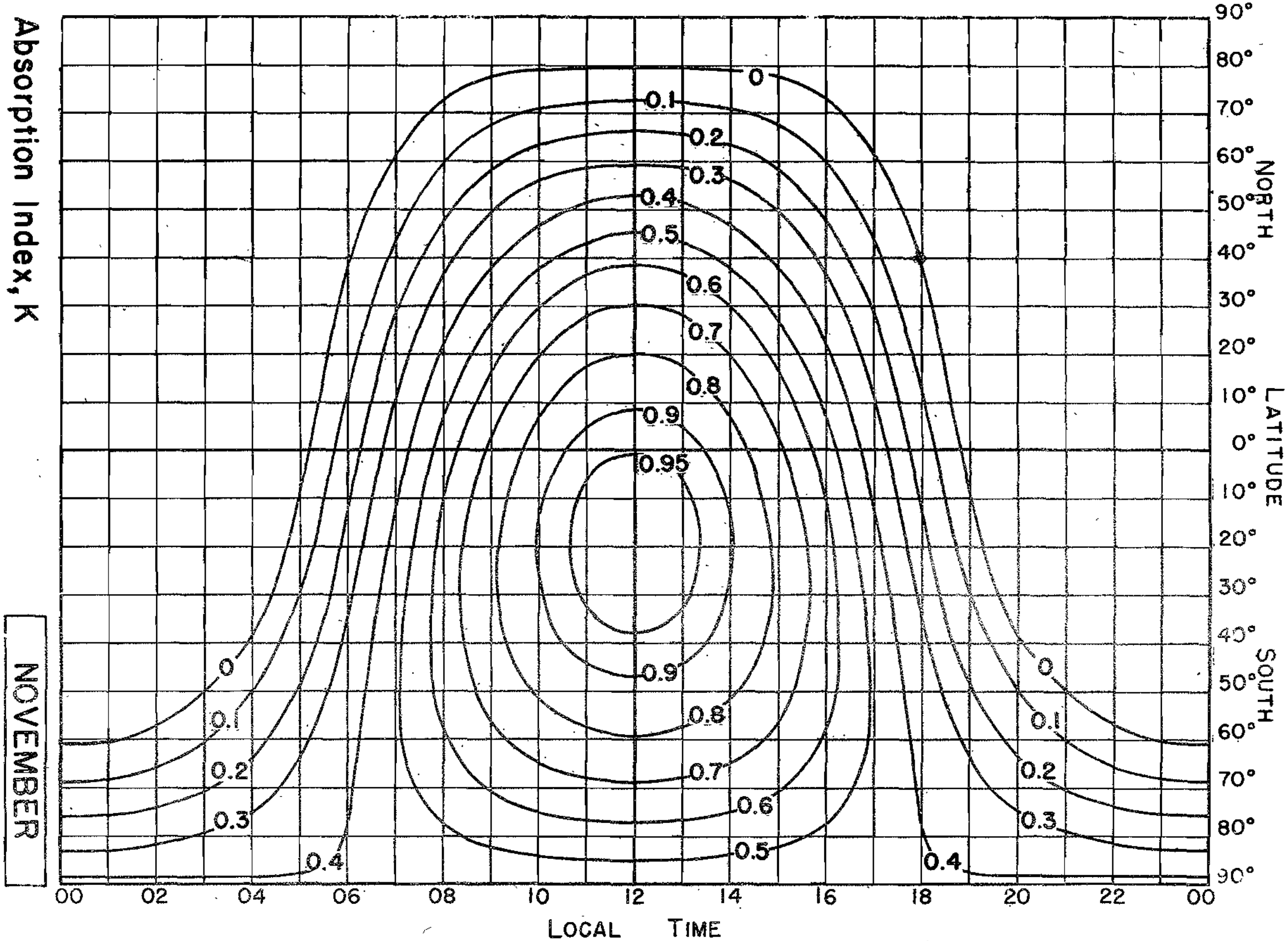


Fig. 90. Absorption index chart, November (excluding auroral zone absorption). Numbers on curves are absorption indexes, K.

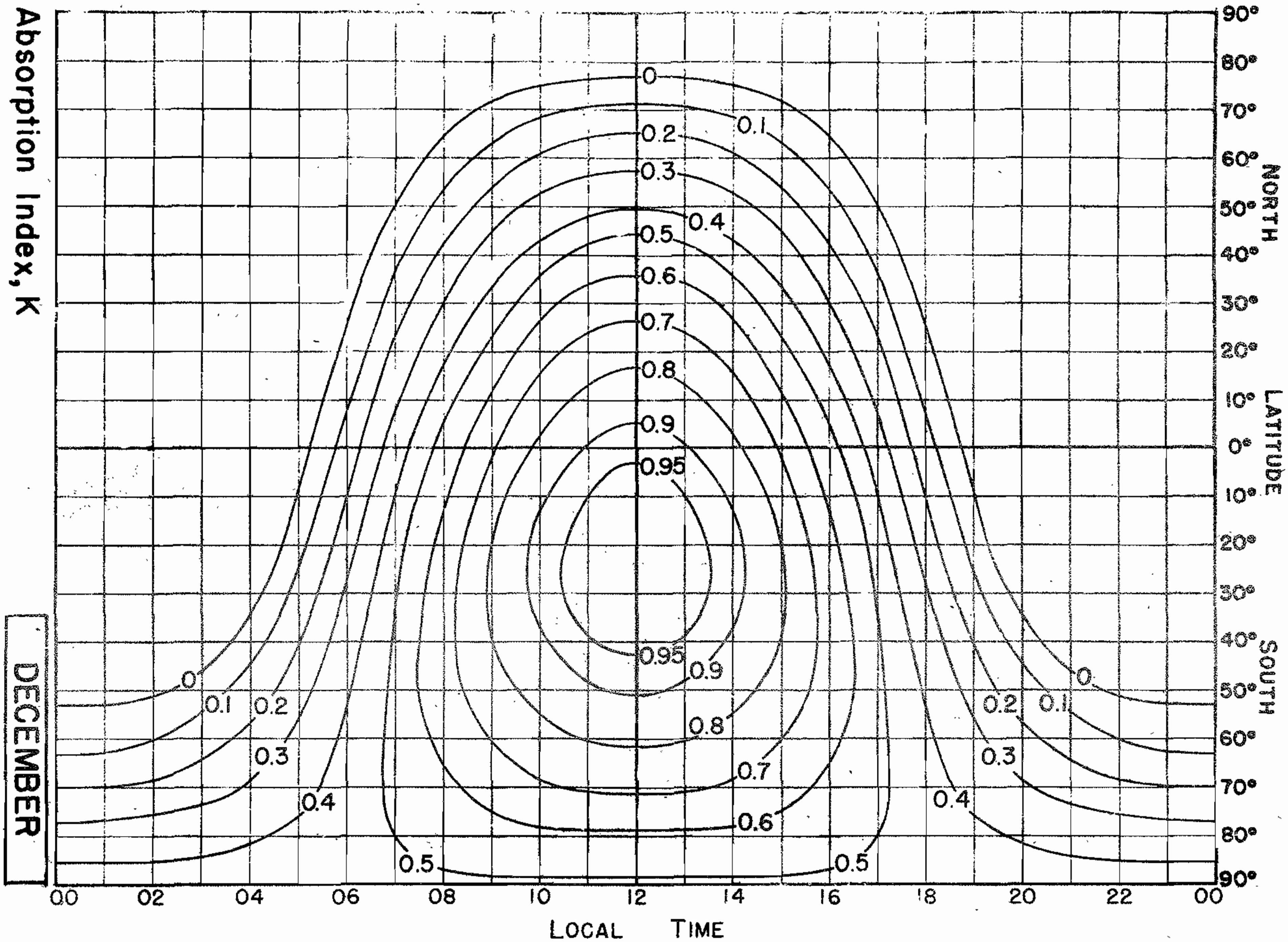


Fig. 91. Absorption index chart, December (excluding auroral-zone absorption.) Numbers on curves are absorption indexes, K.

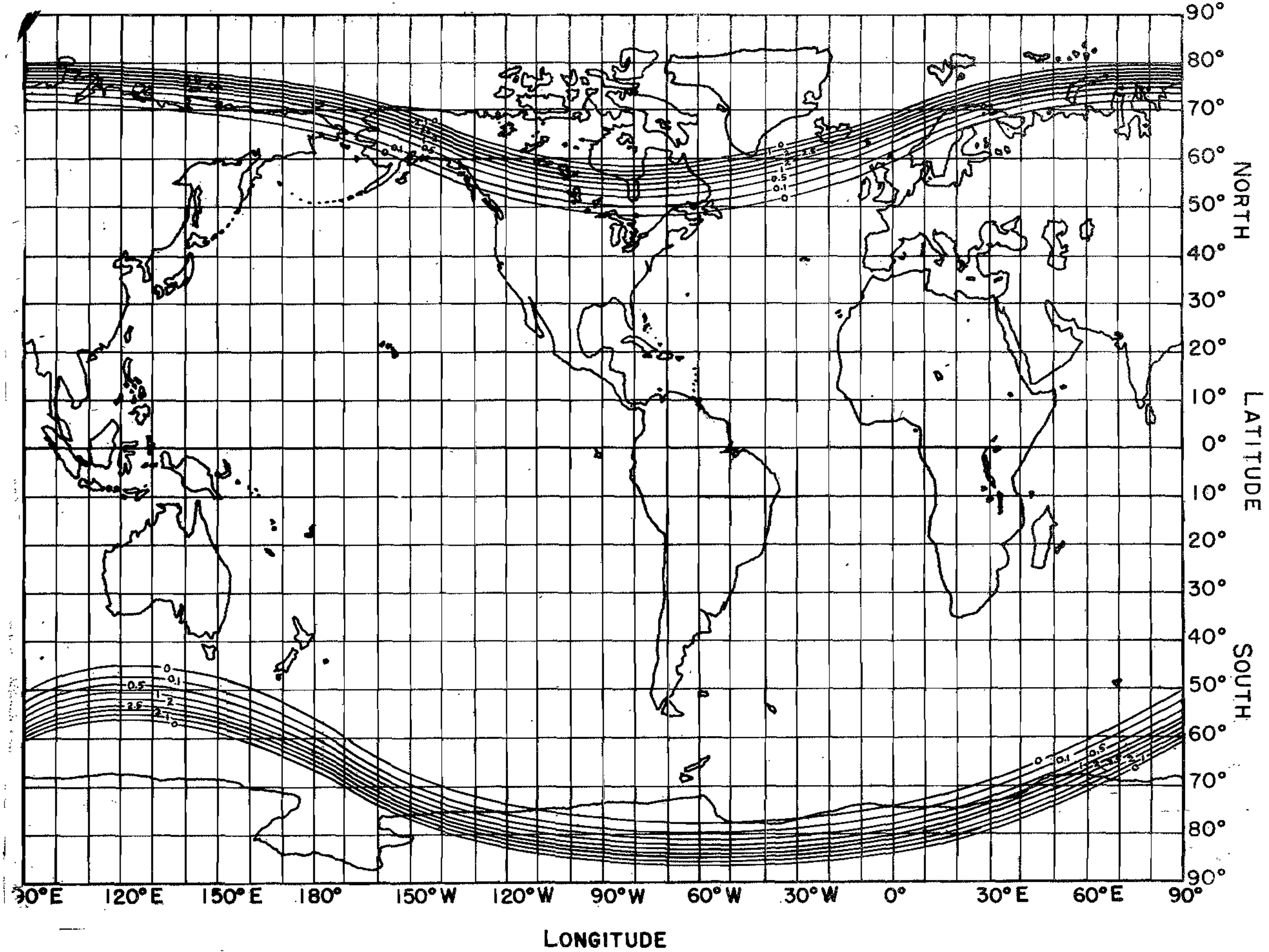


Fig. 92. Auroral zone absorption map. Numbers on curves are absorption indexes, K.

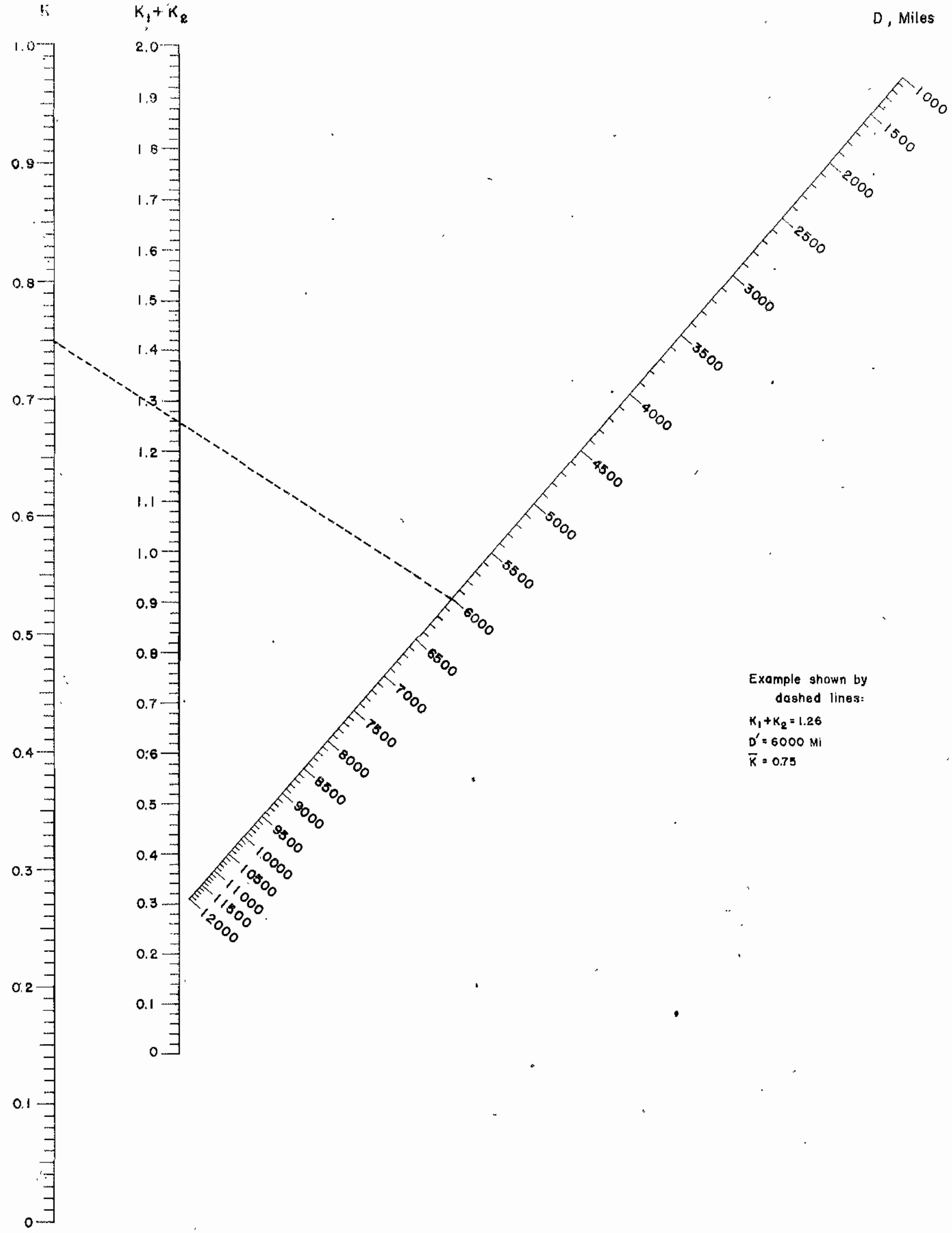
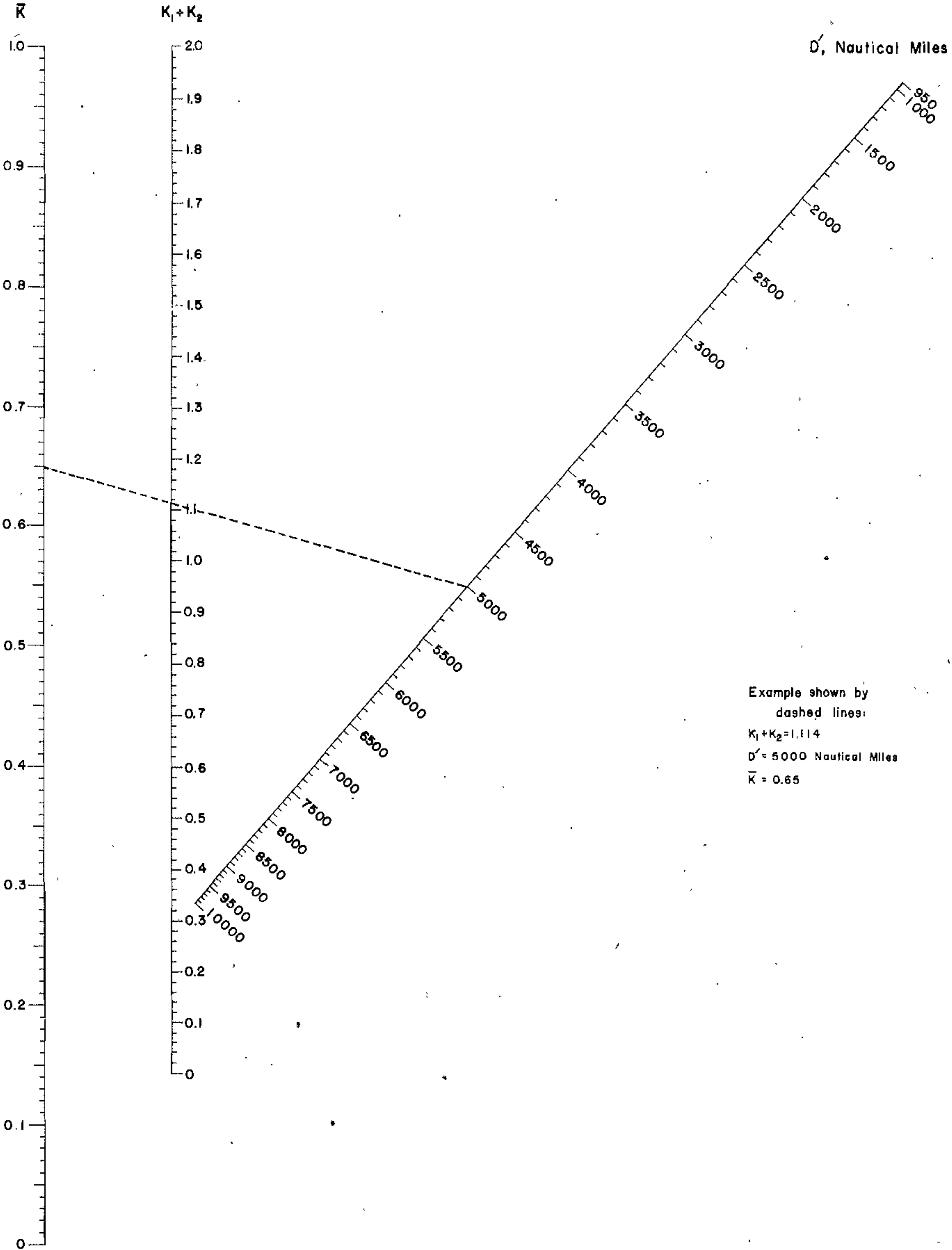
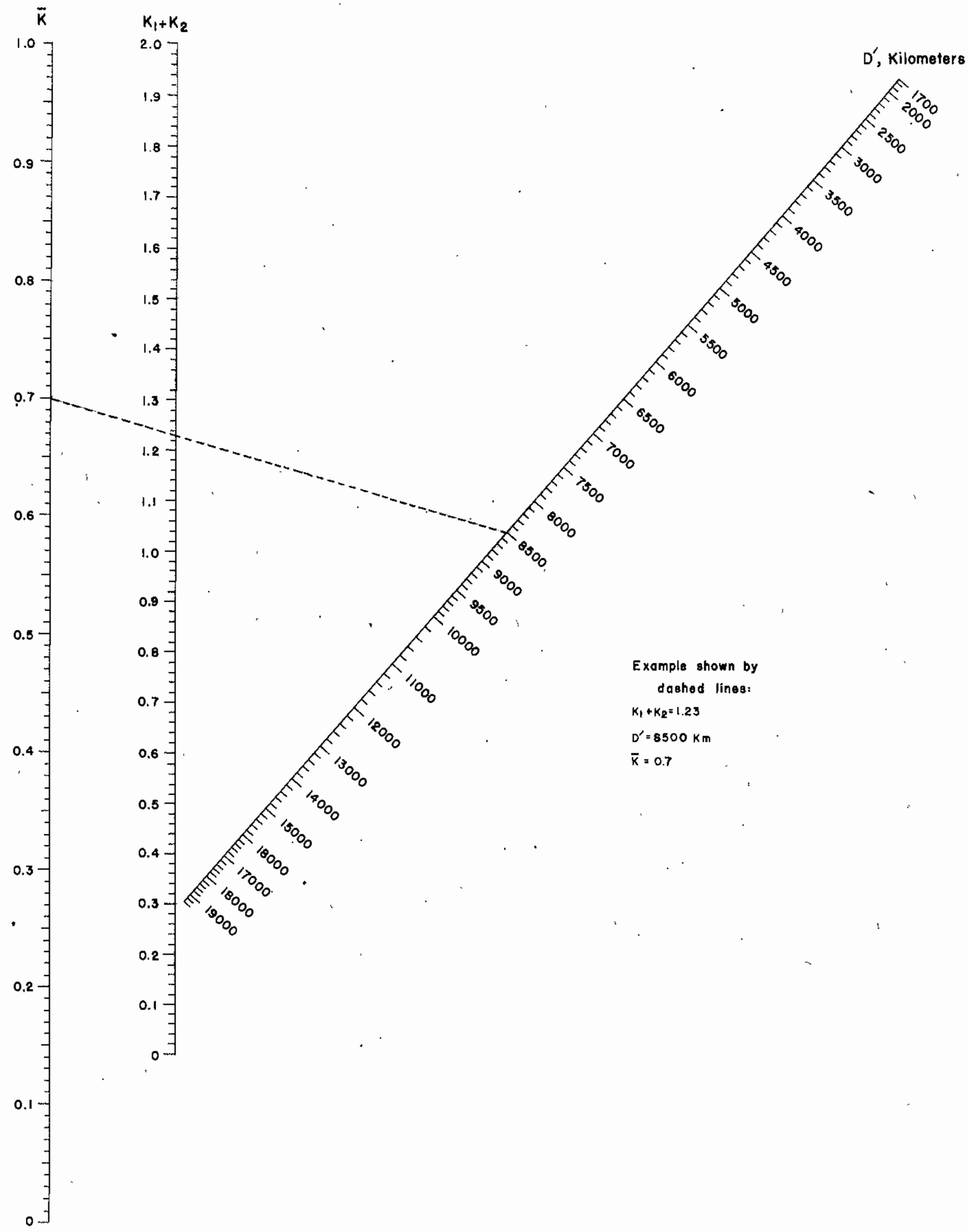


Fig. 93. Nomogram giving values of $\overline{K}$, (average absorption index over path) for given values of $K_1 + K_2$ (sum of absorption indexes at terminal points of path), and given lengths of path, D', within the solar absorption region. (Distance in miles.)



Example shown by dashed lines:
$K_1 + K_2 = 1.114$
$D' = 5000$ Nautical Miles
$\bar{K} = 0.65$

Fig. 94. Nomogram giving values of K, (average absorption index over path) for given values of $K_1 + K_2$ (sum of absorption indexes at terminal points of path), and given lengths of path, D', within the solar absorption region. (Distance in nautical miles.)



Example shown by dashed lines:

$K_1+K_2=1.23$

$D'=8500$ Km

$\overline{K}=0.7$

Fig. 95. Nomogram giving values of $\overline{K}$, (average absorption index over path) for given values of $K_1 + K_2$ (sum of absorption indexes at terminal points of path), and given lengths of path, D', within the solar absorption region. (Distance in kilometers.)

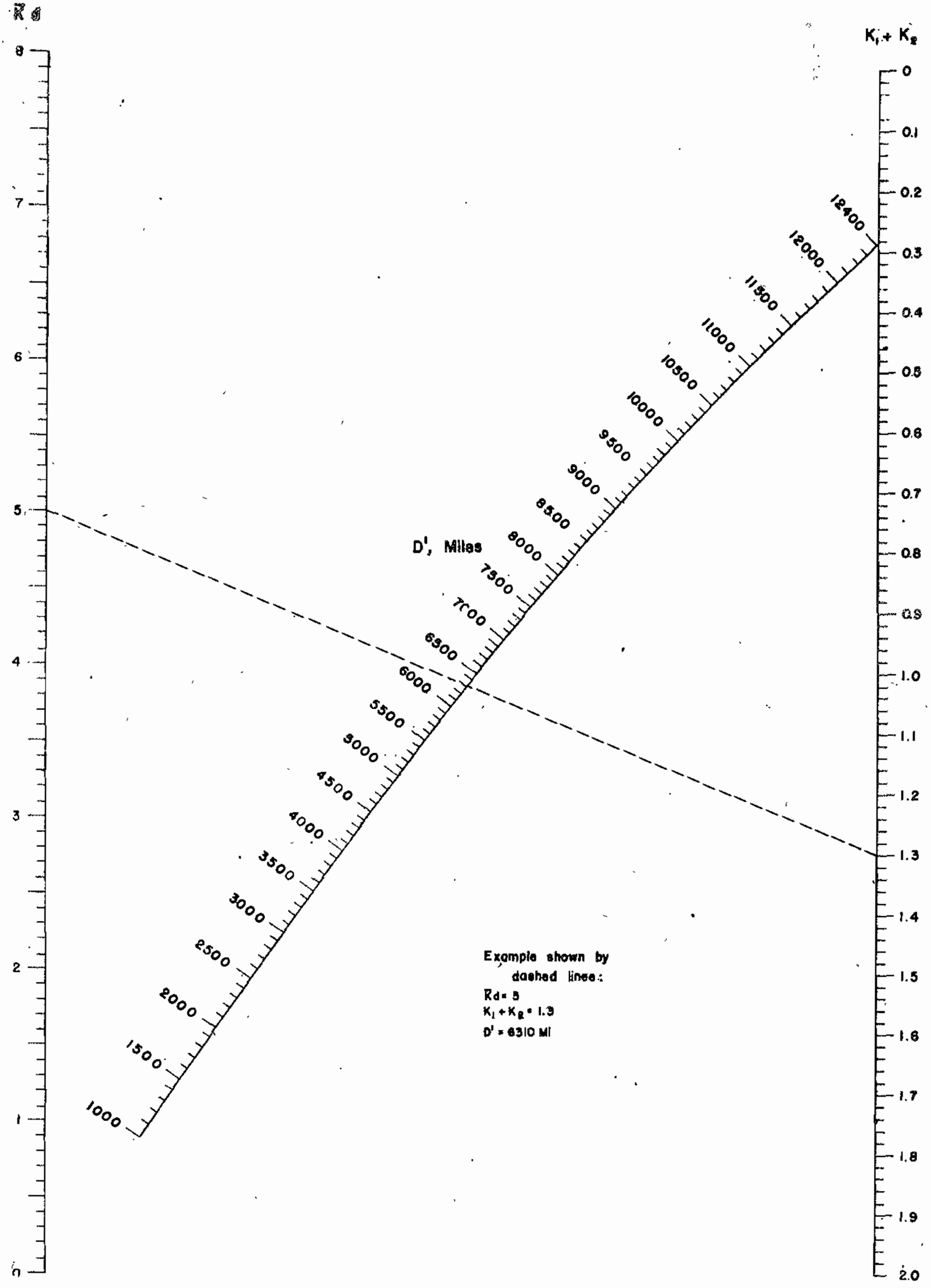
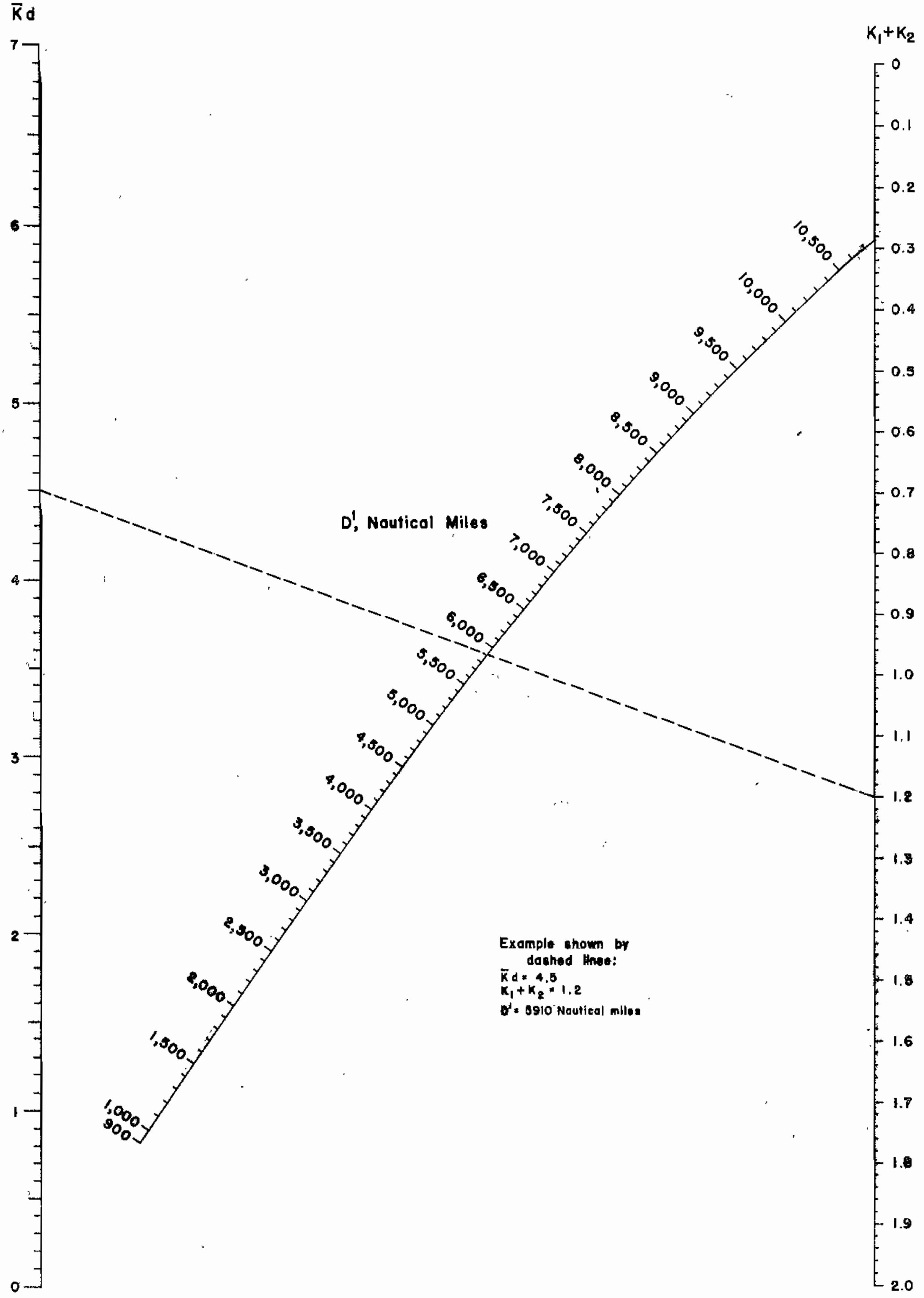


Fig. 96. Nomogram giving variation of $\bar{K}$ d (product of the average absorption index for total transmission path and the transmission distance) with transmission distance, d, and $K_1 + K_2$ (sum of the absorption indexes at terminal points of the transmission path). (Distance in miles, up to 12430 miles.)



Example shown by dashed lines:
$\overline{K}$ d = 4.5
K_1+K_2 = 1.2
D' = 5910 Nautical miles

Fig. 97. Nomogram giving variation of $\overline{K}$ d (product of the average absorption index for total transmission path and the transmission distance) with transmission distance, d, and $K_1 + K_2$ (sum of the absorption indexes at terminal points of the transmission path.) (Distance in nautical miles, up to 10794 nautical miles.)

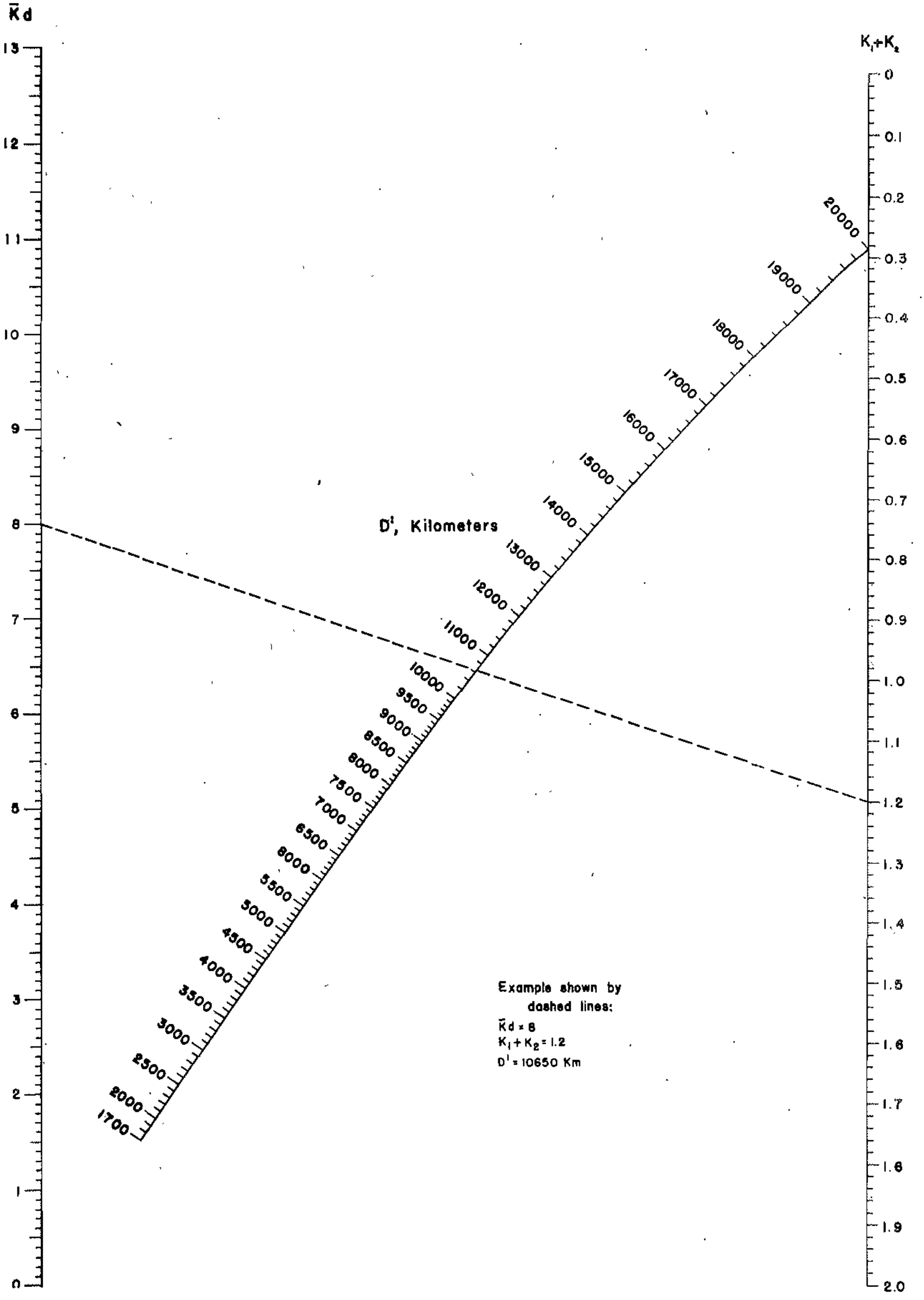


Fig. 98. Nomogram giving variation of $\overline{K}$ d (product of the average absorption index for total transmission path and the transmission distance) with transmission distance, d, and $K_1 + K_2$ (sum of the absorption indexes at terminal points of the transmission path.) (Distance in kilometers, up to 20000 kilometers.)

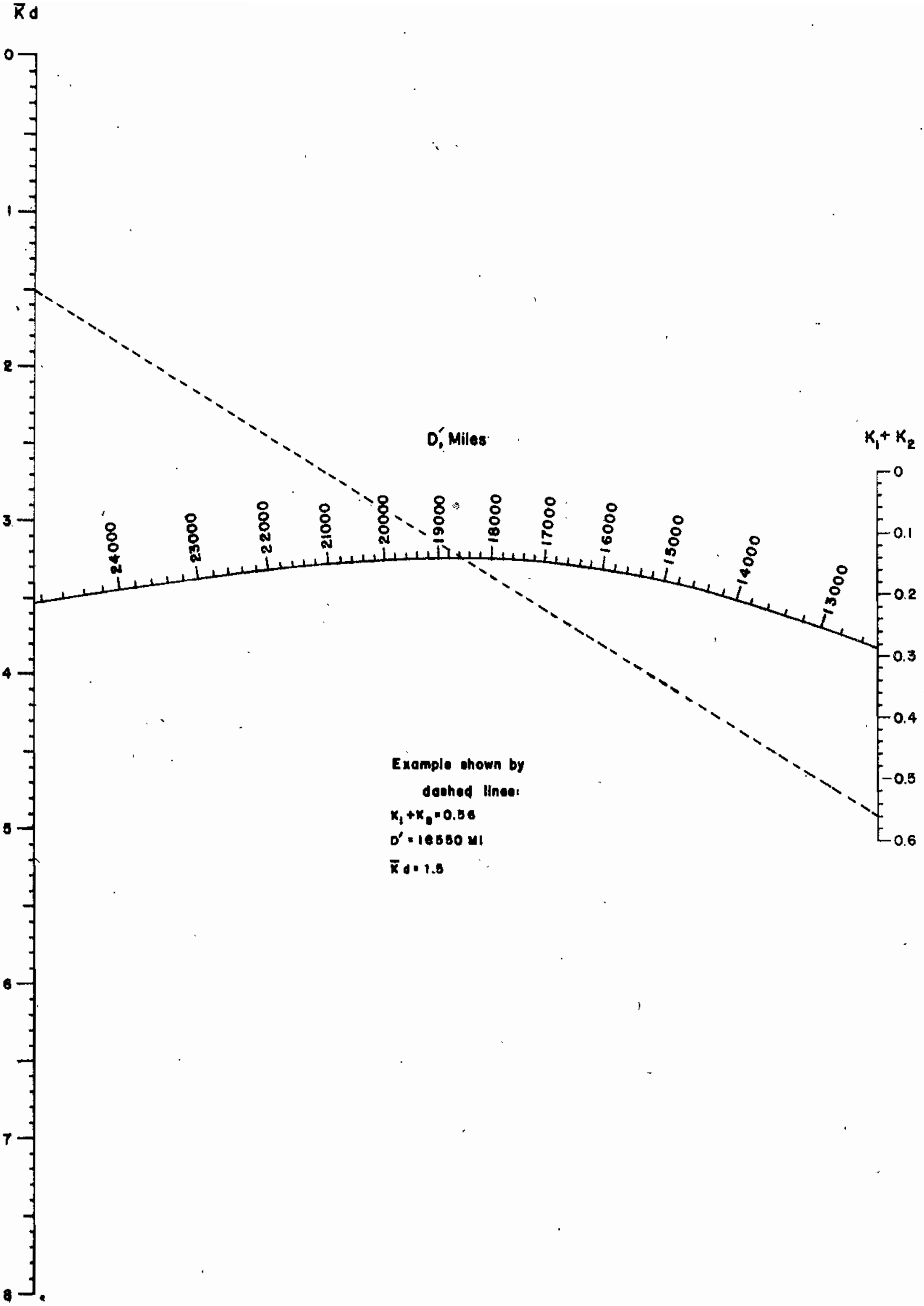
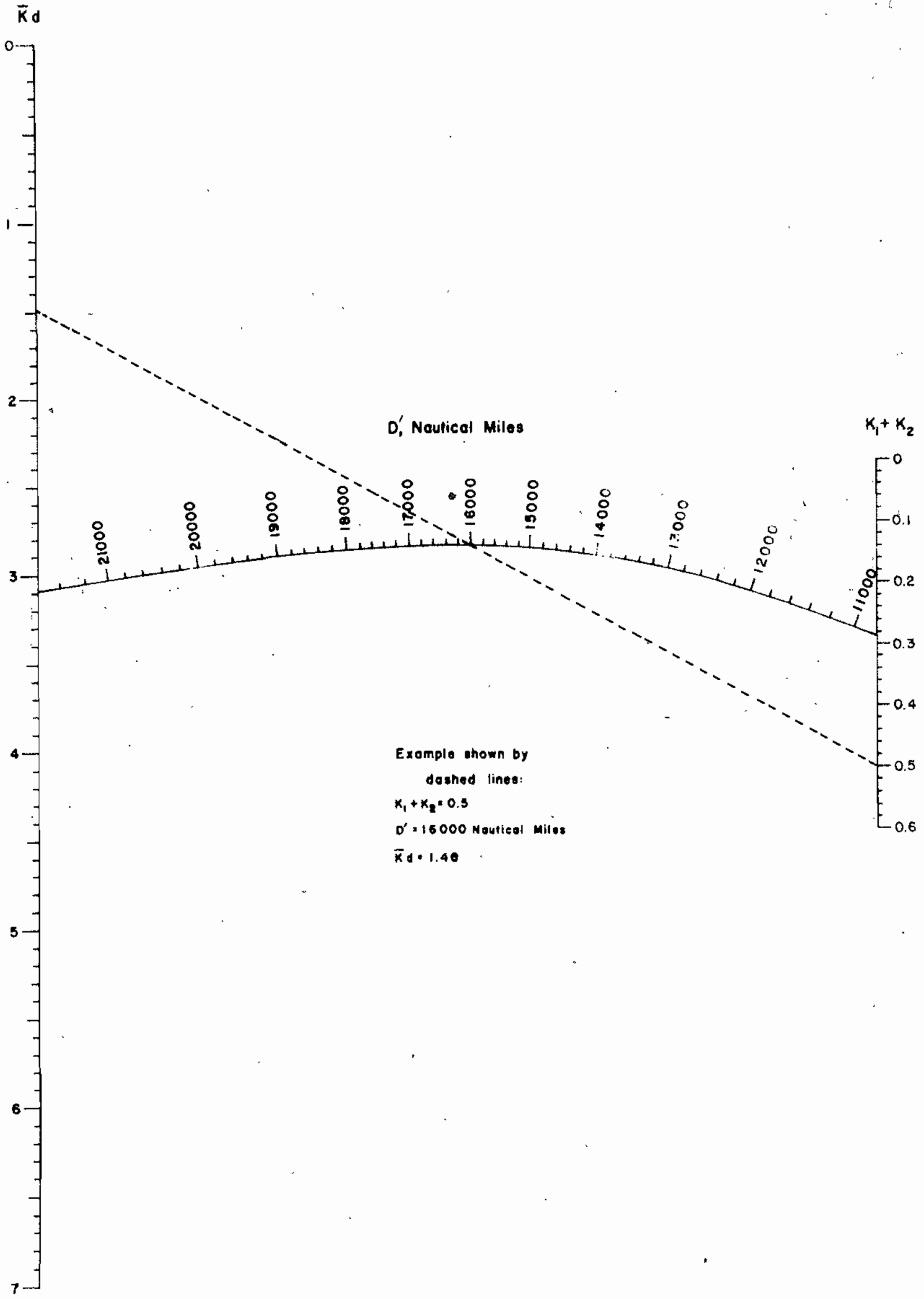


Fig. 99. Nomogram giving variation of $\overline{K}$ d (product of the average absorption index for total transmission path and the transmission distance) with transmission distance, D, and $K_1 + K_2$ (sum of the absorption indexes at terminal points of the transmission path.) Distance in miles, between 12430 and 24860 miles.)



Example shown by dashed lines:
$K_1 + K_2 = 0.5$
D′ = 16000 Nautical Miles
$\bar{K}$ d = 1.46

Fig. 100. Nomogram giving variation of $\bar{K}$ d (product of the average absorption index for total transmission path and the transmission distance) with transmission distance, d, and $K_1 + K_2$ (sum of the absorption indexes at terminal points of the transmission path.) (Distance in nautical miles, between 10794 and 21588 nautical miles.)

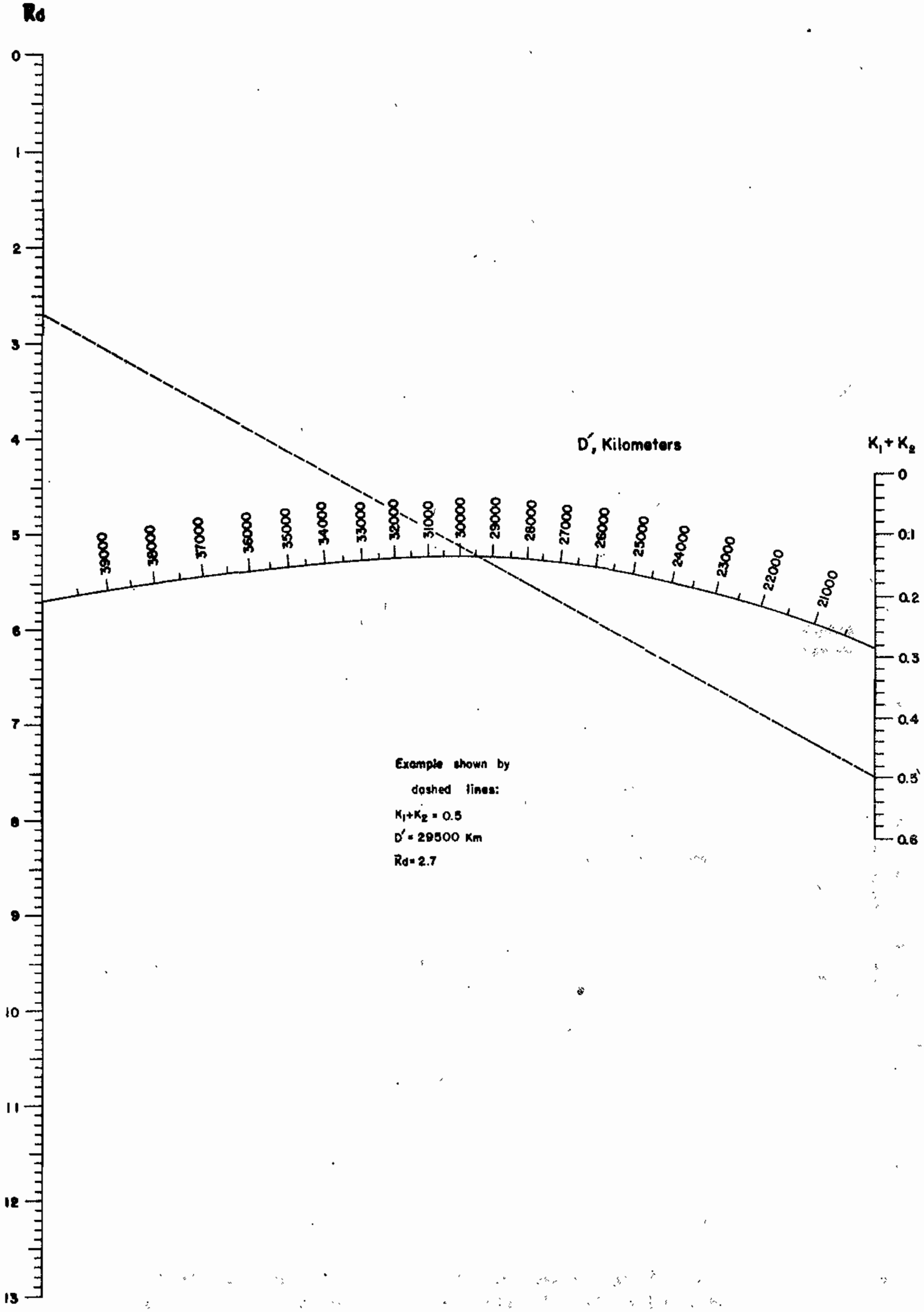


Fig. 101. Nomogram giving variation of $\overline{K}$ d (product of the average absorption index for total transmission path and the transmission distance) with transmission distance, D, and $K_1 + K_2$ (sum of the absorption indexes at terminal points of the transmission path.) Distance in kilometers, between 20000 and 40000 kilometers.)

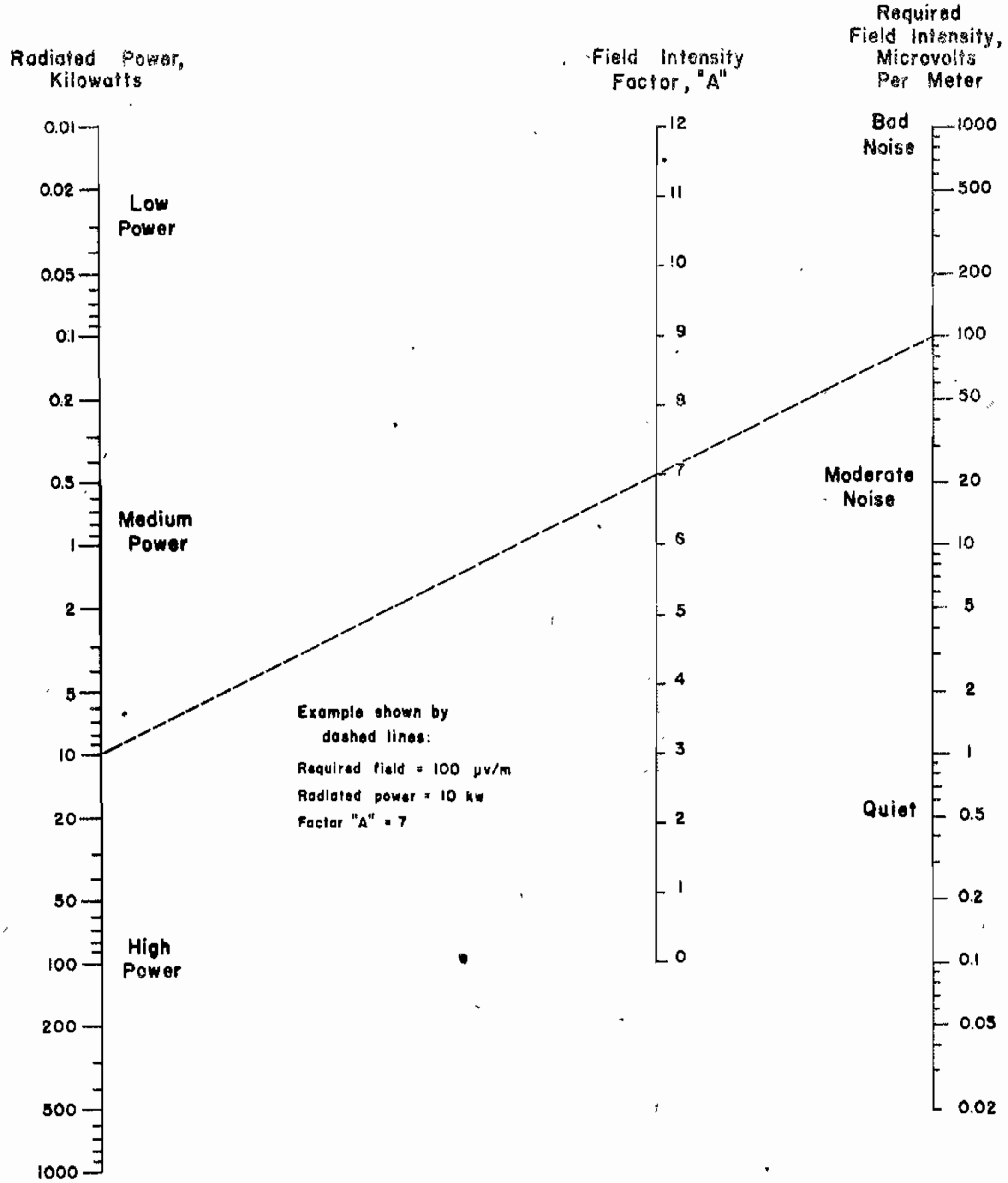


Fig. 102. Nomogram giving relationship of field-intensity factor A, radiated power, P, and required field intensity, F.

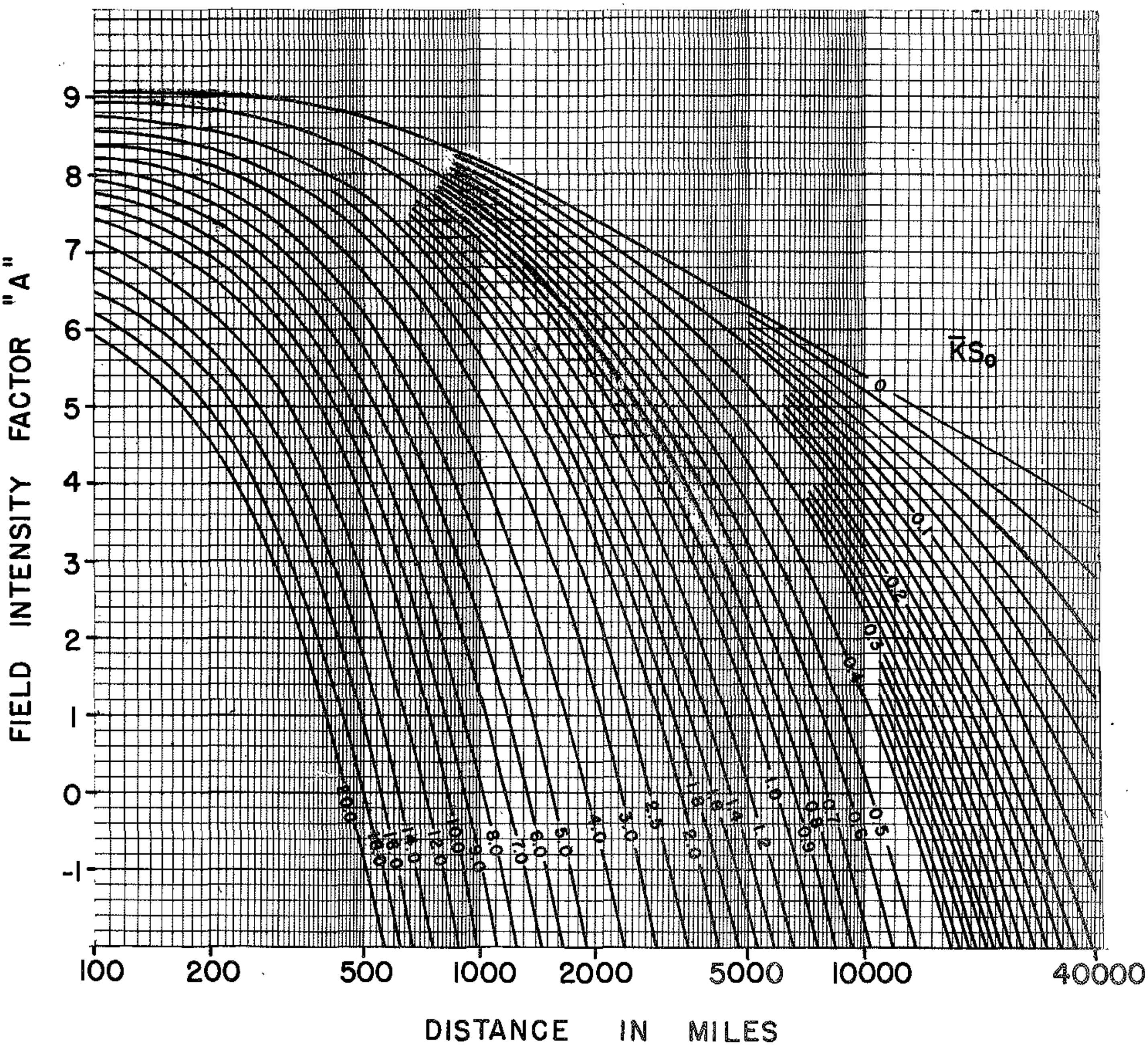


Fig. 103. Variation of field intensity factor, A, with distance, d, and absorption, $\overline{K}, S_0$. (Distance in miles.)

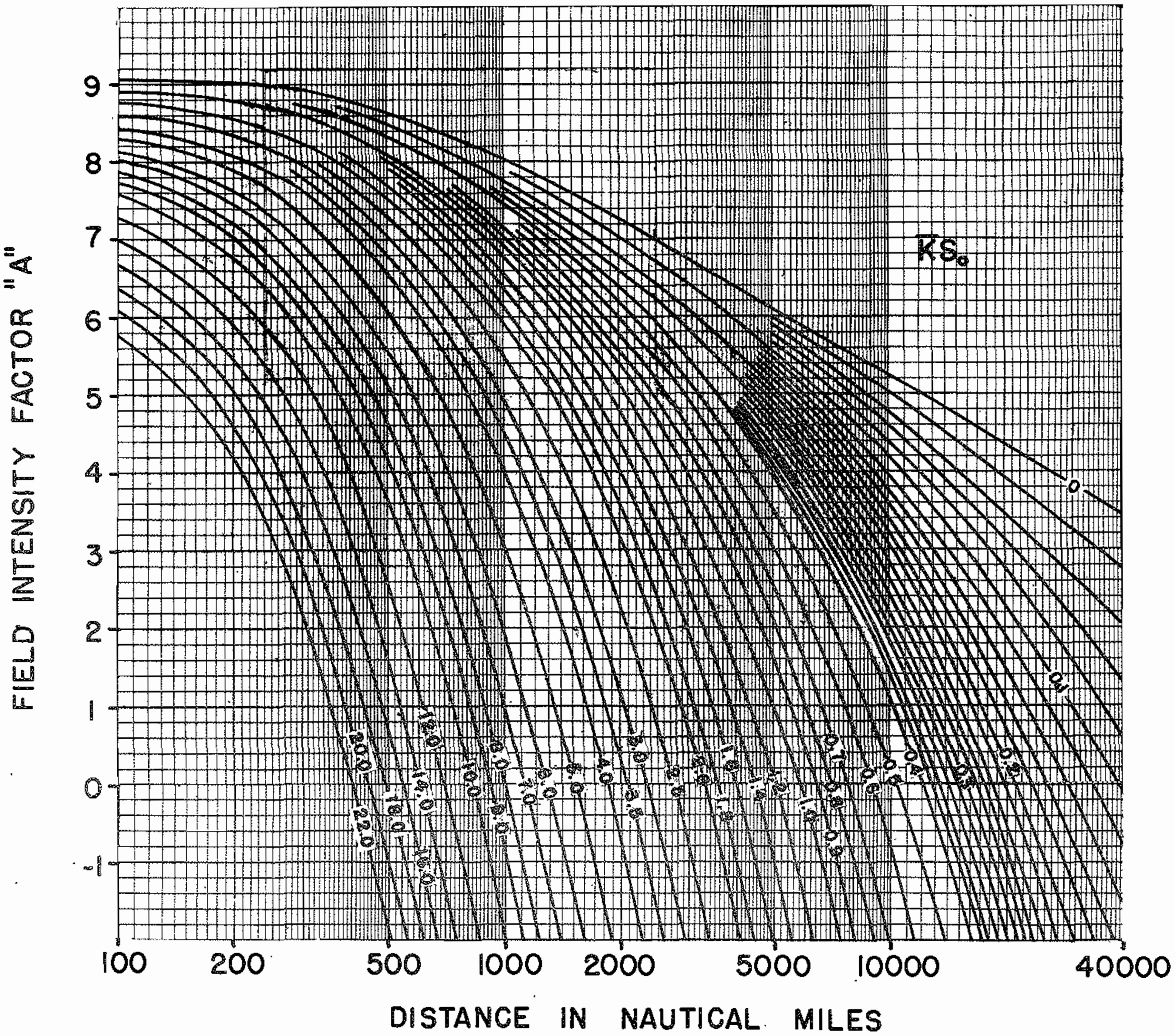


Fig. 104. Variation of field-intensity factor, A, with distance, d, and absorption, $\overline{K}\ S_o$. (Distance in nautical miles.)

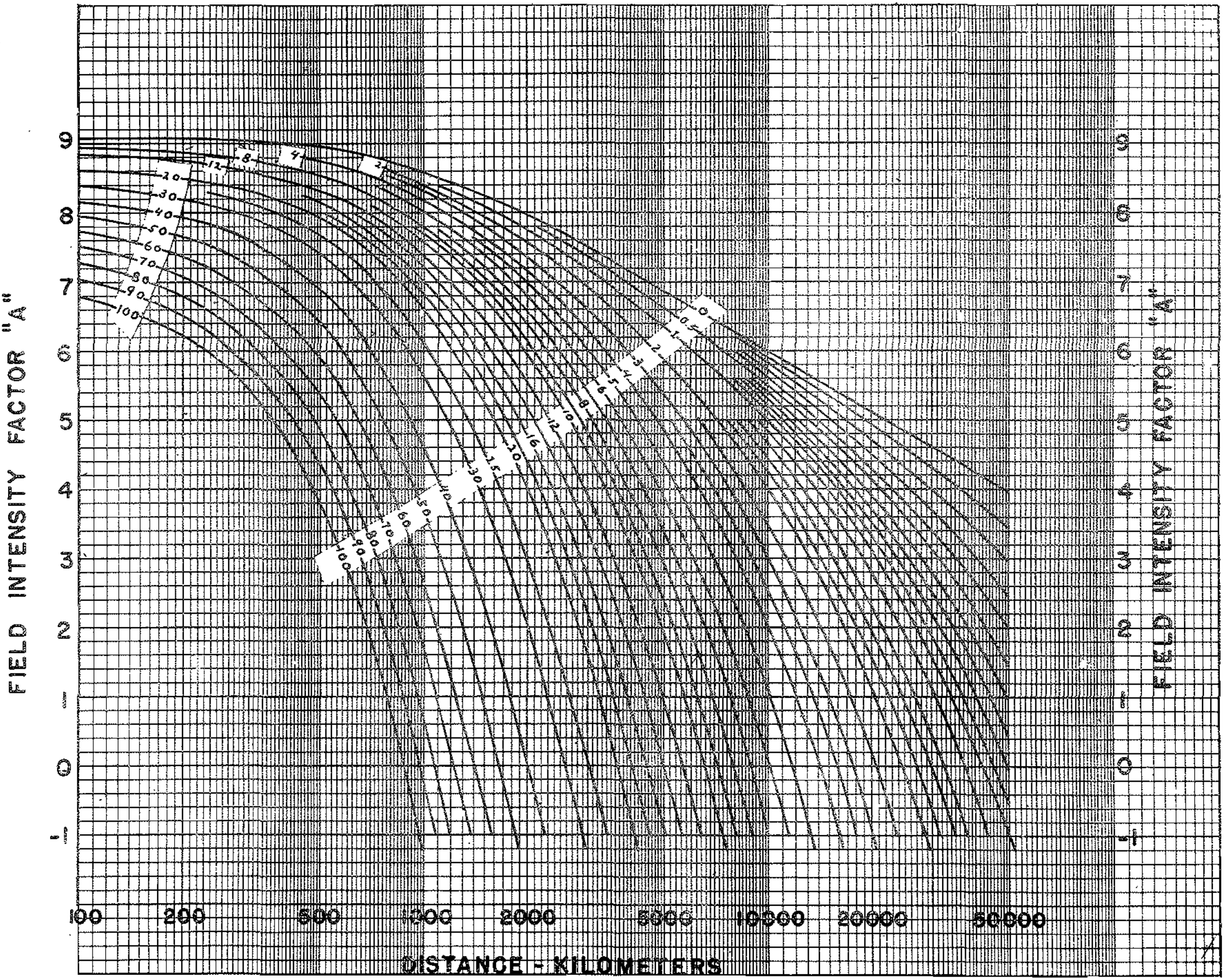
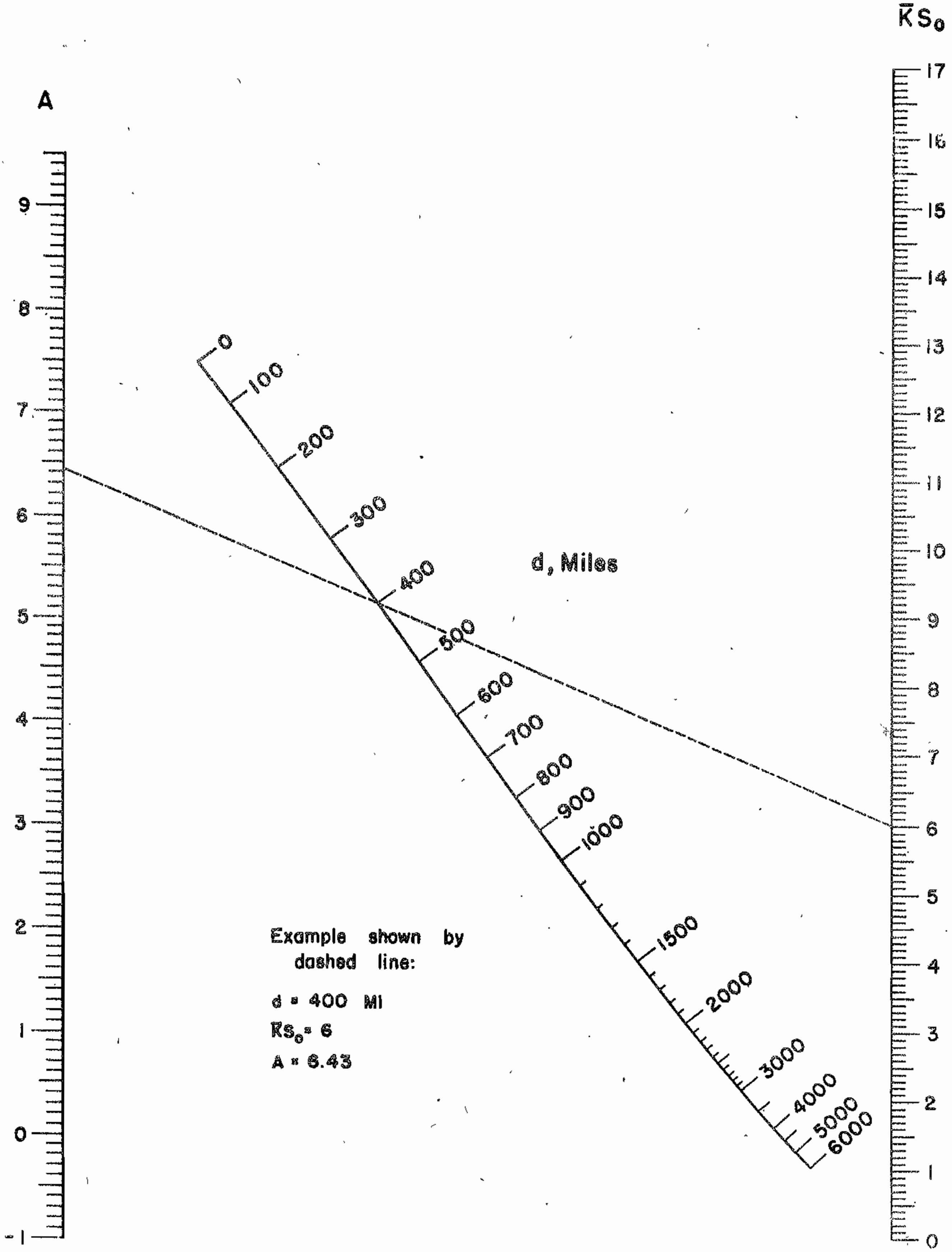


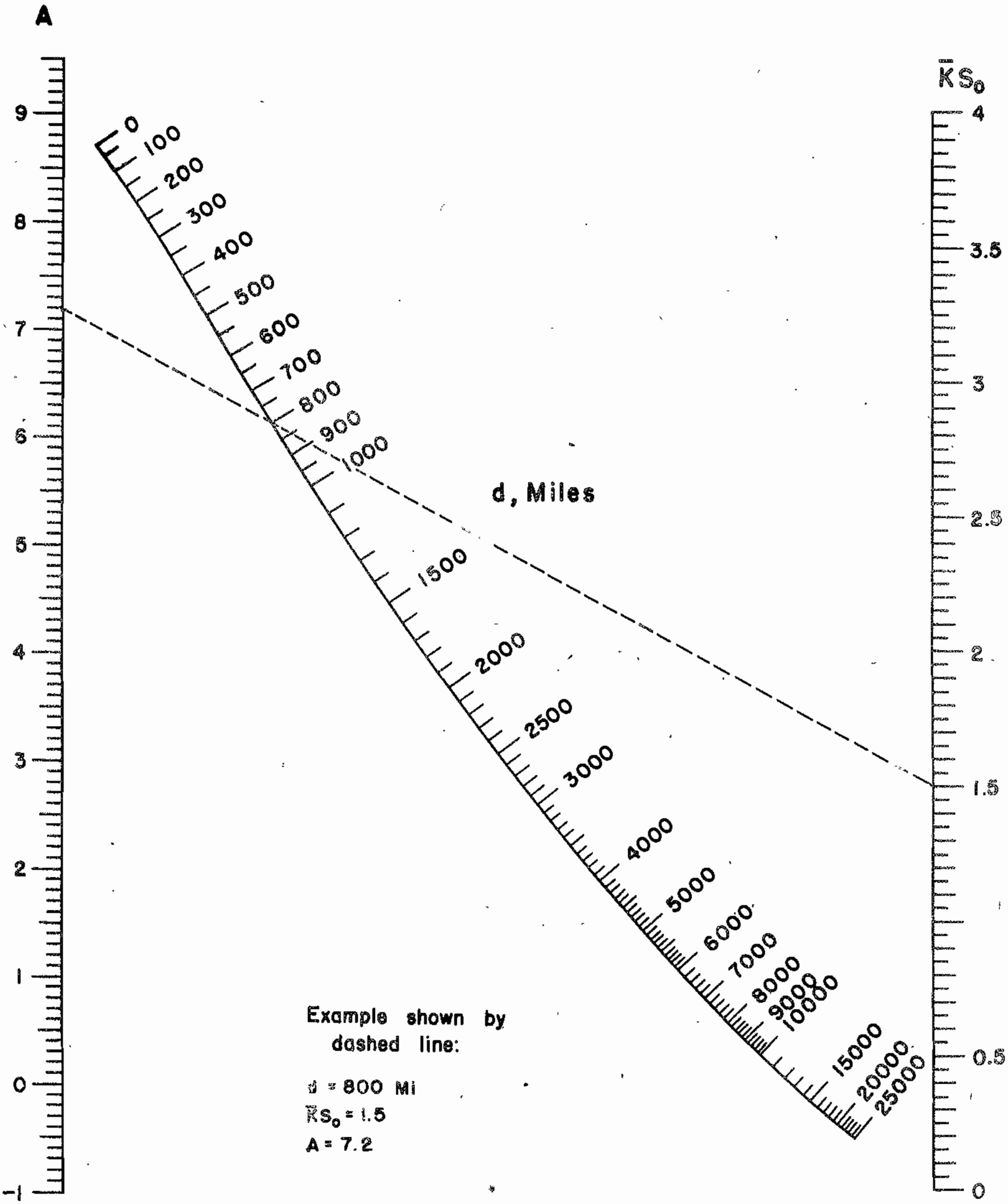
Fig. 105. Variation of field intensity factor, A, with distance, d, and absorption, $\overline{K}\ S_o$. (Distance in kilometers.)



Example shown by dashed line:

d = 400 MI
$\bar{K}S_0$ = 6
A = 6.43

Fig. 106. Nomogram giving relationship of distance range d, values of field-intensity factor A, and absorption, $\bar{K}\,S_0$. (Other ranges of values are given in nomograms, Figs. 107 and 108.) (Distances in miles.)



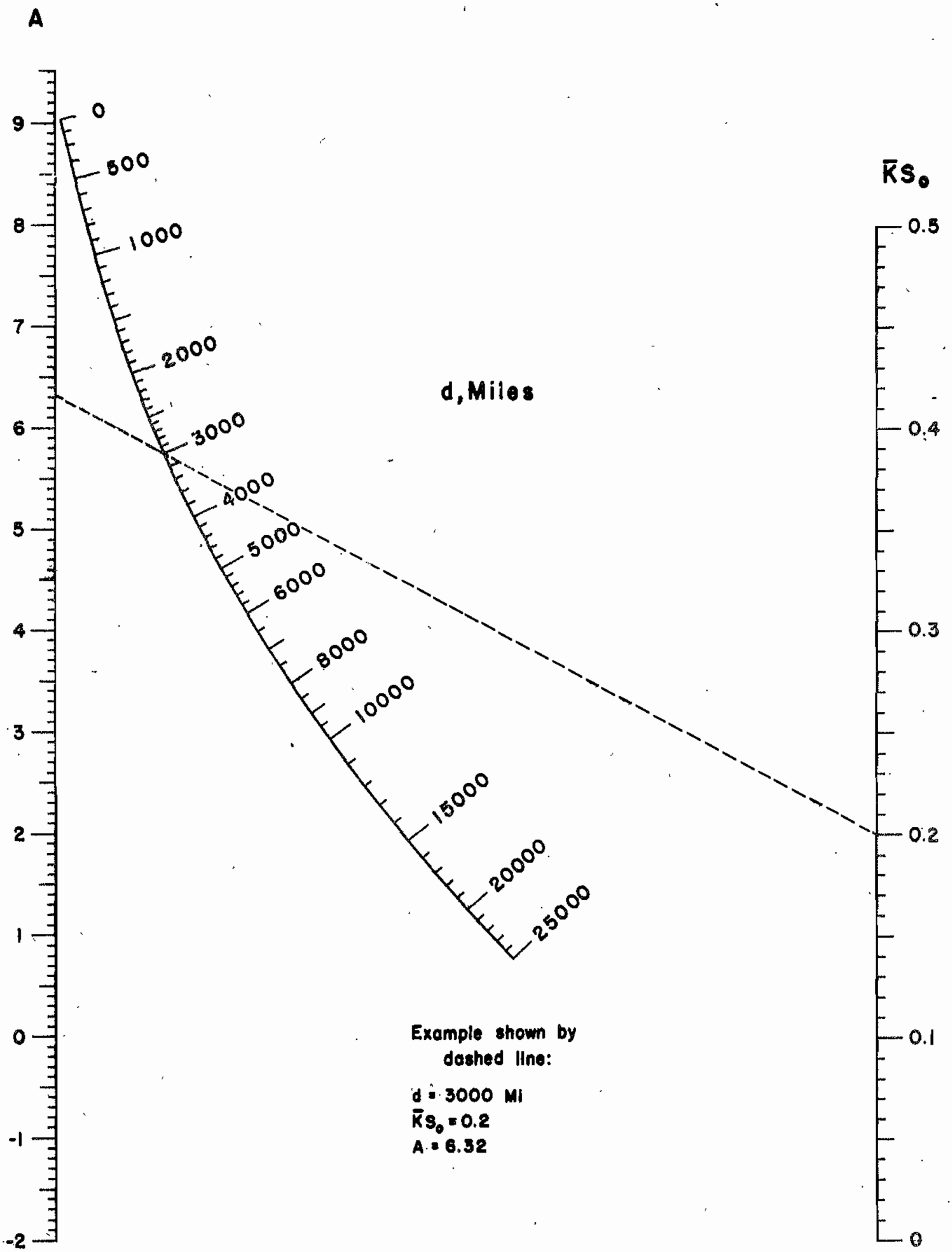
Example shown by dashed line:

d = 800 Mi

$\bar{K}S_o$ = 1.5

A = 7.2

Fig. 107. Nomogram giving relationship of distance range d, values of field-intensity factor A, and absorption, $\bar{K}\,S_o$. (Other ranges of values are given in nomograms, Figs. 106 and 108.) (Distances in miles.)



Example shown by dashed line:

d = 3000 MI
$\bar{K}S_o = 0.2$
A = 6.32

Fig. 108. Nomogram giving relationship of distance range d, values of field-intensity factor A, and absorption, $\bar{K}\ S_o$. (Other ranges of values are given in nomograms, Figs. 106 and 107.) (Distances in miles.)

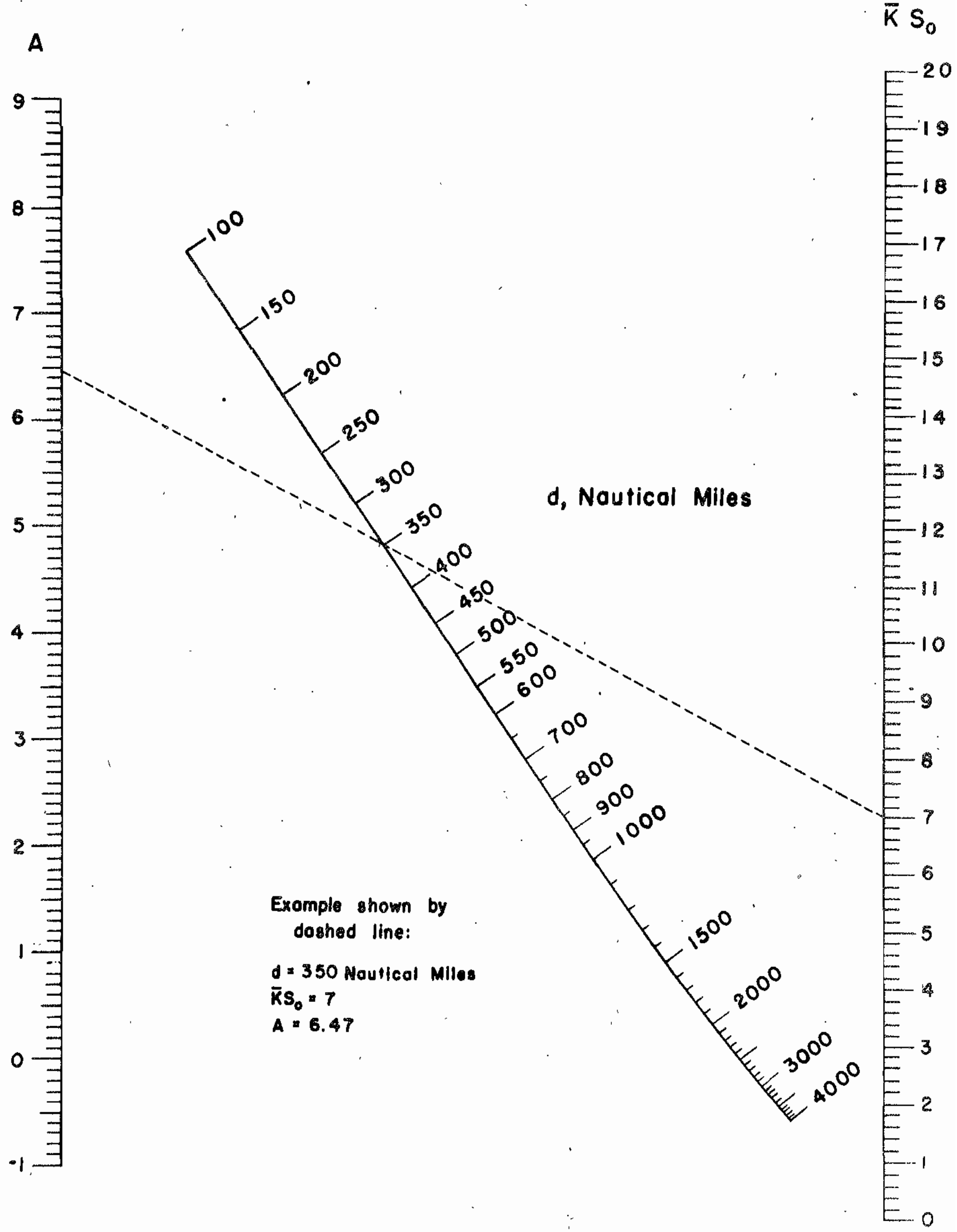
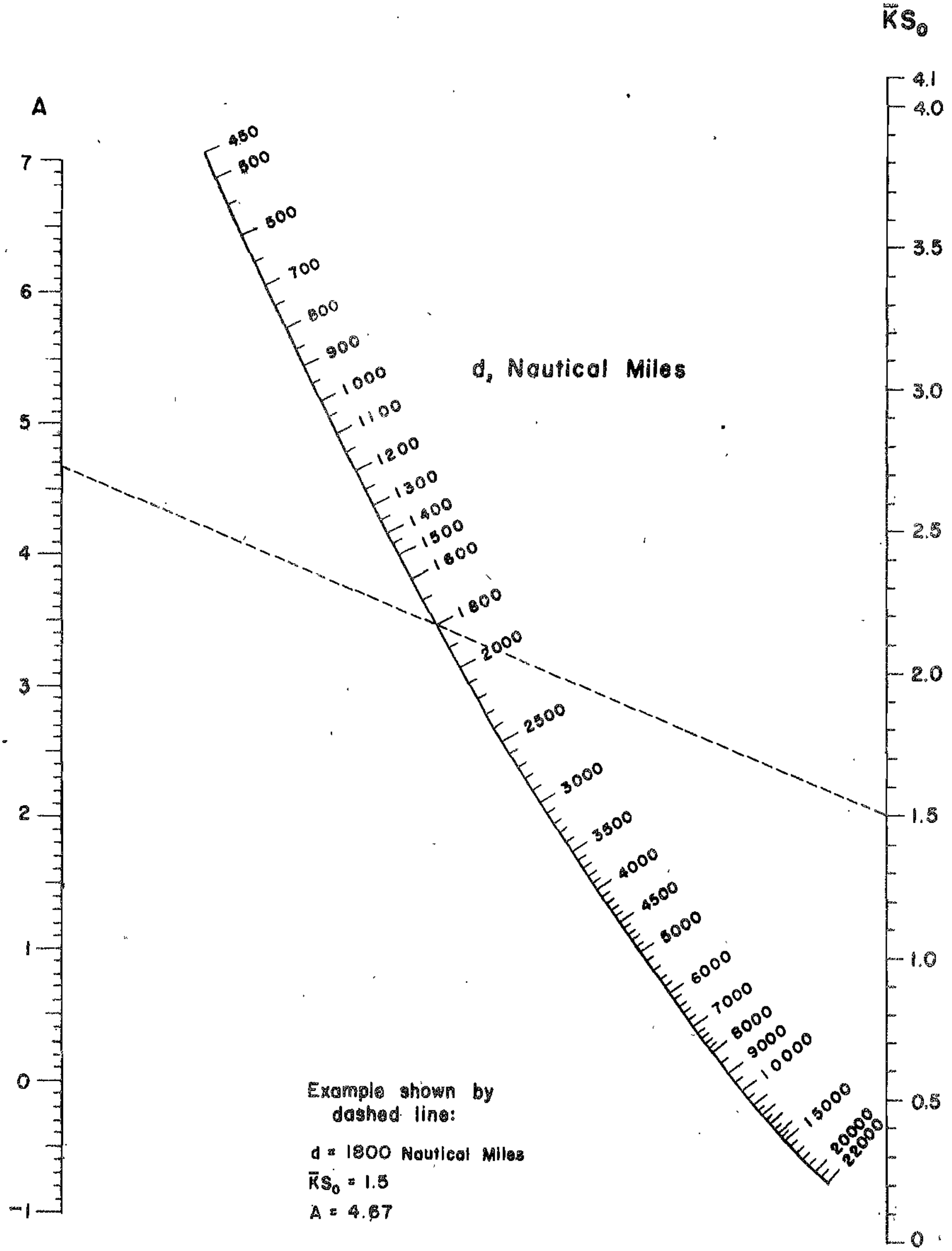


Fig. 109. Nomogram giving relationship of distance range d, values of field-intensity factor A, and absorption, $\bar{K}$ S_0. (Other ranges of values are given in nomograms, Figs. 110 and 111.) (Distances in nautical miles.)



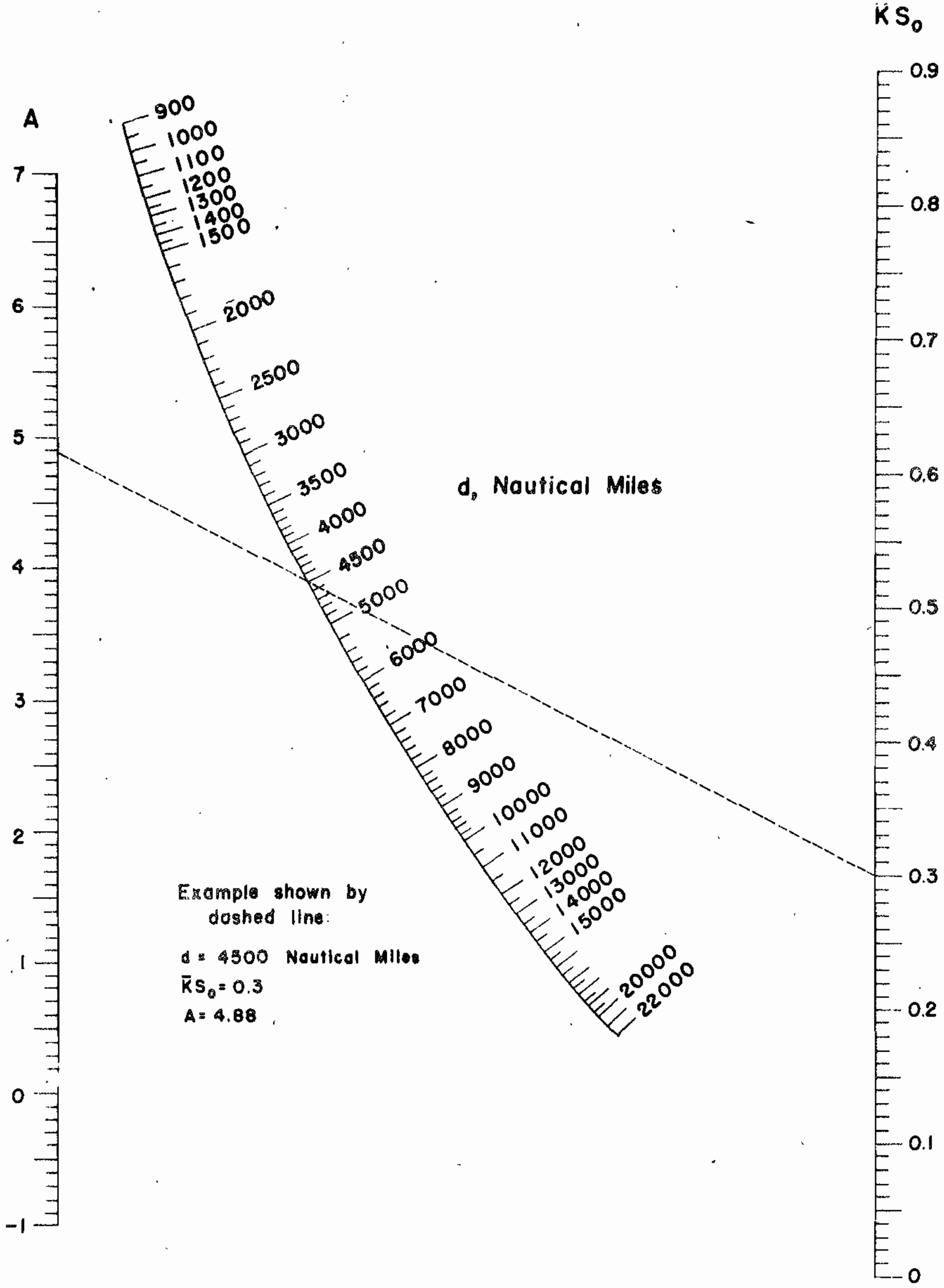
Example shown by dashed line:

d = 1800 Nautical Miles

$\bar{K}S_0 = 1.5$

A = 4.67

Fig. 110. Nomograms giving relationship of distance range d, values of field-intensity factor A, and absorption, $\bar{K}S_0$. (Other ranges of values are given in nomograms, Figs. 109 and 111.) (Distances in nautical miles.)



Example shown by dashed line:

d = 4500 Nautical Miles

$\bar{K}S_0 = 0.3$

A = 4.88

Fig. 111. Nomogram giving relationship of distance range d, values of field-intensity factor A, and absorption, $\bar{K}S_o$. (Other ranges of values are given in nomograms, Figs. 109 and 110.) (Distances in nautical miles.)

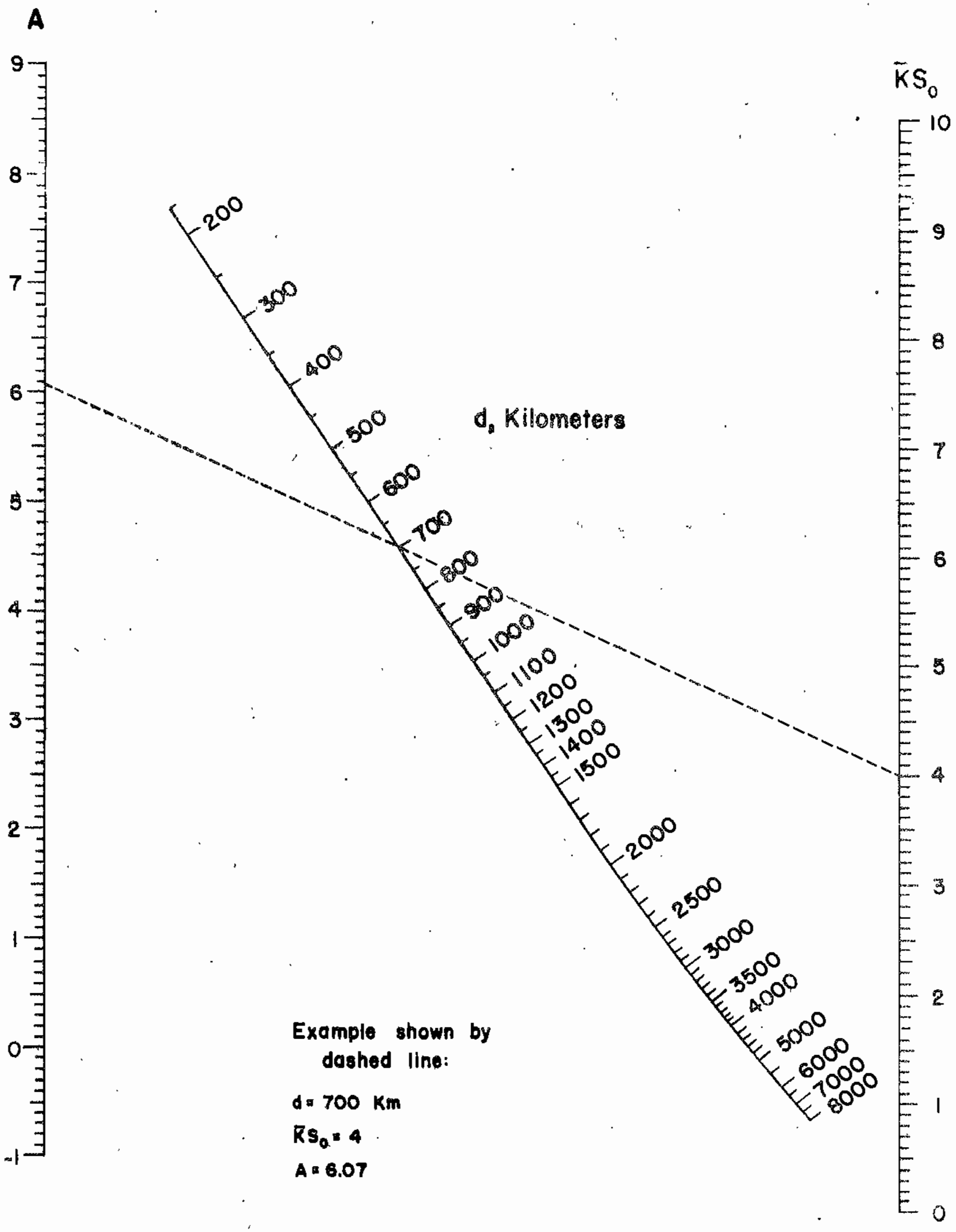


Fig. 112. Nomogram giving relationship of distance range d, values of field-intensity factor A, and absorption, $\bar{K} S_0$. (Other ranges of values are given in nomograms, Figs. 113 and 114.) (Distances in kilometers.)

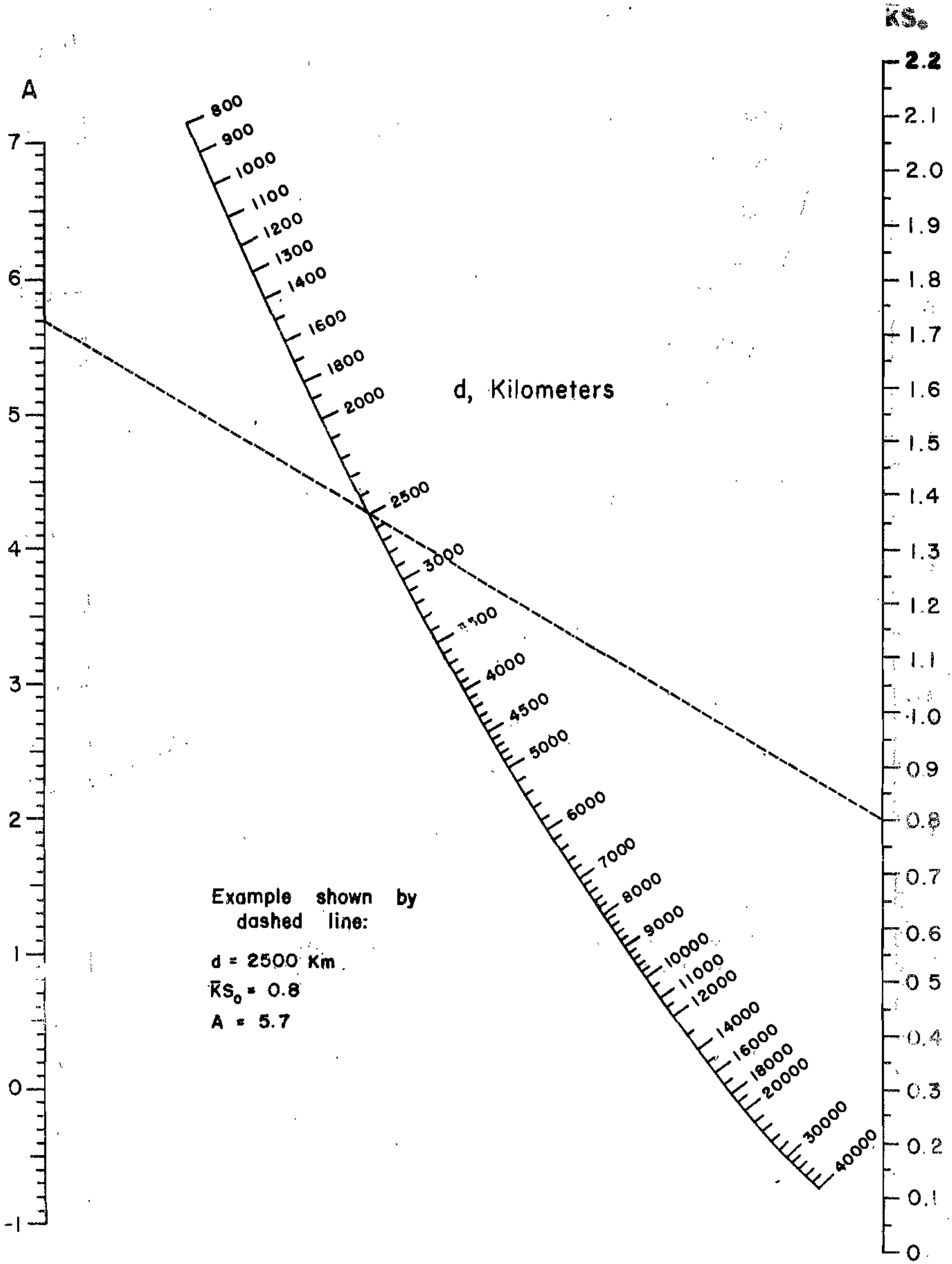


Fig. 113. Nomograms giving relationship of distance range d, values of field-intensity factor A, and absorption, $\overline{K}\,S_o$. (Other ranges of values are given in nomograms, Figs. 112 and 114.) (Distances in kilometers.)

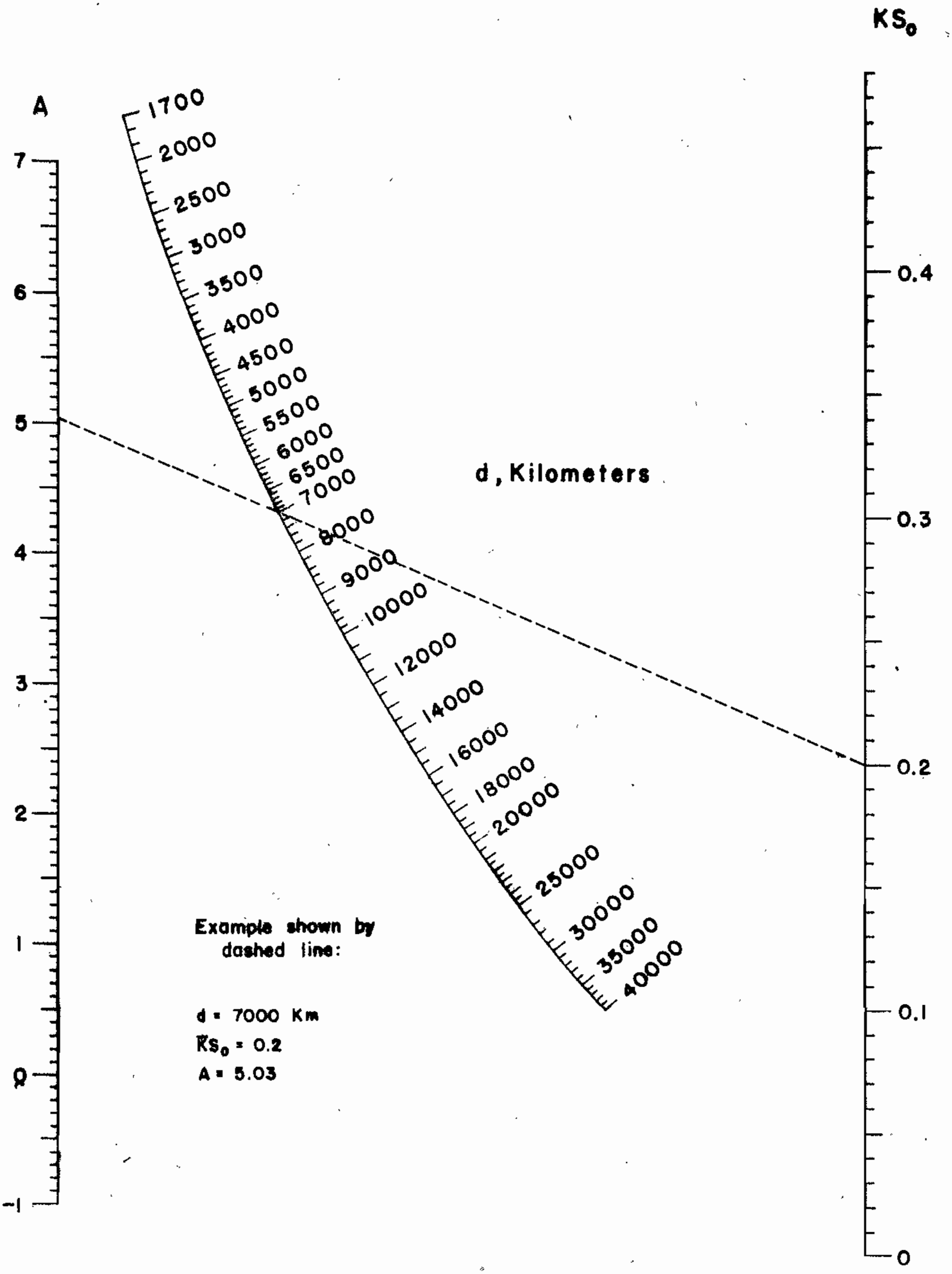


Fig. 114. Nomograms giving relationship of distance range d, values of field-intensity factor A, and absorption, $\bar{K} S_0$. (Other ranges of values are given in nomograms, Figs. 112 and 113.) (Distances in kilometers.)

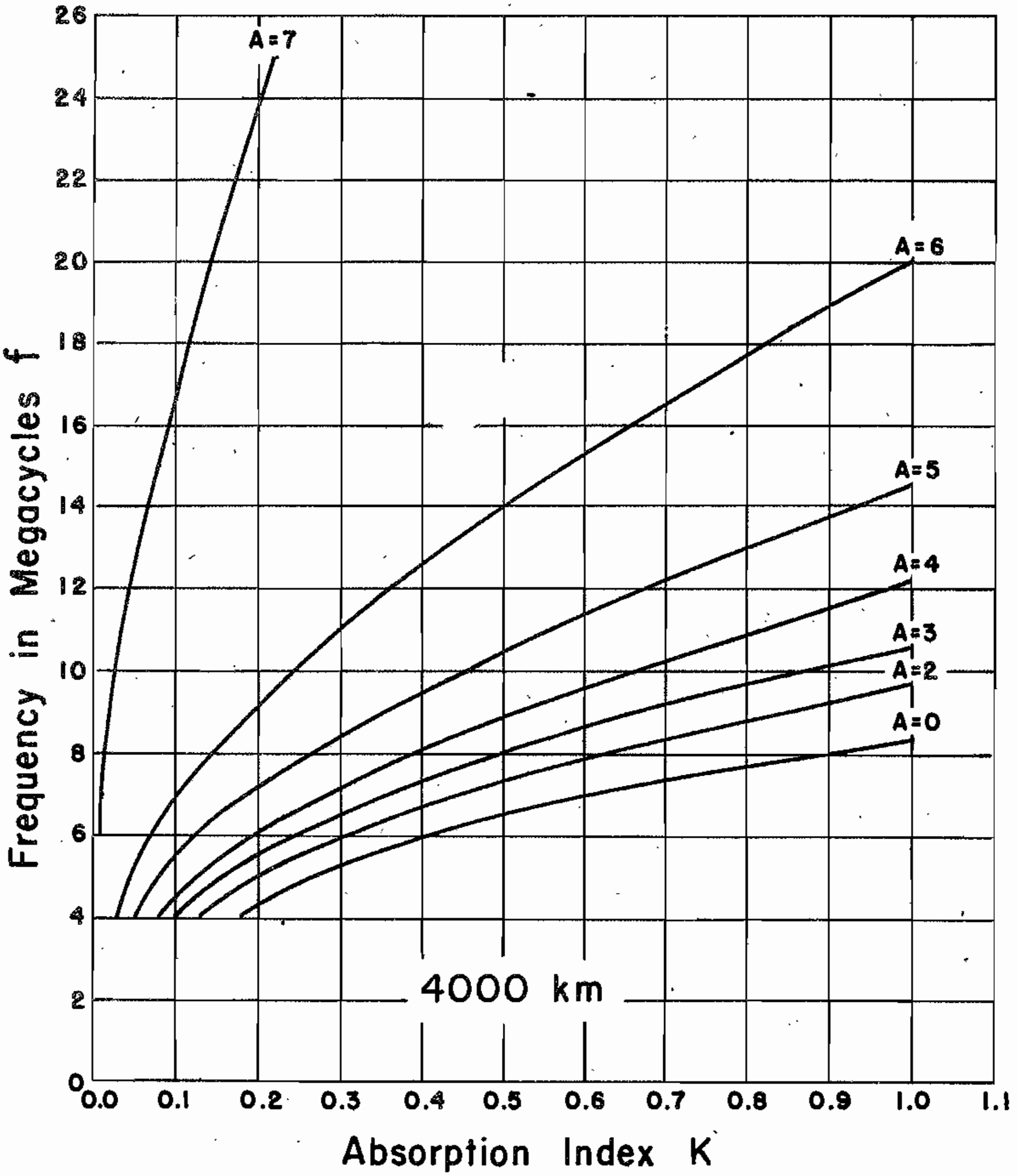


Fig. 115. Relation between average absorption index $\overline{K}$ with frequency f, for various values of field-intensity factor A, for a transmission distance of 4000 kilometers.

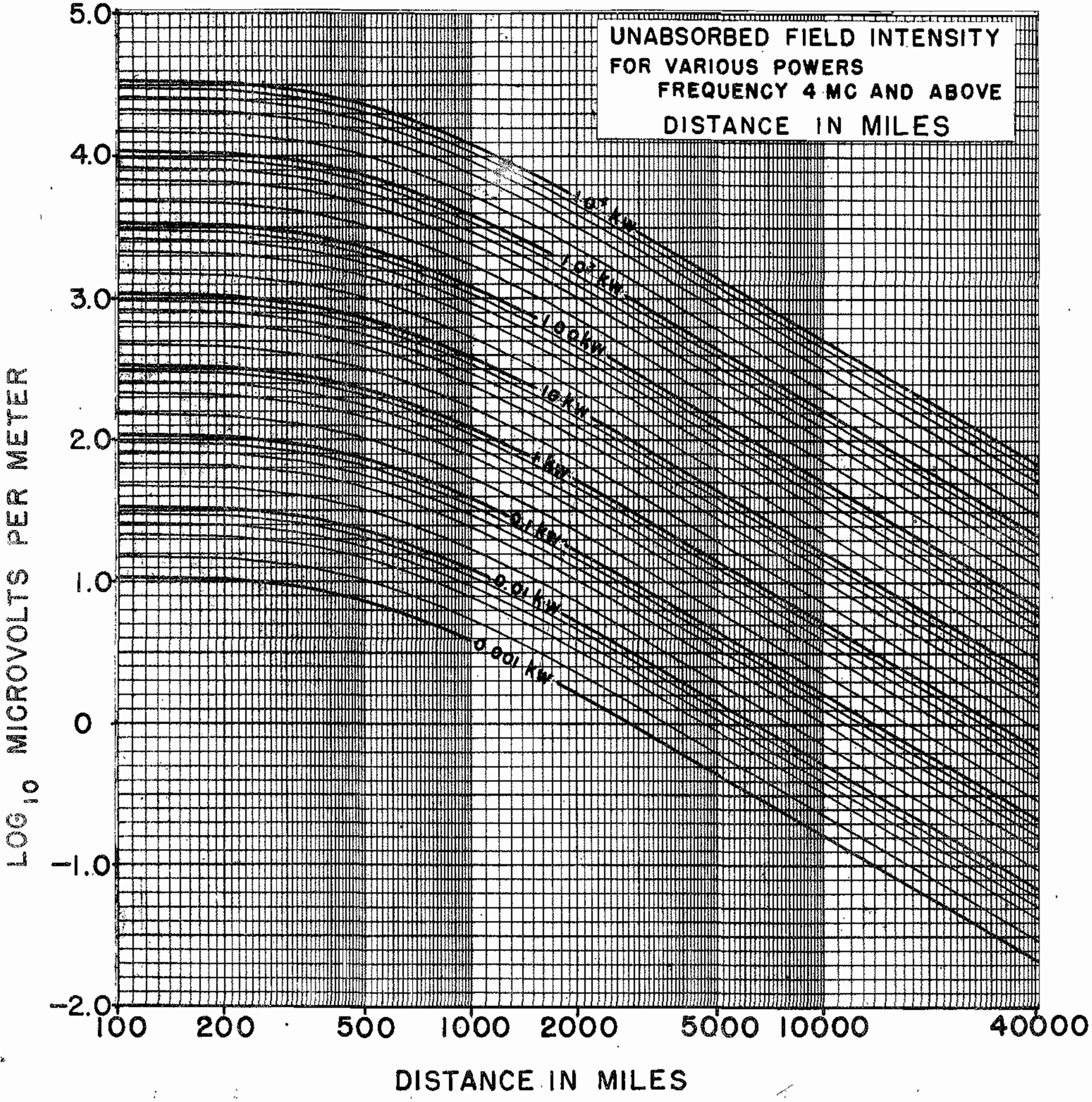
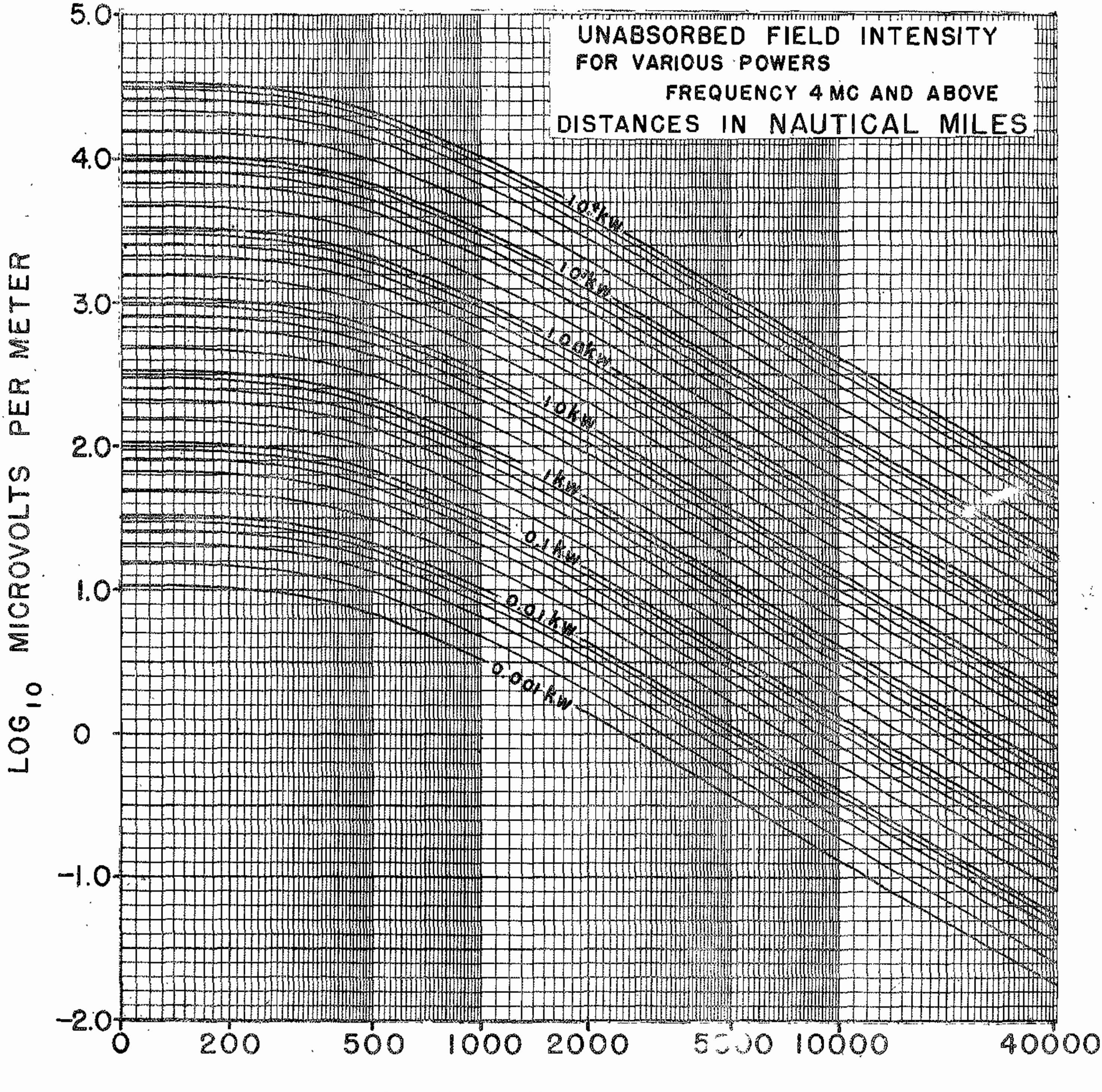


Fig. 116. Logarithm to the base 10 of unabsorbed field-intensity factor F_o, at frequencies above 4 Mc as a function of distance for various values of radiated power. (Distances in miles.)

Fig. 117. Logarithm to the base 10 of unabsorbed field-intensity factor f_o, at frequencies above 4 Mc as a function of distance for various values of radiated power. (Distances in nautical miles.)


UNABSORBED FIELD INTENSITY
FOR VARIOUS POWERS
FREQUENCY 4 MC AND ABOVE
DISTANCES IN NAUTICAL MILES
10^4kw
10^3kw
100kw
10kw
1kw
0.1kw
0.01kw
0.001kw
5.0
4.0
3.0
2.0
1.0
0
-1.0
-2.0
LOG$_{10}$ MICROVOLTS PER METER
0
200
500
1000
2000
5000
10000
40000
DISTANCE IN NAUTICAL MILES

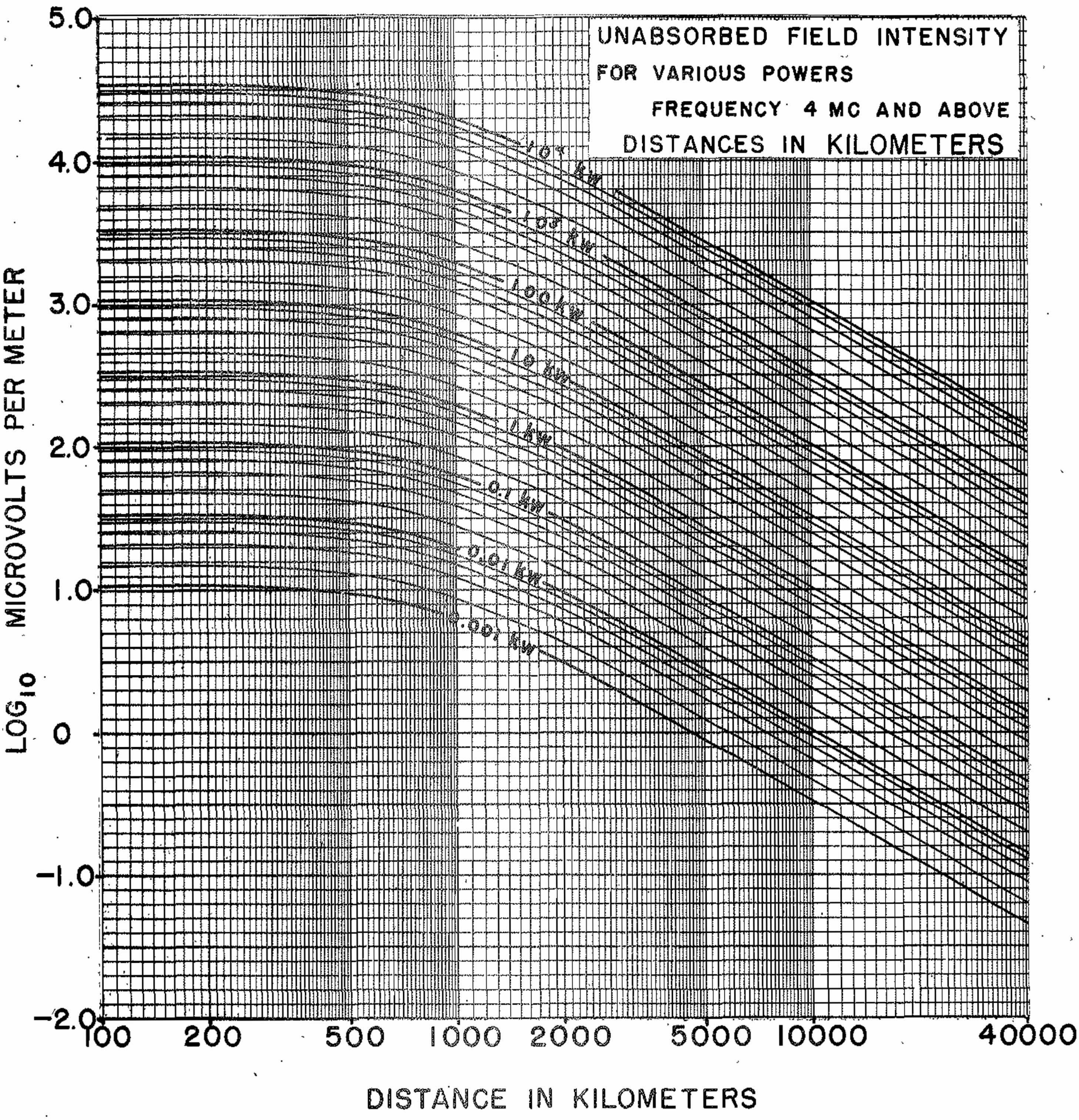


Fig. 118. Logarithm to the base 10 of unabsorbed field-intensity factor F_0, at frequencies above 4 Mc as a function of distance for various values of radiated power. (Distances in kilometers.)

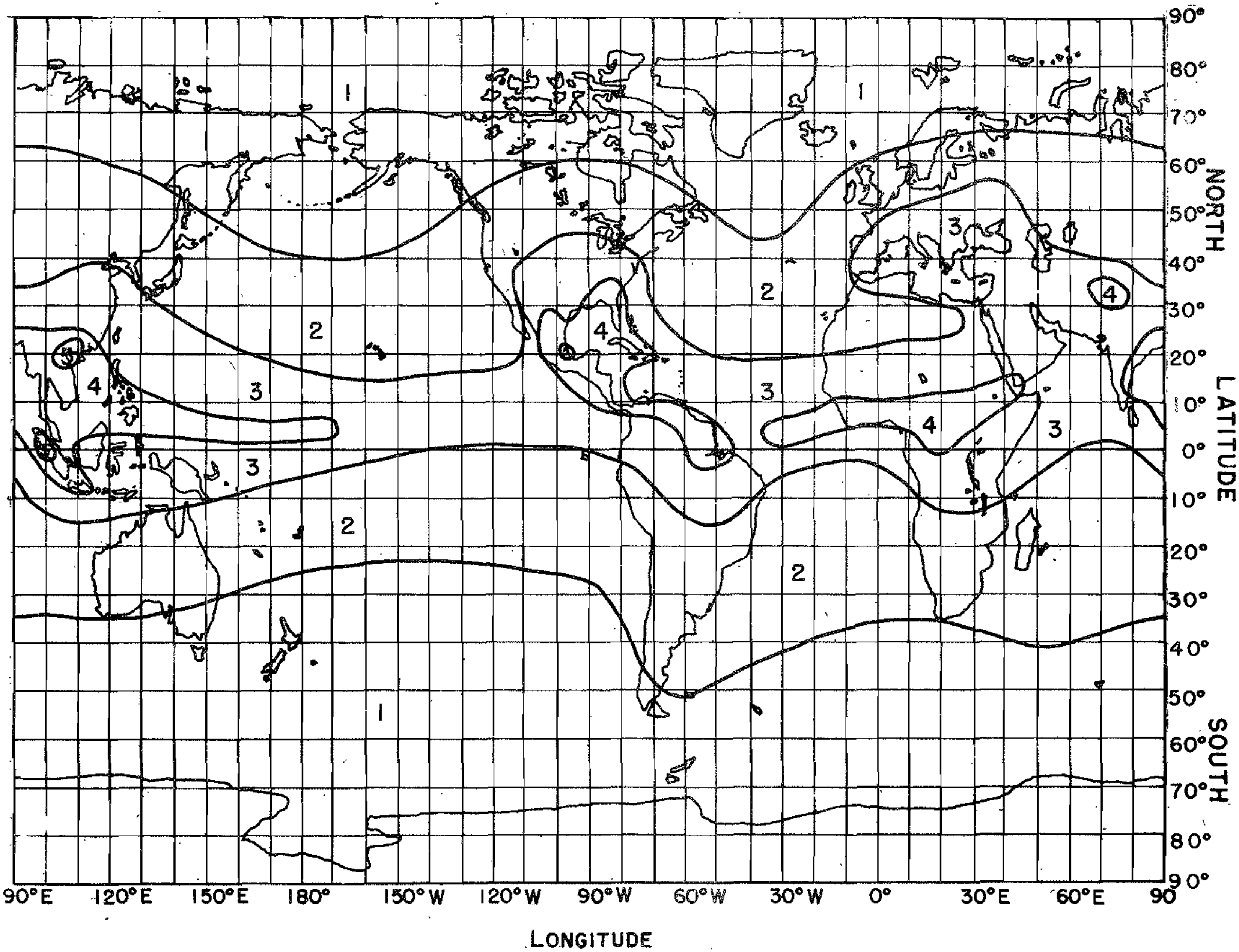


Fig. 119. World map indicating noise zones for the period May through September. Figures in zones give noise grades corresponding to those used in Figs. 121 through 125.

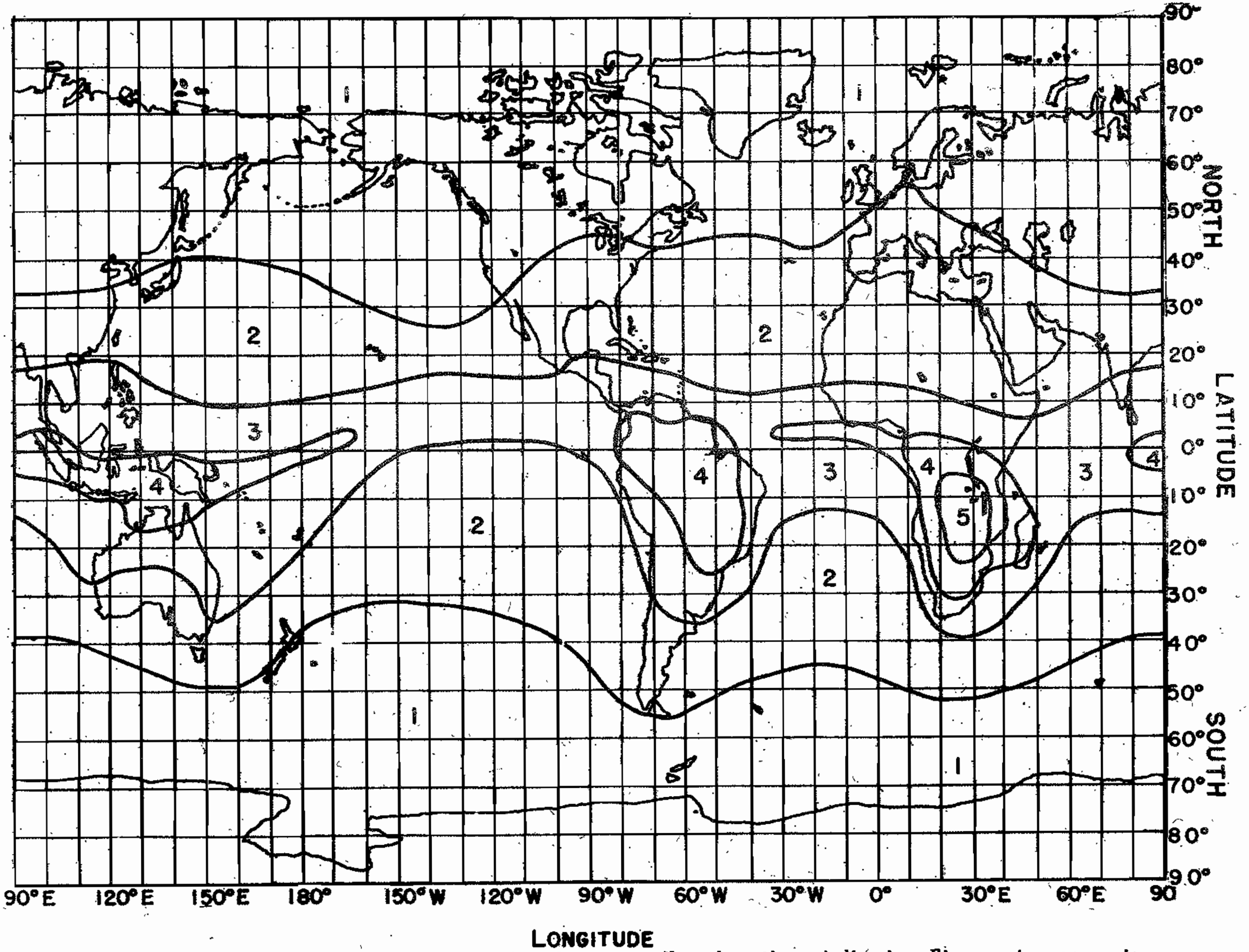


Fig. 120. World map indicating noise zones for the period November through March. Figures in zones give noise grades corresponding to those used in Figs. 121 through 125.

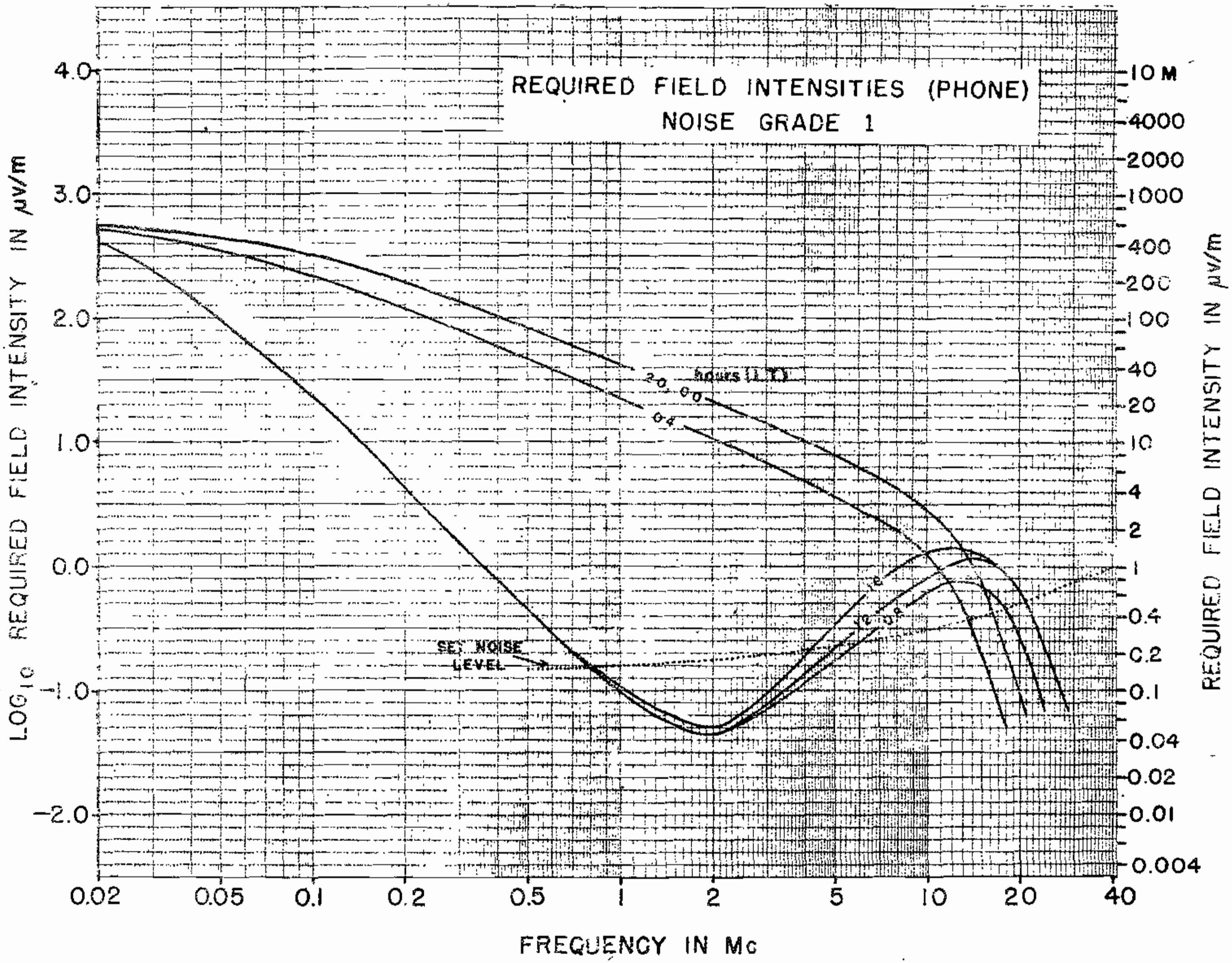


Fig. 121. Logarithms to the base 10 of required field intensities for phone reception for locations in regions of noise grade 1. For CW reception, field intensities required are 0.1 as great, i.e., decrease logarithm by 1. Numbers on curves are local times at receiving station.

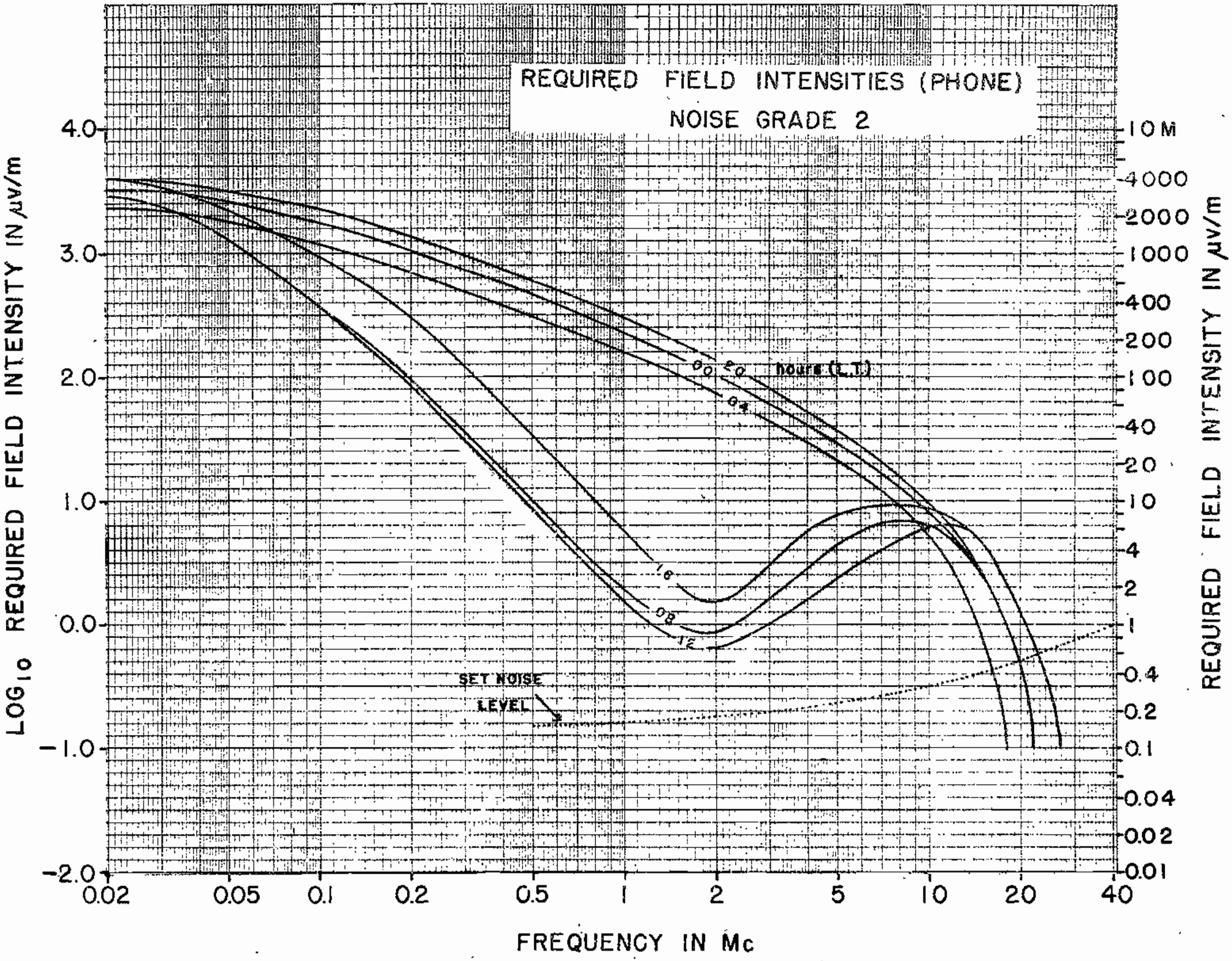


Fig. 122. Logarithms to the base 10 of required field intensities for phone reception for locations in regions of noise grade 2. For CW reception, field intensities required are 0.1 as great, i.e., decrease logarithm by 1. Numbers on curves are local times at receiving station.

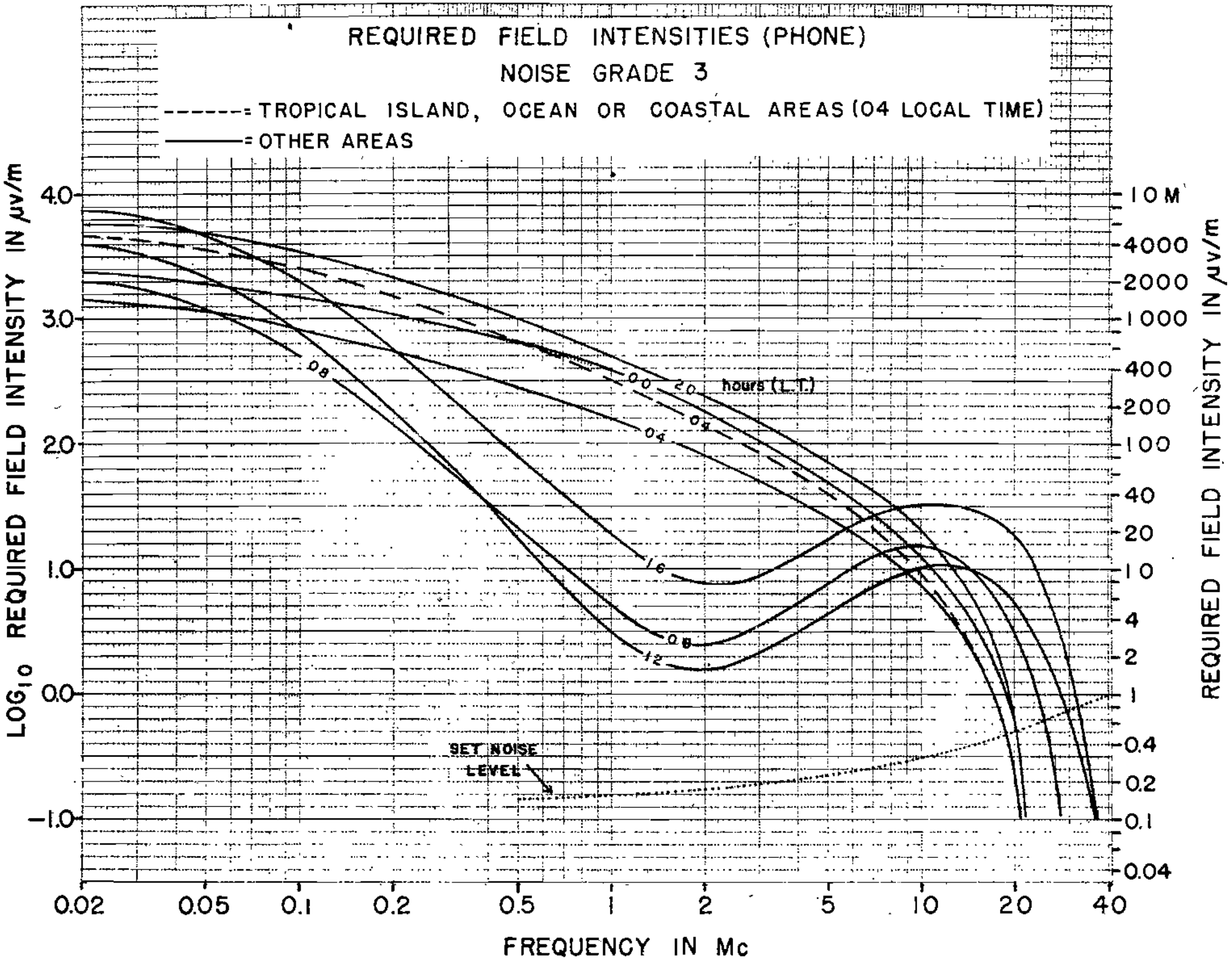


Fig. 123. Logarithms to the base 10 of required field intensities for phone reception for locations in regions of noise grade 3. For CW reception, field intensities required are 0.1 as great, i.e., decrease logarithm by 1. Numbers on curves are local times at receiving station.

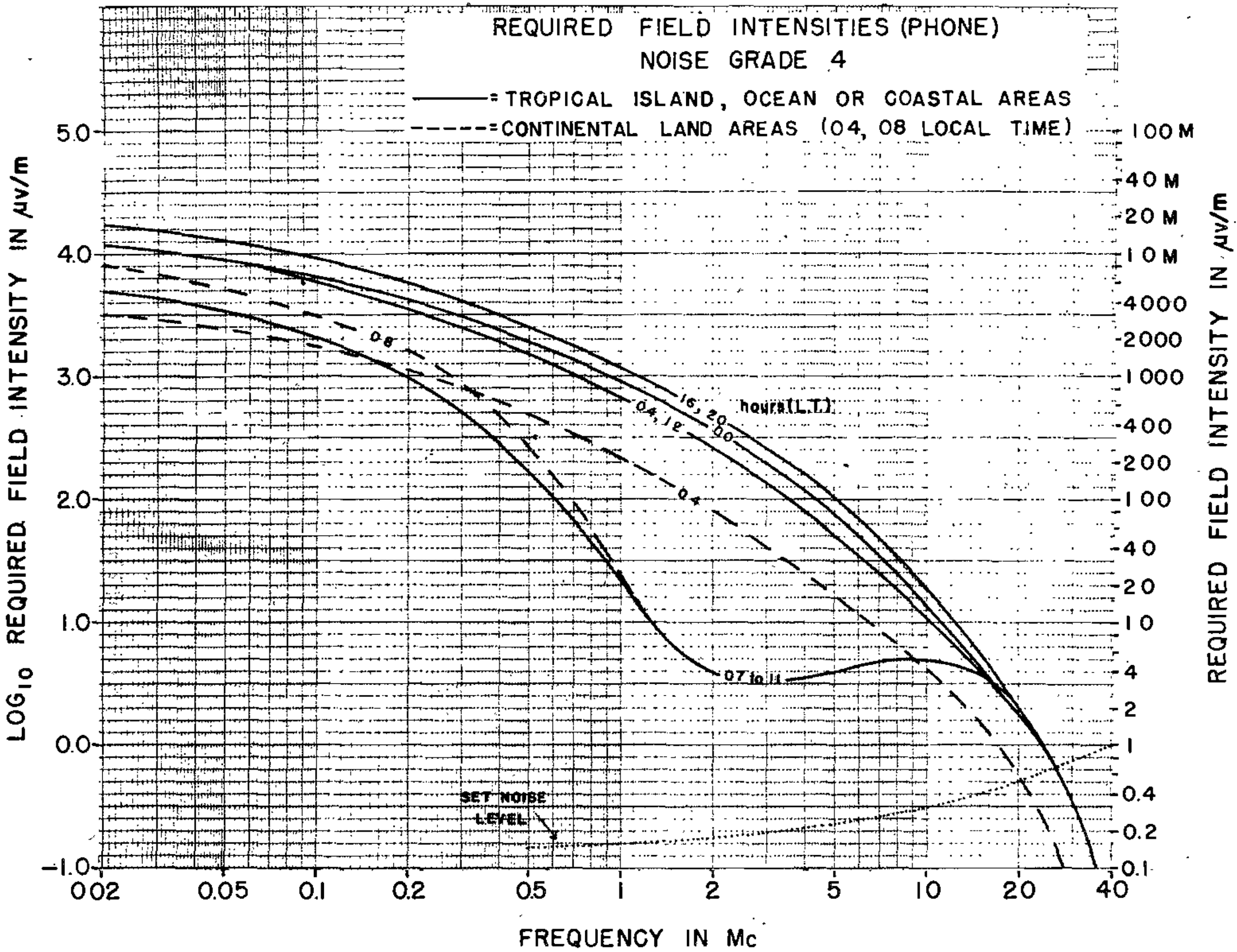


Fig. 124. Logarithms to the base 10 of required field intensities for phone reception for locations in regions of noise grade 4. For CW reception, field intensities required are 0.1 as great, i.e., decrease logarithm by 1. Numbers on curves are local times at receiving station.

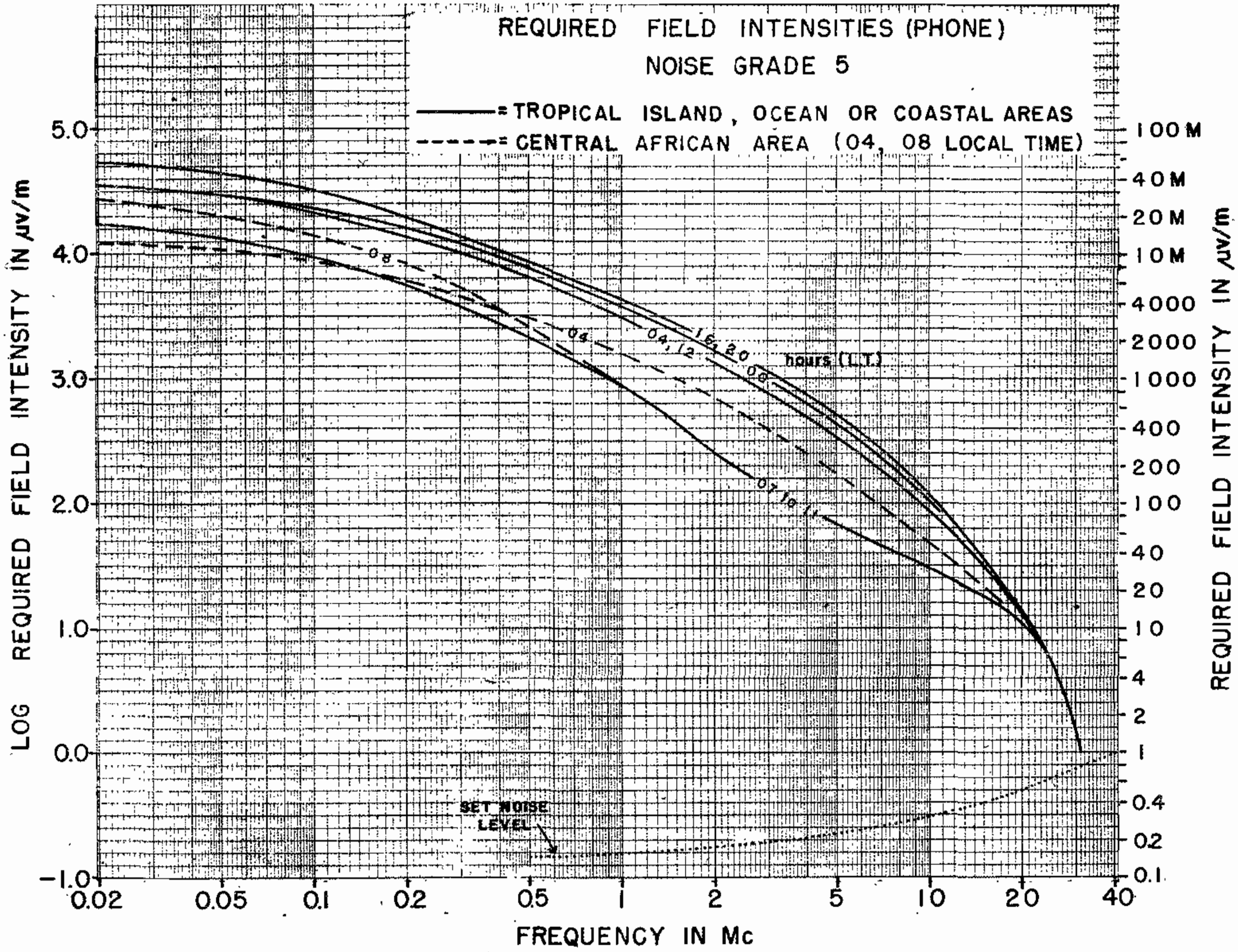


Fig. 125. Logarithms to the base 10 of required field intensities for phone reception for locations in regions of noise grade 4. For CW reception, field intensities required are 0.1 as great, i.e., decrease logarithm by 1. Numbers on curves are local times at receiving station.

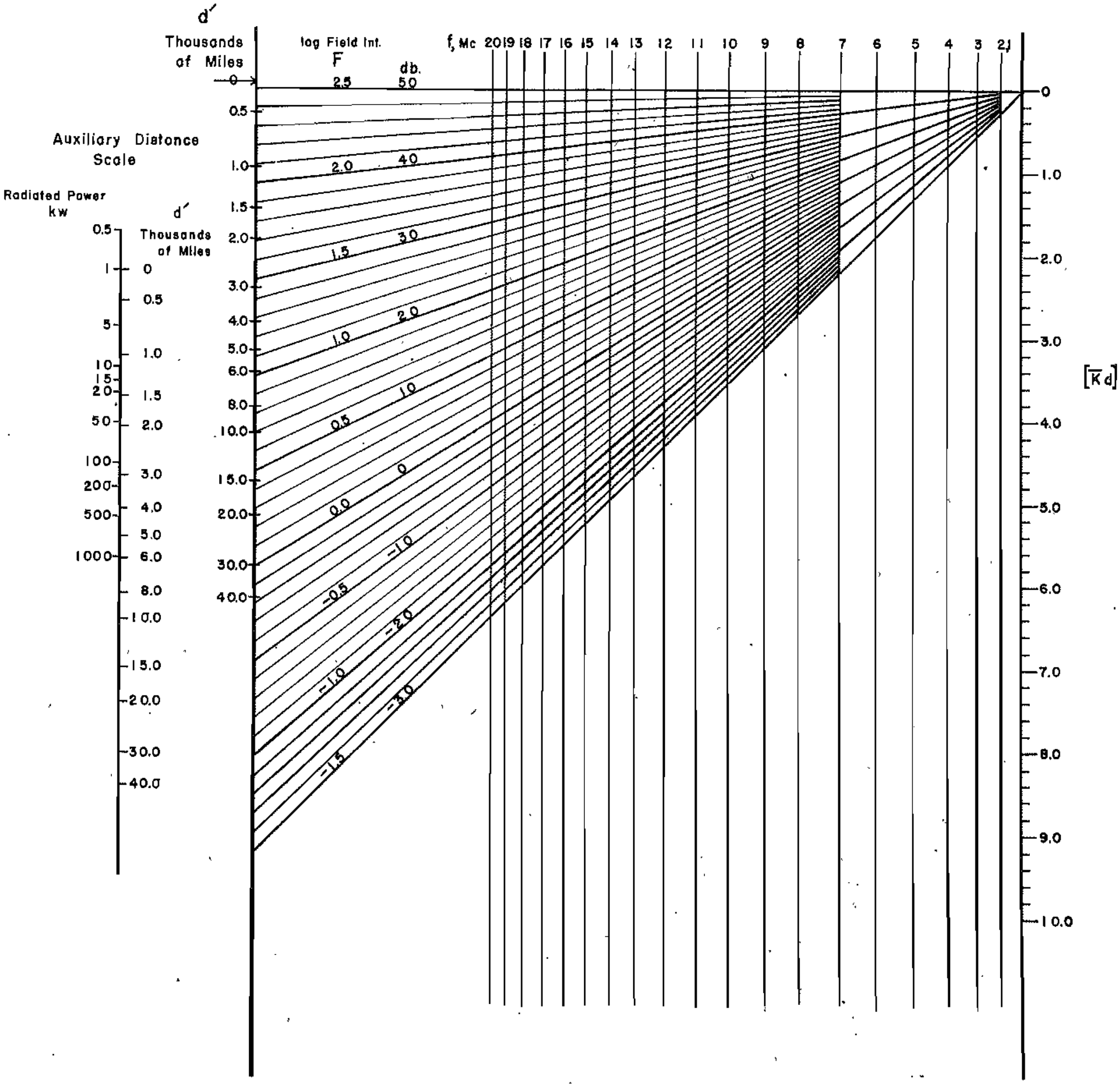


Fig. 126. Master nomogram for plotting arbitrary variations of required field intensity with frequency in order to determine rapidly the l.u.h.f. for various values of $\overline{K}$ d. (Distances in miles.)

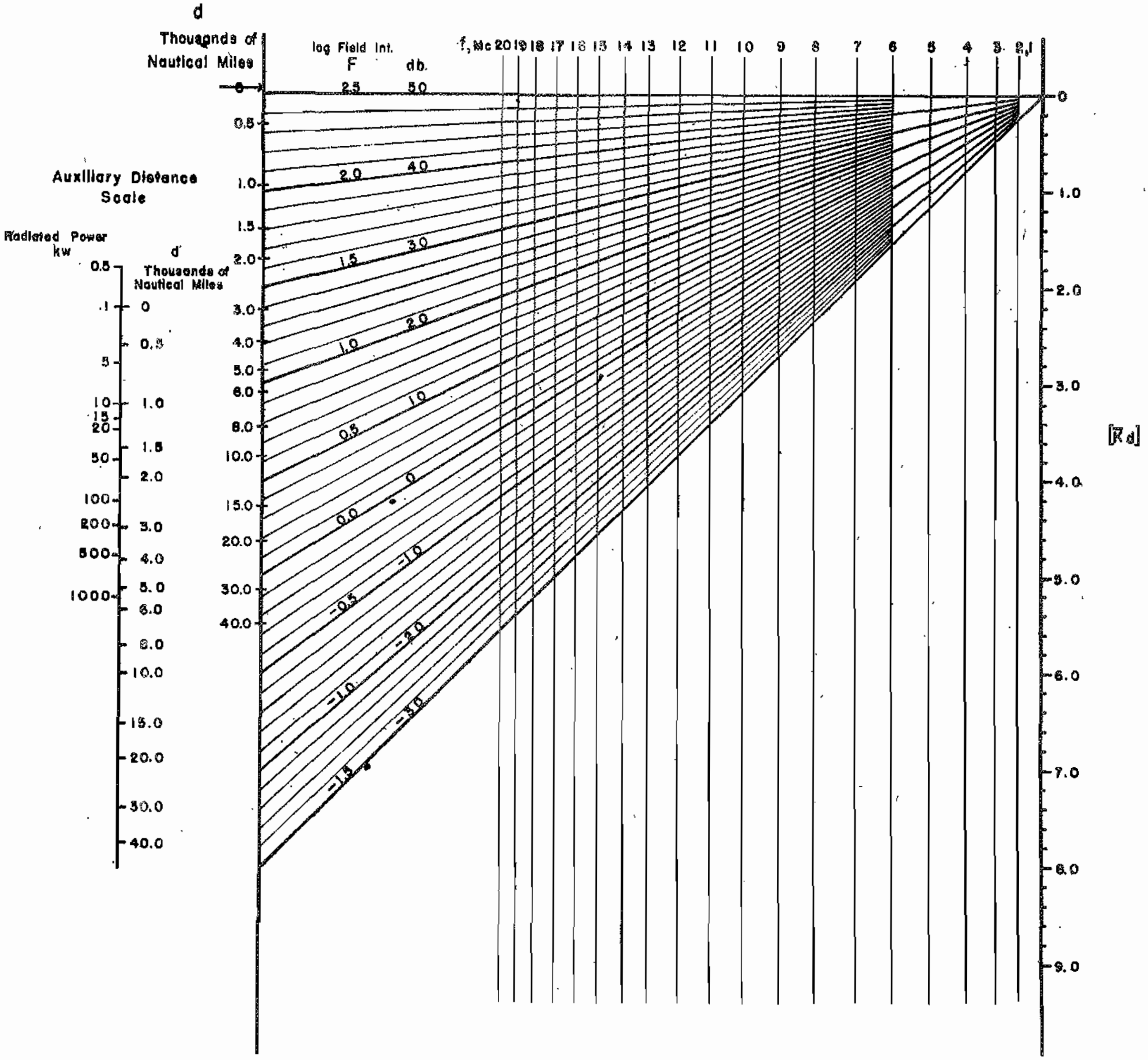


Fig. 127. Master nomogram for plotting arbitrary variations of required field intensity with frequency in order to determine rapidly the l.u.h.f. for various values of $\bar{K}$ d. (Distance in nautical miles.)

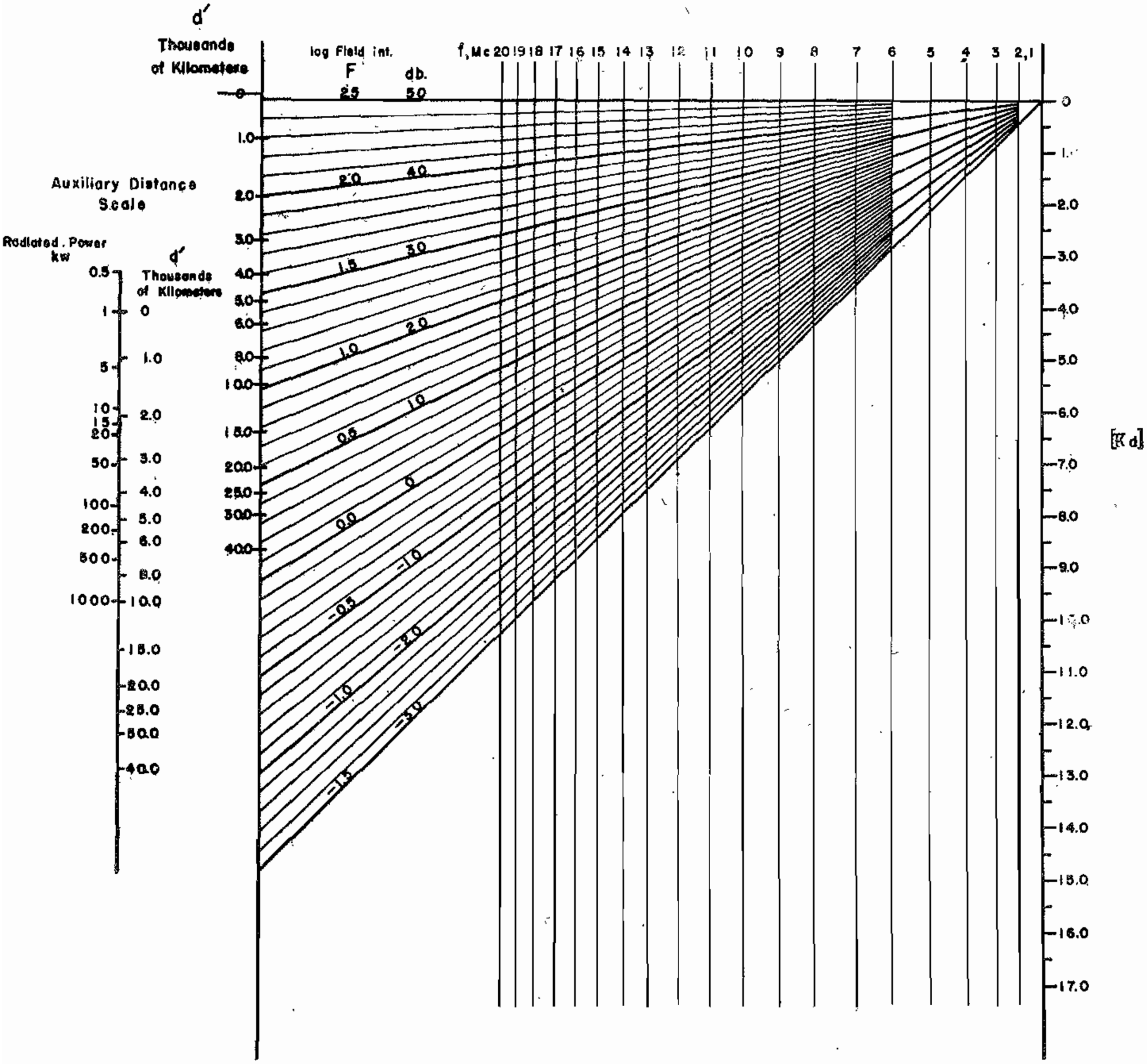


Fig. 128. Master nomogram for plotting arbitrary variations of required field intensity with frequency in order to determine rapidly the l.u.h.f. for various values of $\overline{K}$ d. (Distance in kilometers.)

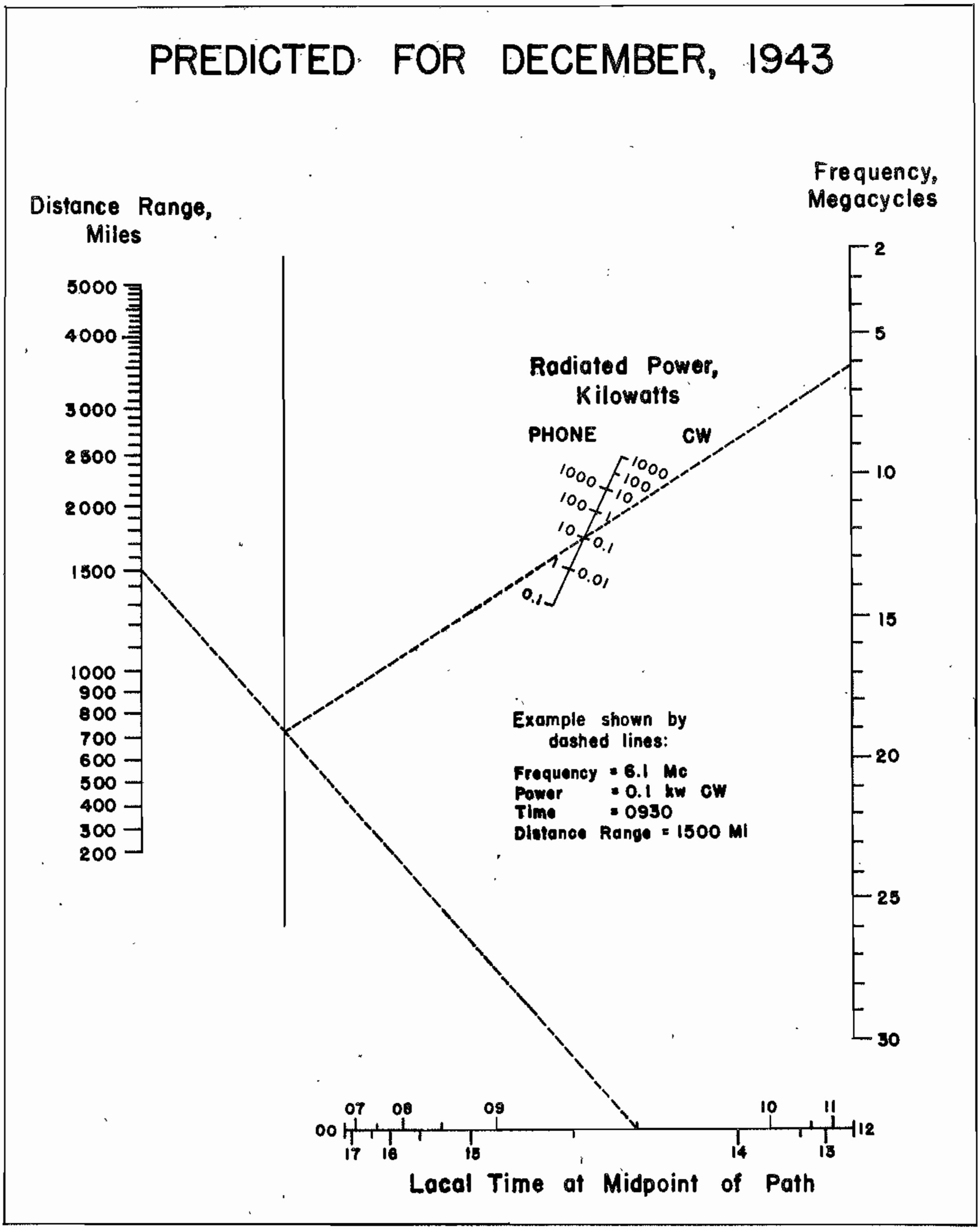
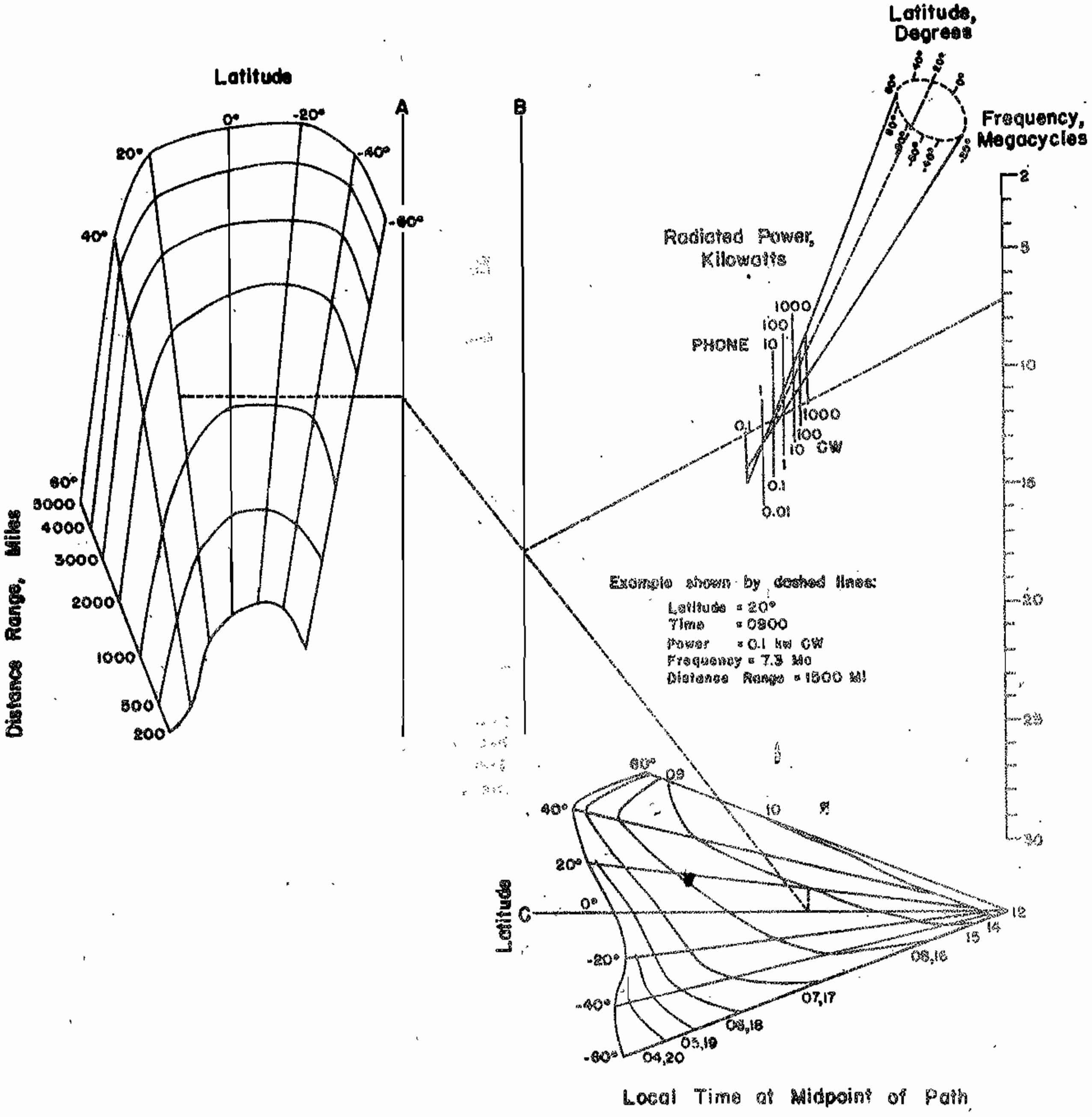


Fig. 129. Nomogram giving distance ranges and lowest useful high frequencies for transmission paths whose midpoints lie between latitude 30°N and 50°N, predicted for December, 1943 (average for quiet days), for transmission by way of the regular ionosphere layers, over or near land.

PREDICTED FOR DECEMBER, 1943



Example shown by dashed lines:

Latitude = 20°
Time = 0900
Power = 0.1 kw CW
Frequency = 7.3 Mc
Distance Range = 1500 Mi

Fig. 130. Nomogram giving distance ranges and lowest useful high frequencies for transmission paths whose midpoints lie between latitude 60°N and 60°S, predicted for December, 1943 (average for quiet days), for transmission by way of the regular ionosphere layers, over or near land.