NAVELEX 0101,103

NAVAL
SHORE ELECTRONICS
CRITERIA

HF RADIO PROPAGATION
AND
FACILITY SITE SELECTION

DEPARTMENT OF THE NAVY
NAVAL ELECTRONIC SYSTEMS COMMAND
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FOREWORD

PURPOSE

This handbook presents planning criteria and judgement factors for engineers and planners involved in the propagation path aspects of high-frequency circuit design.

SCOPE

The role of this handbook is to review some fundamentals concerning HF radio wave propagation, to describe methods of predicting propagation performance for an HF radio circuit, and to discuss factors that should be considered in connection with the selection of sites for HF communications terminals. Major attention is given to ionospheric (sky-wave) propagation since this is the principal application of HF radio. Ground-wave propagation is considered briefly in connection with the problem of using HF radio for short-distance communications.

Since the propagation path is only part of a circuit, it is apparent that this handbook is not intended as a guide for complete circuit planning, user-to-user. Criteria concerning signal processing and associated standards can be found in NAVELEX 0101, 102, and the reader should refer to NAVELEX 0101, 104 for a detailed discussion of HF radio antennas and the trade-offs to be considered in antenna selection.

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CHAPTER 1

INTRODUCTION

1.1 HISTORICAL BACKGROUND

The Navy began using high frequencies for radio communications at about the time of World War I when a few communication systems were operated on frequencies near 3 MHz. In view of the extensive present-day use of high frequencies for long distance communications, it seems curious now that those Navy systems were intended for very short-range communications on the order of a few miles. The general belief at the time was that frequencies above 1.5 MHz were useless for communication purposes. Consequently, it was left to the amateurs to demonstrate that high frequencies were suitable for long-distance communications and to thereby expose the great potentialities of the high-frequency (HF) spectrum.

In spite of some difficulties posed by the propagating medium, the technical simplicity and low cost of HF systems relative to low- and mid-frequency communication systems led to rapid exploitation of the HF band. In this band, ionospheric refraction makes long-distance communication possible with considerably less power and much cheaper antenna systems than are required in the LF and MF bands.

1.2 PROPAGATION DIFFICULTIES

One of the salient features of high-frequency long-distance communication is the variable nature of the propagation medium. Successful transmission of HF signals over long distances is dependent upon refraction (apparent reflection) of radio waves by layers of the ionosphere. The height and density of these layers, formed primarily by ultraviolet radiation from the sun, vary significantly with the time of day, season of the year, and the eleven-year cycle (approximately) of sunspot activity. Because of these variations, it is generally necessary to use more than a single frequency, sometimes up to four or five, to maintain communications on a circuit.

Changes in the characteristics of the ionosphere during the eleven-year solar cycle cause a variation of approximately 2:1 in the portion of the HF band usable for long-distance communication. During periods of high solar activity the entire HF spectrum is usable, but during periods of low solar activity only the lower portion up to approximately 15 MHz can be relied upon for long-distance communication by ionospheric refraction.

At relatively short distances within approximately 300 miles of a transmitter, high-frequency communication becomes difficult because the minimum range for sky-wave propagation is beyond the receiving point while the signal strength of a ground wave may be inadequate for suitable quality reception.

HF radio circuits are prone to fading, and, in particular, to a selective type of fading which results from multiple reflections from the ionosphere, or multipath transmission. They are subject also to interference from atmospheric disturbances and other natural causes, and to interruption from magnetic storms caused by solar flares.

Because high frequencies can be used effectively with relatively low power for long-distance communications, the range of potential interference between stations is also large, and the number of stations that can use the same frequency without mutual interference is limited.

As a result of many years of intensive study, these disturbing effects are now understood well enough so that HF communications can be conducted with a high degree of reliability under all but the most extreme ionospheric conditions.

1.3 SPECTRUM CONGESTION

In spite of the difficulties encountered with HF propagation, the economic and technical advantages of using high frequencies have led to rapid expansion of the use of the HF band. Ultimately, as the number of users increased, use of the HF spectrum approached saturation. In 1950 President Truman cited crowding of the HF band as being the most pressing communication problem of the times. In 1964 the Joint Technical Advisory Committee of the IEEE and the Electronic Industries Association suggested that this band appears to be heading toward chaos as world requirements are expected to continue to exceed, at an increasing rate, the limited supply of usable frequencies. (ref. 1)

The HF band is shared by many users, both foreign and domestic, and only portions scattered throughout the band are allocated to the military services. In common with other agencies, Navy requirements have grown so as to severely tax the capacity of the Navy's assigned portion of the HF spectrum. The use of single-sideband equipment and the application of independent sideband techniques have increased the capacity, but not enough to catch up with the demand. Some predict that satellite communication will eventually relieve congestion in the HF band and that, for some types of service, it will replace HF for long-distance communications. Nevertheless, it appears that the HF spectrum will continue to be in high demand for some time to come.

1.4 TYPICAL NAVY HF COMMUNICATION SYSTEMS

Naval communications within the HF band can be grouped into four general types of services: point-to-point, ship-to-shore, ground-to-air, and fleet broadcast. Some of these services involve ships and aircraft which present special problems because of their physical characteristics and mobility. Generally, the less than optimum HF performance of these mobile terminals is at least partially offset by powerful transmitters and sensitive receiving systems at the shore terminals.

1.4.1 Point-to-Point Communications

Point-to-point systems are those established to communicate over long-distance trunks or links between fixed terminals. Generally, sufficient real estate is acquired at the terminals to permit the use of large, high-gain antennas aimed at opposite terminals of each link. This increases the effective radiated power and the sensitivity of the receiving system, and it also reduces susceptibility of a circuit to interference. With the path length and direction fixed, accommodation of the other propagation variables is simplified and highly reliable communications can be achieved.

Within the Defense Communications System (DCS), the standard bandwidth, 12 kHz, for each operating frequency is divided into four 3-kHz channels so that each channel can contain information different from the others. One is generally used as a voice frequency carrier telegraph channel (VFCT) which can accommodate sixteen teletype circuits. The others can be used for facsimile, voice, orderwire or other forms of data transmission. Navy point-to-point circuits that do not interface with the DCS are not constrained to the DCS standard bandwidth and channel alignment. Therefore, the bandwidths indicated in the emission designations given in JANAP 195 are used for these Navy circuits. (A table of these emission designators is included in NAVELEX 0101, 102 and a more detailed discussion is contained in ref. 21.)

1.4.2 Ship-to-Shore Communications

This application of the HF band is more difficult than the point-to-point case since one terminal, the ship, is mobile. In this case the path length and direction are variable. At the ship terminal the limited space and other restrictions prohibit installation of large, efficient HF antennas, and, because of the mobility of ships, shipboard antennas are designed to be as nearly omnidirectional as possible.

The constraints are not as severe at the shore terminal where there is sufficient space for more efficient omnidirectional antennas or arrays designed for area coverage. Moreover, at the shore terminal, a rotatable, high-gain antenna, or one of the fixed point-to-point antennas may be used under appropriate circumstances. For example, a rhombic antenna may serve admirably for long-haul ship-to-shore communications when the ship is at a distance such that its operating area is within the coverage of the antenna at that distance.

Several frequencies are usually assigned for each circuit so that the best frequency can be chosen for the propagation path conditions between the shore terminal and the ship's location. The length of the path, among other things, determines whether sky-wave or ground-wave propagation will be effective for the link. Ships relatively close to shore usually depend upon the ground wave for communication with the shore terminal. Alternatively, high-angle sky-wave propagation can be used for communications within the skip distance; however, the probability of ionospheric support at high angles is relatively low.

1.4.3 Ground-to-Air Communications

The application of HF radio to communications between the ground and airborne aircraft is similar to the ship-to-shore case except the aircraft terminal changes position much more rapidly than does a ship. Transmitter power and antenna restrictions imposed by the airframe design limit the effectiveness of the airborne HF radio terminal so that all major circuit improvements must be made by the application of suitable techniques at the ground terminal. For example, higher-powered transmitters, lower-noise receiving installations, and more efficient antennas can be used on the ground. HF antenna considerations for ground-to-air communications are discussed in NAVELEX 0101, 104 — "HF Radio Antenna Systems."

1.4.4 Fleet Broadcasts

As the name implies, this type of service involves broadcast area coverage from shore-based transmitters to ships at sea. Messages addressed to a ship in a designated broadcast area are delivered by various means to the appropriate fleet broadcast station where they are broadcast for pickup by the ships. To overcome the propagation difficulties discussed earlier, the same information is broadcast simultaneously on several frequencies. That is, most fleet broadcasts are frequency-diversity transmissions. This gives flexibility for the receiving terminal to choose the best frequency for the path conditions at the time.

1.5 PLANNING CRITERIA

Most Navy point-to-point circuits are included in the DCS and, therefore, must be designed to satisfy the requirements imposed by the Defense Communications Agency (DCA) which prescribes engineering standards for the point-to-point circuits of the DCS. Since the DCA standards apply principally to circuit quality requirements over which control can be exercised only within the terminals of a circuit, these standards are discussed in NAVELEX 0101, 102 — "Naval Communications Station Design." Other than to prescribe a signal-to-noise ratio of 32 dB (for all types of service) and to specify the use of certain sunspot numbers for making propagation predictions, the DCA standards do not state circuit quality standards for the propagation path.

The Navy's ship-to-shore, ground-to-air, and fleet broadcast applications of HF radio are not directly controlled by the DCA standards since these circuits are not a part of the DCS. The interface between these services and the DCS does, however, come under control of the DCA, as does any circuit entering the DCS.

Although some HF system components aboard a mobile terminal, such as a ship or aircraft, may be comparable in performance to those ashore, other limitations force acceptance of mobile terminal performance that often is marginal at best. For effective two-way communications between a shore terminal and a mobile terminal, both the transmitting and receiving systems ashore should be superior to those aboard ships and aircraft. Generally, overall circuit performance can be improved by installing efficient antennas at low-noise-level sites ashore.

1.5.1 Navy Planning Documentation

Of the three basic types of documents used by NAVELEX for planning and controlling shore station electronic installation work, two are applicable to the propagation aspects of communications station design. The Communications Operating Requirements (COR), promulgated by OPNAV, states the functional requirements in terms of circuits and pertinent characteristics of each circuit. A Base Electronic System Engineering Plan (BESEP), developed by NAVELEX, translates the operational requirements of the COR into a detailed technical plan for meeting those requirements. The third type of planning document, NAVELEX Standard Plans, is not applicable to the radio propagation requirements of a circuit. Instead, reliance must be placed on propagation predictions for the types and grades of service required.

1.5.2 HF Radio Propagation Analysis

To bound the content of this handbook, the approach has been taken that the reader will be involved only in those aspects of planning directly related to high-frequency radio pro agation. It is assumed that others will be responsible for equipment selection and installation engineering at the terminals.

In most cases some form of feasibility determination has been made before the requirement for a high-frequency circuit is stated. Generally, experience alone is sufficient to establish whether an HF circuit is feasible for the type of communication service needed. So, rather than being overly concerned with determining the feasibility, the planner is interested primarily in achieving optimum long-term performance over the propagation path. Nevertheless, his work will either confirm the feasibility of the HF circuit or it will provide data concerning circuit limitations imposed by the propagation path.

The propagation aspects of HF radio circuit design involve (1) an estimate of long-term propagation conditions for a given path, (2) a determination of system characteristics (transmitter power, antenna design, etc.) necessary for reliable communications within a range of variable propagation conditions, and (3) the selection of terminal sites that favor HF radio transmission and reception. The bulk of this handbook is devoted to discussion of these three topics.

CHAPTER 2

IONOSPHERIC PROPAGATION

2.1 INTRODUCTION

Long-distance transmission in the HF band depends entirely upon refraction of radio waves by the ionosphere, a region in the upper atmosphere where free electrons are produced by the ionizing effect of ultraviolet light and soft x-rays from the sun. Under favorable conditions, a radio wave reaching the ionosphere will be bent earthward and may return to earth at a great distance from the transmitter.

Radio waves that follow such a path through the ionosphere and back to earth are known as sky waves and are often spoken of as being reflected by the ionosphere. Although this concept of the mechanics of sky-wave propagation is practical in terms of the end result, the dominant physical phenomenon is refraction, not reflection. The electron density varies gradually, rather than abruptly, with height, and this causes radio waves to follow curved paths through the ionosphere instead of being reflected in a manner analogous to reflection of light from a mirror.

Since many of the complexities of ionospheric propagation have no practical role in long term circuit planning, a comprehensive treatment of the subject is not attempted here. Rather, this discussion is intended as background or refresher material to foster understanding of the prediction procedures described later in this chapter. Reference 2 is an excellent text for those who wish to pursue the subject in greater depth.

2.2 STRUCTURE OF THE IONOSPHERE

Ionization density in the ionosphere tends to peak at various heights above the earth as a result of differences in the physical properties of the atmosphere at different heights. The levels at which the electron density reaches a maximum are termed layers and these are identified as the D, E, F1 and F2 layers in order of increasing height and ionization density. The relative distribution of these layers above the earth is shown in figure 2-1. The number of layers, their heights, and their ionization (electron) density vary both geographically and with time.

2.2.1 D Layer

The D layer lies between heights of about 30 and 55 miles above the earth, and absorption in this layer is the principal cause of the daytime attenuation of high-frequency sky waves. The D layer exists only in the daylight hours and its ionization density correlates with the elevation angle of the sun. Compared to the other layers at higher altitudes the electron density is relatively low, but the free electrons are excited by the presence of an electromagnetic wave, and pronounced energy losses occur because of collisions between the electrons and the molecules of the atmosphere. The refractive index is so near unity that little or no bending of radio waves takes place.

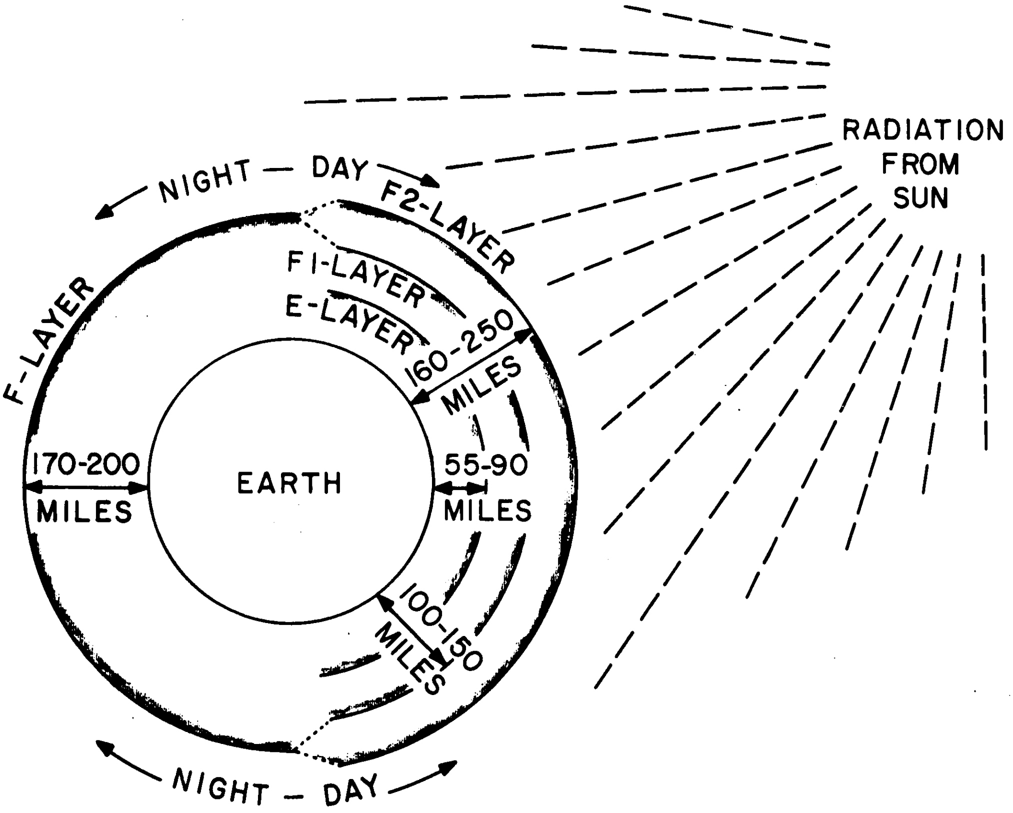


Figure 2-1. Distribution of Layers in the Ionosphere

2.2.2 E Layer

The E layer, the second layer in order of height, exists between 55 and 90 miles above the earth's surface with maximum density relatively constant at about 70 miles. This layer is sometimes called the Kennelly-Heaviside region, after the names of the men who first proposed its existence. The variations of this layer are regular and quite predictable. The intensity of ionization follows the sun's altitude closely, reaching a maximum about noon, and fading to such a weak level during the night as to be practically useless as an aid to HF radio communication. The density of electrons in the E layer is usually great enough to refract to earth radio waves at frequencies as high as 20 MHz. The height of this layer and its refractive properties make it important for HF daytime propagation at distances less than approximately 1200 miles. Longer distance transmission via the E layer is usually impractical because of the low layer height and correspondingly low vertical angle of departure of the transmitted wave. With this geometry, multiple reflections between the E layer and the earth's surface are required for long distance transmission, and a wave following such a path suffers pronounced absorption during its travel through both the D and E layers.

2.2.3 F Region

For HF radio communications, the F region is the most important part of the ionosphere. Long-term studies of the structure of the F region by remote probing techniques show conclusively the existence of two distinct layers, called the F1 and F2 layers. These two merge at night into a single F layer at a height of 170 to 200 miles. During the day the F1 layer has a lower limit of approximately 100 miles, while the F2 layer has a lower limit of about 160 to 250 miles depending upon the season of the year and the time of the day.

a. F1 Layer. The F1 layer has not been as well defined as the F2 layer in terms of its predictable characteristics. This layer occasionally is the refracting region for HF transmission, but usually oblique-incidence waves that penetrate the E layer also penetrate the F1 layer and are bent earthward by the F2 layer. The principal effect of the F1 layer is to introduce additional absorption of such waves.

b. F2 Layer. The F2 layer is by far the most important layer for HF radio communications, and, unfortunately, it is also the most variable. It is the most highly ionized of all the layers and its height and ionization density vary diurnally, seasonally and over the 11-year sunspot cycle. The degree of ionization does not follow the altitude of the sun in any simple fashion but it generally peaks in the afternnon and decreases gradually throughout the night. The absence of the F1 layer at night, and reduction in absorption in the E layer, cause nighttime signal intensities (and noise) to be generally higher than they are during daylight hours.

2.3 SKY-WAVE PROPAGATION

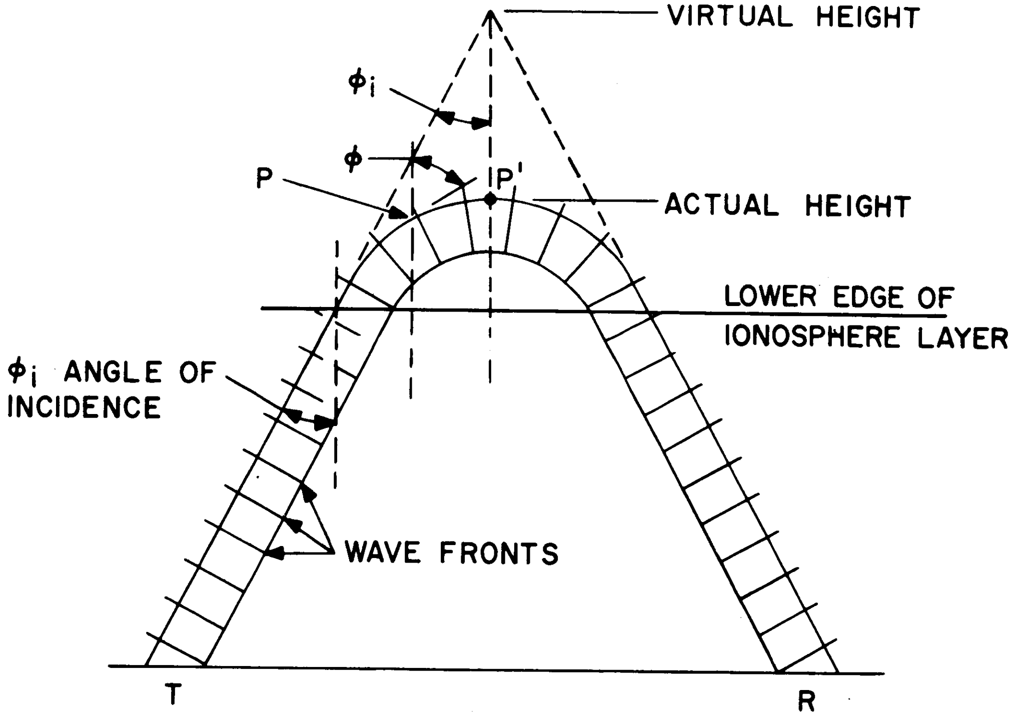
2.3.1 Refraction of Radio Waves

A radio wave traveling through the ionosphere obeys ordinary optical laws and, consequently, follows a curved path. Free electrons in the ionosphere reduce the refractive index below that of the atmosphere so that the path of a radio wave bends away from regions of high electron density toward regions of lower electron density. The refractive index is related to electron density by the following expression:

$$n = \sqrt{1 - \frac{81N}{f^2}} \qquad (2\text{-}1)$$

where n = refractive index
N = number of electrons per cc
f = frequency, kHz

It is apparent from equation (2-1) that the refractive index is not a constant, but rather a variable depending upon the frequency of the wave and the change of electron density through the ionosphere. Since, for a given ionospheric layer, the electron density increases with height to a maximum and then decreases, the refractive index decreases with height to a minimum and then increases. Consequently, since the phase velocity of a radio wave is inversely proportional to the refractive index, the part of the wavefront at a height of low refractive index travels faster than the portion of the wavefront at a height of higher refractive index. This causes the wave path to bend as shown in figure 2-2.



LEGEND:

ϕ = ANGLE OF REFRACTION AT ANY POINT P
ϕ_i = ANGLE OF INCIDENCE AT THE LOWER EDGE OF THE IONOSPHERE
P' = TOP OF THE PATH WHERE O = 90°

Figure 2-2. Refraction of a Radio Wave

This bending of a radio-wave path caused by the ionosphere depends also upon the angle of incidence according to Snell's law,

$$n \sin \phi = \sin \phi_i \qquad (2\text{-}2)$$

where n = refractive index of any point P (figure 2-2)
ϕ = angle of refraction of any point P
ϕ_i = angle of incidence at the lower edge of the ionosphere

Equations (2-1) and (2-2) indicate that the path of a wave through the ionosphere is determined by the frequency of the incident wave, its angle of incidence and the refractive index.

For a given frequency, the smaller the angle of incidence (the more nearly vertical the wave) the lower the refractive index (the higher the electron density) required to return the wave to earth. For a given angle of incidence, the higher the frequency, the deeper will be the penetration of the wave into the ionosphere. That is, the higher the frequency, the greater the electron density required to refract the wave earthward.

At the top of the path, point P' in figure 2-2, where $\emptyset = 90°$, equation 2-2 becomes

$$n = \sin\emptyset_i \tag{2-3}$$

The relationship of equation (203) must be satisfied if a wave reaching the ionosphere is to be returned to earth. If the refractive index is too great to satisfy this relationship for the frequency and angle of incidence involved, the wave path will not be curved sufficiently to return to earth.

2.3.2 Critical Frequency, MUF, FOT

Depending on the electron density at each layer, there is a highest frequency, termed the critical frequency, at which the layer returns a vertically incident wave. At vertical incidence, $\emptyset_i = 0$ in equation 2-3, and, therefore, for a vertically incident wave to be returned to earth, the electron density at some point in a layer must be sufficient to reduce the refractive index to zero. The critical frequency for a layer is the frequency for which this point of zero refractive index is reached at the height of the maximum electron density of the layer. If the maximum electron density is too low for a given frequency, the radio wave will pass on through the layer.

Waves of critical and lower frequencies will be reflected from the layer regardless of the angle of incidence. Waves of a frequency higher than the critical frequency will be reflected at oblique incidence only if the angle of incidence is large enough to satisfy equation (2-3) at the frequency involved. The highest frequency that can be propagated in this way over a given path between specified terminals is called the maximum usable frequency (MUF).

The MUF will vary as ionospheric conditions over the path change. In particular, the highly variable characteristics of the F2 layer cause the F2-layer MUF to vary appreciably from the values given by propagation prediction services. Predictions of MUF are made for the monthly median value, the value equaled or exceeded 50 percent of the days during the month at a specified time of day. Consequently, the MUF is not a practical operating frequency for propagation via the F2 layer. A lower frequency, 0.85 times the MUF, is taken as a practical value that will be equaled or exceeded 90 percent of the days during the month. This frequency has been called the optimum working frequency or optimum traffic frequency and is abbreviated FOT. (The international abbreviation, FOT, is formed from the initial letters of the French words for optimum working frequency, "Frequence Optimum de Travail.") This 85 percent limit provides some margin for ionospheric irregularities as well as for day-to-day deviations from the monthly median MUF.

The day-to-day variations of the E-layer MUF and the F1-layer MUF can be considered negligible for operational use. Because of the stability of the E and F1 layers, no adjustment is made such as that above and the monthly median MUF is used as the FOT for these layers.

2.3.3 Ray Paths and Skip Distance

Figure 2-3 illustrates the effect of the ionosphere on the path of a radio wave of a given frequency as the angle of incidence is varied. When the angle of incidence is relatively large (ray 1), the propagation path is long and the wave is returned to earth after only

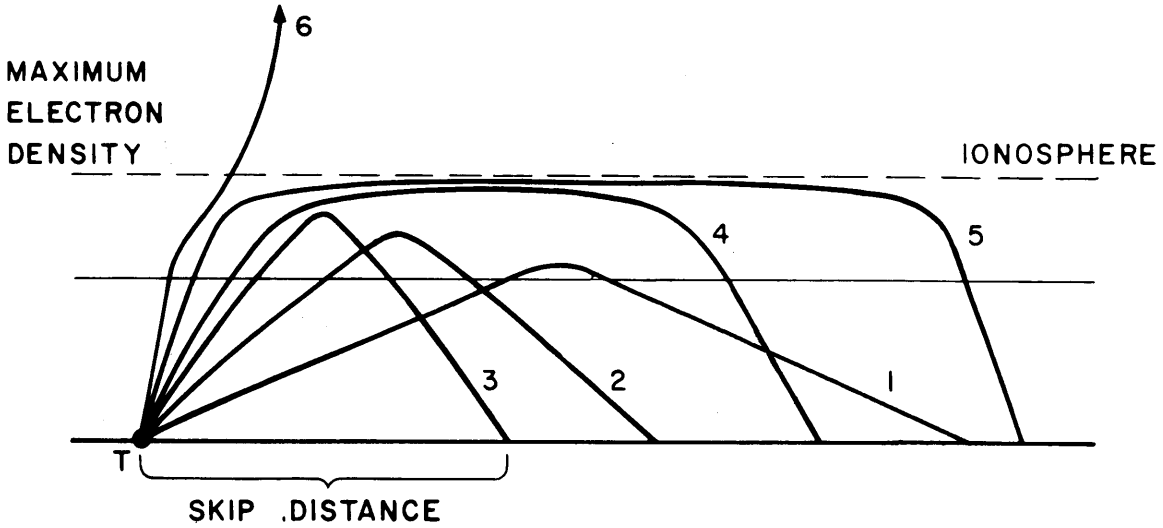


Figure 2-3. Ray Paths for a Fixed Frequency with Varying Angles of Incidence

slight penetration of the layer. As the angle of incidence decreases (rays 2 and 3), penetration into the layer increases and the ground range decreases until an angle of incidence is reached at which the distance is a minimum (ray 3). This minimum distance, called the skip distance, represents the minimum distance from the transmitter at which a sky wave of a given frequency will be returned to earth by the ionosphere. As the angle of incidence is decreased further, the ground range at first increases (rays 4 and 5) and then, eventually, the wave penetrates the layer (ray 6).

The upper, or Pedersen rays, rays 4 and 5 in figure 2-3, are usually not of great practical importance since the field intensity at the ground receiving point is considerably lower than is the case with the lower rays, rays 1, 2 and 3.

2.3.4 Multipath Transmission

A particular propagation path may be pictured as consisting of one or more hops, or successive reflections between the ionosphere and ground. Often more than one path is possible for a given operating frequency and distance. Rays may reach a receiver via two different paths through one layer (an upper and a lower ray), via paths involving two or more layers, via paths corresponding to different numbers of hops, or by combinations of multiple-hop and multiple-layer propagation.

The case of propagation of a radio wave by two layers is illustrated in figure 2-4. For this example, the frequency of the wave is assumed to be such that the E-layer ionization density is sufficient to refract earthward the energy arriving at a large angle of incidence (ray 1) whereas energy arriving at more nearly vertical incidence (ray 2) penetrates the E layer and is returned to earth by the F layer. Although the energy penetrates the E layer its path may be bent considerably as shown by ray 2.

Figure 2-5 illustrates the case of energy reaching the receiver simultaneously from two paths involving different numbers of hops (rays 1 and 2). For average heights of the ionospheric layers, 4000 kilometers is about the maximum great circle distance for one-hop low ray F2-layer propagation, and 2000 kilometers is about the maximum for one-hop E-layer propagation. Greater distance lower ray propagation is possible only by means of two or more hops, as shown by ray 3 of figure 2-5. Abnormal

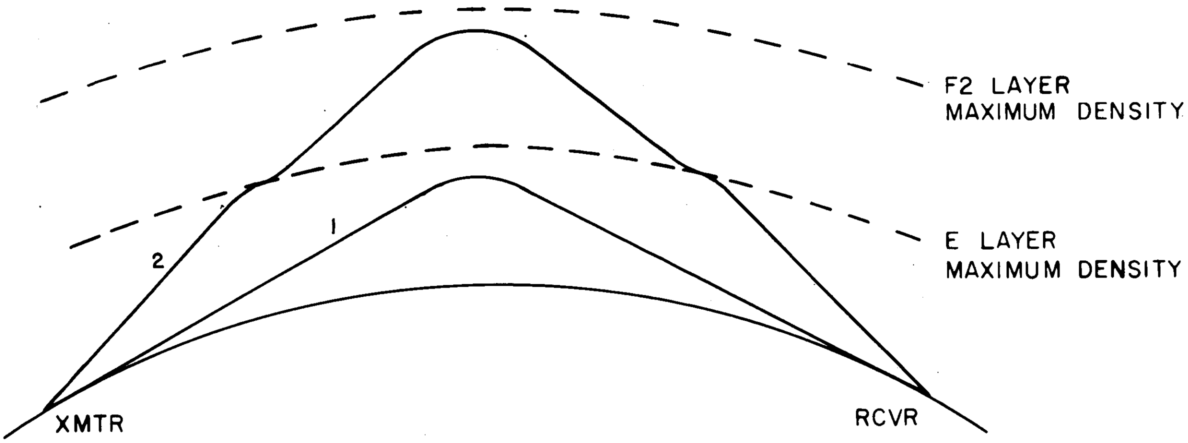


Figure 2-4. Typical Ray Paths with Two Layers Present

ionospheric conditions are sometimes responsible for extended range F2-layer propagation (as great as 10,000 kilometers) without ground reflection, but these ionospheric anomalies are not dependable for long-term planning.

The possible combinations of modes of propagation are virtually unlimited. The E layer may be effective on the daylight side of an east-west path but essentially absent on the nighttime side of the path. Depending upon the frequency and the radiation angle, such a path could include two hops via the F2 layer, it could involve one hop via the E layer and one hop via the F2 layer, or energy could be received via both paths. Usually, the longer the distance and the lower the operating frequency below the MUF, the greater is the number of possible paths.

2.3.5 Multipath and Interference

Since energy may arrive at the receiving terminal by each of several transmission modes, there are differences in time of arrival corresponding to the geometry of the paths. The magnitude and length of these multipath delays depend on combinations of operating frequency, path length, time of day, season, and path location. When an

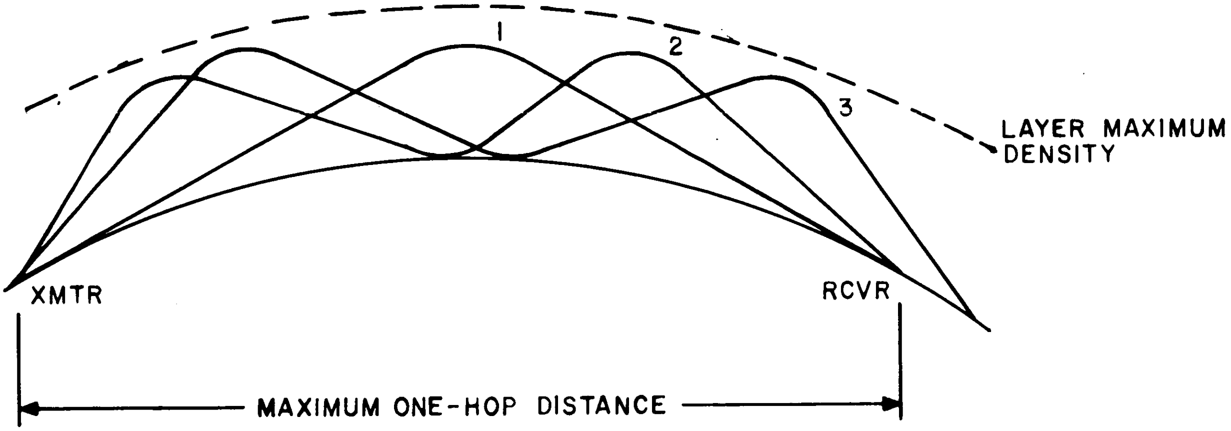


Figure 2-5. Two-Path Transmission

operating frequency very close to the MUF is chosen, the multipath delay is quite short. As the operating frequency is reduced below the MUF, the delay increases up to a maximum for path lengths of approximately 2000 km.

There are two effects of multipath: The first, due to relatively short delays with respect to the signal element length, causes selective fading which affects each subcarrier frequency of a frequency-division multiplex system, in some cases completely destroying the signal element. The second is due to multipath signals that are delayed long enough so that the end of the last arriving multipath signal element interferes with the first arriving component of the next signal element, thus reducing the maximum possible signaling speed. Generally, the delayed signals represent larger numbers of hops and arrive at higher angles than do the more useful signals. Since antenna characteristics of both transmitter and receiver may discriminate in favor of a certain path, suitable antenna design can help to reduce multipath difficulties, but the variability of the ionosphere precludes a complete solution of the problem by this means.

2.4 VARIATIONS IN THE IONOSPHERE

Since the reflecting and absorbing layers of the ionosphere are produced and controlled by radiation from the sun, there is a high correlation between solar activity and ionospheric characteristics. Some of the variations in ionospheric characteristics are more or less regular and can be predicted; other variations, resulting from abnormal behavior of the sun, are irregular and unpredictable.

2.4.1 Regular Variations

a. The Sunspot Cycle. One of the most notable phenomena on the sun's surface is the appearance and disappearance of certain dark areas known as sunspots. Their lifespan is variable and their exact nature is not known, but they appear to be vortices in the matter comprising the photosphere (visible surface of the sun). It is known that unusually strong magnetic fields are associated with the sunspots, and since about 1850 it has been known that sunspot activity varies according to a more or less regular cycle. Although there is some variation in the number of sunspots from one maximum to the next and there are some differences in the time between successive maxima, the average sunspot cycle is very close to eleven years.

For many years the index of solar activity has been the smoothed Zurich sunspot number (sometimes referred to as the Wolf number) which is the number of isolated spots plus 10 times the number of groups of spots visible with a standard low-power telescope. Authorities on the subject agree that the validity of the sunspot number as an index of solar activity is questionable. Nevertheless, it is valuable because its availability for a period of about 200 years provides a large homogeneous sample of data.

During times of maximum sunspot activity, the ionization density of all layers increases. Because of this the critical frequencies for the E and F layers increase and absorption in the D layer increases. At these times higher frequencies can be used for long-distance communications; in fact, they must be used to avoid increased absorption of lower frequencies in the D layer.

b. Twenty-Seven Day Cycle. There are periods, particularly near the 11-year minima when a 27-day (approximate) cycle, corresponding to the period of rotation of the sun, is discernible. Magnetic and ionospheric disturbances have been identified frequently with very active sunspots radiating toward the earth at 27-day intervals. Also, as one might expect, rotation of the sun is one factor causing the number of sunspots on the visible surface to change from day to day. This 27-day cycle contributes to the day-to-day variations of the ionosphere over a wide geographic range, but the cycle is neither very predictable nor significant compared to other factors.

c. Seasonal Variations. As the sun moves from one hemisphere to another, variations in the ionosphere take place corresponding to changes in the season. The seasonal variations of the D, E and F1 layers are in phase with the sun's zenith angle; thus the ionization density of these layers is greatest during the summer. The F2 layer, however, does not follow this pattern and its ionization density and height are greatest in winter and least in summer. Separation of the F1 and F2 layers is not as well defined in summer since the F2 layer tends to be lower then.

In the summer, absorption in the ionosphere tends to be linearly related to the sun's zenith angle, but in the winter months the absorption is unexpectedly high. This increased absorption, an effect known as the "winter anomaly," does not occur uniformly over all days, but appears in the form of high absorption on certain groups of days. Apparently, it is a middle latitude effect since it vanishes in polar regions where, in winter, the D region is in prolonged periods of darkness. Fortunately, the winter anomaly is not a serious factor concerning radio communications because the critical frequencies of the F2 layer are higher in winter than in summer, so that higher frequencies can be used. The decrease in absorption due to the use of higher frequencies usually more than compensates for the increased absorption due to the "winter anomaly."

d. Diurnal Variations. The diurnal, or daily, changes in the ionosphere have been discussed in connection with the description of the layers. To summarize here, the salient characteristics are (1) the D, E and F1 layers virtually disappear at night, their ionization density correlating with the altitude of the sun, (2) likewise, the critical frequencies of the E and F1 layers depend primarily on the zenith angle of the sun, and hence follow a regular diurnal cycle, being maximum at noon and tapering off on either side, and (3) the F2 layer exists continuously and its degree of ionization undergoes appreciable, unpredictable day-to-day variations.

2.4.2 Irregular Variations

In addition to the more or less regular variations in the characteristics of the ionosphere, a number of transient unpredictable phenomena have an important, sometimes drastic, effect on HF radio propagation. Some of the more prevalent of these phenomena are: sporadic E, sudden ionospheric disturbances, and ionospheric storms.

a. Sporadic E. Irregular cloud-like areas of unusually high ionization, called sporadic E and abbreviated E_s, often occur near the height of maximum ionization of the regular E layer. The physical processes that produce the quite unpredictable E ionization are not fully known, but the frequency of occurrence and the degree of ionization vary significantly with latitude.

Sometimes the E_s layer, or cloud, is opaque to radio waves and blankets the upper layers. At other times the E_s may be so thin that, although its presence can be verified, radio waves penetrate it easily to be returned to earth by the upper layers. These characteristics can be either helpful or harmful to radio communications. For example, blanketing E_s may block propagation via a more favorable regular layer in a certain frequency range or cause additional attenuation at other frequencies. Partially reflecting E_s can cause serious multipath interference especially detrimental to data transmission systems. On the other hand, sporadic E may enable long-distance transmission at very high frequencies, or may permit short-distance transmission to locations that would ordinarily be in a skip zone.

b. Sudden Ionospheric Disturbances. At times, high-frequency sky-wave transmission over the daylight hemisphere of the earth is "blacked out" by what is known as a sudden ionospheric disturbance (SID). This is the most startling of all the irregularities of the ionosphere since its sudden onset often leads radio operators to believe that their radio receivers have suddenly gone dead. Such a disturbance may last from a few minutes to several hours. The effect is caused by a solar burst of ultraviolet light (solar flare) which is not absorbed in the normal F2, F1 and E layers, but it produces intense ionization in the D region where the air density is relatively high. This results in almost complete absorption of waves above 1 or 2 MHz passing through the D region. The frequency of occurrence of these radio fadeouts is related to the 11-year cycle of flares and sunspots, and the magnitude of an SID generally corresponds with the solar zenith angle.

c. Ionospheric Storms. Ionospheric storms are disturbances in the ionosphere that are associated with magnetic storms, the rapid and excessive fluctuations that occur in the earth's magnetic field. They tend to develop rather suddenly, and recovery to normal conditions may span several days. These storms show a tendency to recur at 27-day intervals, as mentioned earlier, and are associated with sunspots in some manner not fully understood.

The most prominent features of ionospheric storms are an abnormal decrease in F2-layer critical frequencies and an increase in D-layer ionization, and hence absorption. The effects on the E and F1 layers are usually less pronounced. The practical consequence of an ionospheric storm on high-frequency radio transmission is the narrowing of the range of frequencies that are useful for communication over a given circuit. An unusually severe storm may make all high frequencies unusable. The effect of an ionospheric storm tends to be more severe when the transmission path passes near the earth's magnetic pole.

2.4.3 Effect of the Earth's Magnetic Field

The earth's magnetic field exerts a deflecting force on the electrons in the ionosphere causing them to vibrate in elliptical paths when they are under the influence of a radio wave. A plane polarized wave becomes elliptically polarized as it travels through the ionosphere. The degree of polarization change is greater the lower the frequency and also depends upon the relative orientation of the magnetic flux lines with respect to the plane of polarization of the wave. When the earth's magnetic field is perpendicular to the electric field of the radio wave, the effect is maximum; when the two fields are parallel, there is no effect.

The magnetic field is also responsible for an effect, called magneto-ionic splitting, whereby a radio wave is split into two components, an ordinary ray and an extraordinary ray. Generally, these rays are elliptically polarized with opposite senses of rotation and refracted along slightly different paths by the ionosphere. The adverse effects of this action are important at frequencies below about 3 MHz and in low-latitude regions.

2.5 TRANSMISSION LOSSES

Three main mechanisms account for almost all the energy losses of a radio transmission: free-space loss, ground reflection loss and absorption loss in the ionosphere. These losses are discussed briefly below, and the method of accounting for transmission losses as a part of HF circuit planning will be shown later in an example problem.

2.5.1 Free-Space Loss

Normally, the major energy loss is due to the geometrical spreading of the energy over progressively larger areas as the signal travels away from the transmitter. For practical purposes, it is sufficiently accurate to consider that this free-space loss causes signal power to diminish in proportion to the inverse square of the ray path distance.

2.5.2 Ground Reflection Loss

When a multiple-hop propagation mode is the means of transmission, energy is lost as the radio wave is reflected at the earth's surface. This loss depends upon the frequency, the angle of incidence, ground reflection irregularities, and the conductivity and dielectric constant of the ground at the reflecting surface.

2.5.3 Absorption Loss in the Ionosphere

As a radio wave propagates into the ionosphere, the electric field vector of the wave produces a force on the free electrons in the atmosphere, setting them into vibration. The resonant frequency of this vibration is known as the gyrofrequency. Except for energy lost by collisions between these electrons and other particles, the electrons release the energy acquired from the radio wave by radiating spherical waves of the same frequency as the original wave. Even though the gas pressure in the ionosphere is very low, the electrons will from time to time collide with gas molecules. When this happens the kinetic energy the electron has acquired from the radio wave is lost insofar as the radio wave is concerned. The amount of energy absorbed in this way from a radio wave depends upon the gas pressure (likelihood of a vibrating electron colliding with a gas molecule) and upon the velocity the electron acquires in its vibration (energy lost per collision), as well as the number of electrons. Consequently, most of the absorption loss occurs in the D region and the lower edge of the E layer where the atmospheric pressure is greatest. Normally, very little loss occurs higher in the ionosphere because the atmospheric pressure is very low. The absorption loss tends to decrease as the frequency is increased because the average velocity of the electrons, and therefore the energy lost per collision, is inversely proportional to frequency.

2. 6 NOISE

In every communications system noise is the limiting factor that determines whether the signal is usable for the transmission of information. The three major sources of radio path noise with which the HF signal must compete are galactic, atmospheric and man-made. In general, the composite noise level from these three sources decreases with increasing frequency.

2. 6. 1 Galactic Noise

The term galactic noise is used loosely here to describe noise generated in outer space, that is, noise from all extraterrestrial sources including our own stellar system, the Milky Way, other galaxies, and so on. The distinctions between cosmic, galactic and solar noise are not important to this discussion but may be pursued further in reference 8.

2. 6. 2 Atmospheric Noise

The term atmospheric noise is used to designate earth-bound or terrestrial noise generated by natural phenomena. The largest portion of this noise is generated by electrical discharges in the atmosphere. Generally, the level of this "static" decreases with increasing frequency and latitude, and is of minor significance above about 20 MHz.

2. 6. 3 Man-Made Noise

Man-made noise arises from electrical devices such as relays, voltage regulators, arc-welders, diathermy machines and ignition systems of internal combustion engines. Consequently, man-made noise is especially strong in cities and particularly in industrial areas. Such noise is frequently cyclic in nature because of the periodicity of the generating devices, and it may vary in intensity throughout the working day.

2. 6. 4 Composite Noise Level

Man-made noise is frequently the performance limiting factor at HF radio receiving sites where urban or suburban encroachment has become a problem. In the absence of man-made noise, atmospheric noise is usually the factor that determines the minimum usable signal. The tremendous energy released by electrical discharges in the atmosphere is transmitted over considerable distances by the same propagating mechanism as is a high-frequency radio signal. Thus the intensity of atmospheric noise or static follows propagation conditions, being high when conditions are favorable for long-distance propagation, and low when propagation conditions are such that the only static able to reach the receiver is that which is generated locally.

In figure 2-6, atmospheric noise curves extracted from CCIR Report 322 have been added to a graph from references commonly used for estimating man-made and galactic noise to illustrate the relative magnitude of the three basic noise sources. The advantage of a rural site is clearly evident as is the inverse relationship between frequency and noise.

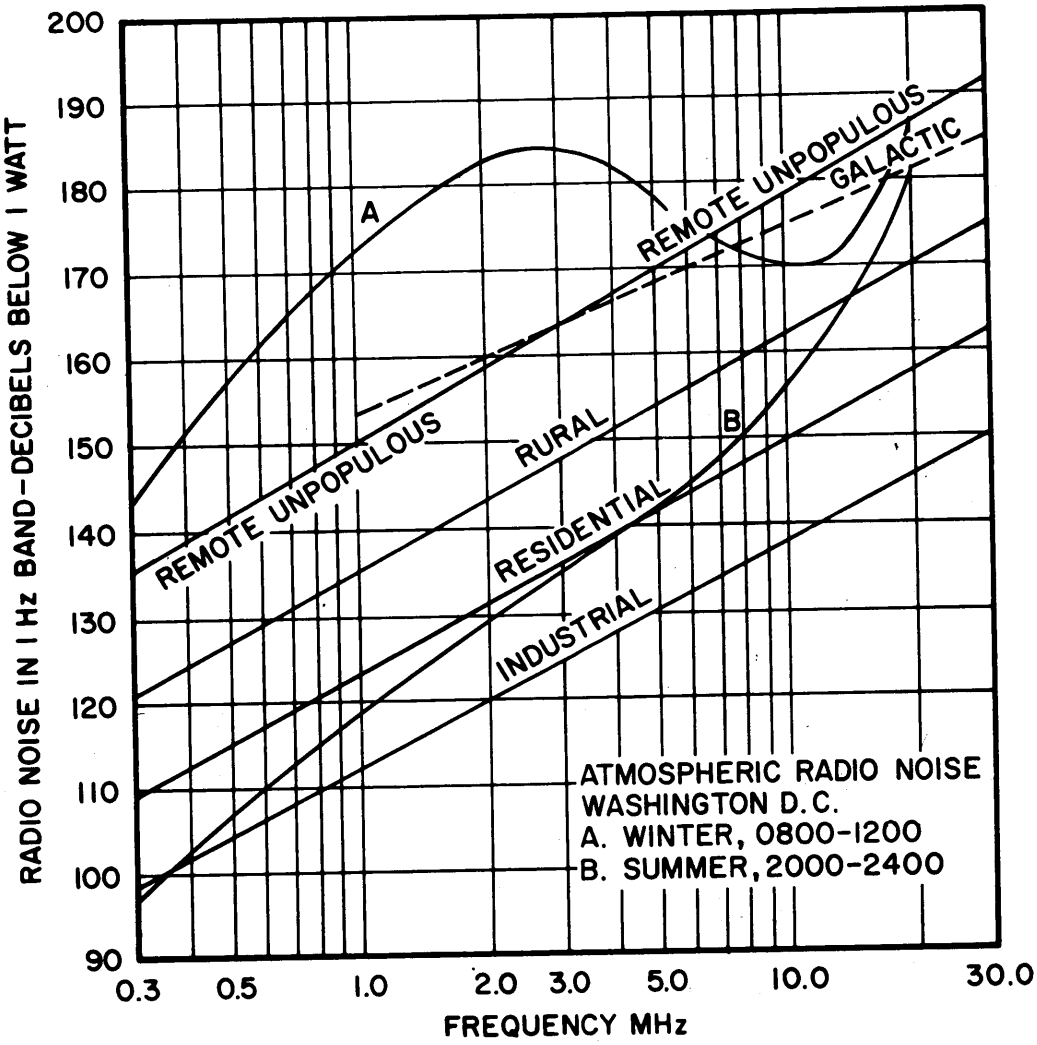


Figure 2-6. Typical Man-Made, Galactic, and Atmospheric Noise

2.6.5 Lowest Usable Frequency (LUF)

Both noise and ionospheric absorption increase with decreasing frequency. Consequently, for a given transmitter output power, as the operating frequency is decreased the signal power at the receiver usually decreases; the noise increases causing the signal-to-noise ratio to deteriorate and the circuit reliability to decrease. The frequency below which the reliability is unacceptable is called the lowest usable frequency (LUF). The LUF depends upon transmitter power, the factors that determine the path loss (e.g., frequency, season, number of hops, geographic location), and the noise level (mainly frequency and receiver location). One of the main factors is ionospheric absorption, and, since this normally varies with the sun's elevation angle, the LUF peaks around noon. The LUF at midday may be higher than the FOT for other times of the day.

2.6.6 Required Signal-to-Noise Ratio

The probability of successful HF sky-wave communications depends upon the probability of the operating frequency being supported by ionospheric refraction and the probability that the signal-to-noise ratio will exceed some acceptable level. An acceptable signal-to-noise ratio depends, in turn, upon the type of signal being transmitted, i.e., the type of service. Determining the S/N required for a particular type of service has often been based solely on past experience with the same or similar transmission mode. In recent years, investigations by various agencies have resulted in diverse recommendations concerning the signal-to-noise ratios required for various types of service under both stable and fading conditions. Reference 22 contains useful background information on this subject and includes the recommendations of the Institute for Telecommunication Sciences, Boulder, Colorado.

2.7 MANUAL PROPAGATION PREDICTIONS

Various kinds of ionospheric propagation predictions are issued monthly by laboratories in a number of different countries. In the United States, the Institute for Telecommunication Sciences (ITS) issues forecasts of ionospheric disturbances and a monthly brochure, "Basic Radio Propagation Predictions," which includes a three-month forecast for use in determining optimum frequencies for HF communications. These relatively short-term predictions are useful in circuit operation, but not for the planning of terminal installations.

For long-term planning, the more predictable characteristics of the ionosphere are relied upon in anticipating the general performance that may be expected for a particular propagation path during a complete sunspot cycle. From this prediction can be drawn the complement of frequencies and radiation angles that will make optimum use of the path as well as the effective radiated power needed to produce a useful signal at the receiving terminal.

The behavior of the E and F1 layers is so regular that permanent nomograms can be used for long-term predictions. On the other hand, the behavior of the F2 layer is very irregular, and data accounting for variations as a function of geography, the time of day, the season and the sunspot number must be used. Therefore, long-term predictions for the F2 layer are based on data for the seasonal extremes (June and December) at a high point and a low point in the solar cycle. For design purposes, NAVELEX uses sunspot numbers 10 and 100 as representative of the normal excursions of conditions associated with solar activity.

The general computational procedure involves the assumption that the ionospheric layers are concentric with the earth's surface and that ionospheric conditions over a path are approximated by conditions at certain reflection areas or control points. For distances up to 4000 kilometers — the normal maximum one-hop distance via the F2 layer — a control point at the midpoint of the path is assumed. For path distances greater than 4000 kilometers, ionospheric conditions are examined at control points 2000 kilometers from each end of the path, and certain mid-path information is added to give an adequate estimate of absorption along the path. Experience has shown that the two-control point method gives useful results, although it ignores the details of propagation between the control points. The method is sometimes used for the E layer also by including an additional pair of control points 1000 kilometers from each end of the path. However, there is less justification for this course than is the case with F2 propagation.

2.7.1 Great Circle Path Computations

Knowledge of the transmitter and receiver locations is basic to any propagation prediction problem. The geographic coordinates of the terminal ends of a path can be taken from any standard map having sufficient detail and accuracy so that the coordinates can be determined to the nearest degree. Then, using these coordinates, the shorter of the great-circle distances between the terminals and the bearing from each terminal to the other may be calculated. Estimating the distance with a world map in conjunction with a great-circle map is sufficient for propagation predictions, but, ultimately, a mathematical method must be used to determine the distance to within 5 kilometers and the bearing to within 0.1 degree.

A computer can solve the spherical trigonometry problem quickly, but the manual method is somewhat tedious and time consuming. The formulas and sample problems can be found in a number of texts and handbooks such as reference 20.

2.7.2 Calculations for Path Distances of 4000 km or Less

In this section, a path between Cincinnati, Ohio, and Baton Rouge, Louisiana, will be used as an example to discuss the manual procedures for predicting the general performance for path lengths of 4000 kilometers or less. The example is foreshortened by performing the operations for only the month of June at sunspot number 10. As mentioned earlier, the complete solution requires repetition of the procedure for the month of June at SSN 100 and for the month of December at sunspot numbers 10 and 100.

To pose a problem, assume that the circuit will be used for single-sideband suppressed carrier telephony and that the service must be of good commercial quality with 90 percent circuit reliability. The transmitter and the antennas have not been selected. Find the combination of transmitter output power and antenna gains required to provide the service specified.

The graphic materials needed to solve the problem will be found in appendix A, and three foldout worksheets at the end of the handbook are used to illustrate a method and sequence of recording data. Line numbers are continued in sequence from one worksheet to the next to facilitate cross referencing in the step-by-step instructions given below.

a. Record Basic Data

Step 1. From a map or records determine the coordinates of the terminals and record them on the worksheet, foldout 2-1.

Step 2. Place transparent paper over the world map, figure A-1. (The world is divided into three geomagnetic zones, E, I, and W, to take into consideration the variation of F2-layer characteristics with longitude.)

Step 3. Draw the equator and the 0° and 180° meridians on the transparency and label them.

Step 4. Place dots on the transparency at the geographic coordinates of the transmitter and receiver.

Step 5. Transfer the transparency to the great-circle chart, figure A-2, and, keeping the equators coincident, slide the transparency horizontally until the terminal locations lie on the same great circle (solid lines) or a proportionate distance between adjacent great circles.

Step 6. Sketch the great-circle path on the transparency.

Step 7. If the path distance has not been calculated, use the broken lines to estimate the path distance and record it on the worksheet, foldout 2-1.

Step 8. Mark the midpoint of the path on the transparency and record the coordinates in the worksheet heading.

Step 9. Record the geomagnetic zone of the path midpoint.

Step 10. Transfer the transparency to the map of geomagnetic latitudes, figure A-3, and read the geomagnetic latitude of the path midpoint. Record this on the worksheet heading.

Step 11. Transfer the transparency to the world map of E-region gyrofrequency, figure A-4, and read and record the gyrofrequency at the path midpoint.

For the individual line entries on the worksheet the detailed instructions are:

Line 1. MIDPATH LOCAL TIME. Divide the longitude of the path midpoint by 15. Add the quotient to, or subtract it from, the GMT depending upon whether the midpoint is east or west of Greenwich, and then adjust the result to within the normal 24-hour day.

Line 2. F2-ZERO MUF. Place the transparency on the F2-ZERO MUF prediction chart for June, SSN 10, and Zone W (figure A-5). With the equators carefully aligned, place the Greenwich meridian of the transparency on the 00 local time line of the chart and read and record the MUF at the path midpoint. Move the Greenwich meridian of the transparency to the 02 local time line of the chart and again read and record the MUF at the path midpoint. Continue in this manner to complete the tabulating of the F2-ZERO MUF for the even hours of the day. (These are median values for the month.)

Line 3. F2-4000 MUF. Repeat the procedure described for line 2 using the transparency and the F2-4000 MUF chart for June, SSN 10, Zone W (figure A-6).

Line 4. SUN'S ZENITH ANGLE. Place the transparency over the sun's zenith angle chart for June (figure A-7), and, following the procedure described for line 2, read and record the sun's zenith angle for each time block. If the sun's zenith angle exceeds 102 degrees, enter a dash on line 4.

Line 5. ABSORPTION INDEX, I. The ionospheric absorption index, I, is a function of solar activity and the zenith angle of the sun. Enter the nomogram of ionospheric absorption index (figure A-8) with the sunspot number (10 in this case) and the sun's zenith angle from line 4 to determine the absorption index at the path midpoint for each time block.

b. Determine MUFs and FOTs for the Path

The next step is to determine the optimum traffic frequencies for the path. Continuing with the worksheet, foldout 2-1, the instructions for each line entry are:

Line 6. F2-MUF. Use the F2-layer MUF conversion nomogram (figure A-9) to determine the MUFs for the path distance. Place a straightedge between the F2-ZERO MUF (line 2) and the F2-4000 MUF (line 3) and read the frequency at the point where the straightedge intersects the vertical line corresponding to the path distance. Repeat the procedure for each time block.

Line 7. F2-FOT. Either multiply each MUF on line 6 by 0.85 or use the conversion scale on the right-hand side of figure A-9 to convert the maximum usable frequencies to optimum traffic frequencies.

Line 8. E-2000 MUF. Use the nomogram for obtaining E-layer 2000 MUF (figure A-10). Enter the nomogram with the sunspot number and the sun's zenith angle from line 4. Read and record the E-2000 MUF for each time block.

Line 9. E-MUF. Enter the F1 and E-layer MUF conversion nomogram (figure A-11) with the path distance and the E-2000 MUF from line 8. Read and record the path E-layer MUF for each time block. Ordinarily the overall path distance is used without regard to the possible number of hops in the path. In a case such as this, however, a one-hop E mode can be ruled out since 2000 km normally is the maximum one-hop distance for E-layer propagation. Therefore, half the path distance is used in this example to determine the E-MUF for a two-hop E mode.

Line 10. CIRCUIT FOT. Enter the higher of the F2-FOT (line 7) or the E-MUF (line 9).

A curve may now be drawn to portray graphically the median optimum traffic frequencies for the month of June, SSN 10. Such a curve for the example problem is shown in figure A-12.

c. Determine Possible Modes

For clarity and convenience, the example is further abbreviated at this point to show the procedures for only one time, 1200Z. Usually the work described is done for 4-hour intervals through the day. Foldout 2-2 is used with reference to the following instructions for entries to be made on each line. Enter heading information from the previous worksheet.

Line 11. OPERATING FREQUENCY. At this point an operating frequency must be designated for the time 1200Z. If a complement of frequencies has been assigned for the circuit, the highest one below the FOT is a reasonable first choice. Otherwise enter the FOT from the preceding worksheet.

Line 12. F2-LAYER HEIGHT. Place the great-circle path transparency on the F2-layer height chart for June (figure A-13), and, with the equators and the Greenwich meridian of the transparency on the 1200 local time line, read and record the layer height at the path midpoint.

Line 13. MODES CONSIDERED. No entry required. The modes to be considered for paths of 4000 kilometers or less are already entered on line 13. 1E indicates one hop via the E layer; 2F indicates two hops via the F layer, etc.

Line 14. DISTANCE PER HOP. Divide the path distance (in the data sheet heading) by the number of hops in line 13.

Line 15. RADIATION ANGLE Δ. The vertical radiation angle corresponding to each mode is obtained from figure A-14 which gives the radiation angle as a function of great-circle distance and layer height. Enter with the distance per hop (line 14) and a layer height of 110 km for the E modes and with distance per hop and F2-layer height (line 12) for the F modes.

Line 16. MAXIMUM E Δ, MINIMUM F Δ. The maximum possible radiation angle for E-layer propagation (the critical angle) is obtained from figure A-15, "Nomogram to Estimate E-layer Penetration Frequency at any Radiation Angle." Enter with the operating frequency from line 11 and the absorption index from line 5. If the radiation angle for either of the E modes, as recorded on line 15, is greater than the maximum possible radiation angle entered on line 16, eliminate that mode from further consideration. Since F-layer propagation requires penetration of the E layer, the minimum vertical radiation angle for the F layer is considered to be the same as the maximum radiation angle for the E layer. Therefore, eliminate any F modes for which the radiation angle on line 15 is less than the minimum radiation angle on line 16.

Line 17. MINIMUM F DISTANCE. Enter figure A-9 with the F2-ZERO MUF from line 2 and the F2-4000 MUF from line 3. At the operating frequency (line 11), read the minimum distance (skip distance) for F2-layer propagation. If this distance is greater than any of the distances per hop shown for F modes on line 14, eliminate those modes from further consideration.

If all the F modes are eliminated because of the line 15 radiation angle limitations, introduce additional modes by increasing the number of hops. If all modes are eliminated, and the operating frequency is below the FOT, introduce a combination E and F layer mode (EF mode) using the average of 110 km and the F-layer height (line 12).

d. Estimate Path Loss

Line 18. IONOSPHERIC LOSS PER HOP. The average absorption loss per hop is obtained from the ionopsheric absorption nomogram (figure A-16). Enter with the absorption index from line 5 and the radiation angle from line 15 for the path being considered. Mark the center line of the nomogram. Add the gyrofrequency, from the data sheet heading, to the operating frequency. A line from this sum on the right-hand scale, through the point previously marked on the center line, to the left-hand scale yields the absorption loss per hop.

Line 19. TOTAL IONOSPHERIC LOSS. Multiply the ionospheric loss per hop on line 18 by the number of hops, line 13.

Line 20. GROUND LOSS PER REFLECTION. The loss at each ground reflection is estimated from the appropriate reflection loss chart (figure A-17 or A-18). Select the chart most nearly approximating the terrain at the path midpoint, either ground or sea water. Enter the operating frequency and the radiation angle, line 15, and read the ground reflection loss.

Line 21. TOTAL GROUND LOSS. Multiply each ground loss on line 20 by the number of ground reflections (the number of hops minus one) to get an estimate of total ground reflection loss.

Line 22. RAY-PATH DISTANCE LOSS. Loss due to spreading of the radio energy as it travels is obtained from the nomogram of figure A-19. Enter with the path distance from the worksheet heading and the radiation angle from line 15. Mark the reference line. Enter with the reference mark and the operating frequency and read the distance loss. Repeat the procedure for each mode still being considered.

Line 23. QUASI-MINIMUM PATH LOSS. The lowest hourly median path loss that normally can be expected is estimated by adding lines 19, 21, and 22.

Line 24. ADJUSTMENT TO MEDIAN. The difference between the quasi-minimum path loss (lowest hourly median loss expected within the month) and the monthly median of the hourly median can be estimated from figure A-20. Determine the appropriate curve according to the geomagnetic latitude of the path midpoint (recorded on foldout 2-1) and read the path loss adjustment at the median (50%) ordinate.

Line 25. MEDIAN PATH LOSS. Add the entry in line 24 to the lowest entry in line 23 to obtain the expected monthly median of the hourly median path loss.

Line 26. ADJUSTMENT FOR 90% SERVICE. This adjustment is obtained from figure A-21, "Daytime Reliability of Sky-Wave Circuits below 60° Geomagnetic Latitude." Read the reliability correction expressed in decibels at the intersection of the operating frequency with the 90% contour. The 90% contour is used because Navy standard practice is to design for a circuit reliability of at least 90%.

Line 27. PATH LOSS FOR 90% SERVICE. Add the entries on lines 25 and 26.

e. Estimate HF Noise at the Receiver Location

An estimate of the high-frequency radio noise is required before the signal requirement, and ultimately the radiated power and path antenna gain, can be determined. Foldout 2-3 is used to continue with the abbreviated example begun on the path loss worksheet. Heading information is taken from the other worksheets. The instructions for the line entries are:

Line 28. LOCAL TIME. Divide the longitude of the receiving terminal by 15. Add the quotient to, or subtract it from, the GMT, depending upon whether the receiving terminal longitude is east or west of Greenwich, and then adjust the result to within the normal 24-hour period.

Line 29. F2-ZERO MUF. Transcribe the F2-ZERO MUF from line 2.

Line 30. 1 MHz NOISE LEVEL. To estimate the noise in dB above kTb at 1 MHz, use the noise distribution chart (figure A-22) and read the noise level at the receiver location. Local time is the basis for selecting the appropriate chart from the series presented in reference 9.

Line 31. ATMOSPHERIC NOISE, 1-Hz BANDWIDTH. Use the atmospheric radio noise chart (figure A-23). Enter with the operating frequency and the 1-MHz noise level from line 30. Read and record atmospheric noise.

Line 32. GALACTIC NOISE. Galactic noise will be important only if the operating frequency is above the critical frequency of the F2 layer in the receiving vicinity. This critical frequency is approximated by the F2-ZERO MUF. If the operating frequency is below the F2-ZERO MUF, line 29, enter a dash on line 32. If the operating frequency is above the F2-ZERO MUF enter figure A-24 with the operating frequency and read the galactic noise.

Line 33. MAN-MADE NOISE. If at all possible, measurements of man-made noise should be made for each individual case, but if measurements at the receiving site are not available, man-made noise may be approximated from figure A-24. Enter with frequency and read noise from the curve most typical of the receiving location. A rural location is assumed for the sample problem.

Line 34. NOISE AT RECEIVING ANTENNA, 1-Hz BANDWIDTH. Enter the highest of the entries in lines 31, 32 and 33.

f. Estimate Power Required

Continuing on with foldout 2-3, the following instructions lead to an estimate of the path effective radiated power required; that is, the combination of transmitter power and antenna gains required to overcome the path loss and provide an acceptable signal-to-noise ratio.

Line 35. NOISE, 3-kHz BANDWIDTH. Since the noise level in line 34 is for a 1-Hz bandwidth, a correction must be made to express the noise in the bandwidth occupied by the signal, 3-kHz. Add 35 dB (10 log 3000, rounded off) algebraically to the 1-Hz noise power in line 34.

Line 36. REQUIRED S/N. For this problem the ITS recommendations of reference 22 were adopted and it was assumed that dual diversity would be employed. Reference 22 recommends 67 dB as the signal-to-noise ratio required for good commercial quality SSB suppressed carrier telephony under fading conditions with dual diversity. This value, which is referenced to noise in a 1-Hz band, must be corrected for the actual bandwidth of the noise, 3 kHz. Subtracting 35 dB yields 32 dB as the required signal-to-noise ratio.

Line 37. SIGNAL REQUIRED. Record the algebraic sum of lines 35 and 36.

Line 38. PATH LOSS FOR 90% SERVICE. Enter the value from line 27.

Line 39. PATH EFFECTIVE POWER. Add lines 37 and 38 algebraically to obtain the combination of transmitter power (at the antenna terminals) and transmitting and receiving antenna gains required. With the effective power determined for the type of service and circuit reliability required, a trade-off between transmitter power and path antenna gain can be made to lead to selection of the transmitter and the antennas. Usually, the simplest and most economical way to contribute power to a circuit is by using high gain antennas.

2.7.3 Calculations for Path Distances Greater Than 4000 km

It should be clearly evident from the abbreviated example above that the work of making HF radio path performance predictions is quite tedious when it is done manually. To continue on with an example for a path length greater than 4000 kilometers would simply add to the bulk of this handbook while contributing very little more to a basic understanding of the computational procedure. Those who desire to investigate manual computational procedures more thoroughly should refer to the literature on the subject. The method for paths greater than 4000 kilometers generally follows that described for the short path, except additional control points are used. These control points introduce some additional minor complications.

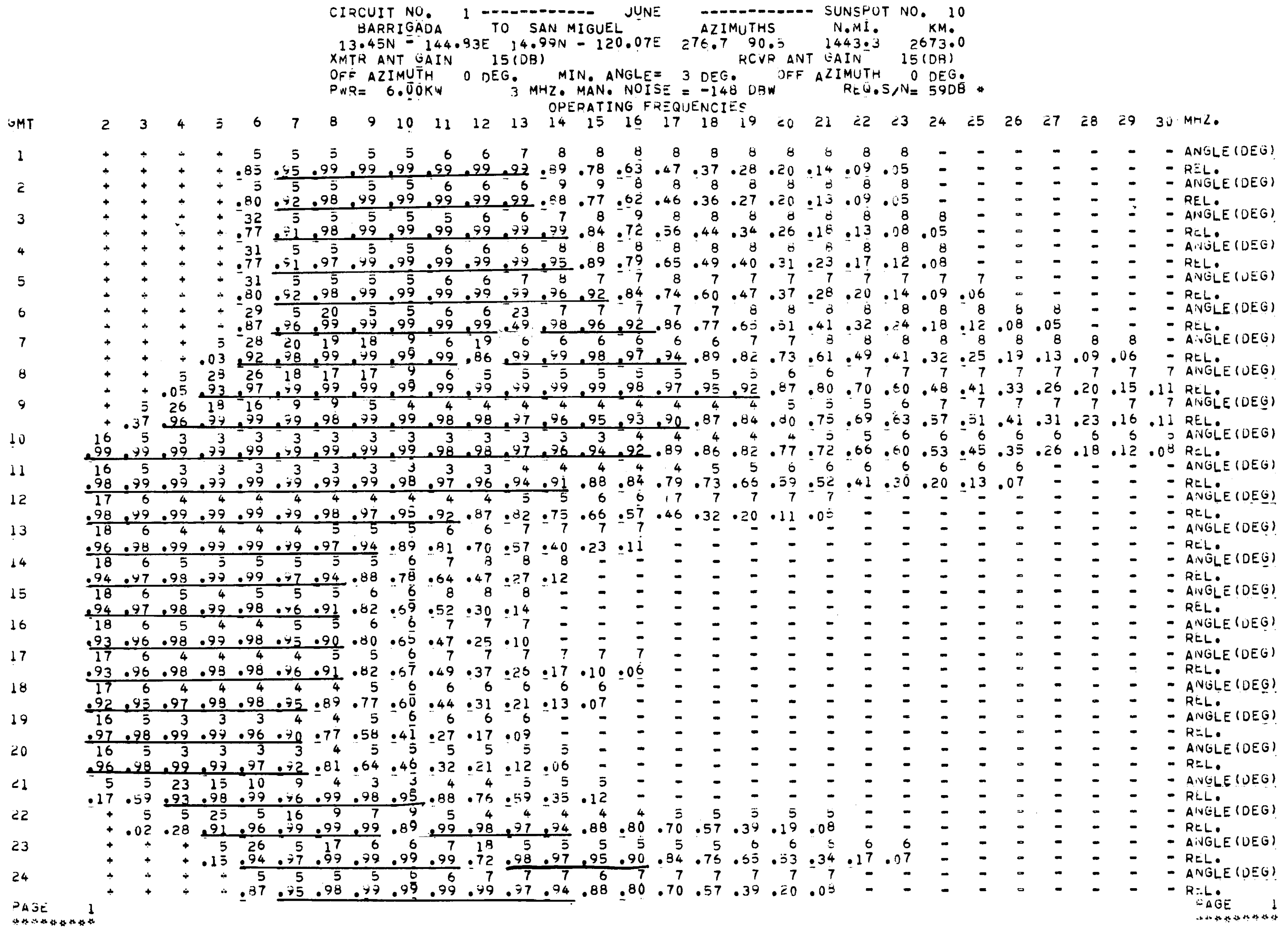
2.8 COMPUTER PROPAGATION PREDICTION PROGRAMS

A technique called numerical mapping is used in computer programs to tabulate and store basic ionospheric data. With this technique, a table of numerical coefficients is used to define a function of latitude, longitude and time to produce a "numerical map" of an ionospheric characteristic. The resultant numerical map represents the world-wide and diurnal variations of a particular characteristic, for example, the median F2-ZERO MUF for a given month. Numerous tables of coefficients can be calculated and stored in a computer for use on demand in predicting ionospheric characteristics for many variations of season and solar activity. As new data become available, the coefficients can be easily revised using the computer.

In a computer program, all the computations described in the example illustrating the manual procedures (and a few more) are made by the computer for each hour at 1 MHz intervals from 2 to 30 MHz. For each hour and for each frequency, seven possible modes are chosen: three F modes, two E modes, and two EF modes. For each of the seven possible modes the probability of ionospheric support is calculated, and the mode with the highest value is chosen as the most probable mode. There are various options that can be exercised concerning the output data to be printed. For example, the mode, radiation angle, transmission delay for the most probable mode, probability of ionospheric support via at least one sky-wave path, signal-to-noise ratio at the receiving antenna terminals and system loss are illustrative of the types of data that can be supplied. The particular mix of output data printed depends upon the input parameters specified and upon the desires of the user of the data. The computer printouts used by NAVELEX omit much of the optional data in order to reduce the bulk of the data to that which is essential for radio link and antenna design purposes.

Two basic approaches are used by NAVELEX for obtaining ionospheric prediction data via a computer. In one case, the transmitter power and antenna gains are specified (among other parameters) and the computer printout gives the radiation angle and circuit reliability. For the other approach, the reliability is specified and the computer prints the radiation angle and the power required.

a. Reliability Prediction Program. Figure 2-7 shows a computer printout for a specific circuit giving the radiation angle and circuit reliability at 1-MHz intervals for each hour of the day. The heading entries from left to right are:



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                      CIRCUIT NO.   1 ------------   JUNE     ------------ SUNSPOT NO.  10
                         BARRIGADA      TO  SAN MIGUEL        AZIMUTHS      N.MI.      KM.
                       13.45N - 144.93E  14.99N - 120.07E  276.7  90.5    1443.3    2673.0
                      XMTR ANT GAIN     15(DB)                   RCVR ANT GAIN     15(DB)
                      OFF AZIMUTH    0 DEG.     MIN. ANGLE=  3 DEG.     OFF AZIMUTH    0 DEG.
                      PWR=  6.00KW        3 MHZ. MAN. NOISE = -148 DBW       REQ.S/N= 59DB *
                                                     OPERATING FREQUENCIES
GMT    2   3   4   5   6   7   8   9  10  11  12  13  14  15  16  17  18  19  20  21  22  23  24  25  26  27  28  29  30 MHZ.

  1    +   +   +   +   5   5   5   5   5   6   6   7   8   8   8   8   8   8   8   8   8   8   -   -   -   -   -   -   - ANGLE(DEG)
       +   +   +   + .85 .95 .99 .99 .99 .99 .99 .92 .89 .78 .63 .47 .37 .28 .20 .14 .09 .05   -   -   -   -   -   -   - REL.
  2    +   +   +   +   5   5   5   5   5   6   6   6   9   9   8   8   8   8   8   8   8   8   -   -   -   -   -   -   - ANGLE(DEG)
       +   +   +   + .80 .92 .98 .99 .99 .99 .99 .99 .88 .77 .62 .46 .36 .27 .20 .13 .09 .05   -   -   -   -   -   -   - REL.
  3    +   +   +   +  32   5   5   5   5   5   6   6   7   8   9   8   8   8   8   8   8   8   8   -   -   -   -   -   - ANGLE(DEG)
       +   +   +   + .77 .91 .98 .99 .99 .99 .99 .99 .99 .84 .72 .56 .44 .34 .26 .16 .13 .08 .05   -   -   -   -   -   - REL.
  4    +   +   +   +  31   5   5   5   5   6   6   6   8   8   8   8   8   8   8   8   8   8   8   -   -   -   -   -   - ANGLE(DEG)
       +   +   +   + .77 .91 .97 .99 .99 .99 .99 .99 .95 .89 .79 .65 .49 .40 .31 .23 .17 .12 .08   -   -   -   -   -   - REL.
  5    +   +   +   +  31   5   5   5   5   6   6   7   8   7   7   8   7   7   7   7   7   7   7   7   -   -   -   -   - ANGLE(DEG)
       +   +   +   + .80 .92 .98 .99 .99 .99 .99 .99 .96 .92 .84 .74 .60 .47 .37 .28 .20 .14 .09 .06   -   -   -   -   - REL.
  6    +   +   +   +  29   5  20   5   5   6   6  23   7   7   7   7   7   8   8   8   8   8   8   8   8   8   -   -   - ANGLE(DEG)
       +   +   +   - .87 .96 .99 .99 .99 .99 .99 .49 .98 .96 .92 .86 .77 .65 .51 .41 .32 .24 .18 .12 .08 .05   -   -   - REL.
  7    +   +   +   5  28  20  19  18   9   6  19   6   6   6   6   6   6   7   7   8   8   8   8   8   8   8   8   8   - ANGLE(DEG)
       +   +   + .03 .92 .98 .99 .99 .99 .99 .86 .99 .99 .98 .97 .94 .89 .82 .73 .61 .49 .41 .32 .25 .19 .13 .09 .06   - REL.
  8    +   +   5  28  26  18  17  17   9   6   5   5   5   5   5   5   5   5   6   6   7   7   7   7   7   7   7   7   7 ANGLE(DEG)
       +   + .05 .93 .97 .99 .99 .99 .99 .99 .99 .99 .99 .99 .98 .97 .95 .92 .87 .80 .70 .60 .48 .41 .33 .26 .20 .15 .11 REL.
  9    +   5  26  18  16   9   9   5   4   4   4   4   4   4   4   4   4   4   5   5   5   6   7   7   7   7   7   7   7 ANGLE(DEG)
       + .37 .96 .99 .99 .99 .98 .99 .99 .98 .98 .97 .96 .95 .93 .90 .87 .84 .80 .75 .69 .63 .57 .51 .41 .31 .23 .16 .11 REL.
 10   16   5   3   3   3   3   3   3   3   3   3   3   3   3   4   4   4   4   4   5   5   6   6   6   6   6   6   6   5 ANGLE(DEG)
     .99 .99 .99 .99 .99 .99 .99 .99 .99 .98 .98 .97 .96 .94 .92 .89 .86 .82 .77 .72 .66 .60 .53 .45 .35 .26 .18 .12 .08 REL.
 11   16   5   3   3   3   3   3   3   3   3   3   4   4   4   4   4   5   5   6   6   6   6   6   6   6   -   -   -   - ANGLE(DEG)
     .98 .99 .99 .99 .99 .99 .99 .99 .98 .97 .96 .94 .91 .88 .84 .79 .73 .66 .59 .52 .41 .30 .20 .13 .07   -   -   -   - REL.
 12   17   6   4   4   4   4   4   4   4   4   4   5   5   6   6   7   7   7   7   7   -   -   -   -   -   -   -   -   - ANGLE(DEG)
     .98 .99 .99 .99 .99 .99 .98 .97 .95 .92 .87 .82 .75 .66 .57 .46 .32 .20 .11 .05   -   -   -   -   -   -   -   -   - REL.
 13   18   6   4   4   4   4   5   5   5   6   6   7   7   7   7   -   -   -   -   -   -   -   -   -   -   -   -   -   - ANGLE(DEG)
     .96 .98 .99 .99 .99 .99 .97 .94 .89 .81 .70 .57 .40 .23 .11   -   -   -   -   -   -   -   -   -   -   -   -   -   - REL.
 14   18   6   5   5   5   5   5   5   6   7   8   8   8   -   -   -   -   -   -   -   -   -   -   -   -   -   -   -   - ANGLE(DEG)
     .94 .97 .98 .99 .99 .97 .94 .88 .78 .64 .47 .27 .12   -   -   -   -   -   -   -   -   -   -   -   -   -   -   -   - REL.
 15   18   6   5   4   5   5   5   6   6   8   8   8   -   -   -   -   -   -   -   -   -   -   -   -   -   -   -   -   - ANGLE(DEG)
     .94 .97 .98 .99 .98 .96 .91 .82 .69 .52 .30 .14   -   -   -   -   -   -   -   -   -   -   -   -   -   -   -   -   - REL.
 16   18   6   5   4   4   5   5   6   6   7   7   7   -   -   -   -   -   -   -   -   -   -   -   -   -   -   -   -   - ANGLE(DEG)
     .93 .96 .98 .99 .98 .95 .90 .80 .65 .47 .25 .10   -   -   -   -   -   -   -   -   -   -   -   -   -   -   -   -   - REL.
 17   17   6   4   4   4   4   5   5   6   7   7   7   7   7   7   -   -   -   -   -   -   -   -   -   -   -   -   -   - ANGLE(DEG)
     .93 .96 .98 .98 .98 .96 .91 .82 .67 .49 .37 .25 .17 .10 .06   -   -   -   -   -   -   -   -   -   -   -   -   -   - REL.
 18   17   6   4   4   4   4   4   5   6   6   6   6   6   6   -   -   -   -   -   -   -   -   -   -   -   -   -   -   - ANGLE(DEG)
     .92 .95 .97 .98 .98 .95 .89 .77 .60 .44 .31 .21 .13 .07   -   -   -   -   -   -   -   -   -   -   -   -   -   -   - REL.
 19   16   5   3   3   3   4   4   5   6   6   6   6   -   -   -   -   -   -   -   -   -   -   -   -   -   -   -   -   - ANGLE(DEG)
     .97 .98 .99 .99 .96 .90 .77 .58 .41 .27 .17 .09   -   -   -   -   -   -   -   -   -   -   -   -   -   -   -   -   - REL.
 20   16   5   3   3   3   3   4   5   5   5   5   5   5   -   -   -   -   -   -   -   -   -   -   -   -   -   -   -   - ANGLE(DEG)
     .96 .98 .99 .99 .97 .92 .81 .64 .46 .32 .21 .12 .06   -   -   -   -   -   -   -   -   -   -   -   -   -   -   -   - REL.
 21    5   5  23  15  10   9   4   3   3   4   4   5   5   5   -   -   -   -   -   -   -   -   -   -   -   -   -   -   - ANGLE(DEG)
     .17 .59 .93 .98 .99 .96 .99 .98 .95 .88 .76 .59 .35 .12   -   -   -   -   -   -   -   -   -   -   -   -   -   -   - REL.
 22    +   5   5  25   5  16   9   7   9   5   4   4   4   4   4   5   5   5   5   5   -   -   -   -   -   -   -   -   - ANGLE(DEG)
       + .02 .28 .91 .96 .99 .99 .99 .89 .99 .98 .97 .94 .88 .80 .70 .57 .39 .19 .08   -   -   -   -   -   -   -   -   - REL.
 23    +   +   +   5  26   5  17   6   6   7  18   5   5   5   5   5   5   6   6   5   6   6   -   -   -   -   -   -   - ANGLE(DEG)
       +   +   + .15 .94 .97 .99 .99 .99 .99 .72 .98 .97 .95 .90 .84 .76 .65 .53 .34 .17 .07   -   -   -   -   -   -   - REL.
 24    +   +   +   +   5   5   5   5   6   6   7   7   7   6   7   7   7   7   7   7   -   -   -   -   -   -   -   -   - ANGLE(DEG)
       +   +   +   + .87 .95 .98 .99 .99 .99 .99 .97 .94 .88 .80 .70 .57 .39 .20 .08   -   -   -   -   -   -   -   -   - REL.
PAGE    1                                                                                                                  PAGE     1
*********                                                                                                                  *********
```

Figure 2-7. Computer Printout for Reliability Prediction Program

First Line

(1) sequential number of circuit as entered into machine,
(2) month of year,
(3) solar activity level.

Second Line

(1) transmitter and receiver locations,
(2) azimuths (forward and backward),
(3) nautical miles,
(4) kilometers.

Third Line

(1) geographic coordinates of transmitter and receiver in hundredths of degrees,
(2) azimuths from transmitter to receiver and then from receiver to transmitter,
(3) great-circle distance of path in nautical miles,
(4) great-circle distance of path in kilometers.

Fourth Line

(1) transmitting antenna description, or antenna gain.
(2) receiving antenna description, or antenna gain.

Fifth Line

(1) off azimuth of transmitting antenna, degrees;
(2) minimum angle above the horizon for which any mode will be calculated, degrees;
(3) off azimuth of receiving antenna, degrees.

Sixth Line

(1) average output power of the transmitter at the antenna terminals,
(2) measured or assumed man-made noise level at the receiving antenna site in dB relative to 1 watt at 3 MHz in a 1-Hz bandwidth,
(3) required signal-to-noise ratio (dB)
    (a) the median signal power required in the occupied bandwidth relative to the noise power in a 1-Hz bandwidth;
    (b) the signal power required must be the average power to be consistent with the power indicated at the transmitting antenna terminals.

In the body of the printout, GMT is the ordinate and the operating frequency is the abscissa. The radiation angle for the most probable path and the reliability are shown for each frequency and hour. Dashes in a column below a frequency mean that the probability of all sky-wave paths inspected fell below .05. A plus sign indicates that the probability of ionospheric support was greater than .05, but reliability was less than .005.

For the sample shown in figure 2-7, rhombic antennas with a nominal gain of 15 dB were assumed for both the transmitter and receiver sites. For any circuit planning that includes installation of new antennas, zero degrees off azimuth is specified. That is, it is assumed the antennas can be installed on the correct azimuth. A minimum radiation angle of three degrees is commonly specified in recognition of the practical limitations on acheiving lower take-off angles. Also, man-made noise at 3 MHz is usually taken from the rural curve of figure A-24 unless measured noise data is available.

It is important to note the effect of the choice between antenna gain and antenna description as an input parameter. Although the computer program can calculate the theoretical directive gain of real antennas, the transmitting and receiving antennas in the example were assumed to have a constant gain (15 dB). This approach offers some advantages over specifying a particular antenna. In the latter case the vertical radiation pattern of the antenna will enter into the computations and the reliability figures will be affected by the variation of antenna gain with radiation angle. As a result, there could be a number of computations indicating excellent path reliability, but, because of insufficient antenna gain at the radiation angle required, the computer printout may show that the path is unreliable. The most probable path might be eliminated in this way. The computer printout does not indicate which unsatisfactory reliability results were due to poor antenna gain, and one cannot see the results of antenna design adjustments except by running the program again with a different antenna specification.

On the other hand, if a constant antenna gain is assumed, the predictions are not affected by any antenna pattern. As far as the computer program is concerned, the antenna gain will be constant, 15 dB in the example, at any radiation angle needed. The antenna design can then be adjusted for maximum gain at the radiation angle most suitable for the path.

Another important point concerns the designation of power and signal-to-noise ratio required. The power specified must be the average power in the occupied bandwidth, and the signal-to-noise ratio required must be adjusted to allow for the fact that the computer program noise computation is for a 1-Hz bandwidth. In the example, the specified signal-to-noise ratio, 59 dB, is the sum of 24 dB, the required signal-to-noise ratio for a signal in a 3-kHz band and noise in a 3-kHz band, and 35 dB, the factor to convert to a signal-to-noise ratio with the signal in a 3-kHz band and the noise in a 1-Hz band as required by the prediction program.

On the sample computer printout, all the circuit reliability figures of 90 and higher have been underlined to give a quick graphic impression of the frequencies and radiation angles appropriate for use at various times throughout the day. For predictions covering a complete solar cycle there would be, in addition to the sheet shown, a printout for June, SSN 100; one for December, SSN 10; and one for December, SSN 100.

b. Power Prediction Program. This program is a relatively recent development sponsored by the Naval Electronic Systems Command and implemented by the ITS. Historically, power was never considered to be a predictable system parameter. Rather, it was treated as one of the system parameters that must be specified prior to the start of the prediction process. In many cases, this was and still is, the direct route to the desired result, namely, the propagation predictions for a specified power. In other cases, however, the desired result is the power required to achieve a given reliability for a specified class of service. For the latter cases the power had to be determined by a trial and error process involving repetitive computer runs for each set of values for all the variables in question. This wasteful, large expenditure of man-hours and of computer time is avoided by this new program.

Figure 2-8 shows a computer printout for the same circuit as in figure 2-7, this one being for December and SSN 100. This time, however, the reliability (90% on line 6) was specified and the computer program was required to determine the power required to achieve that reliability. In this case isotropic antennas were specified (0 dB gain) and no allowance for signal bandwidth was added to the required signal-to-noise ratio (24 dB). The dashes in the body of the printout have the same meaning as in the previous example, i. e., the probability of ionospheric support was less than 0.05. The double asterisks indicate that the probability of ionospheric support was less than the required circuit reliability, in which case no amount of power will suffice.

As a general observation, this type of printout shows the effect of power on extending the useful frequency range. Note that propagation reliability, rather than power, is the determining factor at the higher frequencies, while power is the controlling factor at the lower frequencies. That is, increasing the power can increase the usable low frequencies, but not the high. This is as one might expect since both noise power and absorption loss increase with decreasing frequency.

The power prediction program offers several advantages over the reliability prediction program for long-term circuit planning, and the choices of input parameters shown in this example (figure 2-8) capitalize on these advantages. Since the required power is expressed in decibels above 1 watt, one can consider it an effective power and can perform easily any desired tradeoffs among transmitter power, antenna gains, required signal-to-noise ratio, and bandwidth. Assuming 0 dB antenna gain further simplifies these tradeoffs since the predictions will not have been affected by any prior assumptions concerning antenna gain.

To relate this example to the previous one, consider the input parameters for figure 2-7 as follows:

Transmitter power: 10 log 6000 = 37.8 dBw
Antenna gain, transmit = 15 dB
Antenna gain, receive = 15 dB
Effective signal power = 67.8 dBw
3-kHz noise bandwidth adjustment = −35 dBw
Available signal power = 32.8 dBw

From this computation, one can see that the assumed transmitter power and antenna gains will satisfy the circuit reliability requirement for all frequencies and times for which the predicted power requirement is less than 33 dB. As with the previous example, lines drawn under the power predictions, as in figure 2-8, give a quick impression of the range of frequencies usable as a function of time of day. One would expect that assuming the same input parameters for both prediction programs would yield the same set of frequencies from both approaches. This is true. They correspond exactly, although an example of each type of printout for the same month and the same sunspot number would be needed to show this.

```
                        CIRCUIT NO.  1 ------------ DECEMBER  ------------ SUNSPOT NO. 100
                         BARRIGADA     TO  SAN MIGUEL          AZIMUTHS     N.MI.    KM.
                        13.45N - 144.83E  14.99N - 120.07E  276.7  90.5    1443.3   2673.0
                        XMTR ANT GAIN      0(DB)                      RCVR ANT GAIN   0(DB)
                        OFF AZIMUTH    0 DEG.    MIN. ANGLE=  3 DEG.    OFF AZIMUTH    0 DEG.
                        REL= 0.900           3 MHZ. MAN. NOISE = -148 DBW       REQ.S/N= 24DB**
                                              OPERATING FREQUENCIES
GMT    2   3   4   5   6   7   8   9  10  11  12  13  14  15  16  17  18  19  20  21  22  23  24  25  26  27  28  29  30 MHZ.

 1     5   5   5   5  29  27  27  18  18  17  17  17  17   6   5   5   5   5   5   5   5   5   5   5   6   6   6  **  ** ANGLE(DEG)
     177 130  97  75  36  30  26  19  17  15  13  11  10   7   6   6   5   4   4   3   4   3   2   2   2   3   7  **  ** POWER(DBW)
 2     5   5   5   5  31  29  28  20  19  19  19  19  19   7   6   6   6   6   6   6   6   6   6   7   7  **  **  **  ** ANGLE(DEG)
     196 144 107  83  38  32  28  20  18  16  14  12  10   7   6   6   5   4   5   4   4   3   4   5  10  **  **  **  ** POWER(DBW)
 3     5   5   5   5  32  30  29  20  20  19  19  20   7   8   7   7   6   6   6   7   7   7   7  **  **  **  **  **  ** ANGLE(DEG)
     204 150 112  86  39  33  28  20  18  16  14  12  10   7   7   7   6   5   5   4   4   5   7  **  **  **  **  **  ** POWER(DBW)
 4     5   5   5   5  32  30  22  20  20  20  20  20   7   8   7   7   7   7   7   7   7   7   7   8  **  **  **  **  ** ANGLE(DEG)
     200 147 110  85  38  32  24  20  18  15  13  12  10   7   6   6   5   4   5   4   4   4   6  16  **  **  **  **  ** POWER(DBW)
 5     5   5   5   5  31  29  21  20  19  19  19  19  19   7   6   6   6   6   6   6   6   6   7   7   7  **  **  **  ** ANGLE(DEG)
     185 136 101  78  36  31  23  19  17  15  13  11  10   7   6   6   5   4   4   3   4   3   4   5  11  **  **  **  ** POWER(DBW)
 6     5   5   5   5  29  28  20  18  18  18  18  18   7   6   5   5   5   5   5   5   5   6   6   6   6   6  **  **  ** ANGLE(DEG)
     158 117  87  67  33  28  21  17  15  13  12  10   7   6   5   6   5   4   4   3   3   2   3   3   4   7  **  **  ** POWER(DBW)
 7     5   5   5  30  27  20  18  17  17  17   6   6   5   5   5   5   5   5   5   5   5   5   5   6   6   6   6  **  ** POWER(DBW)
     125  92  69  35  29  21  19  16  14  12   9   8   7   6   5   6   5   4   4   3   4   3   3   3   4   6  13  **  ** ANGLE(DEG)
 8     5   5  30  27  19  18  17  17   6   5   5   5   5   5   5   5   5   5   5   5   5   5   6   6   6   6  **  **  ** POWER(DBW)
      83  62  30  26  19  17  14  12   9   8   7   6   6   5   4   4   4   3   3   3   3   2   2   3   4   8  **  **  ** ANGLE(DEG)
 9    28  18  17   5   5   4   4   4   4   4   4   5   5   5   5   5   5   5   5   5   6   6   6  **  **  **  **  **  ** POWER(DBW)
      26  20  16  12  10   9   8   6   6   5   5   4   4   3   3   3   3   3   3   4   5   7  19  **  **  **  **  **  ** ANGLE(DEG)
10    18   6   5   5   4   4   4   5   5   5   5   5   5   5   5   5   5   5   6   6   6  **  **  **  **  **  **  **  ** POWER(DBW)
      11   9   7   7   6   6   5   4   4   4   3   3   3   2   2   2   2   2   3   4   7  **  **  **  **  **  **  **  ** ANGLE(DEG)
11    18   6   5   5   5   4   4   5   5   5   5   5   5   5   5   5   5   5   6   6   6  **  **  **  **  **  **  **  ** POWER(DBW)
      11   9   7   7   6   6   5   4   4   4   3   3   3   2   2   2   3   3   4   5  11  **  **  **  **  **  **  **  ** ANGLE(DEG)
12    18   6   5   4   4   4   4   4   4   4   4   5   5   5   5   5   5   5   5   6   6  **  **  **  **  **  **  **  ** POWER(DBW)
      11   9   7   7   6   6   5   4   4   4   3   3   3   2   2   2   3   3   4   5  10  **  **  **  **  **  **  **  ** ANGLE(DEG)
13    17   6   4   4   4   4   4   4   4   4   4   4   4   4   4   4   5   5   5   5  **  **  **  **  **  **  **  **  ** POWER(DBW)
      12  10   9   8   8   7   6   6   6   5   4   4   4   4   4   4   4   5   6   9  **  **  **  **  **  **  **  **  ** ANGLE(DEG)
14    17   6   4   3   3   3   3   3   3   3   3   4   4   4   4   4   4   4   5   5  **  **  **  **  **  **  **  **  ** POWER(DBW)
      13  12  10  10   9   8   6   5   6   5   4   4   4   4   4   4   5   5   8  12  **  **  **  **  **  **  **  **  ** ANGLE(DEG)
15    16   5   3   3   3   3   3   3   3   3   3   3   3   3   4   4   4   4   4  **  **  **  **  **  **  **  **  **  ** POWER(DBW)
      13  12  10   9   9   7   5   6   6   5   4   4   4   4   5   5   6   8  28  **  **  **  **  **  **  **  **  **  ** ANGLE(DEG)
16    16   5   3   3   3   3   3   3   3   3   3   3   3   3   3   4   4  **  **  **  **  **  **  **  **  **  **  **  ** POWER(DBW)
      14  12  10   9   8   6   6   6   6   5   4   4   5   4   5   6  10  **  **  **  **  **  **  **  **  **  **  **  ** ANGLE(DEG)
17    16   5   3   3   3   3   3   3   3   3   3   3   3   3  **  **  **  **  **  **  **  **  **  **  **  **  **  **  ** POWER(DBW)
      14  12  10   9   8   6   6   6   6   6   6   7   8  11  **  **  **  **  **  **  **  **  **  **  **  **  **  **  ** ANGLE(DEG)
18    16   5   3   3   3   3   3   3   3   3   4   4  **  **  **  **  **  **  **  **  **  **  **  **   -   -   -   -   - POWER(DBW)
      14  12  10   9   8   7   6   6   7   7   8  13  **  **  **  **  **  **  **  **  **  **  **  **   -   -   -   -   - ANGLE(DEG)
19    17   6   4   4   4   4   4   4   4  **  **  **  **  **  **  **  **  **   -   -   -   -   -   -   -   -   -   -   - POWER(DBW)
      12  10   9   7   6   6   7   8  19  **  **  **  **  **  **  **  **  **   -   -   -   -   -   -   -   -   -   -   - ANGLE(DEG)
20    17   6   4   4   4   4  **  **  **  **  **  **  **   -   -   -   -   -   -   -   -   -   -   -   -   -   -   -   - POWER(DBW)
      11  10   8   7   8  11  **  **  **  **  **  **  **   -   -   -   -   -   -   -   -   -   -   -   -   -   -   -   - ANGLE(DEG)
21    17   6   4   4   4   4   4   4   4   5   5  **  **  **  **  **   -   -   -   -   -   -   -   -   -   -   -   -   - POWER(DBW)
      18  13  12  10   8   7   6   5   5   4   6  **  **  **  **  **   -   -   -   -   -   -   -   -   -   -   -   -   - ANGLE(DEG)
22     5   5  27  18  17  16  16   5   5   4   4   4   4   4   5   5   5   5   6  **  **  **  **  **  **  **   -   -   - POWER(DBW)
      67  50  27  20  17  15  12   9   8   7   6   6   5   4   4   4   4   6  15  **  **  **  **  **  **  **   -   -   - ANGLE(DEG)
23     5   5   5  28  26  18  17  16  16  16   6   5   4   4   4   4   4   4   4   4   4   5   5   5   5   6  **  **  ** POWER(DBW)
     111  82  62  33  27  21  18  15  13  12   9   8   7   6   5   5   4   4   4   3   3   3   3   3   5  14  **  **  ** ANGLE(DEG)
24     5   5   5   5  27  26  19  17  16  16  16  16   6   5   5   4   4   4   4   4   4   4   5   5   5   5   5   6   6 POWER(DBW)
     148 110  82  64  33  29  21  18  16  14  13  11   8   7   6   6   5   5   5   4   4   3   3   3   3   3   3   5  15 ANGLE(DEG)
PAGE    7                                                                                                                POWER(DBW)
*********                                                                                                                PAGE     7
                                                                                                                         *********
```

Figure 2-8. Computer Printout for Power Prediction Program

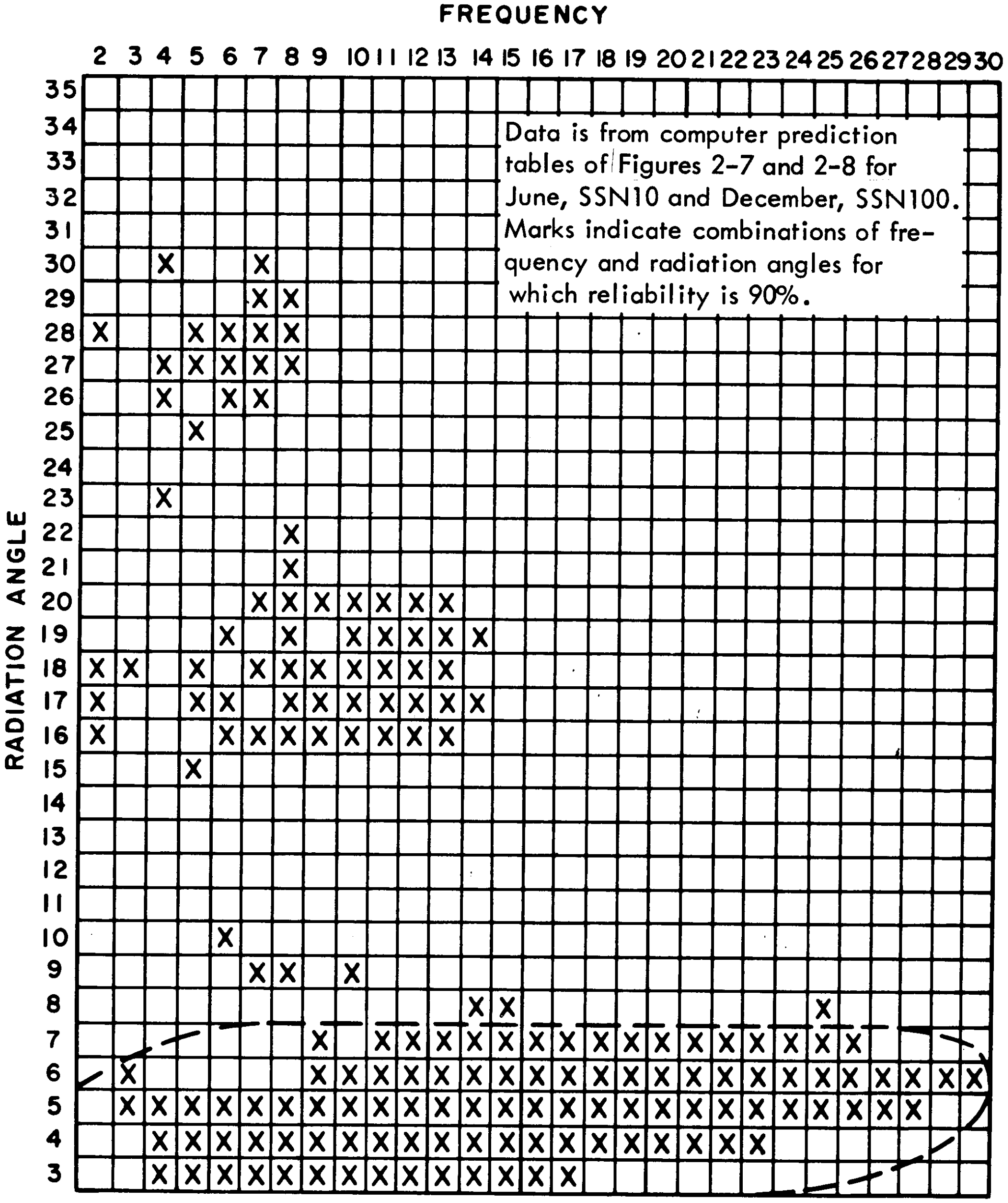
As mentioned earlier, the antenna gains specified in the first example and used to relate the second example to the first were arbitrary, though achievable, values. With the power predictions in hand for June and December for each of the two sunspot numbers, 10 and 100, the designer can give serious attention to selecting a practical antenna. An intermediate step is useful, though, to collect data from the four computer printouts into a composite summary for the complete solar cycle.

A convenient format for collecting data from the four computer-printed prediction tables is a simple matrix such as that shown in figure 2-9. Each frequency column of the four prediction tables is examined and all of the radiation angles underlined are indicated for each frequency in the matrix by marks opposite those radiation angles. The example shows the result of collecting data from just the two printouts of figures 2-7 and 2-8. The trend and grouping of required radiation angles as a function of frequency can be seen, but data from the two other tables (not shown) must be added to complete the matrix. When the matrix is completed, the grouping of radiation angles will be evident. The designer can then use a catalogue of standard rhombic antenna designs to select antennas that have adequate gain and vertical radiation patterns that match the radiation angle-frequency pattern of the predictions. Rhombic antennas, two to cover the HF band, are indicated here because they are the most common for long-haul point-to-point circuits, but this is not meant to imply that the procedures described above are restricted to any particular type of antenna.

A note of caution is in order here concerning the use of a radiation angle/frequency matrix as the basis for antenna design. Although the matrix is a very useful adjunct to the prediction tables, figures 2-7 and 2-8, it should not be used as the sole reference for determining the antenna system design. Doing so could lead to an unnecessarily complicated and expensive antenna system that includes performance features beyond those needed. For instance, the sample matrix of figure 2-9, taken by itself, could be interpreted to indicate that the vertical radiation pattern of the antenna system should include three principal lobes aligned with the pattern of radiation angles shown by the matrix. On the other hand, examination of the prediction tables of figures 2-7 and 2-8 shows that the two higher groups of radiation angles can be ignored (at least for the seasons and sunspot number of those computer runs) since there are frequencies that can be used with low radiation angles to maintain communication throughout the day. The matrix must be evaluated in conjunction with the four computer prediction tables (for June and December, and SSNs 10 and 100 for each month) to determine the minimum complement of frequencies and radiation angles that will satisfy the circuit requirements. The result of such an evaluation is illustrated by the dotted line of figure 2-9 which encloses the group of low radiation angles for which the antenna should be designed. The practical aspects of antenna selection or design are discussed in greater detail in NAVELEX 0101, 104 — "HF Radio Antenna Systems."

Propagation path analysis as discussed here is primarily applicable to point-to-point circuits. The same general procedure can be used to determine path requirements for other types of communications, such as ship-to-shore, but the voluminous computations involved limit practical application.

c. LUF-HUF Tables. As a by-product of the power prediction program, the computer can print tables of the LUF (lowest useful frequency) and the HUF (highest useful frequency) for a given circuit reliability. Such a table is shown in figure 2-10. An "x" in the table indicates that the LUF and the MUF do not exist. The frequencies are given in tenths of megahertz, a refinement over the lowest and highest frequencies that would be tabulated by underlining the prediction tables as was done in figures 2-7 and 2-8.



FREQUENCY

Data is from computer prediction tables of Figures 2-7 and 2-8 for June, SSN10 and December, SSN100. Marks indicate combinations of frequency and radiation angles for which reliability is 90%.

RADIATION ANGLE	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
35																													
34																													
33																													
32																													
31																													
30			X			X																							
29						X	X																						
28	X			X	X	X	X																						
27			X	X	X	X	X																						
26			X		X	X																							
25				X																									
24																													
23			X																										
22							X																						
21							X																						
20						X	X	X	X	X	X	X																	
19					X		X		X	X	X	X	X																
18	X	X		X		X	X	X	X	X	X	X																	
17	X			X	X		X	X	X	X	X	X	X																
16	X				X	X	X	X	X	X	X	X																	
15				X																									
14																													
13																													
12																													
11																													
10					X																								
9						X	X		X																				
8													X	X										X					
7								X		X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X				
6		X						X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
5		X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X		
4			X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X							
3			X	X	X	X	X	X	X	X	X	X	X	X	X	X													

Figure 2-9. Radiation Angle/Frequency Matrix

```
CIRCUIT NO.   2 ------------     JUNE      ------------ SUNSPOT NO.  10
   MIDWAY          TO  CLAM LAGOON         AZIMUTHS      N.MI.     KM.
 28.22N - 177.35W  51.90N - 176.70W        1.0 181.4     1422.1   2633.7
XMTR ANT GAIN     10(DB)                       RCVR ANT GAIN    10(DB)
OFF AZIMUTH    0 DEG.     MIN. ANGLE=  3 DEG.     OFF AZIMUTH    0 DEG.
PWR=  0.10KW         3 MHZ. MAN. NOISE = -148 DBW         REQ.S/N= 59DB.


THE LOWEST ( L ) AND THE HIGHEST ( H ) 90.0 PERCENT RELIABLE FREQUENCIES VERSUS THE HOUR GMT

                                GMT   L     H

                                 1    X     X
                                 2    X     X

                                 3    X     X
                                 4    X     X

                                 5    X     X
                                 6    X     X

                                 7  12.2  14.7
                                 8   8.8  15.0

                                 9   7.5  14.0
                                10   8.1   9.3

                                11   7.6   8.7
                                12   7.4   8.2

                                13   7.4   7.9
                                14    X     X

                                15    X     X
                                16    X     X

                                17    X     X
                                18    X     X

                                19    X     X
                                20    X     X

                                21    X     X
                                22    X     X

                                23    X     X
                                24    X     X
```

Figure 2-10. LUF-HUF Table

CHAPTER 3

GROUND-WAVE PROPAGATION

3.1 INTRODUCTION

Any discussion of Navy HF radio communications would be incomplete without some consideration of ground-wave propagation. The lower frequencies (2 to 4 MHz) of the HF band are used extensively in the ground-wave mode for local area broadcasts and close-in (from line of sight out to approximately 300 miles) ship-to-shore communications to fill the skip-distance gaps left by ionospheric propagation. The low end of the HF band is used for this purpose, in spite of high attenuation at these frequencies, primarily because efficient transmitting antennas for frequencies below the HF band are too large for shipboard installation.

A detailed discussion of ground-wave propagation is more appropriate for a handbook concerned with frequencies above and below the HF band, and, since handbooks covering communication systems in other parts of the spectrum are planned for future publication, the discussion of ground-wave propagation here will be brief.

3.2 DEFINITION OF GROUND-WAVE PROPAGATION

Ground-wave propagation is defined in various ways in the technical literature. For the discussion here the term "ground-wave" is defined as a radio wave traveling over the surface of the earth without dependence on reflection from either the ionosphere or the ground. This definition is not strictly accurate according to some authorities, but it is a common concept and, at the low end of the HF band, the inaccuracy is of no practical consequence.

3.3 MECHANICS OF GROUND-WAVE PROPAGATION

The physical mechanics of ground-wave progation are less complicated than those of sky-wave propagation. Ground waves are propagated within the troposphere (the first 7 to 10 miles above the earth's surface), there are fewer variables involved, and these are not subject to such random behavior and extreme excursions as is the case for sky-wave transmission.

Refraction in the troposphere and diffraction of energy toward the earth's surface account for the tendency of a ground wave to follow the contour of the earth's surface and thereby achieve transmission distances beyond the line of sight. In the troposphere, the index of refraction normally decreases with height so that a ground wave is bent, or tilted, toward the earth in a manner similar to the refraction of radio waves in the ionosphere. Additional tilting of the wave front is caused by diffraction of energy downward from upper portions of the wave to partially replenish energy absorbed by the earth.

The earth's surface exhibits electrical characteristics similar to a resistance shunted by a capacitive reactance. Since a horizontal electric vector represents a difference of potential directly across the earth's impedance, a horizontal electric field tends to be short-circuited by the earth. As a consequence, a horizontal electric field is attenuated much more rapidly than a vertical one. Therefore, vertical polarization must be used to obtain transmission distances of more than a few miles.

As a ground wave travels over the surface of the earth, energy is lost as a result of induced currents flowing through the earth's resistance. This ground loss, which increases with increasing frequency, depends upon the conductivity and dielectric constant of the surface of the earth. The effect of these ground constants is frequency dependent, and, moreover, the apparent thickness of the surface of the earth is also frequency dependent. At sufficiently low frequencies the earth appears to be predominently resistive and conductivity is the dominant factor; at sufficiently high frequencies the earth appears to be primarily a capacitive reactance and the effect of the dielectric constant is dominant. The surface depth contributing to these effects increases with decreasing frequency. At the frequencies of interest here, 2 to 4 MHz, conductivity is the dominant factor, especially over sea water, with the dielectric constant exerting some influence over land. In any case, sea water is the best "ground" because its conductivity and dielectric constant are much higher than any to be found in a land mass.

Typical values of ground constants normally associated with various types of terrain are given in table 4-4, but classifying ground as poor, good or sea water is adequate for practical purposes. The ground constants chosen to represent good and poor ground vary slightly in the literature but not enough to affect field strength calculations significantly. The ground-wave propagation curves included in this chapter are those for commonly used values, namely:

	Conductivity (mho/meter)	Dielectric Constant
Sea water	5	80
Good ground	10^{-2}	15
Poor ground	10^{-3}	5

Figure 3-1 shows the manner in which polarization and the three types of ground affect field intensities.

3.4 FIELD INTENSITY CALCULATIONS

Ground-wave propagation curves have been derived by rigorous mathematical analysis of the problem and are available for predicting field intensity as a function of frequency and of distance from the transmitter. Figures 3-2, 3-3 and 3-4 are sets of such curves for the three types of terrain defined in the preceding section. The curves are referred to an unattenuated field intensity of 186.3/D millivolts per meter, where D is the distance in miles from the transmitter. That is, the inverse distance line on the set of curves represents the field intensity that would exist, relative to 186.3 mV/m at one mile, if there were no losses other than spreading of the wavefront with distance. The reference field, 186. 3 mV/m at one mile (300 mV/m at one kilometer), corresponds to the case of an electrically short, lossless, vertical antenna, radiating 1 kW, placed on the surface of a perfectly conducting earth. This is an elementary monopole with a gain of 4. 76 dB relative to an isotropic antenna. The curves are for a smooth homogeneous earth, no allowance being made for the effects of hills, cities, vegetation, and the like.

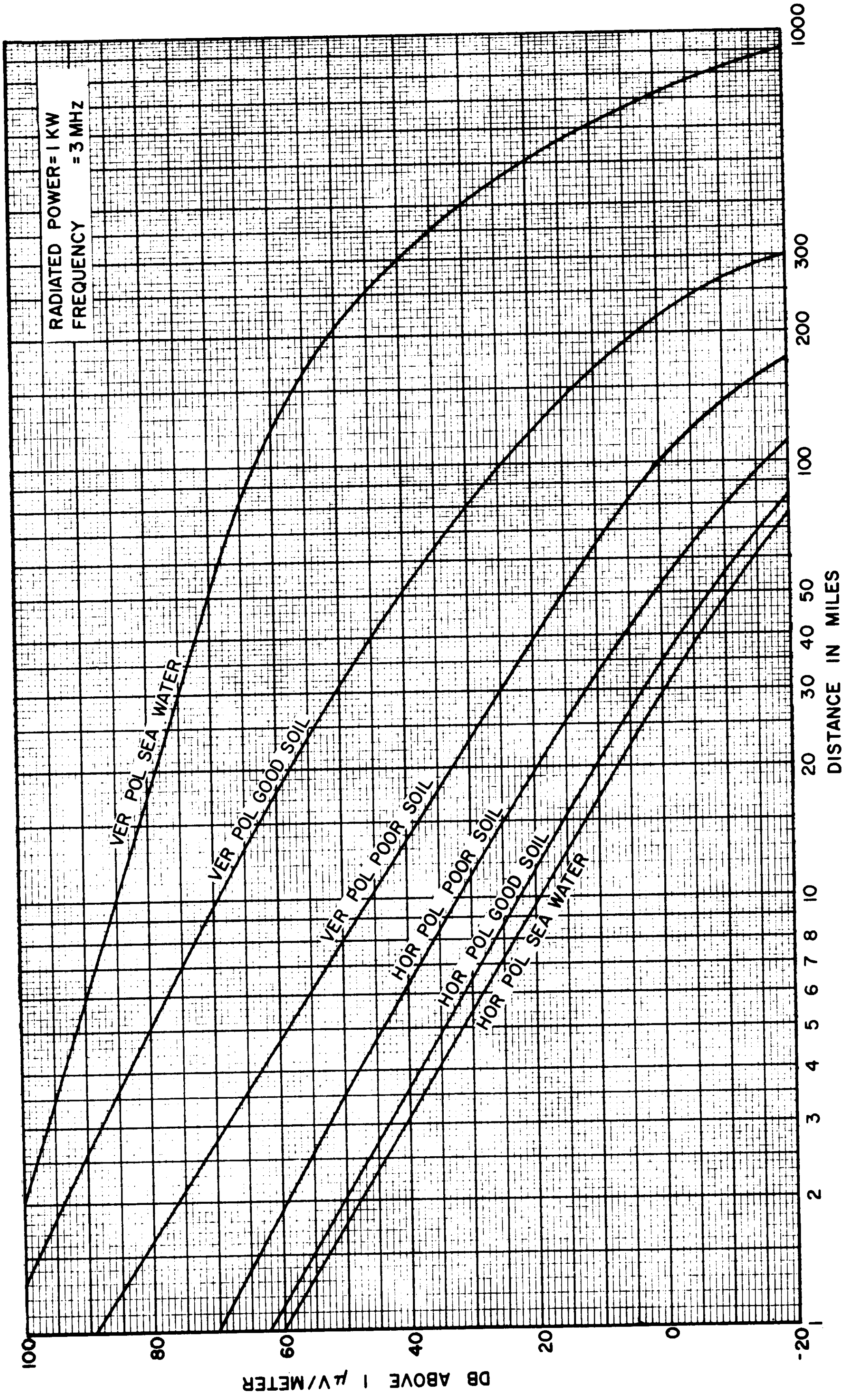


Figure 3-1. Elementary Dipole Propagation, Vertical and Horizontal Polarization

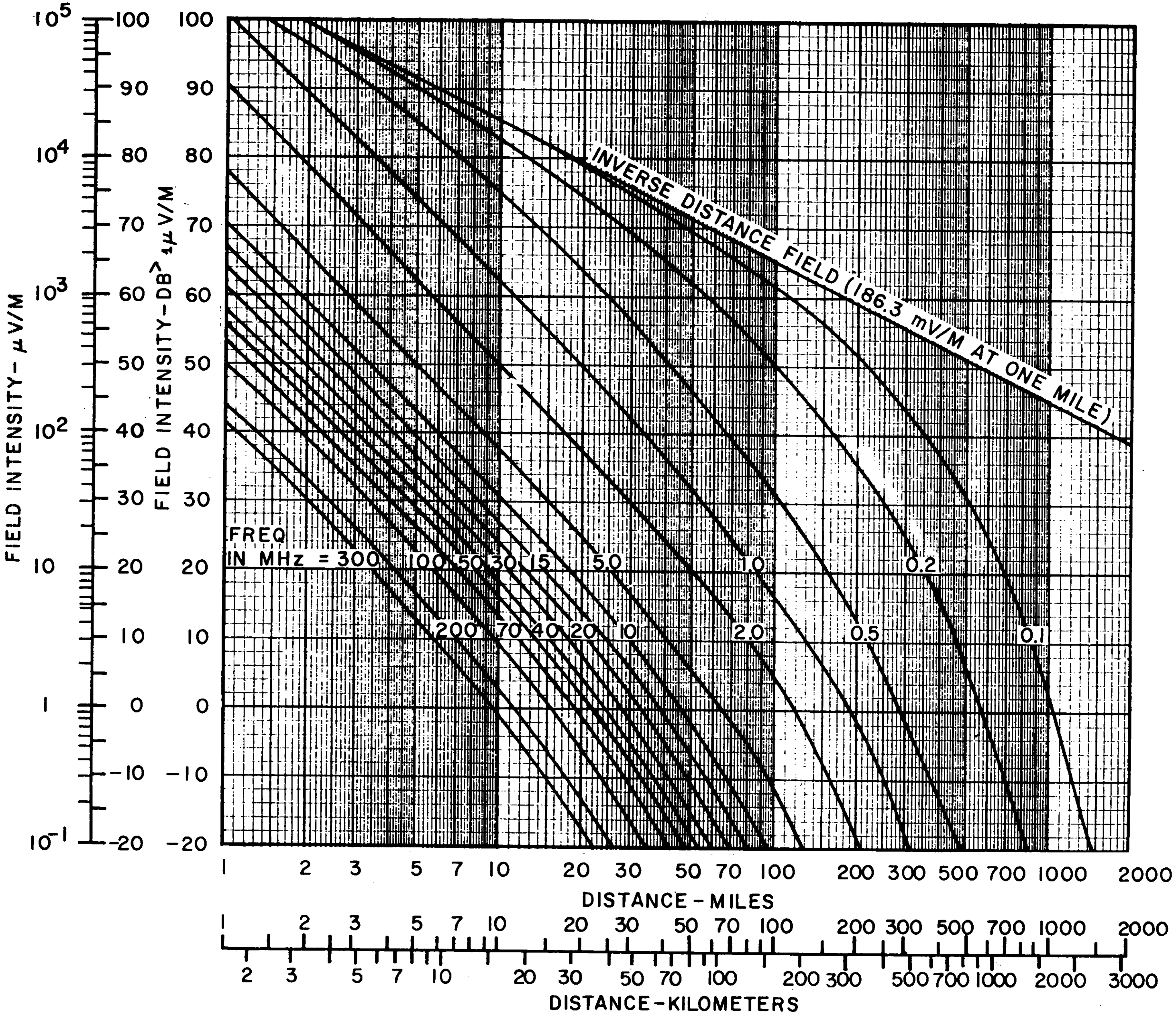


Figure 3-2. Ground-Wave Propagation Curves, "Poor Ground"

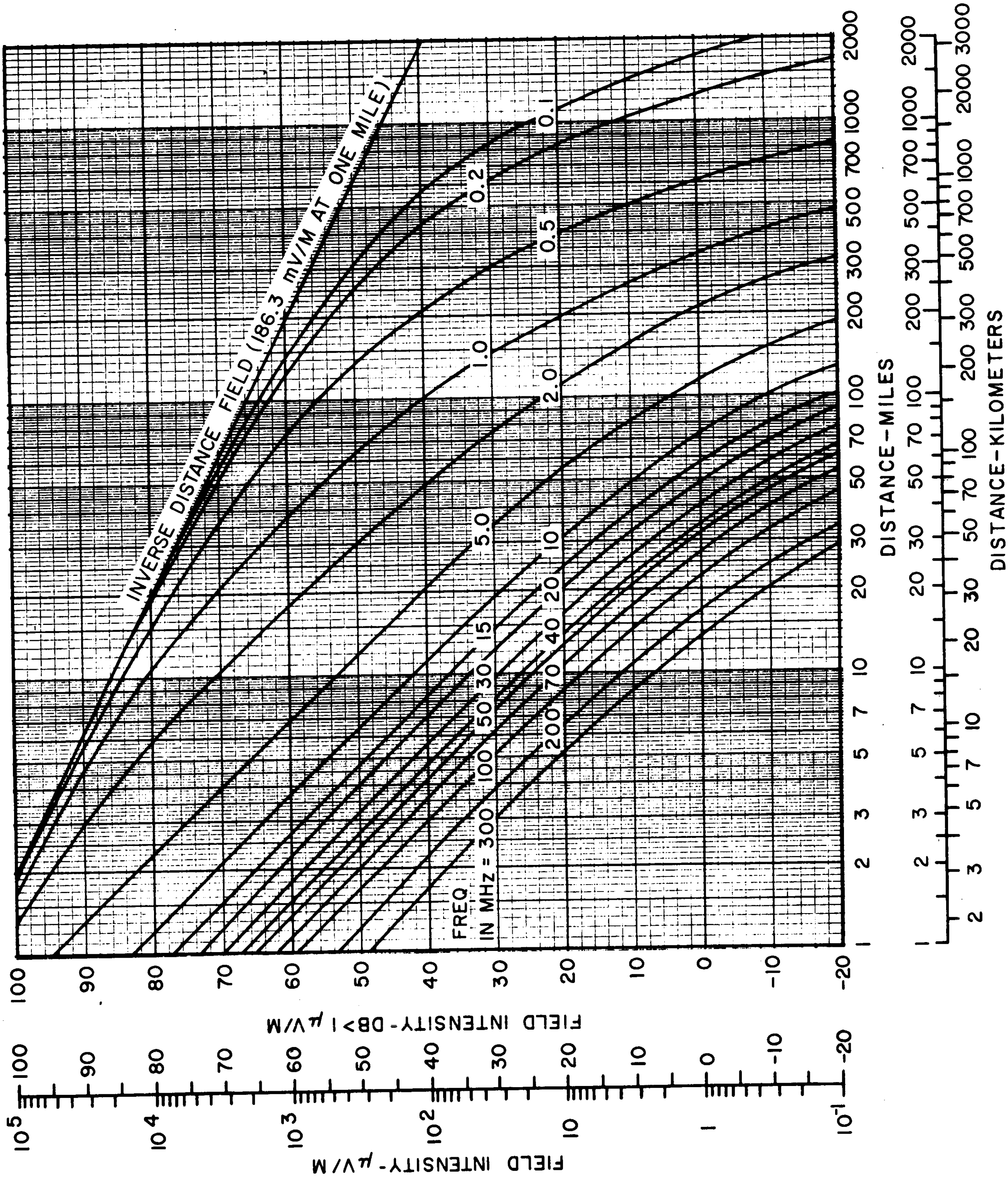


Figure 3-3. Ground-Wave Propagation Curves, "Good Ground".

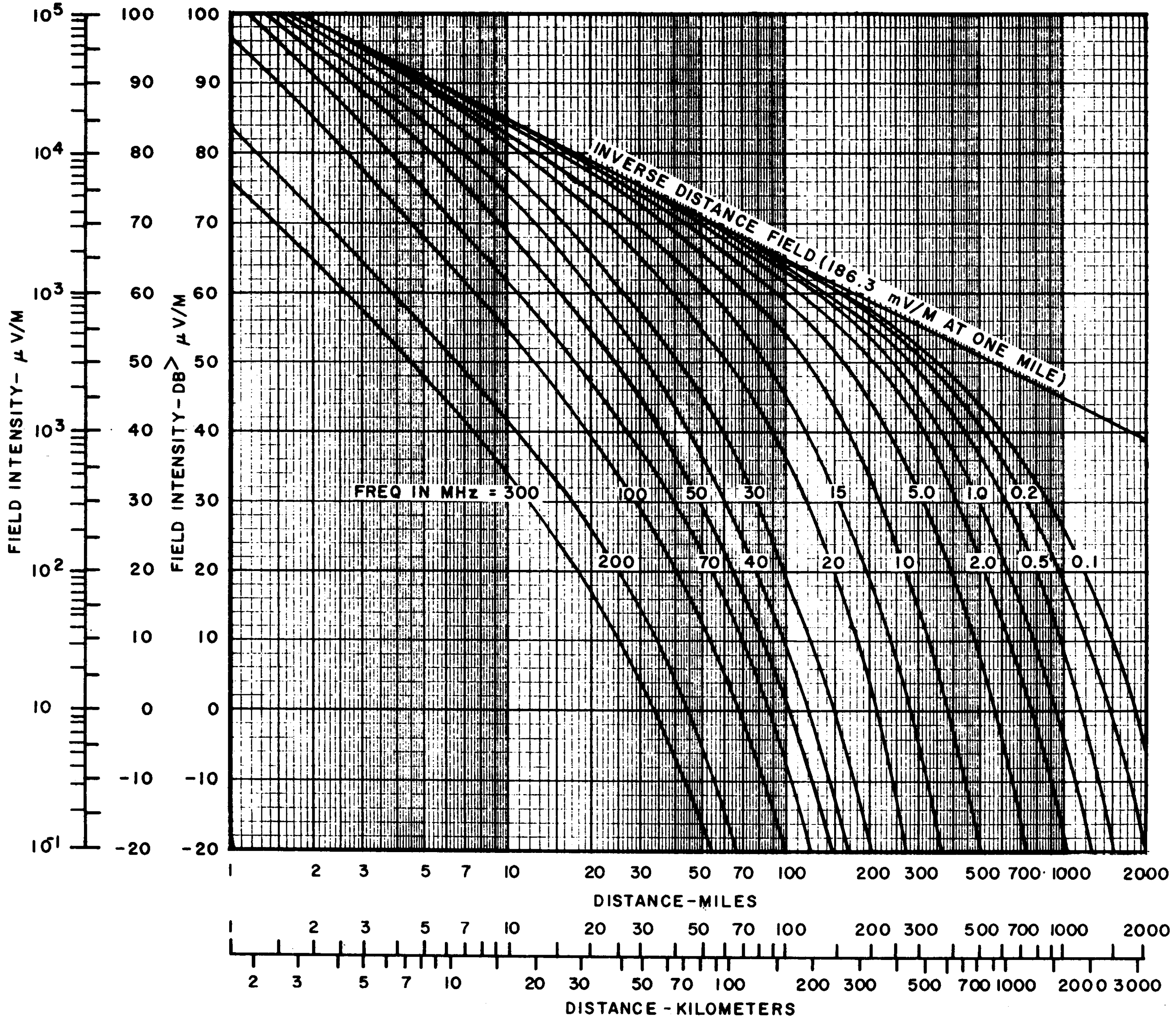


Figure 3-4. Ground-Wave Propagation Curves, Sea Water

3.4.1 Sample Field Intensity Calculations

The propagation curves can be used to predict ground-wave field intensities for conditions other than those for which they were drawn. The general procedure is to find the field intensity at the frequency and distance of interest, using the set of curves for the type of ground in the path, and then to correct this field intensity for the conditions that differ from those specified for the curves. To illustrate the procedure, two examples will be considered: one for the case where the terrain for the entire path can be considered as one type, i.e., either poor ground, good ground or sea water; and one for a mixed path where part of the distance is over land and part over sea water. Corrections for antenna height above ground are not considered since vertical HF antennas for surface communications are on or very near the ground.

a. Example 1 — Transmission path over good ground. Assume that the field intensity is required for the following conditions:

Transmission distance	100 miles
Operating frequency	2 MHz
Transmitting antenna gain	2 dB (above elementary monopole)
Antenna input power	2 kW
Type of intervening ground	Good

Figure 3-3 shows the field intensity at 100 miles on the 2 MHz curve as being 23 dB above 1 μV/m. This field intensity is corrected for the example conditions as follows:

Reference field intensity	23 dB
Antenna Gain	2 dB
Antenna input power (dB relative to 1 kW)	3 dB
Expected field intensity (dB above 1 μV/m)	28 dB

The conversion scale on the chart can be used to convert the result to approximately 25 μV/m.

b. Example 2 — Transmission over a mixed path. Two sets of curves (figures 3-2 and 3-4) are used for this case. To illustrate, assume the following conditions:

Transmission distance	100 miles
Operating frequency	2 MHz
Transmitting antenna gain	2 dB (above elementary monopole)
Antenna input power	2 kW
Type of ground	
First 20 miles from transmitter	Poor
Next 80 miles from transmitter	Sea water

The poor ground curve is used for the first 20 miles and then the sea water curve is used for 80 miles beyond the distance at which the sea water curve has the same field intensity as the poor ground curve has at 20 miles. From the set of curves for poor ground, figure 3-2, the field intensity at 20 miles on the 2 MHz curve is read as 37 dB above 1 μV/m. This field intensity is then used to enter the sea water curves, figure 3-4. The 37-dB field intensity intersects the 2-MHz curve at a distance of 340 miles. Then the field intensity for the mixed path is obtained by reading the value on the 2-MHz curve at a distance 80 miles greater, 420 miles. The result is 30 dB above 1 μV/m. The corrections for differences from the reference conditions are the same as for example 1 where the antenna gain and input power corrections amounted to 5 dB. Therefore, the field intensity to be expected at 100 miles is 35 dB above 1 μV/m, or 56 microvolts per meter.

3.5 POWER REQUIREMENT PREDICTIONS

Calculations of signal field intensities for a given frequency and distance from a transmitter are of little value unless the signal strengths are compared to the noise level likely to prevail at the receiving site. Moreover, there are occasions when, rather than to find the field intensity at a given location, it is more useful to determine the effective radiated power required to produce an acceptable signal-to-noise ratio at that location. In this case, instead of proceeding from a given transmitted power to a predicted signal field intensity, as in the previous examples, one must work backwards from a required signal-to-noise ratio to the required radiated power. To illustrate the procedure, assume that a signal-to-noise ratio of 29 dB is required 300 miles at sea from a transmitting station close to the shore line. Further, assume that the operating frequency is 3 MHz and the signal bandwidth is 3 kHz.

The noise level can be estimated in the manner described in paragraph 2.7.2e of chapter 2 using figures A-22, A-23 and A-24. Assume for this example that the noise estimate for a selected time and season, say 0400-0800 in summer, turns out to be –142 dBW for a 1-Hz bandwidth. This noise power level cannot be compared directly to signal levels read from the ground-wave propagation curves, since, for these curves, signal strength is expressed in terms of field intensity (μV/m). The nomogram of figure 3-5, extracted from CCIR Report 322, must be used to convert this noise power into noise field intensity. In figure 3-5, the noise factor F_a is defined by:

$$F_a = 10 \log \frac{p_n}{kT_o b} \qquad (3\text{-}1)$$

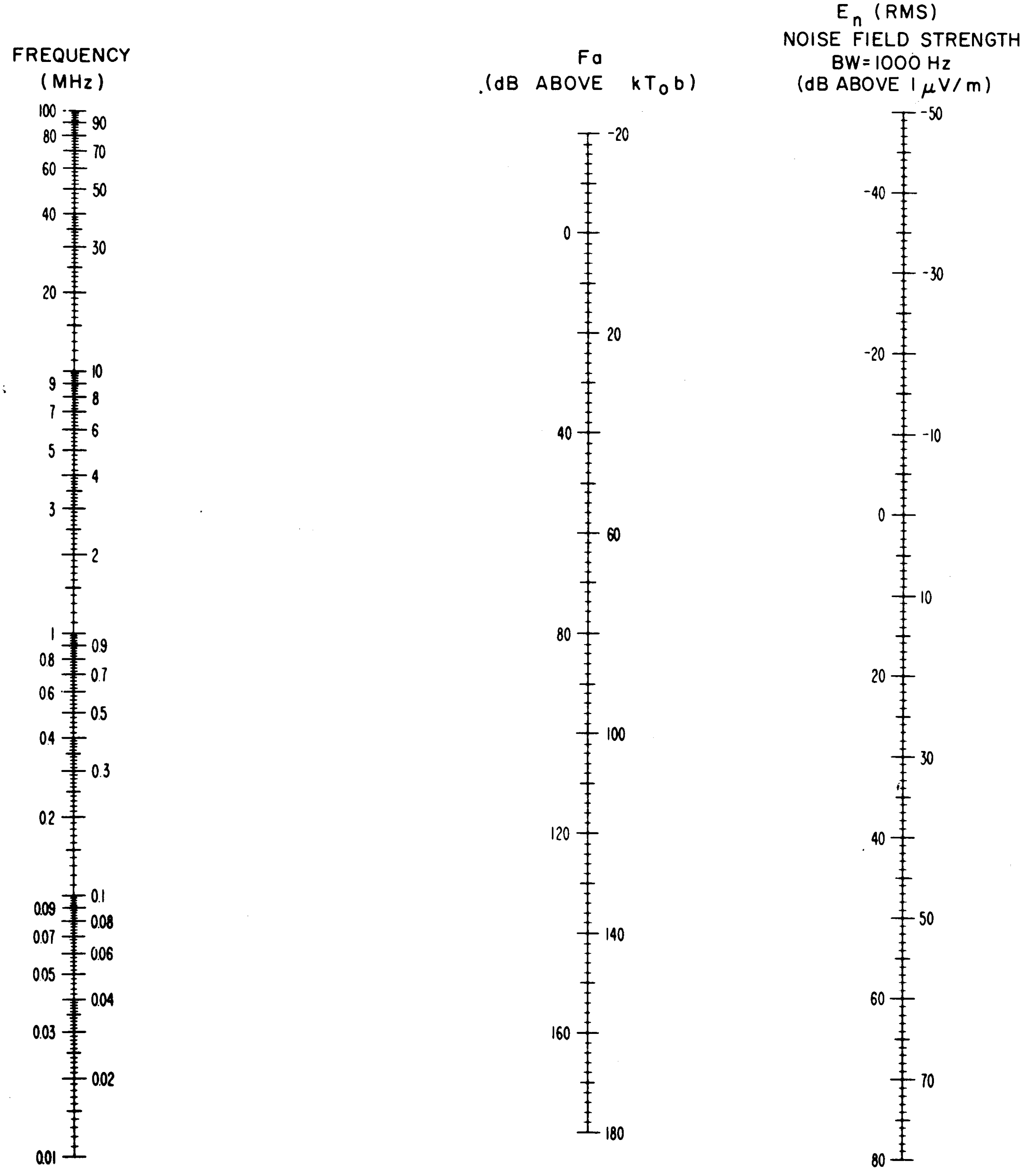
where p_n = noise power received from sources external to the antenna (watts)

k = Boltzman's constant = 1.38×10^{-23} Joules per degree Kelvin

T_o = reference temperature, 288° K

b = effective noise bandwidth (H_z)

If b is specified as 1 Hz, which must be done to match the bandwidth for the noise estimate above, 10 log $kT_o b$ is equivalent to 204 dB below one watt, or –204 dBW.



NOTE: FOR BANDWIDTH (BW) OTHER THAN 1000 Hz ADD $(10 \log_{10} BW/1000)$ TO E_n

Figure 3-5. Nomogram for Transforming Noise Power to Noise Field Strength

Therefore, the noise level, −142 dBW (1-Hz bandwidth), is equivalent to 62 dB above kT_0b, and the noise factor F_a is 62.

The nomogram, figure 3-5, can now be entered with the frequency, 3 MHz, and F_a = 62 to find the noise field strength E_n, in dB relative to 1 μV/m for a 1-kHz bandwidth. The result, E_n = 6 dB, is the noise field strength for a 1000-Hz bandwidth and must be adjusted to match the signal bandwidth of 3 kHz. This is done by following the instructions in the note on the nomogram, and in this case the correction is 10 log 3 = 4.8 dB. This correction factor is added to 6 dB to yield 10.8 dB above 1 μV/m for the noise field strength in the occupied bandwidth. The required signal field intensity to produce a 29-dB signal-to-noise ratio, then, is 29 + 10.8 or approximately 40 dB above 1 μV/m.

From figure 3-4, the field intensity at 300 miles for 3 MHz is 38 dB. This is the field that would be produced by a short vertical antenna radiating one kilowatt, and it is 2 dB less than the required 40 dB calculated above. The effective radiated power (ERP) to produce the desired signal field intensity is found from the relationship,

$$10 \log \mathrm{ERP}/1000 = 2 \text{ dB},$$

from which, the ERP = 1582 or approximately 1600 watts.

Trade-offs can now be made between antenna gain and transmitter output power to select the transmitter and antenna design to produce the required effective radiated power.

In this example, the computation was made for only one time block in one season. In practice, to establish requirements for a permanent station, the procedure would be repeated for other time blocks and seasons. This would establish a broader base of data and would reveal the worst-case conditions. Moreover, some allowance, in terms of additional radiated power, normally would be made for excursions of noise power above the median valves given in the predictions.

CHAPTER 4

SITE SELECTION

4.1 PRIMARY REQUIREMENTS

The primary consideration in the selection of any shore radio site is the suitability, or technical adequacy, of the site for meeting the communication performance objectives. Generally, the objectives are (1) maximum signal-to-noise ratio at the receivers and (2) maximum effective power radiated in the desired direction from the transmitters. However, other factors enter into the selection of sites for communication facilities and certain compromises are usually involved before the final selection is made. This is a normal situation for engineering work, but the planner must determine that compromises in favor of economy, logistic convenience, or other factors will not preclude satisfactory circuit performance.

Radio-frequency noise and topography are the principal considerations for technical adequacy, but suitability for construction at reasonable cost, link requirements between components of the communications station, land costs, and logistic support requirements must also be considered.

The considerations leading to the selection and proper development of the site must be understood and applied to the site development plan. These considerations must be taken into account in arriving at the basic requirements for the project, and should be cited in the BESEP. The BESEP (or possibly another type of planning document) contains detailed resource requirements for a proposed communication facility and sets forth technical details bearing on site selection. Numerous factors, including those listed in this chapter, must be considered carefully in the final selection of a site. A preliminary study of topographic maps and other information concerning the area may help in eliminating certain sites from consideration. At the same time, potential sites can be identified. Then these sites can be investigated more thoroughly by on-site survey teams. Forms for use by teams investigating potential sites are contained in appendices B, C and D. Appendix B is to be used for surveying a proposed receiver site, appendix C for a transmitter site, and appendix D for a communication center site.

Numerical limitations are not specified for individual factors involved in the choice of a site since final selection is a matter of subjective judgement based on a composite of many factors, not all of which are technical. The choice of a site usually involves compromises which should not be affected by arbitrary decisions concerning any single factor.

The possibilities for future expansion are an important consideration in site selection, and comments concerning the expansion potential should be included in the site survey report whether or not requirements for expansion are given in the BESEP.

4.2 SIGNAL SURVEYS

Because of the variable behavior of the ionosphere, it is generally impractical to evaluate long-distance signal reception at a proposed site by means of signal field-strength measurements. Statistically significant data for sky-wave transmissions cannot be obtained by measurements taken over a short time. It is, however, feasible to assess the utility of a site for successful transmission or reception of ground-wave signals and to make measurements for this purpose.

4.3 RF NOISE LEVEL

The radio-frequency noise level is of primary significance for a receiver site and of less importance for a communications center or a transmitter site.

4.3.1 Receiver Site

For reliable reception of weak signals from distant stations, the receiving antennas must be located in an electromagnetically quiet area, one relatively isolated from man-made noise. Of the three major sources of RF noise, galactic, atmospheric, and man-made, the latter is of chief concern since it is the one over which some control can be exercised. The importance of locating a receiver site in an electromagnetically quiet area is illustrated in figure 2-8. A comparison of the curves of man-made noise levels for "remote unpopulous, " "rural, " "residential, " and "industrial" areas clearly points out the difference in noise level between the "industrial" and "remote unpopulous" areas (approximately 40 dB for frequencies between 10 and 30 MHz). The galactic and atmospheric noise curves shown in the figure illustrate the inverse relationship between frequency and noise. The radio noise levels of figure 2-8 (and also of A-28) for "remote unpopulous" areas may be converted directly to the values of the CCIR Report 322, which expresses noise in terms of KT_ob, by subtracting the valves of figure 2-8 from 204.

Once established in a quiet area, a receiver site must be protected from encroachment to ensure it will remain quiet. Wherever possible, this protection should be secured by legal procedures. Future construction that may adversely affect communications should be legally prohibited within a zone, shown in figure 4-1, surrounding the site beyond the station-owned protective corridor. Registry of this encircling land area in accordance with local and state laws to restrict further development is the most desirable means of providing necessary site protection. Alternative methods of ensuring protection of the quiet zone are through zoning regulations which limit land development (again, registry in accordance with local and state laws is required), or by entering into land-use covenants with all owners of the required restricted land area. However, these two alternative methods are generally less effective because of increased real estate costs, time consumed in negotiation, and possible future litigation.

a. Receiver Site Isolation Requirements. Table 4-1 gives criteria for separation of a receiver site from other components of a communications station and from sources of interference. This data, although proven valid by experience, is usually verified by signal and noise measurements at the sites being considered.

b. Receiver Site Man-Made Noise and Unwanted Signal Survey Requirements. Field strength measurements must be made at receiver sites to evaluate the level and population of unwanted signals, to establish the ambient noise level, and to

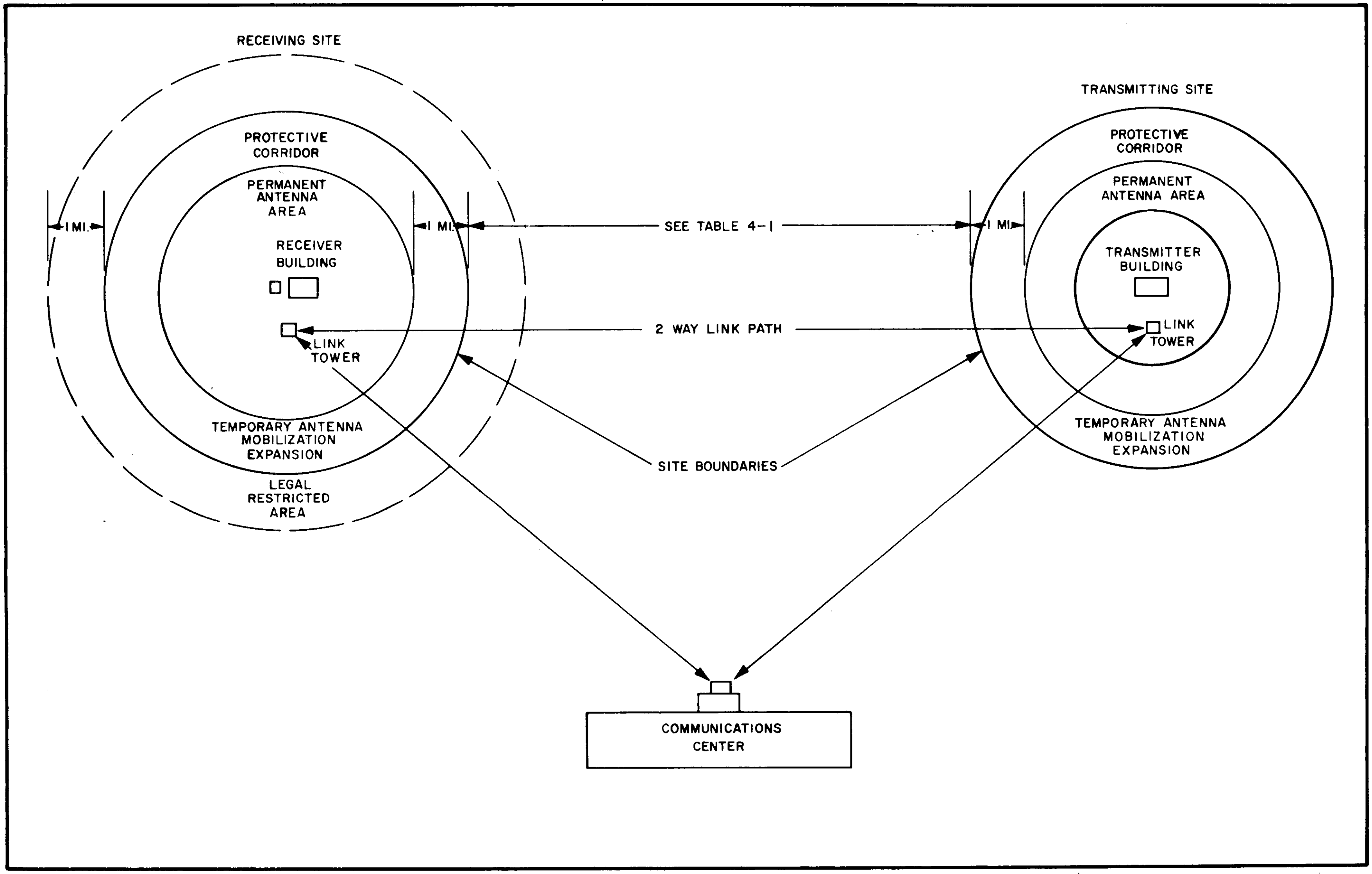


Figure 4-1. Separation Criteria for Naval Communications Station Components

Table 4-1. Receiver Station Separation Distances

SOURCES OF INTERFERENCE	MINIMUM DISTANCE
High-power transmitter stations:	
VLF	25 mi
LF/HF	15 mi
Other transmitters not under Navy control	5 mi (see note 1)
High-voltage power lines 100 kV or greater:	2 mi
Receiver station power feeders:	1000 ft from nearest antenna
Airfields and glide paths:	
For general communications	5 mi
For aeronautical receiving at air station	1500 ft
Teletype and other electromechanical systems:	
Low level operation or installed in shielded room	No minimum
High level operation installed in unshielded room	
Large installation (communications center)	2 mi from nearest antenna
Small installation (1 to 6 instruments)	200 ft from nearest antenna
Main highways:	1000 ft
Habitable areas (beyond limits of restriction) :	1 mi
Areas capable of industrialization (beyond limits of restriction - see note 2) :	
Light industry	3 mi
Heavy industry	5 mi
Radar installation:	(See note 3)
Primary power plants:	5 mi

Note 1: The following NAVELEX requirements also govern distances to non-Navy transmitter stations:
(a) Signal from non-Navy station shall not exceed 10 millivolts per meter (field intensity) at Navy site boundary.
(b) Harmonic or spurious radiation from the non-Navy station shall not exceed 5 microvolts per meter (field intensity) at the Navy site boundary.

Note 2: The restriction limit is the protective corridor; i.e., that area between the outer limits of antenna field and the site boundary.

Note 3: Calculate using "Electromagnetic Prediction Techniques for Naval Air Stations," White Electromagnetics, Inc., Rockville, Maryland, NObsr 87466.

locate sources of RF interference. An initial survey with mobile equipment is well advised. Spot checks on main highways and country roads located within ten miles of the site can identify noise sources and give an indication of the potential interference level. The utility of this type of preliminary noise survey improves in proportion with the time one spends in obtaining data at various times of the day at many locations.

Ultimately, a final survey must be conducted from near the center of each receiver site being considered seriously. This survey should extend over sufficient time (usually several days) to gather statistically significant data for the man-made noise characteristics of the site. Noise field strength measurements must be recorded to determine the ambient noise level for the site throughout the frequency spectrum of interest at various times of the day.

It is not always possible to separate individual noise sources from the composite noise level. One way to determine the level of a particular source is to make measurements at the source and determine the effect at the receiving site by calculating the attenuation as the inverse of the distance squared. Use of a loop antenna to provide directivity will aid in determining the direction of the source of interference from the station.

4.3.2 Transmitter Site

The principal concern in selecting a transmitter site is its potential for creating RF interference with other operations such as receiving stations and local commercial broadcast reception. This, and the large area needed for the antenna park forces the choice of a site remote from populated and industrial areas.

An extensive noise survey is usually not required. Siting transmitters in an area where interference will not cause adverse effects is more important than choosing a site with a low ambient noise level. The criteria given in table 4-2 apply to separation of the transmitter site from other facilities.

4.3.3 Communications Center

In general, the RF noise level ranks low among other factors that influence or dictate the location of a communications center. Operational and administrative considerations are often decisive, as long as other less-than-ideal conditions can be either tolerated or improved.

As with the transmitter site, a noise survey is not generally required, but care should be taken to separate the communications center from large generators, power transformer stations, heavy industrial equipment, high-powered HF transmitters and other obvious sources of interference. A principal objective is to prevent high-level noise or signals from interfering with DC signaling within the communications center. The established separation criteria are given in table 4-3.

Many communications centers are located on naval stations near the commands being served. However, proximity to the subscribers is only one factor to consider, not a controlling consideration. The site must be selected on the basis of overall operating efficiency consistent with economy and technical requirements. For example, a site selected for direct line of sight between the communications center and the transmitter and receiver sites will reduce the difficulty and expense

Table 4-2. Transmitter Station Separation and Clearances

FACILITY	MINIMUM DISTANCE
Overhead high-tension power lines	1000 feet from nearest antenna
Main highways	1000 feet
Other transmitter stations	3 miles
Airfields and glide paths	3 miles when the station is used for general purpose communications — 1500 feet when the station is used in conjunction with air operations
Communications center	25 miles when VLF transmitters are installed — 15 miles when LF and HF transmitters are installed
Receiver site	25 miles when VLF transmitters are installed — 15 miles when LF and HF transmitters are installed

of establishing microwave links between the sites. This advantage may outweigh other factors such as proximity to a major command.

4.3.4 Relationship Between Sites

The criteria shown in figure 4-1 for separation between components of a communications station are intended primarily to avoid radio frequency interference. Additionally, the requirement for interconnecting links is important in selecting relative locations favorable to line-of-sight microwave transmission. The maximum distance between transmitter and receiver stations is limited only by the microwave path and logistics. For the majority of applications this distance should be limited to about 30 miles. This normally will permit operation of a single-hop microwave system and will allow each component of the station to be supported logistically from a centralized location.

4.4 TOPOGRAPHY

An accurate, detailed description of the surface features of potential HF transmitting and receiving sites is necessary before a meaningful trade-off study can be undertaken to select the best site. However, a preliminary survey or map study of the general area may quickly rule out obviously unsuitable sites and may establish the marginal features of those sites to be investigated further.

Table 4-3. Communications Center Separation and Clearances

SOURCE OF INTERFERENCE	MINIMUM DISTANCE
VLF transmitters	25 miles
LF, HF transmitters	15 miles
Transmitters not under Navy Control	5 miles*
Main highways	1000 feet
Areas capable of industrialization	3 miles (light industry) 5 miles (heavy industry)
Radar installation	1500 feet
Primary HF receiver building and antenna field	1 mile
Primary power plant	1500 feet

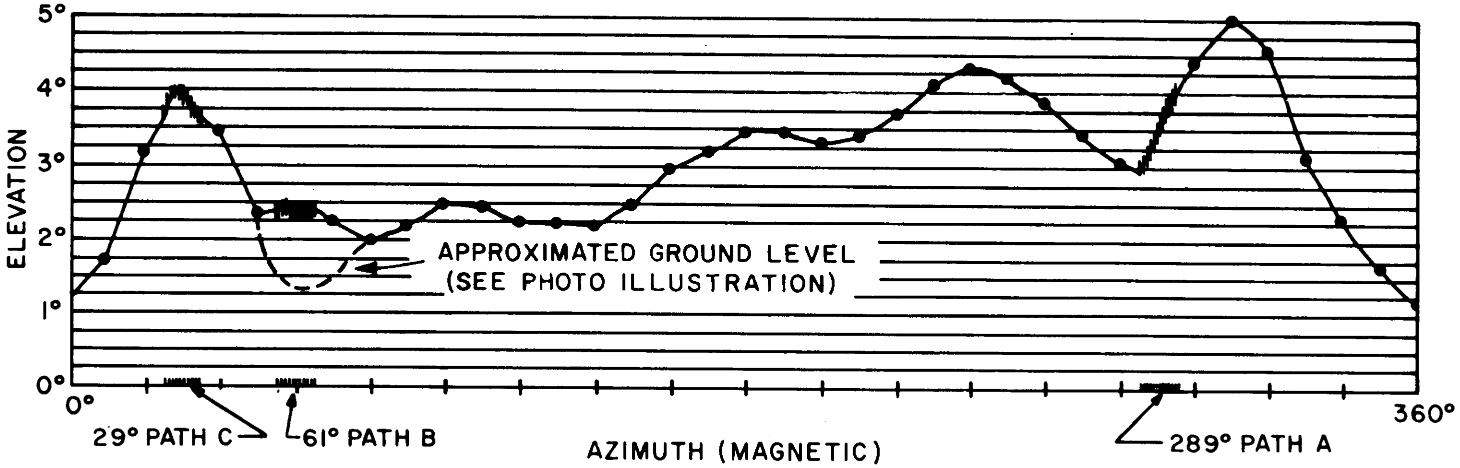
*Signal from a non-Navy station may not exceed 10 millivolts per meter (field intensity) at the location of the building.

4.4.1 Practical Objectives

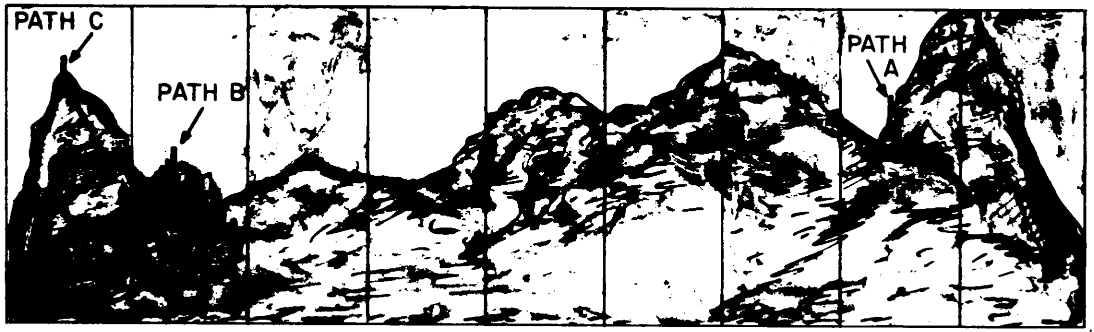
Ideally, an antenna park should be located on flat, highly conductive ground with no obstructions on the horizon. The practical objective, however, is to find a sufficiently large area of reasonably flat or rolling terrain with no obstructions extending more than 5° above the horizontal plane from any point in the antenna field. Areas of rock outcroppings should be avoided since this type of ground will have non-uniform ground constants and will increase construction costs. Again, being practical, an obstruction above the 5° radio horizon may be acceptable depending upon its location relative to the desired directions of propagation.

4.4.2 Site Profiles

The radio horizon profile of each potential site should be documented in a manner appropriate for the site being considered. In some cases, a simple statement that the land is flat with a perfectly clear horizon all around is sufficient. In other cases, such as when an installation must be made in generally undesirable terrain, a detailed azimuth-elevation profile must be made. Such a profile may be drawn by using a transit and a compass with the azimuth readings corrected for the local magnetic variation. Normally, plotting the elevation at 10 increments of azimuth will be satisfactory. In those cases where sites with obstructions must be considered, additional data should be plotted near the azimuths of the anticipated



a. PROFILE DRAWING



b. COMPOSITE PANORAMIC PHOTOGRAPH (ILLUSTRATION)

Figure 4-2. Site Profile Presentations

propagation paths. A sample plotted profile is shown in figure 4-2a with additional elevation plots centered on the azimuth of each of three anticipated paths.

Photographic techniques can be used to produce site profiles that show considerably more detail than does a plotted profile. When such detail is considered necessary, a leveling transit used with a panoramic camera is the simplest, most direct approach. However, the specialized equipment needed is normally available only by contracting for the work. Alternatively, an ordinary camera can be used to portray the horizon by making a number of exposures around the horizon and identifying the azimuths of prominent skyline features so that the photographs can be combined into a composite such as that shown in figure 4-2b.

4.5 GROUND CONSTANTS

The conductivity and dielectric constant of the earth are of concern in site selection primarily because of their effect on ground-wave propagation. Secondary considerations involve the effect of these electrical characteristics on antenna patterns and on the ability to obtain a satisfactory ground connection for power and for the electronic equipment.

4.5.1 Effect on Ground-Wave Propagation

As discussed in chapter 3, the conductivity and dielectric constant of the ground along the propagation path have a marked effect on ground-wave signal strength. The propagation charts of chapter 3 show these effects clearly.

If a site will be used for ground-wave transmissions to or reception from ships, a location close to the shoreline is obviously best. However, if a shore site cannot be obtained and inland sites must be considered, suitability can be estimated initially from the charts given in chapter 3. Figure 4-3 shows typical values of ground conductivity within the United States and table 4-4 lists typical values of dielectric constant and conductivity for various types of terrain. For practical purposes assume "Poor" ground conditions for initial computations. Although methods of measuring soil conductivity exist (two methods are presented in NAVELEX 0101, 102, chapter 12), a more practical method of investigating propagation conditions is to transmit signals from various sites and measure their respective signal strengths along the coast line or preferably aboard a ship at sea.

4.5.2 Effect on Antenna Performance

The electrical characteristics of the ground for an antenna park affect the antenna radiation patterns, but in a relatively minor way. The importance of a uniformly high soil conductivity has decreased as antenna design techniques have improved.

Ideally, vertically polarized antennas should be located in areas of high ground conductivity to provide a low-loss return path for ground currents. In actual practice, however, the importance of high ground conductivity is minimized by the fact that vertical antennas (discones, sleeves, conical monopoles, etc.,) normally are installed over a metallic ground system to ensure the low-loss return current path, and to provide impedance stability over the design bandwidth of the antenna.

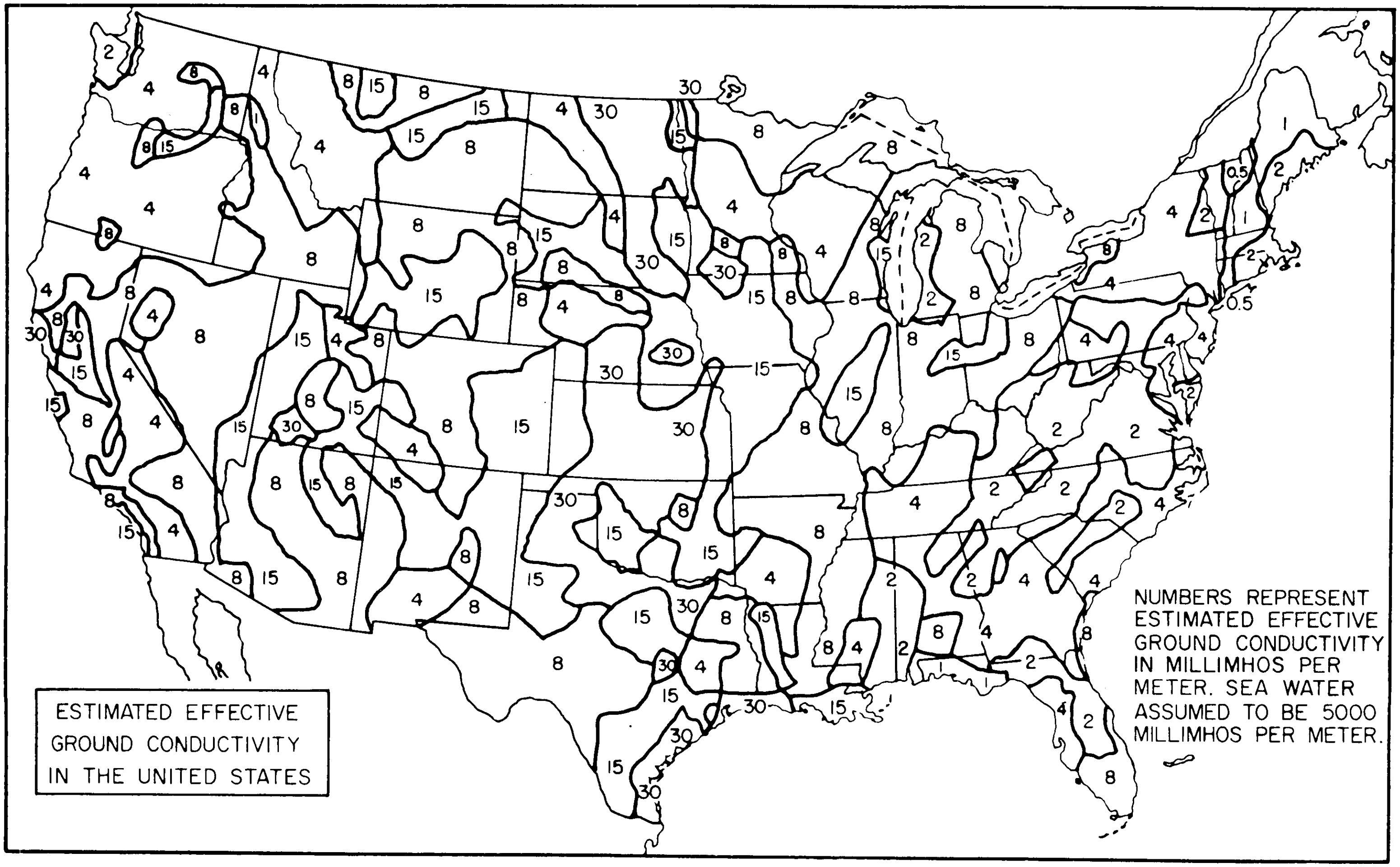


Figure 4-3. Ground Conductivity in United States

Table 4-4. Typical Ground Constants

TYPE OF TERRAIN	DIELECTRIC CONSTANT	CONDUCTIVITY, mhos/meter
Fresh Water	80	1×10^{-3}
Sea water, minimum attenuation	81	4.64
Pastoral, low hills, rich soil, typical of Dallas, Texas; Lincoln, Nebraska area	20	3×10^{-2}
Flat country, marshy, densely wooded, typical of Louisiana near Mississippi River	12	7.5×10^{-3}
Pastoral, medium hills and forestation, typical of Maryland, Pennsylvania, New York, exclusive of mountainous territory and seacoasts	13	6×10^{-3}
Rocky soil, steep hills, typical of New England	14	2×10^{-3}
Sandy, dry, flat, typical of coastal country	10	2×10^{-3}
City, industrial areas, average attenuation	5	1×10^{-3}
City, industrial areas, maximum attenuation	3	1×10^{-4}

*To convert mhos per meter to emu, multiply by 10^{-11}.

In cases of horizontally polarized antennas, e.g., rhombics, an ideal location is one where a body of water extends several miles in front of the antenna. However, these antennas perform efficiently if they are located over reasonably flat ground, and have an unobstructed path in the desired propagation direction. Generally, horizontal antennas do not require high ground conductivity for effective sky-wave propagation. The electrical characteristics of the earth have little effect so long as the antenna is erected at least one-quarter wavelength above the earth's surface.

Since the soil conductivity at a potential antenna park is of relatively minor importance compared to other factors, extensive measurements of conductivity throughout the area are not required. Reasonably flat terrain, and economic and logistic support requirements for the site are overriding considerations in most cases.

4.5.3 Effect on Establishing Station Ground

Soil conductivity measurements are required to determine the feasibility and difficulty of establishing a ground connection adequate for personnel and equipment protection. In general, one connection to ground is made for this purpose, and all power and equipment grounds are connected to a ground bus leading to this connection. This subject is discussed in NAVELEX 0101, 102, chapter 12, where a standard method of measuring the ground connection is given.

4.6 HF RADIO FREQUENCY HAZARDS

Radio frequency (RF) radiation is a potential hazard to personnel, certain types of ordnance material, and fuel supplies. As such, it is a factor to be considered in selecting HF transmitter sites.

In recognition of RF hazards, various criteria have been established by responsible commands and agencies. A recent confidential directive, NAVORD 3565/NAVAIR 16-1-529 — "Technical Manual, Radio Frequency Hazards to Ordnance, Personnel, and Fuel" (U), has been issued on the subject. Although the principal criteria set forth in this directive concern the shipboard RF environment, some criteria for shore stations are also prescribed.

Compliance with the separation and clearance criteria for location of HF transmitter sites given in table 4-2 will eliminate much of the potential hazard normally associated with electromagnetic radiation.

4.6.1 Hazards to Personnel

RF radiation can be hazardous to personnel in two different ways — either through absorption of radiated energy by various parts of the body or through physical contact with induced voltages resulting in shock and/or RF burns.

a. Absorbed Radiation. Presently known detrimental effects of overexposure to RF radiation are associated with the average power of the absorbed radiation, are thermal in nature, and are observed as an increase in overall body temperature, or as a temperature rise in certain sensitive organs of the body. It has been determined that normally for any significant effect to occur, a person's height would have to correspond to at least one-tenth of a wavelength at the radiation frequency.

The Bureau of Medicine and Surgery has established safe limits based on the power density of the radiation beam and the exposure time of the human body in the radiation field as follows:

(1) Continuous Exposure. Average power density not to exceed 10 milliwatts per square centimeter.

(2) Intermittent Exposure. Incident energy level not to exceed 300 millijoules per square centimeter per 30-second interval. (Power density, in mw/cm^2, divided into 300 gives the portion of a 30-second interval that is safe for intermittent exposure.)

(3) Hazardous Areas. All areas in which the RF levels exceed prescribed safe limits shall be considered hazardous. As a general rule, small aperture antennas such as dipoles operated at high power levels present the greatest potential hazard because their power density is concentrated in a small area near the antenna.

The area in the vicinity of HF transmitting antennas should be restricted to prevent inadvertent entry into hazardous areas. In all cases, restriction must be enforced to prevent personnel from being exposed to either continuous or intermittent power levels in excess of the prescribed safe limits.

b. Shock and RF Burn Hazards. In addition to the direct radiation hazards to personnel there also exist hazards from shock and RF burns. The hazard attendant to physical contact with a radiating antenna is well recognized, but shock hazards can also arise from voltages induced upon metal objects by electromagnetic radiation. These induced voltages can be of sufficient magnitude to create a shock hazard and/or cause RF burns to personnel. Similarly, the induced voltages may produce open sparks or arcs when contact between conductive objects is made or broken. Hazardous conditions caused by RF induced voltages can be reduced considerably by proper grounding and bonding of buildings and equipments. Methods for grounding and bonding of buildings and equipments are discussed in NAVELEX 0101, 102.

4.6.2 Hazards of Electromagnetic Radiation to Ordnance (HERO)

Electromagnetic radiation can, under certain conditions, detonate electroexplosive devices (EEDs) contained in ordnance materials. NAVORD 3565/NAVAIR 16-1-529 lists three classifications of ordnance materials based on the susceptibility of these materials to radiation hazard: (1) HERO SAFE, (2) HERO SUSCEPTIBLE, and (3) HERO UNSAFE.

The HERO UNSAFE ordnance materials are the most susceptible to RF radiation and constitute the "worst case" situation for shore communications transmitters. Any ordnance item is defined as being HERO UNSAFE when any of the following conditions exist:

a. When its internal wiring is physically exposed.

b. When additional electrical connections are required for the item being tested.

c. When handling or loading EEDs having exposed wire leads.

d. When assembling or disassembling the item.

e. When the item is in a disassembled condition.

Ordnance items that are in one of the above conditions may be exempted from being classified as HERO UNSAFE as the result of previous HERO tests or analyses which are recorded for specific equipments in the NAVORD/NAVAIR directive.

The above directive prescribes that measurements of field intensity will be used to ascertain the magnitude of an electromagnetic field, and further prescribes that the field intensity of electromagnetic fields at communications frequencies (200 kHz to 1000 MHz) will be referred to in terms of vertical electric field strength in units of volts per meter. A chart in the directive indicates that for HERO UNSAFE ordnance the maximum safe field intensity is 0.2 V/m throughout the 2 to 32 MHz frequency range.

The established criteria of a maximum vertical field strength of 0.2 V/m for HERO UNSAFE ordnance could become a stringent restriction for radiation from communication transmitters of reasonably high power. A table in the NAVORD/NAVAIR directive shows a minimum distance of 8700 feet for HERO UNSAFE ordnance exposed to a 5-kW transmitter operating in the CW mode, and 17,400 feet for the same transmitter operating amplitude modulated.

The foregoing distance and field intensity restrictions are based on unprotected HERO UNSAFE ordnance materials which present the worst conditions that may be encountered. However, a number of ordnance systems are HERO SAFE (not susceptible to radiation) under all conditions, and a large majority of other ordnance systems are classified as HERO SUSCEPTIBLE under most conditions. The maximum safe field intensity prescribed for HERO SUSCEPTIBLE ordnance is 2.0 V/m throughout the 2 to 32 MHz frequency range.

Since the allowable maximum safe field intensity varies widely for the three classifications of ordnance systems it is quite important to ascertain from competent authorities whether ordnance systems will be handled or stored in the vicinity of a proposed transmitter site. If items of ordnance are to be handled or stored, the classification of the ordnance most sensitive to RF radiation will determine the maximum field strength that can be tolerated.

4.6.3 Fuel Hazards

Although the problem of fueling in an RF environment has been the subject of extensive research and study, precise criteria have not been developed.

a. General Guidance. General guidance, based on NAVSO P-2455 — "Safety Precautions for Shore Activities," is as follows:

(1) Transmitters with 250 watts radiated output or less should not be installed within 50 feet of fuel handling or fueling areas, and

(2) Transmitters with over 250 watts radiated output should not be installed within 200 feet of fuel handling or fueling areas.

Although the second portion of the above guidance implies that no problem would exist for distances greater than 200 feet, regardless of the radiated power, this is not the case. For transmitters with output power in excess of 250 watts, separation from a fuel handling or fueling area should be such that the power density in the fueling area is no greater than would exist at a distance of 50 feet from 250 watts radiated output. Figure 4-4 shows the distance in feet from a conical monopole antenna required for various transmitter power outputs to provide the equivalent power density that would exist at a distance of 50 feet from 250 watts radiated power output. Because of the many factors involved, the above approach is considered only as general guidance and therefore should serve as an approximate method of determining whether a fuel hazard may exist. Upon completion of an installation, tests should be conducted to determine if arcing occurs in fuel handling or fueling areas.

b. Conditions for Gasoline Ignition. In order for high octane gasoline to be ignited by RF induced arcs, all of the following conditions must exist simultaneously:

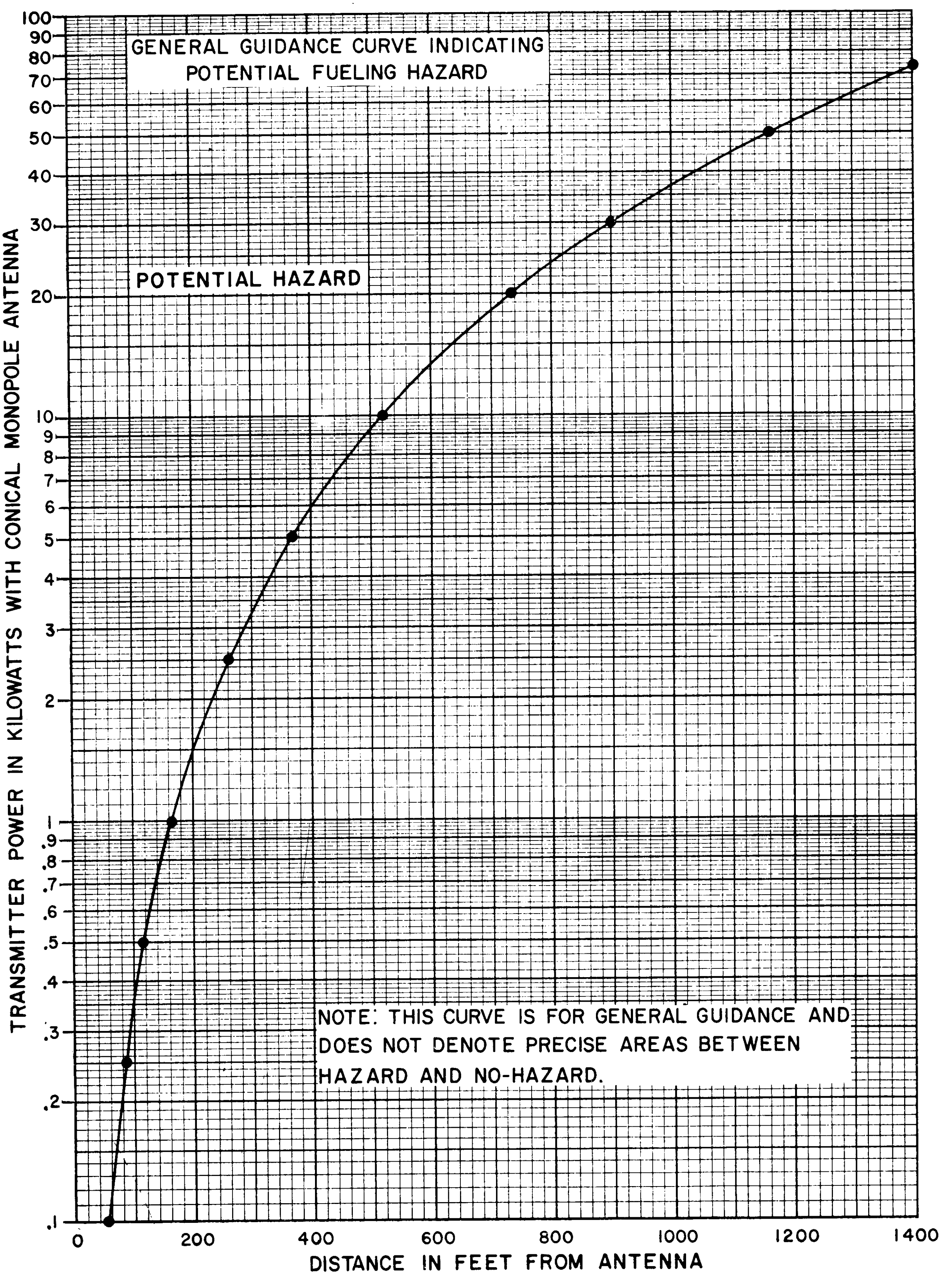


Figure 4-4. General Guidance Curve Indicating Potential Fueling Hazard

(1) A flammable fuel-air mixture must be present within range of the induced arcing. The limits of flammability of most gasolines are between 1.25 and 7.6 percent by volume of gasoline vapor in air. With air movement, the vapor is diluted and swept away reducing the zone of possible ignition.

(2) The spark must contain a sufficient amount of energy to cause ignition. Tests aboard ship have revealed that a volt-ampere (VA) product of 50 or more was required to ignite gasoline in an explosive vapor test device.

(3) The gap across which the spark occurs must be a certain minimum distance. A minimum spark gap of about 0.02 inch is required for ignition of a proper fuel-air mixture. This requires metal-to-metal contact and subsequent withdrawal to produce a drawn arc of sufficient length to ignite such a mixture. Drawn sparks may be observed in an RF environment where the VA product is less than the 50 required for ignition, but such an arc is not of sufficient length to cause ignition.

NOTE

Although the probability of these three conditions occurring simultaneously is relatively low, extreme caution must be exercised since the possibility does exist and the consequences of an explosion are usually quite severe.

APPENDIX A

MATERIAL FOR SAMPLE MANUAL PREDICTION PROBLEM

This appendix contains the charts and nomograms referenced in chapter 2 in connection with manual ionospheric propagation prediction procedures.

Except for figures A-5 and A-6, these materials were taken from references, 2, 5, 9, 12 and 13. The F2-layer MUF prediction charts were obtained from the Environmental Science Services Administration, Boulder, Colorado.

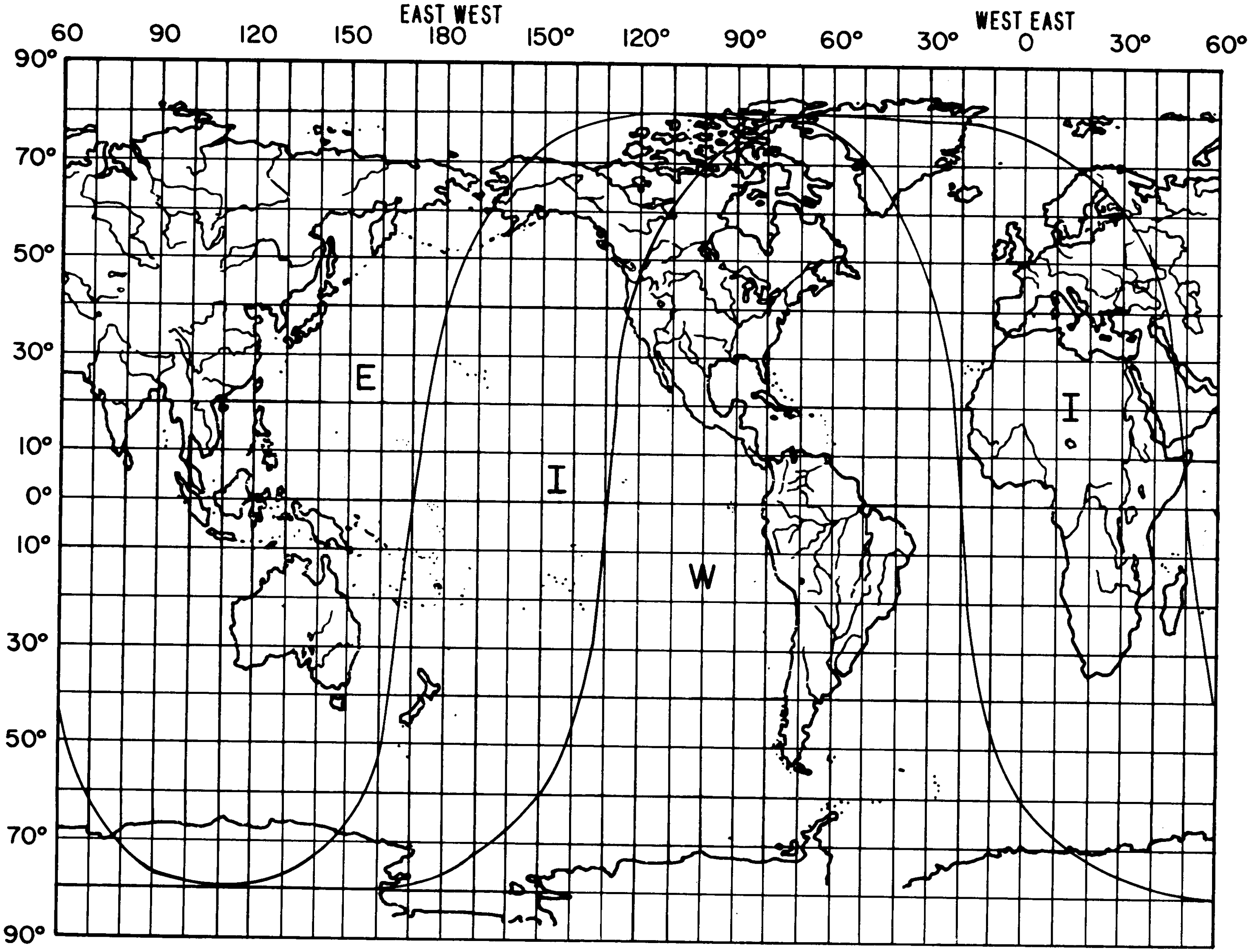


Figure A-1. World Map

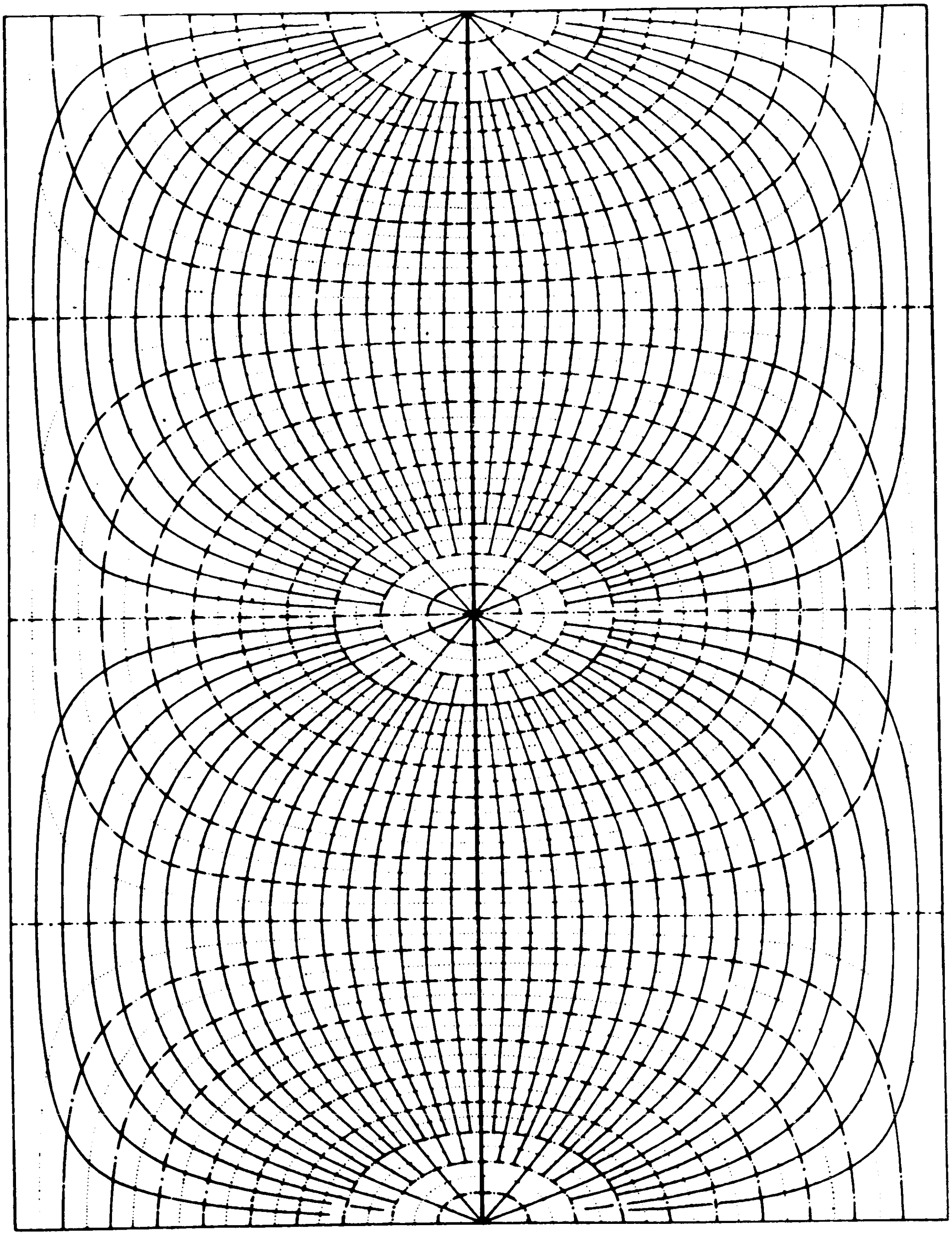


Figure A-2. Great-Circle Chart (Solid Lines Are Great Circles, Dot-Dash Lines Indicate Distance in Thousands of Kilometers)

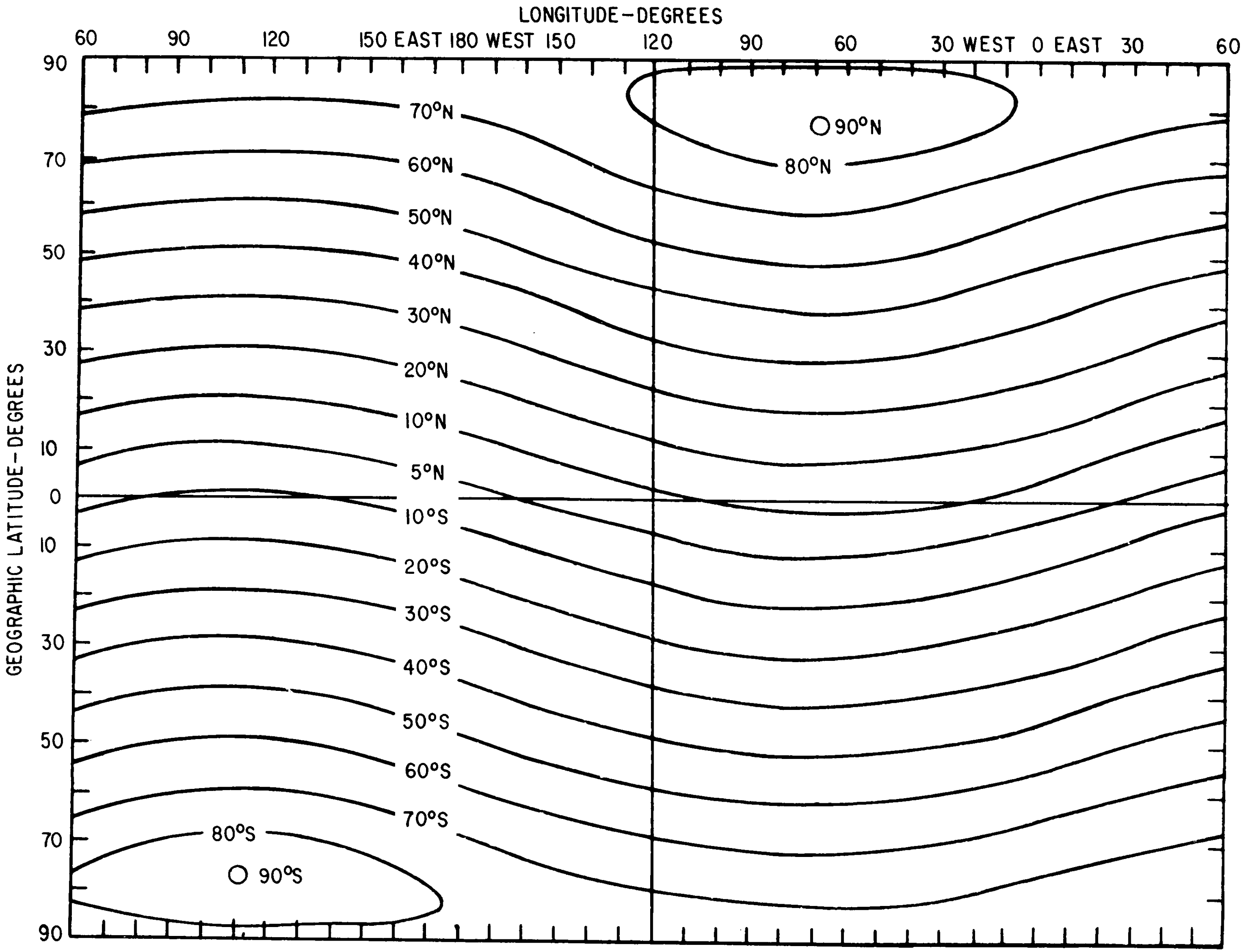


Figure A-3. World Map of Geomagnetic Latitudes

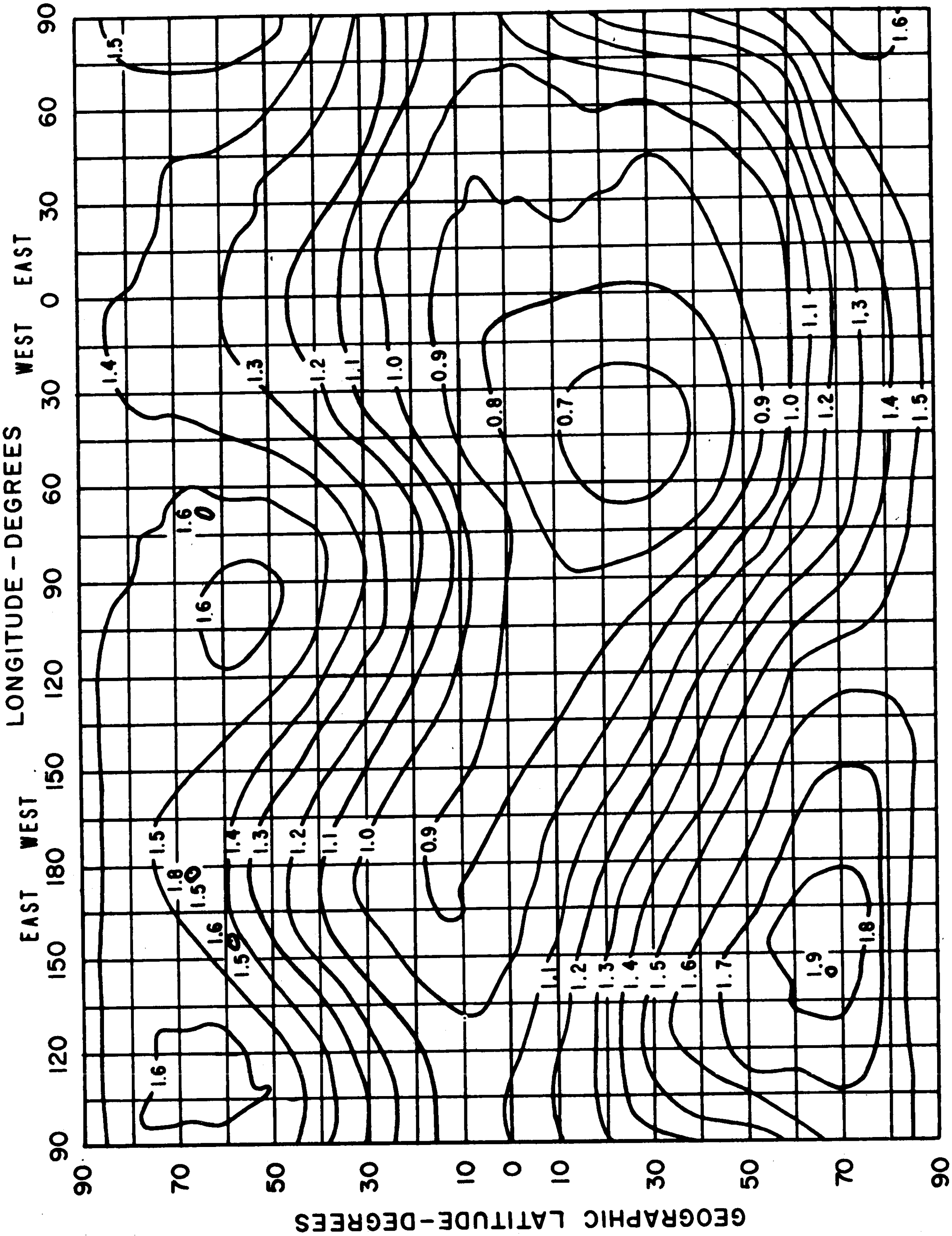


Figure A-4. World Map of E-Region Gyrofrequency, MHz

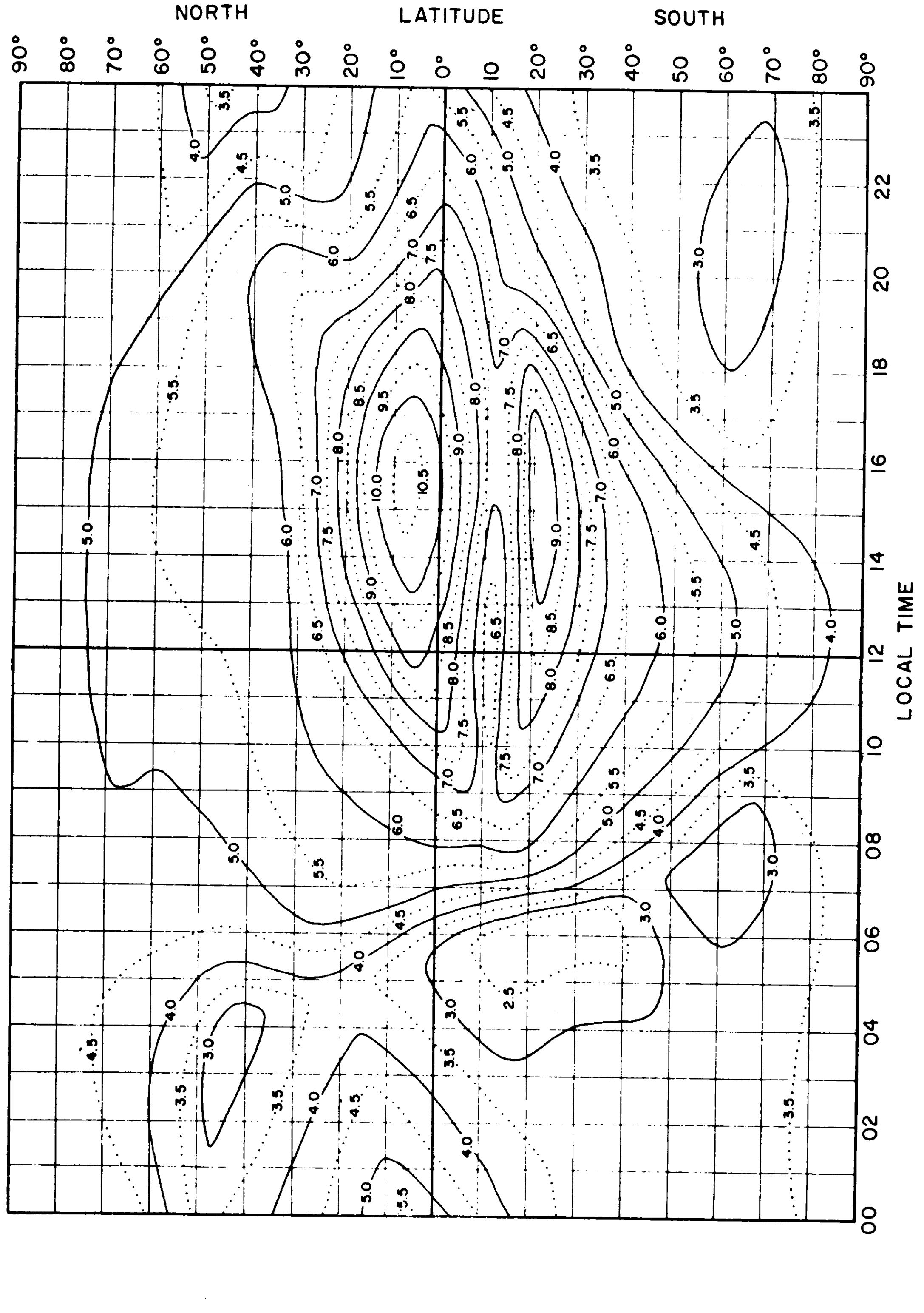


Figure A-5. F2-Zero MUF, Zone W, June, SSN 10

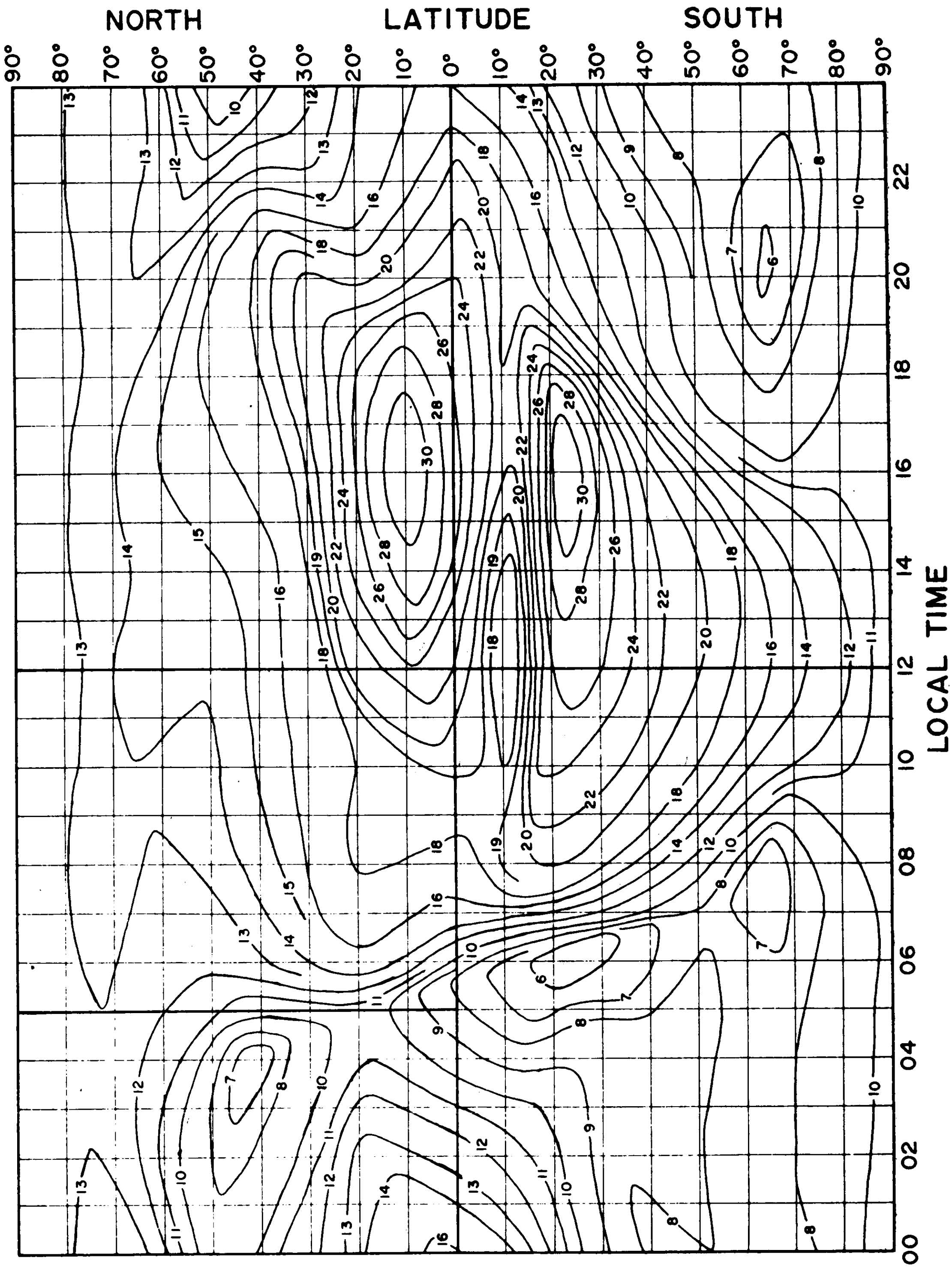


Figure A-6. F2-4000 MUF, Zone W, June, SSN 10

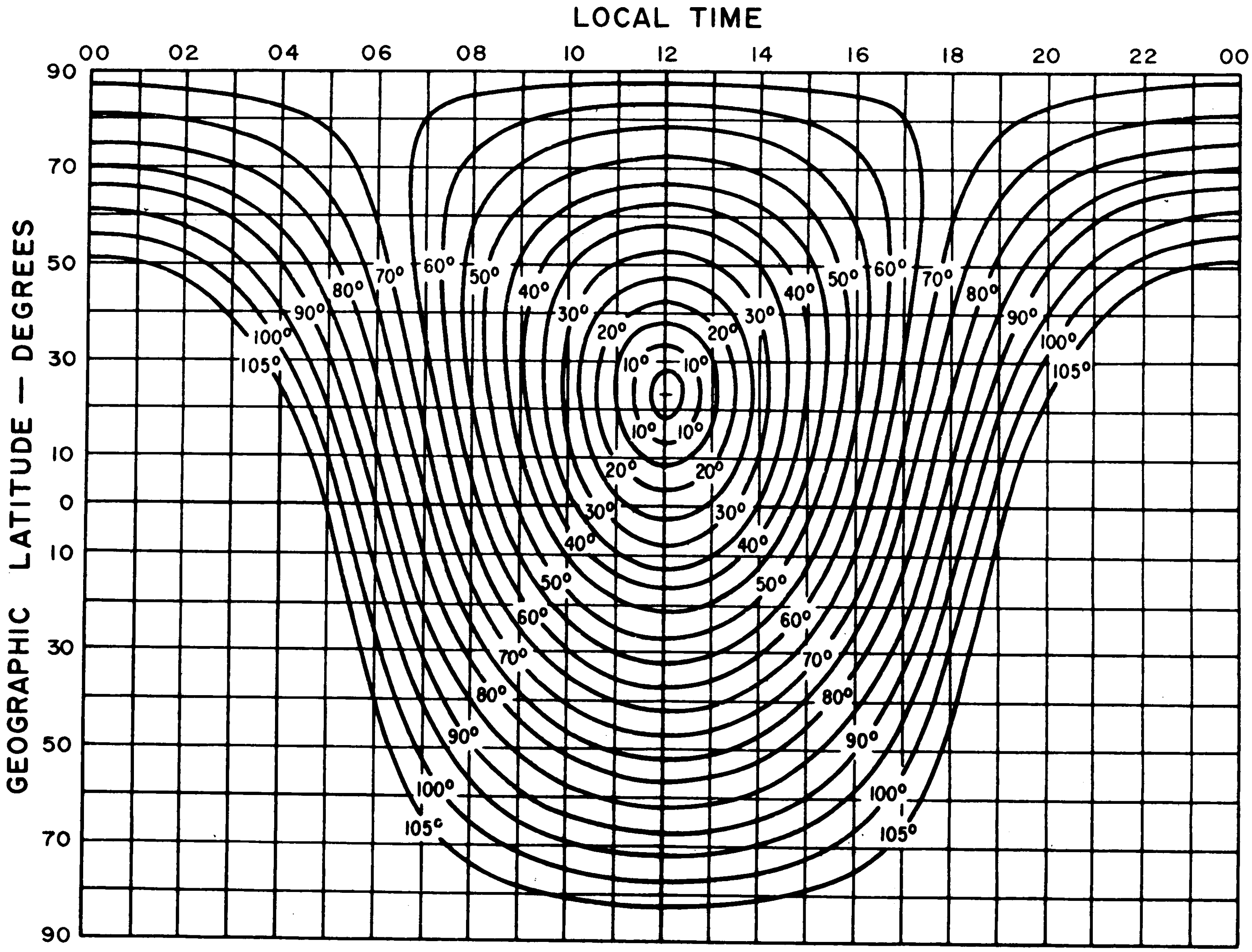


Figure A-7. Sun's Zenith Angle for June

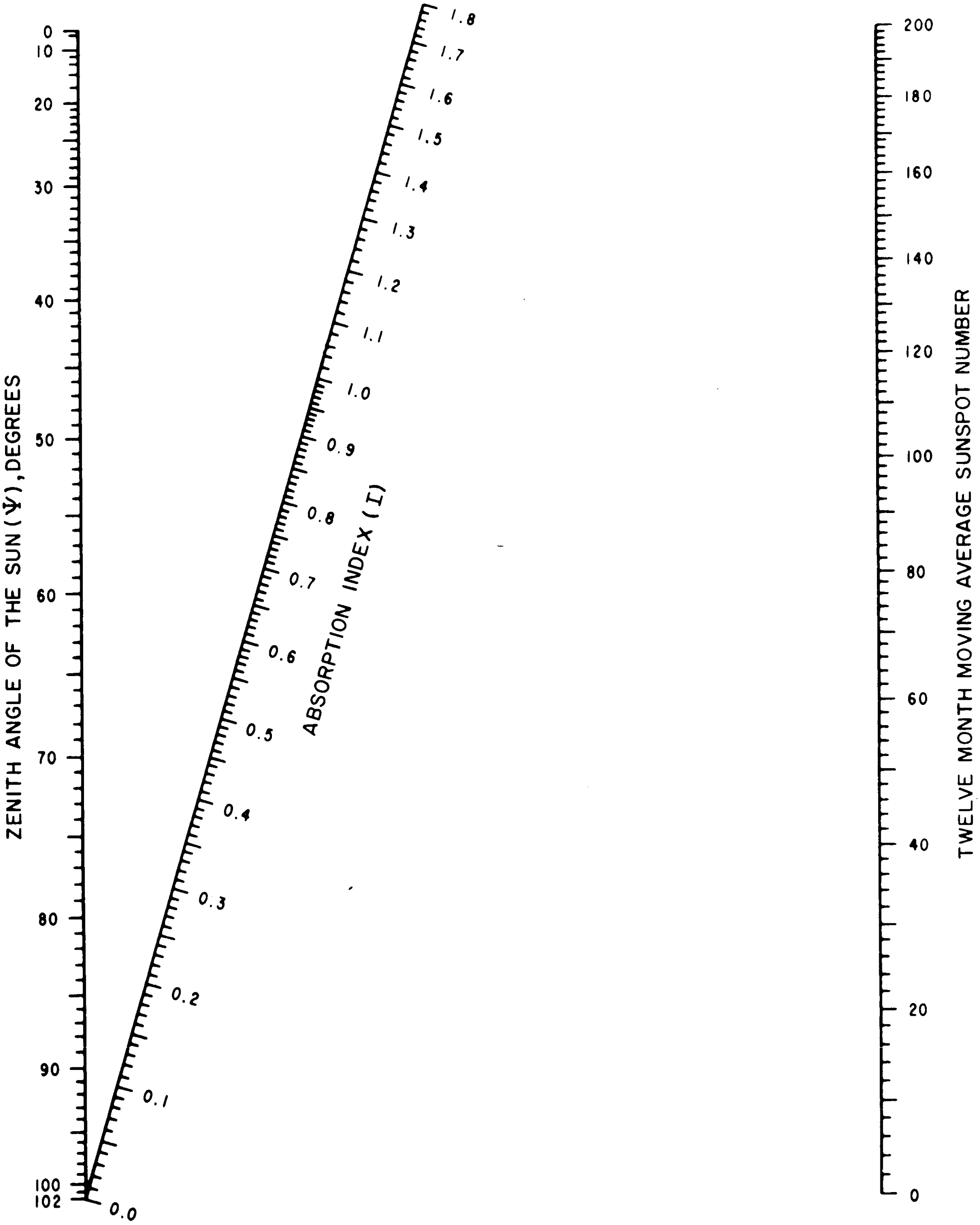
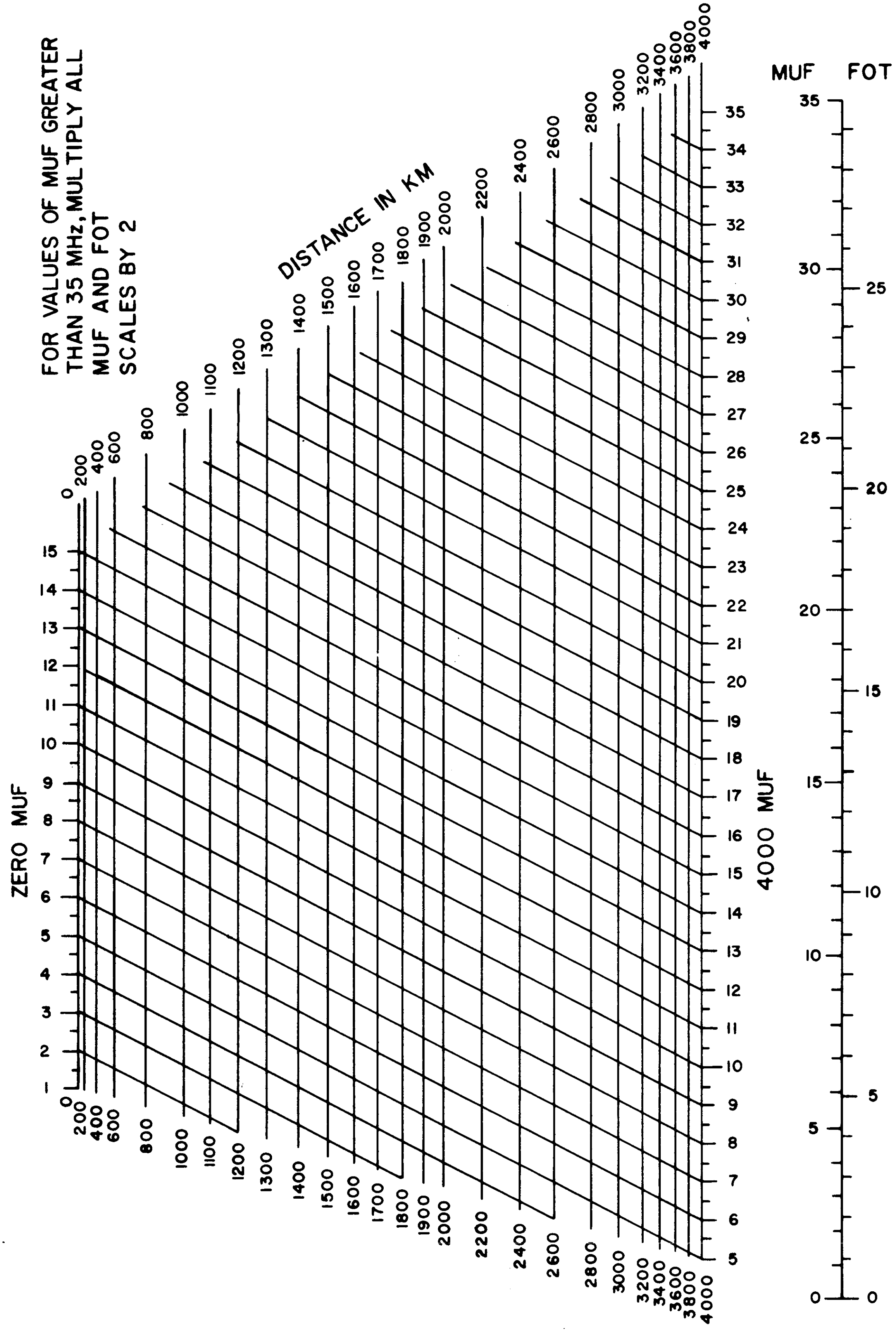


Figure A-8. Nomogram of Ionospheric Absorption Index (I)



FOR VALUES OF MUF GREATER THAN 35 MHz, MULTIPLY ALL MUF AND FOT SCALES BY 2

Figure A-9. MUF Conversion Nomogram, F2 Layer

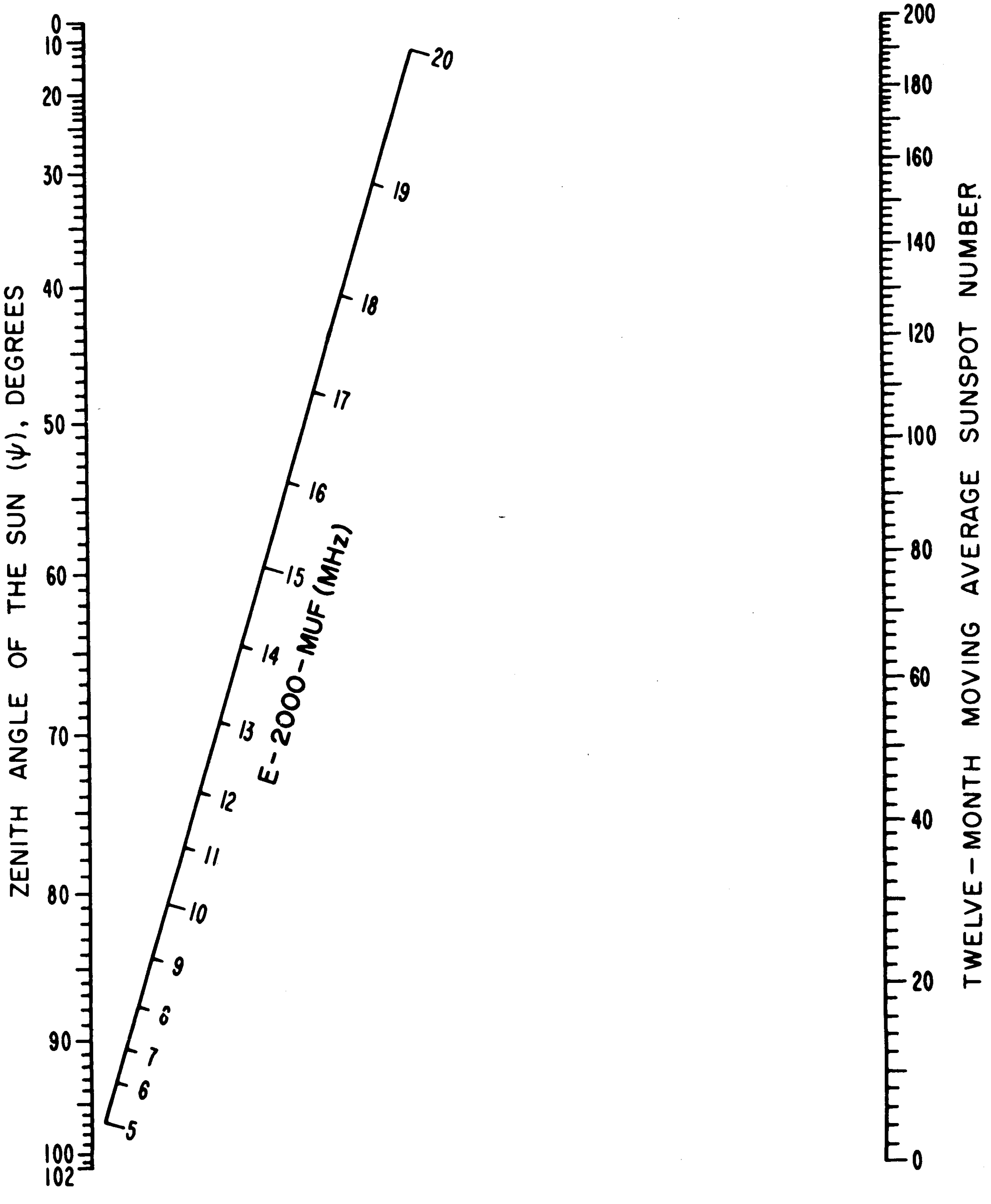


Figure A-10. Nomogram for Obtaining E-Layer 2000 MUF from 12-Month Moving Average Sunspot Number and Zenith Angle of Sun

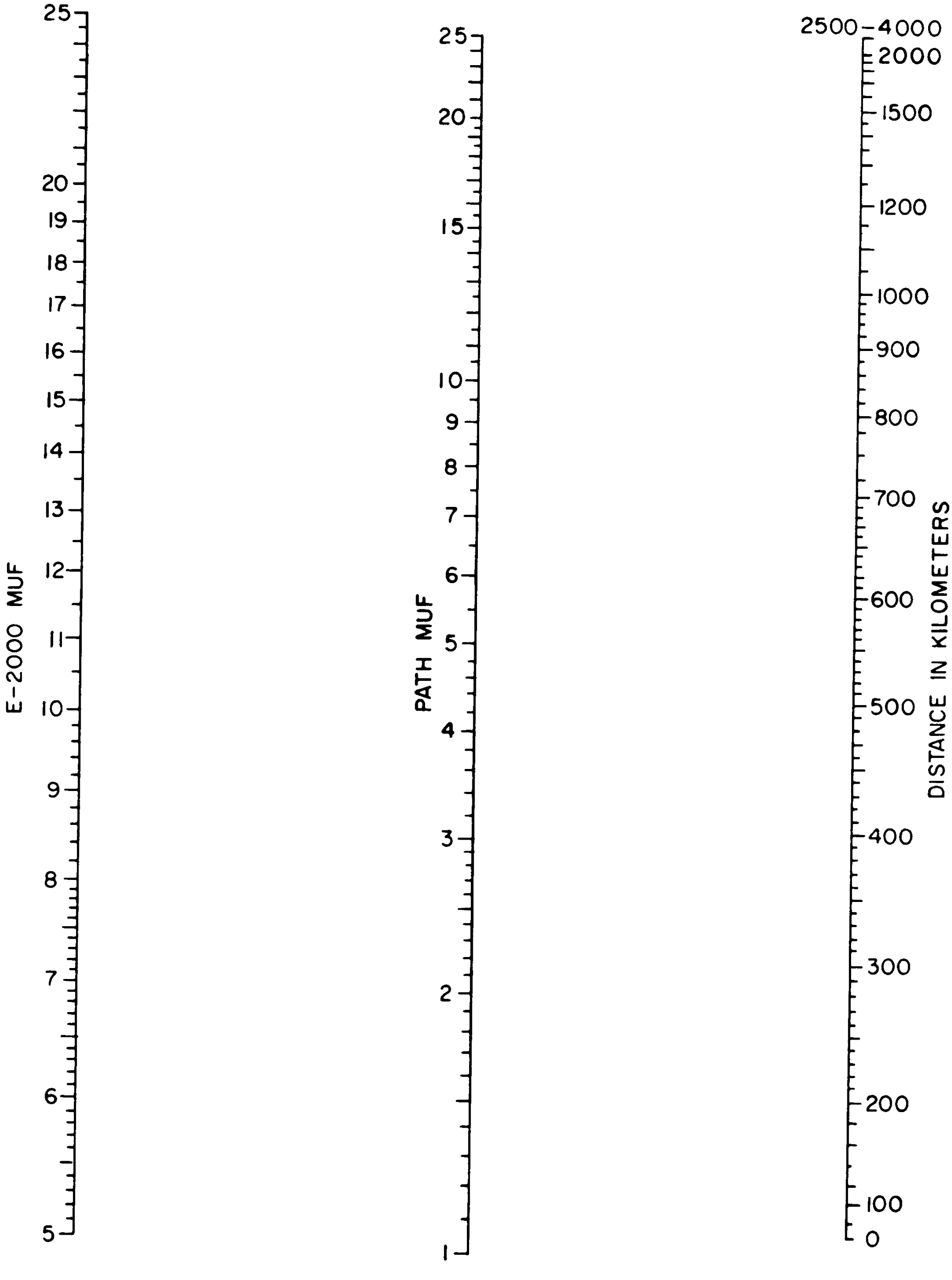


Figure A-11. MUF Conversion Nomogram, F1 and E Layers

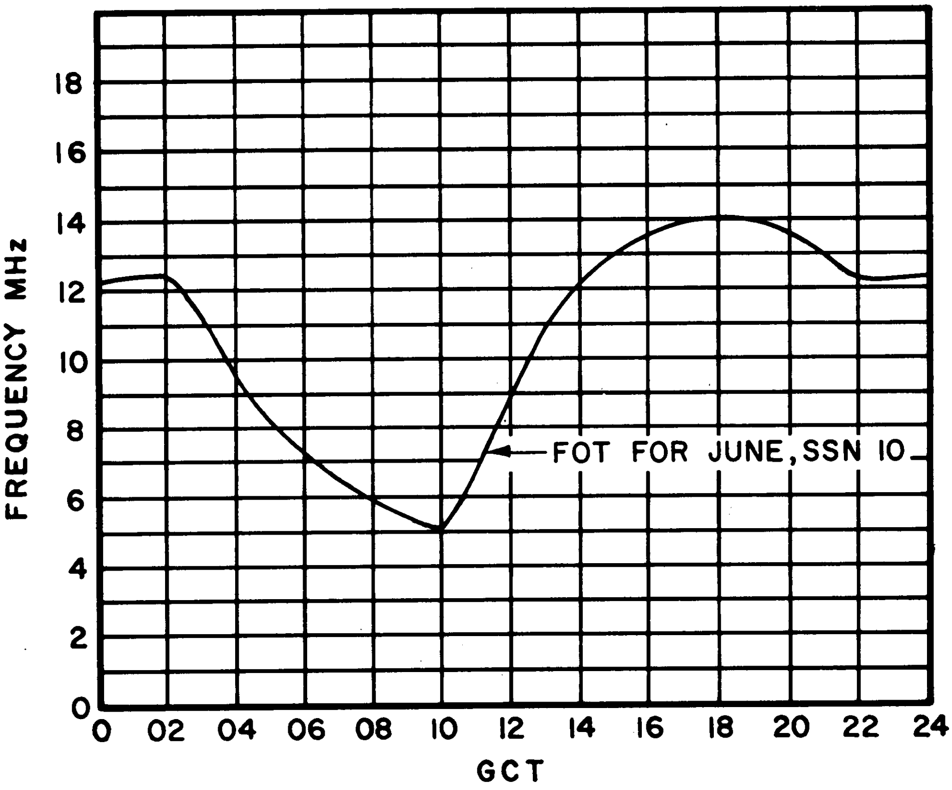


Figure A-12. FOT Curve for Cincinnati-Baton Rouge Path

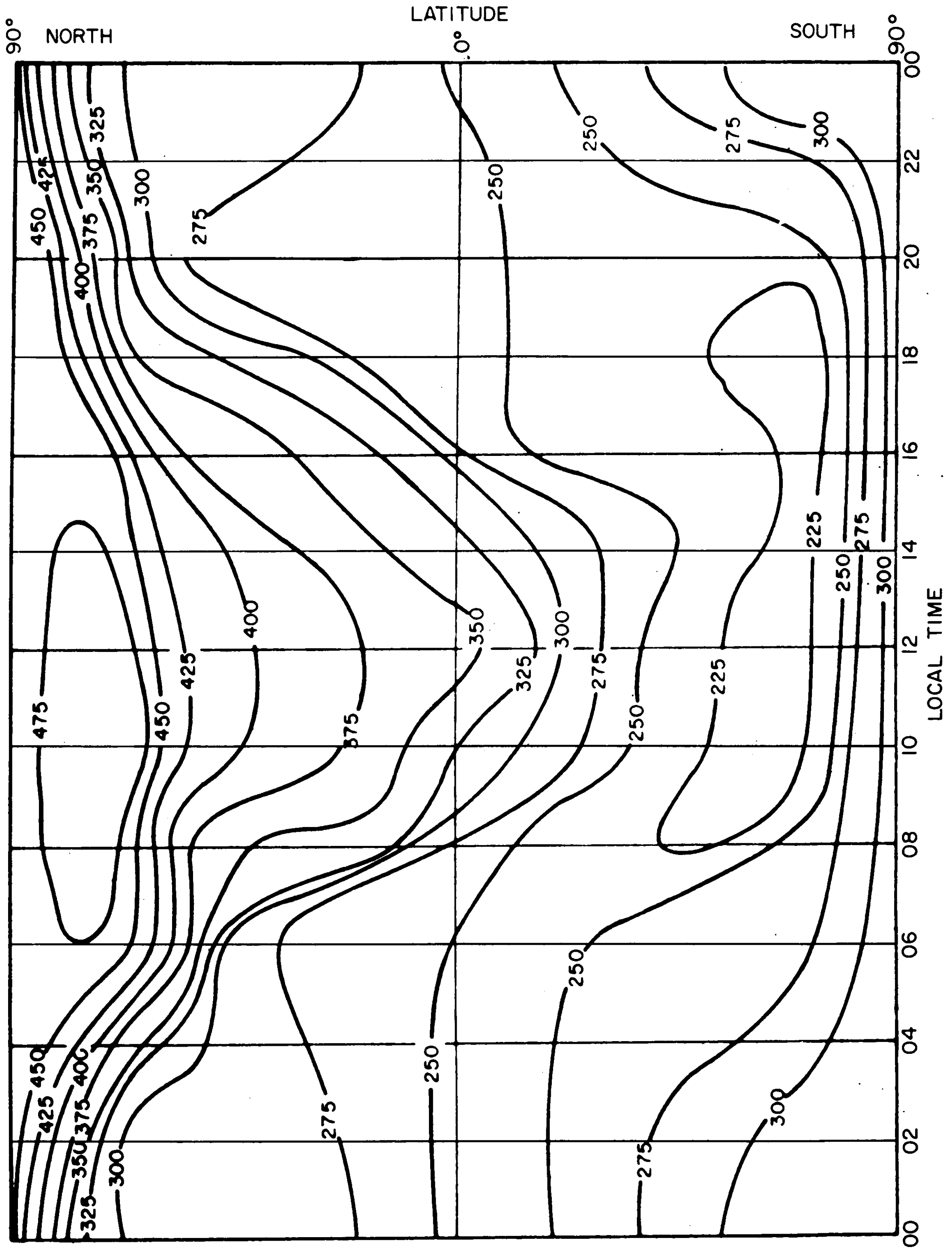


Figure A-13. Typical Height of the F2 Layer in June (Kilometers)

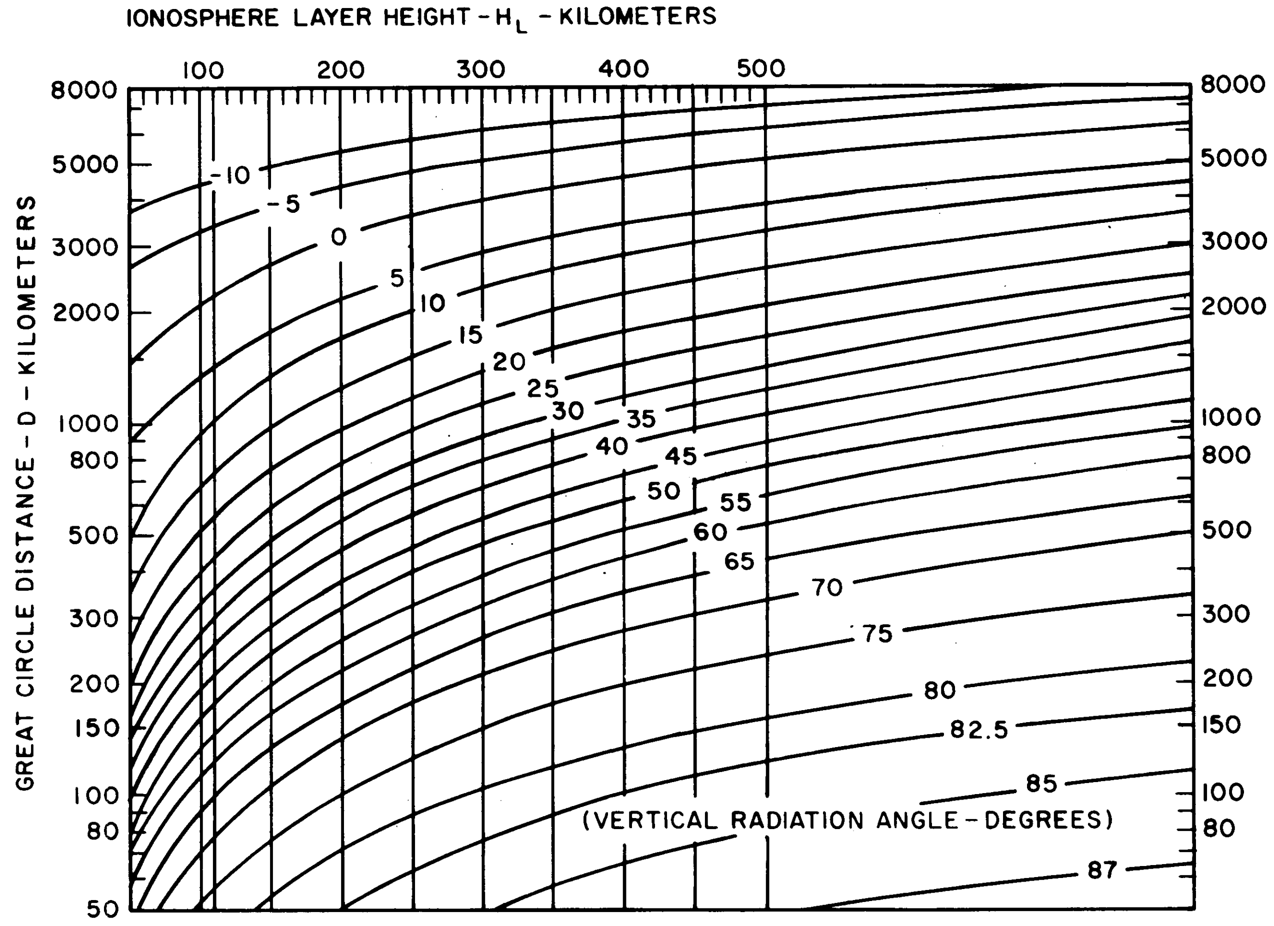


Figure A-14. Radiation Angle (Δ) as a Function of Great-Circle Distance and Ionospheric Layer Height

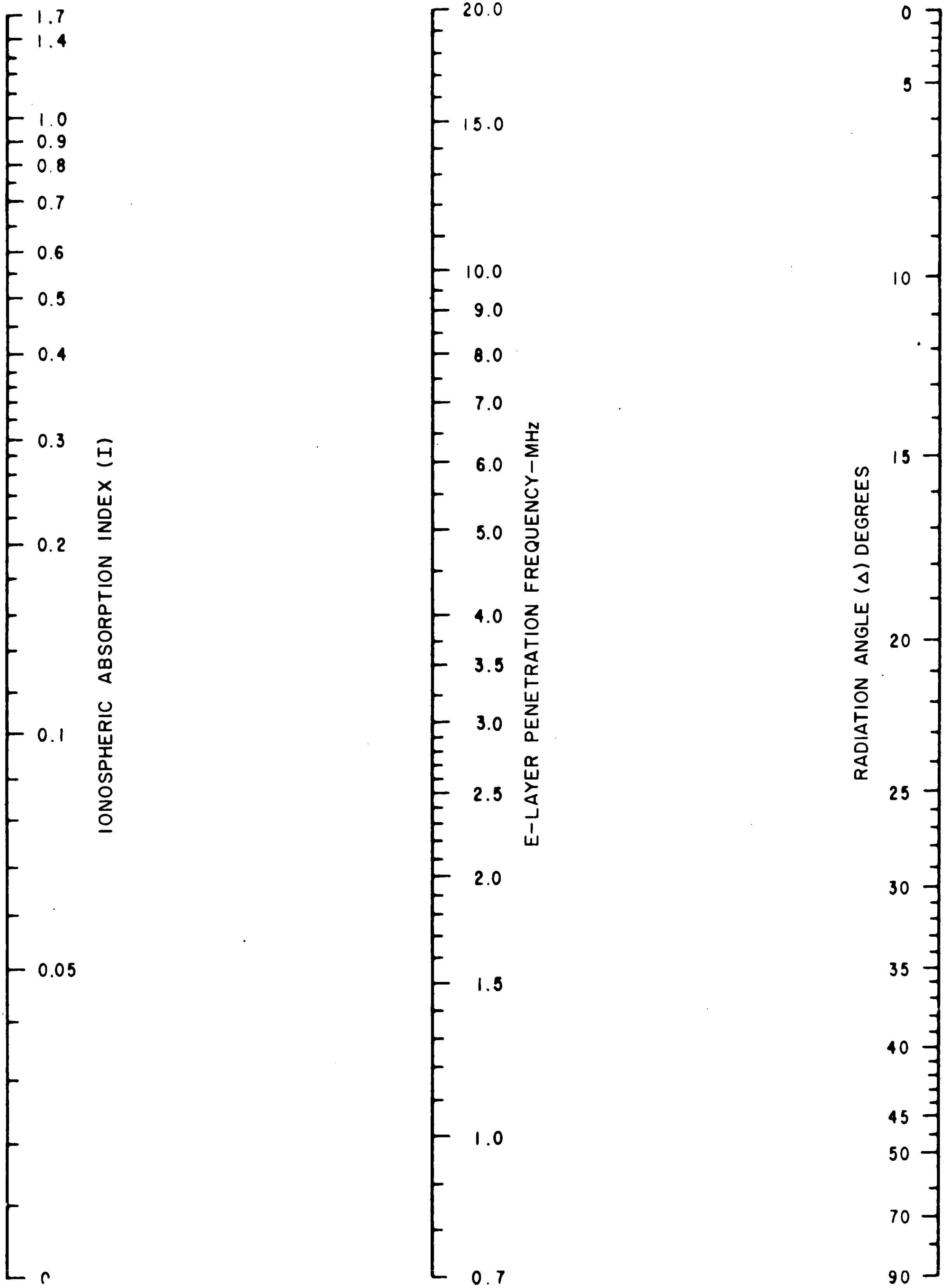
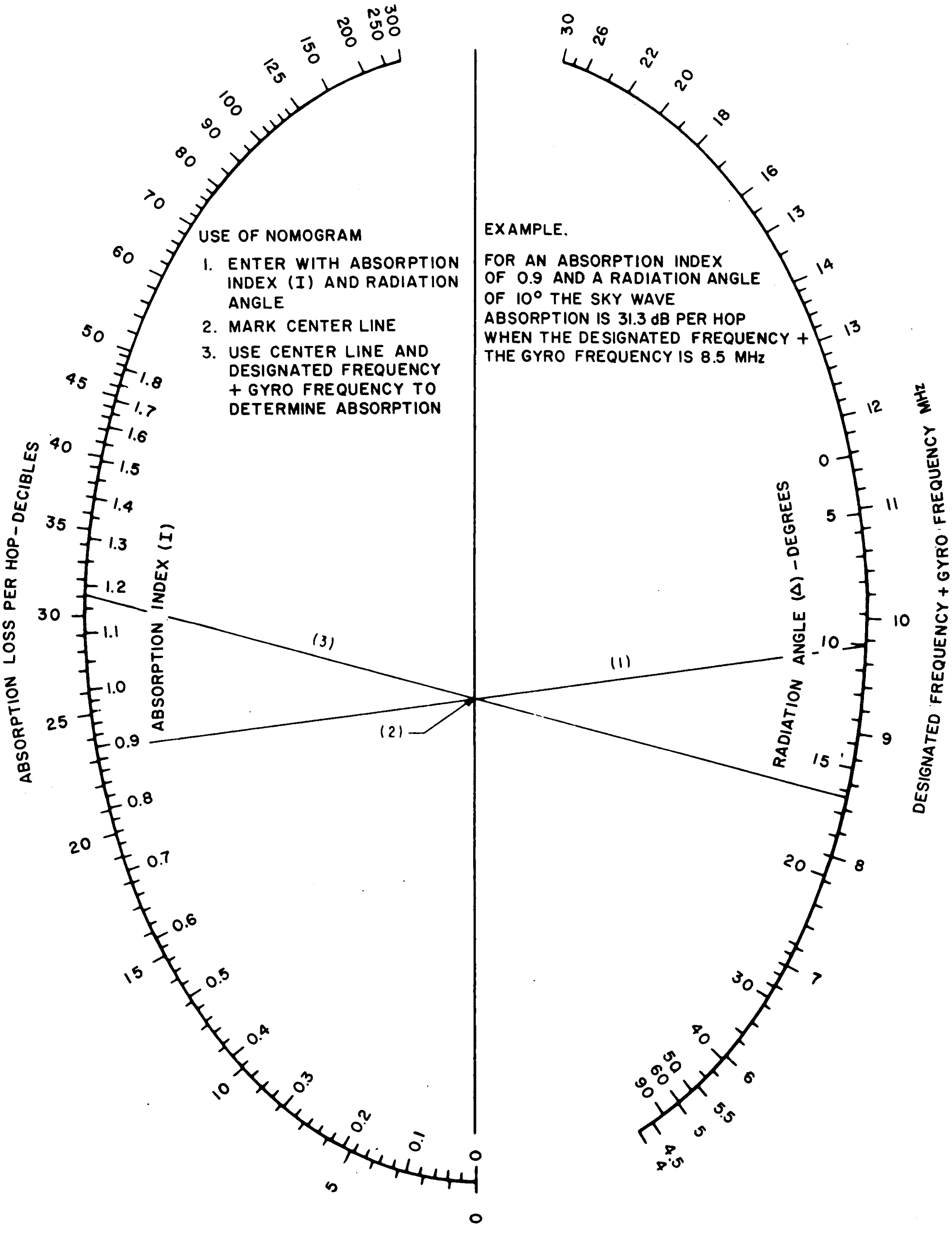


Figure A-15. Nomogram to Estimate E-Layer Penetration Frequency at any Radiation Angle



USE OF NOMOGRAM

1. ENTER WITH ABSORPTION INDEX (I) AND RADIATION ANGLE
2. MARK CENTER LINE
3. USE CENTER LINE AND DESIGNATED FREQUENCY + GYRO FREQUENCY TO DETERMINE ABSORPTION

EXAMPLE.

FOR AN ABSORPTION INDEX OF 0.9 AND A RADIATION ANGLE OF 10° THE SKY WAVE ABSORPTION IS 31.3 dB PER HOP WHEN THE DESIGNATED FREQUENCY + THE GYRO FREQUENCY IS 8.5 MHz

Figure A-16. Nomogram of Ionospheric Absorption

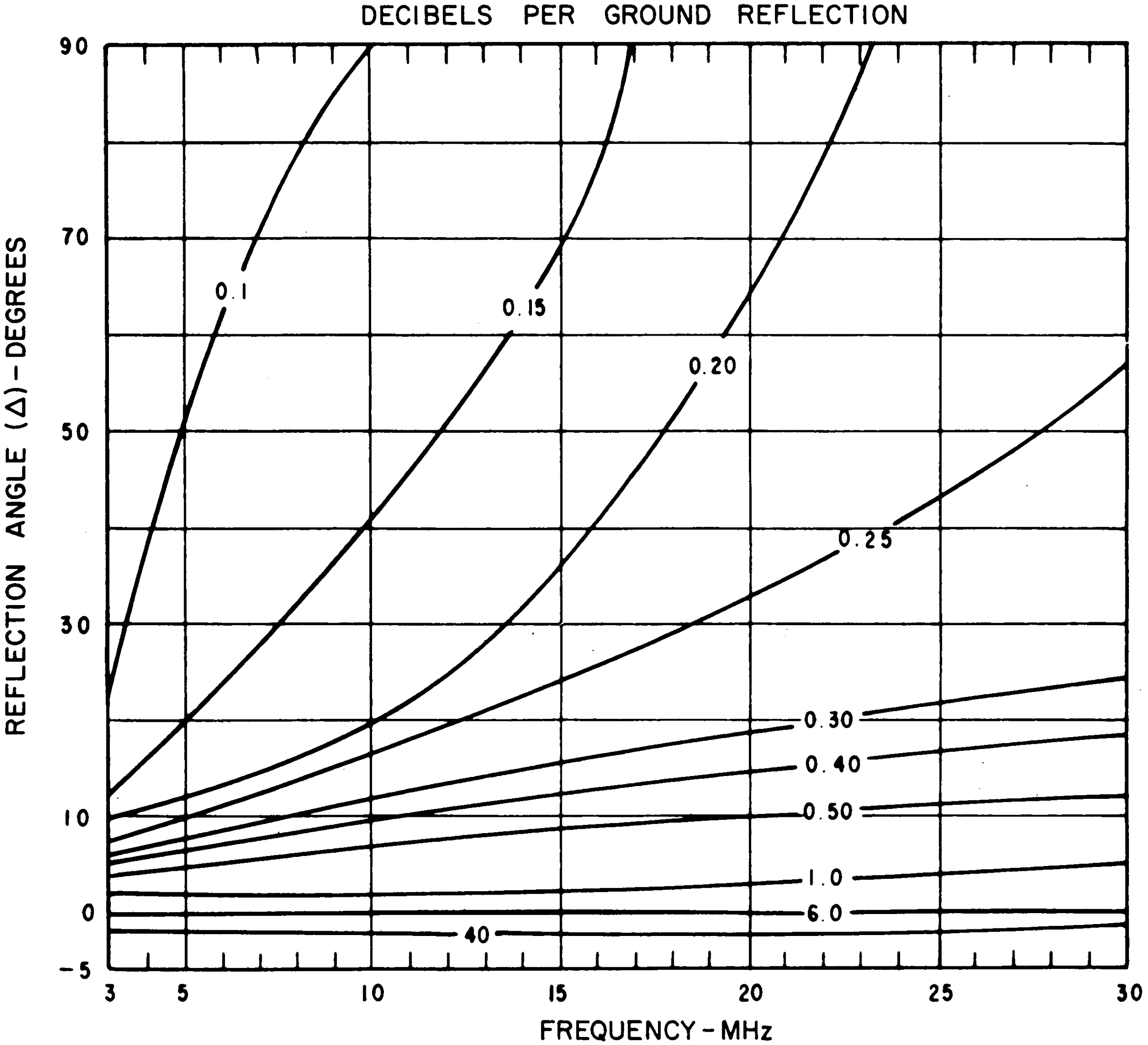


Figure A-17. Sea Water Reflection Loss

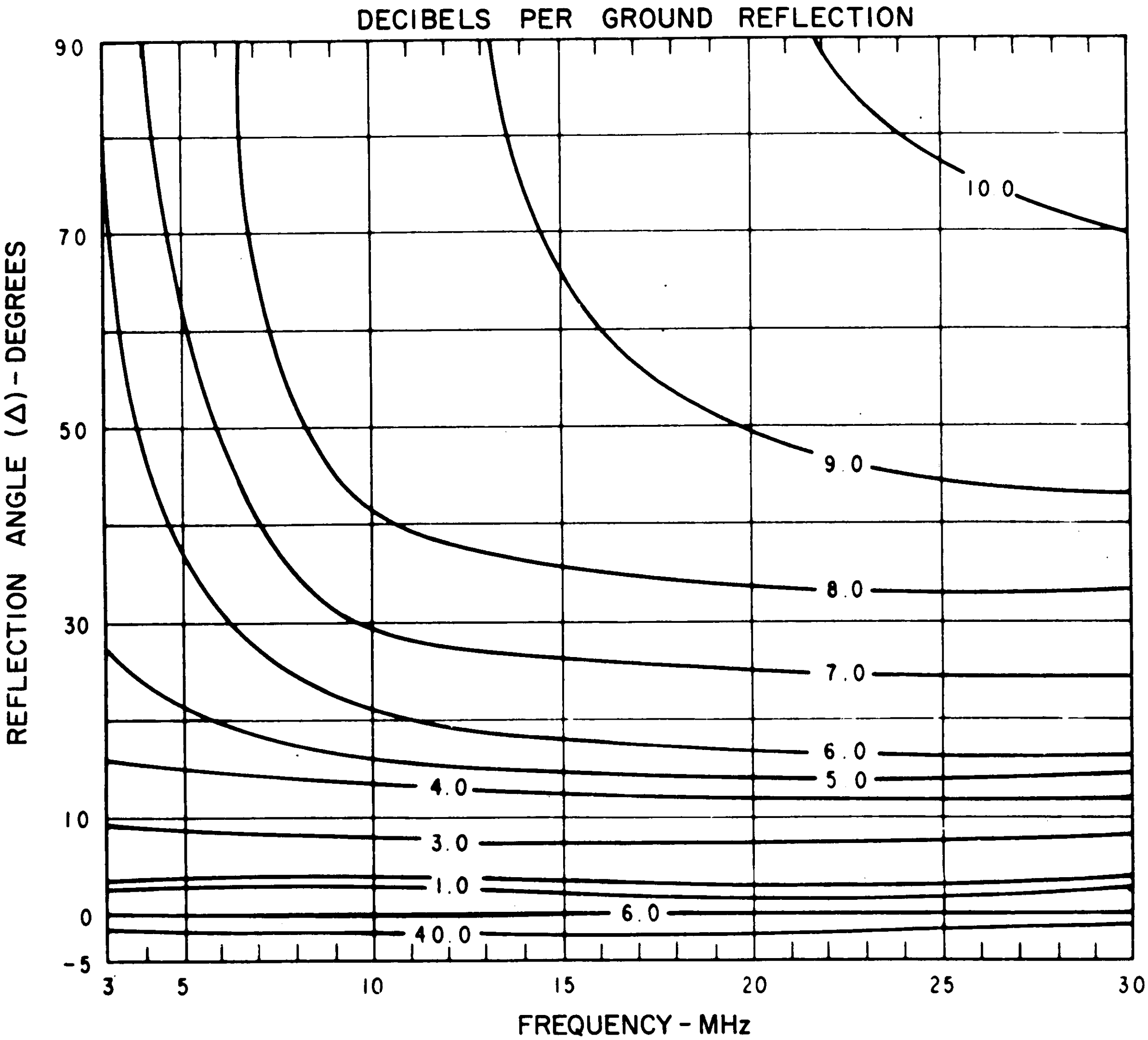
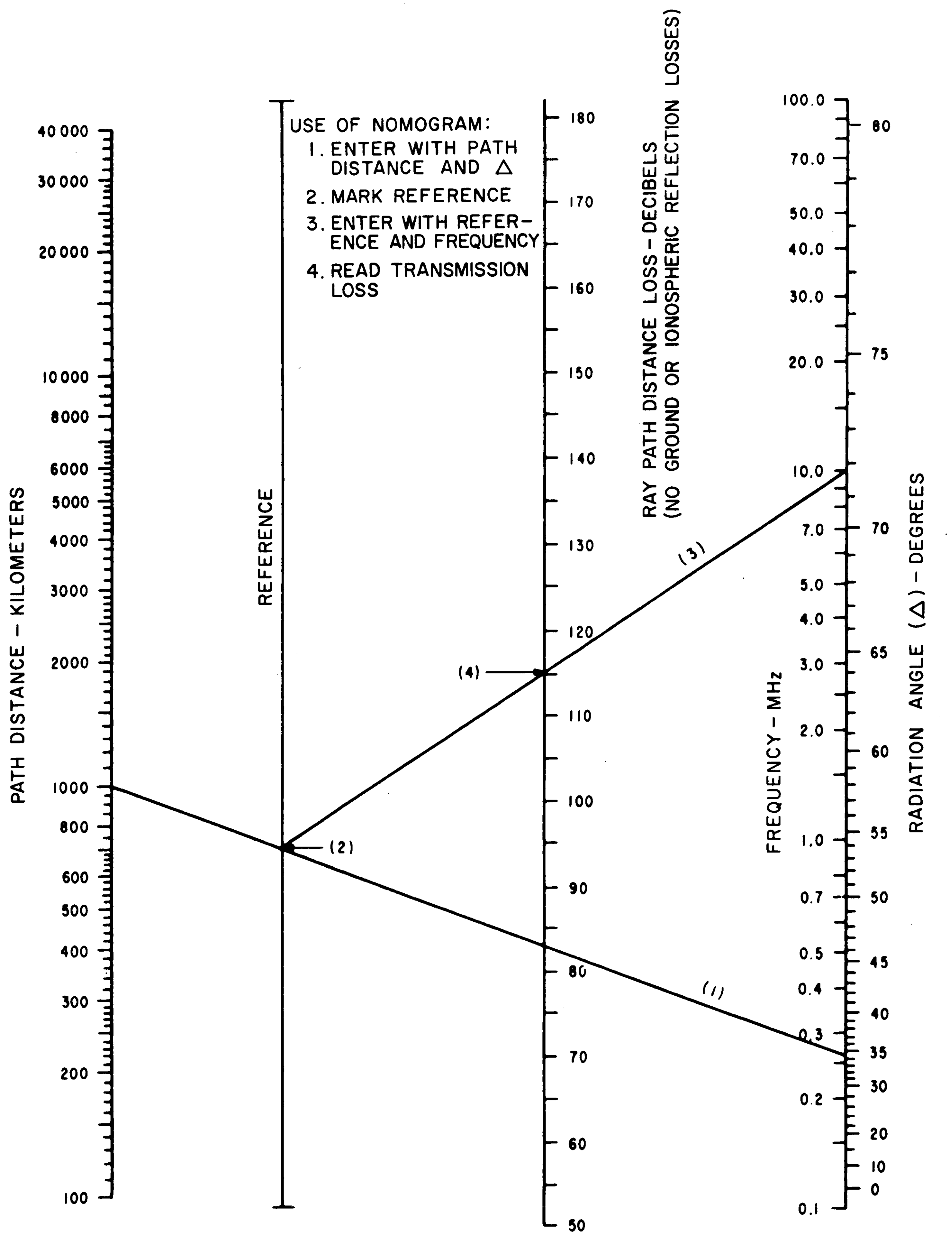
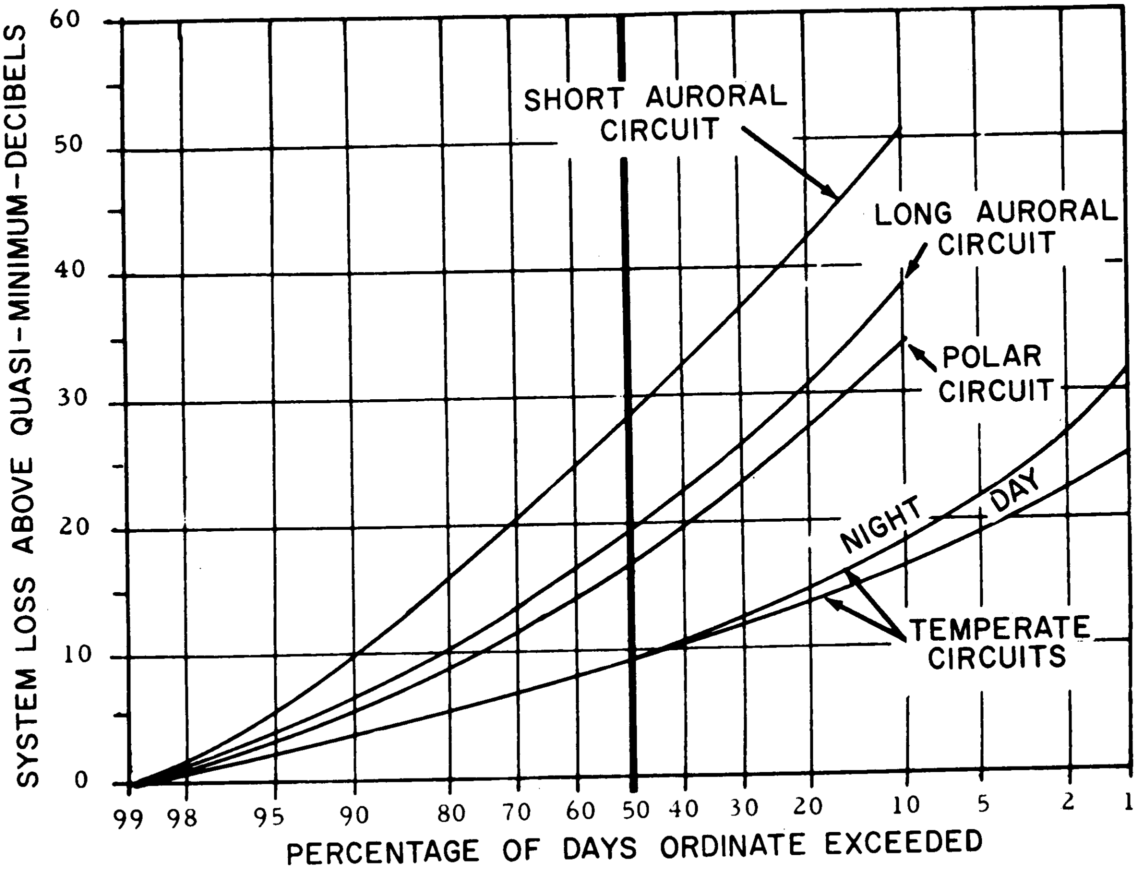


Figure A-18. Poor Earth Reflection Loss



USE OF NOMOGRAM:
1. ENTER WITH PATH DISTANCE AND Δ
2. MARK REFERENCE
3. ENTER WITH REFERENCE AND FREQUENCY
4. READ TRANSMISSION LOSS

Figure A-19. Nomogram of Transmission Loss Due to Ray-Path Distance



Polar Circuit.	All Circuit Control Points above 70° Geomagnetic Latitude
Short Auroral Circuit. . .	Circuits 4000 Km or Less with the Circuit Mid Point Between 60° & 70° Geomagnetic Latitude
Long Auroral Circuit . . .	Circuits 4000 Km or Greater with one or both Control Points Between 60° and 70° Geomagnetic Latitude

Figure A-20. Typical Probability Distribution of Hourly Median Sky-Wave System Loss

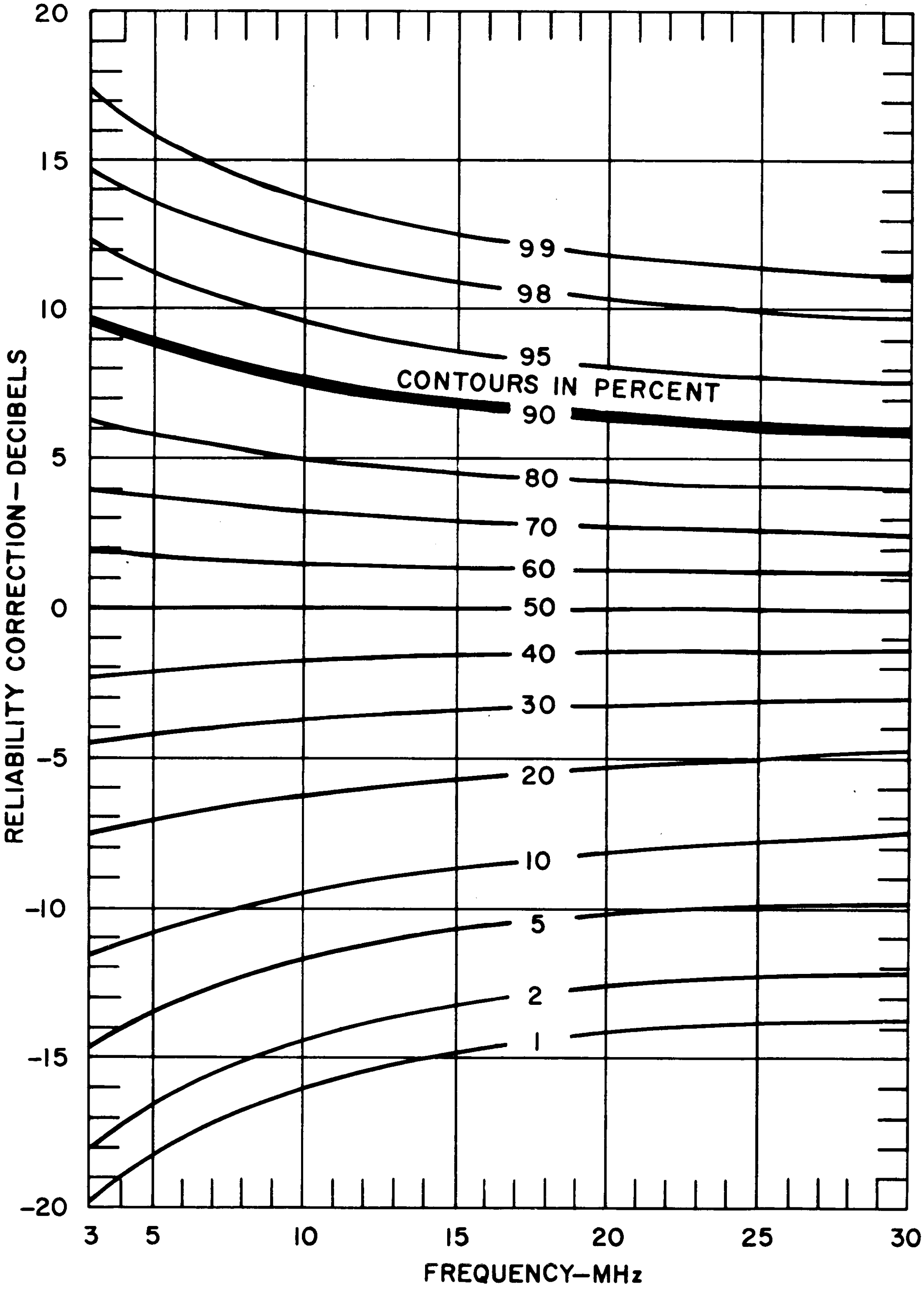


Figure A-21. Chart to Estimate Daytime Reliability of Sky-Wave Circuits Below 60° Geomagnetic Latitude

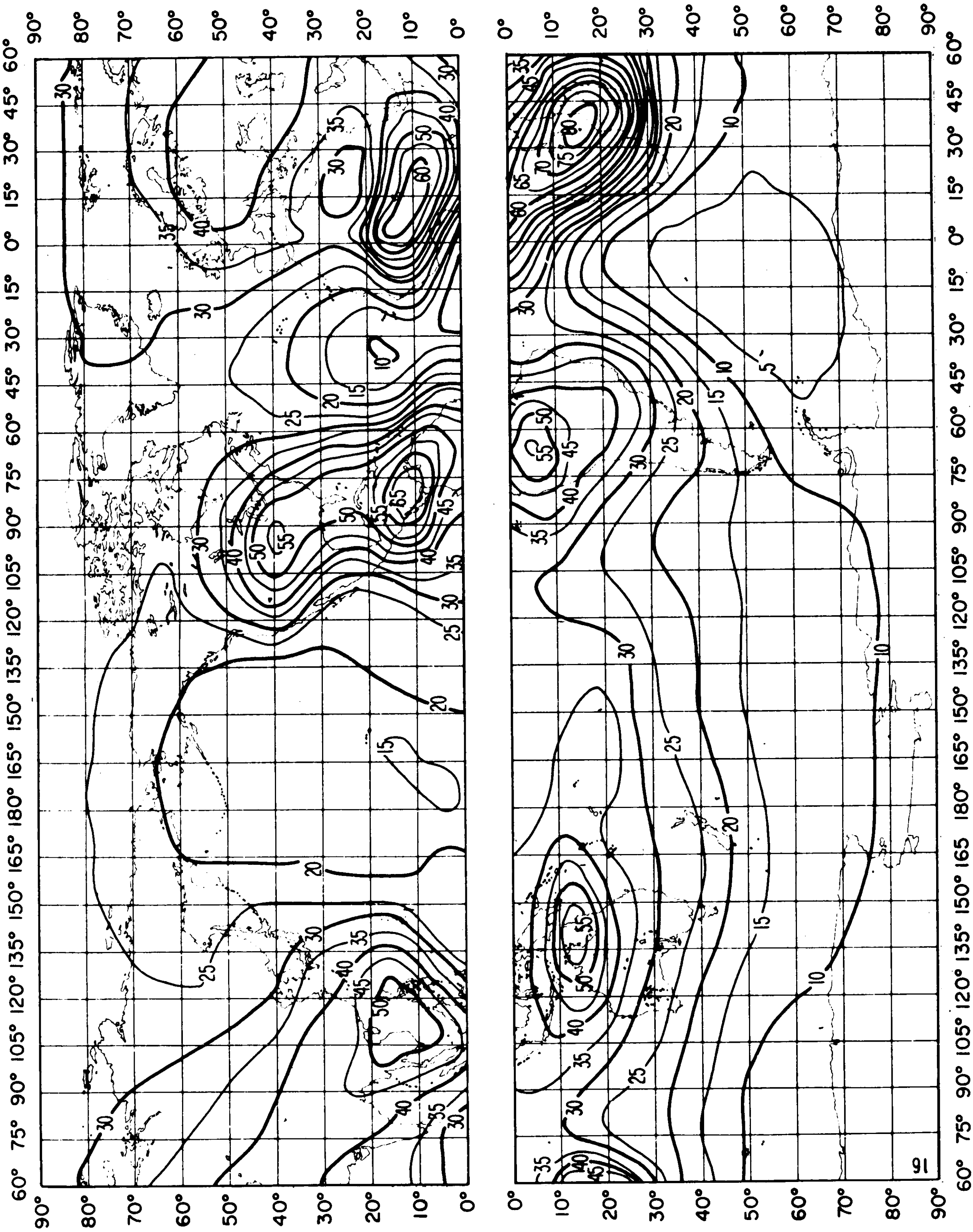


Figure A-22. Expected Values of Atmospheric Radio Noise (dB above kTb at 1 MHz)
(Summer 0400-0800)

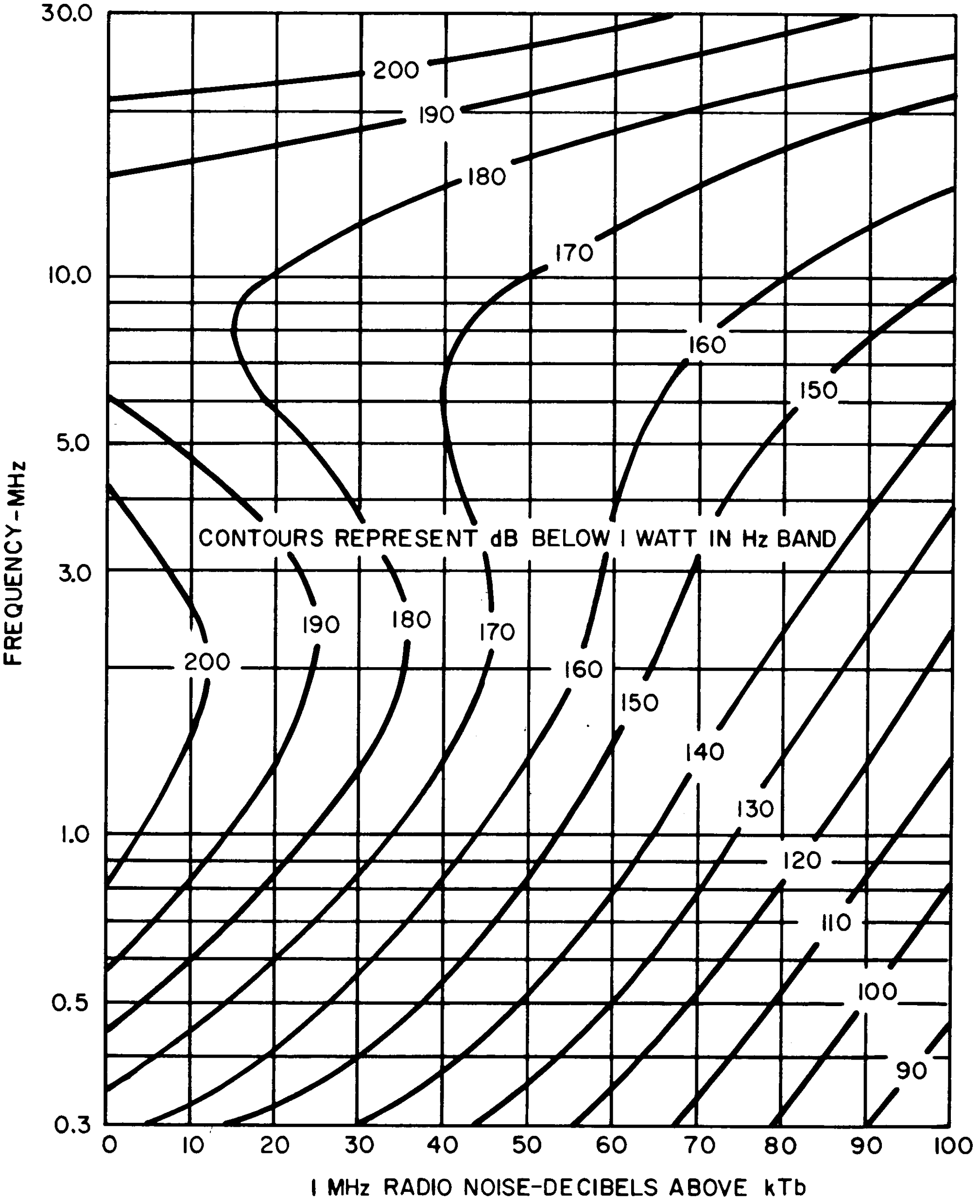


Figure A-23. Daytime Atmospheric Radio Noise — Median Values Expected for the Time Blocks 08-12 and 12-16 for all Seasons, 04-08 and 16-20 for Spring and Summer

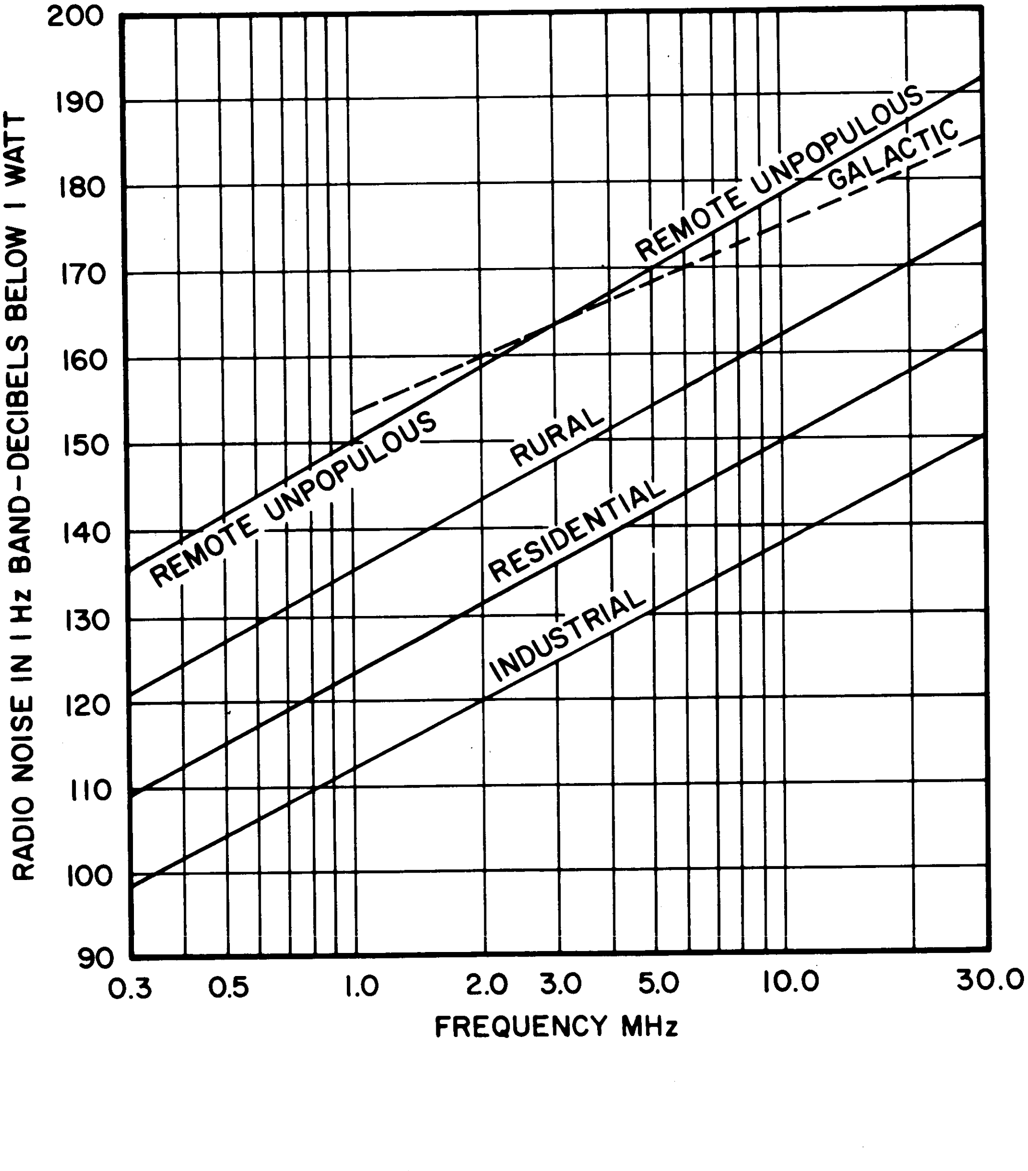


Figure A-24. Typical Man-Made and Galactic Radio Noise
(from NBS Report 7249, November 1962)

APPENDIX B

HF RECEIVER SITE SURVEY

1. GENERAL SUITABILITY (Comment on each item. Attach separate sheets as necessary.)

a. Logistic support accessibility —
  (1) Remoteness of area (air, rail, truck, bus)
  (2) Proximity to paved roads
  (3) Access road requirement
  (4) Availability of naval supply facilities
  (5) Availability of other government facilities (25 mile radius)
  (6) Availability of commercial supply facilities
  (7) Other comments

b. Utility services availability —
  (1) Availability of commercial power
  (2) Availability of station power
  (3) Availability of water supply
  (4) Availability of sewage services
  (5) Availability of fire protection services
  (6) Availability of telephone services

c. Climatological conditions —
  (1) Extremes of climate to be expected
  (2) Frequency of hurricanes, typhoons, or blizzards
  (3) Other comments

d. Future continuing suitability —
  (1) Stability of existing conditions
  (2) Anticipated industrial encroachment
  (3) Government ownership
  (4) Treaty arrangements
  (5) Political stability
  (6) Area future planning
  (7) Other comments

e. Defensibility —
  (1) Physical defense features
  (2) Security arrangements
  (3) Proximity to primary targets
  (4) Other comments

f. Recreation availability
  (1) Availability of recreational facilities
  (2) Types of facilities available
  (3) Proximity to facilities
  (4) Other comments

g. Personnel logistics availability —
  (1) Proximity to established naval station
  (2) Availability of on-base personnel housing
  (3) Availability of off-base personnel housing
  (4) Mess facilities
  (5) Exchange facilities
  (6) Other comments

2. LAND AREA REQUIRED

(Attach separate sheets for comments as necessary.)

a. Topographic map of area (minimum scale — 1:50, 000)

b. Acreage under consideration

c. Adequacy of site to meet requirements

d. Restricted area situation

e. Present ownership of site and restricted area

f. Proposed acquisition arrangements

g. Host/tenant agreements required

h. Treaty arrangements required

i. Advantages of proposed site

j. Limitations of proposed site

k. Estimated costs of acquisition

l. Other comments

3. INTERFACE ASPECTS

a. Distance, azimuth, and measured field intensity from existing and planned radio transmitters: (Note 1)

	Distance	Azimuth	Freq. (Note 3)	μV/m
(1) Navy VLF transmitter site	—			
(2) Navy LF-HF transmitter site (Note 2)	—			
(3) Other military transmitters (Note 2)	—			
(4) Non-military transmitters (identify)	—			

b. Distance, azimuth, and measured field intensity from: (Note 1) (Note 4)

	Distance	Azimuth	Freq.	μV/m
(1) Navy (specify type) —				
(2) Other (specify) —				

c. Distance, azimuth, and measured field intensity from man-made noise sources: (Note 1)

	Distance	Azimuth	μV/m
(1) Teletype/electromechanical systems —			
(2) Primary power plant —			
(3) Highways/roads (vehicles per hour average) —			
(4) Industrial area —			
(5) Commercial area —			
(6) Residential area —			
(7) Overhead power lines —			
(8) Airfield (including glide path) —			
(9) Other (specify) —			

4. TERRAIN CHARACTERISTICS

(Attach separate sheets for comments as necessary.)

a. Unobstructed 5° wavepath (vertical angle) above horizontal plane for all antennas. Attach horizon plot and photograph keyed to site topographic map. Site map is desired with scale of 1:24,000 and contour intervals of not more than 10 feet.

☐ Yes ☐ No ☐ Comment

b. Scraping, grading, earthmoving required —

☐ Extensive ☐ Minimal ☐ Comment

c. Type of soil as related to ground conductivity and uniformity. (If soil characteristics are not uniform provide a descriptive sketch.) —

(comment)

d. Soil conductivity measurement data.

e. Water table depth and variability. (If not uniform or excessive seasonal variability, provide descriptive information.)

f. Buildings on or adjacent to site and within restricted zone. Locate on site or area map. Describe, identify ownership and land usage, and evaluate interference capability. Identify land use covenants.

g. Undergound structures. Identify and locate underground facilities such as cables and pipe lines.

5. MICROWAVE LINK LINE-OF-SIGHT DISTANCE: (Attach separate sheets for comments as necessary.)

a. Miles to transmitter site —

b. Miles to communications center —

c. Path obstructions — (Comment)

6. POTENTIAL ENCROACHMENT: (Comment on each item. Attach separate sheets as necessary.)

a. Military

b. Industrial

c. Commercial

d. Residential

e. Highways/roads

f. Power lines

g. Airfields

h. Other (specify)

7. MAXIMUM FUTURE EXPANSION CAPABILITY: (Attach separate sheets for comments as necessary.)

a. Receiver buildings (sq. ft.) —

b. Logistics buildings (sq. ft. each building) —

c. Antenna park (acres) —

d. Vehicle parking (sq. ft.) —

e. Recreation area (acres) —

NOTE 1: Field intensity measurements are made at the center of the proposed site. For the man-made noise survey a number of spectrum scans must be made at various times throughout the day and should cover the full range of operating frequencies expected to be used by the proposed receiver station during the various periods of a day.

NOTE 2: Field intensity measurements made at planned antenna location to evaluate signal reception from distant transmitters.

NOTE 3: Field intensity measurements must include low, middle and high frequencies of the band (minimum).

NOTE 4: Measurements must include pulse repetition rate.

APPENDIX C

HF TRANSMITTER SITE SURVEY

1. GENERAL SUITABILITY (Comment on each item. Attach separate sheets as necessary).

   a. Logistic support accessibility —
      (1) Remoteness of area (air, rail, truck, bus)
      (2) Proximity to paved roads
      (3) Access road requirement
      (4) Availability of naval supply facilities
      (5) Availability of other government facilities (25-mile radius)
      (6) Availability of commercial supply facilities
      (7) Other comments

   b. Utility services availability —
      (1) Availability of commercial power
      (2) Availability of station power
      (3) Availability of water supply
      (4) Availability of sewage services
      (5) Availability of fire protection services
      (6) Availability of telephone services

   c. Climatological conditions —
      (1) Extremes of climate to be expected
      (2) Frequency of hurricanes, typhoons, or blizzards
      (3) Other comments

   d. Future continuing suitability —
      (1) Stability of existing conditions
      (2) Anticipated industrial encroachment
      (3) Government ownership
      (4) Treaty arrangements
      (5) Political stability
      (6) Area future planning
      (7) Other comments

   e. Defensibility —
      (1) Physical defense features
      (2) Security arrangements
      (3) Proximity to primary targets
      (4) Other comments

   f. Recreation availability —
      (1) Availability of recreational facilities
      (2) Types of facilities available
      (3) Proximity to facilities
      (4) Other comments

g. Personnel logistics availability —
  (1) Proximity to established naval station
  (2) Availability of on-base personnel housing
  (3) Availability of off-base personnel housing
  (4) Mess facilities
  (5) Exchange facilities
  (6) Other comments

2. LAND AREA REQUIRED

(Attach separate sheets for comments as necessary.)

a. Topographic map of area (minimum scale — 1:50,000)

b. Acreage under consideration

c. Adequacy of site to meet requirements

d. Present ownership of site

e. Proposed acquisition arrangements

f. Host/tenant agreements required

g. Treaty arrangements required

h. Advantages of proposed site

i. Limitations of proposed site

j. Estimated costs of acquisition

k. Other comments

3. INTERFACE ASPECTS

a. Distance and azimuth to existing and planned communications facilities:

	Distance	Azimuth
(1) Communications center —		
(2) Navy receiver site —		
(3) Other military/government receivers (identify) —		
(4) Other transmitters (identify) —		

b. Distance and azimuth to other significant locations:

	Distance	Azimuth
(1) Main highways		
(2) Airfield (including glide path)		
(3) Residential area		
(4) Industrial area		

	Distance	Azimuth
(5) Commercial area —		
(6) Overhead power lines —		
(7) Other (specify) —		

4. TERRAIN CHARACTERISTICS:

a. Unobstructed 5° wavepath (vertical angle) above horizontal plane for all antennas. Attach horizon plot and photograph keyed to site topographic map. Site maps desired with scale of 1:24, 000 and contour intervals of not more than 10 feet. — ☐ Yes ☐ No ☐ Comment

b. Scraping, grading, earth moving, required — ☐ Extensive ☐ Minimal ☐ Comment

c. Type of soil as related to ground conductivity and uniformity. (If soil characteristics are not uniform, provide a descriptive sketch.) — (Comment)

d. Soil conductivity measurement data. —

e. Water table depth and variability. (If not uniform or excessive seasonal variability, provide descriptive information.) —

f. Underground structures. Identify and locate underground facilities such as cables and pipelines. —

5. MICROWAVE LINK LINE-OF-SIGHT DISTANCE: (Attach separate sheets for comments as necessary.)

a. Miles to receiver site —

b. Miles to communications center —

c. Path obstructions — (Comment)

6. POTENTIAL ENCROACHMENT: (Comment on each item. Attach separate sheets for comments as necessary.)

a. Military —

b. Industrial —

c. Commercial —

d. Residential —

e. Highways/roads —

f. Power lines —

g. Airfields —

h. Other (specify) —

7. MAXIMUM FUTURE EXPANSION CAPABILITY: (Attach separate sheets for comments as necessary.)

a. Transmitter building (sq. ft.) —

b. Logistics buildings (sq. ft. each) —

c. Antenna park (acres) —

d. Vehicle parking (sq. ft.) —

e. Recreation area (acres) —

APPENDIX D

COMMUNICATIONS CENTER SITE SURVEY

1. GENERAL SUITABILITY

(Comment on each item. Attach separate sheets as necessary.)

a. Logistic support accessibility —
   (1) Remoteness of area (air, rail, truck, bus)
   (2) Proximity to paved roads
   (3) Access road requirement
   (4) Availability of naval supply facilities
   (5) Availability of other government facilities (25 mile radius)
   (6) Availability of commercial supply facilities
   (7) Other comments

b. Utility services availability —
   (1) Availability of commercial power
   (2) Availability of station power
   (3) Availability of water supply
   (4) Availability of sewage services
   (5) Availability of fire protection services
   (6) Availability of telephone services
   (7) Other comments

c. Climatological conditions —
   (1) Extremes of climate to be expected
   (2) Frequency of hurricanes, typhoons, or blizzards
   (3) Other comments

d. Future continuing suitability —
   (1) Stability of existing conditions
   (2) Anticipated industrial encroachment
   (3) Government ownership
   (4) Treaty arrangements
   (5) Political stability
   (6) Area future planning
   (7) Other comments

e. Defensibility —
   (1) Physical defense features
   (2) Security arrangements
   (3) Proximity to primary targets
   (4) Other comments

f. Recreation availability —
   (1) Availability of recreational facilities
   (2) Types of facilities available
   (3) Proximity to facilities
   (4) Other comments

g. Personnel logistics availability —
  (1) Proximity to established naval station
  (2) Availability of on-base personnel housing
  (3) Availability of off-base personnel housing
  (4) Mess facilities
  (5) Exchange facilities
  (6) Other comments

2. LAND AREA REQUIRED

(Attach separate sheets for comment as necessary)

a. Topographic map of area (minimum scale — 1:50,000)

b. Acreage under consideration

c. Adequacy of site to meet requirements

d. Present ownership of site

e. Proposed acquisition arrangements

f. Host/tenant agreements required

g. Treaty arrangements required

h. Advantages of proposed site

i. Limitations of proposed site

j. Estimated costs of acquisition

k. Other comments

3. INTERFACE ASPECTS

a. Distance, azimuth, and measured field intensity from existing and planned communications facilities: (Note 1)

	Distance	Azimuth	Freq. (Note 2)	μV/M
(1) Navy VLF transmitters —				
(2) Navy LF-HF transmitters —				
(3) Other military transmitters —				
(4) Non-military transmitters (identify) —				
(5) Navy receiver site —				N/A
(6) Other military/government receivers —				N/A

b. Distance, azimuth, and measured field intensity from radar: (Note 1) (Note 3)

	Distance	Azimuth	Freq.	µV/m
(1) Navy (specify type)				
(2) Other (specify)				

c. Distance, azimuth, and measured field intensity from man-made noise sources: (Note 1)

	Distance	Azimuth	Freq.	µV/m
(1) Primary power plant —				
(2) Highways/roads —				
(3) Industrial area —				
(4) Commercial area —				
(5) Residential area —				
(6) High-tension power lines—				
(7) Airfield (including glide path) —				
(8) Other (specify) —				

4. TERRAIN CHARACTERISTICS: (Attach separate sheets for comments)

a. Scraping, grading, earth moving required— ☐ Extensive ☐ Minimal ☐ Comment

b. Water table depth and variability. (If not uniform or excessive seasonal variability, provide descriptive information.) —

c. Underground structures. Identify and locate underground facilities such as cables and pipe lines. —

5. MICROWAVE LINK LINE-OF-SIGHT DISTANCE: (Attach separate sheets for comments)

a. Miles to transmitter site —

b. Miles to receiver site —

c. Path obstructions — (Comment)

6. POTENTIAL ENCROACHMENT: (Comment on each item. Attach separate sheets for comments.)

   a. Military —

   b. Industrial —

   c. Commercial —

   d. Residential —

   e. Highways/roads —

   f. Power lines —

   g. Airfields —

   h. Other (specify) —

7. MAXIMUM FUTURE EXPANSION CAPABILITY: (Attach separate sheets for comments)

   a. Message center (sq. ft.) —

   b. Relay/automatic switching center (sq. ft.) —

   c. Control link area (sq. ft.) —

   d. Cryptographic center (sq. ft.) —

   e. Logistics buildings (sq. ft. each) —

   f. Vehicle parking (sq. ft.) —

   g. Recreation area (sq. ft.) —

8. PROXIMITY TO SUBSCRIBERS:

   a. Navy (specify activities) —

   b. Other military/government (specify) —

NOTE 1: Field intensity measurements made at planned building site.

NOTE 2: Field intensity measurements must include low, middle, and high frequencies of the band (minimum).

NOTE 3: Measurements must include pulse repetition rate.

APPENDIX E

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WORKSHEET FOR PATHS ≤4000 km

BASIC DATA, MUF AND FOT

PATH DISTANCE 2400 km MONTH June SSN 10

TRANSMITTER Washington, D.C. (LOCATION) 38.9°N 77.0°W (COORDINATES) LAND (TERRAIN)

RECEIVER Boulder Colorado (LOCATION) 40.0°N 105.0W (COORDINATES) LAND (TERRAIN)

MIDPATH 40.4°N 91.0°W (COORDINATES) 49°N (GEOMAGNETIC LATITUDE) LAND (TERRAIN)

MIDPATH ZONE W, GYRO FREQUENCY 1.5 MHz

	GMT	00	02	04	06	08	10	12	14	16	18	20	22
1	MIDPATH LOCAL TIME	1756	1956	2156	2356	0156	0356	0556	0756	0956	1156	1356	1556
2	F2-ZERO MUF	6.0	6.1	5.0	3.8	3.2	3.0	4.5	5.2	5.5	5.7	5.8	5.9
3	F2-4000 MUF	18.0	18.1	13.6	10.4	8.5	7.0	12.9	14.5	15.1	15.3	15.6	16.9
4	SUN'S ZENITH ANGLE	75	96	–	–	–	96	75	53	31	17	33	55
5	ABSORPTION INDEX	0.32	0.05	–	–	–	0.05	0.32	0.63	0.88	0.99	0.89	0.61
6	F2-MUF	14.4	14.6	11.0	8.5	7.0	6.0	10.4	11.7	12.3	12.5	12.7	13.7
7	F2-FOT	12.2	12.4	9.4	7.2	5.9	5.1	8.8	10.0	10.5	10.6	10.8	11.6
8	E-2000 MUF	11.0	5.2	–	–	–	5.2	11.0	14.6	16.6	17.2	16.7	14.7
9	E-MUF	9.0	4.3	–	–	–	4.3	9.0	12.0	13.6	14.0	13.7	12.1
10	CIRCUIT FOT	12.2	12.4	9.4	7.2	5.9	5.1	9.0	12.0	13.6	14.0	13.7	12.1

Foldout 2-1. Basic Data, MUF and FOT Worksheet for Paths ≤ 4000 km

PATH LOSS WORKSHEET FOR PATHS ≤4000 km

TRANSMITTER Washington, D.C. RECEIVER Boulder Colorado

PATH DISTANCE 2400 km MONTH June SSN 10

GMT 1200 MIDPATH LOCAL TIME 0556

11	OPERATING FREQUENCY	9.0				
12	F2-LAYER HEIGHT	285				
13	MODES CONSIDERED	1E	2E	1F	2F	3F
14	DISTANCE PER HOP	2400	1200	2400	1200	800
15	RADIATION ANGLE Δ	-2	7	8	23	33
16	MAXIMUM EΔ, MINIMUM FΔ	7.7				
17	MINIMUM F DISTANCE	☒	☒	1850		
18	IONOSPHERIC LOSS PER HOP, dB	–	8.5	8.3	–	–
19	TOTAL IONOSPHERIC LOSS, dB	–	17.0	8.3	–	–
20	GROUND LOSS PER REFLECTION, dB	☒	2.0	☒	–	–
21	TOTAL GROUND LOSS, dB	☒	4.0	☒	–	–
22	RAY PATH DISTANCE LOSS, dB	–	120	120	–	–
23	QUASI-MINIMUM PATH LOSS, dB	–	141	128	–	–
24	ADJUSTMENT TO MEDIAN, dB	9				
25	MEDIAN PATH LOSS, dB	137				
26	ADJUSTMENT FOR 90% SERVICE, dB	8				
27	PATH LOSS FOR 90% SERVICE, dB	145				

Foldout 2-2. Path Loss Worksheet for Paths ≤ 4000 km

RADIO NOISE AND SIGNAL POWER WORKSHEET

RECEIVER Boulder, Colorado (LOCATION) 40.°0 N 105°W (COORDINATES)

GMT 1200 MONTH JUNE · FREQUENCY 9.0 MHz

28	LOCAL TIME	0500
29	F2-ZERO MUF	4.5
30	1 MHz NOISE LEVEL, dB ABOVE kTb	59
31	ATMOSPHERIC NOISE, 1 Hz BANDWIDTH, dBW	−167
32	GALACTIC NOISE, dBW	−174
33	MAN-MADE NOISE, dBW	−161
34	NOISE AT RECEIVING ANTENNA, 1 Hz BANDWIDTH, dBW	−161
35	NOISE, 3 kHz BANDWIDTH, dBW	−126
36	REQUIRED S/N, dB	32
37	SIGNAL REQUIRED, dBW	−94
38	PATH LOSS, 90% SERVICE, dB	145
39	PATH EFFECTIVE POWER, dBW	51

Foldout 2-3. Radio Noise and Signal Power Worksheet