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Engineer's Refractive Effects Prediction System (EREPS) Revision 2.0

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ADMINISTRATIVE INFORMATION

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1.0 Introduction

The purpose of this manual is to introduce you to the contents and operation of the Engineer's Refractive Effects Prediction System (EREPS). EREPS is a system of individual stand-alone IBM/PC-compatible programs that have been designed to assist an engineer in properly assessing electromagnetic (EM) propagation effects of the lower atmosphere on proposed radar, electronic warfare, or communication systems. The EREPS models account for effects from optical interference, diffraction, tropospheric scatter, refraction, evaporation and surface-based ducting, and water-vapor absorption under horizontally homogeneous atmospheric conditions.

EREPS revision 2.0 is an upgrade to revision 1.0 released in July 1988 (Hitney, 1988). There are two completely new programs in revision 2.0, COVER and PROPH, described below, and a user-callable propagation-factor source code subroutine that may be helpful to anyone who wants to integrate the EREPS propagation model into their own applications program. The propagation models have changed very little between revisions 1.0 and 2.0, with the single exception of the sea-clutter model that now allows for evaporation ducting effects. Revision 2.0 also allows for transmitter antenna patterns other than omni-directional, which was assumed by PROPR revision 1.0. Because of this addition, the use of the term "pathloss" in revision 1.0 has been replaced by "propagation loss" in revision 2.0 to avoid confusion with widely-accepted definitions.

EREPS is a continuing development. With new propagation models and computer technology, additional programs will become available and old programs will be refined or modified. This user's manual will limit its discussion to EREPS revision 2.0.

EREPS revision 2.0 consists of five executable programs and a program source code listing. These are

1. PROPR - PROPR generates a graphic display of propagation-loss, propagation-factor, or radar signal-to-noise ratio versus range under a variety of environmental conditions from which signal levels relative to a specified threshold or maximum free-space range can be determined.

2. PROPH - PROPH provides graphics similar to PROPR except the independent plot variable is receiver height rather than range.

3. COVER - COVER provides a height-versus-range graphic showing the area where signal levels meet or exceed your specified thresholds.

4. RAYS - RAYS displays altitude-versus-range trajectories of a series of rays for your specified refractive-index profile, and includes an option to display altitude error relative to a standard atmosphere.

5. SDS - SDS displays an annual climatological summary of evaporation duct, surface-based duct, and other meteorological parameters for many 10 degree latitude by 10 degree longitude (Marsden) squares of the earth's surface. SDS may be used as a primary source of environmental data for the PROPR, PROPH, and COVER programs.

6. FFACTR - FFACTR is not an executable program but rather a program source code. It may be compiled external to the EREPS system to produce a stand-alone program or may be incorporated into your programs as a called subroutine, though the latter use might require you to translate FFACTR into another program language. FFACTR is structured as a subroutine that returns propagation factor in dB for specified environmental and EM system parameters.

EREPS contains many similarities to the Integrated Refractive Effects Prediction System (IREPS) described by Patterson et al. (1987) that has been used by the United States Navy and other organizations since 1978. IREPS was developed to provide operational performance assessment to a wide variety of existing EM equipments by means of in-situ measured environmental data. A large portion of IREPS is concerned with maintaining libraries of existing systems parameters and entering divergent sources of environmental data. Thus, IREPS is not well suited to comparing the performance of two sensors that may differ by only one parameter, such as radar pulse length; or to showing relative performance for a given system when only one environmental parameter, such as wind speed or evaporation duct height changes value. EREPS has been specifically designed for these comparative studies using interactive graphics displays. In addition, the "stardardized propagation model" of EREPS has been improved to give better results for low altitude applications.

Appendix A of this manual presents a number of products from PROPR, PROPH, COVER, RAYS, and SDS to illustrate a variety of features available from each program. As an aid in programming, the program source code of FFACTR is reproduced in appendix B.

2.0 Background

2.1 Structure and Characteristics of the Earth's Atmosphere

The earth's atmosphere is a collection of many gases together with suspended particles of liquid and solids. Excluding variable components such as water vapor, ozone, sulfur dioxide, and dust, the gases of nitrogen and oxygen occupy about 99 percent of the volume with argon and carbon dioxide being the next two most abundant gases. From the earth's surface to an altitude of approximately 80 kilometers, mechanical mixing of the atmosphere by heat-driven air currents evenly distributes the components of the atmosphere. At about 80 kilometers, the mixing decreases to the point where the gases tend to stratify in accordance with their weights.

The lower, well-mixed portion of the atmosphere is called the homosphere, while the higher, stratified portion is called the heterosphere. The bottom portion of the homosphere is called the troposphere.

The troposphere extends from the earth's surface to an altitude of 8 to 10 kilometers at polar latitudes, 10 to 12 kilometers at middle latitudes, and up to 18 kilometers at the equator. It is characterized by a temperature decrease with height. The point at which the temperature ceases to decrease with height is known as the tropopause. The average vertical temperature gradient of the troposphere varies between 6 and 7 degrees Celsius per kilometer.

The concentrations of gas components of the troposphere vary little with height, except for water vapor. The water vapor content of the troposphere comes from evaporation of water from oceans, lakes, rivers and other water reservoirs. Differential heating of land and ocean surfaces produces vertical and horizontal wind circulations which distribute the water vapor

throughout the troposphere. The water vapor content of the troposphere rapidly decreases with height. At an altitude of 1.5 kilometers, the water vapor content is approximately half of the surface content. At the tropopause, the content is only a few thousandths of what it is at the surface.

In 1925, the International Commission for Aeronavigation defined the "international standard atmosphere." This is a hypothetical atmosphere having an arbitrarily selected set of pressure and temperature characteristics reflecting an average condition of the real atmosphere.

2.2 Refraction

2.2.1 Index of Refraction

The term refraction refers to the property of a medium to bend an electromagnetic wave as it passes through the medium. The degree of bending is determined by the index of refraction, n, defined as the velocity, c, of propagation in free space (away from the influence of the earth or other objects) to the velocity, v, in the medium.

$$n = \frac{c}{v} \quad (1)$$

2.2.2 Refractivity and Modified Refractivity

The normal value of n for the atmosphere near the earth's surface varies between 1.000250 and 1.000400. For studies of propagation, the index of refraction is not a very convenient number, therefore a scaled index of refraction, N, called refractivity, has been defined. At microwave frequencies, the

relationship between the index of refraction n and refractivity N for air which contains water vapor is given as

$$N = (n - 1)\ 10^6 = \frac{77.6\ p}{T} + \frac{3.73 \times 10^5\ e}{T^2}\ , \qquad (2)$$

where e is the partial pressure of water vapor in millibars or

$$e = \frac{RH}{100} \times 6.105\ \exp(x)\ , \qquad (3)$$

where

$$x = 25.22 \times \frac{(T - 273.2)}{T} - 5.31 \times \log_e \left(\frac{T}{273.2} \right) .$$

p = atmosphere's barometric pressure in millibars
T = atmosphere's absolute temperature in degrees Kelvin
RH = atmosphere's relative humidity in percent

Thus, the atmospheric refractivity near the earth's surface would normally vary between 250 and 400 N units.

Since the barometric pressure and water-vapor content of the atmosphere decrease rapidly with height while the temperature decreases slowly with height, the index of refraction and therefore refractivity, normally decreases with increasing altitude.

As an tool in examining refractive gradients and their effect upon propagation, a modified refractivity, defined as

$$M = N + 0.157\,h \quad \text{for altitude h in meters}$$
$$M = N + 0.048\,h \quad \text{for altitude h in feet,} \qquad (4)$$

is often used in place of the refractivity.

2.2.3 Effective Earth Radius Factor

In free space, an electromagnetic wave will travel in a straight line because the index of refraction is the same everywhere. Within the earth's atmosphere however, the velocity of the wave is less than that of free space and the index of refraction normally decreases with increasing altitude. Therefore, the propagating wave will be bent downward from a straight line. It is frequently more convenient however, to compute refractive effects in terms of waves traveling in straight lines. This may be approximated by replacing the actual earth's radius with an **effective earth radius** and replacing the actual atmosphere by one that is homogeneous in nature.

The effective earth radius factor, k, is defined as the factor that is multiplied by the actual earth radius, a, to give the effective earth radius a_e. Therefore $a_e = ka$. The effective earth radius factor k is the parameter used by PROPR, PROPH, and COVER to account for average refractive effects in the optical region and is related to the average N or M unit gradient by

$$k = 1/(1 - 10^{-6} a\, dN/dz) = 1 / (10^{-6} a\, dM/dz) \qquad (5)$$

where dN/dz and dM/dz are the N and M gradients, respectively, and z is in the same units as a. The mean earth radius, a, is generally taken to be 6.371×10^6 meters. For standard refractivity conditions where dN/dz = -0.039 N-units per meter or dM/dz = 0.118 M-units per meter, k = 1.33 or four thirds.

2.2.4 Refractive Gradients

2.2.4.1 Standard and Normal

It has been observed that the refractivity distribution within the atmosphere is nearly an exponential function of height, Bean (1966). The exponential decrease of N with height close to the earth's surface (within 1 kilometer) is sufficiently regular however, to allow an approximation of the exponential function by a linear function, a linear function which is assumed by the effective earth's radius model. This linear function is known as a **standard gradient** and is characterized by a decrease of 39 N-units per km or an increase of 118 M-units per km. The refractivity and modified refractivity profiles for this condition are illustrated in figure 1. Figure 2 illustrates the wave path for a standard refractive gradient. Gradients that cause effects similar to a standard gradient but vary between 0 and -79 N-units per km or between 79 and 157 M-units per km are known as normal gradients.

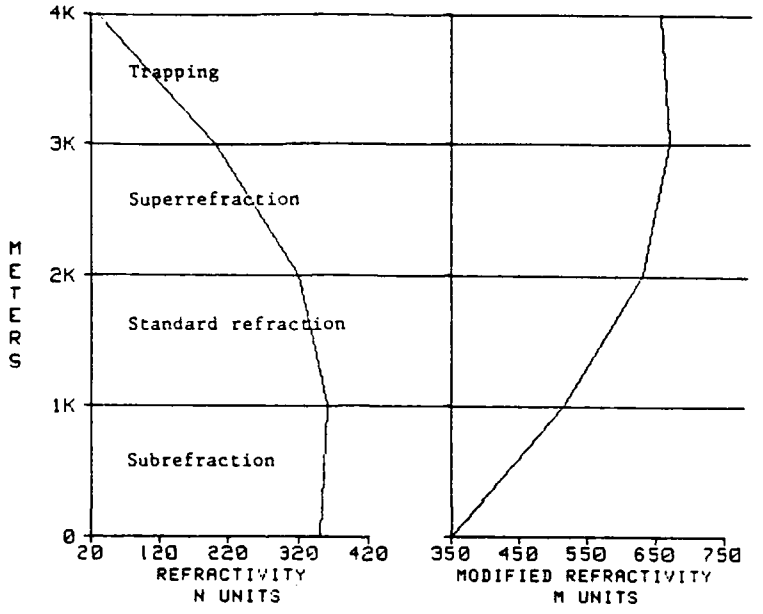


Figure 1: Refractivity N and modified refractivity M versus altitude for various refractive conditions.

2.2.4.2 Subrefraction

If the motions of the atmosphere produce a situation where the temperature and humidity distribution creates an increasing value of N with height, the wave path would actually bend upward and the energy would travel away from the earth. This is termed subrefraction. Although this situation rarely occurs in nature, it still must be considered when assessing electromagnetic systems' performance. Figures 1 and 2 illustrate the refractivity profiles and the wave path, respectively, for subrefraction.

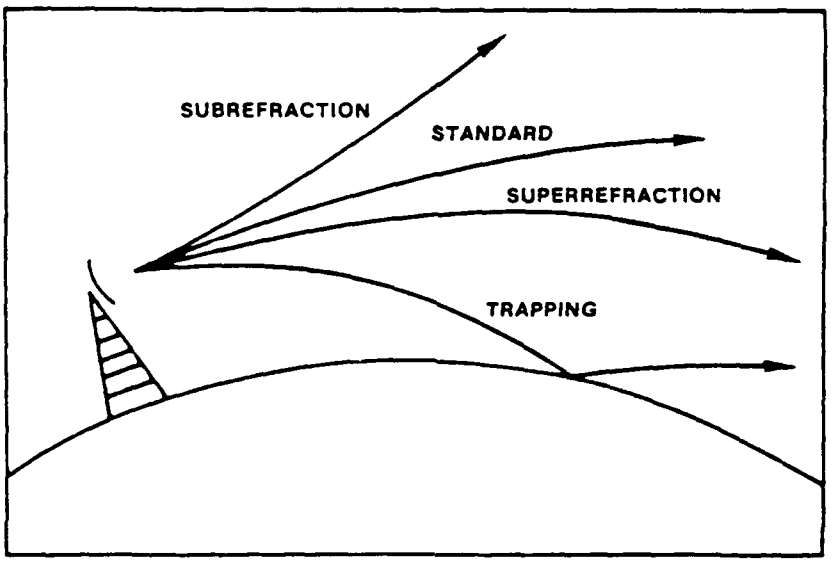


Figure 2: Wave paths for various refractive conditions.

2.2.4.3 Superrefraction

As discussed in section 2.2.3, a standard atmosphere has a refractivity gradient which causes waves to bend downward from a straight line. If the troposphere's temperature increases with height (temperature inversion) and/or the water vapor content decreases rapidly with height, the refractivity gradient will decrease from the standard. The propagating wave will be bent downward from a straight line more than normal. As the refractivity gradient continues to decrease, the radius of curvature for the wave path will approach the radius of curvature for the earth. The refractivity gradient for which the two radii of curvature are equal is referred to as the "critical" gradient. At the critical gradient, the wave will propagate at a fixed height above the ground and will travel parallel to the earth's

surface. Refraction between the normal and critical gradients is known as superrefraction. Figures 1 and 2 illustrate the refractivity profiles and the wave path, respectively, for superrefraction.

2.2.4.4 Trapping

Should the refractivity gradient decrease beyond the critical gradient, the radius of curvature for the wave will become smaller than that of the earth's and the wave will either strike the earth and undergo surface reflection, or enter a region of standard refraction and be refracted back upward, only to reenter the area of refractivity gradient which causes downward refraction. This refractive condition is called trapping since the wave is confined to a narrow region of the troposphere. The common term for this confinement region is a tropospheric "duct" or a tropospheric "waveguide." It should be noted that a tropospheric waveguide is not a waveguide in the true sense of the word since there are no rigid walls which prevent the escape of energy from the guide. Figures 1 and 2 illustrate the refractivity profiles and the wave path, respectively, for trapping.

Table 1 summarizes the refractivity gradients and their associated refractive conditions.

Table 1 : Relation of N and M gradients to refraction.

	N-Gradient	M-Gradient
Trapping	< -157 N/km	< 0 M/km
	< - 48 N/kft	< 0 M/kft
Superrefractive	-157 to - 79 N/km	0 to 79 M/km
	- 48 to - 24 N/kft	0 to 24 M/kft
Normal	- 79 to 0 N/km	79 to 157 M/km
	- 24 to 0 N/kft	24 to 48 M/kft
Subrefractive	> 0 N/km	> 157 M/km
	> 0 N/kft	> 48 M/kft

2.2.5 Atmospheric Ducts

As defined in section 2.2.4.4, a duct is a channel in which electromagnetic energy can propagate over great ranges. To propagate energy within a duct, the angle the electromagnetic system's energy makes with the duct must be small, usually less than one degree. Thicker ducts in general can support trapping for lower frequencies. The vertical distribution of refractivity for a given situation must be considered as well as the geometrical relationship of transmitter and receiver to the duct in order to assess the duct's effect at any particular frequency.

Ducts not only give extended radar detection ranges for systems within the duct, they may also have a dramatic effect upon transmitter/receiver systems which transcend duct boundaries. For example, an air target which would normally be detected, may be missed if the radar is within or just above the duct and the target is just above the duct. This area of reduced coverage is known as a radar or radio "hole" or shadow zone and

is illustrated by figure 3. It should be emphasized that although the duct acts like a waveguide for the energy, this waveguide does not have rigid and inpenetrable boundaries, except for the earth's surface in the case of surface-based ducts. Therefore energy is continually "leaking" from the duct. While the energy level within a radar hole may be insufficent for radar detection, it may be sufficient for ESM intercept of the radar.

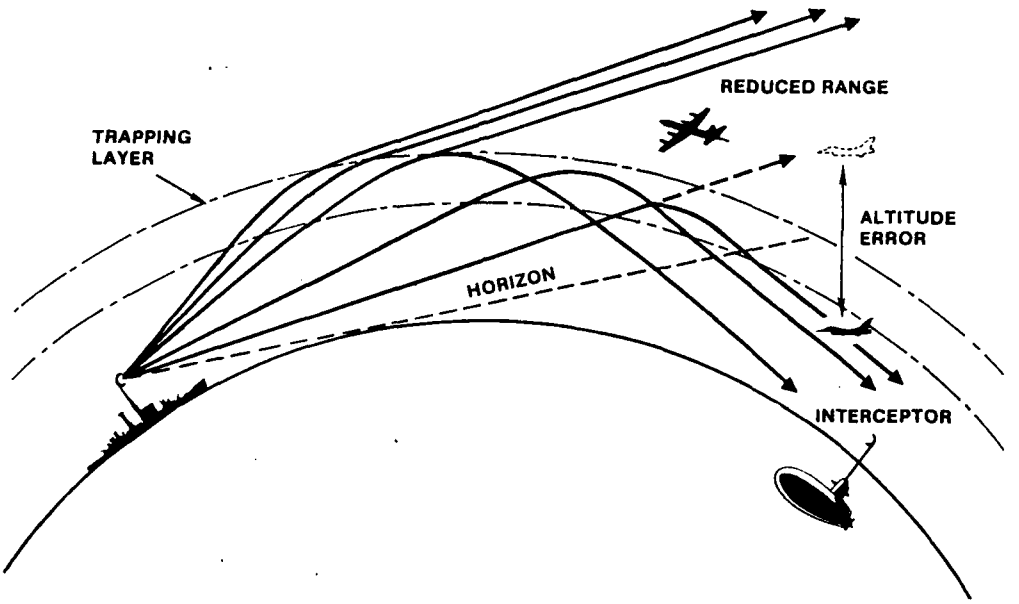
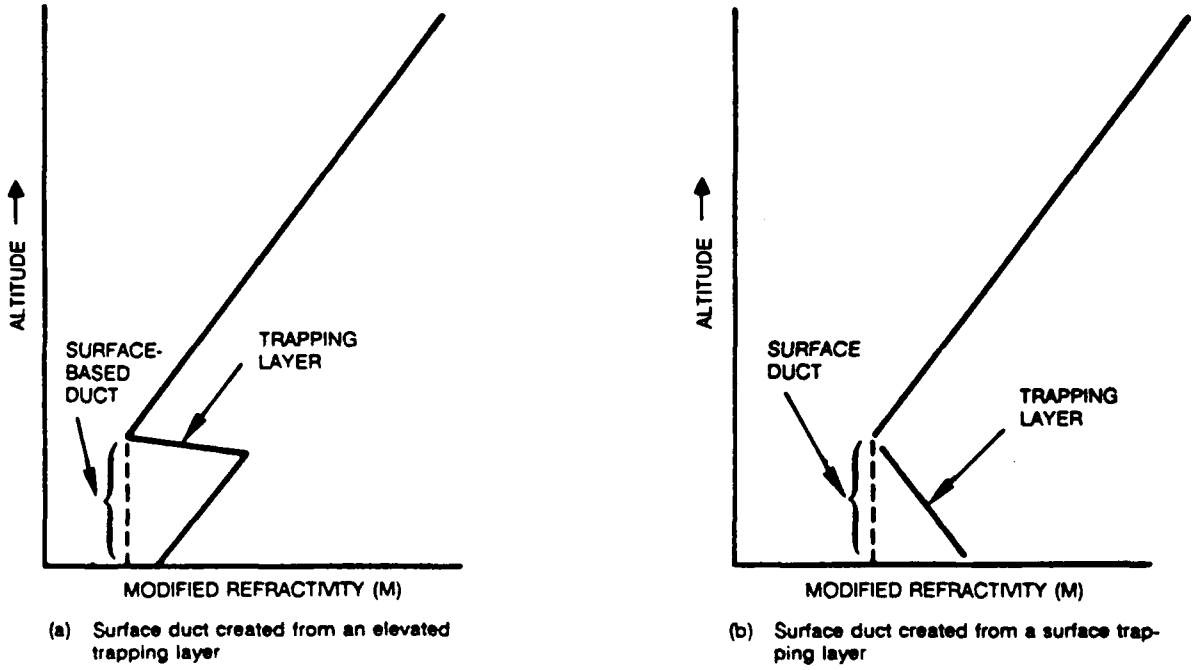


Figure 3: An example of extended detection/ESM intercept for a surface-based radar with its associated radar hole and height error.

There are a number of meterological conditions which will lead to the creation of ducts. If these conditions occur aloft such that the base of the duct is above the surface, the duct is referred to as an **elevated duct**. Should these conditions occur close to or at the earth's surface such that the base of the duct is located at the surface, the duct is referred to as a **surface duct**. There are three catagories of surface ducts depending upon

the meteorological condition which creates the duct and the location of the trapping layer in relationship to the surface. These are a surface duct created from an elevated trapping layer, commonly referred to by IREPS and EREPS as a **surface-based duct**; a surface duct created from a surface-based trapping layer, and a surface duct created by a rapid decrease of relative humidity immediately adjacent to the air-sea interface. Because this latter duct is a nearly permanent world-wide feature, it is referred to as an **evaporation duct**. EREPS provides for sperate inputs for the surface-based duct and the evaporation duct. EREPS models do not allow however, for a surface duct created from a surface-based trapping layer. Figure 4 illustrates the modified refractivity profiles for surface, elevated, and evaporation ducting. Of particular note within figure 4, is the distinction between the actual layer of the troposphere which constitutes the trapping gradient and the resultant duct.



(a) Surface duct created from an elevated trapping layer

(b) Surface duct created from a surface trapping layer

(c) Elevated duct created from an elevated trapping layer

(d) Surface duct (evaporation duct) created by a decrease of humidity immediately adjacent to the sea-surface

Figure 4: M-unit versus height profiles for ducting conditions.

2.3 Standard Wave Propagation Mechanisms

2.3.1 Propagation Loss, Propagation Factor, Signal-to-Noise

PROPR and PROPH present their results in terms of propagation loss, propagation factor, or radar signal-to-noise ratio, all expressed in dB. The definitions of each term, as used within EREPS, is

Propagation loss: The ratio, expressed in dB, of the effective radiated power transmitted in the direction of maximum radiation of the antenna pattern to the power received at any point by an omnidirectional antenna.

Propagation factor: The ratio, expressed in dB, of the actual field strength at a point to the field strength that would occur at the same range in free-space in the direction of maximum radiation.

Signal-to-noise ratio: The ratio, expressed in dB, of the signal received at the input of the radar receiver to the noise generated within the receiver itself. For the purposes of EREPS, the signal level is based upon the reflection from a target of specified radar cross-section, all the engineering parameters of the radar (such as radiated power, antenna gain, losses, etc.), and the applicable propagation factors.

Propagation loss is used within EREPS 2.0 in place of the path loss used in revision 1.0 because directional antenna patterns are now allowed. Widely-used definitions of path loss are based on omnidirectional antennas. In PROPR and PROPH, propagation loss is equivalent to path loss when an omnidirectional antenna is specified. Propagation loss is closely related to many definitions of transmission loss. Transmission loss generally includes effects from both an antenna pattern and the absolute gain of the antenna, whereas propagation

loss only includes the pattern effects, with the gain normalized to 1 (i.e. 0 dB) in the direction of maximum transmission. Therefore, propagation loss would be equal to transmission loss plus the antenna gain in dB.

The EREPS definition of propagation factor is frequently referred to by others as pattern-propagation factor, to clearly indicate that antenna pattern effects are included. We chose to retain the term propagation factor because it is consistent with the term propagation loss. However, you should be aware that the EREPS propagation factor does include the effects of the antenna pattern.

2.3.2 Free-space Propagation

The simplest case of electromagnetic wave propagation is the transmission of a wave between a transmitter and a receiver in free space. Free space is defined as a region whose properties are isotropic, homogeneous, and loss-free, i.e. away from the influences of the earth's atmosphere. In free space, the electromagnetic wave front spreads uniformly in all directions from the transmitter. If a particular point on a wave front is followed over time, the collection of point positions would define a ray. The ray would coincide with a straight line from the transmitter to the receiver. Often wave propagation is illustrated with the aid of rays such as in figure 2.

2.3.3 Standard Propagation

Standard propagation mechanisms are those propagation mechanisms and processes that occur in the presence of a standard atmosphere. These propagation mechanisms are free-space propagation, optical interference (or surface reflection), diffraction, and tropospheric scatter.

2.3.3.1 Optical Interference and Surface Reflection

When an electromagnetic wave strikes a nearly smooth large surface, such as the ocean, a portion of the energy is reflected from the surface and continues propagating along a path that makes an angle with the surface equal to that of the incident ray, as illustrated by figure 5.

The strength of the reflected wave is determined by the reflection coefficient, a value which depends upon the frequency and polarization of radiation, the angle of incidence, and the roughness of the reflecting surface.

For shallow incidence angles and smooth seas, typical values of the reflection coefficient are near unity (i.e., the reflected wave is almost as strong as the incidence wave). As the wind speed increases, the ocean surface grows rougher and the reflection coefficient decreases. For a transmitter near the surface, the reflection process results in two paths to a receiver within the line of sight, as illustrated by figure 6.

As stated above, upon reflection, a portion of the energy is propagated in the direction of initial wave motion. A portion of energy is also reflected backward toward the transmitter. This backward reflected energy is also received by the radar and may interfere with the radar's ability to distinguish a desired target. This backward reflected energy is called clutter.

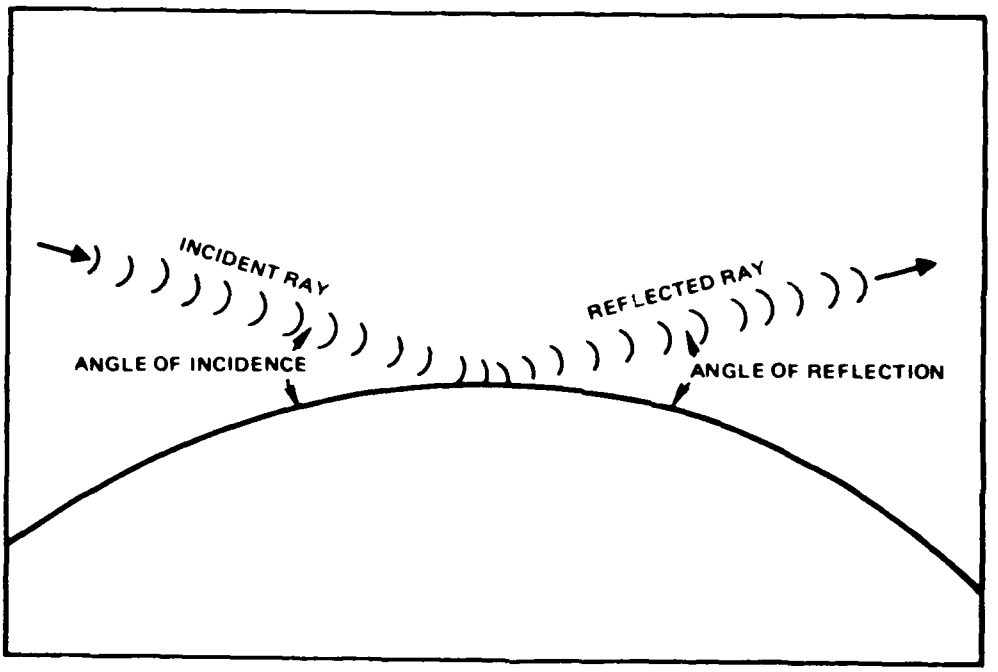


Figure 5: Incident ray and reflected ray illustrating equal angles of reflection.

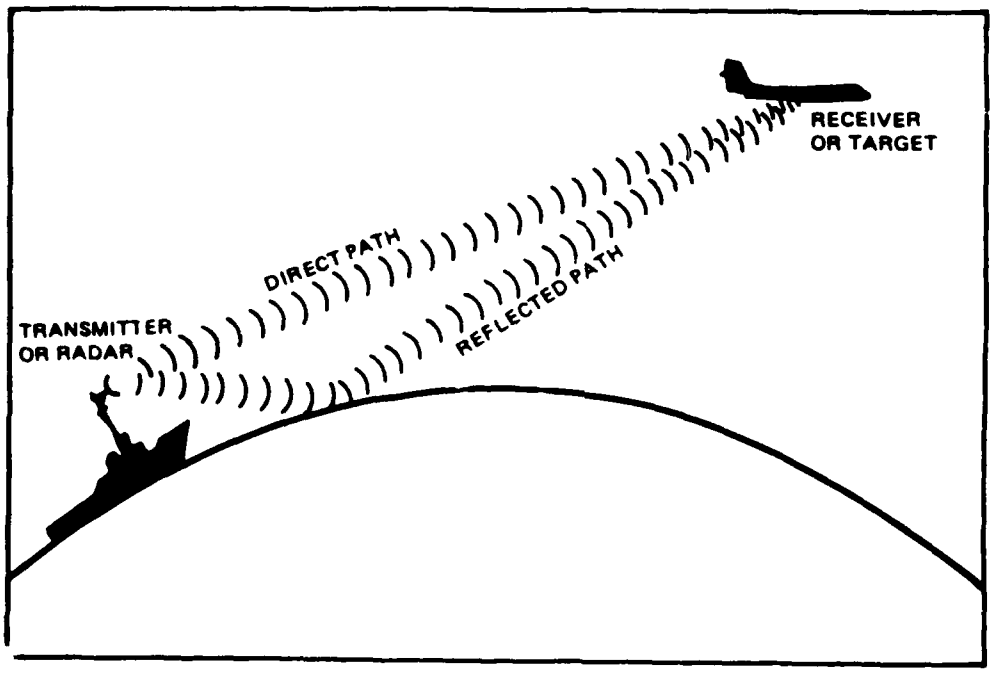


Figure 6: Surface-to-air geometry illustrating direct and sea-reflected paths.

Not only is the magnitude of the reflected wave reduced, but the phase of the wave is also altered. For horizontally or vertically polarized waves at low grazing angles, the phase change upon reflection is approximately 180 degrees. Whenever two or more wave trains traveling over different paths intersect at a point in space, they are said to interfere. If two waves arrive at the same point in phase, they constructively interfere and the electric field strength is greater than either of the two component waves taken alone. If the two waves arrive together out of phase, they destructively interfere and the resultant field strength is weakened.

As the geometry of figure 6 changes, the relative lengths of the direct path and reflected path also change, which results in the direct and reflected wave arriving at the receiver in varying amounts of phase difference. The received signal strength, which is the vector sum of the signal strengths of the direct and reflected wave, may vary up to 6 dB above and 20 dB or more, below the free-space value.

2.3.3.2 Diffraction

Energy tends to follow along the curved surface of an object. Diffraction is the process by which the direction of propagating radiation is changed so that it spreads into the geometric shadow region of an opaque or refractive object which lies in the radiation field. In the earth-atmosphere system, diffraction occurs where the straight-line distance between the transmitter and receiver is just tangent to the earth's surface. For a homogeneous atmosphere, this point of tangency with the earth is referred to as the geometrical horizon. For a nonhomogeneous atmosphere (using an effective earth radius) and at radar and optical frequencies, this point of tangency is referred to as the radar and optical horizon, respectively.

The ability of the electromagnetic wave to propagate beyond the horizon by diffraction is highly dependent upon frequency. The lower the frequency, the more the wave is diffracted. At radar frequencies the wavelength is small when compared to the earth's dimensions and little energy is diffracted. At optical frequencies or very short radar wavelengths, the optical horizon represents the approximate boundary between regions of propagation and no propagation.

2.3.3.3 Tropospheric Scatter

At ranges far beyond the horizon, the propagation loss is dominated by troposcatter. Propagation in the troposcatter region is the result of scattering by small inhomogeneities within the atmosphere's refractive structure as discussed in section 7.1.3.

2.4 Anomalous Propagation Mechanisms

A deviation from the normal atmospheric refractivity leads to conditions of subrefraction, superrefraction and trapping as explained in sections 2.2.4.2, 2.2.4.3, and 2.2.4.4 respectively. The term anomalous propagation, or non-standard propagation, applies to any of the above listed conditions but it is most often used when describing those conditions which lead to radar ranges beyond the normal. Many anomalous propagtion effects may be seen quite well with a raytrace program such as RAYS.

2.4.1 Subrefractive Layers

As stated in section 2.2.4.2, a subrefractive layer of the troposphere would cause the propagating energy to bend upward

or away from the earth's surface, thereby leading to decreased detection ranges and shortened radio horizons. Altitude errors for height-finding radars will also become evident in a subrefractive environment.

Subrefractive layers may be found both at the earth's surface or aloft. In areas where the surface temperature is greater than 30 degrees Celsius and relative humidities are less than 40 percent (i.e. large desert and steppe regions), solar heating will produce a very nearly homogeneous surface layer, often several hundreds of meters thick. Since this layer is unstable, the resultant convective processes tend to concentrate any available moisture near the top of the layer. This in turn creates a positive N gradient or subrefractive stratum aloft. This layer may retain its subrefractive nature into the early evening hours, especially if a radiation inversion develops, trapping the water vapor between two stable layers.

For areas with surface temperatures between 10 and 30 degrees Celsius and relative humidities above 60 percent, i.e. the western Mediterranean, Red Sea, Indonesian Southwest Pacific, etc., surface-based subrefractive layers may develop during the night and early morning hours. It is characteristicly caused by advection (blowing horizontally) of warm, moist air over a relatively cooler and drier surface. While the N gradient is generally more intense than that described above, the layer is often not as thick. Similar conditions may also be found in regions of warm frontal activity.

2.4.2 Superrefractive Layers

Superrefractive conditions, as defined in section 2.2.4.3, are largely associated with temperature and humidity variations near the earth's surface. Inversions aloft, due to large scale subsidence (slow sinking air) will lead to

superrefractive layers aloft. Superrefractive layers will lead to increased radar detection ranges and extensions of the radio horizon.

The effects of a superrefractive layer upon a surface-based system is directly related to its height above the earth's surface. For airborne systems, the effects of a superrefractive layer depend upon the position of the transmitter and receiver relative to the layer. Both of these factors are related to the electromagnetic wave's angle of layer penetration. The steeper the penetration angle, the less of an effect the layer will have upon propagation. Trapping is an extension of superrefraction because the meteorological conditions for both are the same. Additional features of superrefractive layers will be presented in the following section.

2.4.3 Surface-Based Ducts

In a discussion of ducting conditions upon EM wave propagation, the usual concern is propagation beyond the normal horizon. Within the horizon however, ducting also has an effect. Ducting can alter the normal lobing pattern caused by the interference of the direct ray and the surface-reflected ray as illustrated in figure 6. The relative phase between the direct and reflected path may be changed as well as the relative amplitudes of the two rays. The effect of the duct on the line-of-sight propagation is to reduce the angle of the lowest lobe, bringing it closer to the surface.

Surface-based ducts occur when the air aloft is exceptionally warm and dry in comparison with the air at the earth's surface. There are several meteorological conditions which may lead to the formation of surface-based ducts.

Over the ocean and near land masses, warm dry continental air may be advected over the cooler water surface. Examples of this type of advection are the Santa Ana of southern California, the sirocco of the southern Mediterranean, and the shamal of the Persian gulf. This will lead to a temperature inversion at the surface. In addition, moisture is added to the air by evaporation, producing a moisture gradient to strengthen the trapping gradient. This type of meteorological condition routinely leads to a surface duct created by a surface-based trapping condition, a surface duct type not modeled within EREPS. However, as one moves from the coastal environment into the open ocean, this trapping layer may well rise from the surface, thereby creating the surface-based duct known by IREPS and EREPS. Surface-based ducts tend to be on the leeward side of land masses and may occur both during the day or at night. In addition, surface-based ducts may extend over the ocean for several hundred kilometers and may be very persistent (lasting for days).

Another method of producing surface-based ducting conditions is by divergence (spreading out) of relatively cool air under a thunderstorm. While this method may not be as frequent as the other methods, it may still enhance surface propagation during the thunderstorm activity, usually on the order of a few hours.

With the exception of thunderstorm conditions, surface-based ducting is associated with fair weather, with increased occurrence of surface-based ducts during the warmer months, and in more equatorial latitudes. Any time the troposphere is well mixed, such as with frontal activity or with high wind conditions, surface-based ducting is decreased.

An interesting feature of surface-based ducts is the skip zone near the normal horizon, in which the duct has no influence. This skip zone is easily illustrated using a raytrace program such as RAYS, and a model to account for its effects is included

in all the EREPS programs. It should be noted that the surface duct created from a surface-based trapping layer does not have this skip zone phenomenon and again, is not modeled within EREPS.

2.4.4 Elevated Ducts

Great semi-permanent surface high pressure systems, centered at approximately 30 degrees north and south latitude, cover the ocean areas of the world. Poleward of these systems lay the mid-latitude westerly winds and equatorward, the tropical easterlies or the "tradewinds." Within these high pressure systems, there is large scale subsidence of air which is heated as it undergoes compression. This leads to a layer of warm, dry air overlaying a cool, moist layer of air (often called the marine boundary layer). The resultant inversion is referred to as the tradewind inversion and may create a strong ducting condition at the top of the marine boundary layer. Elevated ducts may vary from a few hundreds meters above the surface at the eastern part of the tropical oceans to several thousand meters at the western part. For example, along the southern California coast, elevated ducts occur an average of 40 percent of the time with an average top elevation of 600 meters. Along the coast of Japan, elevated ducts occur an average of 10 percent of the time with an average top elevation of 1500 meters.

It should be noted that the meteorological conditions necessary for a surface-based duct are the same as those for an elevated duct. In fact, a surface-based duct may slope upward to become an elevated duct as warm, dry continental air glides over cool, moist marine air. The tradewind inversion may also intensify thereby turning an elevated duct into a surface-based duct.

2.4.5 Evaporation Ducts

As can be seen from equation 2, a change in the moisture distribution without an accompanying temperature change can also lead to a trapping refractivity gradient. The air in contact with the ocean's surface is saturated with water vapor. A few meters above the surface, the air is not usually saturated so there is a decrease of water vapor pressure from the surface to some value well above the surface. The rapid decrease of water vapor initially causes the modified refractivity M, to decrease with height; but at greater heights the water vapor distribution will cause M to reach a minimum and, thereafter, increase with height, as illustrated in figure 4. The height at which M reaches a minimum is called the evaporation duct.

Evaporation ducts exist over the ocean, to some degree, almost all of the time. The duct height varies from a meter or two in northern latitudes during winter nights to as much as 40 meters in equatorial latitudes during summer days. On a world average, the evaporation duct height is approximately 13 meters. It should be emphasized that the evaporation duct "height" is not a height below which an antenna must be located in order to have extended propagation, but a value which relates to the duct's strength or its ability to trap radiation. The duct strength is also a function of wind velocity. For unstable atmospheric conditions, stronger winds generally result in stronger signal strengths (or less propagation-loss) than do weaker winds.

Since the evaporation duct is much weaker than the surface-based duct discussed in section 2.4.3, its ability to trap energy is highly frequency dependent. Generally, the evaporation duct is only strong enough to affect electromagnetic systems above 3 GHz.

The proper assessment of the evaporation duct can only be performed by making surface meteorological measurements and inferring the duct height from the meteorological processes occurring at the air/sea interface, as demonstrated by Jeske (1965) and Paulus (1985). The evaporation duct height cannot be measured using a radiosonde or a microwave refractometer. With the advent of newer, high resolution sondes which may be lowered to the surface from a ship, the impression is given that the evaporation duct may be measured directly. For practical applications however, this impression is false and a direct measurement should not be attempted. Due to the turbulent nature of the troposphere at the ocean-surface, a refractivity profile measured at one time would most likely not be the same as one measured at another time, even when the two measurements are seconds apart. Therefore, any measured profile would not be representative of the <u>average</u> evaporation ducting conditions, the conditions that an assessment system must consider.

The long-term statistical frequency distribution of evaporation ducts is readily available through the SDS program for most areas of the world.

3.0 Getting Started

3.1 Hardware Requirements

You may run EREPS 2.0 on an IBM PC, Personal Computer AT, PC/XT, or 100% compatible computer with a graphics capability (monochrome or color). EREPS 2.0 requires MS-DOS release 2.0 or greater. Your computer must have a minimum of 150 kilobytes of free random access memory (RAM).

EREPS 2.0 is distributed on three double-sided, double-density, 5 1/4 inch, 360 kilobyte, flexible diskettes. While not required for operation, an internal hard disk drive is recommended.

EREPS 2.0 does not contain any capability to dump graphics or text to a printer. Therefore a printer is not necessary for EREPS 2.0 operation. If you have a printer and want paper copies of an EREPS 2.0 output, there are many commercial graphics dumping programs available. For CGA graphics, the GRAPHICS command supplied by IBM and other vendors will work with Epson-compatible printers. A very good graphics dump program that works with CGA, EGA, and VGA adapters and a wide variety of printers is GrafPlus, available from Jewel Technologies, Inc., 4740 44th Ave. SW, Suite 203, Seattle, WA 98116, (206) 937-1081, for a cost of approximately $50.

EREPS 2.0 programs have been designed to support a mouse. In general, the mouse may be used in place of the arrow keys for controlling the movement of a cursor or crosshair. The program automatically senses the presence of a properly installed mouse.

3.2 Software Support

All of the EREPS 2.0 programs are written in Microsoft QuickBASIC version 3.0 and will be maintained by us. Copies of the EREPS 2.0 programs may be made and freely distributed within a working group. While EREPS 2.0 source code is available by special request, any code changes made by others will not be supported and we assume no responsiblity for any problems resulting from such modifications. Discrepancies in EREPS 2.0 products, difficulties encountered while running the programs, requests for special applications, and questions concerning the use of EREPS should be directed to

Commander
Naval Ocean Systems Center
Code 543
San Diego, CA 92152-5000

Autovon: 553-1428 or commercial 619-553-1428
Fax: 619-553-1417
Electronic mail: 543@nosc.mil

To help us provide technical support for EREPS 2.0, an ASCII file, REGISTER.DOC is provided on the EREPS 2.0 distribution disk. This file contains a registration form which may be filled out and mailed to us at the above address. Registration of your EREPS 2.0 disks will insure your receipt of any future upgrades of the EREPS software, newsletters, or technical supporting documentation. Please limit registration to one per physical location or working group.

3.3 EREPS 2.0 Disk Organization

3.3.1 EREPS Distribution Diskette Files

EREPS revision 2.0 consists of five executable program files, one ASCII program file, three binary and one ASCII data files, an ASCII registration file, and a Microsoft QuickBASIC run-time module. These are

PROPR.EXE - propagation loss versus range program.

PROPH.EXE - propagation loss versus height program.

COVER.EXE - height versus range coverage program.

RAYS.EXE - raytrace program.

SDS.EXE - surface ducting climotology program.

BRUN30.EXE - A Microsoft QuickBASIC run-time module containing the necessary subroutines and functions for execution of any QuickBASIC program.

MSDIST.DAT - a binary data file containing the evaportion duct distribution statistics for the SDS program.

MSINDEX.DAT - a binary data file containing an index to the evaporation duct statistics with the MSDIST.DAT file.

RS.DAT - a binary data file containing the surface-based duct and miscellaneous meteorological parameters for the SDS program.

WLDMAP.ASC - a ASCII data file containing a world map used by the SDS program.

FFACTR.BAS - An ASCII QuickBASIC source code listing to be compiled external to the EREPS system.

REGISTER.DOC - an ASCII file containing the EREPS registration form.

3.3.2 EREPS 2.0 Support Files

With the first execution of any EREPS program, a *.INI file is created which contains start-up defaults for height and range units, color definitions, and path names. With the first execution of the SDS program, one or two binary map files will be created depending upon the graphics adapter installed within the computer. For CGA graphics, this file is CGA.MAP. For EGA graphics, these files are SDSEGA1.MAP and SDSEGA2.map. The *.MAP file(s) will be used on subsequent SDS program executions to reduce the time needed to draw the world map. If any of these files are subsequently deleted, it will be regenerated with the next execution of the particular program.

A number of EREPS programs allow you to create customized data files for subsequent program execution. You are responsible for directory structures and file naming using the conventions defined by the version of MS-DOS being used.

3.3.3 EREPS Directory Structures

3.3.3.1 Floppy Diskettes

A necessary file for the execution of any EREPS program is the BRUN30.EXE support file. Because of disk space limitations, it was not possible to include this support file on all distribution diskettes. Therefore, unless the BRUN30.EXE file is in your directory path, you will not be able to execute

the EREPS programs directly from the distribution diskettes. We recommend you create a seperate diskette for each program, insuring the appropriate files and the BRUN30.EXE are on the diskette. For example, to execute the COVER program, a diskette containing only the COVER.EXE and BRUN30.EXE file should be created. For the SDS program, the supporting binary and ASCII data files described above must also be included on the diskette. In addition, it is always good practice to create working diskettes and then store the original diskettes in a safe place to use as a backup in case something happens to the copy diskettes.

3.3.3.2 Hard Disk

For ease of operation, all files from the EREPS distribution disk may be copied into one subdirectory using the MS-DOS copy command. A single directory structure has the advantage of being able to execute any program without changing directories. Since you have the capability of creating your own data files from any of the EREPS programs however, a single directory structure has the disadvantage of mingling COVER, PROPR, and PROPH system files and RAYS and SDS environmental files. Mingling such files requires the use of a strict file naming convention to avoid later confusion. We recommend you create a separate subdirectory for each EREPS program and its support files.

3.4 Program Execution

Any EREPS 2.0 program may be executed by changing to the directory containing the program, typing the program name, and pressing the <Enter> key. You will be presented with a title page showing the program name, revision number and date, a NOSC point of contact, and a brief description of what the program

does. From the title page, you will be asked to enter the path for user data. The default path is your current directory. If the <Enter> key is pressed without entering a path name, the program will assume that all user data files are contained within your current directory. Any entry of a path name will be stored in the *.INI file and used as the default path for subsequent program use.

To attact your attention to any prompt for input data, the input field is highlighted with inverse video. While this process does not impede the program flow, on slow computers (i.e. 4 MHz machines) there is a slight hesitation during the cursor movement. The inverse video may be turned off by appending a -S to the program name prior to pressing <Enter>. For example, to execute the COVER program, you would type COVER -S and press <Enter>. The -S options has no effect upon the speed with which any graphic product is drawn.

4.0 EREPS Programs and Routines

All of the EREPS 2.0 programs are organized into sections or activities called **modes**. These modes allow for entering, editing, storing or retrieving data; customizing or displaying an output product; or customizing the EREPS program itself. While mode names are for the most part self-descriptive and would allow an inexperienced operator immediate access to the capability of the EREPS 2.0 programs, as you gain operation expertise the full range of EREPS 2.0 flexibility will be discovered. Many modes are common between EREPS 2.0 programs and as such, retain a common name and behavior. Within any particular mode, self-evident screen prompts will direct you through the mode's function. At any point within any program, a HELP mode is available by pressing the F2:HELP special function key. Section 5.0 provides a complete discussion of the individual modes and their functioning.

4.1 PROPR and PROPH

PROPR and PROPH calculate and display propagation loss, propagation factor, or radar signal-to-noise ratio (section 7.1) in a dB versus range or height graphic, respectively. The propagation mechanisms considered within the programs are optical interference, diffraction, tropospheric scatter, evaporation ducting, surface-based ducting, and water-vapor absorption.

From the **INIT** mode, as illustrated in figure 7, you may select the quantity to display in addition to the method of determining a threshold of electric field strength. Figure 8 illustrates the PROPR **EDIT** mode page for direct specification of a threshold. Figure 9 illustrates the PROPH **EDIT** mode page for calculating the threshold based upon ESM system parameters. Figure 10 illustrates the second of two PROPR **EDIT** mode pages for calculating the threshold based upon radar parameters. Figure 11

illustrates the first of two PROPH **EDIT** mode pages for the radar signal-to-noise display.

```
INIT MODE

                                PROPR

Select one of the following displays:

   1 - PROPAGATION LOSS or PROPAGATION FACTOR vs. RANGE with
       up to 4 user defined thresholds.
   2 - PROPAGATION LOSS or PROPAGATION FACTOR vs. RANGE with
       one threshold based on ESM parameters.
   3 - PROPAGATION LOSS or PROPAGATION FACTOR vs. RANGE with
       one threshold based on radar parameters.
   4 - RADAR SIGNAL-TO-NOISE vs. RANGE.


Display option     1
Propagation model  INTERNAL
Vertical axis      PROPAGATION LOSS dB
Height units       ft                  To set startup height and range units
Range units        nmi                 to current units, press key F4.
Maximum range      0
Number of lobes    2


Display option (1,4)
1:KEYS 2:HELP 3:EDIT 4:SET DEFAULT 5:RESET    <Esc>:Quit                10:PLOT
```

Figure 7: PROPR **INIT** mode page format.

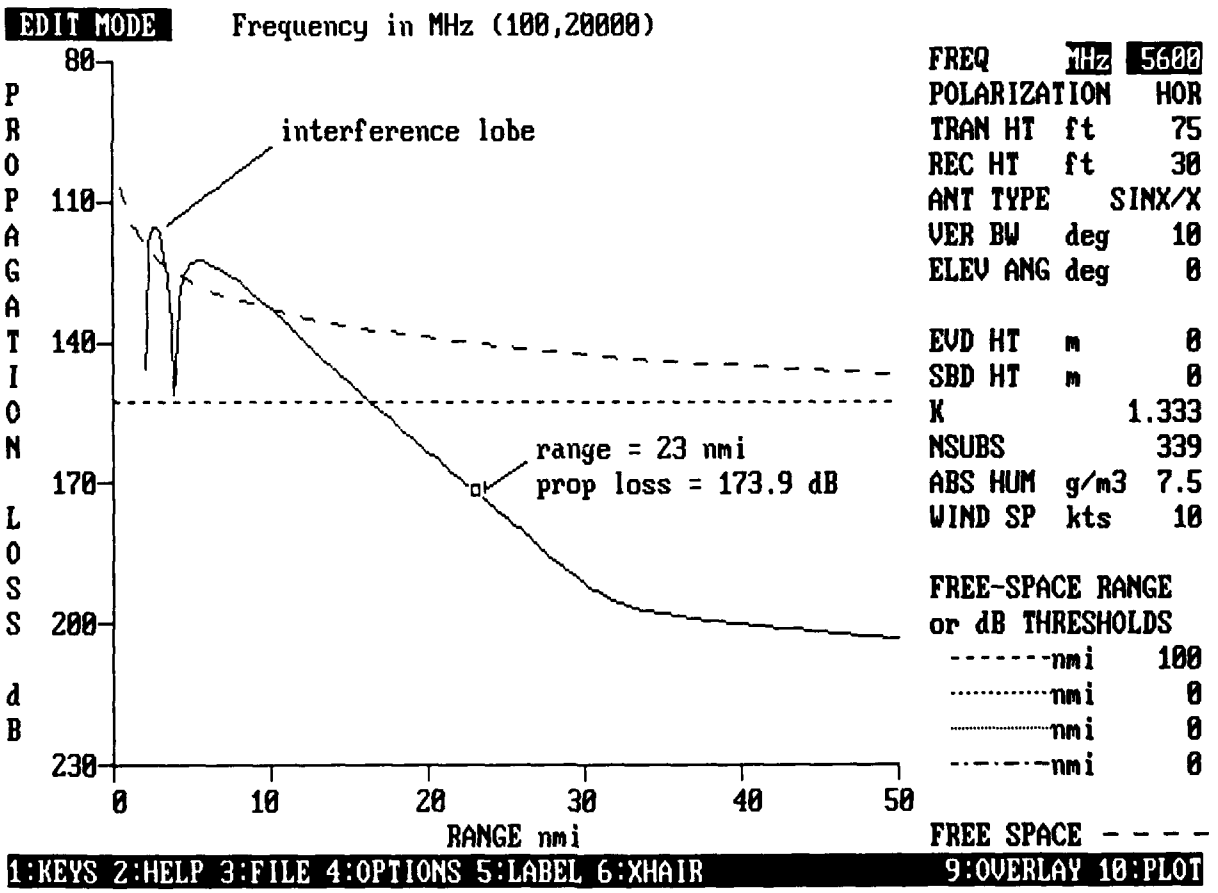


Figure 8: PROPR **EDIT** mode, threshold direct specification.

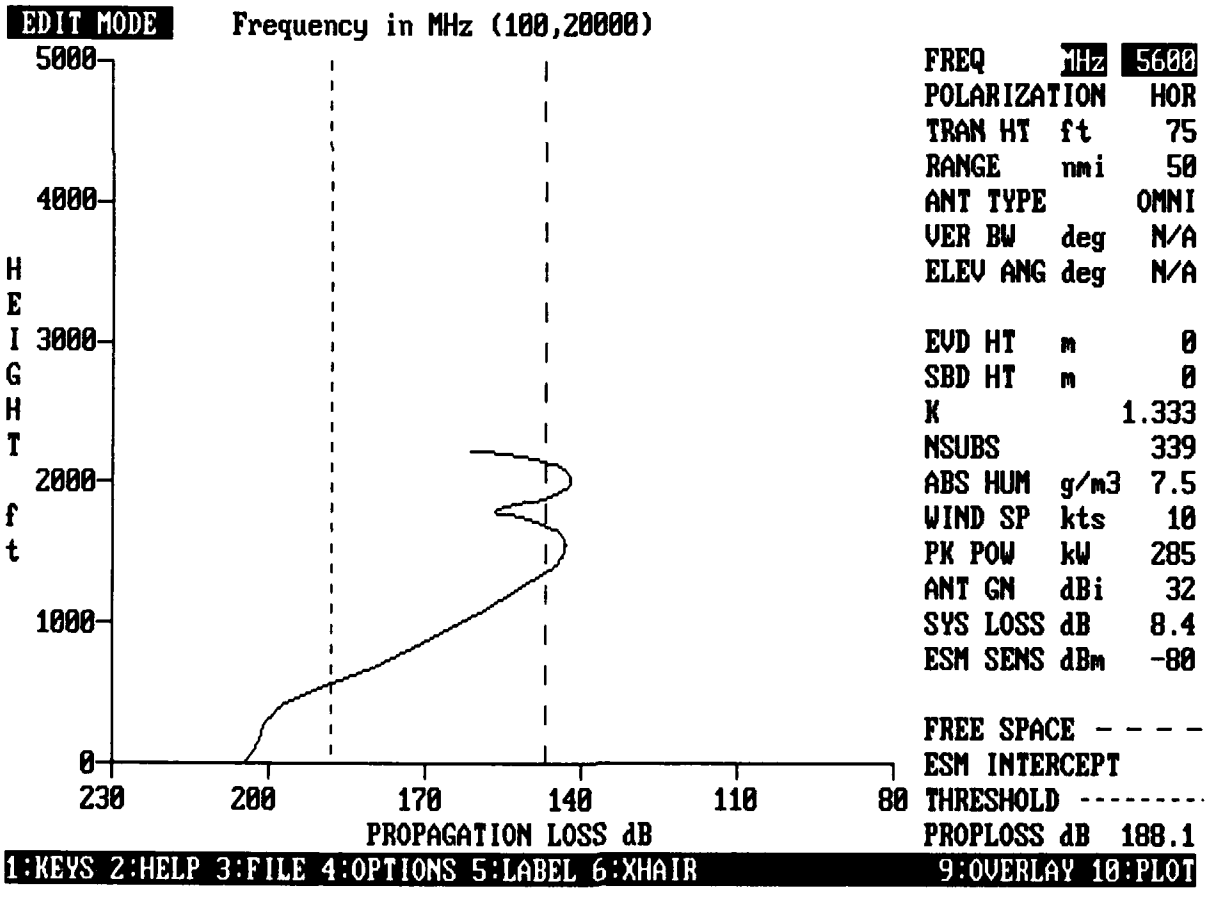


Figure 9: PROPH **EDIT** mode, ESM threshold calculation.

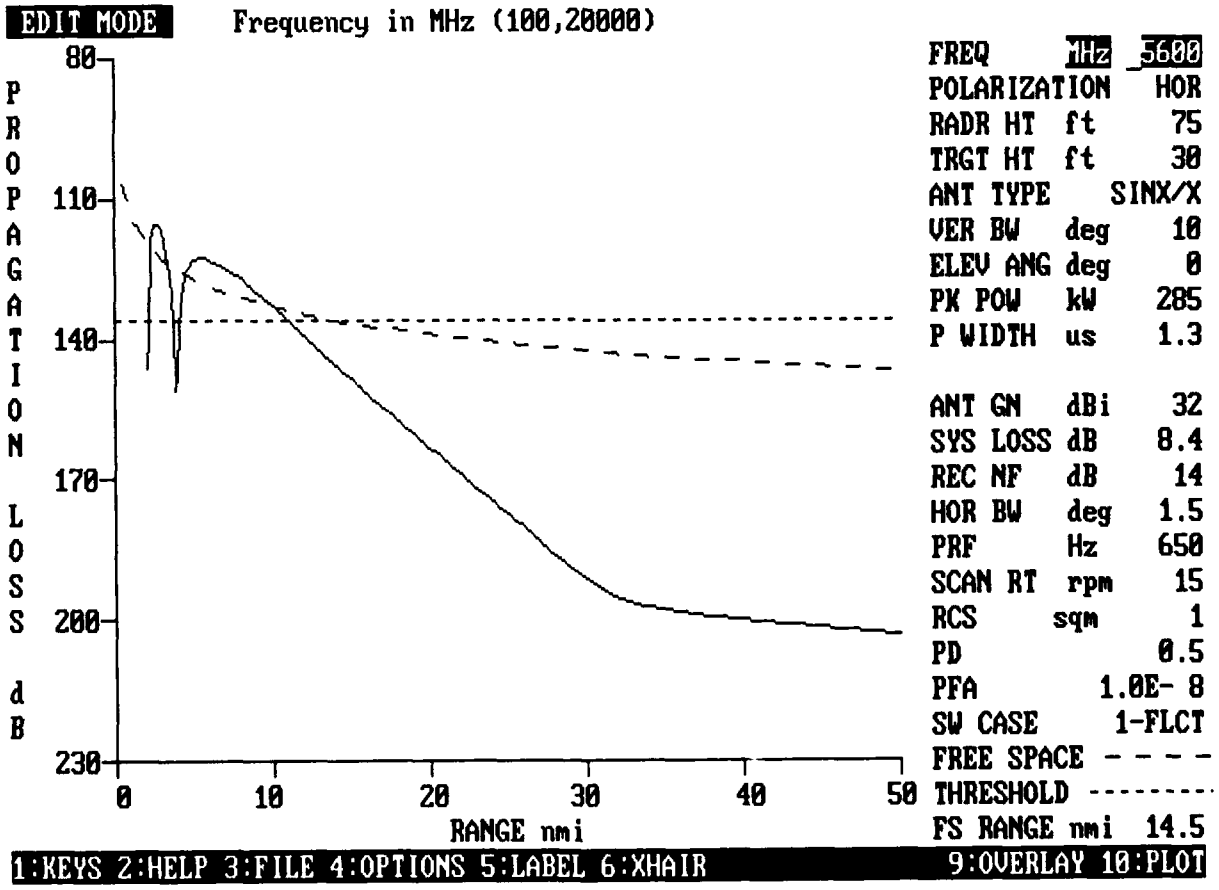


Figure 10: PROPR **EDIT** mode, radar threshold calculation.

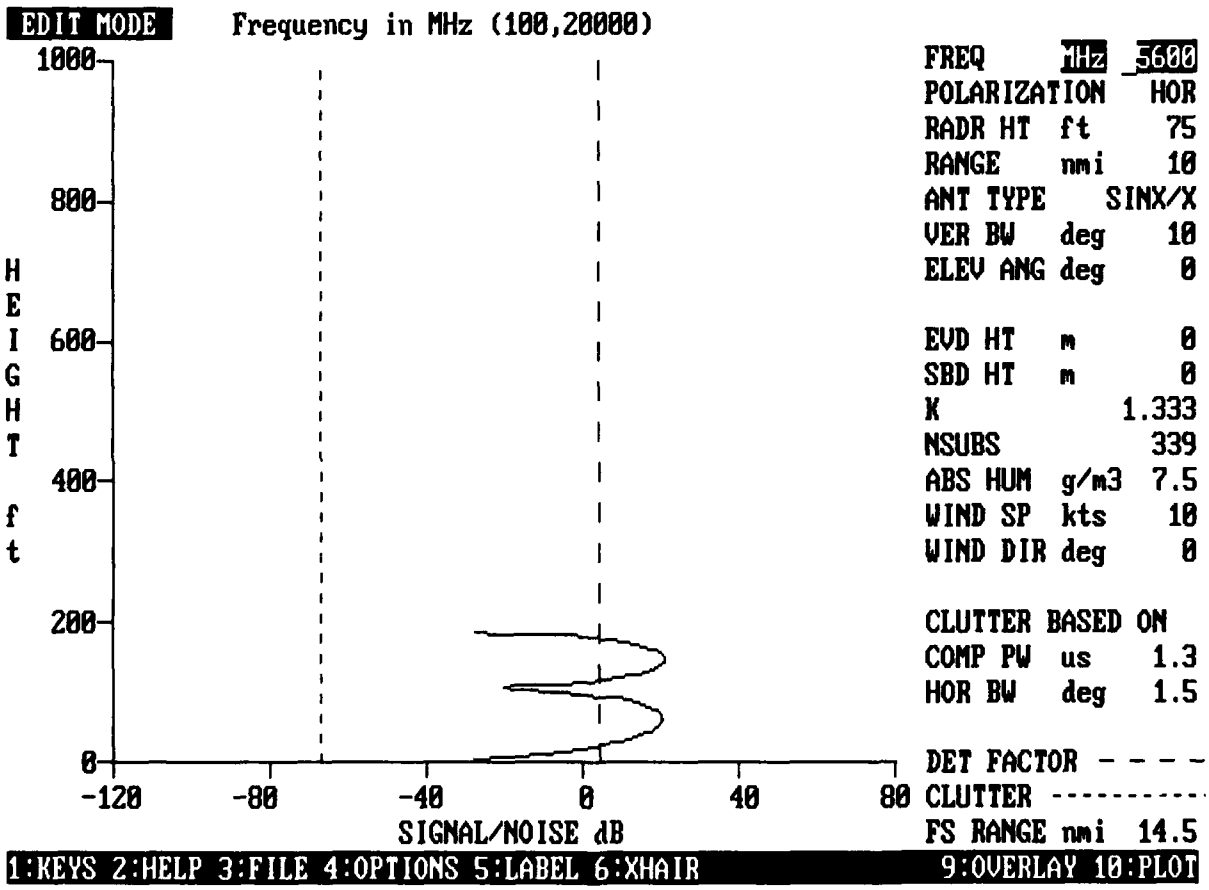


Figure 11: PROPH **EDIT** mode, signal-to-noise versus range.

The electric field strength (system's performance) threshold is represented by a horizontal line on the PROPR display and as a vertical line on the PROPH display. For the system to function, the propagation loss or the signal-to-noise ratio must not exceed the threshold. It is not possible for the system to function when the propagation loss or the signal-to-noise ratio exceeds the threshold. Up to four thresholds may be displayed simultaneously upon any one graphic with each threshold representing a different receiver sensitivity, transmitter power, probability of detection, target radar cross section, etc.

As seen on figures 8 and 11, a free-space and detectibility factor reference line respectively, is provided. Drawing of the free-space reference line may be suppressed within the **OPTIONS** mode. Figure 11 illustrates the display of clutter. Clutter may be displayed as either an average clutter value (a single line) or as an upper and lower clutter bound (double lines) (section 7.3). In cases where the signal strength exceeds clutter, the system should be able to function. Conversely, signal strengths below the clutter level will indicate performance degradation.

Figure 8 illustrates the use of the **LABEL** and **XHAIR** modes to add explanatory text to a graphic for display purposes. In this case, the words "interference lobe", a directing line, a reference mark, and loss/range value labels have been added.

Of particular interest is the **Propagation model** prompt. We are currently developing a parabolic equation model to approximate a solution to the Helmholtz full wave equation. Our model is named the Radio Parabolic Equation (RPE) model. In addition to mainframe computers, RPE will be hosted upon personal computers. RPE will be a stand-alone program which will generate an output data file consisting of a matrix of propagation loss values verses height and range. EREPS will be the display vehicle for these output data files. By responding to the

Propagation model prompt with INTERNAL, the EREPS models will be used to produce the desired graphic. Responding with RPE will cause EREPS to read RPE's independently generated data file and display the data in the fashion as indicated by the EREPS **Display option**. While RPE is not currently available for distribution, EREPS revision 2.0 will sense the presence of an RPE output file and will function properly when RPE becomes available.

You may also choose the parameters which determine the physical appearance of the loss or signal-to-noise graphic. You will also be able to display propagation loss versus height or range calculated with the RPE when it becomes available.

4.2 COVER

The COVER program calculates and displays contours of constant electric field strength in the vertical plane for surface-based systems. The propagation mechanisms considered within COVER are optical interference, diffraction, evaporation ducting, surface-based ducting, and water vapor absorption.

From the **INIT** mode of COVER, as illustrated in figure 12, you may select from two methods of defining the threshold of electric field strength. The first method is by specifying the threshold directly, either by free-space range in units of range or by propagation loss in units of dB. Up to four thresholds may be simultaneously displayed, each representing a different transmitter power, target radar cross section, receiver sensitivity, etc. Figure 13 illustrates the **EDIT** mode page for direct specification of the threshold.

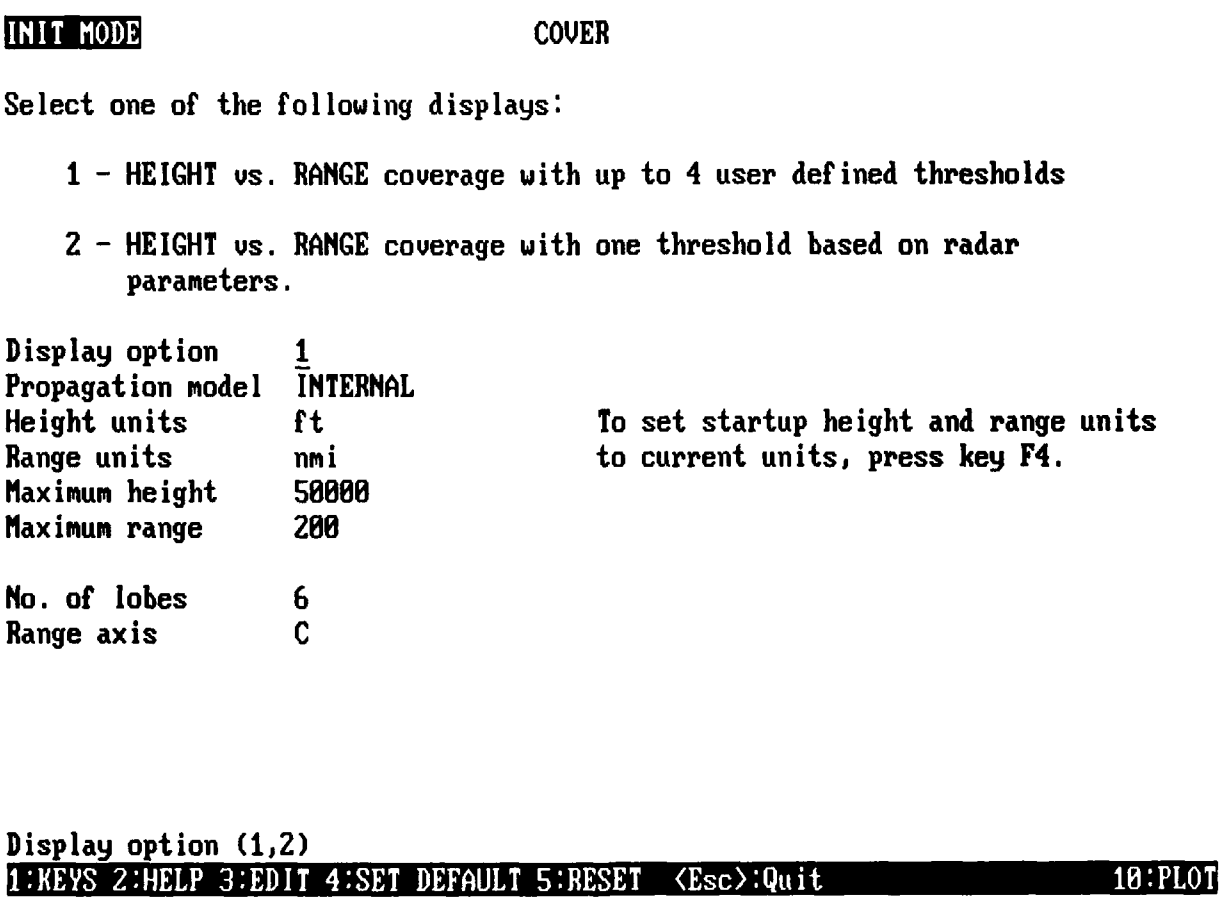


Figure 12: COVER **INIT** mode page format.

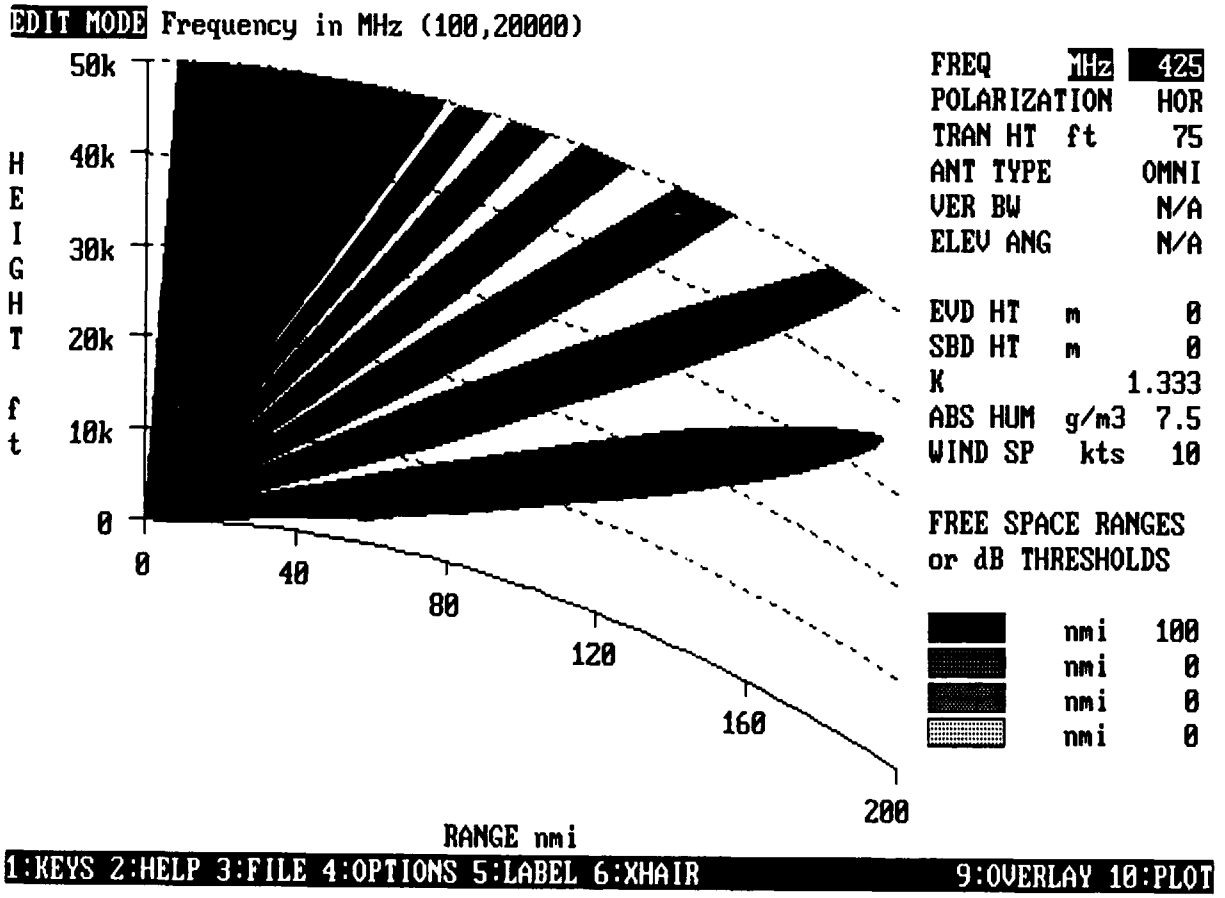


Figure 13: COVER EDIT mode, free-space range specification.

The second method of defining the electric field threshold is by specifying the various electromagnetic system parameters of a radar and the characteristics of the target. Figure 14 illustrates the second of two **EDIT** mode pages for the system's parameters. Note that as each system parameter is changed, the appropriate free-space range value is immediately displayed.

You may also choose the parameters which determine the physical appearance of the cover graphic. For example, the **Range axis** prompt allows for a curved or flat earth presentation. You are cautioned about selecting the graphic height and range combinations employed with the curved earth display as improperly selected values may make the coverage display hard to interpret or misleading upon casual inspection.

The coverage diagram may be used for long-range air-search radars, either 2D or 3D; for surface-search radars when employed against low-flying air targets; and for surface-to-air communications. The coverage display should not be used for surface-search radars employed against surface targets or for any type of gun or missile fire-control radar unless you fully understand the limitations of the coverage models.

For surface-search radars, a major consideration in performance assessment is the target's radar cross section. A target's radar cross section is a function of the target's shape. Large, flat, smooth surfaces may reflect a large amount of energy, but the scattering will be primarily in one direction. Smaller, more angular surfaces may not reflect as much energy, but the area over which the energy is scattered may be very large indeed. It has been shown that the major energy return from a ship target is not from its smooth, large hull but from its superstructure with its highly angled and complicated structure. In addition, for very large targets, the radar cross section also becomes a function of viewing angle. The models employed in

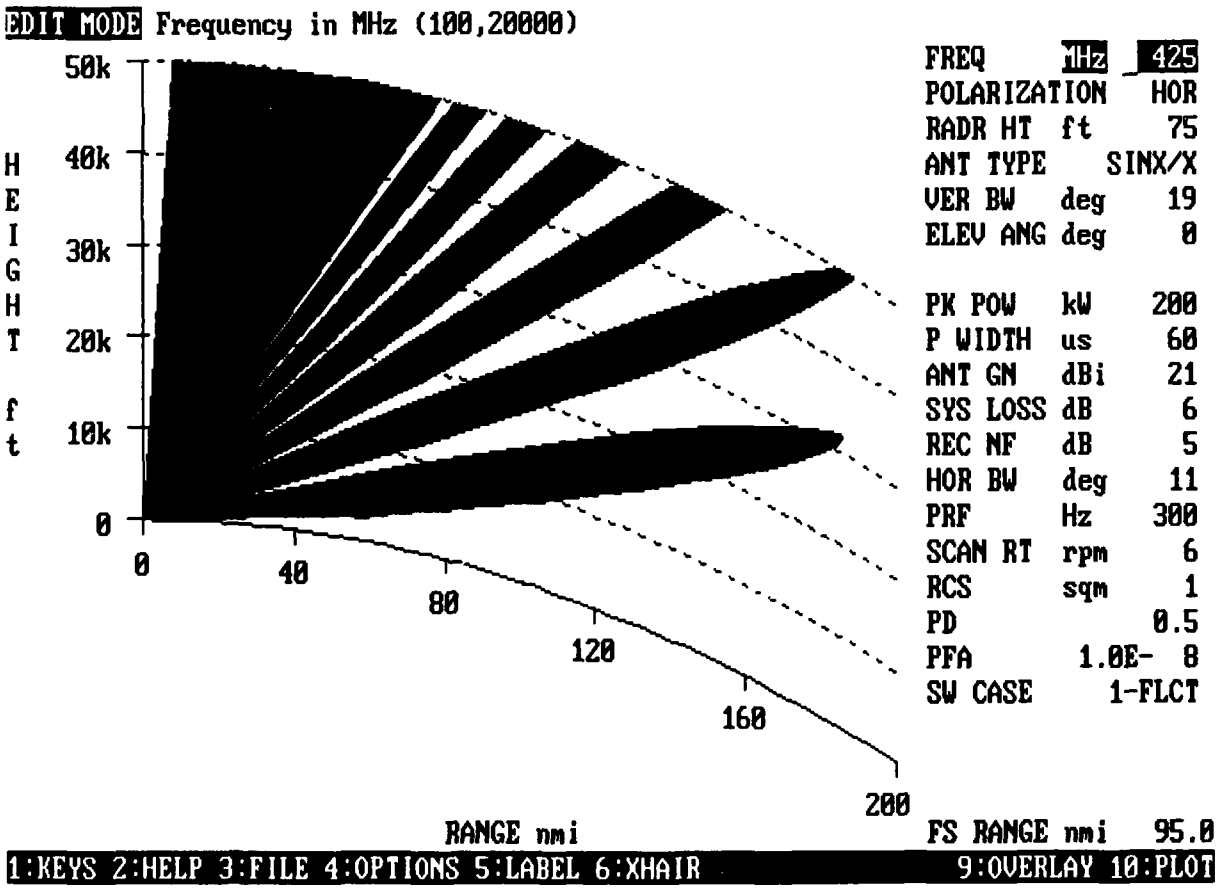


Figure 14: COVER **EDIT** mode, transmitter parameter specification.

generating a coverage display make the assumption that the target is a point source target, independent of viewing angle and composed of only a single reflecting surface.

The very nature of fire-control radars dictates an antenna which trains both in azimuth and elevation. The coverage for an antenna aimed at the horizon will not be the same as the coverage for an antenna when aimed aloft. The coverage display is designed to show coverage of a radar with a fixed antenna elevation angle. If the fire-control radar is employed in a search or track mode at a single elevation angle, such as may be the case of a horizon search for low-flying missile targets, the coverage display will produce an accurate representation of the actual radar coverage. It must be understood however, that once the elevation angle changes, the existing coverage display is no longer valid and coverage must be recomputed based upon the new elevation angle. In addition to considering the antenna elevation angle, the amount of energy directed toward the target must also be taken into account since fire-control radars do not generally scan the target with a single pulse as the antenna rotates. This is accomplished through the use of the proper free-space range.

There are two limitations of the COVER program of which you should be aware. First, COVER uses a parallel ray approximation to the propagation model given in section 7.1. The approximation assumes that the direct and sea-reflected rays arrive nearly parallel at the receiver/target. This assumption is quite good at long ranges and higher heights. However, as ranges and heights decrease the assumption becomes poorer and the COVER program will be in error, with the error becoming worse as ranges and heights decrease. The PROPR and PROPH programs do not make the parallel ray assumption. If the results of the COVER program are suspect, they may be compared to those obtained from PROPR or PROPH which will be correct for all geometries.

Secondly, as frequency increases, the lobe spacing on a coverage diagram decreases (figure 13). For some combinations of frequency, range, and altitude, the graphic routine used to shade the lobes will fail. For these cases, the shading problem may be corrected by increasing the scale and replotting the graphic.

4.3 RAYS

The RAYS program traces the paths, in height and range, of electromagnetic rays, figure 15, based upon a linearly segmented refractivity-versus-altitude profile. The ray tracing is accomplished using the small angle approximation to Snell's law.

The RAYS primary graphic product, and the only product for CGA graphic computers, is a simple raytrace as illustrated in figure 15.

Height-finder radars determine altitude based upon a standard atmosphere ray path. For non-standard refractive conditions, the target's calculated height will be in error (figure 3). If your computer is configured for EGA or VGA graphics, a secondary graphic product of RAYS is a raytrace displaying this height error according to your specified height increment and color scheme. This product is illustrated by figure 16. This product is obtained by responding with a Y (yes) to the **Alt Error** prompt while in the **INIT** or **OPTIONS** mode. Refer to section 5.0 for a discussion on using the **OPTIONS** and **COLORS** modes to make height error color assignments and the **LABEL** and **LEGEND** modes to display the altitude error legend.

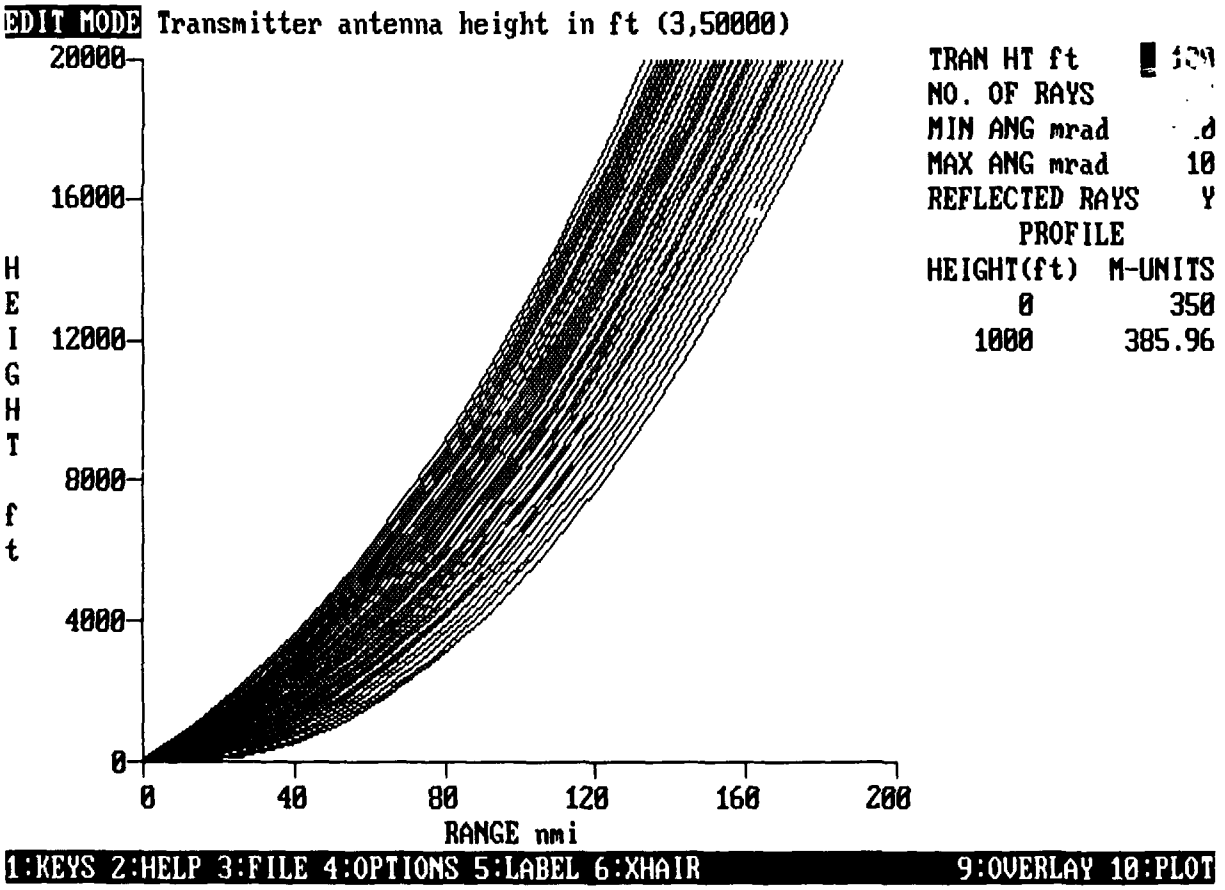


Figure 15: RAYS program simple raytrace.

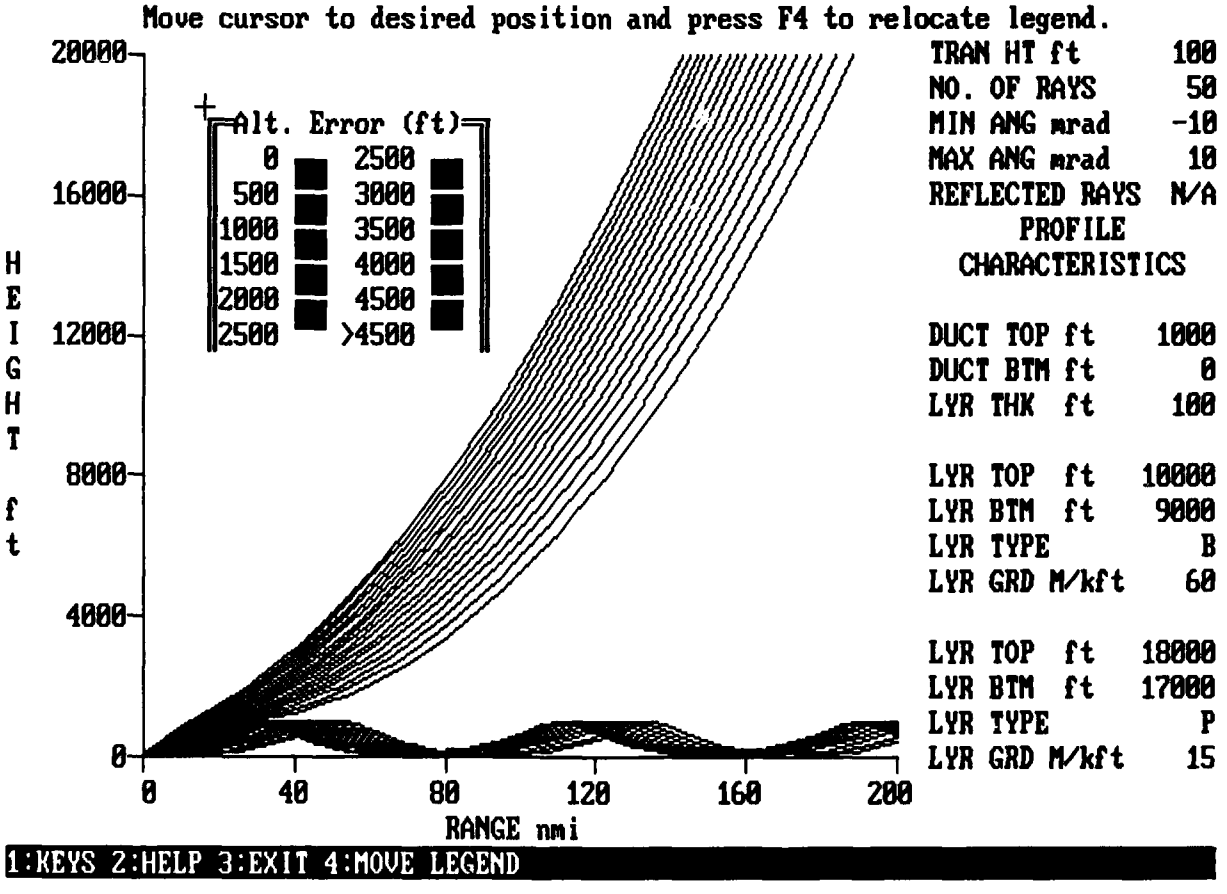


Figure 16: RAYS program altitude error raytrace.

From the **INIT** mode of RAYS, as illustrated in figure 17, you may select from three methods of entering environmental data. You may also choose the parameters which determine the physical appearance of the raytrace graphic. Note that while the height and range units may be set globally with the **Height units** and **Range units** prompt, they may be changed independently for individual prompts such as **Maximum height**. You are advised to exercise caution with this freedom as mixing units may lead to later confusion.

Upon entering the **EDIT** mode with environmental input method 1 (numerical/graphical height-refractivity levels) selected, the page illustrated in figure 18 will be displayed. Height and refractive unit values may now be entered from the keyboard. By pressing the <PgUp> or <PgDn> key, the graphical edit page, figure 19, will be presented. The refractive profile may now be entered with the use of the arrow keys or the mouse.

Upon entering the **EDIT** mode with environmental input method 2 (refractivity profile characteristics) selected, the page illustrated in figure 20 will be displayed. Up to three refractive features may be specified by describing the features' height, strength, and nature. For example, figure 20 illustrates a surface-based duct with a top at 1,000 feet and a trapping layer from 900 to 1,000 feet; an elevated layer from 9,000 to 10,000 feet with a subrefractive M-unit gradient of 60 M/kft; and an elevated layer from 17,000 to 18,000 feet with a superrefractive M-unit gradient of 15 M/kft. While the second and third features are labeled as layers (LYR), their gradients may be specified as T (trapping), thereby creating elevated ducts. Input bounds checking is performed which will prevent one feature being superimposed upon another. It is highly recommended that you do not override the bounds checking at this point.

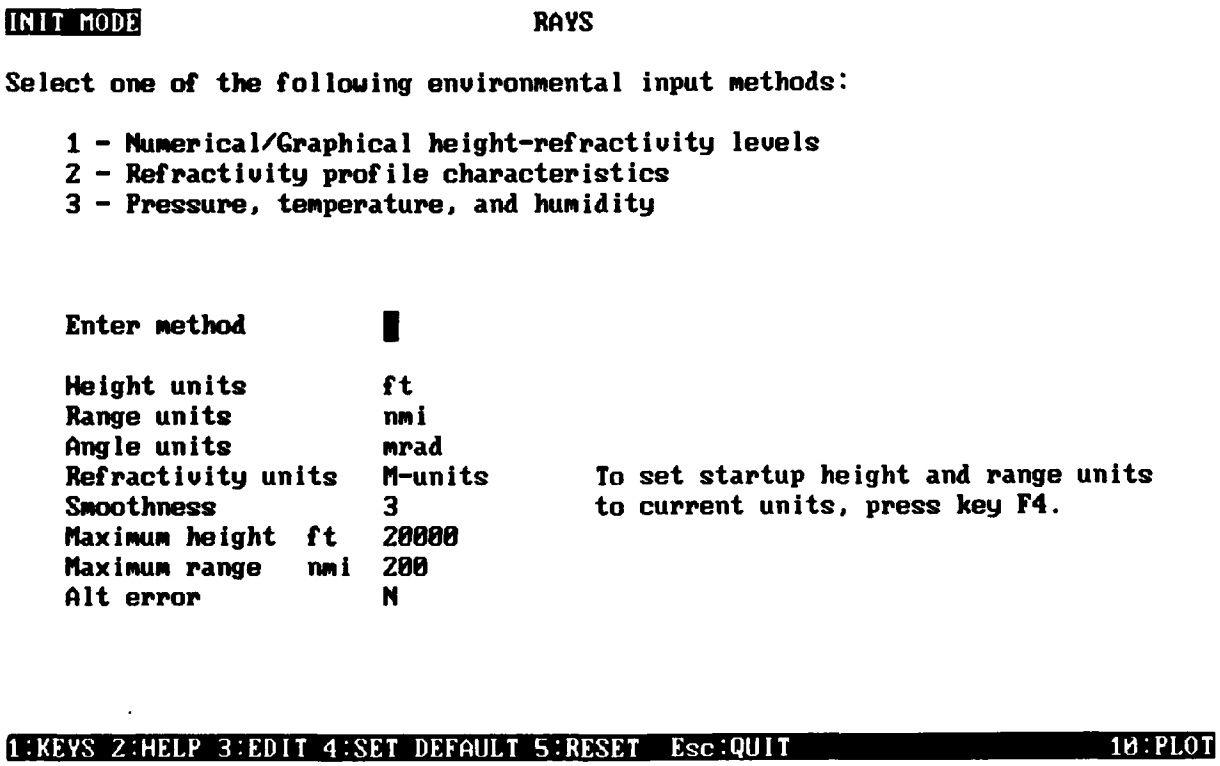


Figure 17: RAYS **INIT** mode page format.

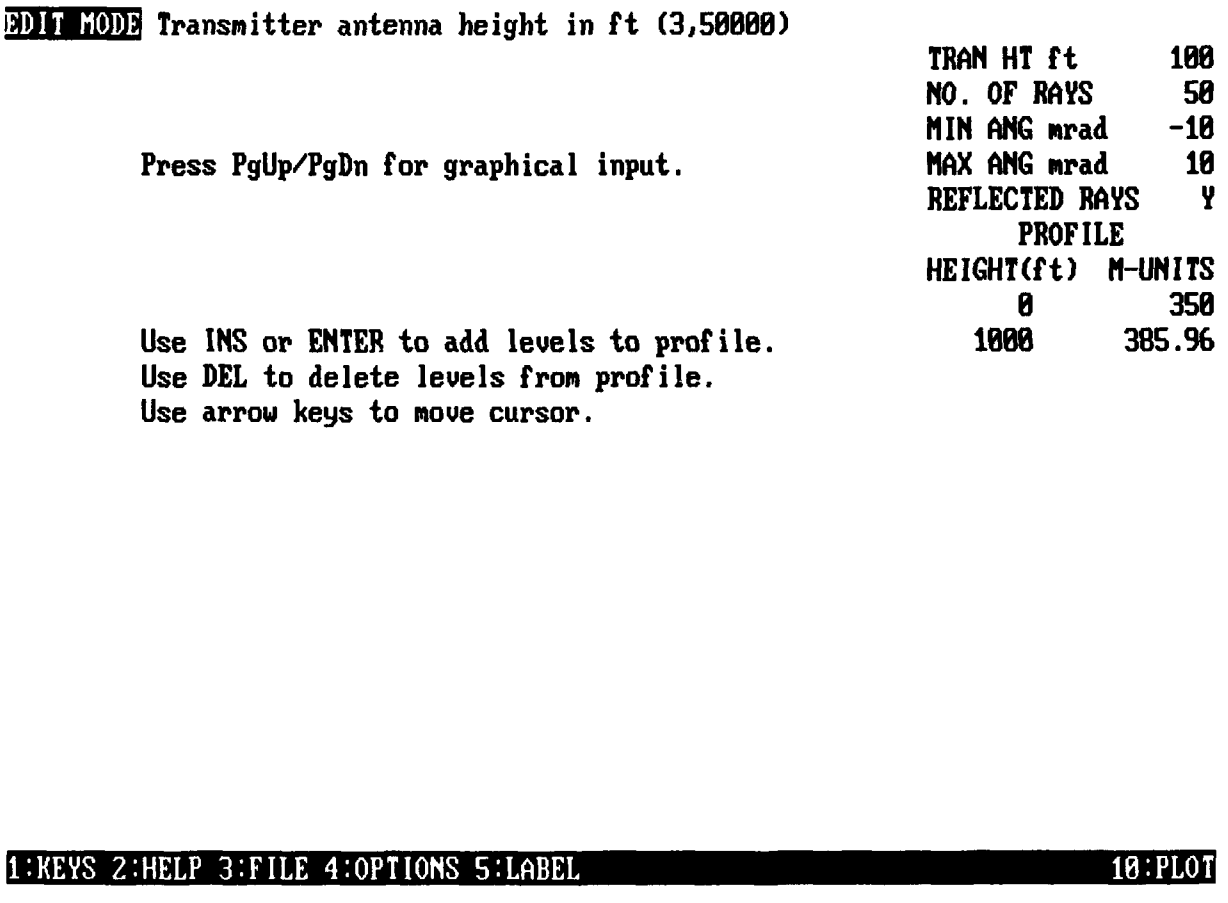
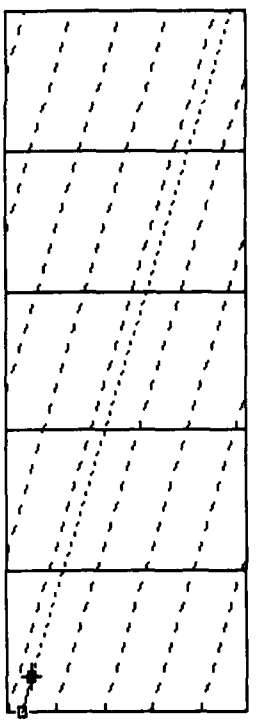


Figure 18: RAYS **EDIT** mode, numerical environmental input.

EDIT MODE

Press PgUp/PgDn for numerical input.
Dashed lines (standard gradient)
are shown for reference.

Use INS or ENTER to add levels to profile.
Use DEL to delete levels from profile.
Use arrow keys to move cursor.



1:KEYS 2:HELP 3:FILE 4:OPTIONS 5:LABEL 7:COARSER 8:FINER 10:PLOT

Figure 19: RAYS **EDIT** mode, graphical environmental input.

Upon entering the **EDIT** mode with environmental input method 3 (pressure, temperature, and humidity) selected, the page illustrated in figure 21 will be displayed. Pressure values must be entered in decreasing order.

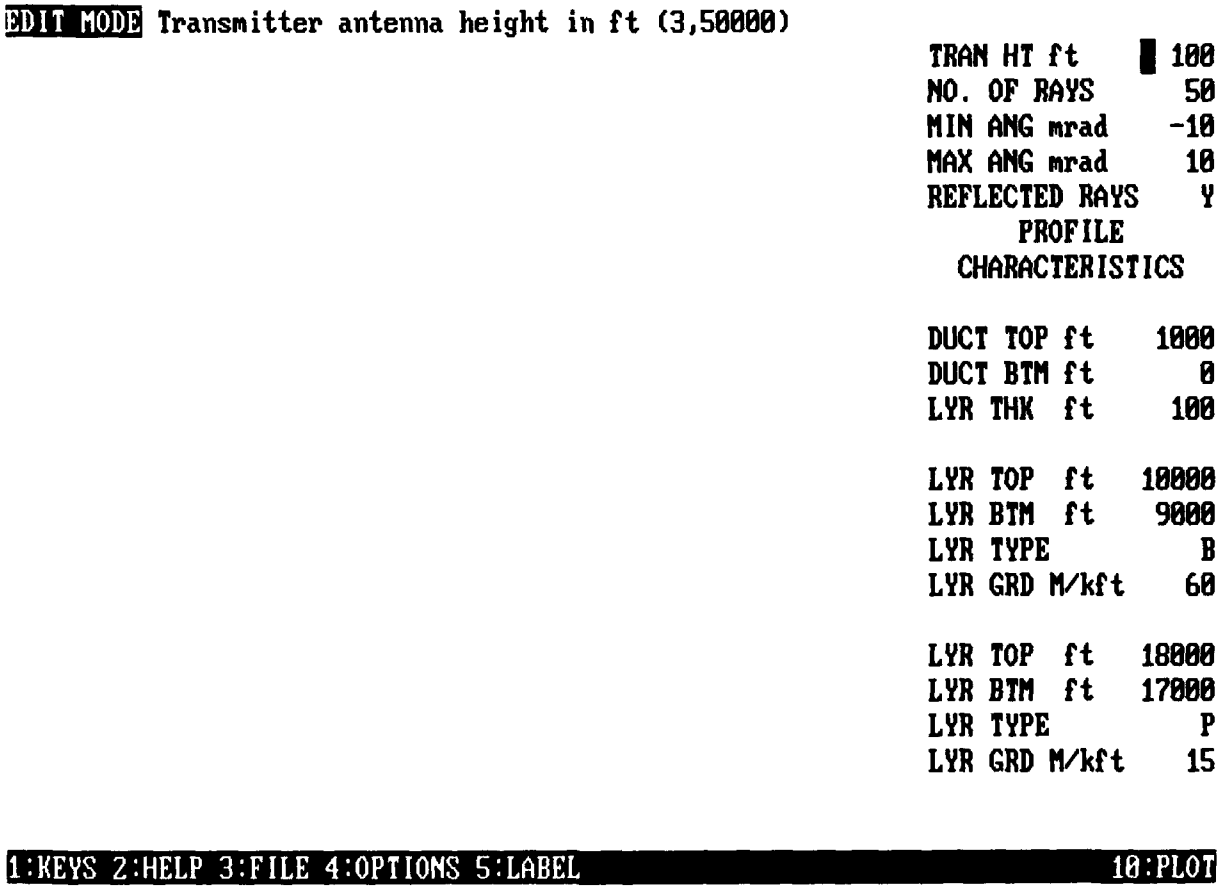


Figure 20: RAYS **EDIT** mode, characteristics environmental input.

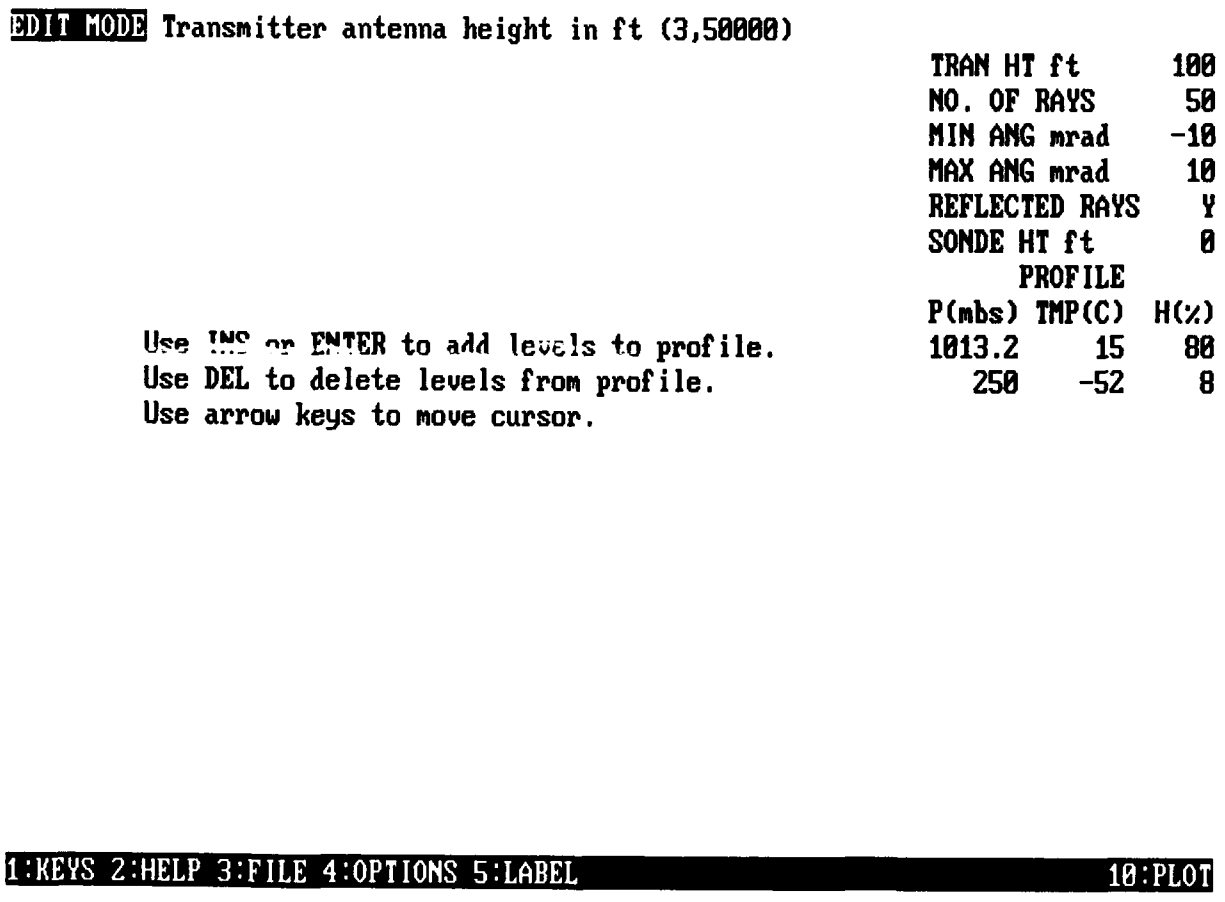


Figure 21: RAYS **EDIT** mode, pressure, temperature and humidity environmental input.

From any page within the **EDIT** mode, pressing the <PgUp> or <PgDn> keys will allow you to view the numerical values of height and refractivity units or the graphical display. The profile may only be edited with the method used to originally enter the data. Returning to the **INIT** page via the <Esc> key and selecting a different input method will reset the environment to the EREPS defaults. Once a raytrace graphic exists on the screen, the reminder text, i.e. "Use INS or ENTER to add ..." will no longer appear on the screen. The editing keys will remain active however.

If the entered environmental profile does not extend to the height of the graphic display, a standard refractive gradient of 118 M/km (36 M/kft) will be appended to the profile. Additionally, if the transmitter height exceeds the graphic plot height, no rays will be drawn.

4.4 SDS

The SDS program displays an annual climatological surface duct summary for one or more Marsden squares.

The summary consists of an evaporation duct histogram showing the percent occurrence of the duct; a surface-based duct description which includes percent of occurrence, average thickness, radiosonde source locations, and number of observations; and a listing of miscellaneous information to include wind velocity, surface refractivity value, and effective earth radius factor.

The statistics displayed within SDS are derived from two meteorological data bases; the Radiosonde Data Analysis II assembled by the GTE Sylvania Corporation and the DUCT63 assembled by the National Climatic Data Center. The GTE Sylvania analysis is based on approximately 3 million worldwide radiosonde

soundings taken during a 5 year period, from 1966 to 1969 and 1973 to 1974. The DUCT63 analysis is a 15 year subset of over 150 years of worldwide surface meteorological observations obtained from ship logs, ship weather reporting forms, published observations, automatic buoys, etc.

While the world is divided into 648 Marsden squares, the SDS climatology is provided for only 293 Marsden squares. This number was selected for two reasons. First, EREPS is specifically designed for maritime application. The 293 Marsden squares cover the open ocean and coastal waters. Second, a minimum of 100 valid observations per month within a square was imposed to reduce the effects of any spurious meteorological measurements on the distributions.

The square(s) of interest is (are) selected from a world map, figure 22, by positioning a cursor over the square(s) and highlighting it (them) with a special function key or a mouse key. As seen in figure 22, as the cursor moves over the map, its latitude, longitude, and Marsden square position is displayed. For this example, Marsden squares 113 and 112 have been selected. The world average of all Marsden squares may be obtained by selecting the box labeled "World Average."

Figure 23 illustrates the summary obtained from Marsden squares 112 and 113. In this example, the surface-duct statistics were obtained from a single radiosonde source, a fixed oceanographic observing station located at 35° North latitude, 48° West longitude. If more than one radiosonde source is located within the selected squares, their averaged observations would be provided. If no radiosonde source is located within the selected square, the closest great-circle source would be used. For this reason, it is important to note the proximity of the source to the location of interest.

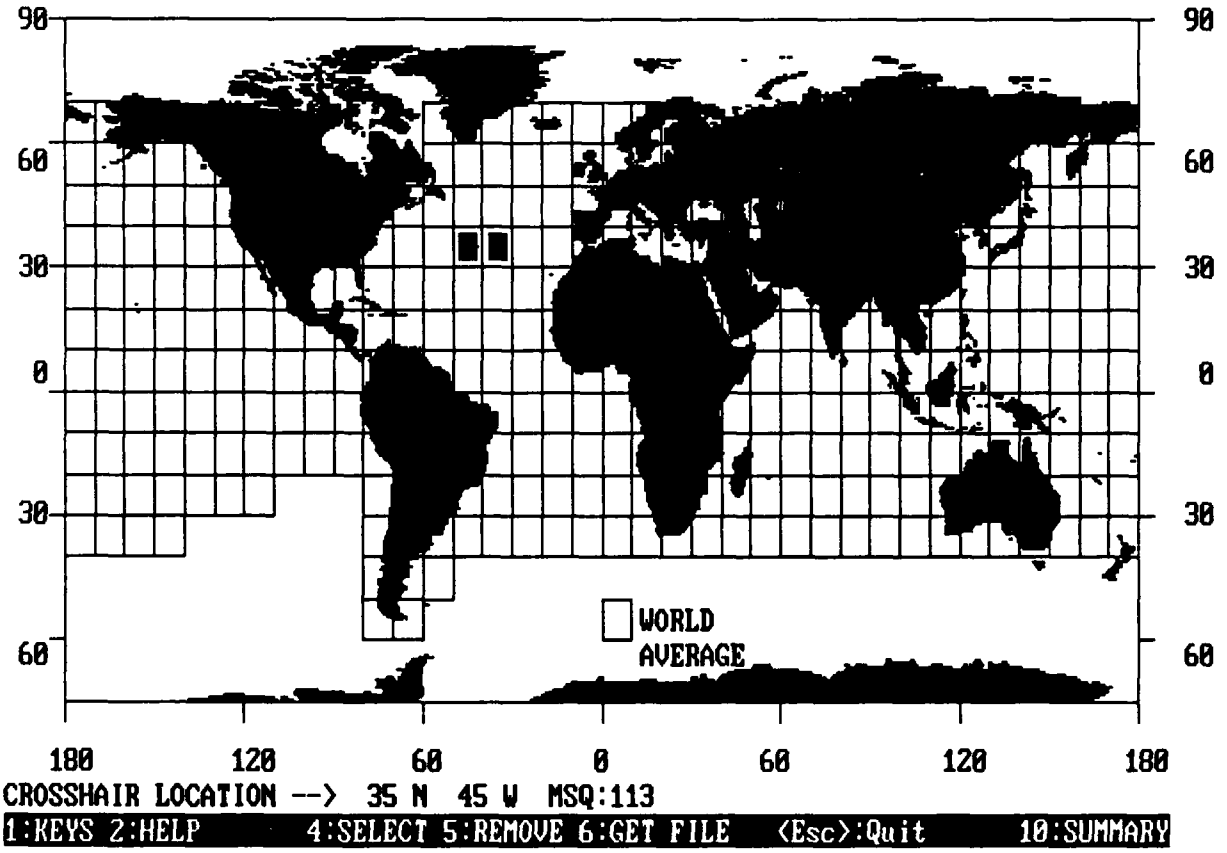


Figure 22: SDS **MAP** mode, Marsden square world map.

Through the use of special function keys, other functions such as screen labeling or file manipulation may also be accomplished.

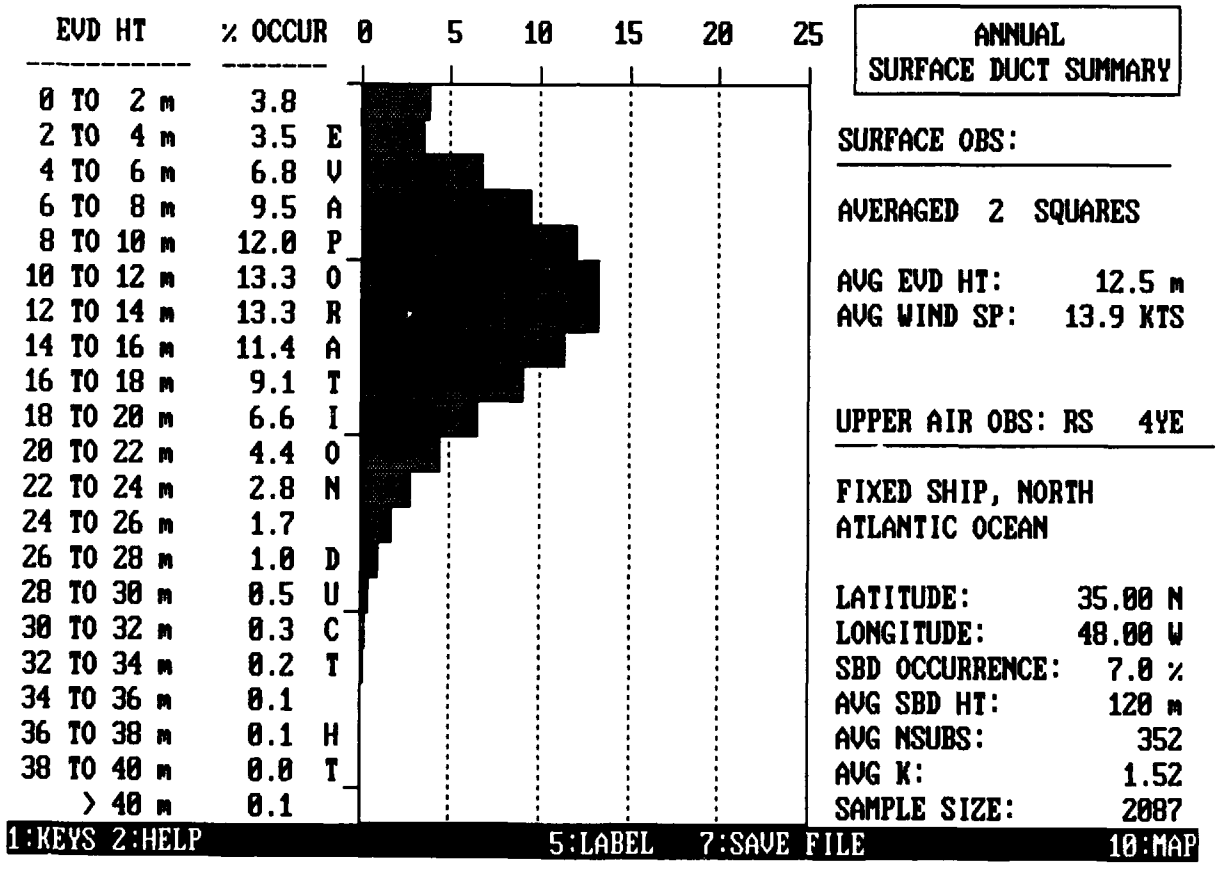


Figure 23: SDS **SUMMARY** mode display

4.5 FFACTR

FFACTR is a collection of models formed into a callable routine, written in Microsoft QuickBASIC, that will compute the pattern propagation factor in dB when provided certain EM system and environmental information. The intent of this routine is to allow you to create your own application programs, incorporating the EREPS propagation models directly. Because this routine may be called in an arbitrary fashion, it may not be structured in the most efficient manner for your particular task. For example, if the loss at a constant height for varying range is desired, a common application, the initialization subroutines need be called only once. They would be extracted from FFACTR and placed within the calling routine.

The FFACTR routine is well documented within the program code. Variables within the routine are passed via a common block and the input parameters are passed to the FFACTR routine through an argument list. A discussion of the FFACTR models appears in section 7.0.

FFACTR is also provided with a demonstration driver program which shows the possible uses for the FFACTR routine. FFACTR may be compiled under Microsoft QuickBASIC 3.0 or 4.5 and executed as a normal program to observe the demonstration.

5.0 Modes, Key Actions, and Input Parameters

Maneuvering between the various EREPS 2.0 program modes or performing actions within a mode is accomplished by pressing a **special function key**, an **edit key**, or a **mouse button**. Labels for the special function keys, F1 through F10, are displayed at the bottom of the screen. Special function keys which are not applicable to a particular mode are not displayed. While special function key labels are to a great extent self-explanatory, their use will become clearer as you gain familiarity with the program. An attempt has been made to retain common special function key numbering assignments between all the EREPS 2.0 programs. In some cases however, this was not always possible. You must be careful therefore to read the labels prior to pressing a special function key.

A summary of the EREPS modes, a reference list of all special function and edit keys and mouse buttons, and a description of EREPS input parameters follows.

5.1 Mode Definitions

COLORS mode - In all EREPS programs except SDS, color is used to enhance the displays. While EREPS 2.0 colors were chosen to give a pleasing visual impression, your special application may require a differing color assignment. Therefore, the COLORS mode presents a "palette" of available colors from which to choose. Each color is assigned a letter and by specifying a particular letter you may change the color of the plot axes, text, overlays, cursors, etc. You may exit the COLORS mode, make color changes permanent (by storing the color changes to the *.INI) or temporary (until you exit the EREPS 2.0 program) by pressing the appropriate active special function key display on the bottom line of the screen. COLORS mode is available only for EGA and VGA systems.

CROSSHAIR mode - The CROSSHAIR mode displays a crosshair at the center of the screen (for the first call to CROSSHAIR) or at the crosshair's last position during the previous call to CROSSHAIR. It is available only when a graphic is displayed on the screen. The crosshair displayed is 5 pixels in the vertical direction by 5 pixels in the horizontal. The abscissa and ordinate values at the center of the crosshair appear in the lower-right corner of the screen. The crosshair is positioned by using the arrow keys or a mouse. If the crosshair is moved beyond a boundary, it will wrap around to the opposite side. Wrapping will not be accomplished when using a mouse to move the crosshair. The <Home> key will place the crosshair in the center of the display. The <End> key will place the crosshair at the rightmost side of the display. The <Enter> key will place the crosshair at the leftmost side of the display. The <PgUp> and <PgDn> keys will place the crosshair at the top and bottom of the display, respectively.

EDIT mode - The EDIT mode serves as the primary data entry/edit point, although other modes may allow minor entry/edit capabilities. Within a mode, any data necessary for the EREPS 2.0 program's operation will be displayed upon the computer's screen. Each screen of data is called a **page**. The format of the page will vary depending upon the program and the quantity of data to display. Each individual piece of data is located upon the page within a **field**. A field may be called a **unit field** or a **value field** depending upon the data it contains. For example, a program input may be transmitter height. The unit of height, say feet, will appear within the unit field. The actual height, say 1000, will appear within the value field. The value field and its associated unit field (if units are appropriate to the value) will appear adjacent to each other with the unit field to the left of the value field.

A unit or value may be selected for change by using an arrow, tab, reverse tab, backspace, space key, or a mouse to position the flashing cursor over the item, typing the new value, and then pressing the <Enter> key. As the cursor moves over the fields, an informational prompt will appear on the screen. The prompt will consist of a long title description of the item, an abbreviated title, a list of possible units if the item is numeric, and a range of valid responses. In addition, a default will appear within the field. All allowable units are pre-programmed and you will not be able to deviate from them. They may be selected by "toggling" through a list of choices by using the <space> bar. In some cases, no alternate choice of units will be possible. You have complete control of the values however, as you are allowed the option of overriding the recommended range of validity by simultaneously pressing <Ctrl> and <Enter>. Note! An entered value which is outside of the valid range may yield erroneous results, cause the program to abort with a runtime error, cause loss of computer memory, or cause some other undesirable consequence. You are encouraged therefore, to adhere to the recommended limits when changing a value.

You may exit the EDIT mode at any time by pressing the <Esc> key which will return you to the INIT mode, or by pressing one of the active special function keys (F1 through F10) displayed on the bottom line of the screen.

FILE mode - The FILE mode allows you to save entered data to a disk file for future use, retrieve previously stored data, or delete a previously saved data file. In addition, you may change the directory in which files are to be stored, create new directories, or list the contents of existing directories. These filing operations are accomplished by pressing one of the active special functions keys (F1 through F10) displayed at the bottom

of the screen. Additional screen prompts will be provided as needed.

For PROPR, you may retrieve a file that was stored using EREPS revision 1.0. However, parameters not found but required by EREPS 2.0 will assume EREPS 2.0 default values. You cannot retrieve a RAYS file that was stored using EREPS revision 1.0. In addition, any custom screen labeling you may have done under the LABEL mode or previous overlays of results will not be saved since it is only the current parameter values that are stored in the saved files. When changing directories, if the directory name you enter does not exist, it will be created.

EREPS 2.0 programs follow the conventions of MS-DOS file naming and do not add an extension to file names stored under the FILE mode. When listing files within a directory, data files may be easily distinguished from executable or other program files by adding a .DAT extension to the files. Another way to prevent file confusion is to crate a separate data file directory for each of the EREPS programs.

You may exit the FILE mode at any time by pressing the EXIT key or the <Esc> key which will return you to the INIT mode.

INIT mode - The INIT mode is the logical starting point for all EREPS programs, except SDS. This mode may be reached from any point within a program by pressing the <Esc> key. In this mode you may select a display type or method of data entry and set units (e.g., nmi or km) and parameter values that control the physical appearance of the display. SDS does not have an INIT mode since there are no choices on the physical appearance of the display. The logical starting point for SDS is its MAP mode, described below.

Once units are selected from within the INIT mode, they are considered the default units for the remainer of the program session. If you usually work with units other than the defaults provided by EREPS 2.0, the units you enter may be saved for use as future default units by pressing a special function key. Units may be changed on various pages throughtout the entire program. Once changed, they will remain until changed again. Units stored by pressing the special function key will remain for future default use however.

You may exit the INIT mode at any time by pressing the <Esc> key which will terminate the program, or by pressing one of the active special function keys (F1 through F10) displayed on the bottom line of the screen. Upon pressing <Enter> at the last field on the page, you will be placed in the EDIT mode.

LABEL mode - The LABEL mode allows you to enter custom labels or to modify EREPS legends by typing any character at normal row/column positions anywhere on the screen, except the bottom line, which is reserved for special function key labels. You may use the arrow keys or a mouse to move the cursor. The <Del> key and <space> bar will both erase the current character. The <Backspace> key will move the cursor left one column and erase the character in that column. The <Tab> key will move the cursor right to the next tab position (11, 21, 31, etc.) or to the next row down if already past column 81. The <Enter> key will move the cursor to the left side of the screen and down one row. The <PgUp> and <PgDn> keys will place the cursor at the top and bottom of the screen respectively.

LEGEND mode - Within the RAYS program, if the Altitude Error option is chosen, the program will display a color legend in the center of the screen with a crosshair shown at the upper left corner of the legend box. Each colored segment of a ray

corresponds to the height difference, using the error increment specified, as compared to the same ray (equal launch angle) in a standard atmosphere. In addition, the legend may be moved anywhere on the screen by using the arrow keys or a mouse. The LEGEND mode is entered from the LABEL mode. Upon exiting the LABEL mode, the legend will disapper from the screen. This will preclude later confusion with an overlay should the legend also contain as a background, a portion of a previous raytrace.

MAP mode - Within the SDS program's MAP mode, a world map with a superimposed 10 degree latitude by 10 degree longitude Marsden square grid is displayed on the screen. A Marsden square defines an area from which climatological data may be retrieved. A single Marsden square or combination of squares may be selected (or a previously selected square unselected) by placing a crosshair, using the arrow keys or the mouse, within the square and pressing a special function key or a mouse button. For reference, each selected square will be highlighted by a change of color. When all desired squares have been selected, pressing the <Enter> or a special function key will produce the SDS climatological summary display. You may exit the MAP mode by pressing the <Esc> key which will exit the SDS program or perform other functions such as filing data by using the active special function keys displayed on the bottom line of the screen.

OPTIONS mode - The OPTIONS mode allows you to change the scale of the plot axes and other parameters that were initially prompted for in INIT mode. Prompts in OPTIONS and INIT mode are essentially equivalent, except in the OPTIONS mode, any previously created graphics display remains on the screen. Other operations such as changing display colors, resetting EREPS defaults, etc. or exiting the OPTIONS mode may be accomplished by pressing one of the active special function keys displayed on the bottom line of the screen.

One special function key exception is the OVERLAY key. You may not change the vertical or horizontal scales of a graphics display and then overlay the new display upon the previous dislay. Overlaying two graphics displays with differing scales is not allowed.

SUMMARY mode - Within the SDS program, the summary mode is used to display the evaporation duct height histogram and the surface-based duct climatology. You may exit the SUMMARY mode by pressing the MAP special function key or the <Esc> key, both of which will return you to the MAP mode.

5.2 Special Function Key Definitions

The special function keys used within EREPS 2.0 are

CHANGE PERMANENT: Active in COLORS mode. When pressed, any changes made to color definitions will be stored in the *.INI file for use as start-up defaults.

CHANGE THIS SESSION: Active in COLORS mode. When pressed, any changes made to color definitions will remain changed until you exit the program.

CHOOSE UPPER AIR: Active when in summary display of SDS. Allows selection of a single radiosonde station when multiple stations are used for the summary of a given square.

COLORS: Active in OPTIONS mode. Places you in the COLORS mode whereby color definitions may be changed.

COARSER: Active whenever movement of a crosshair is required. It is used to increase the step size for arrow key movements. COARSER has no effect upon any mouse movements.

DELETE FILES: Active in the FILE mode. Allows deletion of previously stored data files.

EDIT: Active in the INIT mode. Places you in the EDIT mode whereby parameter values or units may be entered or changed.

EXIT: Active in all modes except INIT, COLORS, and EDIT. Exits from current mode to previous mode. For instance, if you enter the CROSSHAIR mode from the EDIT mode, pressing EXIT will return you to the EDIT mode.

EXIT W/O CHANGE: Active in the COLORS mode. Exits the COLORS mode, ignoring all color changes made.

FILE: Active in the EDIT mode. Places you in the FILE mode whereby parameter values may be saved or retrieved from files.

FINER: Active whenever movement of a crosshair is required. It is used to decrease the step size for arrow key movements. FINER has no effect upon any mouse movements.

GET FILE: Active in the FILE and MAP modes. Allows retrevial of previously stored data files.

HELP: Active in all modes. Displays definitions for all active special function keys within the current mode.

KEYS: Active in all modes. It is used to remove the display of special function key labels from the bottom line of the screen thereby allowing "clean" hardcopying for viewgraphs, etc.

LABEL: Active in the EDIT mode and in the summary display of SDS. Places you in the LABEL mode.

LEGEND: Active in the LABEL and LEGEND modes of RAYS when the altitude-error display option is chosen. From the LABEL mode, places you in the LEGEND mode.

LINE: Active in the CROSSHAIR mode. Will draw a line from a previously defined point to the current cursor position. Pressing the LINE key or the right mouse button will signify the beginning point for a line. Moving the cursor with the arrow keys or a mouse will activate a "rubberband" line. After the rubberband line is positioned as desired, pressing the LINE key or the right mouse button will draw a solid line from the beginning to the ending point of the rubberband line. The entire process must be repeated to draw a subsequent line segment.

LIST DIR: Active in the FILE mode. Displays a list of files in the current directory.

MAP: Active in the summary display of SDS. Places you in the MAP mode from which one or more Marsden squares may be selected.

MARK: Active in the CROSSHAIR mode. Draws a small marker on the screen at the crosshair's current position.

MOVE LEGEND: Active in the LEGEND mode. Will display the color legend at the cursor's current position.

NEW DIR: Active in the FILE mode. Allows you to create a new directory for data file storage.

OPTIONS: Active in the EDIT mode. Places you in the OPTIONS mode where scaling and other display-oriented parameters may be changed.

OVERLAY: Active in the EDIT mode. Superimposes a new graphics display upon a previous graphics display. Note! In the

COVER program, this function is not active when display option 1 is selected and more than one threshold is given.

PLOT: Active in the INIT, EDIT, and OPTIONS modes. Clears the current graphic from the screen and displays a new graphic. Note! The plot key will only display the graphics for the current set of input parameters. If you change a parameter and want to observe the effects of the change compared with those of the old parameter, use the Overlay key.

REMOVE: Active in MAP mode. Unselects a Marsden square from the world map.

RESET: Active in the OPTIONS mode. Resets all current values to the EREPS' default values and places you in the EDIT mode.

SAVE FILE: Active in the FILE and MAP modes. Allows you to store data to a data file.

SELECT: Active in the MAP mode. Allows you to specify a Marsden square of interest for retrieving climatological information.

SET DEFAULT: Active in the INIT mode. Saves the current height and range units to the *.INI file for use as default units in subsequent program use.

SUMMARY: Active in the MAP mode. Displays annual surface-duct summary from selected Marsden squares.

XHAIR: Active in the EDIT mode. Places you in the CROSSHAIR mode such that graphics result values may be digitized.

5.3 Edit Key Definitions

The edit keys used within EREPS 2.0 are:

Backspace key - Moves the cursor one space to the left within a field and enters a blank character.

Ctrl Enter - Same as Enter, except no test is performed to insure that the entered value is within recommended limits.

Del - Within the EDIT mode of the RAYS program, this key will delete the environmental level highlighted by the cursor.

Down arrow key - Moves the cursor to the next field below its present field position. If the present field is a unit field, the cursor will move right to its associated value field. If the cursor is at the bottommost value field on the page, the cursor will wrap to the topmost value field on the page. The cursor will not enter a units field from above.

End key - Moves the cursor to the last value field on the page.

Enter key - Accepts the currently displayed unit or value if it's within acceptable limits and moves the cursor to the next field to the right or below. If a value is not within limits, a beep will sound and an error message will be displayed on the topmost line of the page. Note that **Ctrl Enter** will override the limit testing.

Esc key - When pressed from any page other than the INIT or MAP page, moves the cursor to the first value field on the INIT or MAP page. When pressed from the INIT or MAP page, the program will terminate.

Home key - Moves the cursor to the first value field on the page.

Ins - Within the EDIT mode of the RAYS program, this key will allow you to insert an environmental level. A level line will be opened immediately above the current cursor position.

Left arrow key - Moves the cursor one character position to the left within a value field. If the cursor is in the left most position of a field, the cursor will move to the field immediately adjacent to the left (generally the unit field associated with the value field) or to the value field above if the value has no associated unit.

Mouse - May be used to position the cursor or the crosshair on the page. Within the MAP mode, clicking the left mouse button will select and the right mouse button will unselect a Marsden square. Within the CROSSHAIR mode, clicking the left mouse button will draw a mark on the screen at the current crosshair position The right mouse button will simulate the LINE key. Within the LEGEND mode, clicking the left mouse button will draw the legend on the screen at the current crosshair position. Within the EDIT mode of the RAYS program when the environmental data is being entered graphically, clicking the left mouse button will enter an environmental level. Clicking the right mouse button will delete an environmental level.

PgUp/PgDn keys - Changes the page displayed on the screen to the next or previous page. If no additional pages are available, a beep will be heard.

Right arrow key - Moves the cursor one character position to the right within a field. If the cursor is in the rightmost position of a field, then the cursor will move to the next value field below. The cursor will not enter a unit field from the left.

Shift tab key - Moves the cursor to the next field to the left or above. This key may also be used to enter a unit field from an associated value field.

Space bar - For numeric or character values, enters a blank. For fields which contain a limited number of specific choices, such as km, nmi, or sm for units of range, it will toggle between choices.

Tab key - Moves the cursor to the next field to the right or below. The cursor will not enter a unit field from the left.

Up arrow key - Moves the cursor to the next value field above its present field position. If the cursor is at the topmost field on the page, the cursor will wrap to the bottommost value field on the page.

5.4 Input Parameter Definitions

The following is a reference listing, in alphabetical order, of short titles, any associated units, and the default values for all input parameters within EREPS 2.0.

ABS HUM - absolute humidity. Units are fixed at g/m3 (grams per cubic meter). Value must be $\geq$ 0 and $\leq$ 12. Default is 7.5.

ALT ERROR - produce an altitude error display. This display is available only for computers equipped with an EGA or VGA card and 64 kilobytes or more of memory. Value must be Y (yes) or N (no). Default is N.

ANGLE UNITS - units associated with raytrace starting angle. The value may be degs (degrees) or mrads (milliradians). Default is mrads.

ANT GN - transmitter antenna gain. Units are fixed at dBi (decibel over isotropic). Value must be ≥ 0 and ≤ 100. Default is 32 for PROPR and PROPH, 21 for COVER.

ANT TYPE - transmitter antenna radiation pattern type. Values are

1. OMNI (omnidirectional)
2. SINX/X (sin(x)/X)
3. CSC-SQ (cosecant-squared)
4. HT-FIN (generic height-finder)
5. GAUSS (Gaussian)

Default is SINX/X for radar applications and OMNI otherwise. OMNI may not be used for radar applications (i.e. display options 3 or 4 in PROPR/PROPH or display option 2 in COVER).

CLTR TYPE - type of clutter model to use within calculations. This prompt appears only if display option 4 is chosen in PROPR or PROPH. Value may be AVERAGE or BOUNDS. Default is AVERAGE.

The clutter model incorporated in PROPR and PROPH is taken from the Georgia Institute of Technology (GIT) sea clutter model, modified by NOSC to account for ducting effects, and is thought to be accurate within ±5 dB within the radar horizon. A value of AVERAGE will display the average clutter. A value of BOUNDS will display lower and upper clutter bounds (2 dashed lines) representing the minimum and maximum amount of clutter that may be present for a given range or height.

COMP PW - radar compressed pulse width. Units may be ms (milliseconds), us (microseconds), ns (nanoseconds), or ps

(picoseconds). Value must be ≥ 0.1 and ≤ 9,999. Default is 1.3 us.

dB BOTTOM - the propagation loss, propagation factor, or signal-to-noise ratio to appear at the bottom of the vertical ordinate for the PROPR graphic product. Units are fixed at dB. Value must be ≥ -200 and ≤ 300. For display of propagation loss or signal-to-noise ratio, the default is 80. For display of propagation factor, the default is 20. Note! Normally, the dB scale is plotted with propagation loss increasing and propagation factor or signal-to-noise ratio decreasing toward the bottom on the ordinate. It is possible however to reverse the graphic by reversing the entries for top and bottom. If the top and bottom dB values are equal, the dB value at the bottom of the ordinate will default to 10 units different than the top.

dB TOP - the propagation loss, propagation factor, or signal-to-noise ratio to appear at the top of the ordinate for the PROPR graphic product. Units are fixed at dB. Value must be ≥ -200 and ≤ 300.

dB LEFT - the propagation loss, propagation factor, or signal-to-noise ratio to appear at the left of the abscissa for the PROPH graphic product. Units are fixed at dB. Value must be ≥ -200 and ≤ 300. For display of propagation loss or signal-to-noise ratio, the default is 80. For display of propagation factor, the default is 20. Note! Normally, the dB scale is plotted with propagation loss increasing and propagation factor or signal-to-noise ratio decreasing toward the left on the abscissa. It is possible however to reverse the graphic by reversing the entries for left and right. If the left and right dB values are equal, the dB value at the left of the abscissa will default to 10 units different than the top.

dB RIGHT - the propagation loss, propagation factor, or signal-to-noise ratio to appear at the right of the abscissa for

the PROPH graphic product. Units are fixed at dB. Value must be ≥ -200 and ≤ 300.

DET FAC - detectability factor. Units are fixed at dB. Value must be ≥ -25 and ≤ 25. Default is 0.

DISPLAY OPTION -

For COVER the display options are

1. HEIGHT versus RANGE coverage with up to 4 user-defined thresholds.
2. HEIGHT versus RANGE coverage with one threshold based on radar parameters.

Default is 1.

For PROPR and PROPH, the display options are

1. Display propagation loss or pattern propagation factor versus range or height with up to four user-defined thresholds.
2. Display propagation loss or pattern propagation factor versus range or height with one threshold based on ESM parameters.
3. Display propagation loss or pattern propagation factor versus range or height with one threshold based on radar parameters.
4. Display radar signal-to-noise versus range or height.

Default is 1.

DUCT BTM - the bottom of a duct specified by **Enter method** 2 of the RAYS program. Units may be ft or m. The value must be less than that specified with **DUCT TOP**. The default is 0.

DUCT TOP - the top of a duct specified by **Enter method** 2 of the RAYS program. Units may be ft or m. The value must be ≥ 0 and ≤ the maximum graphic height. The default is 1,000 ft.

ELEV ANG - transmitter antenna elevation angle. Units may be degs or mrads. Value must be ≥ -10 and ≤ 10 degs or -200 and 200. Default is 0 degs.

Enter method - For the RAYS program, the environmental input methods are

1. Numerical/Graphical height-refractivity levels. This method allows you to input an environmental profile numerically and/or graphically in height and refractivity levels. The default atmosphere obtained by this method is one with a standard gradient of 118 M-units/km.
2. Refractivity profile characteristics. Using this method enables you to describe a duct with its top and bottom height and thickness of its trapping layer in addition to two additional atmospheric layers. The two additional layers are described by their height, refractivity gradient, and relationship to any previously entered duct. The default atmosphere obtained by this method is one with a 1,000 foot surface-based duct formed by a trapping layer from 900 to 1,000 feet with a gradient calculated to produce the same M-unit value at 1,000 feet as at 0 feet; an elevated subrefractive layer from 9,000 to 10,000 feet with a gradient of 60 M/kft; and an elevated super-refractive layer from 17,000 to 18,000 feet with a gradient of 15 M/kft.
3. Pressure, temperature, and humidity. Using this method enables you to enter levels of pressure in millibars (mbs), temperature (C or F), and humidity (%), from which an M-unit or N-unit versus height profile will be calculated. The default atmosphere obtained by this method is one with a standard gradient of 118 M-units/km.

Default method is 1.

ENVIRO @ RANGE 0 - This is a screen label and not a prompt for an operator input. RPE will allow multiple specifications of environment as a function of range. Each environment will be stored within its own disk file. If **Propagation model** is specified as RPE, the initial environmental file name will be listed under this label.

ERROR INCR - altitude-error increment. Defines the color scale of the altitude error display. Units may be ft or m. Value must be ≥ 1 and ≤ 2,000 ft or 1 and 1,000 m. Default is 500 ft.

ESM SENS - ESM antenna and receiver sensitivity. Units are fixed at dBm (decibel referred to 1 milliwatt). Value must be ≥ -200 and ≤ 0. Default is -80.

EVD HT - evaporation duct height. Units may be ft or m. Value must be ≥ 0 and ≤ 40 meters or 0 and 130 feet. Default is 0 m.

FREE-SPACE RANGE/dB THRESHOLD - a system's performance threshold either specified directly, calculated from radar parameters, or calculated from ESM parameters. Up to four thresholds may be specified. Units may be nmi, km, sm, or dB. For PROPR and PROPH, the range value must be ≥ 0 and ≤ 99,999 and the dB value must be between -200 and 300. For COVER, the range value must be ≥ 0 and ≤ 400 and the dB value must be ≥ 0 and ≤ 180. The defaults are 100, 0, 0, and 0 nmi.

FREE SPACE REF - display the free-space propagation loss reference line within PROPR and PROPH. Value must be Y or N. Default is Y.

FREQ - transmit frequency. Units may be MHz (megahertz) or GHz (gigahertz). Value must be ≥ 100 and ≤ 20,000 MHz or 0.1

and 20 GHz. Default is 5,600 MHz for PROPR and PROPH, 425 MHz for COVER.

H - relative humidity for environmental **Enter method** 3 of RAYS. Units are fixed at percent. Value must be ≥ 0 and ≤ 100. Within the atmosphere, a relative humidity of 0 is not a natural occurrence. By specifying 0 percent however, RAYS will be applicable to optical refraction. Two arbitrary defaults are provided which define a standard refractive gradient. The first is 80% at a pressure of 1013.2 millibars. The second is 8% at an average tropopause pressure of 250 millibars.

HEIGHT UNITS - For PROPR, PROPH, and COVER, the value may be ft, m, kft (kilofeet), or km (kilometers). For RAYS, the value may be ft or m. Default is ft. This input will serve as the default units of height for other values such as transmitter height, receiver height, or environmental inputs.

HOR BW - transmitter horizontal beamwidth. Units may be degs or mrads. Value must be > 0 and ≤ 360 degs or 0 and 6,283 mrads. Default is 1.5 degs for PROPR and PROPH, 11 degs for COVER.

HORIZONTAL AXIS - the quantity displayed on the horizontal axis of a graphic. Value may be PROPAGATION LOSS dB or PROPAGATION FACTOR dB. Default is PROPAGATION LOSS dB.

INTEG TYPE - type of signal integration model used in calculations of radar free-space range. Value may be I (incoherent) or C (coherent). Default is I.

K - effective earth radius factor. Value must be > 1 and ≤ 5. Default is 1.333 (a standard 4/3's earth).

LYR BTM - the bottom altitude of a layer as defined with **Enter method** 2 of the RAYS program. Units may be ft or m. The

value must be greater than or equal to any lower layer or duct top; less than any above layer or duct bottom; and less than its own layer top. The default is 9,000 and 17,000 ft for the first and second layer respectively.

LYR GRD - the gradient of refractivity or modified refractivity used within layers as defined with **Enter method** 2 of the RAYS program. Units may be N/kft, N/km, M/kft, or M/km. The value must be those defined within table 1. The default for a subrefractive, standard, superrefractive, and trapping layer is 60 M/kft, 35.9 M/kft, 15 M/kft, and -10 M/kft respectively.

LYR THK - the thickness of the trapping layer used to create a duct as defined with **Enter method** 2 of the RAYS program. The units may be ft or m. The value may range from 0 up to but not including the height of **DUCT TOP**. The default is 100 ft.

LYR TOP - the top height of a layer as defined with **Enter method** 2 of the RAYS program. Units may be ft or m. The value must be less than or equal to any higher layer or duct bottom; greater than any lower layer or duct top; and greater than its own bottom. The default is 10,000 and 18,000 ft for the first and second layers respectively.

LYR TYPE - the type of refractive gradient used within layers as defined with **Enter method** 2 of the RAYS program. The value must be T (trapping), P (superrefractive), B (subrefractive), or S (standard). The default is B and P for the first and second layers respectively.

MAX ANG - transmitting antenna's maximum elevation angle. Units may be degs or mrads. Value must be $\geq$ -10 and $\leq$ 10 degs or -99 and 99 mrads. Default is 10.

MAX HEIGHT - maximum graphics height. Units may be ft, m, kft, or km. For COVER, the value must be > 0 and $\leq$ 99,999 ft,

25,000 m, 100 kft, and 25 km with a default of 50,000 ft. For RAYS, the value must be ≥ 100 and ≤ 50,000 ft or 30 and 30,000 m with a default of 20,000 ft. For PROPH, the value must be ≥ 0 and ≤ 9,999. If a value of 0 is entered, the graphic will self-scale to present a reasonable display. The default is 0.

MAX RANGE - maximum graphics range. Units may be nmi, km, or sm. For COVER the value must be ≥ 10 and ≤ 500 with a default of 200 nmi. For RAYS, the value must be ≥ 10 and ≤ 5,000 with a default of 200 nmi. For PROPR the value must be ≥ 0 and ≤ 1,000. If a value of 0 is entered, the graphic will self-scale to present a reasonable display. Default is 0.

MIN ANG - transmitting antenna's minimum elevation angle. Units may be degs or mrads. Value must be ≥ -10 and ≤ 10 degs or -99 and 99 mrads. Default is -2 degs or -10 mrads, depending upon the units selected in **Angle unit** above.

MIN HEIGHT - minimum graphics height for PROPH. Units may be ft, m, kft, or km. The value must be ≥ 0 and ≤ the specified maximum height. The default is 0 ft.

MIN RANGE - minimum graphics range for PROPR. Units may be nmi, km, or sm. The value must be ≥ 0 and ≤ the specified maximum range. The default is 0.

NO. OF LOBES - number of constructive interference lobes displayed within the optical region. For COVER, the value must be ≥ 1 and ≤ 10 with a default of 6. For PROPR and PROPH, the value must be ≥ 1 and ≤ 100 with a default of 2.

NO. OF RAYS - number of rays to draw on the RAYS graphic. The value must be ≥ 1 and ≤ 300. Default is 50.

NSUBS - surface refractivity. The units are fixed to N. The value must be ≥ 0 and ≤ 450. Default is the world average of 339.

P - pressure for environmental **Enter method** 3 of RAYS. Units are fixed at mbs (millibars). Value must be ≤ 1100 and ≥ 250. Two standard atmosphere defaults are provided. The first is a world average earth's surface pressure of 1013.2 mbs. The second is 250 mbs which is an average tropopause pressure.

P WIDTH - transmitter pulse width. Units may be ms, us, ns, or ps. Value must be ≥ 0.1 and ≤ 9,999. Default is 1.3 us for PROPR and PROPH, 60 us for COVER.

PD - probability of detection. Value must be ≥ 0.1 and ≤ 0.9. Default is 0.9 for PROPR and PROPH, 0.5 for COVER.

PFA - probability of false alarm exponent. Value must be ≤ 12 and ≥ 2 (e.g., probability of false alarm must be between 1 x 10^{-12} and 1 x 10^{-2}). Default is 8.

PK POW - transmitter peak power. Units may be mW (milliwatts), W (watts), kW (kilowatts), MW (megawatts), dBm (decibels referred to 1 milliwatt), or dBW (decibel referred to 1 Watt). Value must be ≥ 0.1 and ≤ 10,000. Default is 285 kW for PROPR and PROPH, 200 kW for COVER.

POLARIZATION - transmitter antenna polarization. Values are HOR (horizontal), VER (vertical), or CIR (circular). Default is HOR.

PRF - pulse repetition frequency. Units may be Hz (Hertz) or kHz (kilohertz). Value must be ≥ 1 and ≤ 9999. Default is 650 Hz for PROPR and PROPH, 300 Hz for COVER.

PROPAGATION MODEL - electromagnetic wave propagation model used to generate the graphic. Value may be INTERNAL for the EREPS models or RPE for NOSC's Radio Parabolic Equation (RPE) model. When RPE is selected, propagation loss is read from previouly-stored files generated by the NOSC RPE program. (Note. EREPS 2.0 does not contain the RPE program. Refer to section 4.1.) Default is INTERNAL.

PULSES - number of pulses to integrate within the signal integration model. Value must be ≥ 1 and ≤ 99,999. Default is 10.

RADAR CALCS - radar free-space range calculation technique. Value may be S (simple), I (integration), or D (detectability). Simple calculation is used mainly for rotating pulse radars that use noncoherent pulse integration. By selecting S, the number of pulses integrated will be calculated from the antenna's horizontal beamwidth and horizontal scan rate and the transmitter's pulse repetition frequency. By selecting I, you must enter the number of pulses to integrate and if coherent or incoherent integration is used. By selecting D, you must enter the detectability factor, i.e., the minimum signal-to-noise ratio required for a given probability of detection and probability of false alarm. Default is S.

RANGE - receiver/target range. Units may be nmi, km, or sm. Value must be ≥ 1 and ≤ 10,000. Default is 50 nmi.

RANGE AXIS - For COVER, determines the appearance of the range axis, either as a flat or curved earth graphic. For a curved-earth display, the radius of curvature is dependent on the earth's radius times the standard effective earth's radius factor of 4/3. Value may be F (flat) or C (curved). Default is C.

RANGE UNITS - units may be nmi, km, or sm. Default is nmi. This input will serve as the default unit of range for other values such as maximum graphics range or free-space range.

RCS - target's radar cross section. Units may be sqm (square meters) or dBsm (decibels above a square meter). Value must be > 0 and ≤ 99,999 sqm or ≥ -30 and ≤ 50 dBsm. Default is 1 sqm.

REC NF - receiver noise figure. Units are fixed at dB. Value must be ≥ 0 and ≤ 100. Default is 14 for PROPR and PROPH, 5 for COVER.

REC/TRGT HT - receiver/target height. Units may be ft, m, kft, or km. Value must be ≥ 3 and ≤ 30,000 ft, 1 and 30 kft, 1 and 10,000 m, or 1 and 10 km. Default is 30 ft.

REFLECTED RAYS - display reflected rays within the RAYS graphics. Value may be N (no) or Y (yes). If **ALT ERROR** is Y, this entry is not applicable and the symbols N/A will appear within the input field. Default is Y.

REFRACTIVITY UNITS - Units of refractivity to be used for environmental input. Value may be N-units (refractivity) or M-units (modified refractivity). Default is M-units.

RESOLUTION - the method of displaying RPE output data upon the computer screen. Value must be PIXEL or FILE. By specifying PIXEL, the RPE data will be interpolated to produce a value corresponding to each screen pixel. Using this method, every screen pixel will be activated. By specifying FILE, uninterpolated data will be plotted at its proper pixel location under the specified graphics resolution. While this method of display is faster than that of PIXEL, for RPE files which contain data in a courser mesh than the number of pixels on the screen, a

"spotty" display may result since not every screen pixel will be activated.

SBD HT - surface-based duct height. Units may be ft or m. Value must be ≥ 0 and ≤ 1,000 m or 0 and 3,000 ft. Default is 0 m.

SCAN RT - transmitter's antenna horizontal scan rate. Units are fixed at rpm (revolutions per minute). Value must be ≥ 1 and ≤ 9,999. Default is 15 for PROPR and PROPH, 6 for COVER.

SMOOTHNESS - ray smoothness factor. This is the number of milliradians incremented at each new angle in performing the ray trace. Using angular increments allows you to vary the appearance of the rays by adjusting the smoothness factor, i.e., small increments making the rays appear very smooth and large increments making the rays appear more jagged. You should note that the smaller the smoothness factor, the smaller the angular increments and, therefore, the greater the time needed to perform the ray trace. Units are fixed at milliradians. The value must be ≥ 0.1 and ≤ 10. Default is 3.

SONDE HT - radiosonde launch height. Units may be ft or m. The value must be ≥ 0 and ≤ 30,000 feet or 0 and 10,000 meters. Default is 0.

SW CASE - Swirling case number. Value may be 0-STDY (steady) or 1-FLCT (slowly fluctuating). Default is 1-FLCT.

SYS LOSS - system losses such as line, beamshape, etc. Units are fixed at dB. Value must be ≥ 0 and ≤ 100. Default is 8.4 for PROPR and PROPH, 6 for COVER.

TEMPERATURE UNITS - Units of temperature for environmental input. Value may be C (Celsius) or F (Fahrenheit). Default is C.

TMP - temperature for environmental **Enter method** 3 of RAYS. Units may be C or F. Value must be ≥ -80° and ≤ 50° C, and ≥ -110° and ≤ 125° F. Two standard atmosphere defaults are provided. The first is a world average earth's surface temperature of 15° C. The second is -52° C, which is 15° C reduced with a standard atmospheric lapse rate of -6.5° C/km to a pressure of 250 millibars.

TRAN/RADR HT - transmitter/radar height. Units may be ft or m. Value for COVER must be ≥ 3 and ≤ 250 ft or 1 and 100 m. The default is 100 ft. Values for PROPR and PROPH must be ≥ 3 and ≤ 300 ft or 1 and 100 m. Default is 75 ft. Value for RAYS must be ≥ 3 and ≤ 50,000 feet or 1 and 30,000 meters. Default is 100 feet.

VER BW - antenna vertical beamwidth. Units may be degs or mrads. Value must be ≥ 0.5 and ≤ 45 degs or 9 and 785 mrads. Default is 10 degs for PROPR and PROPH, 19 degs for COVER.

VERTICAL AXIS - the quantity displayed on the vertical axis of the graphic. This prompt is active only when PROPR **Display option** is 1, 2, or 3. Value may be PROPAGATION LOSS dB or PROPAGATION FACTOR dB. Default is PROPAGATION LOSS dB.

WIND DIR - wind direction relative to upwind. Units may be degs or rads (radians). Value must be ≥ 0 and ≤ 180 degs or 0 and 2 rads. Default is 0 degs.

WIND SP - wind speed. Units may be kts (knots), m/s (meters/second), mph (miles per hour), or km/h (kilometers/hour). Value must be ≥ 0 and ≤ 100 kts, 0 and 50 m/s, 0 and 99 mph, or 0 and 99 km/h. Default is 10 kts.

6.0 EREPS Limitations

The limitations of the EREPS programs are as follows:

a. Frequency: 100 MHz to 20 GHz in PROPR, PROPH, COVER and FFACTR.

b. Over-water paths: With the single exception of troposcatter, the PROPR, PROPH, COVER, and FFACTR models apply only to over-water paths. The models are not valid for terrestrial paths.

c. Horizontal homogeneity: All models assume a horizontally homogeneous atmosphere. It is believed this limitation is justified at least 85% of the time, as described by Hitney (1985).

d. Effective earth radius factor (K): The diffraction and evaporation duct models are not dependent upon K. Variations in K should only be used to study changes in the optical region nulls. Otherwise K should be kept at a value near 1.33.

e. Optical region: If a large number of lobes are requested, the elevation angles may exceed the small-angle assumptions, causing null locations to be in error. No check is made by the programs for these large angles.

f. Evaporation duct height: All the programs use a single-mode model of propagation for an evaporation duct and may be in error for duct heights greater than 30 meters at 3 GHz, 22 meters at 5 GHz, 14 meters at 10 GHz, and 10m at 18 GHz. Below 2 GHz, all programs should give acceptable results for all ducts between 0 and 40 meters.

g. Surface-based ducts: All programs, except RAYS, use a single-mode empirical model to approximate surface-based duct

propagation which is best used to illustrate the skip zone effect and range extensions. This surface-based duct is one created from an elevated trapping layer and not from a surface-based trapping layer (see section 2.4.3). An exact vertical refractivity profile would have to be provided to a full-wave-solution program in order to achieve accurate results, this is beyond the scope of the EREPS programs.

h. Model approximations: COVER uses a parallel ray approximation to the geometric model given in section 7.1. The approximation assumes that the direct and sea-reflected rays arrive nearly parallel at the receiver/target. This assumption is quite good at long ranges and higher heights. However, as ranges and heights decrease the assumption becomes poorer and the COVER program will be in error, with the error becoming worse as ranges and heights decrease. The PROPR and PROPH programs do not make the parallel ray assumption. If the results of the COVER program are suspect, they may be compared to those obtained from PROPR or PROPH.

i. Graphics shading routines: As the frequency or antenna height increase, the lobe spacing as shown by figure 13, decreases. For some cases of the COVER program, the spacing may become so small that the graphic routine used to shade the lobes will fail. For these cases, the shading problem may be corrected by increasing the scale and replotting the graphic.

7.0 EREPS Models

The various models underlying the EREPS programs are described below in section 7.1 through 7.5. PROPR, PROPH, COVER, RAYS, and FFACTR are all based on these models; however, for considerations of speed and graphics presentation, each program is implemented somewhat differently. The implementations for each model are briefly described in Section 7.6.

7.1 Propagation Models

The simplest case of electromagnetic wave propagation is the transmission of a wave between a transmitter and a receiver in free space. Free space is defined as a region whose properties are isotropic, homogeneous, and loss-free, i.e., away from the influences of the earth's atmosphere. In free space, the electromagnetic wave front spreads uniformly in all directions from the transmitter.

While the total amount of energy transmitted does not vary, i.e., no losses to absorption, etc., the energy is distributed over an ever enlarging surface. Thus the energy level along any one ray decreases inversely with the square of the sphere's radius. This is called the **free-space path-loss**. The power density, (W/m^2), over a sphere at any point in free-space, P_a is

$$P_a = \frac{P_t}{4\pi \quad r^2}, \qquad (6)$$

where P_t is the power radiated by the transmitter in Watts and r is the radius of the sphere in meters.

In free space, the power density at a loss-free, isotropic receiving antenna is the power density over the entire sphere's surface times the area of the sphere covered by the receiver antenna, also called the antenna's effective aperture, A_e. The effective aperture is related to the wavelength (λ) of radiation by

$$A_e = \frac{G \lambda^2}{4 \pi} , \qquad (7)$$

where G is the antenna's gain. For a loss-free, isotropic antenna, G is unity. Thus the power at the receiver, P_r is

$$P_r = P_a A_e = \frac{P_t \lambda^2}{(4\pi r)^2} . \qquad (8)$$

The free-space path loss is expressed as

$$L_{fs} = \frac{P_t}{P_r} = \frac{(4\pi r)^2}{\lambda^2} , \qquad (9)$$

where r and λ are in the same units. The free-space path loss expressed in terms of frequency is

$$L_{fs} = 32.44 + 20\text{LOG}_{10}(r) + 20\text{LOG}_{10}(f) , \qquad (10)$$

for r in kilometers and f in MHz.

If non-isotropic antenna radiational patterns are considered within the loss calculations, the loss is refered to as **propagation loss** rather than path loss. The propagation loss can be described with the aid of the **propagation factor** which is defined as the ratio of the actual field strength at a point in space to the field strength that would exist at the same range under free-space conditions with the beam of the transmitter directed toward the point in question. Symbolically this is

$$F = \frac{|E|}{|E_o|} , \qquad (11)$$

where E_o is the magnitude of the electric field under free-space conditions and E is the magnitude of the field to be investigated at the same point.

The propagation factor is a desirable quantity since it is an identifiable parameter in most radar-detection-range equations. It contains all the information necessary to account for such effects as sea-surface reflection, atmospheric refraction, scattering from inhomogeneties in the atmosphere, and diffraction from the bulge of the earth's surface. Thus, if the functional form of F is known then the propagation loss at any point can be determined since the calculation of the free-space field is quite simple. The propagation loss (in dB) including antenna patterns, is equivalent to

$$L = L_{fs} - 20LOG_{10}(F) . \qquad (12)$$

There are three distinct regions which require different methods for obtaining signal strength (or, equivalently, propagation loss) as a function of range. The first region is

called the optical interference, or optical region. This region extends roughly from the transmitter to the radio horizon. In the optical region, propagation is dominated by two-path coherent interference between direct and surface-reflected waves. The other distinct region is the diffraction/troposcatter region which begins just beyond the radio horizon. A third region, called the intermediate region, lies between the optical and the diffraction region. The signal levels in this region are obtained by a linear interpolation between F values in the optical and diffraction regions.

In the discussion of the models all heights are in meters, all ranges are in kilometers, and angles in radians unless specifically stated otherwise.

7.1.1 Optical Interference Region Models

For naval EM systems operated near the earth's surface, the electric field at a receiving antenna or radar target is the vector sum of the field components which arrive at that point via the direct and sea-reflected paths as shown in figure 6. The phase component of the reflected ray will lag the phase of the direct path because of the difference in path lengths. The total phase lag, θ, of the reflected ray with respect to the direct ray is the sum of the path-length difference, δ, and the phase change, Φ, due to reflection from the surface. In EREPS the assumption is made that the direct and sea-reflected rays have very nearly the same spatial direction, such that the major factor in their addition is the phase difference. Kerr (1951) gives the following expression for F in the absence of abnormal absorption or refractive effects as

$$F = [f(\epsilon_1)^2 + (f(\epsilon_2)\ D\ R)^2 + 2\ D\ R\ f(\epsilon_1)\ f(\epsilon_2)\ COS(\theta)]^{1/2} \quad (13)$$

The $f(\epsilon_i)$ factors describe the (normalized to 1) antenna pattern and the angles, ϵ_i, are shown in figure 24. D is called the divergence factor and takes into account the spherical nature of the reflecting surface. R is the reflection coefficient of the reflecting surface (the ratio of the magnitudes of the reflected and incident fields). F varies from maximum to minimum as the total phase lag, θ, changes by π and can assume values between 0 and 2.

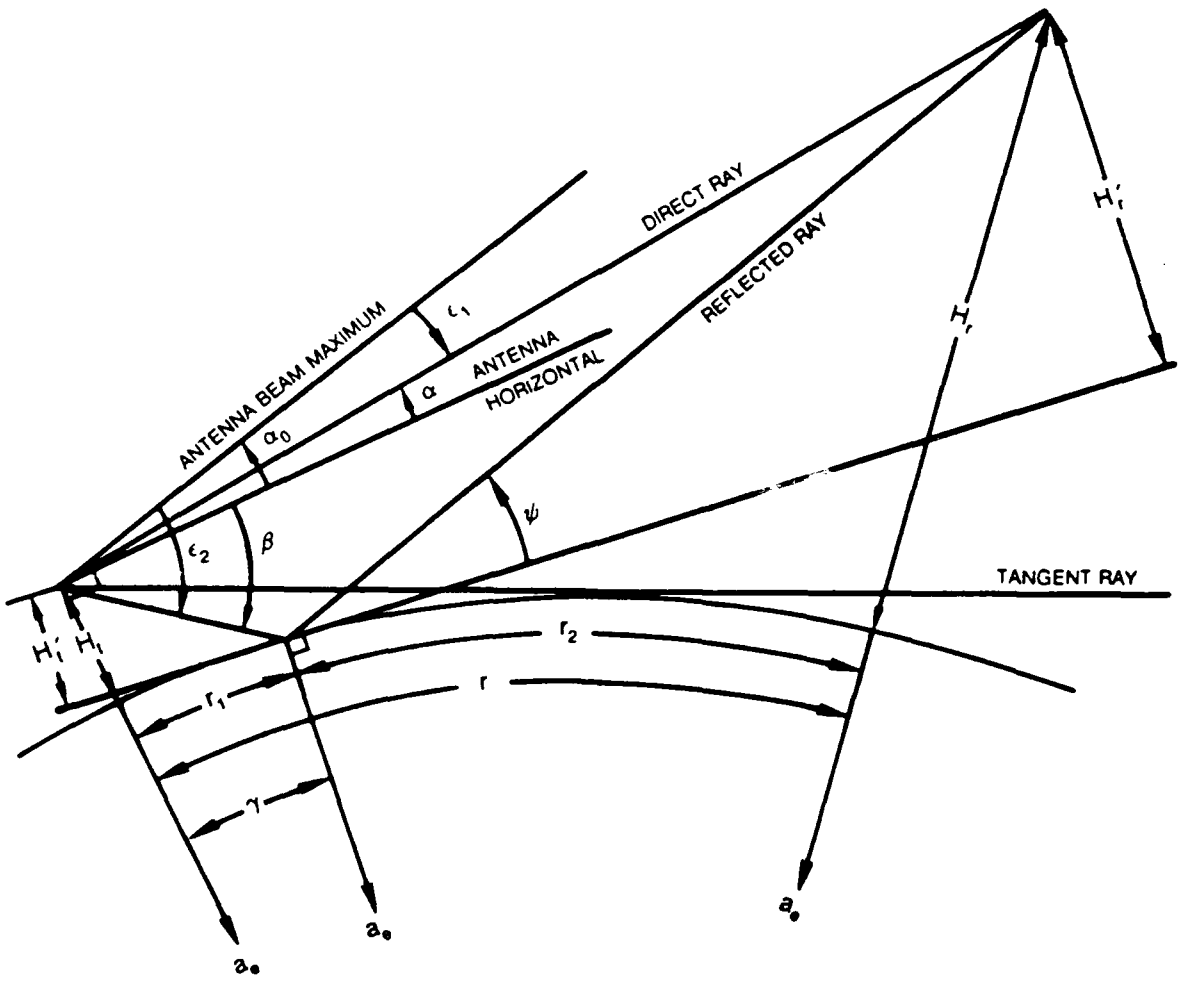


Figure 24: Two path optical interference region.

The expression for F in equation 13 is valid for all values of θ such that the path-length difference, δ, is greater than or equal to one-quarter wavelength, or at which the grazing angle is equal to a limit given by Reed and Russell (1966) at which the spherical earth divergence factor becomes invalid. This limit is given by the expression

$$\psi_{lim} = TAN^{-1}[(.001\ \lambda)/(2\ \pi\ a_e)]^{1/3} \simeq (.01957)/(k\ f)^{1/3} \quad (14)$$

where ψ is the grazing angle, λ is the wavelength in meters, a_e is the effective earth radius, and f is the frequency in MHz. a_e is defined as the earth radius times the effective earth radius factor k. The optical region maximum range is reduced from that calculated by the applicable optical region limit above if the evaporation duct is not zero. If the (scaled) evaporation duct height is less than 10.25 meters in height the end of the optical region is obtained by finding the range where the first optical region peak occurs ($\theta = 2\pi$) and using the following formula

$$\theta_{lim} = 1 + (\Delta/10.25)(2\pi - \theta_1)\ , \quad (15)$$

where θ_1 represents the value of θ at the quarter wavelength or grazing angle limit, and Δ is the scaled evaporation duct height. Scaled evaporation duct heights greater than 10.25 meters use $\theta = 2\pi$ as the optical region maximum value.

For all programs except COVER, the path length difference, δ, in radians, between the direct and reflected rays is given by

$$\delta = 2\pi\ (2\ H_t'\ H_r')/(1000\ r\ \lambda). \quad (16)$$

Here r is the total ground range, and H_t' and H_r' the effective antenna heights. H_t' and H_r' are shown in figure 24 and are given by

$$H_t' = H_t - (1000\ r_1^2)/(2\ a_e) \quad (m), \tag{17}$$

$$H_r' = H_r - (1000\ r_2^2)/(2\ a_e) \quad (m), \tag{18}$$

where H_t and H_r are the transmitter and receiver/target heights respectively. r_1 and r_2 are the reflection point ranges. r_1 can be determined by solving the cubic equation

$$2\ r_1^3 - 3\ r\ r_1^2 + (r^2 - .002\ a_e(H_t + H_r))r_1 + .002\ a_e\ H_t\ r = 0\ . \tag{19}$$

This equation is frequently solved using a Newton-method iterative technique, but also has the formal solution ($H_r \geq H_t$)

$$r_1 = r/2 - p\ \cos((\Phi + \pi)/3), \tag{20}$$

where

$$p = [(4/3)(.001\ a_e(H_t + H_r) + (r/2)^2)]^{1,2} \tag{21}$$

and

$$\Phi = \cos^{-1}[(.002\ a_e(H_r - H_t)r)/p^3]. \qquad (22)$$

The antenna pattern factors, $f(\epsilon_i)$, require angular information about the angles α and β as shown in figure 24. The magnitude, R, and phase shift, Φ, require knowledge of the grazing angle, ψ. These angles, in radians, are

$$\alpha = .001(H_r - H_t)/r - r/(2\ a_e)\ , \qquad (23)$$

$$\psi = .001\ H_t'/r_1\ , \qquad (24)$$

$$\gamma = r_1/a_e\ , \qquad (25)$$

$$\beta = -\gamma - \psi\ , \qquad (26)$$

in terms of quantities shown in figure 24. The divergence factor can be calculated using the equation

$$D = [1 + (2\ r_1\ r_2)/(r\ a_e\ \psi)]^{1/2}\ . \qquad (27)$$

For the COVER program only, the path-length difference is based on the assumption that the direct and reflected rays are parallel. The path-length difference for this model is given by

$$\delta = (4\pi/\lambda)\ [H_t^2 + 1000a_e(1000a_e + H_t)\gamma^2]^{1/2}\ \mathrm{SIN}^2(\psi)\ , \qquad (28)$$

where

$$\gamma = [TAN^2(\alpha)/9 + 2000H_t/(3a_e)]^{1/2} - TAN(\alpha)/3. \quad (29)$$

The grazing angle for the COVER program is calculated using

$$\psi = \alpha + \gamma , \quad (30)$$

and β, the launch angle of the reflected ray, is equal to

$$\beta = -\alpha - 2\gamma. \quad (31)$$

The divergence factor is given in terms of the quantities of equations 29 and 30 as

$$D = [1 + 2\gamma/SIN(\psi)]^{1/2} . \quad (32)$$

The parallel ray assumption simplifies the determination of the cover contours since each contour is described by

$$r = R_{fs}F\ COS(\alpha) , \quad (33)$$

for all angles α within the main beam of the antenna and greater than the lower angular limit of the optical region. Here R_{fs} is the free-space range in kilometers.

The magnitude and phase shift of the reflected ray can be calculated as a function of the grazing angle ψ. The magnitude, R, and the phase shift, Φ, of the reflected ray for horizontal and vertical polarizations, respectively, are

$$R_H = 1 \ , \qquad (34)$$

$$\Phi_H = \pi \ , \qquad (35)$$

$$R_V e^{i\Phi_V} = \frac{n^2 \ SIN(\psi) - [n^2 - COS^2(\psi)]^{1/2}}{n^2 \ SIN(\psi) + [n^2 - COS^2(\psi)]^{1/2}} \ , \qquad (36)$$

where n is the (complex) index of refraction and the subscripts H and V indicate the polarization. The reflection coefficient for circular polarization is calculated in terms of the horizontal and vertical coefficients

$$R_C = .5[R_V^2 + R_H^2 + 2R_V R_H \ COS(\Phi_H - \Phi_V)]^{1/2}, \qquad (37)$$

$$\Phi_C = \Phi_H - SIN^{-1}(R_V \ SIN(\Phi_H + \Phi_V)/(2 \ R_C)). \qquad (38)$$

The magnitude of the reflected ray is also affected by the roughness of the reflecting surface. Surface roughness is included following the models of Ament (1953), Beard (1961), and Barrick (1971) using the formulas

$$R = R_o \ EXP(-2 \ ([2 \ \pi \ h \ SIN(\psi)]/\lambda)^2) \qquad (h \ \psi)/\lambda < .110 \ , \qquad (39)$$

$$R = R_o(.5018913 - (.2090248 - ((h\,\psi)/\lambda) - .55819)^2)^{1/2})$$
$$.110 \leq (h\,\psi)/\lambda \leq .260 , \quad (40)$$

$$R = .15\,R_o \qquad (h\,\psi)/\lambda > .260 , \quad (41)$$

where R_o is the reflection coefficient for a smooth surface, h is the root-mean-squared wave height and λ the wavelength. The rms wave height is obtained as a function of wind speed using the Phillips (1966) ocean-wave model

$$h = .0051\,W_s^2 , \quad (42)$$

for wind speed (W_s) in meters/sec.

The square of the index of refraction required to make the calculation of R and Φ for vertical and circular polarizations is given by

$$n^2 = \epsilon - i(18000\,\sigma)/f , \quad (43)$$

where ϵ and σ are the ordinary dielectric constant and conductivity, respectively, of sea water, and f is the EM system frequency in MHz. The constants themselves are obtained as a function of frequency using Blake's (1970) equations, as follows

Case 1: $f \leq 1500$

$$\epsilon = 80 \quad (44)$$

$$\sigma = 4.3 \; . \quad (45)$$

Case 2: $1500 < f \leq 3000$

$$\epsilon = 80 - 0.00733(f - 1500) \quad (46)$$

$$\sigma = 4.3 + 0.00148(f - 1500) \; . \quad (47)$$

Case 3: $3000 < f \leq 10000$

$$\epsilon = 69 - 0.00243(f - 3000) \quad (48)$$

$$\sigma = 6.52 + 0.001314(f - 3000) \; . \quad (49)$$

For frequencies greater than 10,000 MHz the 10,000 MHz values are used.

The remaining terms in equation 13, $f(\epsilon_i)$, the normalized antenna pattern factors, are determined as a function of the antenna pattern type, beamwidth, and pointing angle. Five different antenna types are used in EREPS 2.0; omnidirectional, sin(x)/x, cosecant-squared, generic height-finder, and Gaussian beam. The simplest case is that of the omnidirectional antenna which, as its name implies, has a gain of unity in all directions. That is, $f(\mu) = 1$ for all angles μ.

The second case is the sin(x)/x antenna type. The radiation pattern of this antenna is symmetric about the

elevation (pointing) angle of the antenna. The pattern factor for this antenna is given by Blake (1970) as

$$f(\mu) = SIN(x)/x \qquad f(\mu) \geq 0.03, \qquad -\mu_{max} \leq \mu \leq \mu_{max}, \quad (50)$$

where

$$x = c\ SIN(\mu - \mu_o)\ , \quad (51)$$

and μ_o and μ_{max} are the elevation angle and maximum angle in the main beam, respectively. The value of c is chosen so that $f(\mu) = 0.7071$ when $\mu = \mu_o \pm BW/2$, where BW is the beamwidth. This normalization ensures that the antenna half-power points [$20\ LOG_{10}(f(\mu)) = -3$ dB] occur at $\mu = \mu_o \pm BW/2$, which is the usual definition of the beamwidth of the antenna. That is

$$c = 1.39157/SIN(BW/2). \quad (52)$$

Pattern factor calculations are limited to those angles within the main beam of the antenna down to the -30 dB level ($f(\mu) \geq 0.03$). Angles greater than

$$\mu_{max} = \mu_o \pm TAN^{-1}(A\ /\ (1 + A)^{1/2})\ , \quad (53)$$

where $A = \pi/x$ are limited to a pattern factor of 0.03. This is equivalent to an antenna with its first sidelobes at -30 dB, a condition easily achieved with modern antennas.

The generic height-finder antenna is a special case of the sin(x)/x antenna. Height-finder antennas typically sweep the beam upward in elevation. This can be simulated by subsituting the direct ray angle, μ, for the elevation angle μ_o. Then $f(\mu) = 1$ for all values, μ, of the direct ray set. As the antenna beam is swept upward the pattern factor for the reflected ray gradually tapers to the -30 dB level.

A fourth antenna type is the cosecant-squared antenna. This antenna pattern is not symmetric about the elevation angle. The pattern factor is calculated using

$$f(\mu) = 1 \qquad \mu_o \leq \mu \leq \mu_o + BW , \qquad (54)$$

$$f(\mu) = SIN(BW)/SIN(\mu) \qquad \mu > \mu_o + BW , \qquad (55)$$

$$f(\mu) = [1 - (\mu_o - \mu)/BW] \qquad f(\mu) \geq 0.03, \ \mu < \mu_o . \qquad (56)$$

This antenna pattern is different from the sin(x)/x or Gaussian beam antennas since the beamwidth of this antenna does not coincide with the -3 dB, or half-power, points of the antenna. The orientation of the antenna given above is the one that would be used for shipboard radars. Cosecant-squared antennas used on an airborne radar are normally oriented in the reverse sense such that the first two equations above would describe the direct ray angles below the elevation angle μ_o. The third equation would then describe the beam taper above the elevation angle. The antenna orientation is not optional in EREPS, the antenna is always assumed to be that of a surface-based system.

The final antenna option is the Gaussian beam antenna. The pattern factor for this antenna is symmetric about the pointing angle and is given by

$$f(\mu) = \mathrm{EXP}[-W^2 (P - P_o)^2/4] ,$$

$$f(\mu) \geq 0.03, \; -\mu_{max} \leq \mu \leq \mu_{max} , \qquad (57)$$

where

$$P = \mathrm{SIN}(\mu) , \qquad (58)$$

$$P_o = \mathrm{SIN}(\mu_o) , \qquad (59)$$

$$W = (2 \, \mathrm{LOG}_e(2))^{1/2}/\mathrm{SIN}(BW/2) , \qquad (60)$$

and where the normalization factor W is chosen such that $f(\mu) = 0.7071$ when $\mu = \mu_o \pm BW/2$, similar to the sin(x)/x antenna. The maximum angle is calculated using equation 53 for a value of

$$A = [10.11779 \, \mathrm{SIN}^2(BW/2)]^{1/2} . \qquad (61)$$

7.1.2 Diffraction/Intermediate Region Models

Beyond the horizon, the chief contributions to the electric field are from diffraction and, at somewhat greater ranges, tropospheric scatter. The diffraction field can be

represented as a sum over the possible number of modes which are the solution to the fundamental equation of mode theory. For a standard atmosphere, the series describing the field converges rapidly and only a single mode is necessary to adequately determine the field. A single mode may also describe the field in the presence of evaporation ducts or surface-based ducts due to elevated layers, especially the former. However, close to the horizon the series solution converges rather slowly. This is the "intermediate region" and a method of "bold interpolation" originally described by Kerr (1951) is used to estimate the field in this region. This method involves a linear interpolation on the logarithm of the pattern propagation factor from the last valid range in the optical region to the first range in the diffraction region.

The minimum range at which the diffraction field solutions are applicable and the intermediate region ends is given by Reed and Russell (1966) as

$$r_d = r_{hor} + 230.2\ (k^2/f)^{1/3} \quad \text{(km)}\ , \qquad (62)$$

where the horizon range is given by

$$r_{hor} = 3.572\ ((k\ H_t)^{1/2} + (k\ H_r)^{1/2}) \quad \text{(km)}\ , \qquad (63)$$

for H_t and H_r is meters. A minimum effective earth radius of k = 1.33 is assumed for the calculation of r_d.

The diffraction/intermediate region models are used to determine path loss as a function of height and range for ranges and heights below the lower angular limit of the optical interference region. There are four models used to calculate

loss in this region. If the evaporation duct height is zero, then the standard diffraction loss is calculated by the methods outlined by Blake (1970). If the evaporation duct height is not zero, then the least loss from standard diffraction or a model derived from the NOSC waveguide program is used. If a surface-based duct is present an empirical model is used to calculate loss. At somewhat greater ranges troposcatter loss is calculated using a model taken from Yeh (1960) which has been modified by the addition of a "frequency gain" factor from Rice, et al. (1965) that gives better values for low-altitude paths. The troposcatter loss is calculated for all range height combinations beyond r_d and added to the standard diffraction or evaporation duct loss until the troposcatter loss is 18 dB less than the applicable loss. Beyond that point only the troposcatter loss is calculated.

7.1.2.1 Standard Diffraction Model

The total propagation loss due to standard diffraction is given by (from equation 12)

$$L = L_{fs} - 20\ LOG_{10}(F) - L_d \ , \qquad (64)$$

in terms of previously defined quantities. The loss term L_d is determined using

$$L_d = 20\ LOG_{10}(f(\mu)) \ , \qquad (65)$$

where the antenna pattern factor, $f(\mu)$, gives a measure of how much energy is directed toward this region and μ represents the lowest direct ray angle in the optical region. Blake's (1980)

standard diffraction model specifies the one-mode solution for F as

$$F = V(x) \mid U(z_1)\, U(z_2) \mid , \qquad (66)$$

for a standard atmosphere. x, z_1 and z_2 are the receiver/target range, transmiting antenna height and receiver/target height, respectively, expressed in "natural units." The natural units scale factors of range, R_s, and height, H, are given by

$$R_s = 190\ f^{-1/3}, \qquad (67)$$

$$H = 2129.4\ f^{-2/3}, \qquad (68)$$

for R_s in kilometers, H in meters, and f in MHz. The natural range, x, is equal to r/R_s where r is the actual range, and the natural height, z_1, is equal to H_t/H. Similarly, $z_2 = H_r/H$.

The V(x) term is called the attenuation factor and is equal to

$$V(x) = 10.99 + 10\ LOG_{10}(x) - 17.55\ x \qquad (dB). \qquad (69)$$

The U(z) are the height-gain functions and are calculated, in decibels, as follows

$$U(z) = 20\ LOG_{10}(z) \qquad z \leq 0.6\ , \qquad (70)$$

$$U(z) = -4.3 + 51.04\,[\mathrm{LOG}_{10}(z/0.6)]^{1.4} \qquad 0.6 < z < 1.0 \quad (71)$$

$$U(z) = 19.85\,(z^{0.47} - 0.9) \qquad z \geq 1.0. \quad (72)$$

Strictly speaking these equations are only valid for horizontal polarization and a perfectly conducting earth, but they are generally applicable to other polarizations at frequencies above 100 MHz.

7.1.2.2 NOSC Evaporation Duct Model

The evaporation duct loss (in dB) may be written as

$$L = 51.1 + \Gamma - F_{zt} - F_{zr} + 10\,\mathrm{LOG}_{10}(\rho) + \alpha\rho - L_d . \quad (73)$$

L_d is defined by equation 65. Γ is the excitation factor, F_{zt} and F_{zr} the height-gain functions for the EM system transmitter and radar target/receiver, respectively, ρ the (scaled) range and α the attenuation rate. The specific values of these quantities are obtained as functions of the duct height. The functions which produce these values are the result of curve-fitting the various quantities to waveguide program solutions. F is obtained by subsitution of equation 73 into equation 12.

The waveguide solutions which were used to develop the evaporation duct model were made at a single frequency, 9.6 GHz. The evaporation duct solutions for other frequencies share a family resemblance, the height of the duct which produces a particular propagation characteristic varying inversely with the frequency. This fact allows the solutions at 9.6 GHz to be

scaled to other frequencies. All actual ranges and heights are multiplied by the scale factors

$$R_N = 4.705\ 10^{-2}\ f^{1/3}, \qquad (74)$$

and

$$Z_N = 2.214\ 10^{-3}\ f^{2/3}, \qquad (75)$$

respectively, to scale the solutions at other frequencies to the 9.6 GHz values. The coefficients ensure $R_N = Z_N = 1$ when the frequency is set equal to 9600 MHz. Using these scale factors, the actual evaporation duct, receiver, and transmitter heights are scaled to the 9.6 GHz equivalents and the range is similarly changed to conform to the 9.6 GHz requirements. For example, the scaled duct height, Δ, is equal to the actual evaporation duct height, δ, times Z_N. Similarly, if r is the actual range and H_t the actual EM system transmitter height then the scaled range, ρ, is R_N times r and the scaled transmitter height, z_t, is given by Z_N times H_t.

The height-gains expressed as a function of scaled duct height are of two different forms, depending on whether or not the duct height is sufficient to support a well-trapped mode. The height gain function (in dB) for scaled duct heights less than 10.25 meters may be written as

$$F(z) = C1\ z^{C2} + C3\ z^{C4} + C5 \qquad z \geq 1.0\ , \qquad (76)$$

where z is the scaled height of either the EM system transmitter or the radar target/receiver. For well-trapped modes, scaled duct heights between 10.25 and 23.3 meters, two functions are necessary to obtain the height-gains in dB

$$F(z) = C1\ \mathrm{LOG}_e[\mathrm{SIN}(C2\ (z/4.72)^{C3}] + C4 \qquad 1.0 \le z \le Z_{max}, \quad (77)$$

$$F(z) = C5\ (z/4.72)^{C6} + C7 \qquad z > Z_{max} \ . \quad (78)$$

In either case, the coefficients Ci are determined from the scaled duct height, z is the scaled height of the EM system transmitter or radar target/receiver and Z_{max} is calculated using the formula

$$Z_{max} = 4\ e^{-.31(\Delta\ -\ 10.0)} + 6 \ , \quad (79)$$

where Δ is the scaled duct height. The coefficients for scaled duct heights less than 10.25 meters are calculated using the following formulas

$$C1 = (-2.2\ e^{-.244\Delta} + 17).211864^{C2} \ , \quad (80)$$

$$C2 = (4.062361\ 10^4 - (\Delta\ + 4.4961)^2)^{1/2} - 201.0128 \ , \quad (81)$$

$$C3 = (-33.9\ e^{-.517\Delta} - 3).211864^{C4} \ , \quad (82)$$

$$C4 = (1.43012\ 10^4 - (\Delta\ + 5.32545)^2)^{1/2} - 119.569 \ , \quad (83)$$

$$C5 = 41\, e^{-.41\Delta} + 61 \quad . \qquad (84)$$

The coefficients for scaled duct heights between 10.25 and 23.3 meters, are calculated using the following formulas

$$C1 = -.1189\Delta + 5.5495 \quad , \qquad (85)$$

$$C2 = (1.3291\ \mathrm{SIN}(.218(\Delta - 10)^{.77}) + .2171\ \mathrm{LOG}_e(\Delta)) \quad , \qquad (86)$$

$$C3 = 3/2 \quad , \qquad (87)$$

$$C4 = 87 - (313.29 - (\Delta - 25.3)^2)^{1/2} \quad , \qquad (88)$$

$$C5 = (F_{max}/((Z_{max}/4.72)^{C6})) \quad , \qquad (89)$$

$$C6 = (Z_{max}/4.72)(S/F_{max}) \quad , \qquad (90)$$

$$C7 = 49.4e^{-.1699(\Delta - 10)} + 30 \quad , \qquad (91)$$

where

$$S = 1.5\ C1\ C2\ (Z_{max}/4.72)^{1/2}/\mathrm{TAN}(C2\ (Z_{max}/4.72)^{3/2}) \quad , \qquad (92)$$

and

$$F_{max} = C1 \, LOG_e(SIN(C2 \, (Z_{max}/4.72)^{3/2})) + C4 - C7 \quad , \qquad (93)$$

which are necessary to make the two functions F(z) and their slopes continuous about Z_{max}. Using these coefficients in the equations will produce height-gain curves which increase with height for scaled duct heights below 10.25 meters. The well-trapped modes have an initial increase with height for a limited range of z near the surface, peak and then decrease with height to some value, thereafter displaying very little variation with height. The minimum scaled height used for calculating the height-gains is 1.0 meter and heights below this are set equal to this value.

Scaled duct heights greater than 23.3 meters have more than one mode which can propagate in the guide. The effect of the multiple modes is to add constructively at some range/height combinations and destructively at others, a condition similar to the optical region interference. Since this variation is not predictable without using a waveguide program, the scaled duct heights greater than 23.3 meters are treated as 23.3 meter ducts. Examples of the height-gain curves for evaporation ducts are shown in figure 25.

Two factors from equation 73 remain to be specified, Γ and α. The excitation factor, which is a measure of the relative strength of the mode, in dB may be obtained using

$$\Gamma = 216.7 + 1.5526\Delta \qquad \Delta \leq 3.8 \quad , \qquad (94)$$

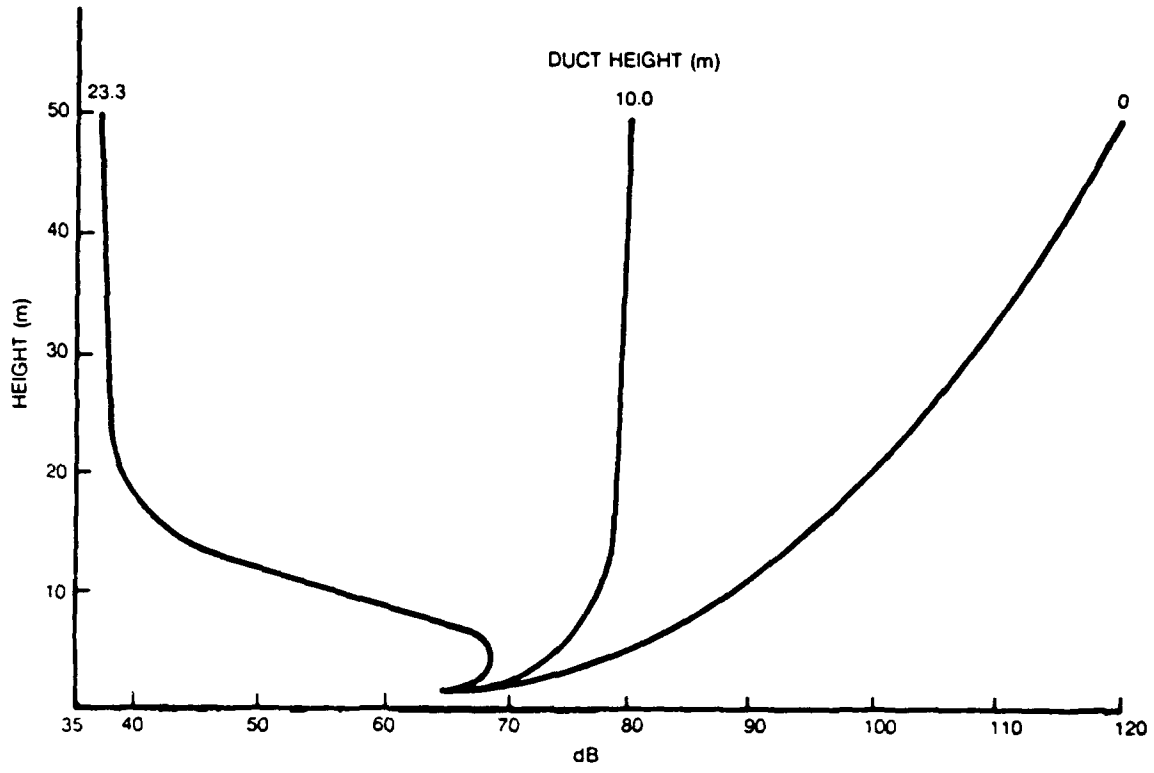


Figure 25: Example of 9.6 GHz height-gain curves.

$$\Gamma = 222.6 - 1.1771(\Delta - 3.8) \qquad \Delta > 3.8 \ . \qquad (95)$$

The attenuation rate in dB/km is

$$\alpha = (92.516 - (8608.7593 - (\Delta - 20.2663)^2)^{1/2}) \ , \qquad (96)$$

for values of $\alpha \geq 0.0009$, which is the lowest attenuation rate used. It is convenient to replace the attenuation rate term in equation 73, $\alpha\rho$, with βr, where r is the actual range and

$$\beta = \alpha R_N. \qquad (97)$$

The attenuation rates for the higher duct heights may be several orders of magnitude smaller than the standard diffraction (zero meter duct height) rate.

7.1.2.3 NOSC Surface-Based Duct Model

The NOSC model for a surface-based duct from elevated layers is not as complex as the evaporation duct model. It is based on an empirical fit of experimental data. The loss (in dB) may be written

$$L = C - F_{zr} + 20\ LOG_{10}(r) - L_d, \qquad (98)$$

where F_{zr} is the height-gain function for the receiver/target height and L_d is defined in equation 65. Here C (in dB) is given by $C = 32.44 + 20\ LOG_{10}(f)$. The attenuation rate term is not used in this model and no range or height scale factors are used either. Similarly the only height-gain term used in equation 98 is the height gain of the radar target/receiver height. As the "guide" dimensions are normally on the order of hundreds of meters, these ducts affect frequencies of 100 MHz and below, unlike the evaporation duct which only affects frequencies greater than 1 GHz. This model has the disadvantage of being anisotropic with choice of terminal heights. The height-gain term used in EREPS for this model is always calculated for the terminal height specified as the radar target/receiver height. F is obtained by subsitution of equation 98 into equation 12.

The height-gain function for the surface-based duct model is calculated as a function of frequency and duct height for any arbitrary radar target/receiver height z:

Case 1: $100 < f \leq 150$

$$F_{zr} = -60(z/D - .5)^2 \qquad z/D < .8 , \qquad (99)$$

$$F_{zr} = 1.14(z/D)^{-6.26} - 10 \qquad z/D \geq .8 . \qquad (100)$$

Case 2: $150 < f \leq 350$

$$F_{zr} = 10 - 200(z/D - .5)^4 \qquad z/D < 1.0 , \qquad (101)$$

$$F_{zr} = 7.5(z/D)^{-13.3} - 10 \qquad z/D \geq 1.0 . \qquad (102)$$

Case 3: $f > 350$

$$F_{zr} = 10 - 200(z/D - .5)^4 \qquad z/D < 1.0 , \qquad (103)$$

$$F_{zr} = 12.5(z/D)^{-8} - 15 \qquad z/D \geq 1.0 . \qquad (104)$$

Here D is the duct height. Examples of the height-gain curves produced by these formulas are given in figure 26. The shapes of the height-gain curves are characteristic of well-trapped modes as should be expected from a surface-based duct.

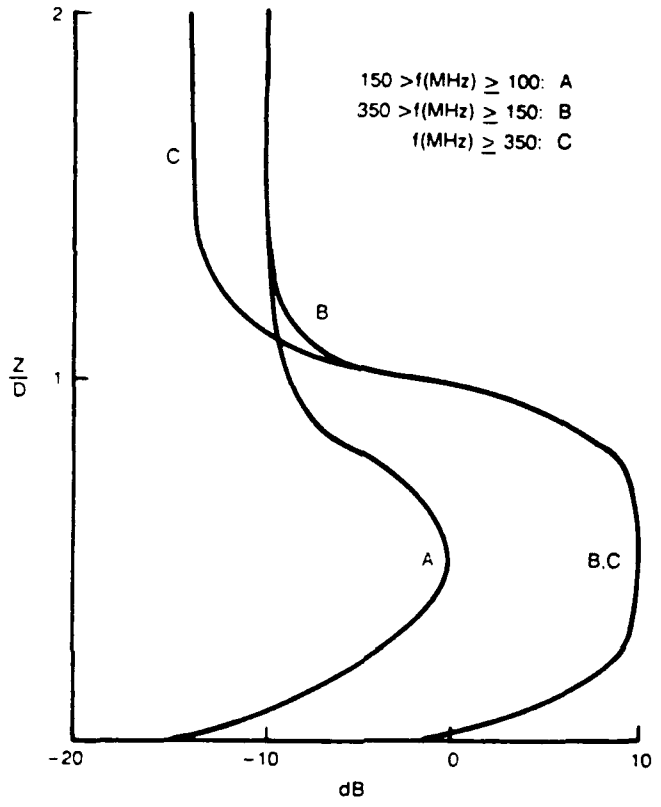


Figure 26: Height-gain curve for surface-based duct of arbitary height.

The surface-based duct model assumes a certain shape to the M-versus-height profile. The assumption is that the upper 10% of the duct is a trapping layer and that the difference in modified refractivity between the top of the duct and the surface is zero. Below the trapping layer the refractivity gradient is equal to the inverse of the effective earth radius ($dM/dh = 10^{-3}/a_e$). If both the transmitter and the radar target/reciever height are below the trapping layer a "skip-zone" is modeled. A minimum ray path between the two terminal heights is calculated and the resulting range is set as the minimum range at which full trapping by the duct exists (i.e, the far end of the skip zone).

At lesser ranges, an increase of loss is set as 1 dB/km for all frequencies, based on measured data. At greater ranges, the model is given by equation 98.

7.1.3 Troposcatter Region Model

At ranges sufficiently greater than the horizon scattering from irregularities in the troposphere begins to dominate the electric field. Yeh (1960) gives the troposcatter loss in decibels as

$$L = 114.9 + 0.08984(r - r_{hor})/k + 20\ LOG_{10}(r)$$

$$+ 30\ LOG_{10}(f) - 0.2\ N_s - L_d + H_o. \qquad (105)$$

Here r is the range, r_{hor} is the horizon range, N_s is the surface refractivity value, and H_o is the frequency-gain function from Rice et al. (1965). L_d is defined in equation 65. F is obtained by subsitution of equation 105 into equation 12. The troposcatter model can be effectively suppressed by setting $N_s = 0$ if comparisons are desired with other models which do not account for troposcatter.

The frequency gain function, H_o, is primarily of importance for low antenna heights, especially if the system frequency is very low. The procedure for obtaining H_o requires a calculation of the effective scattering height, h_o, which is equal to

$$h_o = (s\ r\ \theta)/(1 + s)^2 \qquad (km) \quad , \qquad (106)$$

where r is the ground range, θ the scattering angle, as shown in figure 27, and s is defined by

$$s = \zeta / \chi \qquad 10.0 \geq s \geq 0.10. \qquad (107)$$

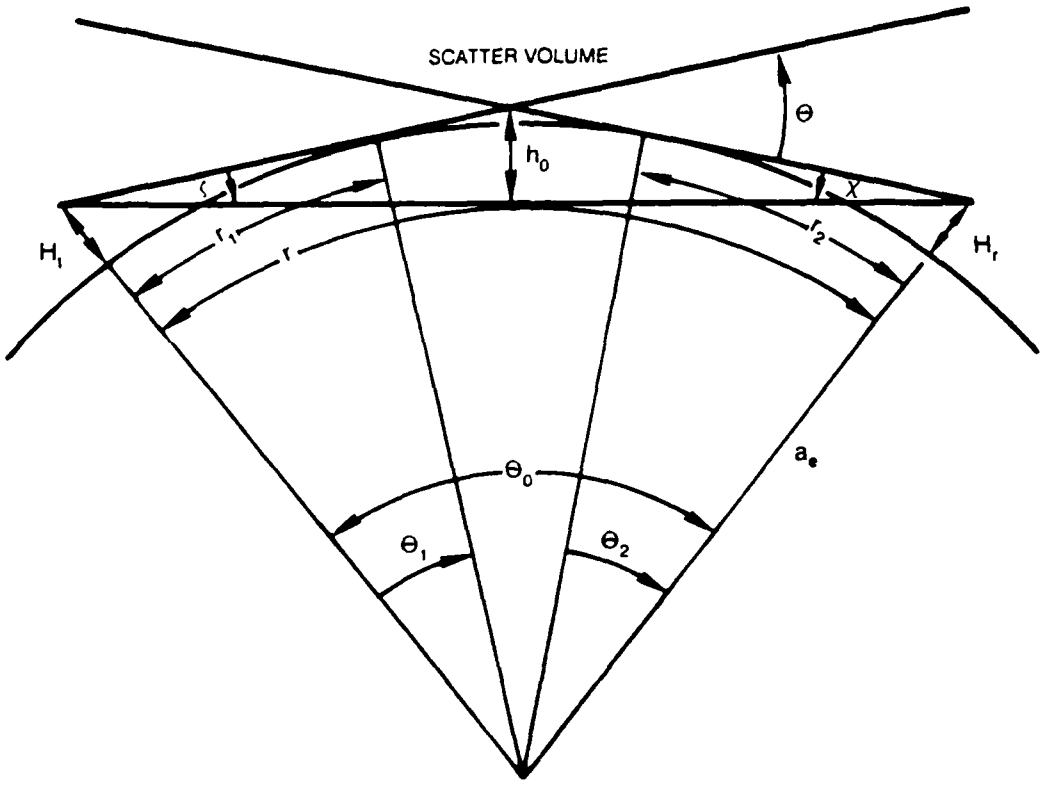


Figure 27: Geometry for troposcatter loss calculations.

The angles from these equations are given by

$$\theta = \theta_0 + \theta_1 + \theta_2 \, , \qquad (108)$$

$$\theta_0 = r/a_e , \tag{109}$$

$$\theta_1 = r_1/a_e , \tag{110}$$

$$\theta_2 = r_2/a_e , \tag{111}$$

$$\zeta = \theta/2 + \theta_1 + (H_t - H_r)/r , \tag{112}$$

$$\chi = \theta/2 + \theta_2 + (H_r - H_t)/r , \tag{113}$$

in terms of the effective earth radius, a_e, the tangent ray ranges r_1 and r_2, terminal heights H_t and H_r, and the total range, r, as shown in figure 27. The tangent ranges, r_1 and r_2, are equal to

$$r_1 = (.002\ a_e\ H_t)^{1/2} \quad \text{(km)} , \tag{114}$$

$$r_2 = (.002\ a_e\ H_r)^{1/2} \quad \text{(km)} . \tag{115}$$

The frequency gain function is then defined as

$$H_o = H_1 + \Delta H_o$$

$$= [H_o(R_1) + H_o(R_2)]/2 + \Delta H_o \qquad H_o \geq 0.0 \quad \text{(dB)} . \tag{116}$$

If ΔH_o is greater than H_1 then H_o is equal to twice the value of H_1. The function H_1 is calculated using

$$H_o(R_1) = c_1 (R_1 + c_2)^{-4/3} , \quad (117)$$

$$H_o(R_2) = c_1 (R_2 + c_2)^{-4/3} , \quad (118)$$

where R_1 and R_2 are functions of the terminal heights' and EM system frequency, f in MHz,

$$R_1 = 0.0419 \; f \; H_t \; \theta , \quad (119)$$

$$R_2 = 0.0419 \; f \; H_r \; \theta , \quad (120)$$

and the terms c_1 and c_2 are defined as

$$c_1 = 16.3 + 13.3 \; \eta_s , \quad (121)$$

$$c_2 = 0.40 + 0.16 \; \eta_s . \quad (122)$$

The factor η_s must be calculated as a function of h_o

$$\eta_s = (0.5696 \; h_o)[1 + (0.031 - 0.00232 \; N_s + 5.67 N_s^2 \; 10^{-6})$$

$$EXP(-3.8 \; h_o^6 \; 10^{-6})] \qquad 5.0 \geq \eta_s \geq 0.01. \quad (123)$$

The remaining term, ΔH_o, is calculated using

$$\Delta H_o = 6[0.60 - LOG_{10}(\eta_s)]LOG_{10}(s)\ LOG_{10}(q) \quad (dB), \qquad (124)$$

where q is given by

$$q = R_2/(s\ R_1) \qquad 10.0 \geq q \geq 0.10\ . \qquad (125)$$

The correction term ΔH_o is zero for $\eta_s = 4.0$, s = 1.0, or q = 1.0 and has a maximum value of 3.6 dB for highly asymmetrical paths when $\eta_s = 1.0$.

7.1.4 Water Vapor Absorption Model

The loss attributable to water vapor absorption is added to all other losses computed by the models of section 7.1. The model is taken directly from CCIR Recommendations (1986) and is dependent on the absolute humidity in grams/cubic meter. A temperature of 15° C is assumed. The water vapor absorption loss is equal to

$$L_{wv} = r\ \alpha_{wv}\ , \qquad (126)$$

where α_{wv} is the water vapor attenuation rate. The water vapor attenuation rate in dB/km is

$$\alpha_{wv} = (0.067 + \alpha_{wv1} + \alpha_{wv2} + \alpha_{wv3})f^2\ H_a\ 100.0\ , \qquad (127)$$

temperature of 15° C is assumed. The water vapor absorption loss is equal to

$$L_{wv} = r\,\alpha_{wv} \quad , \tag{126}$$

where α_{wv} is the water vapor attenuation rate. The water vapor attenuation rate in dB/km is

$$\alpha_{wv} = (0.067 + \alpha_{wv1} + \alpha_{wv2} + \alpha_{wv3}) f^2 \, H_a \, 100.0 \quad , \tag{127}$$

where H_a is the absolute humidity, f is the EM system frequency in MHz and

$$\alpha_{wv1} = 3 \; / \; ((0.001\,f - 22.3)^2 + 7.3) \quad , \tag{128}$$

$$\alpha_{wv2} = 9 \; / \; ((0.001\,f - 183.3)^2 + 6) \quad , \tag{129}$$

$$\alpha_{wv3} = 4.3 \; / \; ((0.001\,f - 323.8)^2 + 10). \tag{130}$$

For frequencies below about 10 GHz, this attenuation is negligible, but at the highest frequencies used in EREPS, 20 Ghz, the contribution can be quite noticeable, in particular at long ranges. No model is included for oxygen absorption, since the attenuation is negligible below 20 GHz.

an M-unit array with the corresponding M-unit value in a like-numbered array. A third array can be constructed from these two arrays which contains the gradient between adjacent layers. The general definition for this array is

$$dMdh_i = 10^{-3}(M_{i+1} - M_i)/(H_{i+1} - H_i) \ , \qquad (131)$$

where the M_j denote the M-unit array and the H_j denote the height array elements, respectively. Negative values of $dMdh_i$ are trapping layers. A standard atmosphere (4/3 earth) gradient is usually defined for the gradient above the highest height array element, that is $dMdh_j = .000118$, where the j is the index of the last element in the H array. dMdh values of zero are not allowed, which is equivalent to not allowing the M-unit values of adjacent height values to be equal.

RAYS also allows you to input the M-profile in terms of pressure, temperature and relative humidity. The models that relate these terms to M are taken from Berry (1945), and Bean and Dutton (1968). M is equal to

$$M(z) = N + 0.0157\ z \ , \qquad (132)$$

where z is the height where N is determined from equation 2 of section 2.2.2.

A critical launch angle can be determined for transmitter heights within ducts. This critical angle is defined as the maximum (positive or negative) angle trapped in the duct. The positive critical angle is given by

$$\alpha_c = 10^{-3}[2\ (M_{Ht} - M_{min})]^{1/2}, \tag{133}$$

while the maximum negative critical angle is equal to $-\alpha_c$. Here M_{Ht} is the M-unit value at the transmitter and M_{min} is the mimimum M-unit value at some height greater than H_t. H_t must be in the duct for equation 133 to be valid, though if H_t is above the duct, $-\alpha_c$ would define the launch angle for a ray tangent to the top of the duct at some range. Rays launched with angles $\alpha_c > \alpha < -\alpha_c$ will be trapped within the duct.

The general raytrace equations using the H, M and dMdh arrays can be divided into three categories, rays with the terminal range known, rays with the terminal height known, and rays with the terminal elevation angle known. Figure 28 illustrates a ray with a positive launch angle, but the equations apply to negative launch angles also when proper care is taken with respect to the layer indices and sign of the launch angle. The equations given apply only to range and height values within individual layers. All heights are in meters and ranges in kilometers.

Case 1: h' known, $\alpha \neq 0$.

$$\alpha' = (\alpha^2 - 0.002\ dMdh_i\ (h' - h))^{1/2}, \tag{134}$$

$$r' = r + (\alpha' - \alpha)/dMdh_i\ . \tag{135}$$

Case 2: r' known, $\alpha \neq 0$.

$$\alpha' = \alpha + dMdh_i\ (r' - r)\ , \tag{136}$$

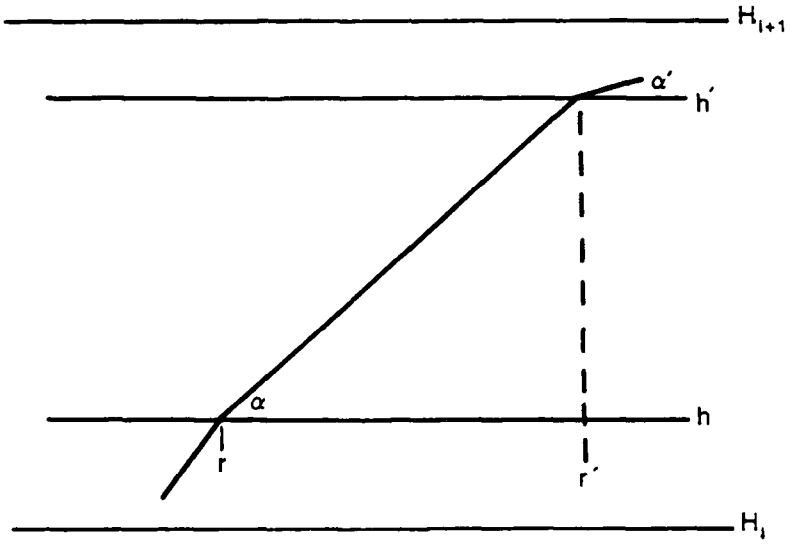


Figure 28: Raytrace Variables

$$h' = h + (\alpha'^2 - \alpha^2)/(0.002\ dMdh_i). \qquad (137)$$

Case 3: α' known.

$$r' = r + (\alpha' - \alpha)/dMdh_i \ , \qquad (138)$$

$$h' = h + (\alpha'^2 - \alpha^2)/(0.002\ dMdh_i) \ . \qquad (139)$$

If the radicand of equation 134 is negative there is no solution for the given height h' since the ray has reached a maximum (or,

in the case of a downgoing ray, a minimum) height less (greater) than h'. In this case the range and height of the ray maximum (minimum) are given by

$$r' = r - \alpha/dMdh_i \ , \tag{140}$$

$$h' = h - \alpha^2/(0.002\ dMdh_i) \ , \tag{141}$$

while $\alpha' = 0$ at this range and height. One unique case not covered by the above equations is the special case $\alpha = 0$. In this case if $dMdh_i > 0$ the ray will become an upgoing ray, if $dMdh_i < 0$ the ray will become a downgoing ray. Equations 134 through 141 can be iteratively used to trace ray paths through the user-specified stratified atmosphere.

One of the user-selected options in RAYS is a display of altitude error. Altitude error is computed as the absolute value of the difference between a ray's height and the height at which a ray with the same elevation angle would be at the same range under standard conditions (i.e., a single gradient of 118 M/km). Superrefractive and trapping gradients usually produce altitude errors such that apparent altitude is greater than the actual altitude.

7.3 Sea Clutter Models

Sea-surface clutter is displayed in EREPS when using PROPR or PROPH graphics option 4. In this graphics option, the radar signal-to-noise level in decibels is plotted versus range or height. The sea clutter level is displayed by superimposing a plot of the ratio of clutter-to-noise power. Either the average clutter power or the average clutter power ± 5 dB, the clutter

power bounds, can be displayed. The clutter-to-noise ratio in decibels is equivalent to $P_c - P_n$, where P_c is the clutter power in dB and P_n is the noise power in dB. The average clutter power in decibels is given by

$$P_c = -123.0 + 10\ LOG_{10}(P_t\ \lambda^2\ r^{-4}\ f(\alpha)^4) + 2\ G_t - L_s + \sigma_c\ , \quad (142)$$

where P_t is the transmitted power in kW, λ is the wavelength in m, r the range in km, L_s is miscellaneous system losses in dB, and σ_c is the average clutter cross section in dB. G_t is the antenna gain in dB and $f(\alpha)$ is the antenna pattern factor associated with the ray launch angle, α, that intercepts the sea surface. The noise power in decibels is

$$P_n = 10\ LOG_{10}(4/(\tau\ 10^{15})) + N_f\ , \quad (143)$$

where N_f is the receiver noise figure in dB and τ is the pulse width in microseconds. In PROPR this clutter-to-noise ratio is a function of range but for PROPH it is a constant.

Sea-surface clutter effects are included in EREPS using a NOSC-modified version of the Georgia Institute of Technology (GIT) model (Horst, 1978). These models differ below 1° grazing angle for low sea states and ducting conditions. The GIT model is thought to be valid to ± 5 dB. The NOSC modifications allow the clutter calculations to be extended beyond the normal horizon under evaporation ducting conditions. The NOSC model provides greater reflectivity than the GIT model for low grazing angle/evaporation ducting conditions. The sometimes dramatic effects of surface-based ducts on the clutter power level are **not** modeled in EREPS.

The GIT model gives the clutter cross-section, in decibels relative to one-square meter, as

$$\sigma_c = \sigma^\circ + A_c \qquad \text{(dBsm)} , \tag{144}$$

where σ° is the average clutter cross section per unit area (dB) and A_c is the area of the radar resolution cell (dB). σ° is a polarization dependent variable, for a horizontally polarized radar

$$\sigma^\circ_H = 10 \, LOG_{10}(.0000039 \, \lambda \, \psi^{0.4} \, A_i \, A_u \, A_w) \qquad \text{(dB)} , \tag{145}$$

and for a vertically polarized radar

$$\sigma^\circ_V = \sigma^\circ_H - 1.05 \, LOG_e(h_{avg} + 0.02) + 1.09 \, LOG_e(\lambda) + 1.27 \, LOG_e(\psi + 10^{-4}) + 9.70 \qquad f \geq 3000 , \tag{146}$$

or

$$\sigma^\circ_V = \sigma^\circ_H - 1.73 \, LOG_e(h_{avg} + 0.02) + 3.76 \, LOG_e(\lambda) + 2.46 \, LOG_e(\psi + 10^{-4}) + 22.2 \qquad f < 3000 , \tag{147}$$

where ψ is the grazing angle, (see figure 24), h_{avg} is the average wave height in meters and λ is the wavelength. σ°_C for a circularly polarized system is calculated following a suggestion by Nathanson (1969)

$$\sigma^\circ_C = \sigma^\circ_{max} - 6 \ , \qquad (148)$$

where σ°_{max} is the larger of σ°_H or σ°_V as calculated above. A_i is the interference factor, A_u is the upwind/downwind factor and A_w is the wind speed factor. Equation 142 is applicable for grazing angles between 0.1° and 10°.

The dependence of σ° on sea state is more strongly a function of wind speed than wave height. However in EREPS, the wave height is assumed to be only a function of wind speed (a "fully arisen" sea). The average wave height is given by

$$h_{avg} = (W_s/8.67)^{2.5} , \qquad (149)$$

where W_s is the wind speed in m/sec. The wind speed factor, A_w, is determined using

$$A_w = [(1.9425\ W_s)/(1 + W_s/15)]^{1.1(\lambda + 0.02)^{-0.4}} . \qquad (150)$$

The interference term, A_i, is defined as

$$A_i = \sigma_\phi{}^4/(1.0 + \sigma_\phi{}^4) \ , \qquad (151)$$

where σ_ϕ is a roughness parameter given by

$$\sigma_\phi = (14.4\ \lambda + 5.5)(\psi\ h_{avg})/\lambda . \qquad (152)$$

The upwind/downwind factor, A_u, is determined using

$$A_u = EXP[0.2\ COS(\phi)\ (1 - 2.8\ \psi)(\lambda + 0.02)^{-0.4}]\ , \qquad (153)$$

where ϕ is the angle between the radar antenna boresight and the upwind direction (0° to 180°). The area of the radar clutter resolution cell, A_c, is calculated using

$$A_c = 10\ LOG_{10}[(1000\ r\ \theta_H\ c\ \tau_c)/(4\ LOG_e(2))]\ , \qquad (154)$$

where r is the range in km, c the speed of light in m/sec, τ_c the radar system compressed pulse width in sec, and θ_H is the radar antenna horizontal beamwidth in radians.

For frequencies below 2 GHz the GIT model is used without alteration for grazing angles in the range 0.1° to 10°. The maximum range where equation 144 is applicable is determined using

$$R_{lim} = 0.5(-2\ \psi\ a_e + ((2\ a_e\ \psi)^2 + .008\ H_t\ a_e)^{1/2})\ , \qquad (155)$$

where the grazing angle ψ = .001745 radians (0.1°). The grazing angle for any range less than R_{lim} is determined by

$$\psi = H_t/(1000\ r) - r/(2\ a_e) \qquad \text{(radians)}\ , \qquad (156)$$

for all $\psi \leq 10°$. The launch angle α associated with each of these values of ψ is given by equation 23 with the H_r term equal to zero.

At radar frequencies of 2 GHz and greater, the maximum range analogous to equation 155 is determined using a raytrace for the evaporation duct profile. The limiting ray for this case is the ray launched at the transmitter height that intersects the surface at the farthest possible range. This ray has a launch angle equal to

$$\alpha = 10^{-3}(2(M_{Ht} - M_{min}))^{1/2} - 10^{-6} \qquad H_t < \delta \quad \text{(radians)}, \quad (157)$$

$$\alpha = -10^{-3}(2(M_{Ht} - M_{min}))^{1/2} - 10^{-6} \qquad H_t \geq \delta \quad \text{(radians)}, \quad (158)$$

where M_{Ht} is the M-unit value at H_t and M_{min} is the minimum value on the evaporation duct height profile (which occurs at the duct height, δ). The M-value at any height z for an evaportion duct is calculated using

$$M(z) = M_s + (z/8) - (\delta/8)\ LOG_e((z + .00015)/.00015), \quad (159)$$

where M_s is equal to the M-unit value at the surface and δ is the evaporation duct height. Thus M_{min} is determined using equation 159 with $z = \delta$. The evaporation duct profile used in the raytrace is determined using equation 159 for heights z = 0.135, 0.368, 1.0, 2.7, 7.4, 20.1 and 54.6 meters as well as $z = \delta$ and $z = H_t$ for $H_t < 54.6$. If $H_t > 54.6$ a standard atmospheric gradient of 118 M/km is added to the M-unit value at 54.6 meters. This piecewise-continuous profile of M versus height is used to trace

rays to determine range for all ranges less than R_{lim} such that $\psi \leq 10°$. The grazing angle associated with α is determined using

$$\psi = (\alpha^2 - 2(M_{Ht} - M_s)10^{-6})^{1/2} , \qquad (160)$$

for all ranges less than R_{lim}.

The clutter level for ranges beyond R_{lim} is determined using the average clutter cross section, $\sigma°$, at R_{lim}. The reflectivity at this limiting grazing angle is modified using the evaporation duct attenuation rate from equation 97. That is

$$\sigma° = \sigma°_{lim} - 2\beta r \qquad r > r_{lim} , \qquad (161)$$

where $\sigma°_{lim}$ denotes the value of $\sigma°$ at the limiting grazing angle associated with R_{lim} determined from equation 156 or 160.

7.4 Radar Models

PROPR, PROPH and COVER all contain the ability to convert radar system parameters such as frequency, pulse length, etc., to free-space range for further use within the program. The models to do this conversion are taken from Blake (1980). Three types of radar calculations are allowed by the program "simple", "integration", and "visibility factor." A "simple" type calculation is normally used for a rotating, pulsed radar that uses noncoherent pulse integration to increase its sensitivity. The signal-to-noise ratio required for a given probability of detection and false alarm rate is known as either the visibility factor or the detectability factor, D_o. For a simple radar with a uniform-weight integrator and a square-law detector D_o is

$$D_o = [X_o/(4\ N_p)]\{1 + [1 + (16\ N_p/X_o)]^{1/2}\}L_f \ , \qquad (162)$$

where

$$X_o = (g_{fa} + g_d)^2 \ , \qquad (163)$$

$$g_{fa} = 2.36[-LOG_{10}(P_{fa})]^2 \ , \qquad (164)$$

$$g_d = 1.23\ t(1 - t^2)^{1/2} \ , \qquad (165)$$

$$t = 0.9(2\ P_d - 1) \ . \qquad (166)$$

Here N_p is the number of pulses integrated by the detector (hits per scan), L_f is the fluctuation loss, P_d is the probability of detection, and P_{fa} is the probability of false alarms. For the simple radar

$$N_p = (\theta_H\ f_p)/(6\ \phi_h) \qquad N_p \geq 1.0 \ , \qquad (167)$$

where θ_H is the horizontal beam width in degrees, f_p is the pulse repetition frequency in Hz, and ϕ_h is the horizontal scan rate in rpm. The fluctuation loss, L_f, is 1 for a Swerling Case 0, non-fluctuating target. If a fluctuating target is selected L_f is calculated for a Swerling Case 1, kF = 1, chi-square target

$$L_f = [-LOG_e(P_d)\ (1 + g_d/g_{fa})]^{-1} . \qquad (168)$$

While equation 162 assumed a square-law detector, the difference between square-law detectors and the more commonly used linear detectors is generally less than 1 dB. D_o for the "integration" type radar where coherent integration is used

$$D_o = [X_o/(4N_p)] \{1 + [1 + (16/X_o)]^{1/2}\} L_f , \qquad (169)$$

where all quantities have been previously defined. If the radar calculation type is set to "visibility factor", then the user must supply the value of visibility factor to be used in place of equation 162. This option may be the most useful to users dealing with modern sophisticated radar systems that use complicated signal processing schemes.

Blake's (1980) equation 1.34 is used to calculate the radar free-space detection range. The bandwidth correction factor, C_b, of equation 1.34 was arbitrarily set to 1, and the system noise temperature set to 290° K. With some algebra this equation becomes

$$R_{fs} = 58.0 [(P_t \sigma \tau Z)/f^2]^{1/4} \quad \text{(km)} , \qquad (170)$$

where P_t is the transmitter power in kW, σ is the target cross-section in square meters, τ is the pulse width in μs, f is the EM system's frequency in MHz, and Z is a function of several radar parameters. Z is given by

$$Z = 10^{[2G - N_f - D_o - L_s]/10} , \qquad (171)$$

where G is the antenna gain in dB, N_f is the receiver noise figure in dB, D_o is previously defined, and L_s is the miscellaneous system losses in dB. All losses not specifically mentioned above must be accounted for in the system losses, such as transmission line loss, filter mismatch loss, signal processing loss, beam-shape loss, etc. The free-space range threshold for PROPH or PROPR can be obtained by subsituting the range from equation 170 into equation 12 of section 7.1.

The radar target signal-to-noise ratio is derived from target signal power calculated from Blake's equation 1.18. The signal-to-noise ratio is equal to the target power received divided by the sytem noise power, which in dB is

$$S/N = P_r - P_n \ , \qquad (172)$$

where P_r is the received target power in dBW and P_n is the system noise power in dBW. The noise power is a function of the pulse width and the receiver noise figure given by equation 143. The received target power in dBW is

$$P_r = -73.4 + 10\ LOG_{10}[(P_t\ \sigma\ F^4)/(f^2\ r^4\ L_f)] + 2G - L_s, \qquad (173)$$

where r is the range in km, F is the pattern propagation factor, and all other terms are as previously defined. The calculation of F is discussed in section 7.1.

7.5 ESM Models

The propagation threshold for ESM systems is calculated as the decibel difference between the effective radiated power

and the ESM receiver sensitivity, as adjusted by appropriate system losses. For peak power P in kW, transmitter antenna gain G in dBi, ESM system sensitivity S in dBm, and system losses L_s in dB, the propagation threshold T in dB, is calculated as

$$T = 10LOG_{10}(P) + 60 + G - S - L_s. \quad (174)$$

For example, if P = 100 kW, G = 30 dBi, S = -80 dBm, and L_s = 5 dB, then T = 185 dB. Normally, ESM system sensitivity includes receiving antenna gain and line losses. Thus L_s would be used to account for the emitter's transmission line losses and other losses associated with the transmitter. Under PROPR display option 2, the threshold loss T is plotted on the propagation-loss display as a dashed line. Propagation losses less than the threshold correspond to intercept capability.

The same display option and system parameters may be used to assess communications systems. The only difference is that system sensitivity should be adjusted to account for the signal-to-noise ratio margin associated with a given level of communications quality.

7.6 Implementations of the Models

7.6.1 PROPR

The purpose of PROPR is to present propagation loss (or other quantities already described) versus range, showing sufficient detail to clearly define the structure of optical region lobes and other relevant propagation mechanisms. The program begins by determining the maximum range from the transmitter to the reflection point r1 such that optical region calculations are valid. Computations for each lobe in the

optical region are performed to find the next smaller r_1 corresponding to a null using a Newton-method iteration. The r_1 interval between either the last null or the starting point and the next null is divided linearly into 8 points at which the propagation loss and corresponding total range are computed and plotted. The vectors connecting these loss and range points have been found to give sufficient resolution to the optical region without requiring excess computation. After the optical region computations are completed, the minimum valid range for diffraction models r_d is found. Linear interpolation of the propagation factor in dB is used between the last point in the optical region and the first point in the diffraction region. For ranges at and beyond r_d, the applicable diffraction, ducting, and/or troposcatter models are used. For all ranges beyond the optical limit, surface-based duct loss is computed (for duct heights greater than zero) and is used when it is less than the loss from the other models. At all ranges within PROPR, water-vapor attenuation loss is computed and added to the other losses. Of particular note in PROPR is the use of rl as the independent variable in the optical region, as already described, and the use of total range r for all other regions. At ranges beyond the optical limit, a range increment of 1/100th the total plotted range is used.

7.6.2 PROPH

PROPH generates a plot of loss versus receiver height at a fixed range. The first step is to determine the receiver height at the optical limit, in a similar manner as described for PROPR. Computations for each lobe in the optical region are made to determine the next higher receiver height corresponding to a null using a Newton-method iteration. The height interval between successive nulls is split into multiple segments for which loss is computed and plotted. For each height below the optical limit, a check is made to determine if the fixed range exceeds

the minimum valid range for diffraction. If it is, the appropriate diffraction, ducting, and/or troposcatter model is used. Otherwise, linear interpolation is used on the propagation factor in dB between the optical-limit maximum range and the diffraction-region minimum range at the current receiver height. As with PROPR, at heights below the optical limit, the lesser loss from the surface-based duct model (for non-zero duct heights) and the other models is used. At all heights, the water-vapor attenuation is added to the loss. Note that in PROPH the independent variable is receiver height for all calculations, with the increment being set to 1/300th of the maximum plotted height in the optical region, 1/10th of the height between the optical and diffraction limits in the interpolation region, and the greater of 2 meters or 1/300th of the maximum plotted height otherwise.

7.6.3 COVER

The purpose of COVER is to generate an altitude-versus-range contour that defines an area within which propagation loss will always be less than a specified value. In the optical region, an assumption has been made that the ray path between the transmitter and receiver is parallel to the ray path from the reflection point to the receiver. This assumption is quite good at long ranges, but can be in substantial error at short ranges and low receiver altitudes. However, it results in the propagation factor being a constant for any elevation angle, which in turn permits fast and easy computation of the maximum range at that angle. When applying COVER to short ranges and low receiver heights, it is a good idea to check the results with PROPR. If there is a substantial difference in results, PROPR is the model to use.

The COVER algorithm begins by determining the elevation angle at the optical limit. In the optical region, a Newton-method iteration is used to find the next higher elevation angle corresponding to a predetermined phase angle between the direct and reflected paths. Fourteen such phase angles are used per lobe to give good definition to the shape of the lobes. After the required lobes have been completed, an "envelope" contour of the ranges at the maximum of all higher-angle lobes is drawn up to an angle that depends on the antenna pattern and beamwidth selected. For heights and ranges below the optical limit, the independent variable is receiver height. For ducting conditions, a sufficiently small height increment is used to give good definition to the vertical height-gain factors. Otherwise a height increment of 1/20th of the total plot height is used. All contours created by each lobe, the envelope region, and the over-the-horizon region are filled with a single shade and color. Water-vapor absorption is included in the optical region through an iterative solution of maximum range, and in the beyond-horizon region through addition of the absorption loss to the diffraction or ducting losses. Troposcatter effects are not considered in COVER, since they will almost always be at such high values as to not affect the coverage diagram.

7.6.4 RAYS

The purpose of RAYS is to calculate and plot a series of ray-path trajectories on a height-versus-range display. The user specifies the refractive-index profile, the transmitter height, the elevation angle limits, and number of rays desired. Each ray is traced based on a series of calculations that are performed within each linear-refractivity layer specified in the profile. To give the best compromise of speed and resolution, the independent variable in the raytrace is elevation angle along the ray. At each step, this angle is incremented and a new height and range are found within the current layer. If the ray leaves

the current layer, then the range is calculated at the layer boundary, and the elevation angle is incremented in the layer above or below. As each layer is entered, the refractivity gradient must be examined to determine if the elevation angle in that layer will be increasing or decreasing. Tests must be included to determine where rays will reach a maximum or minimum height, to ensure that the corresponding elevation angle of zero is considered. For the last step only, a height is calculated at the maximum range within the current layer.

For the altitude-error option, a second raytrace for a standard atmosphere is computed at each point along the ray, such that the altitude difference between the actual and standard ray paths can be determined. The color of each ray segment is then determined based on the height difference and a user-defined scale.

7.6.5 FFACTR

The purpose of FFACTR is to return a single value of the propagation factor in dB for a series of specified system, geometry, and environmental parameters. The first step is to calculate the optical limit range. If the specified range is less than the optical limit, a solution to the cubic equation to determine the reflection point in the optical region is performed along with all other optical region calculations to determine the propagation factor. If the specified range is greater than the optical limit, the minimum range for valid diffraction calculations is determined. If the specified range is between these two limits, linear interpolation of the propagation factor in dB versus range is performed to compute the desired result. For ranges beyond the minimum diffraction range, the appropriate diffraction, ducting, and/or troposcatter model is used. For all ranges beyond the optical limit, the lesser loss of the surface-based duct model (for non-zero duct heights) and the other

applicable models is used. At all ranges, the loss from water vapor absorption is added.

8.0 Application Example

This application example is included to illustrate how PROPR and SDS may be used together to assess statistical propagation performance. The example is based on a propagation experiment performed between the Greek Islands of Naxos and Mykonos in 1972 and reported on by Richter and Hitney (1988). On Naxos, transmitters at 1.0 GHz (L band), 3.0 GHz (S band), and 9.6 GHz (X band) were located at 4.8 m above mean sea level (msl). Also a transmitter at 18.0 GHz (Ku band) was located at 4.5 m above msl. Three receiving antennas were positioned at Mykonos for each frequency, at 19.2 m above msl for L, S, and X bands and at 17.8 m above msl for Ku band. The range separation was 35.2 km, corresponding to a somewhat over-the-horizon propagation path. Horizontal polarization was used at all four frequencies. Propagation loss was measured for four three-week periods in February, April, August, and November, except for Ku band which was measured only during August and November. All data were averaged over a 5 minute period and recorded every 15 minutes, 24 hours per day.

The first step in using EREPS to assess propagation effects is to obtain the climatology for the Greek Islands area, illustrated by figure 29. The evaporation duct height distribution shown indicates that evaporation ducting effects are quite strong.

The next step in this example is to use PROPR to investigate the sensitivity of propagation loss to environmental parameters. At X band for example, figure 30 indicates a propagation loss of 173 dB for the geometries of the Greek Islands experiment under standard atmospheric conditions.

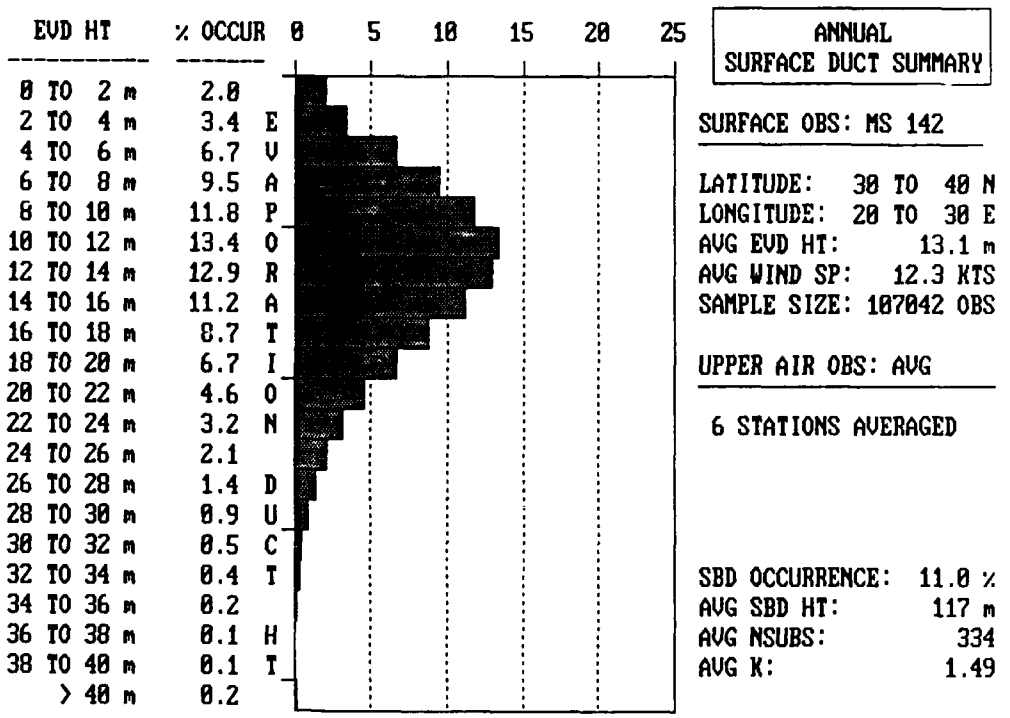


Figure 29: SDS summary for Marsden square 142.

Note that while the XHAIR mode may be readily used to read the propagation loss values from the display, one user may read values that are slightly different than another due to display resolution. In any case, readings should be accurate to about 0.5 dB, which is better than the probable overall accuracy of the models. By using other EREPS programs or by varying one parameter at a time and using the overlay feature of PROPR, you can easily simulate various conditions and see the effects on

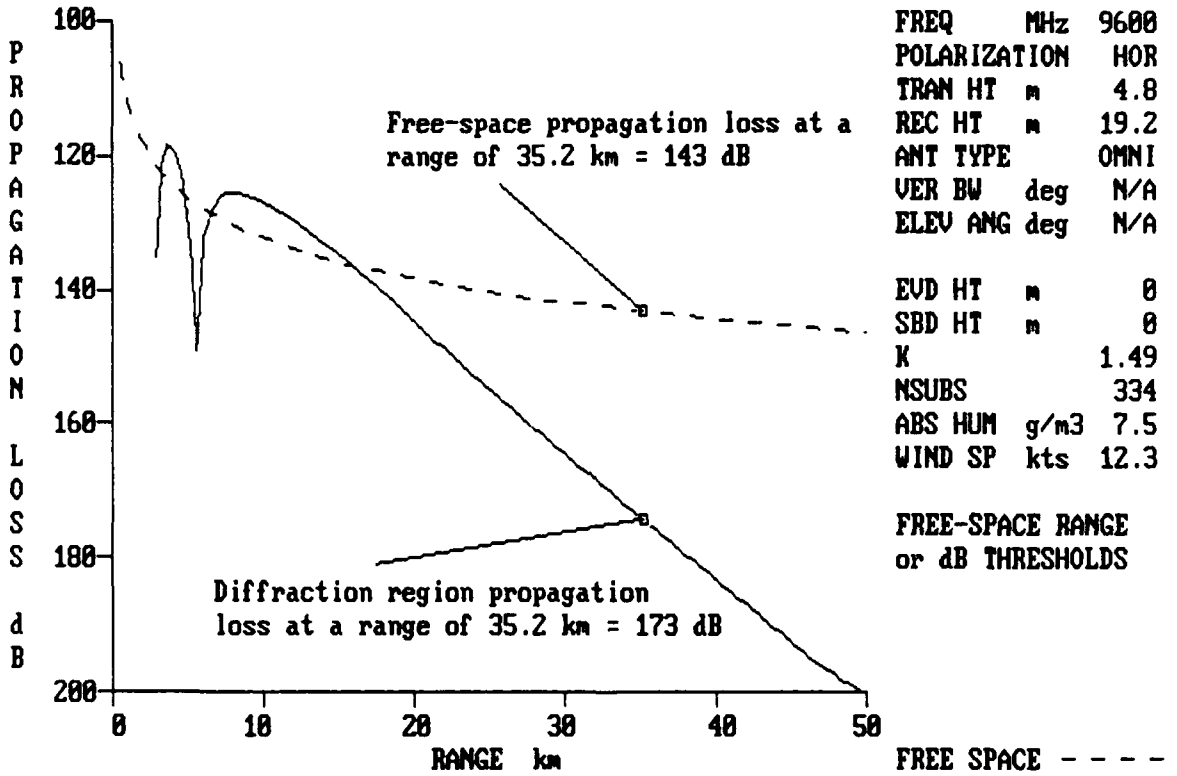


Figure 30: PROPR display for X band frequency and geometries in the Greek Island experiment within a non-ducting environment.

propagation loss over the given path. For example, figure 31 shows a RAYS product for a 117 m thick surface-based duct. For a receiver of 19.2 m, the skip zone from 25 to 68 km is quite evident, with the receiver located well within the skip zone. Therefore, one can conclude that surface-based ducts are not likely to affect the propagation loss in this case, even though such ducts will occur about 11 percent of the time (figure 29) in the Greek Islands area . On the other hand, varying the evaporation duct height through the range of expected values

(figure 32), shows that propagation loss will vary substantially. This is particularly true for the higher frequencies.

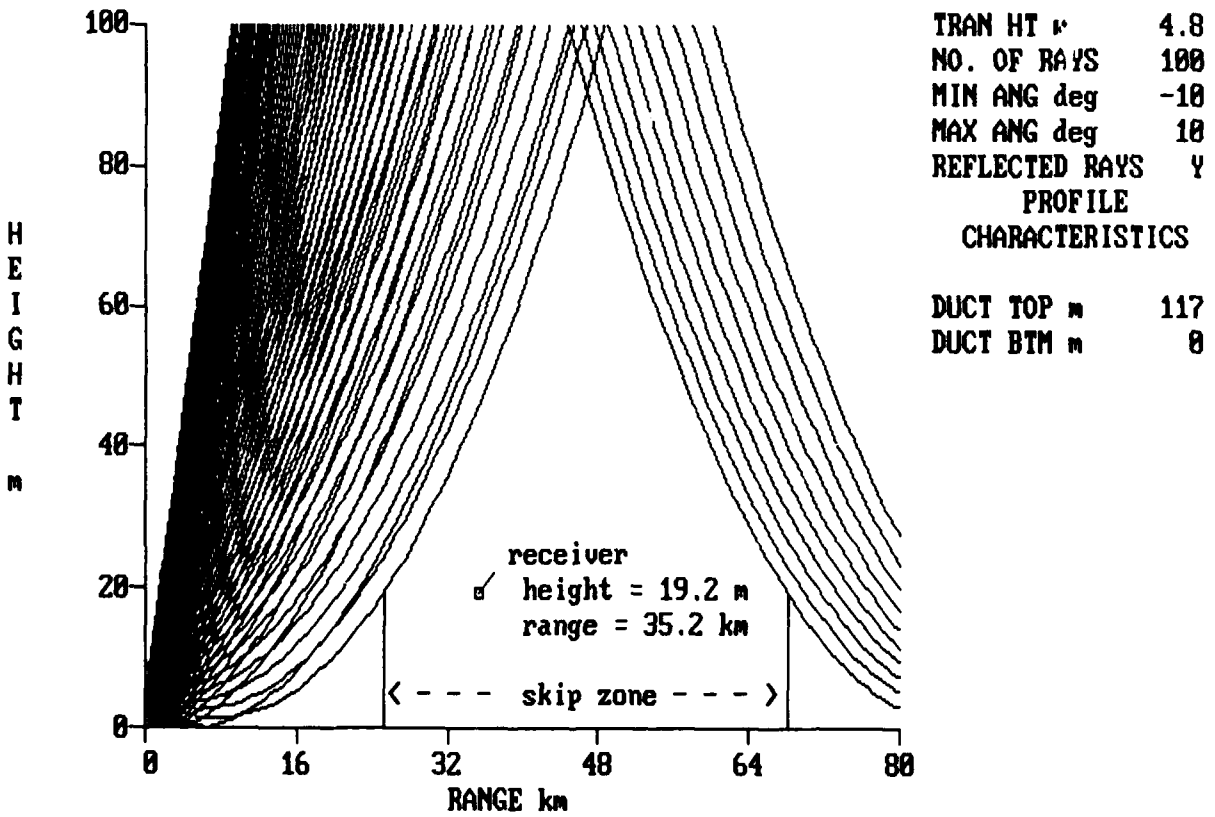


Figure 31: RAYS display for the frequency and geometries in the Greek Island experiment under surface-based ducting conditions.

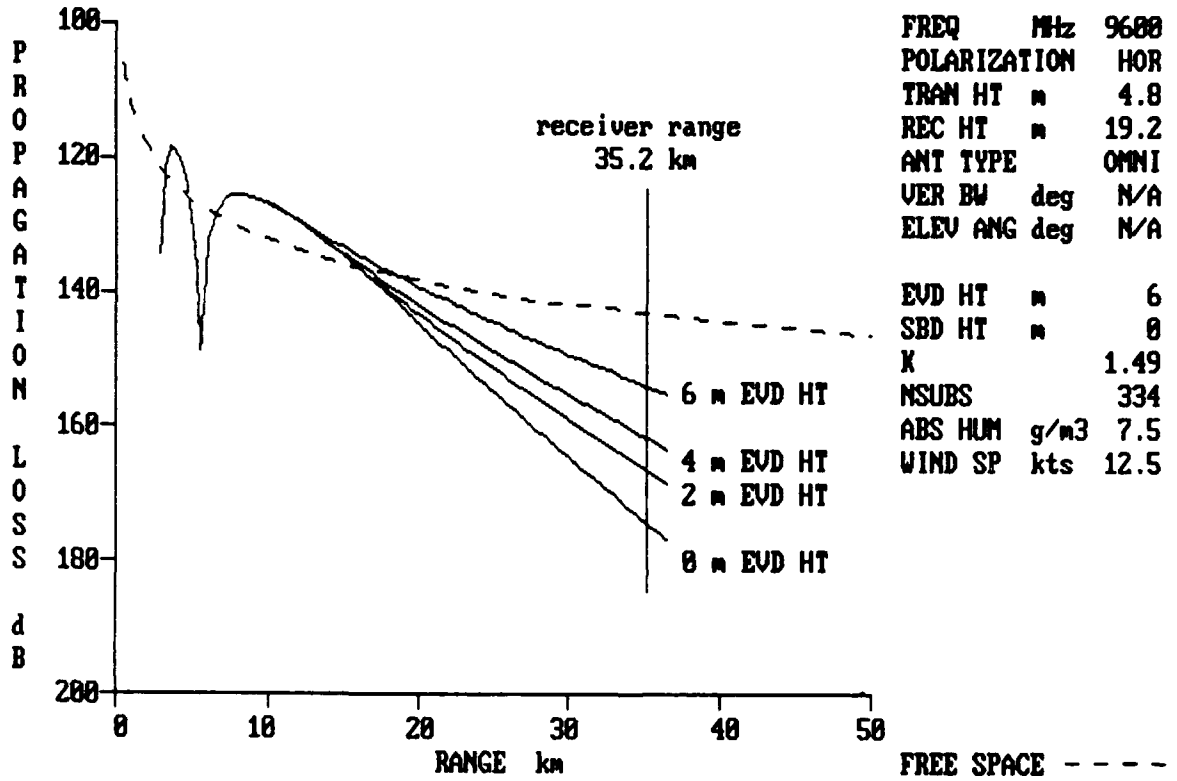


Figure 32: PROPR display for the frequency and geometries of the Greek Island experiment under multiple evaporation ducting environments.

Table 2 shows the propagation loss from PROPR-versus-evaporation duct height for the four frequencies and corresponding geometries with a * indicating duct heights beyond those recommended in section 6.0 for use in PROPR.

Table 2: Propagation loss values from PROPR-versus-evaporation duct height for the Greek Islands experiment frequency bands and geometries described. A * indicates duct heights beyond those recommended for use in PROPR.

EVD HT m	L	S	X	Ku
0	152.9	161.7	172.9	181.9
2	152.5	161.6	166.1	168.1
4	152.3	160.5	161.8	157.3
6	151.9	158.9	154.0	146.0
8	151.4	157.4	146.8	145.1
10	151.0	155.3	139.7	155.8
12	150.7	152.2	140.2	166.1*
14	150.4	148.4	143.5	172.6*
16	150.1	145.1	148.3*	172.6*
18	149.9	142.3	152.0*	172.6*
20	149.2	139.4	154.7*	172.6*
22	147.8	136.4	155.8*	172.6*
24	147.1	135.1	153.3*	172.6*
26	145.4	133.9	153.3*	172.6*
28	144.4	133.7	153.3*	172.6*
30	143.8	134.2	153.3*	172.6*
32	142.7	135.8*	153.3*	172.6*
34	141.2	137.0*	153.3*	172.6*
36	140.0	138.1*	153.3*	172.6*
38	139.0	139.1*	153.3*	172.6*
40	137.6	140.2*	153.3*	172.6*

Comparing the duct heights from table 2 with the duct height distribution of figure 29 indicates that EREPS can yield statistical assessments of propagation loss at L and S bands, but will be questionable at X and Ku bands. The most useful

statistical presentation is often the accumulated frequency distribution of propagation loss, which can be quite easily determined from figure 29 and table 2. For example, at L band, propagation loss will always exceed 130 dB. Propagation loss greater than 140 dB occurs for duct heights less than 36 m, which from figure 29 is 99.6 percent. Propagation loss greater than 150 dB corresponds to duct heights less than 17 m, or 75.2 percent. The accumulated frequency distributions thus determined are presented in table 3 for all four frequency bands. Also shown are the observed distributions as given by Richter and Hitney (1988).

Table 3: Percent of time propagation loss is exceeded for the Greek Islands experiment as calculated by EREPS from annual duct height distributions and as observed for all seasons measured at each frequency band. Geometries as stated in text.

Loss	L		S		X		Ku	
dB	EREPS	OBS	EREPS	OBS	EREPS	OBS	EREPS	OBS
120	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
130	100.0	95.8	100.0	80.6	100.0	94.3	100.0	100.0
140	99.6	89.5	84.6	65.3	83.6	74.1	100.0	98.9
150	75.2	64.5	40.1	39.3	41.6	38.5	81.3	70.5
160	0.0	9.5	8.8	3.9	7.1	4.7	64.5	27.3
170	0.0	0.0	0.0	0.0	1.0	0.9	48.8	7.1
180	0.0	0.0	0.0	0.0	0.0	0.0	0.5	0.8
190	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1

Examination of table 3 shows that L, S, and X band calculations are in reasonably good agreement with the observations, but Ku band calculations indicate substantially higher propagation loss values than were observed. This

disagreement is due to the frequent occurrence of duct heights in Marsden Square 142 that are beyond the recommended limits of EREPS at Ku band. Note that X band agrees quite well in spite of some duct heights occurring beyond the recommended limit. For applications in other areas where duct heights are predominantly low, such as in the North Atlantic Ocean, the EREPS assessments would prove to be good even at the highest frequencies.

There is a substantial reduction in propagation loss attributable to the evaporation duct when compared to diffraction levels without an evaporation duct. For example, figure 30 shows that at X band the diffraction propagation loss is 173 dB and the free-space propagation loss is 143 dB. Interpolation of table 3 shows the propagation loss exceeded 50 percent of the time is 148 dB. Thus, the evaporation duct has resulted in a signal strength improvement of 25 dB over diffraction with the median observed (or calculated) propagation loss much closer to free space than to diffraction.

You should note that similar methods as those used in this example may be applied to maximum detection, communication, or ESM ranges. You would employ PROPR to determine maximum range versus duct height and then use the duct height distributions from SDS to compute distributions of maximum range. In addition, PROPR or PROPH could be used to estimate frequency distributions of propagation factor, or signal-to-noise ratio over a particular path.

9.0 Glossary

The following is a glossary of all equation symbols used within the document. When appropriate, FFACTR source code variable names are enclosed within brackets, i.e., [].

α - direct ray launch angle in radians. (see figure 24). Also used as attenuation rate in NOSC evaporation duct model. [alpha]

a - earth radius (6371) in kilometers.

a_e - effective earth radius (k x a) in kilometers. [ae]

A - a constant within the antenna pattern factor calculation.

A_c - area of radar resolution cell in dB.

A_e - antenna effective aperture.

A_w - wind speed factor within the clutter model.

β - reflected ray launch angle in radians. (see figure 24). [beta] Also used as scaled attenuation rate in NOSC evaporation duct model.

BW - transmitting antenna's beamwidth in radians. [bwidth = degrees; antbwr = radians]

c - speed of light (3×10^8 m/sec). Also used as a constant in the antenna pattern factor.

Δ - scaled evaporation duct height in meters. [del]

dMdh - modified refractivity gradient in M per km.

D - divergence factor. [divfac] Also surface-based duct height in meters.

D_o - visibility factor within the radar model.

δ - path-length difference between direct and sea reflected rays in radians. Also used as evaporation duct height in meters. [delta]

ϵ - ordinary dielectric constant of sea water. [eps]

ϵ_i - internal angles as seen in figure 24.>

e - ambient water vapor pressure in millibars.

E - electric field strength at a point.

E_o - electric field strength under free-space conditions.

F - propagation factor. [ff]

F_{zr} - receiver height-gain function within the NOSC evaporation duct model. [fzr]

F_{zt} - transmitter height-gain function within the NOSC evaporation duct model. [fzt]

f - transmitter's frequency in Megahertz or Gigahertz. [freq]

f_p - pulse repetition frequency in Hertz.

γ - angle shown in figure 24. [gamma]

Γ - excitation factor within the NOSC evaporation duct model. [tlm]

G - antenna gain in dB.

h_o - effective scattering height within the troposcatter model. [hsub0]

H - scale factor for natural units of height in standard diffraction model. [fqterm]

H_a - absolute humidity in grams per cubic meter. [humid]

H_o - frequency gain function within the troposcatter model. [h0]

H_r - height of receiver/target in meters. [hr]

H_t - height of transmitter antenna in meters. [ht]

h - root-mean-squared wave height in meters. [hbar]

k - effective earth radius factor. [rk]

λ - wavelength in meters

L - propagation loss in dB.

L_d - diffraction field antenna pattern loss, a measure of how much energy is radiated toward the horizon. [exloss]

L_f - radar target fluctuation loss in dB.

L_{fs} - free-space path loss in dB.

L_s - miscellaneous system losses in dB.

M - modified refractivity.

N - refractivity

N_f - receiver noise factor in dB.

N_p - number of pulses integrated within the radar model.

N_s - surface refractivity value. [nsubs]

μ - an arbitrary angle.

n - complex index of refraction.

ψ - grazing angle in radians. (see figure 24). [psi]

ψ_{lim} - grazing angle limit in radians, Reed (1966). [psilim]

Φ - reflection coefficient phase shift where subscripts C, H, and V stand for circular, horizontal, and vertical antenna polarization. [phi]

ϕ - angle betweena the radar antenna boresight and the upwind direction in degrees.

ϕ_h - antenna horizontal scan rate in revolution-per-minute.

P - a constant within the antenna pattern factor calculation.

P_a - power density in Watts per square meter.

P_c - clutter power in dB.

P_d - probability of detection in percent.

P_n - noise power in dB.

P_t - power transmitted in Watts.

P_r - power received in Watts.

ρ - a scaled range within the evaporation duct loss.

r - ground range in kilometers (see figure 24). [r]

r_1 - range from transmitter to reflection point in kilometers. (see figure 24). [r1]

r_2 - range from reflection point to receiver/target in kilometers. (see figure 24). [r2]

r_d - range to start of diffraction field in kilometers [rsubd]

r_{hor} - horizon range in kilometers. [horizn]

R - reflection coefficient magnitude where subscripts o, C, H, and V stand for smooth surface, circular, horizontal, and vertical polarization. [rmag]

R_N - scale factor for range in the NOSC evaporation duct model. [rfac]

R_s - scale factor for natural units of range in standard diffraction model. [fterm]

RH - relative humidity in percent.

R_{fs} - radar free-space range in kilometers.

σ - conductivity of sea water. [sigma] Also target radar cross section in square meters.

σ^0 - average clutter cross section per unit area in dB.

σ_ϕ - surface roughness parameter within the clutter model.

θ - total path-length difference, in radians, between the direct and sea-reflected rays including the phase lag due to reflection. [theta] Also used as a scattering angle, in radians, within the troposcatter model.

θ_H - horizontal beamwidth in radians.

S/N - signal-to-noise ratio in dB.

τ - pulse width in microseconds. Also the compressed pulse width in seconds.

T - temperature in degrees Kelvin. Also used as a threshold level in the ESM models.

U - height-gain functions in dB. [fzt or fzr for evaporation duct transmitter and receiver respectively. fofz for surface-based duct]

V - attenuation factor in dB. [tlvx]

W - antenna pattern normalization factor.

W_s - surface wind velocity in meters per second. [wind]

x - a constant within the antenna pattern factor.

z - an arbitrary height in meters.

Z_N - scale factor for height within the NOSC evaporation duct model. [zfac]

10.0 References

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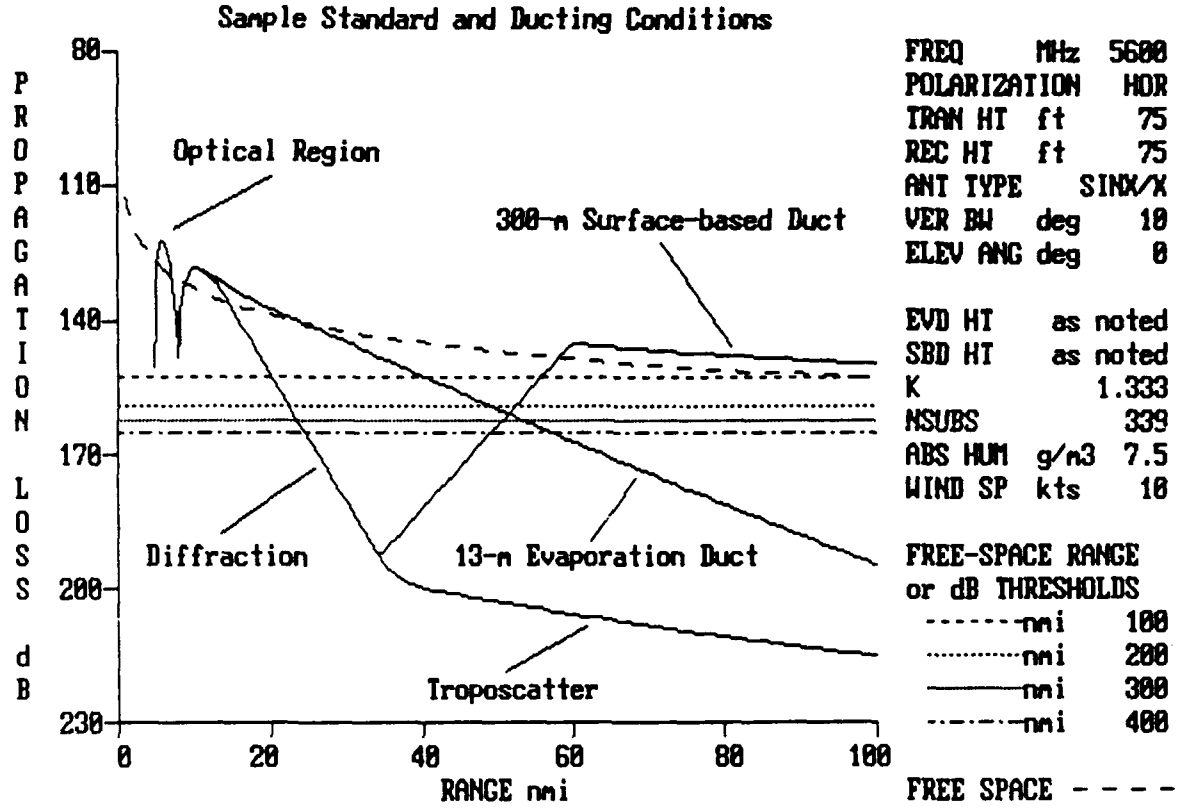
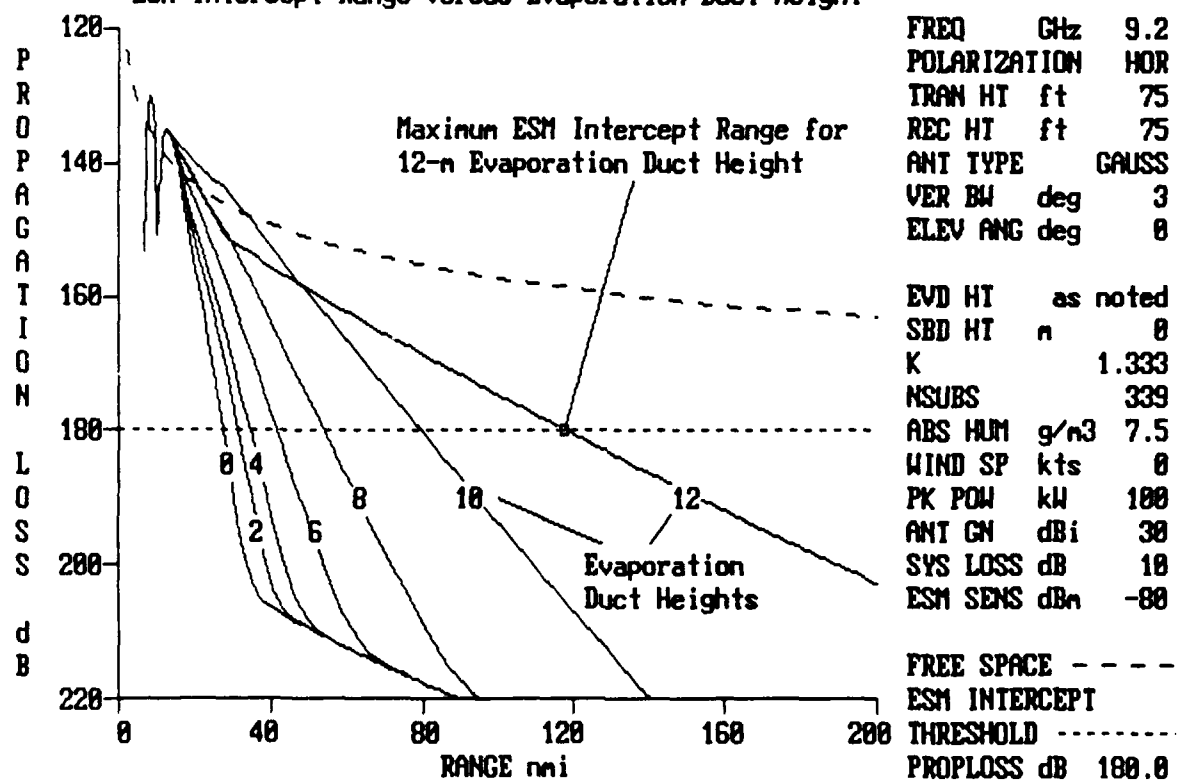
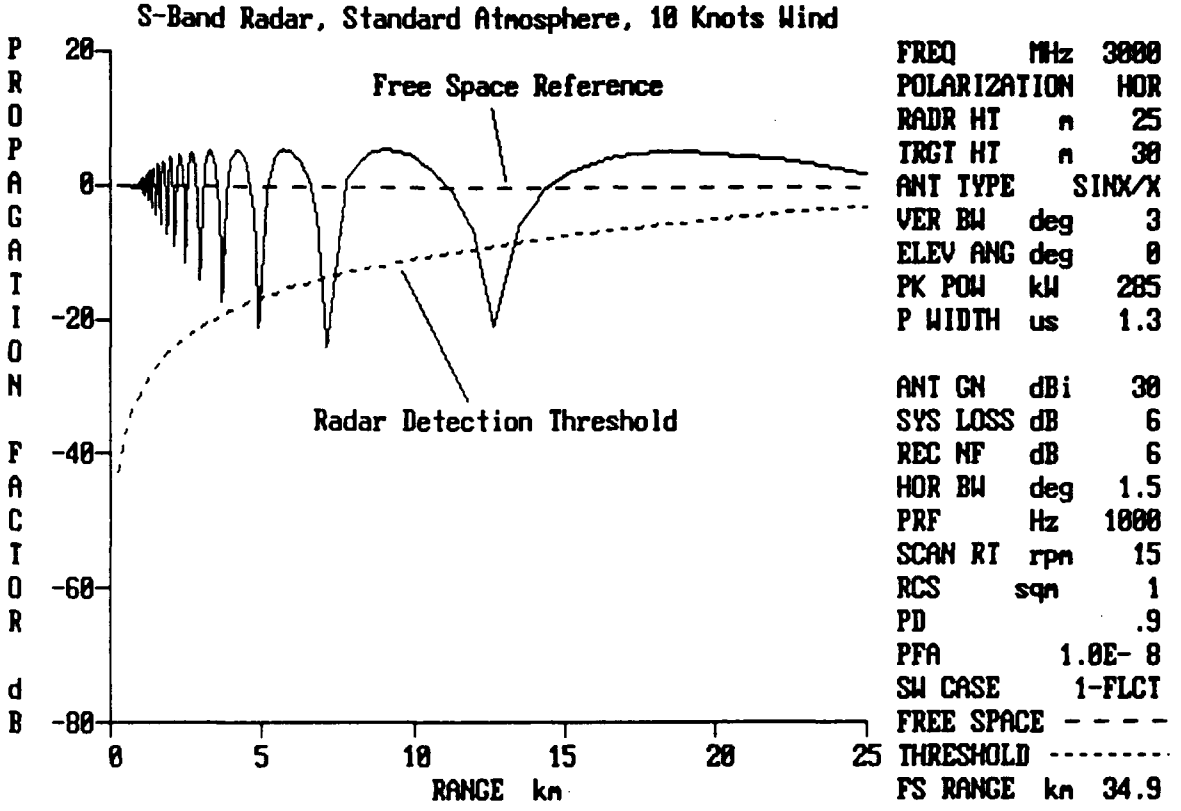
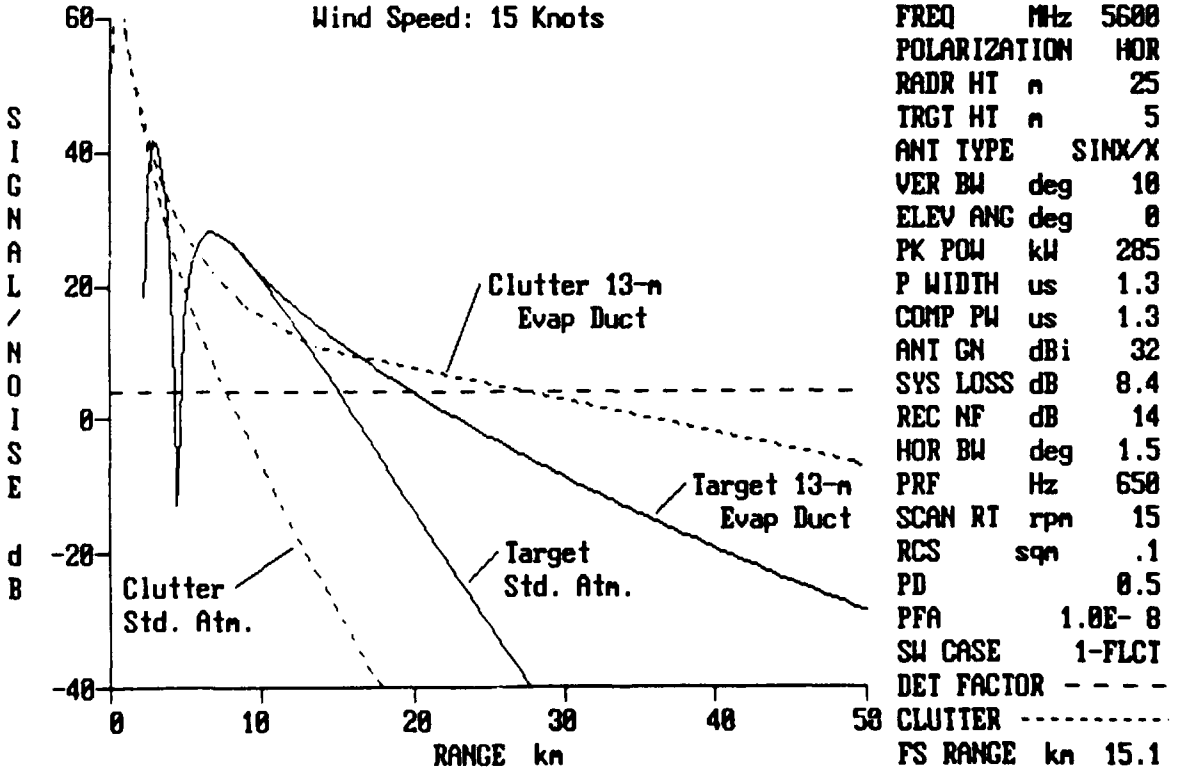
Appendix A

The following EREPS products fro PROPR, PROPH, COVER, RAYS, and SDS illustrate a variety of features available from each program. Each sample was generated with an EGA-equipped computer and a LaserJet Series II printer with 1 Megabyte of additional memory using the GRAFLASR program supplied with GRAFPLUS from Jewell Technologies, Inc. This combination of hardware and software yields a resolution of 300 dots per inch.

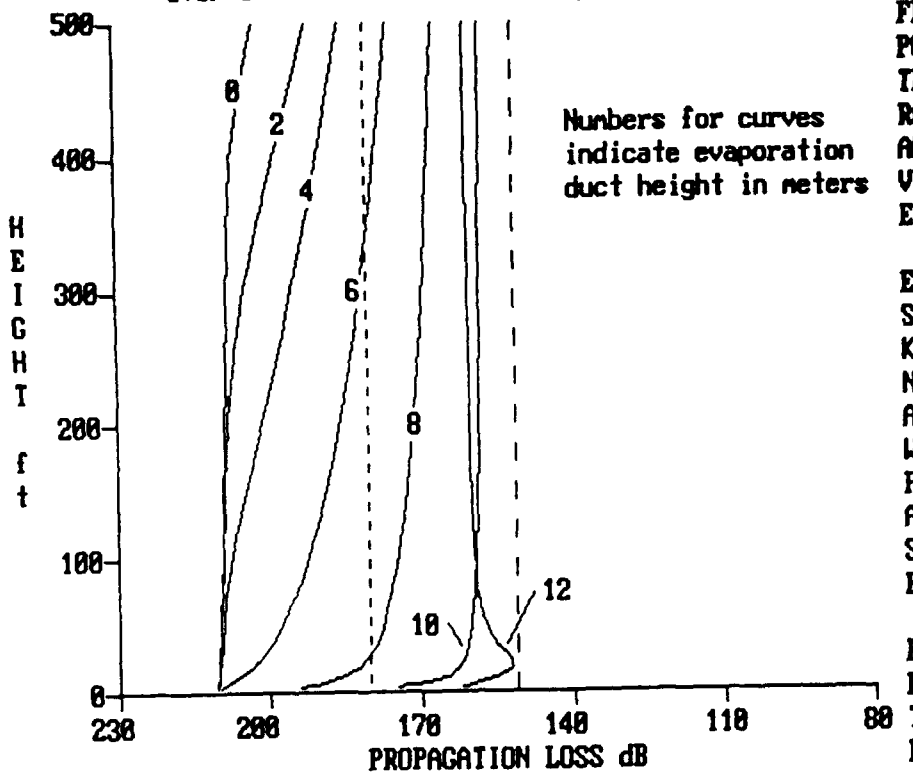

Sample Standard and Ducting Conditions
PROPAGATION LOSS dB
80
110
140
170
200
230
0
20
40
60
80
100
RANGE nmi
Optical Region
300-n Surface-based Duct
Diffraction
13-n Evaporation Duct
Troposcatter
FREQ MHz 5600
POLARIZATION HOR
TRAN HT ft 75
REC HT ft 75
ANT TYPE SINX/X
VER BW deg 10
ELEV ANG deg 0
EVD HT as noted
SBD HT as noted
K 1.333
NSUBS 339
ABS HUM g/m3 7.5
WIND SP kts 10
FREE-SPACE RANGE
or dB THRESHOLDS
nmi 100
nmi 200
nmi 300
nmi 400
FREE SPACE


ESM Intercept Range versus Evaporation Duct Height
PROPAGATION LOSS dB
120
140
160
180
200
220
0
40
80
120
160
200
RANGE nmi
Maximum ESM Intercept Range for
12-n Evaporation Duct Height
0
4
2
6
8
10
12
Evaporation
Duct Heights
FREQ GHz 9.2
POLARIZATION HOR
TRAN HT ft 75
REC HT ft 75
ANT TYPE GAUSS
VER BW deg 3
ELEV ANG deg 0
EVD HT as noted
SBD HT n 0
K 1.333
NSUBS 339
ABS HUM g/m3 7.5
WIND SP kts 0
PK POW kW 100
ANT GN dBi 30
SYS LOSS dB 10
ESM SENS dBm -80
FREE SPACE
ESM INTERCEPT
THRESHOLD
PROPLOSS dB 100.0


S-Band Radar, Standard Atmosphere, 10 Knots Wind
PROPAGATION FACTOR dB
20
0
-20
-40
-60
-80
Free Space Reference
Radar Detection Threshold
0
5
10
15
20
25
RANGE km
FREQ MHz 3000
POLARIZATION HOR
RADR HT m 25
TRGT HT m 30
ANT TYPE SINX/X
VER BW deg 3
ELEV ANG deg 0
PK POW kW 285
P WIDTH us 1.3
ANT GN dBi 30
SYS LOSS dB 6
REC NF dB 6
HOR BW deg 1.5
PRF Hz 1000
SCAN RT rpn 15
RCS sqn 1
PD .9
PFA 1.0E- 8
SW CASE 1-FLCT
FREE SPACE - - - -
THRESHOLD ---------
FS RANGE km 34.9


C-Band Radar Target & Clutter S/N Ratios
Wind Speed: 15 Knots
SIGNAL/NOISE dB
60
40
20
0
-20
-40
Clutter 13-n
Evap Duct
Target 13-n
Evap Duct
Target
Std. Atm.
Clutter
Std. Atm.
0
10
20
30
40
50
RANGE km
FREQ MHz 5600
POLARIZATION HOR
RADR HT m 25
TRGT HT m 5
ANT TYPE SINX/X
VER BW deg 10
ELEV ANG deg 0
PK POW kW 285
P WIDTH us 1.3
COMP PW us 1.3
ANT GN dBi 32
SYS LOSS dB 8.4
REC NF dB 14
HOR BW deg 1.5
PRF Hz 650
SCAN RT rpn 15
RCS sqn .1
PD 0.5
PFA 1.0E- 8
SW CASE 1-FLCT
DET FACTOR - - - -
CLUTTER ---------
FS RANGE km 15.1

Over-The-Horizon ESM Interception

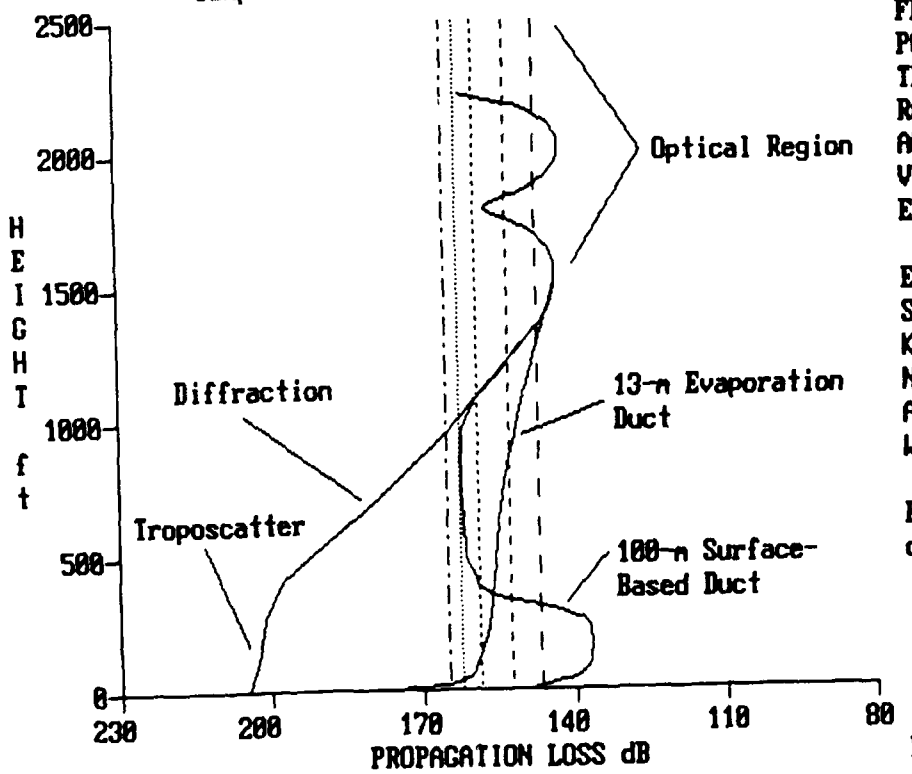


Numbers for curves indicate evaporation duct height in meters

FREQ	MHz	9200
POLARIZATION		HOR
TRAN HT	ft	75
RANGE	nmi	50
ANT TYPE		OMNI
VER BW	deg	N/A
ELEV ANG	deg	N/A
EVD HT		as noted
SBD HT	m	0
K		1.333
NSUBS		339
ABS HUM	g/m3	7.5
WIND SP	kts	10
PK POW	kW	100
ANT GN	dBi	30
SYS LOSS	dB	10
ESM SENS	dBm	-80

FREE SPACE - - - -
ESM INTERCEPT
THRESHOLD ---------
PROPLOSS dB 100.0

Sample Standard and Ducting Conditions

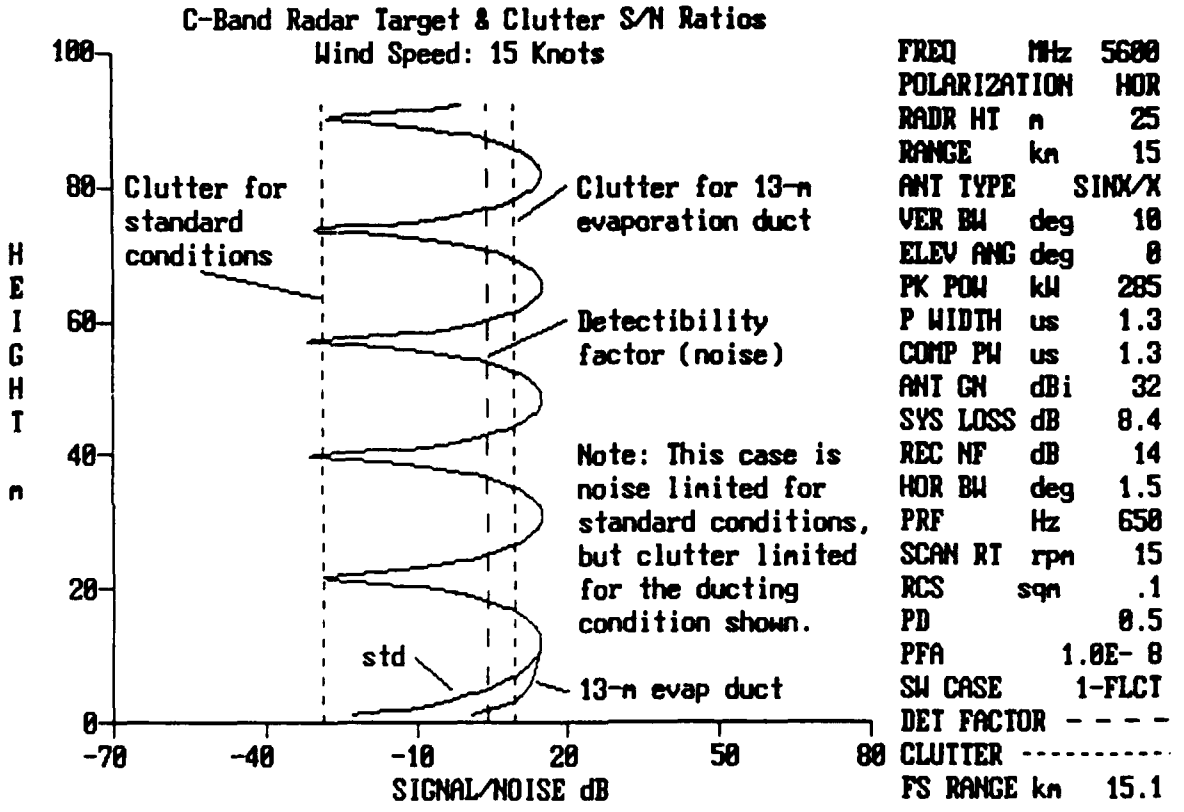


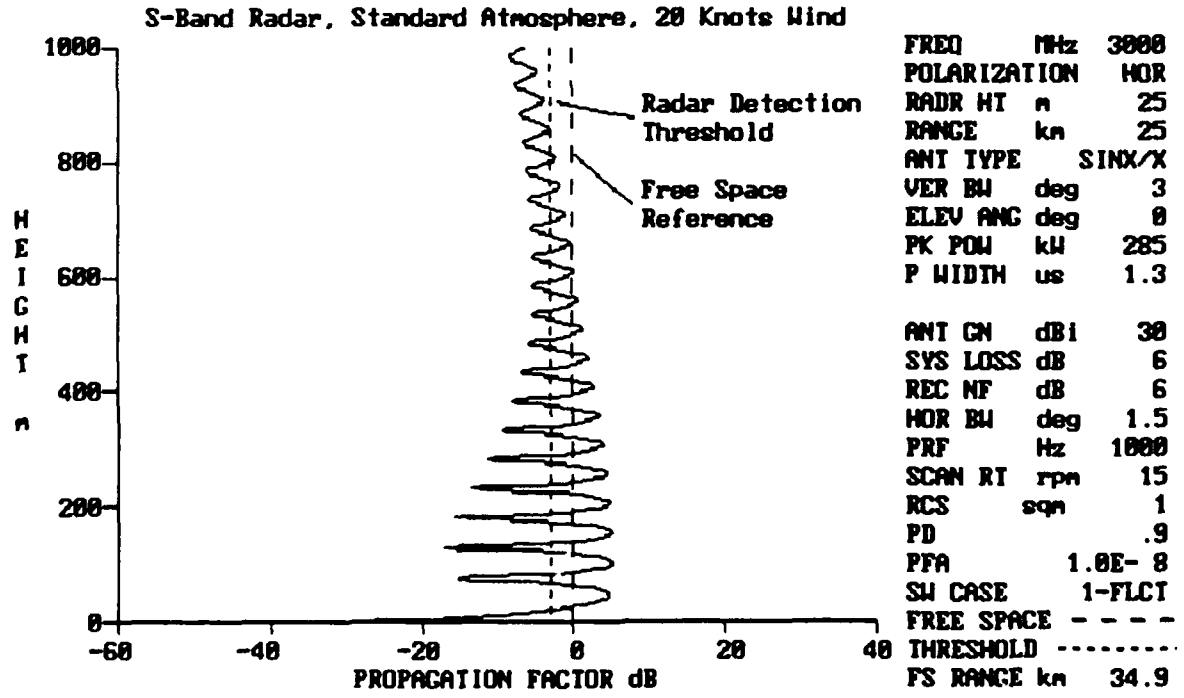
FREQ	MHz	5600
POLARIZATION		HOR
TRAN HT	ft	75
RANGE	nmi	50
ANT TYPE		OMNI
VER BW	deg	N/A
ELEV ANG	deg	N/A
EVD HT		as noted
SBD HT		as noted
K		1.333
NSUBS		339
ABS HUM	g/m3	7.5
WIND SP	kts	10

FREE-SPACE RANGE or dB THRESHOLDS

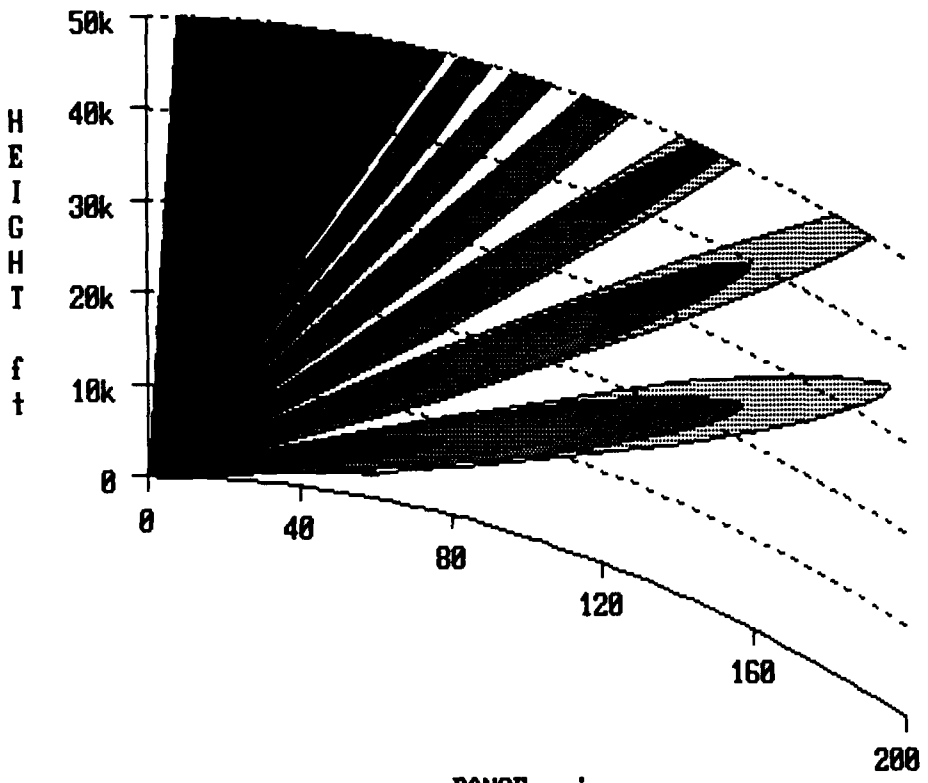
------	nmi	100
.....	nmi	200
———	nmi	300
-·-·-	nmi	400

FREE SPACE - - - -


C-Band Radar Target & Clutter S/N Ratios
Wind Speed: 15 Knots
HEIGHT m
100
80
60
40
20
0
-70
-40
-10
20
50
80
SIGNAL/NOISE dB
Clutter for standard conditions
Clutter for 13-m evaporation duct
Detectibility factor (noise)
Note: This case is noise linited for standard conditions, but clutter linited for the ducting condition shown.
std
13-m evap duct
FREQ MHz 5600
POLARIZATION HOR
RADR HT m 25
RANGE km 15
ANT TYPE SINX/X
VER BW deg 10
ELEV ANG deg 0
PK POW kW 285
P WIDTH us 1.3
COMP PW us 1.3
ANT GN dBi 32
SYS LOSS dB 8.4
REC NF dB 14
HOR BW deg 1.5
PRF Hz 650
SCAN RT rpm 15
RCS sqm .1
PD 0.5
PFA 1.0E- 8
SW CASE 1-FLCT
DET FACTOR - - - -
CLUTTER ----------
FS RANGE km 15.1


S-Band Radar, Standard Atmosphere, 20 Knots Wind
HEIGHT m
1000
800
600
400
200
0
-60
-40
-20
0
20
40
PROPAGATION FACTOR dB
Radar Detection Threshold
Free Space Reference
FREQ MHz 3000
POLARIZATION HOR
RADR HT m 25
RANGE km 25
ANT TYPE SINX/X
VER BW deg 3
ELEV ANG deg 0
PK POW kW 285
P WIDTH us 1.3
ANT GN dBi 30
SYS LOSS dB 6
REC NF dB 6
HOR BW deg 1.5
PRF Hz 1000
SCAN RT rpm 15
RCS sqm 1
PD .9
PFA 1.0E- 8
SW CASE 1-FLCT
FREE SPACE - - - -
THRESHOLD ---------
FS RANGE km 34.9

UHF Radar Coverage in Standard Conditions

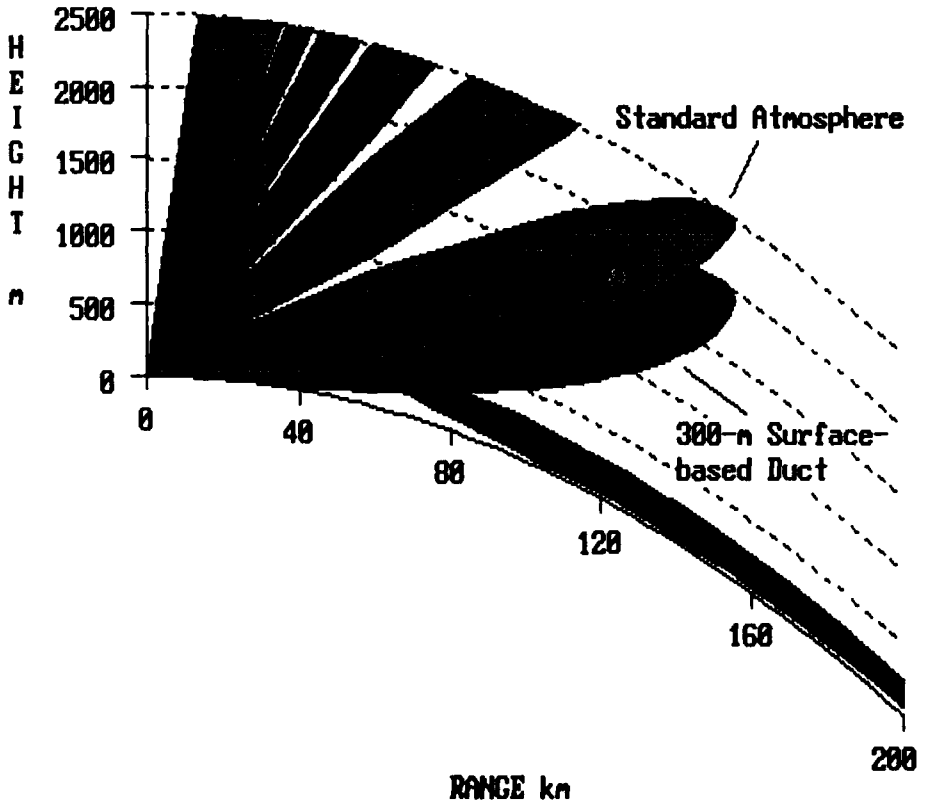


FREQ	MHz	425
POLARIZATION		HOR
TRAN HT	ft	75
ANT TYPE		OMNI
VER BW		N/A
ELEV ANG		N/A
EVD HT	m	0
SBD HT	m	0
K		1.333
ABS HUM	g/m3	7.5
WIND SP	kts	10

FREE SPACE RANGES
or dB THRESHOLDS

	nmi	40
	nmi	60
	nmi	80
	nmi	100

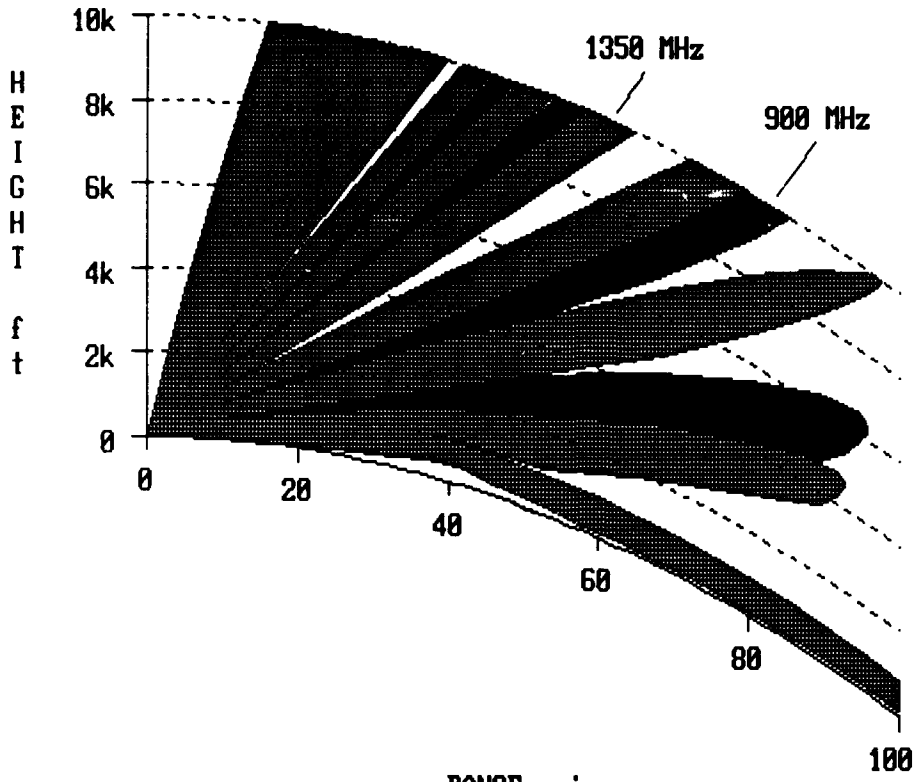
Range Extension from a Surface-based Duct



FREQ	MHz	450
POLARIZATION		HOR
TRAN HT	m	25
ANT TYPE		SINX/X
VER BW	deg	10
ELEV ANG	deg	0
EVD HT	m	0
SBD HT		as noted
K		1.333
ABS HUM	g/m3	7.5
WIND SP	kts	10

FREE SPACE RANGE
80 km

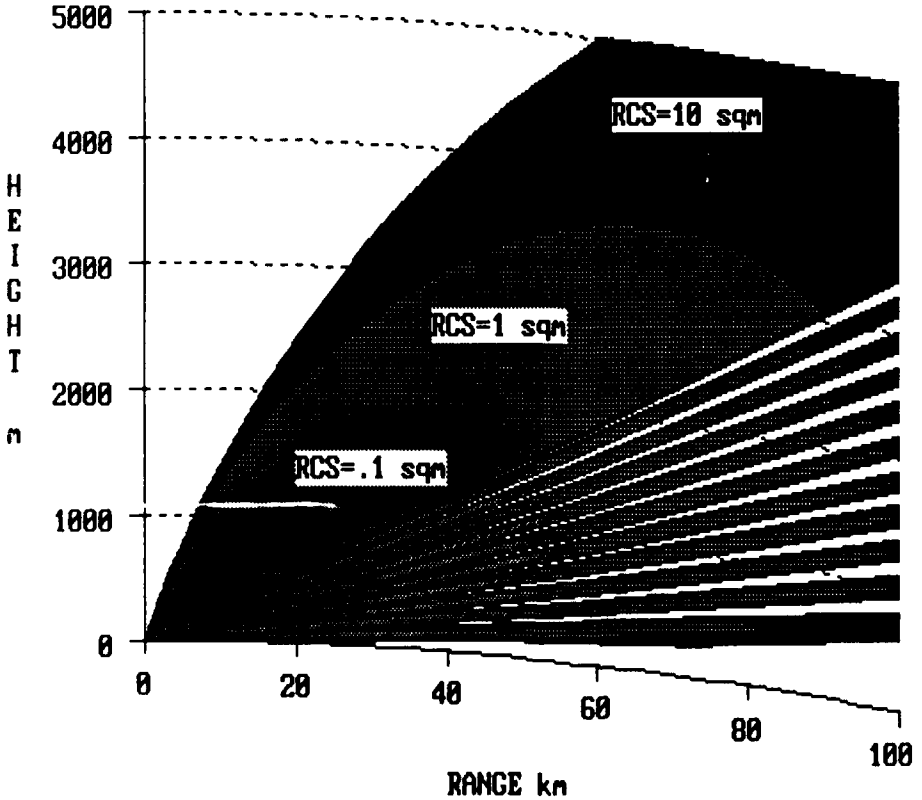
Effects of Frequency Diversity



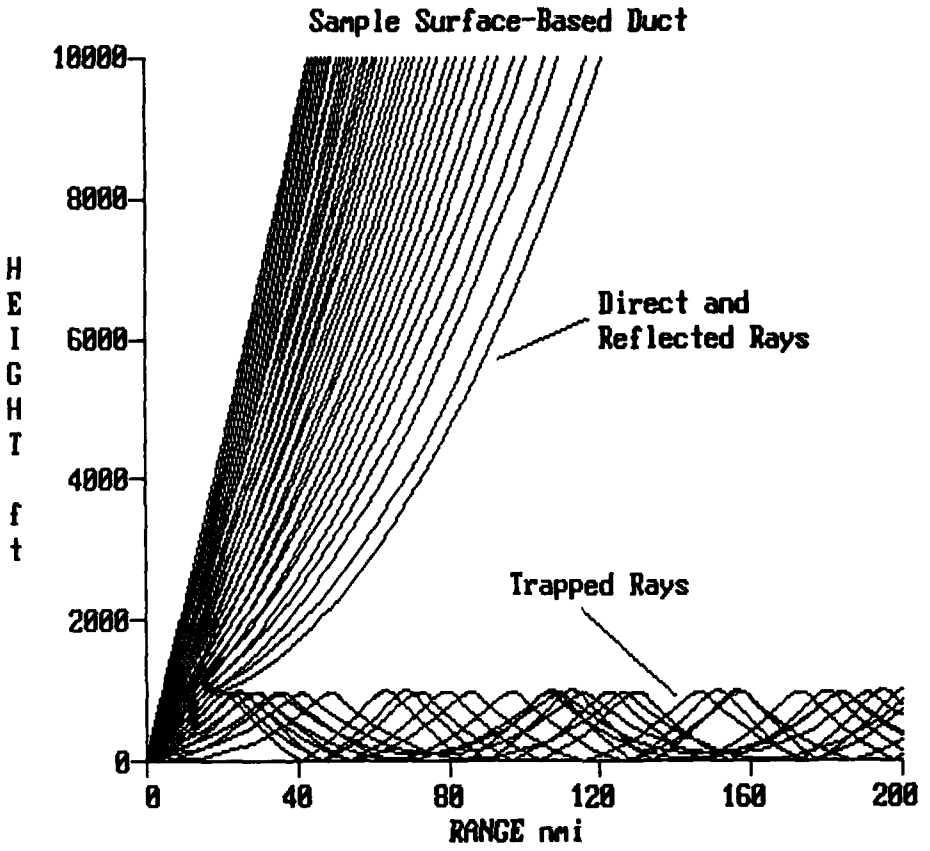
FREQ		as noted
POLARIZATION		HOR
TRAN HT	ft	60
ANT TYPE		SINX/X
VER BW	deg	6
ELEV ANG	deg	0
EVD HT	m	0
SBD HT	m	300
K		1.333
ABS HUM	g/m3	7.5
WIND SP	kts	10

FREE SPACE RANGE
50 nmi

Radar Performance versus Radar Cross Section



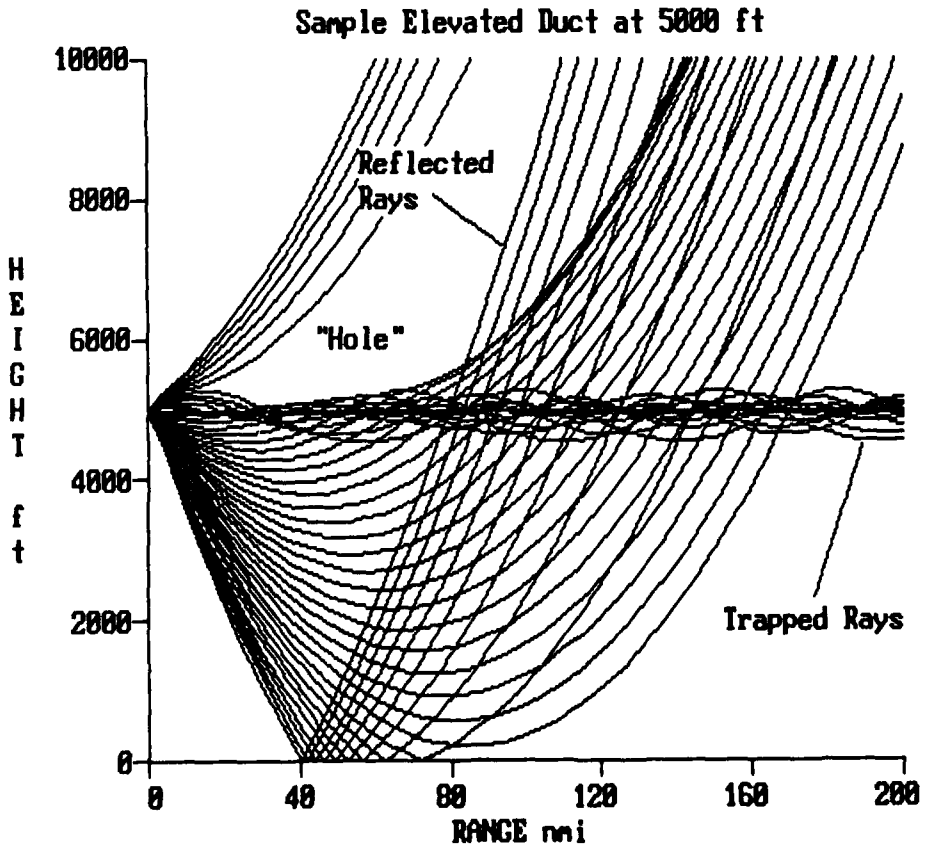
FREQ	MHz	3000
POLARIZATION		HOR
RADR HT	ft	60
ANT TYPE		GAUSS
VER BW	deg	6
ELEV ANG	deg	0
PK POW	kW	1000
P WIDTH	us	1
ANT GN	dBi	30
SYS LOSS	dB	6
REC NF	dB	5
HOR BW	deg	3
PRF	Hz	1000
SCAN RT	rpm	15
RCS		as noted
PD		.9
PFA		1.0E- 8
SW CASE		1-FLCT



TRAN HT ft	100
NO. OF RAYS	50
MIN ANG deg	-2
MAX ANG deg	2
REFLECTED RAYS	Y

PROFILE

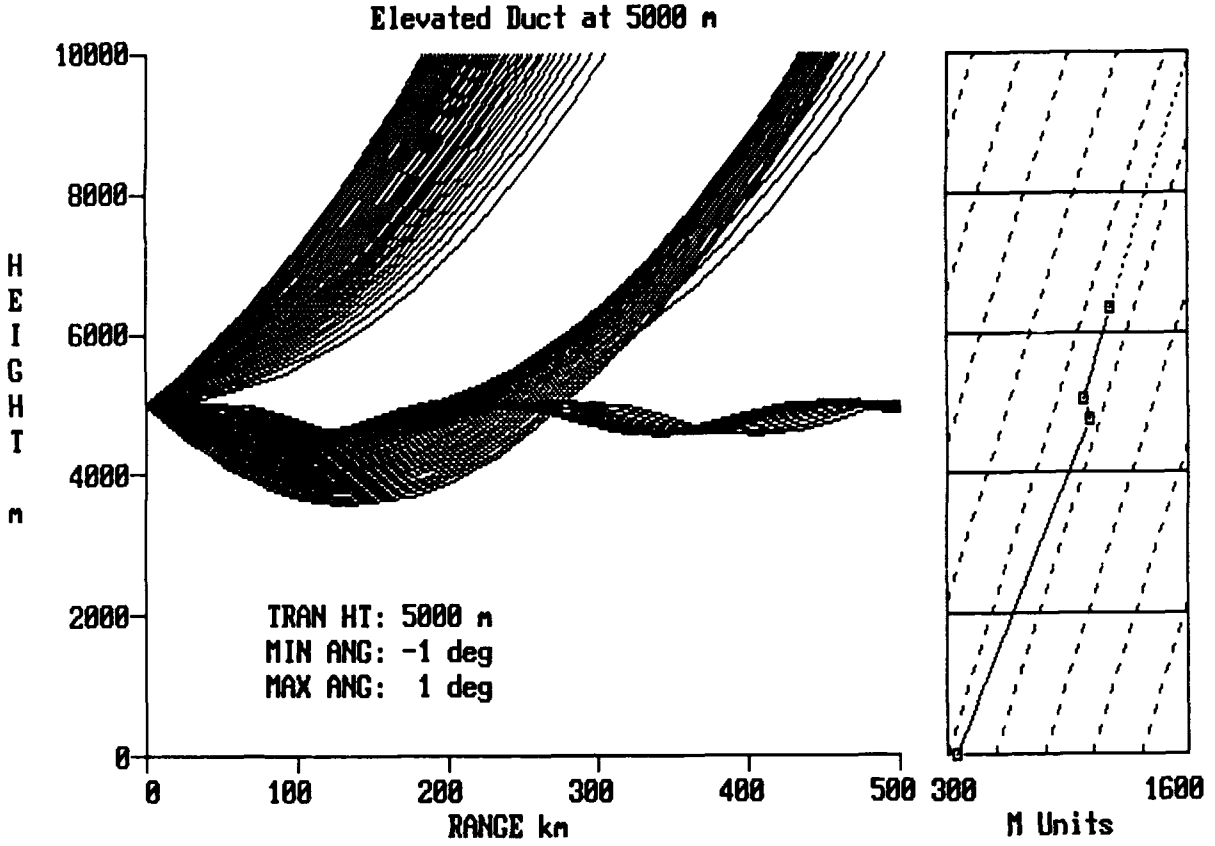
HEIGHT(ft)	M-UNITS
0	350
900	382
1000	330
2000	366

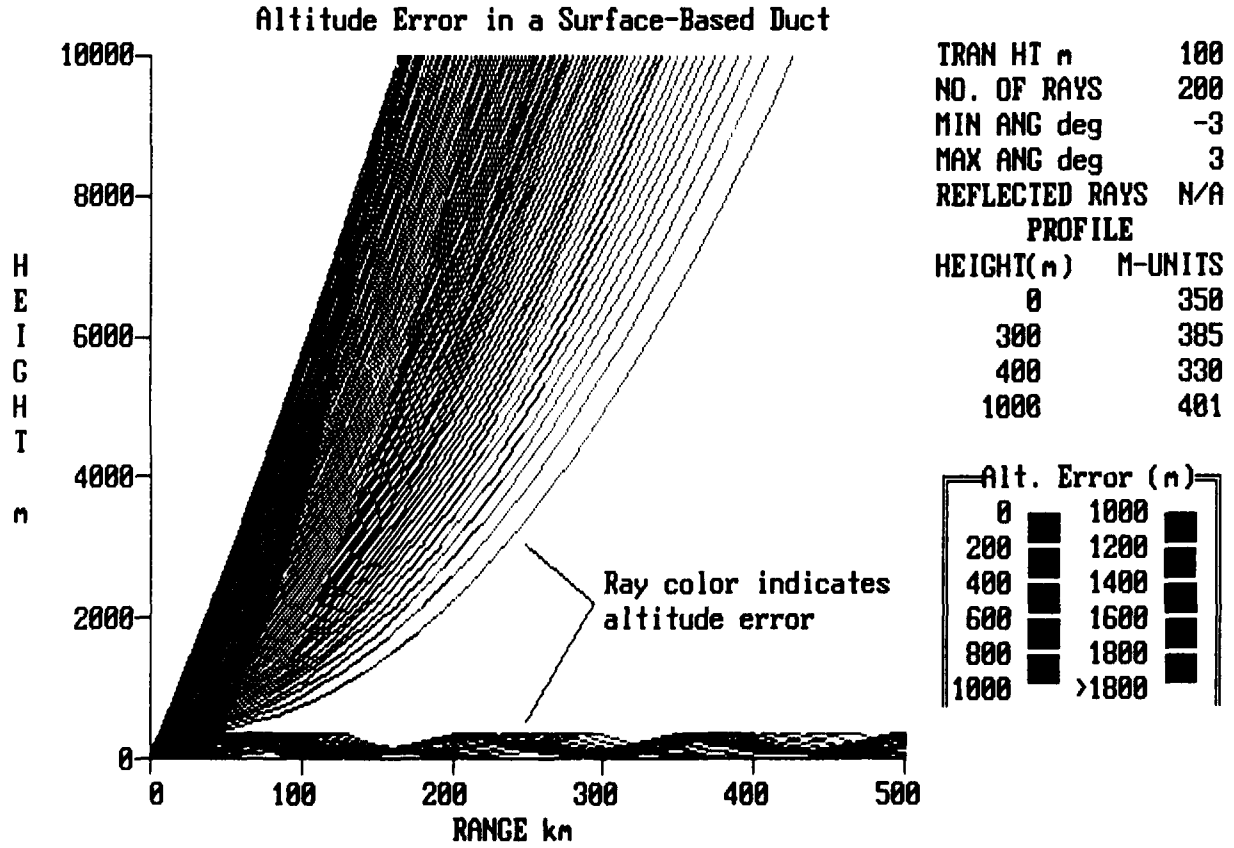


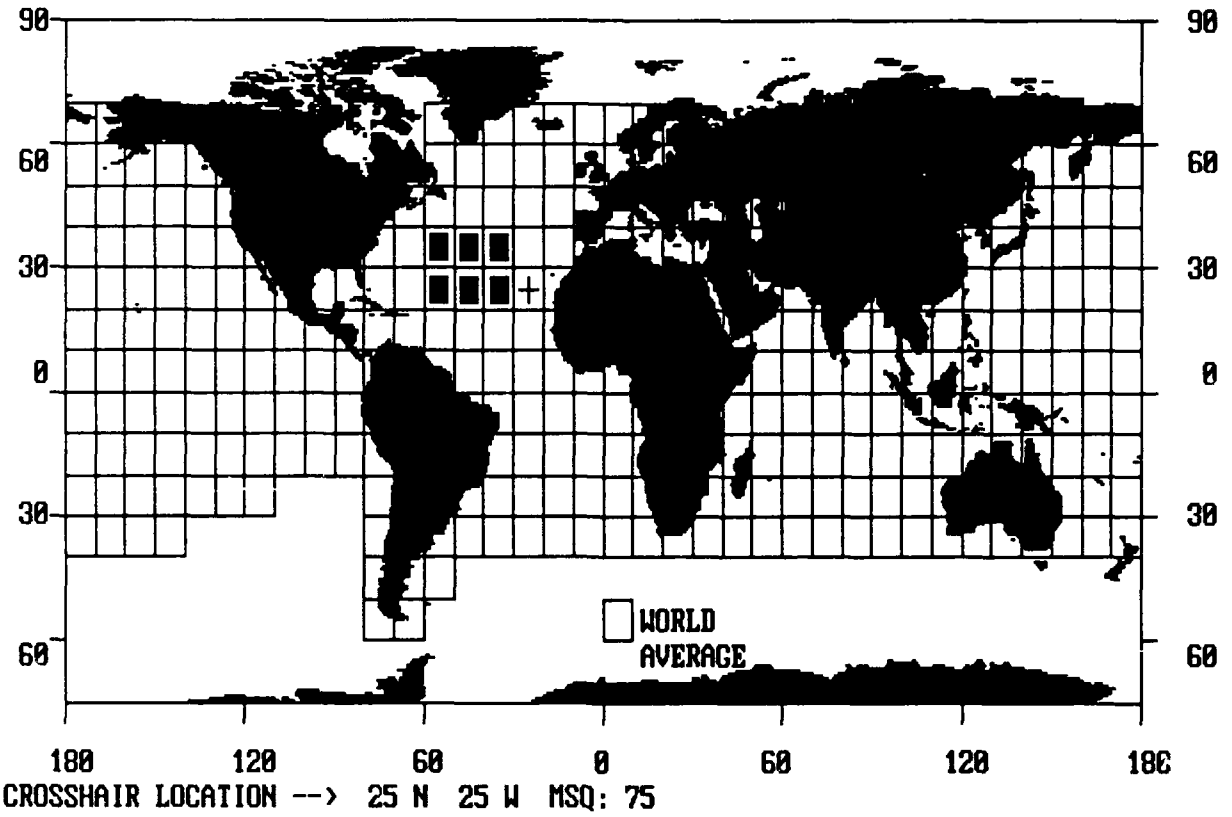
TRAN HT ft	5000
NO. OF RAYS	50
MIN ANG mrad	-25
MAX ANG mrad	10
REFLECTED RAYS	Y

PROFILE CHARACTERISTICS

DUCT TOP ft	5300
DUCT BTM ft	4500
LYR THK ft	300
LYR TOP ft	0
LYR BTM ft	0
LYR TYPE	None
LYR GRD M/kft	None
LYR TOP ft	0
LYR BTM ft	0
LYR TYPE	None
LYR GRD M/kft	None

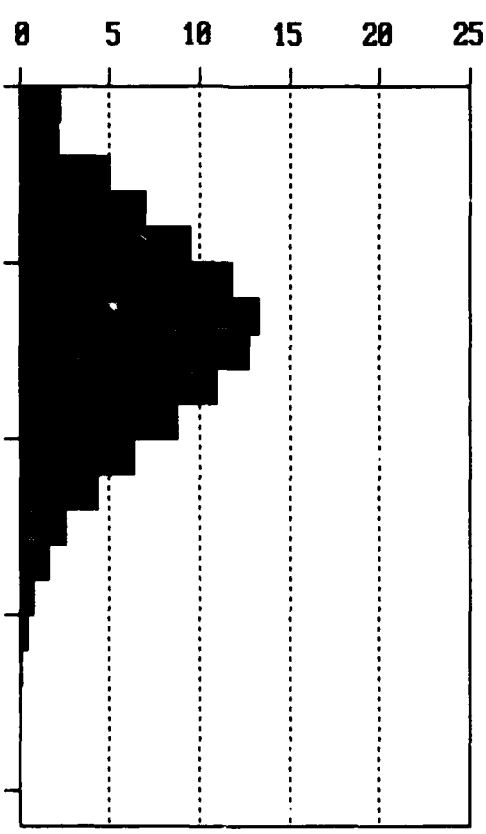

Elevated Duct at 5000 m
10000
8000
6000
4000
2000
0
HEIGHT m
TRAN HT: 5000 m
MIN ANG: -1 deg
MAX ANG: 1 deg
0
100
200
300
400
500
RANGE km
300
1600
M Units


Altitude Error in a Surface-Based Duct
10000
8000
6000
4000
2000
0
HEIGHT m
Ray color indicates
altitude error
0
100
200
300
400
500
RANGE km
TRAN HT m 100
NO. OF RAYS 200
MIN ANG deg -3
MAX ANG deg 3
REFLECTED RAYS N/A
PROFILE
HEIGHT(m) M-UNITS
0 350
300 385
400 330
1000 401
Alt. Error (m)
0
200
400
600
800
1000
1000
1200
1400
1600
1800
>1800



CROSSHAIR LOCATION --> 25 N 25 W MSQ: 75

EVD HT	% OCCUR	
0 TO 2 m	2.3	
2 TO 4 m	2.1	E
4 TO 6 m	5.0	V
6 TO 8 m	7.0	A
8 TO 10 m	9.5	P
10 TO 12 m	11.8	O
12 TO 14 m	13.3	R
14 TO 16 ..	12.7	A
16 TO 18 m	11.0	T
18 TO 20 m	8.7	I
20 TO 22 m	6.3	O
22 TO 24 m	4.3	N
24 TO 26 m	2.6	
26 TO 28 m	1.6	D
28 TO 30 m	0.8	U
30 TO 32 m	0.5	C
32 TO 34 m	0.2	T
34 TO 36 m	0.1	
36 TO 38 m	0.1	H
38 TO 40 m	0.0	T
> 40 m	0.1	



ANNUAL SURFACE DUCT SUMMARY

SURFACE OBS:

AVERAGED 6 SQUARES

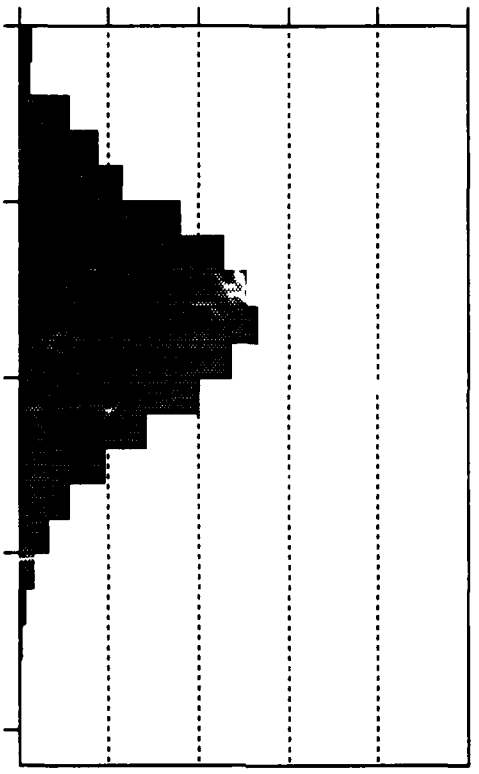
AVG EVD HT: 14.1 m
AVG WIND SP: 13.0 KTS

UPPER AIR OBS: RS 8594

SAL (CABO VERDE), PORTUGAL

LATITUDE: 16.73 N
LONGITUDE: 22.95 W
SBD OCCURRENCE: 15.0 %
AVG SBD HT: 186 m
AVG NSUBS: 349
AVG K: 1.83
SAMPLE SIZE: 1603

EVD HT	% OCCUR	
0 TO 2 m	0.7	
2 TO 4 m	0.6	E
4 TO 6 m	2.8	V
6 TO 8 m	4.3	A
8 TO 10 m	5.7	P
10 TO 12 m	9.0	O
12 TO 14 m	11.4	R
14 TO 16 m	12.6	A
16 TO 18 m	13.3	T
18 TO 20 m	11.8	I
20 TO 22 m	10.0	O
22 TO 24 m	7.1	N
24 TO 26 m	4.8	
26 TO 28 m	2.8	D
28 TO 30 m	1.6	U
30 TO 32 m	0.8	C
32 TO 34 m	0.4	T
34 TO 36 m	0.2	
36 TO 38 m	0.1	H
38 TO 40 m	0.0	T
> 40 m	0.0	



ANNUAL SURFACE DUCT SUMMARY

SURFACE OBS: MS 28

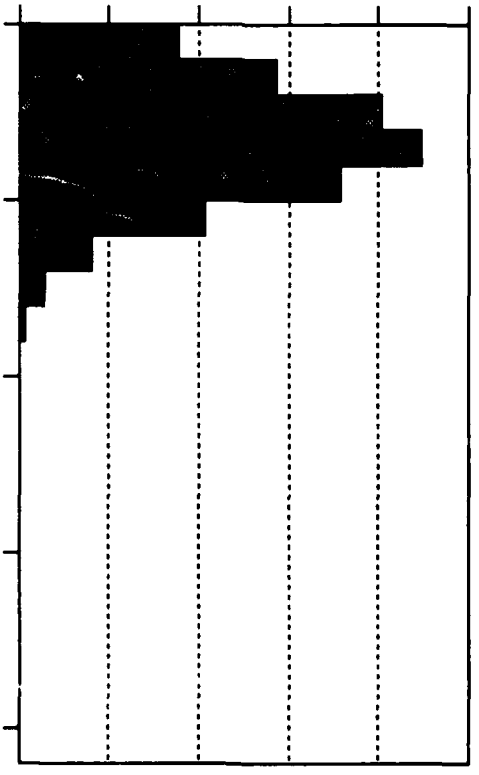
LATITUDE: 0 TO 10 N
LONGITUDE: 80 TO 90 E
AVG EVD HT: 16.5 m
AVG WIND SP: 12.1 KTS
SAMPLE SIZE: 53032 OBS

UPPER AIR OBS: RS 43466

COLOMBO, CEYLON

LATITUDE: 6.90 N
LONGITUDE: 79.87 E
SBD OCCURRENCE: 10.0 %
AVG SBD HT: 94 m
AVG NSUBS: 387
AVG K: 1.71
SAMPLE SIZE: 192

EVD HT	% OCCUR	
0 TO 2 m	8.9	
2 TO 4 m	14.3	E
4 TO 6 m	20.2	V
6 TO 8 m	22.4	A
8 TO 10 m	17.9	P
10 TO 12 m	10.3	O
12 TO 14 m	4.0	R
14 TO 16 m	1.4	A
16 TO 18 m	0.4	T
18 TO 20 m	0.1	I
20 TO 22 m	0.1	O
22 TO 24 m	0.0	N
24 TO 26 m	0.0	
26 TO 28 m	0.0	D
28 TO 30 m	0.0	U
30 TO 32 m	0.0	C
32 TO 34 m	0.0	T
34 TO 36 m	0.0	
36 TO 38 m	0.0	H
38 TO 40 m	0.0	T
> 40 m	0.0	



ANNUAL SURFACE DUCT SUMMARY

SURFACE OBS: MS 252

LATITUDE: 60 TO 70 N
LONGITUDE: 0 TO 10 E
AVG EVD HT: 6.7 m
AVG WIND SP: 17.9 KTS
SAMPLE SIZE: 121114 OBS

UPPER AIR OBS: RS 1241

ORLAND, NORWAY

LATITUDE: 63.70 N
LONGITUDE: 9.43 E
SBD OCCURRENCE: 1.0 %
AVG SBD HT: 71 m
AVG NSUBS: 317
AVG K: 1.33
SAMPLE SIZE: 3180

Appendix B

```
'  Subroutine:  FFACTR          Date:  02/01/90

'  ************************************************************

'  Process:

'    For electromagnetic systems, computes the pattern propaga-
'    tion factor in decibels for a specified range.  Positive
'    values indicate a signal level above the free-space field
'    strength.  Negative values indicate a signal level below
'    free-space field strength.

'  ************************************************************

'  Subroutines:        Functions:        QuickBASIC functions
'    antpar              FNAMAX            abs
'    antpat              FNAMIN            atn
'    dconst              FNUZ              cos
'    difint                                exp
'    dloss                                 log (natural)
'    gtheta                                sin
'    hgain                                 sqr
'    opconst                               swap
'    opffac                                tan
'    opticf
'    oplimit
'    rliter
'    ref
'    ruff
'    sbd
'    skipzone
'    tropo

'  When calling subroutines within FFACTR, convention is to use
'  lower case variable names for the input parameters and upper
'  case variable names for the returned parameters.
```

```
' Input parameters:
'
'   Electromagnetic system:
'      antyp$ -  Antenna type
'                  OMNI - Omnidirectional
'                  SINX/X - SIN(X)/X
'                  GAUSS - Gaussian beam
'                  CSC-SQ - Cosecant-squared
'                  HT-FINDER - Generic height finder
'      bwidth -  Antenna beam width  (0.5 - 45.0 degs)
'      elevat -  Antenna elevation angle  (-10.0 to +10.0 degs)
'                  0o is horizontal normal pointing angle for
'                  shipboard radar systems
'      freq   -  Frequency   100 - 20000 MHz
'      hr     -  Receiver/target height  (1 - 10000 m)
'      ht     -  Transmitter antenna height  (1 - 10000 m)
'                  one of the above terminal height should
'                  be < 100 m for pulsed systems
'      polar$ -  Antenna polarization
'                  H - horizontal
'                  V - vertical
'                  C - circular
'      r      -  Desired range for F-Factor  (1 - 1000 km)
'
'   Environmental:
'      delta  -  Evaporation duct height  (0 - 40 m)
'      humid  -  Absolute humidity   (0 - 14 grams/m^3)
'                  World average is 7.5 grams/m^3
'      rk     -  Effective earth radius factor (1.0 - 5.0)
'                  4/3 is a "standard" atmosphere
'      rnsubs -  Surface refractivity   (0 - 450)
'                  World average is 339 N-units
'      sbdht  -  Surface-based duct height  (0 - 1000 m)
'      wind   -  Surface wind velocity  (0 - 100 KNOTS)
'
'
'
' Output parameter:
'      ff     -  20*LOG10(Pattern propagation factor) in dB
'                  ff values that are positive indicate a
'                  signal level above the free-space field
'                  at that range. Negative values indicate
'                  signal levels below the free-space field.
```

The following program is a demonstration driver for the FFACTR subroutine. It is included to show possible uses for the FFACTR subroutine. The FFACTR subroutine is structured to return a value (in dB) representing the ratio of the actual field strength at a range, to the free-space field strength at that same range. Because the FFACTR subroutine may be called in any arbitrary fashion, it is not the most efficient structure for producing a product such as a loss-versus-range (or height). If only the range is to be varied, with constant terminal heights, a commom application, the OPCONST and the DCONST subroutine calls should be made only once at the start of the application program. This would necessitate removing them from the FFACTR subroutine and placing them in the calling program.

Three sets of input parameters and resulting pathloss and propagation factors are provided below for testing of this subroutine after a language conversion. This demonstration program calls FFACTR only with the first input set:

Set 1 input parameters and output values - standard atmo

Enivronmental:		Electromagnetic system:	
Delta	= 0.0	Antype$	= "SINX/X"
Humid	= 7.5	Bwidth	= 2.0
Rnsubs	= 339.0	Elevat	= 0.0
Rk	= 4./3.	Freq	= 5600.0
Sbdht	= 0.0	Hr	= 20.0
Wind	= 10.0	Ht	= 20.0
		Polar$	= "H"

Range (km)	Propagation loss (dB)	Propagation factor (dB)
55.0	183.81	-41.59
50.0	175.91	-34.52
45.0	168.34	-27.86
40.0	160.65	-21.20
35.0	152.83	-14.54
30.0	144.83	- 7.88
25.0	136.59	- 1.21
20.0	129.41	4.03

Set 2 input parameters and output values - 10m evap duct

Enivronmental:		Electromagnetic system:	
Delta	= 10.0	Antype$	= "CSC-SQ"
Humid	= 7.5	Bwidth	= 4.0
Rnsubs	= 339.0	Elevat	= 0.0
Rk	= 4./3.	Freq	= 9600.0
Sbdht	= 0.0	Hr	= 100.0
Wind	= 0.0	Ht	= 10.0
		Polar$	= "V"

```
'      Range (km)  Propagation loss (dB)  Propagation factor (dB)
'        55.0            145.28                 1.63
'        50.0            143.66                 2.42
'        45.0            141.96                 3.21
'        40.0            140.14                 3.99
'        35.0            140.90                 2.08
'        30.0            142.73                -1.09
'        25.0            137.51                 2.54
'        20.0            133.03                 5.09

'    Set 3 input parameters and output values - 100m sbd
'      Enivronmental:              Electromagnetic system:
'        Delta   = 10.0              Antype$ = "GAUSS"
'        Humid   = 7.5               Bwidth  = 4.0
'        Rnsubs  = 339.0             Elevat  = 0.0
'        Rk      = 2.1               Freq    = 400.0
'        Sbdht   = 100.0             Hr      = 50.0
'        Wind    = 20.0              Ht      = 10.0
'                                    Polar$  = "C"

'      Range (km)  Propagation loss (dB)  Propagation factor (dB)
'        55.0            110.61                 8.69
'        50.0            115.61                 2.86
'        45.0            120.61                -3.05
'        40.0            125.61                -9.08
'        35.0            130.61               -15.24
'        30.0            127.63               -13.59
'        25.0            123.65               -11.19
'        20.0            119.31                -8.80

'   Start demonstration program

    defint i-n
    const Pi = 3.14159
    const revision$ = "1.00"
    const rev.date$ = "01 FEB 1990"
```

```
    common shared / comffactr / ae, ae2, aeth, alpha, antbwr
    common shared / comffactr / antelr, antfac, antyp$, atten
    common shared / comffactr / bwidth, c1, c2, c3, c4 ,c5, c6, c7
    common shared / comffactr / del, delta, difac, dtot, elevat
    common shared / comffactr / elmaxr, exloss, f3, fofz, freq
    common shared / comffactr / fsloss, fsterm, fterm, h1, h2
    common shared / comffactr / h14pil, h24pil, h24ae2, hbar
    common shared / comffactr / hbfreq, hdif, hlm, hmin, horizn
    common shared / comffactr / horiznl, hr, ht, humid, opmaxd
    common shared / comffactr / opmaxl, patd, patrfac, polar$, psi
    common shared / comffactr / rllim, rlmin, rk, rmag, rmax
    common shared / comffactr / rn2.imag, rn2.real, rns2, rnsterm
    common shared / comffactr / rnsubs, rsbd, rsbdloss, rsubd
    common shared / comffactr / sbdht, tfac, thefac, tsub1, tsub2
    common shared / comffactr / twoae, wind, wv.atten, zfac

    antyp$ = "SINX/X"
    bwidth = 2.0
    elevat = 0.0
    freq = 5600.0
    hr = 20.00
    ht = 20.00
    polar$ = "H"

    delta = 0.0
    humid = 7.5
    rk = 4./3.
    rnsubs = 339.0
    sbdht = 0.0
    wind = 10.0
    fsterm = 32.45 + 8.686*LOG(freq)
    dr = 5.0
    r = 60.0
    for i = 1 to 8
       r = r - dr
       call ffactr(freq,ht,hr,polar$,antyp$,bwidth,elevat,delta,_
          sbdht,humid,rk,rnsubs,wind,R,FF)
       rloss = fsterm + 8.686*LOG(r) - ff
       print r,rloss,ff
    next i
END

'   End of demonstration program
```

```
'  NOSC defined functions

DEF FNAMAX(elem1,elem2)
'  function to find maximum of two constants

   IF elem1 >= elem2 THEN FNAMAX = elem1
   IF elem1 <  elem2 THEN FNAMAX = elem2
END DEF

DEF FNAMIN(elem1,elem2)
'  function to find minimum of two constants

   IF elem1 <= elem2 THEN FNAMIN = elem1
   IF elem1 >  elem2 THEN FNAMIN = elem2
END DEF

DEF FNU(z)
'  function to define standard atmosphere height-gain: U(z)

   IF Z<=.6          THEN FNU = 8.686*LOG(Z)
   IF Z<1 AND Z>.6 THEN FNU = 15.88*LOG(Z/.6)^1.4 - 4.3
   IF Z>=1           THEN FNU = 19.85*(Z^.47-.9)
END DEF
```

```
SUB FFACTR(freq, ht, hr, polar$, antyp$, bwidth, elevat, delta,_
       sbdht, humid, rk, rnsubs, wind, r, FF) static

   h1 = ht
   h2 = hr
   IF h1 > h2 THEN swap h1,h2      ' swap antenna heights

'  initialize optical region constants
   call opconst

'  initialize diffraction/troposcatter region constants
   call dconst
   wvloss = wv.atten * r           ' water vapor absorbtion loss

'  Initialize antenna parameters
   call antpar

'  Calculate range to skipzone if surface-based duct present
   IF sbdht > 0 THEN call skipzone

'  Calculate free-space loss value
   fsloss = fsterm + 8.686 * LOG(r)

   rlmin = 0.01*r*h1 / (h1+h2)     ' approximate r1 at 1% of range
   call oplimit(OPMAXD, OPMAXL)    ' max range in optical region

   IF r >= rsubd THEN
      call dloss(r, DIFF)
      IF sbdht > 0.0 THEN
         call sbd(r, SBDLOSS)
         dfloss = sbdloss - fsloss
         IF dfloss < diff THEN diff = dfloss
      END IF
      ff = diff
   ELSE
      IF  r > opmaxd THEN
         call difint(opmaxd, opmaxl, r, FF)
      ELSE
         IF r <= opmaxd THEN call opticf(r, FF)
      END IF
   END IF
   ff = -(ff + wvloss)
END SUB
```

```
SUB antpar static

'   Process:  Initialize antenna parameters
'   Inputs from common block:  antyp$, bwidth, elevat
'   Outputs to common block:  antbwr,antelr,antfac,elmaxr,patrfac
'   Subroutines called:  None
'   Subroutine called by:  FFACTR

    antbwr = 1.745e-2 * bwidth
    antelr = 1.745e-2 * elevat
    elmaxr = 1.047
    IF antyp$ <> "OMNI" THEN
       IF antyp$ = "GAUSS" THEN
          antfac = - LOG(2.0)/(2.0 * SIN(antbwr/2.0)^2.0)
          patrfac = SIN(antelr)
          amax = SQR(10.11779 * SIN(antbwr/2.0)^2.0)
          elmaxr = antelr + ATN(amax / SQR(1.0 - amax^2))
       ELSE
          IF antyp$ = "CSC-SQ" THEN
             elmaxr = antelr + 0.78525
             antfac = SIN(antbwr)
          ELSE
             IF (antyp$ = "SINX/X") or (antyp$ = "HT-FINDER") THEN
                antfac = 1.39157 / SIN(antbwr/2.0)
                amax = PI/antfac
                patrfac = -ATN(amax / SQR(1.0 - amax^2))
                IF antyp$ = "SINX/X" THEN elmaxr = antelr-patrfac
             END IF
          END IF
        END IF
    END IF
END SUB
```

```
SUB antpat(angle, PATFAC) static

'   Process:  Calculate the pattern factor
'   Inputs from common block:  alpha, antbwr, antelr, antfac
'       antyp$, patrfac
'   Inputs from argument list:  angle
'   Outputs to common block:  None
'   Outputs to argument list:  patfac
'   Subroutines called:  None
'   Subroutine called by:  opffac

   patfac = 1.0
   IF antyp$ <> "OMNI" THEN
      IF antyp$ = "HT-FINDER" AND angle > antelr THEN
         alpha0 = alpha
      ELSE                        'SINX/X or CSC-SQ or GAUSS
         alpha0 = antelr
      END IF
      apat = angle - alpha0

      IF antyp$ = "CSC-SQ" THEN
         patfac = FNAMIN(1.0, FNAMAX(0.03, 1.0 + apat/antbwr))
         IF apat>antbwr THEN patfac = SIN(antbwr)/SIN(ABS(apat))

      ELSEIF antyp$ = "GAUSS" THEN
         patfac = EXP(antfac * (SIN(angle) - patrfac)^2.0)
         IF patfac < 0.03 THEN patfac = 0.03

      ELSE              'SIN(X)/X
         IF apat<>0.0 THEN
            IF angle <= alpha0 + patrfac THEN
               patfac = 0.03
            ELSE
               ufac = antfac * SIN(apat)
               patfac = FNAMIN(1.0, FNAMAX(0.03, SIN(ufac)/ufac))
            END IF
         END IF
      END IF
   END IF
END SUB
```

```
SUB dconst static

'   Process:  Initialize variables for the diffraction and
'             troposcatter region
'   Inputs from common block: ae, delta, freq, fsterm, h1, h2
'             rk, rnsubs
'   Outputs to common block:  atten, c1, c2, c3, c4, c5, c6, c7
'             del, difac, dtot, fterm, f3, h14pi1, h24pi1, h1m
'             hmin, horizn, rnsterm, rns2, rsubd, tfac, tsub1
'             tsub2, zfac
'   Subroutines called:  hgain
'   Subroutine called by:  FFACTR

    tsub1 = SQR(h1 * ae/500.0) / ae
    tsub2 = SQR(h2 * ae/500.0) / ae
    h14pi1 = h1 * 0.0419*freq
    h24pi1 = h2 * 0.0419*freq
    rnsterm = 0.031 - 0.00232 * rnsubs + 5.67E-6 * rnsubs^2
    horizn = 3.572 * (SQR(rk*h1) + SQR(rk*h2))
    tfac = 0.08984 / rk
    f3 = freq^3
    rns2 = 0.2 * rnsubs

'   Diffraction region constants
    qrfreq = freq^(1.0/3.0)
    fterm = qrfreq / 190.0
    fqterm = qrfreq^2 / 2129.94
    uht = FNU(fqterm*h1)
    uhr = FNU(fqterm*h2)
    dtot = fsterm - uht - uhr

    rkmin = rk
    IF rkmin < 1.3333 THEN rkmin = 1.3333
    horiznmin = 3.572 * (sqr(rkmin*h1)+sqr(rkmin*h2))
    rsubd = horiznmin + 230.2 * (rkmin^2 / freq)^(1.0/3.0)

    IF delta = 0 THEN                ' no evaporation duct height
       del = 0
    ELSE

'      Following terms for NOSC evaporation duct model
       rfac = 0.04705 * qrfreq
       zfac = 0.002214 * qrfreq^2
       hmin = 1.0
       z1 = h1 * zfac
       IF hmin > z1 THEN z1 = hmin
       z2 = h2 * zfac
       IF hmin > z2 THEN z2 = hmin
       del = delta * zfac
       IF del > 23.3 THEN del = 23.3
       IF del >= 10.25 THEN
```

```
'         Duct height greater than 10.25 meters
          c1 = -0.1189 * del + 5.5495
          c3 = 1.3291*SIN(0.218*(del-10.0)^0.77)+0.2171*LOG(del)
          c4 = 87.0 - SQR(313.29 - (del - 25.3)^2)
          hlowmax = 4.0 * exp(-0.31*(del - 10.0)) + 6.0
          hlm = hlowmax/4.72
          arg = c3 * hlm^1.5
          slope = c3 * c1 * 1.5 * SQR(hlm) / TAN(arg)
          c7 = 49.4 * exp(-0.1699*(del - 10.0)) + 30.0
          fmax = c1 * LOG(SIN(arg)) + c4 - c7
          c6 = hlm * slope / fmax
          c5 = fmax / hlm^c6
       ELSE

'         Duct height less than 10.25 meters
          c2 = SQR(40623.61 - (del + 4.4961)^2) - 201.0128
          c1 = (-2.2 * exp(-0.244*del) + 17.0) * 4.72 ^ (-C2)
          c4 = SQR(14301.2 - (del + 5.32545)^2) - 119.569
          c3 = (-33.9 * exp(-0.5170001*del) - 3.0) * 4.72 ^ (-C4)
          c5 = 41.0 * exp(-0.41*del) + 61.0
       END IF

'      determine the height-gain function for the evaporation
'      duct.  Note!  The variable "DUMMY" contains the height-
'      gain function for a surface-based duct which is not used
'      in this subroutine.
       call hgain(h1, DUMMY, FZT)
       call ngain(h2, DUMMY, FZR)

'      Note.  The # symbol is QuickBASIC double precision notation
       atten = 92.516 - SQR(8608.7593# - (del - 20.2663)^2)
       IF atten < 0.0009 THEN atten = 0.0009
       atten = atten * rfac
       IF del <= 3.8 THEN tlm = 216.7 + del * 1.5526
       IF del >  3.8 THEN tlm = 222.6 - (del - 3.8) * 1.1771
       difac = 51.1 + tlm - fzt - fzr + 4.343*LOG(rfac)
    END IF
END SUB
```

```
SUB difint(opmaxd, opmaxl, r, FF)  static

'   Process:  Calculates 20 times the natural logarithm for the
'             propagation factor within the intermediate region,
'             i.e. for ranges greater than opmaxd and less than
'             rsubd.

'   Inputs from common block:  fsloss, rsubd, sbdh
'   Inputs from argument list: diff, opmaxd, opmaxl, r, sbdloss
'   Outputs to common block:  None
'   Outputs to argument list: ff, r, rsubd
'   Subroutines called:  dloss, sbd
'   Subroutine called by:  FFACTR

   call dloss(rsubd, DIFF)
   deltaf = (r - opmaxd) * (opmaxl - diff) / (opmaxd-rsubd)
   ff = opmaxl + deltaf
   IF sbdht > 0.0 THEN
      dloss = ff + fsloss
      call sbd(r, SBDLOSS)
      IF sbdloss < dloss THEN dloss = sbdloss
      ff = dloss - fsloss
   END IF
END SUB
```

```
SUB dloss(r, DIFF)  static

'  Process:  Calculate the diffraction region loss
'  Inputs from common block:  atten, delta, difac, dtot, fsterm
'            fterm
'  Inputs from argument list:  r, tloss
'  Outputs to common block:  None
'  Outputs to argument list:  diff, r
'  Subroutines called:  tropo
'  Subroutine called by:  FFACTR, difint

'  Calculate diffraction region loss using Kerr's model
   x = fterm * r
   tlvx = 10.99 + 4.343 * LOG(x) - 17.55 * x
   diff = dtot + 8.686 * LOG(r) - tlvx
   IF delta <> 0.0 THEN
      diffe = difac + 4.343 * LOG(r) + atten * r
      IF diffe < diff THEN

'        Use lesser of Kerr and NOSC models
         diff = diffe
      END IF
   END IF
   diff = diff + exloss
   call tropo(r, TLOSS)

'  Add the troposcatter loss to the diffraction loss
   dif = diff - tloss
   IF dif >= 18.0 THEN
      diff = tloss
   ELSEIF dif >= -18.0 THEN
      diff = diff - 4.343 * LOG(1 + EXP(dif/4.343))
   END IF

'  Return 20*LOG(F) at range = r in diffraction region
   diff = diff - fsterm - 8.686*LOG(r)
END SUB
```

```
SUB gtheta(p$, rl, R, THETA, R2)  static

'  Process:  Calculates optical phase-lag difference angle,
'            theta, from reflection point range, rl.
'  Inputs from common block:  ae2, aeth, hl, h2, h24ae2, rl
'            thefac
'  Inputs from argument list:  p$, rl, phi
'  Outputs to common block:  psi
'  Outputs to argument list: p$, psi
'  Subroutines called:  ref
'  Subroutine called by: oplimit, rliter

   hlp = hl - rl^2 / ae2
   rkpsi = hlp / rl
   psi = 0.001 * rkpsi
   r2 = (sqr(rkpsi^2 + h24ae2) - rkpsi) * aeth
   r = rl + r2
   h2p = h2 - r2^2 / ae2
   call ref(p$, psi, PHI)
   theta = phi + thefac * hlp * h2p / r
END SUB
```

```
SUB hgain (h, FZBD1, FZBD2) STATIC

'   Process:  Calculates height-gain factor in dB for a specified
'             height
'   Inputs from common block:  c1, c2, c3, c4, c5, c6, c7, del
'             freq, h, hlm, hmin, sbdht, zfac
'   Inputs from argument list:  h
'   Outputs to common block:  None
'   Outputs to argument list: fzbd1, fzbd2
'   Subroutines called: None
'   Subroutine called by: dconst, skipzone


    fzbd1 = 0
    fzbd2 = 0

'   Surface-based duct height-gain factor
    IF (sbdht > 0) THEN
       z1 = h / sbdht
       IF ((Freq <= 150!) AND (z1 < .8)) THEN_
          fzbd1 = -60! * (z1 - .5) ^ 2
       IF ((Freq <= 150!) AND (z1 >= .8)) THEN_
          fzbd1 = 1.14 * z1 ^ (-6.26) - 10!
       IF ((Freq > 150!) AND (z1 < 1.0)) THEN_
          fzbd1 = 10! - 200 * (z1 - .5) ^ 4
       IF ((Freq > 150!) AND (Freq <= 350!) AND (z1 >= 1!)) THEN_
          fzbd1 = 7.5 * z1 ^ (-13.3) - 10!
    END IF
    IF ((Freq > 350!) AND (z1 >= 1!)) THEN_
       fzbd1 = 12.5 * z1 ^ (-8!) - 15!

'   Evaporation duct height-gain factor
       IF (del > 0) THEN
          z2 = h * zfac
          IF z2 < hmin THEN z2 = hmin
          z2 = z2 / 4.72
          IF (Del >= 10.25) THEN
             IF (z2 > hlm) THEN
             fzbd2 = C5 * (z2 ^ C6) + C7
          ELSE
             fzbd2 = C1 * LOG(SIN(C3 * (z2 ^ 1.5))) + C4
          END IF
       ELSE
          fzbd2 = (C1 * z2 ^ C2) + (C3 * z2 ^ C4) + C5
       END IF
    END IF
END SUB
```

```
SUB opconst static

'   Process:  Initializes constants for optical region
'   Inputs from common block:   antype$, freq, h1, h2, hr, ht
'             humid, polar$, rk, wind
'   Outputs to common block:  ae, ae2, aeth, fsterm, h24ae2, hbar
'             hbfreq, hdif, horiznl, rllim, rn2.imag, rn2.real
'             thefac, wv.atten
'   Subroutines called:  None
'   Subroutine called by: FFACTR


'   Variables for REF subroutine
    IF polar$ <> "H" THEN
       IF freq <= 1500 THEN
          eps = 80                          'salt water permittivity
          sigma = 4.3                       'salt water conductivity
       ELSEIF freq <= 3000 THEN
          eps = 80 - 0.00733 * (freq - 1500)
          sigma = 4.3 + 0.00148 * (freq - 1500)
       ELSEIF freq <= 10000 THEN
          eps = 69 - 0.00243 * (freq - 3000)
          sigma = 6.52 + 0.001314 * (freq - 3000)
       ELSE
          eps = 51.99
          sigma = 15.718
       END IF

'      real & imaginary part of square of index of refraction
       rn2.real = eps
       rn2.imag = (-18000) * sigma/freq
    END IF

'   Variables for RUFF subroutine
    hbar = 0.0051 * (0.51477*wind)^2        'rms wave height
    hbfreq = 0.02094 * freq * hbar          '(hbar*2*Pi)/wavelength

'   Variables for miscellaneous subroutines
    ae = rk * 6371                      ' effective earth radius - km
    twoae = 2.0 * ae
    aeth = rk * 6.371
    ae2  = aeth * 2.0
    h24ae2 = h2 * 4.0/ae2
    thefac = freq * 4.193E-5                ' 4*Pi / wavelength
    hdif = (hr - ht) * 1.0E-3
    fsterm = 32.45 + 8.686 * LOG(freq)      ' free space loss term
    freqg = freq / 1000.0                   ' frequency in GHz
    wv1 = 3.0 / ((freqg- 22.3)^2 + 7.3)
    wv2 = 9.0 / ((freqg-183.3)^2 + 6.0)
    wv3 = 4.3 / ((freqg-323.8)^2 + 10.)

'   water vapor attenuation rate in dB/km
    wv.atten = (0.067 + wv1 + wv2 + wv3) * freqg^2 * humid/10000.0
```

```
'   Variable for R1ITER subroutine
    horizn1 = 3.572 * (SQR(rk*h1))

'   Variables for OPLIMIT subroutine  Note: r1lim = r1 at psilim
    psilim = 0.01957 / (rk*freq)^(1./3.) ' grazing angle limit
    rkpsi = 1000 * psilim
    r1lim = (SQR(rkpsi*rkpsi + h1*4/ae2) - rkpsi)*aeth

END SUB



'   ************************************************************

SUB opffac(gamma, range, psi, r1, r2, PATD, DR)  static

'   Process:  Calculates parameters used to determine the pattern
'             propagation factor, F, in the optical region.
'             Calculate antenna pattern factor for direct ray,
'             alpha, and reflected ray, beta.
'   Inputs from common block:  ae, hdif, patfac, patrfac, psi
'             rmag, twoae
'   Inputs from argument list:  gamma, patfac, range, r1, r2, ruf
'   Outputs to common block:  alpha
'   Outputs to argument list:  alpha, beta, sinpsi, patd, dr
'   Subroutines called:  antpat, ruf
'   Subroutine called by:  oplimit, opticf

    patfac = 1
    alpha = (hdif/range) - (range/twoae)
    sinpsi = SIN(psi)
    CALL antpat(alpha, PATFAC)
    patd = patfac
    beta = -(gamma + psi)
    CALL antpat(beta, PATFAC)

'   Calculate surface roughness coefficient
    call ruff(sinpsi, RUF)
    divfac = 1 / (sqr(1.0 + (2.0*r1*r2/ae) / (range*sinpsi)))
    dr = patfac * ruf * divfac * rmag
END SUB
```

```
SUB opticf(r, FF) static

'   Process:  Calculates the optical path-length difference angle,
'             theta, by solving a cubic equation for the
'             reflection point range, r1.
'   Inputs from common block:  ae, aeth, ae2, h1, h2, ht, hr
'             polar$, thefac
'   Inputs from argument list:  dr, patd, phi, r
'   Outputs to common block:  psi
'   Outputs to argument list: ff, gamma, polar$, psi, r, r1, r2
'   Subroutines called:  opffac, ref
'   Subroutine called by:  FFACTR

   r1 = (h1 / (h1 + h2)) * r
   t = -1.5 * r
   v = .5 * r * r - aeth * (h1 + h2)
   w = aeth * r * h1
   epsr = 0.050
   dd = 2. * epsr
   jk = 1
   WHILE jk < 10 AND abs(dd) > epsr
      jk = jk + 1
      fr1 = r1^3 + (t * r1^2) + (v * r1) + w
      fpr1 = (3.0 * r1^2) + (2.0 * t * r1) + v
      dd = fr1/fpr1
      r1 = r1 - dd
      IF r1 < 0.0 OR r1 > r THEN r1 = r/2.0
   WEND
   r2 = r - r1
   htp = h1 - r1*r1/ae2
   hrp = h2 - r2*r2/ae2
   psi = 1.e-3 * htp / r1
   call ref(polar$, psi, PHI)
   theta = (thefac * htp * hrp / r) + phi
   IF ht >= hr THEN
      gamma = r2/ae
   ELSE
      gamma = r1/ae
   END IF
   call opffac(gamma, r, psi, r1, r2, PATD, DR)
   fsqrd = patd^2 + dr^2 + (2.0 * dr *patd * COS(theta))
   IF fsqrd < 1.e-7 THEN fsqrd = 1.e-7
   ff = -4.343 * LOG(fsqrd)
END SUB
```

```
SUB oplimit(OPMAXD, OPMAXL) static

'   Process:  Calculates the maximum range, opmaxd, in the optical
'             region and the loss at opmaxd.
'   Inputs from common block:  ae, ae2, del, hr, ht, pi, polar$
'             rllim, rlmin
'   Inputs from argument list:  dr, patd, r, rl, r2, theta
'             thetalim
'   Outputs to common block:  exloss, rllim, rlmin
'   Outputs to argument list: gamma, opmaxd, opmaxl, polar$, r, rl
'             r2, thetalim
'   Subroutines called: gtheta, opffac, rliter
'   Subroutine called by:  FFACTR


'   Initial guess for rl (for wavelength/4 limit based on grazing
'   angle limit, rllim).
    rl = rllim

'   theta value at 1/4 wavelength limit, horizontal polarization
    rtheta = 1.5 * Pi

    call rliter("H", rtheta, R1, R2, R)
    IF rllim > rl THEN rl = rllim   'grazing angle limit applies
    rllim = rl
    IF rllim < rlmin THEN rlmin = 0.5 * rllim

    IF del > 0 THEN
       call gtheta(polar$, rllim, R, THETALIM, R2)
       thetalpk = 2.0 * Pi
       call gtheta(polar$, rlmin, R, THETA, R2)
       IF thetalpk > theta THEN thetalpk = theta
       IF del < 10.25 THEN
          thetalim = thetalim + del/10.25 * (thetalpk - thetalim)
       ELSE
          thetalim = thetalpk
       END IF
       call rliter(polar$, thetalim, R1LIM, R2, R)
    END IF

    rl = rllim
    call gtheta(polar$, rl, R, THETA, R2)
    IF ht >= hr THEN
       gamma = r2/ae
    ELSE
       gamma = rl/ae
    END IF
```

```
   call opffac(gamma, r, psi, r1, r2, PATD, DR)
   fsqrd = patd^2 + dr^2 + (2.0 * dr* patd * COS(theta))
   IF fsqrd < 1.e-7 THEN fsqrd = 1.e-7
   opmaxd = r
   opmaxl = -4.343 * LOG(fsqrd)        ' -20 * LOG10(F)
   exloss = -8.686 * LOG(patd)
END SUB



'  ***************************************************************

SUB rliter(p$, rtheta, R1, R2, R)  static

'  Process:  Finds reflection point range "r1" corresponding to
'            an angle "rtheta"
'  Inputs from common block:  horiznl
'  Inputs from argument list:  f, f1, p$, r, r1, r2, rtheta
'  Outputs to common block:  None
'  Outputs to argument list:  p$, r, r1, r2,
'  Subroutines called:  gtheta
'  Subroutine called by:  oplimit

   irlmda = 0
   dd = r1
   WHILE abs(dd) > 0.001 AND irlmda < 100
      call gtheta(p$, r1, R, F, R2)
      call gtheta(p$, r1+0.001, R, F1, R2)
      fp = (f1 - f) / 0.001
      dd = (rtheta - f) / fp
      irlmda = irlmda + 1
      IF dd > -r1 THEN
         IF dd + r1 <= horiznl THEN
            r1 = r1+dd
         ELSE
            r1 = (r1+horiznl)/2.0
         END IF
      ELSE
         r1 = r1/2.0
      END IF
   WEND
END SUB
```

```
SUB ref(p$, psi, PHI) static

'   Process:  Calculates magnitude, rmag, and phase lag, phi, of
'             the reflection coefficient
'   Inputs from common block:  pi, rn2.imag, rn2.real
'   Inputs from argument list:  p$, psi
'   Outputs to common block: rmag
'   Outputs to argument list:  phi
'   Subroutines called:  None
'   Subroutine called by: gtheta, opticf

    rmag = 1.0
    phi = PI
    IF p$ <> "H" THEN
       sinpsi = SIN(psi)
       y = rn2.imag
       x = rn2.real - COS(psi)^2
       rmagroot = (x^2 + y^2)^0.25
       angroot = ATN(y/x) / 2.0
       root.real = rmagroot * COS(angroot)
       root.imag = rmagroot * SIN(angroot)
       at = rn2.real * sinpsi - root.real
       ct = rn2.real * sinpsi + root.real
       bt = rn2.imag * sinpsi - root.imag
       dt = rn2.imag * sinpsi + root.imag
       refv.real = (at*ct + bt*dt) / (ct^2 + dt^2)
       refv.imag = (bt*ct - at*dt) / (ct^2 + dt^2)
       rcv = sqr(refv.real^2 + refv.imag^2)
       IF refv.real <> 0.0 THEN
          phiv = ATN(refv.imag/refv.real)
          IF refv.real < 0.0 THEN phiv = phiv + PI
       ELSE
          IF refv.imag < 0.0 THEN phiv = -PI / 2.0
          IF refv.imag > 0.0 THEN phiv = PI / 2.0
          IF refv.imag = 0.0 THEN phiv = 0.0
       END IF
       phiv = -phiv
       IF phiv < 0.0 THEN phiv = phiv + 2.0*PI
       rmag = rcv
       phi = phiv
       IF p$ = "C" THEN
          rx = SQR(1.0 + rcv^2 + (2.0 * rcv * COS(PI - phiv)))
          rmag = rx / 2.0
          a = rcv * SIN(phiv + PI) / rx
          a = ATN(a / SQR(1 - a^2))
          phi = PI - a
          phi = -phi
          IF phi < 0.0 THEN phi = phi + 2*PI
       END IF
    END IF
END SUB
```

```
SUB ruff(sinpsi, RUF) static

'   Process:  Calculates the surface-roughness coefficient as a
'             function of psi
'   Inputs from common block:  hbar, hbfreq, psi
'   Inputs from argument list:  sinpsi
'   Outputs to common block:  Nonne
'   Outputs to argument list:  ruf
'   Subroutines called:  None
'   Subroutine called by:  opffac

    ruf = 1.0
    IF hbar <> 0.0 THEN
       hfpsi = hbfreq * psi * .159155
       IF hfpsi <= 0.11 THEN
          ruf = EXP((-2) * (hbfreq*sinpsi)^2)
       ELSEIF hfpsi <= 0.26 THEN
          ruf = 0.5018913 - SQR(0.2090248 - (hfpsi-0.55189)^2)
       ELSE
          ruf = 0.15
       END IF
    END IF
END SUB



'   ************************************************************

SUB sbd(r, SBDLOSS)  static

'   Process:  Calculate surface-based duct loss
'   Inputs from common block:  exloss, fofz, rsbd, rsbdloss, sbdht
'   Inputs from argument list:  r
'   Outputs to common block:  None
'   Outputs to argument list:  sbdloss
'   Subroutines called:  None
'   Subroutine called by:  difint, FFACTR

    IF sbdht = 0.0 THEN
       sbdloss = 1000.0
    ELSE
       IF r < rsbd THEN
          sbdloss = rsbdloss + (rsbd - r) + exloss
       ELSE
          sbdloss = fsterm + 8.686*log(r) - fofz + exloss
       END IF
    END IF
END SUB
```

```
SUB skipzone static

   Process:  Calculates skip-zone range if a surface-based duct
'            is present and calculates the range to the start
'            of the diffraction region.
'  Inputs from common block:  ae, fsterm, rlmin, sbdht
'  Inputs from argument list:  fofz
'  Outputs to common block:  rsbd, rsbdloss, rsubd
'  Outputs to argument list:  h2
'  Subroutines called: hgain
'  Subroutine called by:  FFACTR

   rsbd = 0
   och = 0.9 * sbdht
   IF h1 < och AND h2 < och THEN
      dmdh = 0.001 / ae
      delm2 = och * dmdh * 2.0
      gtrap = och * dmdh / (0.1*sbdht)
      alpha0 = sqr(delm2)
      ray0 = alpha0 / gtrap
      alphat = sqr(delm2 - (och-h1) * 2.0 * dmdh)
      ray1 = ray0 + (alpha0 - alphat)/dmdh
      alphar = sqr(delm2 - (och-h2) * 2.0 * dmdh)
      ray2 = ray0 + (alpha0 - alphar) / dmdh
      rsbd = (ray1 + ray2) / 1000     'SBD start range, km
      IF rsbd < rlmin THEN rsbd = rlmin

'     determine the height-gain function for surface-based
'     duct.  Note!  The variable "DUMMY" contains the height-
'     gain function for an evaporation duct which is not used
'     in this subroutine.
      call hgain(h2, FOFZ, DUMMY)
      rsbdloss = fsterm + 8.686*log(rsbd) - fofz
   END IF
END SUB
```

```
SUB tropo(r, TLOSS) static

'   Process:  Calculate the troposcatter loss based upon Yeh with
'             frequency-gain factor, h0, from NBS 101
'   Inputs from common block:  ae, exloss, f3, h1, h14pil, h2
'             h24pil, horizn, rns2, rnsterm, tfac, tsub1, tsub2
'   Inputs from argument list:  r
'   Outputs to argument list:  tloss
'   Subroutines called:  None
'   Subroutine called by:  dloss

    tsub0 = r / ae
    ttot = tsub0 - tsub1 - tsub2
    zeta = ttot/2.0 + tsub1 + (h1 - h2) / (1000.0*r)
    chi = ttot/2.0 + tsub2 + (h2 - h1) / (1000.0*r)
    rsub1 = h14pil * ttot
    rsub2 = h24pil * ttot
    IF rsub1 < 0.1 THEN rsub1 = 0.1
    IF rsub2 < 0.1 THEN rsub2 = 0.1
    s = zeta / chi
    IF s > 10.0 THEN s = 10.0
    IF s < 0.1  THEN s = 0.1
    q = rsub2 / (s*rsub1)
    IF q > 10.0 THEN q = 10.0
    IF q < 0.1  THEN q = 0.1
    hsub0 = (s * r * ttot) / (1 + s)^2
    etas = 0.5696*hsub0 * (1 + rnsterm * EXP(-3.8e-6 * hsub0^6))
    IF etas > 5.0  THEN etas = 5.0
    IF etas < 0.01 THEN etas = 0.01
    csub1 = 16.3 + 13.3 * etas
    csub2 = 0.4 + 0.16 * etas
    h0r1 = csub1 * (rsub1 + csub2)^-1.333
    h0r2 = csub1 * (rsub2 + csub2)^-1.333
    h0 = (h0r1 + h0r2) / 2.0
    delh0 = 1.13 * (0.6 - 0.434*LOG(etas)) * LOG(s) * LOG(q)
    IF delh0 > h0 THEN h0 = 2.0 * h0 ELSE h0 = h0 + delh0
    IF h0 < 0.0 THEN h0 = 0.0
    tloss = 114.9+tfac*(r-horizn) + 4.343*LOG(r^2*f3) - rns2 + h0
    tloss = tloss + exloss
END SUB
```

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13. ABSTRACT (Maximum 200 words)

The purpose of this document is to introduce the contents and operation of the Engineer's Refractive Effects Prediction System (EREPS), Revision 2.0. EREPS is a system of individual stand-alone IBM/PC-compatible programs that have been designed to assist an engineer in properly assessing electromagnetic (EM) propagation effects of the lower atmosphere on proposed radar, electronic warfare, or communication systems. The EREPS models account for effects from optical interference, diffraction, tropospheric scatter, refraction, evaporation and surface-based ducting, and water-vapor absorption under horizontally homogeneous atmospheric conditions.

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