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## Specification for a Standard Electromagnetic Propagation Model

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## **ADMINISTRATIVE INFORMATION**

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## 1.0 INTRODUCTION

A standard electromagnetic (EM) propagation model has been developed at the Naval Ocean Systems Center. It provides the user with a method of assessing EM propagation from 100 MHz to 20 GHz in the marine environment for a variety of atmospheric conditions. The software implementation of the model returns the pattern propagation factor in decibels when a user supplies the model with the proper environmental and EM system inputs. The pattern propagation factor is defined as the ratio of the actual electric field at some point to the field that would exist at that point under free-space propagation conditions. Free-space propagation is the propagation of energy that would occur if an omnidirectional point-radiating source were placed in outer space. The radiated energy would travel outward in all directions, the wave fronts propagating away from the source with the same velocity in all directions. Obviously these conditions would not be satisfied if the point source was placed in the near-earth environment. Refraction by the atmosphere ensures that the energy is not propagated with the same velocity in all directions, and the surface of the earth can intercept and reflect some portion of the energy. If the functional form of the pattern propagation factor is known, then the propagation loss is known, since the calculation of the free-space loss is simple. The pattern propagation factor is also useful because it appears in the radar-range equation and can be used to assess radar system performance. The model is described in this report in detail and an ANSI Fortran program using the model is provided. The program that implements the model can be either incorporated into an application model that requires EM propagation information or used as a stand-alone program.

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## 2.0 INPUTS, OUTPUTS, AND LIMITS

### 2.1 INPUTS

A number of EM system and environmental inputs are required to determine the pattern propagation factor. The necessary EM system parameters are given in Table 2-1. The required environmental inputs are provided in Table 2-2. The antenna beamwidth and elevation angle parameters of Table 2-1 are not required for an omnidirectional antenna type.

Table 2-1. Required EM system inputs.

| Parameter                             | Units | Valid Input Range                                                                           |
|---------------------------------------|-------|---------------------------------------------------------------------------------------------|
| Frequency                             | MHz   | 100.0 to 20,000.0                                                                           |
| Height of Transmitting Antenna        | m     | 1.0 to 100.0                                                                                |
| Radar Target/ Receiver Antenna Height | m     | 1.0 to 30000.0                                                                              |
| Transmitting Antenna Polarization     | n/a   | Horizontal, vertical or circular                                                            |
| Transmitting Antenna Type             | n/a   | Omnidirectional, $\sin(x)/x$ cosecant-squared, height-finder, specific system height-finder |
| Antenna Beamwidth                     | deg   | > 0 to 45.0                                                                                 |
| Antenna Elevation Angle               | deg   | -10.0 to 10.0                                                                               |
| Range                                 | km    | 1 to 1000.0                                                                                 |

Table 2-2. Required environmental inputs.

| Parameter                                                                         | Units | Valid Input Range |
|-----------------------------------------------------------------------------------|-------|-------------------|
| Evaporation Duct Height                                                           | m     | 0.0 to 40.0       |
| Surface Wind Speed                                                                | kt    | 0.0 to 50.0       |
| Height Array — 2 to 30 Elements                                                   | m     | 0.0 to 10000.0    |
| M-unit Array — Each Element Corresponding to the Like-Number Height Array Element | M     | 0.0 to 2000.0     |

## **2.2 OUTPUTS**

The only output is the calculated pattern propagation factor (in decibels) for the specified inputs of Tables 2-1 and 2-2. Sample program outputs for a variety of environmental and EM system inputs are presented in Section 4.0.

## **2.3 LIMITS**

The standard propagation model described in this document will return a value of the pattern propagation factor in decibels for EM system operational parameters within the range of validity of the inputs of Table 2-1 and for environmental inputs within the range of validity of Table 2-2.

### 3.0 STANDARD PROPAGATION MODEL

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 free-space path loss for isotropic antennas, expressed in terms of frequency, is

$$L_{fs} = 32.44 + 20 \log (r) + 20 \log (f) \quad (1)$$

for  $r$  in kilometers and  $f$  in megahertz.

If nonisotropic antenna radiational patterns are considered within the loss calculations, the loss is referred to as *propagation loss* rather than path loss. The propagation loss can be described with the aid of the *pattern 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. For simplicity, the term *propagation factor* is used throughout this document to refer to the pattern propagation factor. Thus, the effects of the transmitter antenna pattern are implied in all calculations. Symbolically the propagation factor,  $F$ , is given by

$$F = \frac{|E|}{|E_o|} \quad (2)$$

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 inhomogeneities 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 decibels), including antenna patterns, is equivalent to

$$L = L_{fs} - 20 \log (F) \quad (3)$$

Three regions require different methods for obtaining signal strength (or, equivalently, propagation factor or loss) as a function of range. The first region is called the optical interference, or optical, region and 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 propagation factor in this region is obtained by a linear interpolation between  $F$  values in the optical and diffraction regions.

The standard propagation model that will be presented here assumes a single-layer atmosphere. The assumption of a single-gradient atmosphere is somewhat restrictive, since nature does not always provide such a simple propagation medium. The basic assumption of the single-layer model is that refraction can be treated by assuming that the refractive bending of the EM rays can be accounted for by using an *effective earth radius* that is different (usually larger) than the true earth radius. Ray paths over such an earth would then appear to be straight lines rather than curved paths. To obtain an equivalent single-gradient atmosphere from an arbitrary one, a ray trace must be used. A ray is traced from the transmitter height to some arbitrarily distant point through the various atmospheric layers. The height at this range is then used to determine the equivalent single-gradient atmosphere that would be required to trace a ray to this range and height. This equivalent gradient is used to define an *effective earth radius* factor. The procedure is explained in more detail in Section 3.1.4.

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

### 3.1 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 Fig. 3-1. 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,  $\Theta$ , is given by

$$\Theta = \delta + \Phi \quad (4)$$

where  $\delta$  is the path-length difference and  $\Phi$  is the phase change caused by reflection from the surface. Here the assumption is made that the direct and sea-reflected rays have very nearly the same spatial direction, so 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:

$$F = \{f(\epsilon_1)^2 + [f(\epsilon_2) D R]^2 + 2 D R f(\epsilon_1) f(\epsilon_2) \cos(\Theta)\}^{1/2} \quad (5)$$

The  $f(\epsilon_i)$  factors describe the (normalized to 1) antenna pattern, and the angles,  $\epsilon_i$ , are shown in Fig. 3-1.  $D$  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,  $\Theta$ , changes by  $\pi$  and can assume values between 0 and 2.

The path-length difference,  $\delta$ , in radians, between the direct and reflected rays is given by

$$\delta = (4.193 f H_i' H_r' 10^{-5})/r \quad (6)$$

Here  $r$  is the total ground range, and  $H_i'$  and  $H_r'$  the effective antenna heights.  $H_i'$  and  $H_r'$  are shown in Fig. 3-1 and are given by

$$H_i' = H_i - (1000 r_1^2)/(2 a_e) \quad (m) \quad (7)$$

$$H_r' = H_r - (1000 r_2^2)/(2 a_e) \quad (m) \quad (8)$$

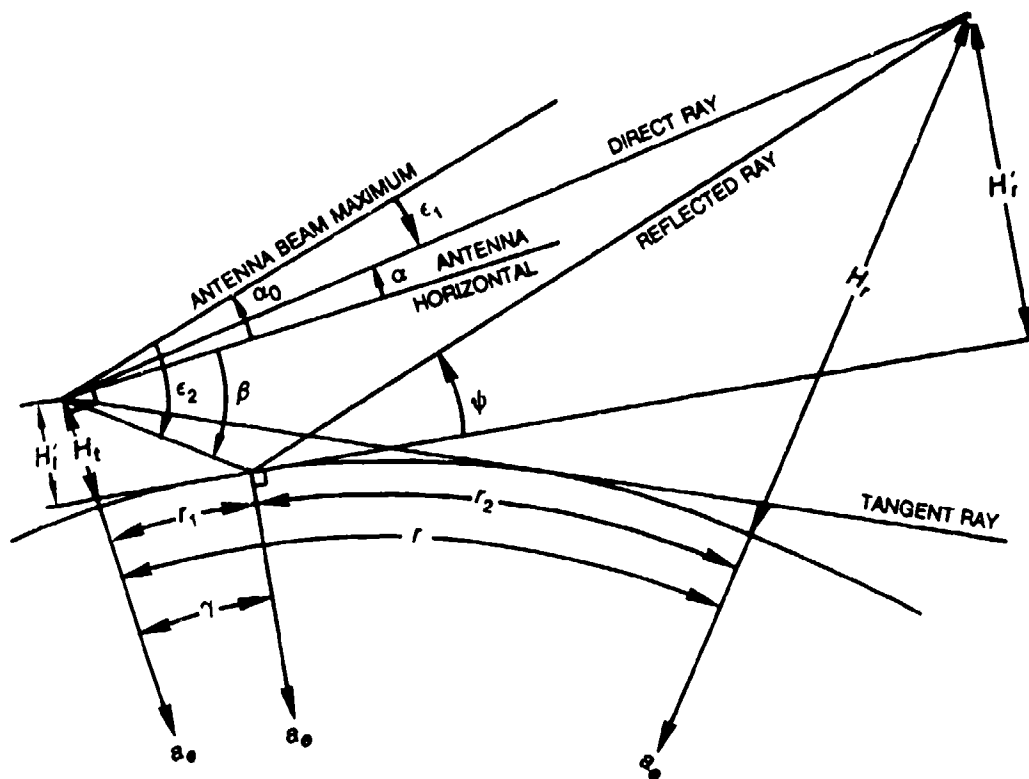


Figure 3-1. Two-path optical interference region.

where  $H_t$  and  $H_r$  are the transmitter and receiver/target heights, respectively.  $a_e$  is the effective earth radius which is defined as the effective earth radius factor,  $k$ , times the mean earth radius of 6371 km.  $r_1$  and  $r_2$  are the reflection point ranges.  $r_1$  can be determined by solving the cubic equation

$$2r_1^3 - 3rr_1^2 + [r^2 - 0.002a_e(H_t + H_r)]r_1 + 0.002a_eH_tr = 0 \quad (9)$$

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

$$r_1 = r/2 - p \cos[(\xi + \pi)/3] \quad (10)$$

where

$$p = \{(4/3)[0.001a_e(H_t + H_r) + (r/2)^2]\}^{1/2} \quad (11)$$

and

$$\xi = \cos^{-1} \{[0.002a_e(H_r + H_t)r]/p^3\} \quad (12)$$

The antenna pattern factors,  $f(\epsilon_i)$ , require angular information about the angles  $\alpha$  and  $\beta$ , as shown in Fig. 3-1. The magnitude,  $R$ , and phase shift,  $\Phi$ , require knowledge of the grazing angle,  $\psi$ . These angles, in radians, are

$$\alpha = 0.001 (H_r - H_i)/r - r/(2 a_e) \quad (13)$$

$$\psi = 0.001 H_i'/r_1 \quad (14)$$

$$\gamma = r_1/a_e \quad (15)$$

$$\beta = -\gamma - \psi \quad (16)$$

in terms of the variables shown in Fig. 3-1. The divergence factor can be calculated by using the equation

$$D = [1 + (2 r_1 r_2)/(r a_e \psi)]^{1/2} \quad (17)$$

Because Eq. 9 only applies for  $H_r \geq H_i$ , these terminal heights are normally swapped if  $H_r < H_i$ , for the calculation of  $r_1$  only. Equation 13 will give correct values of  $\alpha$  for the antenna pattern calculations if the true (unswapped) values of  $H_i$  and  $H_r$  are used in this calculation. However,  $r_1$  in Eq. 15 must be replaced with  $r_2$  to obtain the correct antenna pattern factor for the reflected ray if the terminal heights have been swapped.

### 3.1.1 Reflection Coefficient Models

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

$$R_H = 1 \quad (18)$$

$$\Phi_H = \pi \quad (19)$$

$$R_V = \frac{n^2 \sin(\psi) - [n^2 - \cos^2(\psi)]^{1/2}}{n^2 \sin(\psi) + [n^2 - \cos^2(\psi)]^{1/2}} \quad (20)$$

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

$$R_C = 0.5 [R_V^2 + R_H^2 + 2 R_V R_H \cos(\Phi_H - \Phi_V)]^{1/2} \quad (21)$$

$$\Phi_C = \Phi_H - \sin^{-1} [R_V \sin(\Phi_H + \Phi_V)/(2 R_C)] \quad (22)$$

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) by using the formulas

$$R = R_o \exp(-2 \{[2 \pi h \sin(\psi)]/\lambda\}^2) \quad (h\psi)/\lambda < 0.110 \quad (23)$$

$$R = R_o (0.5018913 - \{0.2090248 - [(h\psi)/\lambda] - 0.55819\}^2)^{1/2} \quad 0.110 \leq (h\psi)/\lambda \leq 0.260 \quad (24)$$

$$R = 0.15 R_o \quad (h\psi)/\lambda > 0.260 \quad (25)$$

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

$$h = 0.0051 W_s^2 \quad (26)$$

for wind speed ( $W_s$ ) in m/s.

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

$$n^2 = \epsilon - i(18,000 \sigma)/f \quad (27)$$

where  $\epsilon$  and  $\sigma$  are the ordinary dielectric constant and conductivity, respectively, of seawater, and  $f$  is the EM system frequency in megahertz. The constants themselves are obtained as a function of frequency by using Blake's (1970) equations, as follows:

Case 1:  $f \leq 1500$

$$\epsilon = 80 \quad (28)$$

$$\sigma = 4.3 \quad (29)$$

Case 2:  $1500 < f \leq 3000$

$$\epsilon = 80 - 0.00733(f - 1500) \quad (30)$$

$$\sigma = 4.3 + 0.00148(f - 1500) \quad (31)$$

Case 3:  $3000 < f \leq 10,000$

$$\epsilon = 69 - 0.00243(f - 3000) \quad (32)$$

$$\sigma = 6.52 + 0.001314(f - 3000) \quad (33)$$

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

### 3.1.2 Antenna Pattern Factor Models

The remaining terms in Eq. 5,  $f(\epsilon_i)$ , the normalized antenna pattern factors, are determined as a function of the antenna pattern type, beamwidth, and pointing angle. Five different antenna types can be used: omnidirectional,  $\sin(x)/x$ , cosecant-squared, generic height-finder, and specific system height-finder. The specific system height-finder antenna type is not discussed here. Antenna patterns for these antennas can be implemented by replacing the antenna pattern functions with user-supplied data. 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  $\mu$ .

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

$$f(\mu) = \sin(x)/x \quad f(\mu) \geq 0.03, \quad -\mu_{max} \leq \mu \leq \mu_{max} \quad (34)$$

where

$$x = c \sin(\mu - \mu_0) \quad (35)$$

and  $\mu_0$  and  $\mu_{max}$  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  $\mu = \mu_0 \pm BW/2$ , where  $BW$  is the beamwidth. This normalization ensures that the antenna half-power points  $\{20 \log[f(\mu)] = -3 \text{ dB}\}$  occur at  $\mu = \mu_0 \pm BW/2$ , which is the usual definition of the beamwidth of the antenna. That is

$$c = 1.39157/\sin(BW/2) \quad (36)$$

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

$$\mu_{max} = \mu_0 \pm \tan^{-1}[A/(1+A)^{1/2}] \quad (37)$$

where  $A = \pi/c$ , 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 substituting the direct ray angle,  $\mu$ , for the elevation angle,  $\mu_0$ . Then  $f(\mu) = 1$  for all values,  $\mu$ , 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 by using

$$f(\mu) = 1 \quad \mu_0 \leq \mu \leq \mu_0 + BW \quad (38)$$

$$f(\mu) = \sin(BW)/\sin(\mu) \quad \mu > \mu_0 + BW \quad (39)$$

$$f(\mu) = [1 - (\mu_0 - \mu)/BW] \quad f(\mu) \geq 0.03, \quad \mu < \mu_0 \quad (40)$$

This antenna pattern is different from the  $\sin(x)/x$  antenna, 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 so that the first two equations above would describe the direct ray angles below the elevation angle  $\mu_0$ . The third equation would then describe the beam taper above the elevation angle. The antenna orientation is not optional, and the antenna is always assumed to be that of a surface-based system.

### 3.1.3 Ray Trace Models

The standard propagation model obtains the required value of the effective earth radius factor,  $k$ , by means of a ray trace. The model allows the user to input an  $M$ -unit-versus-height profile, which is used in performing the ray trace. The ray trace equations are based on small-angle approximations to Snell's law and on the assumption of a linear variation of modified refractivity,  $M$ , with height up to 30 vertical segments. The trace of an individual ray begins with an elevation angle specified at some initial height and range and consists of a series of calculations to determine a series of height and range points along the ray trajectory. The  $M$ -unit profile is constructed so that the  $M$ -unit value at the surface and a zero-meter height are the first elements in the profile arrays. The remainder of the  $M$ -unit profile has a height array of ascending heights, in meters, and 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

$$dMdh_i = 10^{-3}(M_{i+1} - M_i)/(H_{i+1} - H_i) \quad (41)$$

where  $M_i$  denotes the  $M$ -unit array and  $H_i$  the height array elements, respectively. Negative values of  $dMdh_i$  indicate trapping layers. A standard atmosphere (4/3 earth) gradient is usually defined for the gradient above the highest height array element, that is,  $dMdh_k = 0.000118$ , where  $k$  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.

A critical launch angle can be determined for transmitter heights within ducts. This critical angle is defined as the minimum positive launch angle *not* trapped in the duct. The positive critical angle is given by

$$\alpha_c = 10^{-3}[2(M_{H_i} - M_{min})]^{1/2} + 10^{-5} \quad (42)$$

while the minimum negative critical angle is equal to  $-\alpha_c$ . Here  $M_{H_i}$  is the  $M$ -unit value at the transmitter and  $M_{min}$  is the minimum  $M$ -unit value at some height greater than  $H_i$ . If  $H_i$  is in a duct, then the duct is treated as a surface-based duct even if it does not extend to the surface. The height where  $M_{min}$  occurs is the height of the surface-based duct.  $H_i$  must be in the duct for Eq. 42 to be valid, though if  $H_i$  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 ray trace 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 3-2 illustrates a ray with a positive launch angle, but the equations also apply to negative launch angles when proper attention is paid to the layer indices and

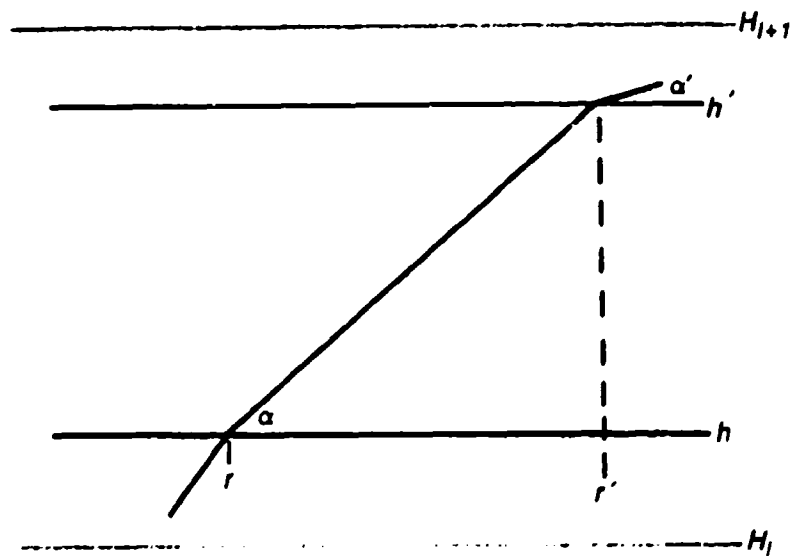


Figure 3-2. Ray trace variables.

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,  $\alpha \neq 0$

$$\alpha' = [\alpha^2 + 0.002 dMdh_i (h' - h)]^{1/2} \quad (43)$$

$$r' = r + (\alpha' - \alpha)/dMdh_i \quad (44)$$

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

$$\alpha' = \alpha + dMdh_i (r' - r) \quad (45)$$

$$h' = h + (\alpha'^2 - \alpha^2)/(0.002 dMdh_i) \quad (46)$$

Case 3:  $\alpha'$  known

$$r' = r + (\alpha' - \alpha)/dMdh_i \quad (47)$$

$$h' = h + (\alpha'^2 - \alpha^2)/(0.002 dMdh_i) \quad (48)$$

If the radicand of Eq. 43 is negative, there is no solution for the given height,  $h'$ , since the ray has reached a maximum (or, in the case of a Jowngoing ray, a minimum) height less (or greater) than  $h'$ . In this case, the range and height of the ray maximum (minimum) are given by

$$r' = r - \alpha/dMdh_i \quad (49)$$

$$h' = h - \alpha^2/(0.002 dMdh_i) \quad (50)$$

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 43 through 50 can be iteratively used to trace ray paths through the user-specified stratified atmosphere.

### 3.1.4 Effective Earth Radius Model

The ray trace equations are used to trace a ray through the specified atmosphere to determine the value of the effective earth radius factor,  $k$ , since  $k$  is only defined for a single-layer atmosphere. A ray with a launch angle  $\alpha = 0$ , or  $\alpha = \alpha_c$  if the transmitter is in a duct, is traced to 370 km (200 nmi). The ray height at that range is compared to the height a ray would reach in a standard atmosphere to calculate a value of  $k$ . The single-layer equivalent  $M$ -unit gradient is given by

$$Q = -(2\alpha)/370 + (0.002 \Delta H)/(370)^2 \quad (51)$$

where  $\Delta H$  is the terminal height of the ray at 370 km minus the launch height,  $H_i$ , and  $\alpha$  is the ray launch angle. Then  $k$  is defined as

$$k = 1/(Q a) \quad 1 \leq k \leq 5 \quad (52)$$

where  $a$  is the mean earth radius of 6371 km. In a standard atmosphere,  $k = 4/3$ .

### 3.1.5 Optical Region Limits

The expression for  $F$  in Eq. 5 is valid for all values of  $\Theta$  so that the path-length difference,  $\delta$ , is greater than or equal to one-quarter wavelength ( $\pi/2$  radians), or 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

$$\psi_{lim} = \tan^{-1} [0.001 \lambda / (2 \pi a_e)]^{1/3} \approx (0.01957)/(k f)^{1/3} \quad (53)$$

where  $\psi$  is the grazing angle,  $\lambda$  is the wavelength in meters,  $a_e$  is the effective earth radius, and  $f$  is the frequency in megahertz.

The optical region maximum range may be reduced from that calculated for the applicable optical region limit above if the surface-based duct height is not zero. If the transmitter is in a surface-based duct, then the end of the optical region must correspond to a direct-ray elevation angle greater than or equal to the critical angle,  $\alpha_c$ . If the value of the elevation angle,  $\alpha$ , corresponding to the quarter-wavelength or grazing angle limit value of  $\Theta$ , above, is not greater than  $\alpha_c$ , then the optical region limit is taken to be the first optical region peak ( $\Theta = 2\pi, 4\pi$ , etc.) that is associated with a value of  $\alpha$  greater than  $\alpha_c$ . This range is determined by finding the value of  $\Theta$  as a function of  $\alpha_c$ .  $\Theta(\alpha_c)$  can be obtained by using the ray trace equations to find the range corresponding to  $\alpha_c$ , that is

$$r(\alpha_c) = \{[\alpha_c^2 + 0.002(H_t - H_i)/a_e]^{1/2} - \alpha_c\}a_e \quad (54)$$

where  $dMdh_i = 1/a_e$  for the single-gradient atmosphere. Once the range is known, the value of  $\Theta$  is obtained by determining, in order, the reflection point range,  $r_1$ , the effective terminal heights, the path-length difference,  $\delta$ , the grazing angle,  $\psi$ , and the magnitude of phase change caused by reflection,  $\Phi$ . If  $\Theta(\alpha_c)$  is less than, or equal to,  $2\pi$  (the first optical region peak) and greater than the

quarter-wavelength or grazing angle limit, then  $\Theta(\alpha_c)$  is the optical region limit. If  $\Theta(\alpha_c)$  is greater than  $2\pi$ , then the next optical region peak with  $\Theta = n2\pi > \Theta(\alpha_c)$ ,  $n = 2, 3, 4$ , etc., is taken to be the end of the optical region. (This range is determined by decreasing the range from that of  $r(\alpha_c)$  and determining a new value of  $\Theta$  for each range until the desired range is found.) If both terminal heights are inside the surface-based duct, then the end of the optical region is defined by the quarter-wavelength or grazing angle limit as before.

### 3.2 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 caused by 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

$$r_d = r_{hor} + 230.2 (k^2/f)^{1/3} \quad (\text{km}) \quad (55)$$

where the horizon range is given by

$$r_{hor} = 3.572 [(k H_t)^{1/2} + (k H_r)^{1/2}] \quad (\text{km}) \quad (56)$$

for  $H_t$  and  $H_r$  in 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 propagation loss as a function of height and range for ranges and heights below the lower angular limit of the optical interference region. There are three models used to calculate loss in this region. If the surface-based duct height is zero, then the loss is calculated by using a model derived from the NOSC waveguide program. If a surface-based duct is present, an empirical model is used to calculate loss. At somewhat greater ranges, troposcatter loss is calculated by using a model taken from Yeh (1960). The model 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 ranges beyond  $r_d$  and added to the surface-based duct 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.

#### 3.2.1 NOSC Evaporation Duct Model

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

$$L = 51.1 + \Gamma - F_{zt} - F_{zr} + 10 \log(\rho) + \alpha \rho - L_d \quad (57)$$

The loss term,  $L_d$ , is determined by using

$$L_d = 20 \log [f(\mu)] \quad (58)$$

where the antenna pattern factor,  $f(\mu)$ , gives a measure of how much energy is directed toward the horizon and  $\mu$  represents the lowest direct ray angle in the optical region.  $\Gamma$  is the excitation factor,  $F_{zt}$  and  $F_{zt}$  the height-gain functions for the EM system transmitter and radar target/receiver, respectively,  $\rho$  the (scaled) range, and  $\alpha$  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 substituting Eq. 57 into Eq. 3.

The waveguide solutions 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 varies 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

$$R_N = 4.705 \cdot 10^{-2} f^{1/3} \quad (59)$$

and

$$Z_N = 2.214 \cdot 10^{-3} f^{2/3} \quad (60)$$

respectively, to scale the solutions at other frequencies to the 9.6-GHz values. The coefficients ensure that  $R_N = Z_N = 1$  when the frequency is set equal to 9600 MHz. When these scale factors are used, 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,  $\Delta$ , is equal to the actual evaporation duct height,  $\delta$ , times  $Z_N$ . Similarly, if  $r$  is the actual range and  $H_t$  the actual EM system transmitter height, then the scaled range,  $\rho$ , is  $R_N$  times  $r$  and the scaled transmitter height,  $z_t$ , is  $Z_N$  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 decibels) for scaled duct heights less than 10.25 meters may be written as

$$F(z) = C1 z^{C2} + C3 z^{C4} + C5 \quad z \geq 1.0 \quad (61)$$

where  $z$  is the scaled height of either the EM system transmitter or the radar target/receiver. The  $Ci$  are constants that are a function of the scaled duct height. For well-trapped modes (i.e., scaled duct heights between 10.25 and 23.3 meters), two functions are necessary to obtain the height-gains in decibels:

$$F(z) = C1 \ln[\sin(C2 z^{C3})] + C4 \quad 1.0 \leq z \leq Z_{max} \quad (62)$$

$$F(z) = C5 z^{C6} + C7 \quad z > Z_{max} \quad (63)$$

As before, the coefficients,  $C_i$ , are determined from the scaled duct height, and  $z$  is the scaled height of the EM system transmitter or radar target/receiver.  $Z_{max}$  is calculated by using the formula

$$Z_{max} = 4 e^{-0.31(\Delta-10.0)} + 6 \quad (64)$$

where  $\Delta$  is the scaled duct height. The coefficients for scaled duct heights less than 10.25 meters are calculated by using the following formulas:

$$C1 = (-2.2 e^{-0.244\Delta} + 17) 4.72^{-C2} \quad (65)$$

$$C2 = [4.062361 10^4 - (\Delta + 4.4961)^2]^{1/2} - 201.0128 \quad (66)$$

$$C3 = (-33.9 e^{-0.517\Delta} - 3) 4.72^{-C4} \quad (67)$$

$$C4 = [1.43012 10^4 - (\Delta + 5.32545)^2]^{1/2} - 119.569 \quad (68)$$

$$C5 = 41 e^{-0.41\Delta} + 61 \quad (69)$$

The coefficients for scaled duct heights between 10.25 and 23.3 meters are calculated by applying the following formulas:

$$C1 = -0.1189 \Delta + 5.5495 \quad (70)$$

$$C2 = \{1.3291 \sin [0.218(\Delta - 10)^{.77}] + 0.2171 \ln (\Delta)\} 4.72^{-C3} \quad (71)$$

$$C3 = 3/2 \quad (72)$$

$$C4 = 87 - [313.29 - (\Delta - 25.3)^2]^{1/2} \quad (73)$$

$$C5 = F_{max} / (Z_{max}^{-C6}) \quad (74)$$

$$C6 = (Z_{max} / 4.72) (S / F_{max}) \quad (75)$$

$$C7 = 49.4 e^{-0.1699(\Delta-10)} + 30 \quad (76)$$

where

$$S = 4.72 C1 C2 C3 (Z_{max})^{1/2} / \tan [C2 (Z_{max})^{C3}] \quad (77)$$

and

$$F_{max} = C1 \ln \{ \sin [C2 (Z_{max})^{C3}] \} + C4 - C7 \quad (78)$$

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. An example of height-gain curves for evaporation ducts is shown in Fig. 3-3.

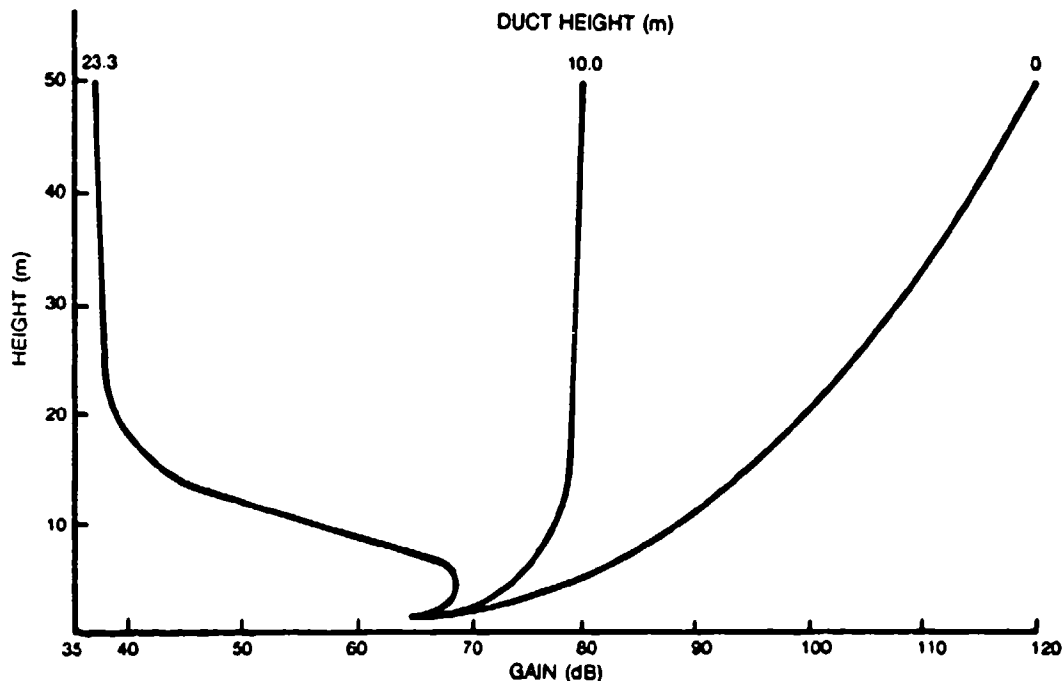


Figure 3-3. Example of 9.6-GHz height-gain curves.

Two factors from Eq. 57 remain to be specified,  $\Gamma$  and  $\alpha$ . The excitation factor, which is a measure of the relative strength of the mode, may be obtained, in decibels, by using

$$\Gamma = 216.7 + 1.5526 \Delta \quad \Delta \leq 3.8 \quad (79)$$

$$\Gamma = 222.6 - 1.1771(\Delta - 3.8) \quad \Delta > 3.8 \quad (80)$$

The attenuation rate in dB/km is

$$\alpha = \{92.516 - [8608.7593 - (\Delta - 20.2663)^2]^{1/2}\} \quad (81)$$

for values of  $\alpha \geq 0.0009$ , which is the lowest attenuation rate used. It is convenient to replace the attenuation rate term in Eq. 57,  $\alpha\rho$ , with  $\beta r$ , where  $r$  is the actual range and

$$\beta = \alpha R_N \quad (82)$$

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

### 3.2.2 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 decibels) may be written

$$L = C - F_{zr} + 20 \log(r) - L_d \quad (83)$$

where  $F_{zr}$  is the height-gain function for the receiver/target height and  $L_d$  is defined in Eq. 58. Here  $C$  (in decibels) is given by  $C = 32.44 + 20 \log(f)$ . 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 Eq. 83 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 the standard propagation model is always calculated for the terminal height, specified as the radar target/receiver height.  $F$  is obtained by substituting Eq. 83 into Eq. 3.

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,  $z$ , as follows:

Case 1:  $100 \leq f \leq 150$

$$F_{zr} = -60(z/D - 0.5)^2 \quad z/D < 0.8 \quad (84)$$

$$F_{zr} = 1.14(z/D)^{-0.26} - 10 \quad z/D \geq 0.8 \quad (85)$$

Case 2:  $150 < f \leq 350$

$$F_{zr} = 10 - 200(z/D - 0.5)^4 \quad z/D < 1.0 \quad (86)$$

$$F_{zr} = 7.5(z/D)^{-13.3} - 10 \quad z/D \geq 1.0 \quad (87)$$

Case 3:  $f > 350$

$$F_{zr} = 10 - 200(z/D - 0.5)^4 \quad z/D < 1.0 \quad (88)$$

$$F_{zr} = 12.5(z/D)^{-8} - 15 \quad z/D \geq 1.0 \quad (89)$$

Here  $D$  is the duct height. An example of the height-gain curves produced by these formulas is given in Fig. 3-4. The shapes of the height-gain curves are characteristic of well-trapped modes, as should be expected from a surface-based duct.

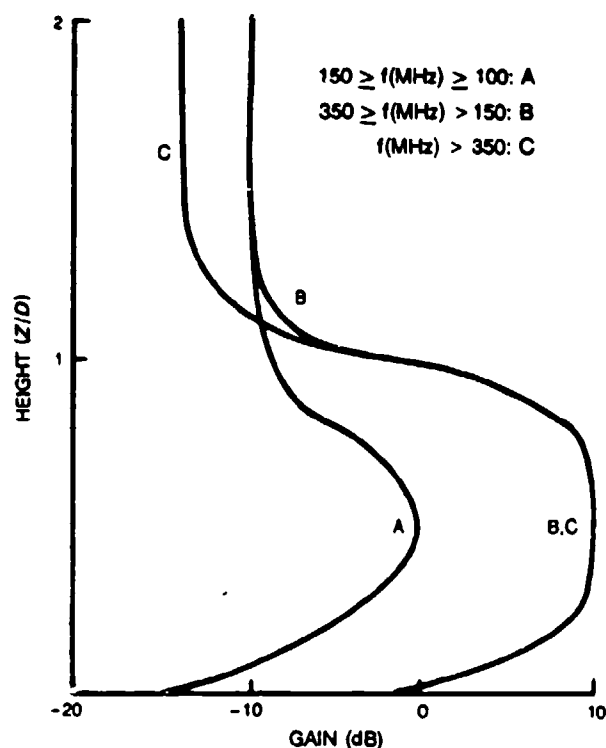


Figure 3-4. Height-gain curve for surface-based duct of arbitrary height.

### 3.2.3 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

$$L = 114.9 + 0.08984(r - r_{hor})/k + 20 \log(r) + 30 \log(f) - 0.2 N_s - L_d + H_o \quad (90)$$

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 Eq. 58.  $F$  is obtained by substituting Eq. 90 into Eq. 3.

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

$$h_o = (s r \Theta)/(1 + s)^2 \quad (\text{km}) \quad (91)$$

where  $r$  is the ground range,  $\Theta$  is the scattering angle, as shown in Fig. 3-5, and  $s$  is defined by

$$s = \zeta / \chi \quad 10.0 \geq s \geq 0.10 \quad (92)$$

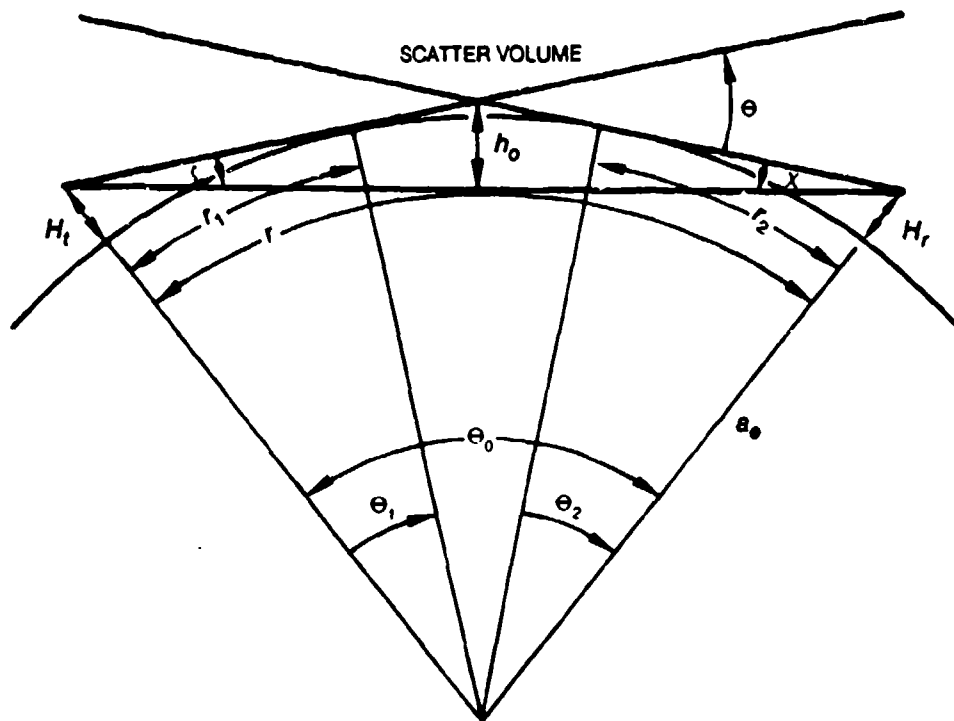


Figure 3-5. Geometry for troposcatter loss calculations.

The angles from these equations are given by

$$\Theta = \Theta_0 + \Theta_1 + \Theta_2 \quad (93)$$

$$\Theta_0 = r/a_e \quad (94)$$

$$\Theta_1 = r_1/a_e \quad (95)$$

$$\Theta_2 = r_2/a_e \quad (96)$$

$$\zeta = \Theta/2 + \Theta_1 + (H_t - H_r)/r \quad (97)$$

$$\chi = \Theta/2 + \Theta_2 + (H_r - H_t)/r \quad (98)$$

in terms of the effective earth radius,  $a_e$ , the tangent ray ranges,  $r_1$  and  $r_2$ , the terminal heights,  $H_t$  and  $H_r$ , and the total range,  $r$ , as shown in Fig. 3-5. The tangent ranges,  $r_1$  and  $r_2$ , are equal to

$$r_1 = (0.002 a_e H_t)^{1/2} \quad (\text{km}) \quad (99)$$

$$r_2 = (0.002 a_e H_r)^{1/2} \quad (\text{km}) \quad (100)$$

The frequency-gain function is then defined as

$$H_o = H_1 + \Delta H_o \quad H_o \geq 0.0 \quad (\text{dB}) \quad (101)$$

where

$$H_1 = [H_o(R_1) + H_o(R_2)]/2 \quad (102)$$

If  $\Delta H_o$  is greater than  $H_1$ , then  $H_o$  is equal to twice the value of  $H_1$ . The function  $H_1$  is calculated by using

$$H_o(R_1) = c_1 (R_1 + c_2)^{-4/3} \quad (103)$$

$$H_o(R_2) = c_1 (R_2 + c_2)^{-4/3} \quad (104)$$

where  $R_1$  and  $R_2$  are functions of the terminal heights and EM system frequency,  $f$ , in megahertz. These variables are calculated as follows:

$$R_1 = 0.0419 f H_t \Theta \quad (105)$$

$$R_2 = 0.0419 f H_r \Theta \quad (106)$$

And the terms  $c_1$  and  $c_2$  are defined as

$$c_1 = 16.3 + 13.3 \eta_s \quad (107)$$

$$c_2 = 0.40 + 0.16 \eta_s \quad (108)$$

The factor  $\eta_s$  must be calculated as a function of  $h_o$  in the following manner:

$$\eta_s = 0.5696 h_o [1 + (0.031 - 0.00232 N_s + 5.67 N_s^2 10^{-6}) \exp(-3.8 h_o^6 10^{-6})] \quad (109)$$

$$5.0 \geq \eta_s \geq 0.01$$

The remaining term,  $\Delta H_o$ , is calculated by using

$$\Delta H_o = 6 [0.60 - \log(\eta_s)] \log(s) \log(q) \quad (\text{dB}) \quad (110)$$

where  $q$  is given by

$$q = R_2/(s R_1) \quad 10.0 \geq q \geq 0.10 \quad (111)$$

The correction term  $\Delta H_o$  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  $\eta_s = 1.0$ .

### 3.3 STANDARD PROPAGATION MODEL FORTRAN PROGRAM

The standard propagation model is implemented in a program called FFACTR. FFACTR is written in ANSI Fortran 77 with the allowable MIL-STD-1753 extensions. FFACTR will return a single value for the propagation factor in decibels for the specified EM system and environmental parameters of Table 2-1 and Table 2-2. To use FFACTR, the operator must compile and link the routines that comprise the program. A complete list of all subroutines is included in the appendix. The subroutines are listed in alphabetical order following lists of the MAIN and FFACTR routines

and the common block "include" files. No EM system or environmental libraries are supplied with FFACTR, though a limited number of environmental and EM system data files are supplied for test purposes.

Because the standard propagation model is designed to return a single value for a collection of input data, FFACTR behaves more like a subroutine than a stand-alone program. A demonstration program, MAIN, which acts as a driver for the FFACTR program, is included to demonstrate one possible use of the program. The driver simulates an inbound radar target by supplying FFACTR with constant environmental and, except for the range, EM system parameters. The range decreases from 100 km to 10 km in 10-km increments. In addition to MAIN, several subroutines are provided which allow the operator to enter environmental and EM system data from the keyboard or files. These subroutines, SYSFIL, ENVFIL, ENVINP, and SYSINP, are not intended as part of the FFACTR program, but only for use in verifying the correct operation of the FFACTR program. The operational sequence of FFACTR is detailed in the following paragraphs.

First, the environmental and EM system data are entered and the FFACTR subroutine is called. FFACTR then calls the MPROF subroutine to process the  $M$ -unit, ( $M_i$ ), and height, ( $H_i$ ), array data and to construct the  $dMdh_i$  array. The profile is inspected for surface-based ducts by the DUCTS subroutine and, if one exists that contains the EM system transmitter height, the critical angle,  $\alpha_c$ , is calculated. Subroutines PUSH and INSRT are used by MPROF to insert an  $M$ -unit array value at the transmitter height. Upon return from the MPROF subroutine, the GETK subroutine is called to perform the raytrace that is used to obtain the effective earth radius factor. Next, several subroutines are called to initialize various constants required by the program. ANTPAR converts the EM system antenna parameters from degrees to radians and establishes the angular limits for the antenna patterns. OPCNST is used to initialize various constants used in the optical region processing, and DCONST performs the same task for the diffraction/troposcatter region calculations.

Once the initialization phase is completed, the next step is to determine if the input range is in the optical, intermediate, or diffraction region. Subroutine OPLIMIT is used to calculate the optical region maximum range and the value of  $L_d$  which is used to determine  $F$  in the diffraction and intermediate regions. OPLIMIT makes use of the ANTPAT, OPFFAC, RIITER, REF, and RUFF subroutines. OPFFAC is used to calculate most of the terms used in antenna pattern factors,  $f(\epsilon_i)$ . REF returns  $R$  and  $\Phi$ , and RUFF returns the surface roughness coefficient. RIITER is used to determine the reflection point range. If the input range is less than the optical region limiting range, subroutine OPTICF is called to determine the exact value of the pattern propagation factor,  $F$ , to be returned. This requires a solution to the cubic equation (Eq. 9) to determine the reflection point range. OPTICF uses a Newton iteration technique to determine the reflection point range and then utilizes OPFFAC, ANTPAT, REF, and RUFF to return the value of the pattern propagation factor,  $F$ .

If the input range is greater than the optical region maximum range, it is compared to  $r_d$ , the minimum range where the diffraction region calculations are valid. If the range value is greater than  $r_d$ , then the DIFF subroutine is used to determine the value of  $F$  for this region. DIFF obtains the appropriate  $F$  value by calling the HGAIN and TROPO subroutines. HGAIN returns the value of the height-gain function for both evaporation and surface-based ducts from elevated layers and TROPO returns  $F$  for the troposcatter region. DIFF calculates the value of  $F$  for either a surface-based duct or an evaporation duct. If a surface-based duct containing the transmitter exists, it is assumed to be the dominant propagation mechanism and  $F$  is calculated by using Eq. 83 and Eq. 3. If no surface-based duct exists, then  $F$  is determined by using Eq. 57 and Eq. 3. The diffraction region  $F$  is then compared to the troposcatter region  $F$ . If the troposcatter  $F$  value is within 18 dB,

the fields are added and the resulting  $F$  is returned. If the troposcatter  $F$  is 18 dB less than the diffraction  $F$  value, then troposcatter is the dominant propagation mechanism and the troposcatter  $F$  is returned.

If the input range is less than  $r_d$  and greater than the optical region maximum range, then the range is in the intermediate region and a linear interpolation of the propagation factor in decibels versus range is performed to obtain  $F$ . This is accomplished by calling the DIFF subroutine to obtain the value of  $F$  at  $r_d$ . Then, a linear interpolation between the value of  $F$  at the optical region maximum range, obtained from OPLIMIT, and  $F$  at  $r_d$  is performed to obtain the value of  $F$  at the specified range.

FFACTR is structured to return a single value of  $F$  for a given set of inputs. This structure is the most efficient one if the input data are going to vary for each case in some arbitrary fashion. This is not the case, for example, in the demonstration program, MAIN, where only the range varies. Since the environment and the rest of the EM system parameters remain constant for each call to FFACTR, there is a fair amount of redundancy in the calculation of the antenna pattern constants, the effective earth radius, and the optical and diffraction region constants. If FFACTR is always going to be used in such a fashion, it would be best to remove these calculations from FFACTR and place them in the calling routine. For example, if the environmental parameters are constant and the EM system height,  $H_t$ , is a constant, then the effective earth radius is also a constant. In this case, the DUCTS, GETK, INSRT, MPROF, and PUSH subroutines should be placed in the calling routine. If the EM system is fixed, then the antenna constants subroutine, ANTPAR, should be in the calling routine. If the environment is a constant and the only independent EM system variable is range, as in the MAIN routine supplied, then the DCONST, OPCNST, and OPLIMIT subroutines should also be placed in the calling routine. This would mean that ANTPAR, DCONST, DUCTS, GETK, INSRT, MPROF, OPCNST, and PUSH subroutines would only be called once for each environment and geometry instead of the multiple calls that occur for each range as the FFACTR routine is presently structured. If the environment is to remain constant, but both the radar target/receiver height and the range can vary in an arbitrary fashion, then the DCONST, OPCNST, and OPLIMIT subroutines would have to remain in FFACTR, but the others could be removed to the calling routine.

## 4.0 TEST CASES

A number of EM system and environmental inputs are required to determine the propagation factor. Table 4-1 lists EM system parameters for five test case systems, Sys1 through Sys5, which are used to verify the proper operation of the FFACTOR program. The input parameters that are listed correspond to the variable names of Section 3.0, except for the polarization and antenna type entries. Range is not listed as an EM system input in Table 4-1, since the demonstration program, MAIN, supplies a constantly decreasing range that varies from 100 km to 10 km in 10-km increments for each EM system and environmental data set selected. Three different environmental test case conditions, Env1 through Env3, are listed in Table 4-2. The environment of Env1 corresponds to a standard atmosphere *M*-unit profile, a 0-meter evaporation duct height, and 10 knots of wind. Env2 uses the same *M*-unit profile as Env1, but the wind speed is 0 knots, and a 10-meter evaporation duct is present. Env3 has an *M*-unit profile that contains a 100-meter surface-based duct, 0-meter evaporation duct, and 5 knots of wind. The environmental data sets also list the parameters using the variable names of Section 3.0. Each of the EM system test cases uses each of the environments.

Table 4-1. EM system test set input data.

| Parameter                 | Sys1    | Sys2   | Sys3   | Sys4   | Sys5     |
|---------------------------|---------|--------|--------|--------|----------|
| $f$ , MHz                 | 100.0   | 300.0  | 5000.0 | 9600.0 | 15,000.0 |
| $H_r$ , m                 | 20.0    | 30.0   | 20.0   | 1.0    | 50.0     |
| $H_s$ , m                 | 30000.0 | 2000.0 | 20.0   | 20.0   | 120.0    |
| Polarization <sup>a</sup> | H       | V      | C      | H      | H        |
| Antenna Type <sup>b</sup> | S       | C      | H      | S      | O        |
| $BW$ , deg                | 10.0    | 10.0   | 2.0    | 2.0    | n/a      |
| $\mu_o$ , deg             | 0.0     | 1.0    | 0.0    | 1.0    | n/a      |

<sup>a</sup>H = horizontal

V = vertical

C = circular

<sup>b</sup>S =  $\sin(x)/x$

C =  $\csc^2$

H = generic height-finder

O = omnidirectional

Table 4-2. Environmental test set input data.

| Parameter           | Env1              | Env2              | Env3              |
|---------------------|-------------------|-------------------|-------------------|
| $\delta$ , m        | 0.0               | 10.0              | 0.0               |
| $W$ , kt            | 10.0              | 0.0               | 5.0               |
| $H_1, M_1$ , (m, M) | (0.0, 339.0)      | (0.0, 339.0)      | (0.0, 350.0)      |
| $H_2, M_2$ , (m, M) | (1000.0, 457.0)   | (1000.0, 457.0)   | (270.0, 381.9)    |
| $H_3, M_3$ , (m, M) | (10000.0, 1519.0) | (10000.0, 1519.0) | (300.0, 340.0)    |
| $H_4, M_4$ , (m, M) | n/a               | n/a               | (1000.0, 422.6)   |
| $H_5, M_5$ , (m, M) | n/a               | n/a               | (10000.0, 1484.6) |

Tables 4-3 through 4-5 list the expected output data for the different environmental test cases. The outputs, in decibels, are listed to the nearest 0.1 dB, and the FFACTOR program is considered to be operating correctly if the output is within 0.1 dB of the value listed in the appropriate table.

Table 4-3 Output data for environment 1.

| Range (km) | F(dB) |      |       |       |       |
|------------|-------|------|-------|-------|-------|
|            | Sys1  | Sys2 | Sys3  | Sys4  | Sys5  |
| 100.0      | -37.2 | -0.6 | -56.1 | -62.5 | -58.0 |
| 90.0       | -25.2 | -5.7 | -55.5 | -61.8 | -50.2 |
| 80.0       | -39.4 | -1.6 | -54.9 | -61.2 | -28.1 |
| 70.0       | -25.8 | 2.4  | -54.1 | -60.5 | -4.7  |
| 60.0       | -25.3 | 1.4  | -49.9 | -59.8 | 0.8   |
| 50.0       | -44.6 | -2.1 | -37.1 | -59.0 | 2.7   |
| 40.0       | -47.4 | 1.0  | -23.1 | -53.7 | 2.7   |
| 30.0       | -26.2 | 1.0  | -9.1  | -38.2 | 0.3   |
| 20.0       | -49.8 | 1.0  | 3.5   | -22.6 | -11.7 |
| 10.0       | -43.2 | -0.1 | -1.6  | -7.7  | -4.0  |

Table 4-4. Output data for environment 2.

| Range (km) | F(dB) |      |       |       |       |
|------------|-------|------|-------|-------|-------|
|            | Sys1  | Sys2 | Sys3  | Sys4  | Sys5  |
| 100.0      | -37.1 | -0.6 | -39.3 | -25.5 | -11.3 |
| 90.0       | -25.1 | -5.7 | -33.7 | -22.9 | -11.8 |
| 80.0       | -39.3 | -1.6 | -28.1 | -20.4 | -8.1  |
| 70.0       | -25.7 | 2.5  | -22.5 | -18.0 | -1.1  |
| 60.0       | -25.1 | 1.4  | -17.0 | -15.6 | 0.8   |
| 50.0       | -44.6 | -2.1 | -11.9 | -13.4 | 2.7   |
| 40.0       | -47.9 | 1.0  | -7.3  | -11.3 | 2.8   |
| 30.0       | -25.9 | 1.0  | -2.8  | -11.1 | 0.6   |
| 20.0       | -61.7 | 1.0  | 3.5   | -12.2 | -18.9 |
| 10.0       | -44.3 | -0.1 | -1.6  | -7.7  | -24.7 |

Table 4-5. Output data for environment 3.

| Range (km) | F(dB) |      |      |       |      |
|------------|-------|------|------|-------|------|
|            | Sys1  | Sys2 | Sys3 | Sys4  | Sys5 |
| 100.0      | -41.7 | -5.1 | 2.9  | 0.1   | 5.6  |
| 90.0       | -24.8 | -4.0 | 2.9  | 0.1   | 1.8  |
| 80.0       | -44.1 | -0.9 | 2.9  | 0.1   | 1.5  |
| 70.0       | -26.0 | 2.8  | 2.9  | 0.1   | -4.9 |
| 60.0       | -25.4 | 0.2  | 2.1  | 0.1   | 0.5  |
| 50.0       | -50.5 | -1.2 | 1.3  | 0.1   | 5.0  |
| 40.0       | -55.4 | 0.5  | 0.5  | -3.2  | 4.6  |
| 30.0       | -25.7 | 0.8  | -0.3 | -7.9  | 5.3  |
| 20.0       | -54.0 | 0.9  | 5.1  | -12.7 | 5.6  |
| 10.0       | -43.6 | -0.1 | 1.6  | -6.6  | 0.6  |

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# Appendix

## STANDARD PROPAGATION MODEL PROGRAM LISTING

```

c ***** MAIN PROGRAM *****
c
c INPUTS:      VARIABLE      VARIABLE DESCRIPTION      (VALID RANGE, UNITS)
c
c EM SYSTEM:   freq          SYSTEM FREQUENCY          (100 - 20000 MHz)
c              ht            TRANSMITTER ANTENNA HEIGHT (1 - 100 m)
c              hr            RECEIVER/TARGET HEIGHT     (1 - 30000 m)
c              polar         ANTENNA POLARIZATION       (HORIZONTAL = "H",
c                                  VERTICAL = "V", CIRCULAR = "C")
c              antype        ANTENNA TYPE              (OMNIDIRECTIONAL = "O",
c                                  SIN(X)/X = "S", COSECANT-SQUARED = "C",
c                                  GENERIC HT-FINDER = "H")
c              bwidth        ANTENNA BEAM WIDTH         (.5 - 45 DEG)
c              elevat        ANTENNA ELEVATION ANGLE    (-10 - +10 DEG)
c                                  (0 DEGREES IS HORIZONTAL, NORMAL POINTING
c                                  ANGLE FOR SHIPBOARD RADAR SYSTEMS)
c              r             RANGE AT WHICH F-FACTOR IS DESIRED (1-1000km)
c
c ENVIRONMENTAL:
c              delta         EVAPORATION DUCT HEIGHT     (0 - 40 m)
c              height(i)     HEIGHT ARRAY IN METERS - UP TO 30 ELEMENTS
c              munits(i)     M-UNIT ARRAY CORRESPONDING TO HEIGHT ARRAY
c              wind          WIND SPEED                 (0 - 50 KNOTS)
c
c PROGRAM OUTPUT:
c              ff            20*LOG10( PATTERN PROPAGATION FACTOR ) dB
c                                  [ff values that are positive indicate a
c                                  signal level above the free-space field
c                                  at that range. Negative values indicate
c                                  signal levels below the free-space field.]
c
c The following program is a demonstration driver for the FFACTOR
c (sub)routine. This program is included to show possible uses for
c the FFACTOR program. The FFACTOR program returns a value (in dB)
c of 20*LOG(F) where F is the pattern propagation factor. F is
c defined as the ratio of the actual field at some point, to
c the free-space field at that same point. (The free-space field
c is determined for an isotropic antenna.) Because FFACTOR can be
c called in any arbitrary fashion it is not necessarily the most
c efficient structure for producing a product such as a loss-versus-
c range plot. If only the range is to be varied, with constant
c terminal heights, then the ANTPAR, DCONST, DUCTS, GETK, INSRT,
c MPROF, OPCNST and PUSH subroutines should be moved to the calling
c routine so they aren't called for every new range point.
c
c START DEMO PROGRAM
c
c include 'envsys.common'
c
c real*4 ff, r, rloss
c integer*2 ZW
c
c Enter the environmental parameters.
c
c call envinp(delta, height, Munits, wind, nmax)
c
c Enter the EM system parameters.

```

```

c      call sysinp(freq,ht,hr,polar,antype,bwidth,elevat)
c
c      fsterm = 32.45 + 20.0 * ALOG10(freq)
c      dr = 10.0
c      r = 100.0 + dr
c
c      Call FFACTR for the EM system and environmental parameters
c      entered above. Calculate the propagation factor for several
c      ranges in the loop below. Print the output values of prop-
c      agation factor and propagation loss for each range.
c
c      ZW = 6
c      DO i = 1, 10
c          r = r - dr
c          call ffactr(r, FF)
c          rloss = fsterm + 20.0 * ALOG10(r) - ff
c          write(ZW,1000) r,rloss,ff
1000  Format('Range = ',f5.1,' km. Loss = ',f6.2,' dB', ' F = ',
1      f6.1,' dB')
c      END DO
c
c      END DEMO PROGRAM
c
c      END

```

```

c
c Subroutine ffactr
c
c FFACTR returns the value of the pattern propagation factor, F, in dB
c for specified range , EM system parameters and environmental para-
c meters.
c
c Variables:      Description:
c
c   alphac        Critical angle - 1st angle not trapped in surface-
c                  based duct.
c   antbwr        Antenna vertical beamwidth in radians.
c   antelr        Antenna elevation angle in radians.
c   antfac        Antenna pattern constant.
c   antype        Antenna type: O = omnidirectional, S = sin(x)/x,
c                  C = cosecant-squared, H = height-finder.
c   bwidth        Antenna vertical beam width in degrees.
c   delta         Evaporation duct height in meters.
c   deltaf        Variable used in linear interpolation of F in the
c                  intermediate region.
c   dffac         Diffraction field constant, dB.
c   difac         Diffraction field constant, dB.
c   elevat        Antenna elevation angle in degrees.
c   elmaxr        Maximum elevation angle in main beam of antenna, rad.
c   ff            Pattern propagation factor, F, in dB.
c   freq          EM system operating frequency in MHz.
c   frsubd        Pattern propagation factor at rsubd.
c   fzs          Evaporation duct height-gain at hr, dB.
c   fzt          Evaporation duct height-gain at ht, dB.
c   height        Array containing environmental input height values
c                  corresponding to the Munit array.
c   hdiff         Height difference between receiver/target and
c                  transmitter heights in km.
c   ht            Transmitter height in m.
c   hr            Receiver/target height in m.
c   h1            Lower height of hr, ht, in m
c   h2            Higher height of hr, ht, in m.
c   lvlant        Transmitter height level in hmrs and dMdh arrays.
c   Munits        Array containing environmental input M-unit values.
c   nmax          Integer number of layers in Munits and height arrays.
c   opmaxd        Maximum range in the optical interference region, km.
c   opmaxf        F at opmaxd.
c   patrfac       Antenna pattern constant.
c   pd            Path-difference between direct and sea-reflected rays.
c   polar         Antenna polarization: H = horizontal, V = vertical,
c                  C = circular.
c   psi           Grazing angle in radians.
c   r             Range in km.
c   rsdfac        Constant used to calculate rsubd.
c   rsubd         Minimum range where diffraction field solutions are
c                  applicable, km.
c   sbdht         Surface-based duct height, m.
c   theta         Total phase difference between direct and sea-
c                  reflected rays including phase lag due to reflection.
c   wind          Wind speed in kts.
c

```

```

SUBROUTINE ffactr(r, FF)

```

```

c
c   real*4 deltaf, ff, fzs, fzt, opmaxd, opmaxf, frsubd, r
c   real*4 dMdh(32), hmrs(32)
c   integer*2 lvlant, ntot
c

```

```

include 'ffac.common'
include 'envsys.common'

c      Call mprof to insert a profile level at Ht and determine if
c      any surface-based ducts are present.  If a surface-based duct
c      is present calculate critical angle, alphac.
c
1 call mprof(height, Munits, ht, NMAX, ALPHAC, DMDH, HMRS,
      SBDHT, NTOT)

c      Call getk to determine the effective earth radius factor, rk.
c
c      call getk(alphac, dMdh, hmrs, ntot, ht, RK)

c      Define h1, h2 for opticf subroutine.  These are swapped for
c      ht>hr because the iteration loop for rl in opticf works most
c      efficiently when the lowest height is the transmitter height.
c
IF (ht .GT. hr) THEN
  h1 = hr
  h2 = ht
ELSE
  h1 = ht
  h2 = hr
END IF

c      Define optical region constants.
c      call openst
c      hdif = (hr - ht) * 1.0e-3
c      Initialize antenna parameters.
c      call antpar(antype,bwidth,elevat,ANTBWR,ANTEL,ANTFAC,
1          ELMAXR,PATRFAC)

c      Define diffraction/troposcatter region constants.
c      call dconst
c      call hgain(hr, FZR)
c      IF (sbdht .EQ. 0.0) THEN
c        call hgain(ht, FZT)
c        dffac = dffac - fzt
c      END IF
c      difac = dffac - fzs
c      rsubd = 3.572 * (SQRT(rkmin * ht) + SQRT(rkmin * hr)) + rsdfac
c      Determine maximum range and f-factor in optical region.
c      call oplimit(OPMAXD,OPMAXF)
c      IF (r .GE. rsubd) THEN
c        Calculate loss for range in diffraction/troposcatter region.
c        call diff(r, FF)
c      ELSE
c        IF (r .GT. opmaxd) THEN
c          Range is in intermediate region - use linear interpolation
c          on log of the f-factor.
c          call diff(rsubd,FRSUBD)
c          deltaf = (r - opmaxd) * (opmaxf - frsubd) / (opmaxd-rsubd)
c          ff = opmaxf + deltaf
c        ELSE
c          Range is in the optical interference region.
c          IF (r .LE. opmaxd) call opticf(polar,r,PD,PSI,THETA,FF)
c        END IF
c      END IF
c      ff = - ff
c      RETURN
c      END

```

```

c      'envsys.common' include file
c
c      EM system parameter common blocks
c
common / emsystem / freq, hr, ht
common / emsystem / polar, antype, bwidth, elevat
c
c      Environmental parameter common blocks
c
common / enviro / delta, height, Munits, nmax, wind
c
c
real*4 delta, height(30), Munits(30), wind
real*4 freq, ht, hr, bwidth, elevat
character*1 antype, polar
integer*2 nmax
c

c
c      'ffac.common' include file
c
common / comffactr / ae, ae2, aeth, alpha, alphac, antbwr
common / comffactr / antelr, antfac, atten
common / comffactr / c1, c2, c3, c4, c5, c6, c7
common / comffactr / del, dffac, difac, elmaxr, exloss
common / comffactr / fsterm, hbar, hbfreq, hdif, hmin, hl
common / comffactr / h2, horznl, patd, patrfac, rk, rkmin
common / comffactr / rnimag, rnreal, rsdfac, rsubd, sbdht
common / comffactr / thefac, twoae, zfac, zmax

real*4 ae, ae2, aeth, alpha, alphac, antbwr, antelr, antfac,
1      atten, c1, c2, c3, c4, c5, c6, c7, del, dffac, difac,
2      elmaxr, exloss, fsterm, hbar, hbfreq, hdif, hmin,
3      horznl, hl, h2, patd, patrfac, rk, rkmin, rnimag,
4      rnreal, rsdfac, rsubd, sbdht, thefac, twoae, zfac, zmax
c

```

```

C
C Subroutine antpar
C
C ANTPAR is used to initialize antenna parameters for use in
C calculating antenna pattern factors.
C
C Variable:      Description:
C
C   Antbwr      Antenna beam width in radians.
C   Antelr      Antenna elevation angle in radians.
C   Antfac      Antenna pattern constant.
C   Antype      Antenna type:  O - omnidirectional
C                           S - Sin(x)/x
C                           C - Cosecant-squared
C                           H - generic Height-finder
C   Bwidth      Antenna beam width, degrees.
C   Elevat      Antenna elevation angle, degrees.
C   Elmaxr      Maximum angle in main beam of antenna, radians.
C   Patrfac     Pattern factor constant for Sin(x)/x antennas,
C               used to calculate Elmaxr for Sin(x)/x antennas.
C
C   SUBROUTINE antpar(antype,bwidth,elevat,ANTBWR,ANTEL,R,ANTFAC,
1      ELMAXR,PATRFAC)
C
C   real*4 antbwr, antelr, antfac, amax, bwidth, elmaxr,
1      elevat, pi, patrfac, patrfac
C   character*1 antype
C
C   PI = 3.14159
C   Convert beam width and elevation angle to radians.
C   antbwr = 1.745e-2*bwidth
C   antelr = 1.745e-2*elevat
C   elmaxr = 1.047
C   IF (antype .NE. "O") THEN
C     IF (antype .EQ. "C") THEN
C       Cosecant-squared antenna pattern constants.
C       elmaxr = antelr + .78525
C       antfac = SIN(antbwr)
C     ELSE
C       IF ((antype .EQ. "S").OR.(antype .EQ. "H"))THEN
C         Sin(x)/x and height-finder antenna pattern constants.
C         antfac = 1.39157/SIN(antbwr/2.0)
C         amax = PI/antfac
C         patrfac = -ATAN(amax/SQRT(1.0 - amax*amax))
C         IF (antype .EQ. "S") elmaxr = antelr - patrfac
C       END IF
C     END IF
C   END IF
C   RETURN
C   END

```

```

c
c Subroutine antpat
c
c ANTPAT returns the antenna pattern factor for a given angle
c and antenna type.
c
c Variable:      Description:
c   alpha        Direct r-y launch angle, radians.
c   antbwr        Antenna beam width in radians.
c   antelr        Antenna elevation angle in radians.
c   antfac        Pattern constant.
c   angle         The angle for which the pattern factor is desired.
c   antype        Antenna pattern type: 0 - omnidirectional
c                                     S - sin(x)/x
c                                     C - cosecant-squared
c                                     H - generic height-finder
c   patfac        The antenna pattern factor for the given angle.
c   patrfac       Pattern constant.
c
c
c SUBROUTINE antpat(antype,alpha,antbwr,antelr,antfac,patrfac,
1      angle,PATFAC)
c
c
c   real*4 alpha, alpha0, antbwr, antelr, antfac, angle, apat,
1      patfac, patrfac, ufac
c   character*1 antype
c
c   patfac = 1.0
c   IF (antype .NE. "0") THEN
c       Antenna types other than omni require calculation.
c       IF ((antype .EQ. "H").AND.(alpha .GT. antelr)) THEN
c           alpha0 = alpha
c       ELSE
c           alpha0 = antelr
c       END IF
c       apat = angle - alpha0
c       IF (antype .EQ. "C") THEN
c           Cosecant-squared antenna type.
c           patfac = AMIN1(1.0, AMAX1(0.03, 1.0 + apat/antbwr))
c           IF (apat.GT.antbwr) patfac = SIN(antbwr)/SIN(ABS(apat))
c       ELSE
c           SIN(X)/X antenna type.
c           IF (apat .NE. 0.0) THEN
c               IF ((angle .LE. alpha0 + patrfac) .OR.
1              (angle .GE. alpha0 - patrfac)) THEN
c                   Antenna pattern is limited to main lobe only.
c                   patfac = 0.03
c               ELSE
c                   Sin(x)/x calculation.
c                   ufac = antfac*SIN(apat)
c                   patfac = AMIN1(1.0, AMAX1(0.03, SIN(ufac)/ufac))
c               END IF
c           END IF
c       END IF
c   END IF
c   RETURN
c   END

```

```

c
c Subroutine dconst
c
c DCONST initializes variables for the diffraction and troposcatter
c region routines.
c
c Variable:      Description:
c   arg          Evaporation duct model temporary variable.
c   atten        Diffraction region attenuation rate in dB/km.
c   c1 - c7      Evaporation duct constants for height-gain function.
c   del          Scaled evaporation duct height (delta * zfac).
c   delta        Evaporation duct height, m.
c   dffac        Diffraction field constant in dB.
c   fmax         Evaporation duct model temporary variable.
c   freq         EM system frequency in MHz.
c   fsterm       Free-space loss term, dB.
c   gamma        Evaporation duct excitation factor in dB.
c   hmin         Minimum allowable height, m.
c   rfac         Evaporation duct range scale factor.
c   rk           Effective earth radius factor.
c   rkmin        Minimum rk used for calculation of the diffraction
c               region minimum range, rsubd.
c   rsdfac       Constant used for rsubd calculation.
c   sbdht        Surface-based duct height, m.
c   zfac         Evaporation duct height scale factor.
c   zmax         Evaporation duct height variable. Height where the
c               two different equations for the height-gain factors
c               must be equal (del >= 10.25 meters).
c
c SUBROUTINE dconst
c
c   real*4 arg, fmax, gamma, rfac, slope
c
c   include 'ffac.common'
c   include 'envsys.common'
c
c   Diffraction region constants.
c
c   IF (sbdht .GT. 0.0) THEN
c
c     Surface-based duct model.
c
c     del = 0.0
c     hmin = 1.0
c     atten = 0.0
c     dffac = fsterm
c
c   ELSE
c
c     The following terms are for NOSC evap duct model.
c
c     rfac = 0.04705 * freq**(1./3.)
c     zfac = 0.002214 * freq**(2./3.)
c     hmin = 1.0
c     del = AMIN1(delta * zfac, 23.3)
c
c     Constants for scaled evap. duct heights >= 10.25 meters.
c
c     c1 = -0.1189 * del + 5.5495
c     c3 = 3./2.
c     c2 = 1.3291 * SIN(0.218 * (del-10.0)**0.77) + 0.2171*ALOG(del)
c     c2 = c2 * 4.72**(-c3)

```

```

c4 = 87.0 - SQRT(313.29 - (del - 25.3)**2)
zmax = 4.0 * EXP(-0.31*(del - 10.0)) + 6.0
arg = c2 * zmax**c3
slope = 4.72 * c1 * c2 * c3 * SQRT(zmax) / TAN(arg)
c7 = 49.4 * EXP(-0.1699*(del - 10.0)) + 30.0
fmax = c1 * ALOG(SIN(arg)) + c4 - c7
c6 = (zmax/4.72) * slope / fmax
c5 = fmax / zmax**c6
ELSE
c
c      Constants for scaled evap. duct heights <= 10.25 meters.
c
c2 = SQRT(40623.61 - (del + 4.4961)**2) - 201.0128
c1 = (-2.2 * EXP(-0.244*del) + 17.0)*4.72*(-c2)
c4 = SQRT(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
atten = 92.516 - SQRT(8608.7593 - (del - 20.2663)**2)
IF (atten .LT. 0.0009) atten = 0.0009
atten = atten * rfac
IF (del .LE. 3.8) gamma = 216.7 + del * 1.5526
IF (del .GT. 3.8) gamma = 222.6 - (del - 3.8) * 1.1771
dffac = 51.1 + gamma + 10.0 * ALOG10(rfac)
END IF
c
c      Constants used to calculate rsubd, the minimum
c      range at which the diffraction field solutions are valid.
c
rkmin = AMAX1(rk, 1.3333)
rsdfac = 230.2 * (rkmin**2 / freq)**(1.0/3.0)
c
RETURN
END

c
c Subroutine diff
c
c Subroutine DIFF returns the diffraction field propagation factor
c as a function of range.
c
c VARIABLES:      DESCRIPTION:
c   atten         NOOSC model attenuation rate in dB/km
c   delta         Evaporation duct height in meters
c   dfloss        - 20*LOG(F), where F is the propagation factor
c   dloss         Diffraction field strength in dB
c   dif           Temporary variable
c   difac         NOOSC evaporation duct model constant
c   diffe         NOOSC evaporation duct model loss in dB
c   exloss        Antenna loss for lowest angle in optical region (dB)
c   r             range in km
c   tloss         Troposcatter loss from Tropo Subroutine in dB
c
c SUBROUTINE diff(r, DFLOSS)
c

```

```

      real*4    dif, dfloss, dloss, diffe, r, tloss, tlr
c
      include 'ffac.common'
      include 'envsys.common'
c
      tlr = 10.0*ALOG10(r)
      IF (sbdht .EQ. 0.0) THEN
c          Calculate the evaporation duct loss.
          dloss = difac + tlr + atten*r
      ELSE
c          Calculate the surface based duct loss.
          dloss = difac + 2.0*tlr
      END IF
      dloss = dloss + exloss
c
c          Calculate troposcatter loss and compare to dloss. If the
c          difference is +/- 18 dB add the two fields together.
c
      call tropo(r,tloss)
      dif = dloss - tloss
      IF (dif .GE. 18.0) THEN
c          Troposcatter field dominates.
          dloss = tloss
      ELSEIF (dif .GE. -18.0) THEN
c          Add troposcatter and diffractions fields together.
          dloss = dloss - 10.0*ALOG10(1.0 + 10.0**(dif/10.0))
      END IF
c
c          -20*LOG(F) = actual loss - free space loss
c
      dfloss = dloss - fsterm - 2.0*tlr
      RETURN
      END

```

```

c
c  Subroutine ducts
c
c  DUCTS builds an array containing the top, bottom, and
c  minimum refractivity of all the major ducts in the
c  atmosphere refractivity profile.
c
c  Variable:      Description:
c    dct          3,* duct parameters array.
c                 1,n bottom of duct 'n', meters.
c                 2,n top of duct 'n', meters.
c                 3,n minimum refractivity of duct 'n', M-units.
c    lvls         Number of refractivity level in rmu, rhts.
c    ndcts        in: the maximum number of ducts allowed.
c                 out: the number of ducts found.
c    nq           Duct counter.
c    rht          Height array, meters.
c    rmu          Modified refractivity, M-unit array, elements
c                 correspond to like-number elements of rht array.
c
c
c

```

```

SUBROUTINE ducts(rmu,rht,lvls,DCT,NDCTS)
c
c      real*4 dct,delu,delh,deltu,hbot,htop,rht(32),rmu(32)
c      integer*2 lvls,ibot,iduct,iend,iq,itop,ndcts,nq
c      dimension dct(3,8)
c
c      Locate all major ducts
c      nq=0
c      iq=3*ndcts
c      itop=lvls
c      iend=ndcts
c      ndcts=0
c      DO iduct=1,iend
c
c          Look for top of next duct
c      1010  continue
c           htop=rht(itop)
c           if(itop.eq.1) go to 1060
c           ibot=itop-1
c           if(rmu(itop).le.rmu(ibot)) go to 1020
c           itop=itop-1
c           go to 1010
c
c          Look for bottom of the duct
c      1020  continue
c           hbot=rht(ibot)
c           if(rmu(ibot).lt.rmu(itop)) go to 1030
c           if(ibot.eq.1) go to 1040
c           ibot=ibot-1
c           go to 1020
c
c          Calculate bottom of duct using linear interpolation
c      1030  continue
c           delu=rmu(ibot+1)-rmu(ibot)
c           delh=rht(ibot+1)-rht(ibot)
c           deltu=rmu(itop)-rmu(ibot)
c           if(delu.lt.0.01) go to 1040
c           hbot=rht(ibot) + deltu*delh/delu
c
c          Store duct parameters in array dct
c      1040  continue
c           amu=rmu(itop)
c           call push(dct,iq,nq,amu)
c
c           call push(dct,iq,nq,htop)
c           call push(dct,iq,nq,hbot)
c           ndcts=iduct
c           itop=ibot
c           END DO
c
c      1060 continue
c           RETURN
c           END

```

```

c
c Subroutine envfil
c
c ENVFIL lists the available environmental files and allows the
c user to select one. The selected environmental file is read
c and closed. The data from the file is returned to the calling
c routine.
c
c Variable:      Description:
c   delta        Evaporation duct height in m.
c   height       Array of up to 30 elements containing the heights
c                of the M-unit profile.
c   levels       The number of levels in the height, Munits arrays.
c   Munits       Array of up to 30 elements containing the M-unit
c                values of the upper-air profile.
c   wind         Wind speed in knots.
c
c
c   SUBROUTINE envfil(delta, height, Munits, wind, levels)
c
c   real*4 delta, height(30), Munits(30), wind
c   integer*2 levels, ZR, ZW
c   character*12 filename
c
c   Initialize read, write channels
c   ZR = 5
c   ZW = 6
c
c   write (ZW, '(' Available Environmental Files: ')')
c   List all files beginning with "E".
c   call system ('ls [E]* l>&2'//char(0))
c   write (ZW, '(/, "Enter input file name: ", $)')
c   read (ZR, '(a12)') filename
c   open (10, FILE=filename)
c
c   Read wind speed in knots and evaporation duct height in m.
c   read (10, '(f4.1)') delta
c   read (10, '(f4.1)') wind
c   Read the number of levels in M-unit profile.
c   read (10, '(i2)') levels
c   Read the height and M-unit profile array values.
c   DO i=1, levels
c     read (10, '(2f10.1)') height(i), Munits(i)
c   END DO
c   Close environmental file.
c   close(10)
c
c   RETURN
c   END

```

```

c
c Subroutine envinp
c
c Subroutine ENVINP prompts the user to enter environmental parameters
c and returns. Environments can be entered over the keyboard or from
c a file. If the environment is entered over the keyboard it can be
c saved in a file for future use.
c
c Variable:      Description:
c   delta      Evaporation duct height in m.
c   height     Array of up to 30 elements containing the heights
c               of the M-unit profile.
c   levels     The number of levels in the height, Munits arrays.
c   Munits     Array of up to 30 elements containing the M-unit
c               values of the upper-air profile.
c   wind       Wind speed in knots.
c
c
c   SUBROUTINE envinp(Delta, Height, Munits, Wind, Levels)
c
c   real*4 delta, height(30), Munits(30), wind
c   character*20 A, dummy, filename
c   integer*2 k, kt, levels, ZW, ZR
c
c   Specify the read (5) and write (6) channel numbers.
c   ZW = 6
c   ZR = 5
c
c   Initialize environmental parameters.
c   wind = 0.0
c   delta = 0.0
c   levels = 2
c   DO i = 1,30
c     height(i) = 0.0
c     Munits(i) = 0.0
c   END DO
c
c   Enter the environmental data parameters.
c   write(ZW,('Enter environmental data parameters. You may enter'))
c   write(ZW,('up to 30 layers or enter data from a file. '))
c
c   Select environmental file.
c   write(ZW,('Enter data from a file? (yes or no) ', $))
c   read(ZR, '(A)') dummy
c   IF ((dummy(1:1) .eq. 'y').or.(dummy(1:1) .eq. 'Y')) THEN
c     call envfil(delta, height, Munits, wind, levels)
c   ELSE
c     write(ZW,('Adjcent layers must have different M-values and'))
c     write(ZW,('at least two layers are required. '))
c
c     height(1) = 0.0
c     Munits(1) = 0.0
c     write(ZW,1000)
1000  format(/, 'Enter M-unit Profile - (Height in meters, M-units)'
1      /, 'Starting height is at surface (0 meters) ')
c
c   DO loop to enter profile data (Height and Munit arrays).
c
c   DO i = 1, 30
100  write(zw,('Enter height in meters (or end) ', $))
c     read(zr, '(A)') dummy
c     IF ((dummy(1:1) .EQ. 'e').OR.(dummy(1:1) .EQ. 'E')) goto 200
c     k = 1
c     kt = 1
c     DO WHILE((kt .eq. 1) .and. (k .le. 20))
c       IF (dummy(k:k) .EQ. ' ') dummy(k:k) = '.'

```

```

        IF (dummy(k:k).EQ.'.') kt = 0
        k = k + 1
    END DO
    IF (i .gt. 1) THEN
        read(dummy,'(f10.2)')height(i)
        IF (height(i) .LE. height(i-1)) THEN
1010         write(zw,1010)
            format('Heights must increase, re-enter height ')
            goto 100
        END IF
    END IF
    levels = 1
    write(zw,'(" Enter M-unit value at level ",$)')
    read(zr,'(A)')dummy
    k = 1
    kt = 1
    DO WHILE((kt .EQ. 1) .AND. (k .LE. 20))
        IF (dummy(k:k).EQ.'.') dummy(k:k) = '.'
        IF (dummy(k:k).EQ.'.') kt = 0
        k = k + 1
    END DO
    read(dummy,'(f10.2)')Munits(i)
    IF ((i .NE. 1) .AND. (Munits(i) .EQ. Munits(i-1))) THEN
        Munits(i) = Munits(i) + 0.1
    END IF
200  END DO
    continue
    write(ZW,1020)
c
1020  format('Enter evaporation duct height in meters (0 to 40) ', $)
    read(ZR,*) delta
    IF (delta .LT. 0.0) delta = 0.0
    IF (delta .GT. 40.0) delta = 40.0
c
    write(ZW,1030)
1030  format('Enter wind speed in knots (0 to 50) ', $)
    read(ZR,*) wind
    IF (wind .LT. 0.0) wind = 0.0
    IF (wind .GT. 50.0) wind = 50.0
c
    write(ZW,'("Do you wish to store this environment in a file?",
1    " (yes or no) ", $)')
    read(zr,'(A)')dummy
    IF ((dummy(1:1) .eq. 'y').or.(dummy(1:1) .eq. 'Y')) THEN
        write (ZW,'(" Current Environmental Files: ")')
        call system ('ls [E]* 1>&2'//char(0))
        write (ZW, 1040)
1040  format("Enter file name (First letter MUST be E) ", $)
        read (ZR,'(a12)') filename
        open (10,FILE=filename)
c
c    Write wind speed in knots and evaporation duct height in m.
        write(10, '(f4.1)') delta
        write(10, '(f4.1)') wind
c    Write the numbers of levels in M-unit profile.
        write(10, '(i2)') levels
        DO i=1, levels
            write(10, '(2f10.1)') height(i), Munits(i)
        END DO
c        close file
        close(10)
    END IF
c
END IF

```

c

RETURN  
END

c

Subroutine getk

c

Subroutine GETK is used to determine the effective earth radius factor k. Getk accomplishes this by tracing a ray from the transmitter height to 200 NMi (370 km). The ray launch angle is 0 deg. if no surface-based duct exists, or alphac, the critical angle if one does.

c

| Variable: | Description:                                                                              |
|-----------|-------------------------------------------------------------------------------------------|
| alphac    | Critical angle necessary to escape duct. If alphac = 0 then no surface-based duct exists. |
| a0        | Initial ray launch angle, radians.                                                        |
| al        | Ray angle at top of layer, radians.                                                       |
| deld      | Range difference, km.                                                                     |
| delh      | Height difference, meters.                                                                |
| delM      | M-unit difference.                                                                        |
| delmdh    | M-unit gradient.                                                                          |
| dMdh      | M-unit gradient array.                                                                    |
| hlast     | Height at 370 km.                                                                         |
| hmrs      | Array of height elements, in meters.                                                      |
| ntot      | Maximum number of elements in hmrs and dMdh arrays.                                       |
| rdeld     | Range incremented in ray trace.                                                           |
| rmax      | Maximum range for ray trace - 370 km.                                                     |
| rng       | Range, km.                                                                                |
| rk        | Effective earth radius factor.                                                            |
| xmtr      | Transmitter height in meters.                                                             |

c

SUBROUTINE getk(alphac, dMdh, hmrs, ntot, xmtr, RK)

c

real\*4 alphac, a0, al, deld, delh, delM, delmdh, dMdh(32)  
real\*4 hlast, hmrs(32), rdeld, rmax, rng, rk, xmtr  
integer\*2 ntot, i

c

rmax = 370.0  
h = xmtr  
rng = 0.0  
a0 = alphac

c

Loop to trace ray through the atmospheric layers.

```
DO i=2,ntot-1
  delm = (hmrs(i+1) - h)*dMdh(i)*1.0E-3
  al = SQRT(a0*a0 + 2.0*delm)
  deld = (al - a0)/dMdh(i)
  rdeld = rng + deld
  IF(rdeld .GT. rmax) GOTO 1000
  a0 = al
  h = hmrs(i+1)
  rng = rdeld
```

END DO

i = ntot

1000 continue

c

Ray trace in final layer to range rmax.  
deld = rmax - rng

```

a1 = a0 + dMdh(i) * deld
delM = (a1*a1 - a0*a0)*0.5
delh = 1000.0*delM/dMdh(i)
hlast = hmrs(i) + delh
c   Determine the equivalent single-gradient atmosphere that
c   would be required to trace a ray launched at alphac that
c   would arrive at height = hlast at a range of 370 km.
delmdh = (-alphac)*2.0/rmax + 2.0E-3*(hlast - xmtr)/(rmax*rmax)
rk = 1.0/(6371.0 * delmdh)
IF(rk .GT. 5.0) rk = 5.0
IF(rk .LE. 0.5) rk = 0.50

RETURN
END

```

```

c
c Subroutine gtheta
c
c GTHETA calculates optical phase-lag difference angle 'theta'
c between direct and sea-reflected rays using the reflection
c point range 'r1'

```

```

c Variable:      Description:
c   ae2          Effective earth radius * 2000.
c   h1           Height of transmitting antenna, m.
c   h2           Height of receiver/target, m.
c   hlp          Effective height of h1, m.
c   h2p          Effective height of h2, m.
c   plr          Antenna polarization: H = horizontal
c               V = vertical
c               C = circular
c   psi          Grazing angle in radians.
c   phi          Phase lag due to reflection, radians.
c   r            Total ground range, km.
c   r1           Reflection point range, (from h1), km.
c   r2           Reflection point range, (from h2), km.
c   rmag         Magnitude of the reflection coefficient.
c   theta        Total phase lag between direct and reflected
c               rays including phi.

```

```

c SUBROUTINE gtheta(plr,r1,R,THETA,R2,PSI,RMAG)
c
c
c   real*4 hlp, h2p, psi, phi, r, r1, r2, rmag, theta
c   character*1 plr
c
c   include 'ffac.common'
c   include 'envsys.common'
c
c   hlp = h1 - r1*r1/ae2
c   psi = 1.0e-3 * hlp/r1
c   IF (psi .GT. 0.03) psi = ATAN(1.0e-3 * hlp/r1)
c   Ray trace equation used to determine r2 based on psi.
c   r2 = ( SQRT(psi*psi + 2.0e-3 * h2/ae) - psi ) * ae
c   r = r1 + r2
c   h2p = h2 - r2*r2/ae2
c   call ref(plr,psi,RMAG,PHI)

```

```

c      Calculate theta = Path-length difference + phase lag due
c      to reflection (phi).
      theta = phi + thefac*h1p*h2p / r
      RETURN
      END

```

```

c
c      Subroutine hgain
c
c      HGAIN returns a height-gain factor in dB for a specified height.
c
c      Variable:      Description:
c      cl - c7        Constants used to calculate fzdb for evap. ducts.
c      del            Scaled evaporation duct height.
c      delta          Evaporation duct height, m.
c      freq           EM system frequency in MHz.
c      fzdb           Height-gain factor in dB.
c      h             The height for which the height-gain factor is
c                   required, m.
c      hmin           Minimum height.
c      sbdht          Surface-based duct height, m.
c      rfac           Evaporation duct range scale factor.
c      zfac           Evaporation duct height scale factor.
c      zmax           Height above which different eqn.s are used for height-
c                   gain calculations for del>10.25m.
c      z1             Scaled height for surface-based ducts.
c      z2             Scaled height for evaporation duct heights.
c
c      SUBROUTINE hgain (h, FZDB)
c
c      real*4 fzdb, h, z1, z2
c
c      include 'ffac.common'
c      include 'envsys.common'
c
c      fzdb = 0.0
c      IF (sbdht .GT. 0.0) THEN
c         Calculate surface-based duct height-gain factor.
c         z1 = h / sbdht
c         IF ((Freq .LE. 150.0).AND.(z1 .LT. 0.8)) THEN
c            fzdb = -50.0 * (z1 - 0.5)**2
c         END IF
c         IF ((Freq .LE. 150.0).AND.(z1 .GE. 0.8)) THEN
c            fzdb = 1.14 * z1**(-6.26) - 10.0
c         END IF
c         IF ((Freq .GT. 150.0).AND.(z1 .LT. 1.0)) THEN
c            fzdb = 10.0 - 200.0 * (z1 - 0.5)**4
c         END IF
c         IF ((Freq .GT. 150.0).AND.(Freq .LE. 350.0)
c            .AND.(z1 .GE. 1.0)) THEN
c            1  fzdb = 7.5 * z1**(-13.3) - 10.0
c         END IF
c         IF ((Freq .GT. 350.0).AND.(z1 .GE. 1.0)) THEN
c            fzdb = 12.5 * z1**(-8.0) - 15.0
c         END IF
c      ELSE

```

```

c      Calculate evaporation duct height-gain factor.
      z2 = AMAX1(h * zfac, hmin)
      IF (Del .GE. 10.25) THEN
c      Calculate height-gain for del>=10.25 meters.
      IF (z2 .GT. zmax) THEN
        fzdb = c5 * (z2**c6) + c7
      ELSE
        fzdb = c1 * ALOG(SIN(c2 * (z2**c3))) + c4
      END IF
    ELSE
c      Calculate height-gain for del<10.25 meters.
      fzdb = (c1 * z2**c2) + (c3 * z2**c4) + c5
    END IF
  END IF
RETURN
END

```

```

c
c Subroutine insrt
c
c INSRT inserts (or appends) a new level into the M-unit profile. It
c does this by locating the new height relative to the existing pro-
c file heights. If the new height is greater than the top level, then
c append a new level for the new height. If the new height is between
c two levels, then insert a new level for the new height. If the new
c height is equal to an existing level's height, do not add a new
c level for the new height.

```

| Variable: | Description:                                                                              |
|-----------|-------------------------------------------------------------------------------------------|
| amu       | Modified refractivity array, M-units.                                                     |
| hmrs      | Height array, meters, each element corresponding to<br>the like-number amu array element. |
| iq        | Number of levels in amu and hmrs.                                                         |
| hgt       | Height of new level to be added, meters.                                                  |
| ipnt      | Index pointer to new level.                                                               |

```

c
c SUBROUTINE insrt(amu,hmrs,iq,hgt,ipnt)
c
c      real*4 amu(32),hmrs(32),hgt
c      integer*2 iq,ipnt
c
c      DO i=1,iq
c        ilevel=i
c        IF(ABS(hgt-hmrs(ilevel)).LE.0.01) go to 1020
c        IF(hmrs(ilevel).GT.hgt) go to 1030
c      END DO
c
c      Hgt > amu(iq)
c      iq=iq+1
c      ipnt=iq
c      grdnt=0.1181102
c      amu(ipnt)=amu(iq-1) + (hgt-hmrs(iq-1))*grdnt
c      hmrs(ipnt)=hgt
c      go to 1050

```

```

c
c      Hgt = hmrs(ilevel)
1020 continue
      ipnt=ilevel
c      amu(ipnt)=amu(ilevel)
      hmrs(ipnt)=hgt
      go to 1050

c
c      Hmrs(ilevel) > hgt > hmrs(ilevel-1)
1030 continue
c      Shift levels above new height up one
      DO i=ilevel,iq
        j=iq - (i-ilevel)
        hmrs(j+1)=hmrs(j)
        amu(j+1)=amu(j)
      END DO
      iq=iq+1
      ipnt=ilevel
      grdnt=(amu(ipnt+1)-amu(ipnt-1))/(hmrs(ipnt+1)-hmrs(ipnt-1))
      amu(ipnt)=amu(ipnt-1) + (hgt-hmrs(ipnt-1))*grdnt
      hmrs(ipnt)=hgt
c      go to 1050
c
1050 continue
      RETURN
      END

```

```

c
c Subroutine mprof
c
c MPROF modifies the M-unit and height arrays by inserting a level at
c the antenna height using straight line interpolation (or a standard
c atmosphere gradient) to calculate its M-unit value. The new profile
c is then used to locate any ducts that might be contained in the pro-
c file. If the bottom of the duct is below the EM system antenna
c height, and the top above the antenna height, then a critical angle
c is calculated for the EM system in the surface-based duct. (It is
c assumed that low-elevated ducts are surface ducts if the EM system is
c in the duct.)

```

| Variable: | Description:                                                        |
|-----------|---------------------------------------------------------------------|
| alphac    | The critical penetration angle necessary to escape duct             |
| amu       | An array of M-unit values                                           |
| antena    | EM system antenna height                                            |
| antmu     | M-unit value at the EM system antenna height                        |
| dcts      | 24 duct parameter array                                             |
|           | 1,n bottom of duct 'n', meters                                      |
|           | 2,n top of duct 'n', meters                                         |
|           | 3,n minimum refractivity of duct 'n', m-units                       |
| dMdh      | M-unit gradient array                                               |
| hbot      | Height of the bottom of a duct                                      |
| htop      | Height of the top of a duct                                         |
| height    | Height array with the original profile heights                      |
| hmrs      | Height array with elements corresponding to the dMdh array elements |
| lvlant    | EM system antenna level                                             |
| lvltop    | Maximum number of layers in the hmrs array                          |

```

c   Munits      M-unit array with elements corresponding to the height
c               array elements
c   ndcts       The number of ducts stored in 'dcts'
c   nmax        The number of elements in the height and Munit arrays
c   ntot        The number of elements in the dMdh and hmrs arrays
c   rma         M-unit value at the minimum on the duct profile
c   sbdht       The height of the surface-based duct

```

```

c   Variables not listed are temporary variables.
c
c

```

```

1  SUBROUTINE mprof(height,Munits,antena,nmax,ALPHAC,DMDH,HMRS,
    SBDHT,NTOT)

```

```

c
c
c   real*4 alphac,amu(32),antena,dmdh(32),hmrs(32),height(30)
c   real*4 Munits(30),sbdht
c   real*4 antmu,dcts,hb,ht,rma
c   integer*2 lvlant,lvltop,nmax,ntot
c   integer*2 ndcts
c   dimension dcts(3,8)

```

```

c
c   lvltop = nmax
c   alphac = 0.0
c   sbdht = 0.0

```

```

c   Copy height and m-unit arrays.
c

```

```

c   lvltop = nmax
c   DO i = 1, nmax
c       hmrs(i)=height(i)
c       amu(i)=Munits(i)
c   END DO

```

```

c   Insert new level at the antenna height.
c

```

```

c   call insrt(amu,hmrs,lvltop,antena,lvlant)
c   antmu=amu(lvlant)

```

```

c   Locate all major ducts.
c   ndcts=8
c   call ducts(amu,hmrs,lvltop,dcts,ndcts)

```

```

c   Define trapping duct parameters.
c   IF(ndcts .NE. 0) THEN
c       DO iduct=1,ndcts
c           hb=dcts(1,iduct)
c           ht=dcts(2,iduct)
c           rma=dcts(3,iduct)
c           IF((antena .GT. hb) .AND. (antena .LT. ht)) go to 1040
c           IF(hb.lt.0.01) go to 1040
c       END DO
c   END IF

```

```

c   Antenna not inside a major duct.
c   go to 1050

```

```

c
c      The antenna is inside a low-level elevated duct
c      or inside a surface-based duct.
c 1040  continue
c      sbdht = ht
c      alphac=1.0e-3*sqrt(2.0*(antmu-rma)) + 1.0e-5
c 1050  continue
c
c      Delete all levels between the surface and the antenna level.
c      DO i = lvlant,lvltop
c          j=i-(lvlant-2)
c          hmrs(j)=hmrs(i)
c          amu(j)=amu(i)
c      END DO
c      lvltop=j
c      lvlant=2
c
c      Calculate the M-unit gradient array.
c      iend=lvltop-1
c      DO i = 1, iend
c          delu=amu(i+1)-amu(i)
c          delh=hmrs(i+1)-hmrs(i)
c          dmdh(i)=1.0e-3*delu/delh
c      END DO
c      dmdh(lvltop)=0.1181102e-3
c
c      ntot = lvltop
c      RETURN
c      END

```

```

c
c  Subroutine opcnst
c
c  OPCNST initializes optical region constants.
c
c  Variable:      Description:
c  ae             Effective earth radius, (rk * 6371), km.
c  aeth           Effective earth radius * 1000.
c  ae2            Aeth * 2
c  eps            Dielectric constant of sea-water, epsilon.
c  freq           EM system frequency in MHz.
c  fsterm         Free-space loss constant in dB.
c  hbar           RMS wave height due to wind in m.
c  hbfreq         Constant for subroutine ruff,
c                 (hbar * 2 * PI / wavelength).
c  polar          EM system antenna polarization:
c                 H = horizontal, V = vertical, C = circular
c  rk             Effective earth radius factor.
c  rnreal         Real part of the square of the index of refraction.
c  rnimag         Imaginary part of the square of the index of refract.
c  thefac         Constant used to calculate path-length difference
c                 between direct and sea-reflected rays.
c  twoae          Constant (ae * 2).
c  wind           Wind speed in kts.
c
c

```

```

SUBROUTINE opcnst
c
c
c   real*4 eps, sigma
c
c   include 'ffac.common'
c   include 'envsys.common'
c
c   fsterm = 32.44 + 20.0 * ALOG10(freq)
c       Exclusively for REF subroutine
c   IF (polar .NE. "H") THEN
c       eps is the permittivity of salt water
c       sigma is the conductivity of salt water
c       IF (freq .LE. 1500.0) THEN
c           eps = 80.0
c           sigma = 4.3
c       ELSEIF (freq .LE. 3000.0) THEN
c           eps = 80.0 - 0.00733 * (freq - 1500.0)
c           sigma = 4.3 + 0.00148 * (freq - 1500.0)
c       ELSEIF (freq .LE. 10000.0) THEN
c           eps = 69.0 - 0.00243 * (freq - 3000.0)
c           sigma = 6.52 + 0.001314 * (freq - 3000.0)
c       ELSE
c           eps = 51.99
c           sigma = 15.718
c       END IF
c       Define the real and imaginary parts of the square of
c       the index of refraction of sea-water.
c       rnreal = eps
c       rnimag = (-18000.0) * sigma/freq
c       END IF
c       Define rms wave-height for subroutine RUFF
c       hbar = 0.0051 * (0.51477*wind)**2
c       hbfreq = 0.02094 * freq * hbar
c
c       ae = rk * 6371.0
c       twoae = 2.0 * ae
c       aeth = rk * 6.371
c       ae2 = aeth * 2.0
c       thefac = freq * 4.193E-5
c
c   RETURN
c   END

```

```

c
c Subroutine opffac
c
c OPFFAC calculates quantities used to determine the pattern
c propagation factor (F) in the optical interference region.
c
c Variable:      Description:
c   ae           Effective earth radius, km.
c   alpha        Direct ray launch angle, radians.
c   angle        Angle for which antenna pattern factor desired.
c   beta         Reflected ray launch angle, radians.
c   divfac       Divergence factor.
c   dr           Constant - product of antenna pattern factor for
c               reflected ray * divergence factor * reflection
c               coefficient * surface roughness factor.
c   gamma        Earth's interior angle (r1/ae).
c   psi          Grazing angle, radians.
c   r1           Reflection point range, km.
c   r2           Reflection point range, km.
c   range        Total ground range in km.
c   rmag         Magnitude of reflection coefficient.
c   ruf          Sea-surface roughness coefficient.
c   sinpsi       Sin(psi).
c   twoae        2*ae
c
c
c SUBROUTINE opffac(gamma,range,psi,r1,r2,rmag,ELANG,DPAT,DR)
c
c   real*4 angle, beta, divfac, dpat, dr, elang, gamma, psi, r1,
c   1      r2, range, rmag, ruf, sinpsi
c
c   include 'ffac.common'
c   include 'envsys.common'
c
c   patfac = 1.0
c   Calculate direct ray launch angle, alpha.
c   alpha = hdif/range - range/twoae
c   angle = alpha
c   elang = alpha
c   Determine antenna pattern factor for direct ray alpha.
c   call antpat(antype,alpha,antbwr,antelr,antfac,
c   1           patrfac,angle,PATFAC)
c   patd = patfac
c   dpat = patfac
c   beta = - (gamma + psi)
c   angle = beta
c   Determine antenna pattern factor for reflected ray beta.
c   call antpat(antype,alpha,antbwr,antelr,antfac,
c   1           patrfac,angle,PATFAC)
c   Determine surface roughness coefficient.
c   sinpsi = SIN(psi)
c   call ruff(hbar, hbfreq, psi, sinpsi, RUF)
c   Calculate the divergence factor.
c   divfac = 1.0/(SQRT(1.0 + (2.0 * r1 * r2)/(ae * range * sinpsi)))
c   dr = patfac * ruf * divfac * rmag
c
c RETURN
c END

```

```

c
c Subroutine oplimit
c
c OPLIMIT calculates the maximum range in the optical region, opmaxd,
c and opmaxl = -20 LOG(F) at opmaxd, where F is the pattern propagation
c factor.
c
c Variable:      Description:
c   ae           Effective earth radius, km.
c   ae2          ae * 2000
c   alpha        Direct ray launch angle, radians.
c   alphac       Critical angle in radians.
c   al           An angle used to determine rl(psilim).
c   exloss       A measure of how much of the antenna's energy
c               is directed toward the horizon, dB.
c   freq         EM system frequency, MHz.
c   fsqrd        Square of the pattern propagation factor, F.
c   gamma        Earth's interior angle.
c   hdif         Difference in height between h1 and h2.
c   horznl       Tangent ray distance for height h1, km.
c   h1           Transmitter height, m.
c   hlp          Effective transmitter height, m.
c   h2           Receiver/target height, m.
c   h2p          Effective receiver/target height, m.
c   opmaxd       Maximum range in optical region, km.
c   opmaxl       Propagation factor in dB at opmaxd.
c   pd           Path-length difference between direct and
c               sea-reflected rays.
c   phi          Phase lag due to reflection from sea-surface.
c   psilim       Grazing angle limit to optical region.
c   psi          Grazing angle in radians.
c   r            Total ground range, km.
c   rl           Reflection point range (from h1), km.
c   r2           Reflection point range (from h2), km.
c   rk           Effective earth radius factor.
c   theta        Total phase difference between direct and sea-reflected
c               rays (pd) and phase-lag due to reflection, phi.
c   thefac       Constant used to calculate path-length difference.
c   thnext       The next value of theta to be determined.
c
c
c SUBROUTINE oplimit(OPMAXD,OPMAXL)
c
c   real*4 al, dr, fsqrd, gamma, halfpi, hlp, h2p, pd, phi,
c   l         pi, psi, psilim, r, rl, r2, rmag, theta, thnext
c
c   include 'ffac.common'
c   include 'envsys.common'
c
c   PI = 3.14159
c   halfpi = PI / 2.0
c   horznl = 3.572 * SQRT(rk * h1)
c   psilim = 0.01957/(freq*rk)**0.33333
c   If both terminals are in the duct set alphac = 0.0
c   IF ((alphac .GT. 0.0) .AND. (h2 .LT. sbdht)) alphac = 0.0
c   Initial guess for rl is based on grazing angle limit range.
c   Use ray trace equations to determine rl and r2.
c   psi = psilim
c   al = SQRT(psi**2 + 2.0e-3*h1/ae)
c   rl = (al - psi)*ae
c   r2 = rl
c   IF (h2 .GT. h1)r2 = r2 + (SQRT(al**2 + 2.0*ABS(hdif)/ae) - al)*ae
c   r = rl + r2
c   hlp = h1 - rl*rl/ae2

```

```

h2p = h2 - r2*r2/ae2
call ref(polar,psi,RMAG,PHI)
pd = thefac*hlp*h2p / r
c
c      Calculate theta based on grazing angle limit.
c
theta = phi + pd
alpha = hdif/r - r/twoae
IF (alphac .GT. 0.0) THEN
  IF ((alpha .LT. alphac) .OR. (pd .GT. halfpi)) THEN
c
c      Calculate theta based on range obtained from alphac.
c
    r = (SQRT(alphac**2 + 2.0*ABS(hdif)/ae) - alphac)*ae
    call opticf(polar,r,PD,PSI,THETA,FF)
  END IF
END IF
IF ((alphac .GT. 0.0) .AND. (pd .GT. halfpi), THEN
c
c      If theta>(2 PI) then optical limit is 1st peak
c      with theta greater than theta(alphac).
c
  IF (theta .GT. 6.28319) THEN
    thnext = INT(theta/(2.0*PI) + 1)*(2.0 * PI)
    call rliter(polar,thnext,R1,R2,R,PSI,RMAG)
    theta = thnext
  END IF
ELSE
c
c      Optical limit is grazing angle limit or 1/4 wavelength limit.
c
  IF ((pd .GT. halfpi) .OR. (psi .NE. psilim)) THEN
c
c      Determine theta value @ 1/4 wavelength limit, (H polar).
c
    thnext = 1.5 * PI
    call rliter("H",thnext,R1,R2,R,PSI,RMAG)
    IF (polar .NE. "H") THEN
      call ref(polar,psi,RMAG,PHI)
      theta = halfpi + phi
    ELSE
      theta = thnext
    END IF
  END IF
END IF
IF (ht .GE. hr) THEN
  gamma = r2/ae
ELSE
  gamma = r1/ae
END IF
call opffac(gamma,r,psi,r1,r2,rmag,ALPHA,PATD,DR)
fsqrd = (patd*patd + dr*dr + 2.0*dr*patd*COS(theta))
c      Limit fsqrd to prevent runtime errors when taking LOG(fsqrd).
IF (fsqrd .LT. 1.0e-7) fsqrd = 1.0e-7
opmaxd = r
opmaxl = - 10.0 * ALOG10(fsqrd)
exloss = - 20.0 * ALOG10(patd)
RETURN
END

```

```

c
c Subroutine opticf
c
c Subroutine OPTICF calculates the total phase difference, theta,
c between direct and sea-reflected ray paths, including phase
c change due to reflection from sea-surface. It then uses theta
c to determine the value of the pattern propagation factor, F, in
c the optical region, and returns 20Log(F).
c
c
c Variable:      Description:
c   ae           Effective earth radius, km.
c   ae2          Ae*2000, km.
c   aeth         Ae*1000, km.
c   alpha       Direct ray launch angle, radians.
c   dr          Product of divergence factor, surface roughness
c               coefficient, reflection coefficient and antenna
c               pattern factor for the reflected ray.
c   epsr        Iteration loop range tolerance, km.
c   ff          Pattern propagation factor, F, in dB.
c   fprl        Value of the derivative of the cubic equation at rl.
c   frl         Value of the cubic equation for a given rl.
c   fsqrd       Square of the pattern propagation factor.
c   gamma       Earth's interior angle (rl/ae) in radians.
c   hrp         Effective receiver/target height, m.
c   htp         Effective transmitter height, m.
c   h1          The transmitter height, m.
c   h2          The receiver/target height, m.
c   pd          The path-length difference between direct and re-
c               flected rays in radians.
c   phi         Phase lag due to reflection from sea surface, rad.
c   psi         Grazing angle in radians.
c   r           Total ground range, km.
c   rl          Reflection point range, (from xmtr), km.
c   rlsqrd      Square of the reflection point range.
c   r2          Reflection point range, (from rcvr/target), km.
c   rr          Iteration loop variable - range difference.
c   rmag        Magnitude of reflection coefficient.
c   t           Iteration loop variable.
c   theta       Total phase lag between direct and sea-reflected
c               rays, in radians. (theta = pd + phi)
c   thefac      Constant used to calculate theta.
c   v           Iteration loop variable.
c   w           Iteration loop variable.
c
c
c   SUBROUTINE opticf(plr,r,PD,PSI,THETA,FF)
c
c   real*4 dr, epsr, ff, frl, fprl, fsqrd, gamma, hrp, htp,
1  phi, psi, r, rl, rlsqrd, r2, rmag, rr, t, theta, v, w
c   character*1 plr
c   integer*2 jk
c
c   include 'ffac.common'
c   include 'envsys.common'
c
c   rl = (h1/(h1 + h2))*r
c   t = .15 * r
c   v = 0.5 * r * r - aeth * (h1 + h2)
c   w = aeth * r * h1
c   epsr = 0.050
c   rr = 2.0 * epsr
c   jk = 1
c

```

```

c      WHILE ((jk .LT. 10).AND.(abs(rr) .GT. epsr))
c
c      Use Newton-Raphson iteration to solve Kerr's cubic equation
c      for reflection point range of the sea-reflected ray. (This
c      equation may be solved explicitly using an inverse cosine.)
c      The Newton iteration works best if h1 is less than h2.
c
c      DO WHILE ((jk .LT. 10).AND.(abs(rr) .GT. epsr))
c      jk = jk + 1
c      rlsqrd = r1 * r1
c      Kerr's cubic equation for reflection point range.
c      frl = r1*rlsqrd + t*rlsqrd + v*r1 + w
c      Derivative of the cubic equation.
c      fprl = 3.0*rlsqrd + 2.0*t*r1 + v
c      rr = frl/fprl
c      r1 = r1 - rr
c      IF ((r1 .LT. 0.0).OR.(r1 .GT. r)) r1 = r/2.0
c
c      WEND
c      END DO
c      r2 = r - r1
c      htp = h1 - r1*r1/ae2
c      hrp = h2 - r2*r2/ae2
c      psi = 1.0e-3 * htp / r1
c      IF (psi .GT. 0.3) psi = ATAN(1.0e-3 * htp/r1)
c      call ref(plr,psi,RMAG,PHI)
c      pd = thefac*htp*hrp/r
c      theta = pd + phi
c      IF (ht .GE. hr) THEN
c      gamma = r2/ae
c      ELSE
c      gamma = r1/ae
c      END IF
c      call opffac(gamma,r,psi,r1,r2,rmag,ALPHA,PATD,DR)
c      fsqrd = patd*patd + dr*dr + 2.0*dr*patd*COS(theta)
c      Limit F-factor to -70 dB.
c      IF (fsqrd .LT. 1.0e-7) fsqrd = 1.0e-7
c      ff = - 10.0 * ALOG10(fsqrd)
c
c      RETURN
c      END

```

```

c
c Subroutine push
c
c PUSH stores elements in an array and returns.
c
c Variable:      Description:
c
c   array      iq array to hold data elements
c   iq         Size of data array
c   nq         Number of data elements stored in data array
c   data       The data element to be stored
c
c

```

```

c      SUBROUTINE push(ARRAY,iq,nq,data)
c
c      real*4 data,array
c      integer*2 iq,nq
c      dimension array(iq)
c
c      Shift array elements down one
c      do i=iq,2,-1
c      DO j=2,iq
c         i=iq-(j-2)
c         array(i)=array(i-1)
c      END DO
c
c      Store new data element in top of array
c      array(1)=data
c      nq=nq+1
c      IF(nq.GT. iq) nq = iq
c      RETURN
c      END

```

```

c
c Subroutine rliter
c
c RLITER determines a reflection point range 'rl' corresponding
c to 'rtheta'. The desired reflection point range is determined by
c a Newton-Raphson iteration technique to vary the reflection point
c point range until the correct value is found.
c
c Variable:      Description:
c
c   r            Distance, or range, in km.
c   rl           Distance from the transmitting antenna to reflection
c                point in km.
c   r2           Distance from the target/receiver antenna to the
c                reflection point in km.
c   f            Function (Total path difference between direct and
c                sea-reflected rays: Theta) used in iteration loop.
c   fl           Finite derivative of f.
c   irlmda       Iteration loop counter.
c   phi          Phase-lag due to sea-surface reflection - radians.
c   plr          EM system polarization [H = horizontal, V = vertical,
c                C = circular].
c   psi          Grazing angle in radians.
c   r            Range, in km.

```

```

c      r1          Distance from the transmitting antenna to reflection
c                  point in km.
c      r2          Distance from the target/receiver antenna to the
c                  reflection point in km.
c      rmag        Magnitude of the reflection coefficient.
c      rtheta      The desired value of theta.
c
c      SUBROUTINE rliter(plr,rtheta,r1,r2,R,PSI,RMAG)
c
c      real*4  f, fl, phi, psi, r, r1, r2, rmag, rr, rtheta
c      character*1 plr
c      integer*2 irlmda
c
c      include 'ffac.common'
c      include 'envsys.common'
c
c      irlmda = 0
c      rr = r1
c
c      WHILE ((abs(rr) .GT. 0.001).AND.(irlmda .LT. 100))
c          (Equivalent to: 100 IF ((...).and(...)) THEN
c              ...
c              GOTO 100
c
c      DO WHILE ((abs(rr) .GT. 0.001).AND.(irlmda .LT. 100))
c
c          Calculate phase difference, theta, corresponding to
c          reflection point range r1. Then use finite derivative
c          method to iterate to the range where theta is equal to
c          the target value: rtheta.
c
c          call gtheta(plr,r1,R,F,R2,PSI,RMAG)
c          call gtheta(plr,r1+0.001,R,F1,R2,PSI,RMAG)
c          fp = (f1 - f) / 0.001
c          rr = (rtheta - f) / fp
c          irlmda = irlmda + 1
c          IF (rr .GT. -r1) THEN
c              IF (rr + r1 .LE. horznl) THEN
c                  r1 = r1 + rr
c
c              ELSE
c                  r1 = (r1+horznl)/2.0
c              END IF
c          ELSE
c              r1 = r1/2.0
c          END IF
c      END DO
c      WEND
c      RETURN
c      END

```

```

c
c Subroutine ref
c
c Subroutine REF returns the magnitude and phase lag of the reflection
c coefficient for reflection from the (smooth) sea surface. These
c quantities are calculated as a function of the grazing angle psi.
c The complex square roots are done by separating the complex variables
c into their real and imaginary parts. No complex function calls are
c used.
c
c
c VARIABLE:      DESCRIPTION:
c   rnreal      Real part of the square of the index of refraction,
c               (the dielectric constant of sea-water).
c   rnimag      Imaginary part of the square of the index of
c               refraction (the conductivity of sea water
c               times the wavelength times other constants).
c   phi         Phase change (lag) in radians.
c   plr         EM system antenna polarization: H - horizontal;
c               V - vertical; C - Circular.
c   psi         Grazing angle in radians.
c   rmag        Magnitude of the reflection coefficient.
c   sinpsi      SIN(psi).
c
c   various      All variables not listed above are temporary.
c
c   SUBROUTINE ref(plr, psi, RMAG, PHI)
c
c   real*4 angrt, at, bt, ct, dt, phi, phiv, pi, psi,
1   rcv, rmag, rmagrt, rtimag, rtreal,
2   rvimag, rvreal, rx, sinpsi, x, y
c   character*1 plr
c
c   include 'ffac.common'
c   include 'envsys.common'
c
c   PI = 3.14159
c   Define RMAG, PHI for horizontal polarization.
c   rmag = 1.0
c   phi = PI
c   IF (plr .NE. "H") THEN
c       Calculate RMAG, PHI for vertical polarization.
c       sinpsi = SIN(psi)
c       Y = rnimag
c       X = rnreal - COS(psi)**2
c       rmagrt = (x*x + y*y) ** 0.25
c       angrt = ATAN(y/x) / 2.0
c       rtreal = rmagrt * COS(angrt)
c       rtimag = rmagrt * SIN(angrt)
c       at = rnreal * sinpsi - rtreal
c       ct = rnreal * sinpsi + rtreal
c       bt = rnimag * sinpsi - rtimag
c       dt = rnimag * sinpsi + rtimag
c       rvreal = (at*ct + bt*dt) / (ct**2 + dt**2)
c       rvimag = (bt*ct - at*dt) / (ct**2 + dt**2)
c       rcv = SQRT(rvreal**2 + rvimag**2)
c       IF (rvreal .NE. 0.0) THEN
c           phiv = ATAN(rvimag/rvreal)
c           IF (rvreal .LT. 0.0) phiv = phiv + PI
c       ELSE
c           IF (rvimag .LT. 0.0) phiv = -PI / 2.0
c           IF (rvimag .GT. 0.0) phiv = PI / 2.0
c           IF (rvimag .EQ. 0.0) phiv = 0.0
c       END IF

```

```

      phiv = -phiv
      IF (phiv .LT. 0.0) phiv = phiv + 2.0*PI
      rmag = rcv
      phi = phiv
      IF (plr .EQ. "C") THEN
c       Calculate RMAG, PHI for circular polarization.
      rx = SQRT(1.0 + rcv**2 + 2.0*rcv * COS(PI - phiv))
      rmag = rx/2.0
      a = rcv * SIN(phiv + PI) / rx
      a = ATAN( a/SQRT(1 - a*a) )
      phi = PI - a
      phi = -phi
      IF (phi .LT. 0.0) phi = phi + 2.0*PI
      END IF
    END IF
  RETURN
END

```

```

c
c Subroutine ruff
c
c Subroutine RUFF returns the sea-surface roughness correction for
c the magnitude of the sea-reflected ray.
c
c
c VARIABLE:      DESCRIPTION:
c   hbar          rms wave height in meters.
c   hbfreq        (2*PI*hbar)/wavelength.
c   hfpsi         (hbar*psi)/wavelength.
c   psi           Grazing angle in radians.
c   sinpsi        SIN(psi).
c   rufco         Sea-surface roughness coefficient.
c
c
c   SUBROUTINE ruff(hbar, hbfreq, psi, sinpsi, RUFCO)
c
c   real*4 hbar, hbfreq, hfpsi, psi, rufco, sinpsi
c
c
c   rufco = 1.0
c   IF (hbar .NE. 0.0) THEN
c     hfpsi = hbfreq * psi * 0.159155
c     IF (hfpsi .LE. 0.11) THEN
c       rufco = EXP((-2.0) * (hbfreq*sinpsi)**2)
c     ELSEIF (hfpsi .LE. 0.26) THEN
c       rufco = 0.5018913 - SQRT(0.2090248 - (hfpsi - 0.55189)**2)
c     ELSE
c       rufco = 0.15
c     END IF
c   END IF
c   RETURN
c   END

```

```

c
c Subroutine sysfil
c
c SYSFIL list available system files and allows the user to select an
c EM system file.
c
c Variable:      Description:
c   antena      Height of EM system antenna in m.
c   antype      Antenna type:
c                O - omnidirectional
c                S - sin(x)/x
c                C - cosecant-squared
c                H - generic height-finder
c   bwidth      Antenna beam width in degrees.
c   elevat      Antenna elevation angle in degrees.
c   filename    Name of System file.
c   freq        EM system frequency in MHz.
c   polar       Antenna polarization:
c                H - horizontal
c                V - vertical
c                C - circular
c   rectar      Receiver/target height, m.
c
c   SUBROUTINE sysfil(freq, antena, rectar, polar, antype, bwidth,
1      elevat)
c
c
c   real*4 antena, bwidth, elevat, freq
c   integer*2 ZR, ZW
c   character*1 antype, polar
c   character*20 filename
c
c   Initialize read and write channels.
c   ZR = 5
c   ZW = 6
c
c   call system ('ls [S]* 1>&2'//char(0))
c   write (ZW, '(//,"Enter input file name: ",$)')
c   read (ZR, '(a12)') filename
c   open (10, FILE=filename)
c
c   read (10, '(f10.1)') freq           ! radar freq
c   read (10, '(f10.1)') antena         ! radar antenna ht
c   read (10, '(f10.1)') rectar        ! receiver/target height
c   read (10, '(a1)') polar             ! antenna polarization
c   read (10, '(a1)') antype            ! antenna type
c   read (10, '(f10.1)') bwidth         ! vert. beam width
c   read (10, '(f10.1)') elevat        ! ant. elev. angle
c   close(10)
c
c   RETURN
c   END

```

```

c
c Subroutine sysinp
c
c Subroutine SYSINP prompts the user for EM system parameters and re-
c turns. System parameters can be entered from the keyboard or from a
c file. If the system is entered from the keyboard it can be stored in
c a file.
c
c Variable:      Description:
c   atype        Antenna type:
c                 O - omnidirectional
c                 S - sin(x)/x
c                 C - cosecant-squared
c                 H - height-finder
c   beam         Beam width in degrees.
c   elang        Antenna pointing (elevation) angle in degrees.
c   fmhz         EM system frequency in MHz.
c   filename     EM system filename.
c   rectar       Receiver/radar target height, m.
c   plr          Antenna polarization:
c                 H - horizontal
c                 V - vertical
c                 C - circular
c   rectar       Receiver/target height, m.
c   xmtr         EM system antenna height, m.
c
c
c   SUBROUTINE sysinp(FMHZ, XMTR, RECTAR, PLR, ATYPE, BEAM, ELANG)
c
c   real*4 beam, elang, fmhz, rectar, xmtr
c   character*1 atype, dummy, plr
c   character*20 filename
c   integer*2 ZW, ZR
c
c   Specify the read (5) and write (6) channel numbers.
c   ZW = 6
c   ZR = 5
c
c   Enter EM system parameters from file or keyboard.
c   write(ZW,('You may enter EM system from a file or keyboard.'))
c   write(ZW,('Enter EM system data from file? (yes or no) ', '$'))
c   read(ZR, '(A1)') dummy
c   IF ((dummy(1:1) .eq. 'y').or.(dummy(1:1) .eq. 'Y')) THEN
c       Enter EM system data from a file.
c       call sysfil(fmhz,xmtr,rectar,plr,atype,beam,elang)
c   ELSE
c       Enter the EM system parameters from keyboard.
c       write(ZW,('Enter EM System Parameters: '))
c
c       Initialize EM system variables.
c       fmhz = 5600.0
c       xmtr = 25.0
c       rectar = 25.0
c       plr = "H"
c       atype = "O"
c       beam = 0.0
c       elang = 0.0
c
c       write(ZW,1010)
1010  format('Enter frequency in MHz (100 to 20,000) ', '$')
c       read(ZR,*) fmhz
c       IF (fmhz .LT. 100.0) fmhz = 100.0
c       IF (fmhz .GT. 20000.0) fmhz = 20000.0

```

```

c
write(ZW,1015)
1015 format('Enter transmitter height in meters (1 to 100) ', $)
read(ZR,*) xmtr
IF (xmtr .LT. 1.0) xmtr = 1.0
IF (xmtr .GT. 100.0) xmtr = 100.0

c
write(ZW,1020)
1020 format('Enter receiver/target height in meters (1 to 30000) ', $)
read(ZR,*) rectar
IF (rectar .LT. 1.0) rectar = 1.0
IF (rectar .GT. 30000.0) rectar = 30000.0

c
write(ZW,1025)
1025 format('Enter EM system polarization (H, V, C) ', $)
read(ZR, '(A1)') plr
IF ((plr .EQ. "c") .OR. (plr .EQ. "C")) plr = "C"
IF ((plr .EQ. "v") .OR. (plr .EQ. "V")) plr = "V"
IF ((plr .NE. "V") .AND. (plr .NE. "C")) plr = "H"

c
write(ZW,1030)
1030 format('Enter antenna type - options are: Omnidirectional, '
1 /, 'Sin(x)/x, Cosecant-squared, Height-finder (O, S, C, H)) ', $)
read(ZR, '(A1)') dummy
IF ((dummy .EQ. "o") .OR. (dummy .EQ. "O")) atype = "O"
IF ((dummy .EQ. "s") .OR. (dummy .EQ. "S")) atype = "S"
IF ((dummy .EQ. "c") .OR. (dummy .EQ. "C")) atype = "C"
IF ((dummy .EQ. "h") .OR. (dummy .EQ. "H")) atype = "H"
IF ((atype .NE. "S") .AND. (atype .NE. "H") .AND.
1 (atype .NE. "C")) atype = "O"

c
beam = 0.0
elang = 0.0
IF(atype .NE. "O") THEN
write(ZW,1035)
1035 format('Enter antenna beam width in degrees (>0.0 to 45) ', $)
read(ZR,*) beam
IF (beam .LE. 0.0) beam = 0.10
IF (beam .GT. 45.0) beam = 45.0

c
write(ZW,1040)
1040 format('Enter antenna elevation angle in degrees (-10.0 to 10.0)'
1 /, '(0 is normal) ', $)
read(ZR,*) elang
IF (elang .LT. -10.0) elang = -10.0
IF (elang .GT. 10.0) elang = 10.0
END IF
write(ZW, '("Do you wish to store this EM system in a file?",
1 " (yes or no) ", $)')
read(zr, '(A)') dummy
IF ((dummy(1:1) .eq. 'y') .or. (dummy(1:1) .eq. 'Y')) THEN
write (ZW, '(" Current System Files: ")')
call system ('ls [S]* 1>&2'//char(0))
write (ZW, 1045)
1045 format("Enter file name (First letter MUST be S): ", $)
read (ZR, '(a12)') filename
open (10, FILE=filename)

c
Write frequency and antenna heights in file.
write(10, '(f10.1)') fmhz
write(10, '(f10.1)') xmtr
write(10, '(f10.1)') rectar

c
Write the antenna characteristics in file.
write(10, '(a1)') plr

```

```

        write(10, '(a1)') atype
        write(10, '(f10.1)') beam
        write(10, '(f10.1)') elang
c      close file
        close(10)
      END IF
    END IF
c
    RETURN
  END

```

```

c
c Subroutine tropo
c
c Subroutine TROPO returns the troposcatter loss for a given range.
c Troposcatter loss is based on models by Yeh with a frequency-gain
c correction term, H0, from National Bureau of Standards Document
c NBS 101. Frequency gain factor gives additional loss for low
c frequency, low-sited antennas.
c
c VARIABLE:      DESCRIPTION:
c   ae           Effective earth radius in kilometers
c   exloss       Antenna gain for lowest optical region ray in dB
c   fcubed       Frequency cubed
c   horizon      Horizon range in kilometers
c   h1           Transmitter height in meters
c   h2           Radar target/receiver height in meters
c   h0           Frequency gain factor in dB
c   r            Ground range in km
c   rnsterm      Constant involving Surface Modified refractivity
c   rnsubs       Modified refractivity value at the sea surface
c   rone          $4\pi h_1 \text{ttot} / \text{wavelength}$ 
c   rtwo          $4\pi h_2 \text{ttot} / \text{wavelength}$ 
c   tfac         Troposcatter region constant
c   tloss        Troposcatter loss in dB
c   tsub0        Angle, theta sub 0, associated with total range r
c   tsub1        Angle, theta sub 1, associated with horizon range r1
c   tsub2        Angle, theta sub 2, associated with horizon range r2
c   ttot         Scattering angle, (theta in NBS 101)
c
c various        All variables not listed above are temporary. Most
c                variables use the names given in NBS 101.
c
c SUBROUTINE tropo(r,tloss)
c
c      real*4 chi, csub1, csub2, delh0, etas, horizon, hsub0,
1      h0, h0r1, h0r2, q, r, rnsterm, rnsubs, rone, rtwo,
2      s, tfac, tloss, tsub0, tsub1, tsub2, ttot, zeta
c
c      include 'ffac.common'
c      include 'envsys.common'
c
c      rnsubs = Munits(1)
c      tfac = 0.08984 / rk
c      horizon = 3.572 * ( SQRT(rk * h1) + SQRT(rk * h2) )
c      tsub0 = r / ae

```

```

tsub1 = SQRT(h1 * ae/500.0) / ae
tsub2 = SQRT(h2 * ae/500.0) / 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)
rone = h1 * 0.0419 * freq * ttot
rtwo = h2 * 0.0419 * freq * ttot
IF (rone .LT. 0.1) rone = 0.1
IF (rtwo .LT. 0.1) rtwo = 0.1
s = zeta / chi
IF (s .GT. 10.0) s = 10.0
IF (s .LT. 0.1) s = 0.1
q = rtwo / (s * rone)
IF (q .GT. 10.0) q = 10.0
IF (q .LT. 0.1) q = 0.1
hsub0 = s * r * ttot / (1.0 + s)**2
etas = 0.5696*hsub0 * (1.0 + rnsterm*EXP(-3.8e-6 * hsub0**6))
IF (etas .GT. 5.0) etas = 5.0
IF (etas .LT. 0.01) etas = 0.01
csub1 = 16.3 + 13.3*etas
csub2 = 0.4 + 0.16*etas
h0r1 = csub1 * (rone + csub2)**(-1.333)
h0r2 = csub1 * (rtwo + csub2)**(-1.333)
h0 = (h0r1 + h0r2) / 2.0
delh0 = 1.13 * (0.6 - ALOG10(etas)) * ALOG(s) * ALOG(q)
IF (delh0 .GT. h0) THEN
    h0 = 2.0*h0
ELSE
    h0 = h0 + delh0
END IF
IF (h0 .LT. 0.0) h0 = 0.0
tloss = 114.9 + tfac*(r-horizn) + 10.0*ALOG10(r*r*freq**3)
tloss = tloss - rnsubs*0.2 + h0 + exloss

c
RETURN
END

```

# REPORT DOCUMENTATION PAGE

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