antenna to its horizon should not be less than 1/10, or more than three times, the corresponding smooth-earth distance.

Section 2 discusses atmospheric and terrain parameters, and section 3 explains how transmission loss is calculated. The topics treated in the annexes are as follows:

Annex 1 shows how the computed reference values, A_{cr}, are adjusted to provide long-term median estimates, A(0.5), of attenuation relative to free space for any given set of data. This annex also gives estimates of the variability in time and with location and shows how to estimate prediction errors.

Annex 2 shows how various path parameters have been derived from studies of terrain profiles.

Annex 3 gives detailed formulas and procedures required to calculate the median reference attenuation A_{cr}. A computer program listing, flow diagram, and sample computations are included.

Annexes 1 and 3 each contain a list of symbols used in that annex, with their definitions.

2. ATMOSPHERIC AND TERRAIN PARAMETERS

2.1 Atmospheric Effects

Radio transmission loss in tropospheric propagation depends on characteristics of the atmosphere and of terrain. For predicting a long-term median reference value of transmission loss, the refractive index gradient near the earth's surface is the most important atmospheric parameter. This surface gradient largely determines the bending of a radio ray as it passes through the atmosphere. Rays may be represented as straight lines, within the first kilometer above the earth's surface, if an "effective earth's radius", a, is defined as a function of the refractivity gradient or of the mean surface refractivity, N_s. In calculating the long-term reference value, the minimum monthly mean value of N_s is chosen to characterize average atmospheric conditions.

The effective earth's radius, which allows for regional differences in average atmospheric conditions, is defined as

$$a = 6370 \left[1 - 0.04665 \exp(0.005577 N_s)\right]^{-1} \text{ km}, \qquad (1)$$

where the actual radius of the earth is taken to be 6370 km.

The minimum monthly mean value of surface refractivity may be obtained from measurements or from maps showing a related parameter, N_o. The refractivity, N_o, represents surface refractivity reduced to sea level. Figure 1, reproduced from Bean, Horn, and Ozanich (1960) shows minimum monthly mean values of N_o throughout the world. The corresponding surface refractivity N_s is then

$$N_s = N_o \exp(-0.1057 h_s), \qquad (2)$$

where h_s is the elevation of the earth's surface in kilometers above mean sea level. The elevation h_s is determined at the base of the lower antenna for line-of-sight paths. For a transhorizon path, N_s is taken as the average of two values computed by substituting the heights of the horizon obstacles, h_{L1} and h_{L2}, in (2). If an antenna is more than 150 m below its horizon, h_s and N_o should be determined at the antenna location. A commonly used value of N_s is 301 with an effective earth's radius a = 8497 km, which corresponds to 4/3 of the actual radius.

Other atmospheric effects, such as changes in the refractive index, changes in the amount of turbulence or stratification, as well as absorption by oxygen, water vapor, clouds, and precipitation, are allowed for by empirical adjustments. Adjustments to the median, allowing for differences in climate, and estimates of variability relative to the median are described in annex 1.

MINIMUM MONTHLY SURFACE REFRACTIVITY VALUES REFERRED TO MEAN SEA LEVEL

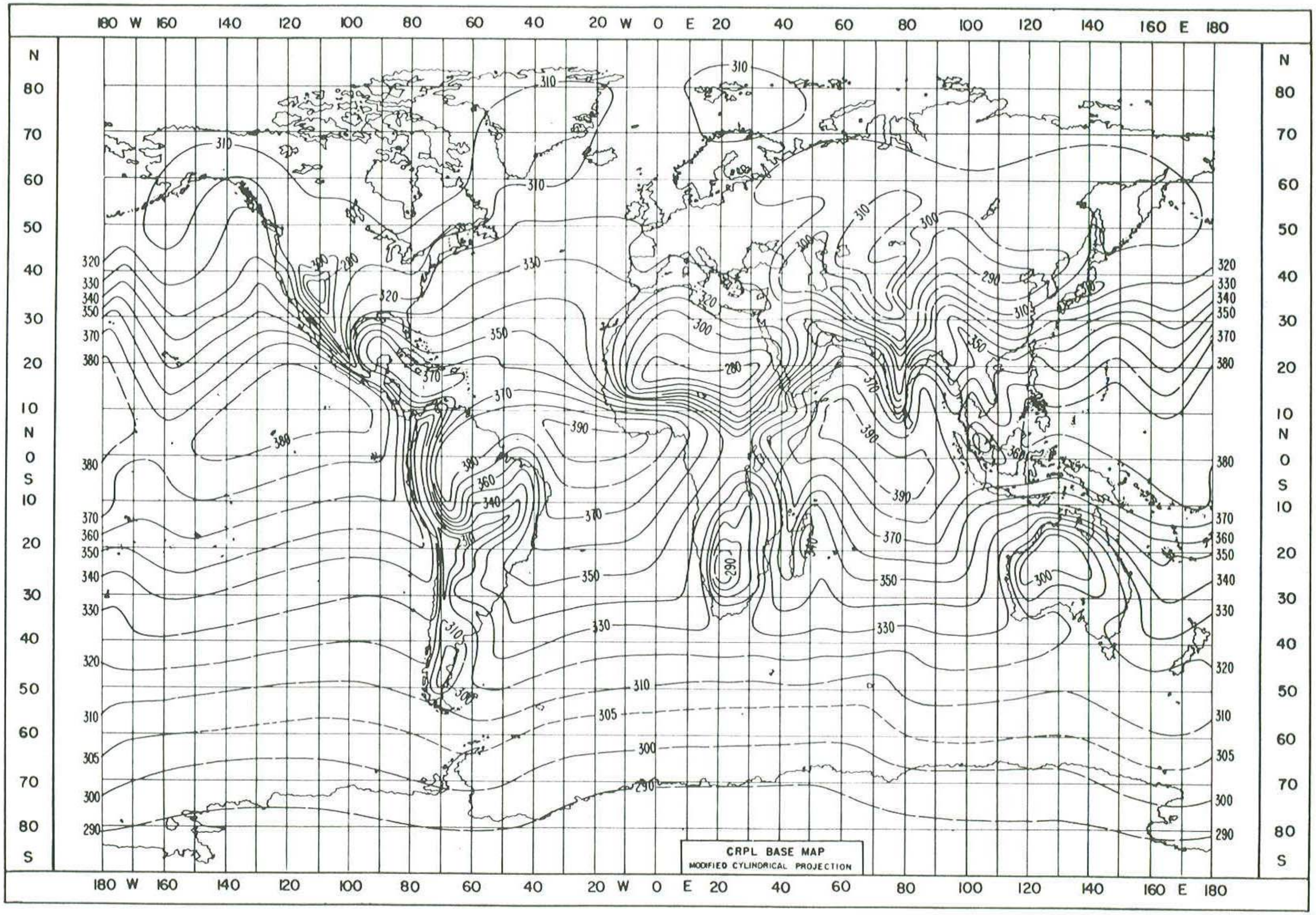

Figure 1

2.2 Description of Terrain

Transmission loss may be calculated for specific paths where detailed profiles are available, but the prediction method is particularly useful when little is known of the details of terrain for actual paths. To characterize terrain, profiles may be read at regular intervals in both N-S and E-W directions, forming a uniform grid over an area. Or an actual or proposed deployment of propagation paths, representing a wide variety of terrain conditions, may be combined to provide a single set of profiles for which an estimate of median propagation conditions is desired. The interdecile range, $\Delta h(d)$, of terrain heights above and below a straight line fitted to elevations above sea level, is calculated at fixed distances. Usually median values of $\Delta h(d)$ increase with path length to an asymptotic value, Δh, which is used to characterize the terrain.

When terrain profiles are not available, estimates of Δh may be obtained from table 1.

Table 1. Estimates of Δh.

Type of Terrain	Δh in Meters
Water or very smooth plains	0 - 5
Smooth plains	5 - 20
Slightly rolling plains	20 - 40
Rolling plains	40 - 80
Hills	80 - 150
Mountains	150 - 300
Rugged mountains	300 - 700
Extremely rugged mountains	>700

Median estimates of $\Delta h(d)$ at desired distances may be obtained from the following relationship, which is based on a study of a large number of profiles:

$$\Delta h(d) = \Delta h \left[1 - 0.8 \exp(- 0.02\, d)\right] \text{ m}, \tag{3}$$

where $\Delta h(d)$ and Δh are in meters and the distance d is in kilometers. Studies of terrain are described in annex 2.

2.3 Parameters Required to Compute Transmission Loss

For any specific application, a minimum of four essential parameters must be supplied in order to calculate reference values of transmission loss. These are the carrier frequency f in megahertz, the path distance d in kilometers, and the transmitting and receiving antenna heights above ground h_{g1} and h_{g2} in meters. Other path parameters used in the computations, such as horizon distances and elevation angles, may be derived from these values and available terrain information as described in the next subsection. When detailed profiles for individual paths are available one may compute these additional path parameters using the methods outlined in annex 3.

In addition to estimates of surface refractivity N_s and the terrain parameter Δh, previously discussed, the ground constants applicable to the intervening terrain should be considered. The conductivity, σ, of the earth's surface and its permittivity or relative dielectric constant, ϵ, enter into the calculations for line-of-sight and diffraction attenuation. When these constants are not known for a given path or area the following values may be assumed:

Table 2. Typical Ground Constants

Type of surface	σ mho/m	ϵ
Poor ground	0.001	4
Average ground	0.005	15
Good ground	0.02	25
Sea water	5	81
Fresh water	0.01	81

At sufficiently low frequencies, the effect of the conductivity σ is dominant, while at sufficiently high frequencies, the dielectric constant ϵ has the dominant effect. For oversea transmission, this transition occurs between 300 and 3000 MHz, while over "average" ground, the transition is between 5 and 50 MHz. For propagation over irregular terrain, at frequencies above 100 MHz, and with antennas more than 5 m above ground, the effects of the ground constants are slight, and the results for horizontal and vertical polarization are nearly the same. Under these conditions the method may be simplified considerably by assuming the magnitude of the theoretical reflection coefficient $R_{h,v} \simeq 0.95$ and the phase shift $c \simeq 0$. For many applications this results in an estimate of the effective reflection coefficient $R_e \simeq 0.9$, and the attenuation A in (3.2) may be calculated directly, bypassing the calculations shown in equations (3.5) through (3.15) in annex 3. These approximations are not applicable for transmission over the sea. For oversea transmission $R_{h,v}$ and c may be computed using the equations given in annex 3 or estimated from figure III.1 or figure III.5 of annex III, volume II of the report by Rice et al. (1967).

The parameters required for computing reference values of transmission loss L_{cr}, or the corresponding attenuation below free space A_{cr}, are then: frequency f in megahertz, distance d in kilometers, antenna heights above ground h_{g1} and h_{g2} in meters, as well as estimates of surface refractivity N_s, the terrain irregularity Δh in meters, the conductivity σ mho/m, and the relative dielectric constant ϵ of the ground.

The next subsection shows how additional path parameters are obtained from these basic parameters.

2.4 Effective Antenna Heights, Horizon Distances, and Elevation Angles

Additional path parameters that must be known or estimated to calculate long-term reference values of transmission loss are the effective antenna heights h_{e1} and h_{e2}, the horizon distances d_{L1} and d_{L2}, and the horizon elevation angles θ_{e1} and θ_{e2}. Horizon distances and elevation angles are shown in figure 2. When a detailed terrain profile is available for a given path, these parameters may be computed by the methods described by Rice et al. (1967) and outlined in annex 3 of this report. Otherwise, estimates of effective antenna heights and of horizon distances and angles must be calculated. Such estimates are based on the terrain factor Δh, on the antenna heights above ground h_{g1} and h_{g2}, and on the method used for selecting antenna sites.

When antennas are high and the terrain is relatively smooth, the actual horizon distances d_{L1} and d_{L2} are approximately equal to the smooth-earth horizon distances d_{Ls1} and d_{Ls2}. When antennas are low and randomly located with respect to hills or other obstructions, as with many tactical communication nets, the actual horizon distances will vary greatly and their median values may be less than the corresponding smooth-earth values. When sites are chosen to take advantage of hilltops, with propagation across valleys, as for radio relays, the horizon distances and effective antenna heights may be greatly increased. Consequently the following estimates are used:

GEOMETRY OF A TRANSHORIZON RADIO PATH

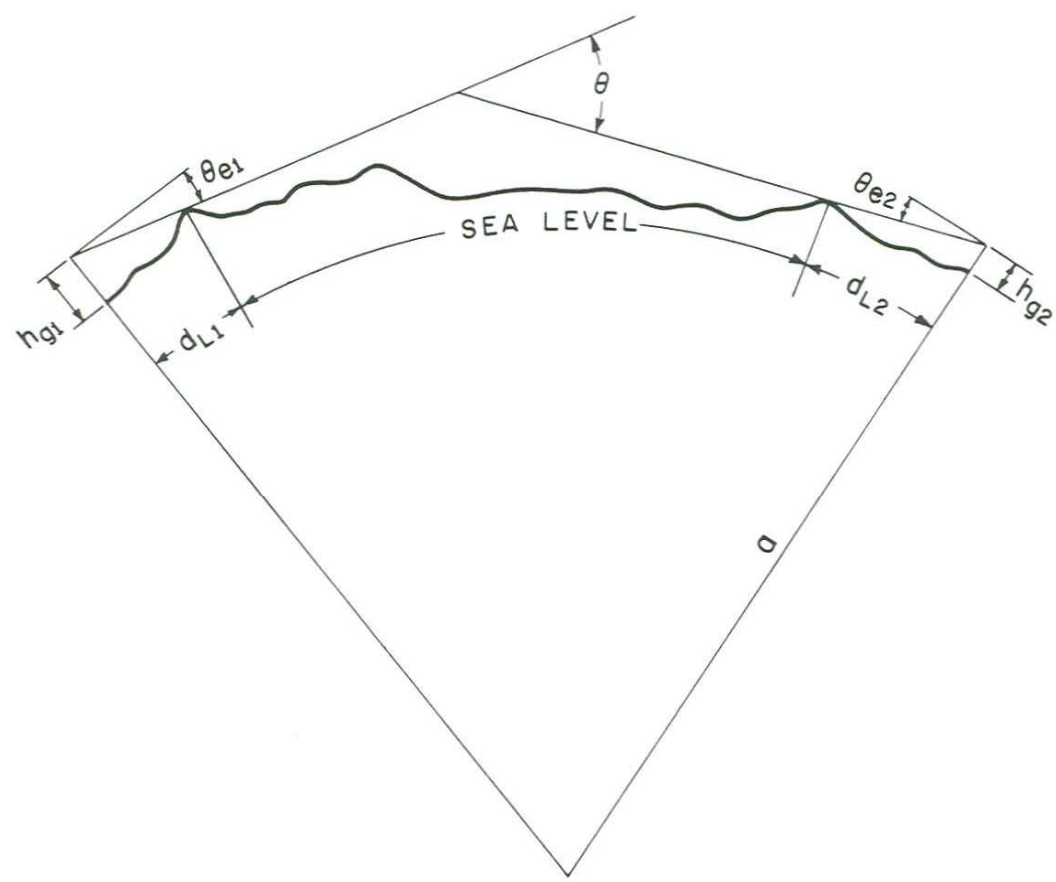

Figure 2

a) For net-type communications, with random antenna siting, the effective antenna heights h_{e1} and h_{e2} are assumed to be equal to the structural heights above ground:

$$h_{e1,2} = h_{g1,2} \quad m. \tag{4a}$$

b) For radio relay links, with antennas located on or near hilltops, the effective heights are larger than the structural heights by an amount whose median value depends on the structural heights and the terrain irregularity Δh:

$$h_{e1,2} = h_{g1,2} + k \exp(-2\, h_{g1,2}/\Delta h) \quad m. \tag{4b}$$

Studies of terrain have shown that the maximum difference to be expected between median values of structural and effective height is 50 m, in which case k would be equal to 50. But in most situations such a difference would be unrealistic, especially with low antennas and limited freedom in site selection. Over moderately hilly to mountainous terrain, with structural antenna heights less than or equal to 10 m, the following estimates of k may be used:

When antenna sites are rather carefully selected in an area of limited extent,

$$k = \begin{cases} 1 + 4 \sin(\pi\, h_{g1,2}/10) & \text{if} \quad 0 \le h_{g1,2} \le 5, \\ 5 \text{ otherwise.} \end{cases} \tag{4c}$$

When antenna sites are still more carefully selected,

$$k = \begin{cases} 1 + 9 \sin(\pi\, h_{g1,2}/10) & \text{if} \quad 0 \le h_{g1,2} \le 5, \\ 10 \text{ otherwise.} \end{cases} \tag{4d}$$

For each application the question of a suitable allowance for effective antenna height should be carefully considered. The improved propagation conditions that can be obtained by careful site selection may be highly significant. Further study of definitions of effective antenna height appears to be the most urgent requirement for improving these predictions for low antenna heights over irregular terrain. Different definitions of $h_{e1,2}$ may be found appropriate for line-of-sight and diffraction formulas.

When individual path profiles are not available, median values of the horizon distances d_{L1} and d_{L2} are estimated as functions of the median effective antenna heights h_{e1} and h_{e2} determined above, the terrain irregularity factor Δh, and the smooth-earth horizon distances d_{Ls1} and d_{Ls2}. The distance from each antenna to its horizon over a smooth earth is defined as

$$d_{Ls1,2} = \sqrt{0.002a\, h_{e1,2}} \text{ km}, \tag{5a}$$

where the effective antenna heights $h_{e1,2}$ are in meters and the effective earth's radius a is in kilometers, as defined by (1). The sum of the smooth-earth horizon distances is

$$d_{Ls} = d_{Ls1} + d_{Ls2} \text{ km}. \tag{5b}$$

Median values of horizon distances over irregular terrain are estimated as

$$d_{L1,2} = d_{Ls1,2} \exp(-\,0.07\sqrt{\Delta h / h_e}) \text{ km}, \tag{5c}$$

where

$$h_e = \begin{cases} h_{e1,2} & \text{for } h_{e1,2} \geq 5 \text{ m}, \\ 5 & \text{otherwise.} \end{cases}$$

The total distance, d_L, between the antennas and their horizons is

$$d_L = d_{L1} + d_{L2} \text{ km}. \qquad (5d)$$

For paths whose antennas are within radio line of sight of each other, estimates of transmission loss depend on the particular effective antenna heights that define the dominant reflecting plane between the antennas. Even for known line-of-sight paths an estimate of the sum of the horizon distances, $d_L \geq d$, is required to compute a reference value of attenuation relative to free space A_{cr}, or of transmission loss L_{cr}, as described in annex 3, subject to the restriction

$$d_{Ls} \geq d_L \geq d. \qquad (5e)$$

If this condition is not met, a non-line-of-sight path is implied, the estimates of $h_{e1,2}$ are too low, and both should be multiplied by the smallest factor that will satisfy (5e).

The horizon elevation angles θ_{e1} and θ_{e2}, shown in figure 2, are the angles by which the horizon rays are elevated, or depressed, relative to the horizontal at each antenna. When detailed profiles for individual paths are not available, median values of $\theta_{e1,2}$ may be estimated as

$$\theta_{e1,2} = \frac{0.0005}{d_{Ls1,2}} \left[1.3 \left(\frac{d_{Ls1,2}}{d_{L1,2}} - 1 \right) \Delta h - 4 h_{e1,2} \right] \text{ radians}. \qquad (6a)$$

The sum of the elevation angles is

$$\theta_e = \theta_{e1} + \theta_{e2} \quad \text{or} \quad - d_L/a \text{ radians}, \tag{6b}$$

whichever is larger algebraically. In (6) all distances are in kilometers and heights are in meters.

For transhorizon paths the path length d is equal to or greater than the sum of the horizon distances d_L. The angular distance for a transhorizon path is always positive and is defined as

$$\theta = \theta_e + d/a \text{ radians}, \tag{7}$$

where d is the path length and a is the effective earth's radius, both in kilometers.

These additional path parameters, $h_{e1,2}$, $d_{L1,2}$, $\theta_{e1,2}$, and θ, are used in computing reference values of attenuation relative to free space A_{cr}, or transmission loss L_{cr}. When only the basic parameters are supplied, estimates of these additional parameters are calculated using equations (4) through (7). When detailed profiles are available for desired paths, these additional parameters are obtained as described by Rice et al. (1967) and outlined in annex 3.

3. TRANSMISSION LOSS CALCULATIONS

This section describes how the various parameters discussed in section 2 are used to compute transmission loss. Median reference values A_{cr} of attenuation below free space are computed first. The reference values L_{cr} of transmission loss are then the sum of the free space basic transmission loss, L_{bf}, and the reference attenuation relative to free space, A_{cr}:

$$L_{cr} = L_{bf} + A_{cr} \text{ dB}. \tag{8}$$