CHAPTER 2

LOS PROPAGATION PATH

2.1 BASIC THEORY

Radio waves are a form of electromagnetic radiation similar to heat and light radiation, but differ in the manner of generation, detection and frequency range. There are a number of mechanisms by which radio waves may propagate from a transmitting to a receiving antenna. The normal propagation paths which exist between two antennas are illustrated in figure 2-1. The various paths shown are dependent upon antenna directivity, launching angle, frequency range, and power levels. The surface (or ground) wave consists of electric and magnetic fields associated with currents induced in the ground. The space wave represents energy that travels from the transmitting to the receiving antenna in the earth's troposphere and usually consists of two components. One is a wave that travels directly from transmitter to receiver (direct wave), while the other is a wave that reaches the receiver as a result of reflection from the surface of the earth (ground reflected wave). The sky wave depends on the presence of the ionized layers above the earth that reflect back some of the energy that otherwise would be lost in outer space. The tropospheric scatter wave depends upon atmospheric turbulence to produce sections of the atmosphere with refractive indexes that are sharply different from those of the surrounding atmosphere. When irradiated by a microwave signal, these sections of the atmosphere reradiate the signal, scattering it in all directions. Some of this scattering is in the forward direction producing a wave at the receiver.

All of the possible paths shown in figure 2-1 exist in any radio propagation problem, but some are negligible in certain frequency ranges. At frequencies less than 1500 kHz, surface waves provide primary coverage, and the sky wave helps to extend this coverage at night when ionospheric absorption is at a minimum. At frequencies above 30 to 50 MHz, direct and ground reflected waves are frequently the only important paths. At these frequencies the surface wave can usually be neglected as long as the antenna heights are not too low, and the sky wave is ordinarily a source of occasional long distance interference rather than a reliable signal for communication purposes.

At frequencies of the order of thousands of megahertz, where the microwave systems under discussion operate, the direct wave is usually controlling on good optical paths. The tropospheric scatter wave is only utilized in systems with high power transmitters, large antennas, and sensitive receivers in multiple diversity arrangements.

Since radio transmission at microwave frequencies is generally confined to space waves, propagation paths are then limited to line-of-sight paths. A line-of-sight path is a path that provides optimum clearance, above the earth's surface or obstructions, for maximum transfer of the desired portion of the propagated energy.

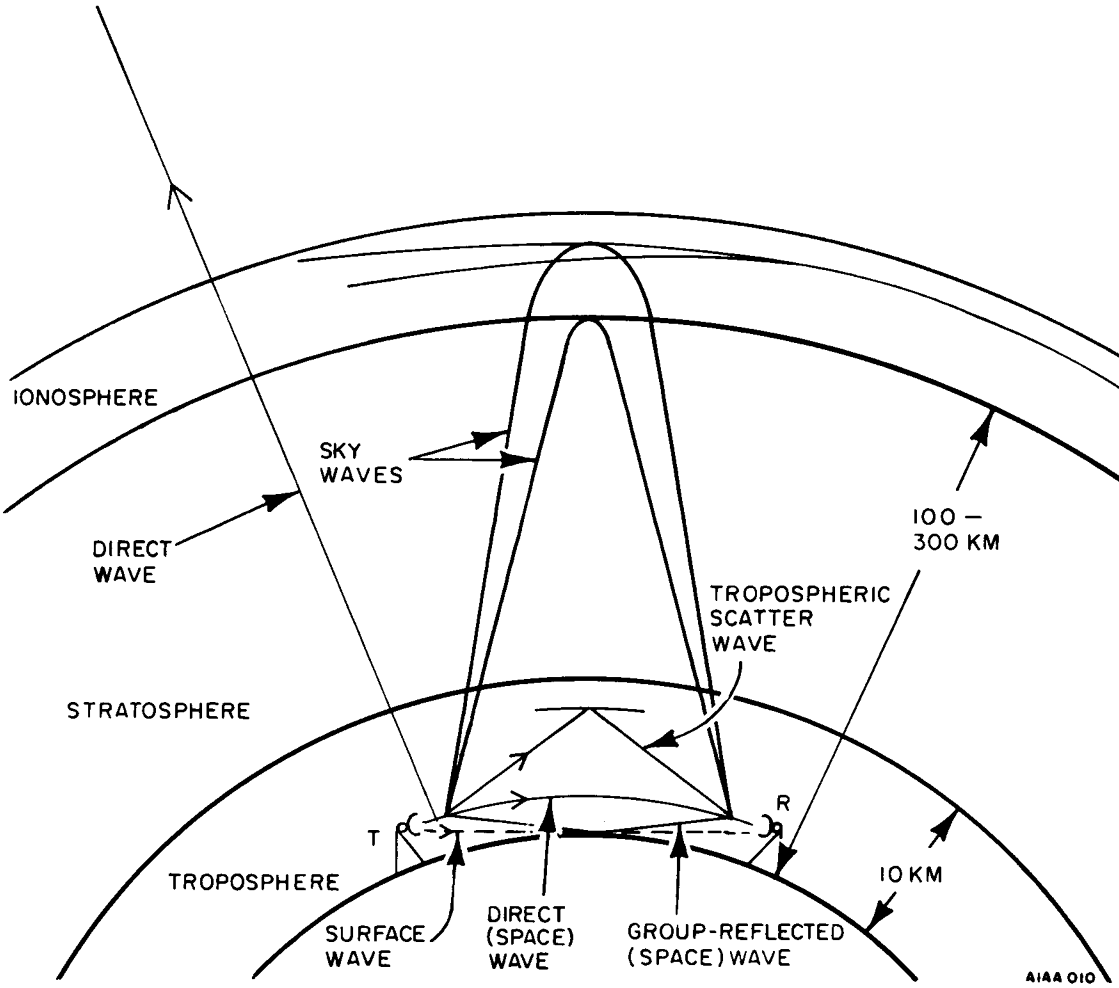


Figure 2-1. Normal Propagation Paths

Radio waves at microwave frequencies and light waves have many similar characteristics. Since the behavior of light waves is well known through the science of optics, and microwaves have many of the same properties, certain optical principles are useful in describing radio wave propagation. The most useful of these are refraction, defraction and reflection. Individually or in combination, these properties can greatly affect reception of the microwave signal at the receiver and, therefore, influence the per-hop or system propagation reliability.

2.1.1 Refraction (K Factor)

At microwave frequencies, radio energy travels along an approximately straight-line path, and the practical range of transmission is said to be limited to line-of-sight conditions. The limitation imposed on the transmission range is due, primarily, to normal earth curvature. At first, it might seem that microwave communication beyond the range at which the receiving antenna can actually be seen from the transmitting antenna would be impossible (that is, limited to the optical horizon). In actual practice, however, this is not true. The actual range extends considerably beyond the optical horizon because of the refractive effect of the earth's atmosphere upon the transmitted wave. This refractive effect causes radio waves to bend in a downward direction and to follow a path which closely approximates the earth's curvature. The point at which the radio waves become tangent to the earth's surface is known as the radio horizon. Under normal conditions in the lower atmosphere, called the troposphere, the line-of-sight path from a point of given elevation to the radio horizon is approximately 15 percent greater than the path to the optical horizon. The basic relationship between the optical and radio horizon is shown in figure 2-2.

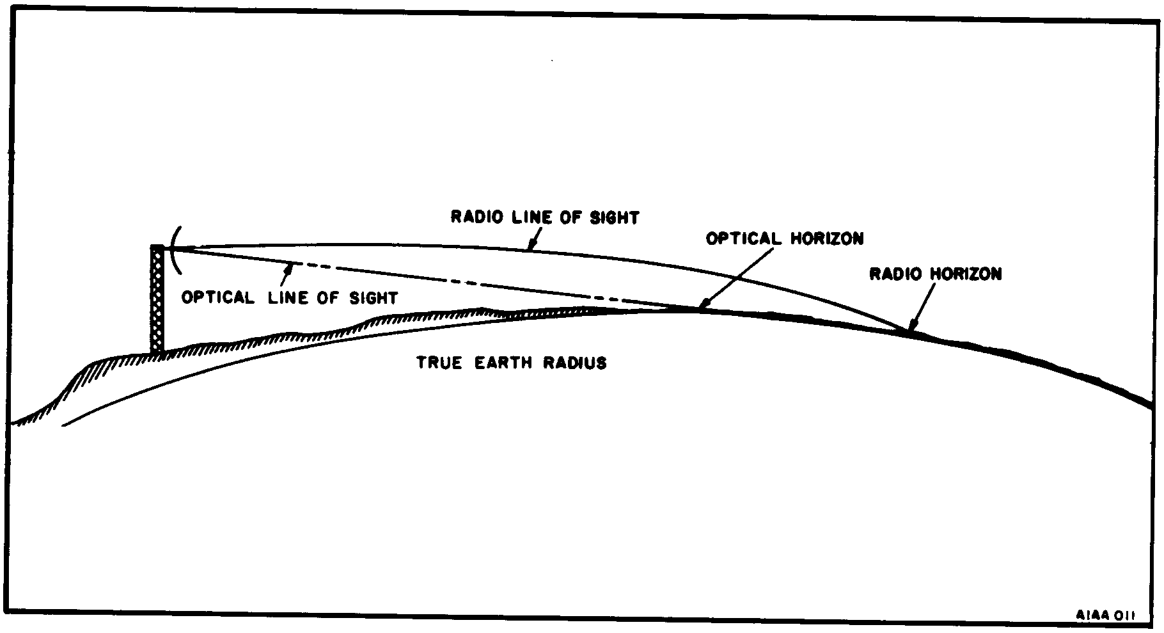


Figure 2-2. Optical and Radio Horizons Relationship

Angular refraction through the atmosphere occurs because radio waves travel with differing speeds in a media of varying dielectric constants. In free space (a vacuum) the speed is a maximum, but in the atmosphere where the dielectric constant is slightly larger due to the presence of gas and water molecules, the radio wave travels slower. In a standard atmosphere the pressure, temperature, and water vapor content (humidity) all decrease linearly with increasing altitude. The dielectric constant, being a single parameter combining the resultant effect of these three meteorological properties, also decreases with altitude. Since electromagnetic waves travel faster in a medium of lower dielectric constant, the upper part of a wave front begins to travel faster than that lower portion which is still in the denser region causing a downward deflection of the wave. In a uniform atmosphere where the change in air density is gradual, this bending or refraction of the radio wave may be essentially continuous, so that the beam is gently curved away from the thinner to the denser atmosphere. The beam then tends, generally, to follow the earth's curvature.

Under these conditions, the earth's radius appears to the microwave beam to be larger than the true radius; that is, the earth appears flatter because of the tendency of the beam to refract downward in the atmosphere and follow the earth. The ratio of this apparent or fictitious earth's radius to the actual earth's radius is referred to as the "effective earth's radius factor" and is designated K. K is approximately equal to 4/3 during the "standard" atmospheric conditions previously described in which the refractive gradient is uniform.

It is worth noting that if the atmosphere were homogeneous throughout the path, the microwave beam would travel in a straight line between the stations. This condition does often occur and is represented by the K=1, homogeneous atmosphere line of figure 2-3.

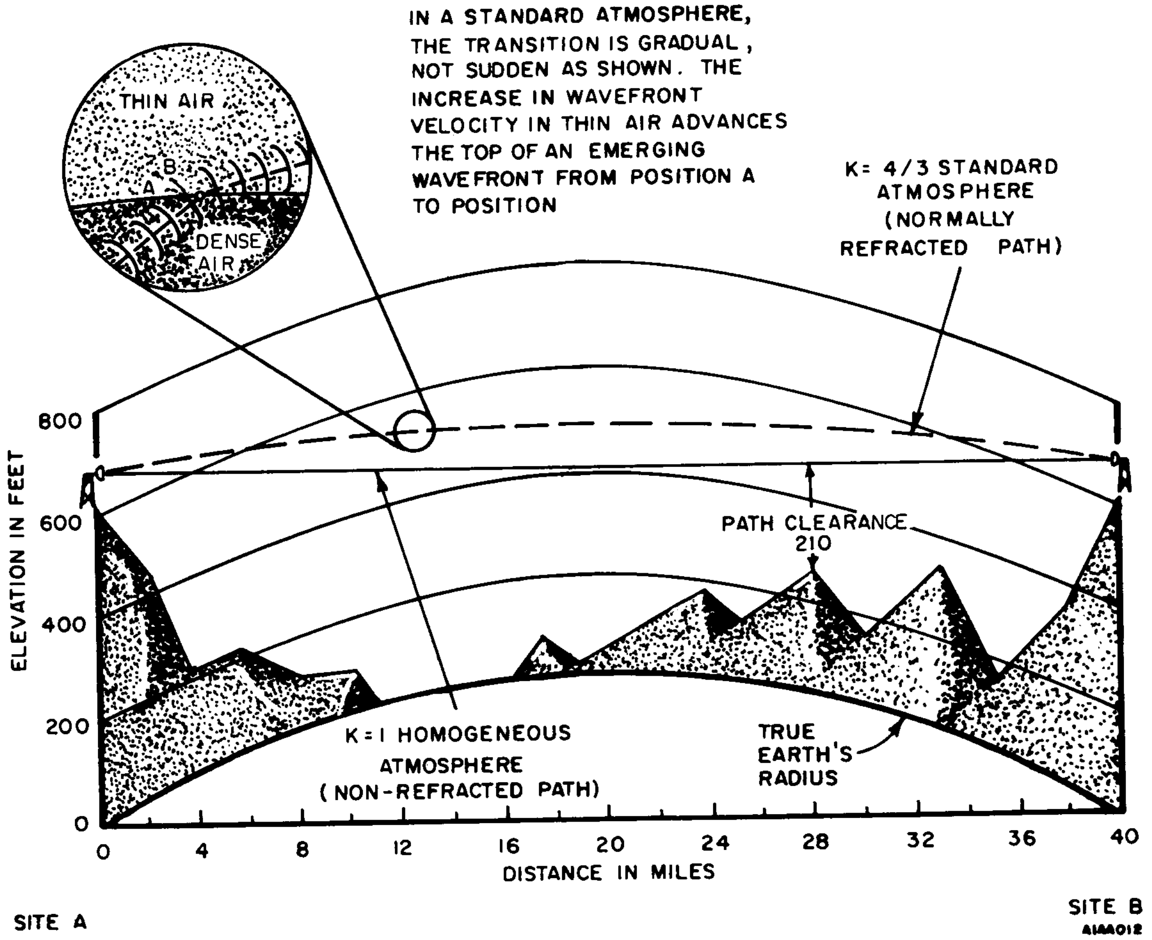


Figure 2-3. Refraction of the Microwave Beam Through Normal Atmosphere on True Earth's Radius of Curvature Profile Paper

Figure 2-4 displays the reconstruction of the profile shown in figure 2-3 based upon an apparent increase in the earth's radius of curvature by a factor of 4/3 (K = 4/3). The normally defracted microwave beam path geometrically becomes a straight line on this type of representation. This makes 4/3 earth's radius profile paper invaluable for studying path clearances, locating reflection points, and establishing antenna heights adequate for microwave propagation during standard atmospheric conditions prevailing up to 80 percent of the time in all parts of the United States. The disadvantage of this type of profile is that it fails to readily lend itself to investigation of path conditions when the microwave beam refraction is other than K = 4/3. In coastal and other areas characterized by high humidity and fog, or reflective terrain, or combinations of these, 4/3 earth's radius profile paper is commonly employed only for a cursory first look at the path.

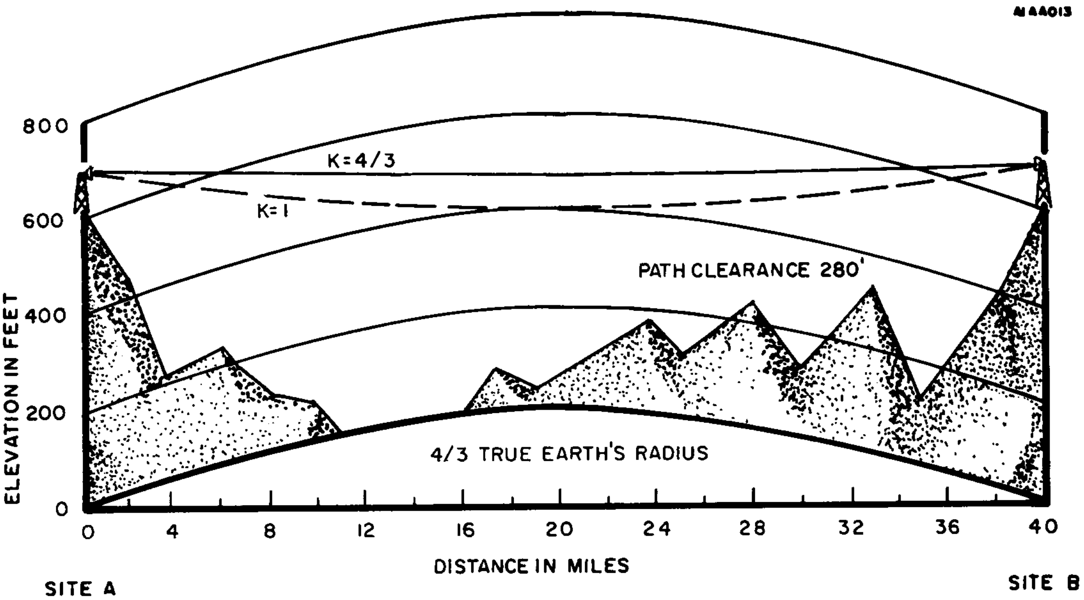


Figure 2-4. Reconstruction of Figure 2-4
on 4/3 Earth's Radius of
Curvature Profile Paper

An interesting comparison between the K = 1 profile and the K = 4/3 profile (refer to figures 2-3 and 2-4) is that the apparent path clearance with the microwave beam represented as a straight line is less (210' versus 280') for the K = 1 than with the K = 4/3 profile. This results in more conservative path engineering evaluation (for example, higher antenna support structures for a given clearance). However, the latter properly assumes some clearance advantage due to standard refraction.

In practice, this nominal value of K = 4/3 is only a mean value occurring in temperate climates. K actually varies between 1 and 2, with lower values existing in cold or dry climates and at high altitudes. The higher values of K are common in coastal areas where the humidity is high. Superstandard values of K from 2 to infinity and substandard values from 1 down to 1/2 and less are encountered occasionally in the United States. This occurs mainly in tropical coastal areas typical of the Gulf of Mexico area and, to a lesser extent, along the East Coast and near the coast of Southern California.

The practical limits of refraction changes in a widely varying atmosphere typical of coastal areas is shown in figure 2-5. The end effect of these changes in K is a wide fluctuation in path clearance, from excessive as K approaches infinity to possibly grazing or less as K drops to 1/2.

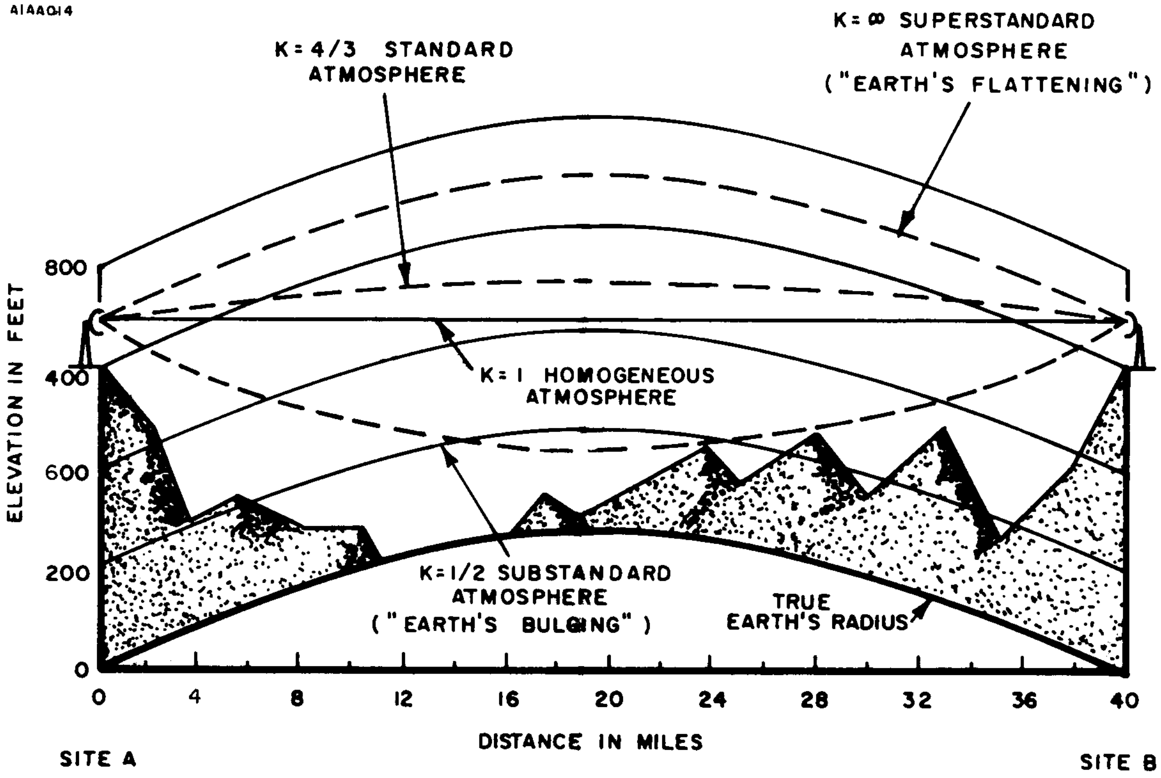
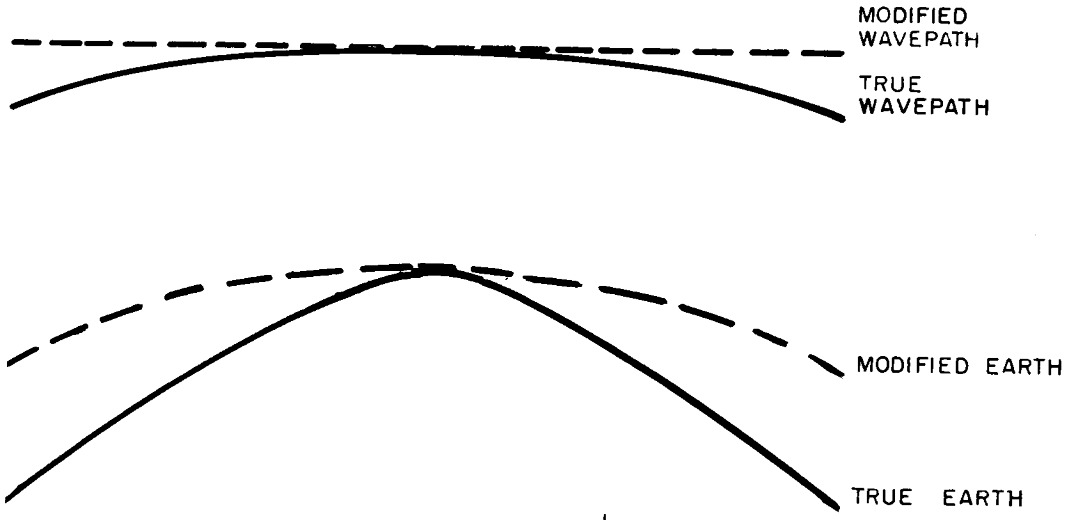


Figure 2-5. Refraction of the Microwave Beam Through Standard Homogeneous, Superstandard, and Substandard Atmospheres on True Earth's Radius of Curvature Profile Paper

Ranges of K and corresponding wave bending effects are illustrated in figure 2-6. It should be noted that, in cases where K is negative, the earth should be considered a plane without any curvature, since geometric optic methods do not hold for a concave surface.



WAVEPATH RADIUS $= \rho$
TRUE EARTH RADIUS $= r$
MODIFIED EARTH RADIUS $= r'$

$$K = \frac{r'}{r}$$

$$\frac{1}{r'} = \frac{1}{r} - \frac{1}{\rho}$$

$$K = \frac{\rho}{\rho - r}$$

$$K = \frac{\text{WAVE CURVATURE}}{\text{EARTH CURVATURE}} = \frac{1/\rho}{1/r}$$ WAVE BENDING

$K = \frac{\rho}{\rho - r}$	$K = \frac{1/\rho}{1/r}$	WAVE BENDING
1/2	−1	SAME AS EARTH BUT UPWARD
1	0	NONE STRAIGHT LINE
1.33	.25	DOWNWARD 1/4 AS MUCH AS EARTH
∞	1	DOWNWARD PARALLEL TO EARTH
−1	2	DOWNWARD TWICE AS EARTH

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Figure 2-6. The Modified Earth's Radius

a. Superstandard Refraction. Superstandard or refraction greater than standard (also called super-refraction) results from such meteorological conditions as a rise in temperature with increasing height (temperature inversion), or a marked decrease in total moisture content in the air. Either of which will cause a reduction in the dielectric constant gradient with height. Under these circumstances K increases, resulting in an effective flattening of the equivalent earth's curvature. One of the conditions which may cause this type of abnormal refraction is the passage of warm air over a cool body of water. Water evaporation will cause an increase in moisture content and a decrease in temperature near the surface, thus producing a temperature inversion. But, it is not only the temperature inversion itself which causes the abnormal bending of the microwave beam. The large increase in water vapor content and, hence, in the dielectric constant near the surface further increases this effect.

In extreme instances of super-refraction, K approaches infinity, as shown in figure 2-5 and a microwave beam which starts parallel to the earth will remain parallel until obstructed or otherwise attenuated.

b. Substandard Refraction. Substandard or less than standard refraction occurs during certain meteorological conditions which cause the dielectric constant to actually increase with height. This condition causes an upward curvature of the microwave beam as shown in figure 2-5, ($K = 1/2$ curve) and is often called inverse beam bending. This unusual refractive condition is also called "earth bulging." A profile constructed with an effective earth's radius factor of $K = 1/2$ is graphically shown in figure 2-7. The microwave beam, substandardly refracted, is represented as a straight line with the $K = 1/2$ fictitious earth bulging to the path.

Substandard refraction occurs less frequently than super-refraction in the coastal areas. This is one of the parameters, along with path length and reflection characteristics, that must be considered in establishing the microwave antenna height. Even if substandard refraction causes path blockage for a total of only 1.4 minutes a day, the microwave reliability considering outages due to this alone will be reduced to 99.9 percent if suitable clearance is not provided.

A substandard atmospheric condition may exist when a low fog is formed by nocturnal cooling of the ground, since the contribution to the increase of the atmospheric dielectric constant due to water in the form of droplets is much less than that due to water in the form of vapor. The dielectric constant will then be lower near the ground than at higher elevations, causing an upward bending of the rays.

c. Radio Standard Atmosphere. The radio refractive index of air, n, is a function of atmospheric pressure, temperature, and humidity. Near the surface of the earth and for VHF-UHF frequencies, n is a number of the order of 1.0003. Since for air, n never exceeds unity by more than a few parts in 10^{+4}, it is convenient to consider climatic variations of n in terms of the "radio refractivity," N, defined as:

$$N = (n-1) \times 10^{6} \qquad (2-1)$$

The average density of the atmosphere varies approximately exponentially with height and the mean values of the refractive index of the atmosphere may be approximated as a function of height by the following exponential function:

$$N(h) = N_s \exp(-ch) \qquad (2-2)$$

where, N_s is the surface value of refractivity, h is the height above the surface in kilometers, and c is determined by the relation:

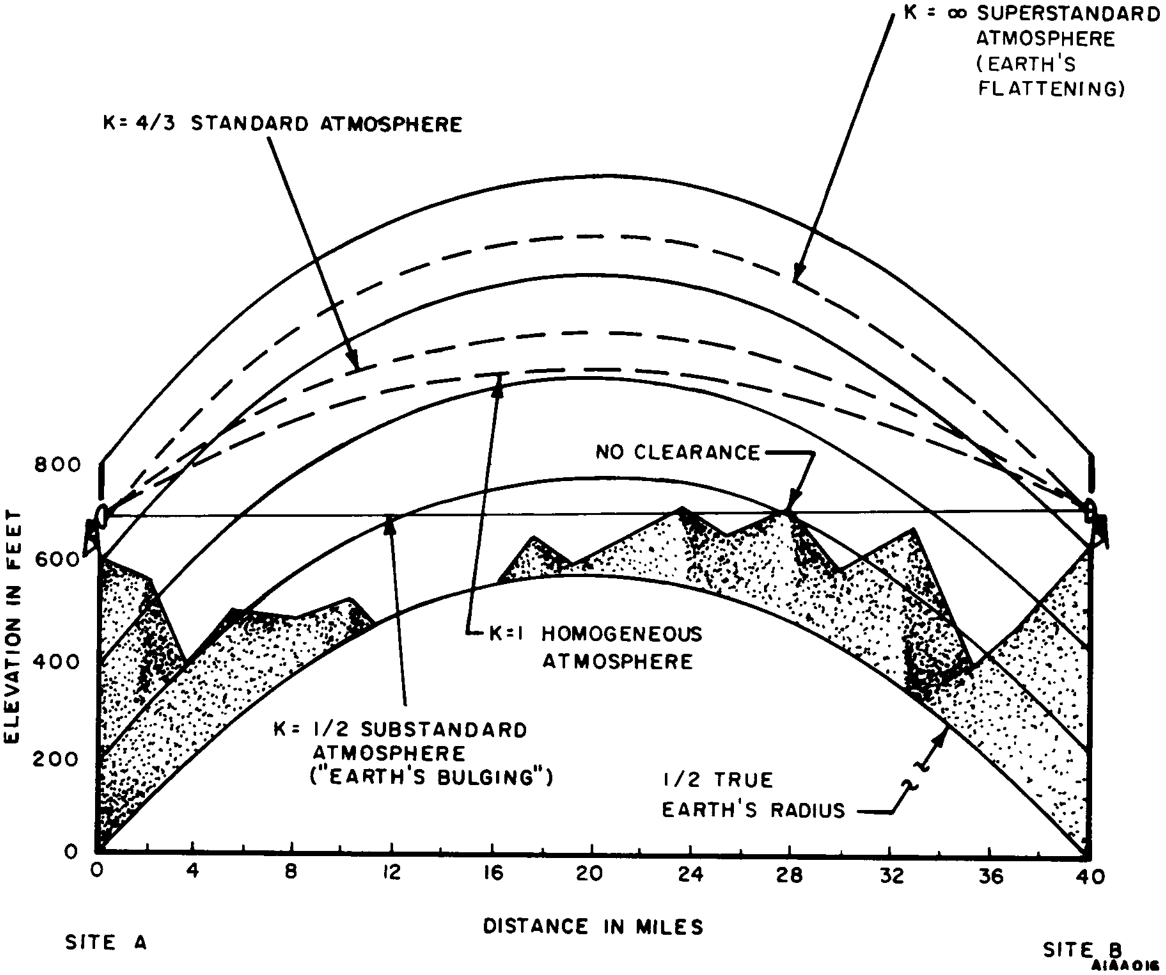


Figure 2-7. Reconstruction of Figure 2-5 on 1/2 Earth's Radius of Curvature Profile Paper

$$c = \ln \frac{N_s}{N_s + \Delta N} \tag{2-3}$$

where, ΔN is the difference in the N values at a height of one kilometer above the surface and at the surface.

N is, in general, correlated with the surface value N_s and may be estimated by the following:

$$-\Delta N = 7.32 \exp(.005577 N_s). \tag{2-4}$$

The effective earth's radius, K, is determined by:

$$K = [(1 - \frac{r_o}{n_s}(cN_s) \times 10^{-6})]^{-1};$$

$$n_s = 1 + N_s \times 10^{-6} \qquad (2\text{-}5)$$

and r_o is taken as 6373.02 km for all value of N_s; where the surface refractivity, N_s, is 289, c becomes 0.136, and the effective earth's radius factor, K, is equal to 1.3332410, or 4/3.

Thus, the Basic Exponential Reference Atmosphere is defined by the relationship:

$$N(h') = 289 \exp(-.136h') \qquad (2\text{-}6)$$

where, h′ is the height above the surface in kilometers.

Table 2-1 lists the constant c and K for the CRPL exponential radio refractivity atmospheres.

Table 2-1. CRPL Exponential Radio Refractivity Atmospheres

$N = N_s \exp(-ch)$			
N_s	$-\Delta N$	K	C
200	22.33177	1.17769	.118399
250	29.33177	1.25016	.125626
289	36.68483	1.33324	.135747
300	39.00579	1.36280	.139284
320	43.60342	1.42587	.146502
350	51.55041	1.55105	.159332
400	68.12950	1.90766	.186719
450	90.01056	2.77761	.223256

The standard model of the atmosphere is obtained by assuming that N decreases linearly in the first kilometer above the surface:

$$N = N_s + \Delta N(h - h_s), \quad h_s \leq h \leq h_s + 1 \qquad (2\text{-}7)$$

where, ΔN is obtained from (2-4), h is the height above sea level and h_s is the height of the surface above sea level in kilometers.

It is assumed that N = 105 at 9 km above sea level and that refractivity decreases exponentially between 1 km above the earth's surface, $h_s + 1$, to the value of 105 at 9 km. This assumption means that N may be expressed by:

$$N = N_1 \exp\,[-c(h - h_s - 1)],\ h_s + 1 \leq h \leq 9 \qquad (2\text{-}8)$$

where,

$$-c = \frac{1}{8 - h_s} \ln \frac{105}{N_1}$$

and, N_1 is the value of N at $h = h_s + 1$. Note that the only two variables in equation (2-8) are the height of the surface above sea level and N_1 which is a function of N_s.

Above 9 km the refractivity is determined by:

$$N = 105 \exp\,[-0.1424\ (h - 9)]\ h \geq 9 \text{ km}$$

This three part model of the atmosphere has been adopted for use at the National Bureau of Standards. The constants adopted are given in table 2-2 and specify the CRPL Reference Refractory Atmosphere.

Table 2-2. Constants for the Standard Reference Atmosphere

N_s	h_s FEET	a′ MILES	-ΔN	K	a_e MILES	c/km
0	0	3960.0000	0	1.00000	3960.00	0
200	10,000	3961.8939	22.3318	1.16599	4619.53	0.106211
250	5,000	2960.9470	29.5124	1.23165	4878.50	0.114559
301	1,000	3960.1894	39.2320	1.33327	5280.00	0.118710
313	900	3960.1324	41.9388	1.36479	5403.88	0.121796
350	0	3960.0000	51.5530	1.48905	5896.66	0.130579
400	0	3960.0000	68.1295	1.76684	6996.67	0.143848
450	0	3960.0000	90.0406	2.34506	9286.44	0.154004

Notes: a_e is the effective earth's radius and is equal to a K

$a' = a + h_s$ where h_s is the height of the earth's surface above sea level

a = 3,960 miles.

$$c = \frac{1}{8 - h_s} \ln \frac{N_1}{105}$$

N can be calculated from radiosonde data by:

$$N = \frac{77.6P}{T} + \frac{3.73 \times 10^5 e}{T^2} = (\text{Dry Term}) + (\text{Wet Term}) \qquad (2\text{-}9)$$

where:

P = atmospheric pressure in millibars

e = vapor pressure in millibars

T = temperature, degrees kelvin

Significant components of N are the "wet" and "dry" terms and the differential effects produced by them in the refractory gradient ΔN. Curvature and hence K, is dependent upon this gradient.

It will not be necessary to use the mean square gradient explicitly in transmission loss calculations. A set of "standard atmospheres" has been defined which show the height dependence of radio refractivity as a function of its value at the surface, N_s. Near the ground, the following empirical relationship is valid between N_s and the difference in refractivity, ΔN, between N_s and N at one kilometer above the earth's surface:

$$\Delta N/\mathrm{km} = -7.32 \exp (0.005577 N_s) \tag{2-10}$$

If (2-10) is inverted, N_s can be obtained as a function of the refractory gradient ΔN:

$$N_s = 412.87 \log|\Delta N| - 356.93 \tag{2-11}$$

Estimates for N_s for winter afternoons (time block 2) may be obtained from figures 2-8 and 2-9 which show the distribution of a related quantity, N_0, for the continental United States, and for the entire world, respectively. In order to allow for climatic conditions different from the northern temperate zone, the N_0 contours on figure 2-9 are plotted for the monthly minimum values in the northern temperate zone.

The quantity plotted on figures 2-8 and 2-9 is the surface refractivity reduced to zero elevation above mean sea level. It is related to the surface refractivity N_s at an elevation h_s above mean sea level by:

$$N_s = N_0 \exp (-0.03222 h_s) \tag{2-12}$$

where, the elevation h_s is expressed in thousands of feet. For within-the-horizon paths, h_s is the average of the horizon elevations.

Figure 2-10 is a plot of equation (2-12). Now, from N_0 we can obtain surface refractivity N_s at any height. Using N_s equation (2-10) provides the refractory gradient per kilometer above the surface and this permits calculation of average values of K.

"K" is a function of the refractory gradient ΔN as well as the surface refractory values N_s. The relationships are given by the following expressions, where a is the actual radius of the earth (approximately 3960 statute miles) and a_e is the effective earth radius:

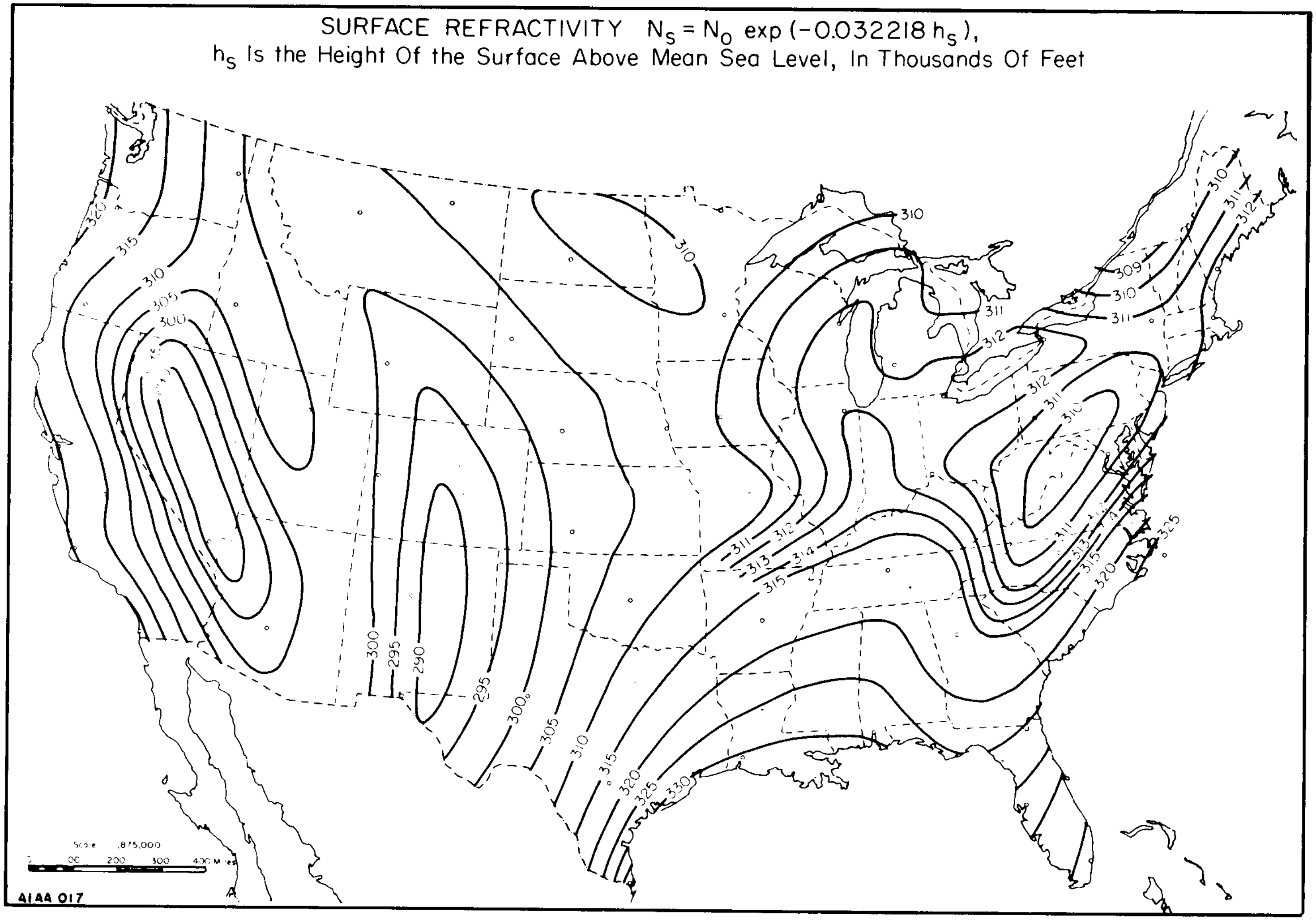


Figure 2-8. Surface Refractivity, November - April, 1 P.M. - 6 P.M. (Time Block No. 2)

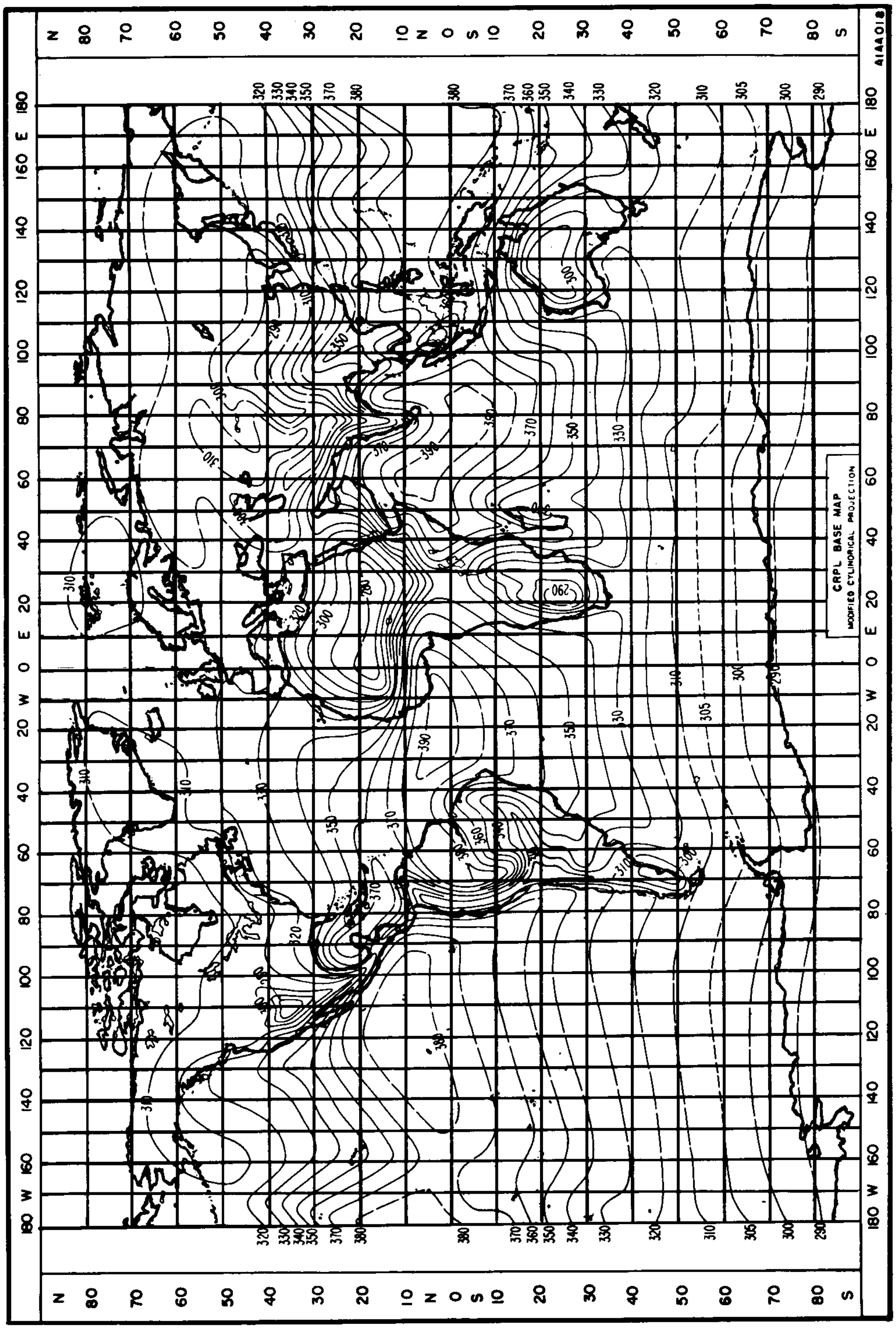


Figure 2-9. Minimum Monthly Mean N_o

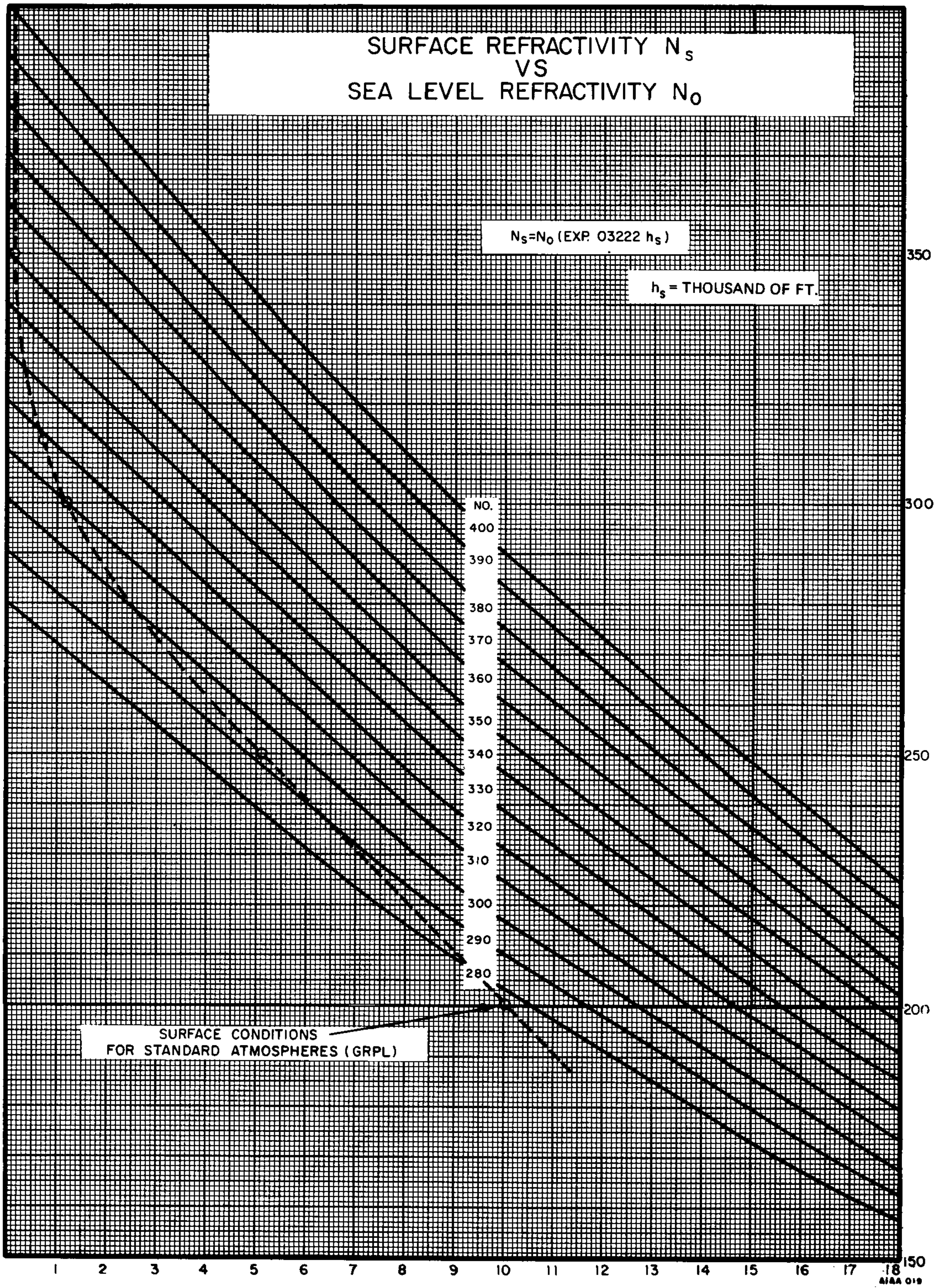


Figure 2-10. Surface Refractivity N_s Versus Sea Level Refractivity N_o

$$K = \frac{a_e}{a} = \left(1 + 0.00637 \frac{\Delta N}{km}\right)^{-1} \qquad (2\text{-}13)$$

$$K = \frac{a_e}{a} = \left[1 - 0.04665 \exp\left(0.005577 N_s\right)\right]^{-1} \qquad (2\text{-}14)$$

Figure 2-11 is a plot of equation (2-13) illustrating the effect of the refractory gradient on K. These expressions will break down, when the quantities in the brackets approach zero. This corresponds to refractive conditions where the earth has become flattened out ($K = \infty$). In this case, as well as in cases where K would become negative, the earth is considered a plane without any curvature, as geometric optics methods used here do not hold for a concave surface.

Figure 2-12 is a plot of refractory gradient $\frac{\Delta N}{km}$ and "K" versus surface refractivity N_s. The limiting values are $\Delta N = 156.9$, corresponding to $N_s = 550$. The latter value rarely will be encountered in practical applications. If actual measurements of ΔN are utilized for calculation of within-the-horizon paths, limiting values may be encountered more frequently.

Table 2-3 lists parameters discussed above for several reference atmospheres, which will be used subsequently in transmission loss calculations.

The usual term "four-thirds earth radius," or "standard refraction" refers to the conditions where the surface refractivity is 301, the gradient is -39.23 N units per kilometer, and the ratio of the effective to the actual earth's radius "K" is very nearly 4/3. It is seen from table 2-3 that the effective earth's radius in this case is 5280 statute miles. This number is also useful in conversions from feet to statute miles.

Since K depends upon the refractivity gradient, it is subject to short and extreme variations with wind, clouds, daylight, etc. These variations must be estimated from rather limited statistical information and are important because they cause fading.

K variations are usually smaller in high, dry climates and greater in low humid areas. Figures 2-13, 2-14 and 2-15 represent a family of estimated K distributions for different local conditions.

2.1.2 Diffraction (Fresnel Zones)

Diffraction of light and radio wavefronts occurs when the wavefront encounters an obstruction which is large compared to the wavelength of the wave. At lower VHF frequencies, the wavefront will tend to bend or diffract around intervening objects with increased attenuation. At microwave frequencies above 3000 MHz, however, this attenuation increases so rapidly (with increasing obstruction such as earth bulge) that except for specialized systems designed for extreme path loss, the system becomes unusable. The amount of energy diffracter around the obstruction is negligible at these microwave frequencies. The actual amount of obstruction loss is dependent upon the area of the microwave beam obstructed as related to the total frontal area of the energy propagated, and to the coefficient of reflectivity of the obstruction.

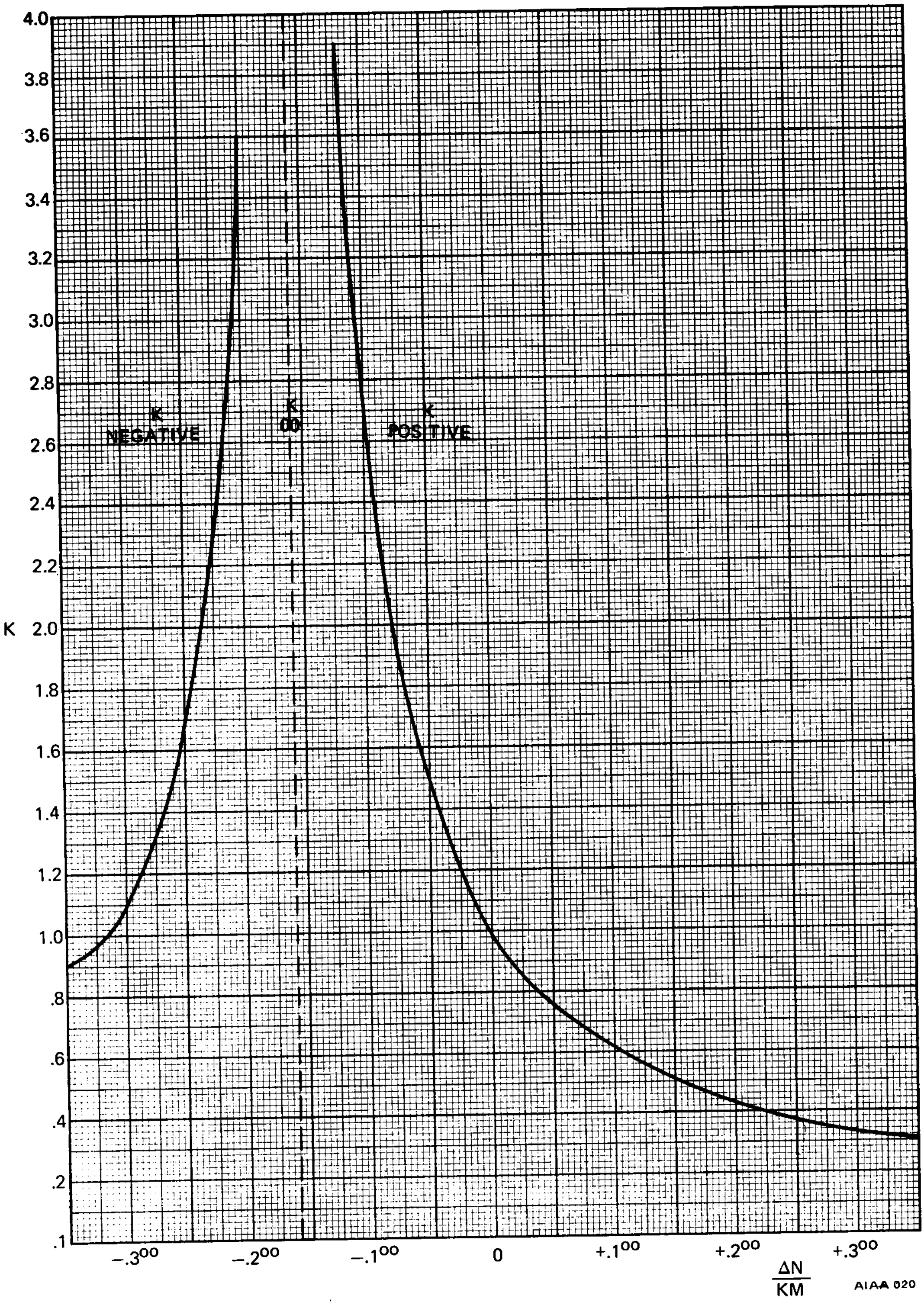


Figure 2-11. Effect of Refractivity Gradient on "K"

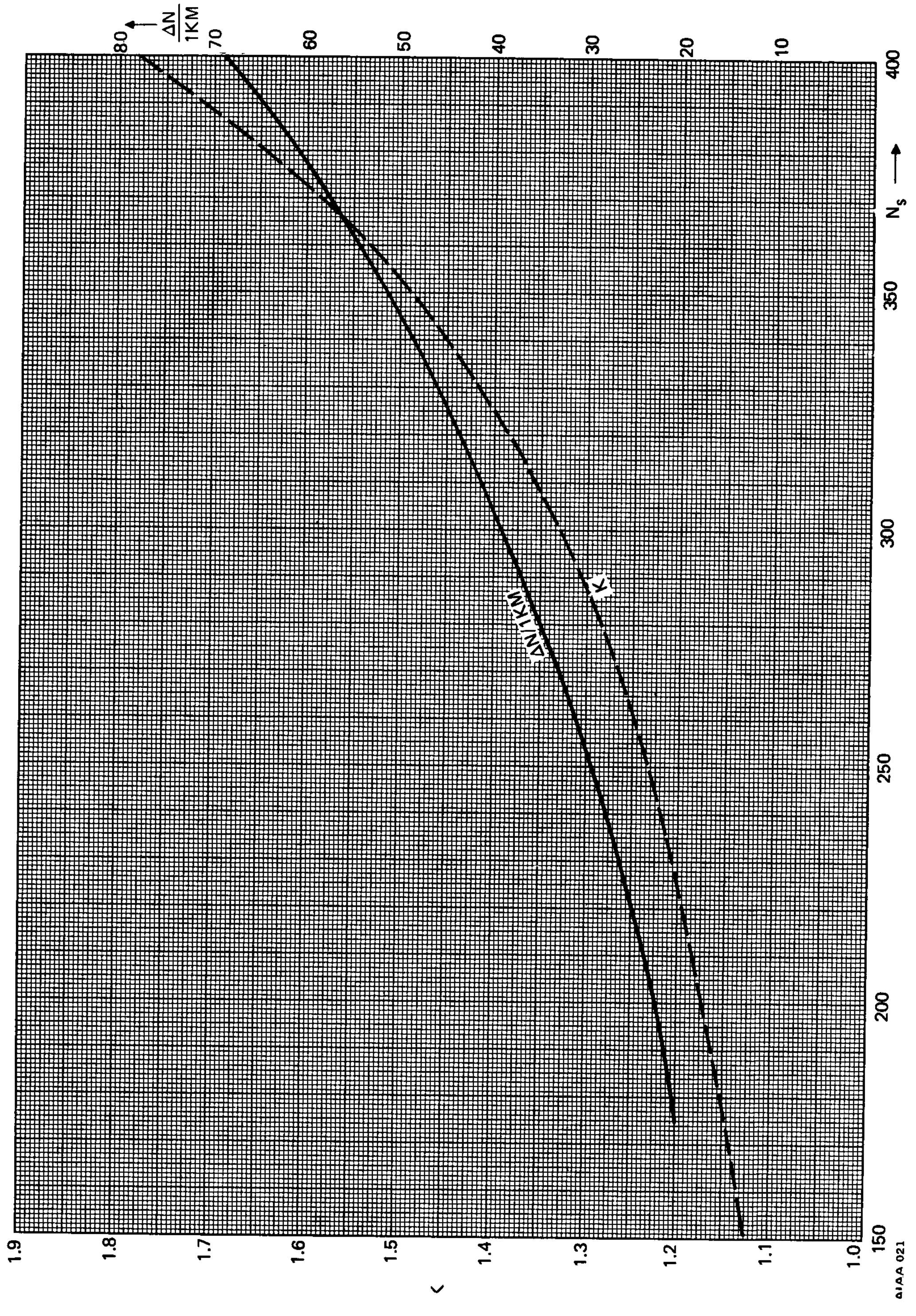


Figure 2-12. Refractivity Gradient ΔN/KM and "K" Versus Surface Refractivity N_S

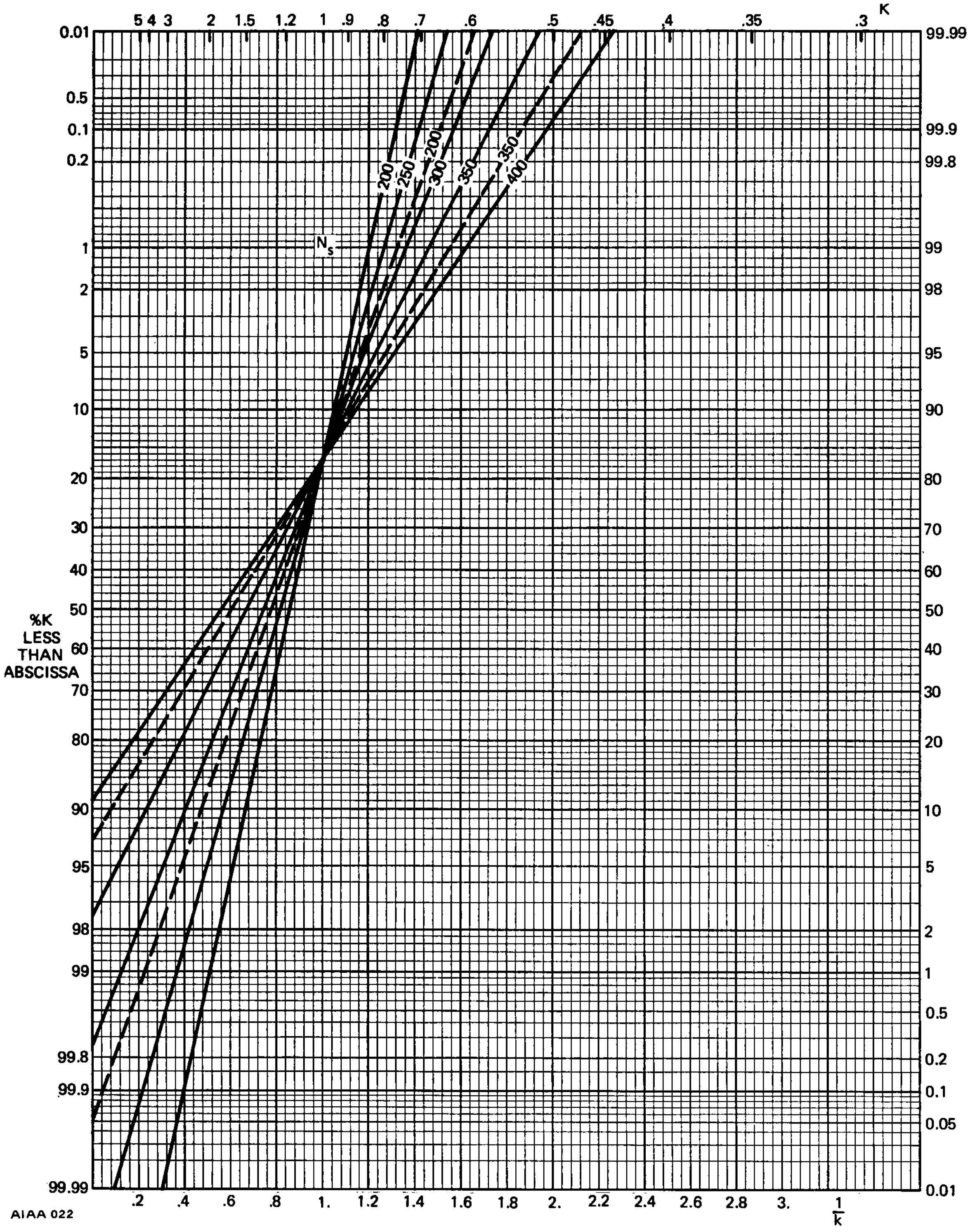


Figure 2-13. No Fog - 30 Miles

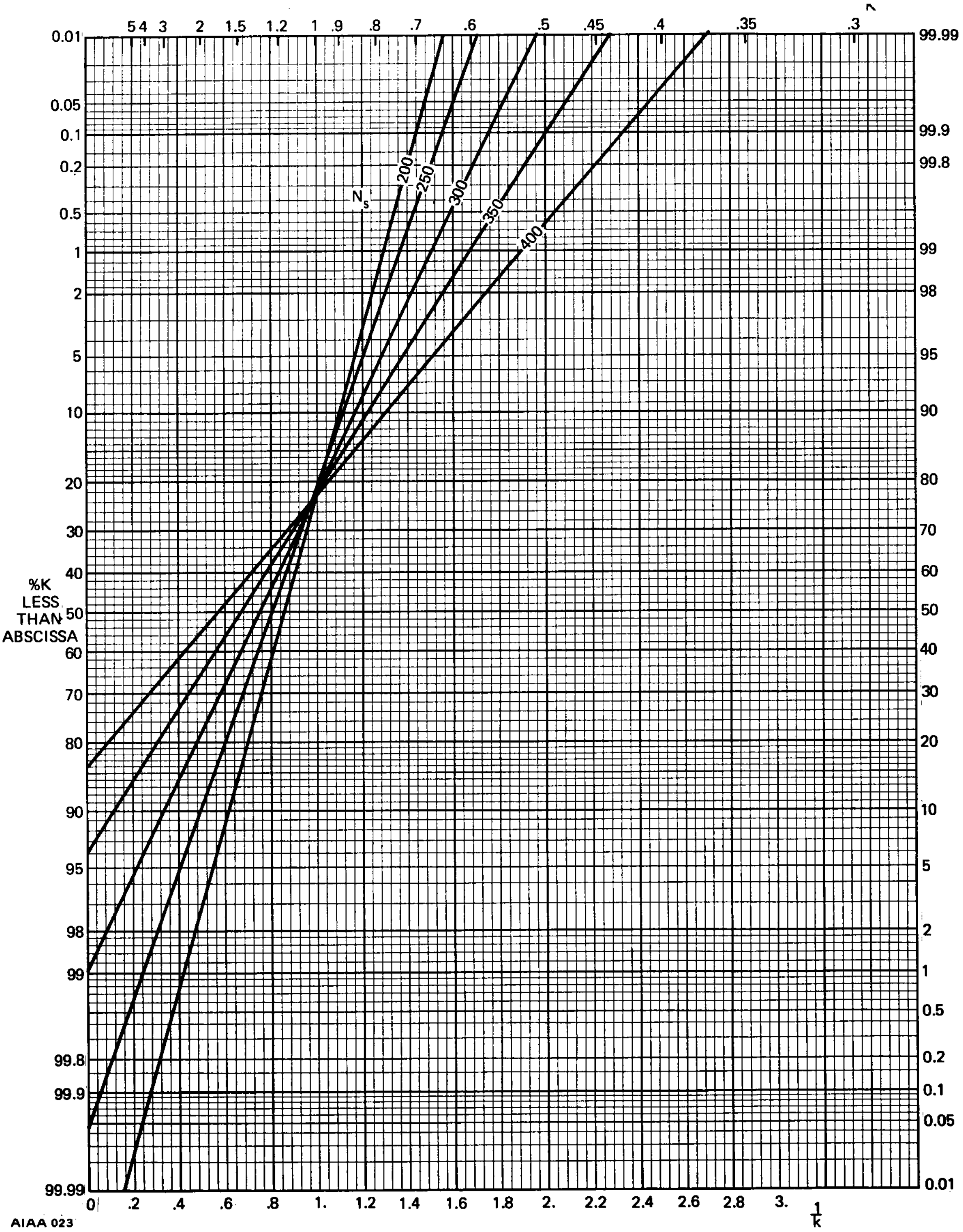


Figure 2-13. Some Fog - 30 Miles

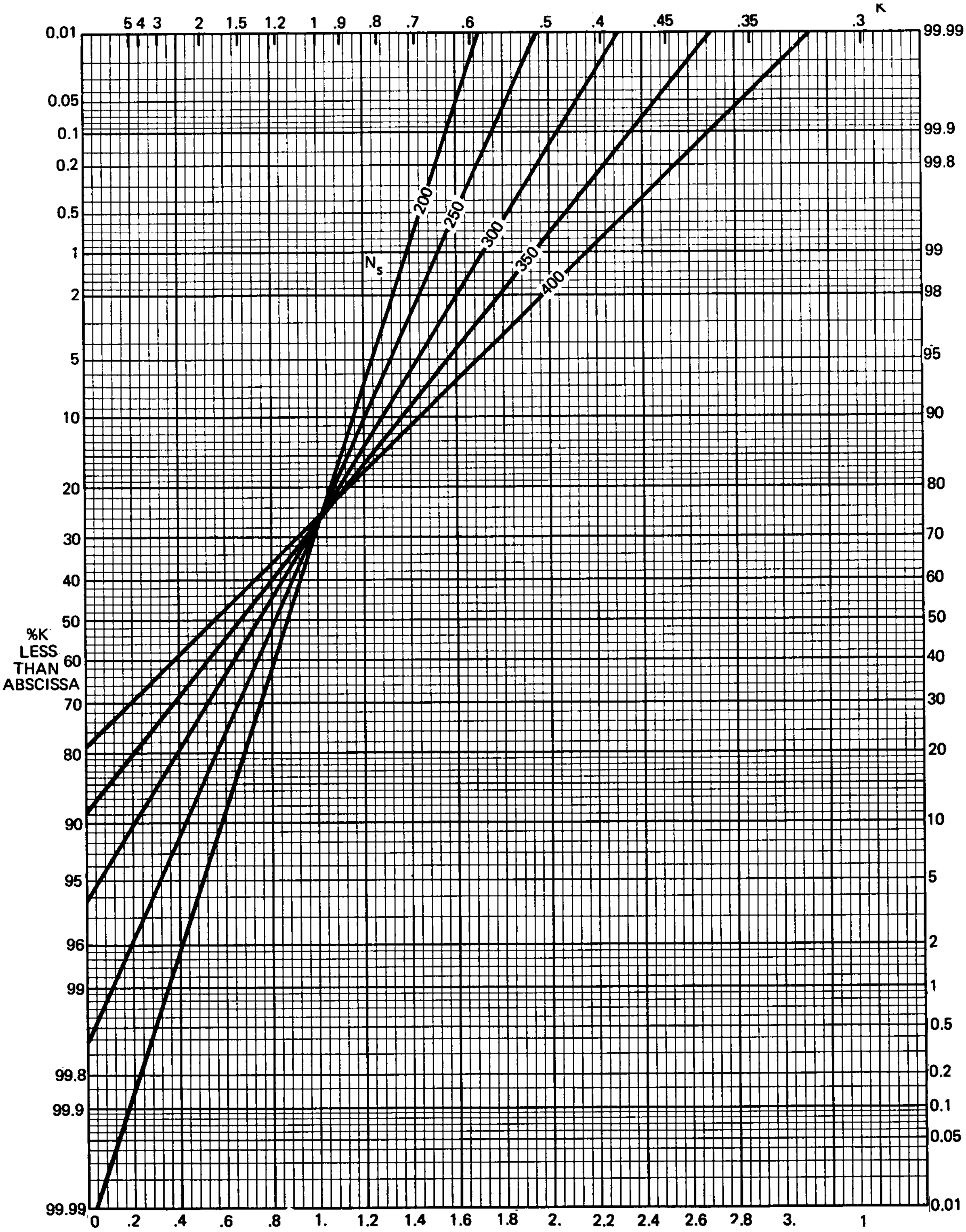


Figure 2-15. Heavy Fog - 30 Miles

Table 2-3. Standard Atmosphere Parameters

SURFACE REFRACTIVITY N_s	REFRACTIVITY GRADIENT NEAR SURFACE $\Delta N/km$	EFFECTIVE EARTH RADIUS a/n STATUTE MILES
250	-29.51	4878.50
301	-39.23	5280.00
350	-51.55	5896.66
400	-68.13	6996.67

Essentially free-space propagation exists when the frontal area of the wave bounded by the limits of six-tenths of the first Fresnel zone is clear of all obstructions on the path. Any obstruction extending into this circular region from any direction will cause significant attenuation of the microwave beam. The first Fresnel zone boundary is formed by the locus of all points from which a wave could be reflected with a total path length increase of 1/2 wavelength over the direct path. Each successive Fresnel zone boundary is described by the increase of reflected path length in multiples of 1/2 wavelength. For example, a ray reflecting at any point on the surface defining the fifth Fresnel zone is physically five 1/2 wavelengths longer than the direct path between antennas. Actually, there are an unlimited number of Fresnel zones on a wave front. However, the region described as the first Fresnel zone accounts for approximately one-quarter of the total received field energy. The first five Fresnel zones for a 40-mile path are shown to scale in figure 2-16. This microwave path is represented as partially obstructed by a hill at a distance of 14 miles from one terminal. This hill is shown at two heights for illustrative purposes. If the path clearance over this hill is equal to the radius of the fifth Fresnel zone (obstruction 1 in figure 2-16), arrival of the reflected wave will be delayed 3 wavelengths behind the direct ray, and the two will add in phase resulting in a received signal level increase of as much as 6 dB. This delay results from a 180° (1/2 wavelength) phase reversal or lag at point of reflection plus five 1/2 wavelengths difference in the physical path length for a total of six 1/2 wavelengths or 3 wavelengths.

If the obstruction were higher and a zero-clearance or grazing condition resulted, as represented by obstruction 2 in figure 2-16, the received signal would decrease from free space values by at least 6 dB and perhaps as much as 15 dB. The wide fluctuations in predicted signal level enhancements due to odd Fresnel zone additions and degradation due to even zone cancellations result from differences in the value of the coefficient of reflection (R) of various obstructions. Wider ranges of signal increase or decrease are apparent when the terrain is highly reflective (R = 0.8 to -1.0, the negative sign making reference to the 180° phase reversal at the reflection point). A special condition occurs at the lower ranges of R (0 to -0.3) when the obstruction is knife edge. Fluctuations in received signal level with varying clearances are attributed more to wavefront diffraction and Fresnel zone obstruction than to reflected ray interference patterns. Table 2-4 lists reflection coefficients of various categories of terrain together with attendant effect on receive signal level. Figure 2-17 is a re-plot of the upper right side of figure 2-16 depicting path attenuation versus path clearance.

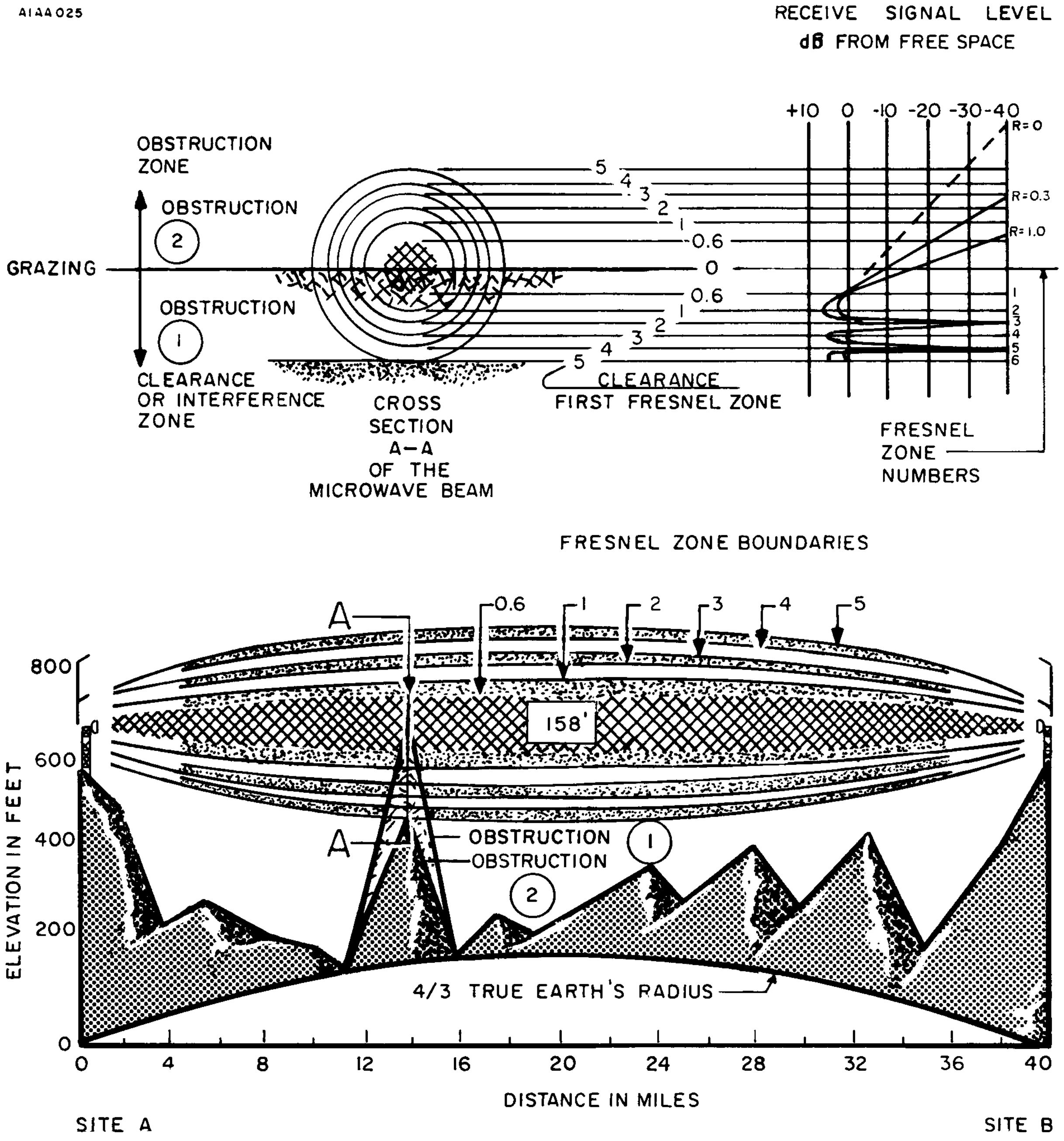


Figure 2-16. Fresnel Zones for a 40-Mile Microwave Path, Standard Atmosphere, on 4/3 Earth's Radius of Curvature Profile Paper (6 GHz)

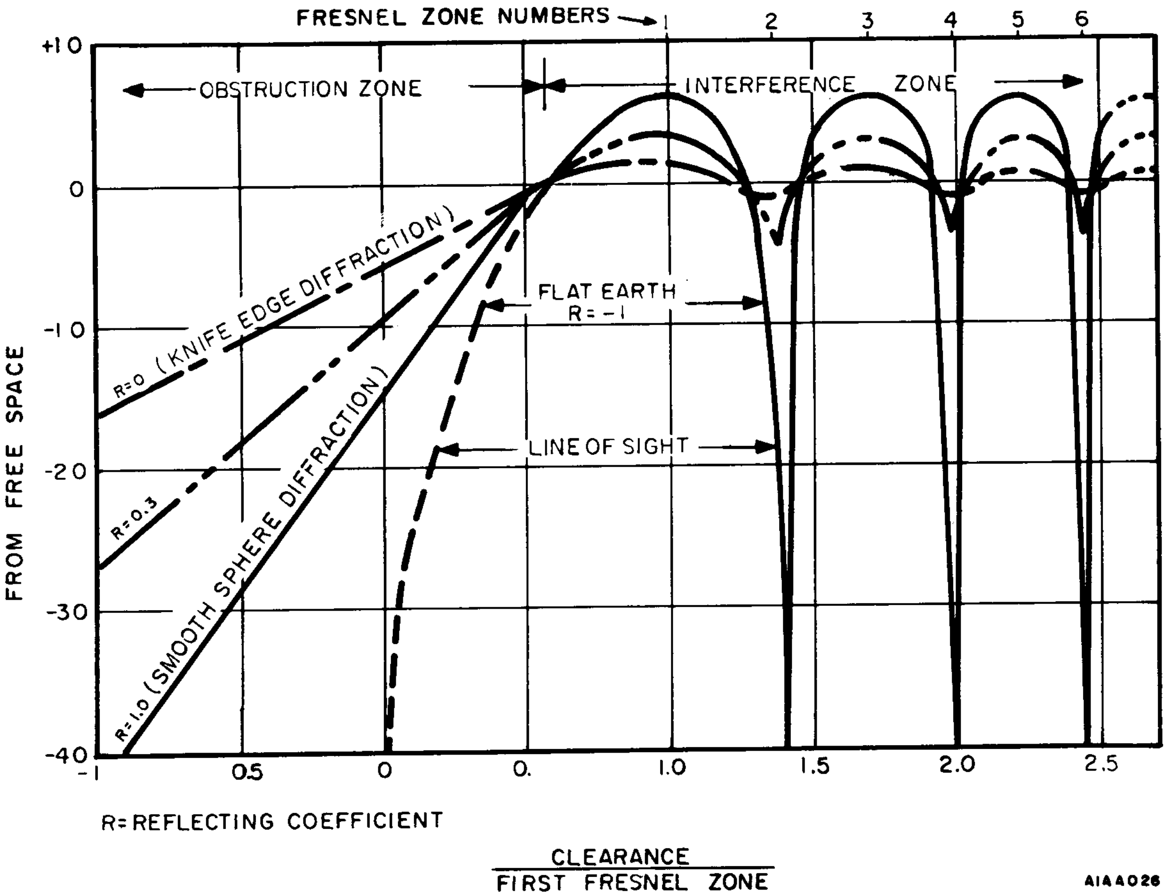


Figure 2-17. Path Attenuation Versus Path Clearance

Table 2-4. Approximate Values of R for Various Terrain

TYPE OF TERRAIN	R	APPROXIMATE DEPTH OF EVEN FRESNEL ZONE FADE dB
Heavily wooded, forest land	0 to -0.1	0 - 2
Partially wooded (trees along roads perpendicular to path, etc.)	-0.1 to -0.4	2 - 5
Sagebrush, high grassy areas	-0.5 to -0.7	5 - 10
Cotton with foliage, rough sea water, low grassy areas	-0.7 to -0.8	10 - 20
Smooth sea water, salt flats, flat earth	-0.9 +	20 - 40+

The values of R given in this table are approximate, of course, but they do give an indication of signal degradation to be expected over various terrain should even lumbered Fresnel zone reflections occur.

Bending or diffraction around obstructions can be explained using Huygens' Principle which states: "All points on a wavefront can be considered point sources for the production of spherical secondary wavelets. After a time, t, the new position of the wavefront will be the surface of tangency to these secondary wavelets."

Figure 2-18 is a free space example. At the time t = o, a portion of the wavefront is shown as ab. Several points (see dots) on the wavefront, ab, serve as centers of radiation (wavelets). At time t, the wavelets have reached the position ct. The new wave front, de, is made up of ct components normal to wave front ab. Vector components parallel to the wave front are equal in magnitude but opposite in direction and therefore cancel. When a knife-edged obstruction is located at a wavelet source as shown in figure 2-19, the components of ct parallel to wave front ab no longer cancel and a portion of the signal is transmitted behind the obstruction (shadow zone). If the obstruction is a smooth sphere instead of a knife edge, a portion of the signal in the shadow zone will be reflected from the spherical surface away from the receiving antenna with some cancellation taking place. The resulting received signal will be much less than in the knife-edge diffraction case.

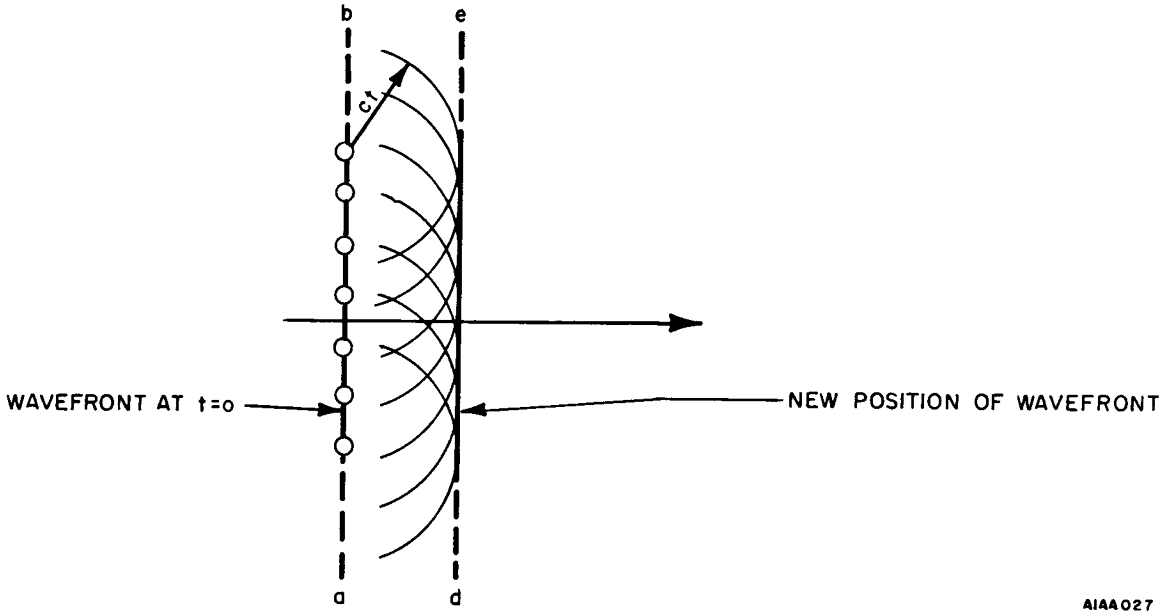


Figure 2-18. The Propagation of a Plane Wave in Free Space as Described by the Huygens' Principle

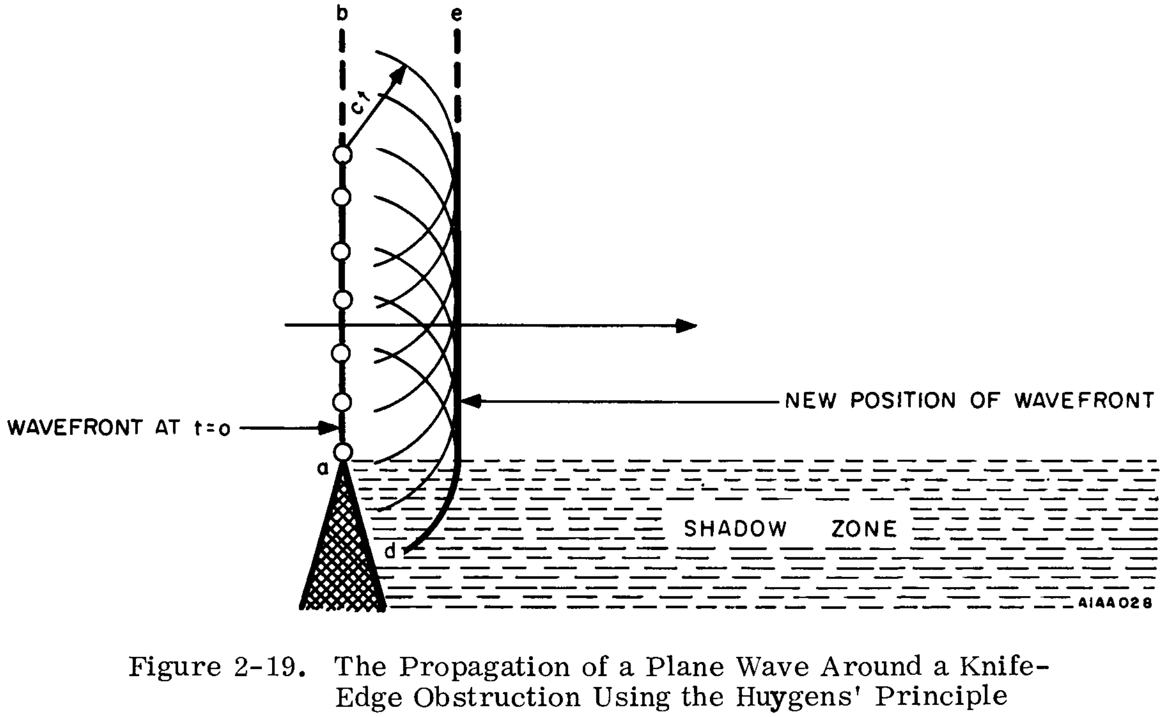


Figure 2-19. The Propagation of a Plane Wave Around a Knife-Edge Obstruction Using the Huygens' Principle

2.1.3 Reflections

When more than six-tenths first Fresnel zone clearance exists on a path, the received signal can be more or less than the free space calculated value depending upon the relative strength and phase of the reflected signal as discussed previously. The direct and reflected waves interfere and result in maxima and minima receive signal strength pattern as the path clearance is increased above grazing over reflective terrain. This condition is often referred to as reflected-ray or Fresnel fading and is illustrated in figures 2-16 and 2-17.

As the transmitting and receiving antennas are elevated simultaneously to increase path clearance from obstructed to free space, the received signal level increases linearly with clearance. Free-space clearance occurs when the actual received signal level corresponds to the previously calculated value assuming free-space propagation conditions. Path clearance over the obstruction at this point is about equal to six-tenths of the radius of the first Fresnel zone, shown cross-hatched in figure 2-16.

As the antennas are raised further, part of the beam may be reflected from the obstruction towards the receiving antenna, assuming the angles of incidence and reflection are equal (a procedure for locating points of reflection meeting this criterion will be discussed). When the length of the reflected path is longer than the direct path by 1/2 wavelength, these rays will arrive in phase, since an additional phase shift of about 180° lagging (1/2 wavelength) takes place at the reflection point. The result will be an increase in the received signal level of from 1 to 6 dB over free-space calculations, depending upon the magnitude of the reflected wave. This reflective surface may be located below the main beam (water or a barren hill), above the main beam (an atmospheric discontinuity or aircraft), or to one side of the path (a nearby building), and the locus of all of these points identifies the first Fresnel zone as previously discussed. The third, fifth, and all remaining odd-order zones occur at the point of reflection when the reflected ray arrives at the receiver in phase (even multiples of 1/2 wavelength) with the direct ray, thus, increasing the resultant signal level.

Conversely, clearance equal to the radii of even Fresnel zones (second, fourth, etc.) at the point of reflection may cause the addition of the main beam with out-of-phase or even-zone reflection components. This will result in a reduction in the received signal, which varies from just a few dB to an infinite amount, depending upon the value of the coefficient of reflection.

Path clearances in terms of Fresnel zone numbers for various values of K over points of reflection are extremely important parameters and must be determined. The nth Fresnel zone radius in feet for any point along a microwave path of length D is given by:

$$F_n = 2280\sqrt{\frac{nd_1 d_2}{fD}} \qquad (2\text{-}15)$$

where:

D, d_1, and d_2 are distances in miles ($d_1 + d_2 = D$)

n = Fresnel zone number, and

f = Frequency, MHz

If the first Fresnel zone radius is known at a particular point on a path, the radius for the nth zone can be readily determined from the relationship;

$$F_n = F_1\sqrt{n} \qquad (2\text{-}16)$$

Computer printouts have been prepared listing the solution of the above equations in tabular form.

Dimensions which are important in the practical engineering of microwave paths over reflective terrain are identified in figure 2-20. The direct ray, r_0, is shown as a straight line over a fictitious earth whose radius is a function of K. The length of the reflected ray r_2 is dependent upon path clearance over the point of reflection. If this clearance is equal to F_2 (the radius of the second Fresnel zone), the path of the reflected ray is physically one wavelength (about 1-3/4 inches at 6.75 GHz) longer than the direct ray. This almost infinitesimal (compared to a typical 20 mile path length) difference may result in almost complete cancellation of the received signal if the coefficient of reflectivity approaches -1. The position of the reflecting point over flat terrain and water is determined with the aid of figure 2-21 which locates this area as a fraction of the total path length for each value of K. As K becomes lower during substandard atmospheric conditions, the reflecting plane tangent is altered, moving the point of reflection toward the higher antenna.

When a radio wave is incident upon the earth's surface, it is not actually reflected from a point on the surface, but from a sizable area. This reflection area may be large enough to include several Fresnel zones, or it may be in the form of a ridge or peak including only a part of the first Fresnel zone. Where the wave is incident upon a plane surface, the resulting Fresnel zones formed on the reflecting surface take the form illustrated in figure 2-22A. Elliptical zones formed on the reflecting surface are similar to those which would be formed on an oblique plane placed between a transmitting source and a receiver in free space, as shown in figure 2-22B. Therefore, earth reflected Fresnel zones are simply a projected image of free space Fresnel zones at the plane of reflection. They may be determined by the same geometry used for free space Fresnel zones.

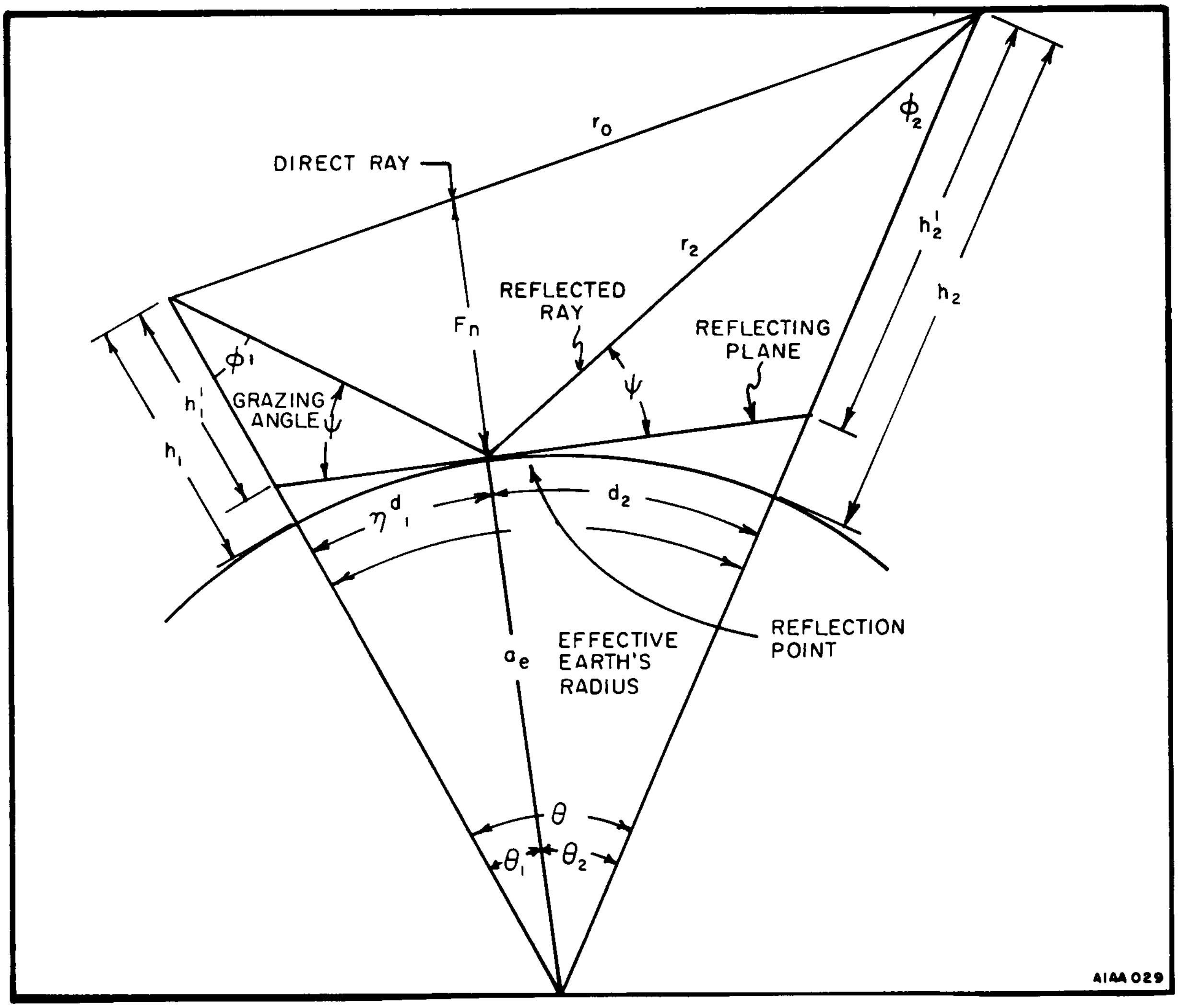


Figure 2-20. Geometry for Within-the-Horizon Paths

The significance of the ground-reflected Fresnel zones is similar to that mentioned for free space Fresnel zones. However, radio waves reflected from the earth's surface are generally changed in phase depending upon wave polarization and the angle of incidence. Horizontally polarized waves at microwave frequencies are reflected from the earth's surface and shifted in phase by approximately 180° effectively changing the electrical path length by 1/2 wavelength. On the other hand, for vertically polarized waves, there will be a considerable variation in the phase angle for different angles of incidence and reflection coefficients. This variation will be between 0° and 180° lag, depending upon ground conditions. Therefore, for horizontally polarized (and in some cases for vertically polarized waves), if the reflecting surface area is large enough to include the total area of any odd-numbered Fresnel zones, resulting wave reflections will arrive out of phase (at the receiving antenna) with the direct wave and cause fading interference.

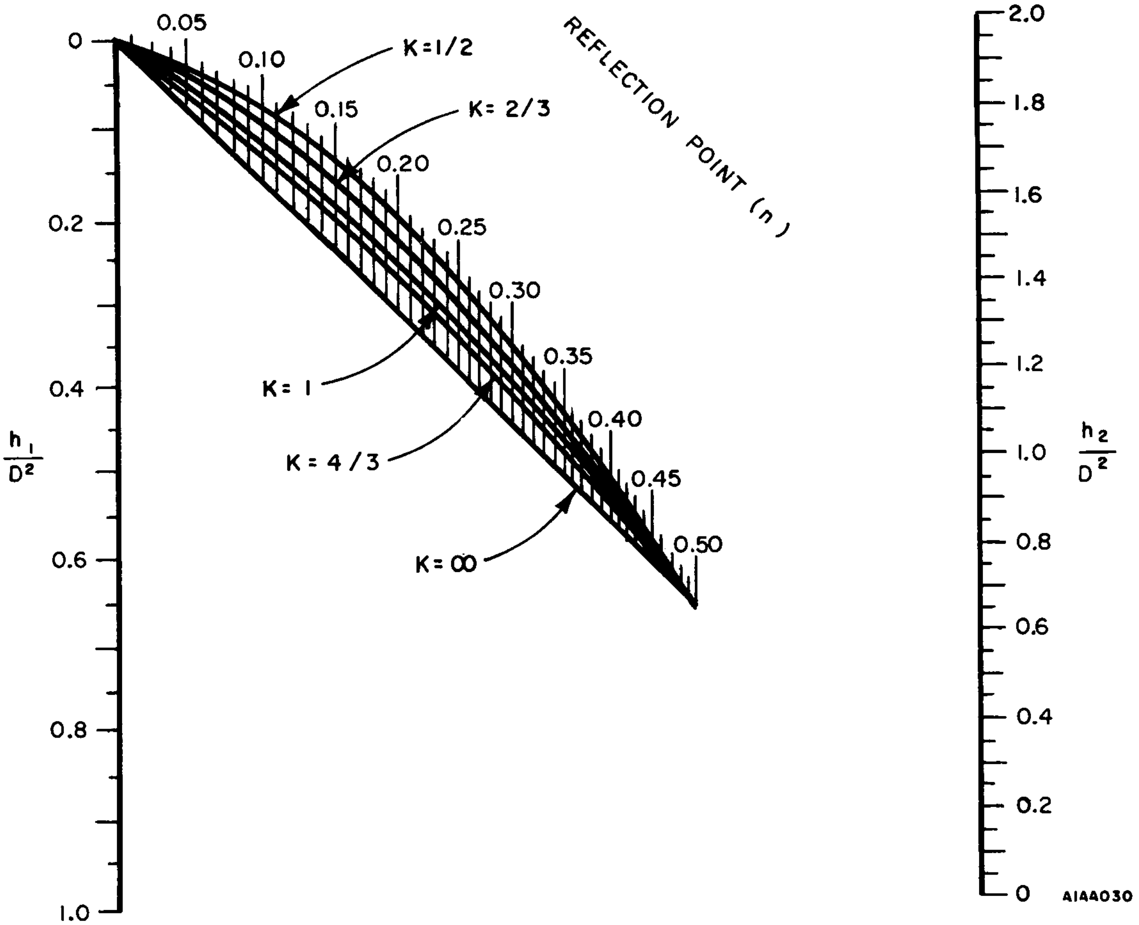


Figure 2-21. Point of Reflection on an Over-Water or Flat Terrain Path

The antenna radiation pattern near a reflecting surface, such as the ground, differs from the free space pattern primarily because of the existence of ground reflections. Since the direct path and reflected path will not be of the same physical length and there will be a phase change upon reflection, the two waves may arrive at the receiving antenna with any phase relationship. This phase relationship of the two waves will cause either an increase or a decrease in signal strength at the receiver. It will also produce the effect of distinct lobes and nulls in the radiation pattern, since the two rays add vectorially at the receiver.

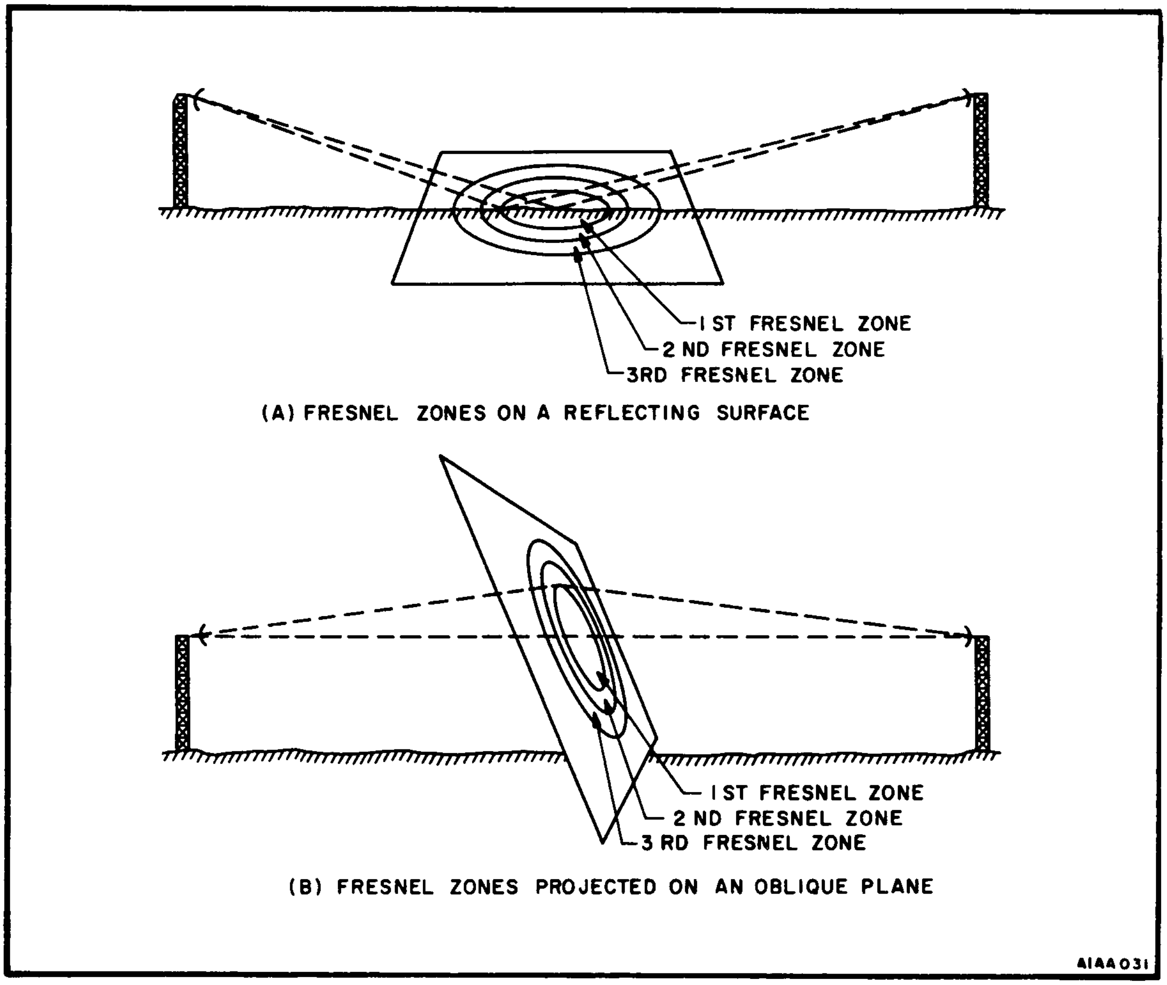


Figure 2-22. Earth Reflected Fresnel Zones

2.1.4 Polarization

In a simple qualitative way, energy radiated by an antenna may be thought of as consisting of packets of electric and magnetic lines of force. Electric lines of force (the E component of the electromagnetic wave) are a measure of force direction and magnitude exerted on a unit positive charge at any point in the field. In an analogous way, magnetic lines of force (H components) give vectorial force information exerted on a north seeking magnetic pole at the same point. If a unit positive charge always moves in a vertical direction when placed in an electromagnetic field (i.e., if the electric lines of force are vertical), the field is said to be vertically polarized. Similarly, if a unit positive charge moves in a horizontal direction (i.e., if the electric lines of force are horizontal), the wave is said to be horizontally polarized. In the radiated field, E and H components are mutually perpendicular and are perpendicular to the direction of wave propagation.

Energy radiated from an antenna may be vertically polarized, horizontally polarized, or in some cases, it may have both horizontally and vertically polarized components. In the latter case, if the horizontal and vertical components are at the same frequency, but not in time phase, elliptical polarization will result. When energy is being radiated on one polarization, a small portion may be converted to the other polarization due to small imperfections in the antenna system. The ratio of power in the desired polarization to the power converted to the other polarization is called cross-polarization discrimination.

2.2 PATH ATTENUATION

Power radiated from a transmitting antenna is ordinarily spread over a relatively large area. As a result, the power available at most receiving antennas is only a small fraction of the radiated power. This ratio of radiated power to received power is called the radio transmission loss, and its magnitude in some cases may be as large as 150 to 200 dB. The transmission loss between transmitting and receiving antennas determines whether the received signal will be useful. Each radio system has a maximum allowable transmission loss, which, if exceeded, results in either poor quality or poor reliability. Reasonably accurate predictions of transmission loss can be made on paths that approximate the ideals of free space or plane earth.

2.2.1 Free Space Transmission Loss

The following definition is based on recommendations of the National Bureau of Standards and CCIR. Transmission loss, L_b, is defined as power lost in transmission between a transmitting antenna at one point and a receiving antenna at a different point. It is measured as the difference between the net power passing the first point and the net power passing the second.

The basic concept in estimating free space transmission loss is the loss expected in a region free of all objects that might absorb or reflect radio energy. This concept is essentially the inverse square law in optics applied to radio transmission. For a one wavelength separation between isotropic (nondirective) antennas, the free space loss is 22 dB, and increases by 6 dB each time the distance is doubled. The basic transmission loss ratio at a distance d, is depicted in figure 2-23 and is given by:

$$L_b = 10 \log \frac{Pr}{Pt} = 10 \log \left(\frac{\lambda}{4\pi d} \right) \qquad (2\text{-}17)$$

where:

Pr, Pt = received power and radiated power, respectively, and measured in same units

λ = wavelength measured in same units as d.

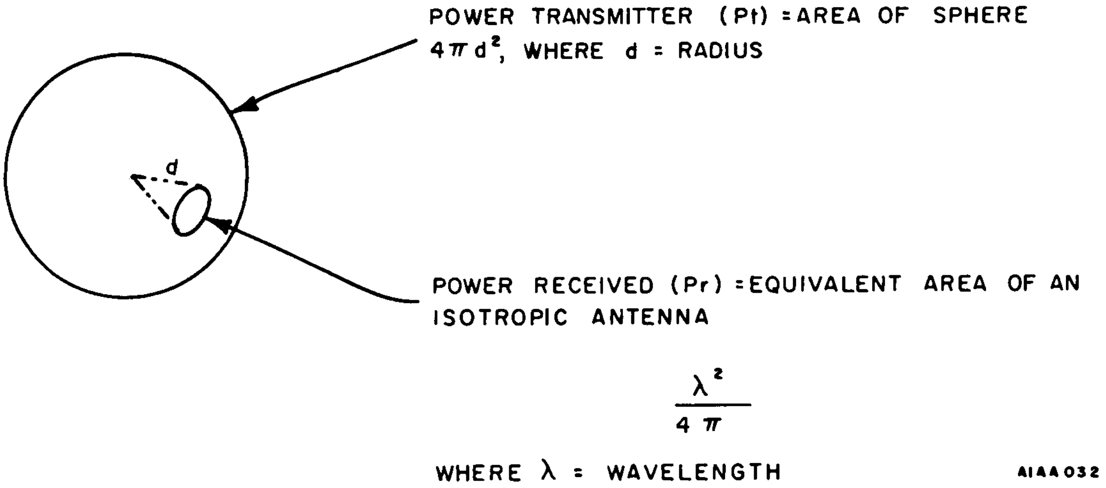
Equation 2-17 is also written as,

$$L_b = 36.6 + 20 \log f + 20 \log d \qquad (2\text{-}18)$$

where:

f = frequency in MHz

d = distance in miles.



POWER TRANSMITTER (Pt) = AREA OF SPHERE $4\pi d^2$, WHERE d = RADIUS

POWER RECEIVED (Pr) = EQUIVALENT AREA OF AN ISOTROPIC ANTENNA

$$\frac{\lambda^2}{4\pi}$$

WHERE λ = WAVELENGTH

Figure 2-23. Transmission Loss Solid Geometry

A chart for the free space transmission loss between isotropic antennas is given in figure 2-24.

Free space transmission loss is not a loss in the dissipative sense, but rather, reflects the condition whereby the loss is the total energy radiated compared to the amount of energy picked up by the area of an isotropic antenna. The total energy radiated is proportional to area of a sphere, since energy is radiated equally in all directions. The amount of energy picked up is proportional to the equivalent area of an isotropic antenna.

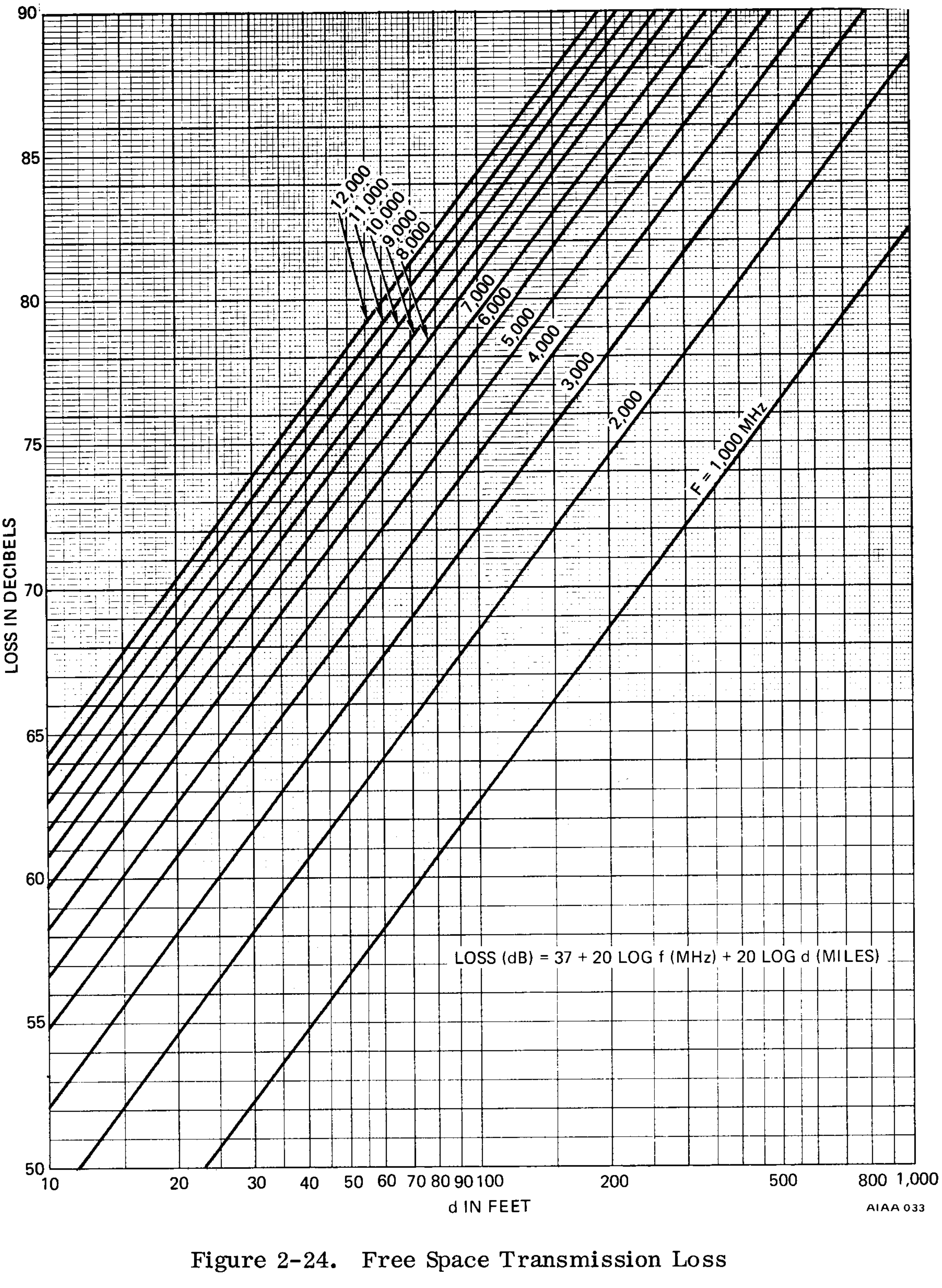


Figure 2-24. Free Space Transmission Loss

2.2.2 Median Received Signal

The median system noise per channel is the sum of noise contributions from individual radio hops plus noise from the multiplex equipment. A limiting noise level value of 38 dBa0 for all sources has been specified for the overall reference circuit (6000NM) not to be exceeded during 50% of all hours of time block 2.

The median noise contribution for noise assignable to just the transmission medium is 37 dBa0 and the remainder being assignable to multiplex equipment. The median transmission medium noise contribution for one link would therefore be 37 dBa0 - 10 log 6 = 29.22 dBa0. Next, dividing the remaining noise into contributions from the individual hops, we have, from chapter 1 that each link is comprised of three sections with each section divided into nominally 13 hops. Therefore, for a 3 x 13 = 39 hop nominal link, we have for the median transmission medium noise contribution for one hop a nominal value of 29.22 dBa0 - 15.91 dBa0 = 13.31 dBa0. The corresponding signal-to-noise (S/N) ratio would be S/N = 82 - dBa0 = 82 - 13.31 = 68.69 dB. The latter equation is defined in chapter 4.

To obtain a corresponding median received signal level for a per channel noise value of 13.31 dBa0, the noise characteristic for the particular radio equipment is required. All radio equipment has a characteristic of derived channel S/N ratio versus received RF signal level, or noise characteristic. Manufacturers supply a noise characteristic for any particular radio equipment, or one can be constructed from adequate specifications on noise contributions by their equipment. Transmitter deviation, baseband width, and load must be specified as they directly affect the noise characteristic. For this reason, there will often be more than one characteristic given for a single type of radio equipment. Refer to chapter 3 for a discussion on noise performance as related to noise characteristics.

2.2.3 Water Vapor

Attenuation due to water vapor (oxygen loss) in the air is negligible at frequencies below 10 GHz but reaches a first peak of about 0.2 dB per kilometer at 24 GHz. Absorption by oxygen in the atmosphere reaches a peak of about 10 dB per kilometer at 60 GHz, but attenuation is only about 0.015 dB per kilometer at 10 GHz decreasing rapidly for frequencies below 2 GHz. Figure 2-25 shows attenuation in dB per kilometer for water vapor and oxygen as a function of frequency.

2.3 FADING

During abnormal propagation conditions, the path loss may differ considerably from the normal. In some cases, the path loss may decrease a small amount (positive gain), but the more usual case is for increases (negative gain) of 10, 20, 30 dB or more to occur for short periods. These variations with time in the path loss are referred to as fading. Fading can be considered as a temporary diversion of energy to some other location rather than the desired location.

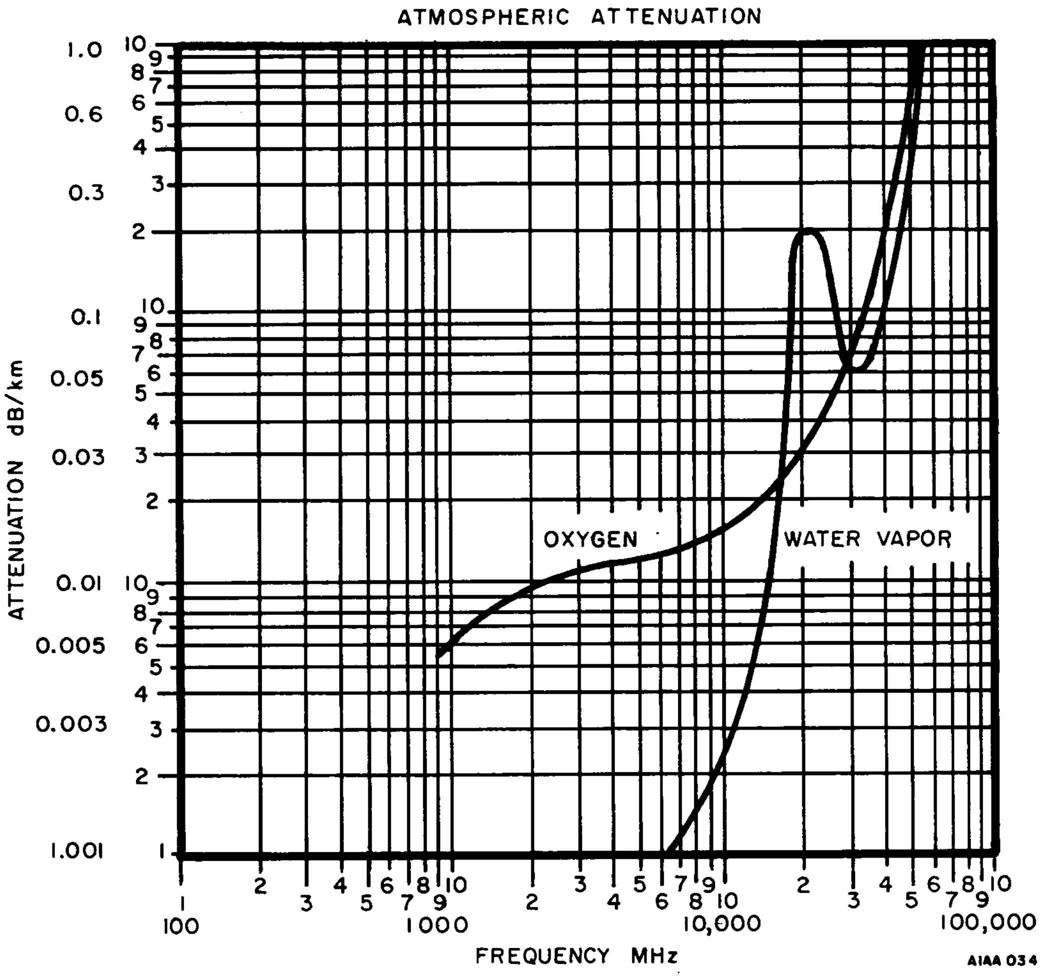


Figure 2-25. Attenuation Due to Atmospheric Gasses

The factors involved in fading phenomena are many and complex. Exact explanations for all fading phenomena are not yet available, but some general characteristics can be stated. It is known that during the daytime, when the lower atmosphere is thoroughly mixed by rising convection currents and winds, the signals on line-of-sight paths are normally steady and near the predicted free-space values. Also, when the humidity content of the atmosphere is low, signal variations are usually small. However, on clear nights with little or no wind, abnormal distributions of temperature and humidity can create steep dielectric constant (or refractory) gradients in the lower atmosphere, thus causing anomalous propagation and fading.

If it were possible to keep all conditions constant, it would be simple to plan the locations of transmitting and receiving antennas so that the difference in path length of two signals would be 1/2 wavelength. Then signals would always arrive at the receiving antenna enchanced to the greater than normal value. Unfortunately, both direct and reflected signals must travel through an atmosphere which is anything but homogeneous with respect to temperature, density, and moisture content. These factors are further subject to the many vagaries which determine our weather hour-to-hour, day-to-day, and season-to-season. The result is that microwaves are bent this way and that while traveling over paths constantly changing in direction and are sometimes longer or shorter, similar to a beam of light through an imperfect and somewhat cloudy lens. The received signal also varies from moment to moment, sometimes strong due to reinforcement and then very weak due to cancellation.

2.3.1 Multipath Fading

The most common type of fading is the result of multiple path transmission. The arrival of one or more interfering rays via atmospheric reflection or refraction paths may result in rapid fluctuations in the received signal level which are completely independent of path clearance. Since it is highly improbable that all transmission paths will be of the same length, phase interference can and often does occur. Signals arriving at the receiving antenna from slightly different angles reinforce or cancel each other, depending upon the phase relationship between them. Since the angle of convergence is small as compared with the antenna beamwidths, antenna pattern discrimination against secondary paths is negligible. Since the various propagation paths do not suffer greatly different attenuations, nearly complete cancellation can occur at the receiving antenna when two signals arrive 180 degrees out of phase.

The phase relationship of reflected rays with respect to the direct ray are completely random in nature. Path length differences between the direct ray and indirect rays of over 50 wavelengths have been measured. Therefore, when signals arrive having different delays, the received carrier level is the summation of all the arriving signals in both amplitude and phase. This leads to an amplitude distribution for which the Rayleigh distribution is a sufficiently accurate fit to measured data. After the multipath fading has reached the Rayleigh distribution, a further increase in either path distance or operating frequency increases the number of fades of a given depth, but decreases the duration so that the product is the constant indicated by the Rayleigh distribution. Representative values of fading on a path with adequate clearance are shown in figure 2-26. The curve shows that atmospheric multipath fades of 25 dB or more from normal may be expected to occur 0.2 percent of the time for frequencies of 4 GHz and higher. Occurrence of multipath fading is not primarily a matter of locality or path clearance. Generally it is much worse in the summer months than at other times of the year. For any particular day, fading is greatest in the early morning hours. Fading is frequency selective, and virtually no correlation is shown on frequencies separated by 160 MHz or more. The average maximum rate of change of fade was found to be 10 dB/second with rates as high as 100 dB/second occurring very seldom.

It is extremely unlikely that all hops of a multi-hop system will have the same worst month. Evidence indicates that probably no more than 30 percent of the hops are in simultaneous worst month or Rayleigh fading during any one month. The remaining hops are probably experiencing less than Rayleigh fading of varying severity.

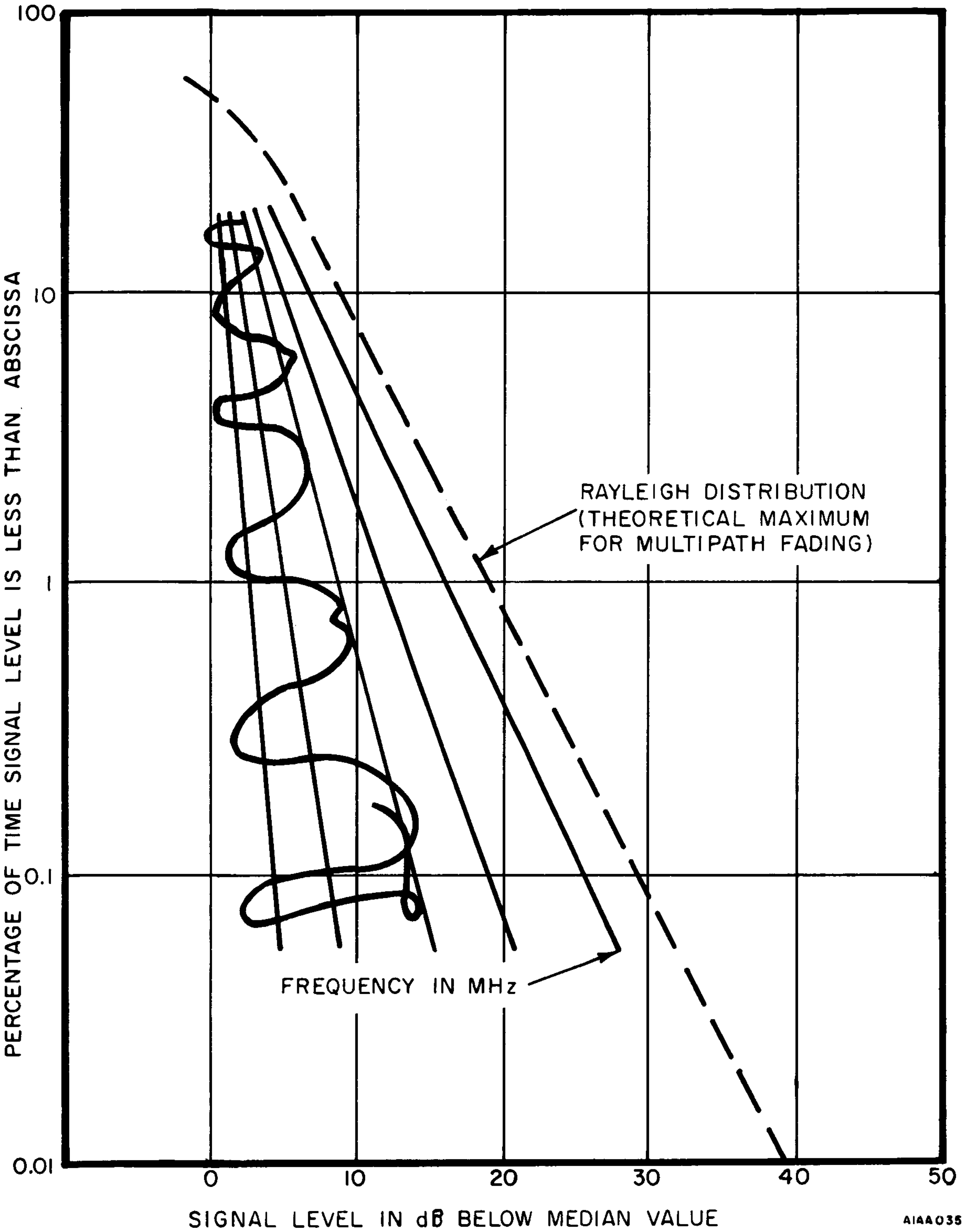


Figure 2-26. Typical Fading Characteristics in the Worst Month on a 30 - to 40 - Mile Line-of-Sight Paths With 50 - to 100 - Foot Clearances

2.3.2 Refractive Fading

Abnormal variations in the atmospheric refractive index cause other types of fading. Normally, the atmospheric refractive index decreases with altitude so that the direct path is usually curved in the direction of the earth's curvature. As discussed earlier, this is equivalent to a flattening of the earth's surface, and frequently an earth radius of 4/3 the actual radius is assumed as the average condition in appraising the path profile.

a. Earth Flattening Effect. If the index of refraction decreases with height more rapidly than normal, bending of the direct path towards the earth's surface will increase. This phenomenon was discussed earlier from the standpoint of origin and varying degrees of the effect as superstandard refraction.

Signal fading may result due to cancellation caused by the time (and hence phase) lag of refracted waves from the lower wavefront portion with the upper wavefront portion at the receiving antenna. Under extreme conditions, propagation path curvature due to downward bending may have a radius less than that of the earth causing the wavefront to strike the earth short of the receiving antenna. In this case, only reflected rays will reach the receiving antenna and fading will result.

b. Earth Bulging Effect. If the index of refraction increases with height in the lower atmosphere, a situation results where the wave is bent upward and away from the earth. This phenomenon was discussed from the standpoint of origin and varying degrees of the effect as substandard refraction.

The upper portion of the wavefront may actually lag so far behind the lower portion that the propagation path curvature is reversed. This form of wave bending is also referred to as "inverse beam bending." This condition also has the effect of reducing path clearance resulting in fading since optimum clearance will no longer exist. Under extreme conditions, the degree of bending may be so severe that the beam actually overshoots the receiving antenna. Fading due to earth bulging may last for several hours; however, the magnitude and frequency of occurrence can be reduced by increasing the normal path clearances. An equivalent earth's radius of 2/3 to 1/2 of the actual radius may have to be assumed in areas of the country where this effect is known to be prevalent.

2.3.3 Reflected Ray Fading (Fresnel Fading)

Another rare type of fading is observed when a reflecting layer forms above or comes into existence below the transmission path. The received signal is subject to interference between the reflected wave and the direct path wave. These reflections may come into existence periodically even though, under normal conditions, path geometry does not permit such reflection.

This condition can result in changes of received signal level up to 6 dB above free space values or to complete signal cancellation depending upon reflected ray phase and magnitude. In regions hwere K is nearly constant with time, the resultant received signal level could remain stable at a value somewhere in this range. As K varies, path clearance and point of reflection are altered with a resultant change in reflected signal amplitude and phase causing fading.

Reflected ray fading is easily identified by very deep, fairly rapid fluctuations in the received signal level as path clearance over the reflective surface changes through even Fresnel zone radii. This type of fading most severely affects the transmission of time-sequenced information (data and supervisory control information) over a microwave link, since its occurrence is somewhat random and may not follow a diurnal or other predictable pattern. Complete path failure lasting for seconds at a time or longer may occur in a varying atmosphere. Unlike ducting and substandard refraction fading, which often provide some semblance of warning minutes and perhaps hours prior to causing a path outage, unpredictability, rapidity and severity are characteristic of fades due to even Fresnel zone reflected ray fading. To circumvent this type of fading on paper is the most time-consuming task related to the path engineering of over-water microwave systems.

2.3.4 Ducting (Surface, Elevated)

Atmospheric focusing is another possible cause of fading which may occur occasionally. This condition occurs when moisture content of the air at the ground surface is very high, but decreases very rapidly with increasing height. In the region where abnormally steep gradients in the refraction index exist, curvature of rays passing through the atmosphere is greater than that of the earth. As a result, energy originating in this region, and initially directed approximately parallel to the earth's surface, tends to be trapped and propagate around the earth's curved surface in a series of hops involving successive earth reflections. This situation is similar to the direct waves being transmitted in a waveguide or duct formed by the earth and a reflecting layer.

When duct propagation exists, line-of-sight and diffraction-zone concepts no longer apply, and energy will travel great distances around the earth's curvature with relatively low attenuation. This concept involves the angle with which the propagated rays impinges on the top of the duct. The angle within which energy trapping occurs is, typically, of the order of 1 degree or less. Rays outside of this angular range ultimately pass out of the duct to the space above.

Typically, duct heights range from tens to hundreds of feet. Ducting may either increase or decrease the received signal level depending upon the antenna's relative position with relation to the duct. Surface ducts occur most commonly over water. In fact, it is believed that such ducts are nearly always present over the ocean, particularly in the trade-wind belts. Surface ducts can also occur over land, but this happens less frequently. It is always a temporary rather than a continuing condition when it does occur.

Under certain meteorological conditions, an elevated duct may occur. In this case, the upper limit is formed by the upper limit of a superstandard or inversion layer, and the lower limit by a substandard layer. During these conditions the beam will tend to remain within the duct limits due to bending toward the duct center. Radio energy concentration within a duct will cause an increase in received signal when both the transmitting and receiving antennas are within the duct. However, this effect cannot be relied upon for satisfactory propagation because conditions producing the duct are subject to change. The terms trapping, super-refraction, or guided propagation also describe the propagation phenomena associated with ducts.

2.3.5 Precipitation

In addition to the fading types discussed, rainfall, snowfall, and fog produce very pronounced effects at higher microwave frequencies. At about 2 MHz and above, the presence of precipitation introduces an absorption in the atmosphere which depends on the amount of moisture and on the frequency.

Rain attenuation increases with frequency and with an increasing rate of rainfall. Rain attenuation on a particular radio communication circuit depends on frequency. Rain attenuation depends on the number of drops per unit volume in the radio path, the square of the drop diameter, and a complex factor representing the ratio of total energy absorbed and scattered by a single drop to the energy in the wavefront area equal to the projected raindrop area.

Rain attenuation curves as a function of rainfall rate for frequencies of 4 MHz, 6 MHz, and 11 MHz are shown in figure 2-27. Below 8 MHz, a linear relationship exists between attenuation and rainfall rate, and attenuation may be expressed in dB/km per millimeter per hour of rainfall. At higher frequencies the loss increases more rapidly with rainfall rate.

Attenuation due to dry snow is a small fraction of that of rain at the same precipitation rate. Attenuation caused by dry snow is very small even at the snowfall rate of five inches (127 mm) per hour. Wet snow attenuation may be comparable with that of rain. Excess attenuation caused by hail is about 1/100 of that caused by rain.

Rain attenuation on a particular path can be estimated from figure 2-27 if the path length and frequency are known, and if the average rainfall rate along the path is known. Monthly rainfall rates for many areas of the world are available, and, in some cases, the time variation of various rainfall rates are also known. However, little information has been published on rain storm spatial distribution. Although it may be possible to determine the percentage of time that a certain rainfall rate may be exceeded at a given weather recording station, it is often difficult to determine over what area this rainfall rate is applicable. High rainfall rates lasting a comparatively short time are likely to be restricted to an area of perhaps a few miles in diameter. Whereas, low rainfall rates may extend over a region measured in hundreds of miles.

In general, it can be said that a rainfall rate of 4 mm/hour is moderate and 15 mm/hour may be considered as heavy. In certain temperate climates a rainfall rate as high as 30 mm/hour may be expected for a few minutes about once per year. In the tropics, however, a rate of several hundred mm/hour may occur for short periods once per year, while values as high as 100 mm/hour may last for an hour. Summary data on the estimated atmospheric absorption for various conditions of rainfall is shown in figure 2-28. It should be noted that the attenuation over any individual band is almost independent of frequency and, therefore, no protection is offered by use of frequency diversity.

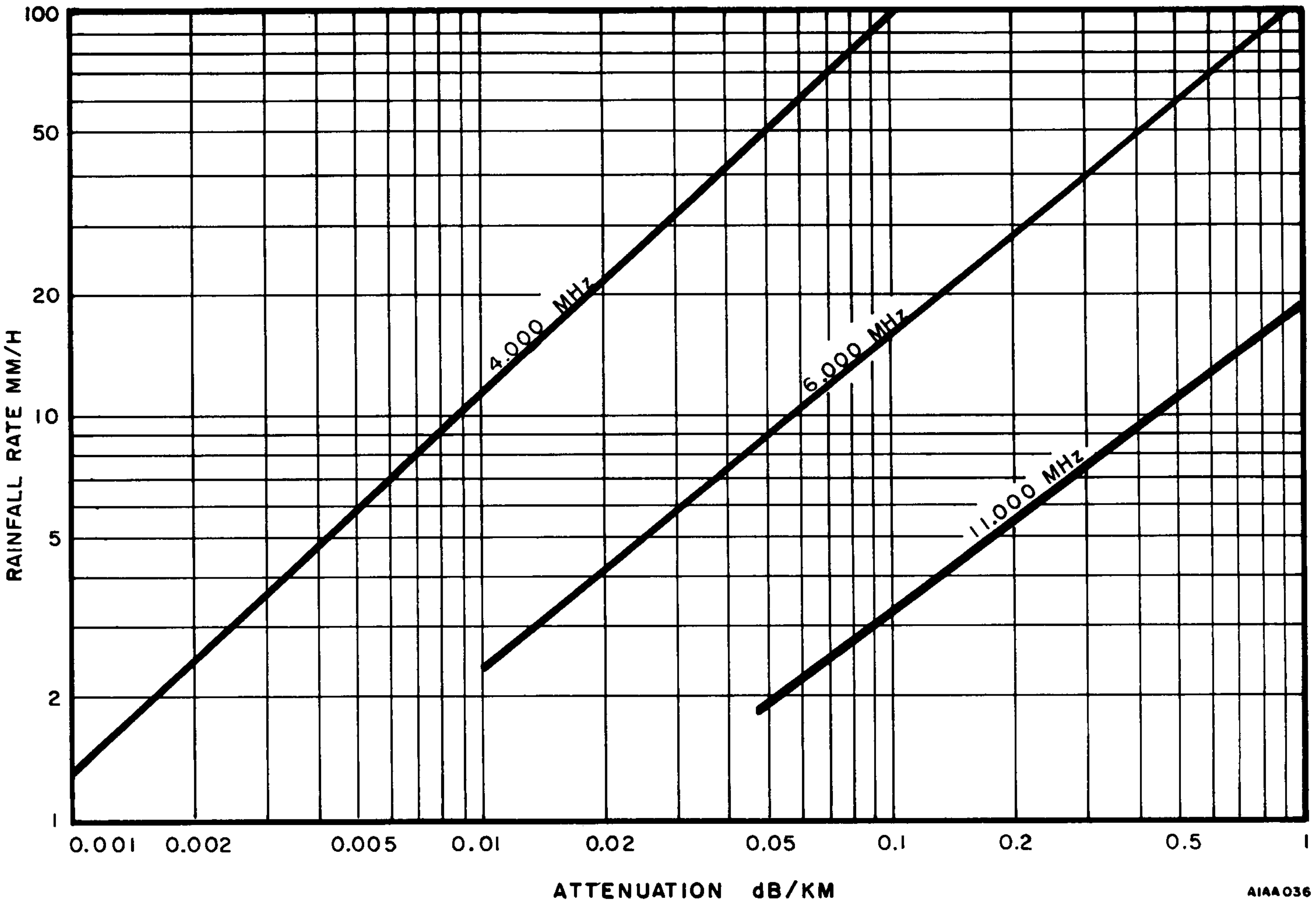


Figure 2-27. Rainfall Attenuation

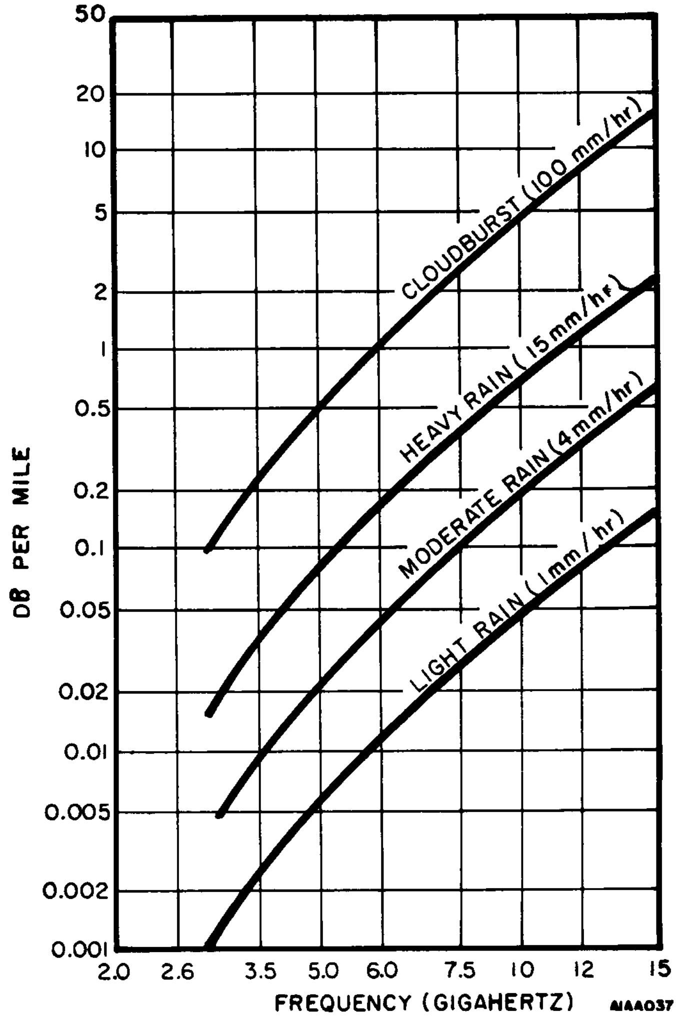


Figure 2-28. Estimated Atmospheric Absorption

Rain attenuation on a particular transmission path at a given time and frequency is proportional to the average rainfall along the path at that time. In order to estimate the rain attenuation exceeded, for example, 0.01% of the year, it is necessary to know what is the path rainfall rate that is only exceeded for about one hour per year. A path rainfall rate is defined as the space average of the point rates along the path. Figure 2-29 provides estimates of the instantaneous path average rainfall rate exceeded for 0.01, 0.1, 1.0 and 5 percent of the year as a function of the distance between terminals, normalized for a total annual rainfall of 100 centimeters. For other annual rainfalls, multiply the average rainfall rate of figure 2-29 by the ratio of 100 to the actual annual rainfall.

Data provided in figures 2-28 and 2-29 can be utilized for determining additional system margin in terminal performance.

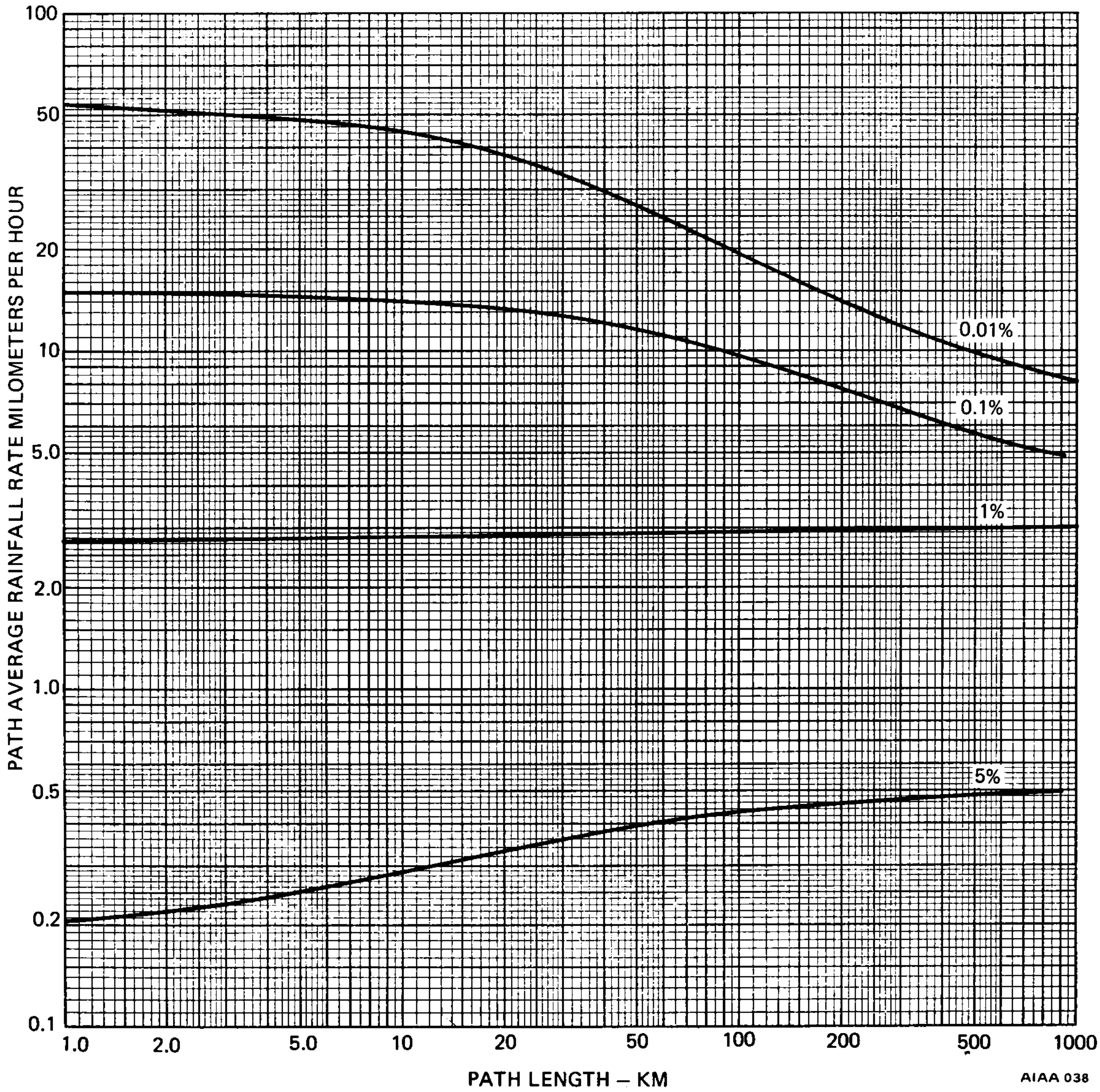


Figure 2-29. Percent of Year That Average Rainfall is Exceeded: Total Annual Rainfall = 100 cm

At frequencies as low as 388 MHz, attenuation due to absorption by condensed water in the air begins to be significant. The attenuation due to fog is about proportional to the visual range. Attenuation due to a dense fog exceeds that due to moderate rain. The drops are much larger in the rain, but the total water content of the dense fog greatly exceeds that of the rain. Little is yet known about the frequency of occurrence or area covered by fogs of various densities in different parts of the world.

In summary, it is evident that precipitation attenuation must be considered for any system at frequencies below 10 GHz in areas where heavy rain occurs frequently. In more temperate climates, rain attenuation effect is less pronounced and no additional fade margin beyond that which is normally provided for reliability against interference type fading would be required. In almost all cases, precipitation is accompanied by winds that minimize stratification and attenuation fading.

2.4 FADE MARGIN AND RANGE

The fade margin to the specified minimum acceptable noise performance point, i.e., 49 dBa0 (refer to table 1-1) is the difference between the received signal level corresponding to 49 dBa0, taken from the equipment noise characteristic and the median received signal also obtained from the noise characteristic. This is the significant fade margin for specification purposes as it is the only one referred to a clearly defined channel noise level.

In general, the number of fades per unit time increases as the path length between antennas and the transmitting frequency are increased. However, during severe fading conditions measurements have shown the duration of a fade of a given depth tends to decrease as path length and frequency are increased. Thus, the percent of time a system experiences a particular depth of fade tends to be independent of repeater spacing and frequency.

Most common in LOS microwave communication systems is for fades of 10 to 30 dB or more to occur for short periods.

Experience has shown that paths with adequate clearance exhibit fading that approaches the Rayleigh Distribution as a worst case. Military systems require a reliability of 99.99 percent, consequently, a fade margin, reference figure 2-30, of 38 dB should be provided.

2.5 TRANSMISSION PATH STUDY AND EVALUATION

It is necessary to have a clear line-of-sight between transmitting and receiving antennas to obtain satisfactory microwave transmission. The microwave transmission path survey allows the selection of suitable station sites and antenna heights. The survey consists of gathering and analyzing elevation data and other information on the possible sites and the intervening terrain.

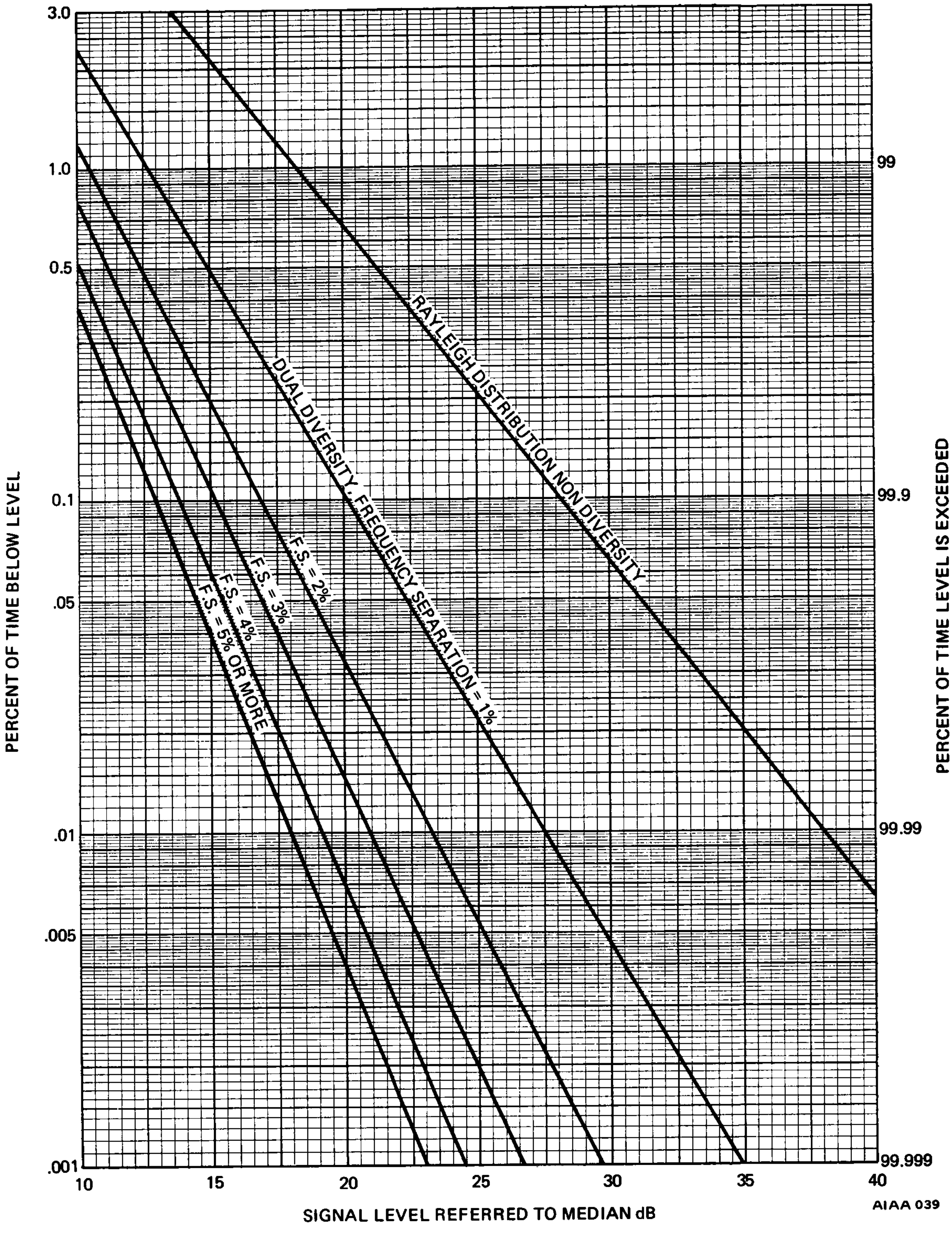


Figure 2-30. Approximate Interference Fading Distribution Versus Order of Diversity and Frequency Separation

A preliminary study is required by DCAC 330-175-1 and must be accomplished prior to actual site survey such that several alternate sites be selected. Maps shall be used with a scale of at least 1 in 250,000 (1 inch = approximately 4 miles) with contours to the nearest 20 meters (approximately 66 feet or 22 yards). Distance shall be determined to the nearest mile.

2.5.1 Feasibility Study

It is sufficient to know that for the purposes of preliminary route survey and site selection, path clearance greater than optical line-of-sight will be required on each radio path. All possible routes between two terminals should be studied, and all available elevation data about the intervening terrain for each radio path should be assembled. When selecting radio sites, availability of electrical power, existing road access, and other pertinent factors should be considered.

This task includes map studies, logistic and environmental considerations, and the requirements of the complete system which must be fulfilled by the station or stations under study. During the desk survey, station equipment is determined considering the approximate physical size. Support requirements of individual stations are outlined, and potential sites are chosen to be surveyed to establish their relative suitability. Based upon system requirements, characteristics of equipment to be installed, and other considerations, the scope of the field survey will be specified. This data is then compiled and supplied to the field survey team.

a. Topographic Map Study. Accurate topographic maps are available for many areas of the United States and some countries.

The Geological Survey is making a series of standard topographic maps for the United States, Alaska, Hawaii, and Puerto Rico. Under the general plan adopted, the unit of survey is a quadrangle bounded by parallels of latitude and meridians of longitude. Quadrangles covering 7-1/2 minutes of latitude and longitude are generally published at the scale of either 1:24,000 (1 inch = 2,000 feet) or 1:31,680 (1 inch = 1/2 mile). Quadrangles covering 15 minutes of latitude and longitude are published at the scale of 1:62,500 (1 inch = approximately 1 mile), and quadrangles covering 30 minutes of latitude and longitude are published at the scale of 1:125,000 (1 inch = approximately 2 miles). In some areas, maps of a new series covering one degree of latitude and two degrees of longitude have been published at the scale of 1:250,000 (1 inch = approximately 4 miles).

For each State and Puerto Rico, index circulars identify all maps distributed. They provide quadrangle location, survey date, name, and publisher (if not Geological Survey). Also listed are special maps and sheets with prices, map agents and federal distribution centers, addresses of map reference libraries, and detailed instructions for ordering topographic maps.

State index circulars and a folder describing topographic maps are furnished free on request. Private agents sell quadrangle maps at their own prices. Names and addresses of private agents are listed in the State index circulars. Special request should be made for copies of maps with woodland coverage.

Aeronautical charts are also useful as a source of information. In general, the Coast and Geodetic Survey publishes and distributes aeronautical charts of the United States, its Territories and Possessions. Charts of foreign areas are published by the USAF Aeronautical Chart and Information Center (ACIC) and are sold to civil users by the Coast and Geodetic Survey. A catalog of aeronautical charts is available from The Director, Coast and Geodetic Survey, Washington 25, D.C. This catalog also gives complete ordering information and a list of district offices from which charts may be obtained. These charts are also available at many airports. The contour lines on these maps are spaced farther apart and consequently do not give as much elevation information as the Geological Survey maps, but they do give much additional information about airports and hazards to air navigation that must be considered when planning a new tower installation.

Accurate topographic maps are available for many areas of Canada. The whole of Canada is covered by maps published on the scales 1:506,880 (8 miles to 1 inch) and 1:1,000,000 (15.783 miles to 1 inch), but coverage on other large scales is not complete. Many areas are covered by maps published on the scales of 1:50,000 (0.79 miles to 1 inch), 1:63,360 (1 mile to 1 inch), 1:126,720 (2 miles to 1 inch, and 1:253,440 (4 miles to 1 inch). The indices to these maps and the maps themselves may be purchased directly from the Department of Mines and Technical Surveys, Geographical Branch, Ottawa.

Additional maps may be obtained from the Department of Mines, Lands and Forests, or Department of Natural Resources of the Provincial Governments in the appropriate provincial capitals. Any available aerial photographs should also be obtainable at these places.

The aeronautical charts on scales 8 miles to 1 inch and 16 miles to 1 inch may also be a useful source of information. These are also obtainable from the Department of Mines and Technical Surveys, Ottawa.

In many areas, county highway maps are available. While these maps seldom give any detailed elevation information, they are useful in planning the exact route of a field survey and are helpful in plotting the exact field party location during the survey. These maps are usually current and contain detailed information on roads, buildings, bridges, and other structures. They are usually drawn to a scale of 1/2 mile to the inch and are quite accurate.

Additional information may be obtained from U.S. Forestry Service maps. Road maps and strip or profile maps available from railroad, oil, or power companies are another data source.

Any of the above maps are useful sources of information, and, for this reason, every available map of a given area should be assembled for study.

b. <u>Feasibility Study Equations and Calculations.</u> After all pertinent information related to the proposed sites has been assembled, preliminary map investigations are begun. Scope of the map study performed at this initial phase should be sufficiently broad to provide all necessary physical detail concerning the site and path areas. Preliminary information to be determined for each site includes:

- Site elevation, location, and general topography characteristics at site areas
- Path length and path azimuths, by means of great circle calculations, from coordinates determined from the mapping
- Path profiles and reflection points
- Accessibility

Feasibility study equations and calculation forms are contained in Appendix B.

2.5.2 Final Study

The final study effort consists of refining the feasibility study data. All preliminary site data must be further analyzed and evaluated for each site considered in a given area. Generally, no single site will satisfy all conditions for each of these factors. Site selection usually entails selecting the one site approximating optimum conditions for each path in the proposed system.

Microwave terminal and possible repeater sites should be plotted on each available map and a straight line should be drawn between adjacent sites. Mark off the distance between sites in miles and use a small paper scale to interpolate distances between marks. Elevation data should be taken from each map and plotted on a profile chart for additional study. The amount of field work required is determined by the amount of path clearance on the profile chart and the accuracy of the information plotted.

If the profile has been plotted from very accurate topographic maps (for example the 7.5 minute series Geological Survey maps), it will only be necessary to make a quick visual survey along the path to determine average tree height or other obstructions and gather information about the terminal sites. If the accuracy of the available maps is doubtful, or if the path has not been surveyed for trees and other possible obstruction, or the path clearance is marginal, it will be necessary to obtain additional information through more detailed field survey work.

Many of the quadrangle maps based on surveys made before 1970 have been found to contain errors in elevation and location of topographic details. In areas not covered by topographical maps, information on benchmarks can often be obtained at the County (or City) Surveyor's Office. In some states, this information is compiled in book form.

a. Path Profiles. After tentative antenna sites have been selected, and terrain relative elevation (and obstacles) between the sites has been determined, a profile chart can be prepared. In some cases, a complete profile will be necessary and in other cases only the end sites and certain hills or ridges need to be plotted.

The relative curvature of the earth and microwave beam is an important factor when plotting a profile chart. From previous sections, it has been shown that, although the earth's surface is curved, a beam of microwave energy tends to travel in a straight line. However, the beam is normally bent downward a slight amount by atmospheric refraction and the amount of bending varies with atmospheric conditions. The degree and direction of bending was defined by an equivalent earth radius factor, K, and fictitious earth curve. The curve was defined as being equivalent to the relative curvature of the microwave beam with respect to the curvature of the earth, that is, it was equal to the curvature of the actual earth minus the curvature of the actual beam of microwave energy. Therefore, any change in the amount of beam bending caused by atmospheric conditions was expressed as a change in K. This relative curvature could be shown graphically; either as a curved earth with radius Ka and a straight line microwave beam, or as a flat earth with a microwave beam having a curvature of Ka. The second method of plotting is preferred because it; permits investigation (and illustration) of the conditions for several values of K to be made on one chart, eliminates the need for special earth curvature graph paper, and facilitates the task of plotting the profile. It is convenient to plot the profiles on 11 x 17 or B size reproducible graph paper with 10 x 10 divisions to the inch.

b. Final Study Equations and Calculations. Pre-site survey data sheets should be completed prior to team departure to the field and should be developed during the system design phase. Coordinates of the site proposed for survey should be established from map studies and the degree of accuracy clearly stated. Actual values given should not imply greater accuracy than the method of attainment warrants.

Triangular point locations or other control points are imperative if an accurate baseline is to be established, and to verify the coordinates in the field.

Appendixes C and D contain the detail study equation and calculation forms, and the great circle calculation forms respectively.

c. Land Options. Assuming a proposed site is acceptable or an alternate site has been selected, proceedings should be initiated to acquire options to purchase or lease the sites. Otherwise, extensive planning would be wasted if the selected site is not obtainable at the time of equipment installation.

d. Field Survey. DCAC 330-175-1 requires that the selected sites be surveyed. A terrain profile must be constructed showing the distances and elevations including the path azimuth and be within an accuracy not less than the following:

- Coordinates to third order accuracy
- Elevations to the nearest 2 meters

The primary field survey objective is to obtain accurate data concerning microwave path clearance above all obstructions. The detailed survey not only verifies the results of the feasibility and final studies, but provides for accumulation of all pertinent field information that makes advanced planning possible. Specific objectives include conducting detailed observations, measurements, and inquiries at the selected station sites and along the microwave radio relay routes. Inquiries concerning weather data, air traffic, and commercial power information must be made. In addition, complete survey reports must be prepared for each site and each hop of the entire system.

(1) Site Survey. To ascertain that all necessary information is obtained when the site survey is made, a field survey notebook is usually issued to the survey group. It is necessary that the handbook be completed in every detail. The field survey notebook is contained in Appendix E.

Site location, dimensions, and contour must be shown, including the proposed shelter and tower location. The site must be large enough to permit the installation of guy anchors for a tower within site limits. Site terrain description is useful in shelter and tower planning. Proximity to airports and airways have a direct bearing on tower height and tower lighting plans. Site accessibility throughout the year must be known to determine the need for standby radio equipment and to determine fuel tank size for standby power equipment. The need for improving existing roads or for building new roads must also be indicated.

Weather information must be acquired to determine heating, cooling, and/or ventilating equipment needs. This information also governs tower design, and shows the need for antenna heaters or protective covers. An accurate altitude measurement should be made at the site. Photographs of the site and the terrain toward each adjacent station should be made for reference purposes. Power information should be collected from the local power company, and measurements made to determine the distance to be spanned to supply power to the site. Fuel types and availability for auxiliary power equipment should be determined.

Equipment shelter needs should be noted and if there is a shelter at the site, it should be described and photographed. The need for establishing telephone lines to the site should be ascertained. Specific site development and/or site improvement requirements should be identified. Another consideration is the need for protection of the site from vandalism.

Information gathered during the field survey of the terrain between stations is usually recorded on a hop report form. In this report, the hop should be defined and the compass bearing to at least one adjacent site should be given. A description of the terrain between sites is vital information, as is the naming of obstructions at critical points. Local agencies should be consulted to ascertain whether construction that might interfere with the microwave hop is contemplated. Any bodies of water along the path must be described, along with other pertinent details. Terrain features such as those just mentioned should be shown in a plan view sketch of the path, along with distance measurements. The altitude of critical points should be accurately measured. Finally, a profile of the hop should be prepared and included with the hop report. This profile is usually plotted on profile paper.

Practically all systems present unusual problems on one or more of the hops. The problem of surmounting or avoiding natural obstructions often requires special attention. Also troublesome is the overwater hop, particularly when the overwater distance is great. A choice must often be made between establishing a hop that is somewhat longer than average and adding another relay station (usually at much greater cost).

(2) <u>Methods of Determining Path Clearances.</u> Various methods of determining path clearances for the survey report are identified and discussed.

o Optical. Often the clearance of a path can be verified by visual sighting from one end to the other with the aid of a pair of field glasses or telescope. If a transit is used, the amount of clearance can be measured more accurately by measuring the depression angle to a high point in the path from both end sites and plotting this information on the profile chart. In other cases, it may be more convenient to carry the transit to the high point on the path and determine the clearance by forward and back sighting to the two end sites. Greater accuracy in measuring angles of depression (or any other angle) can be obtained using a theodolite.

When visibility is poor and restricts sighting directly with optical instruments, the line-of-sight path clearance can often be checked by flashing with a mirror. This technique requires a team at each end of the path with radio communication between the teams. One team should be equipped with a transit or other sighting instrument, and the other team should be equipped with a mirror about one foot square. The object is to reflect a beam of sunlight to the other end of the path so that the other team can take a sighting. This is done by nutating or panning the beam of light in the general direction until the other party indicates, by radio, that a sighting has been made. If a path is partially obstructed so that this technique cannot be used, it is sometimes possible to raise a balloon at one end until it can be sighted from the other end. The height of the balloon can be measured. For easier sighting, hang a piece of aluminum or other reflecting material from the balloon. Use a single cord allowing the reflecting material to swing freely. If sighting is done at night, a flare or any other type of light suspended from the balloon will be helpful. A helicopter can be used if a weighted measuring line is carried aloft and reeled out until it touches the ground when line-of-sight conditions are reached. The observer should be sure that the visual path is not through trees that are seasonably barren.

It should be noted that, like microwave radio beams, horizontal rays of light are refracted in the direction of the earth's curvature. The amount of bending for light is approximately one half as much as for a microwave radio beam. This factor should be considered when plotting optical sighting results. When optical line-of-sight conditions have been established and the data plotted on a profile chart, it is a simple procedure to add the required additional clearance and determine the height required for antennas.

o Altimeter. When information obtained from maps or optical sighting is not sufficient or accurate enough to determine adequate path clearance, the precision altimeter method of field survey should be used, if possible. This method can be used in all cases when critical elevations along a path are accessible by some means of ground transportation or by helicopter. The special equipment required consists of a portable precision surveying altimeter and a precision recording barometer (barograph) of the type available from American Paulin System, 1524 Flower Street, Los Angeles 15, California. Careful use of this equipment will yield elevation data with a probable error in the order of five feet. These instruments should not be confused with the ordinary aneroid altimeter and barograph which have insufficient accuracy for this purpose.

Measured elevations appear on topographic maps in the form of spot elevations at road intersections and other easily identified points, or as benchmarks. These benchmarks can often be located during a survey and are in the form of a concrete post or rock inlay containing a bronze disc about four inches in diameter inscribed with an identifying name. On many of the older benchmarks, the elevation has been stamped into the disc. Information about benchmarks in a given area can be obtained by writing to the Geological Survey Information Center, Washington 25, D. C. Where maps and benchmarks are not available, known elevations can often be found on railroad stations, post offices, water towers, or other structures. Elevation information from railroad stations should be used with caution since not all railroads use standard mean sea level as the basis for their surveys.

In general, the technique is to carry the altimeter to selected points along the microwave path and record indicated altitude, time, temperature, location, and other pertinent data at each point. The altimeter will measure only relative elevation. Therefore, to obtain elevations referred to mean sea level, it will be necessary to measure one or more points of known elevation in vicinity of the path.

Since this technique (called barometric leveling) is dependent on the measurement of air pressure, conditions other than changes in elevation that affect air density (and consequently pressure) introduce errors for which corrections must be applied. One such condition is the variation in barometric pressure caused by a change in local weather conditions, such as an approaching storm. It is impractical to attempt barometric leveling when thunderstorms are occuring or when whirlwinds are forming in the locality. Any measurements made under these conditions should not be relied upon. However, variations in pressure caused by the relatively slow movement of high and low pressure major storm centers and normal pressure changes due to the sun can be measured and automatically recorded with a portable barograph.

The portable barograph is self contained and driven by two clock type motors capable of running for 18 hours or more. This instrument should be set up as near as possible to the points to be measured and should not be disturbed while recording altimeter measurements including recheck of the starting point. The barograph recording identifies atmospheric pressure changes with respect to time that can be applied directly to altimeter measurements made at known times. Complete operating instructions are given in the manual that comes with the instrument.

When a barograph is not available, corrections can be obtained from a second altimeter located at a fixed reference point. This method requires a second operator to make recordings at regular intervals of 5 to 10 minutes of the indicated elevation at the fixed point. Changes in readings taken at the fixed point are the correction factors to be applied to the readings from the roving survey altimeter.

Another condition which affects air density is the ambient temperature. Air density varies inversely to absolute temperature. Therefore, when the air temperature differs from that for which the altimeter is calibrated (at a known elevation), a temperature correction must be applied. The error introduced is approximately 0.2 percent per degree Fahrenheit. Instructions for making this correction are contained in the instruction book included with the altimeter.

The number of altimeter measurements to be made on a given path is dictated by the nature of the terrain and the accuracy or availability of topographical maps. In the more difficult case, where suitable maps are not available, it is advisable to make more than one complete end-to-end and return path survey so that final profile accuracy will be improved. The separate surveys should start at opposite path ends and be conducted on different days. Any discrepancies found in the profile data should be rechecked before the field party leaves the area. In many cases, it will be necessary to check only a few points on a path and the field work will therefore be greatly simplified.

In those cases where there are good maps and many known elevations in the immediate path area, it may be unnecessary to use the barograph or to determine corrections for air density changes. A simplified technique is to make an altimeter measurement at a known elevation point near the unknown point, proceed quickly to the unknown point to make another measurement, and quickly return to the original known point to make a third measurement. The time should be recorded with the altimeter data at each point. If two altimeter measurements at the known elevation coincide, no measurement corrections at the unknown point is necessary. If the two measurements for the known point differ with very little accuracy loss, it can be assumed the change in atmospheric pressure was linear during the time of the measurements (provided the total time was only a few minutes and weather conditions fairly stable). The change (in feet) in altimeter calibration versus time can be obtained directly by dividing the difference between the two measurements at the known elevation by the time elapsed. This factor multiplied by the difference in time between the first measurement and the measurement at the unknown elevation will give the correction to be applied to the measurement made at the unknown point.

o Airborne. In areas where map coverage does not exist and the terrain prohibits travel or access, it may be convenient to search for possible sites by airplane. If a helicopter is available, it may be possible to occupy the sites and prove adequate path clearance by visual methods and by taking photographs.

When it is not possible to sight visually along the entire length of the path, it may be necessary to run path profiles by radar surveying from the air. This technique has been developed to a satisfactory degree. However, it is an expensive method due to the huge investment in airborne radar and other equipment. There are organizations equipped to perform radar surveys on a contractual basis.

Another technique for airborne surveys is the one often used for making topographic maps. This requires making a complete set of accurate stereoscopic photographs of the area from a photo-reconnaissance aircraft and interpreting these photos with special optical instruments to produce a topographic map or profile. This is the most accurate method mentioned, but is prohibitively expensive for microwave surveys.

e. Final Determination. DCAC 330-175-1 requires that final path parameters (path profile) be determined with an accuracy not less than the following:

- All distances to 0.1 mile
- All azimuths to 10 seconds
- Maps utilized shall have a scale of 1 in 25,000 with contours at 5 meter intervals. In areas where maps to this scale are not available, a scale of up to 1 in 100,000 with contours at not more than 30 meter intervals may be used.

f. Field Tests (Propagation). DCAC 330-175-1 requires that wherever requirement for a subsystem or a hop is such that time, funds, manpower and test equipment are available, a path loss measurement should be conducted to determine transmission losses, variability and propagation anomalies. To accomplish these tests, it is necessary to establish temporary microwave stations using portable equipment. Continuous or periodic signal measurements can be made to prove the feasibility of the tentative path. This type of test can provide valuable information for long hops, obstructed hops, or multipath hops (such as overwater hops which present a reflected wave problem). The practicability of employing diversity reception is often investigated in this manner.