Annex I

AVAILABLE DATA, STANDARD CURVES, AND A SIMPLE PREDICTION MODEL

The simplest way to predict long-term median transmission loss values would be to use a best-fit curve drawn through measured data (represented by their overall median values) plotted as a function of path length. Such a method ignores essentially all of our understanding of the physics of tropospheric propagation, is subject to especially large errors over rough terrain, and such empirical curves represent only the conditions for which data are available.

Curves that may be useful for establishing preliminary allocation plans are presented in section I. 2 of this annex. These "standard" curves were prepared for a fixed combination of antenna heights and assume propagation over a smooth earth. The curves are not suitable for use on particular point-to-point paths, since they make no allowance for the wide range of propagation path profiles or atmospheric conditions that may be encountered over particular paths.

A method for computing preliminary reference values of transmission loss is described in section I. 3. This method is based on a simple model, may readily be programmed, and is especially useful when little is known of the details of terrain.

I. 1 Available Data as a Function of Path Length

Period-of-record median values of attenuation relative to free space are plotted vs. distance in figures I. 1 to I. 4 for a total of 750 radio paths, separating the frequency ranges 40-150 MHz, 150-600 MHz, 600-1000 MHz, and 1-10 GHz. Major sources of data other than those referenced by Herbstreit and Rice [1959] are either unpublished or are given by Bray, Hopkins, Kitchen, and Saxton [1955], Bullington [1955], du Castel [1957b], Crysdale [1958], Crysdale, Day, Cook, Psutka, and Robillard [1957], Dolukhanov [1957], Grosskopf [1956], Hirai [1961a, b], Josephson and Carlson [1958], Jowett [1958], Joy [1958a, b], Kitchen and Richmond [1957], Kitchen, Richards, and Richmond [1958], Millington and Isted [1950], Newton and Rogers [1953], Onoe, Hirai, and Niwa [1958], Rowden, Tagholm, and Stark [1958], Saxton [1951], Ugai [1961], and Vvedenskii and Sokolov [1957].

Three straight lines were determined for each of the data plots shown in figures I. 1 to I. 4. Near the transmitting antenna, $A = 0$ on the average. Data for intermediate distances, where the average rate of diffraction attenuation is approximately $0.09\ f^{\frac{1}{3}}$ db per kilometer, determine a second straight line. Data for the greater distances, where the level of forward scatter fields is reached, determine the level of a straight line with a slope varying from 1/18 to 1/14 db per kilometer, depending on the frequency.

The dashed curves of figures I. 1-I. 3 show averages of broadcast signals recorded at 2500 random locations in six different areas of the United States. The data were normalized to 10-meter and 300-meter antenna heights, and to frequencies of 90, 230, and 750 MHz.

For this data sample [TASO 1959], average fields are low mainly because the receiver locations were not carefully selected, as they were for most other paths for which data are shown.

The extremely large variance of long-term median transmission loss values recorded over irregular terrain is due mainly to differences in terrain profiles and effective antenna heights. For a given distance and given antenna heights a wide range of angular distances is possible, particularly over short diffraction and extra-diffraction paths. Angular distance, the angle between radio horizon rays from each antenna in the great circle plane containing the antennas, is a very important parameter for transmission loss calculations, (see section 6). Figure I. 5 shows for a number of paths the variability of angular distance relative to its value over a smooth spherical earth as a function of path distance and antenna heights.

Most of the "scatter" of the experimental long-term medians shown in figures I. 1 - I. 4 is due to path-to-path differences. A small part of this variation is due to the lengths of the recording periods. For all data plotted in the figures the recording period exceeded two weeks, for 630 paths it exceeded one month, and for 90 paths recordings were made for more than a year.

An evaluation of the differences between predicted and measured transmission loss values is discussed briefly in annex V. In evaluating a prediction method by its variance from observed data, it is important to remember that this variance is strongly influenced by the particular data sample available for comparison. Thus it is most important that these data samples be as representative as possible of the wide range of propagation path conditions likely to be encountered in the various types of service and in various parts of the world.

To aid in deciding whether it is worthwhile to use the point-to-point prediction method outlined in sections 4 - 10, instead of simpler methods, figure I. 6 shows the cumulative distribution of deviations of predicted from observed long-term median values. The dash-dotted curve shows the cumulative distribution of deviations from the lines drawn in figures I. 1 - I. 4 for all available data. The solid and dashed curves compare predictions based on these figures with ones using the point-to-point method for the same paths. Note that the detailed point-to-point method could not be used in many cases because of the lack of terrain profiles

Figure I. 6 shows a much greater variance of data from the "empirical" curves of figures I. 1 - I. 4 for the sample of 750 paths than for the smaller sample of 217 paths for which terrain profiles are available. The wide scatter of data illsutrated in figure I. 4 for the frequency range 1 - 10 GHz appears to be mainly responsible for this. Figure I. 4 appears to show that propagation is much more sensitive to differences in terrain profiles at these higher frequencies, as might be expected. The point-to-point prediction methods, depending on a number of parameters besides distance and frequency, are also empirical, since they are made to agree with available data, but estimates of their reliability over a period of years have not varied a great deal with the size of the sample of data made available for comparison with them.

I.2 Standard Point-to-Point Transmission Loss Curves

A set of standard curves of basic transmission loss versus distance is presented in figures I.7 to I.26. Such curves may be useful for establishing preliminary allocation plans but they are clearly not suitable for use on particular point-to-point paths, since they make no allowance for the wide range of propagation path terrain profiles or atmospheric conditions which may be encountered. Similar curves developed by the CCIR [1963g; 1963h] are subject to the same limitation.

The standard curves show predicted levels of basic transmission loss versus path distance for 0.01 to 99.99 percent of all hours. These curves were obtained using the point-to-point predictions for a smooth earth, $N_s = 301$, antenna heights of 30 meters, and estimates of oxygen, water vapor, and rain absorption described in section 3. Cumulative distributions of hourly median transmission loss for terrestrial links may be read from figures I.7 to I.17 for distances from 0 to 1000 kilometers and for 0.1, 0.2, 0.5, 1, 2, 5, 10, 22, 32.5, 60 and 100 GHz. The same information may be obtained from figures I.18 to I.20.

For earth-space links, it is important to know the attenuation relative to free space, A, between the earth station and space station as a function of distance, frequency, and the angle of elevation, θ_h, of the space station relative to the horizontal at the earth station [CCIR 1963i; 1963j]. Using the CCIR basic reference atmosphere*, [CCIR Report 231, 1963e] standard propagation curves providing this information for 2, 5, 10, 22, 32.5, 60 and 100 GHz, for 0.01 to 99.99 percent of all hours, and for $\theta_h = 0$, 0.03, 0.1, 0.3, 1.0, and $\pi/2$ radians are shown in figures I.21-I.26, where A is plotted against the straight-line distance r_o between antennas. The relationship between A and L_b is given by

$$L_b = A + L_{bf} = A + 32.45 + 20 \log f + 20 \log r \quad \text{db} \qquad (I.1)$$

where f is the radio frequency in megahertz and r is the straight-line distance between antennas, expressed in kilometers.

The curves in figures I.7-I.26 provide long-term cumulative distributions of hourly median values. Such standard propagation curves are primarily useful only for general qualitative analyses and clearly do not take account of particular terrain profiles or particular climatic effects. For example, the transmission loss at the 0.1% and 0.1% levels will be substantially smaller in maritime climates where ducting conditions are more common.

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*The transmission loss predictions for this atmosphere are essentially the same as predictions for $N_s = 301$.

PERIOD OF RECORD MEDIANS VERSUS DISTANCE

FREQUENCY RANGE: 40–150 MHz; MEDIAN FREQUENCY: 90 MHz

343 PATHS

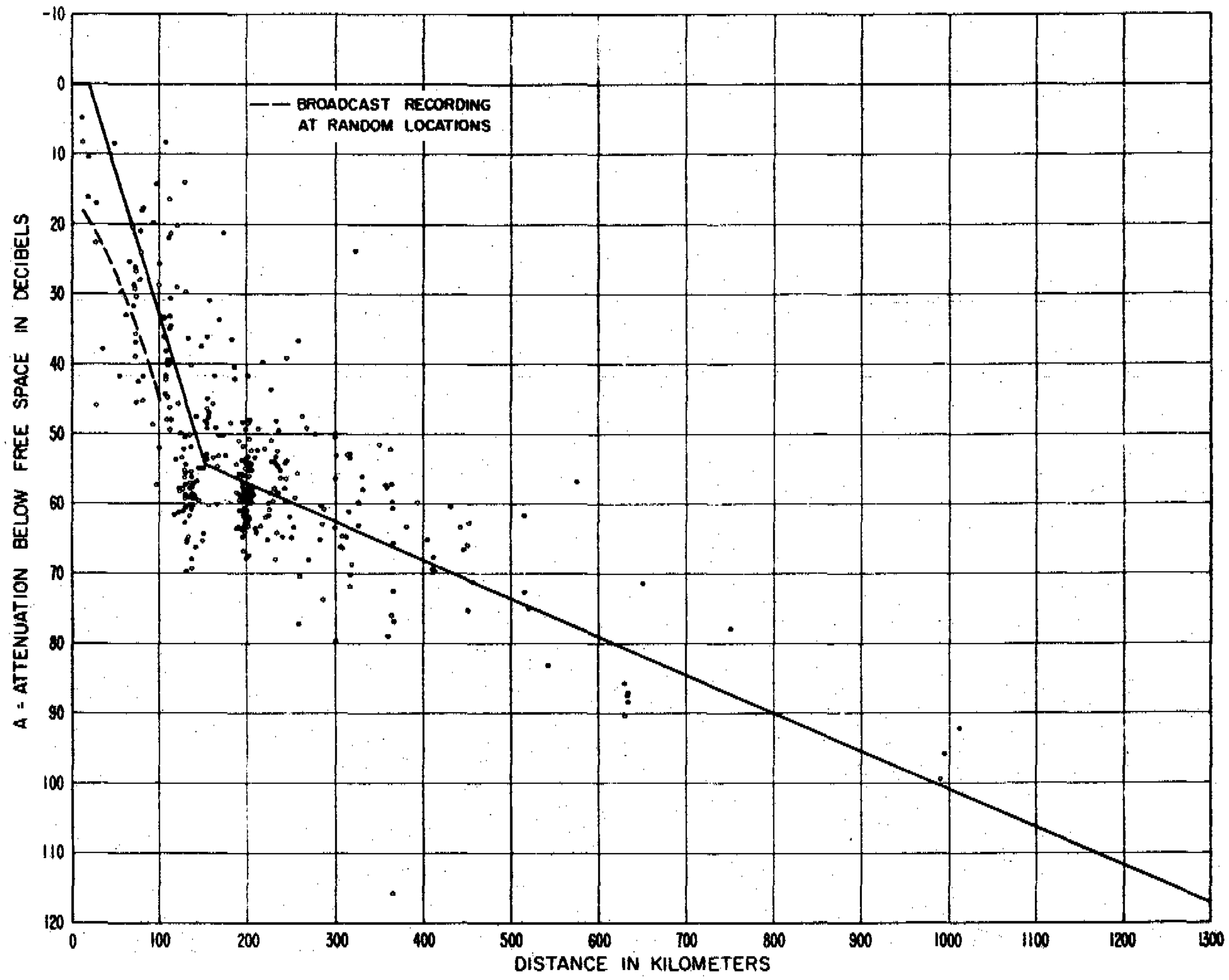


Figure I.1

PERIOD OF RECORD MEDIANS VERSUS DISTANCE

FREQUENCY RANGE: 150-600 MHz; MEDIAN FREQUENCY: 230 MHz

183 PATHS

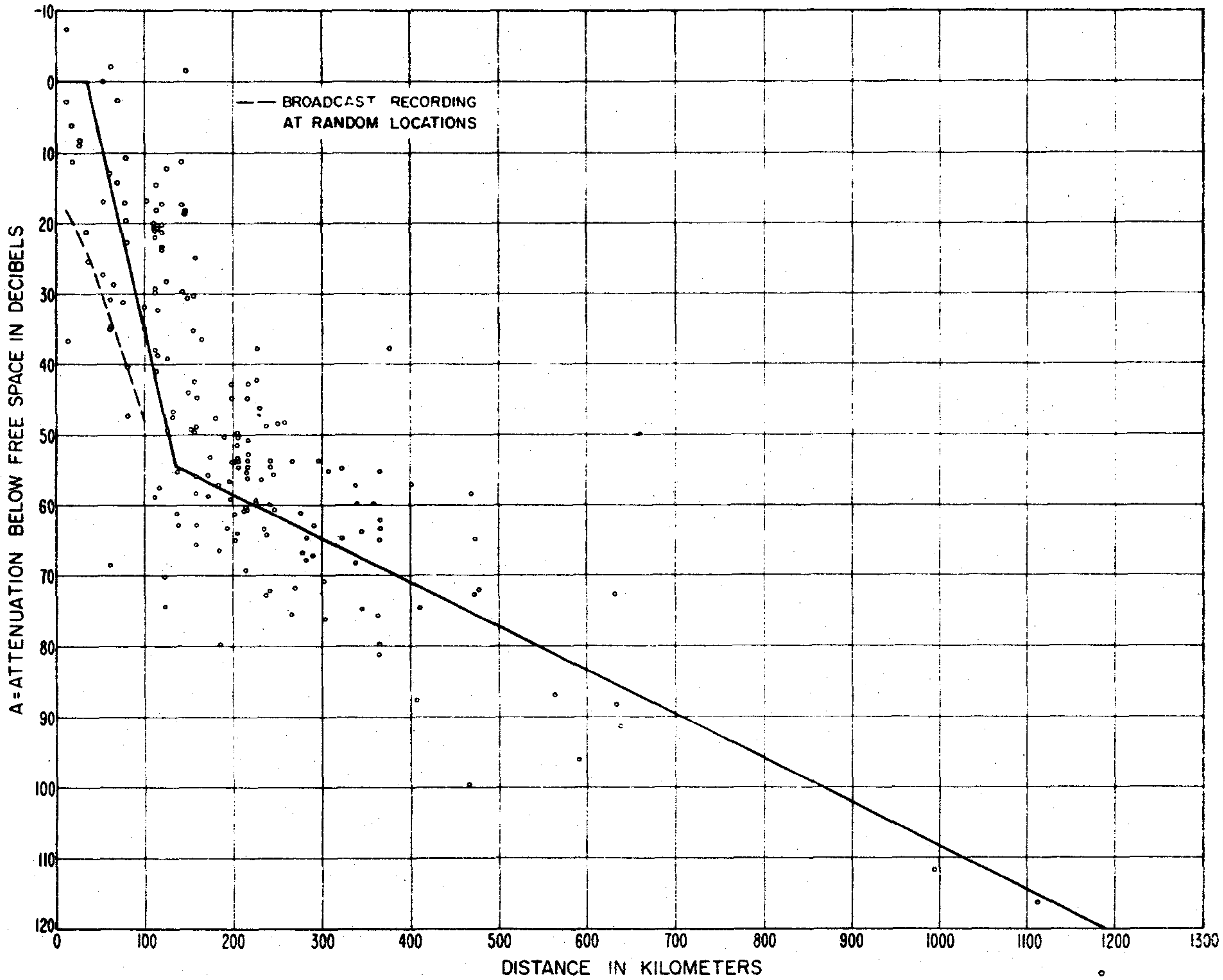


Figure I.2

PERIOD OF RECORD MEDIANS VERSUS DISTANCE

FREQUENCY RANGE: 600-1000MHz; MEDIAN FREQUENCY: 750MHz

108 PATHS

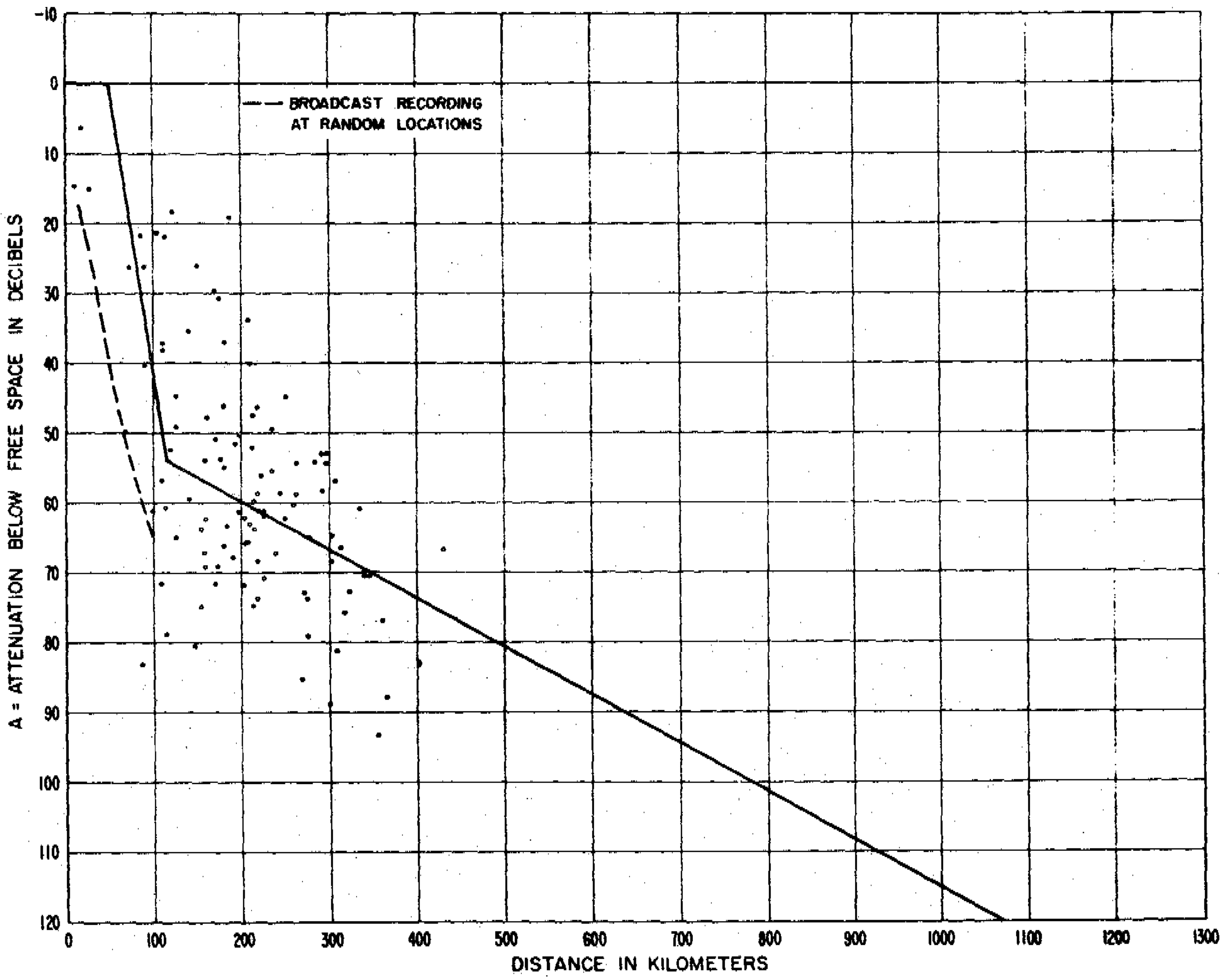


Figure I.3

PERIOD OF RECORD MEDIANS VERSUS DISTANCE

FREQUENCY RANGE: 1000-10,000 MHz; MEDIAN FREQUENCY: 3500 MHz

110 PATHS

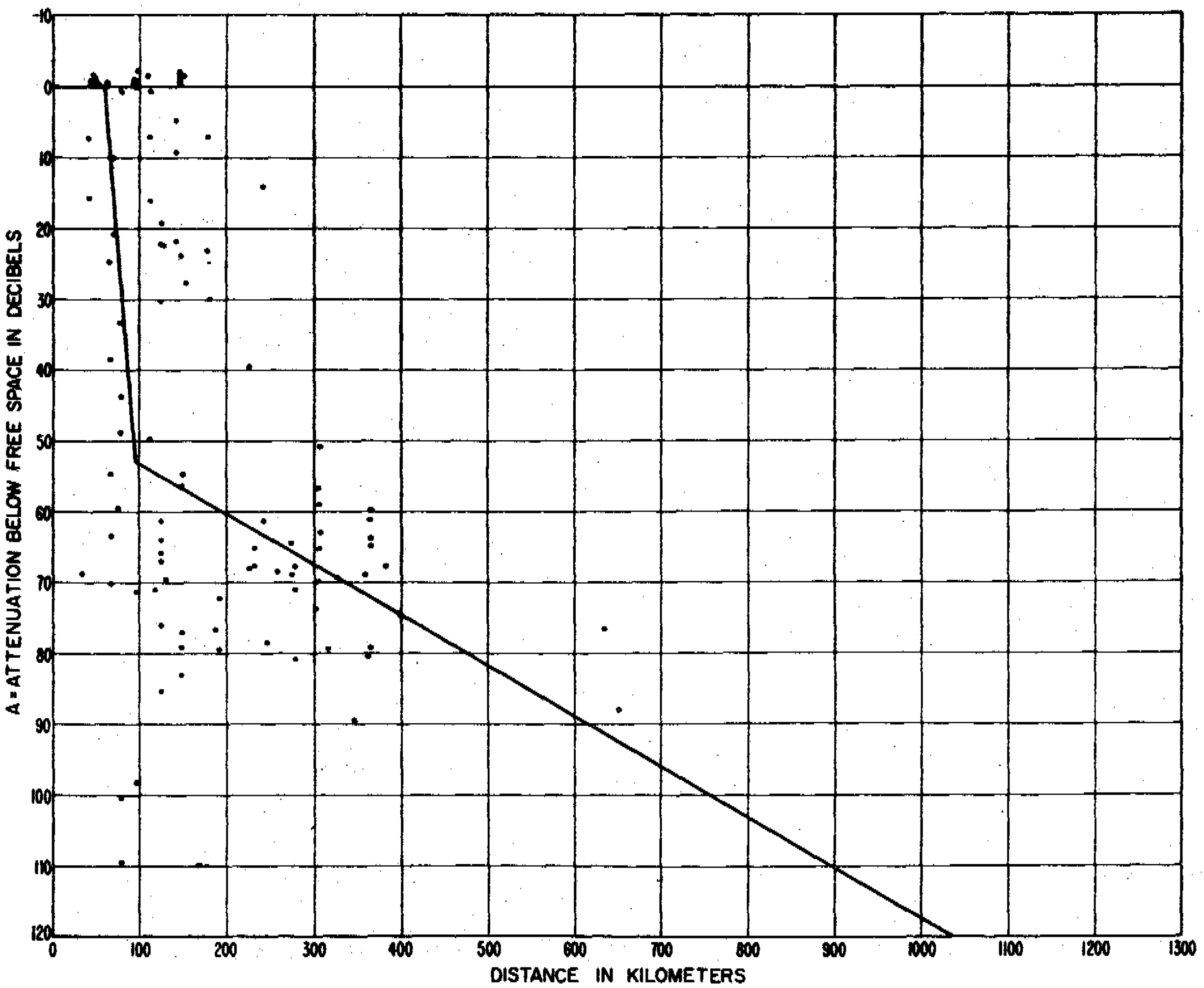


Figure I.4

ANGULAR DISTANCE VERSUS DISTANCE FOR THE 290 PATHS FOR WHICH TERRAIN PROFILES ARE AVAILABLE

THE CURVES SHOW ANGULAR DISTANCE, θ, AS A FUNCTION OF DISTANCE OVER A SMOOTH EARTH OF EFFECTIVE RADIUS = 9000 KILOMETERS

THE WIDE SCATTER OF THE DATA ON THIS FIGURE ARISES ALMOST ENTIRELY FROM DIFFERENCES IN TERRAIN PROFILES, AND ILLUSTRATES THE IMPORTANCE OF ANGULAR DISTANCE AS A PREDICTION PARAMETER

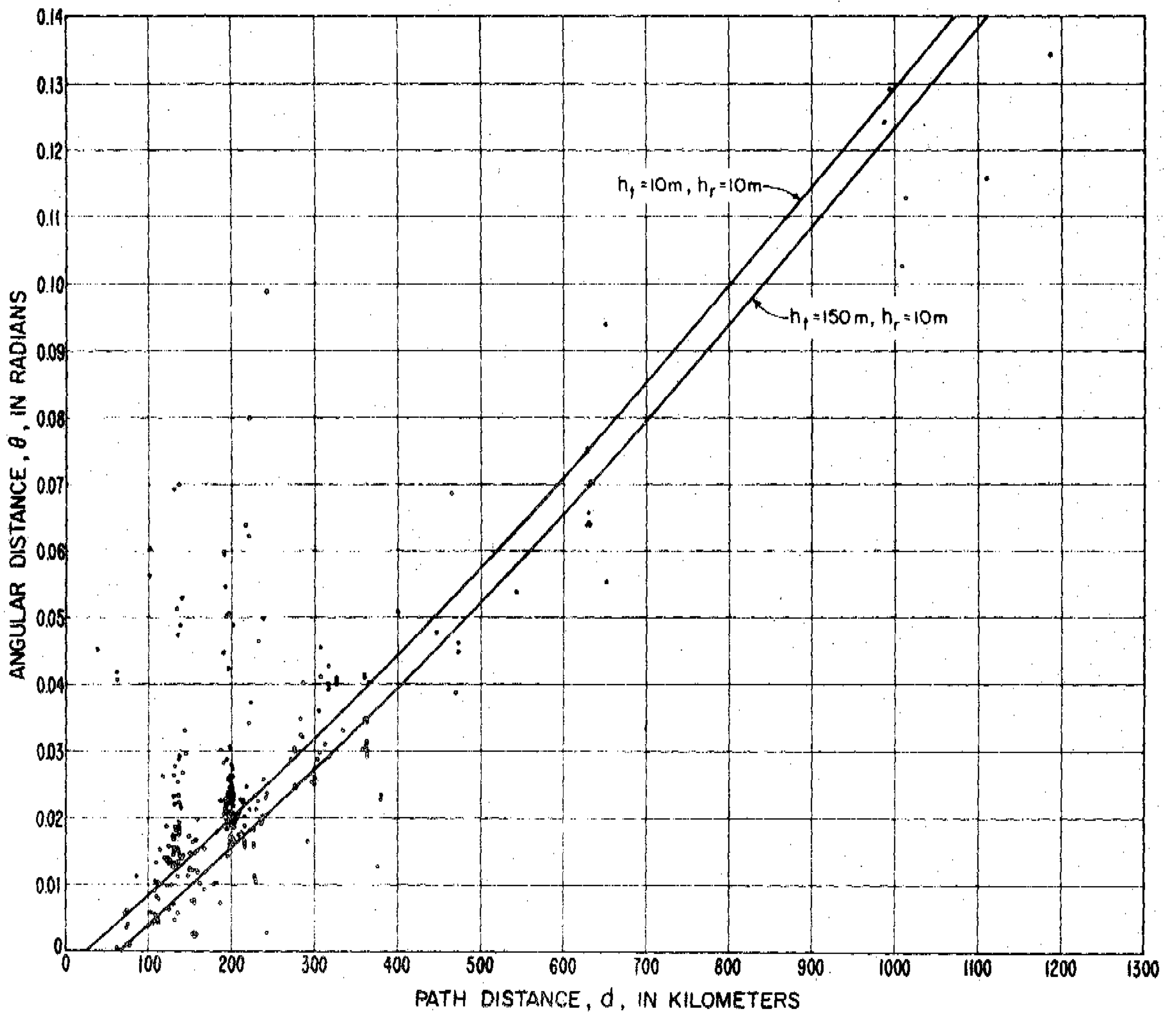


Figure I.5

CUMULATIVE DISTRIBUTION OF DEVIATIONS OF OBSERVED FROM PREDICTED VALUES OF TRANSMISSION LOSS

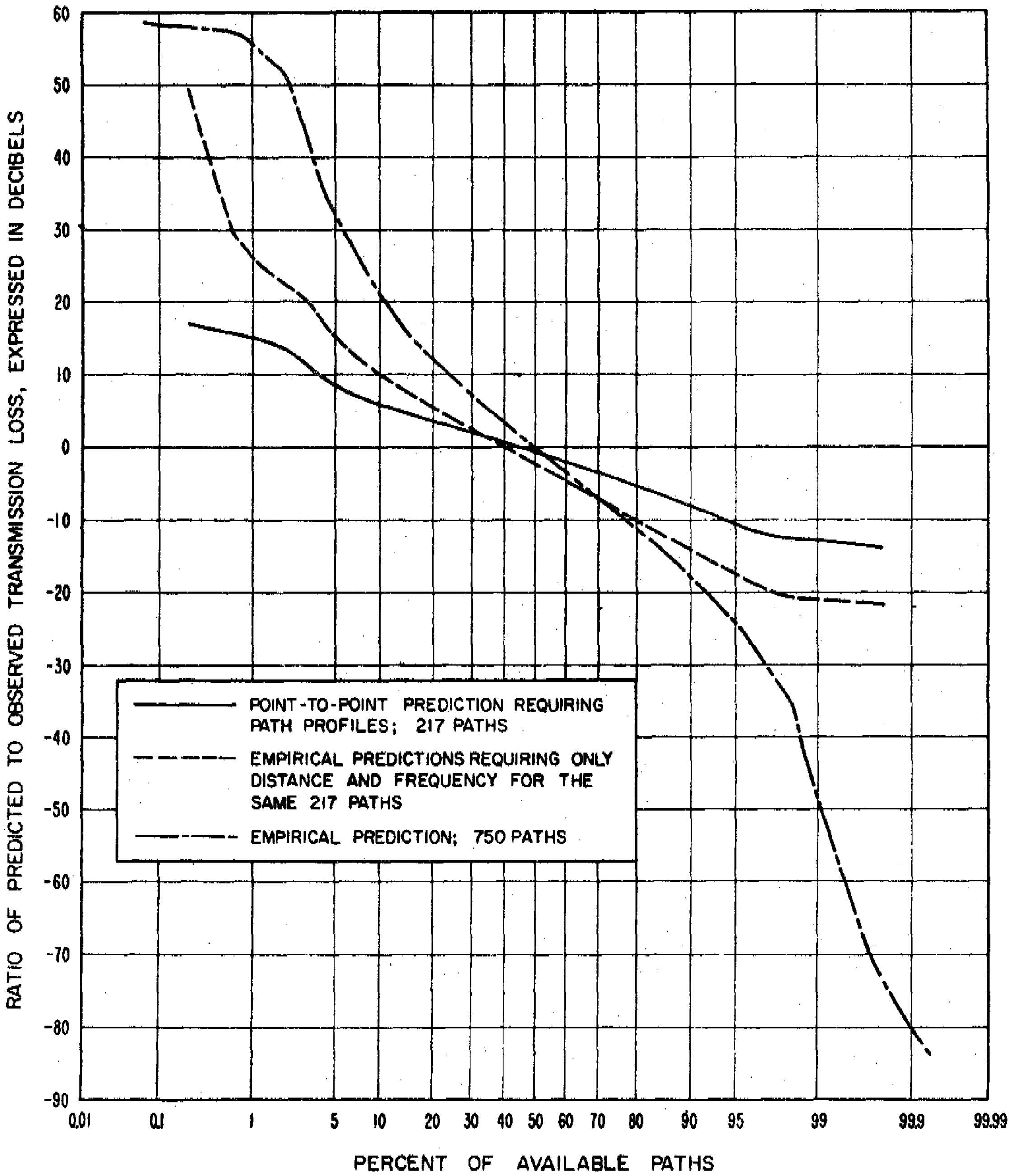


Figure I.6

STANDARD PROPAGATION CURVES
HOURLY MEDIAN BASIC TRANSMISSION LOSS
VERSUS DISTANCE AND TIME AVAILABILITY
FREQUENCY 0.1 GHz $h_{te} = h_{re} = 30$ m

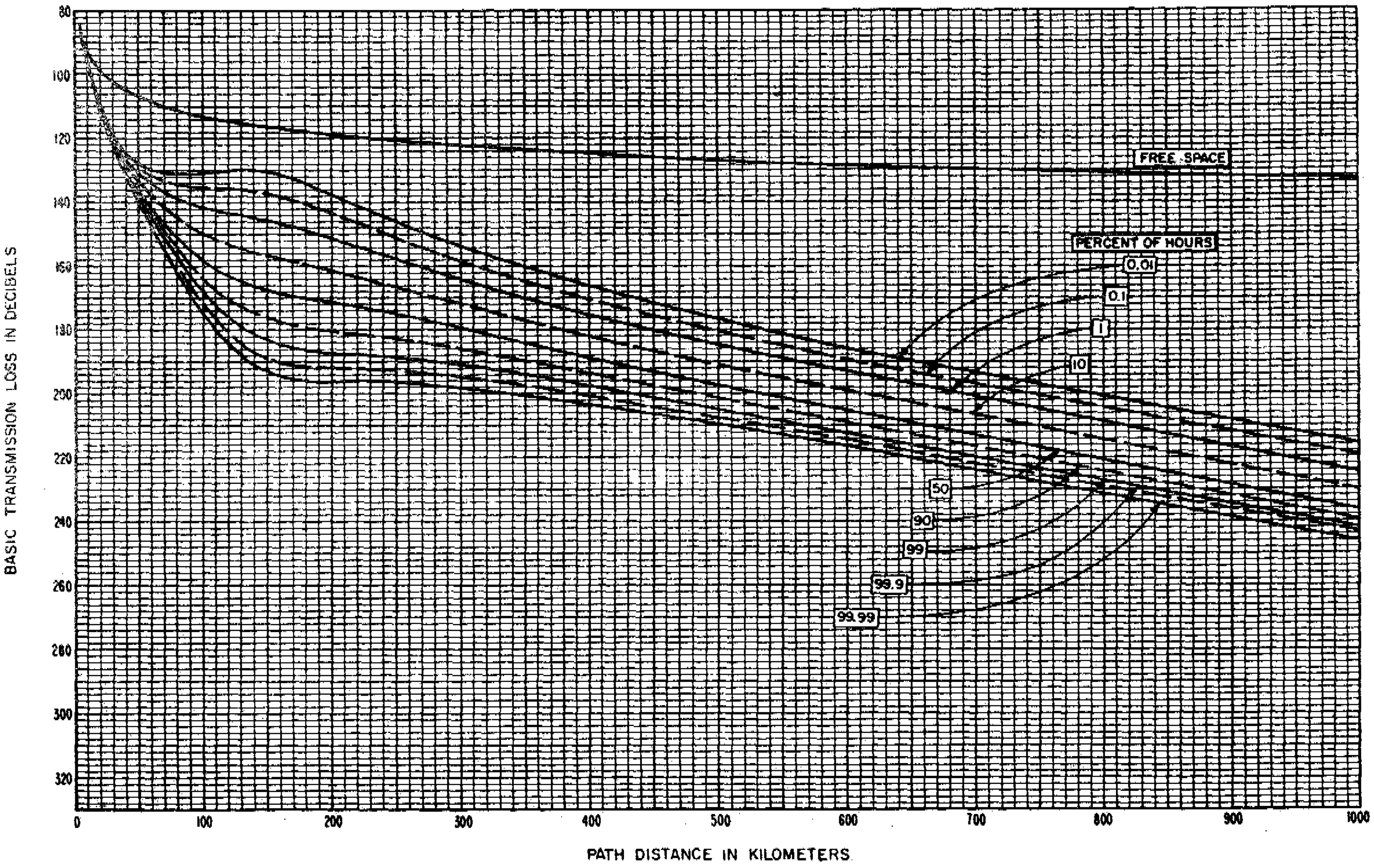


Figure I.7

STANDARD PROPAGATION CURVES

HOURLY MEDIAN BASIC TRANSMISSION LOSS
VERSUS DISTANCE AND TIME AVAILABILITY
FREQUENCY 0.2 GHz $h_{te} = h_{re} = 30\,m$

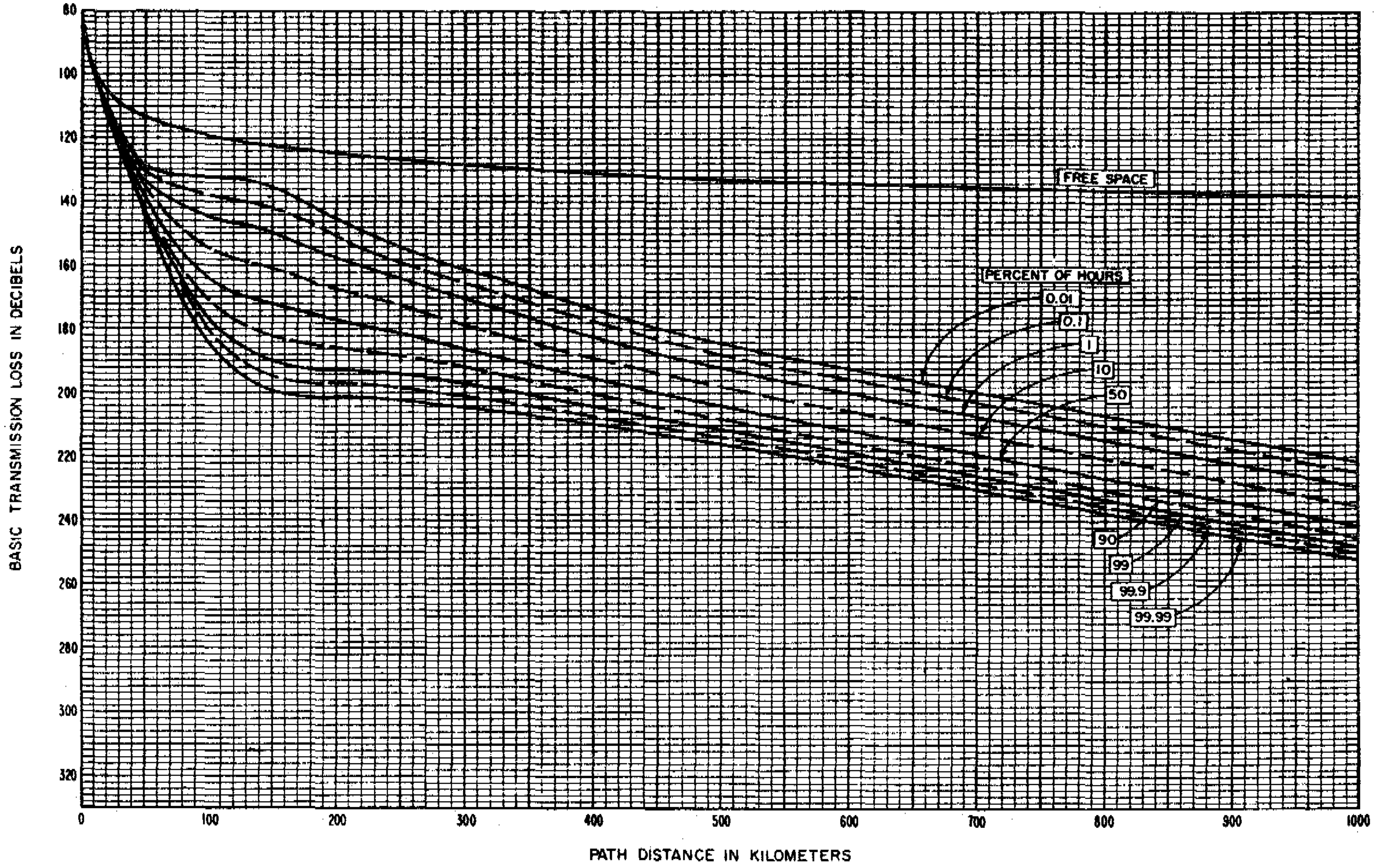


Figure I.8

STANDARD PROPAGATION CURVES
HOURLY MEDIAN BASIC TRANSMISSION LOSS
VERSUS DISTANCE AND TIME AVAILABILITY
FREQUENCY 0.5 GHz $h_{te} = h_{re} = 30$ m

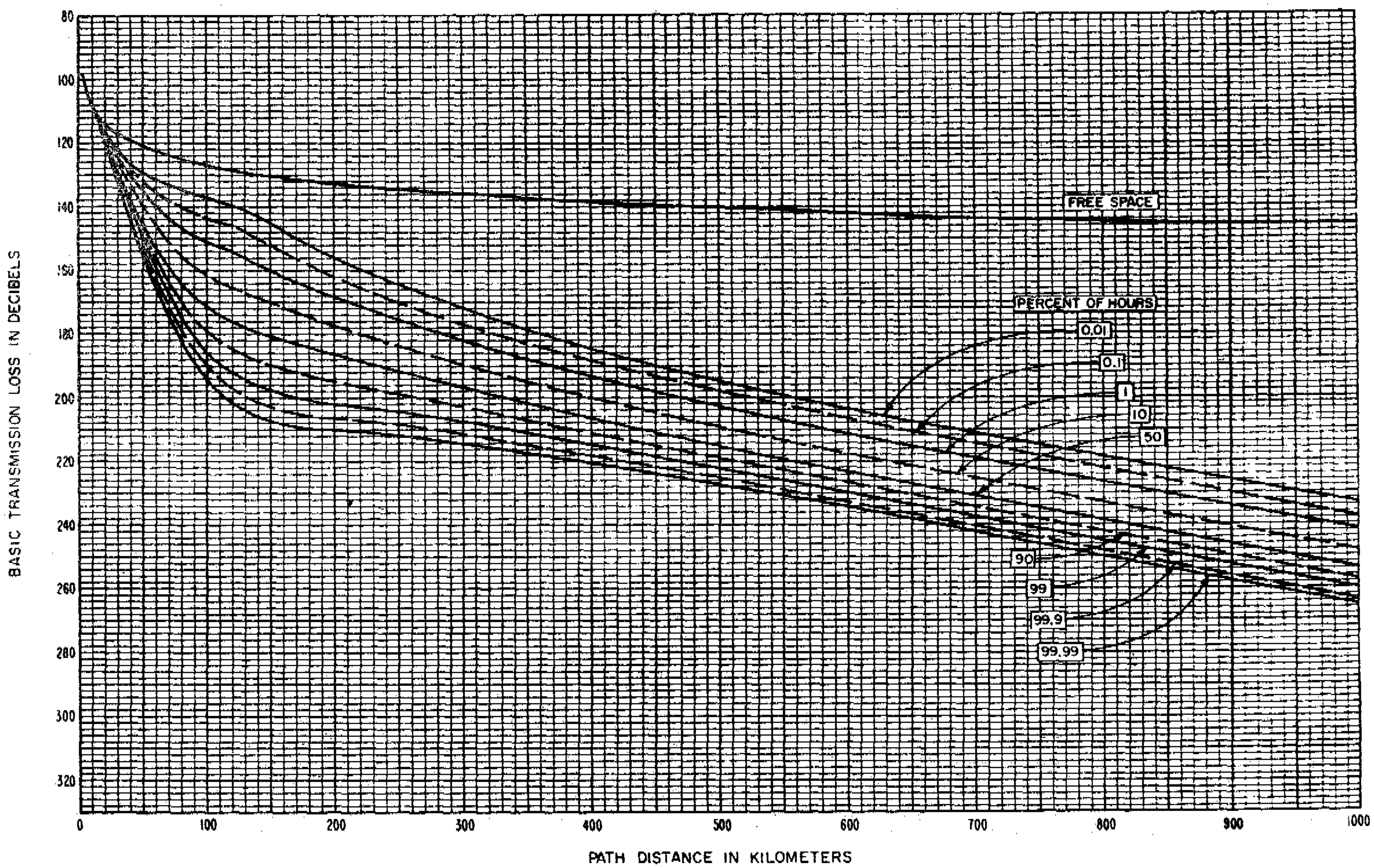


Figure I.9

STANDARD PROPAGATION CURVES

HOURLY MEDIAN BASIC TRANSMISSION LOSS
VERSUS DISTANCE AND TIME AVAILABILITY
FREQUENCY 1 GHz $h_{te} = h_{re} = 30$ m

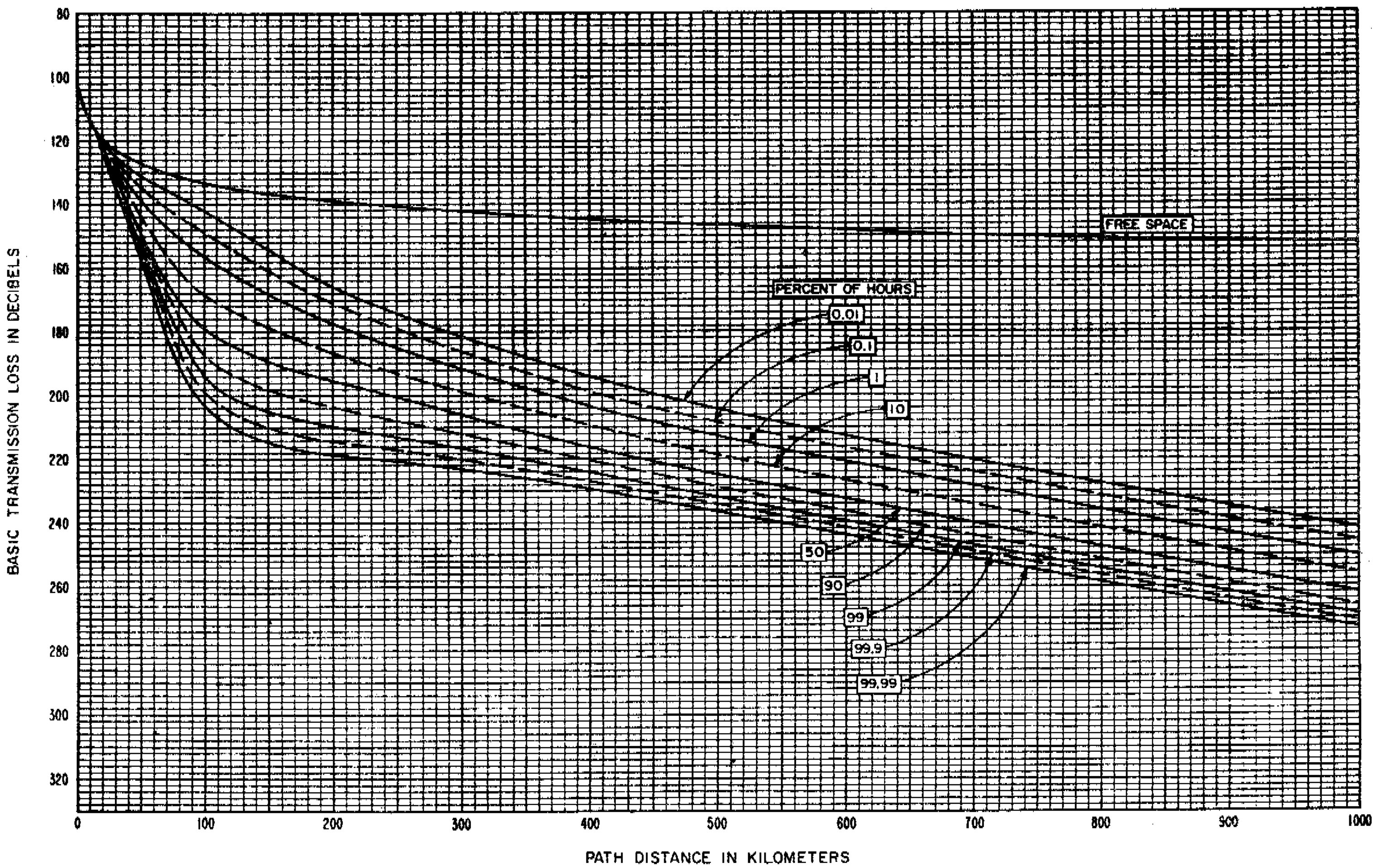


Figure I.10

STANDARD PROPAGATION CURVES

HOURLY MEDIAN BASIC TRANSMISSION LOSS
VERSUS DISTANCE AND TIME AVAILABILITY
FREQUENCY 2 GHz $h_{te} = h_{re} = 30\,m$

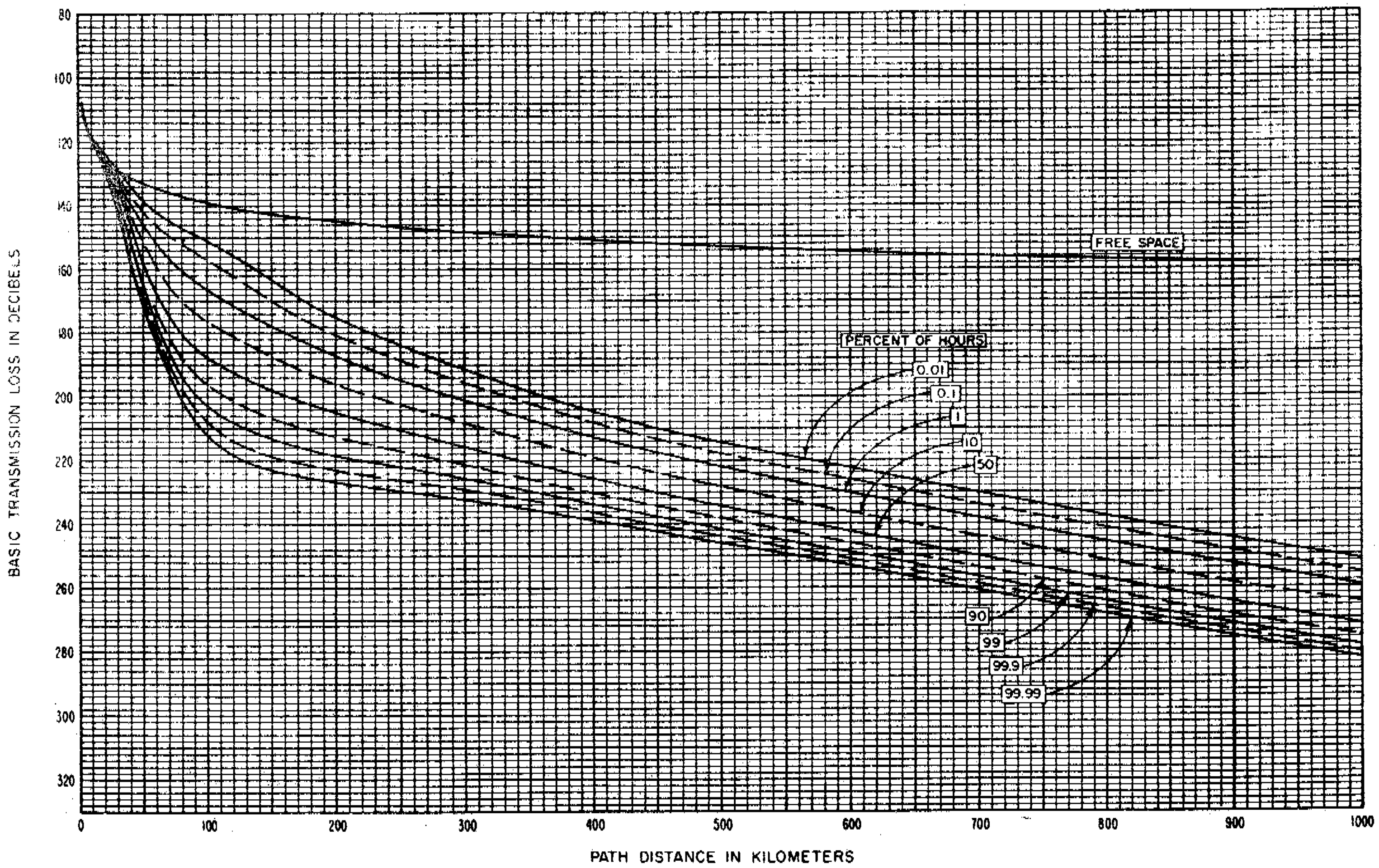


Figure I.11

STANDARD PROPAGATION CURVES

HOURLY MEDIAN BASIC TRANSMISSION LOSS VERSUS DISTANCE AND TIME AVAILABILITY

FREQUENCY 5 GHz $h_{te} = h_{re} = 30$ m

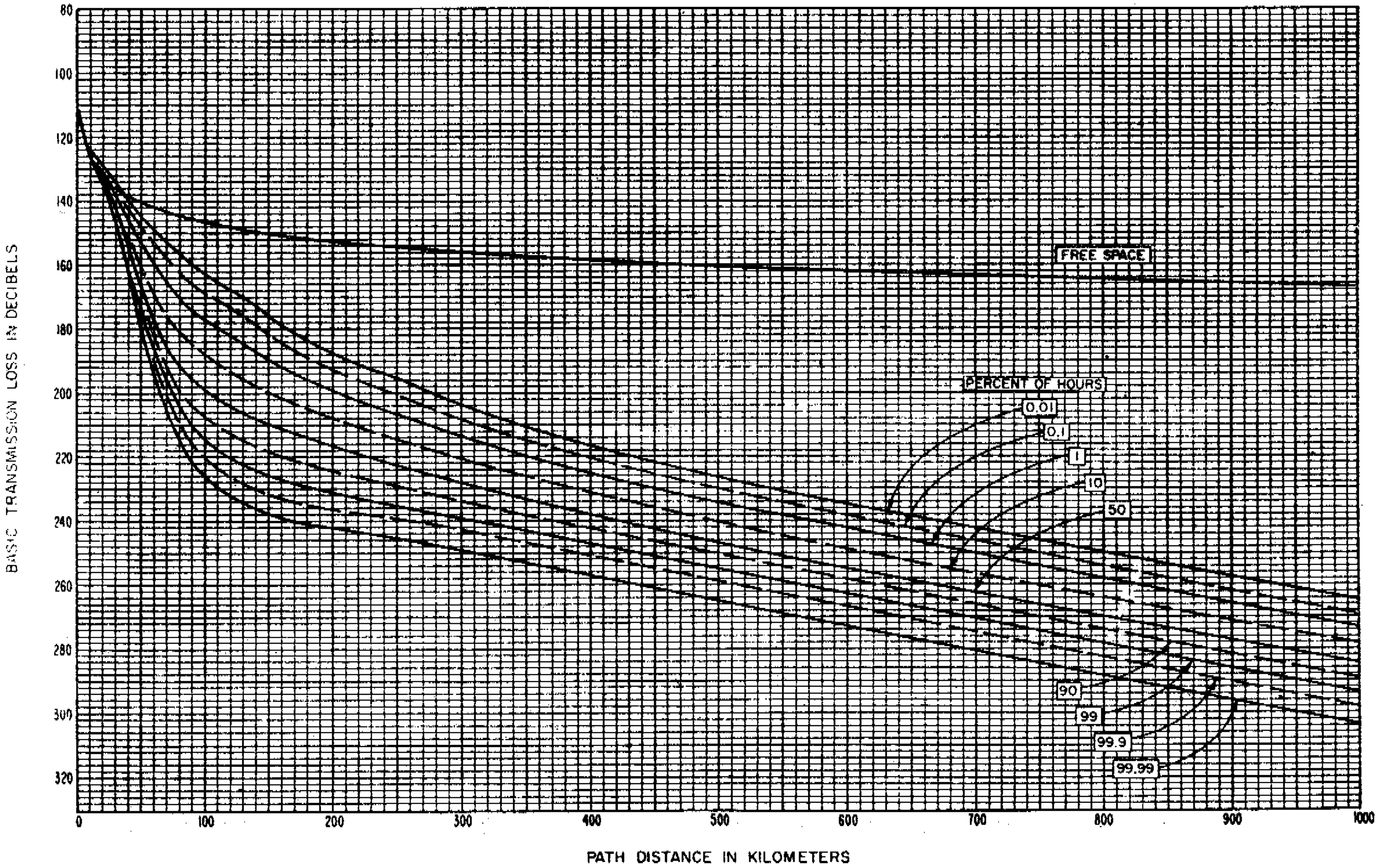


Figure I.12

STANDARD PROPAGATION CURVES

HOURLY MEDIAN BASIC TRANSMISSION LOSS
VERSUS DISTANCE AND TIME AVAILABILITY
FREQUENCY 10 GHz $h_{te} = h_{re} = 30$ m

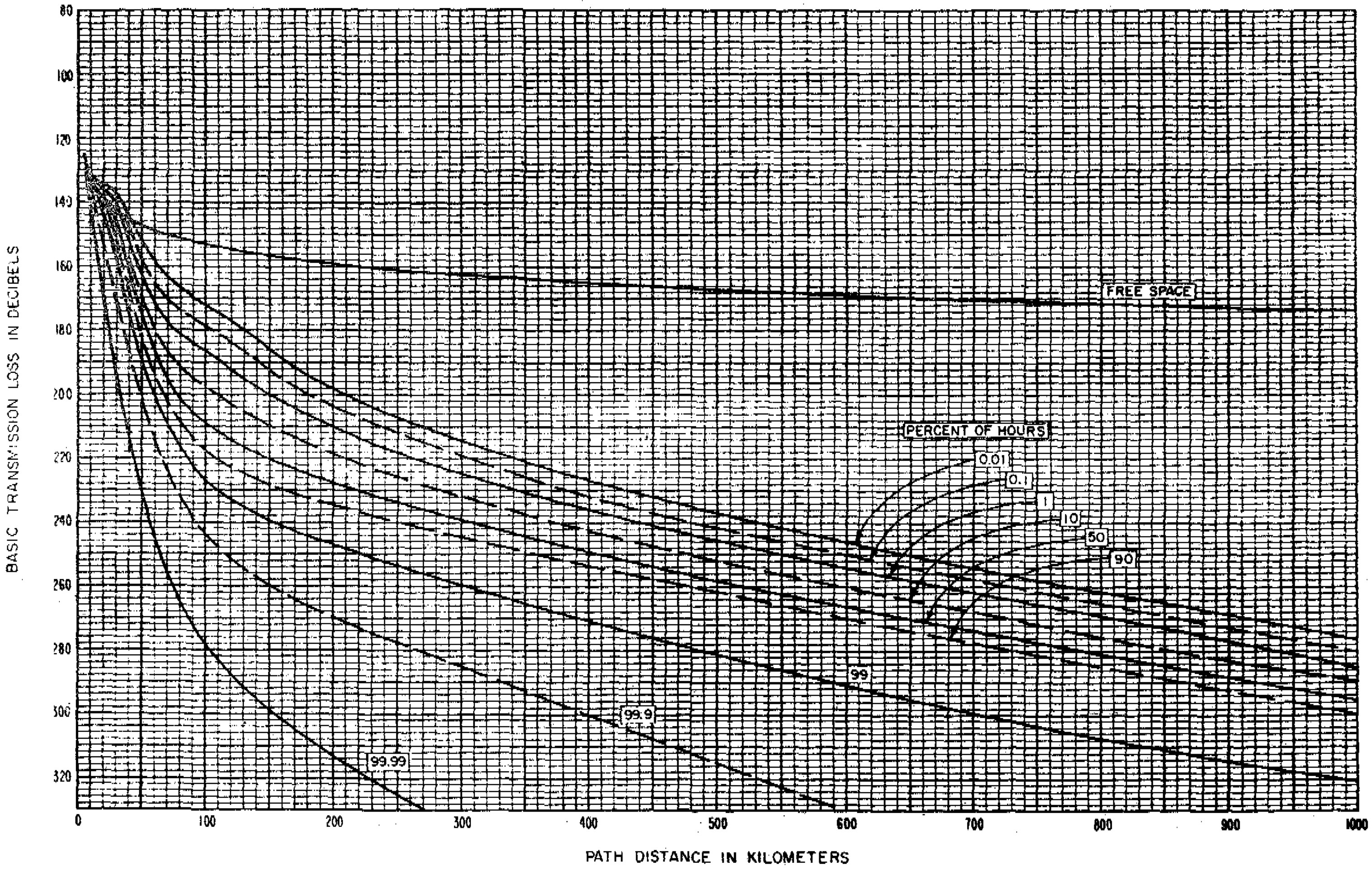


Figure I.13

STANDARD PROPAGATION CURVES

HOURLY MEDIAN BASIC TRANSMISSION LOSS
VERSUS DISTANCE AND TIME AVAILABILITY
FREQUENCY 22.2 GHz $h_{te} = h_{re} = 30m$

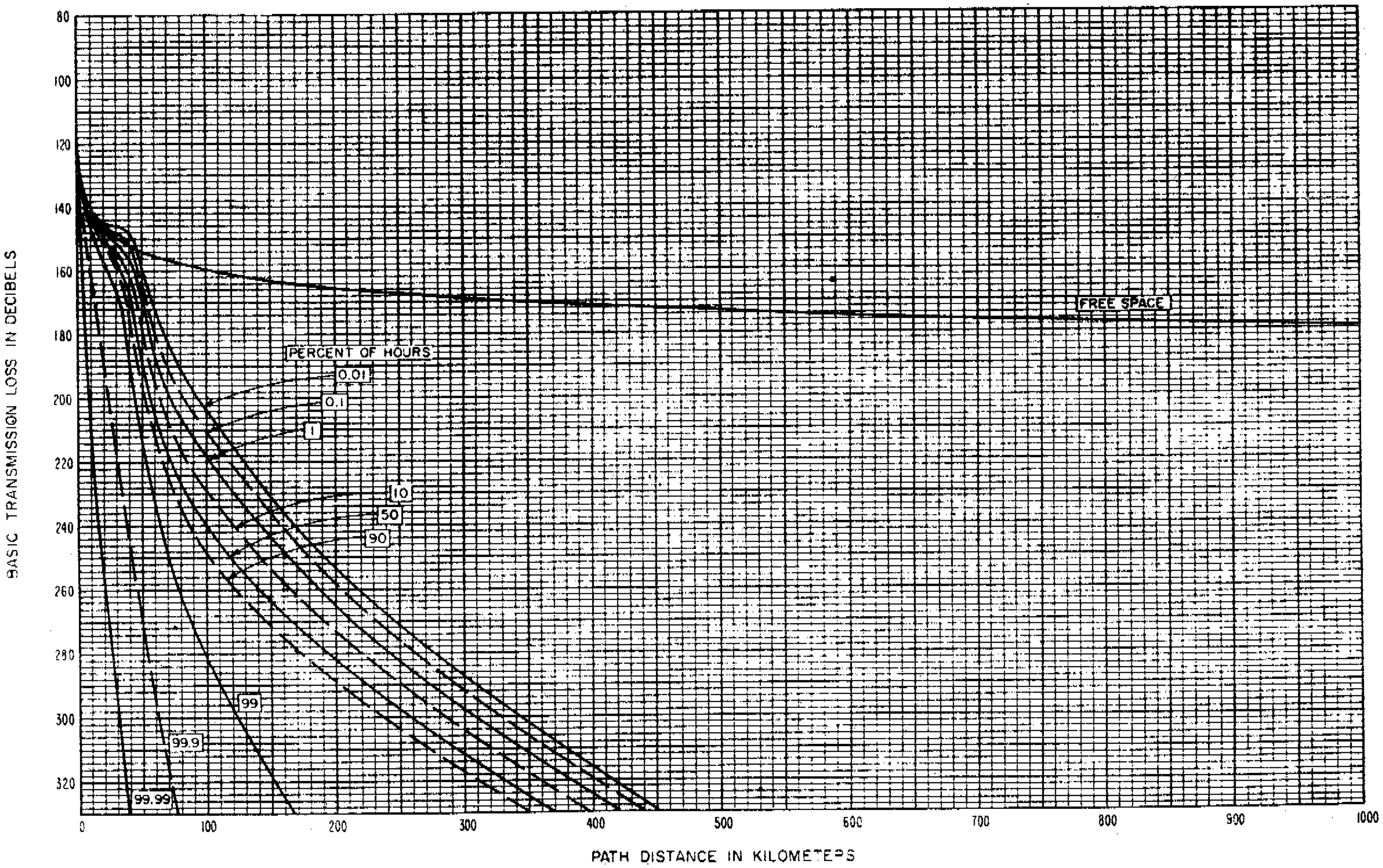


Figure I.14

STANDARD PROPAGATION CURVES
HOURLY MEDIAN BASIC TRANSMISSION LOSS
VERSUS DISTANCE AND TIME AVAILABILITY
FREQUENCY 32.5 GHz $h_{te} = h_{re} = 30$ m

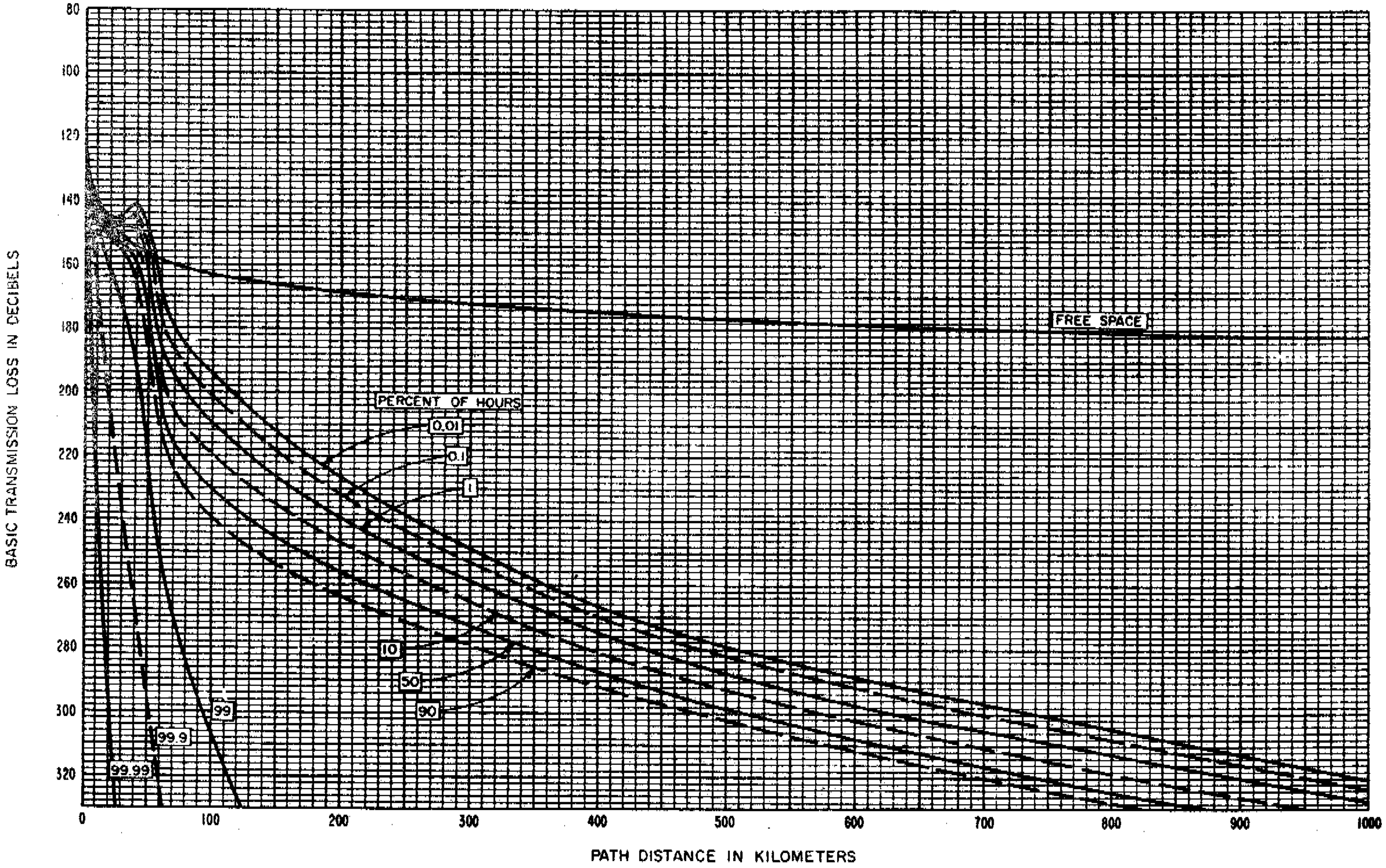


Figure I.15

STANDARD PROPAGATION CURVES

HOURLY MEDIAN BASIC TRANSMISSION LOSS
VERSUS DISTANCE AND TIME AVAILABILITY
$h_{te} = h_{re} = 30$ m

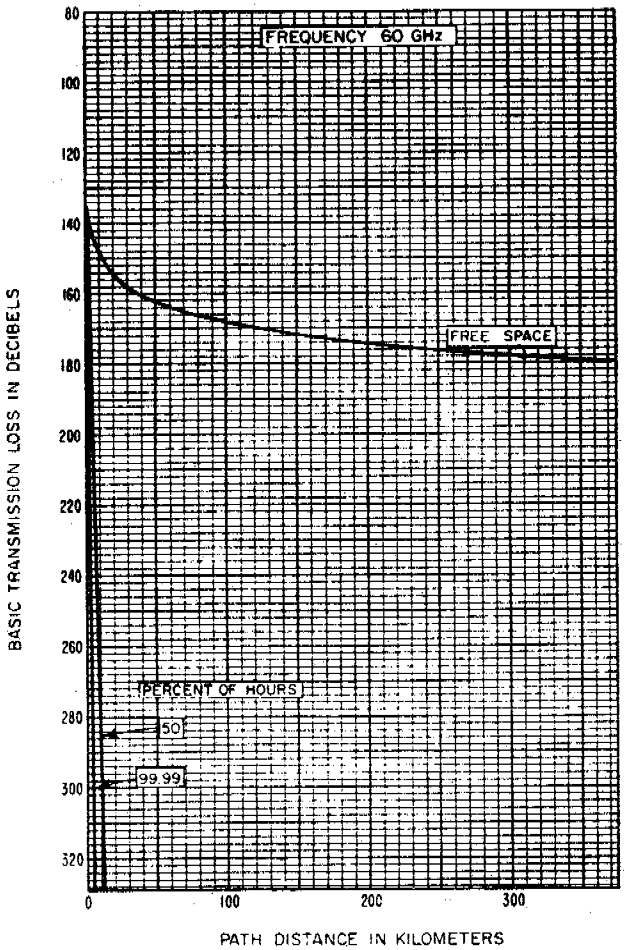


Figure I.16

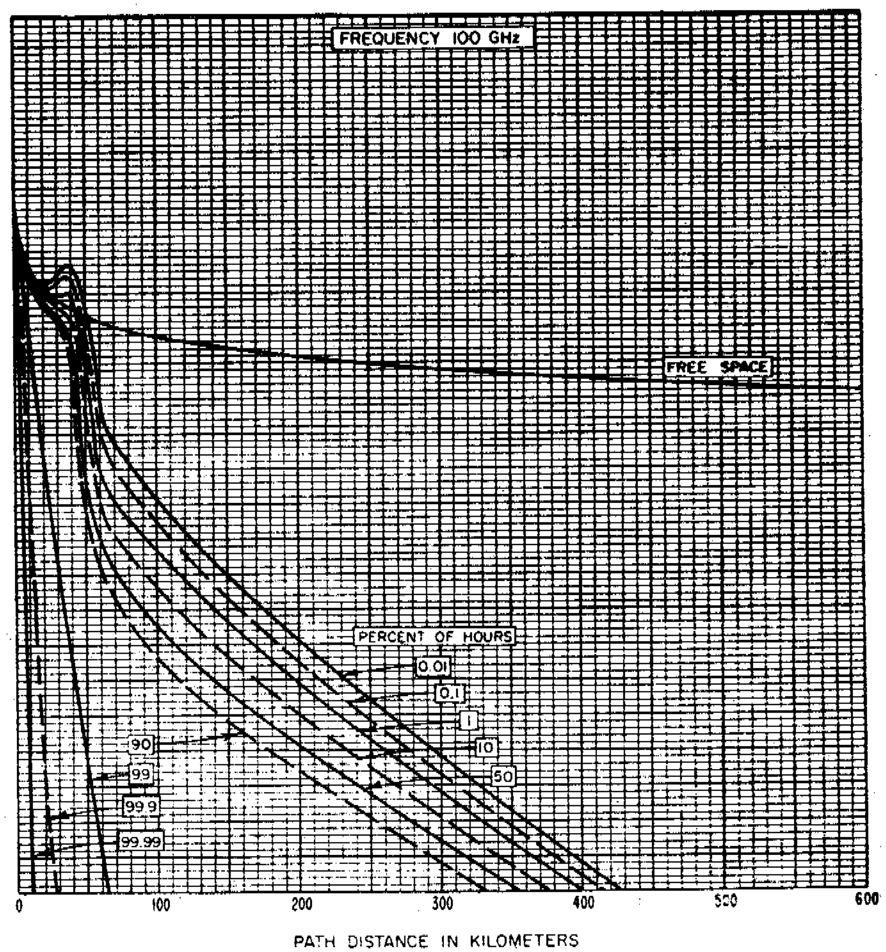


Figure I.17

STANDARD PROPAGATION CURVES
PREDICTED MEDIAN LEVELS OF BASIC TRANSMISSION LOSS
FOR FREQUENCIES FROM 0.1 TO 100 GHz

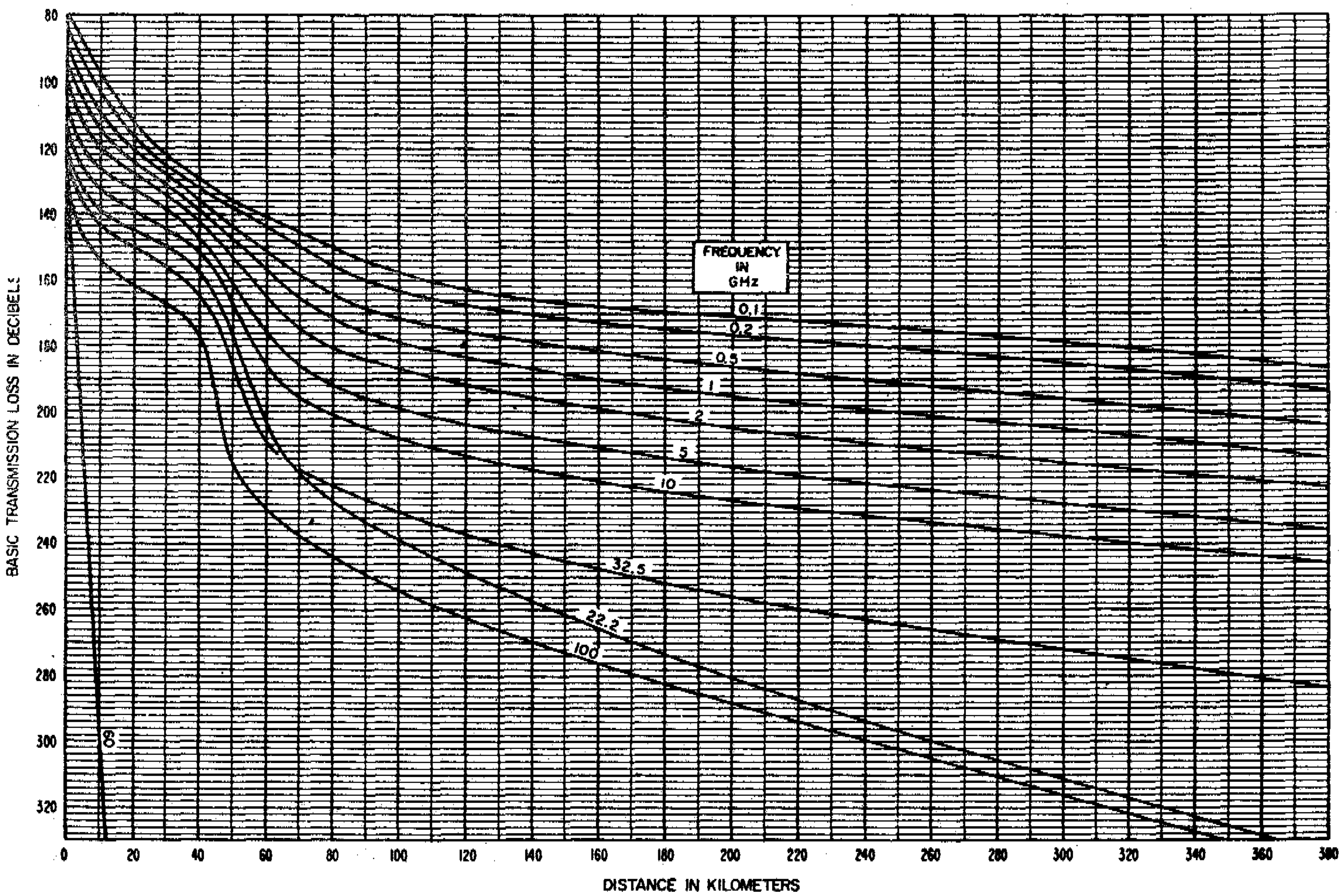


Figure I.18

STANDARD PROPAGATION CURVES

CUMULATIVE DISTRIBUTION OF HOURLY MEDIAN BASIC TRANSMISSION LOSS RELATIVE TO THE LONG-TERM MEDIAN

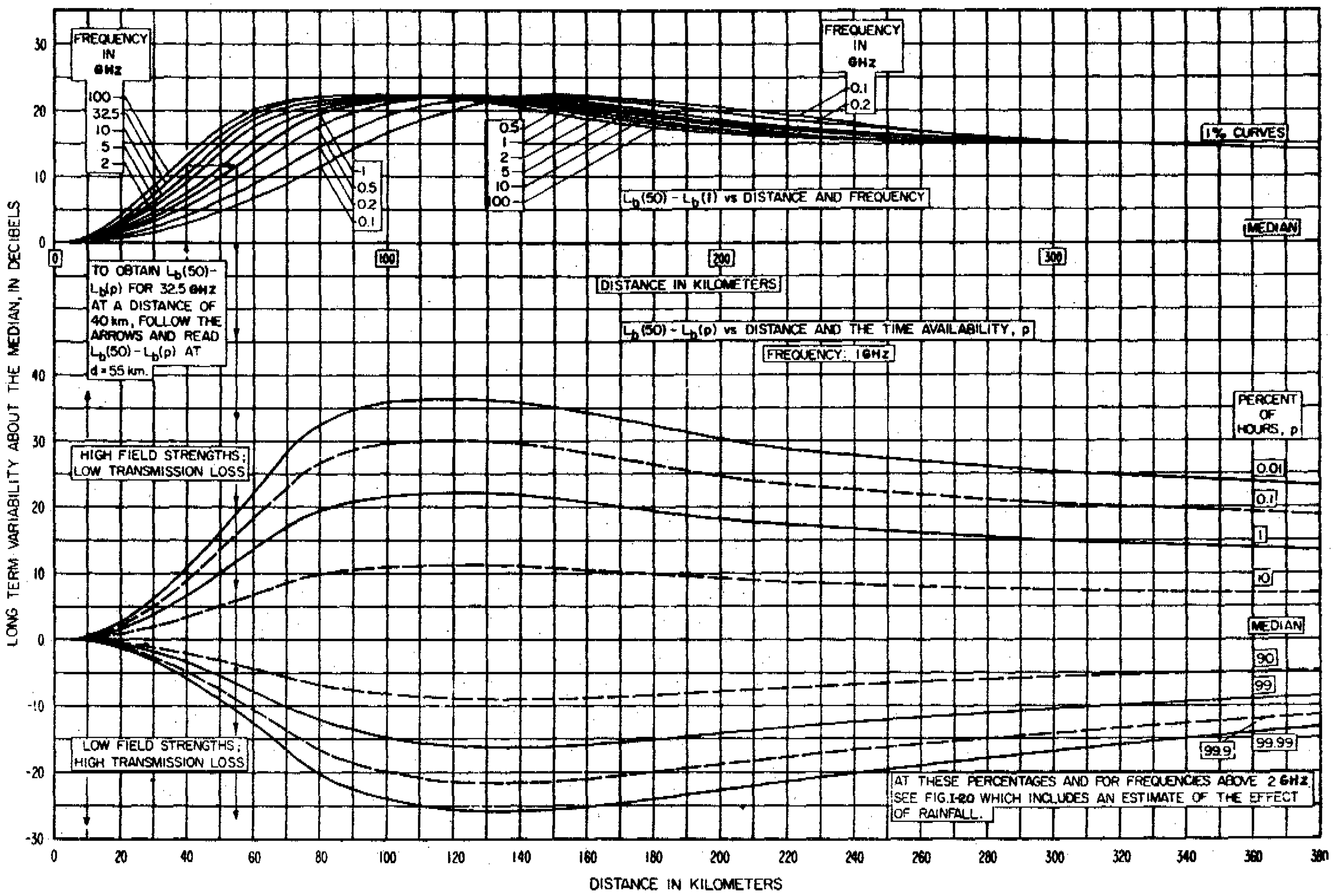


Figure I.19

STANDARD PROPAGATION CURVES

BASIC TRANSMISSION LOSS NOT EXCEEDED FOR 99 AND 99.99 PERCENT OF ALL HOURS
INCLUDING AN ESTIMATE OF ABSORPTION BY RAIN, ASSUMING 100cm TOTAL ANNUAL RAINFALL.
THE CURVES ARE DRAWN FOR FREQUENCIES BETWEEN 5 AND 100 GHz

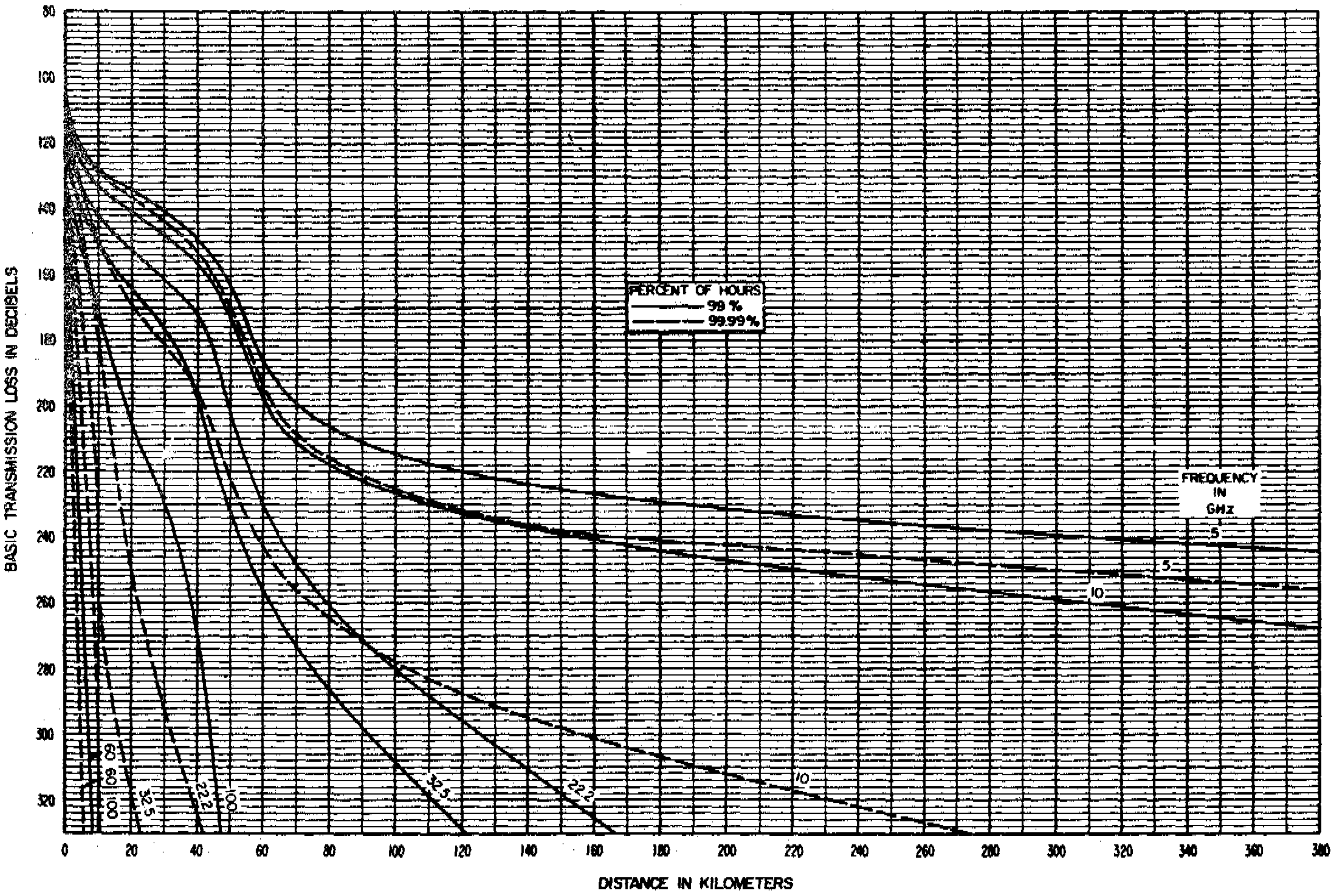


Figure I.20

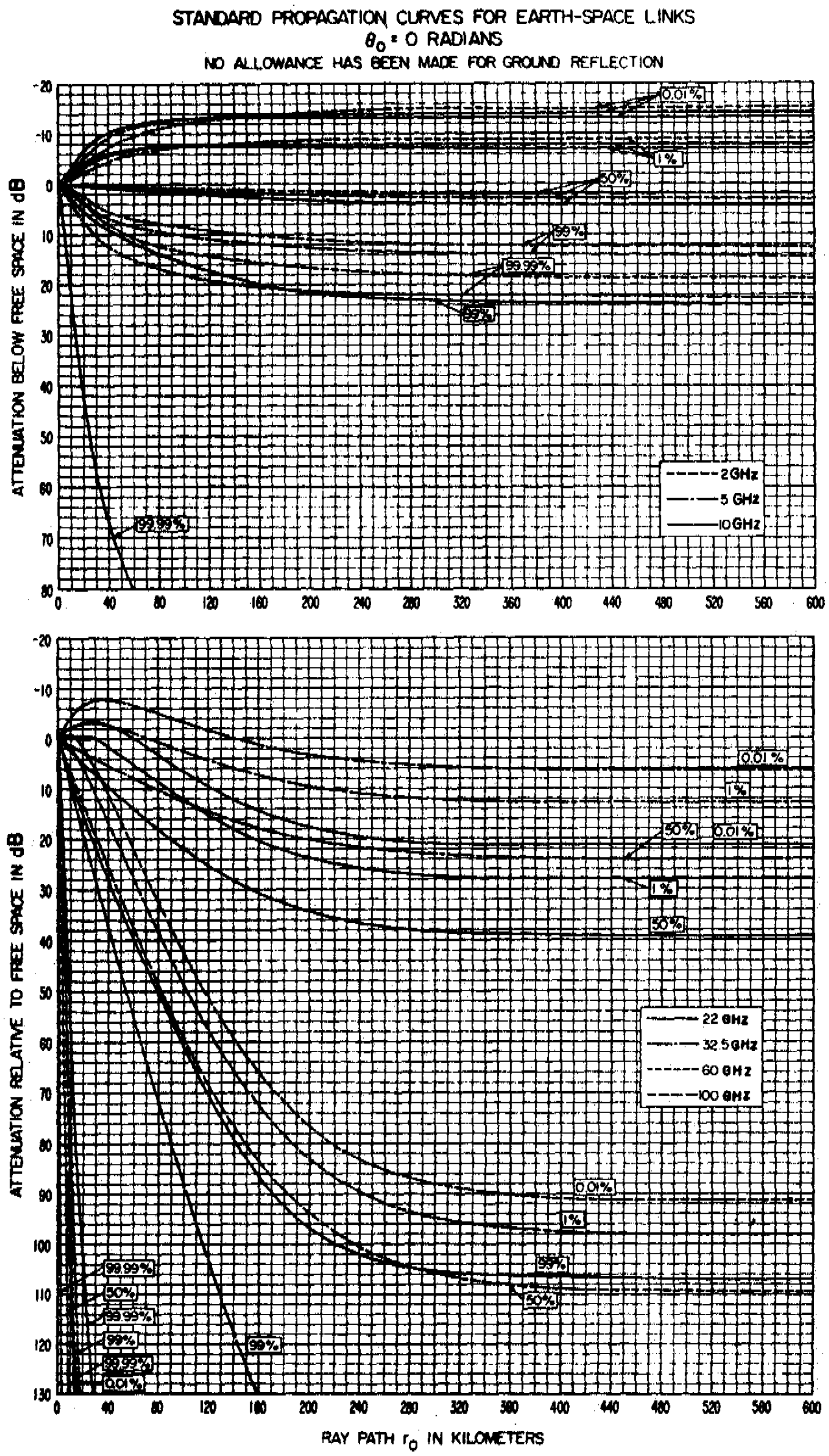
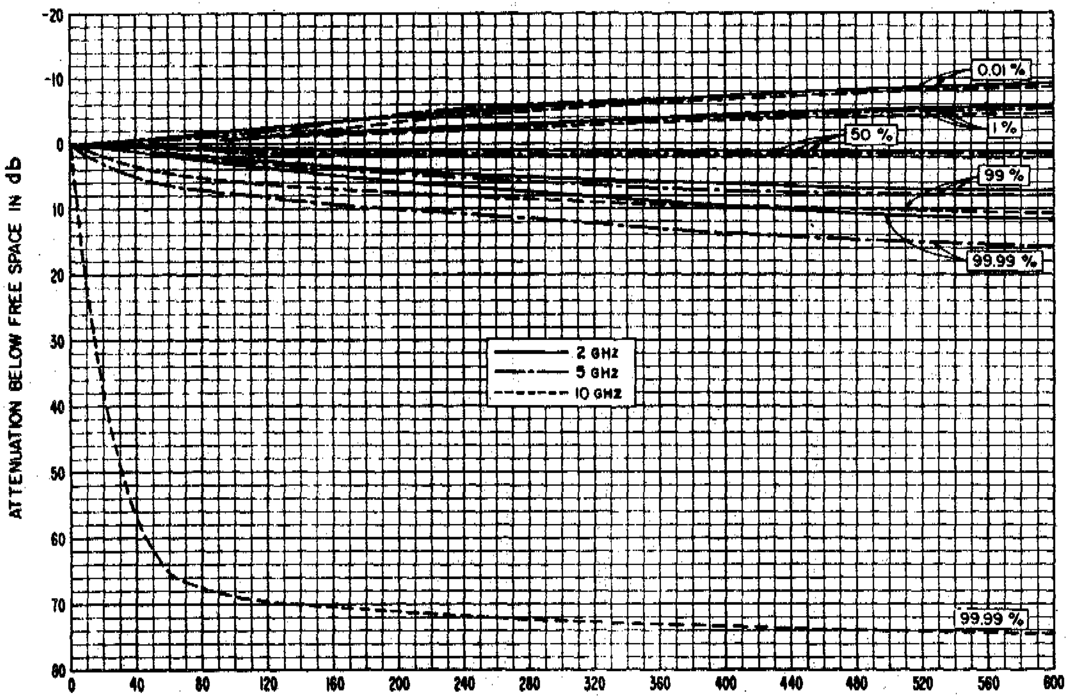

STANDARD PROPAGATION CURVES FOR EARTH-SPACE LINKS
θ_0 = 0 RADIANS
NO ALLOWANCE HAS BEEN MADE FOR GROUND REFLECTION
ATTENUATION BELOW FREE SPACE IN dB
0.01%
1%
50%
99%
99.99%
99%
99.99%
2GHz
5 GHz
10GHz
ATTENUATION RELATIVE TO FREE SPACE IN dB
0.01%
1%
50%
0.01%
1%
50%
22 GHz
32.5 GHz
60 GHz
100 GHz
0.01%
1%
99%
50%
99.99%
50%
99.99%
99%
99.99%
0.01%
99%
RAY PATH r_0 IN KILOMETERS

Figure I.21

STANDARD PROPAGATION CURVES FOR EARTH SPACE LINKS

$\theta_0 = 0.03$ RADIANS

NO ALLOWANCE HAS BEEN MADE FOR GROUND REFLECTION



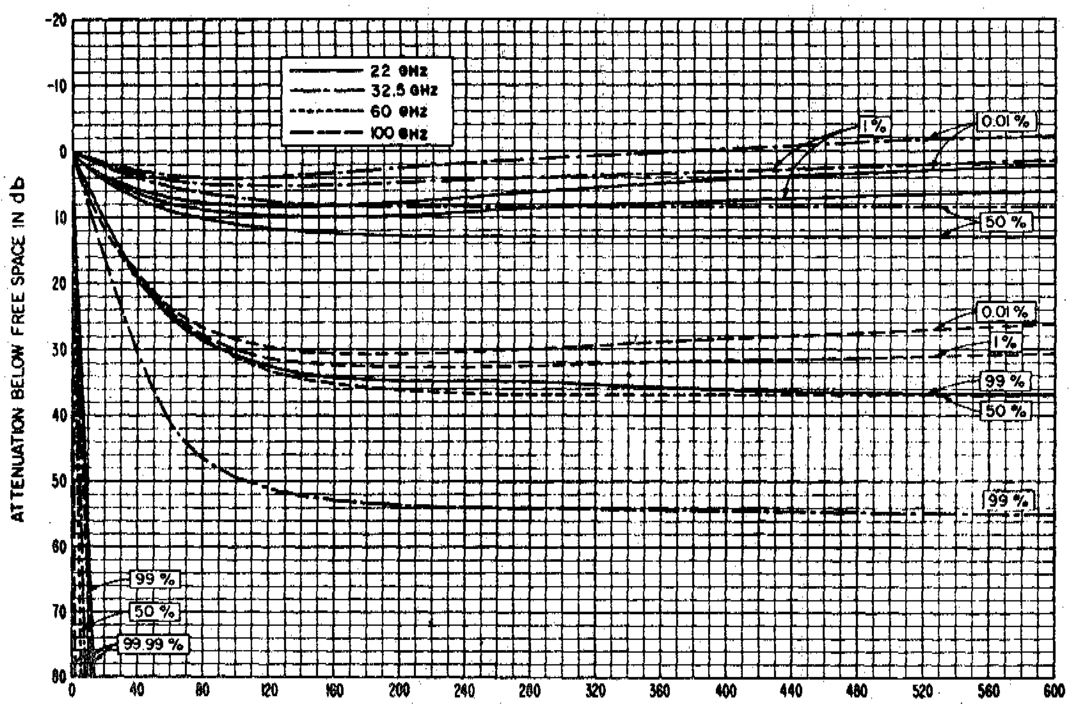


Figure I.22

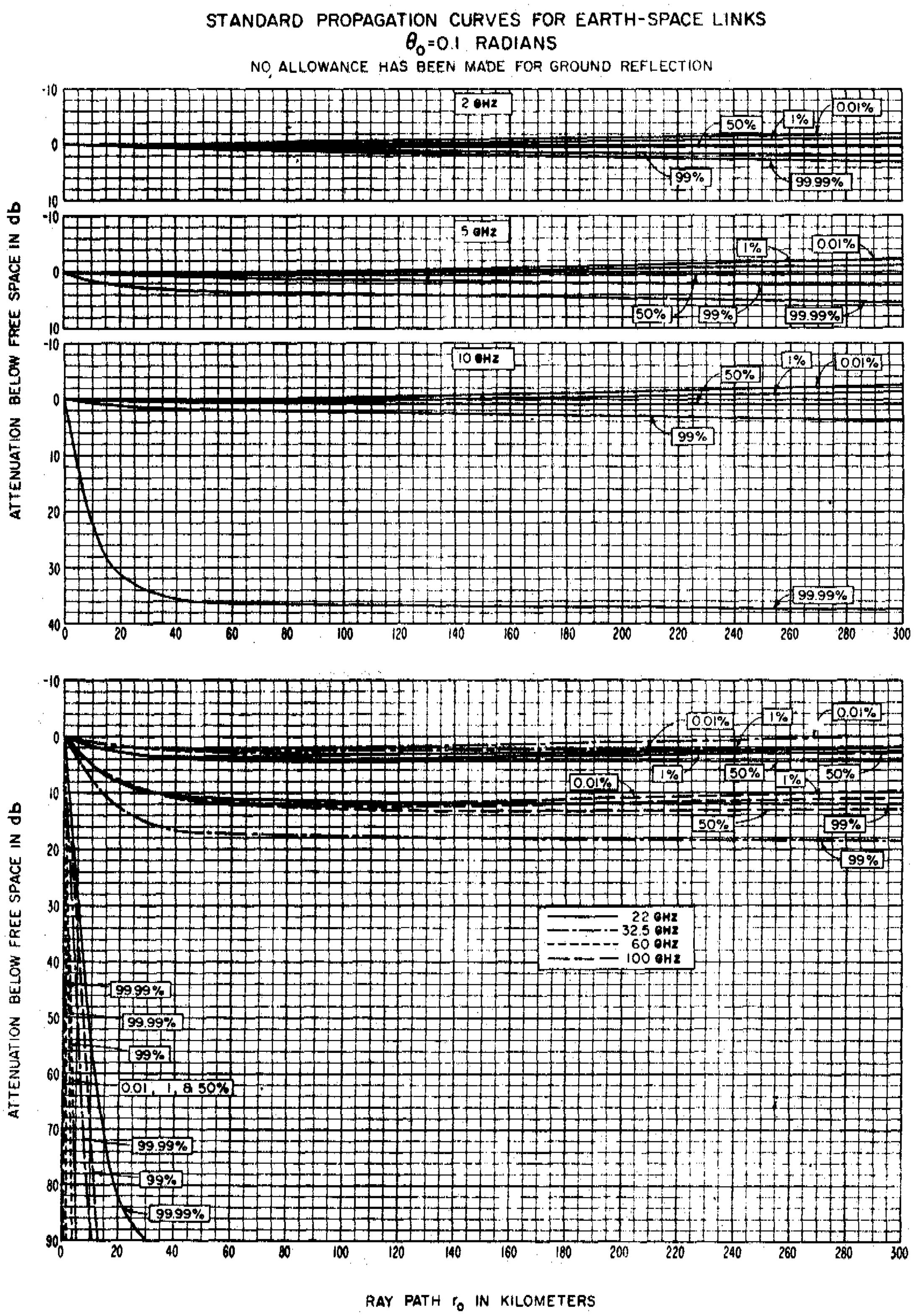

STANDARD PROPAGATION CURVES FOR EARTH-SPACE LINKS
θ_0=0.1 RADIANS
NO ALLOWANCE HAS BEEN MADE FOR GROUND REFLECTION
2 GHz
5 GHz
10 GHz
50%
1%
0.01%
99%
99.99%
0.01, 1, & 50%
22 GHz
32.5 GHz
60 GHz
100 GHz
ATTENUATION BELOW FREE SPACE IN db
RAY PATH r_0 IN KILOMETERS

Figure I.23

STANDARD PROPAGATION CURVES FOR EARTH-SPACE LINKS
θ_0 = 0.3 RADIANS
NO ALLOWANCE HAS BEEN MADE FOR GROUND REFLECTION

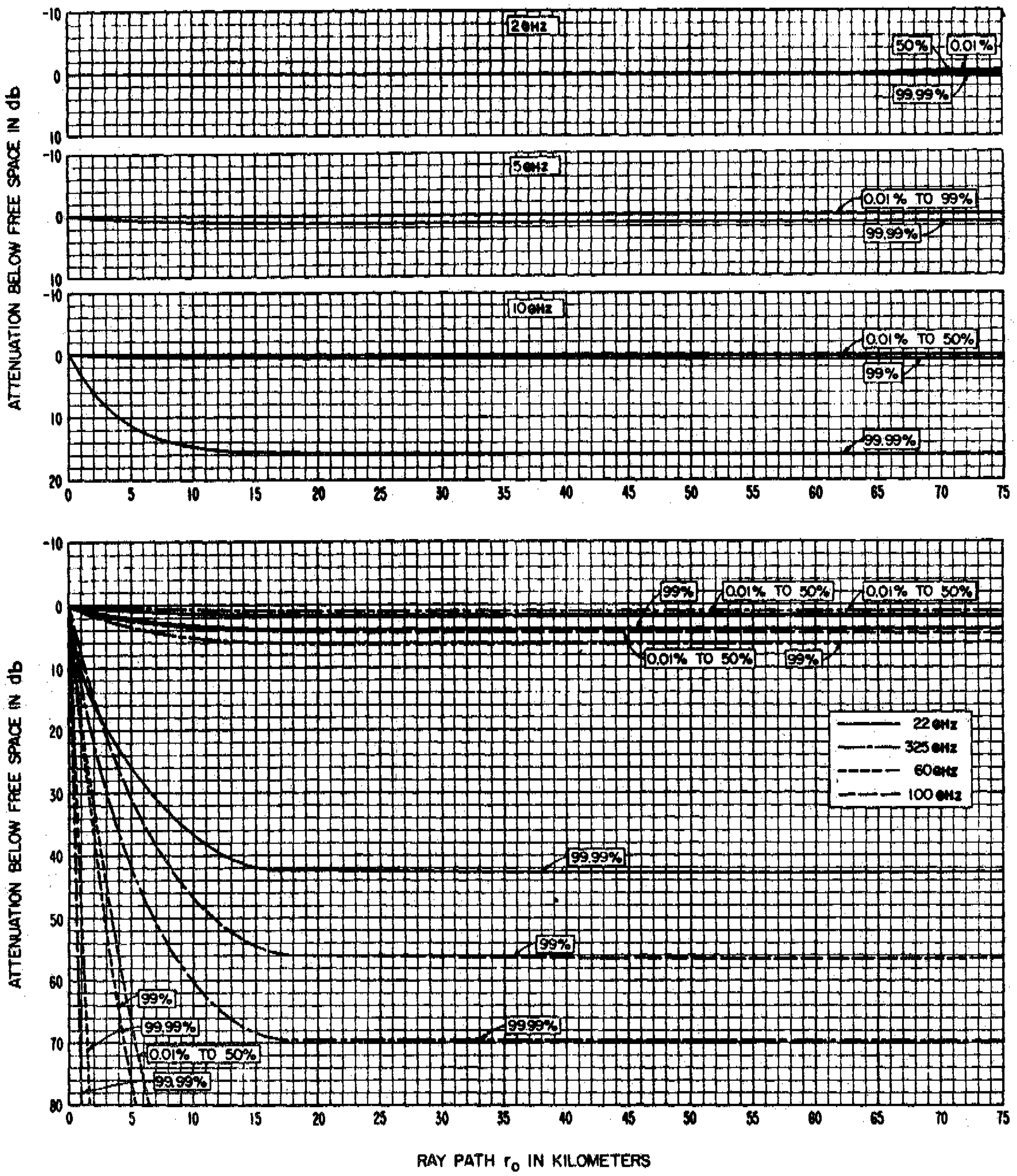


Figure I.24

STANDARD PROPAGATION CURVES FOR EARTH-SPACE LINKS

θ_0 = 1.0 RADIAN

NO ALLOWANCE HAS BEEN MADE FOR GROUND REFLECTION

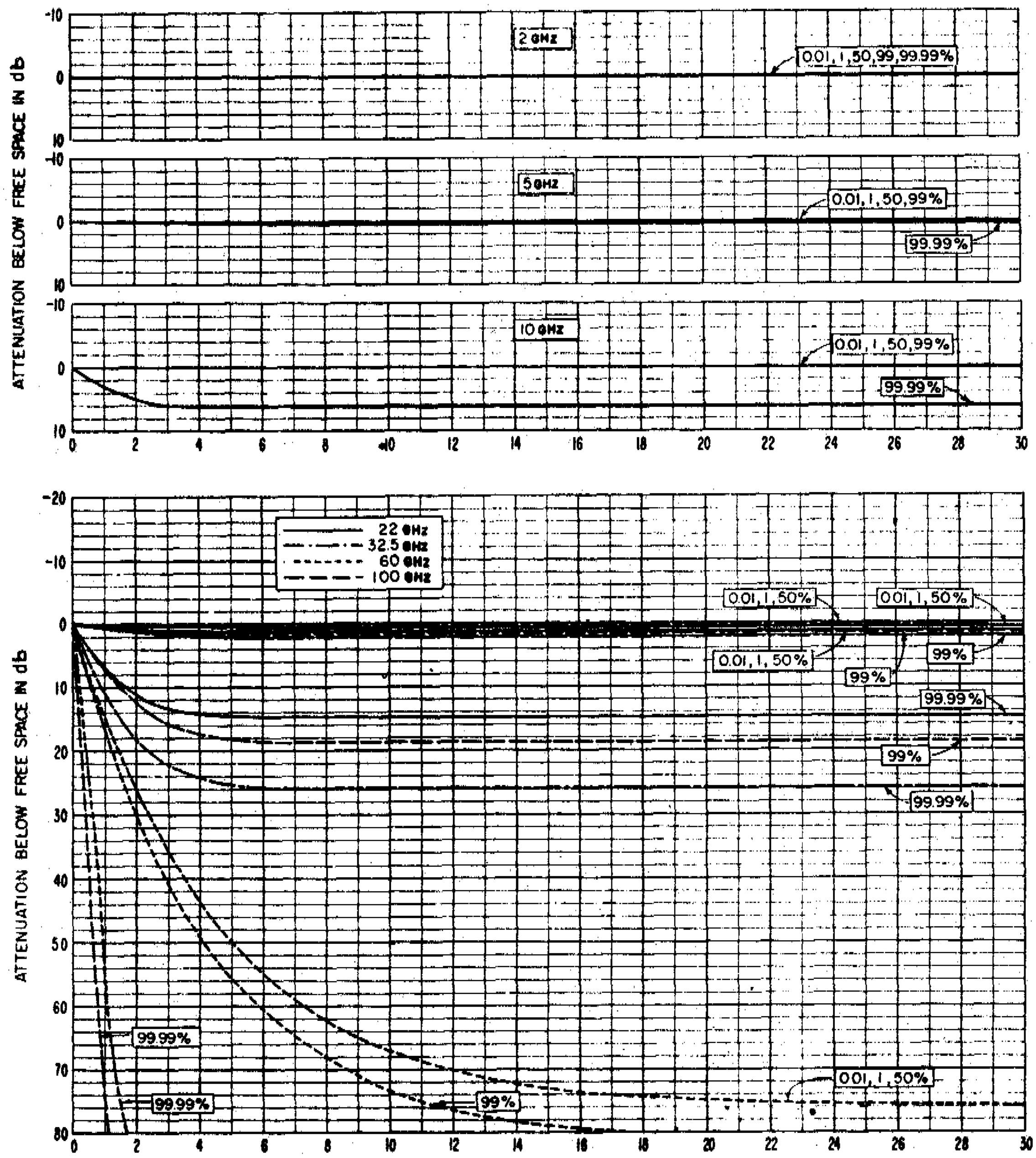


Figure I.25

STANDARD PROPAGATION CURVES FOR EARTH-SPACE LINKS

$\theta_0 = \pi/2$

NO ALLOWANCE HAS BEEN MADE FOR GROUND REFLECTION

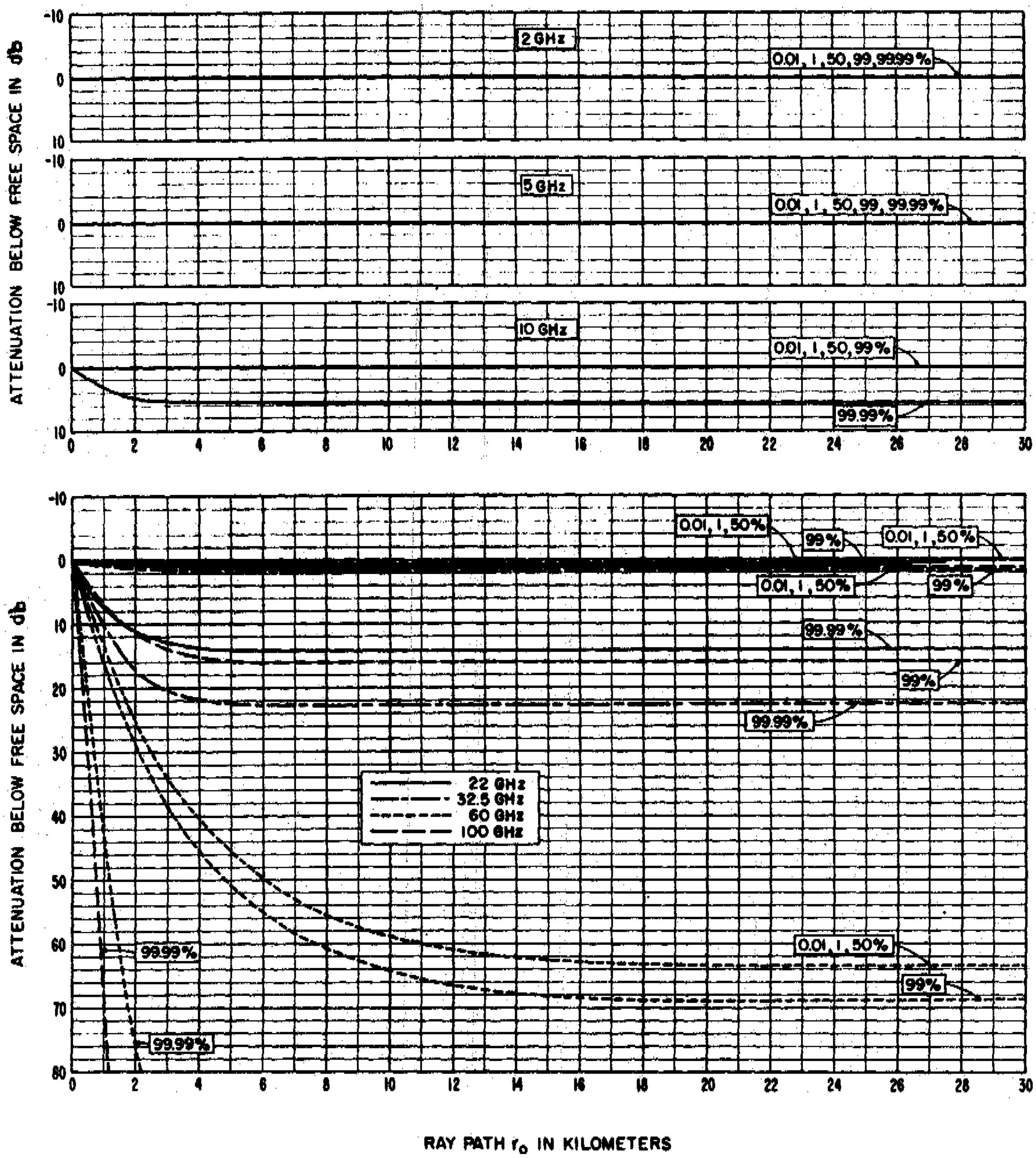


Figure I.26

I.3 Preliminary Reference Values of Attenuation Relative to Free Space, A_{cr}

I.3.1 Introduction

Three main elements of the problem of prediction are the intended application, the characteristics of available data, and the basis of relevant propagation models. The theoretical basis of the model proposed here is simple, and its advantages and limitations are easily demonstrated. Preliminary comparisons with data indicate standard errors of prediction considerably greater than those associated with the specific methods described in volume 1, which are designed for particular applications. However, the method described below is especially useful when little is known of the details of terrain; it may readily be programmed for a digital computer; and it is adequate for most applications where a preliminary calculated reference value A_{cr} of attenuation relative to free space is desired. The minimum prediction parameters required are frequency, path distance, and effective antenna heights. For the other parameters mentioned typical values are suggested for situations where accurate values are not known.

For radio line-of-sight paths the calculated reference value A_{cr} is either a "foreground attenuation" A_f or an extrapolated value of diffraction attenuation A_d, whichever is greater. For transhorizon paths, A_{cr} is either equal to A_d or to a forward scatter attenuation A_s, whichever is smaller.

I.3.2 The Terrain Roughness Factor Δh

Different types of terrain are distinguished according to the value of a terrain roughness factor Δh. This is the interdecile range of terrain heights in meters above and below a straight line fitted to the average slope of the terrain. When terrain profiles are available Δh is obtained by plotting terrain heights above sea level, fitting a straight line by least squares to define the average slope and obtaining a cumulative distribution of deviations of terrain heights from the straight line. Ordinarily Δh will increase with distance to an asymptotic value. This is the value to be used in these computations.

When terrain profiles are not available estimates of Δh may be obtained from the following table:

TABLE I.1

Type of Terrain	Δh (meters)
Water or very smooth terrain	0-1
Smooth terrain	10-20
Slightly rolling terrain	40-60
Hilly terrain	80-150
Rugged mountains	200-500

I. 3. 3 The Diffraction Attenuation A_d

If the earth is smooth $A_d = R$ is computed using the method described in section 8 of volume 1. If the terrain is very irregular, the path is considered as though it were two simple knife edges: a) transmitter-first ridge-second ridge, and b) first ridge-second ridge-receiver. The total diffraction attenuation K is then the sum of the losses over each knife-edge.

$$K = A(v_1, 0) + A(v_2, 0) \tag{I. 1}$$

These functions are defined by (I. 7) to (I. 12).

The main features of a transhorizon propagation path are the radio horizon obstacles, the radio horizon rays and the path distance d, which is greater than the sum d_L of the distances d_{Lt} and d_{Lr} to the radio horizons of the antennas. The diffraction attenuation A_d depends on d, d_{Lt}, d_{Lr}, the minimum monthly mean surface refractivity N_s, the radio frequency f in MHz, the terrain roughness factor Δh, and the sum θ_e of the elevations θ_{et} and θ_{er} of horizon rays above the horizontal at each antenna. The latter parameters may be measured, or may be calculated using (6. 15) of volume 1.

In general, the diffraction attenuation A_d is a weighted average of K and R plus an allowance A_{bs} for absorption and scattering by oxygen, water vapor, precipitation, and terrain clutter:

$$A_d = (1 - \Lambda) K + \Lambda R + A_{bs} \tag{I. 2}$$

where Λ is an empirical weighting factor:

$$\Lambda = \left[1 + 0.045 \left(\frac{\Delta h}{\lambda}\right)^{1/2} \left(\frac{a\,\theta + d_L}{d}\right)^{1/2}\right]^{-1} \tag{I. 3}$$

$$d_L = d_{Lt} + d_{Lr} \quad \text{km} \tag{I. 4}$$

$$\theta = \theta_e + d/a \quad \text{radians,} \tag{I. 5}$$

$$a = 6370/[1 - 0.04665 \exp(0.005577\, N_s)] \tag{I. 6}$$

The angular distance θ is in radians and the wavelength λ is expressed in meters. The parameter $(a\theta + d_L)/d$ in (I.5) is unity for a smooth earth, where $\Delta h/\lambda$ is small and $\Lambda \cong 1$. For very irregular terrain, both $\Delta h/\lambda$ and $(a\theta + d_L)/d$ tend to be large so that $\Lambda \cong 0$.

The following set of formulas used to calculate K and R are consistent with sections 7 and 8, volume 1.

$$v_{1,2} = 1.2915\ \theta\left[f\ d_{Lt,r}\ (d-d_L)/(d-d_L + d_{Lt,r})\right]^{\frac{1}{2}} \tag{I.7}$$

$$A(v,0) = \begin{cases} 6.02 + 9.11\ v - 1.27\ v^2 & \text{for } 0 < v \leq 2.4 \\ 12.953 + 20 \log v & \text{for } v > 2.4 \end{cases} \tag{I.8}$$

$$R = G(x_0) - F(x_1) - F(x_2) - C_1(K_{1,2}) \tag{I.9}$$

$$x_1 = B_{01}\ d_{Lt},\ x_2 = B_{02}\ d_{Lr},\ x_0 = B_{0s}\ D_s + x_1 + x_2 \tag{I.10}$$

$$B_{01} = f^{\frac{1}{3}}\ C_{01}^2\ B_1 \quad B_{02} = f^{\frac{1}{3}}\ C_{02}^2\ B_2 \quad B_{0s} = f^{\frac{1}{3}}\ C_{0s}^2\ B_s$$

$$C_{01} = (8497/a_1)^{\frac{1}{3}} \quad C_{02} = (8497/a_2)^{\frac{1}{3}} \quad C_{0s} = (8497/a_s)^{\frac{1}{3}} \tag{I.11}$$

$$a_1 = d_{Lt}^2/(2\ h_{te}) \quad a_2 = d_{Lr}^2/(2\ h_{re}) \quad a_s = D_s/\theta \tag{I.12}$$

If the path distance d is less than d_3 as given by (I.13), it is advisable to calculate A_d for larger distances d_3 and d_4 and to extrapolate a straight line through the points (A_{d3}, d_3) and (A_{d4}, d_4) back to the desired value (A, d). The following is suggested for d_3 and d_4:

$$d_3 = d_L + 0.5\ (a^2/f)^{\frac{1}{3}}\ \text{km}, \quad d_4 = d_3 + (a^2/f)^{\frac{1}{3}}\ \text{km} \tag{I.13}$$

I.3.4 The Forward Scatter Attenuation, A_s

The scatter attenuation A_s for a transhorizon path depends on the parameters d, N_s, f, θ_e, h_{te}, h_{re} and A_{bs}. If the product θd of the angular distance θ and the distance d is greater than 0.5, the forward scatter attenuation A_s is calculated for comparison with A_d:

$$A_s = \begin{cases} S + 103.4 + 0.332\,\theta d - 10 \log(\theta d) & \text{for } 0.5 < \theta d \le 10 \\ S + 97.1 + 0.212\,\theta d - 2.5 \log(\theta d) & \text{for } 10 \le \theta d \le 70 \\ S + 86.8 + 0.157\,\theta d + 5 \log(\theta d) & \text{for } \theta d \ge 70 \end{cases} \tag{I.14}$$

$$S = H_o + 10 \log(f\theta^4) - 0.1\,(N_s - 301) \exp(-\theta d/40) + A_{bs} \tag{I.15}$$

$$H_o = \left[\frac{1}{h_{te}} + \frac{1}{h_{re}}\right] / \left[\theta f \,|0.007 - 0.058\,\theta|\right] \text{ or}$$

$$H_o = 15 \text{ db, whichever is smaller.} \tag{I.16}$$

The reference attenuation $A_{cr} = A_s$ if $A_s < A_d$.

I.3.5 Radio Line-of-Sight Paths

For line-of-sight paths the attenuation relative to free space increases abruptly as d approaches d_L, so an estimate of d_L is required in order to obtain A_{cr}. For sufficiently high antennas, or a sufficiently smooth earth, (see [I.18]), d_{Lt} and d_{Lr} are expected to equal the smooth earth values d_{Lst} and d_{Lsr}:

$$d_{Lst} = \sqrt{0.002\, a\, h_{te}} \text{ km}, \quad d_{Lsr} = \sqrt{0.002\, a\, h_{re}} \text{ km} \tag{I.17}$$

where a is the effective earth's radius in kilometers and h_{te}, h_{re} are heights in meters above a single reflecting plane which is assumed to represent the dominant effect of the terrain between the antennas or between each antenna and its radio horizon. The effective reflecting plane is usually determined by inspection of the portion of terrain which is visible to both antennas.

For a "typical" or "median" path and a given type of terrain d_{Lt} and d_{Lr} may be estimated as

$$d_{Lt} = d_{Lst}\left[1 \pm 0.9 \exp(-1.5\sqrt{h_{te}/h})\right] \text{ km} \tag{I.18a}$$

$$d_{Lr} = d_{Lsr}\left[1 \pm 0.9 \exp(-1.5\sqrt{h_{re}/h})\right] \text{ km}. \tag{I.18b}$$

If for a median path an antenna is located on a hilltop, the plus sign in the corresponding square bracket in (I.18a) or (I.18b) is used, and if the antenna is behind a hill, the minus sign is used. If $d_L = d_{Lt} + d_{Lr}$ is less than a known line-of-sight path distance d, the estimates (I.18a) and (I.18b) are each increased by the ratio (d/d_L) so that $d_L = d$.

For example, in a broadcasting situation with $h_{te} = 150$ meters, $h_{re} = 10$ meters, and $\Delta h = 50$ meters, (I. 18) using minus signs indicates that $d_{Lt} = 0.97\, d_{Lst}$ and $d_{Lr} = 0.63\, d_{Lsr}$.

For small grazing angles, (5.6) and (5.9) of volume 1 may be combined to describe line-of-sight propagation over a perfectly-conducting smooth plane earth:

$$A = 20 \log \left[\frac{\lambda d \cdot 10^3}{4\pi\, h_{te}\, h_{re}} \right] \text{ db} \tag{I. 19}$$

where d is in kilometers and h_{te}, h_{re}, and the radio wavelength λ are in meters. This formula is not applicable for small values of $\lambda d/(h_{te}\, h_{re})$, where the median value of A is expected to be zero. It is proposed therefore to add unity to the argument of the logarithm in (I. 19).

The expression (I. 19) is most useful when d is large and nearly equal to d_L. Better agreement with data is obtained if d is replaced by d_L and the constant $10^3/(4\pi)$ is replaced by $\Delta h/\lambda$, the terrain roughness factor expressed in wavelengths. Accordingly, the foreground attenuation factor A_f can be written as

$$A_f = 20 \log \left[1 + d_L\, \Delta h/(h_{te}\, h_{re}) \right] + A_{bs} \text{ db.} \tag{I. 20}$$

The absorption A_{bs} defined following (I. 2) is discussed in sections 3 and 5 of volume 1. For frequencies less than 10,000 MHz the major component of A_{bs} is usually due to terrain clutter such as vegetation, buildings, bridges, and power lines.

For distances small enough so that A_f is greater than the diffraction attenuation extrapolated into the line-of-sight region, the calculated attenuation relative to free space A_{cr} is given by (I. 20) and depends only on h_{te}, h_{re}, Δh, A_{bs} and an estimate of d_L. For long line-of-sight paths, the foreground attenuation given by (I. 20) is less than the extrapolated diffraction attenuation A_d, so $A_{cr} = A_d$.

If d_{Lt}, d_{Lr}, and θ_e are known, these values are used to calculate A_d. Otherwise, (I. 18) may be used to estimate d_{Lt} and d_{Lr}, and θ_e is calculated as the sum of a weighted average of estimates of θ_{et} and θ_{er} for smooth and rough earth. For a smooth earth,

$$\theta_{et,\,r} = -0.002\, h_{te,\,re}/d_{Lt,\,r} \text{ radians,}$$

and for extremely irregular terrain it has been found that median values are nearly

$$\theta_{et,\,r} = (\Delta h/2)/(d_{Lt,\,r} \cdot 10^3) \text{ radians.}$$

Using $d_{Lt,\,r}/d_{Lst,\,r}$ and $(1 - d_{Lt,\,r}/d_{Lst,\,r})$ respectively as weights, the following formula is suggested for estimating $\theta_{et,\,r}$ when this parameter is unknown:

$$\theta_{et,r} = \frac{0.0005}{d_{Lst,r}}\left[\left(\frac{d_{Lst,r}}{d_{Lt,r}} - 1\right)\Delta h - 4\, h_{te,re}\right] \text{ radians} \tag{I. 21a}$$

$$\theta_e = \theta_{et} + \theta_{er} \text{ or } \theta_e = -d_L/a, \text{ whichever is larger algebraically,} \tag{I. 21b}$$

As explained following (I. 12), the formulas for A_d require a path distance d greater than d_3. For a line-of-sight path d is always less than d_L, so A_d is calculated for the distances d_3 and d_4 given by (I. 13) and a straight line through the points (A_3, d_3) and (A_4, d_4) is extrapolated back to the desired value (A, d). This straight line has the formula

$$A_d = A_e + M d \quad \text{db} \tag{I. 22}$$

where

$$M = (A_{d_4} - A_{d_3})/(d_4 - d_3) \quad \text{db/km} \tag{I. 23}$$

$$A_e = A_{d4} - M d_4 \quad \text{db.} \tag{I. 24}$$

The straight line given by (I. 22) intersects the level A_f where the path distance is

$$d_f = (A_f - A_e)/M \quad \text{km.} \tag{I. 25}$$

$$\text{For } d \le d_f, \quad A_{cr} = A_f. \tag{I. 26a}$$

$$\text{For } d > d_f, \quad A_{cr} = A_d. \tag{I. 26b}$$

I. 3. 6 Ranges of the Prediction Parameters

These estimates of A_{cr} are intended for the following ranges of the basic parameters:

TABLE I. 2

$20 \le f \le 40{,}000$ MHz	$1 \le d \le 2000$ km
$\lambda/2 \le h_{te,re} \le 10{,}000$ m	$250 \le N_s \le 400$
$-d_L/a \le \theta_e \le 0.2$ radians	$0 \le A_{bs} \le 50$ db
$0.1\, d_{Lst} \le d_{Lt} \le 3\, d_{Lst}$	$0.1\, d_{Lsr} \le d_{Lr} \le 3\, d_{Lsr}$
$0 \le \Delta h \le 500$ m	

I.3.7 Sample Calculations

Table I.3 lists a set of sample calculations referring to the example introduced after Table I.1. Values for the following independent parameters are assumed: h_{te} = 150 m, h_{re} = 10 m, Δh = 50 m, N_s = 301, f = 700 MHz. d_{Lt} = 49.0 km, d_{Lr} = 8.2 km, θ_e = -0.00634 radians, A_{bs} = 0 db. An appropriate equation number is listed in parentheses after each of the calculated parameters in Table I.3. For these calculations the arbitrary distance d_3 was set equal to $d_L + 1$ instead of $d_L + 0.3(a^2/f)^{\frac{1}{3}}$

TABLE I.3

d_L = 57.2 km	(I.4)	a = 8493 km	(I.6)
$\Delta h/\lambda$ = 116.8		A_f = 9.3 db	(I.20)
d_3 = 58.2 km		d_4 = 105.1 km	(I.13)
θ_3 = 0.000514 rad.		θ_4 = 0.00603 rad.	(I.5)
v_3 = 0.096		v_4 = 1.95	(I.7)
v_{13} = 0.0174		v_{14} = 1.014	(I.8)
v_{23} = 0.0166		v_{24} = 0.546	(I.8)
$v_3\ \rho_3$ = 0.10		$v_4\ \rho_4$ = 1.87	(I.9)
ρ_3 = 1.04		ρ_4 = 0.96	(I.9)
$A(v_3, 0)$ = 6.9 db		$A(v_4, 0)$ = 18.9 db	(I.10)
$A(v_{13}, 0)$ = 6.2 db		$A(v_{14}, 0)$ = 14.0 db	(I.10)
$A(v_{23}, 0)$ = 6.2 db		$A(v_{24}, 0)$ = 10.6 db	(I.10)
$A(0, \rho_3)$ = 16.0 db		$A(0, \rho_4)$ = 14.7 db	(I.11)
$U(v_3, \rho_3)$ = -.9 db		$U(v_4, \rho_4)$ = 14.7 db	(I.12)
K_3 = 12.4 db		K_4 = 24.6 db	(I.6)
R_3 = 18.1 dB		R_4 = 55.3 db	(I.5)
$\frac{a\ \theta_3 + d_L}{d_3}$ = 1.058		$\frac{a\ \theta_4 + d_L}{d_4}$ = 1.032	
Λ_3 = 0.667		Λ_4 = 0.669	(I.3b)
A_{d_3} = 29.5 db		A_{d_4} = 58.5 db	(I.3a)
$d_3\ \theta_3$ = 0.0299		$d_4\ \theta_4$ = 0.634	
		H_{04} = 3.8 db	(I.16)
		S_4 = -56.5 db	(I.15)
		A_{S4} = 49.1 db	(I.14)
A_{cr_3} = 29.5 db		A_{cr_4} = 49.1 db	

For this example, M = 0.619 db/km, A_e = -6.49 db, and d_f = 25.5 km. The corresponding basic transmission loss L_{bcr} and field strength E_{bcr} for distances less than d_f are 98.65 + 20 log d db and 97.62 - 20 log d db, respectively, corresponding to a constant value A_{cr} = A_f = 9.3 db. In general:

$$L_{bcr} = 32.45 + 20 \log d + 20 \log f + A_{cr} \quad \text{db} \tag{I.27}$$

$$E_{bcr} = 106.92 - 20 \log d - A_{cr} \quad \text{db} \tag{I.28}$$

For the example given above, $L_{bcr_3} = 154.2$ db, $L_{bcr_4} = 178.9$ db, $E_{bcr_3} = 42.1$ db, and $E_{bcr_4} = 17.4$ db.