NTIA REPORT 89-242

HANDBOOK OF RADIO WAVE PROPAGATION LOSS, PART II (100 - 20,000 MHz)

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FOREWORD

The NLAMBDA Ground Wave Model, a computerized propagation prediction model, was used to calculate the propagation loss values in this document. The methods in the model predict the median value of radio wave propagation loss at far field distances over a smooth spherical earth for the line-of-sight modes of surface wave, free space, and multipath; and for the beyond-line-of-sight modes of smooth earth diffraction and tropospheric scatter. The program includes routines that automatically select the appropriate propagation mode, based on input parameters and path geometry. The NLAMBDA model was developed using propagation methods described in CCIR Study Group 5, Volume V entitled "Propagation in a Non-Ionized Media." The fundamental propagation methodologies used in the NLAMBDA model and a similar Ground Wave Propagation (GRWAVE)[1] model are similar except the NLAMBDA model includes the tropospheric forward scatter mode. The following lists reference CCIR Study Group 5 documents describing the propagation methods incorporated in the NLAMBDA model:

Recommendation 310 - Definitions of Terms Relating to Propagation in the Troposphere
Recommendation 341 - The Concept of Transmission Loss for Radio Links
Recommendation 369 - Reference Atmosphere for Refraction
Recommendation 453 - The Formula for Radio Refractive Index
Recommendation 525 - Calculation of Free Space Attenuation
Recommendation 526 - Propagation by Diffraction
Recommendation 527 - Electrical Characteristics of the Surface of the Earth
Recommendation 530 - Propagation Data Required for Design of Tropospheric-Scatter Trans-Horizon Radio Relay Systems and Earth-Space Telecommunication Systems
Report 229 - Electrical Characteristics of the Surface of the Earth
Report 238 - Propagation Data Required for Trans-Horizon Radio-Relay Systems
Report 563 - Radiometeorological Data
Report 714 - Ground-wave Propagation in an Exponential Atmosphere

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[1] CCIR Report 714-1, "Ground-wave Propagation in an Exponential Atmosphere," Volume V, Propagation in Non-Ionized Media, XVIth Plenary Assembly, Dubrovnik, Poland, 1986.

Report 717 - World Atlas of Ground Conductivities
Report 719 - Attenuation by Atmospheric Gases
Report 878 - Special Features of the Concept of Transmission Loss in the Ground-Wave Propagation Case

ACKNOWLEDGMENT

Special appreciation is expressed for the efforts of Robert Wilson (NTIA) for applying the NLAMBDA computer model for calculating the transmission loss values, for applying graphics programs for preparing the curves and graphs included in this report, and for providing suggestions that were helpful in completing this task.

ABSTRACT

This handbook is intended to provide estimates of radio wave propagation loss between transmitting and receiving antennas of various heights and transmission frequencies above the assumed smooth-earth surface calculated using the NLAMBDA computer model. For many cases involving electromagnetic compatibility analysis, the curves of predicted transmission losses in this report may be used to estimate the transmission losses of the desired and undesired signals. These estimated loss values are given in dB as BASIC MEDIAN TRANSMISSION LOSS for antennas with effective heights up to 5000 meters, operating in the 100 to 20,000 MHz frequency range, over land or sea, at great circle earth surface distances up to 1000 kilometers. This handbook is an expanded version of the initial handbook[2] and includes curves for the additional frequencies of 500 MHz, 2000 MHz, 5000 MHz, 7000 MHz, and 20,000 MHz.

KEY WORDS

Basic Median Transmission Loss
Electromagnetic Compatibility
Radio Wave Propagation
Transmission Loss

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[2] Frazier, William E., Handbook of Radio Wave Propagation Loss (100-10000 MHz), NTIA Report TR-84-165, National Telecommunications and Information Administration, Washington, DC, December 1984, (NTIS-PB-85-200012).

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INTRODUCTION

BACKGROUND

The National Telecommunications and Information Administration (NTIA) is responsible for managing the Federal Government's use of the radio frequency spectrum. NTIA's responsibilities include establishing policies concerning spectrum assignment, allocation and use, and providing the various departments and agencies with guidance to ensure that their conduct of telecommunications activities is consistent with these policies.[3] In support of these requirements, NTIA periodically develops aids to assist in spectrum engineering and analysis techniques. This handbook provides estimates of radio wave far field propagation loss between transmitting and receiving antennas above the assumed smooth surface of the earth using the NLAMBDA ($N\lambda$) computer model. The objective of this handbook is to assist in the manual analysis techniques that must be used when an automated analysis is not possible. This handbook is an expanded version of the initial handbook (see reference 2) and includes curves for the additional frequencies of 500 MHz, 2000 MHz, 5000 MHz, 7000 MHz, and 20,000 MHz.

SCOPE

The curves in this handbook provide estimates of radio wave propagation loss between transmitter and receiver terminals elevated above the assumed smooth surface of the earth. The NLAMBDA ($N\lambda$) computer model was used to calculate or predict all transmission loss values.[2,4,5] These $N\lambda$ computer

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[3] NTIA, Manual of Regulations and Procedures for Federal Radio Frequency Management, National Telecommunications and Information Administration, Washington, DC, Revised January 1989.

[4] NTIS, National Technical Information Service, Master Propagation Systems (MPS11) User's Manual, NTIS-PB83-178624, (Computer Tape NTIS-PB83-173971), 1983.

[5] Maiuzzo, M.A. and W.E. Frazier, A Theoretical Groundwave Propagation Model - $N\lambda$ Model, ESD-TR-68-315, DOD ECAC, Annapolis, MD, December 1968.

model predictions were plotted using a graphics program and a computer-controlled plotter. The values are given in dB, as BASIC MEDIAN TRANSMISSION LOSS, L_{bm}, as defined in Section 3. This terminology is based on the assumption that the transmitting and receiving antennas are isotropic and that the predicted loss is the median (50%) value in dB. An isotropic antenna is a theoretical point source that radiates equally in all directions.

The BASIC MEDIAN TRANSMISSION LOSS predictions are for antennas, up to 5000 meters in height, operating in the 100-20,000 MHz frequency range over great-circle distances up to 1000 kilometers. The antenna heights are "effective antenna heights" above the smooth surface of the earth. Effective antenna heights are discussed in detail later. All predictions are based on vertically polarized transmissions over a homogeneous earth surface, having electrical parameters of either sea water or average land, and a sea level value of refractivity of N_0=301. Sea water is typical of ocean water, having a high salt content that results in a good conducting surface along the transmission path. Average land is assumed to have a moisture content that results in a conductivity characteristic of soil that is neither too moist nor too dry. The conductivity and relative permittivity (dielectric constant) values for sea water and average land assumed in this report are given below in TABLE 1.

TABLE 1

PATH SURFACE ELECTRICAL PARAMETERS

SURFACE	CONDUCTIVITY	RELATIVE PERMITTIVITY
Sea Water	4.64 mhos/meter	81
Average Land	0.005 mhos/meter	15

Transmission paths are assumed to be over a smooth spherical earth with an effective earth radius adjusted to compensate for ray bending at low-to-medium antenna elevations. An exponential reference atmospheric model was used to compensate for ray bending at high antenna elevations.

The transmission loss curves may be used to estimate the signal level (field strength or power density) at the receiver antenna. The curves are based on a median signal level which occurs 50 percent of the time. This is most representative of the desired signal. In an interference situation, there is an interference signal (undesired signal), that is present less than 50 percent of the time. When the transmission loss curves are used for predicting transmission loss for the interference signal, the loss values should be adjusted for a lower probability of occurrence. For example, undesired signal levels due to ducting propagation (not considered in the NLAMBDA Model) occur less than 10 percent of the time and may be 10 dB higher (or more) than the median value obtained from the curves.

Effects of terrain roughness, vegetation, fading relative to the median loss, and tropospheric ducting are not included in the transmission loss curves. References are given for methods and data that may be used to estimate these effects relative to the transmission loss in this handbook.

Figure 1 illustrates the association between smooth-earth-path geometry and the propagation modes represented by the transmission loss curves. The lower part of Figure 1 shows the profile geometry of a smooth-earth path between two antennas. The upper part of Figure 1 shows the transmission loss relative to the path profile given in the lower part of the figure. On the profile, the antennas are separated by a distance that is equal to the smooth-earth radio line-of-sight (LOS) distance. This is the maximum distance at which the radio waves will be unobstructed by the curved surface of the earth for the specified antenna heights. The radio LOS distance is greater than the optical LOS distance on earth in a normal atmosphere for the specified antenna heights. Figure 1 shows that the maximum path distance where the free-space loss is less than the smooth earth loss for specified antenna heights is less than the radio LOS distance. The curve in the upper part of Figure 1 shows that, at short distances, the transmission loss is due to free space or multipath, and at long distances, the transmission loss is due to diffraction or tropospheric scatter. At path lengths less than the maximum free-space-loss distance, reflections from the smooth earth may cause multipath fading as indicated in Figure 1. The smooth earth curves in this handbook do not show the multipath lobes since they follow the peak envelope of the multipath lobes and thus, the transmission loss at short distances is shown to be slightly less than the free-space loss.

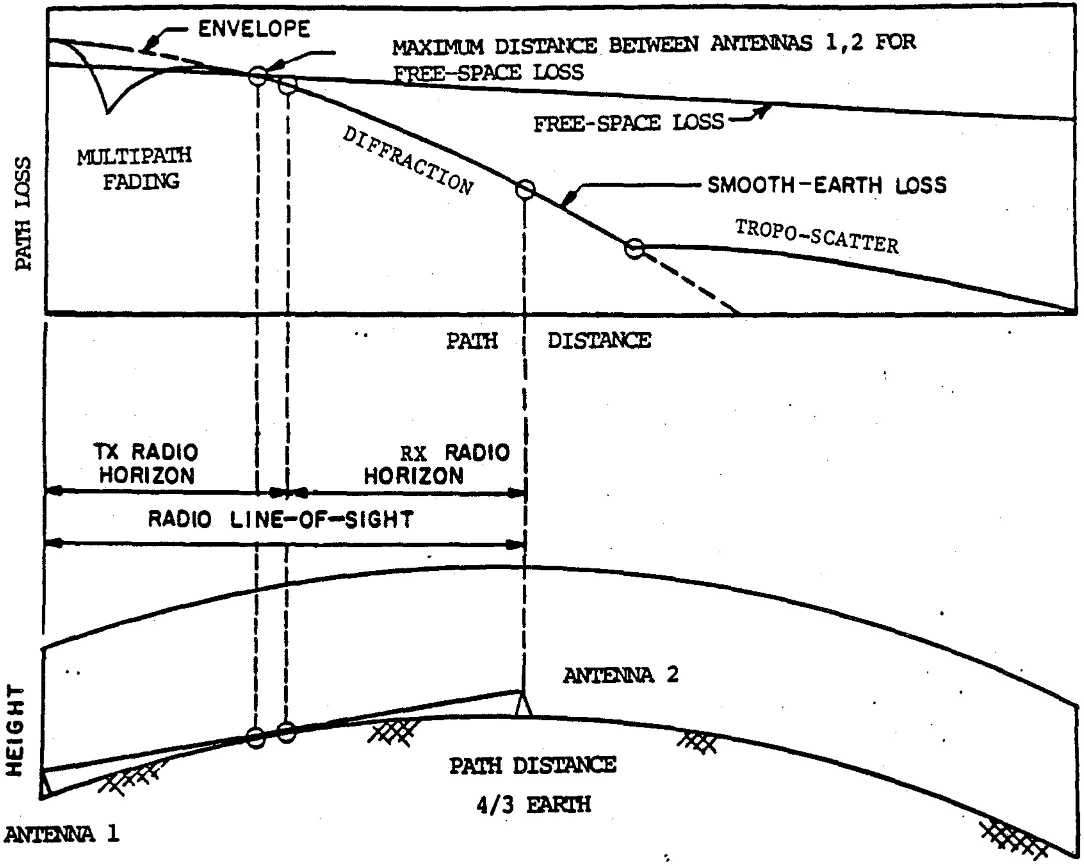

Figure 1. Transmission loss and path geometry.

BASIC MEDIAN TRANSMISSION LOSS CURVES

The basic transmission loss curves in Appendix A are plotted on standardized format graphs as shown in Figures 2a and 2b. All the curves are done on two-cycle semilog graph paper, with the ordinate giving basic median transmission loss, in dB, and the abscissa giving the great-circle distance, in kilometers, along the surface of the earth between the transmitter and receiver antenna sites. The straight line on each graph is the Free-Space Transmission Loss. This is the loss determined by the given frequency and distance in free space, which does not include the effects of the earth or of antenna heights. The other curves give the Smooth-Earth Transmission Loss. This loss includes the effects of a smooth spherical earth and is the value that should be used for the frequency, distance, and effective antenna heights given. All the figures in this handbook have a standardized and abbreviated summary of the parameters under the figure. These standardized abbreviations of the parameters include the transmission frequency,(f), in MHz; one antenna height (h_1), in the meters; the other antenna height (h_2), in meters; V.P. for vertical polarization; and the path surface type (sea water and or land). Note that the path transmission loss will be the same regardless of which antenna is identified as the transmitter or receiver.

All graphs have smooth earth loss curves for vertical polarization (VP) over sea water and land, however, only the first eight graphs, A-1 through A-8, show separate curves for sea water and land similar to the curves in Figure 2a. This is because the curves for sea water and land are different for graphs A-1 through A-8, while the sea water and land curves on graphs A-9 through A-79 are identical.

The graphs A-9 through A-79 have multiple smooth earth curves that represent h_2 antenna heights from 10 m to 5000 m similar to the curves in Figure 2b. In order to include all of the h_2 heights on the curves in the abbreviated summary of parameters under the graph, the words land, sea water, and VP have been replaced with h_2 heights for the curves on the graph. Please note that all the curves on all of the graphs A-9 through A-79 are for both land and sea water, and Vertical Polarization (VP).

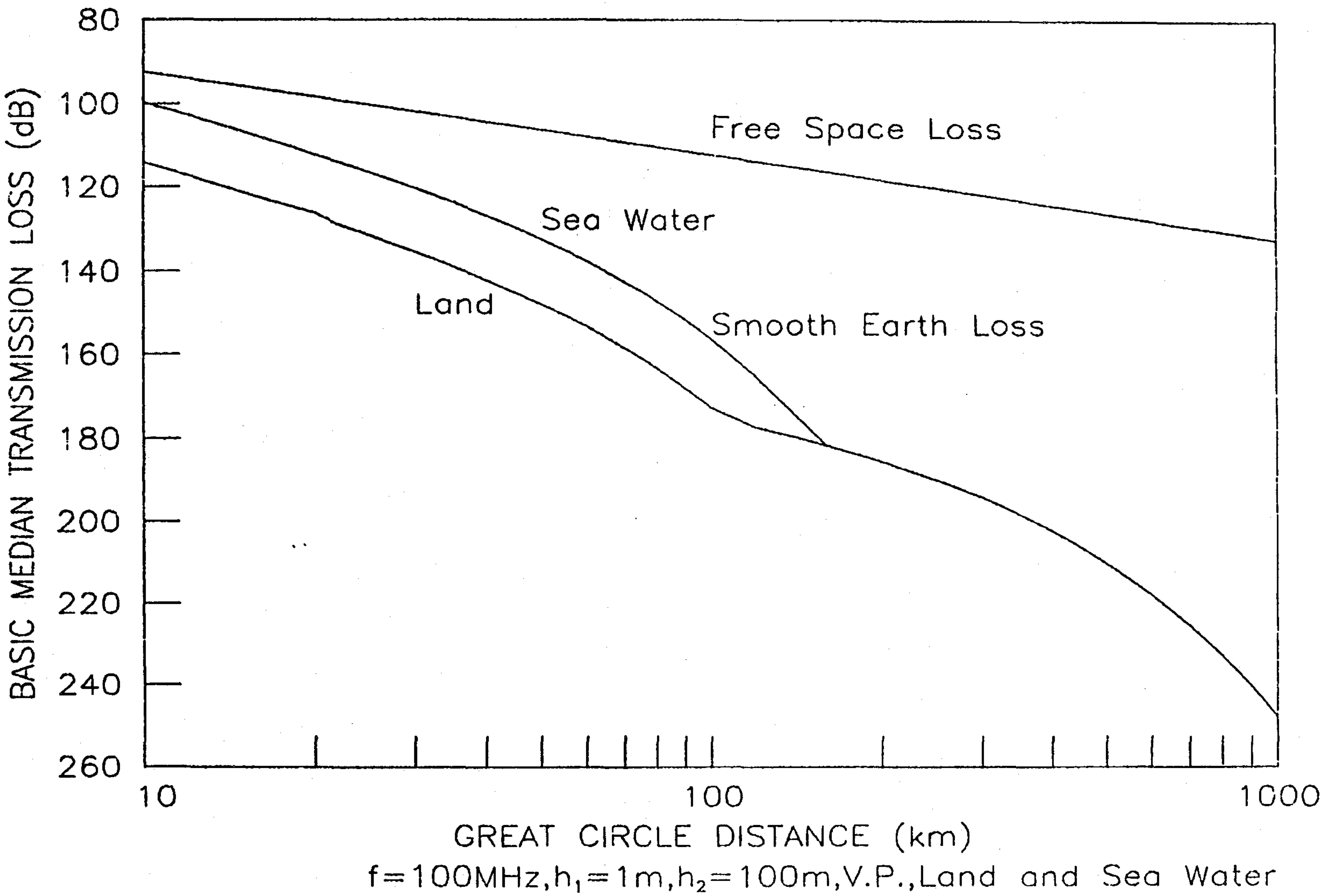

Figure 2a. Sample format of transmission loss curves.

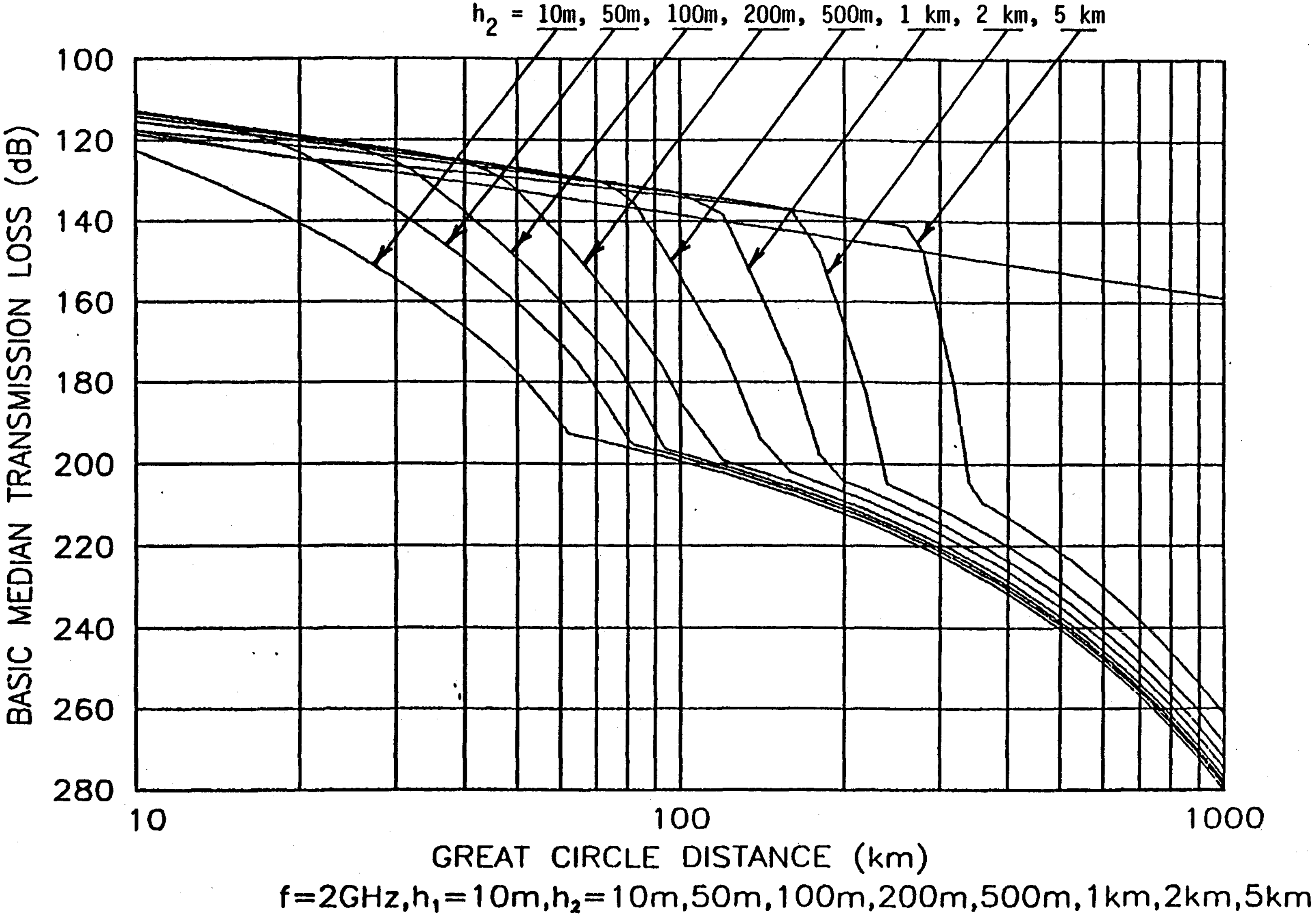

Figure 2b. Sample format of transmission loss curves with multiple curves.

An appropriate interpolation procedure should be used to estimate intermediate values of transmission loss from the curves in APPENDIX A for frequency and antenna heights that are different from those on the curves, but within the range of parameter values on the curves.

EFFECTIVE ANTENNA HEIGHTS

An effective antenna height is the height of the center of radiation of the antenna above the average terrain elevation along the transmission path. The effective antenna height should not be less than the structural antenna height. The structural antenna height is the height of the center of radiation of the antenna above the local site elevation. The input antenna heights to the Nλ model must be the effective antenna heights in order to obtain a valid prediction from the model. Therefore, in order to utilize transmission loss values from the curves, the antenna heights on the curves must be representative of the effective antenna heights for the transmission path.

Figures 3 and 4 are illustrated examples of effective antenna heights and the transmission loss prediction errors that could result from using incorrect effective heights. Figure 3 shows two different transmission path geometries although both have structural antenna heights of 50 meters at each end of the path. Path A has the 50-meter structural antennas located on local terrain elevations of 500 meters, while the average terrain elevation along the path for the left antenna site is 60 meters, and for the right antenna, the average elevation is 20 meters. For this example, these average terrain elevations of 60 km and 20 km are determined for the terrain along the path from 2 km to 10 km along the path from each antenna. For the left antenna, the center of radiation is 550 meters from sea level and 490 meters above the average terrain at the end of the path. Similarly, the right antenna height is 550 meters above sea level and 530 meters above the average terrain elevation at the end of the path. The effective antenna heights for the upper path are thus, 490 meters and 530 meters.

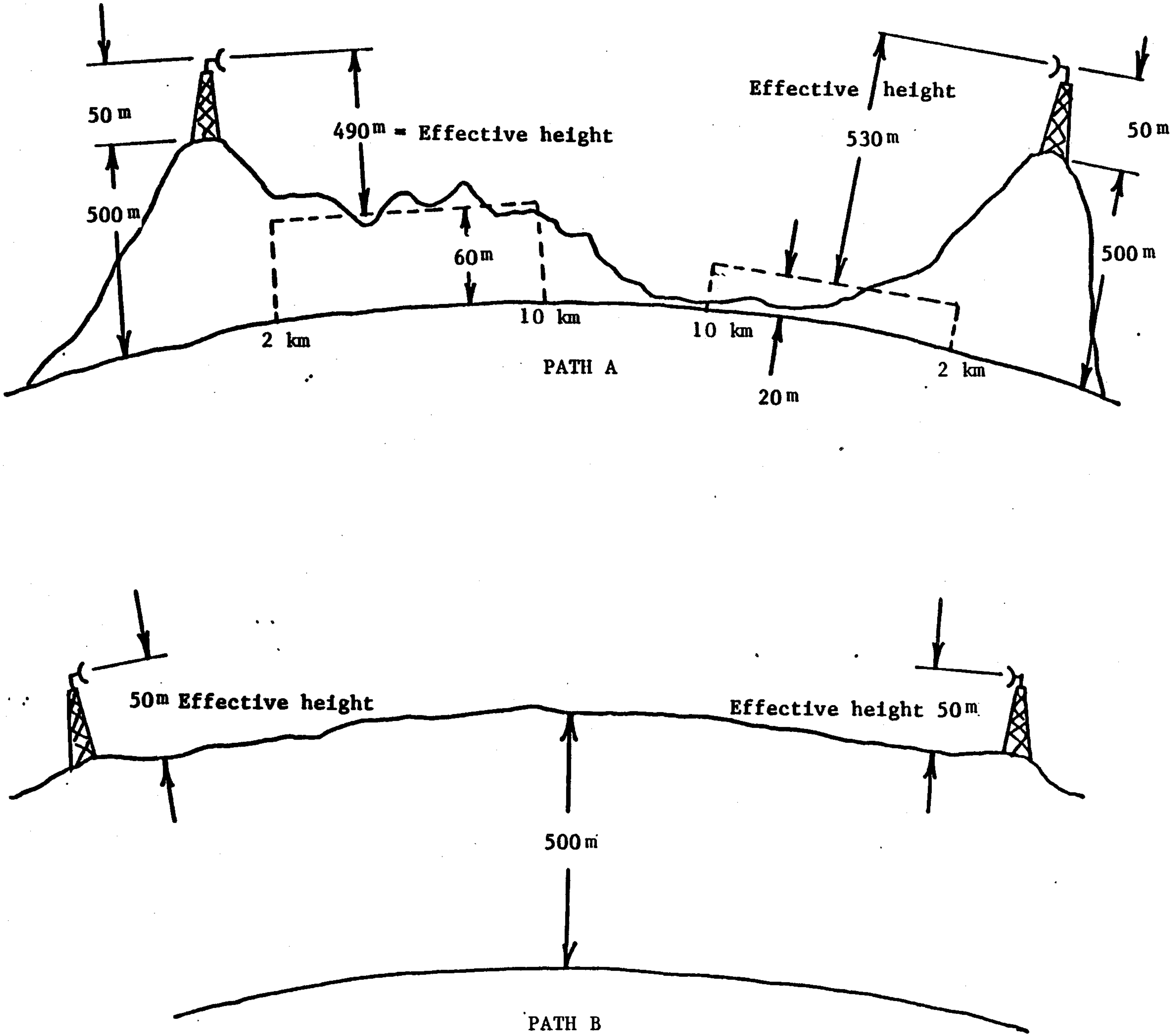

Figure 3. Example of different effective antenna heights for the same structural antenna heights.

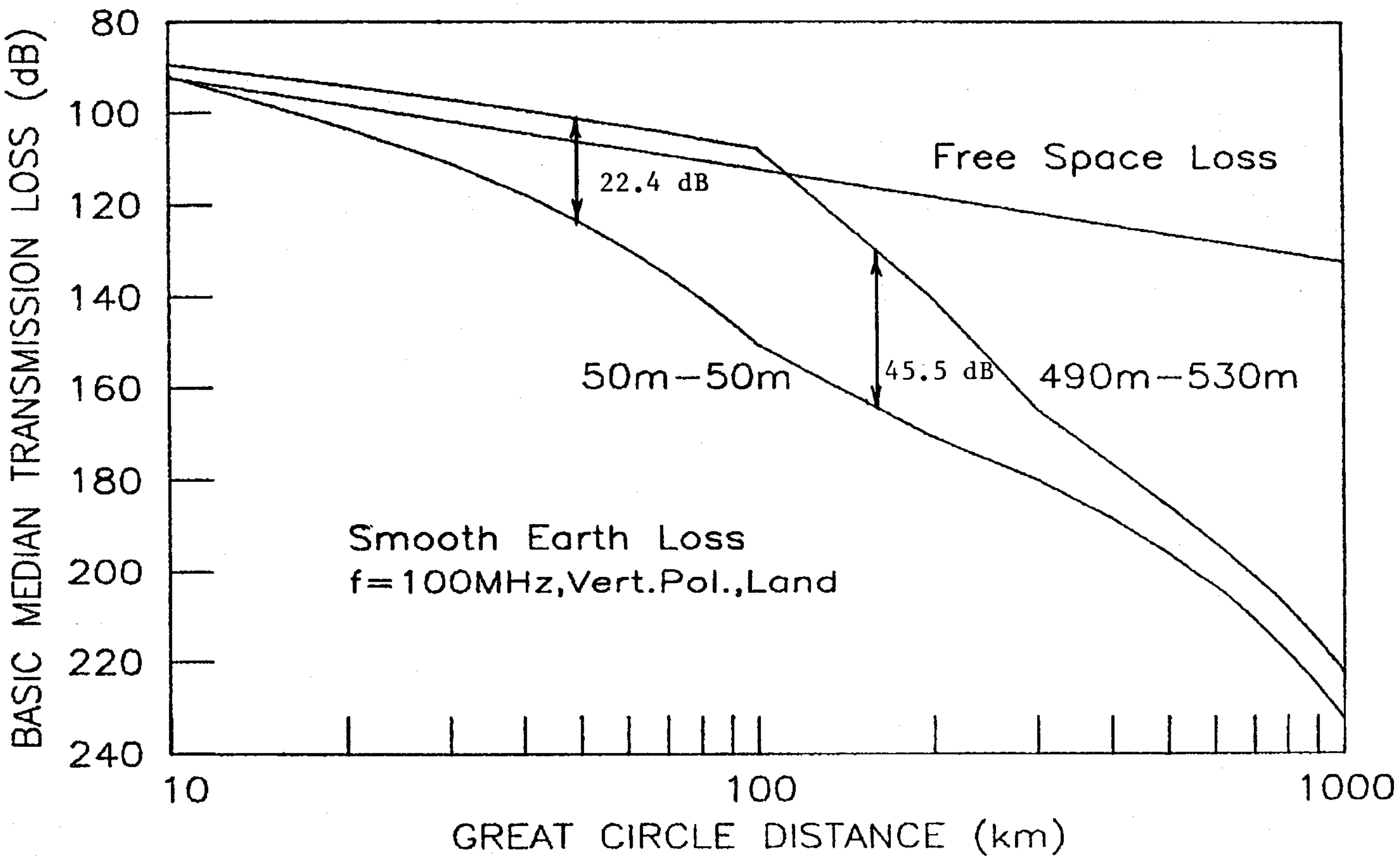

Figure 4. Transmission loss for different effective antenna heights.

Path B has the same 50-meter structural antennas located on a smooth earth surface (plateau) that is 500 meters above sea level. For this path, no terrain adjustments are necessary, since the structural antenna heights are the effective antenna heights. This is because the average terrain elevation along the path is equal to each site elevation. Thus, for Path B, the transmission loss will be the same as if the 50-meter antennas were placed at sea level (assuming atmospheric refractivity changes are negligible).

Figure 4 has transmission loss curves that correspond to Path A and Path B shown in Figure 3. The Path A curve is for effective antenna heights of 490 meters and 530 meters, and the Path B curve is for effective heights of 50 meters and 50 meters. The loss differences between the two curves on Figure 4 are solely due to the differences in the effective antenna heights used in the $N\lambda$ smooth earth model. As shown in Figure 4, for a transmission path distance of 50 km, the transmission loss difference between the curves is 22.4 dB. At a distance of 150 km, the loss difference is 45.5 dB. The 22.4 dB and 45.5 dB differences represent the prediction error that would result for the paths in Figure 3 if the effective antenna heights used in the $N\lambda$ computer model do not represent the path geometry.

SECTION 2

EXAMPLE APPLICATION

GENERAL

Transmission loss is only one parameter in the equation to determine received signal level in, and system performance of, a telecommunication link. It is important to know the relationship of transmission loss to other parameters such as, transmitter power, antenna gains, and interference criteria. To demonstrate this relationship, a summary of the system coupling equation and the important parameters are given in the following section for simple system models. A sample problem is given to illustrate the application of the transmission loss curves in the solution of an interference problem.

The simplest system model for evaluating electromagnetic compatibility (EMC) is one that represents standard deterministic prediction equations for the desired and undesired signals at the receiver input.[6] The desired signal power at the receiver input is determined by Equation 2-1.

$$S_{IN}(\text{dBm}) = S_T(\text{dBm}) + G_T(\text{dBi}) + G_R(\text{dBi}) - L_P(\text{dB}) \qquad (2\text{-}1)$$

where:

S_{IN} = desired signal at the receiver input
S_T = desired signal from the transmitter
G_T = desired transmitter antenna gain (typically mainbeam gain)
G_R = receiver antenna gain
L_P = propagation loss for desired signal path (see Section 3).

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[6] CCIR, Handbook, <u>Spectrum Management and Computer-Aided Techniques</u>, Geneva, Switzerland, 1983.

A simple evaluation would be to compute S_{IN} and compare this value with a performance threshold. If the level of S_{IN} exceeds the threshold, then a level of acceptable desired signal performance is available. The signal could also be readily converted to a signal-to-noise ratio (S/N) since, in Equation 2-2:

$$(S/N)_{IN}(dB) = S_{IN}(dBm) - N_{IN}(dBm) \qquad (2\text{-}2)$$

where:

$(S/N)_{IN}$ = signal-to-noise ratio at the receiver input
N_{IN} = equivalent input noise power

and all other terms are previously defined. A similar analysis can also be performed for the interfering signal in terms of the input power or the input interference-to-noise ratio (I/N). The evaluation of I/N is often employed in EMC analyses.

The undesired signal at the receiver input is given similarly by Equation 2-3.

$$I_{IN}(dBm) = I_T(dBm) + G_{TI}(dBi) + G_R(dBi) - L_I(dB) \qquad (2\text{-}3)$$

where:

I_{IN} = undesired receiver input power
I_T = undesired transmitter signal power
G_{TI} = undesired transmitter antenna gain (mainbeam or sidelobes)
G_R = receiver antenna gain in direction of interference
L_I = basic transmission loss for undesired signal path, (see Section 3).

The next logical step in increasing the complexity of the calculations would be to compute $(S/I)_{IN}$ and compare this to a performance threshold to determine if the level of performance is acceptable or not acceptable. The $(S/I)_{IN}$ is given by Equation 2-4.

$$(S/I)_{IN}(dB) = S_{IN}(dBm) - I_{IN}(dBm) \qquad (2\text{-}4)$$

and the criteria are:

$(S/I)_{IN}$ (dB) > $(S/I)_{TH}$ (dB) acceptable performance

$(S/I)_{IN}$ (dB) < $(S/I)_{TH}$ (dB) unacceptable performance

where

$(S/I)_{TH}$ = desired-to-undesired performance threshold criteria (see CCIR Report 526 for typical performance criteria)

and all other terms are previously defined.

Example Problem

To demonstrate application of the transmission loss curves in this handbook, the curves are used in the solution of an example telecommunications problems. This example problem involves a mobile station receiving two cochannel vertically polarized FM signals simultaneously; one desired signal and one undesired signal. The objective is to determine whether the interference to the mobile station receiver is acceptable. The following parameters are known for the telecommunications systems.

Parameter	Base Station (desired signal transmitter)
S_T = 100 watts	Base station transmitter output power
h_T = 10 meters	Base station effective antenna height
G_T = 8 dBi	Base station antenna gain
	Mobile Station (desired signal receiver)
h_R = 1 meter	Mobile station effective antenna height
G_R = 0 dBi	Mobile station antenna gain
N_{IN} = -128 dBm	Mobile station input noise level
$(S/N)_{IN}$ = 15 dB	Mobile station input signal-to-noise ratio
$(S/I)_{TH}$ = 7 dB	Mobile station criteria for FM to FM marginal performance
	Interfering Station (undesired signal transmitter)
I_T = 15 watts	Interfering station's transmitter output power
h_I = 50 meters	Interfering station's effective antenna height
G_{TI} = 7 dBi	Interfering station's antenna gain

The distance between the base station and a specific location of the mobile station is known to be 60 km over a land path. Since the terrain is smooth along the path, the smooth-earth transmission loss curves in APPENDIX A may be used to estimate the propagation loss. The basic median transmission loss between the base station and the mobile station is determined, using the curve for land in Figure A-1, to be L_b = 171 dB for $h_R = h_1 = 1$ m, $h_T = h_2 =$ 10 m, and f = 100 MHz at a distance of 60 km. The level of desired signal at the input to the mobile station can now be determined using Equation 2-1.

$$\begin{aligned}
S_{IN}(\text{dBm}) &= S_T(\text{dBm}) + G_T(\text{dBi}) + G_R(\text{dBi}) - L_b(\text{dB}) \\
S_{IN}(\text{dBm}) &= 50 + 8 + 0 - 171 \\
S_{IN}(\text{dBm}) &= -113
\end{aligned}$$

The $(S/N)_{IN}$ at the mobile receiver is determined using Equation 2-2.

$$(S/N)_{IN}(dB) = S_{IN}(dBm) - N_{IN}(dBm)$$

$$= -113 - (-128)$$

$$(S/N)_{IN}(dB) = 15$$

The distance between an interfering station and the specific location of the mobile station is known to be 53 km over a smooth land path. The propagation loss between the interfering station and the mobile station is thus determined, using the curve for land in Figure A-128, to be $L_I(dB) = 153$ dB for $h_R = h_1 = 1$ m, $h_I = h_2 = 50$ m, and f = 100 MHz at a distance of 53 km.

The level of the undesired signal at the input to the mobile station is determined using Equation 2-3.

$$I_{IN}(dBm) = I_T(dBm) + G_{TI}(dBi) + G_R(dBi) - L_I(dB)$$

$$= 42 + 7 + 0 - 153$$

$$I_{IN}(dBm) = -104$$

The desired-signal to interference-signal ratio at the mobile receiver input is determined using Equation 2-4.

$$(S/I)_{IN}(dB) = S_{IN}(dBm) - I_{IN}(dBm)$$

$$= -113 - (-104)$$

$$(S/I)_{IN}(dB) = -9$$

The calculated value of $(S/I)_{IN}$(dB) = -9 is compared to the desired-to-undesired performance threshold criteria $(S/I)_{TH}$ = +7. Since the calculated value of $(S/I)_{IN}$ is less than the threshold value of $(S/I)_{TH}$, an unacceptable interference situation exists between the interfering station and the mobile station.

SECTION 3

SIGNAL ATTENUATION FORMULAS

INTRODUCTION

There are many ways of expressing attenuation of signals transmitting between a transmitter and a receiver. The CCIR Study Group 5 has defined some terms concerning tropospheric radio wave propagation for use in the international community. These are contained in CCIR Recommendation 341-2, "The Concept of Transmission Loss for Radio Links." The CCIR defined terms of particular interest are: system loss, transmission loss, basic transmission loss, free space basic transmission loss, ray path transmission loss, and loss relative to free space. For convenience, portions of these definitions are given below with the aid of Figure 5.

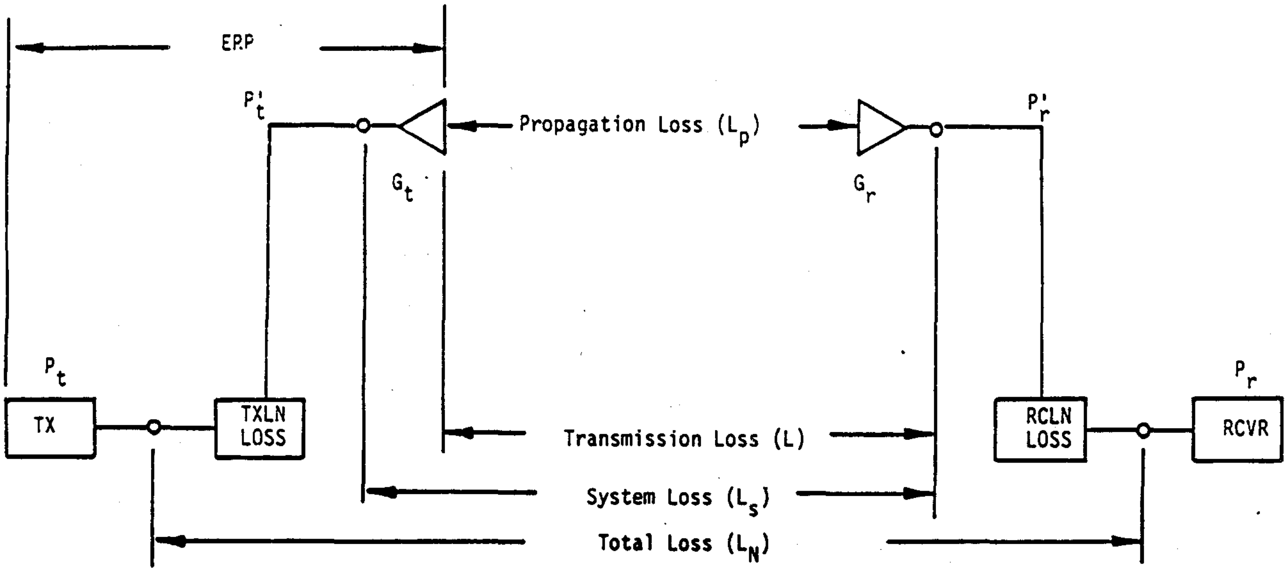

Figure 5. Graphic depiction of terms used in describing signal attenuation.

Terminology used in Figure 5 and throughout Section 3 is presented to be consistent with the terminology in CCIR Report 341-2.

ERP - Effective Radiated Power, watts
TX - Transmitter
p_t - Transmitter Power, watts
p_t' - Transmitter Power less line losses, watts
TXLN - Transmitter transmission line
G_t - Transmitter antenna gain
G_r - Receiver antenna gain
RCVR - Receiver
RCLN - Receiver transmission line
p_r - Receiver input power, watts
p_r' - Power received from the antenna, watts

TRANSMISSION LOSS

1. Radio wave propagation loss, (L_p).

The attenuation of a radio wave that occurs when propagating between a transmitting antenna and a receiving antenna and, thus, does not include antenna gains.

2. System Loss (L_s)

The ratio, usually expressed in decibels, for a radio link, of the radio frequency power input to the terminals of the transmitting antenna and the resultant radio frequency signal power available at the terminals of the receiving antenna

$$L_s = 10 \log (p_t'/p_r') = P_t' - P_r' \qquad \text{dB} \qquad (2-1)$$

where

P'_t = radio frequency power in dBW input to the terminals of the transmitting antenna and

P'_r = resultant radio frequency signal power in dBW available at the terminals of the receiving antenna

3. Total Loss (L_N)

The ratio, usually expressed in decibels, between the power supplied by the transmitter of a radio link and the power supplied to the corresponding receiver.

4. Transmission Loss (L)

The ratio, usually expressed in decibels, for a radio link between the power radiated by the transmitting antenna and the power that would be available at the receiving antenna output.

5a. Basic Transmission Loss (L_b)

The transmission loss that would occur if the antennas were replaced by theoretical isotropic antennas with the same polarization as the real antennas.

5b. Basic Median Transmission Loss (L_{bm})

The basic median transmission loss in dB represents the median value (50%) of a large distribution of measured propagation losses for a given path. This means that if a large number of loss measurements are made over a given path, half of them would be above the median loss and half would be below the median loss. The NLAMBDA model predicts basic median transmission loss.

6. Free-space Basic Transmission Loss (L_{bf})

The transmission loss that would occur if the antennas were replaced by isotropic antennas located in a perfect dielectric, homogeneous, isotropic and unlimited environment.

$$L_{bf}(\mathrm{dB}) = 20 \log (4\pi D/\lambda) \qquad (2\text{-}2)$$

where

D = distance between antennas
λ = wavelength in meters

This loss may also be expressed in decibel form by the equation:

$$L_{bf}(\mathrm{dB}) = 20 \log f(\mathrm{MHz}) + 20 \log D - K_1$$

where

f = frequency

K_1 = 37.9 (for D in feet)
27.6 (for D in meters)
32.45 (for D in kilometers)
-36.6 (for D in statute miles)
-37.8 (for D in nautical miles).

7. Loss Relative to Free Space (A)

The difference between the basic transmission loss and the free-space basic transmission loss, expressed in decibels

$$A = L_b - L_{bf} \quad (\mathrm{dB})$$

MODIFICATIONS TO THE SMOOTH-EARTH MEDIAN TRANSMISSION LOSS

Modifications of the smooth-earth transmission loss from terrain roughness, mixed path surface, foliage, rain, and long-term time-dependent power fading must be determined from other sources and added to the smooth-earth transmission loss predictions obtained using the methods in this handbook. Comments on the effects of these phenomena, relative to the smooth-earth transmission loss, are given in the following paragraphs.

Terrain roughness along the transmission path can produce transmission loss variations above and below the median loss. Generally, the loss will increase over rough terrain for beyond-the-horizon paths relative to the same distance over a smooth earth (providing that effective antenna heights are used in the smooth earth case). Line-of-sight transmission over rough terrain can produce short-term multiple reflections that are referred to as multipath or fast fading. Multipath is characterized by rapid variations about the free space loss that could range from a 6 dB less loss to a deep fade of 30 dB or more of the signal. References for the effects of multipath and rough-earth effects are available from Rice, Powell, and the CCIR[9,10,11,12] and reference 4.

Mixed path surface transmission can be significantly different from transmission over a path having uniform electrical characteristics. A typical mixed path would be from a ship at sea to an inland station. Propagation characteristics could change abruptly at the land-sea boundary. This phenomenon is important for low antennas at frequencies below about 160 MHz. A primary reference for the effects of mixed path propagation is the work of Millington[13] (also see reference 12).

Foliage attenuation must be considered when either antenna is very near, or emersed in, trees or other foliage. Determining the effects of foliage on the propagating signal requires detailed knowledge of the environment. Although in some cases, foliage may reduce the signal attenuation, the usual effect is increased attenuation relative to the median. References for foliage attenuation are available in the literature[14,15,16] (also see references 11 and 12).

Rain attenuation becomes important for transmissions at frequencies above 10 GHz. This phenomenon produces the largest variations in signal phase and amplitude on earth-space line-of-sight paths. References for the effects of rain attenuation are available from Crane[17] and the CCIR[18] (also see reference 12).

Time-dependent power fading (long term) must be considered for propagation over beyond-the-horizon paths. This phenomenon causes variations relative to the median loss due to large-scale slow changes in the atmosphere. It is a function of time of day, time of year, and geographic location. The transmission loss curves in this handbook provide estimates of the median loss (50%) of log normal distribution of transmission losses. The variation about this median for any other percentile (10%, 90%, etc.) can be estimated using an empirical model for long-term time-dependent power fading given in the references below. As an example, for some propagation paths, the transmission loss for a 10% probability may be 10 to 15 dB less than the median loss (50%) and for a 90% probability, the loss may be 30 dB more than the median loss. The method and data to estimate long-term time-dependent power fading are well documented (see references 4,9,10, and 12).

Tropospheric ducting is a significant anomalous propagation mode for frequencies above 100 MHz. The probability of occurrence of tropospheric ducting typically is less than about ten percent of the time. The ducting mode is not typically a reliable or continuous mode of propagation but can produce strong interference signals for intermittent periods of time. Ducting occurs as the result of atmospheric stratification and inversion layers that is found typically in coastal regions. Tropospheric ducting can produce unusually high signal levels relative to the median value. Estimates of the worldwide probability of occurrence of tropospheric ducting and the resultant signal enhancement from ducting may be obtained using newly developed data.[19,20]

REFERENCE LIST FOR SECTION 3

7. CCIR, Recommendation 525-1, "Calculation of Free Space Attenuation," Volume V, Propagation in Non-Ionized Media, XVI Plenary Assembly, Dubrovnik, Poland, 1986.

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APPENDIX A

CURVES OF BASIC MEDIAN TRANSMISSION LOSS

This appendix contains curves of Basic Median Transmission Loss in dB over a smooth spherical earth for frequencies of 100 MHz, 500 MHz, 1000 MHz, 2000 MHz, 5000 MHz, 7000 MHz, 10,000 MHz, and 20,000 MHz. Estimates of transmission loss for frequencies between 100 MHz and 20,000 MHz may be determined by interpolation between the curves. TABLE A-1 is included to help locate the transmission loss curve for a particular combination of frequency and antenna heights.

TABLE A-1: CURVES OF BASIC MEDIAN TRANSMISSION LOSS

LIST OF TRANSMISSION LOSS FIGURES

f(MHz)	h_1(m) \ h_2(m)	1	10	50	100	200	500	1K	2K	5K
100	1		A-1	A-2	A-3	A-4	A-5	A-6	A-7	A-8
	10		A-9							A-9
	50			A-10						A-10
	100				A-11					A-11
	200					A-12				A-12
	500						A-13			A-13
	1K							A-14		A-14
	2K								A-15	A-15
	5K									A-16
500	1		A-17							A-17
	10		A-18							A-18
	50			A-19						A-19
	100				A-20					A-20
	200					A-21				A-21
	500						A-22			A-22
	1K							A-23		A-23
	2K								A-24	A-24
	5K									A-25
1000	1		A-26							A-26
	10		A-27							A-27
	50			A-28						A-28
	100				A-29					A-29
	200					A-30				A-30
	500						A-31			A-31
	1K							A-32		A-32
	2K								A-33	A-33
	5K									A-34

TABLE A-1: CURVES OF BASIC MEDIAN TRANSMISSION LOSS

LIST OF TRANSMISSION LOSS FIGURES

f(MHz)	h₂(m) / h₁(m)	1	10	50	100	200	500	1K	2K	5K
2000	1		A-35							A-35
	10		A-36							A-36
	50			A-37						A-37
	100				A-38					A-38
	200					A-39				A-39
	500						A-40			A-40
	1K							A-41		A-41
	2K								A-42	A-42
	5K									A-43
5000	1		A-44							A-44
	10		A-45							A-45
	50			A-46						A-46
	100				A-47					A-47
	200					A-48				A-48
	500						A-49			A-49
	1K							A-50		A-50
	2K								A-51	A-51
	5K									A-52
7000	1		A-53							A-53
	10		A-54							A-54
	50			A-55						A-55
	100				A-56					A-56
	200					A-57				A-57
	500						A-58			A-58
	1K							A-59		A-59
	2K								A-60	A-60
	5K									A-61

TABLE A-1: CURVES OF BASIC MEDIAN TRANSMISSION LOSS

LIST OF TRANSMISSION LOSS FIGURES

f(MHz)	h_2(m) / h_1(m)	1	10	50	100	200	500	1K	2K	5K
10,000	1		A-62							A-62
	10		A-63							A-63
	50			A-64						A-64
	100				A-65					A-65
	200					A-66				A-66
	500						A-67			A-67
	1K							A-68		A-68
	2K								A-69	A-69
	5K									A-70
20,000	1		A-71							A-71
	10		A-72							A-72
	50			A-73						A-73
	100				A-74					A-74
	200					A-75				A-75
	500						A-76			A-76
	1K							A-77		A-77
	2K								A-78	A-78
	5K									A-79
	1									
	10									
	50									
	100									
	200									
	500									
	1K									
	2K									
	5K									

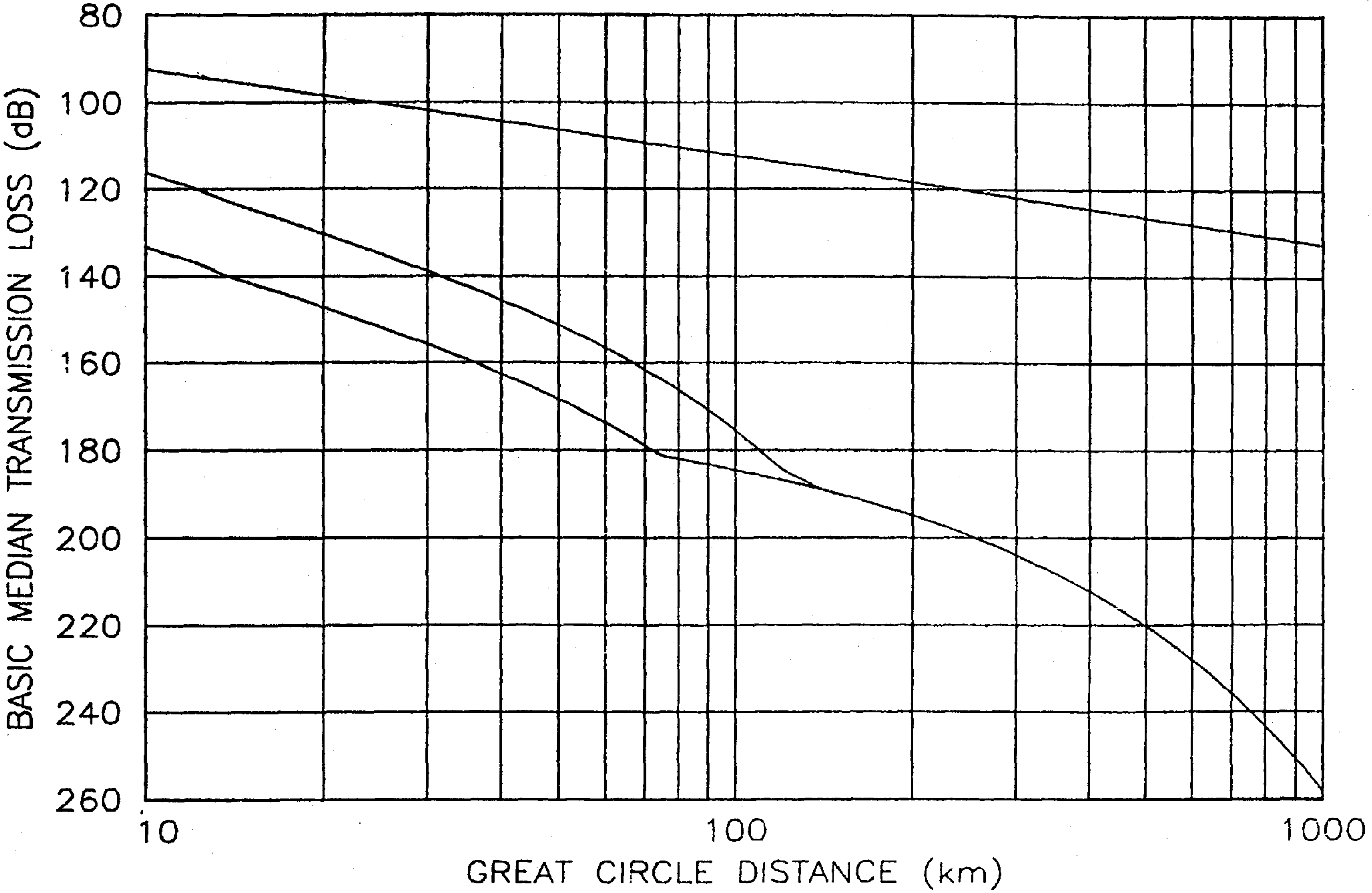

FIGURE A-1. $f=100MHz, h_1=1m, h_2=10m$, V.P., Land and Sea Water

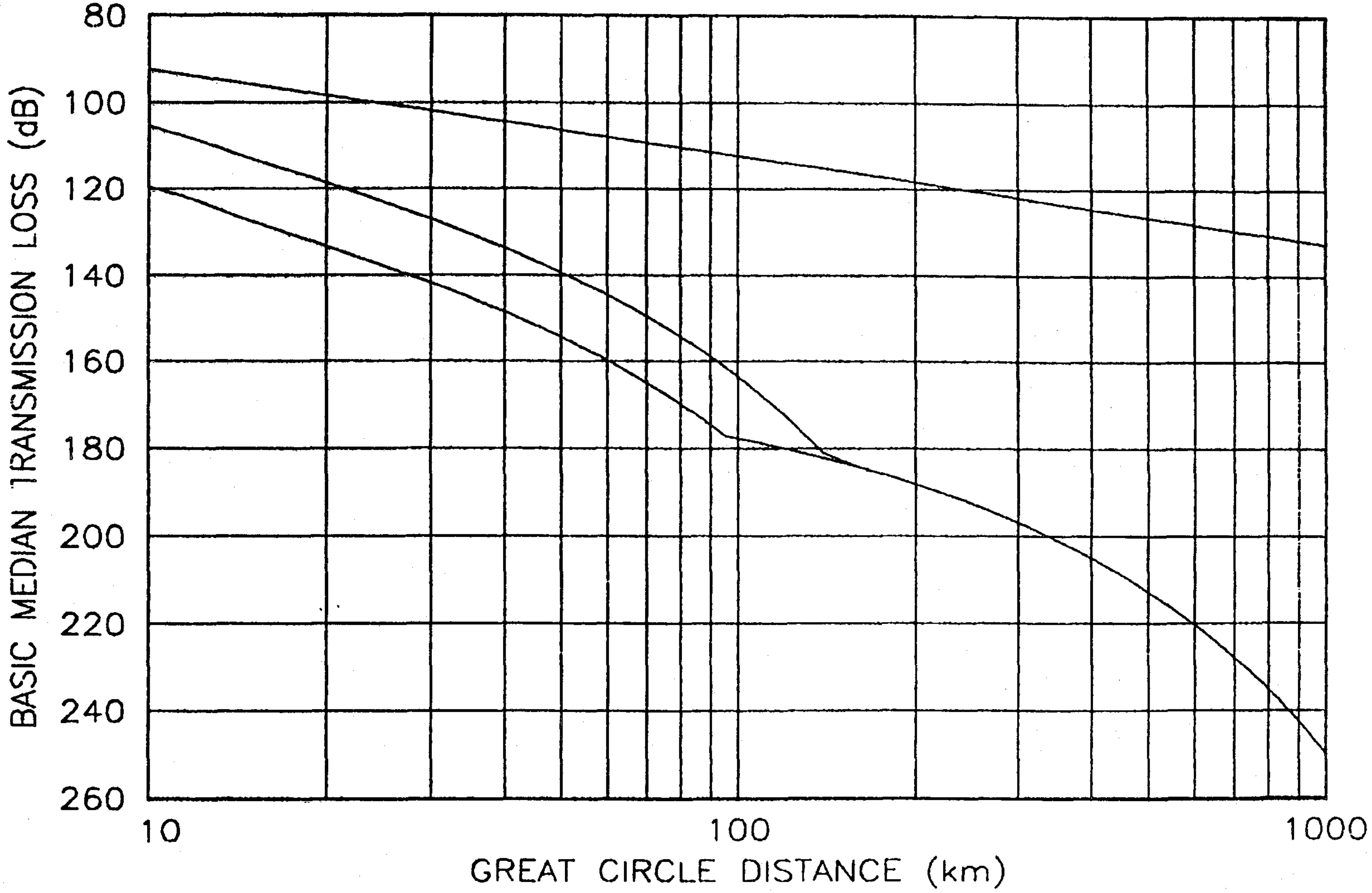

FIGURE A–2. f=100MHz,h_1=1m,h_2=50m,V.P.,Land and Sea Water

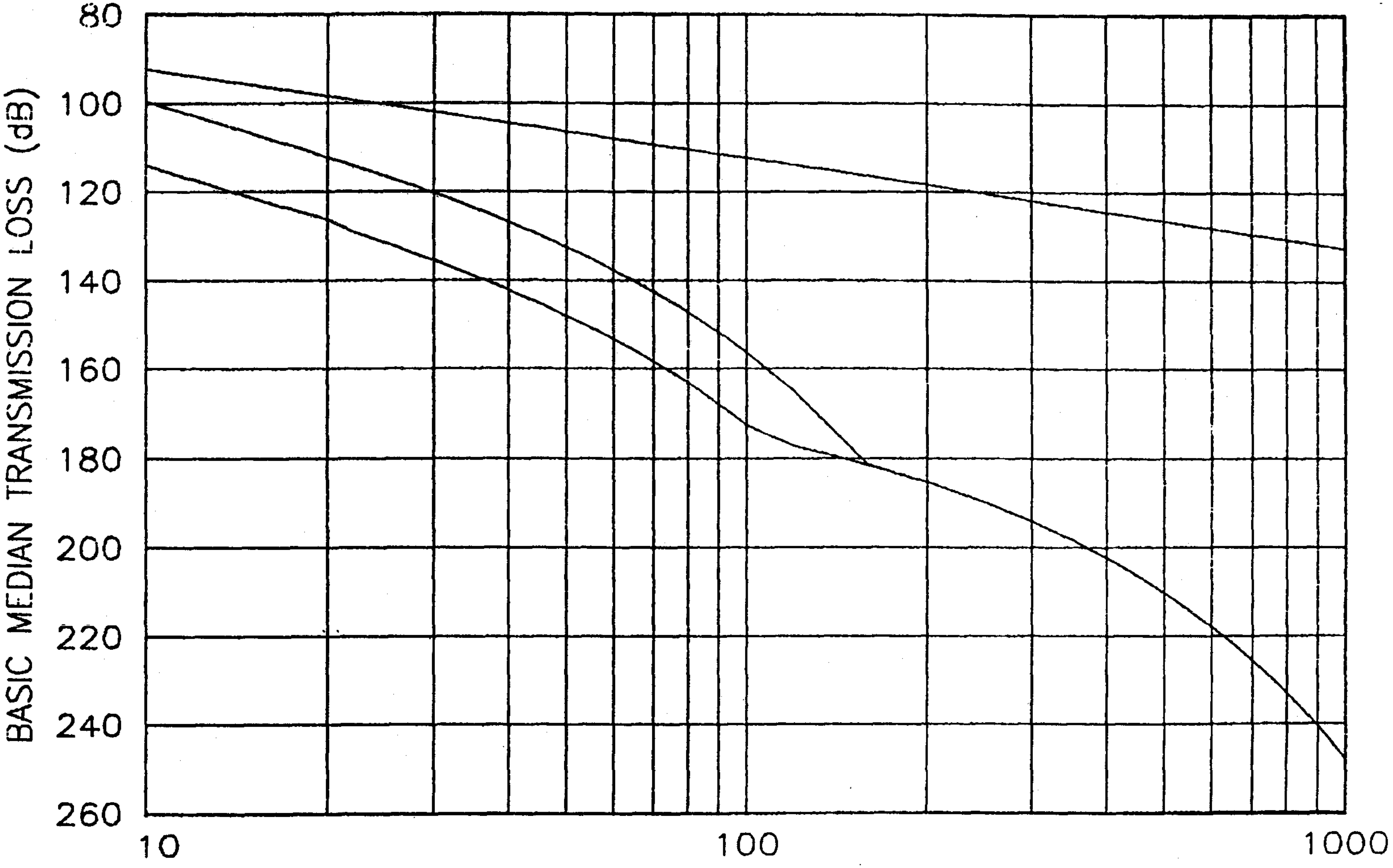

FIGURE A-3. $f=100$MHz, $h_1=1$m, $h_2=100$m, V.P., Land and Sea Water

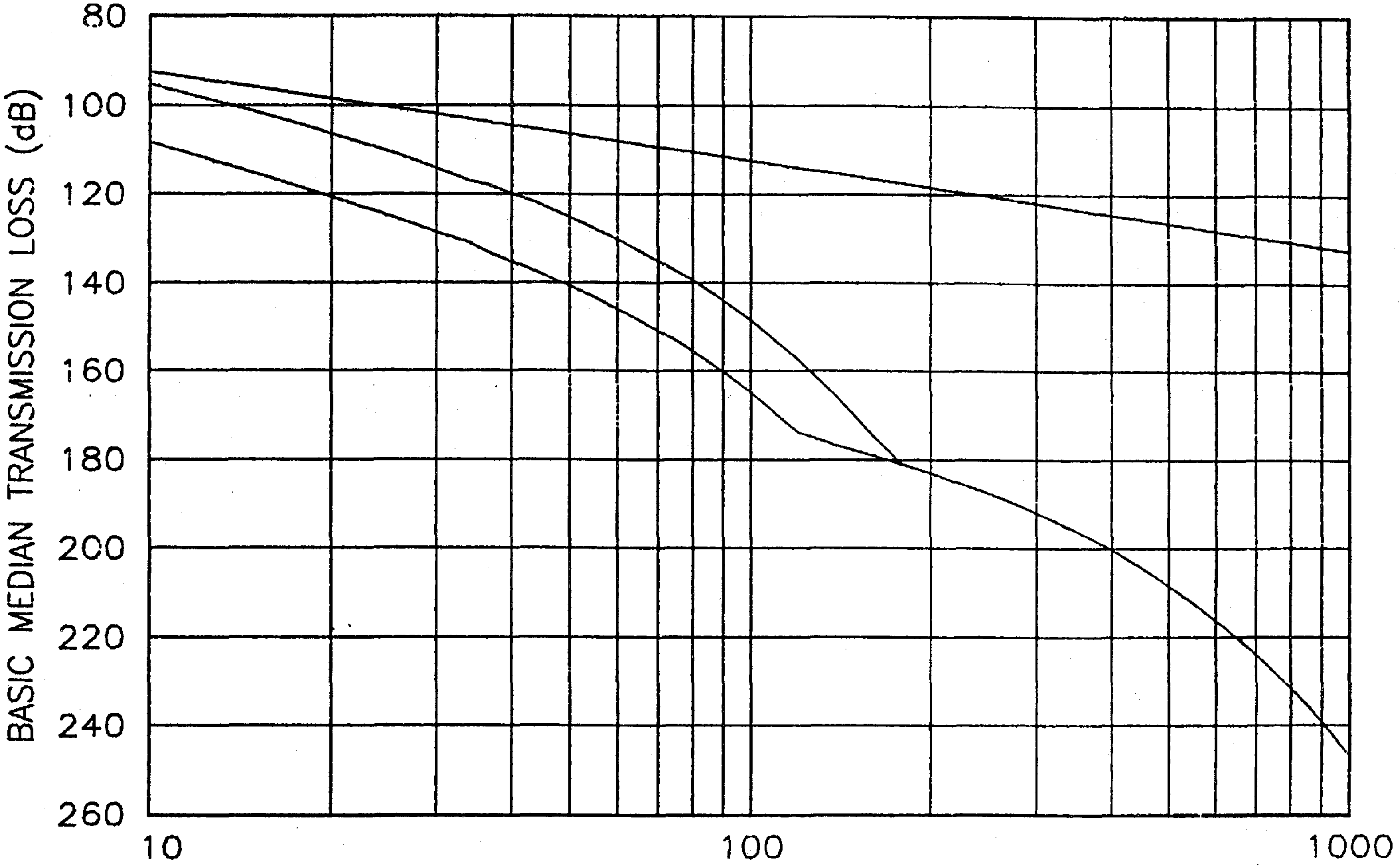

FIGURE A–4. $f=100MHz, h_1=1m, h_2=200m$, V.P., Land and Sea Water

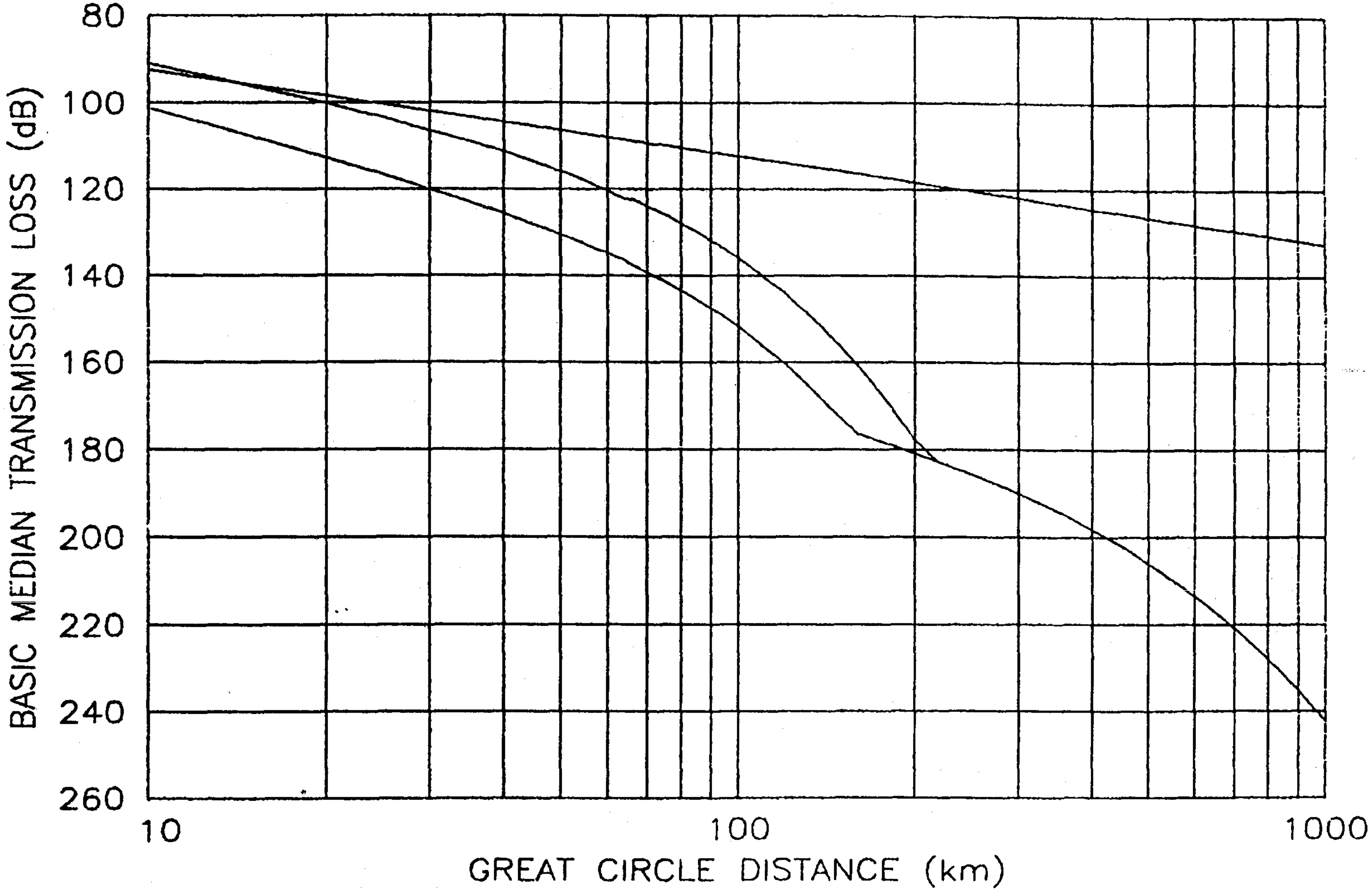

FIGURE A–5. f=100MHz,h_1=1m,h_2=500m,V.P.,Land and Sea Water

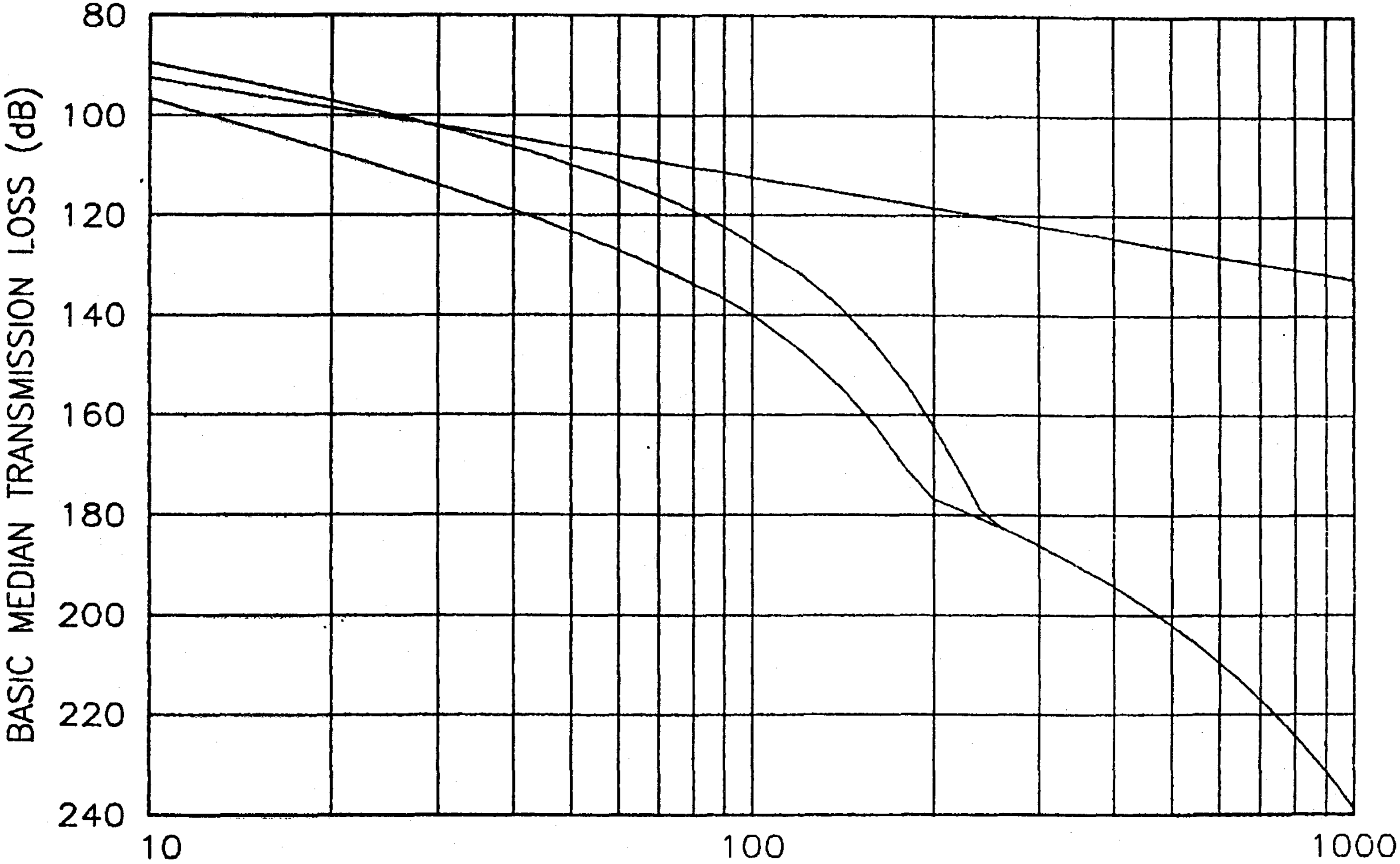

FIGURE A–6. $f=100$MHz,$h_1=1$m,$h_2=1$km,V.P.,Land and Sea Water

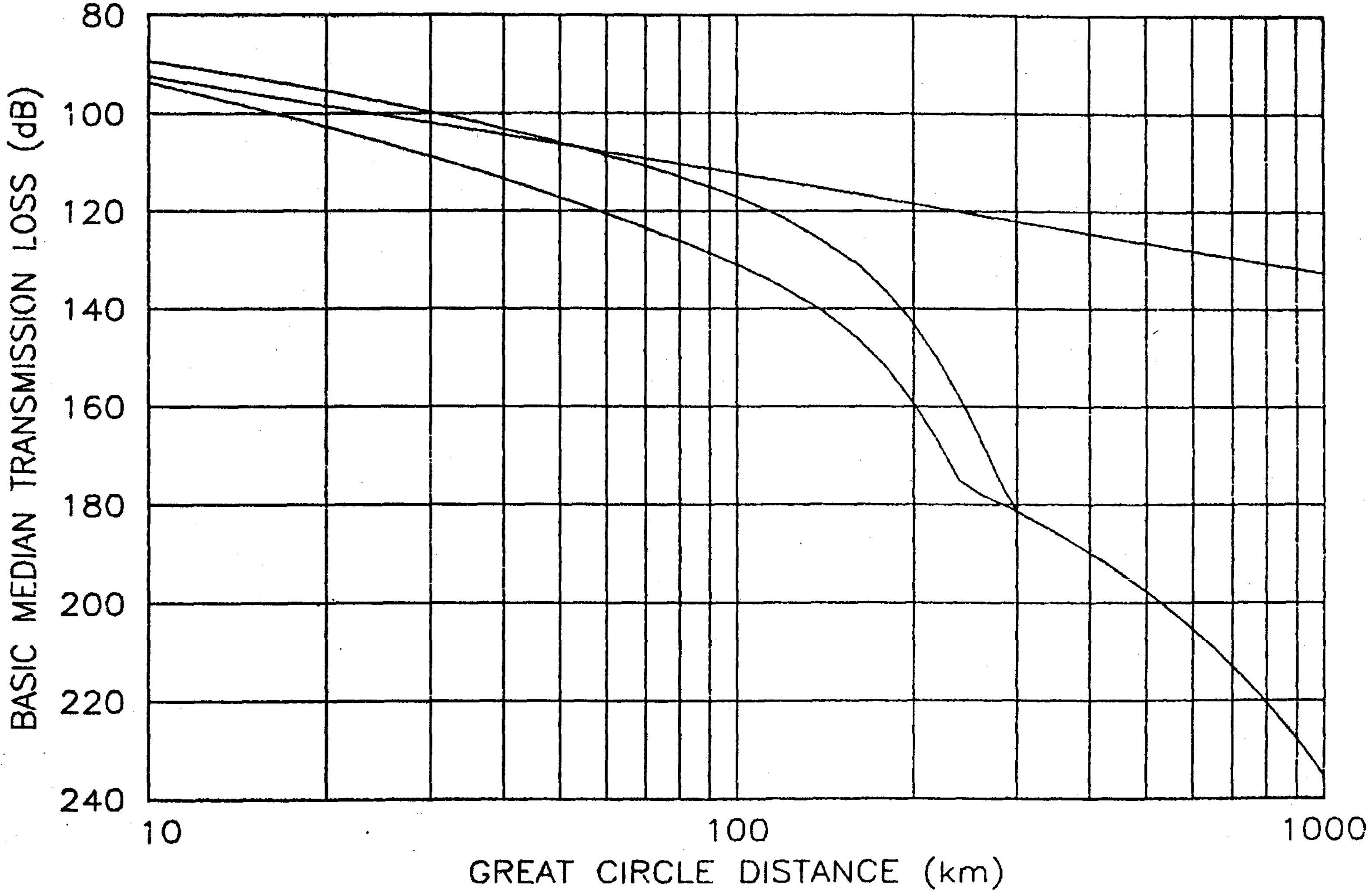

FIGURE A-7. $f=100MHz, h_1=1m, h_2=2km$, V.P., Land and Sea Water

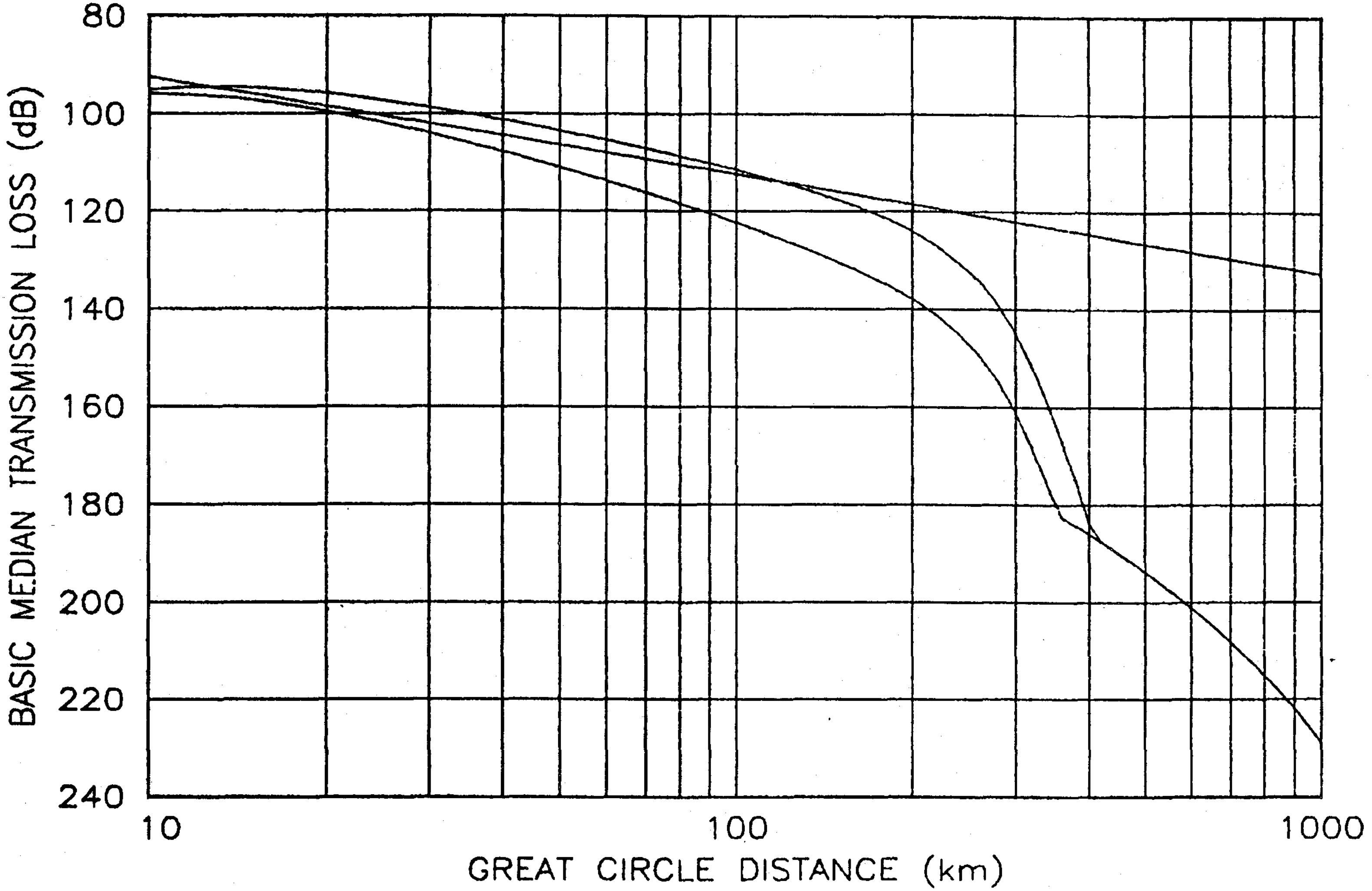

FIGURE A-8. f=100MHz,h_1=1m,h_2=5km,V.P.,Land and Sea Water

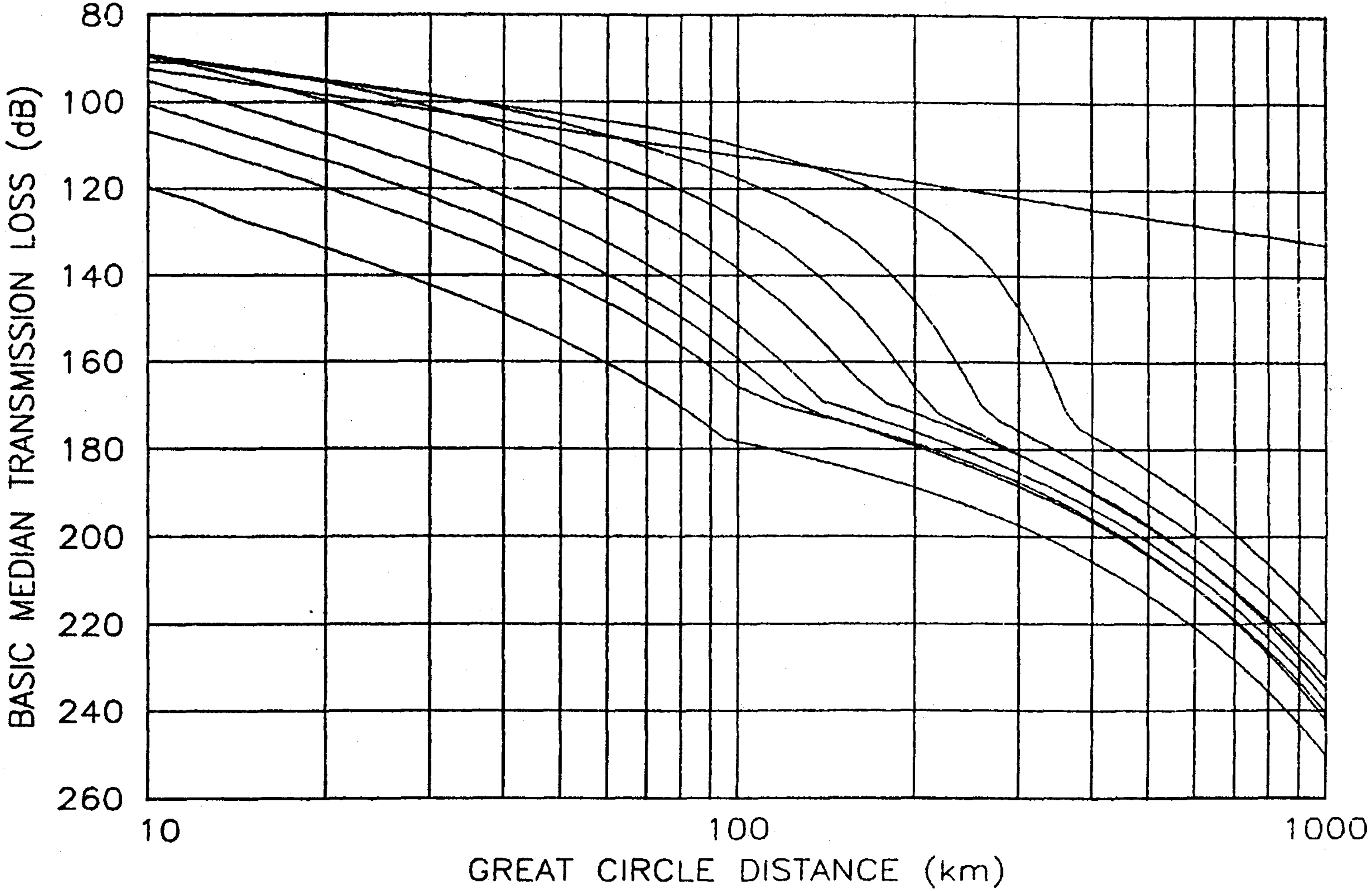

FIGURE A-9. $f=100\text{MHz}, h_1=10\text{m}, h_2=10\text{m}, 50\text{m}, 100\text{m}, 200\text{m}, 500\text{m}, 1\text{km}, 2\text{km}, 5\text{km}$

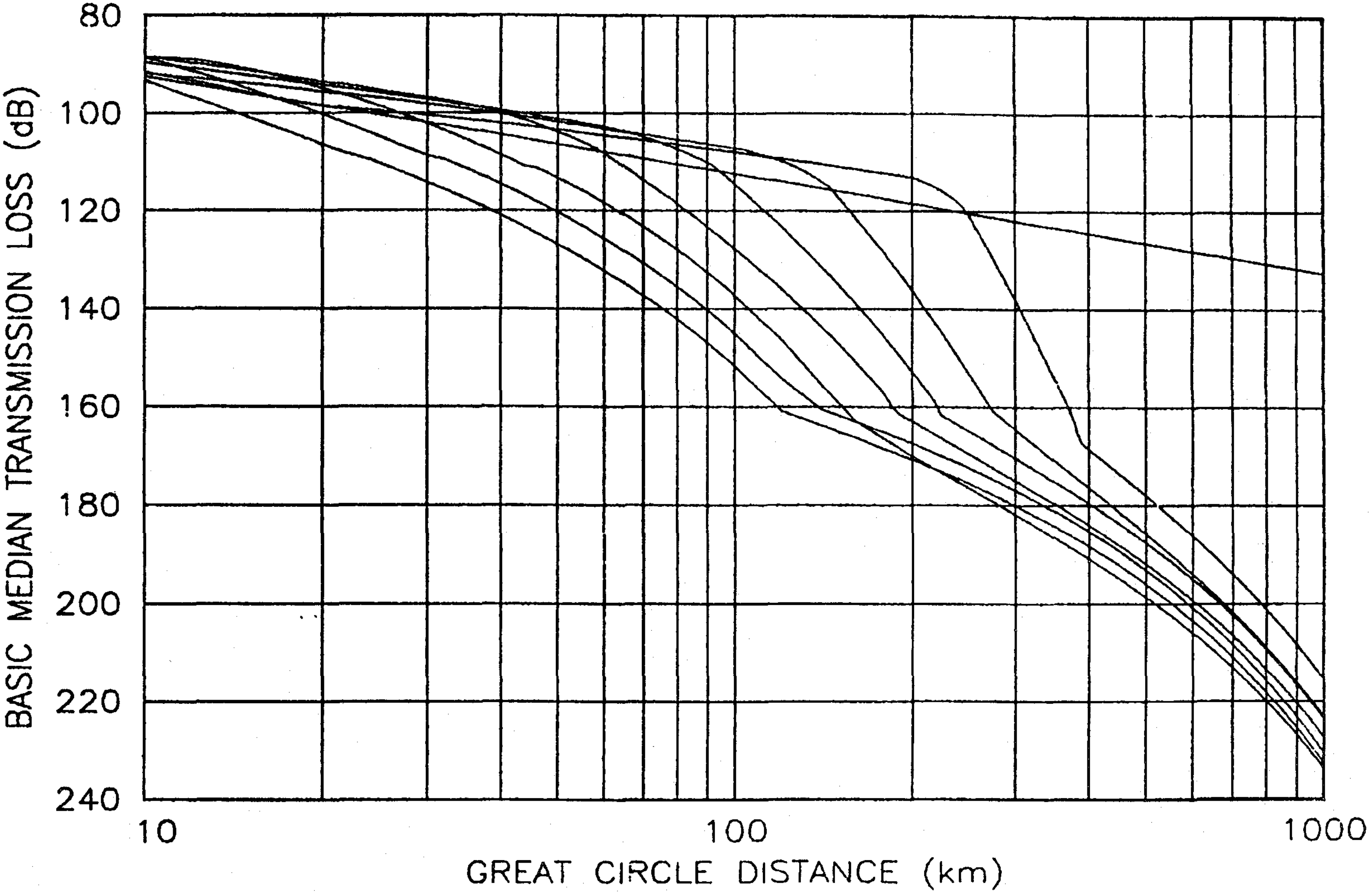

FIGURE A–10. $f=100\text{MHz}, h_1=50\text{m}, h_2=50\text{m}, 100\text{m}, 200\text{m}, 500\text{m}, 1\text{km}, 2\text{km}, 5\text{km}$

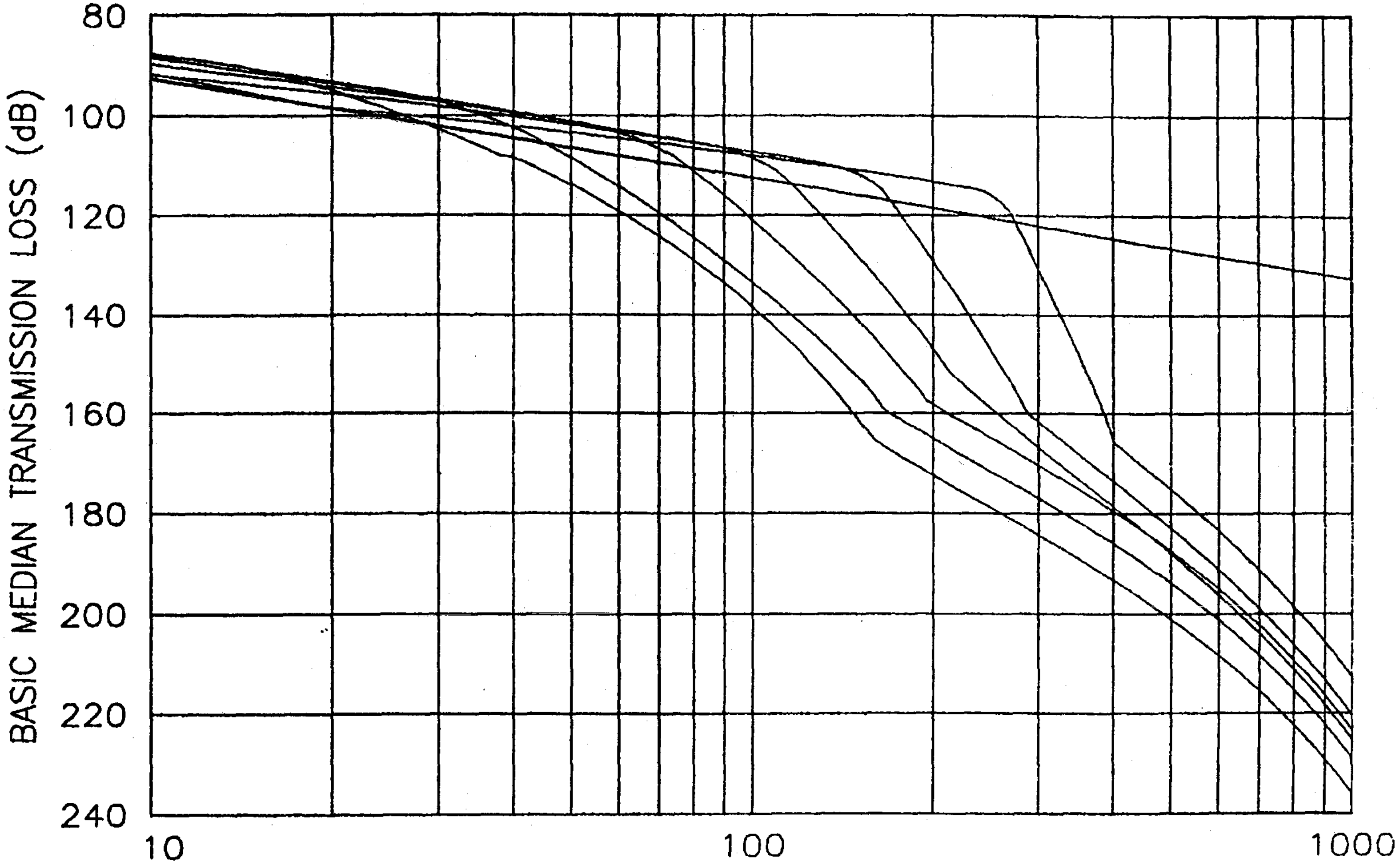

FIGURE A-11. f=100MHz,h_1=100m,h_2=100m,200m,500m,1km,2km,5km

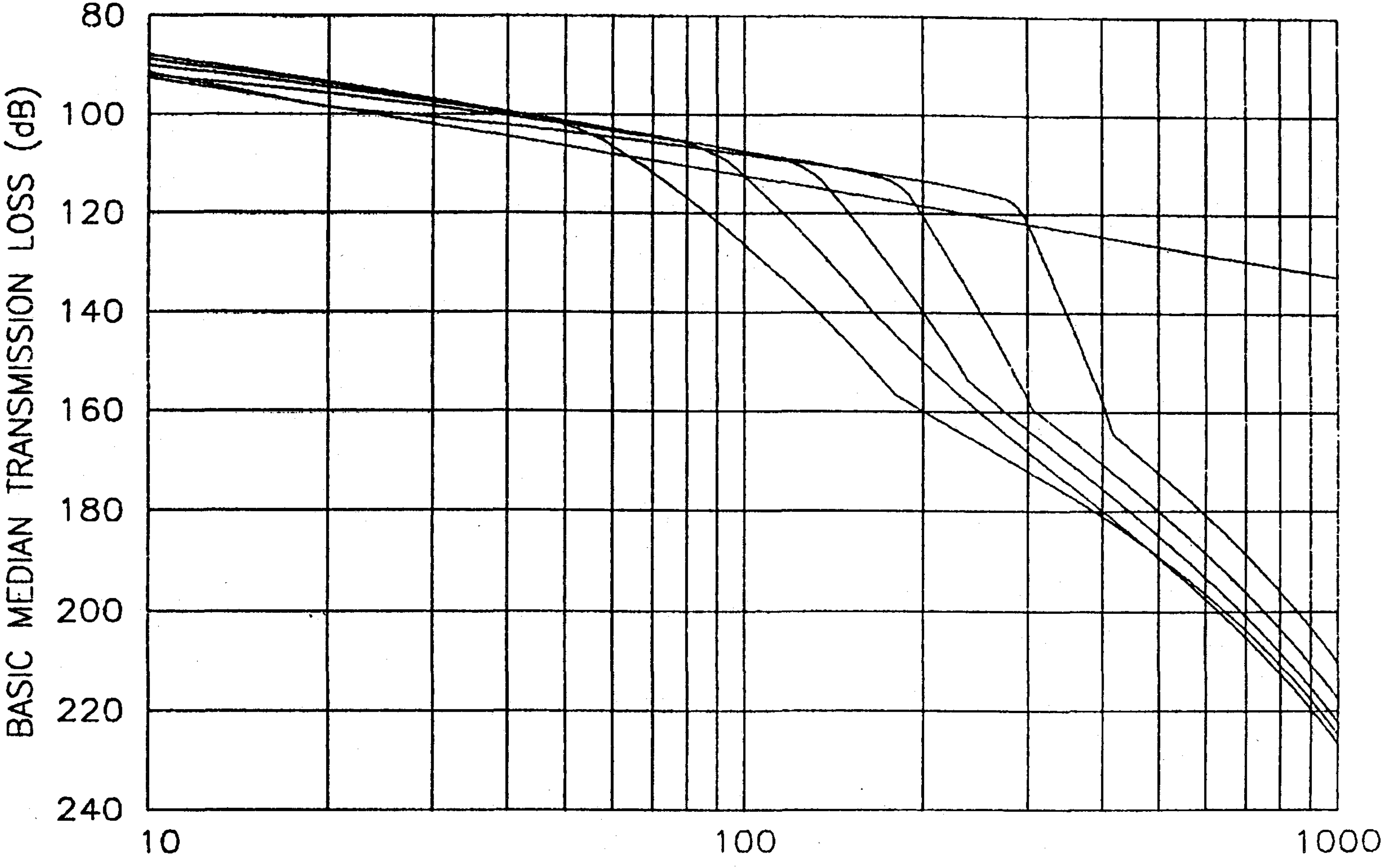

FIGURE A-12. f=100MHz, h_1=200m, h_2=200m, 500m, 1km, 2km, 5km

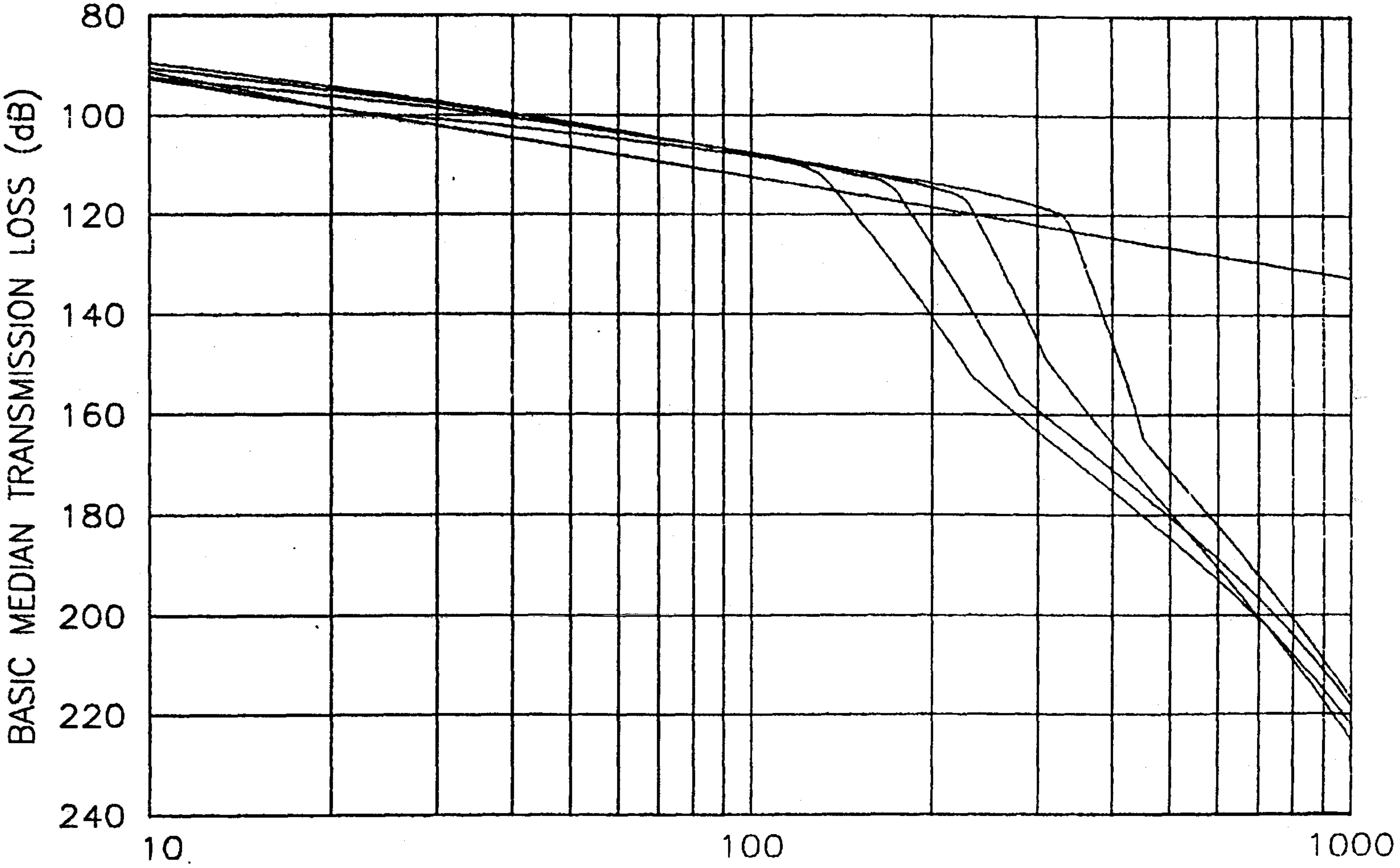

FIGURE A–13. $f=100\text{MHz}, h_1=500\text{m}, h_2=500\text{m}, 1\text{km}, 2\text{km}, 5\text{km}$

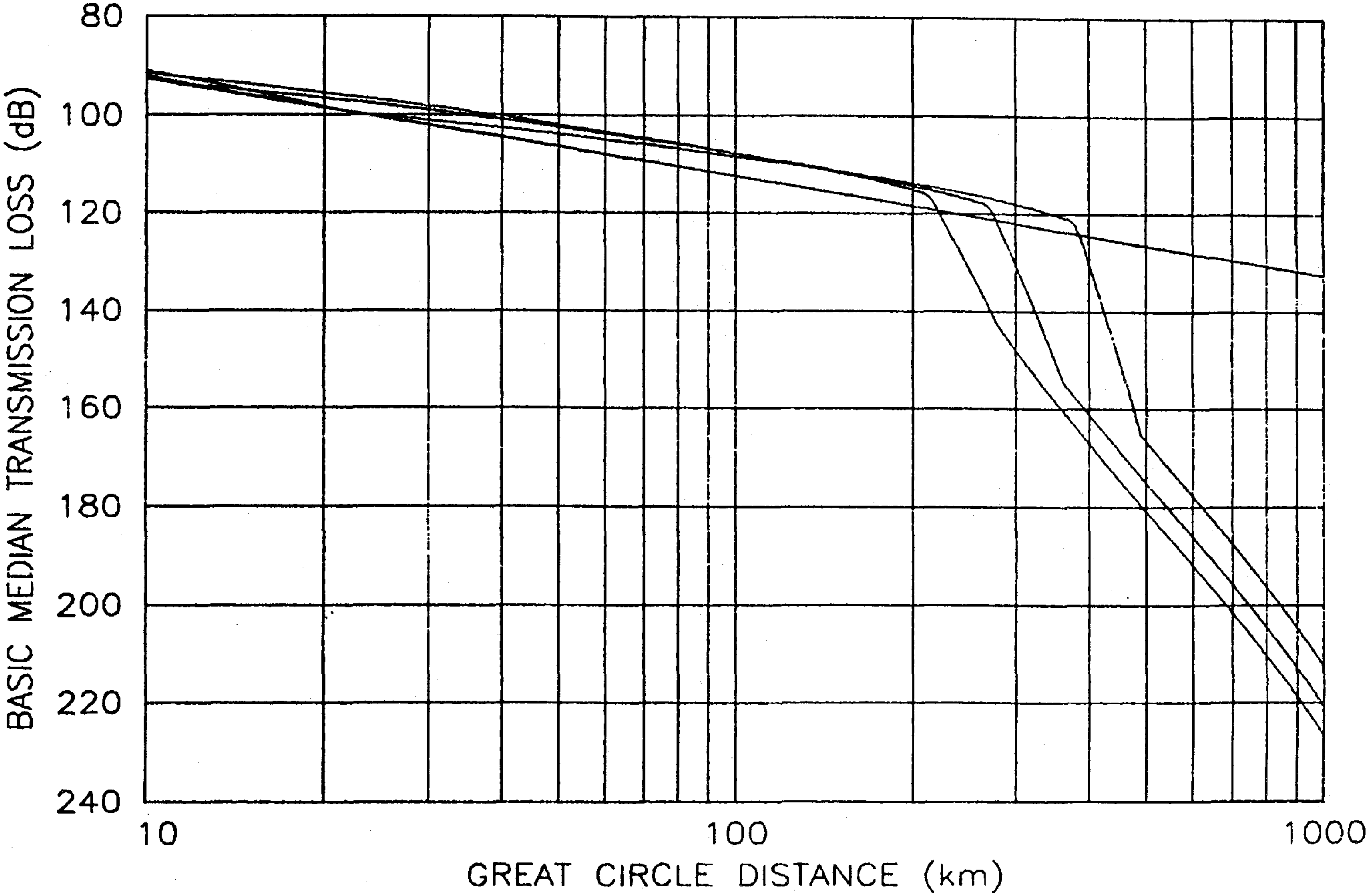

FIGURE A-14. $f=100\text{MHz}, h_1=1\text{km}, h_2=1\text{km}, 2\text{km}, 5\text{km}$

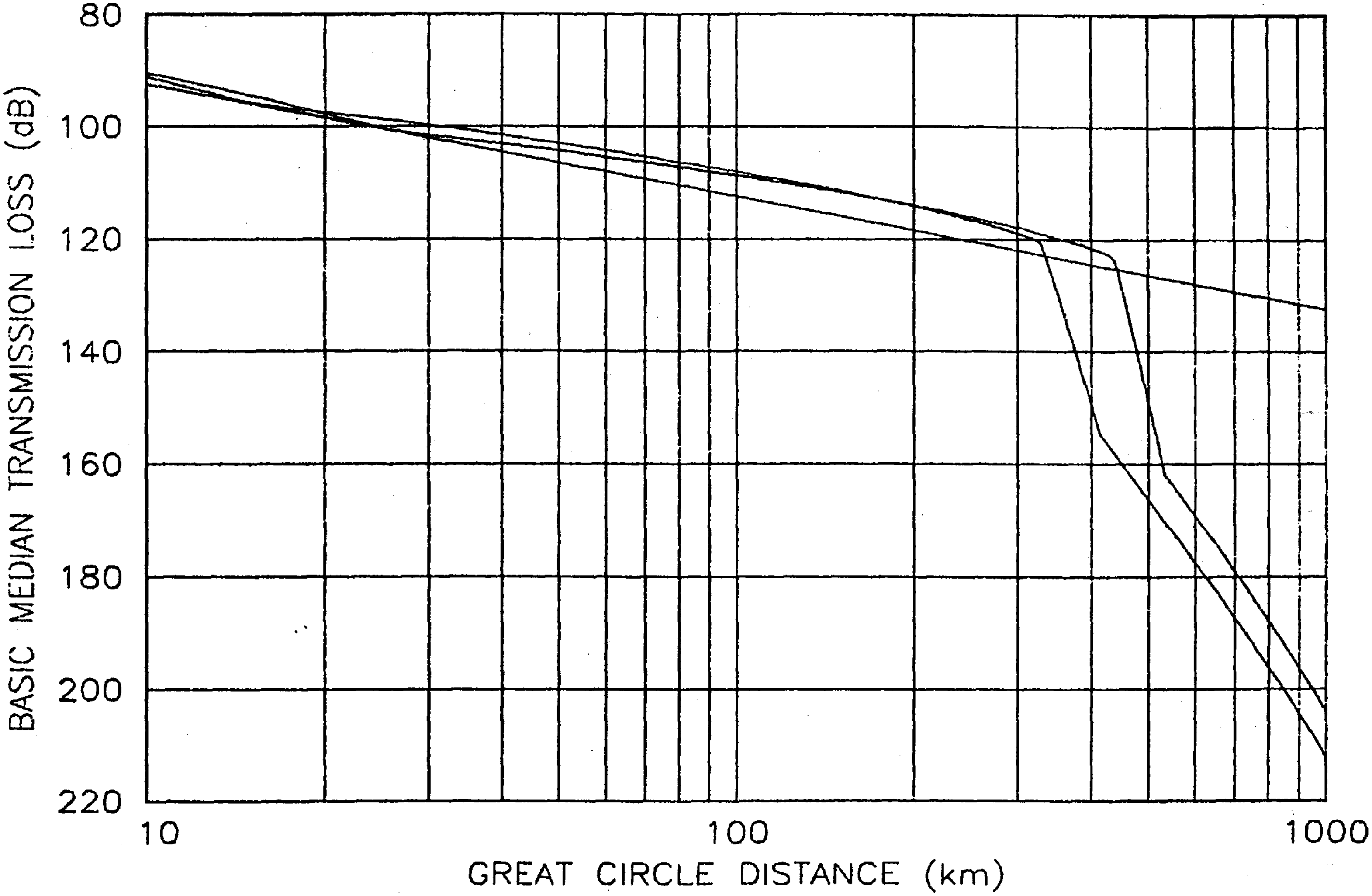

FIGURE A-15. f=100MHz, h_1=2km, h_2=2km,5km

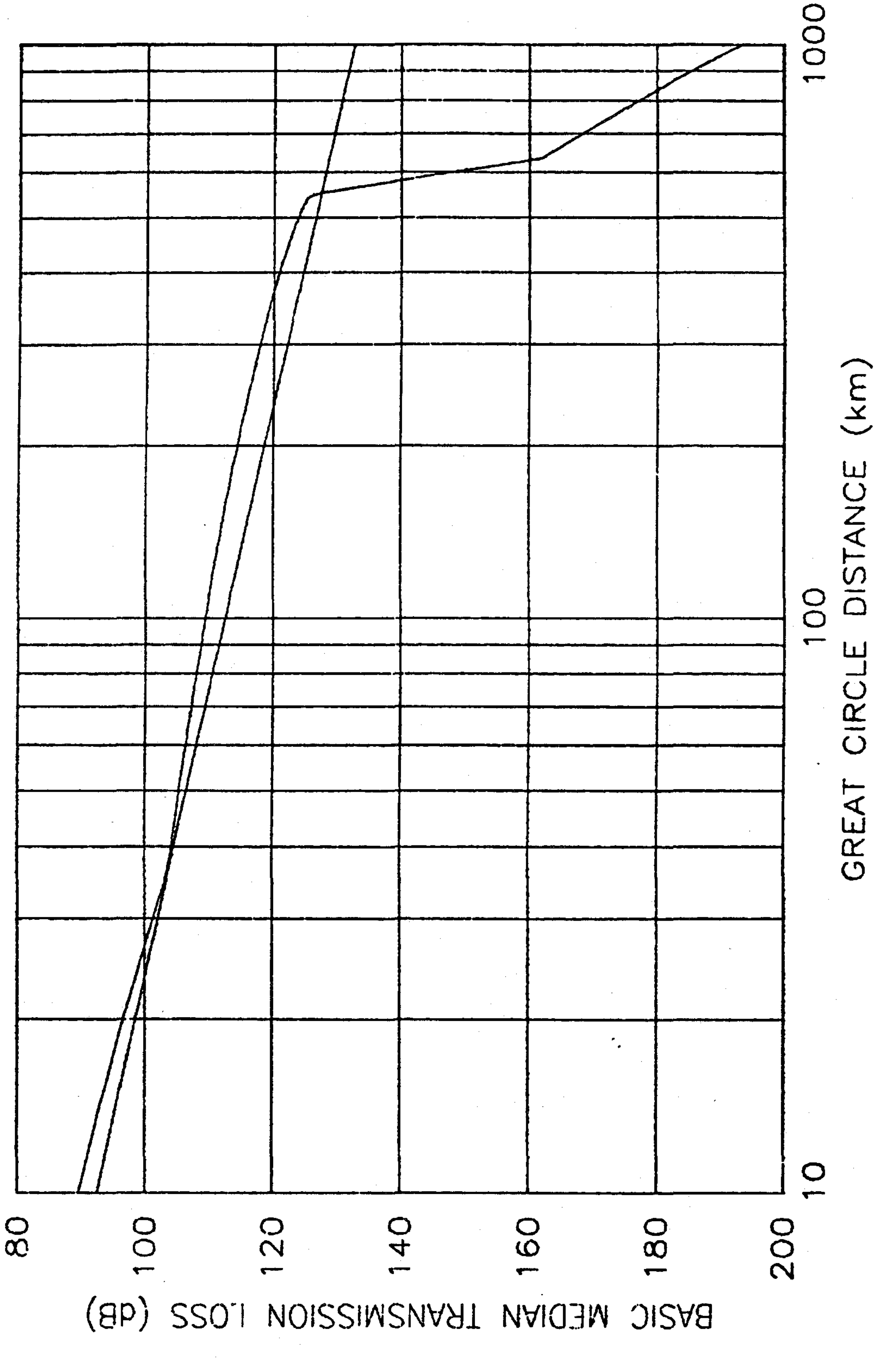

FIGURE A–16. f=100MHz,h_1=5km,h_2=5km

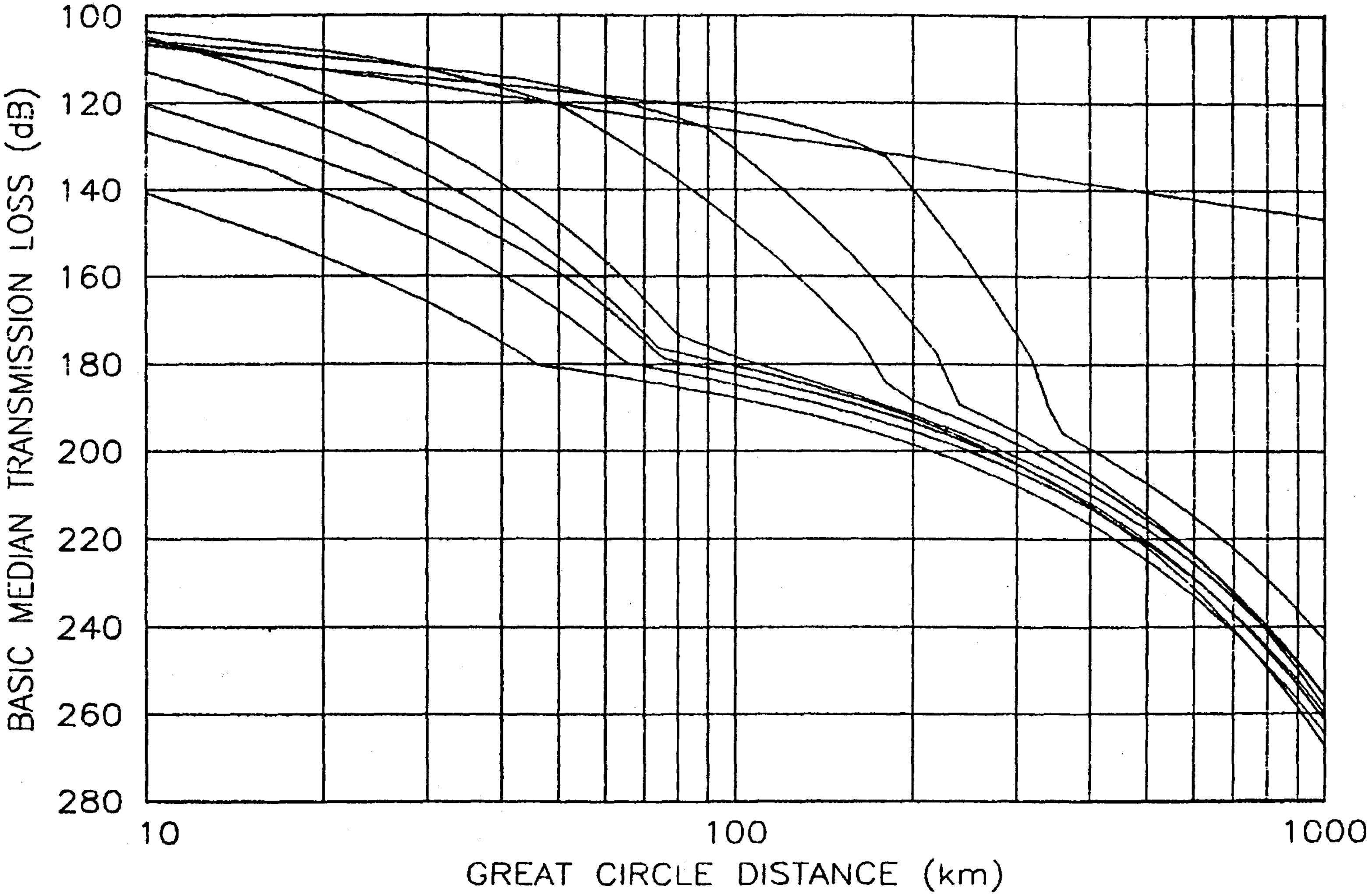

FIGURE A-17. f=500MHz,h_1=1m,h_2=10m,50m,100m,200m,500m,1km,2km,5km

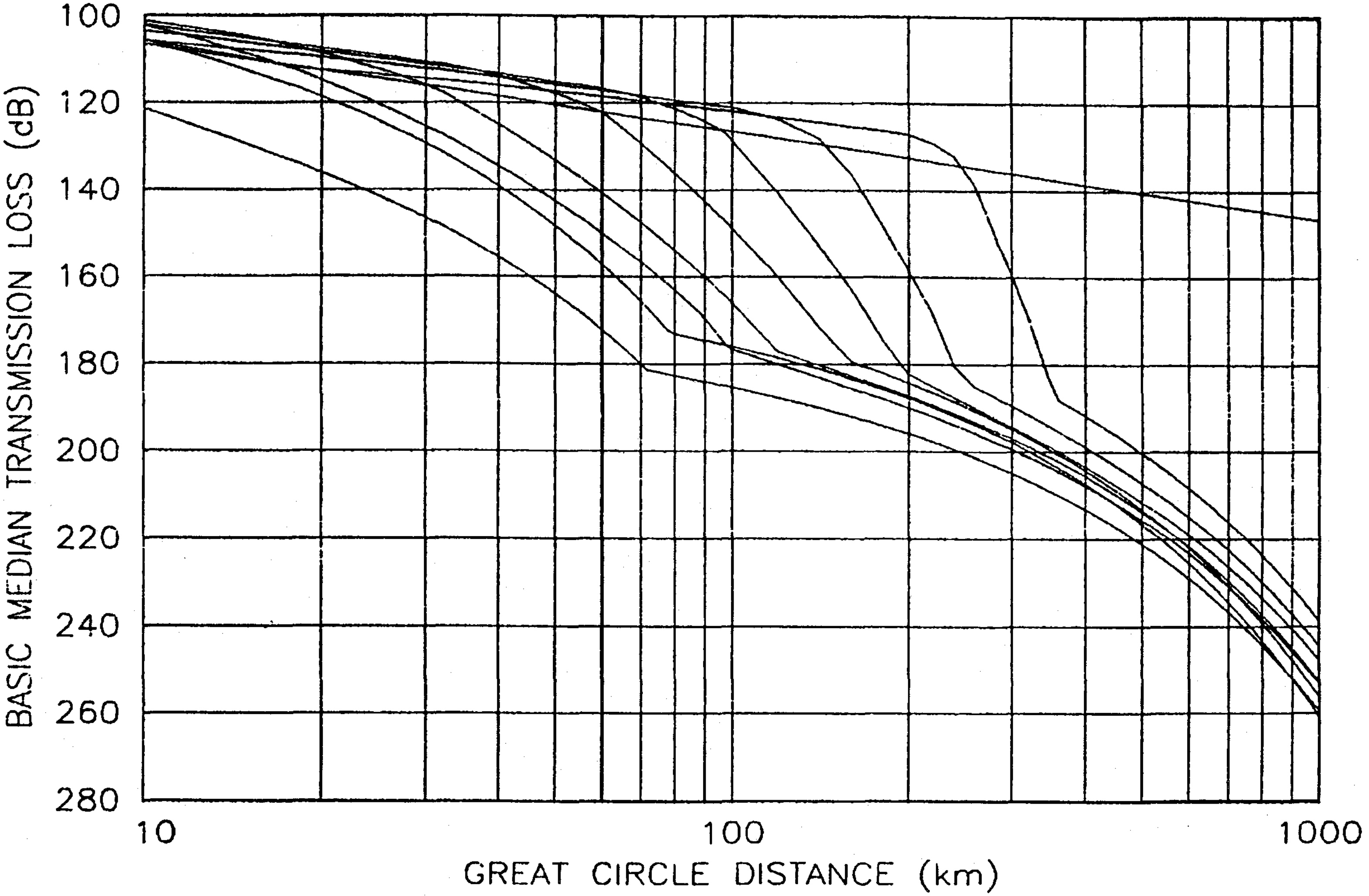

FIGURE A–18. $f=500\text{MHz}, h_1=10\text{m}, h_2=10\text{m}, 50\text{m}, 100\text{m}, 200\text{m}, 500\text{m}, 1\text{km}, 2\text{km}, 5\text{km}$

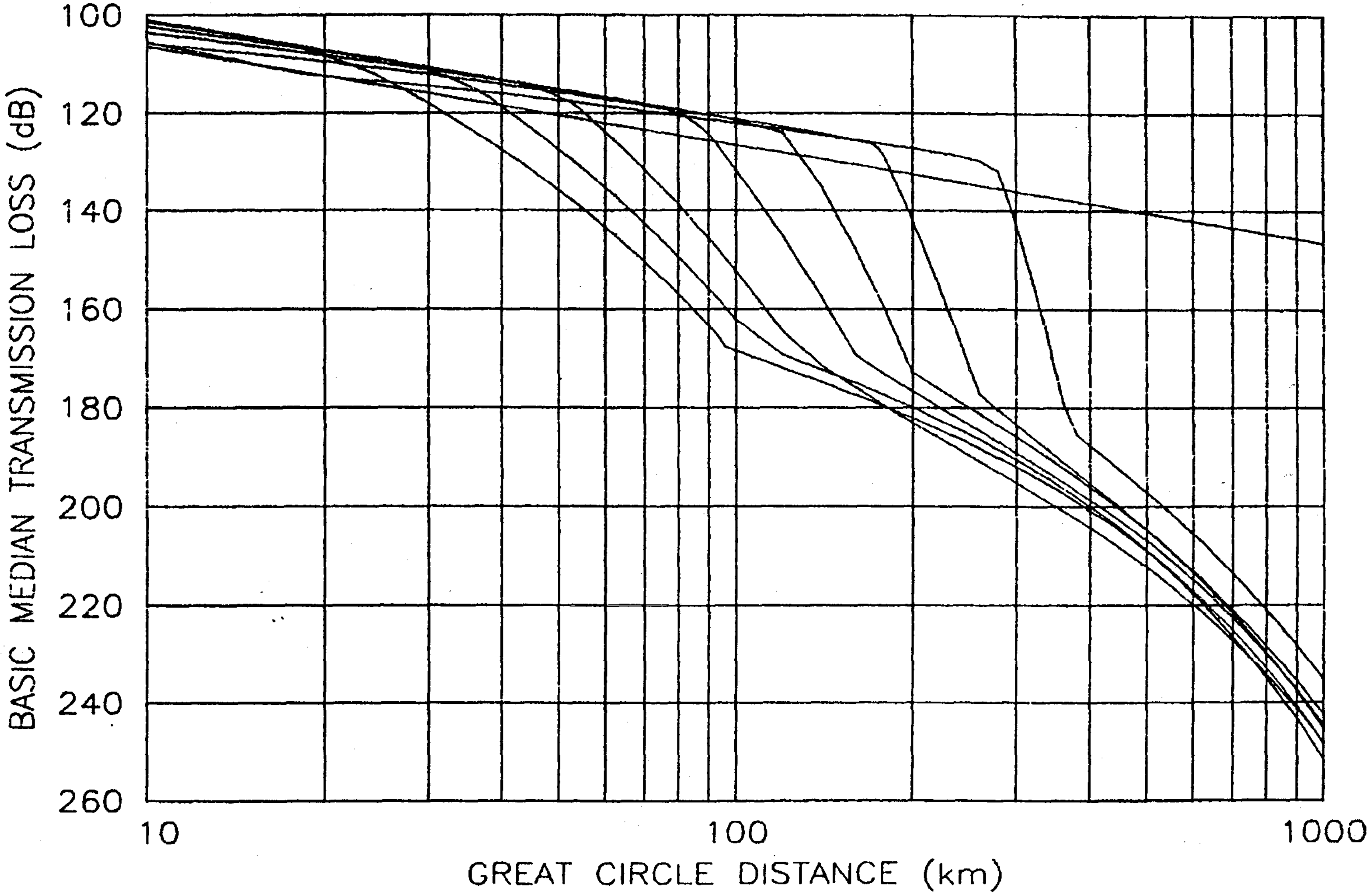

FIGURE A-19. f=500MHz,h_1=50m,h_2=50m,100m,200m,500m,1km,2km,5km

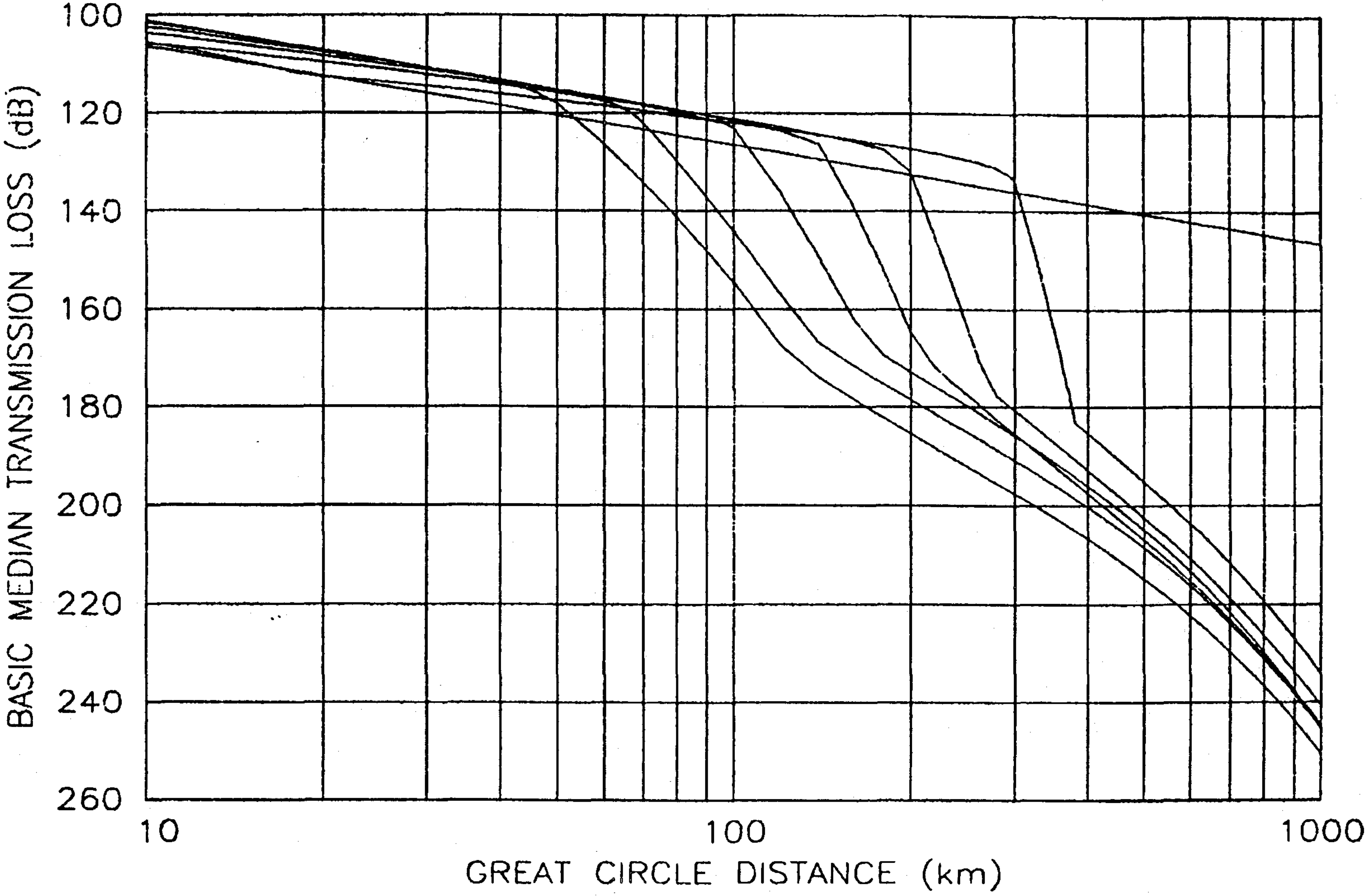

FIGURE A-20. f=500MHz, h_1=100m, h_2=100m, 200m, 500m, 1km, 2km, 5km

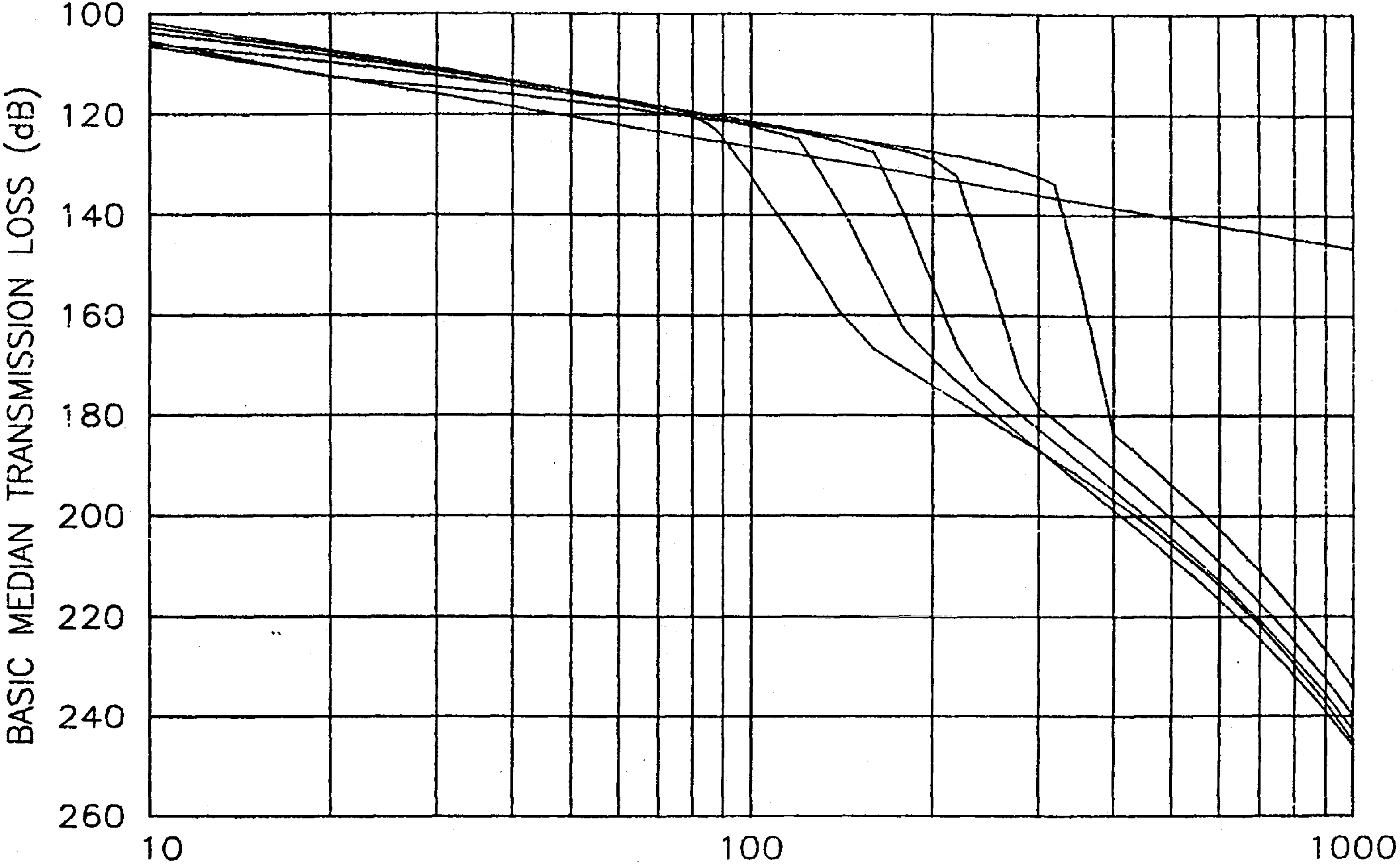

FIGURE A-21. f=500MHz,h_1=200m,h_2=200m,500m,1km,2km,5km

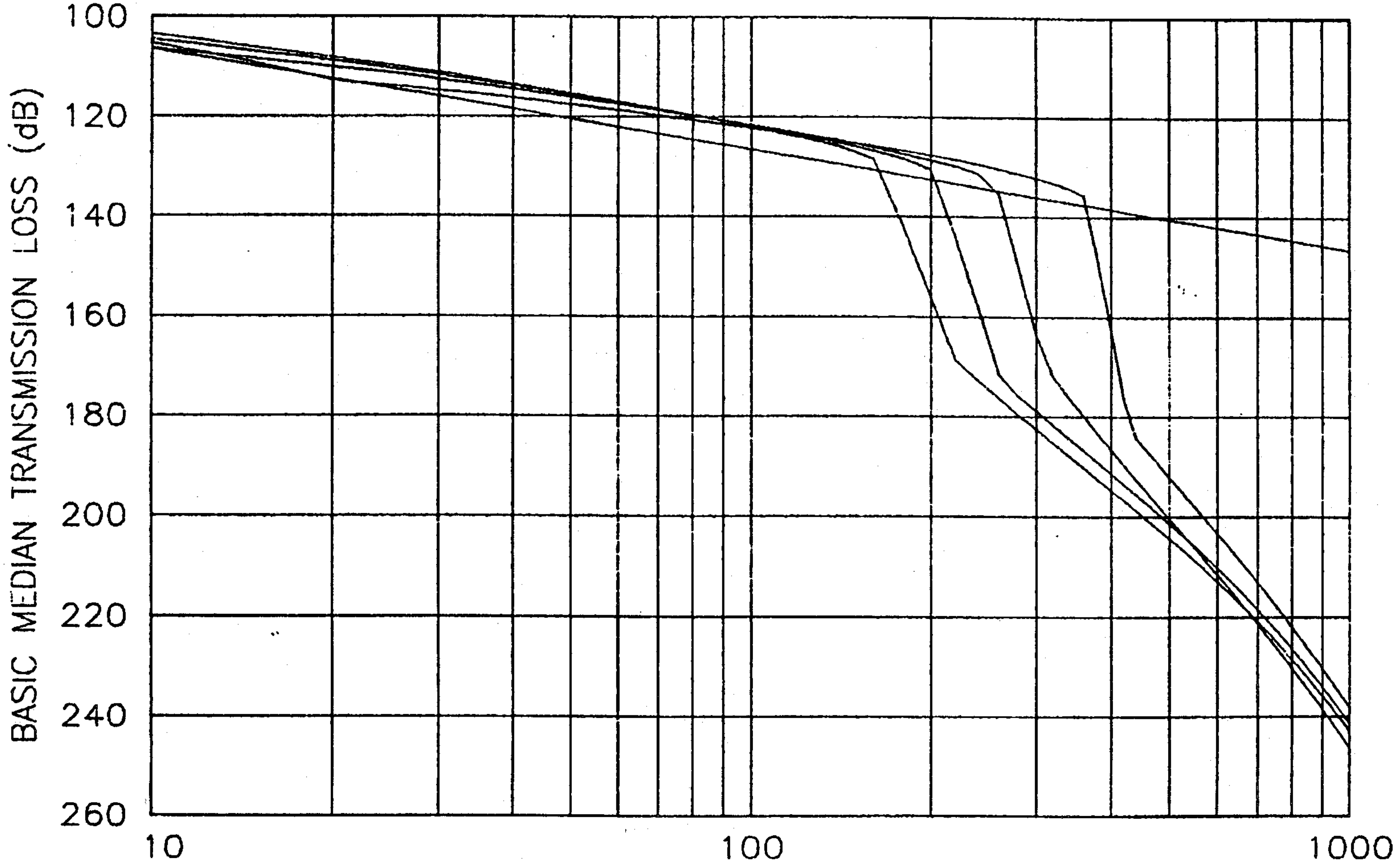

FIGURE A-22. f=500MHz, h_1=500m, h_2=500m, 1km, 2km, 5km

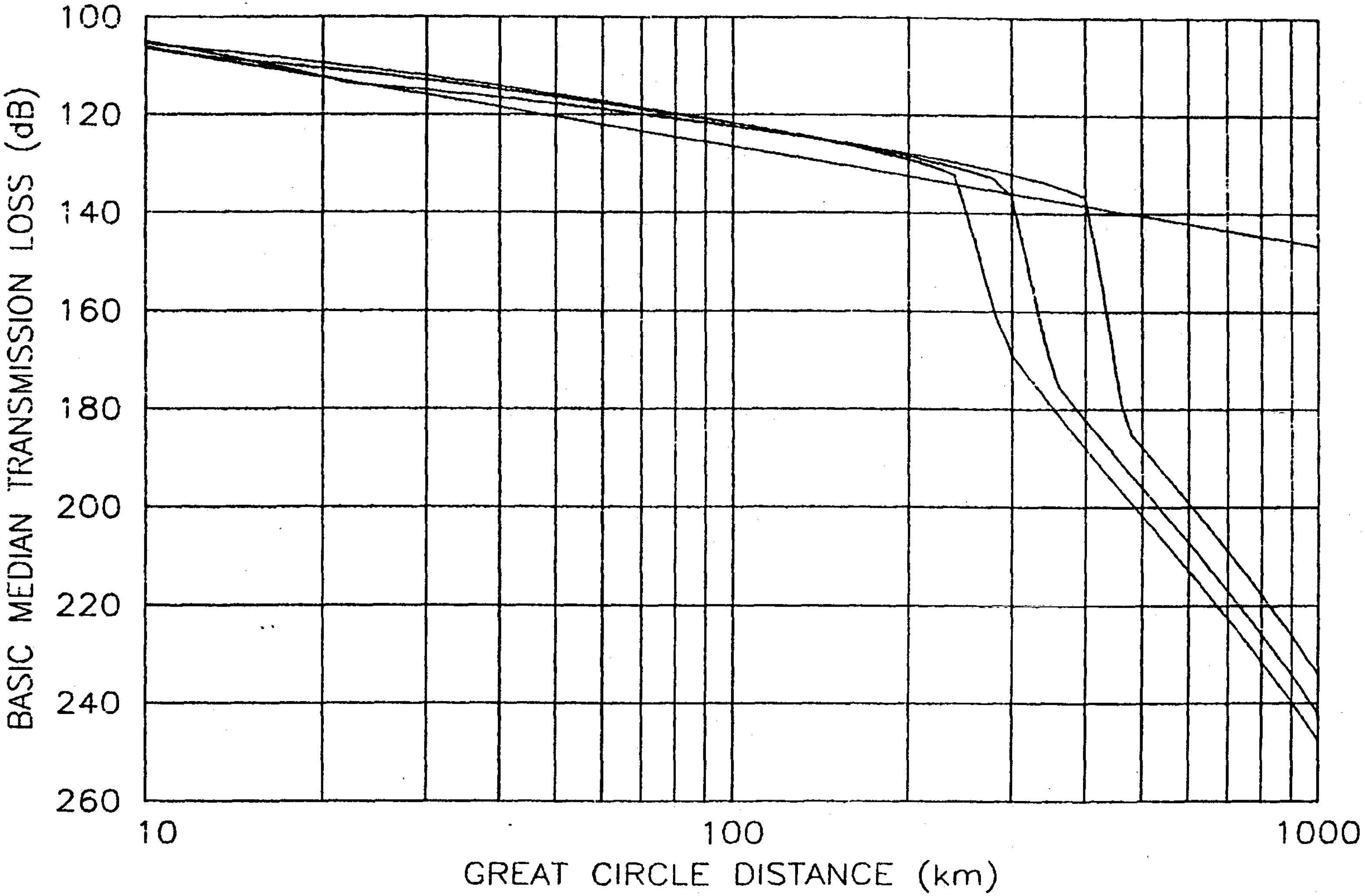

FIGURE A–23. f=500MHz,h_1=1km,h_2=1km,2km,5km

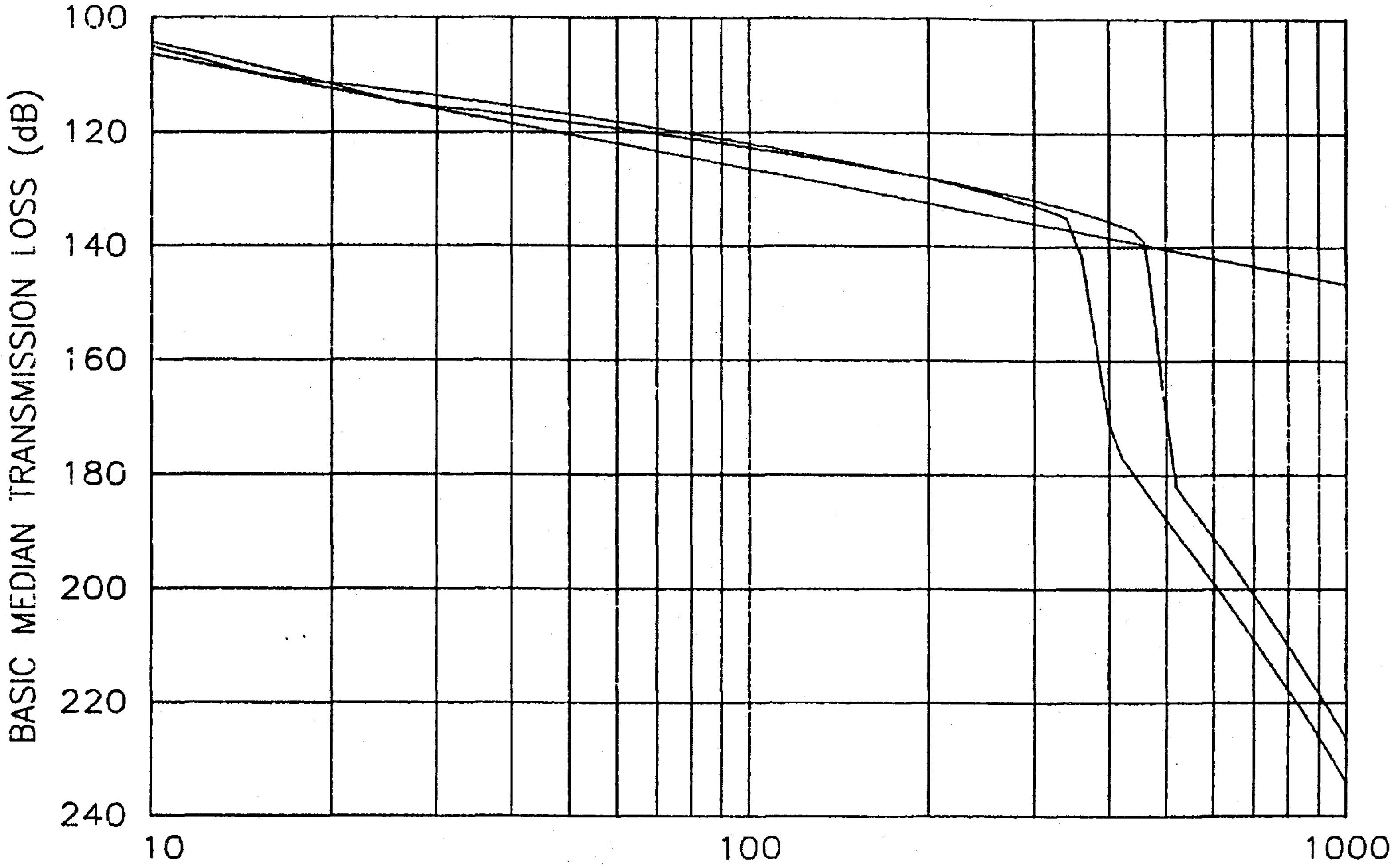

FIGURE A-24. $f = 500 MHz, h_1 = 2 km, h_2 = 2 km, 5 km$

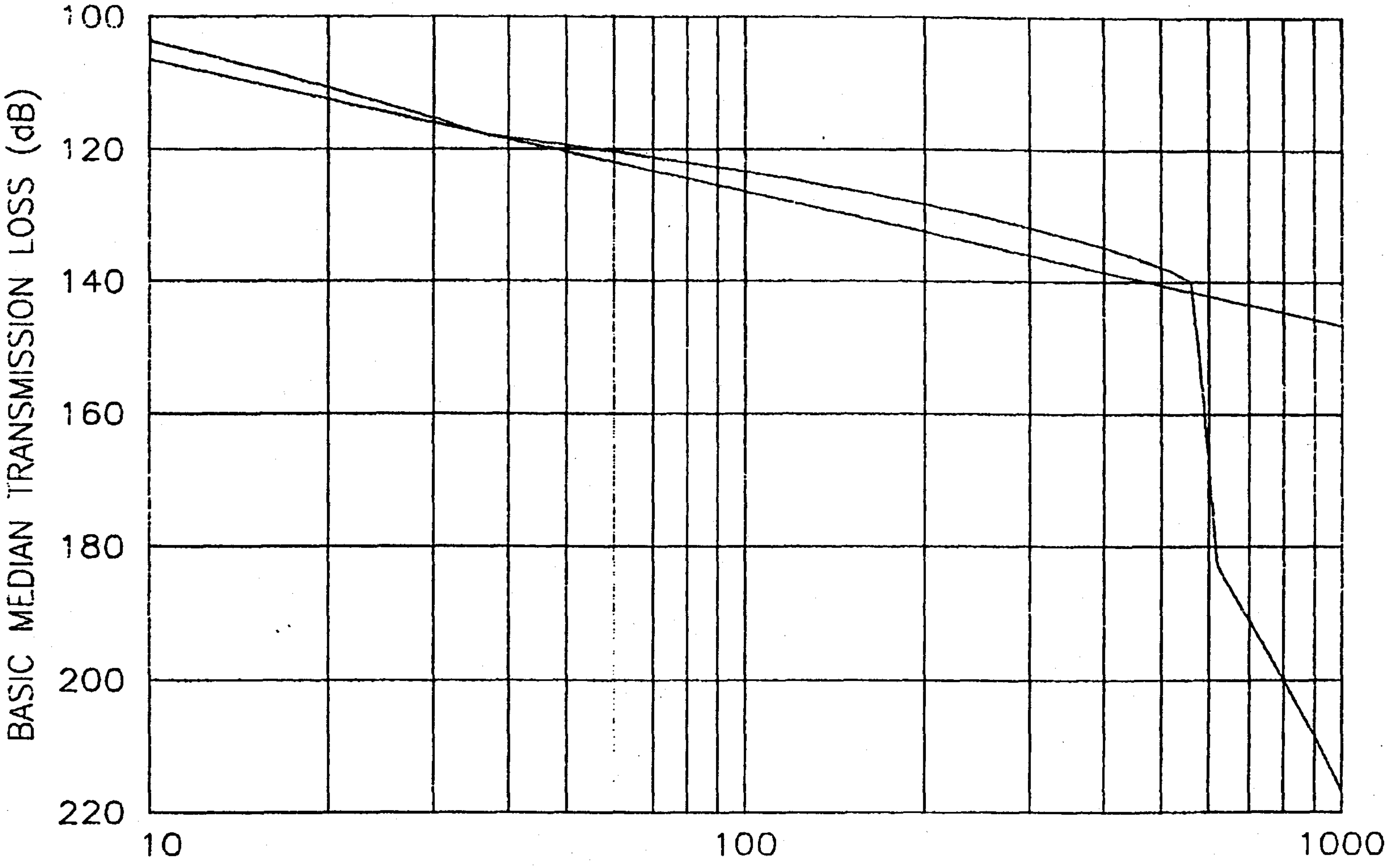

FIGURE A-25. $f=500\text{MHz}, h_1=5\text{km}, h_2=5\text{km}$

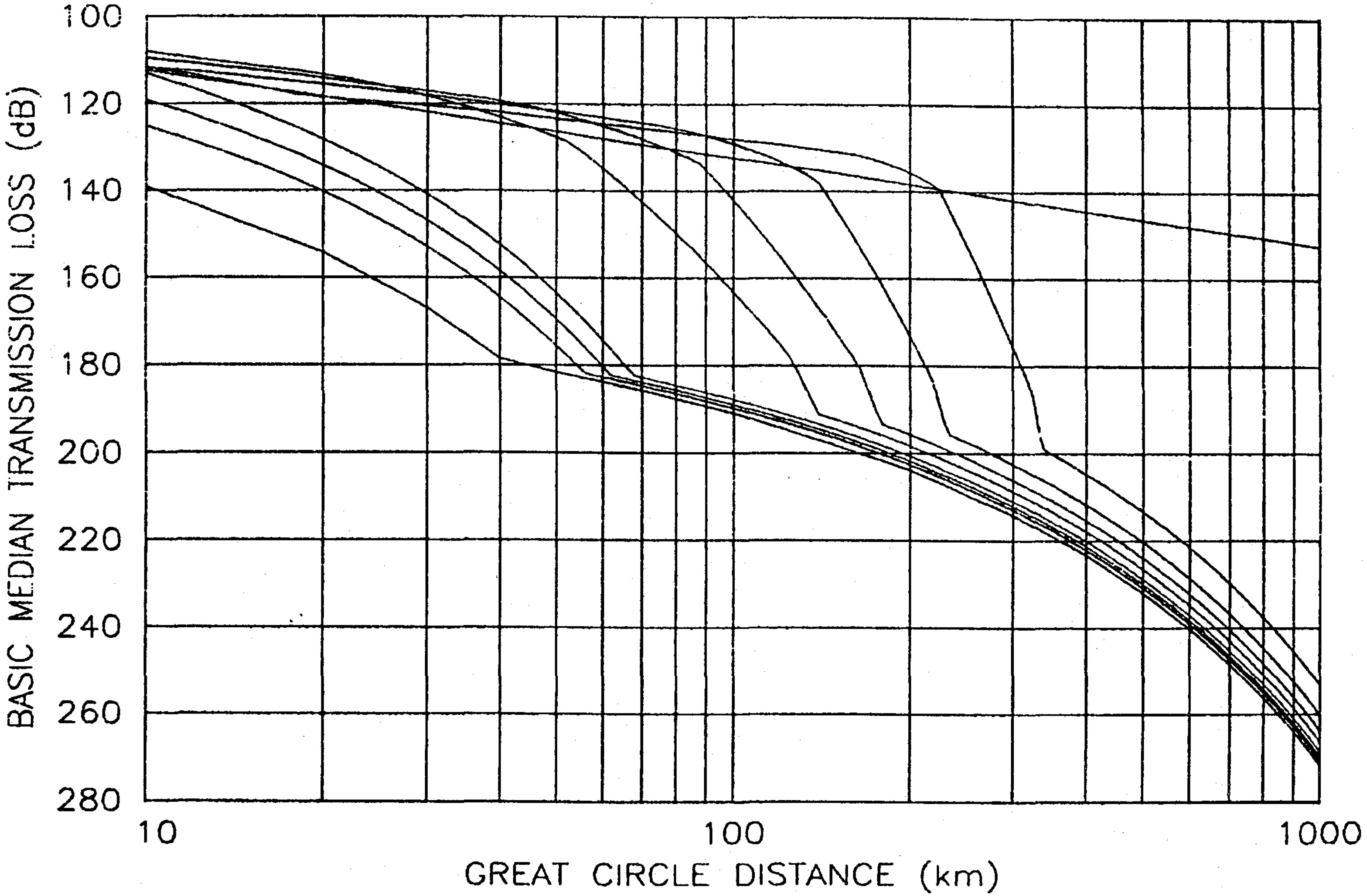

FIGURE A-26. $f=1GHz, h_1=1m, h_2=10m, 50m, 100m, 200m, 500m, 1km, 2km, 5km$

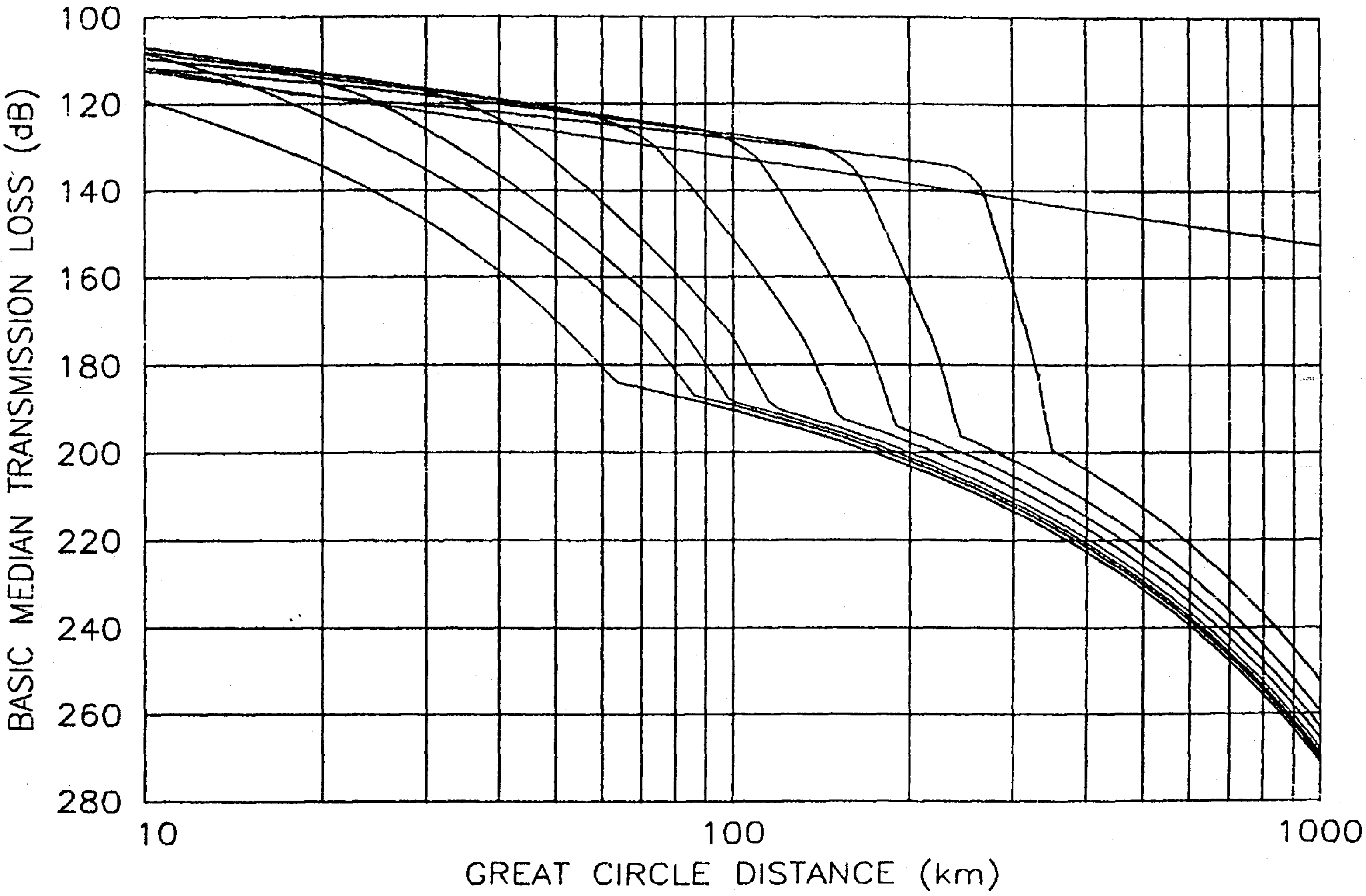

FIGURE A-27. $f=1\text{GHz}, h_1=10\text{m}, h_2=10\text{m}, 50\text{m}, 100\text{m}, 200\text{m}, 500\text{m}, 1\text{km}, 2\text{km}, 5\text{km}$

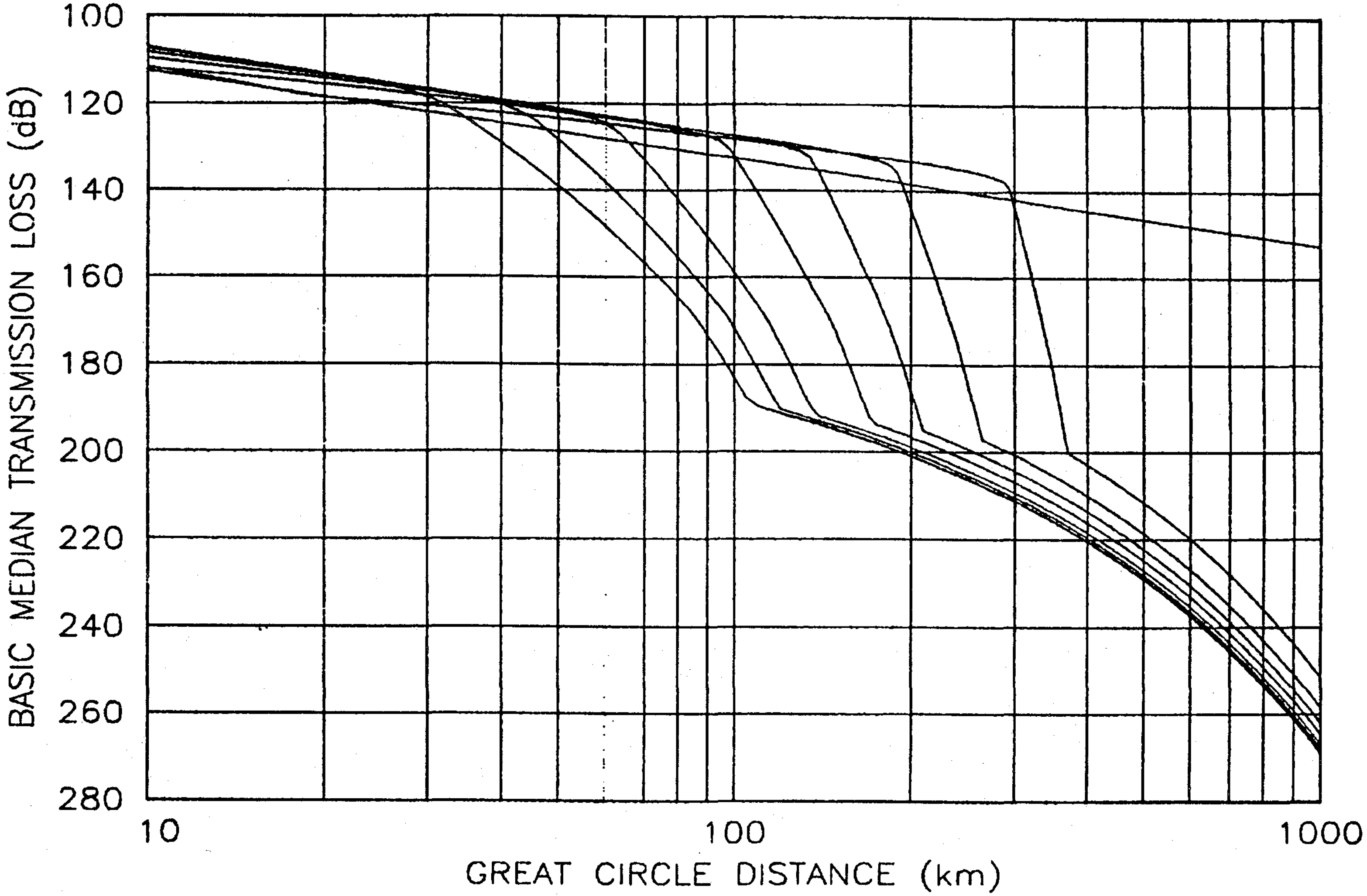

FIGURE A-28. f=1GHz,h_1=50m,h_2=50m,100m,200m,500m,1km,2km,5km

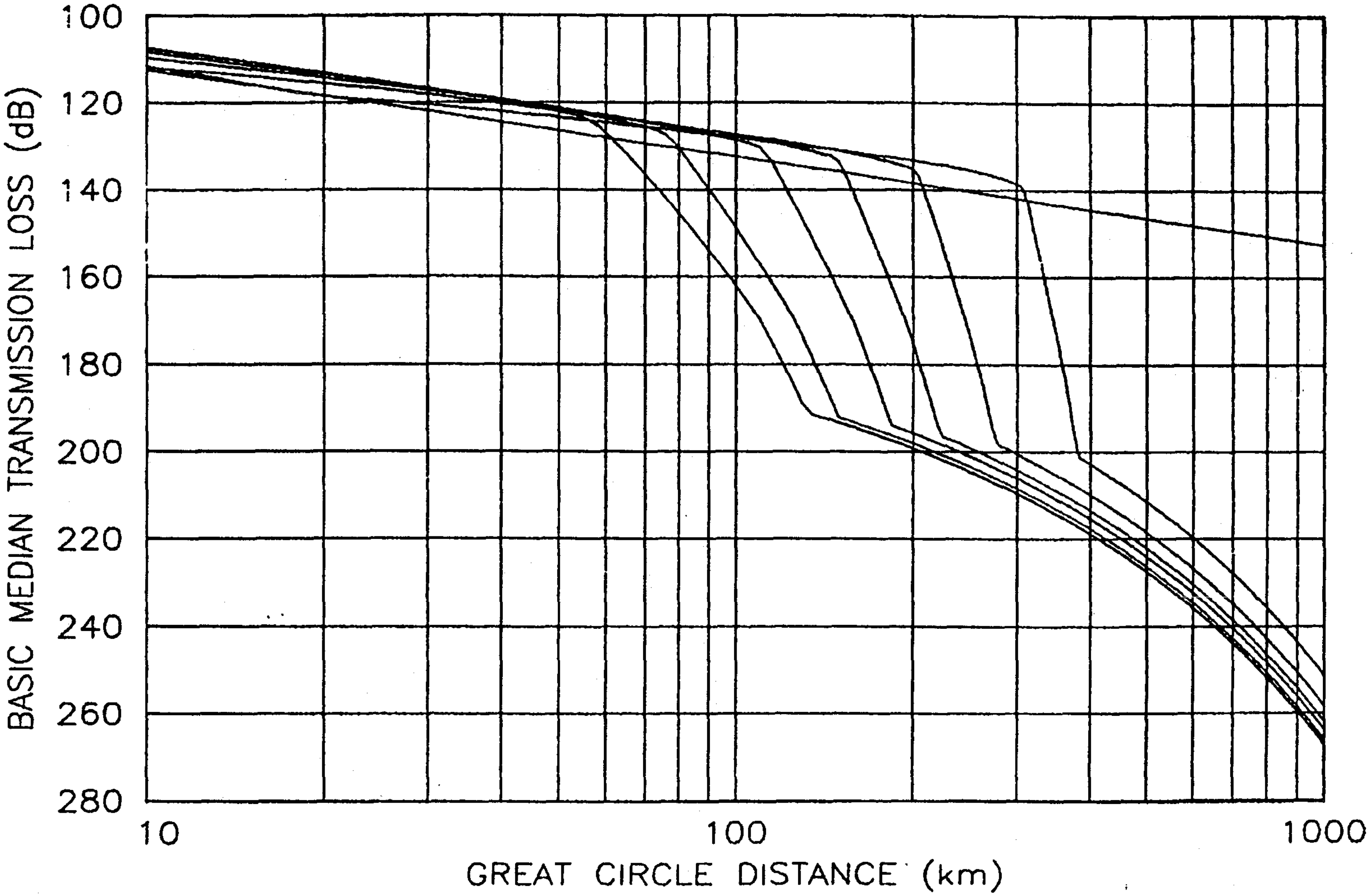

FIGURE A-29. $f = 1\text{GHz}, h_1 = 100\text{m}, h_2 = 100\text{m}, 200\text{m}, 500\text{m}, 1\text{km}, 2\text{km}, 5\text{km}$

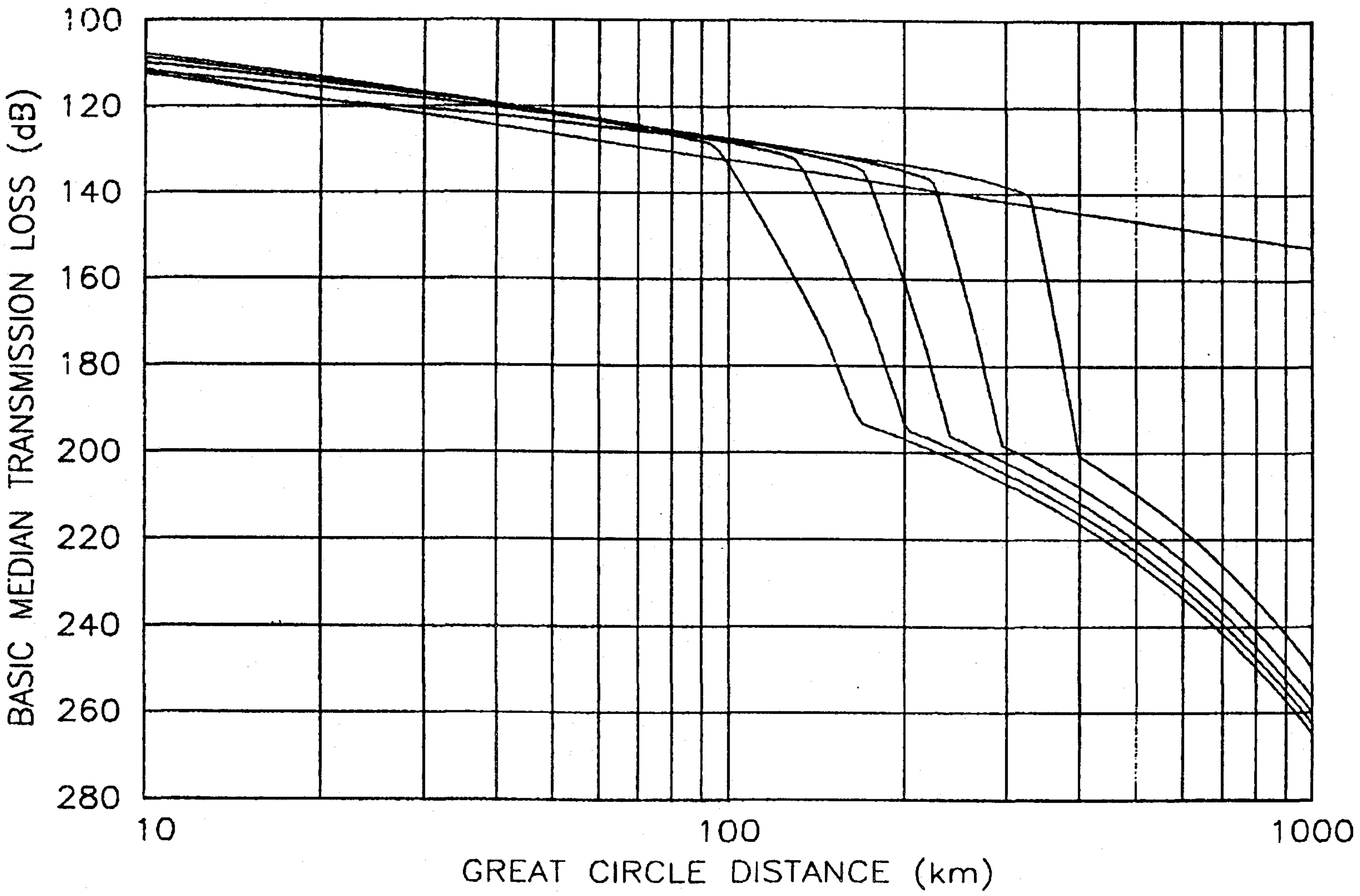

FIGURE A–30. $f=1\text{GHz}, h_1=200\text{m}, h_2=200\text{m}, 500\text{m}, 1\text{km}, 2\text{km}, 5\text{km}$

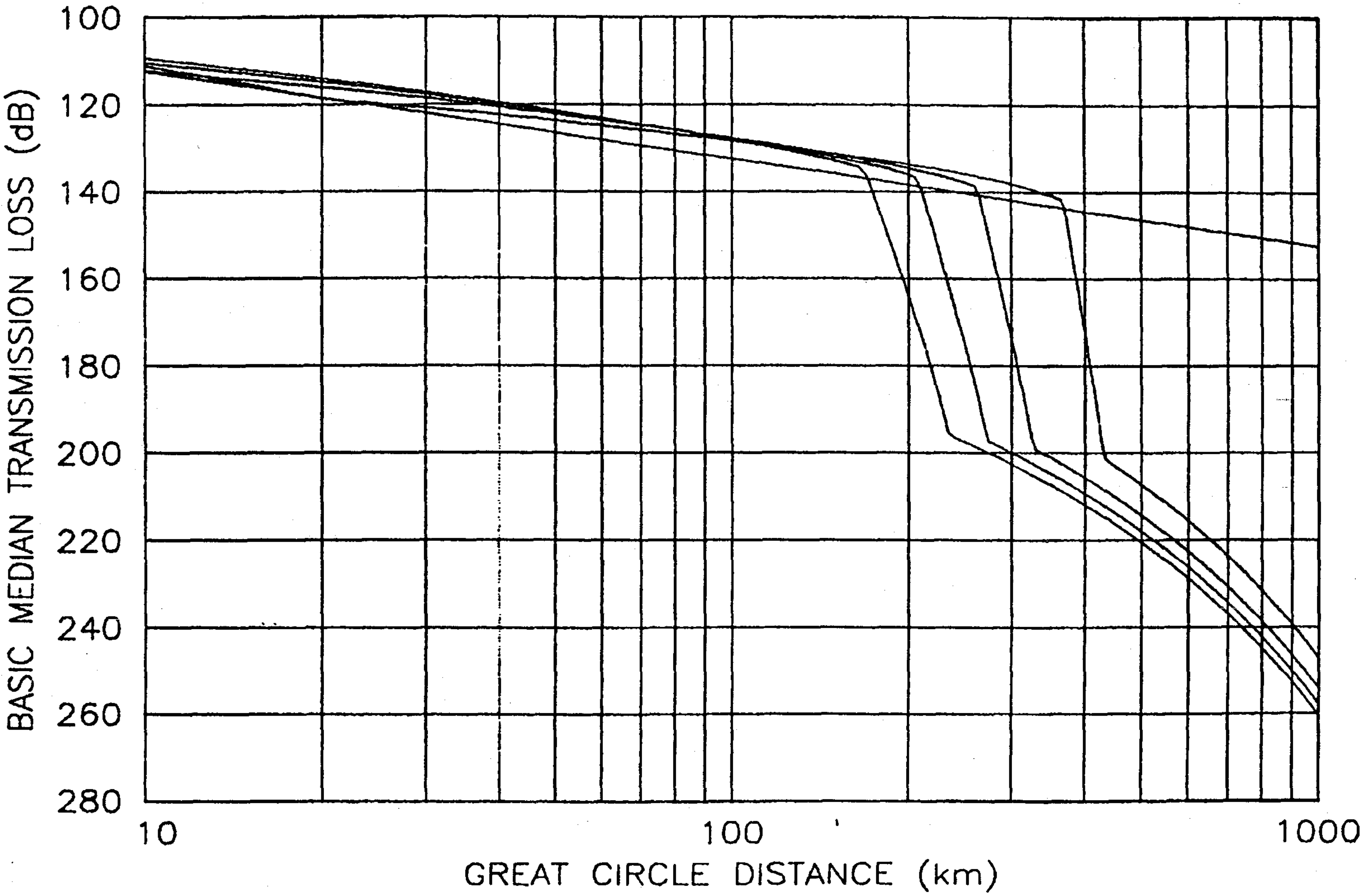

FIGURE A-31. f=1GHz,h_1=500m,h_2=500m,1km,2km,5km

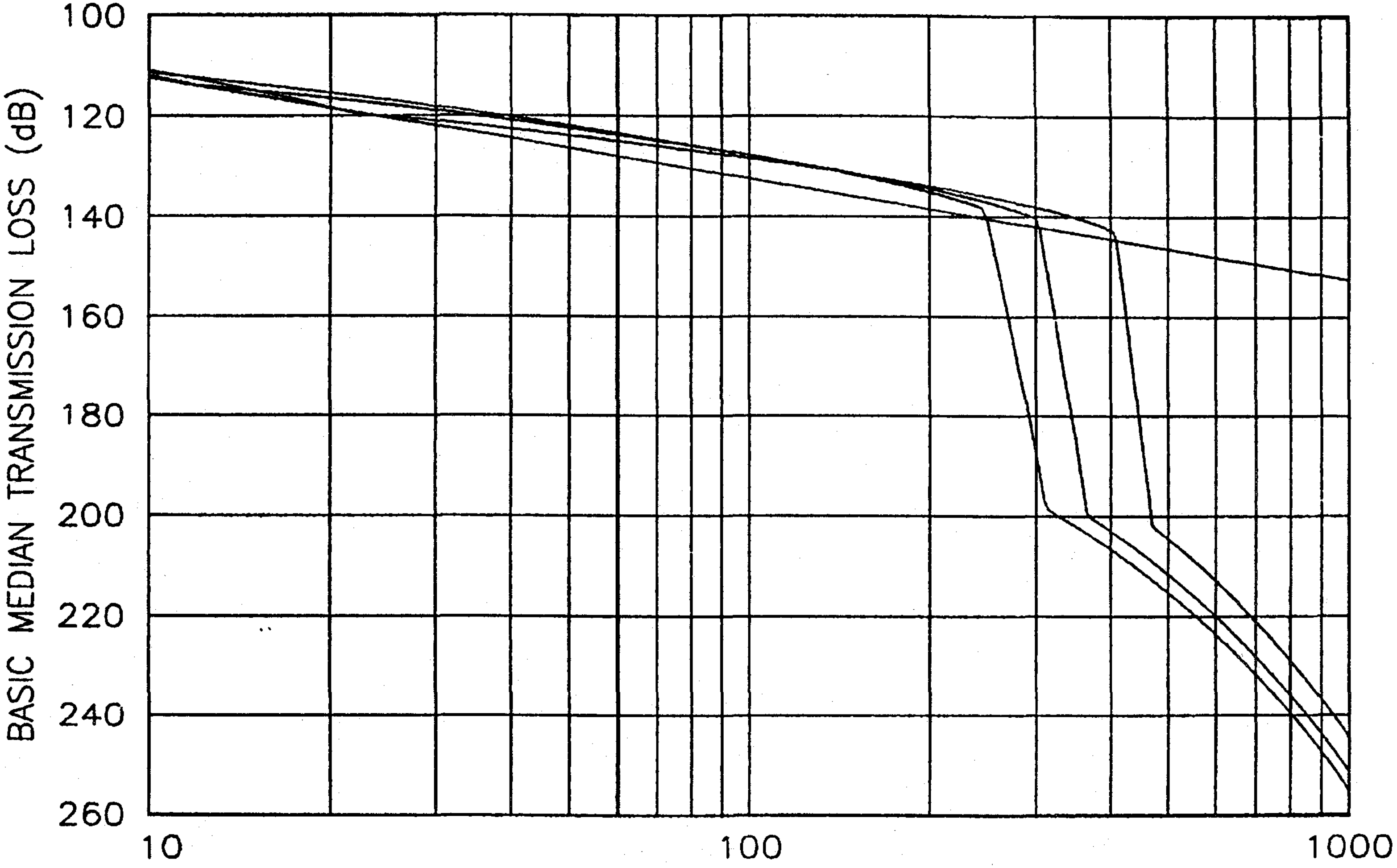

FIGURE A-32. $f=1$GHz,$h_1=1$km,$h_2=1$km,2km,5km

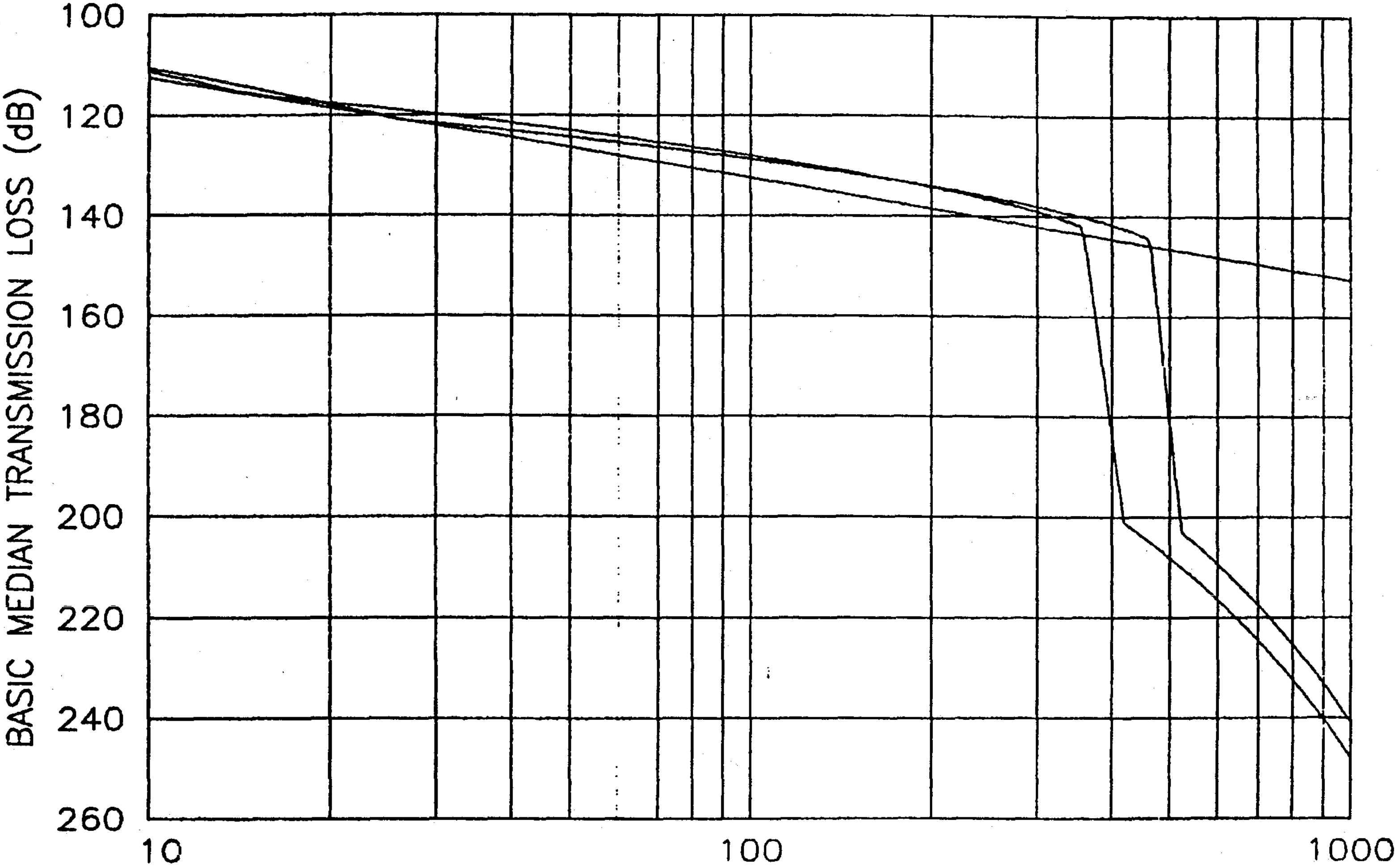

FIGURE A–33. f=1GHz,h_1=2km,h_2=2km,5km

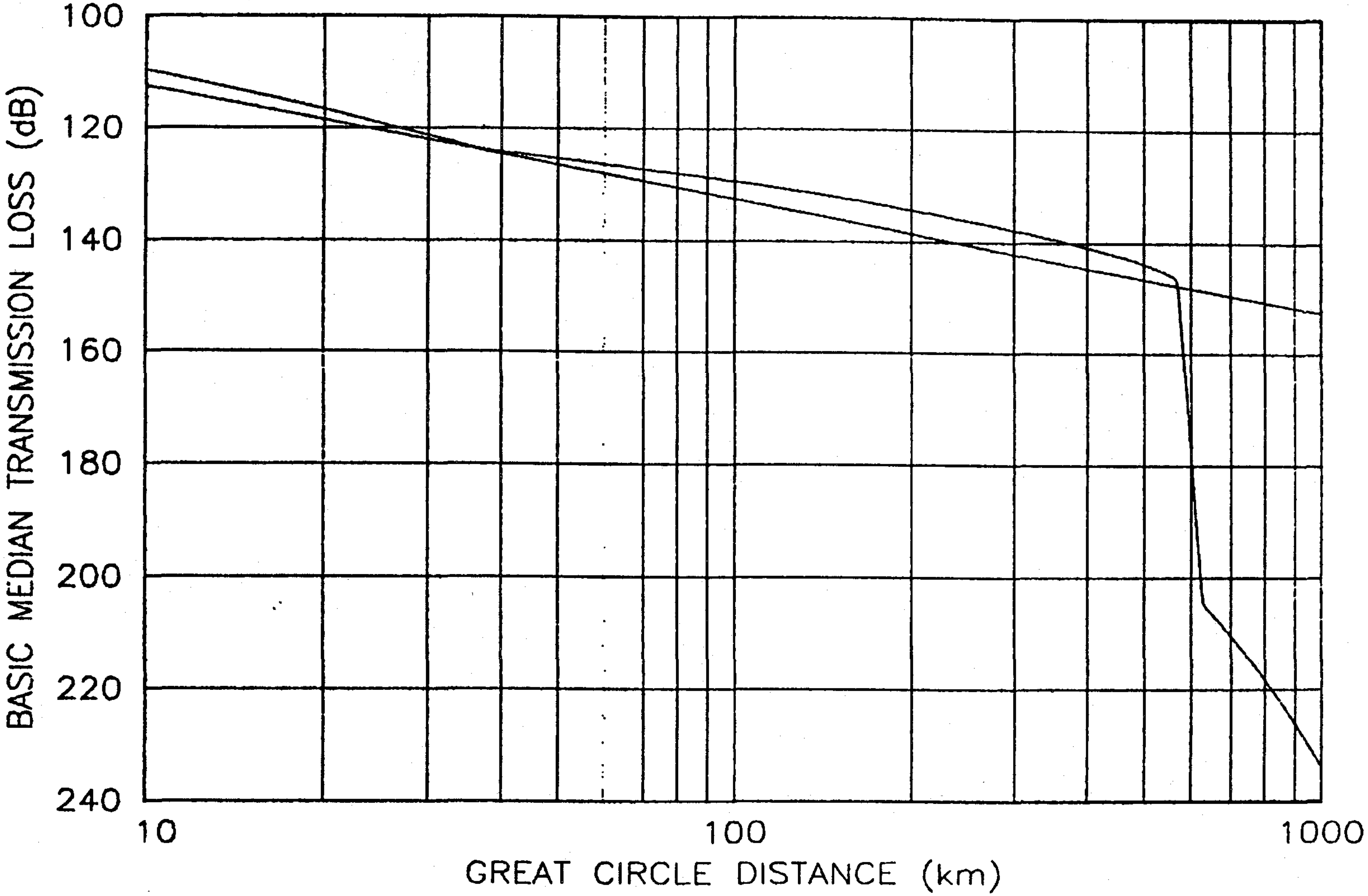

FIGURE A-34. $f=1GHz, h_1=5km, h_2=5km$

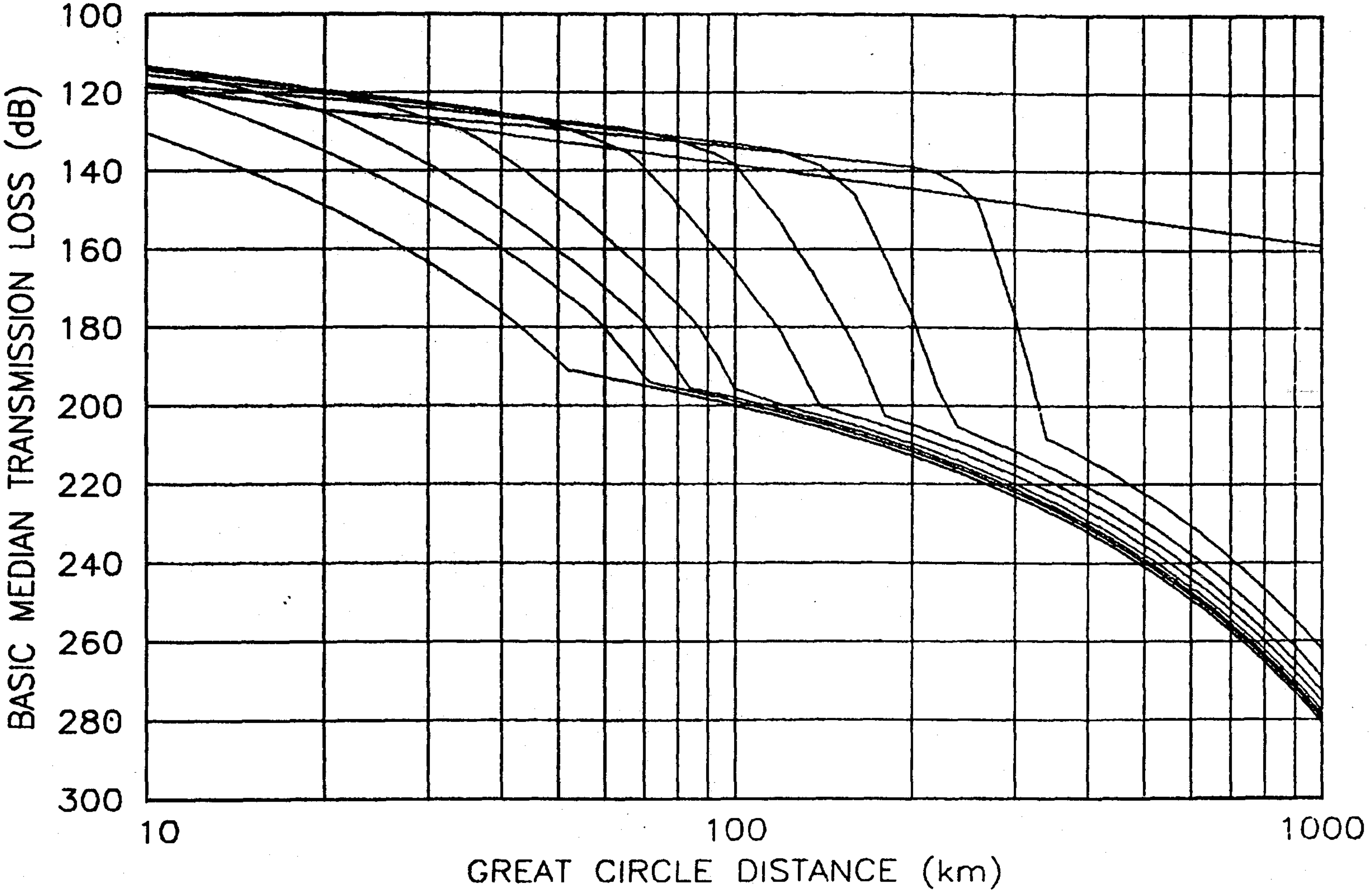

FIGURE A–35. f=2GHz,h_1=1m,h_2=10m,50m,100m,200m,500m,1km,2km,5km

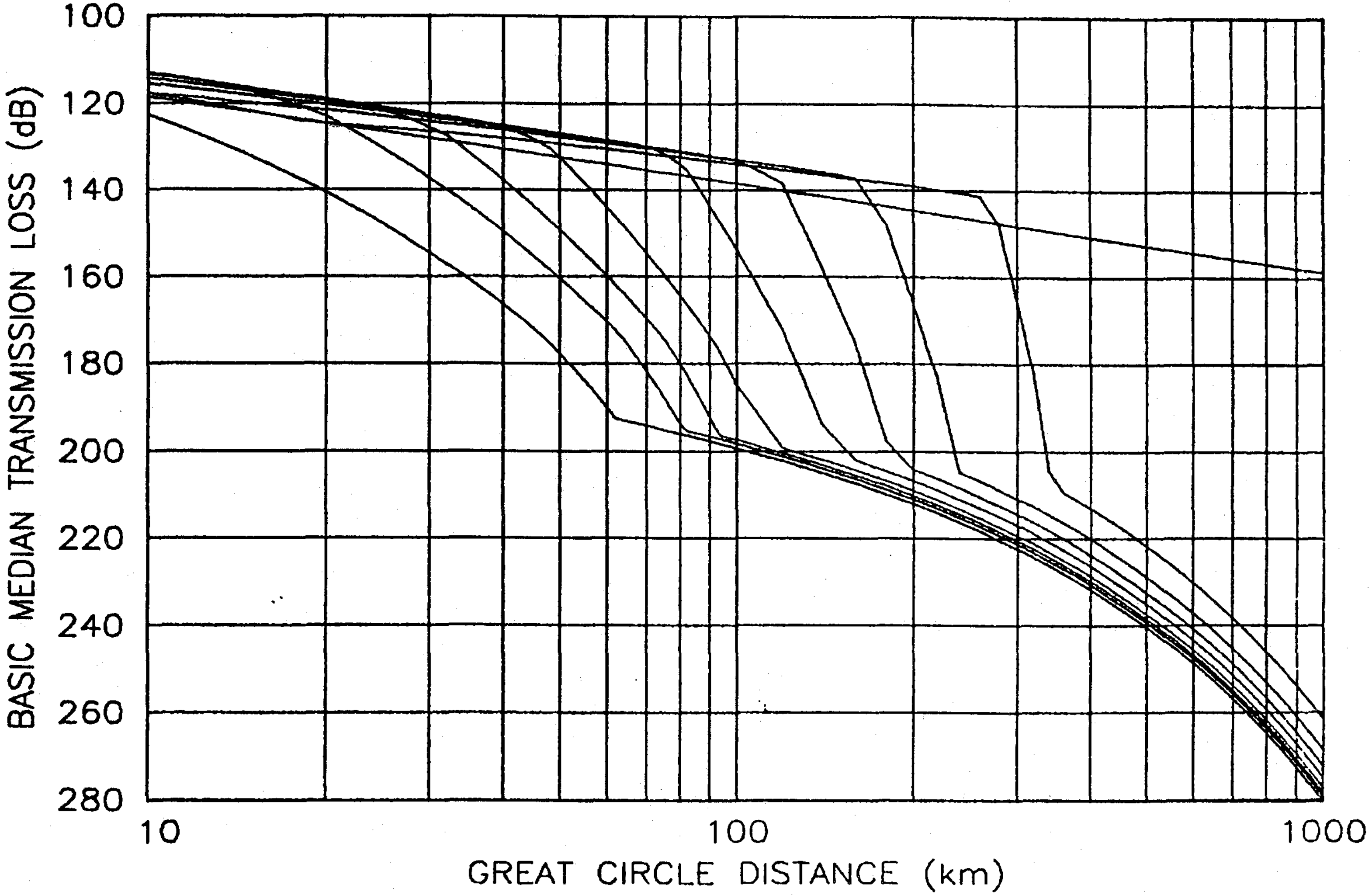

FIGURE A–36. f=2GHz,h_1=10m,h_2=10m,50m,100m,200m,500m,1km,2km,5km

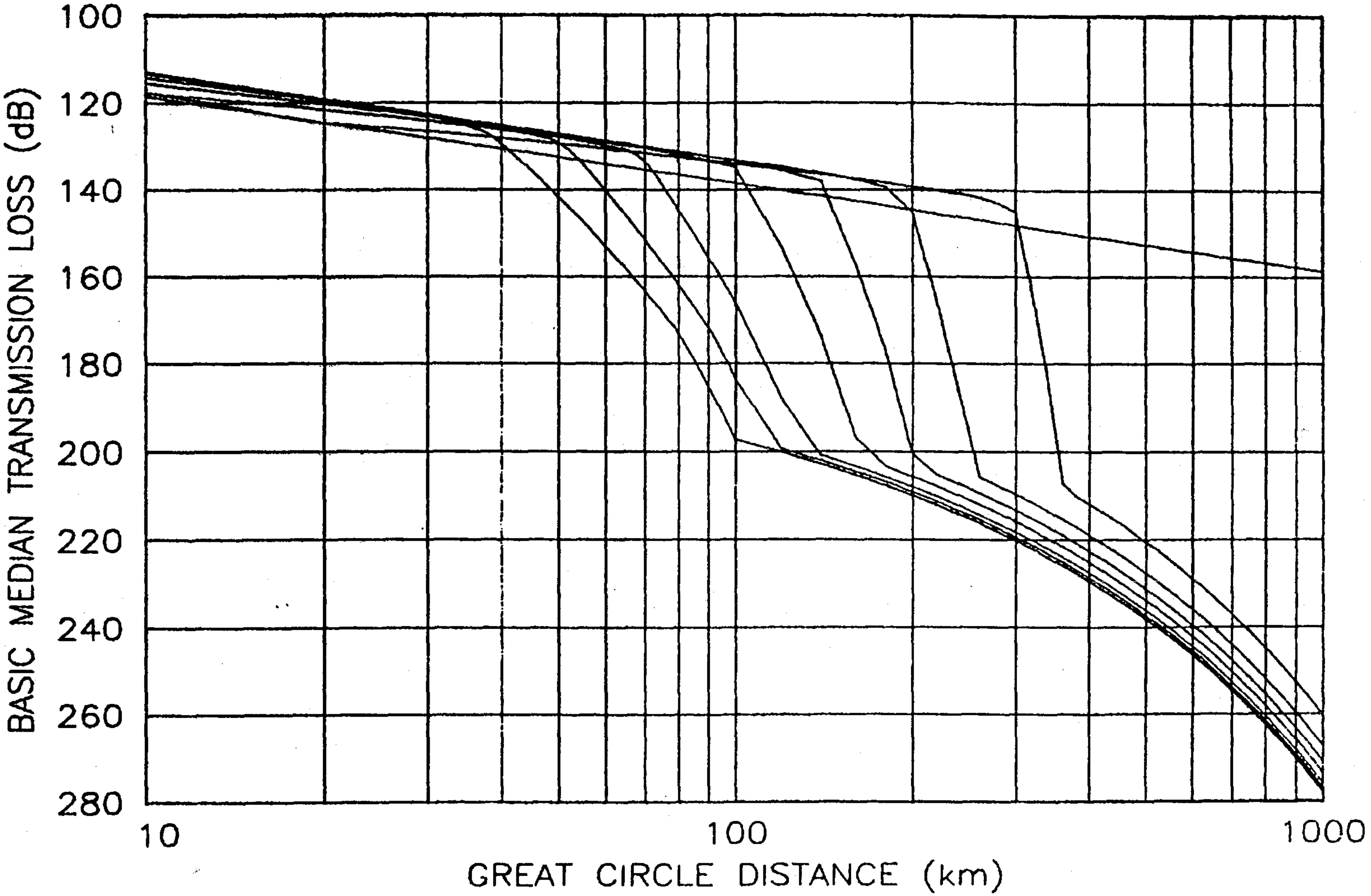

FIGURE A-37. f=2GHz, h_1=50m, h_2=50m, 100m, 200m, 500m, 1km, 2km, 5km

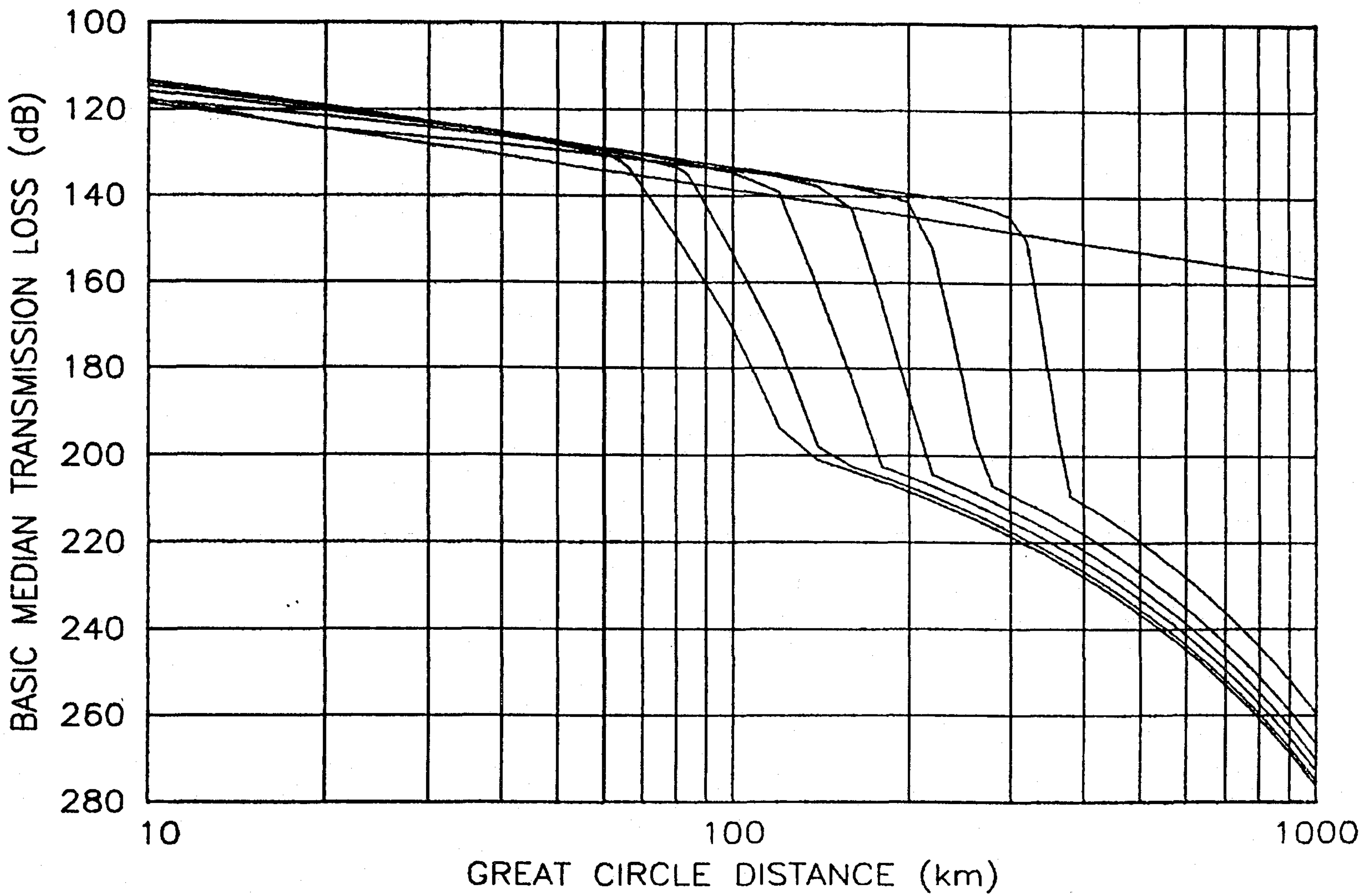

FIGURE A-38. $f=2\text{GHz}, h_1=100\text{m}, h_2=100\text{m}, 200\text{m}, 500\text{m}, 1\text{km}, 2\text{km}, 5\text{km}$

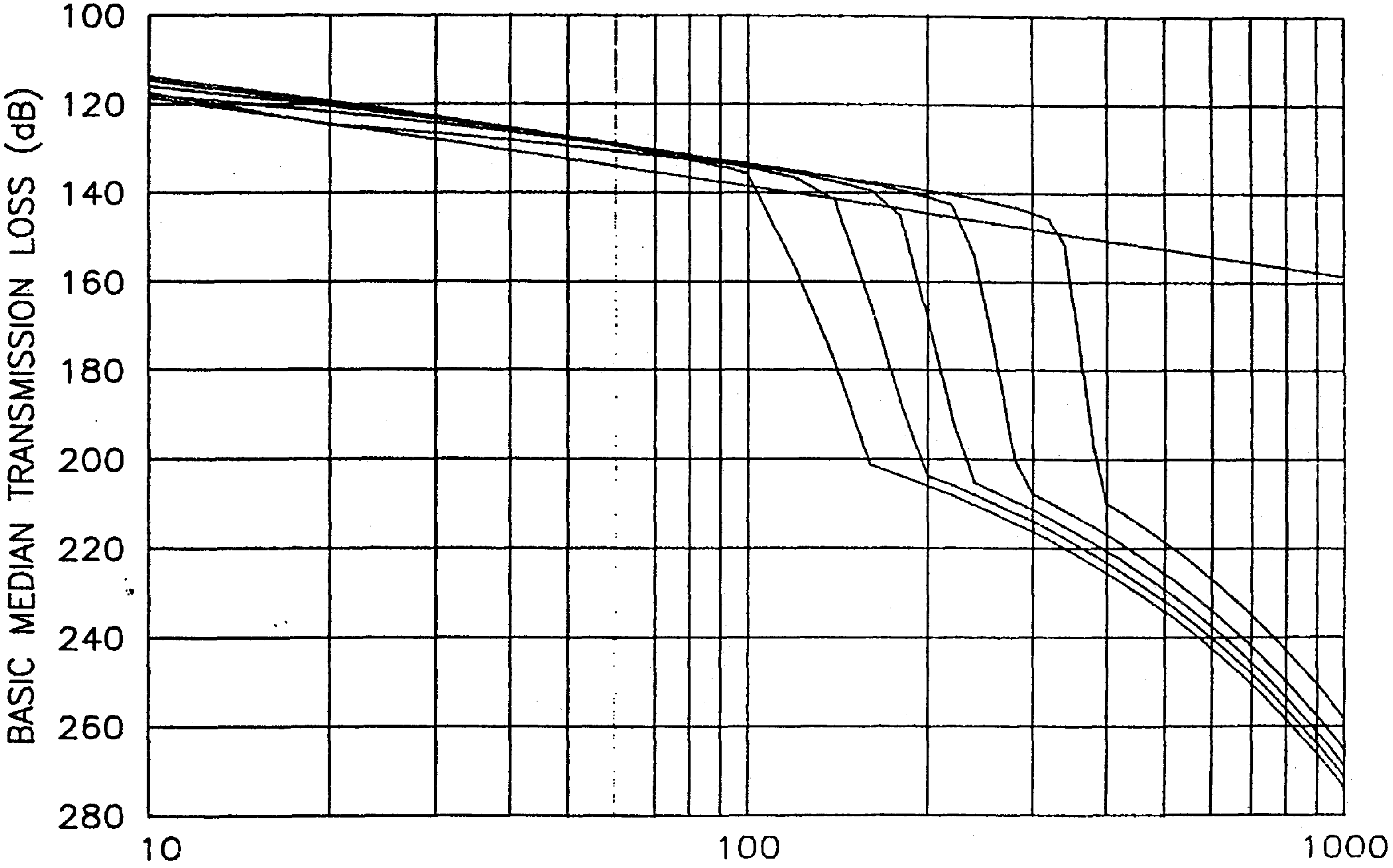

FIGURE A–39. f=2GHz,h_1=200m,h_2=200m,500m,1km,2km,5km

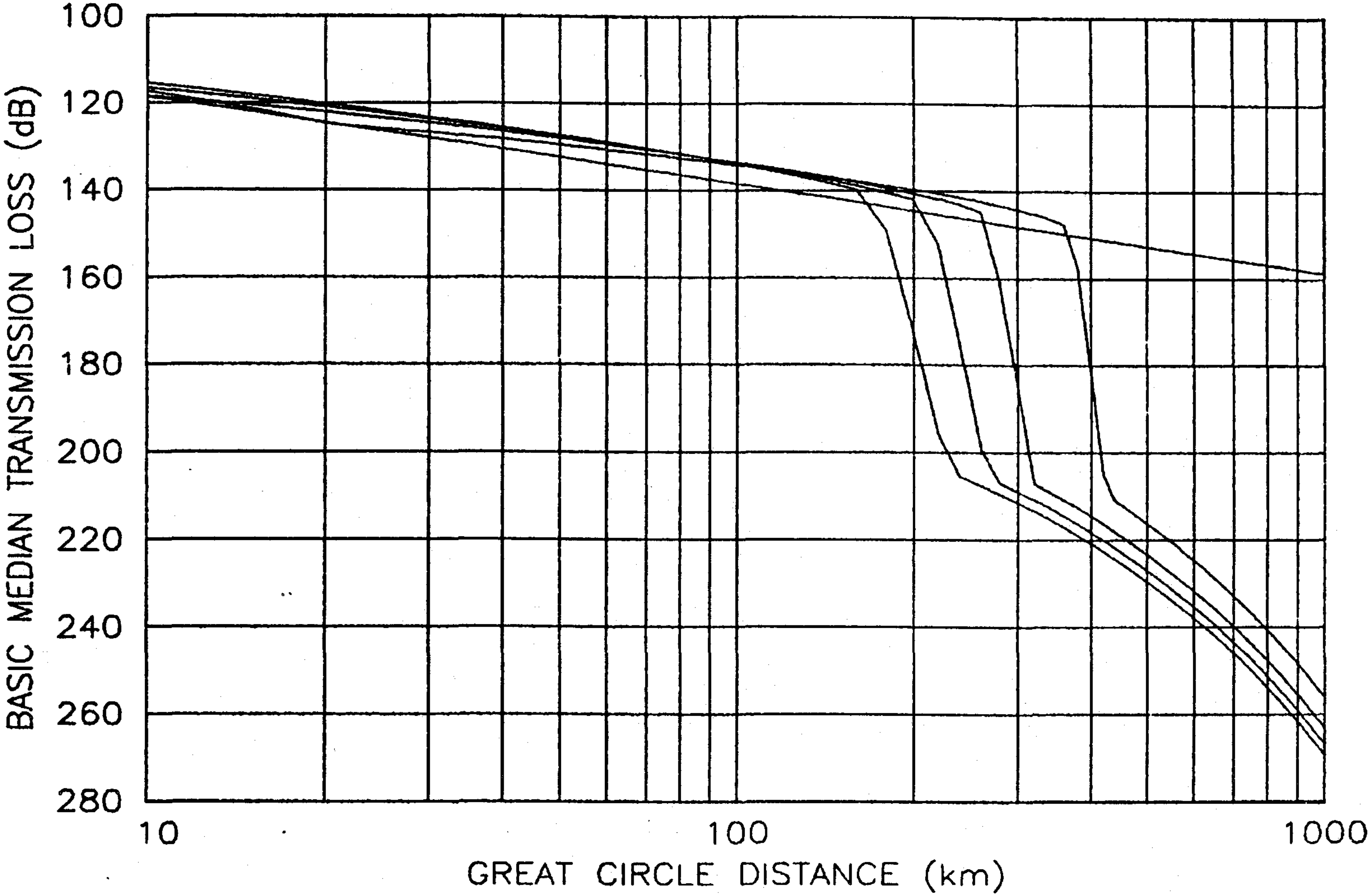

FIGURE A–40. $f=2GHz, h_1=500m, h_2=500m, 1km, 2km, 5km$

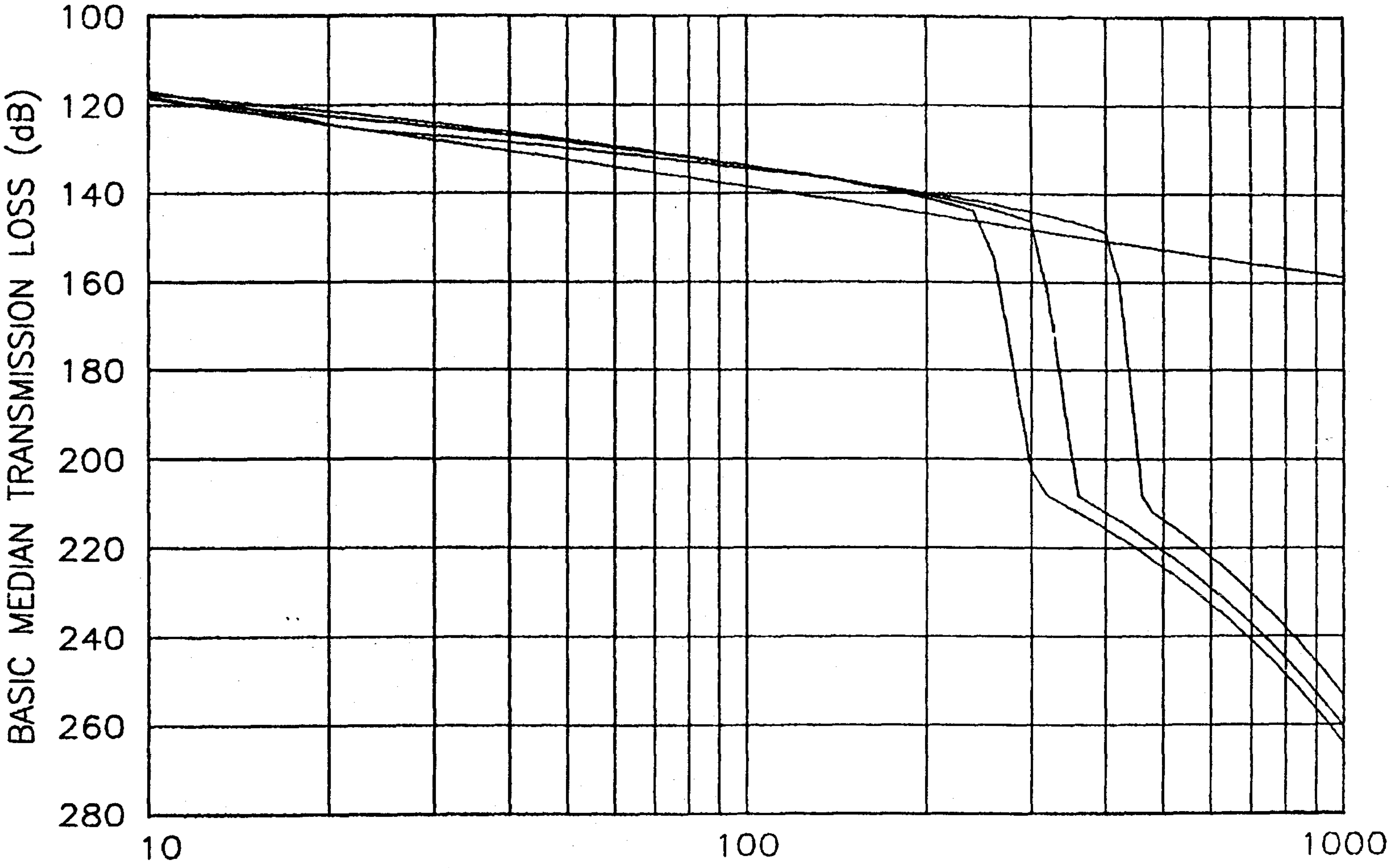

FIGURE A-41. $f=2GHz, h_1=1km, h_2=1km, 2km, 5km$

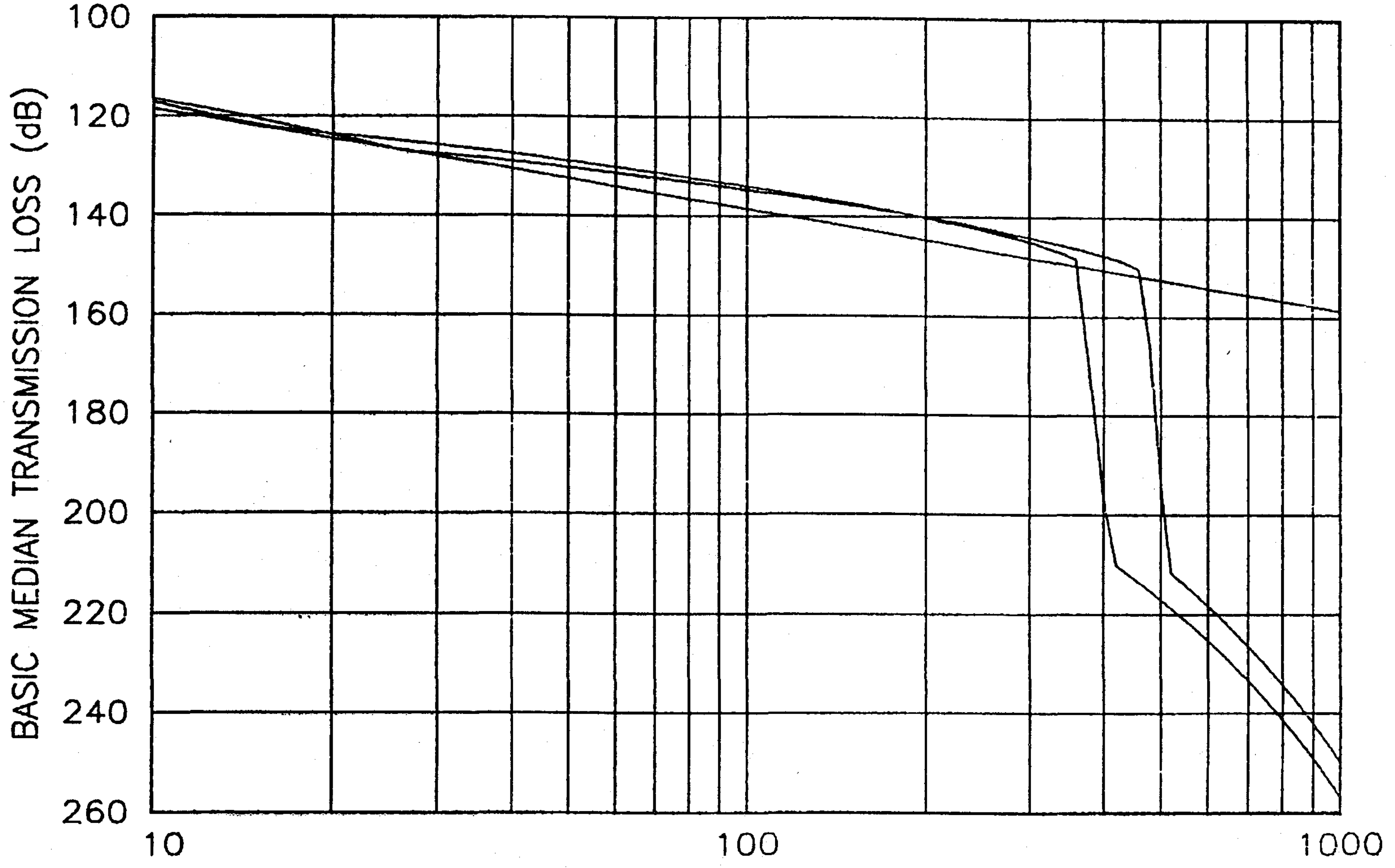

FIGURE A–42. $f=2GHz, h_1=2km, h_2=2km, 5km$

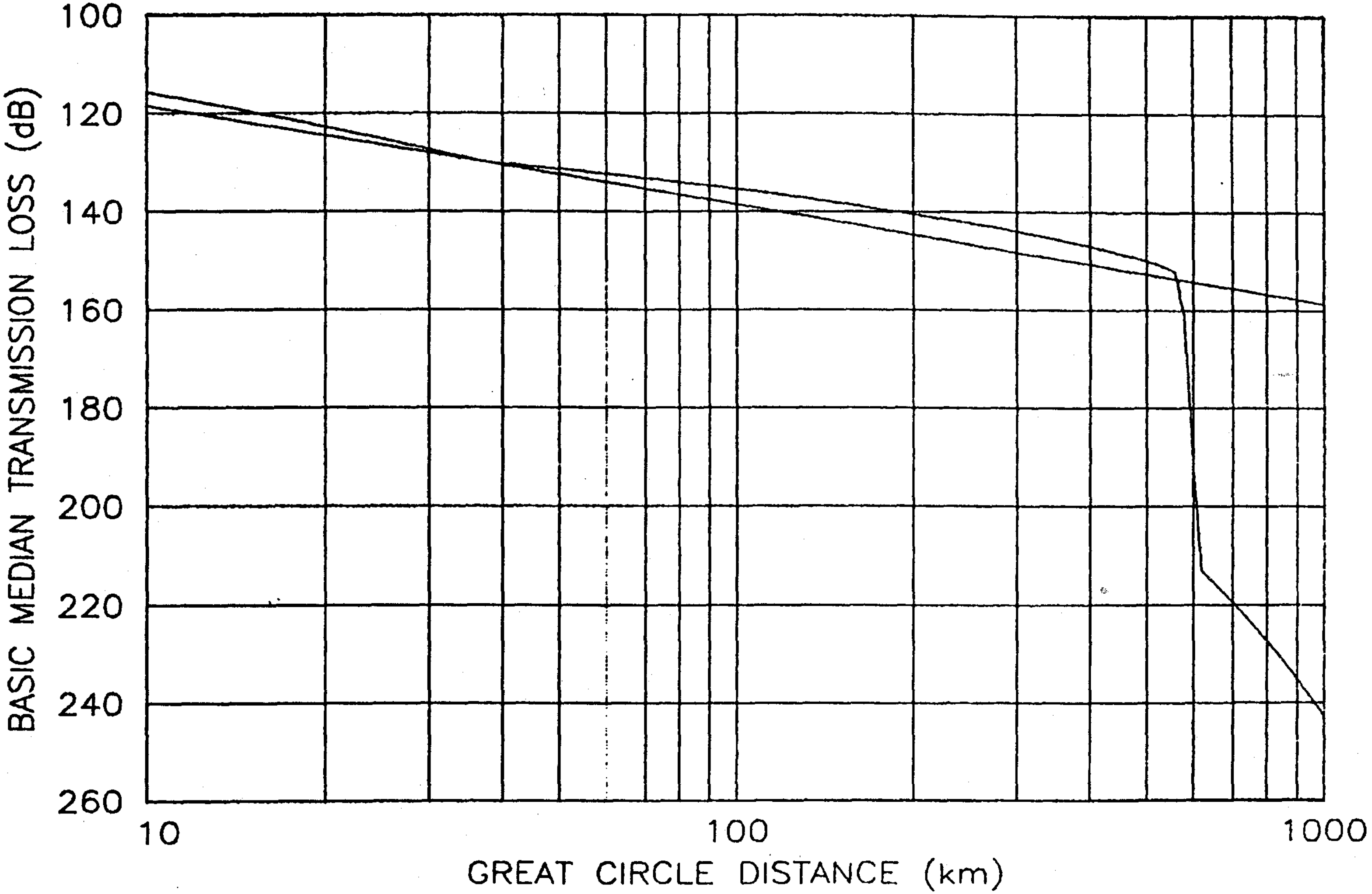

FIGURE A-43. $f = 2GHz, h_1 = 5km, h_2 = 5km$

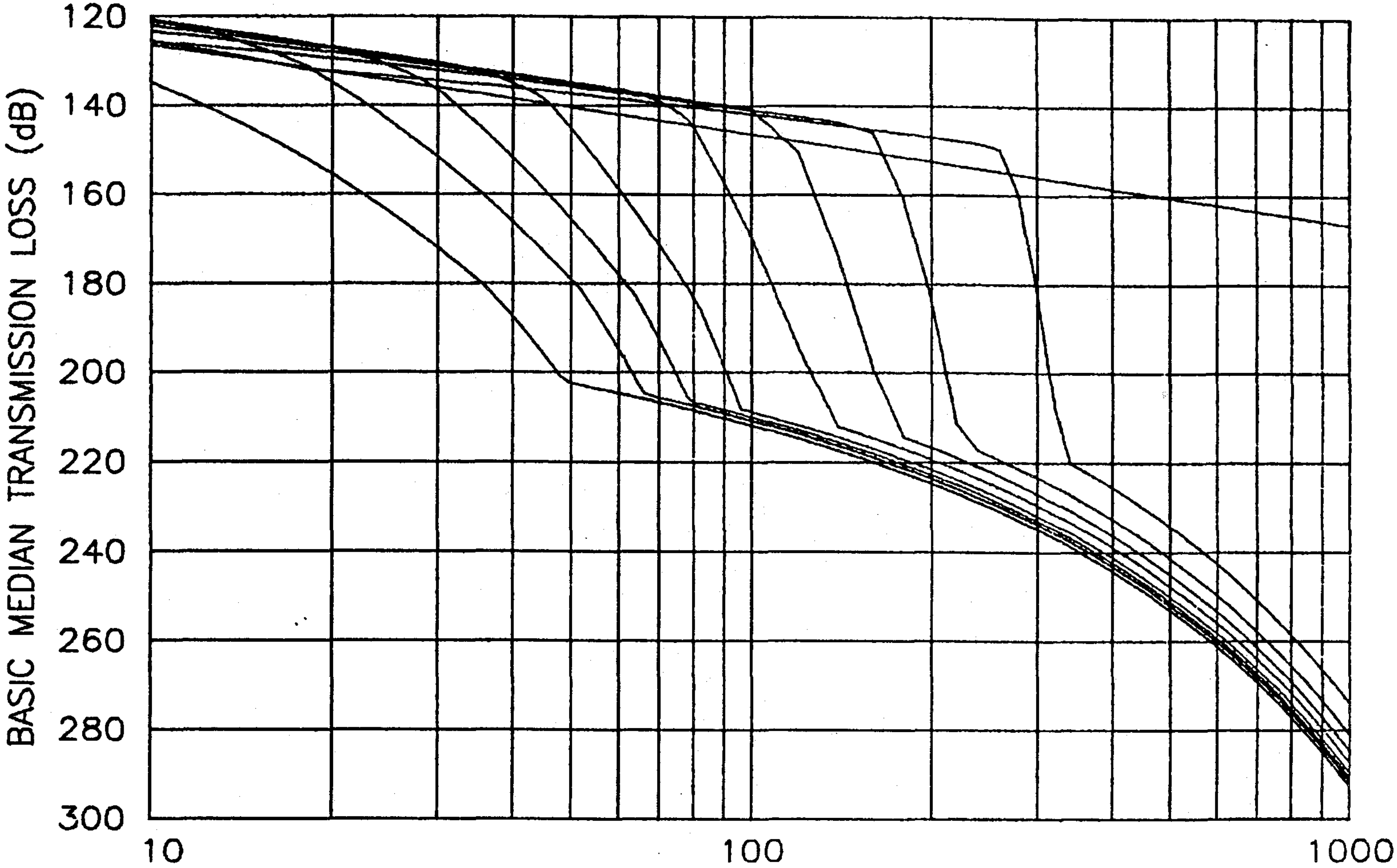

FIGURE A-44. f=5GHz,h_1=1m,h_2=10m,50m,100m,200m,500m,1km,2km,5km

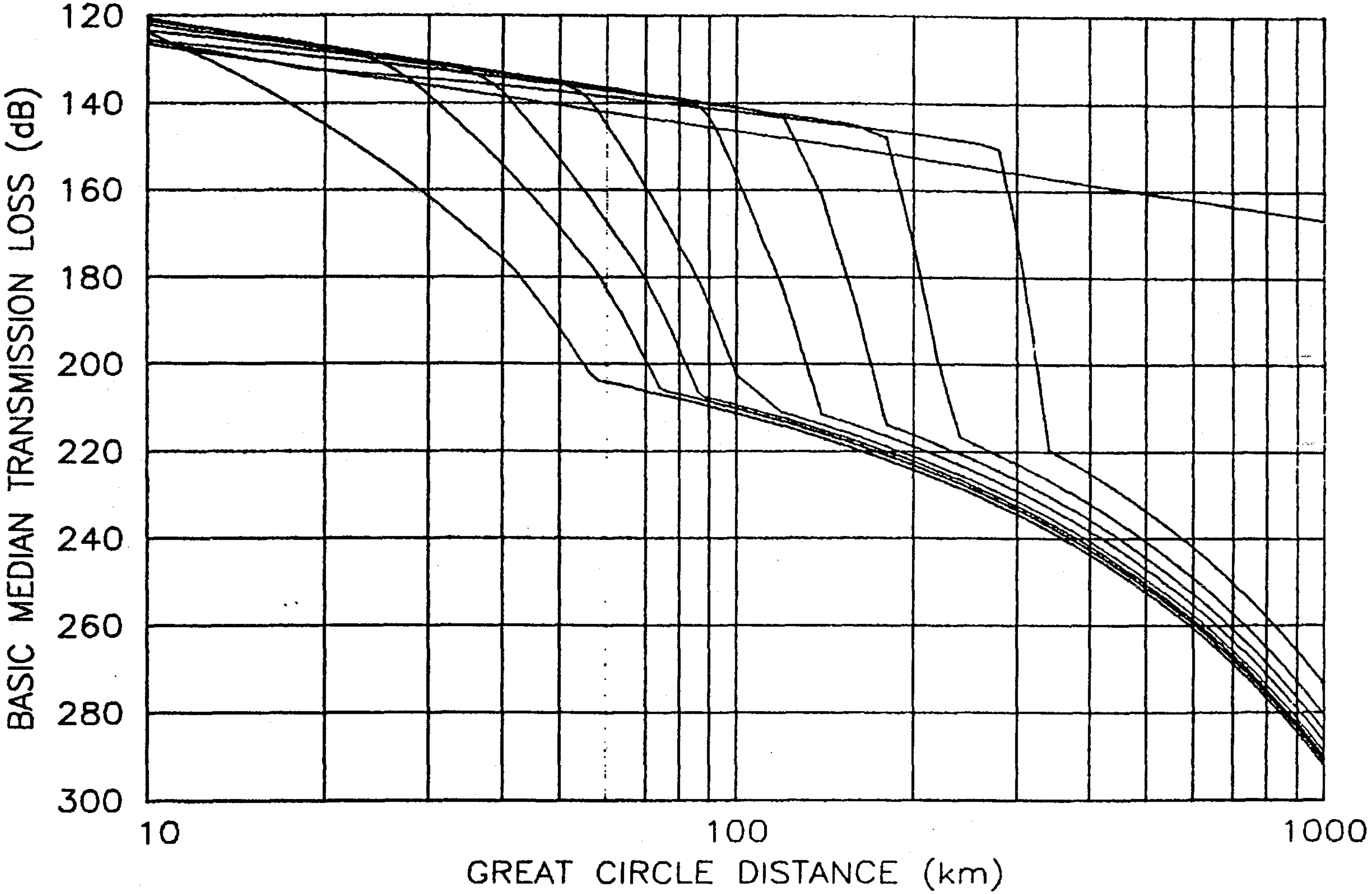

FIGURE A-45. $f = 5GHz, h_1 = 10m, h_2 = 10m, 50m, 100m, 200m, 500m, 1km, 2km, 5km$

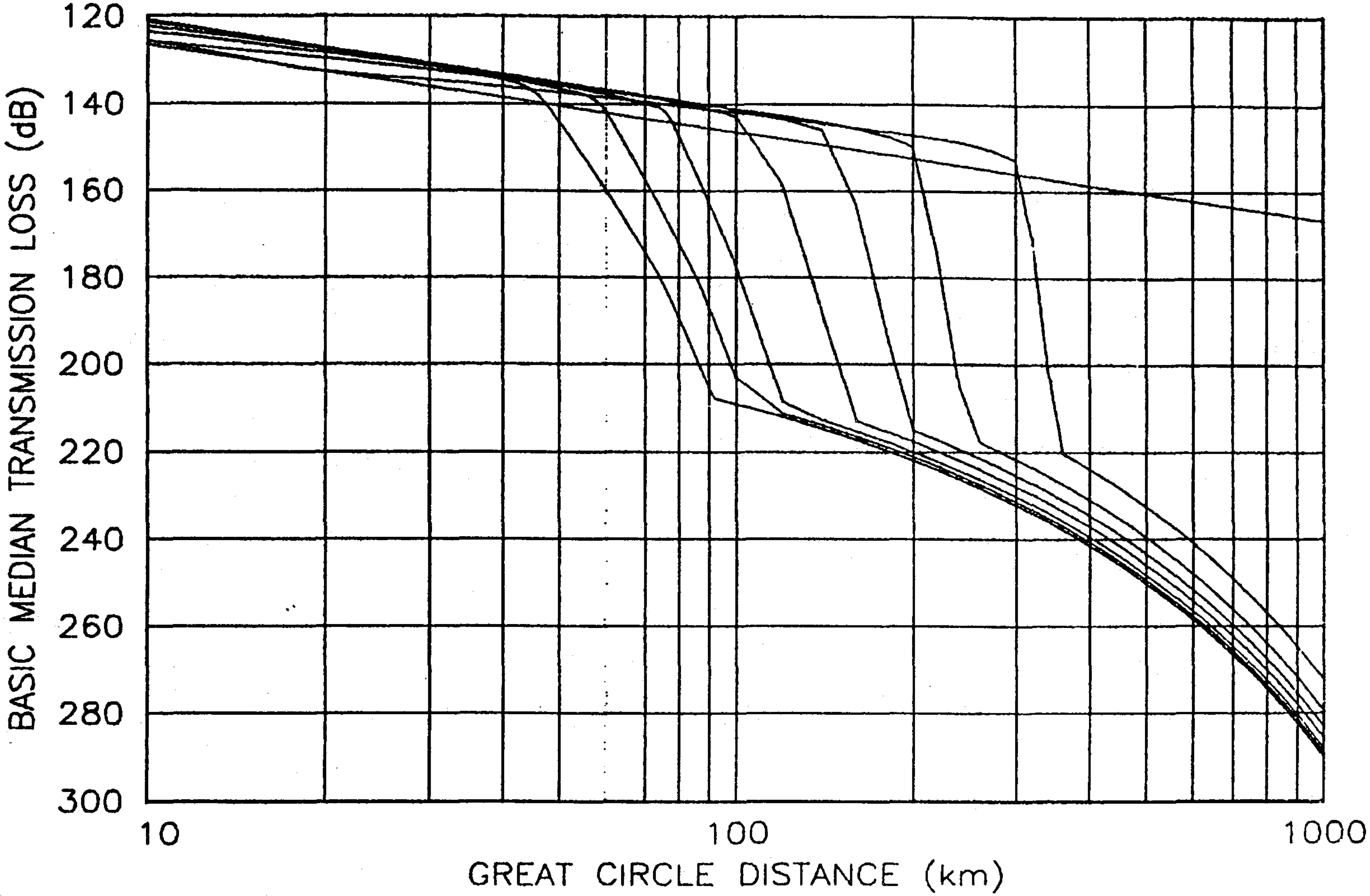

FIGURE A-46. f=5GHz,h_1=50m,h_2=50m,100m,200m,500m,1km,2km,5km

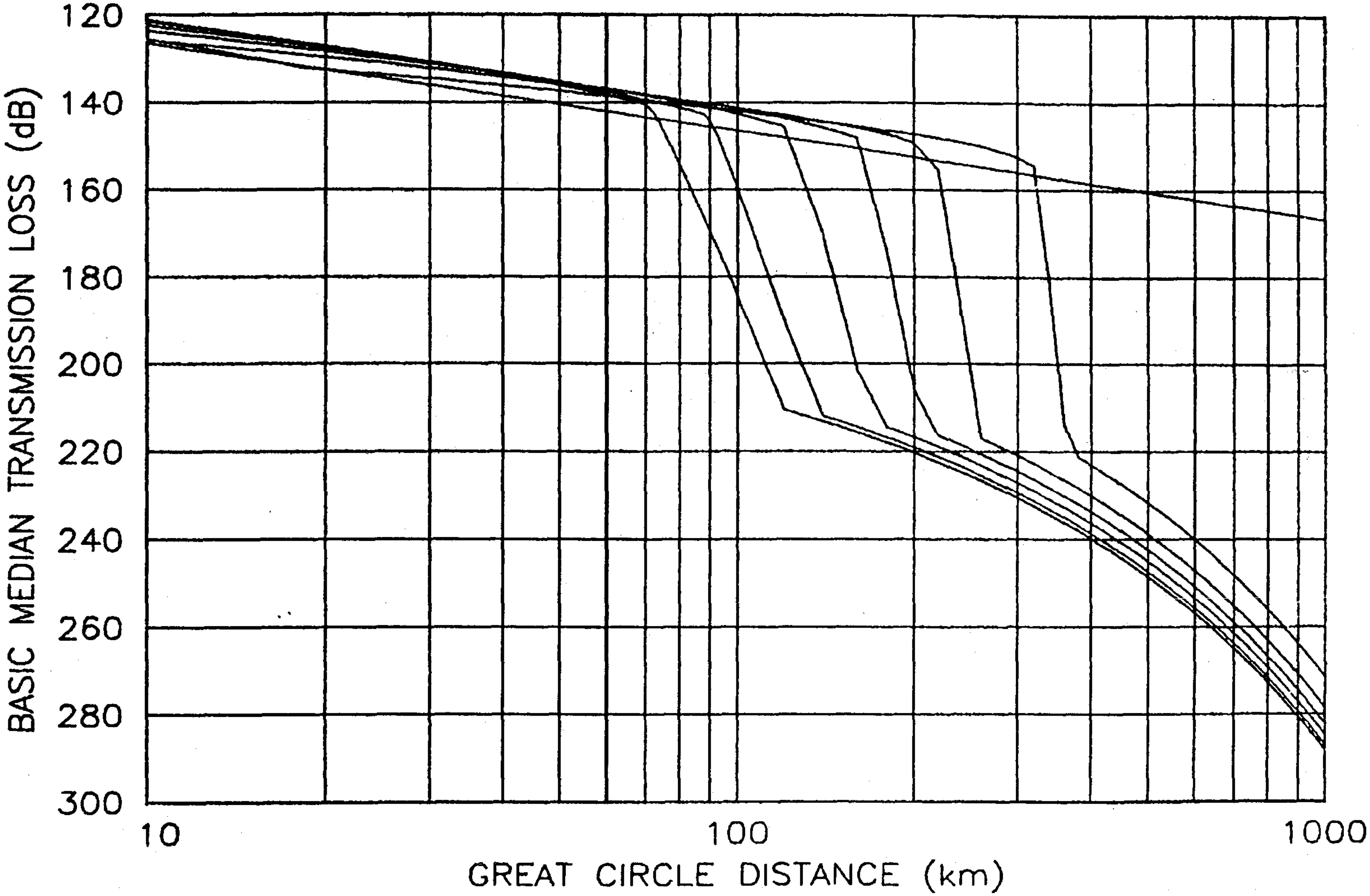

FIGURE A–47. f=5GHz,h_1=100m,h_2=100m,200m,500m,1km,2km,5km

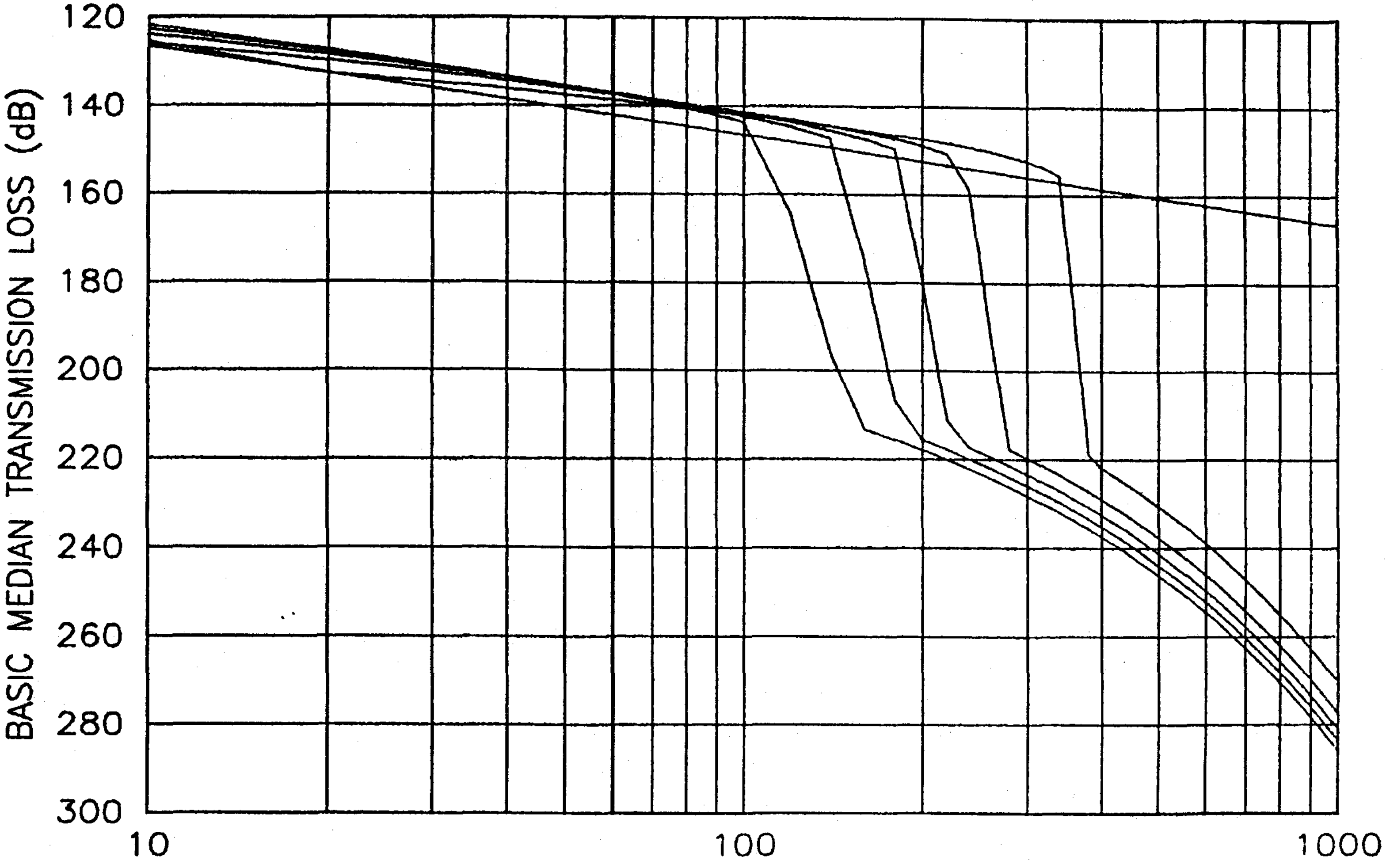

FIGURE A–48. $f=5\mathrm{GHz}, h_1=200\mathrm{m}, h_2=200\mathrm{m}, 500\mathrm{m}, 1\mathrm{km}, 2\mathrm{km}, 5\mathrm{km}$

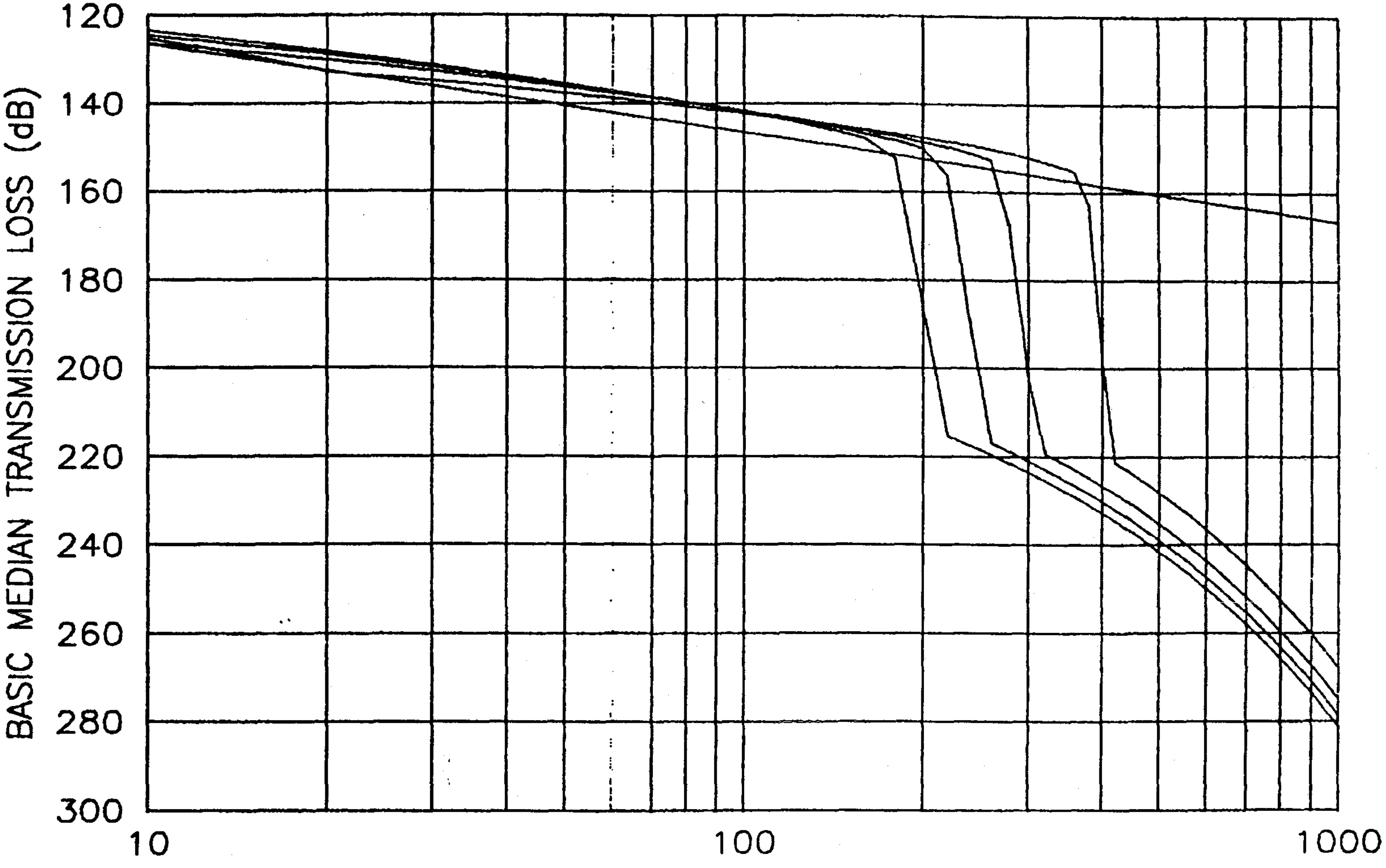

FIGURE A-49. f=5GHz, h_1=500m, h_2=500m, 1km, 2km, 5km

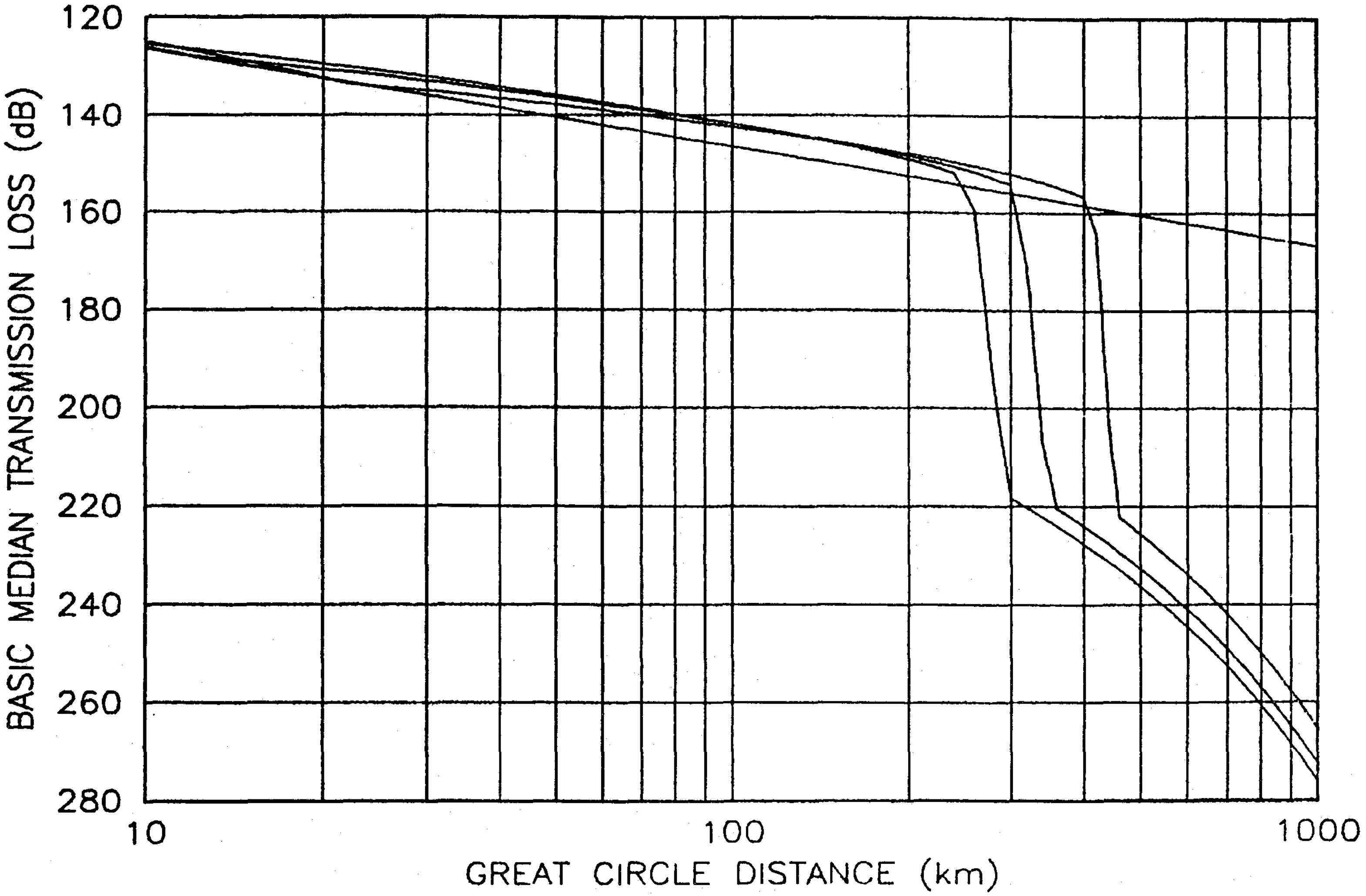

FIGURE A-50. $f=5GHz, h_1=1km, h_2=1km, 2km, 5km$

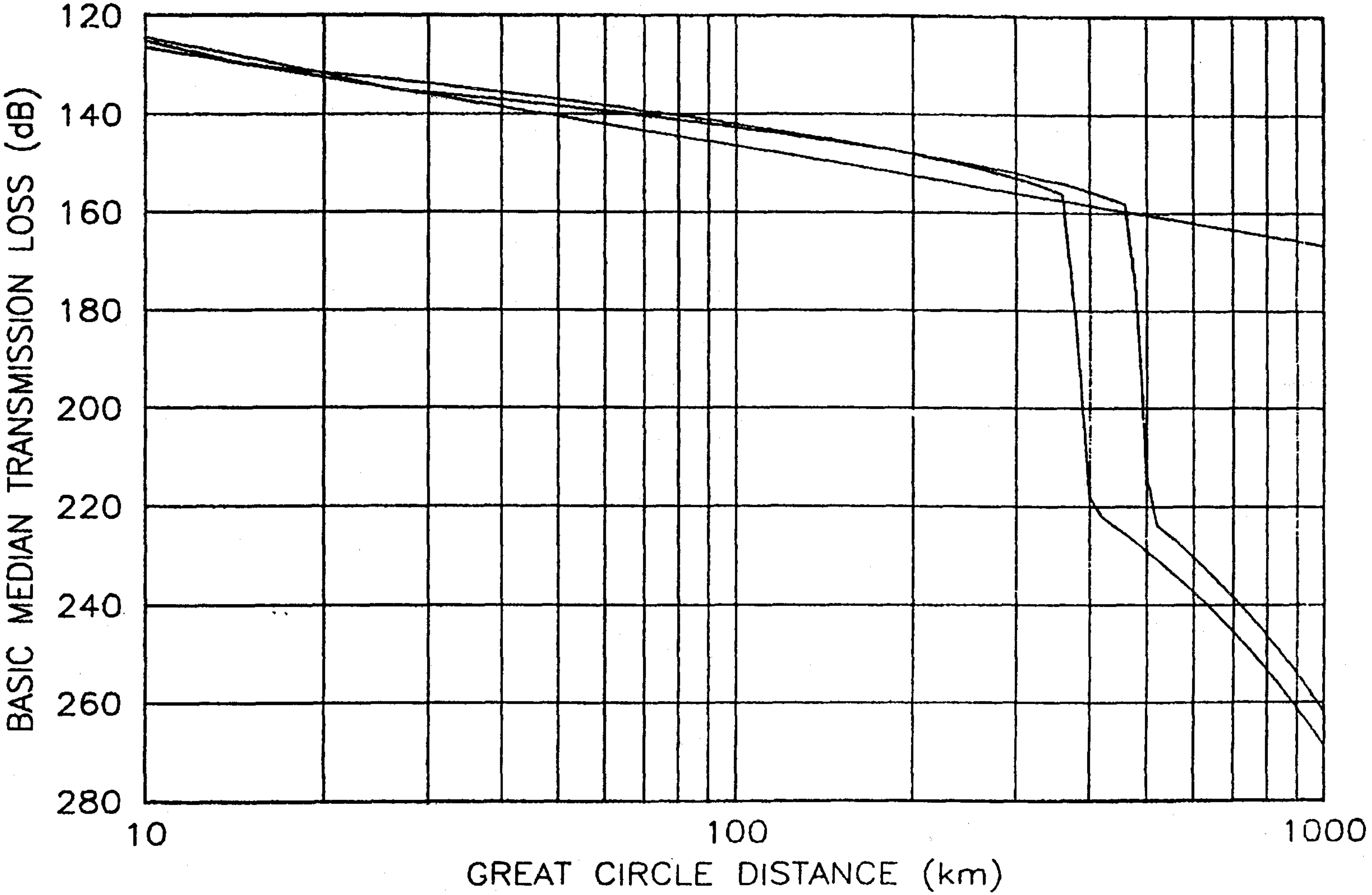

FIGURE A-51. $f=5\text{GHz}, h_1=2\text{km}, h_2=2\text{km}, 5\text{km}$

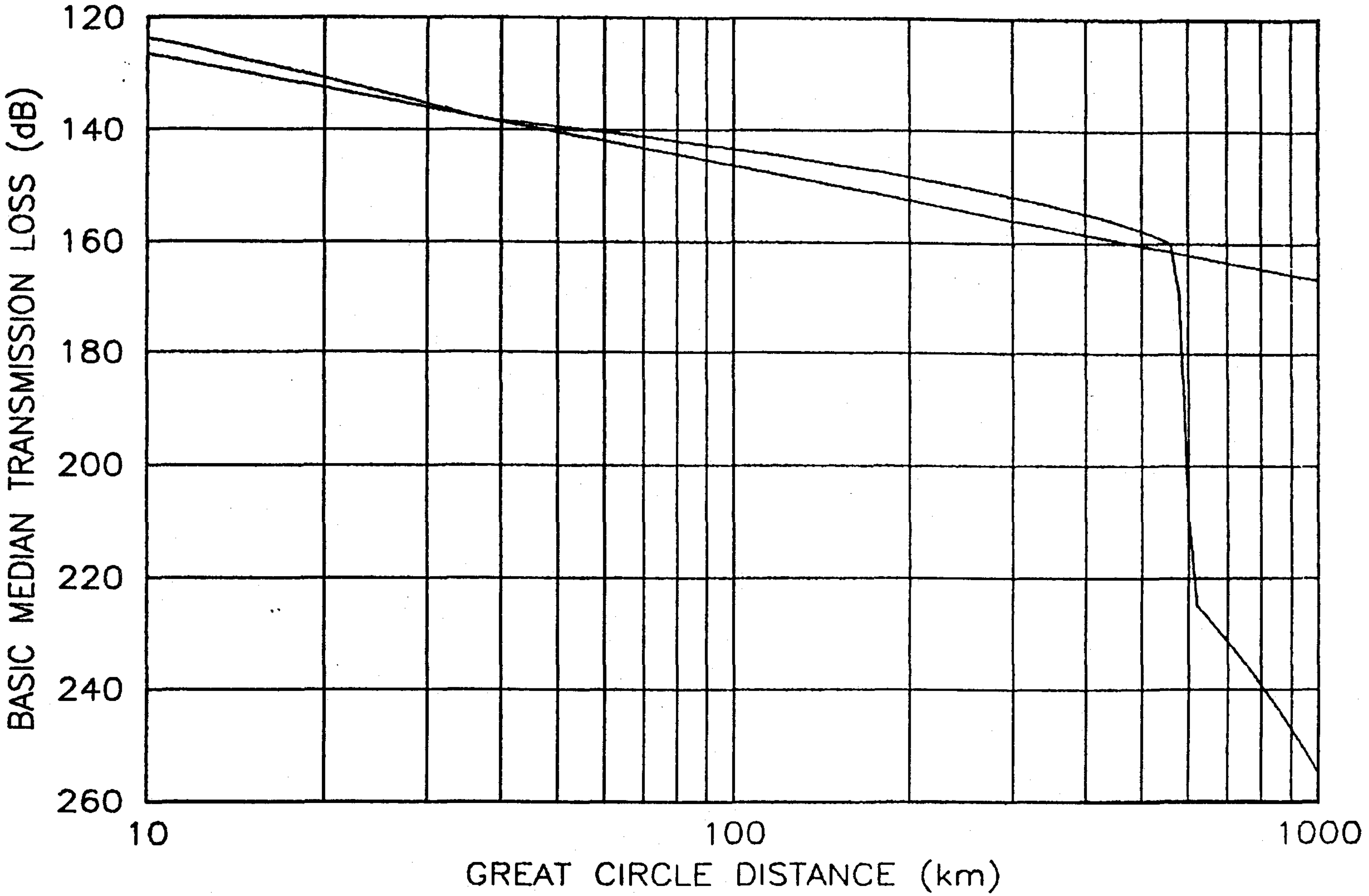

FIGURE A-52. f=5GHz,h_1=5km,h_2=5km

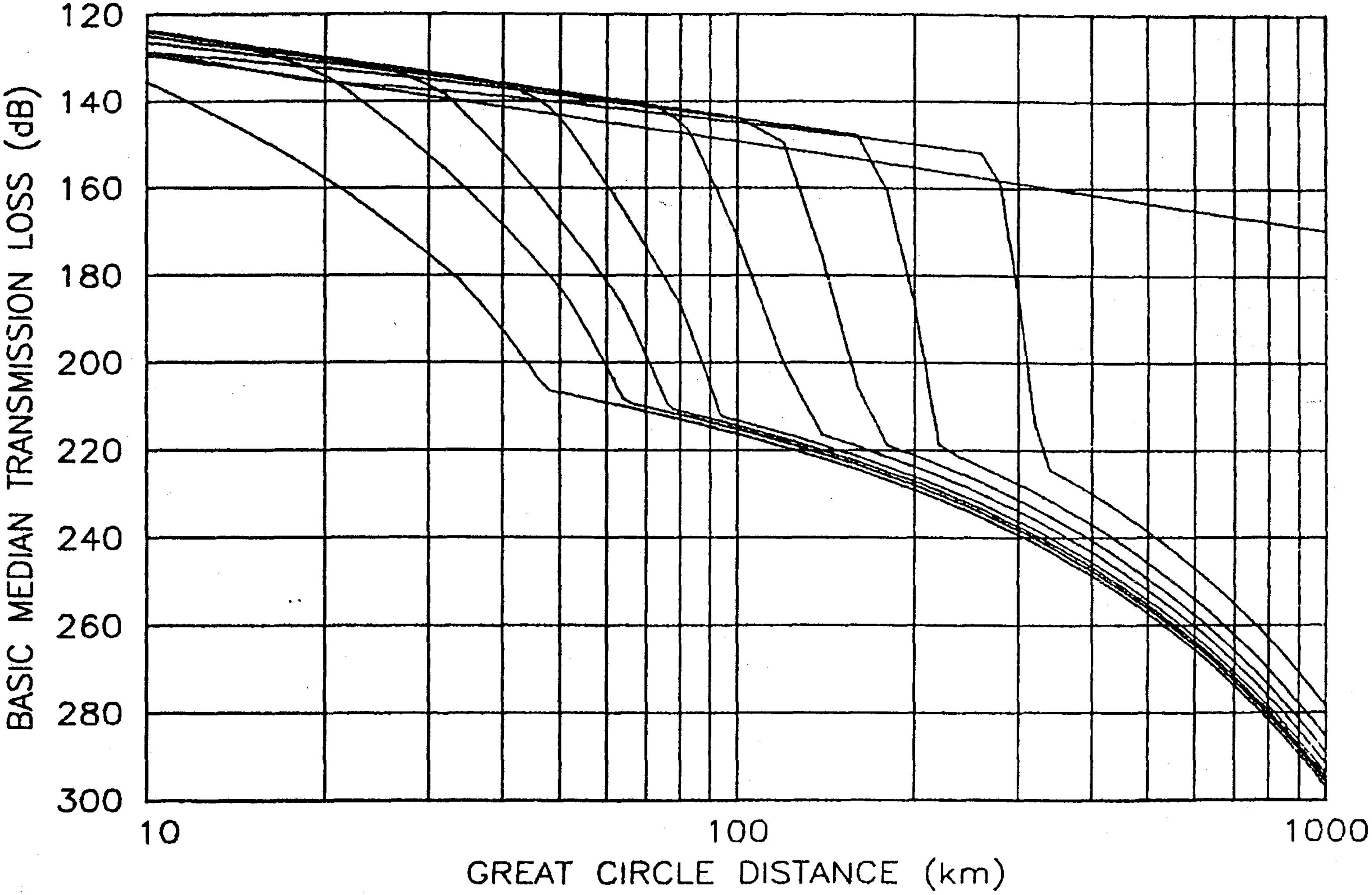

FIGURE A-53. $f=7\text{GHz}, h_1=1\text{m}, h_2=10\text{m}, 50\text{m}, 100\text{m}, 200\text{m}, 500\text{m}, 1\text{km}, 2\text{km}, 5\text{km}$

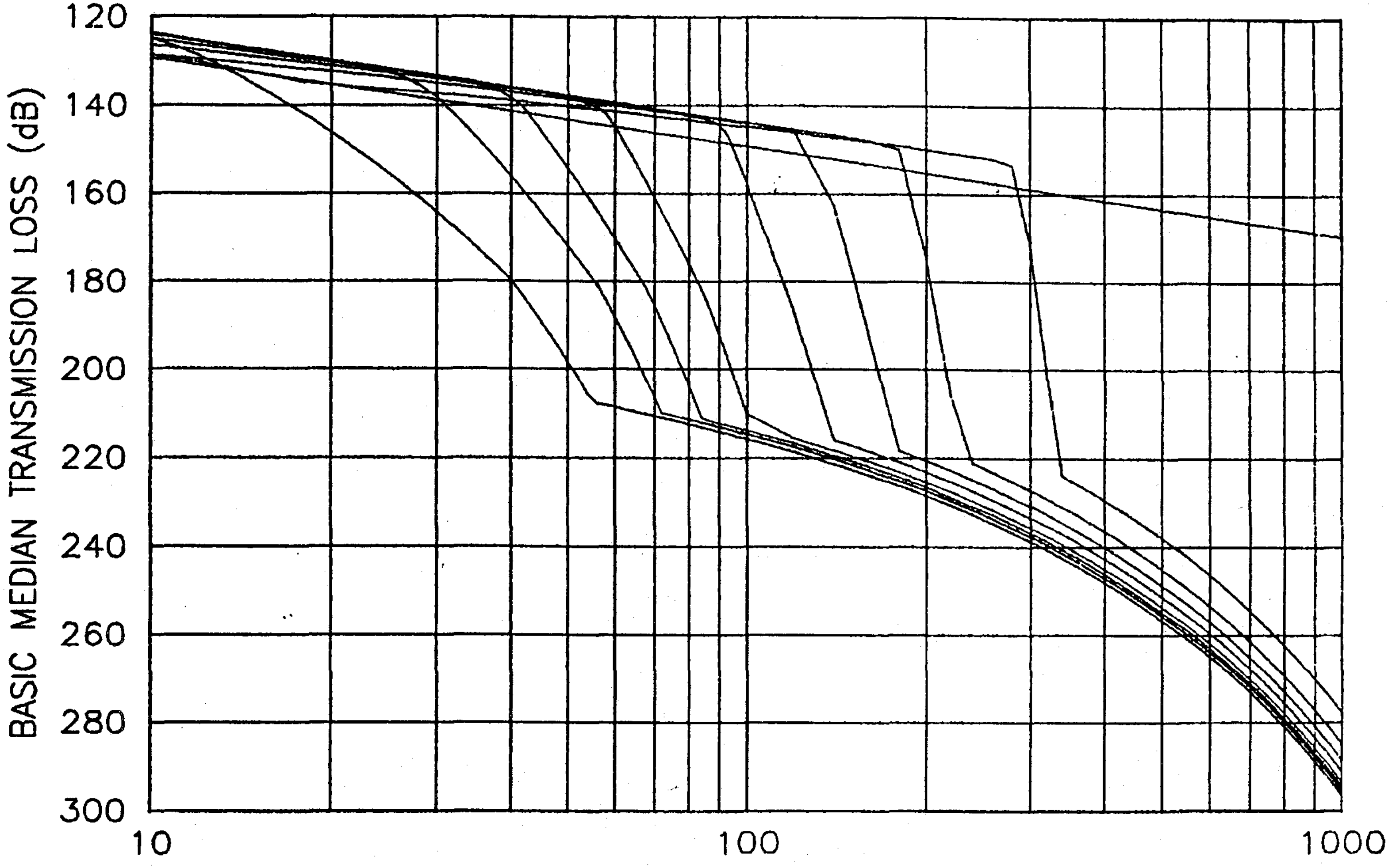

FIGURE A-54. f=7GHz,h_1=10m,h_2=10m,50m,100m,200m,500m,1km,2km,5km

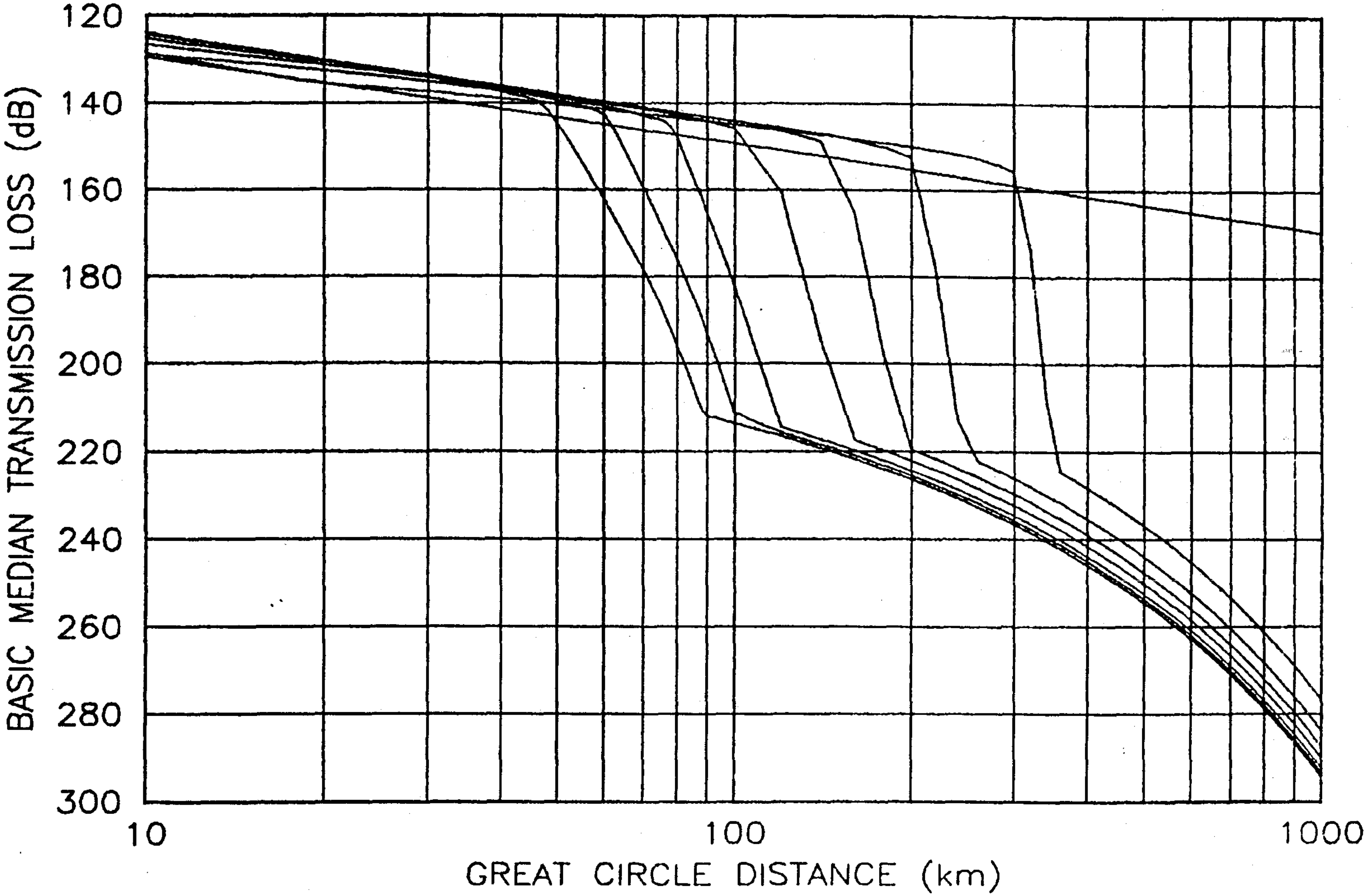

FIGURE A–55. $f=7\text{GHz}, h_1=50\text{m}, h_2=50\text{m}, 100\text{m}, 200\text{m}, 500\text{m}, 1\text{km}, 2\text{km}, 5\text{km}$

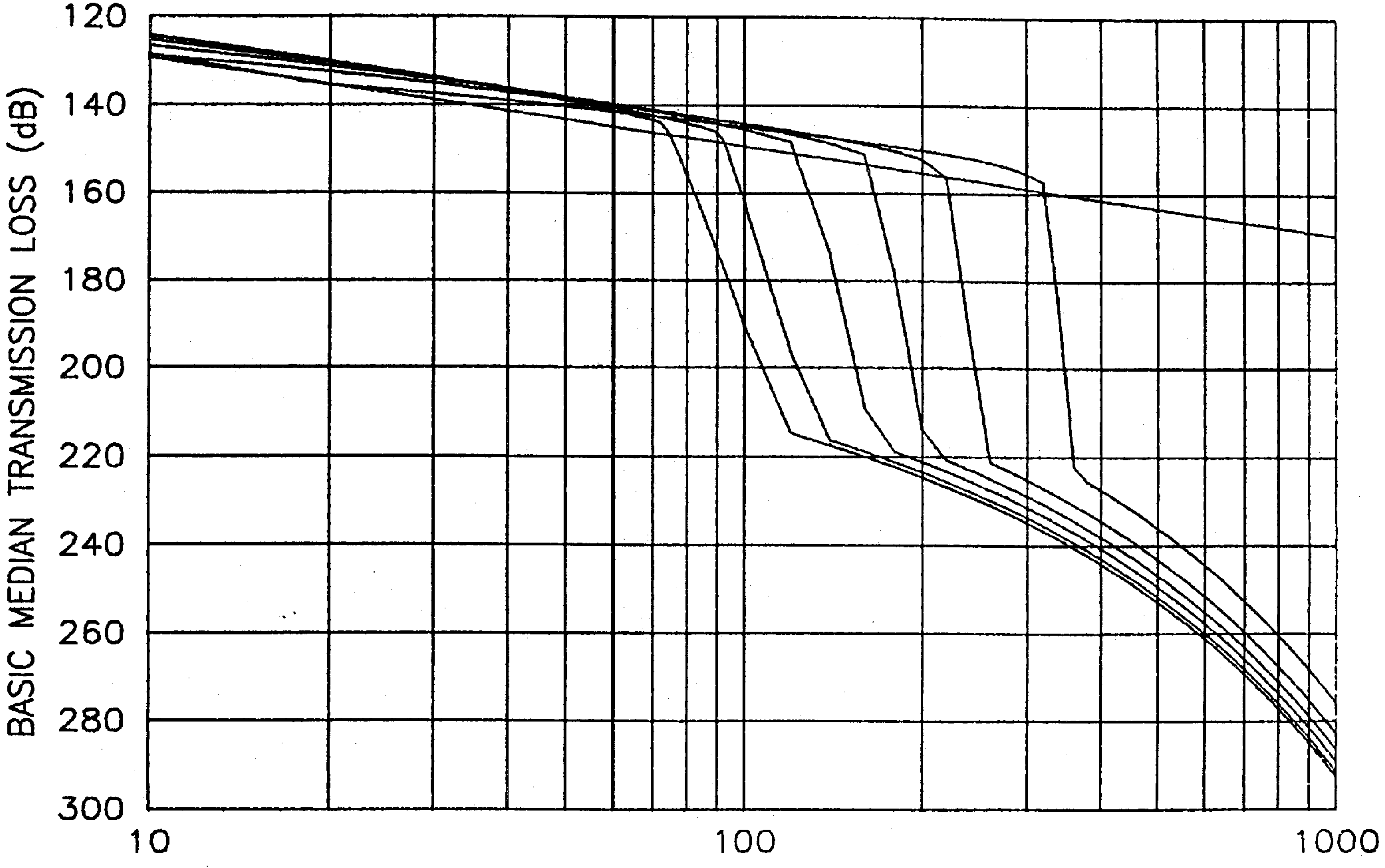

FIGURE A-56. f=7GHz,h_1=100m,h_2=100m,200m,500m,1km,2km,5km

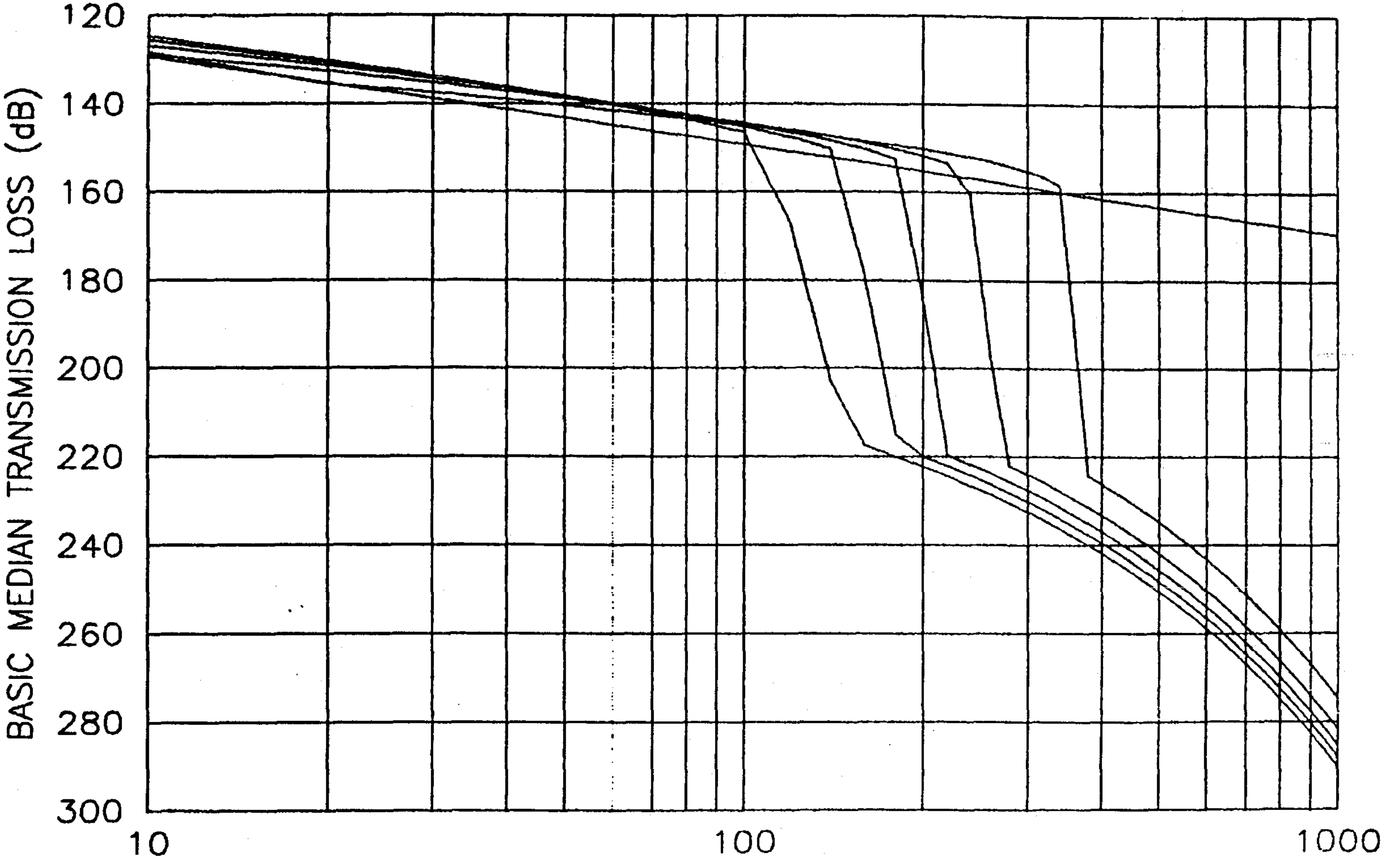

FIGURE A-57. $f=7\text{GHz}, h_1=200\text{m}, h_2=200\text{m}, 500\text{m}, 1\text{km}, 2\text{km}, 5\text{km}$

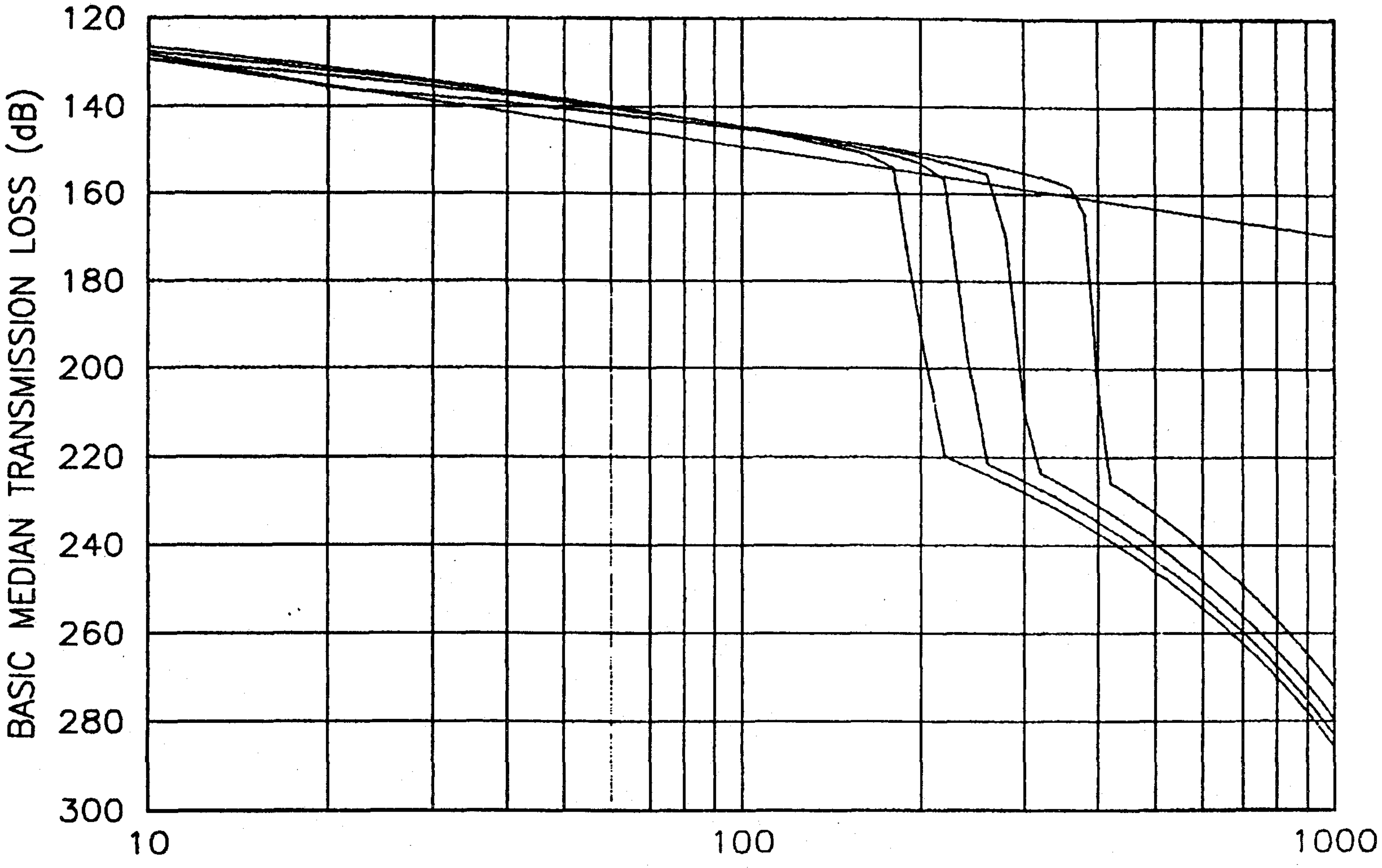

FIGURE A-58. f=7GHz,h_1=500m,h_2=500m,1km,2km,5km

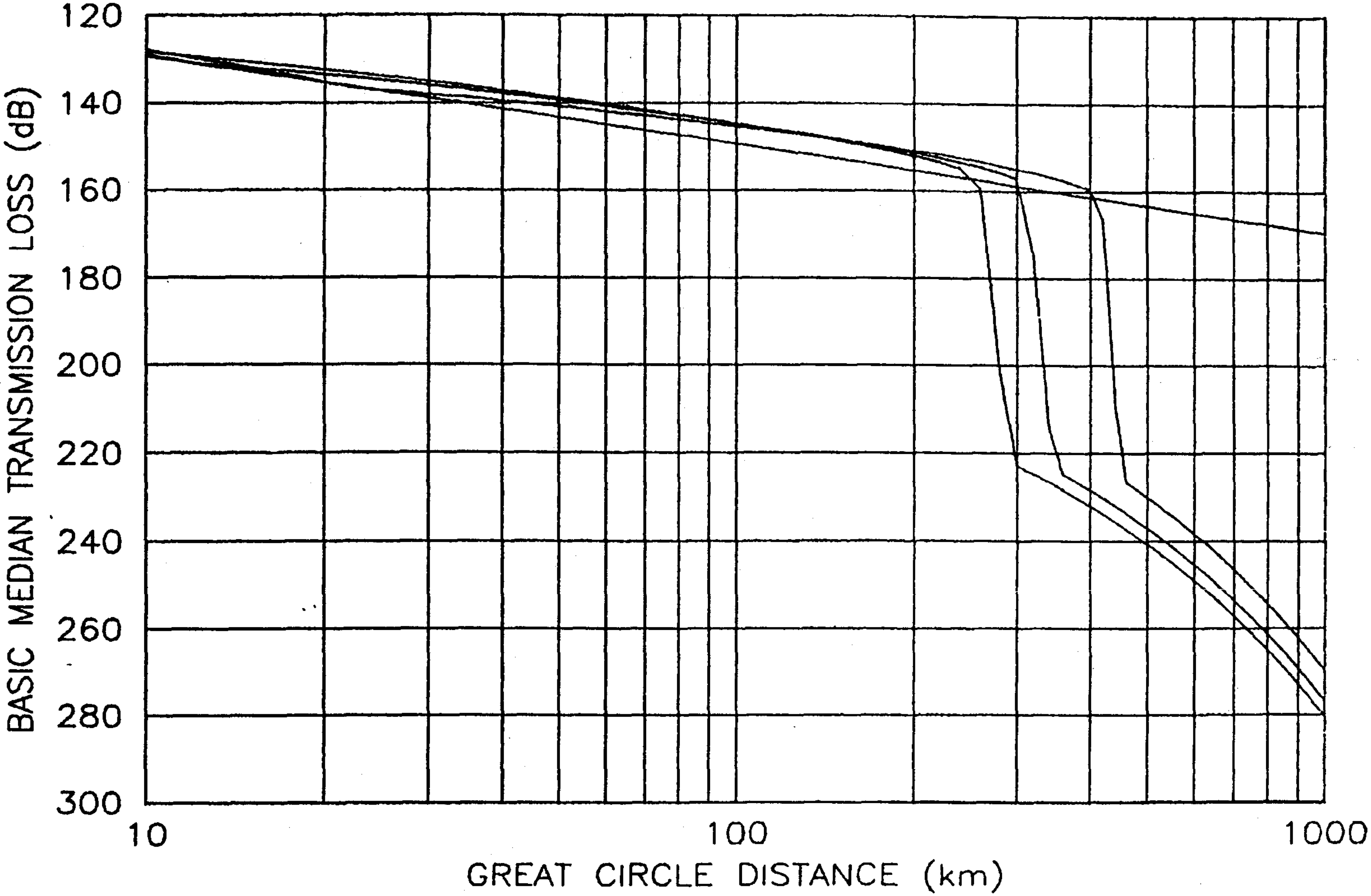

FIGURE A-59. $f = 7\text{GHz}, h_1 = 1\text{km}, h_2 = 1\text{km}, 2\text{km}, 5\text{km}$

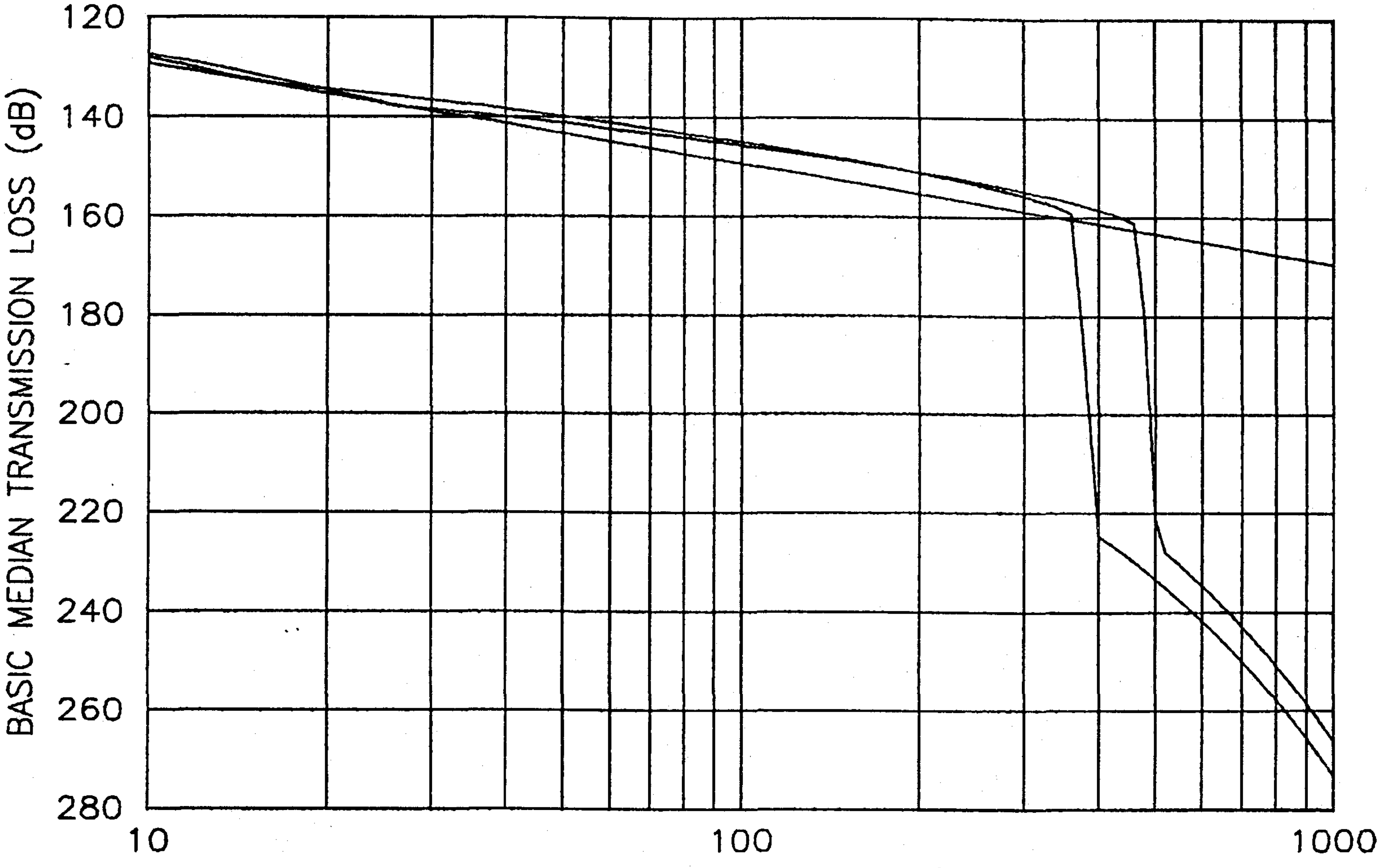

FIGURE A-60. $f=7GHz, h_1=2km, h_2=2km, 5km$

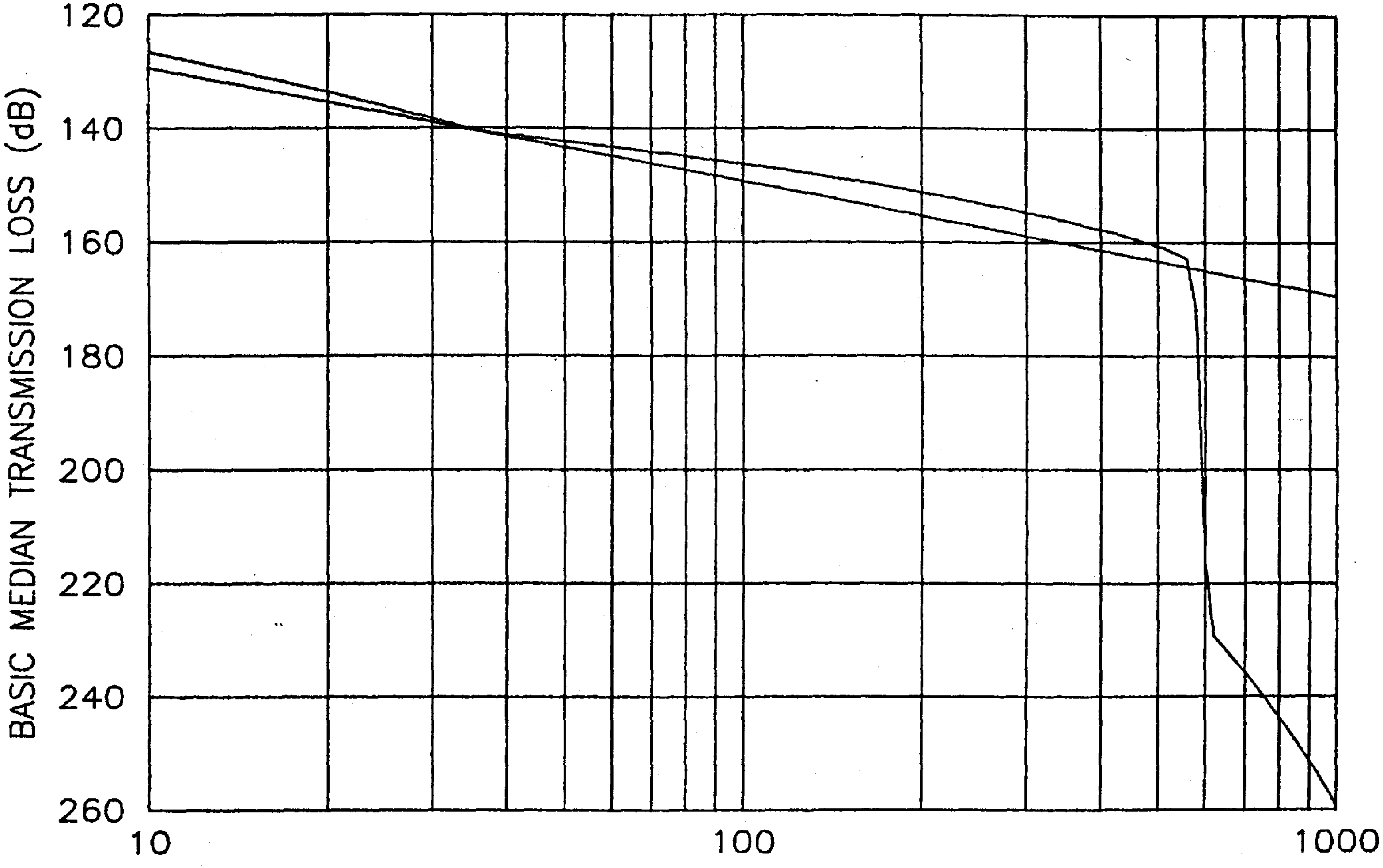

FIGURE A-61. $f=7GHz, h_1=5km, h_2=5km$

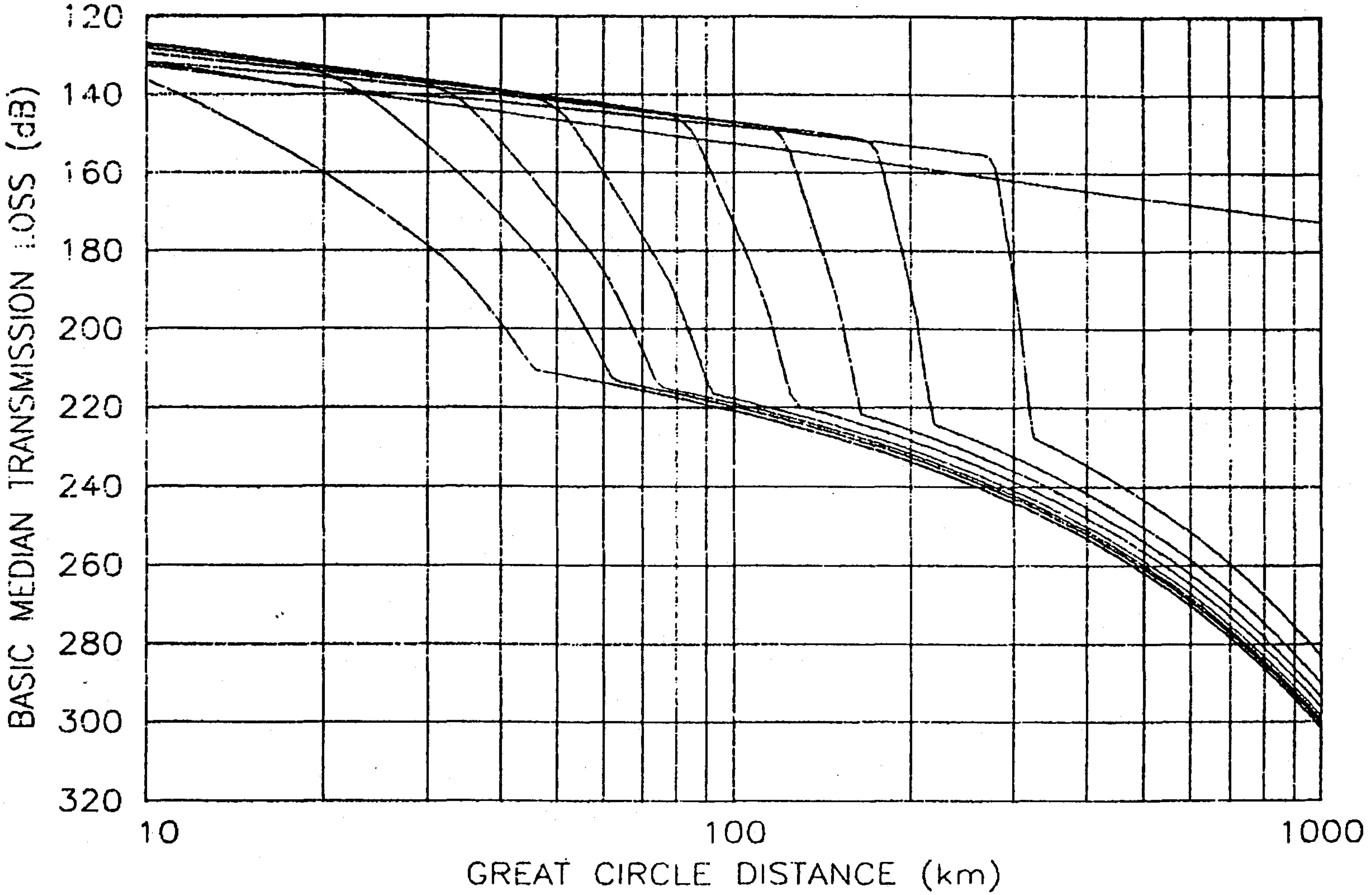

FIGURE A-62. f=10GHz, h_1=1m, h_2=10m, 50m, 100m, 200m, 500m, 1km, 2km, 5km

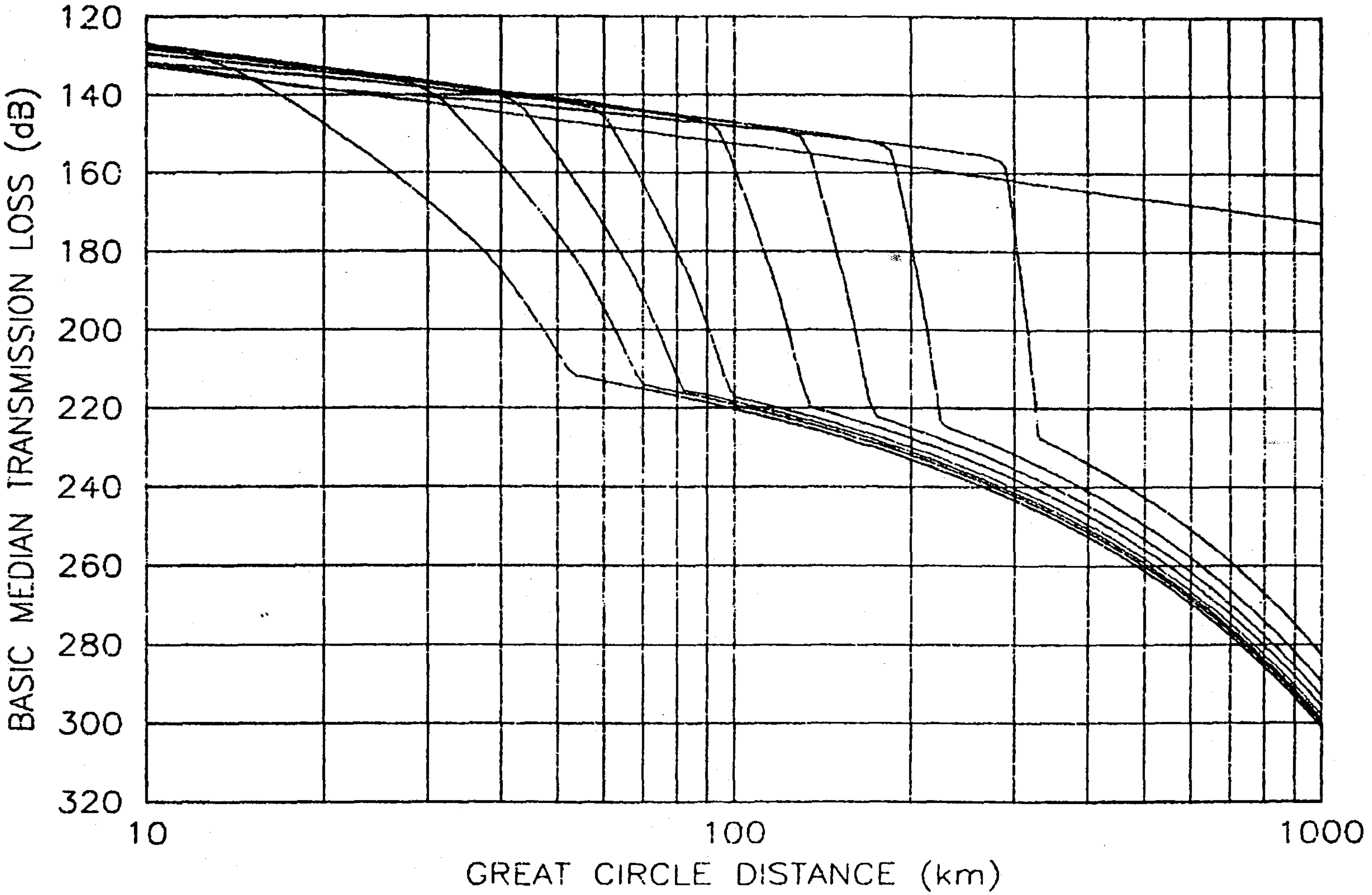

FIGURE A–63. f=10GHz,h_1=10m,h_2=10m,50m,100m,200m,500m,1km,2km,5km

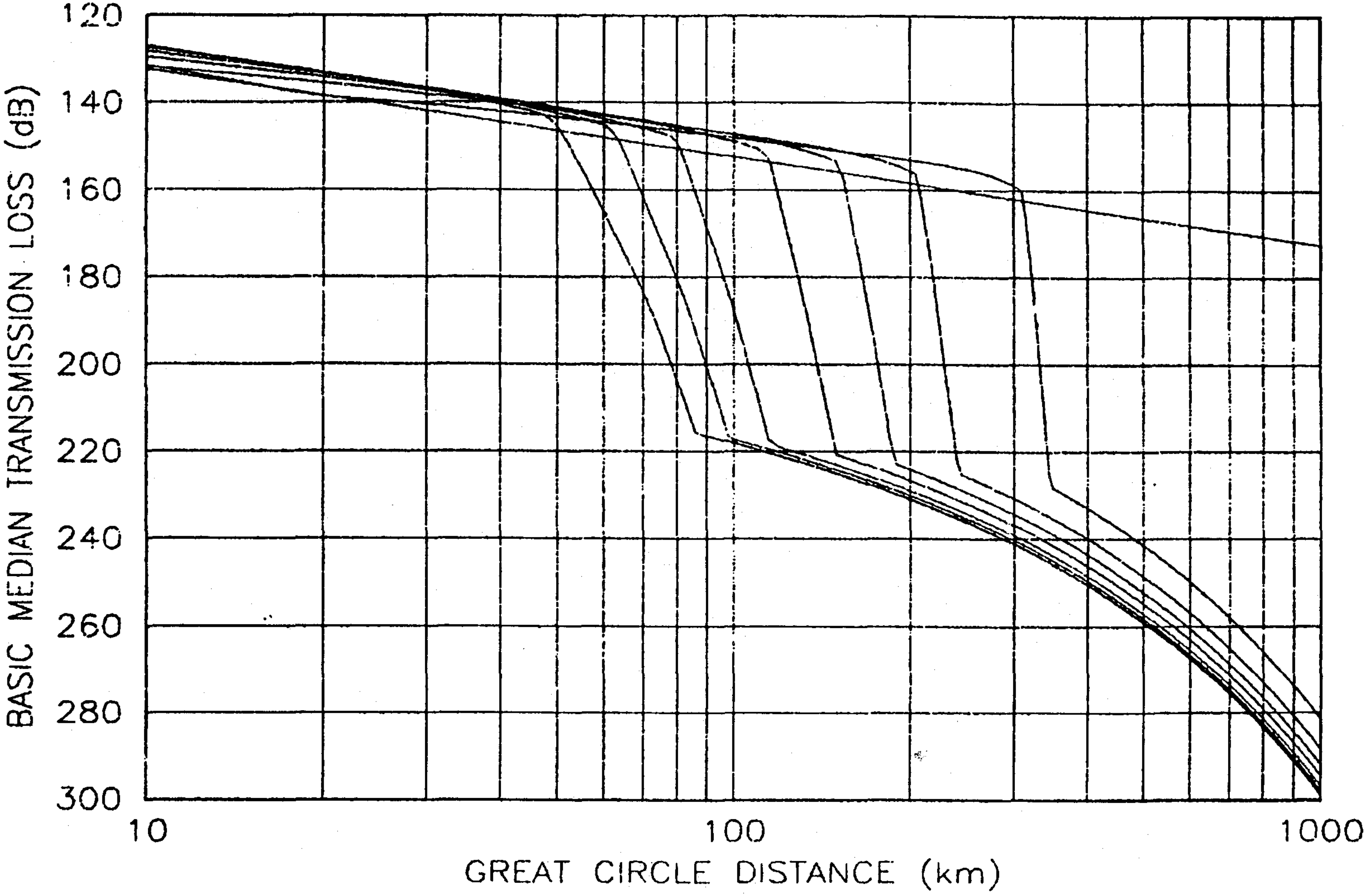

FIGURE A-64. $f=10\text{GHz}, h_1=50\text{m}, h_2=50\text{m}, 100\text{m}, 200\text{m}, 500\text{m}, 1\text{km}, 2\text{km}, 5\text{km}$

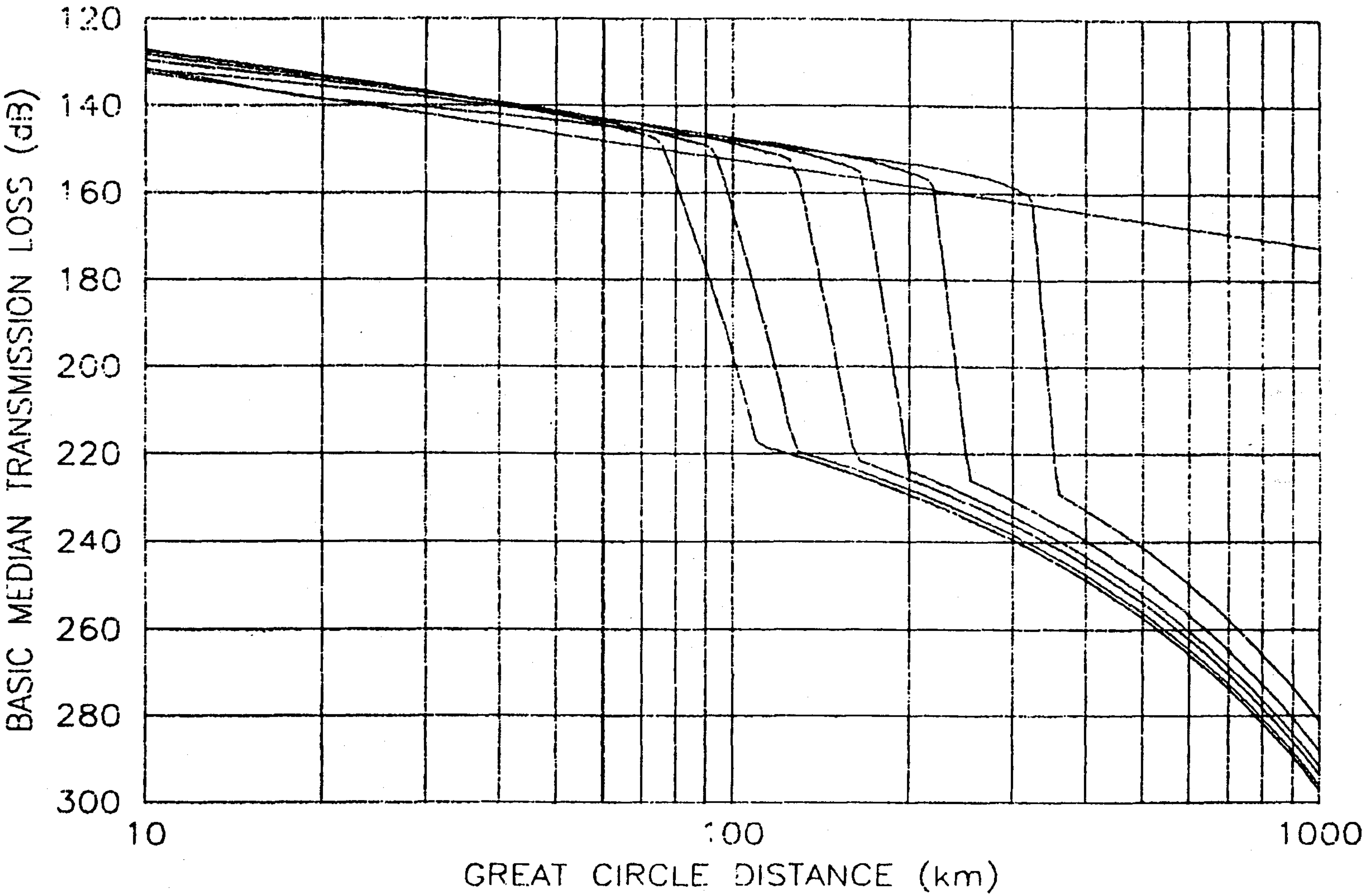

FIGURE A-65. $f=10GHz, h_1=100m, h_2=100m, 200m, 500m, 1km, 2km, 5km$

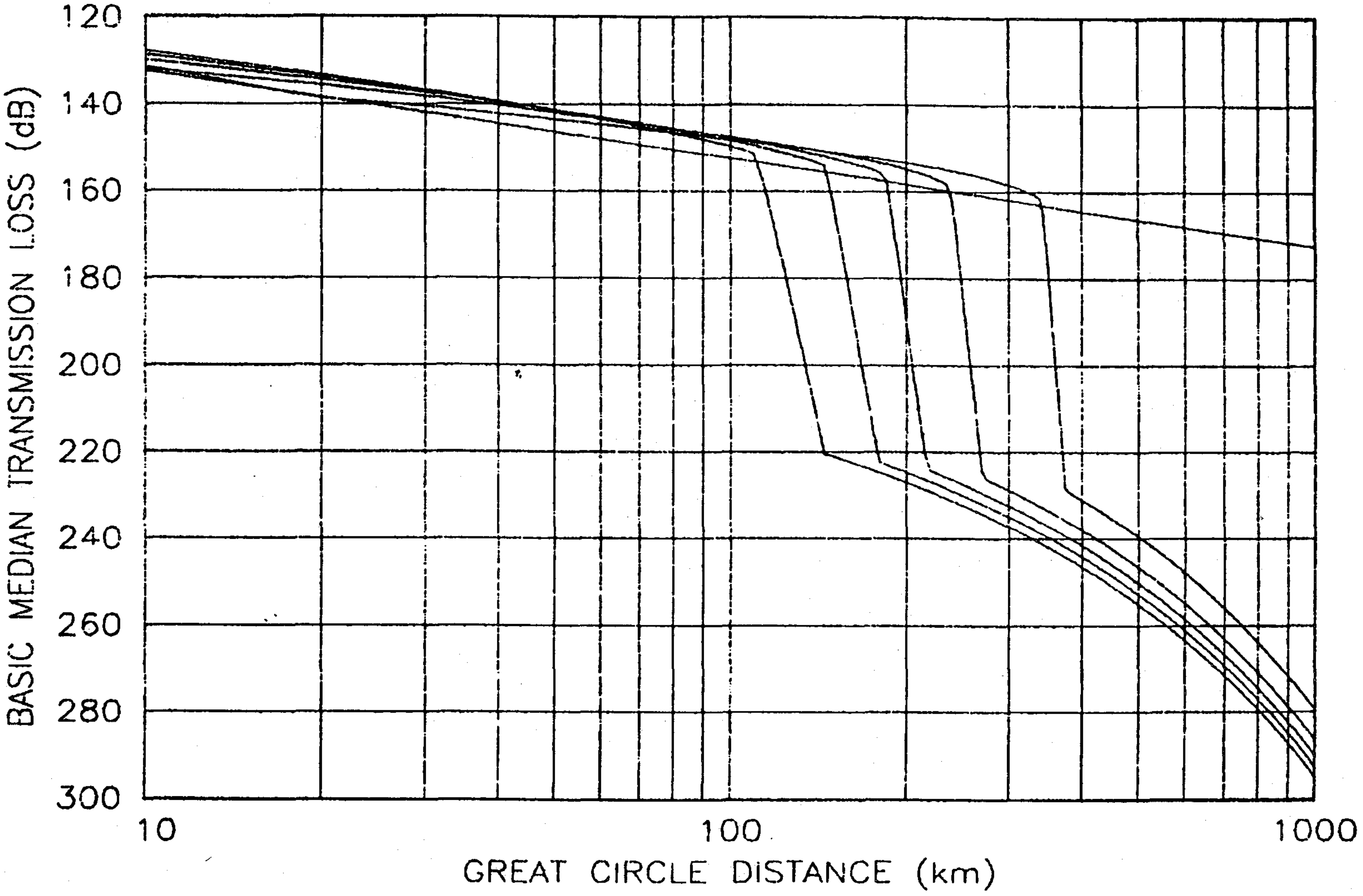

FIGURE A–66. $f=10GHz, h_1=200m, h_2=200m, 500m, 1km, 2km, 5km$

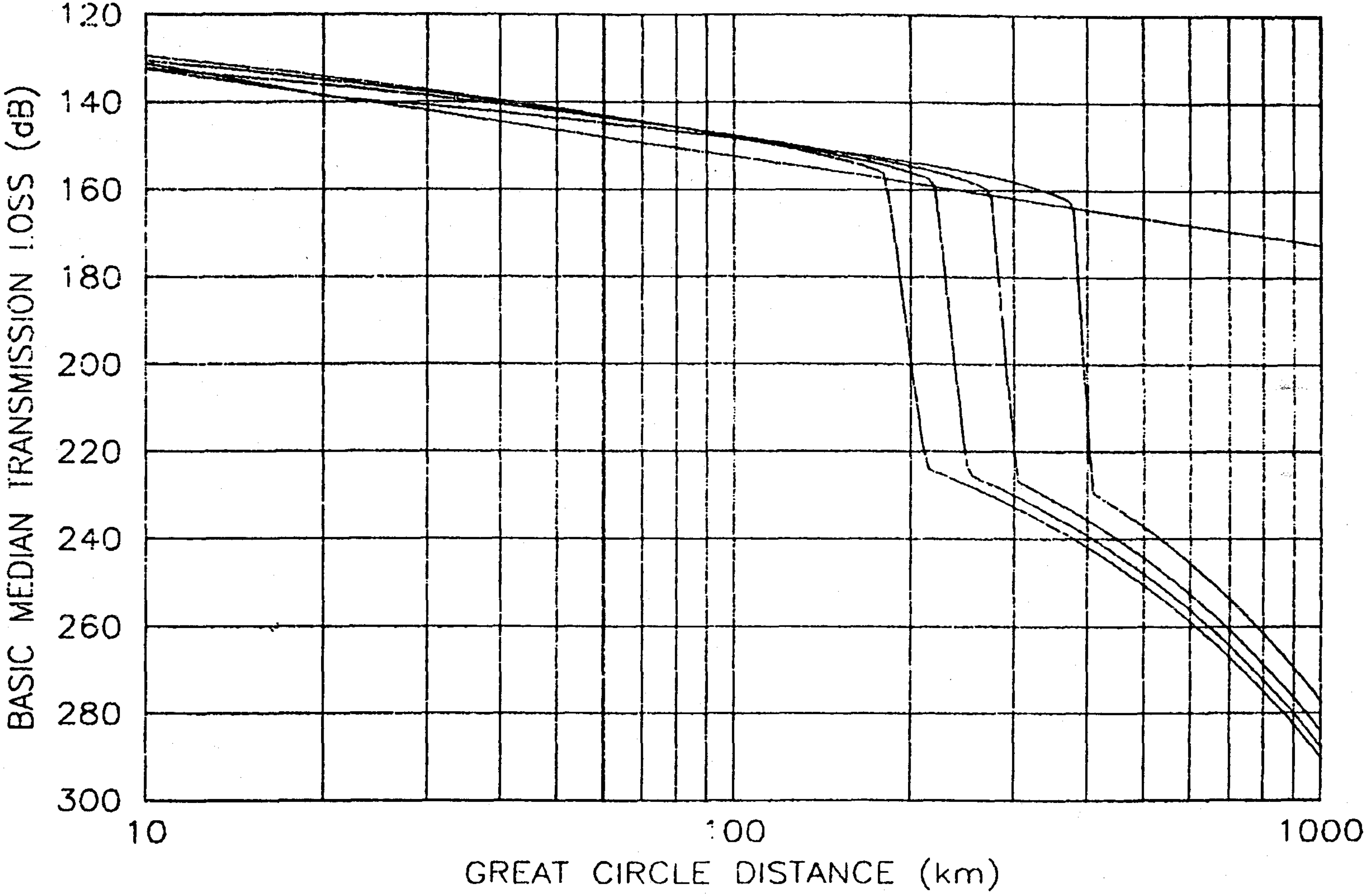

FIGURE A-67. f=10GHz, h_1=500m, h_2=500m, 1km, 2km, 5km

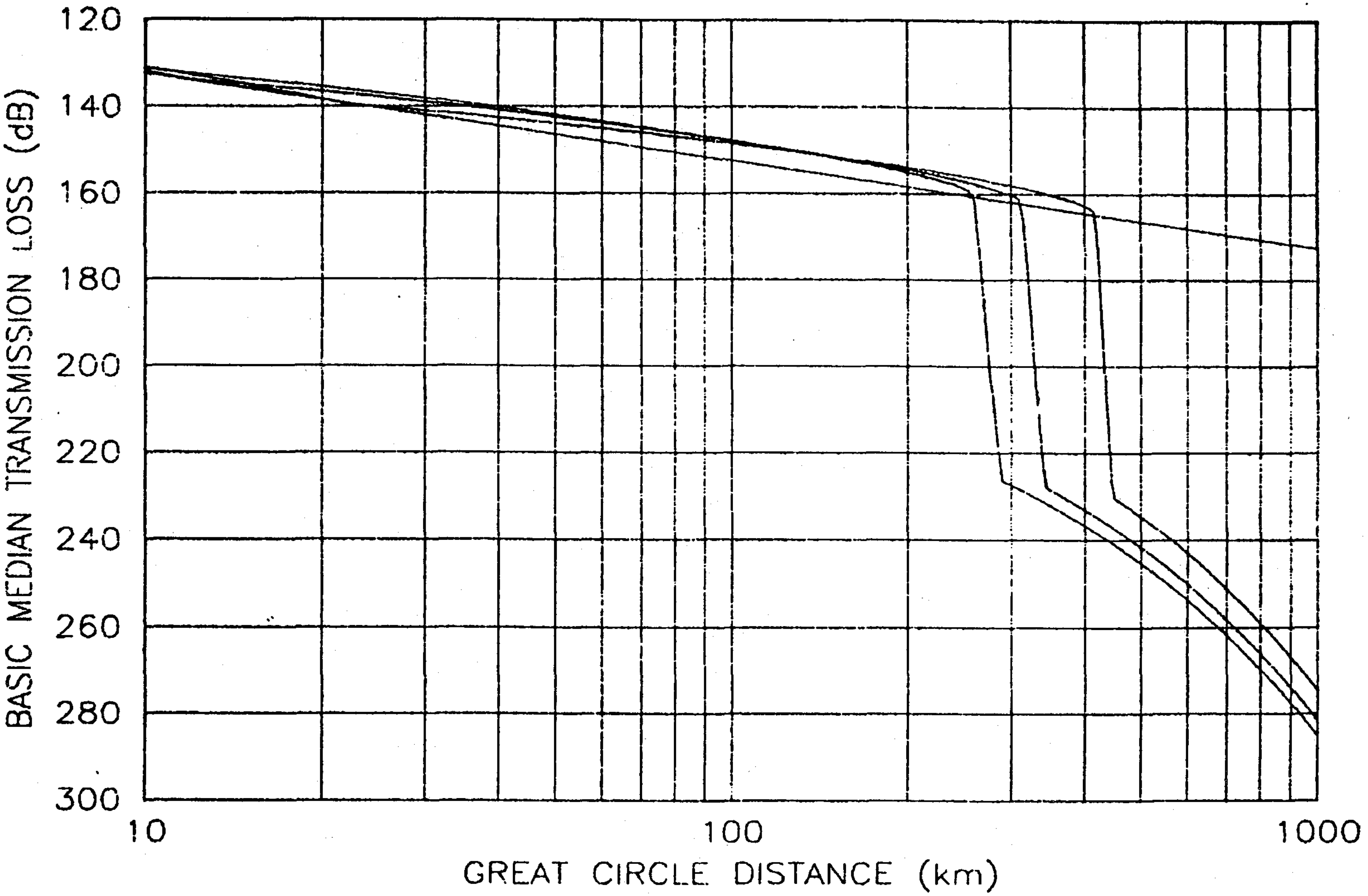

FIGURE A-68. $f=10GHz, h_1=1km, h_2=1km, 2km, 5km$

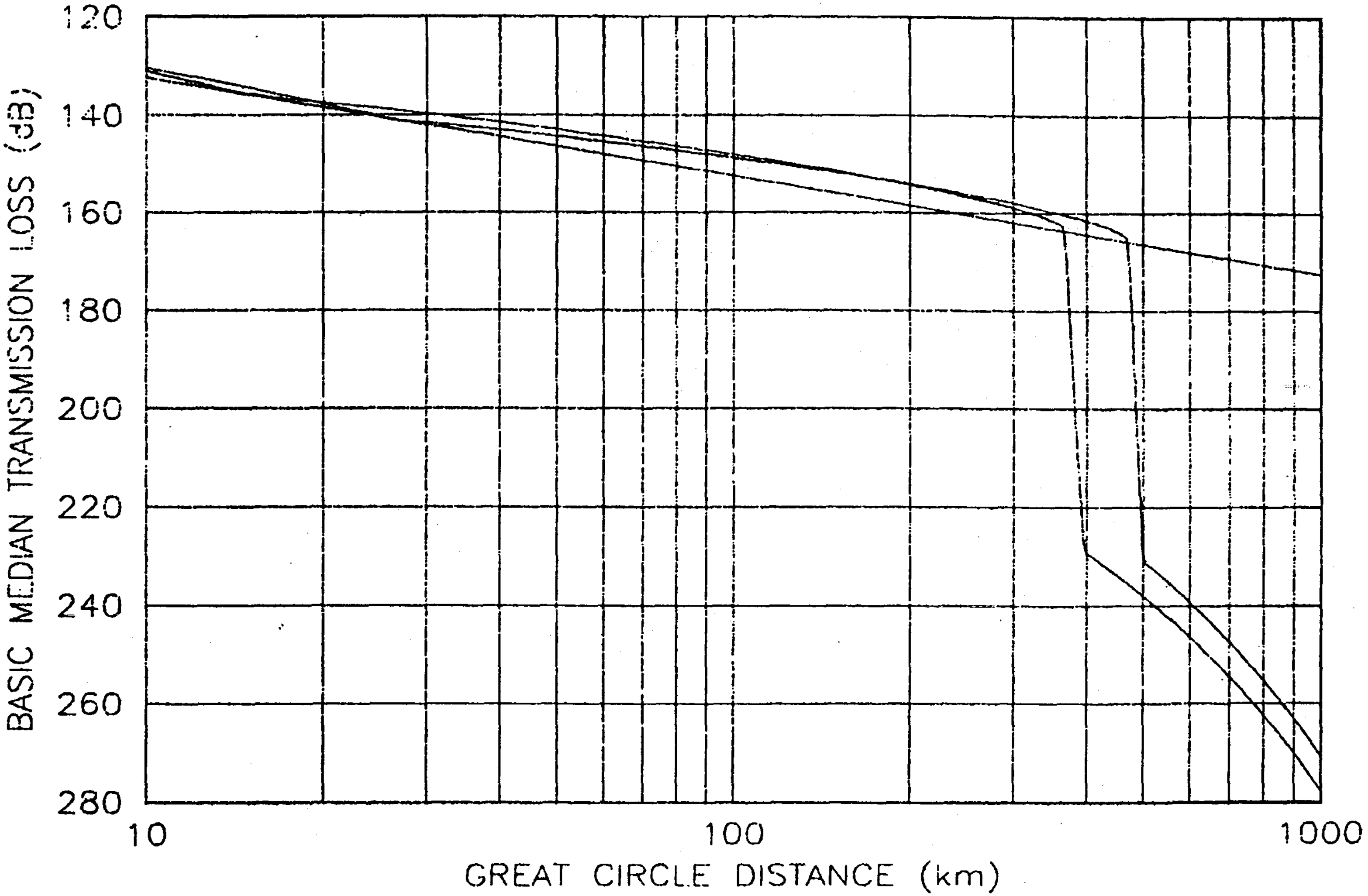

FIGURE A-69. $f=10\text{GHz}, h_1=2\text{km}, h_2=2\text{km}, 5\text{km}$

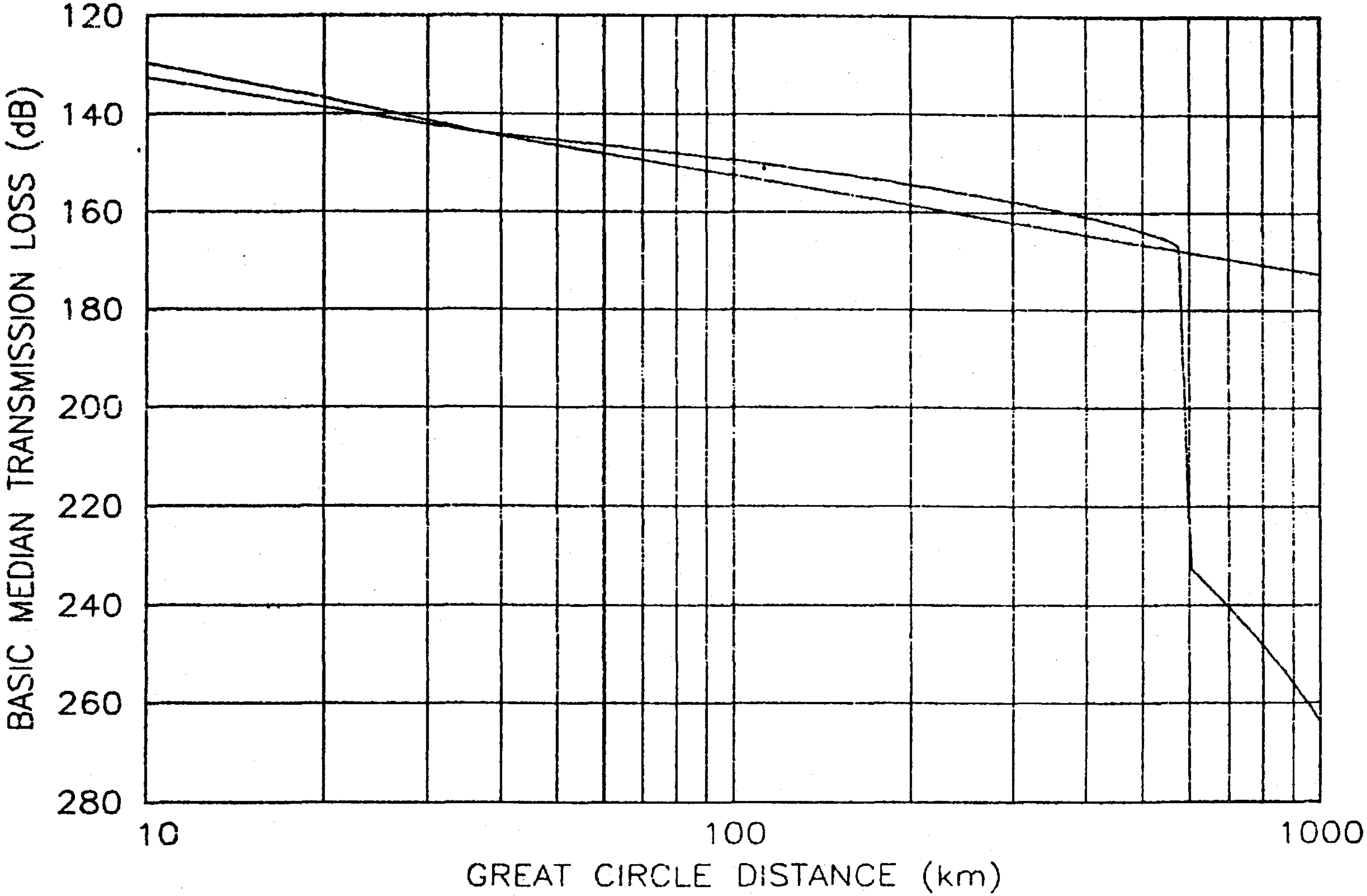

FIGURE A-70. $f=10GHz, h_1=5km, h_2=5km$

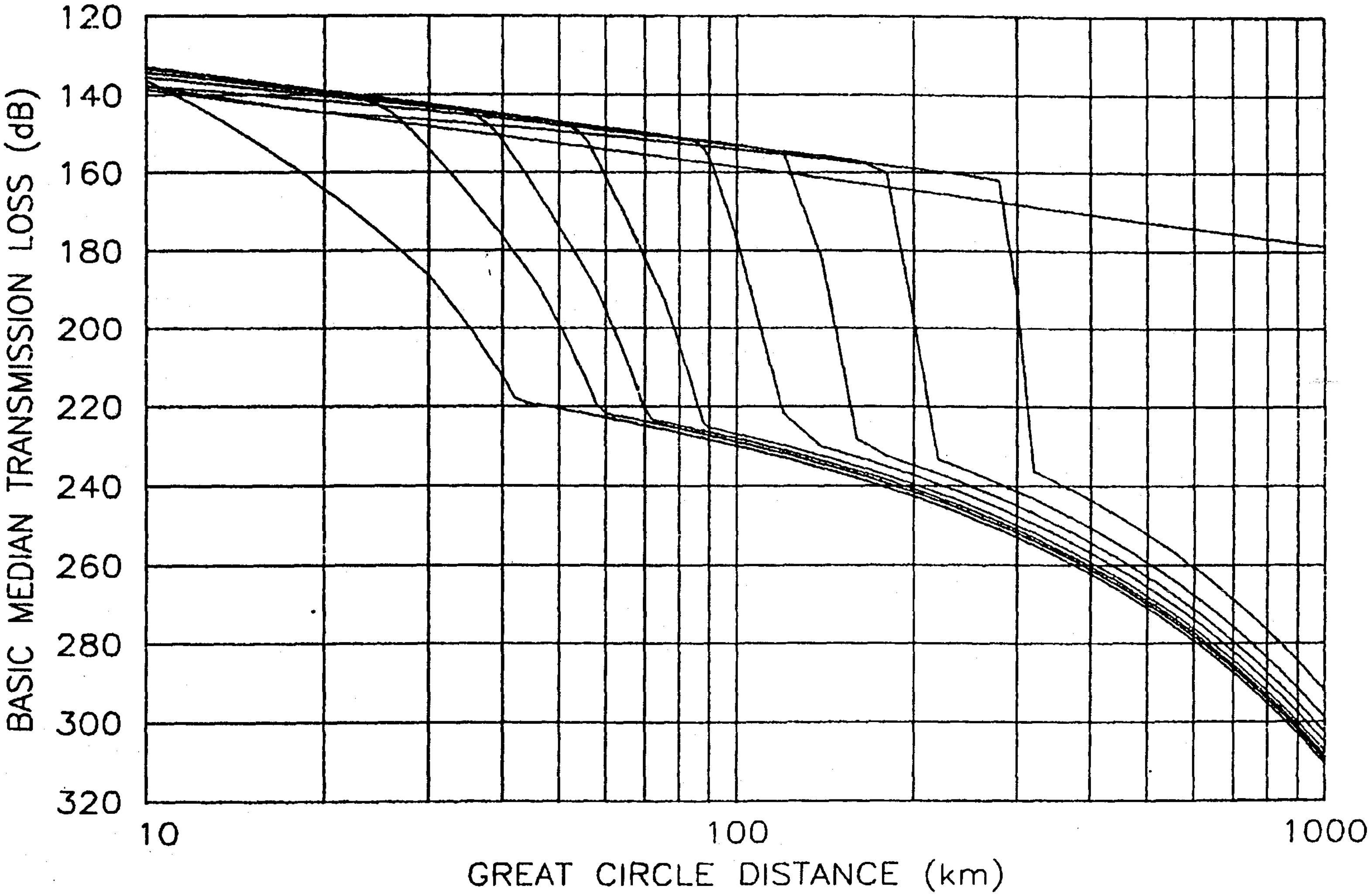

FIGURE A–71. f=20GHz, h_1=1m, h_2=10m, 50m, 100m, 200m, 500m, 1km, 2km, 5km

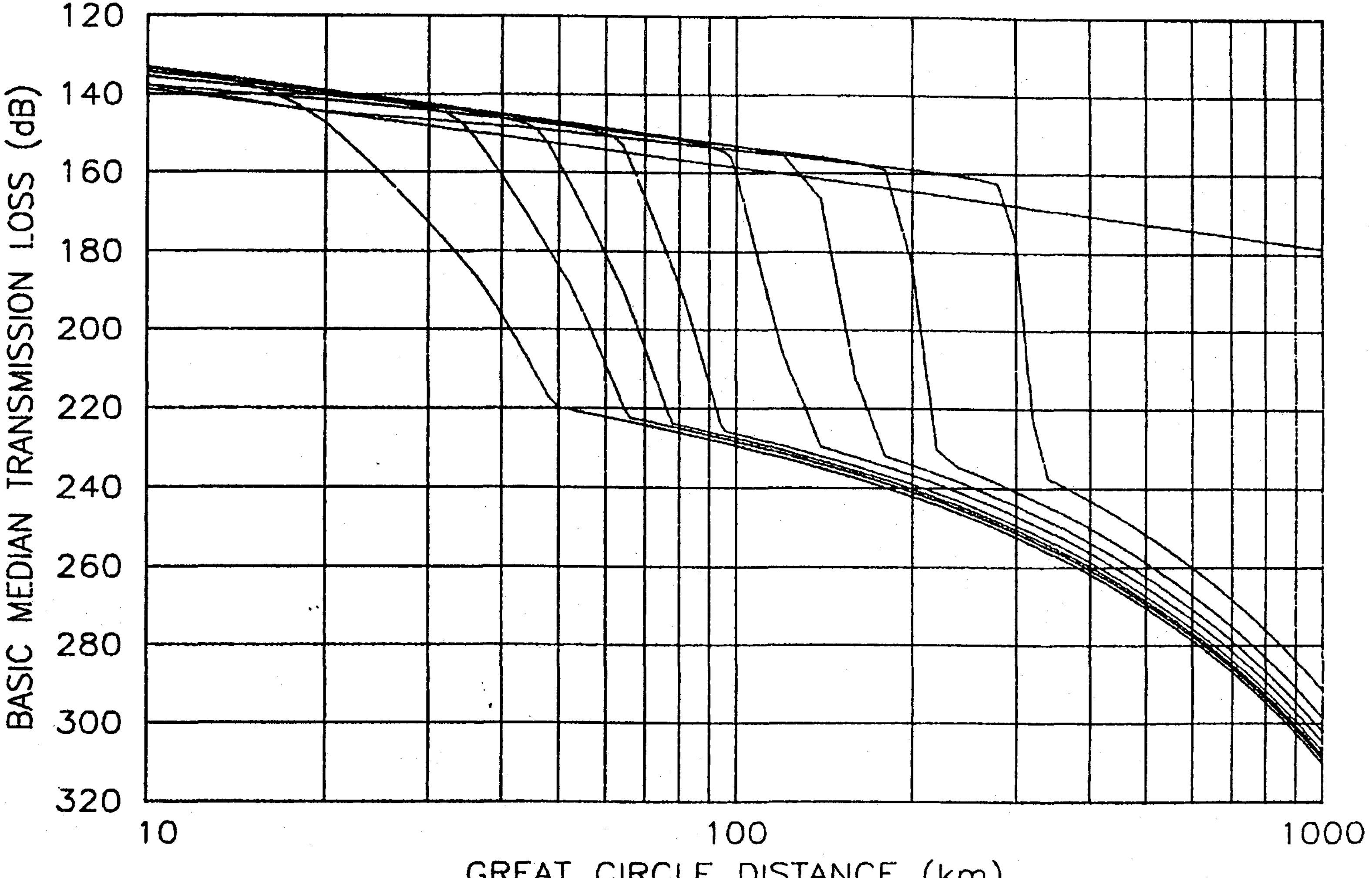

FIGURE A-72. f=20GHz,h_1=10m,h_2=10m,50m,100m,200m,500m,1km,2km,5km

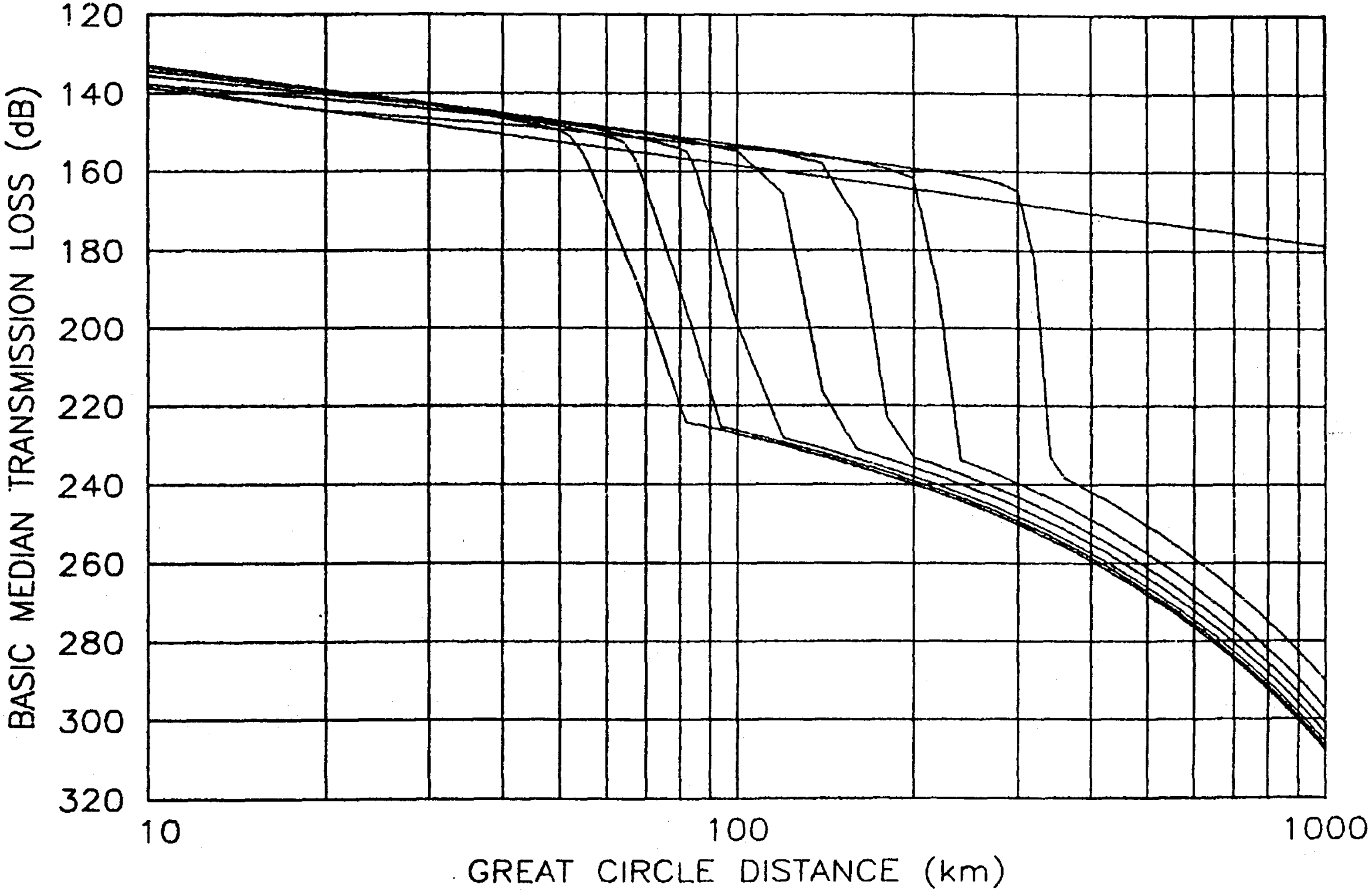

FIGURE A–73. f=20GHz,h_1=50m,h_2=50m,100m,200m,500m,1km,2km,5km

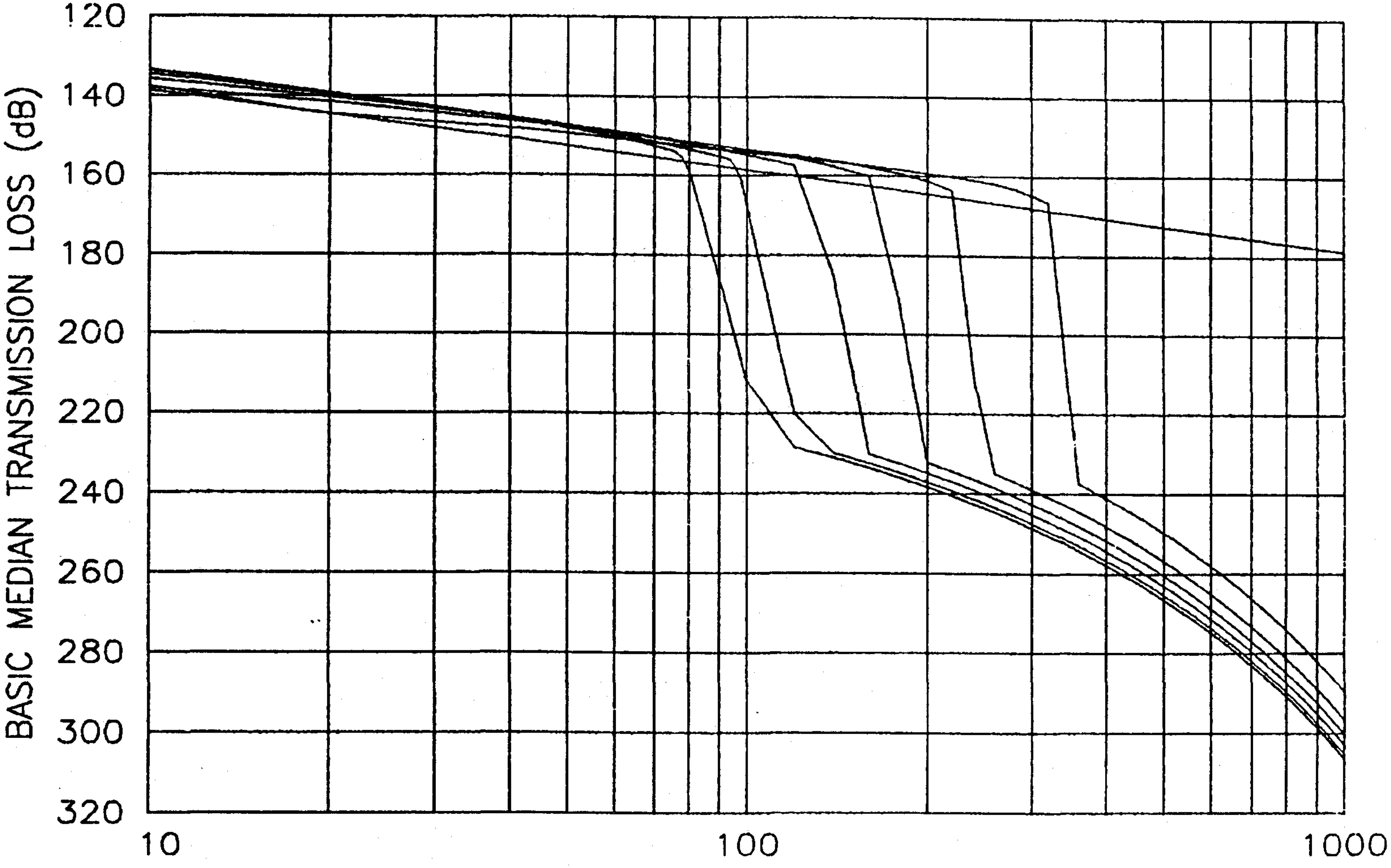

FIGURE A-74. f=20GHz, h_1=100m, h_2=100m,200m,500m,1km,2km,5km

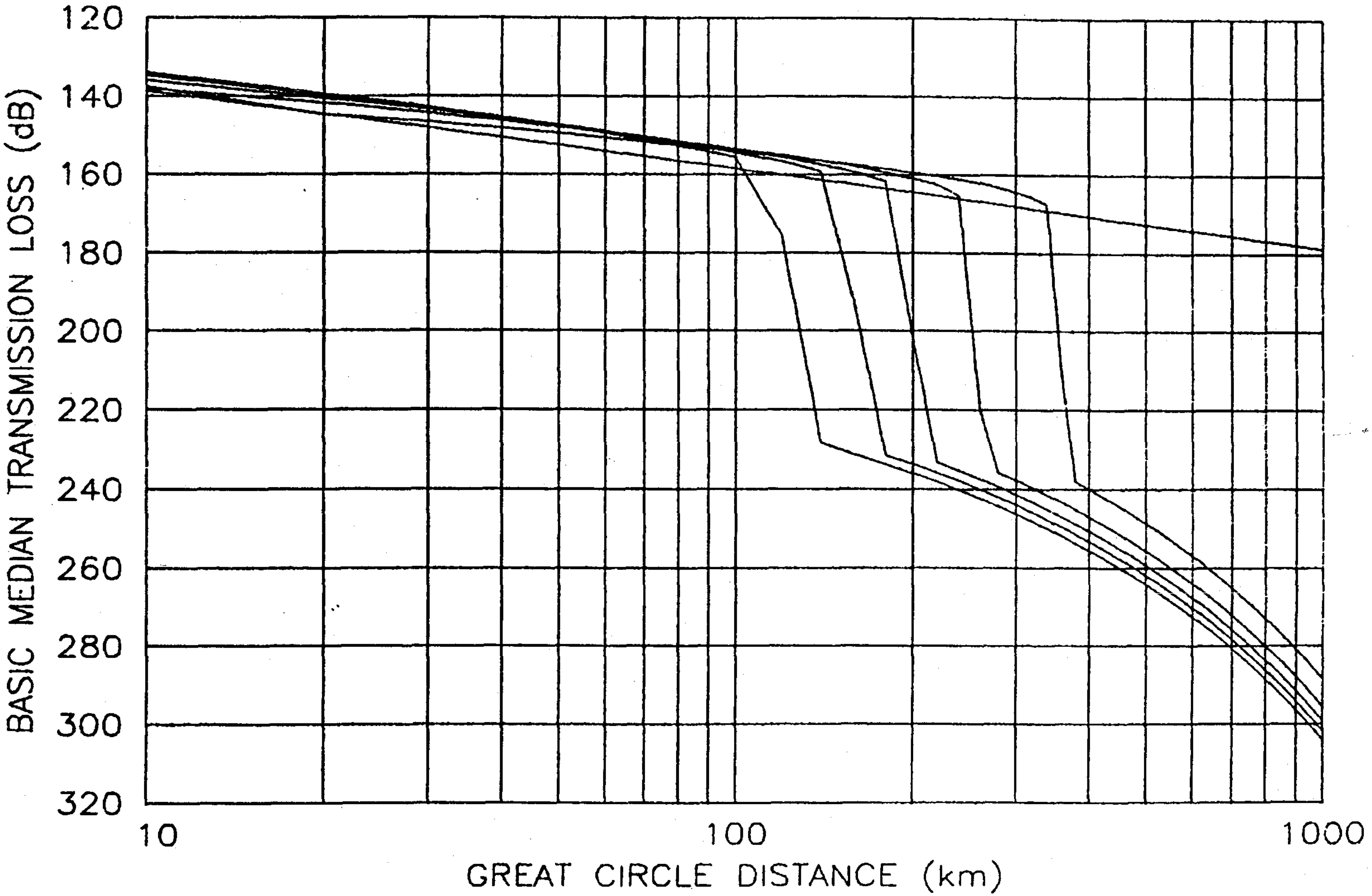

FIGURE A–75. f=20GHz,h_1=200m,h_2=200m,500m,1km,2km,5km

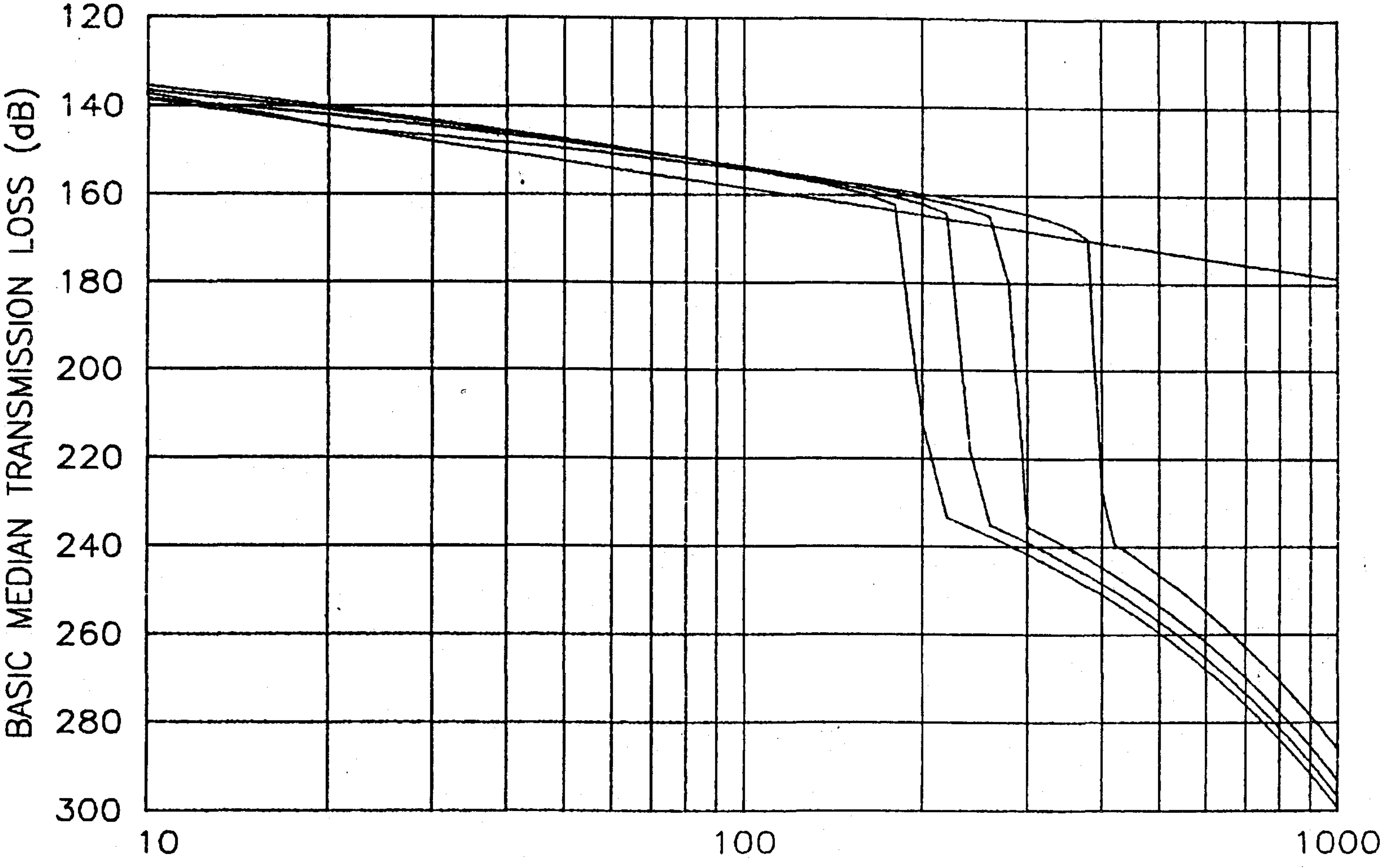

FIGURE A-76. $f=20GHz, h_1=500m, h_2=500m, 1km, 2km, 5km$

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This handbook is intended to provide estimates of radio wave propagation loss between transmitting and receiving antennas of various heights and transmission frequencies above the assumed smooth-earth surface calculated using the NLAMBDA computer model. For many cases involving electromagnetic compatibility analysis, the curves of predicted transmission losses in this report may be used to estimate the transmission losses of the desired and undesired signals. These estimated loss values are given in dB as BASIC MEDIAN TRANSMISSION LOSS for antennas with effective heights up to 5000 meters, operating in the 100 to 20,000 MHz frequency range, over land or sea, at great circle earth surface distances up to 1000 kilometers. This handbook is an expanded version of the initial handbook and includes curves for the additional frequencies of 500 MHz, 2000 MHz, 5000 MHz, 7000 MHz, and 20,000 MHz.

16. Key Words *(Alphabetical order, separated by semicolons)*

Basic Median Transmission Loss; Electromagnetic Compatibility; Radio Wave Propagation; Transmission Loss

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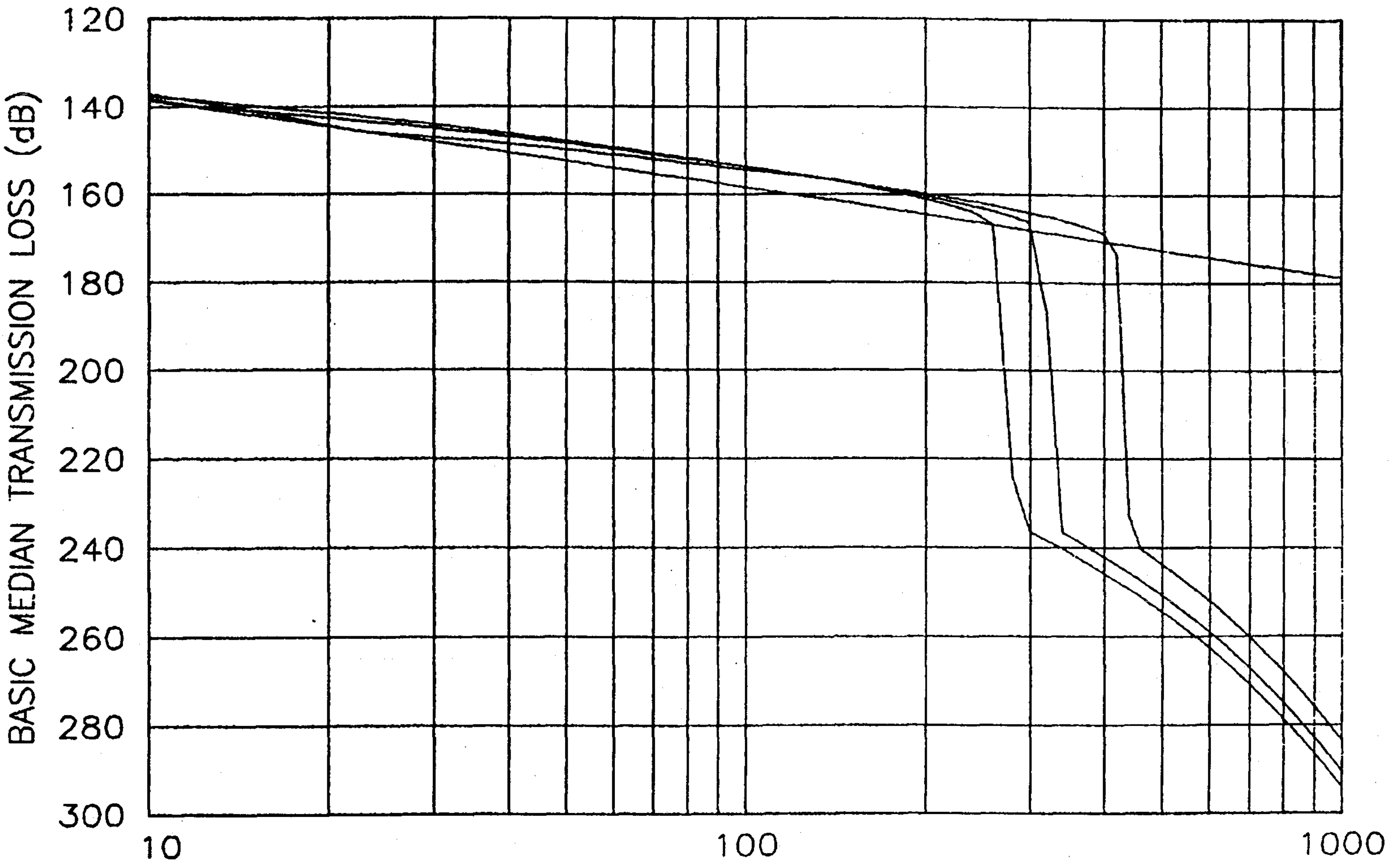

FIGURE A–77. $f=20GHz, h_1=1km, h_2=1km, 2km, 5km$

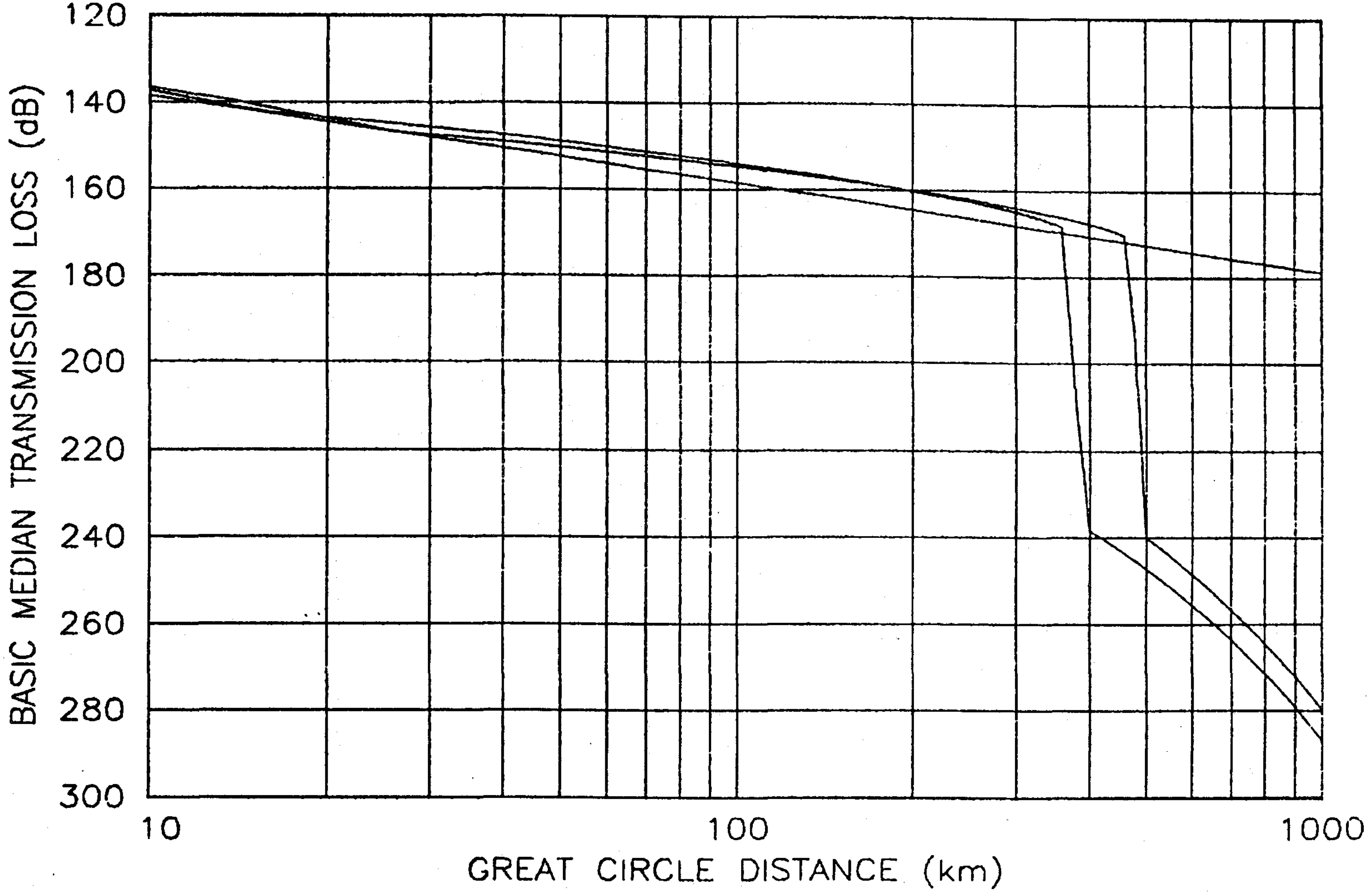

FIGURE A–78. f=20GHz,h_1=2km,h_2=2km,5km

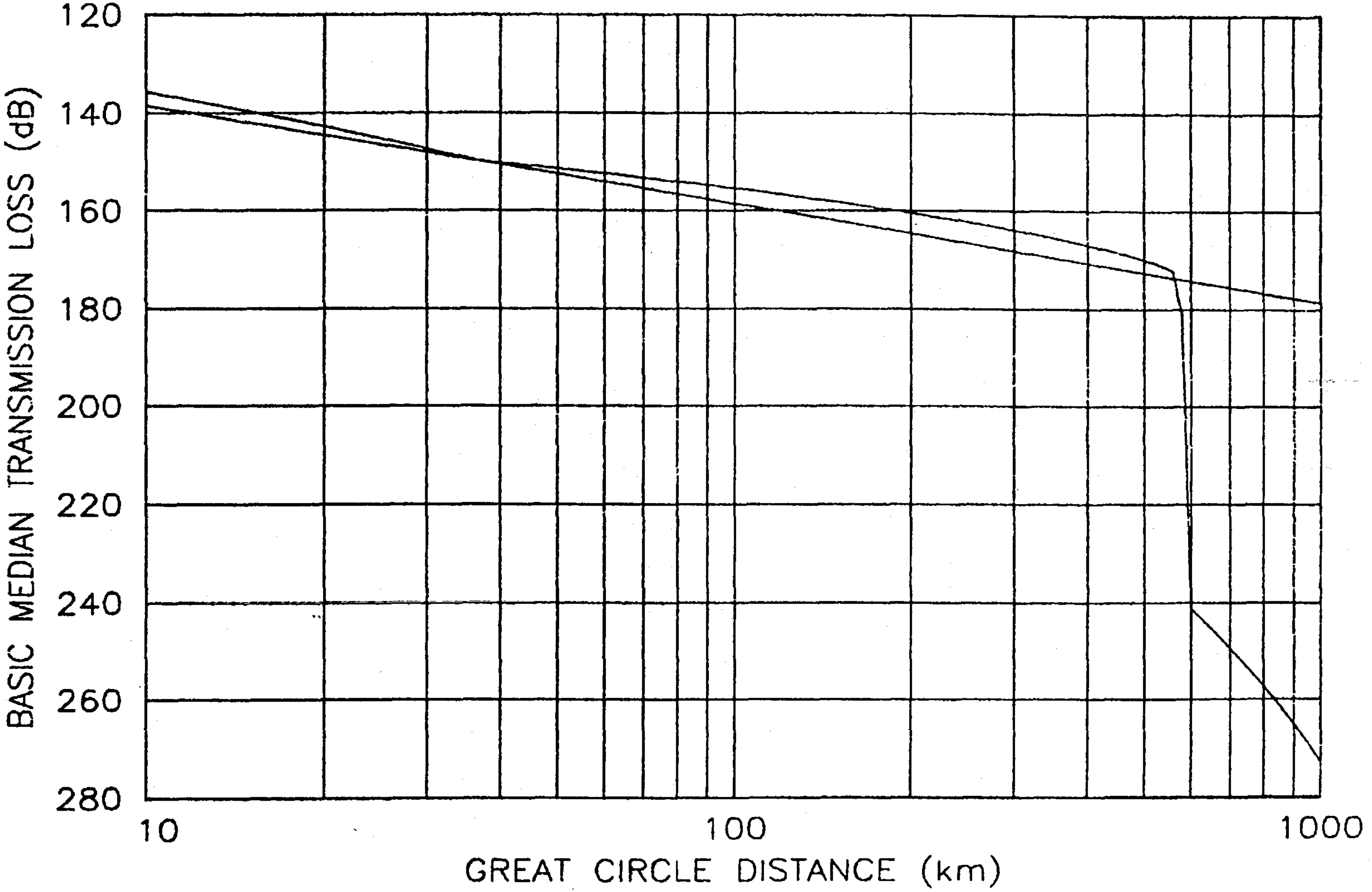

FIGURE A-79. $f=20GHz, h_1=5km, h_2=5km$

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