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Estimates of Millimeter Wave Attenuation for 18 United States Cities

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ESTIMATES OF MILLIMETER WAVE ATTENUATION FOR 18 UNITED STATES CITIES

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Attenuation by the atmosphere can severely limit the use of the radio spectrum above 10 GHz for telecommunication purposes. In this report brief discussions of three mechanisms that attenuate millimeter waves in the atmosphere are presented: rain attenuation, clear air absorption, and atmospheric multipath. Propagation models developed by personnel at the Institute for Telecommunication Sciences and by others were combined with meteorological statistics to obtain estimates of average year attenuation distributions for 18 cities in the United States. The estimates are presented in such a way to elucidate the restrictions on system parameters required for reliable operation, i.e. frequency, path length for terrestrial paths, and path elevation angle for earth-satellite paths. The variation imposed by the diverse climates within the United States is demonstrated. Generally, in regions that have humid climates, millimeter wave systems perform less favorably than in areas where arid or semi-arid conditions prevail.

Key words: millimeter wave attenuation; millimeter wave model; millimeter wave systems; radio propagation

1. INTRODUCTION

In recent years, serious efforts have been devoted toward developing telecommunications capabilities in the millimeter wave (30-300 GHz) portion of the spectrum. This work is motivated by a desire to enhance spectrum utilization, to relieve spectrum congestion, and to exploit the portability of millimeter wave systems. Millimeter wave systems offer the advantage of wide bandwidths (hence more information can be transmitted in a given time interval), high resolution, generally low power consumption, and relatively small size. The increase in millimeter wave research and development activity has been fostered by substantial advances in millimeter wave component technology enabling sources of millimeter wave transmissions to be competitive with those of lower frequencies.

Millimeter waves are attenuated more than microwaves under the same environmental conditions. While this leads to a reduction in the range over which millimeter wave communication systems can effectively operate, it also results in lowered interference potential between systems. The attenuation of the energy of

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a millimeter wave radio signal is due primarily to its absorption by the (molecular) atmospheric constituents oxygen and water vapor, as well as scattering and absorption by rain, snow, and fog. Other factors such as terrain features and atmospheric refraction layers will also influence the overall performance of a millimeter wave system. Refraction layers can cause signals from a millimeter wave transmitter to reach the receiver by more than one propagation path. This phenomenon, called atmospheric multipath, can cause radio waves to interfere with each other, sometimes resulting in fading of the signal.

In this report we illustrate the dominant role the lower atmosphere plays in limiting the usefulness of millimeter waves for telecommunications purposes. Emphasis is placed on specifying the basic characteristics of atmospheric attenuation which substantially determines millimeter wave system performance. The information is presented in a form to aid those individuals who are relatively unfamiliar with millimeter wave radio propagation. Thus, the scope of the material presented has been restricted to keep from obscuring the information pertinent to the intended audience. Many technical details necessary for reliable system planning have been omitted. Discussion of attenuation by clouds and fog, depolarization by rain, and year-to-year variations in attenuation by rain has been severely restricted. Such information is available elsewhere (Ippolito et al. 1981; Dutton and Dougherty, 1979).

In order to provide a meaningful introduction to the use of millimeter waves for telecommunication purposes, we present in this report some location-dependent differences in millimeter wave attenuation within the United States. Propagation models developed at the Institute for Telecommunication Sciences and elsewhere were combined with statistics derived from meteorological observations for 18 major population centers. Maximum path lengths for terrestrial links and minimum path elevation angles for earth-satellite links are presented for frequencies in the 10 to 100 GHz range. The range of path lengths or elevation angles and frequencies for which the signal exceeds various levels is shown to vary widely with location.

In the next section of this report and Appendix B, the models used to evaluate attenuation due to rain, atmospheric constituents of water vapor and oxygen, and multipath phenomena are briefly discussed. In Section 3 and Appendix A, results of combining these models with the climatology information valid for specific locations within the United States are presented.

2. ENVIRONMENTAL LIMITATIONS ON MILLIMETER WAVE SYSTEMS

Because the attenuation of millimeter waves is strongly dependent upon rain, water vapor, and oxygen, it is necessary that realistic models of these effects be available in order to obtain corresponding realistic and useful results. Also, influences on system performance due to multipath require special consideration. In this section, these phenomena are discussed in order to lay the groundwork for the results presented in Section 3.

2.1 Background

A radio communication system normally carries information via radio waves propagating through the atmosphere from a transmitter to one or more receivers. Environmental conditions along the radio path can deteriorate the quality of a transmitted signal. If the impacts are severe enough, the communication system might simply fail to operate. The understanding and prediction of such outage times are of interest to both system planners and users. Outages occur when the signal strength falls below a system-dependent threshold. Signal strength is measured on a log-scale in units of decibels (dB). (Every 3 dB of attenuation reduces the signal power by one half).

The atmospheric propagation medium causes signal attenuation. The most serious, though intermittent, attenuator for millimeter waves is rain. Millimeter waves are also affected by suspended hydrosols (fog, clouds), and by oxygen and water vapor in clear air. Rain, cloud water, oxygen, and water vapor absorbers are easily related to climatological variables. Consequently, the occurrence of outages depends upon the climate. Finally, certain atmospheric stratifications may result in millimeter waves reaching the receiver by more than one path. Multiple propagation paths can interfere with each other. Interaction of direct and reflected rays results in temporal and spatial signal scintillations, or fading. High data rate digital communication systems can experience outages even when the carrier radio wave is near its normal power level. These outages occur from phase distortion within the signal bandwidth. Multipath is believed to be the major source of phase distortions severe enough to cause outages when the high data rates, presently under consideration (< 5 GB/s), are employed.

Rain attenuation, atmospheric absorption, and multipath are discussed below in more detail.

2.2 Rain Attenuation

The attenuation of millimeter wave signals due to rain on a given path depends on the number of rain drops and the size of the rain drops along the path. For attenuation calculations, rain is quantized by the point rain rate along the path making its average the most important parameter for predicting attenuation.

Rain rate probability distributions at specific locations are used to predict signal attenuation. For a given geographical location a point rain rate distribution gives the percentages of time that different rain rates are expected to be exceeded. Average rain rate distributions have been computed from rain rate data measured over many years at a great variety of locations. Methods for deriving expected rain rate distributions, based on the measured distributions, have been developed so that it is possible to estimate average rain rate distributions for United States cities (Rice and Holmberg, 1973; Dutton, 1977).

Using the point rain rate distribution for a given path, an attenuation distribution giving the percentage of time that different values of attenuation are expected to be exceeded can be derived. The attenuation distribution depends on the point rain rate distribution, the radio frequency, and the path length. For earth-satellite paths, the path elevation angle determines the path length through the air mass. Rain attenuation increases with path length. Intense rain occurs only over short distances, hence the attenuation does not increase proportionately with path length. Earth-satellite path attenuation is greater for lower path elevation angles, because a longer portion of the path is in the troposphere where the rain occurs (generally at altitudes below 3 km or the 0°C isotherm). Rain attenuation increases with frequency over the range 10 to 100 GHz. The ratio of attenuation at different frequencies is sensitive to the drop-size distribution of the rain.

Rain attenuation distributions for 20 GHz transmission in Miami, Florida, and Phoenix, Arizona, are displayed in Figure 1. Assuming a value of 20 dB as the system outage threshold leads to an expected 0.2 percent of the year or an accumulated 17.5 hours per year of outage time in Miami and respectively 0.006 percent or one-half hour in Phoenix.

Higher attenuation occurs for smaller percentages of the year and is produced by the high rain rates in thunderstorms. The more frequent lower values are due to rain rates associated with stratiform rain covering a larger area.

The actual attenuation distribution will deviate from the predicted value on a year-to-year basis depending on the variability of the local weather. The occurence

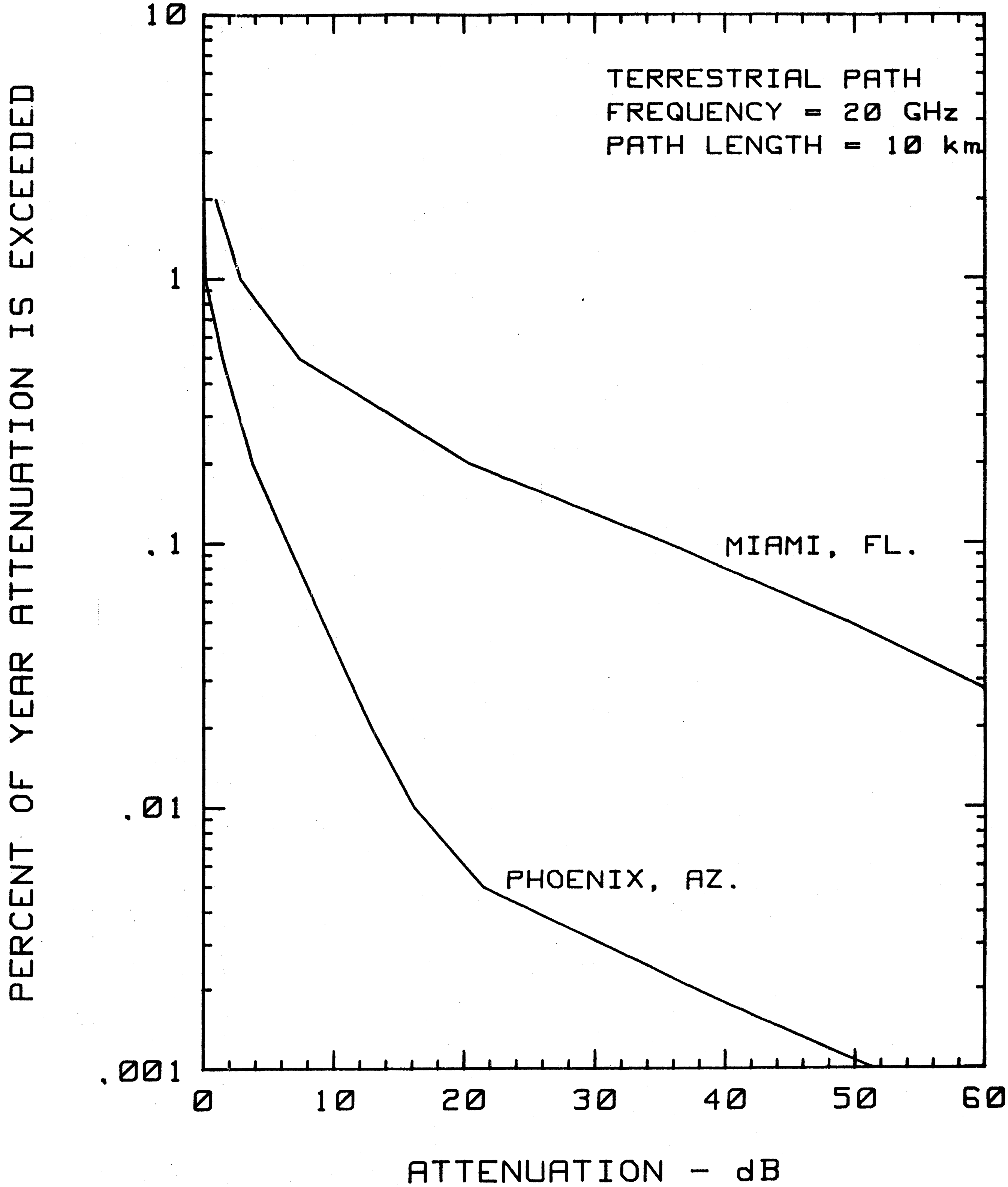

Figure 1. Expected rain attenuation distribution for 10 km terrestrial paths at 20 GHz located in Miami, FL, and Phoenix, AZ.

of rain follows seasonal trends in the United States. Outage time due to rain attenuation is not evenly distributed throughout the year. For most United States cities the highest values of attenuation occur in the spring and summer when thunderstorms are prevalent.

Most methods (including the one in this report that follows from the work of Crane, 1980) that predict rain attenuation on earth-satellite paths do not separate rain and cloud attenuation. In the past the primary concern has been for earth-satellite links operating below 30 GHz, where cloud attenuation is negligible. Above about 60 GHz, however, cloud attenuation associated with thunderstorms is expected to contribute significantly. Note that this fact is not considered in the earth-satellite path attenuation predictions of this report. A description of typical, additional amounts of attenuation due to clouds is given in Section 3.

2.3 Clear-Air Attenuation

Millimeter waves are absorbed in air by molecular resonances of oxygen and water vapor occurring at distinct frequencies (H_2O at 22 and 183 GHz, O_2 at 60 and 119 GHz). At resonance the absorption peaks. When the radio frequency deviates from the resonant frequency, the attenuation drops sharply, at a rate depending on the pressure and temperature of the air. Absorption is proportional to the total number of molecules in the radio path, which depends on pressure, temperature, and path length. The attenuation in decibels is proportional to path length, i.e., twice the path length will double the decibels of attenuation. Many molecular oxygen absorption lines are located around 60 GHz. At sea level pressures, the more than 30 lines combine to one broad absorption region, $\approx 60 \pm 5$ GHz (see Figure 2). Water vapor has an absorption line centered at 22.235 GHz. These two features constitute the strongest gaseous absorption in air between 10 and 100 GHz. Absorption in between the lines (window frequencies around 35 and 90 GHz) is mainly determined by very strong water vapor absorption lines at much higher frequencies (0.5 to 20 THz) contributing a residual continuum attenuation.

Absorption in the 60 GHz range is dominated by oxygen. The magnitude is, to first order, sensitive only to the height variation of pressure. Outside the 60 GHz region, water vapor is the main contributor to absorption. The amount of water vapor in the air is highly variable, and limited by saturation which is a strong function of temperature. Hence, water vapor absorption is influenced by temperature. Warmer climates (deserts are the exception) generally have greater amounts of water vapor in the atmosphere accompanied accordingly with higher absorption rates. Within the United States, absorption for the window frequencies is highest in the southeast and lowest in the west. The months with the greatest absorption are usually July and August.

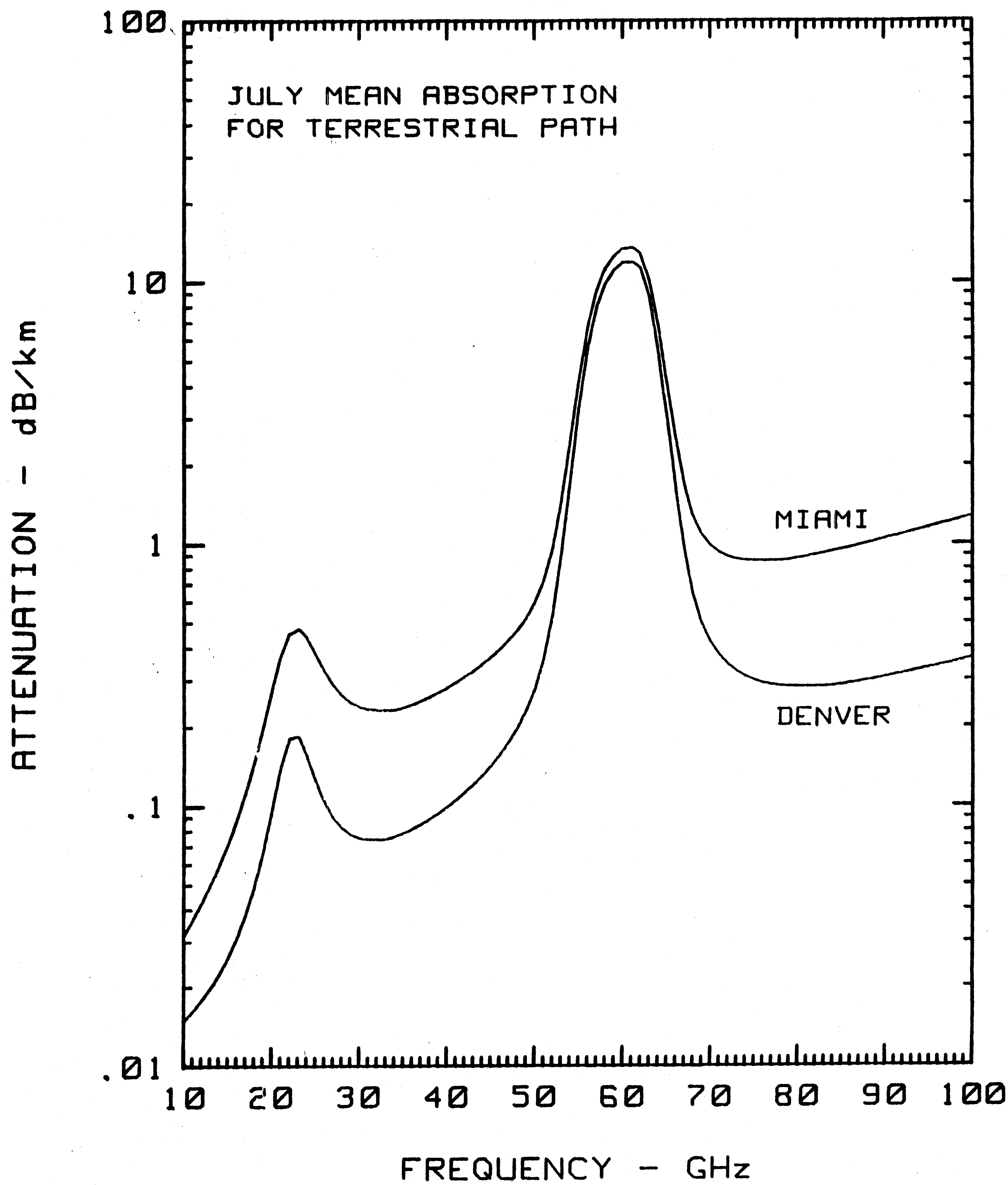

Figure 2. Predicted mean clear air absorption in July for terrestrial paths in Miami, FL, and Denver CO.

Figure 3 shows the clear-air attenuation predicted to be exceeded 99, 95, 90, 50, 10, 5, and 1 percent of the time in the month of July in Washington, DC. Table 1 lists the predicted mean attenuation for a 10 km path during July for selected frequencies and cities. Table 2 lists the absorption that is exceeded 5 percent of the time in July for the same frequencies and cities. The variability of clear-air attenuation within a month is indicated in Figure 3 and by the comparison of entries in Tables 1 and 2. Typically, for frequencies not dominated by oxygen absorption, the clear-air attenuation varies during a month from 0.6 to 1.2 times the monthly mean.

For earth-satellite paths, clear-air attenuation depends on the elevation angle to a satellite measured from the horizon. Minimum attenuation occurs for vertical (zenith) paths. The attenuation increases with the cosecant of the elevation angle down to about 10 degrees.

The calculations of clear-air attenuation for earth-satellite paths in this report take account of pressure, temperature, and humidity distributions over the first 30 km of the atmosphere where all the water related (rain, cloud, vapor) absorption occurs. This height range is sufficient for accurate calculations except near 60 GHz where oxygen absorption prevails up to altitudes of 100 km (Liebe, 1981). The atmosphere is essentially opaque around 60 GHz for earth-satellite paths with nearly 150 dB attenuation occurring in the first 30 km for a zenith path.

Tables 3 and 4 give the predicted mean clear-air attenuation in July and the attenuation exceeded 5 percent of the time in July, respectively, for a zenith path in various cities and at selected frequencies.

2.4 Atmospheric Multipath

Multipath fading occurs when radio waves reach the receiving antenna by more than one path. Interference of these signals can cause deep fades. Two typical multipath conditions occur when: (i) signals arrive at the receiver after being reflected from the ground or other objects along the path, and (ii) refraction layers exist in the atmosphere along the path. Refractive gradients partially bend radio waves leading to several paths between the transmitting and receiving antennas. Multipath generally is not of concern for earth-satellite paths because the usual elevation angles for such paths are generally too large to cause multipath (>10°). In actual system operation, ground multipath can be eliminated by directing antenna beams in such a way that potentially reflecting surfaces are not

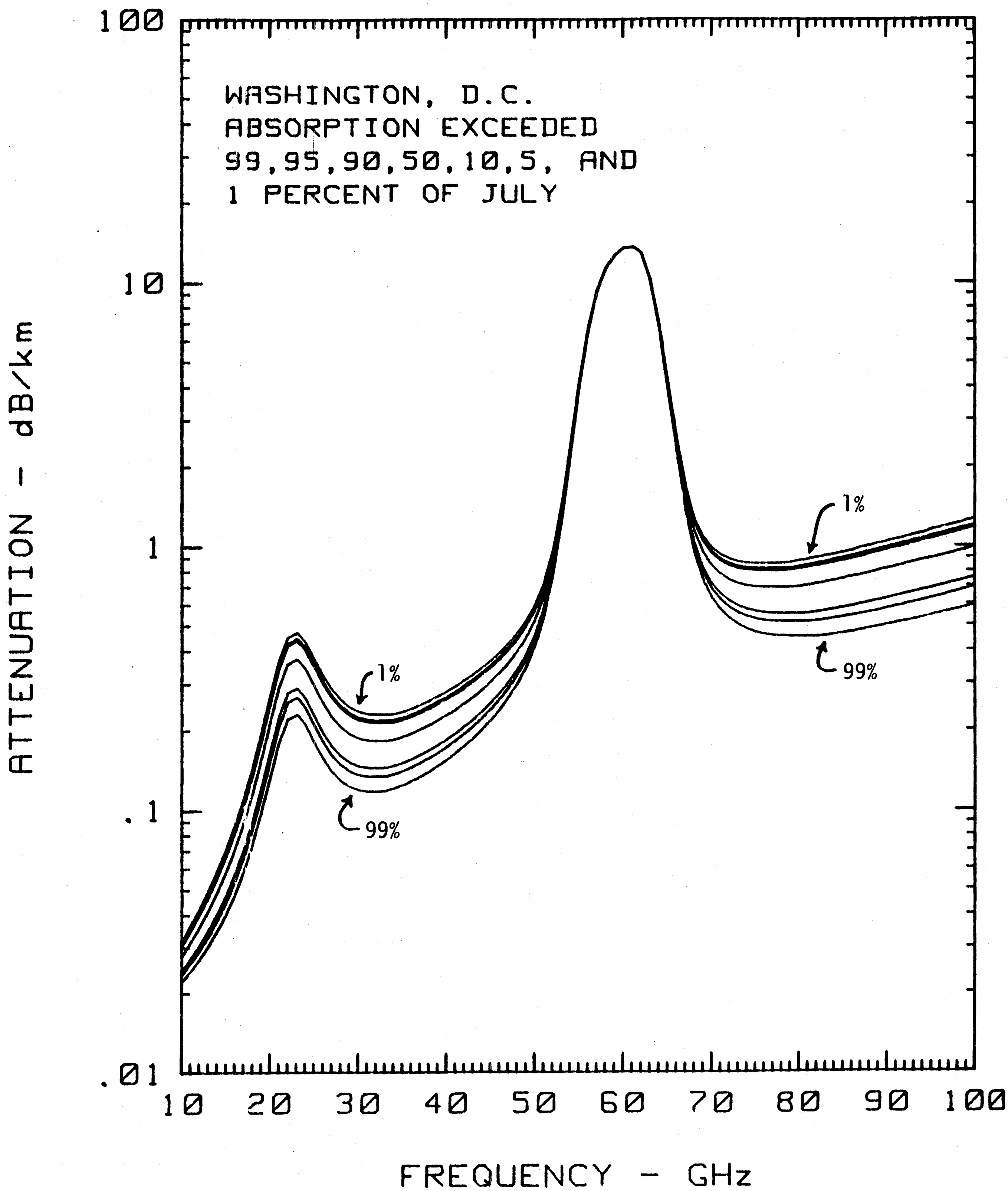

Figure 3. Predicted levels of clear air attenuation exceeded 99, 95, 90, 50, 10, 5, and 1 percent of the time in July for a terrestrial path in Washington, DC.

Table 1. Mean Clear-Air Attenuation in July for a 10 km Terrestrial Path

CITIES	ATTENUATION (dB) FREQUENCY IN GHZ 10	20	30	40	50	60	70	80	90	100
Atlanta, GA	.3	2.2	1.9	2.3	5.1	131.6	8.1	7.0	8.2	10.0
Boston, MA	.3	1.9	1.7	2.1	4.9	138.3	7.7	6.3	7.4	8.9
Chicago, IL	.3	2.0	1.7	2.1	4.9	134.9	7.7	6.4	7.5	9.0
Dallas, TX	.3	2.3	1.9	2.3	5.2	130.2	8.2	7.1	8.4	10.2
Denver, CO	.1	1.0	.7	1.0	2.8	118.5	4.1	2.8	3.1	3.7
El Paso, TX	.2	1.5	1.2	1.5	3.6	120.3	5.5	4.3	5.0	6.0
Fairbanks, AK	.2	1.3	1.2	1.6	4.4	146.1	6.6	4.7	5.2	6.2
Honolulu, HI	.3	2.1	1.8	2.3	5.3	137.2	8.3	7.0	8.2	9.9
Miami, FL	.3	2.8	2.3	2.8	6.0	134.0	9.6	8.8	10.5	12.7
New Orleans, LA	.3	2.7	2.3	2.7	5.8	133.3	9.4	8.4	10.0	12.2
New York, NY	.3	2.0	1.7	2.2	5.1	137.2	7.9	6.5	7.6	9.2
Phoenix, AZ	.2	1.7	1.4	1.7	4.2	125.0	6.4	5.0	5.8	7.0
Omaha, NE	.3	2.0	1.7	2.1	4.8	132.9	7.5	6.3	7.3	8.9
San Diego, CA	.3	1.8	1.5	2.0	4.8	140.6	7.5	5.9	6.8	8.2
San Francisco, CA	.3	1.5	1.4	1.8	4.8	148.5	7.2	5.4	6.1	7.3
Seattle, WA	.2	1.3	1.2	1.6	4.5	147.3	6.7	4.7	5.3	6.3
St. Louis, MO	.3	2.2	1.8	2.3	5.1	134.4	8.1	6.9	8.1	9.8
Washington, DC	.3	2.2	1.9	2.3	5.3	136.0	8.3	7.0	8.2	10.0

Table 2. Clear-Air Attenuation Exceeded 5 Percent of July for a 10 km Terrestrial Path

CITIES	ATTENUATION (dB) FREQUENCY IN GHZ 10	20	30	40	50	60	70	80	90	100
Atlanta, GA	.3	2.7	2.2	2.7	5.6	131.7	9.1	8.3	9.9	12.0
Boston, MA	.3	2.4	2.0	2.5	5.5	138.4	8.8	7.7	9.1	11.0
Chicago, IL	.3	2.4	2.0	2.5	5.5	135.0	8.7	7.7	9.1	11.1
Dallas, TX	.3	2.7	2.3	2.7	5.7	130.2	9.2	8.4	10.1	12.3
Denver, CO	.2	1.4	1.0	1.3	3.3	118.6	5.0	3.9	4.5	5.4
El Paso, TX	.2	1.9	1.5	1.8	4.0	120.4	6.4	5.4	6.4	7.8
Fairbanks, AK	.3	1.8	1.6	2.0	5.0	146.2	7.7	6.1	7.0	8.4
Honolulu, HI	.3	2.6	2.2	2.7	5.8	137.2	9.3	8.3	9.9	12.0
Miami, FL	.3	3.2	2.7	3.2	6.5	134.1	10.7	10.1	12.1	14.8
New Orleans, LA	.3	3.1	2.6	3.1	6.4	133.4	10.4	9.8	11.7	14.3
New York, NY	.3	2.4	2.1	2.6	5.6	137.3	9.0	7.9	9.3	11.3
Phoenix, AZ	.2	2.1	1.7	2.1	4.7	125.1	7.3	6.2	7.3	8.9
Omaha, NE	.3	2.4	2.0	2.5	5.3	133.0	8.5	7.6	9.0	10.9
San Diego, CA	.3	2.2	1.9	2.4	5.4	140.6	8.5	7.2	8.5	10.3
San Francisco, CA	.3	2.0	1.8	2.3	5.4	148.5	8.4	6.8	7.9	9.6
Seattle, WA	.3	1.8	1.6	2.1	5.1	147.3	7.8	6.1	7.1	8.5
St. Louis, MO	.3	2.6	2.2	2.7	5.7	134.5	9.1	8.2	9.8	11.9
Washington, DC	.3	2.6	2.2	2.7	5.8	136.1	9.3	8.3	9.9	12.1

Table 3. Mean Clear-Air Attenuation in July for a Zenith Path

CITIES	ATTENUATION (dB) FREQUENCY IN GHZ 10	20	30	40	50	60*	70	80	90	100
Atlanta, GA	.1	.6	.5	.6	1.9	144.9	2.7	1.8	1.9	2.3
Boston, MA	.1	.5	.4	.6	1.7	146.8	2.5	1.4	1.5	1.8
Chicago, IL	.1	.5	.4	.6	1.8	146.0	2.6	1.6	1.7	2.0
Dallas, TX	.1	.6	.5	.7	1.9	145.5	2.7	1.8	2.0	2.3
Denver, CO	.1	.3	.2	.4	1.2	126.1	1.7	.9	.9	1.1
El Paso, TX	.1	.4	.3	.5	1.4	131.2	2.0	1.2	1.3	1.5
Fairbanks, AK	.1	.4	.3	.5	1.7	148.8	2.4	1.2	1.2	1.4
Honolulu, HI	.1	.5	.4	.6	1.9	149.5	2.7	1.6	1.8	2.1
Miami, FL	.1	.7	.5	.7	2.0	149.9	3.0	2.0	2.2	2.7
New Orleans, LA	.1	.7	.5	.7	2.0	148.5	2.9	2.0	2.2	2.6
New York, NY	.1	.5	.4	.6	1.8	148.6	2.6	1.6	1.7	2.0
Phoenix, AZ	.1	.5	.4	.6	1.7	141.5	2.4	1.5	1.6	1.8
Omaha, NE	.1	.5	.4	.6	1.7	142.5	2.4	1.5	1.6	1.9
San Diego, CA	.1	.5	.4	.5	1.7	145.0	2.5	1.4	1.5	1.7
San Francisco, CA	.1	.3	.3	.5	1.7	147.9	2.3	1.1	1.1	1.3
Seattle, WA	.1	.4	.4	.6	1.8	150.6	2.5	1.4	1.5	1.7
St. Louis, MO	.1	.6	.5	.6	1.9	145.4	2.7	1.7	1.9	2.3
Washington, DC	.1	.5	.4	.6	1.9	148.0	2.7	1.7	1.8	2.1

Table 4. Clear-Air Attenuation Exceeded 5 Percent of July for a Zenith Path

CITIES	ATTENUATION (dB) FREQUENCY IN GHZ 10	20	30	40	50	60*	70	80	90	100
Atlanta, GA	.1	.7	.5	.7	2.0	145.0	2.9	2.0	2.3	2.7
Boston, MA	.1	.5	.4	.6	1.8	146.9	2.7	1.7	1.8	2.1
Chicago, IL	.1	.6	.5	.7	1.9	146.1	2.8	1.8	2.0	2.4
Dallas, TX	.1	.7	.6	.7	2.0	145.5	3.0	2.1	2.3	2.8
Denver, CO	.1	.4	.3	.4	1.3	126.1	1.9	1.2	1.3	1.5
El Paso, TX	.1	.5	.4	.5	1.5	131.3	2.2	1.4	1.6	1.9
Fairbanks, AK	.1	.5	.4	.6	1.8	148.8	2.6	1.5	1.6	1.8
Honolulu, HI	.1	.6	.5	.7	2.0	149.6	2.9	1.9	2.1	2.5
Miami, FL	.1	.8	.6	.8	2.1	145.0	3.2	2.3	2.6	3.1
New Orleans, LA	.1	.8	.6	.8	2.1	148.6	3.1	2.2	2.5	3.0
New York, NY	.1	.6	.5	.7	2.0	148.7	2.8	1.9	2.0	2.4
Phoenix, AZ	.1	.6	.5	.6	1.8	141.6	2.6	1.7	1.9	2.3
Omaha, NE	.1	.6	.5	.6	1.8	142.6	2.6	1.7	1.9	2.3
San Diego, CA	.1	.6	.4	.6	1.8	145.0	2.7	1.7	1.8	2.1
San Francisco, CA	.1	.4	.4	.5	1.7	148.0	2.4	1.4	1.4	1.6
Seattle, WA	.1	.5	.5	.6	1.9	150.6	2.8	1.7	1.9	2.2
St. Louis, MO	.1	.7	.5	.7	2.0	145.5	2.9	2.0	2.3	2.7
Washington, DC	.1	.6	.5	.7	2.0	148.1	2.9	1.9	2.1	2.5

* Attenuation given only for the altitude range from ground to 30 km.

illuminated. In an urban environment, paths between buildings (good reflectors) require special attention in order to mitigate multipath effects.

3. ATTENUATION PREDICTIONS

3.1 Attenuation and Path Parameters

Propagation restrictions for a millimeter wave communication system originate primarily from attenuation due to rain and clear-air attenuation. Attenuation models limited to rain and atmospheric absorption are implements for system planning purposes. User requirements generally predetermine the geographic location and reliability expectations. For planning purposes, presentation of attenuation predictions in terms of frequency, path length (terrestrial path) or elevation angle (earth-satellite path), and attenuation level for the given geographic location and reliability requirement may elucidate the various interdependences better than an attenuation distribution as presented in Figure 1. Such a presentation is given below.

3.2 Terrestrial Paths

Assume for a terrestrial path that both geographic location and reliability requirement of a system are given. Also, in addition, assume that an attenuation threshold is set above which the planned system will experience outages. The path length expected to suffer above threshold attenuation for a given percentage of the year can be computed. Path lengths longer than this "critical path length" would be expected to experience outages for longer time periods over a year. The critical path length depends upon the radio frequency.

Figure 4 exhibits critical path lengths for which attenuation levels of 10 and 30 dB are predicted to be exceeded 0.1 percent of the year in Washington, DC. The information in Figure 4 can be used by system planners who consider millimeter wave communications in Washington, DC, with a reliability requirement that outages occur on the average of 0.1 percent of the year. If a path length of 10 km is specified and the system can suffer 30 dB attenuation before an outage occurs, then any frequency up to about 38 GHz could be used to meet the requirements. However, if only 10 dB attenuation were allowed, then frequency is limited to about 17 GHz. If the frequency, say 30 GHz, was specified instead of the path length, and 30 dB attenuation were allowed, then only path lengths shorter than about 8.5 km could be tolerated. On the other hand, if path length and frequency are specified, say 10 km and 20 GHz, then it can be seen that the system would need to tolerate more than 10 dB attenuation without an outage in order to meet the reliability requirements.

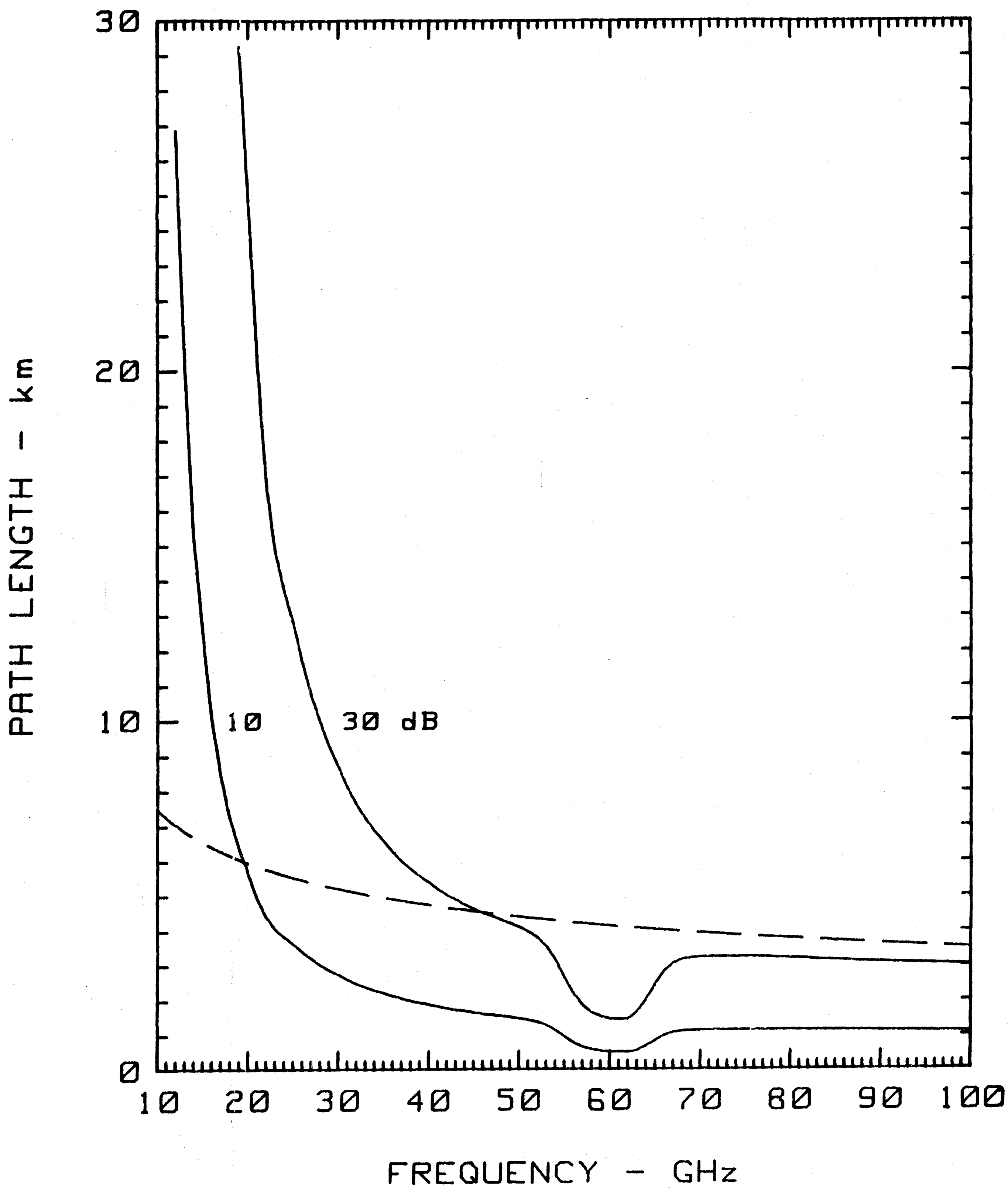

Figure 4. Path lengths predicted to experience attenuation exceeding 10 and 30 dB, 0.1 percent of the year in Washington, DC. The dotted line gives the critical (see text) path length for multipath.

The dotted line in Figure 4 is the minimum path length for which atmospheric multipath is predicted to occur. Path lengths longer than this may or may not experience atmospheric multipath, depending on the local path environment. Because multipath models are largely untested, the indicated path length is an approximate limit above which such effects might be of concern to system planners. Past experience on microwave systems at a given location may serve as the best indication of what to expect.

Figure 5 gives the critical path length at which 30 dB attenuation is predicted to be exceeded 0.1 percent of the year in Miami, Florida, and El Paso, Texas. Of the 18 cities examined, these two have the worst and best environments respectively for millimeter wave propagation. Path lengths of the other 16 cities lie somewhere in between. Path lengths can be the longest in El Paso since precipitation is rare. Path lengths have to be much shorter in Miami where frequent precipitation with high rain rates prevails.

3.3 Earth-Satellite Paths

For earth-satellite paths the path length concept is replaced by a path elevation angle criterion. Figure 6 depicts the "critical elevation angles," for which attenuation levels of 5 and 15 dB are predicted to be exceeded 0.1 percent of the year in Washington, DC. Note that the expected attenuation increases as the elevation angle decreases so that only elevation angles greater than the critical elevation angle would have less average outage time. The dotted line in Figure 6 represents the maximum elevation angle to a geostationary satellite from Washington, DC. Geostationary satellites would appear below this critical value.

Figure 6 can be used for relating the parameters: elevation angle, frequency, and attenuation, thus providing pertinent information for an earth-satellite link, planned in Washington, DC, with a reliability requirement that outages occur on the average of 0.1 percent of the year. If the elevation angle and attenuation margin for an outage are given, then the maximum usable frequency can be found. If the elevation angle and frequency are given, then the required fade margin is fixed. If the frequency and fade margin are given, then the minimum elevation angle allowable can be determined.

Figure 7 gives the critical elevation angle at which 10 dB attenuation is predicted to be exceeded 0.1 percent of the year in Miami, Florida, and El Paso, Texas. Miami and El Paso constitute the worst and best cases of the 18 locations considered here. The propagation environment is slightly better in Fairbanks, Alaska, than in El Paso, for earth-satellite paths. However, the maximum elevation angle to a geostationary satellite from Fairbanks is only 17 degrees.

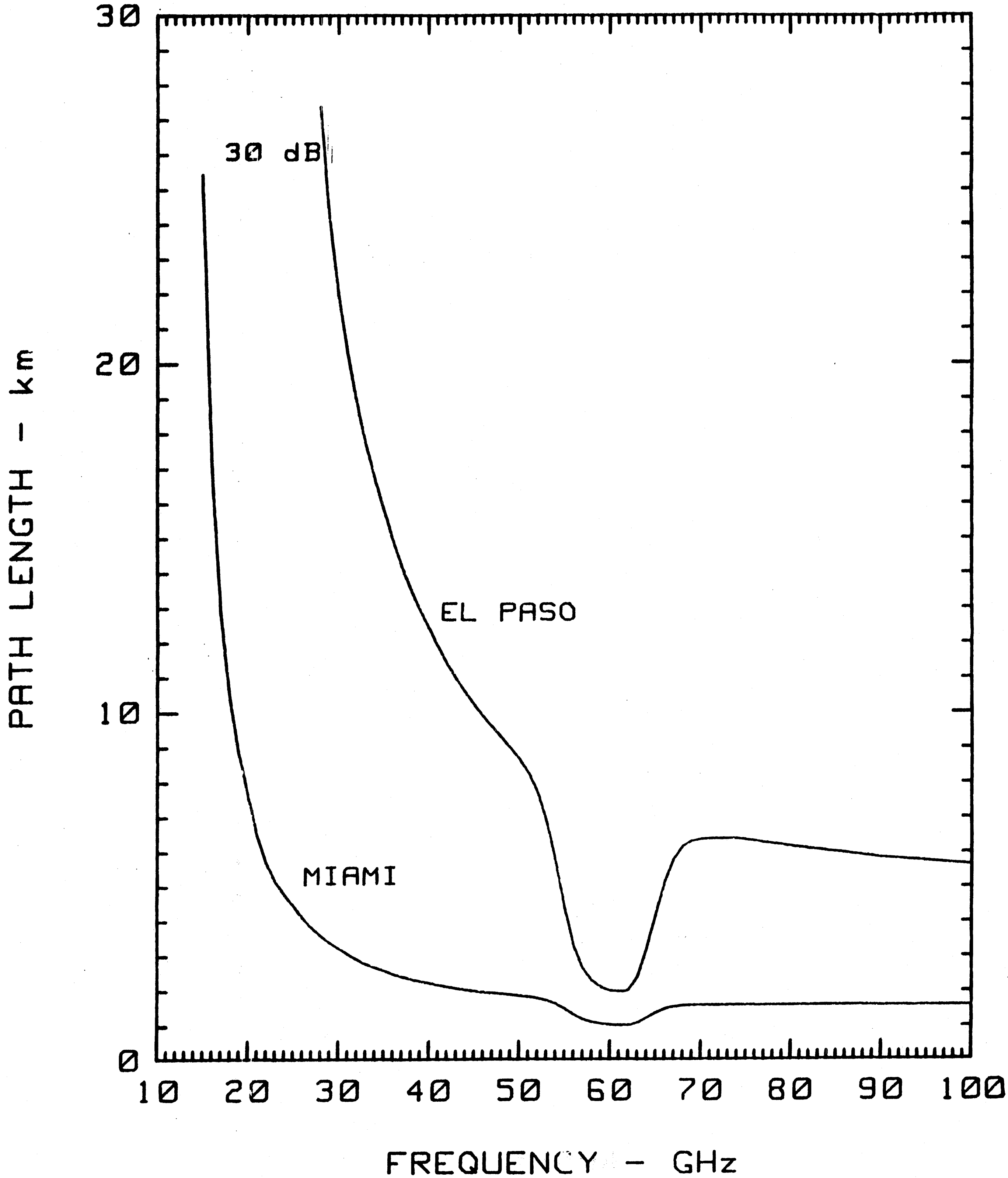

Figure 5. Path lengths predicted to experience attenuation exceeding 30 dB, 0.1 percent of the year in Miami, FL, and El Paso, TX.

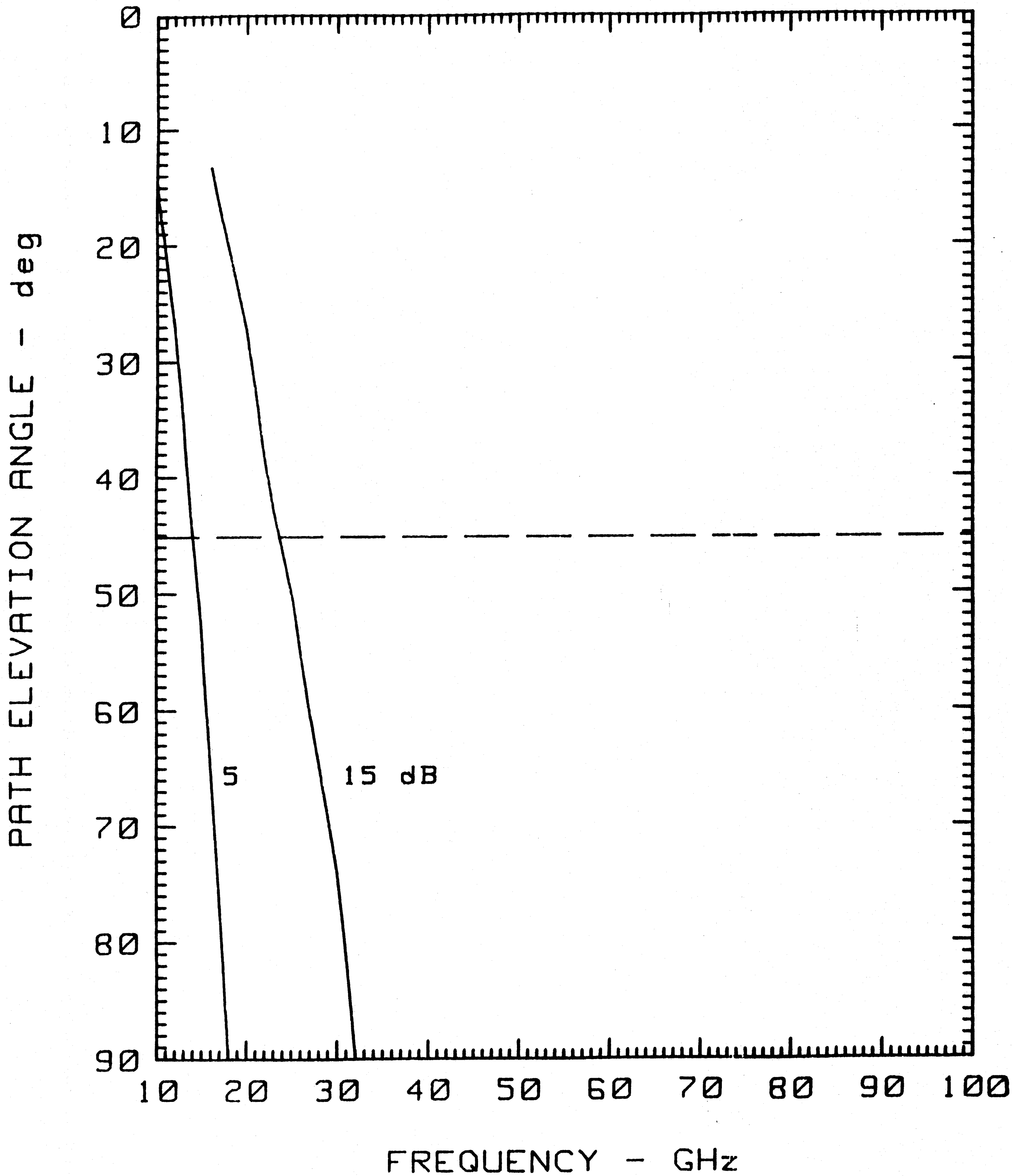

Figure 6. Path elevation angles predicted to experience attenuation exceeding 5 and 15 dB, 0.1 percent of the year in Washington, DC.

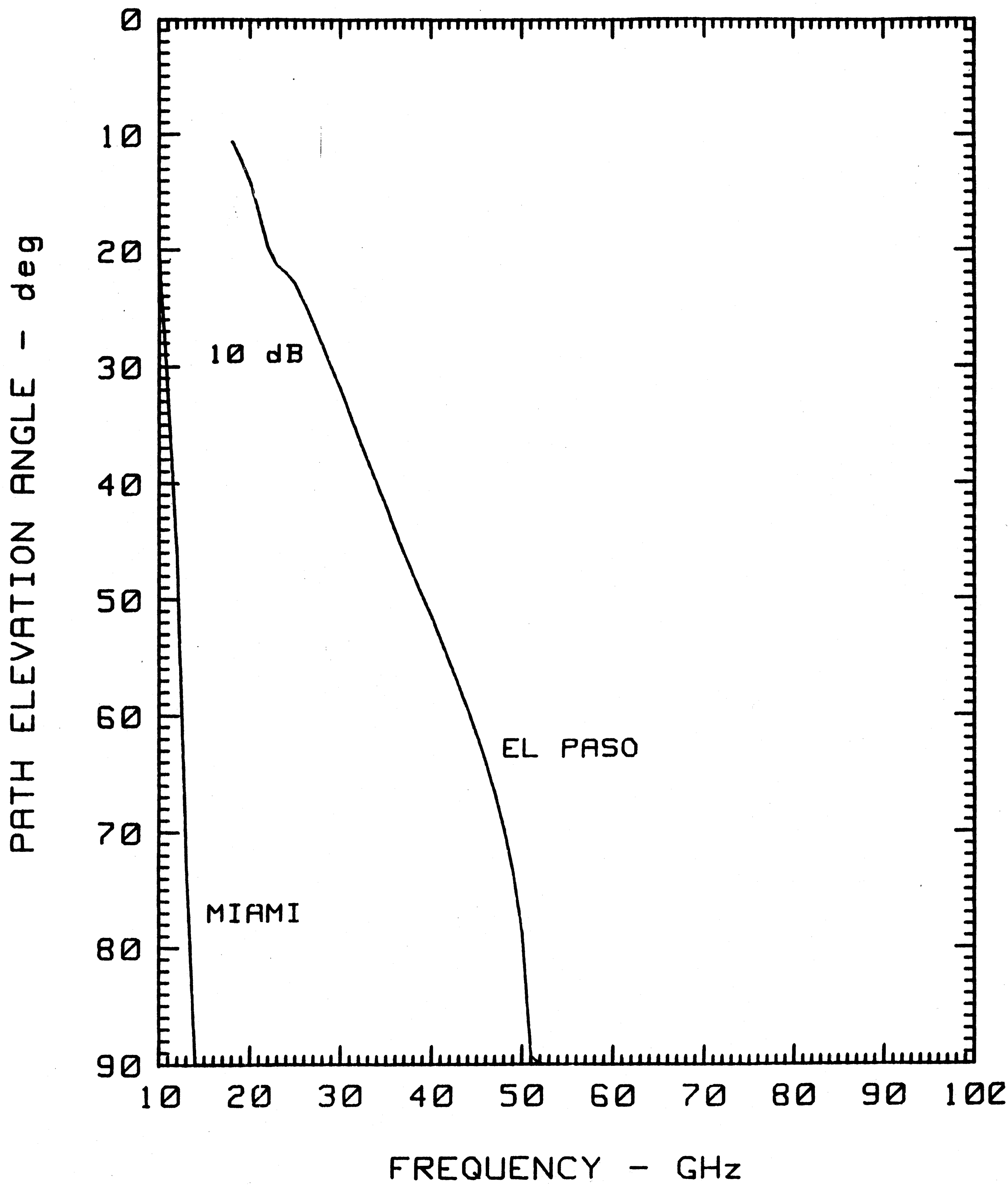

Figure 7. Path elevation angles predicted to experience attenuation exceeding 10 dB, 0.1 percent of the year in Miami, Fl, and El Paso, TX.

The critical elevation angle trace for the other 15 cities (except Fairbanks) are between those of Miami and El Paso (see Appendix A).

The attenuation due to clouds on earth-satellite paths have not been included in the results described above. Models for cloud attenuation are still under development. The effects of cloud attenuation, however, cannot be neglected on earth-satellite paths. Cloud attenuation associated with cumulonimbus (thunderstorms) is most severe. Results of a study (to be reported) indicate that attenuation associated with clouds can be approximated by

$$A = 7.5Rf^2/(14100 + f^2) \tag{1}$$

where A is the attenuation in dB, f is the frequency in GHz, and R is the rain rate in mm/h being produced by the cloud.

The rain rate corresponding to the desired outage requirement should be found from the rain rate distribution for the city of interest. With this rain rate and the given frequency, an estimate of the cloud attenuation exceeded the desired percentage of the year can be found using (1). This additional attenuation can serve to adjust the attenuation margin requirement. For example, a rain rate of 16 mm/hr is predicted to be exceeded 0.1 percent of the year in Washington, DC. At 20 GHz, ((1) then gives a cloud attenuation of 3.3 dB. Figure 6 gives a predicted attenuation of 15 dB for 20 GHz at an elevation angle of 29 degrees. Including cloud attenuation, however, the predicted attenuation would be 18.3 dB for the same conditions. The example discussed illustrates the relative magnitude of thunderstorm cloud attenuation compared to that of a rain rate of 16 mm/hr. Further work is required for cloud attenuation at millimeter wave frequencies.

4. SUMMARY

In this report, results of model calculations of the attenuation of millimeter waves due to propagation through clear air and through rain have been presented. The models used to derive the results depend upon meteorological parameters such as pressure, temperature, relative humidity, and rain rate.

Attenuation predictions which show the relationship between frequency, path length, or elevation angle and attenuation level in Washington, DC, for 0.1 percent of the year have been presented in Figures 4 and 6. Similar graphs for terrestrial and earth-satellite paths and for 1, 0.1, and 0.01 percent of the year are given in Appendix A for the 18 selected United States cities. Rain rate distributions are also presented in Appendix A for each city.

The rain rates used in the calculations of the rain attenuation at specific locations in the United States were values for an average year. The attenuation of millimeter waves due to rain, and hence the performance of millimeter wave telecommunication systems, will vary substantially from year to year depending upon the local weather conditions (Dutton and Dougherty, 1979). The estimates of the clear-air attenuation were derived from models that made use of climatological data obtained during the month of July. Generally, the largest amount of clear-air attenuation at locations in the United States occurs during the month of July. Thus if a millimeter wave telecommunication system can operate satisfactorily in the presence of clear-air attenuation during the month of July, it can be concluded that it will operate satisfactorily at other months, excluding rain. The distribution of rain throughout the year, however, will determine the overall system performance.

By far, rain causes the most severe degradations in the frequency range between 10-100 GHz. The amount of attenuation suffered by a millimeter wave system operating through rain will depend upon the frequency used and the rate at which rain is falling. For example, at 60 GHz a system will be subjected to attenuation on the order of 25 to 30 dB/km when rain with an intensity of 100 mm/hr occurs along the propagation path. On the other hand, attenuation due to water vapor is on the order of 1 dB/km for a terrestrial link and a few dB overall for an earth-satellite path. Near 60 GHz, molecular oxygen absorption dominates. The attenuation is on the order of 15 dB/km for a terrestrial path and more than 150 dB for an earth-satellite path. Multipath phenomena caused by layers in the lower atmosphere are generally insignificant for the shorter propagation paths (a few km) but become significant as the path length increases.

Because of the influence of rain and water vapor, dry climates are more inviting to millimeter wave telecommunication systems. For an operational telecommunication system at a given frequency, path lengths can be longer in the southwestern parts of the United States. Similarly, for a given path length, operations can be conducted at higher millimeter wave frequencies in the drier climates characteristic of the western part of the United States than in the more humid eastern and southeastern regions. Of the 18 cities for which calculations were performed, El Paso, Texas, and Miami, Florida, span the range of the best and worst environments for millimeter wave system performance. Complete results for terrestrial and earth-satellite paths in the selected cities for .01, .1, and 1 percent of the year are presented graphically in Appendix A. A detailed description of the data and the models is given in Appendix B.

Cloud attenuation on earth-satellite paths cannot be neglected above 30 GHz. The results in this report were obtained by doing so. An estimate for cloud attenuation was formulated in Section 3.3 from work under way to develop a more reliable cloud attenuation model.

5. REFERENCES

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APPENDIX A. ATTENUATION DATA FOR SELECTED UNITED STATES CITIES

This appendix contains rain rate distributions and equal attenuation curves for the selected cities in the United States. Table A.1 gives the rain rate distributions for 0.01, 0.1, and 1 percent of the year. Figures A-1 through A-36 give the equal attenuation curves for terrestrial and earth-satellite paths for the selected cities.

For terrestrial paths, curves giving the path length and frequency for which attenuation is predicted to exceed 10, 20, 30, 40, and 50 dB, are presented for indicated percentages of the year (0.01, 0.1, and 1 percent). The dotted line in these figures represents the critical path length indicating that longer paths may experience atmospheric multipath.

For earth-satellite paths, curves giving the path elevation angle and frequency for which attenuation is predicted to exceed 5, 10, 15, 20, and 25 dB, are presented for indicated percentages of the year (0.01, 0.1, and 1 percent). The dotted line in these figures represents the highest elevation angle possible to a geostationary satellite from the corresponding city. Note that elevation angle decreases from the bottom to the top of these figures.

Table A-1. Rain Rate Distributions

Rain rate in mm/hr predicted to be exceeded for
the percentage vs. average year indicated

	PERCENT		
	0.01	0.1	1
Atlanta, GA	90	19	3
Boston, MA	65	14	4
Chicago, IL	74	14	2
Dallas, TX	82	15	2
Denver, CO	31	8	1
El Paso, TX	19	6	0
Fairbanks, AK	18	7	1
Honolulu, HI	43	10	1
Miami, FL	122	45	2
New Orleans, LA	111	34	3
New York, NY	78	15	3
Phoenix, AZ	17	5	0
Omaha, NE	76	13	1
San Diego, CA	17	7	0
San Francisco, CA	22	10	1
Seattle, WA	29	12	3
St. Louis, MO	59	13	2
Washington, D. C.	83	16	2

Figures A-1 - A-36

The following pages contain Figures A-1 - A-36. These figures display equal attenuation curves in the path length-frequency plane (terrestrial path) or path elevation angle-frequency plane (earth-satellite path). These curves represent attenuation levels exceeded on average for 0.01, 0.1, and 1 percent of the year. The figures for the 18 cities are in alphabetical order with figures for terrestrial paths and earth-satellite paths on facing pages.

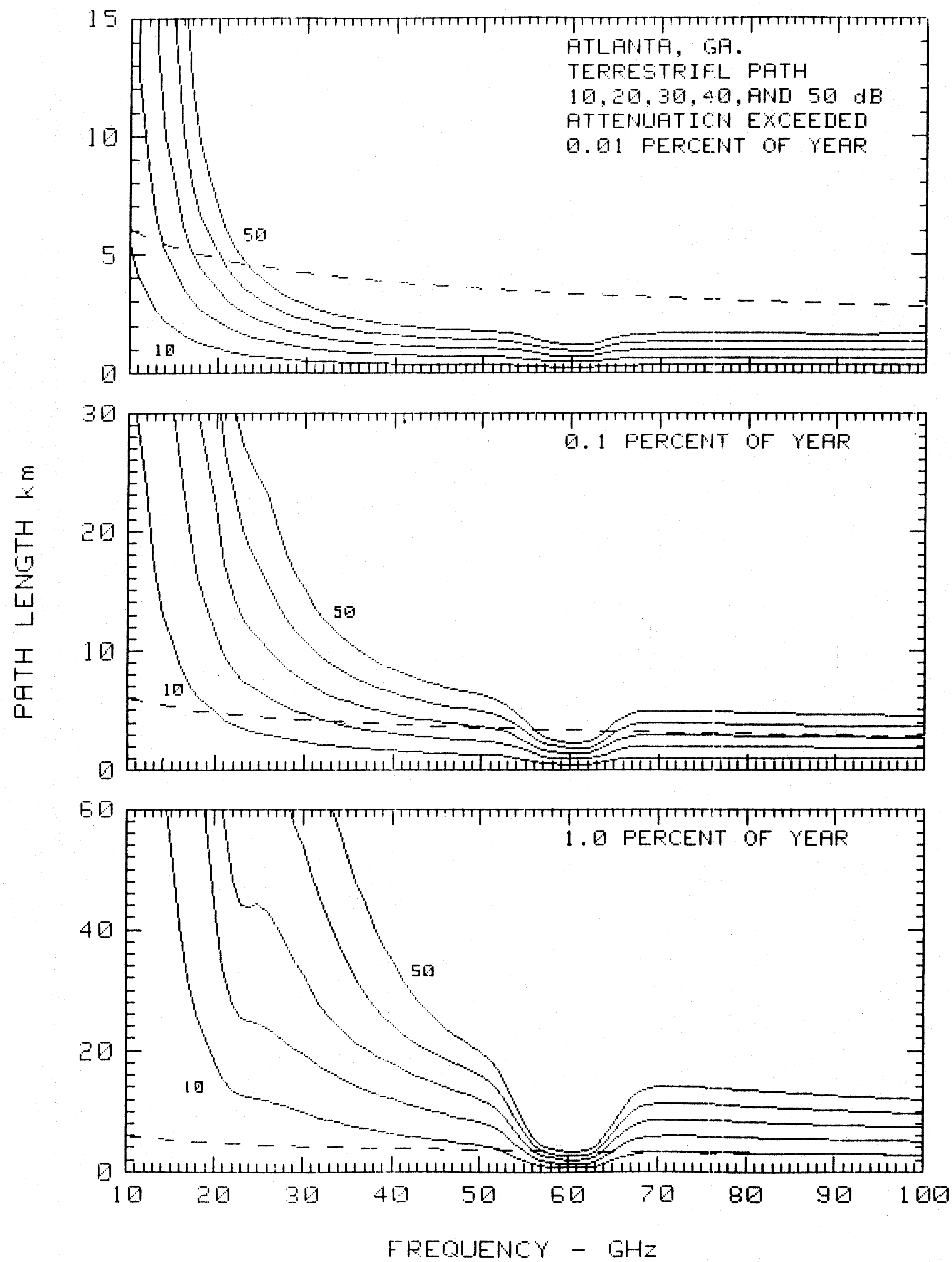

Figure A-1. Atlanta, Ga., terrestrial path.

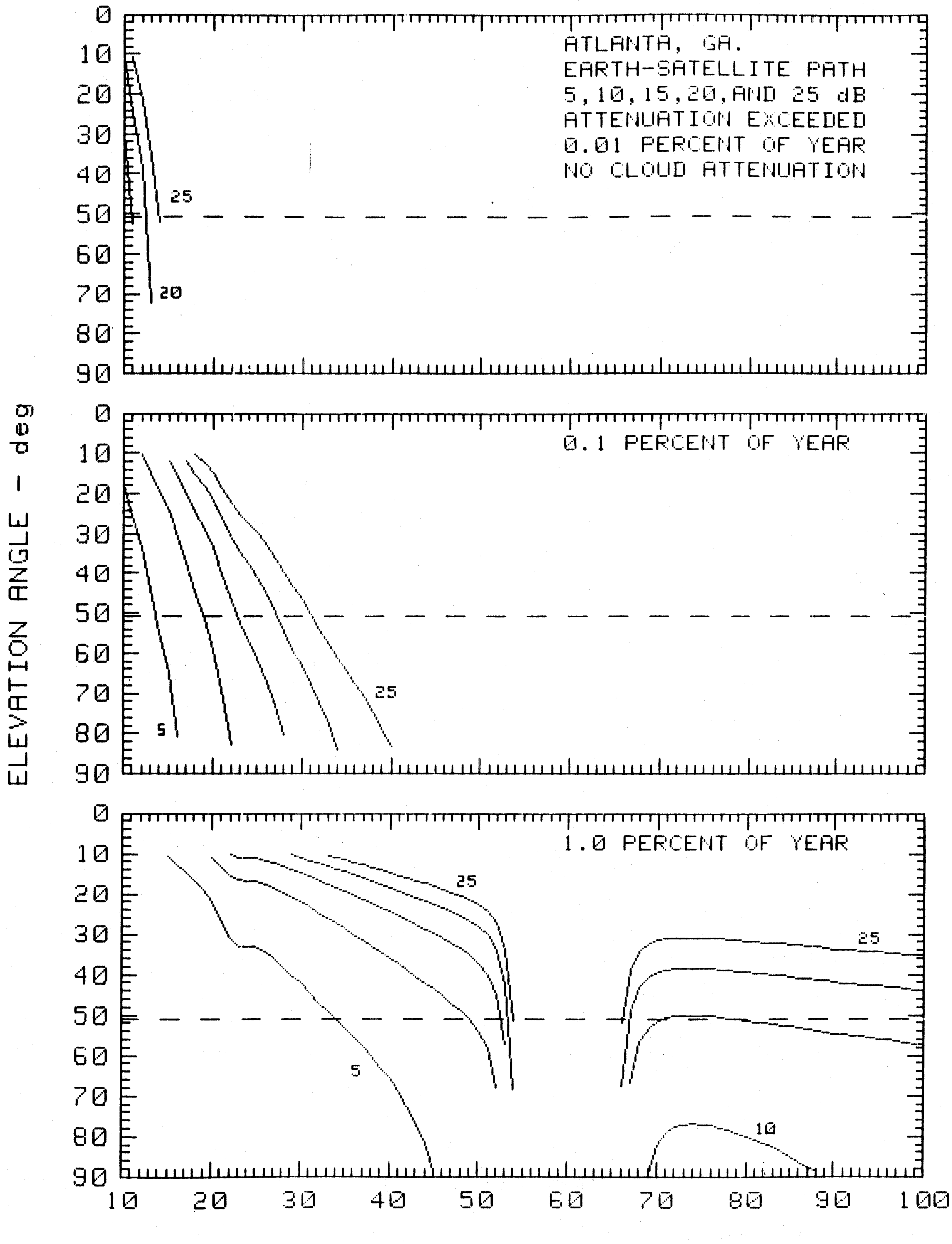

Figure A-2. Atlanta, Ga., earth-satellite path.

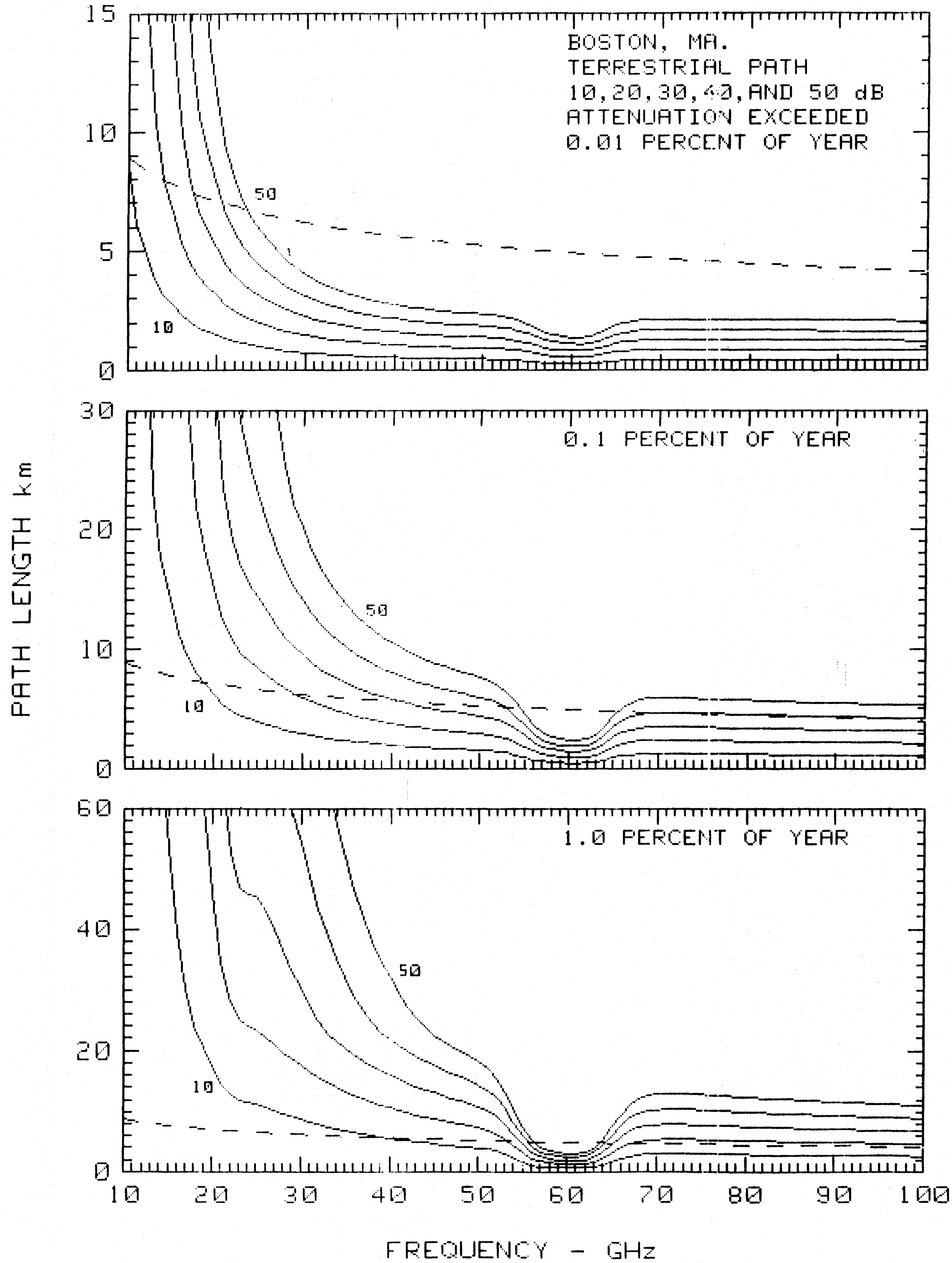

Figure A-3. Boston, Ma., terrestrial path.

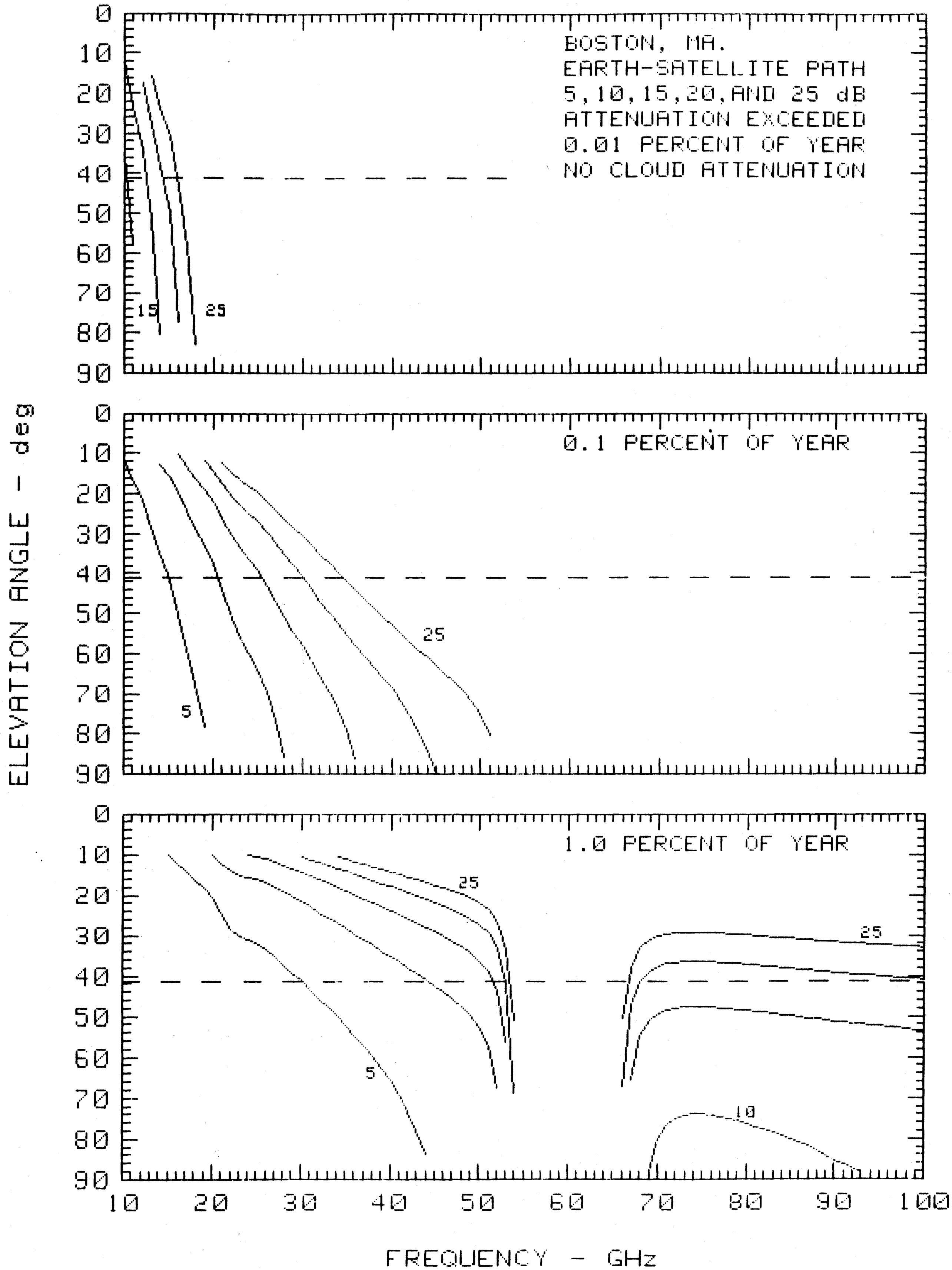

Figure A-4. Boston, Ma., earth-satellite path.

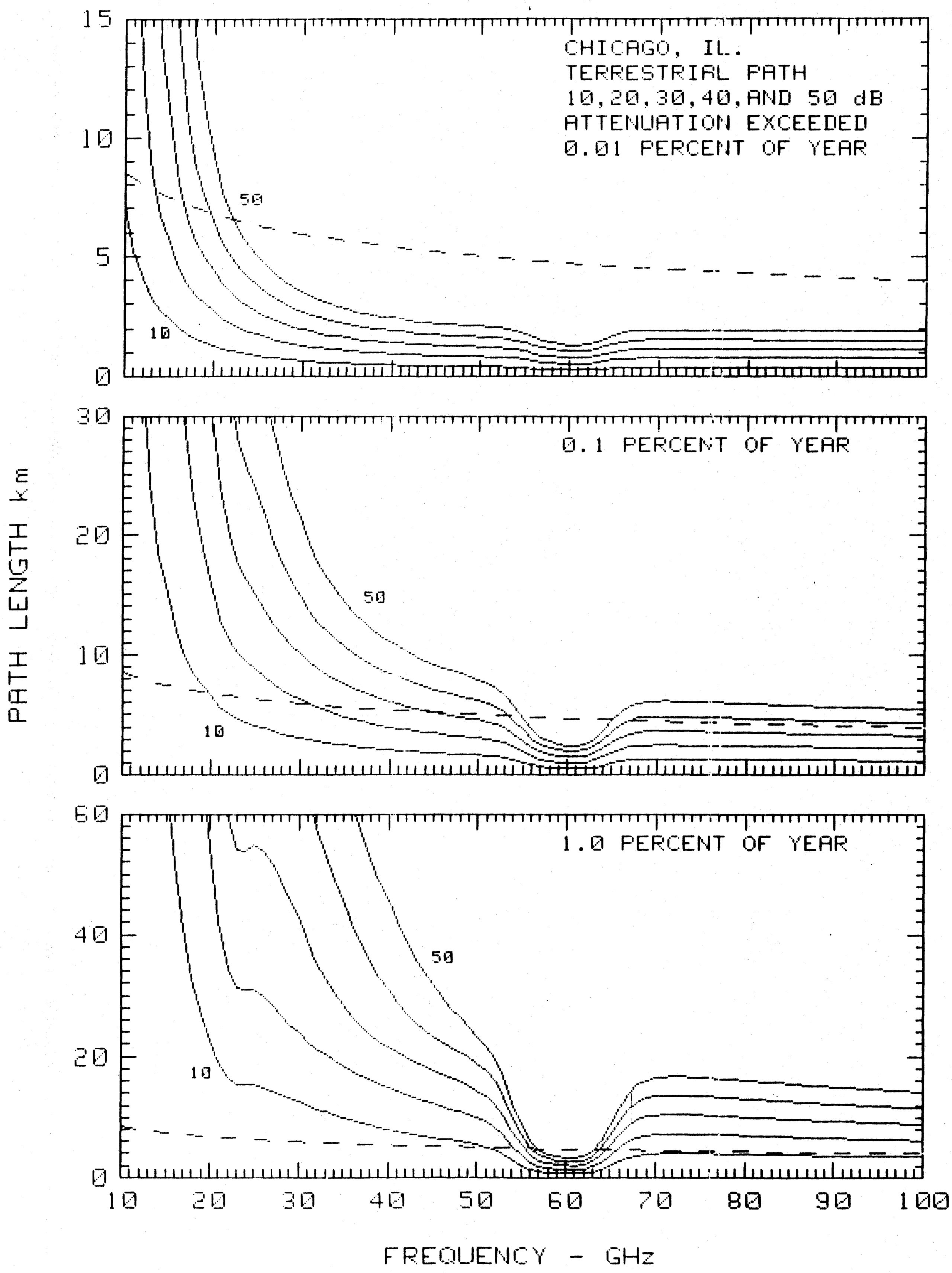

Figure A-5. Chicago, Il., terrestrial path.

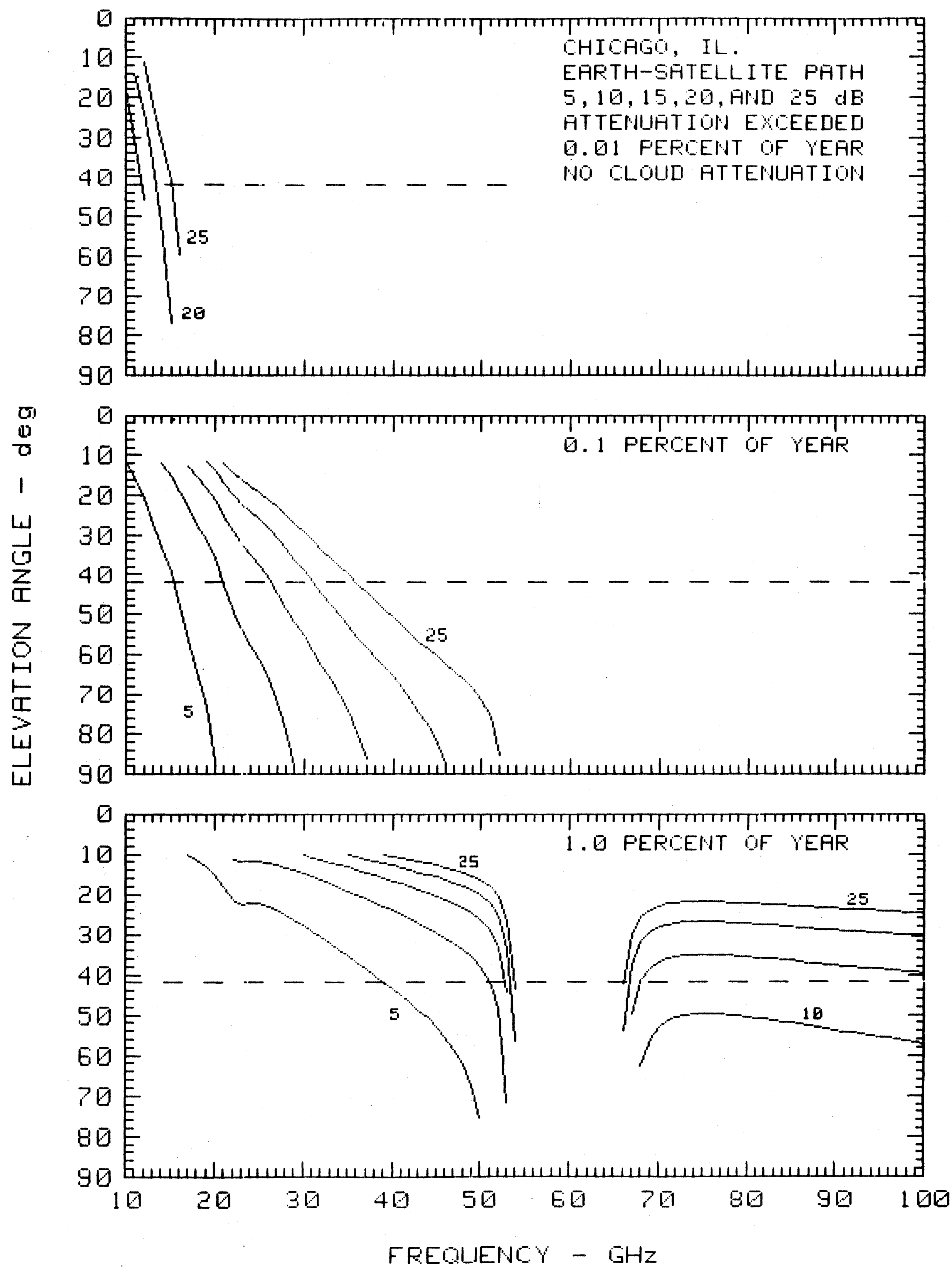

Figure A-6. Chicago, Il., earth-satellite path.

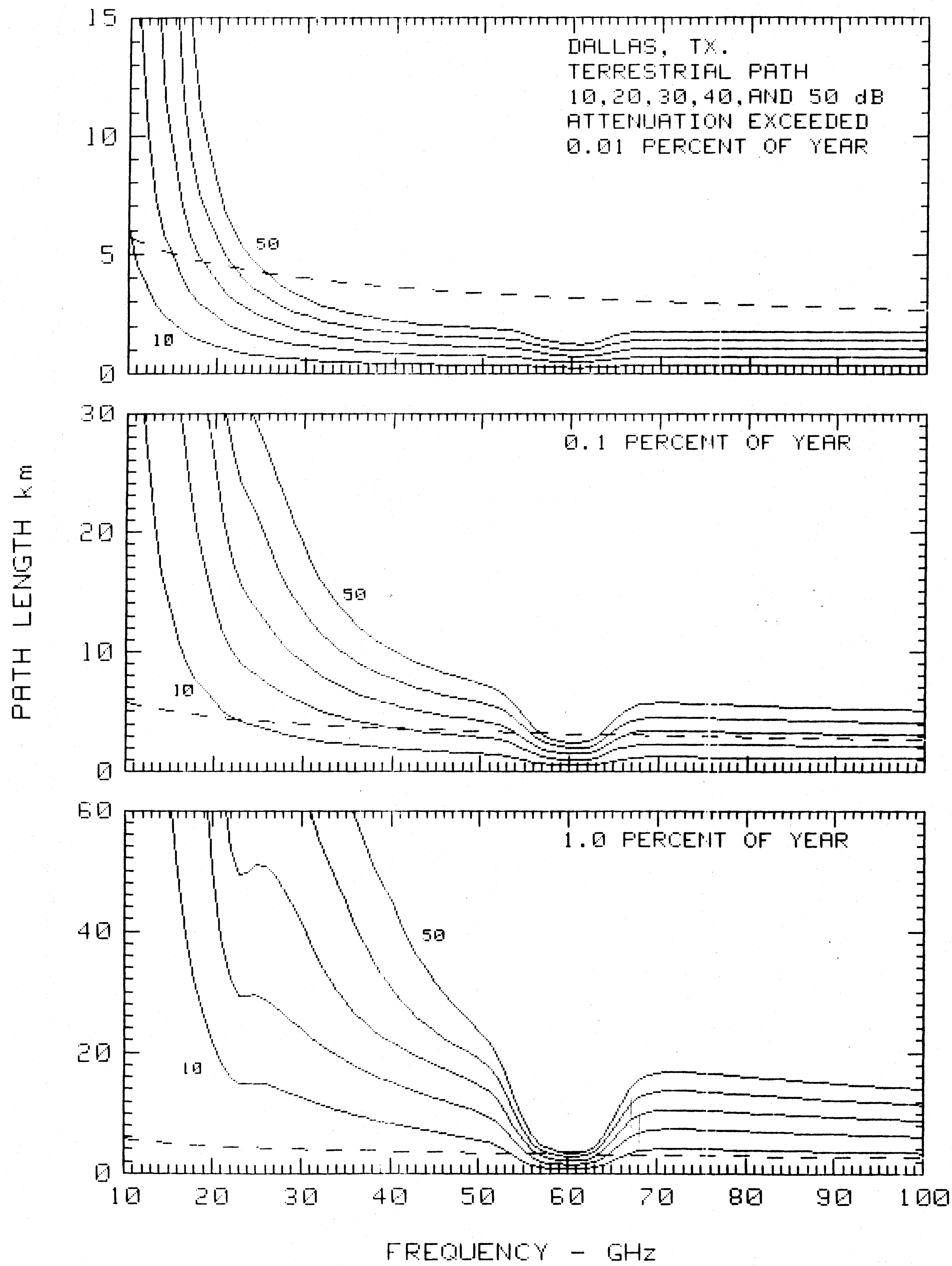

Figure A-7. Dallas, Tx., terrestrial path.

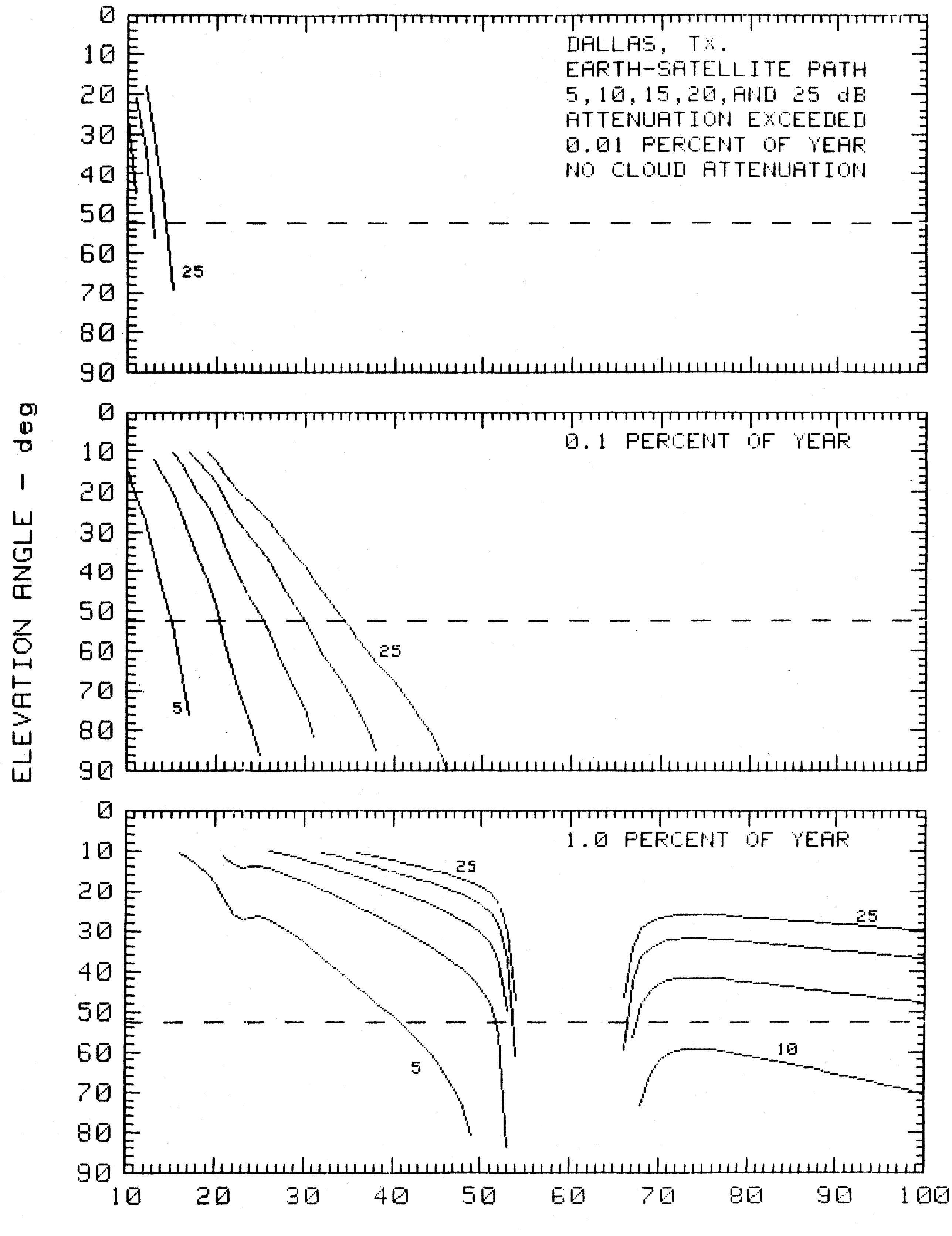

Figure A-8. Dallas, Tx., earth-satellite path.

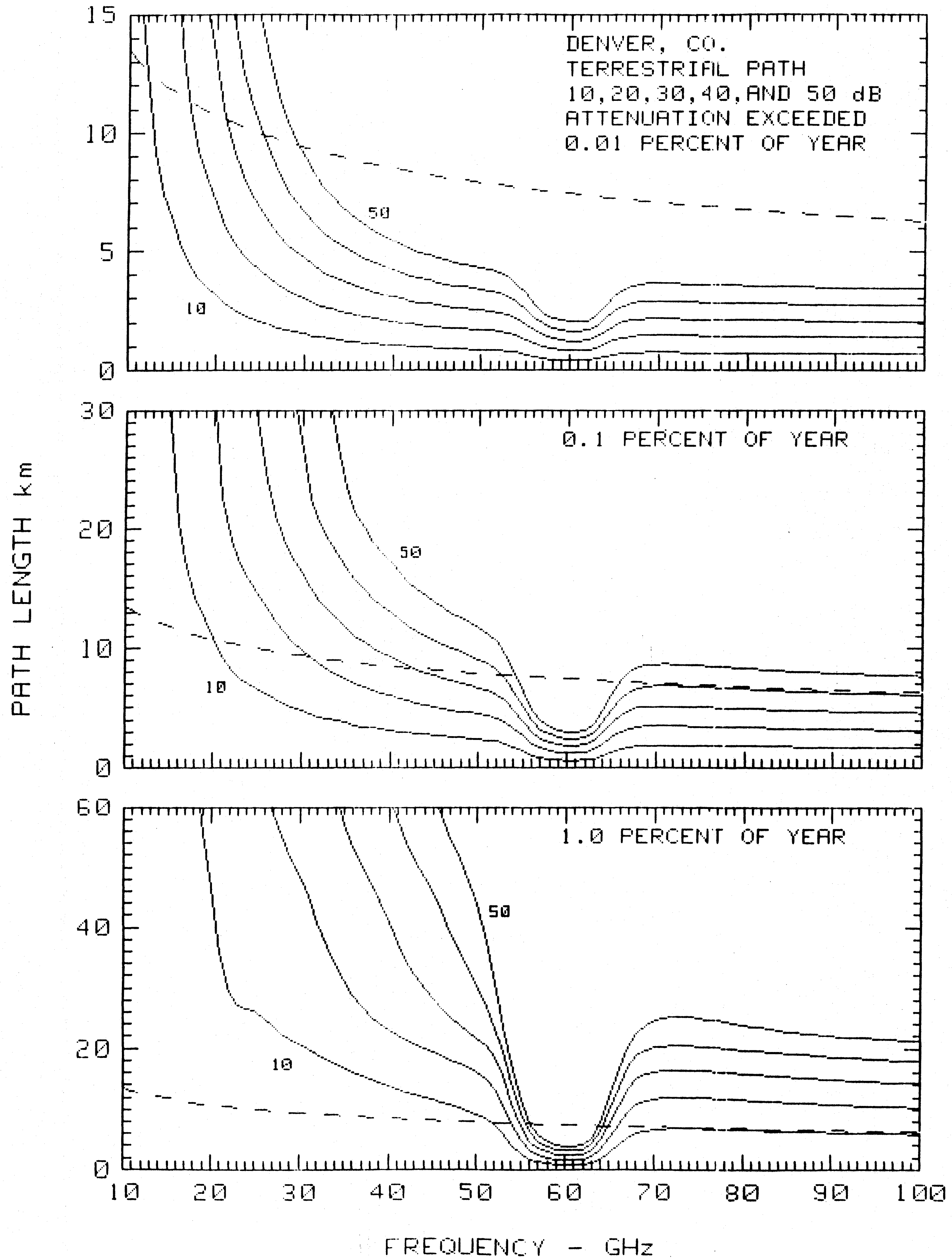

Figure A-9. Denver, Co., terrestrial path.

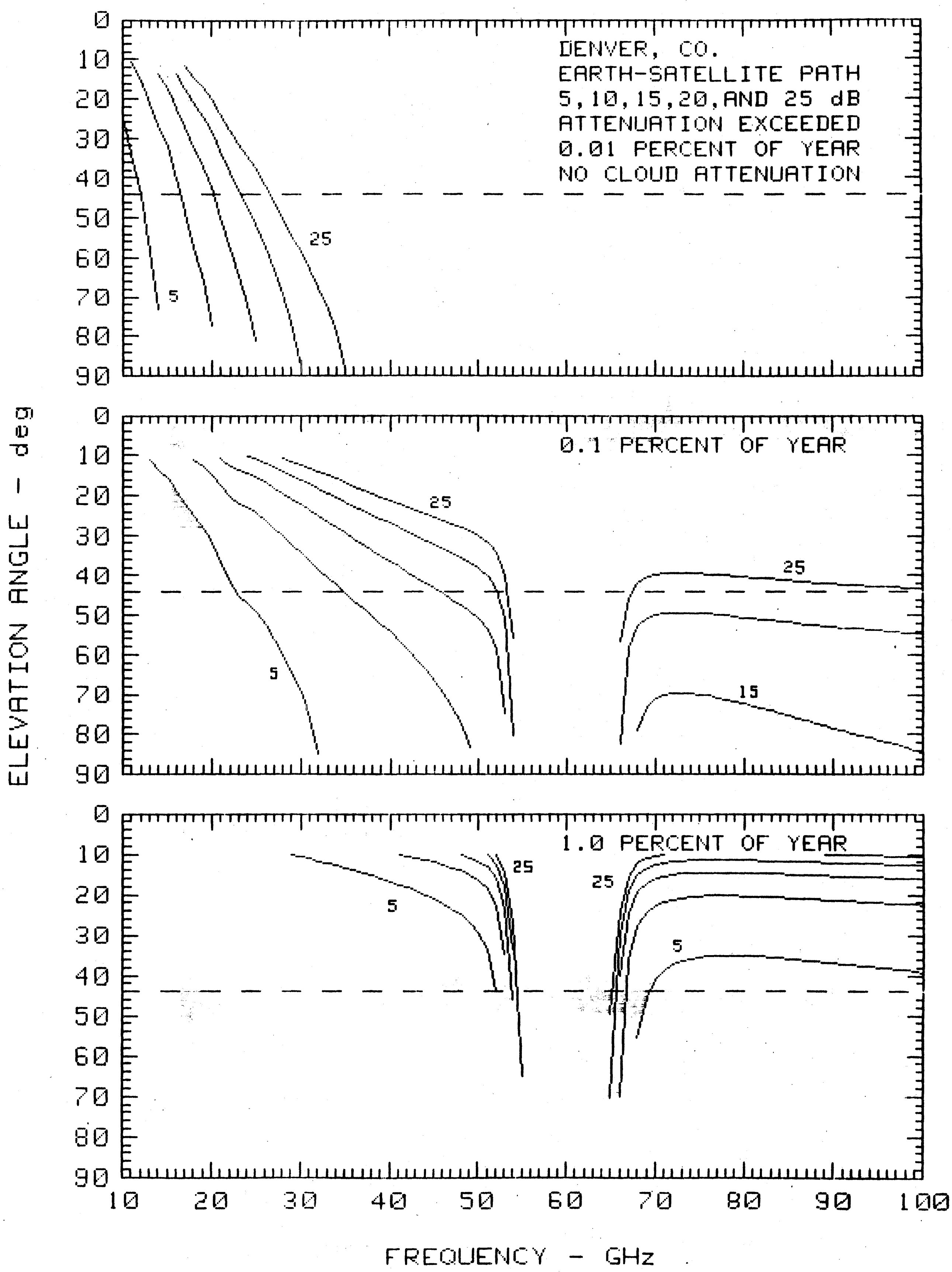

Figure A-10. Denver, Co., earth-satellite path.

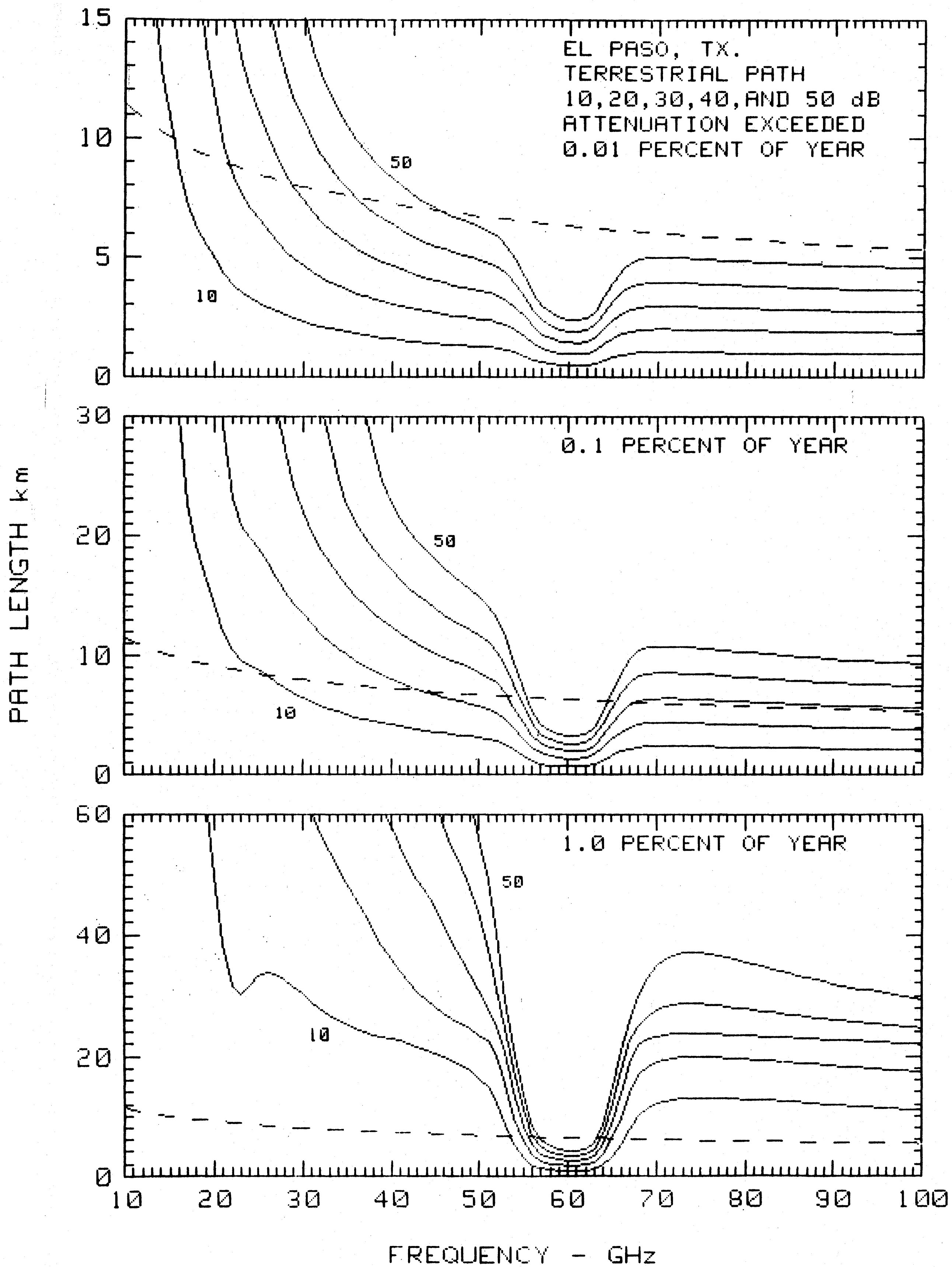

Figure A-11. El Paso, Tx., terrestrial path.

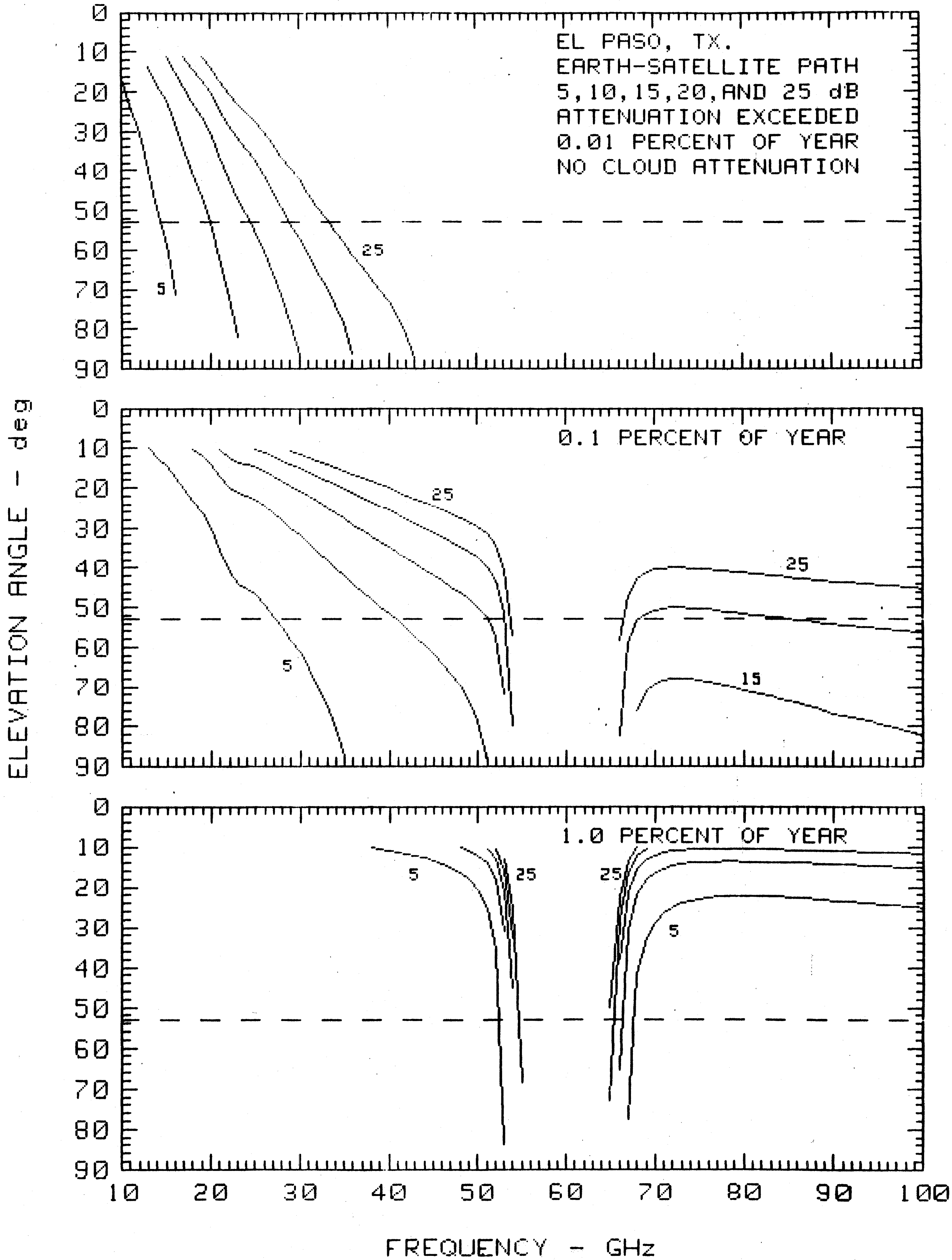

Figure A-12. El Paso, Tx., earth-satellite path.

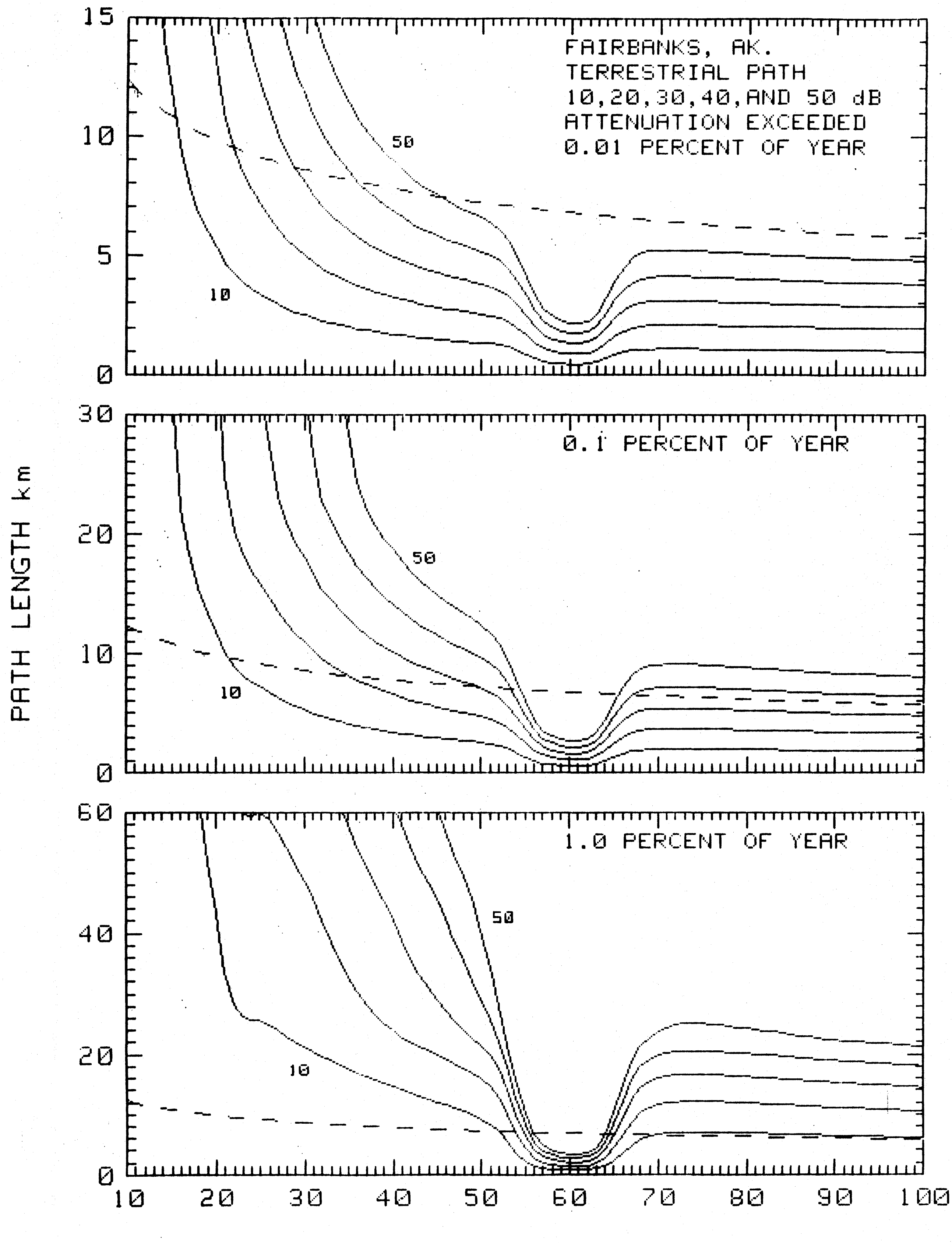

Figure A-13. Fairbanks, Ak., terrestrial path.

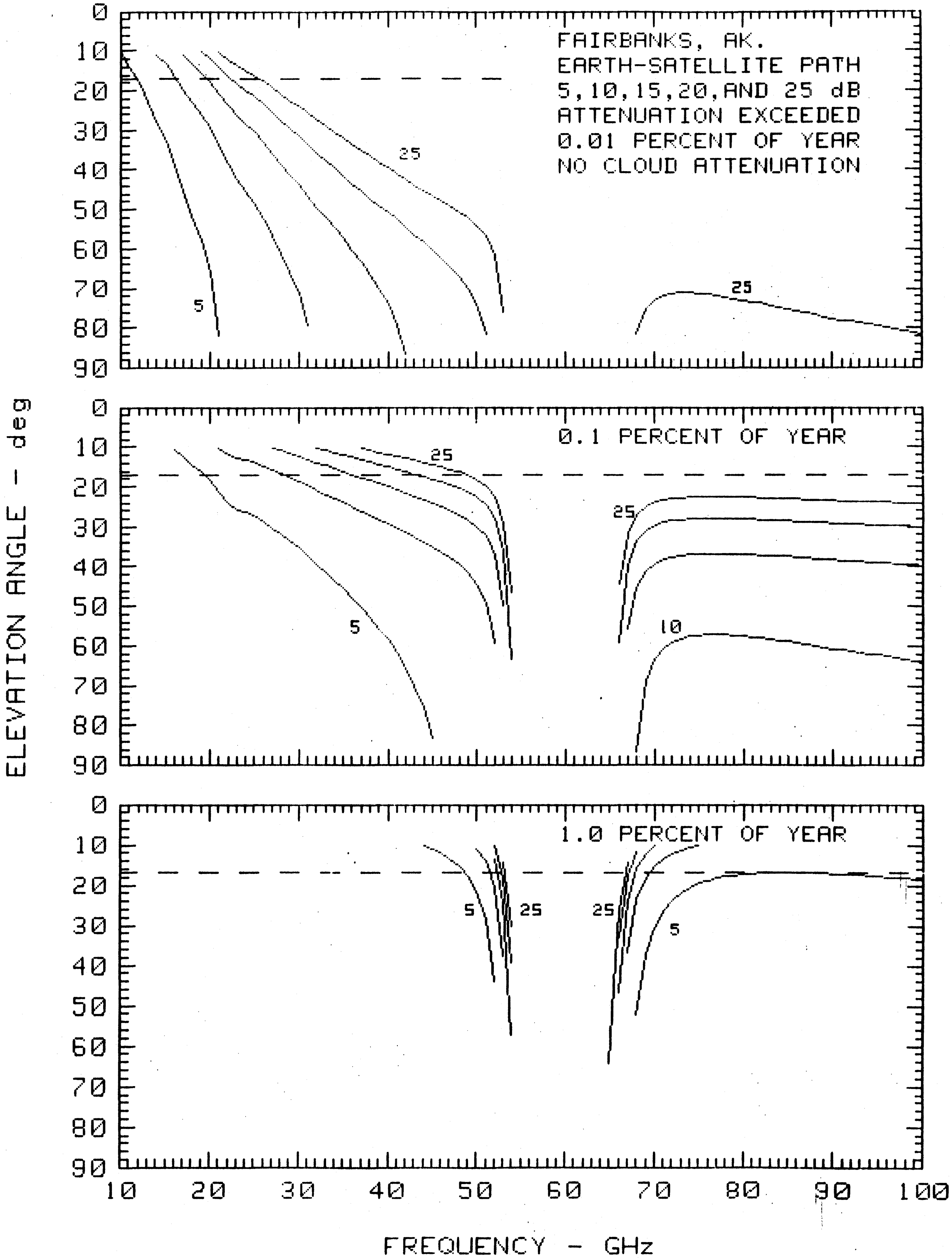

Figure A-14. Fairbanks, Ak., earth-satellite path.

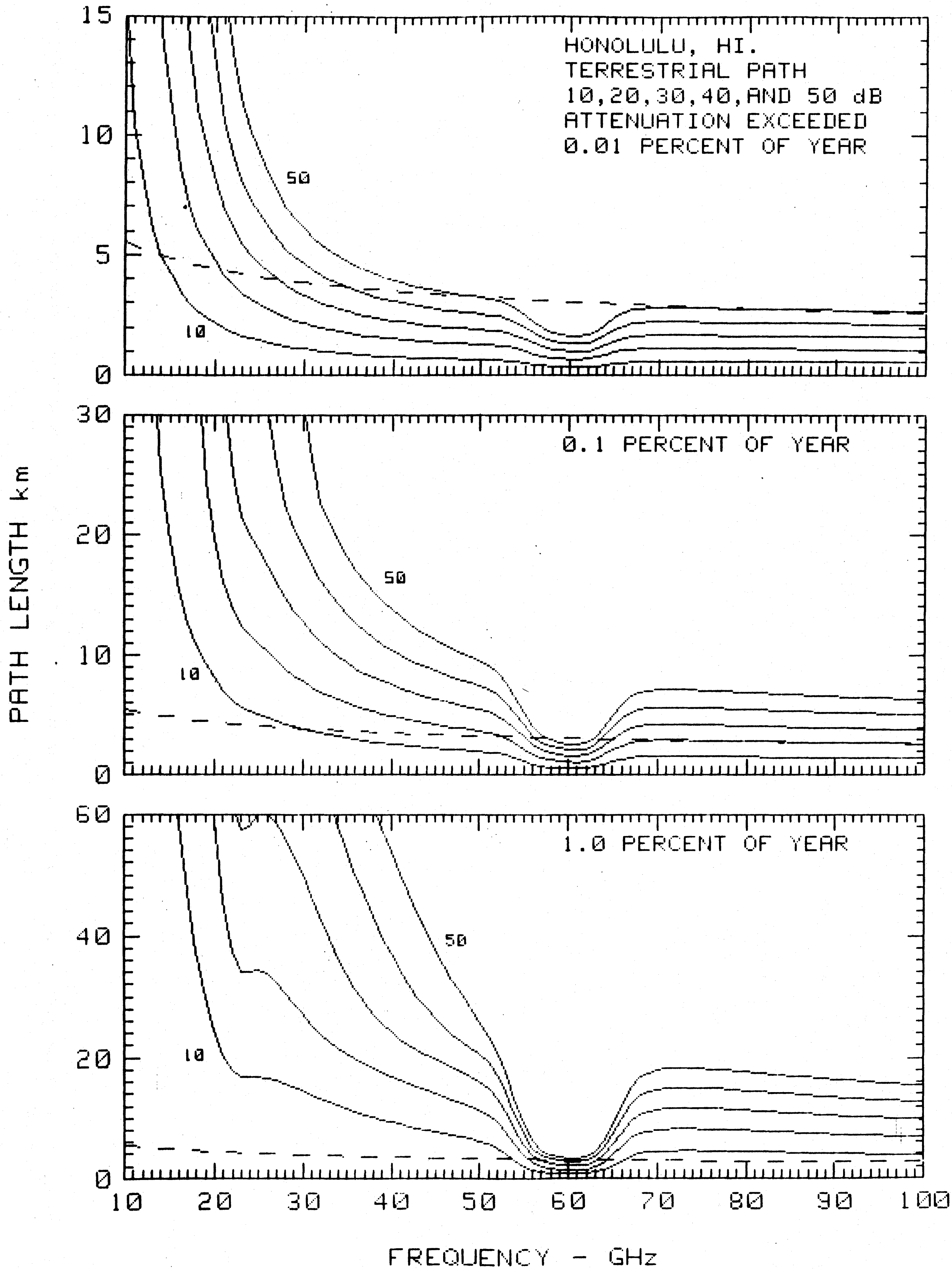

Figure A-15. Honolulu, Hi., terrestrial path.

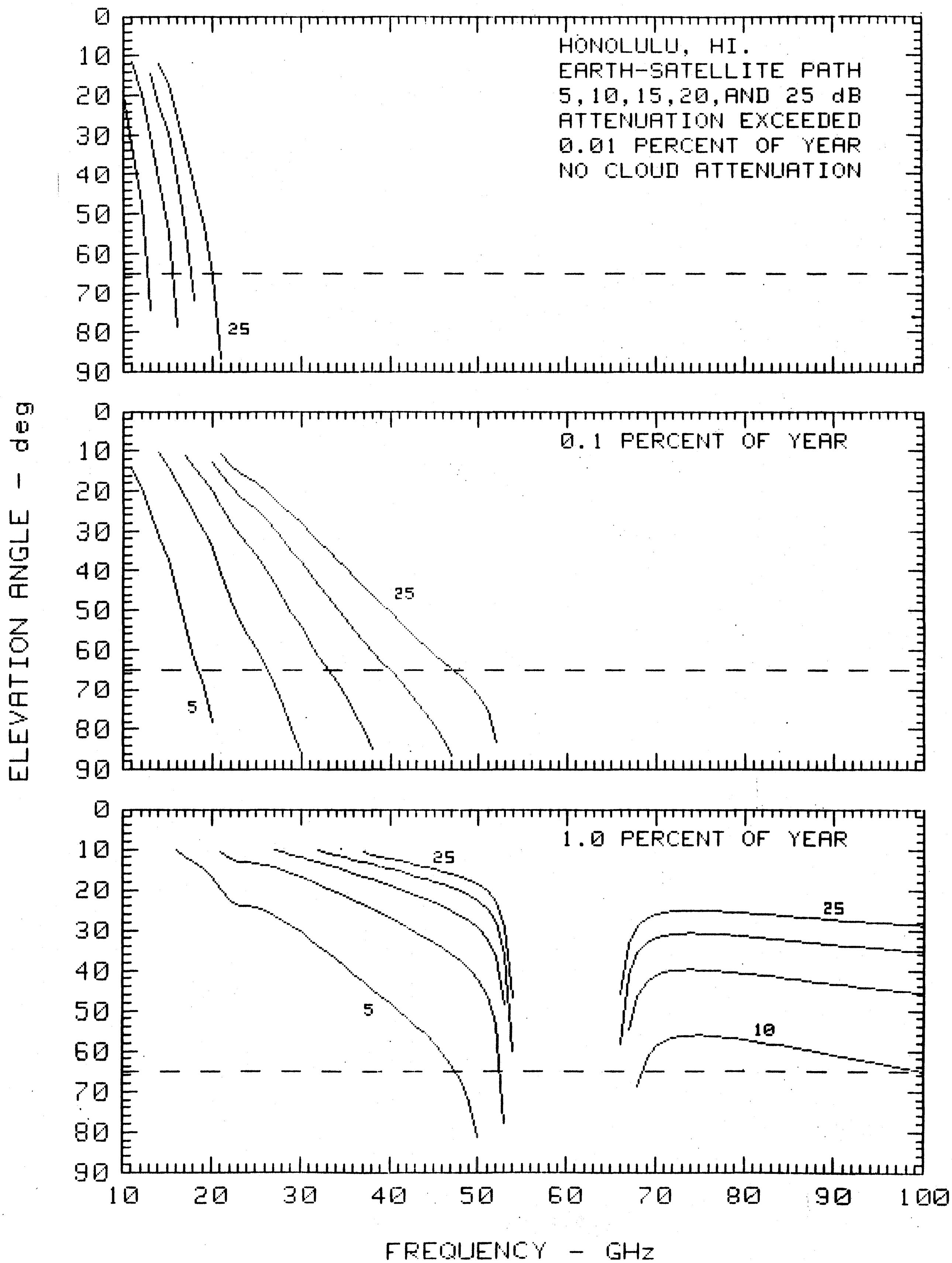

Figure A-16. Honolulu, Hi., earth-satellite path.

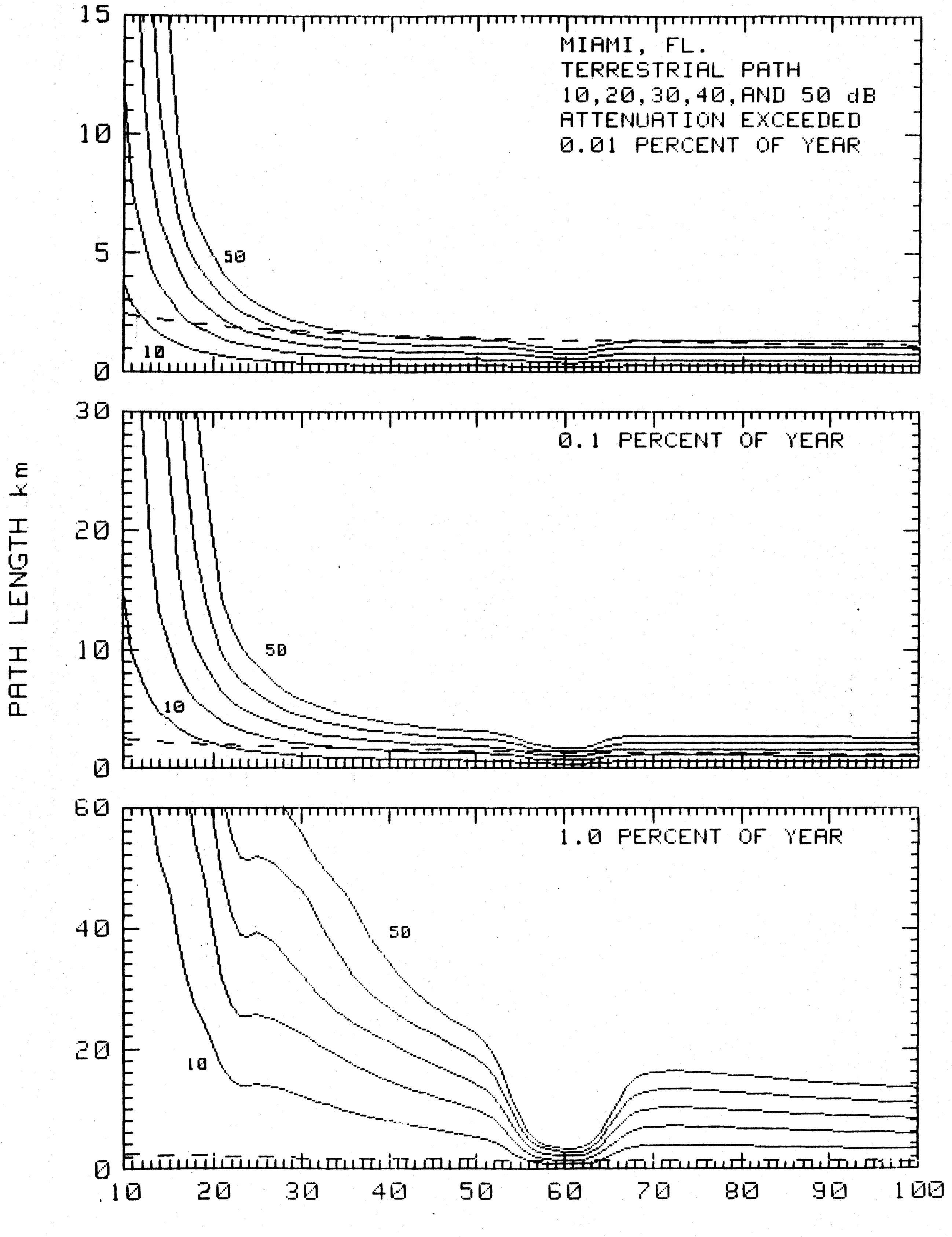

Figure A-17. Miami, Fl., terrestrial path.

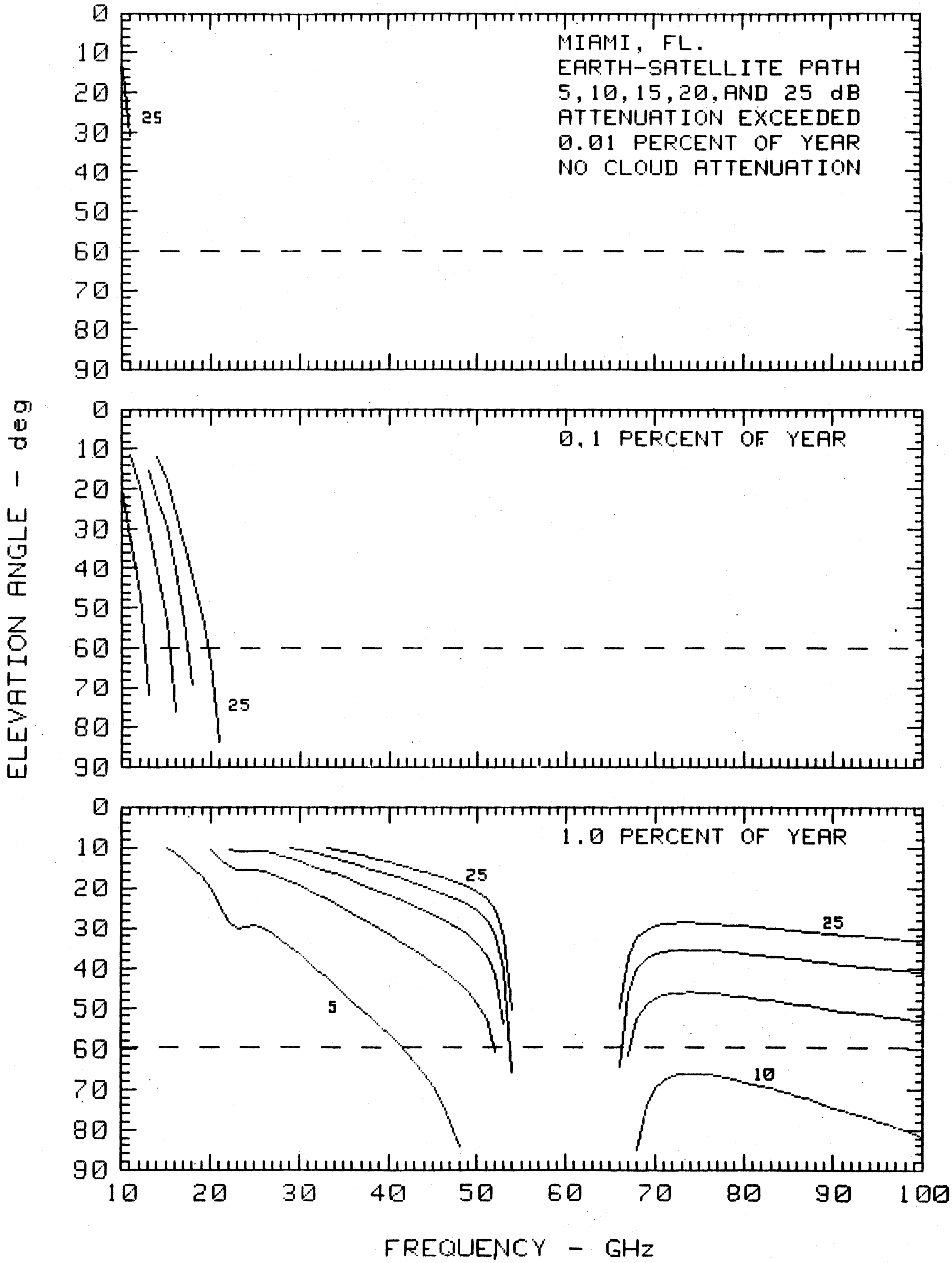

Figure A-18. Miami Fl., earth-satellite path.

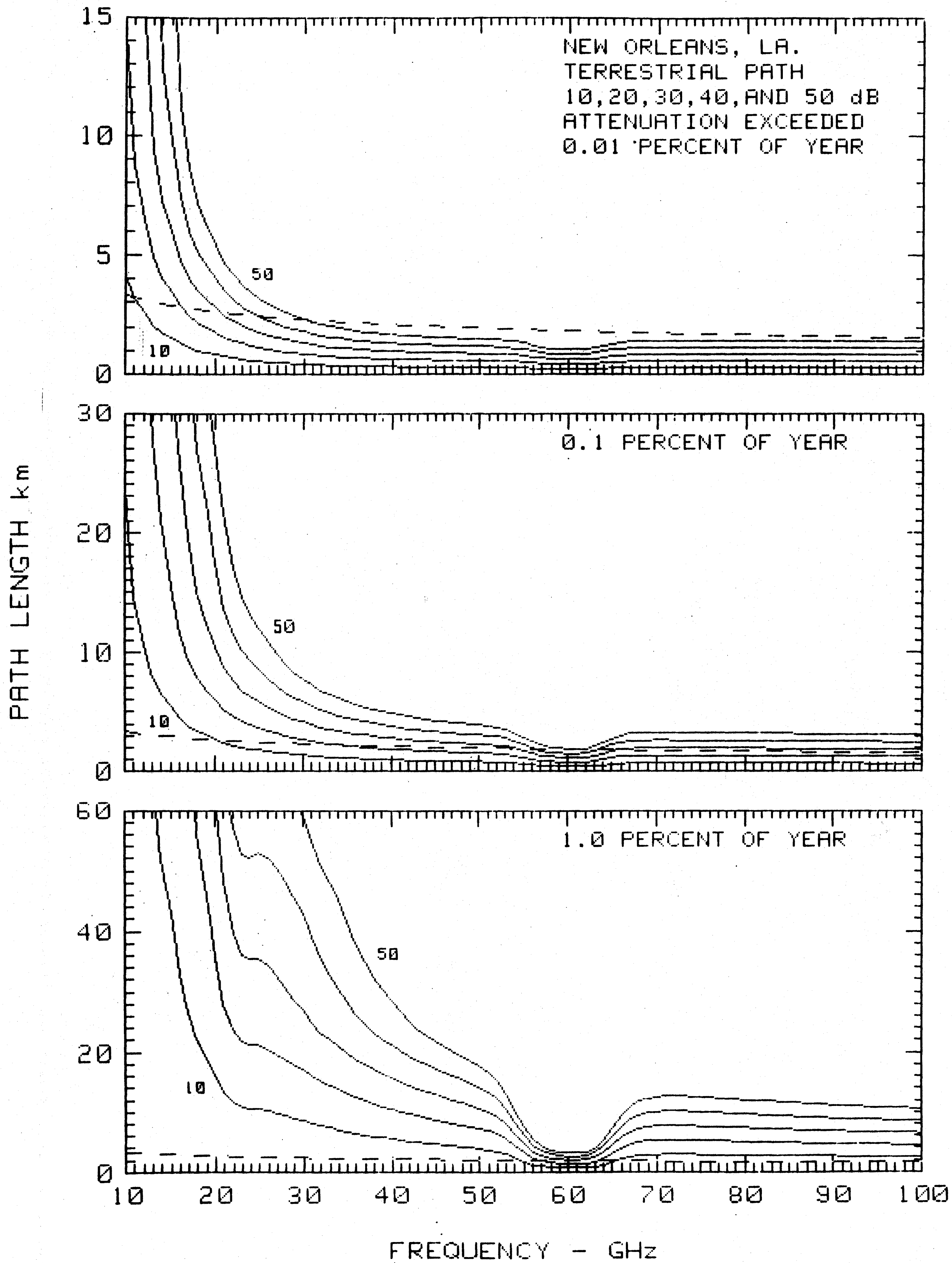

Figure A-19. New Orleans, La., terrestrial path.

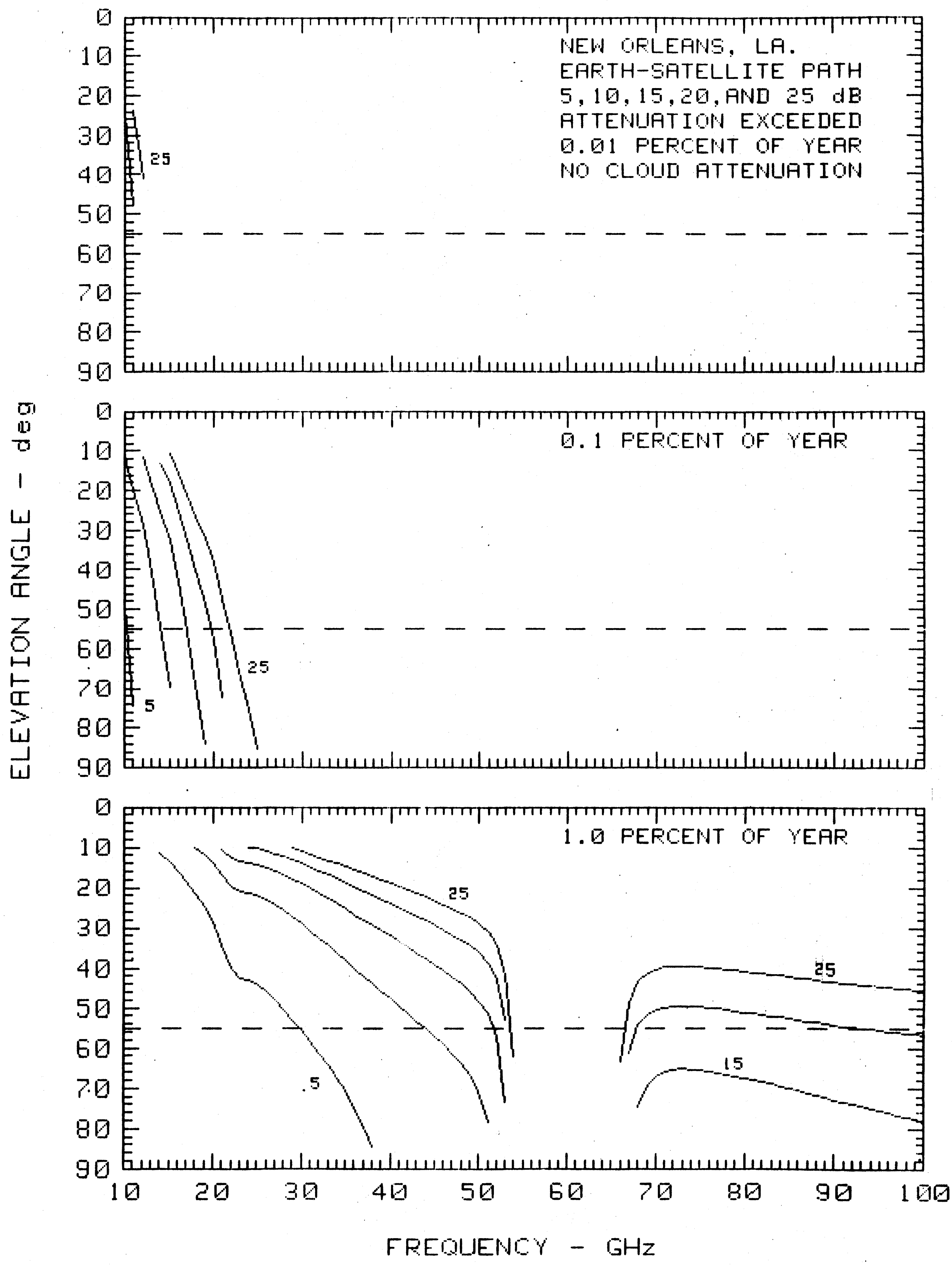

Figure A-20. New Orleans, La., earth-satellite path.

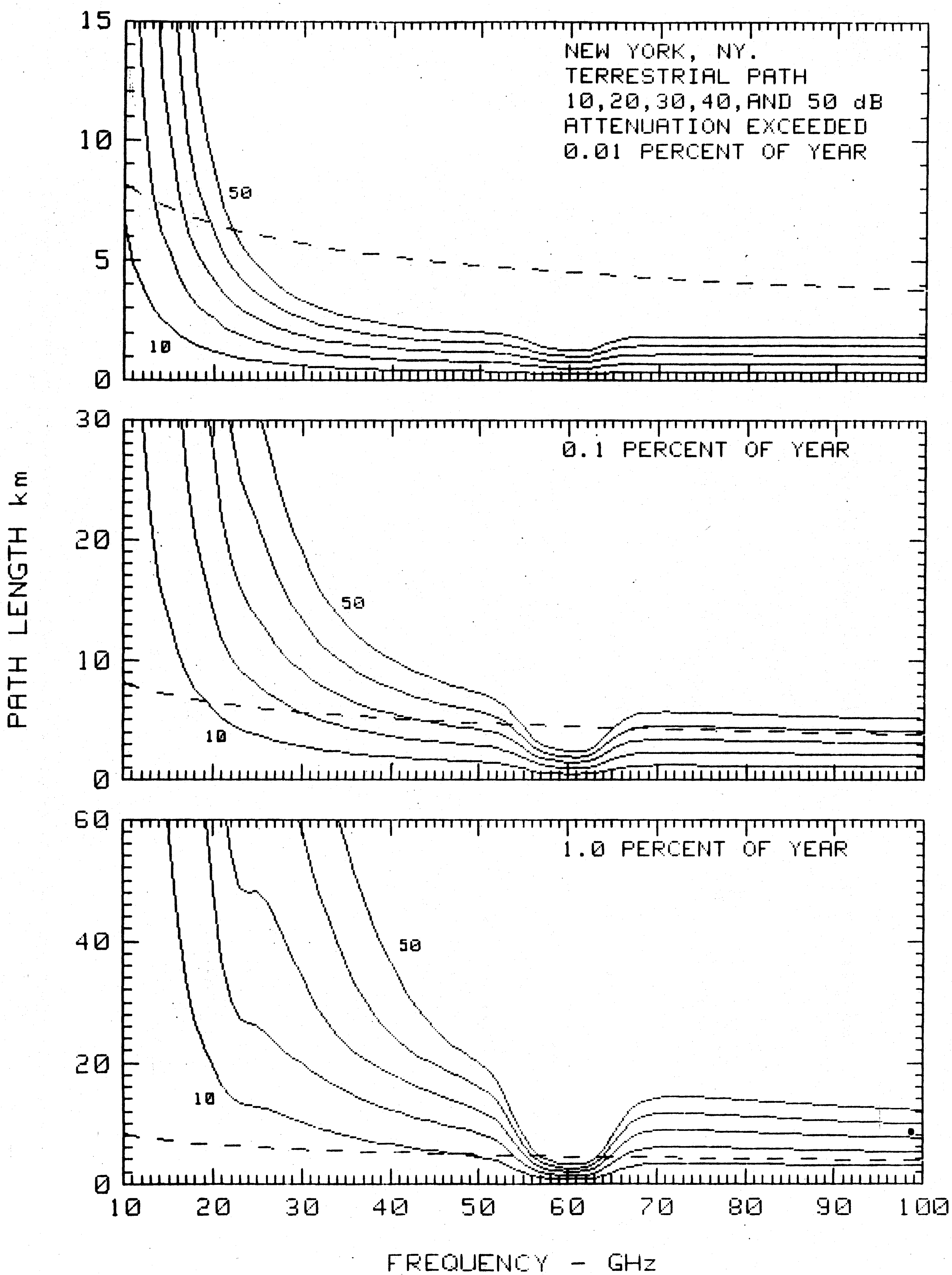

Figure A-21. New York, NY., terrestrial path.

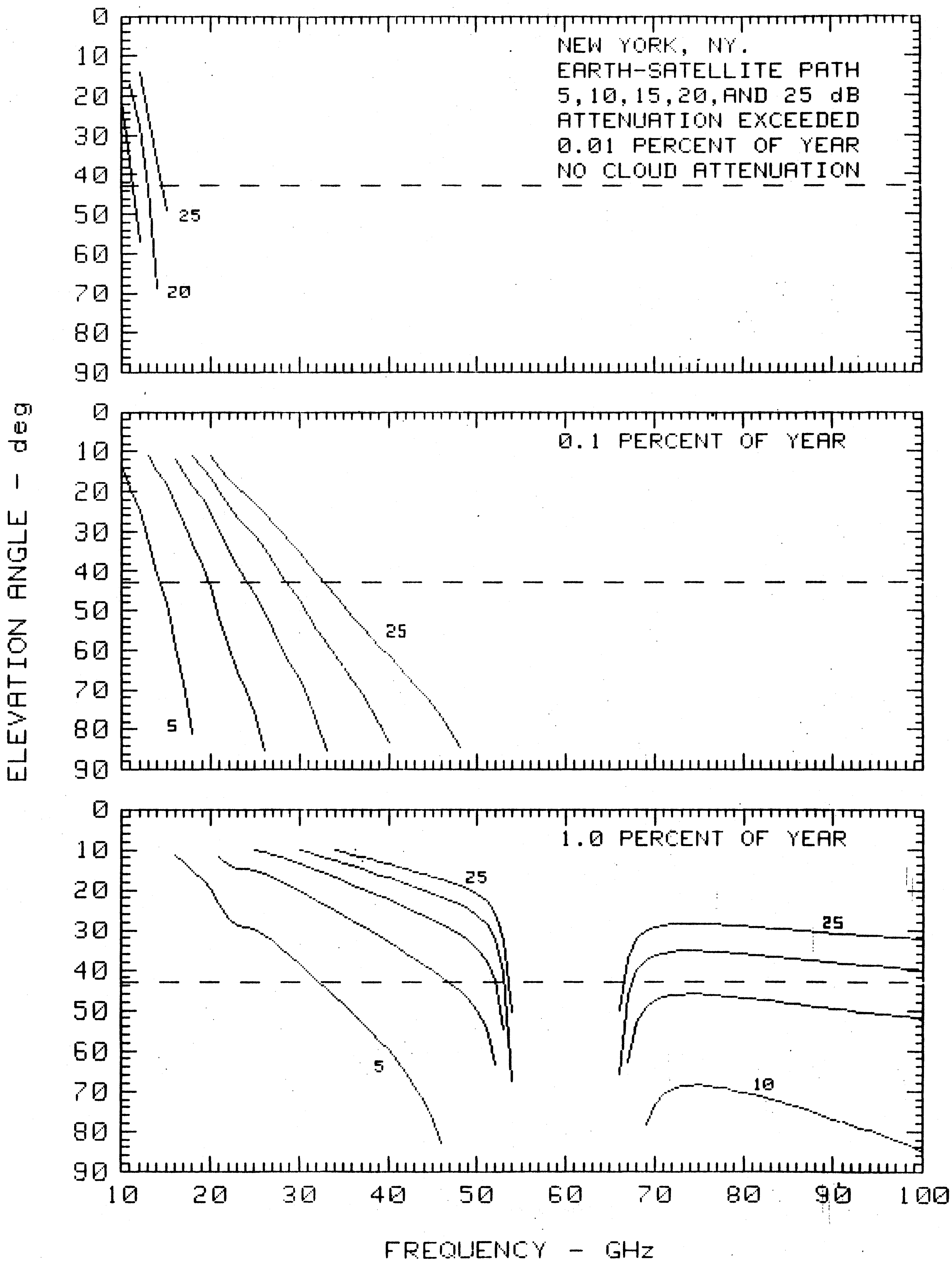

Figure A-22. New York, NY., earth-satellite path.

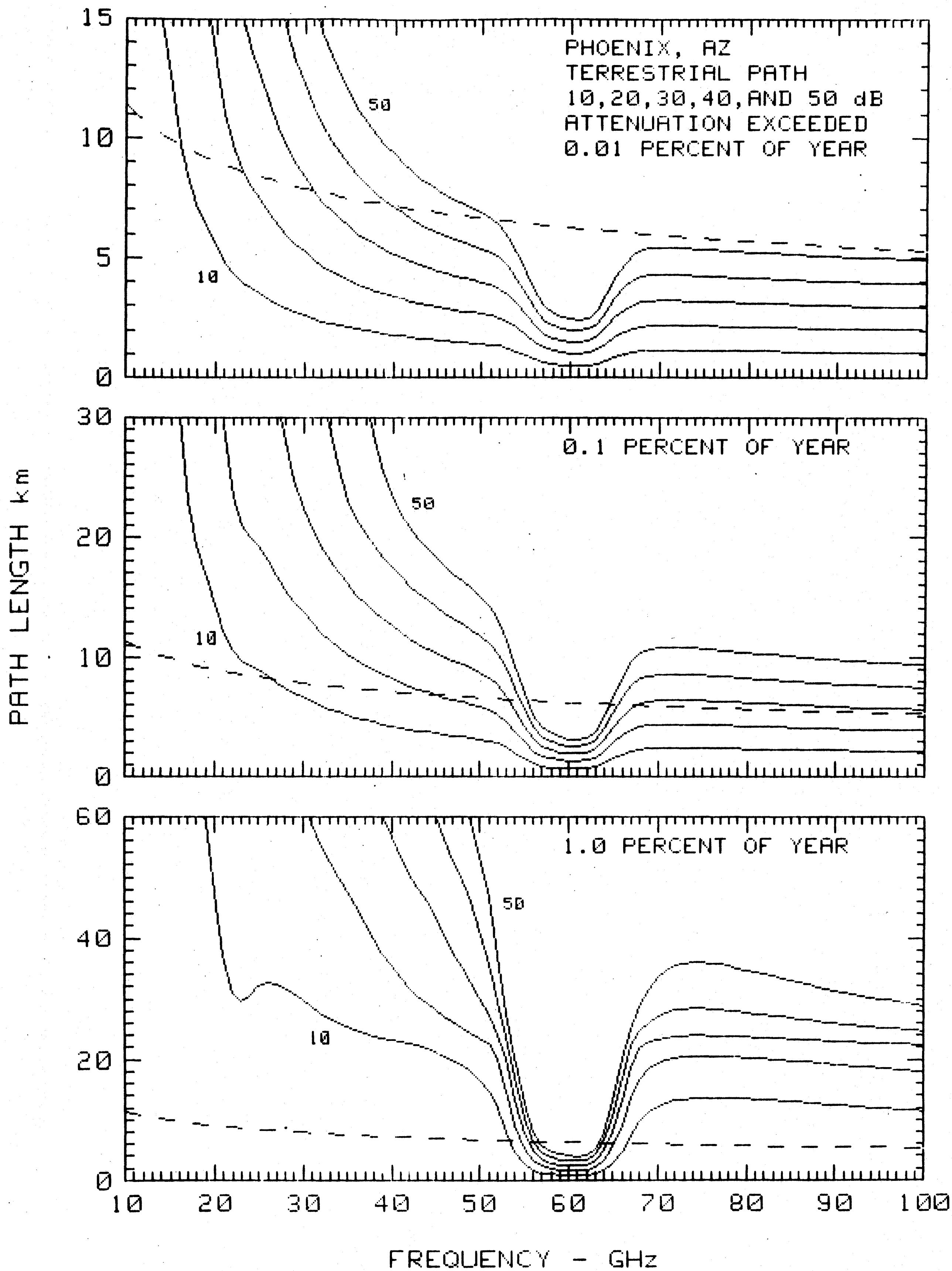

Figure A-23. Phoenix, Az., terrestrial path.

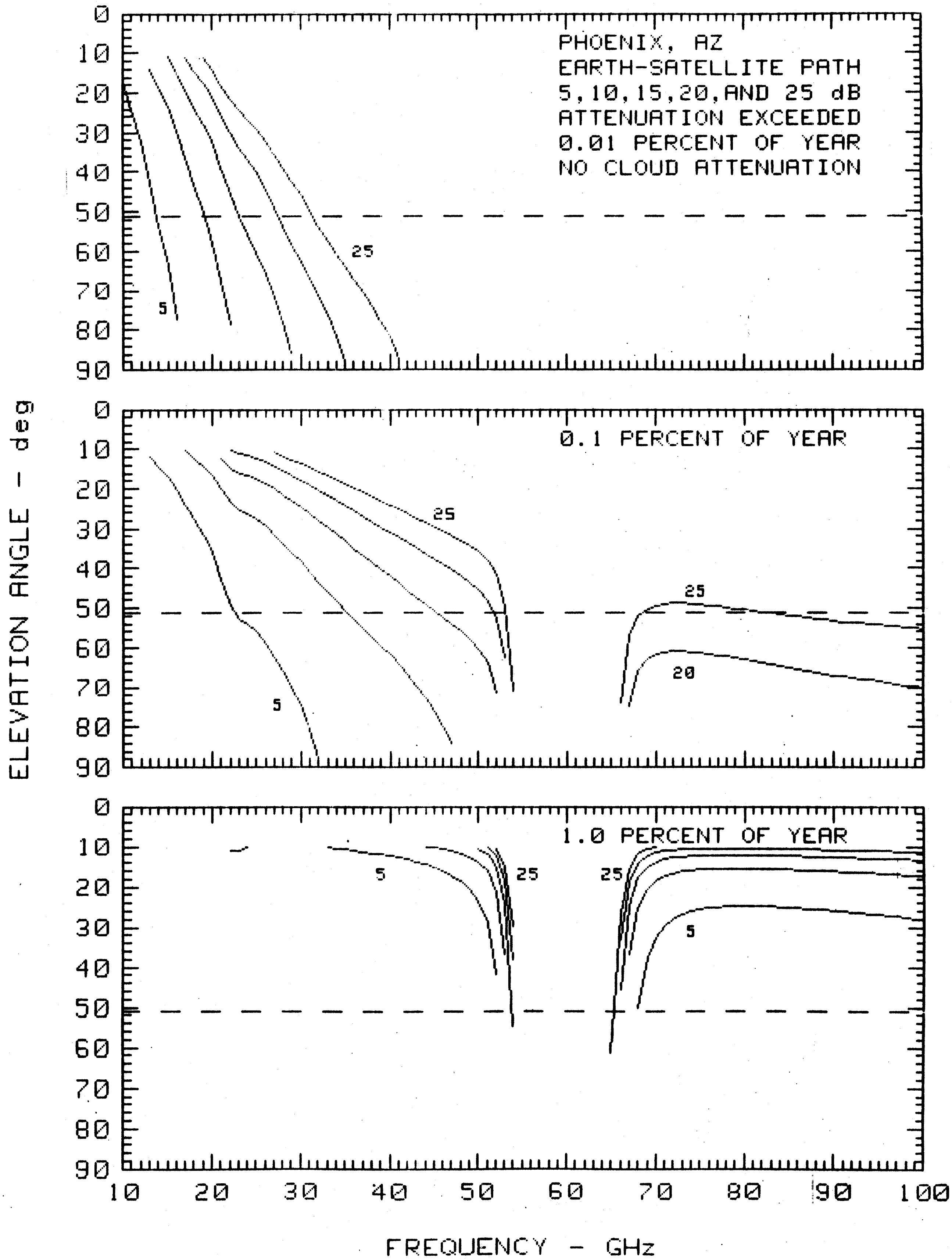

Figure A-24. Phoenix, Az., earth-satellite path.

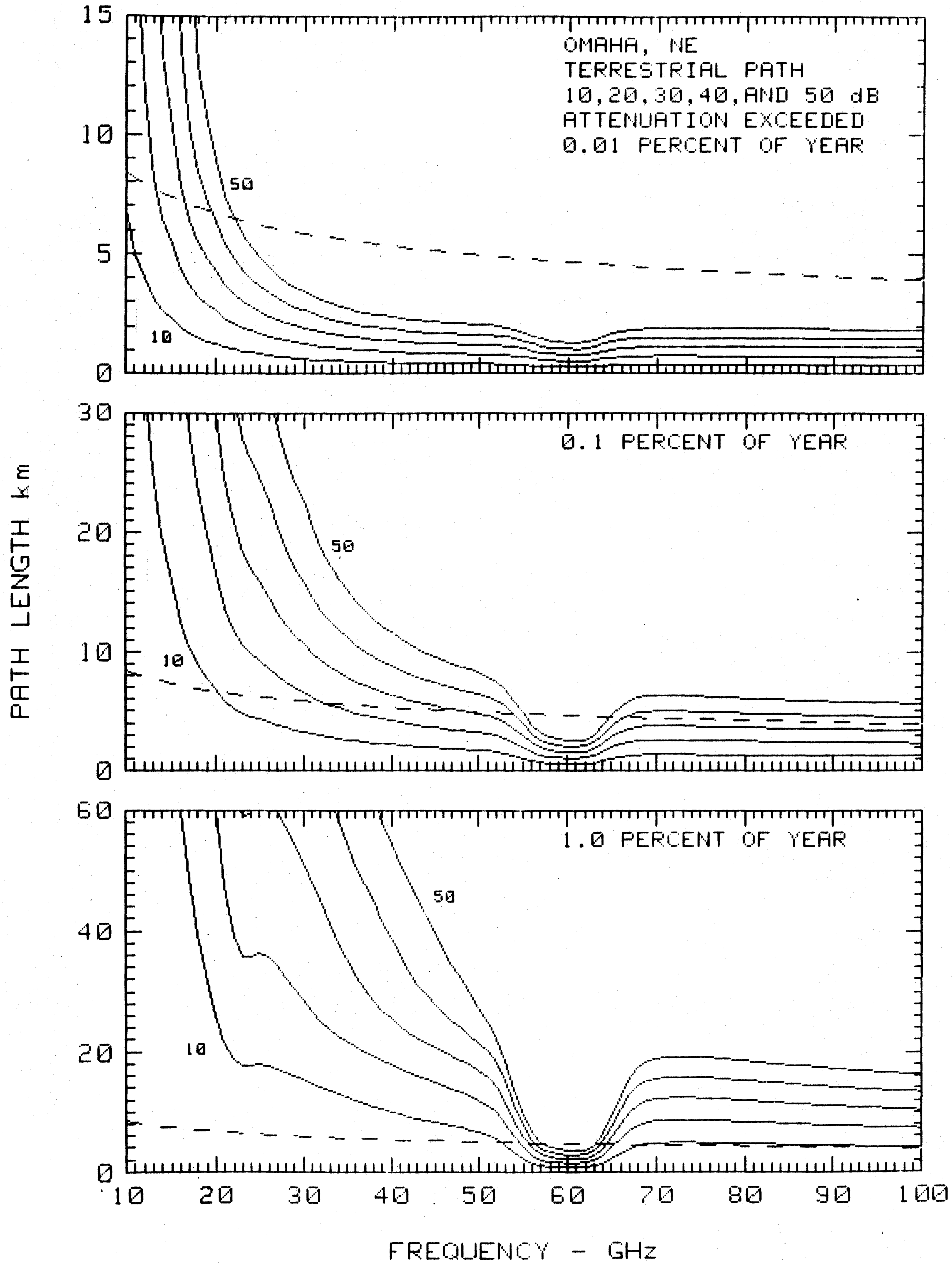

Figure A-25. Omaha, Ne., terrestrial path.

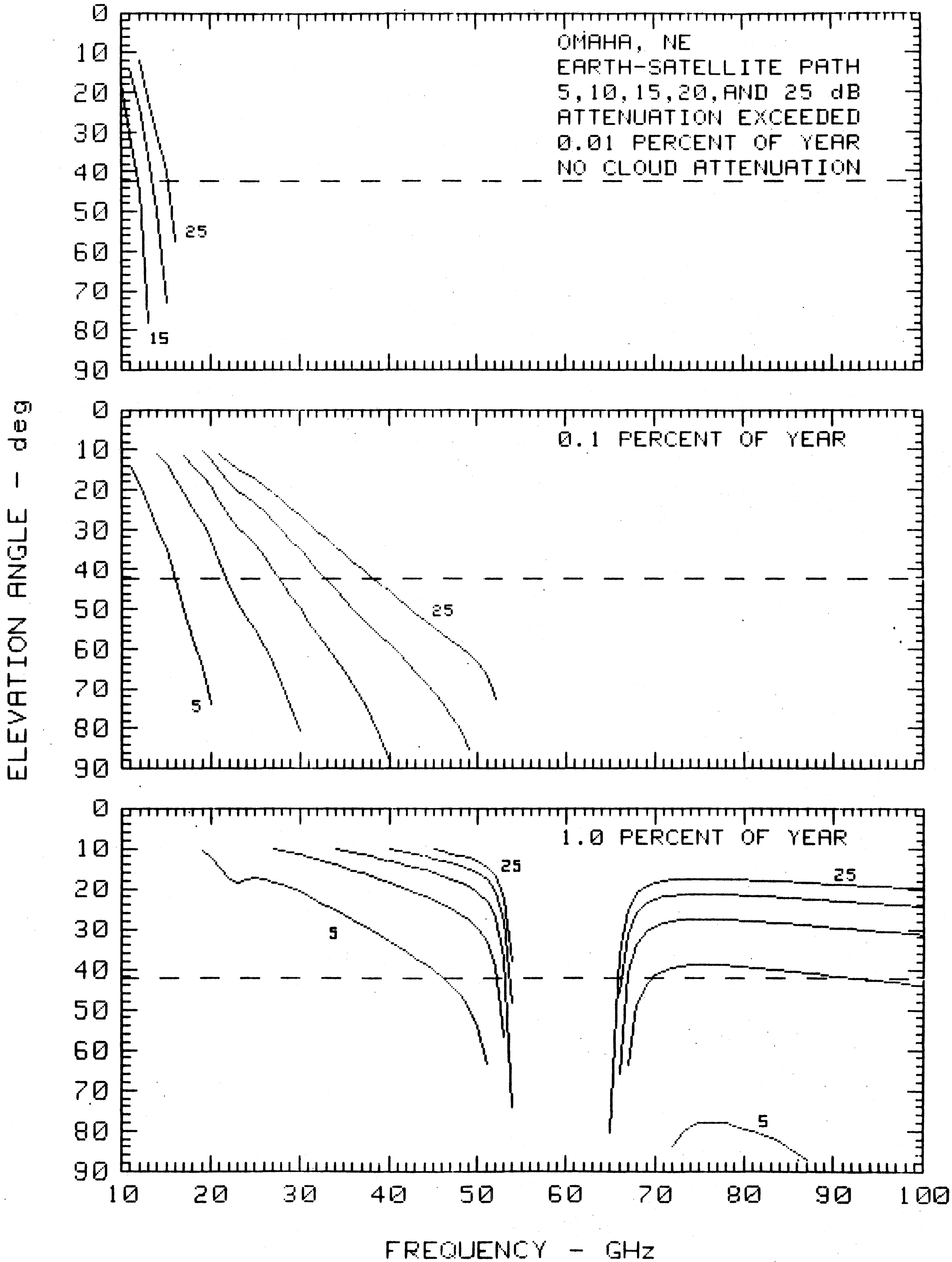

Figure A-26. Omaha, Ne., earth-satellite path.

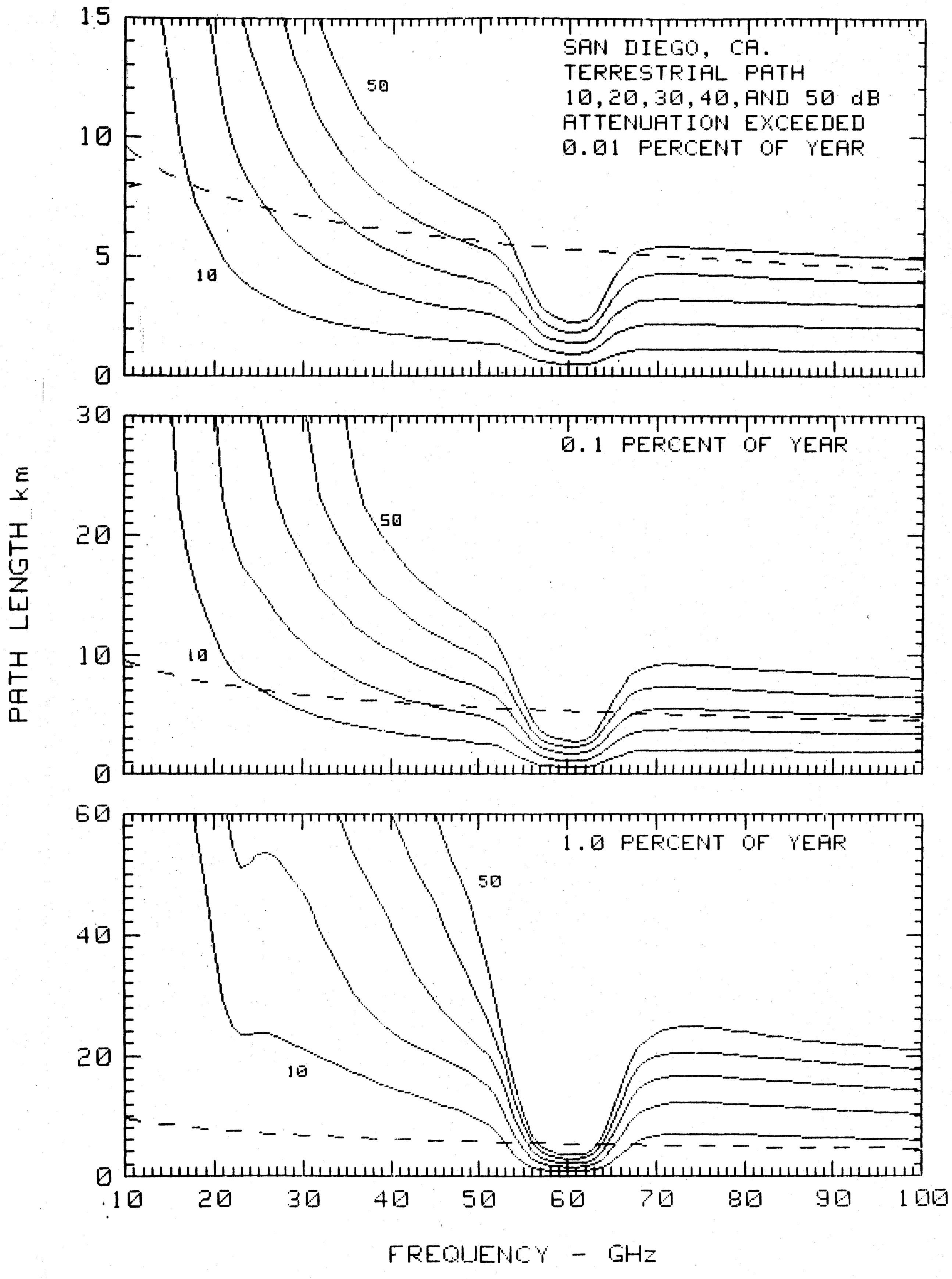

Figure A-27. San Diego., Ca., terrestrial path.

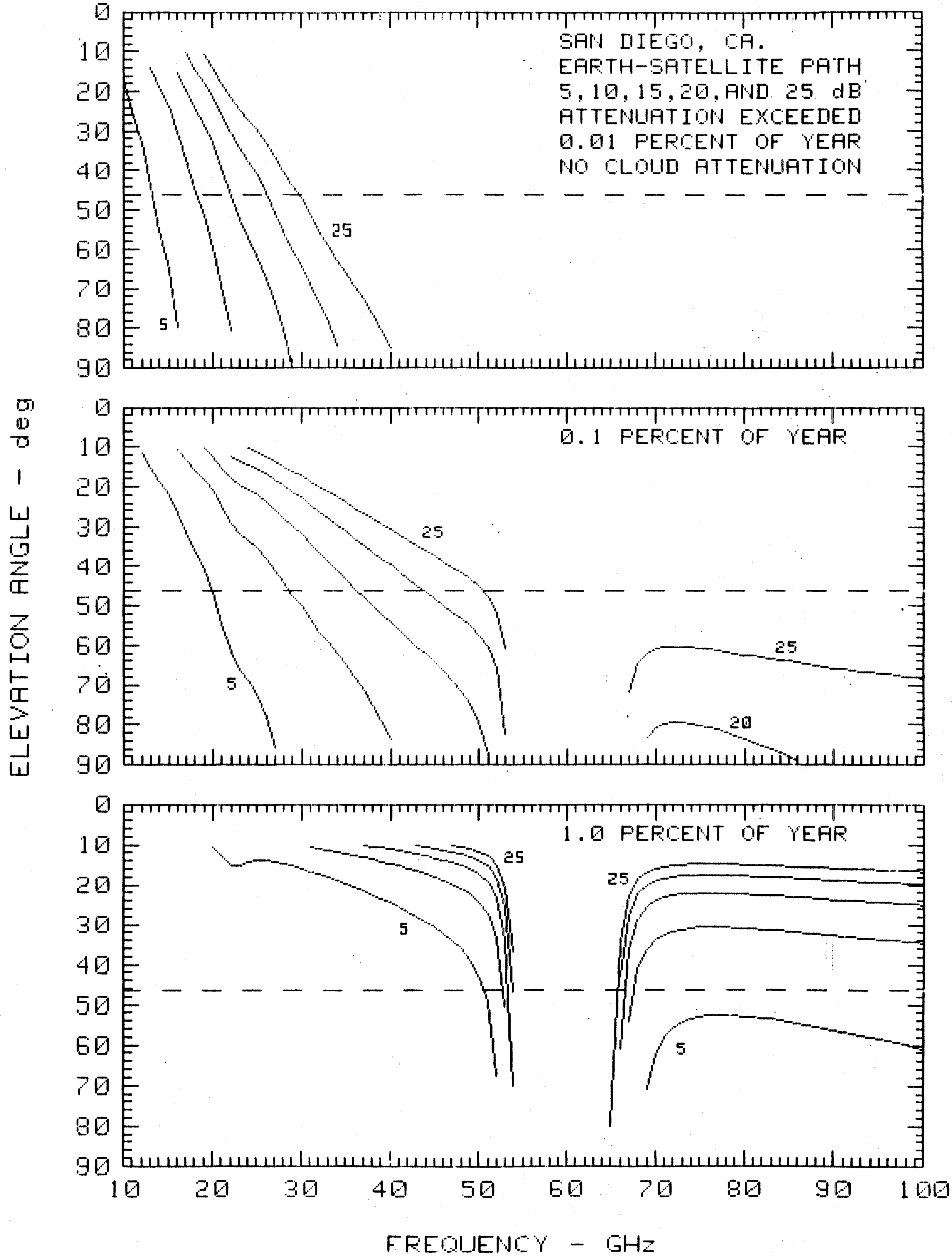

Figure A-28. San Diego, Ca., earth-satellite path.

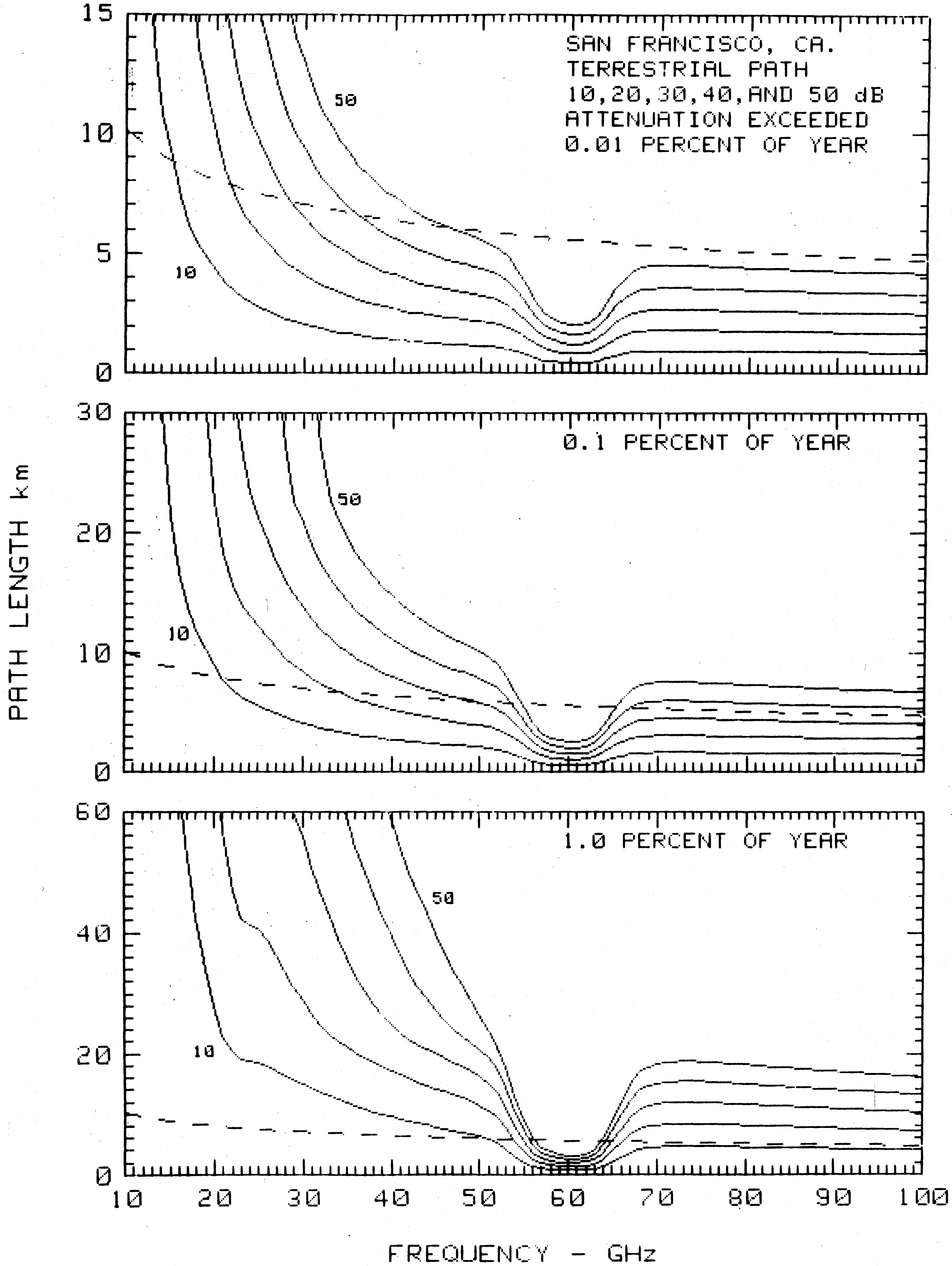

Figure A-29. San Francisco, Ca., terrestrial path.

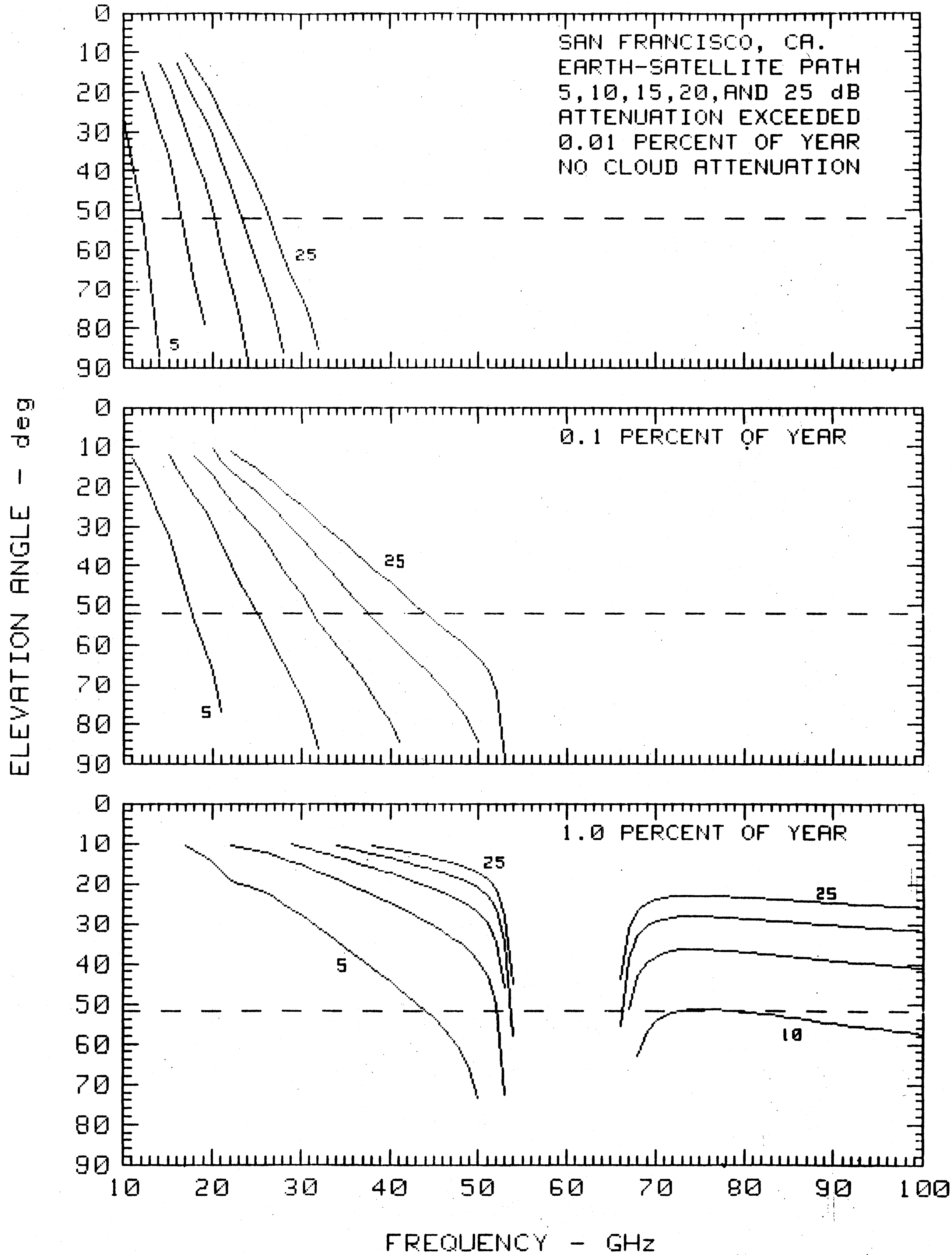

Figure A-30. San Francisco, Ca., earth-satellite path.

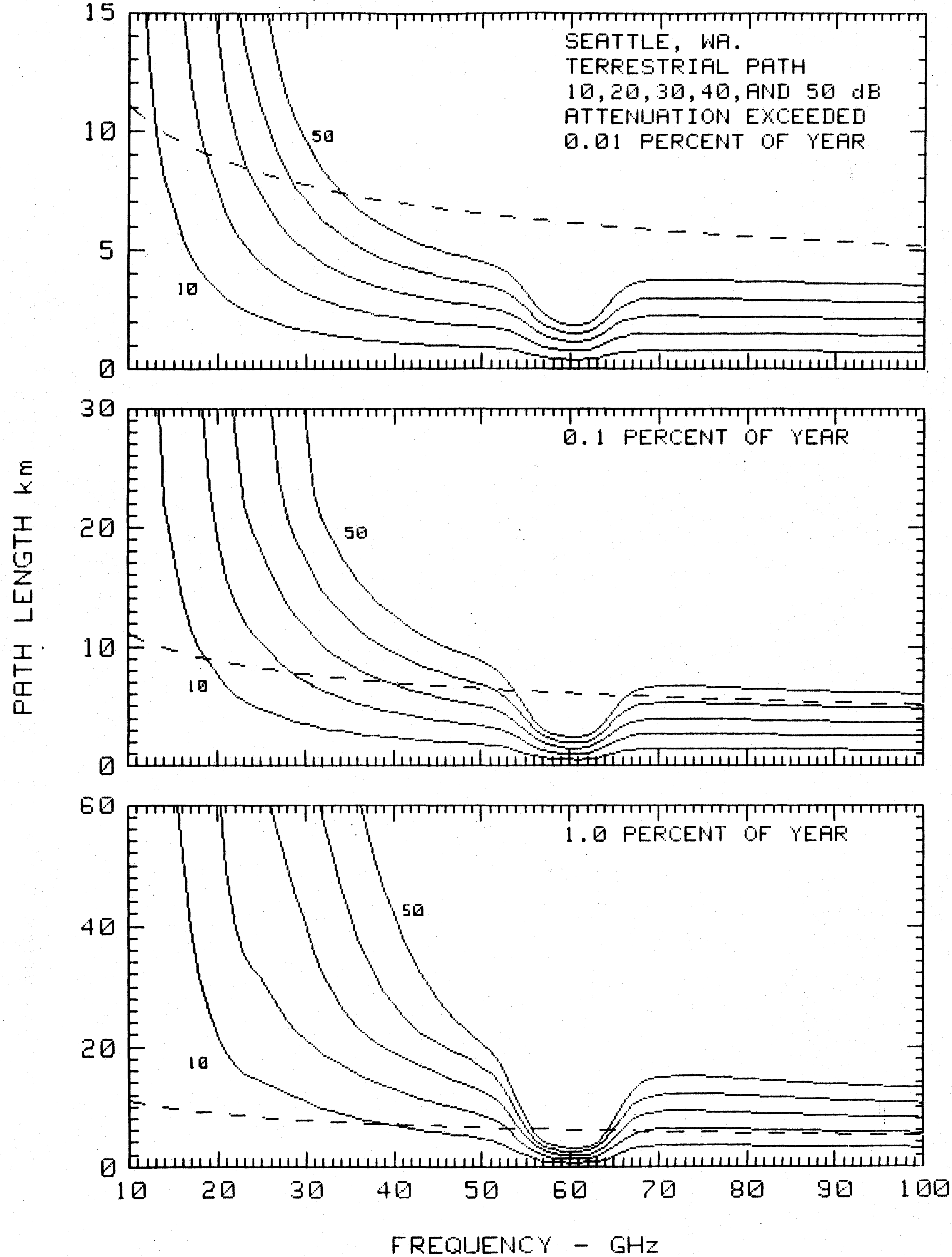

Figure A-31. Seattle, Wa., terrestrial path.

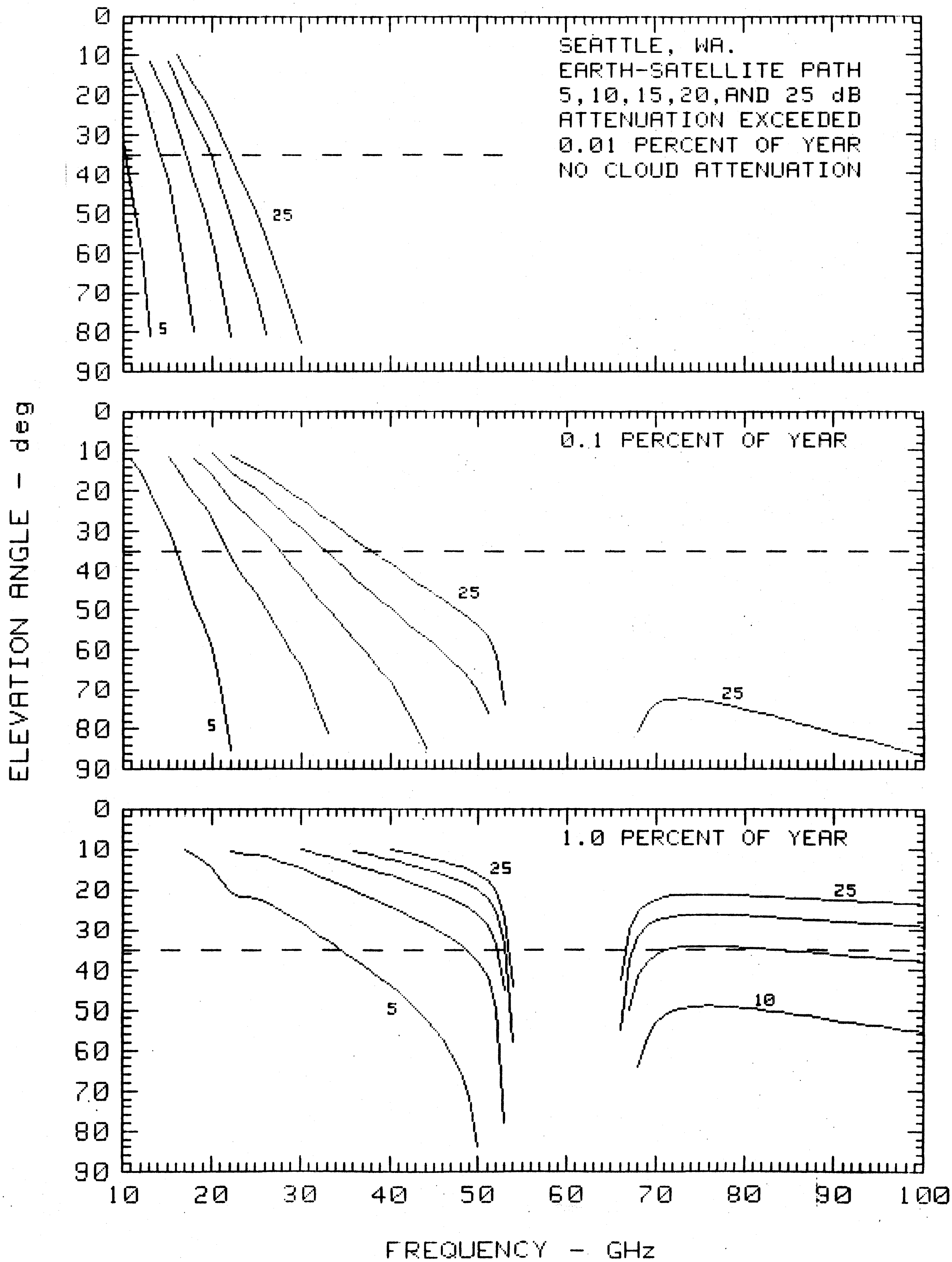

Figure A-32. Seattle, Wa., earth-satellite path.

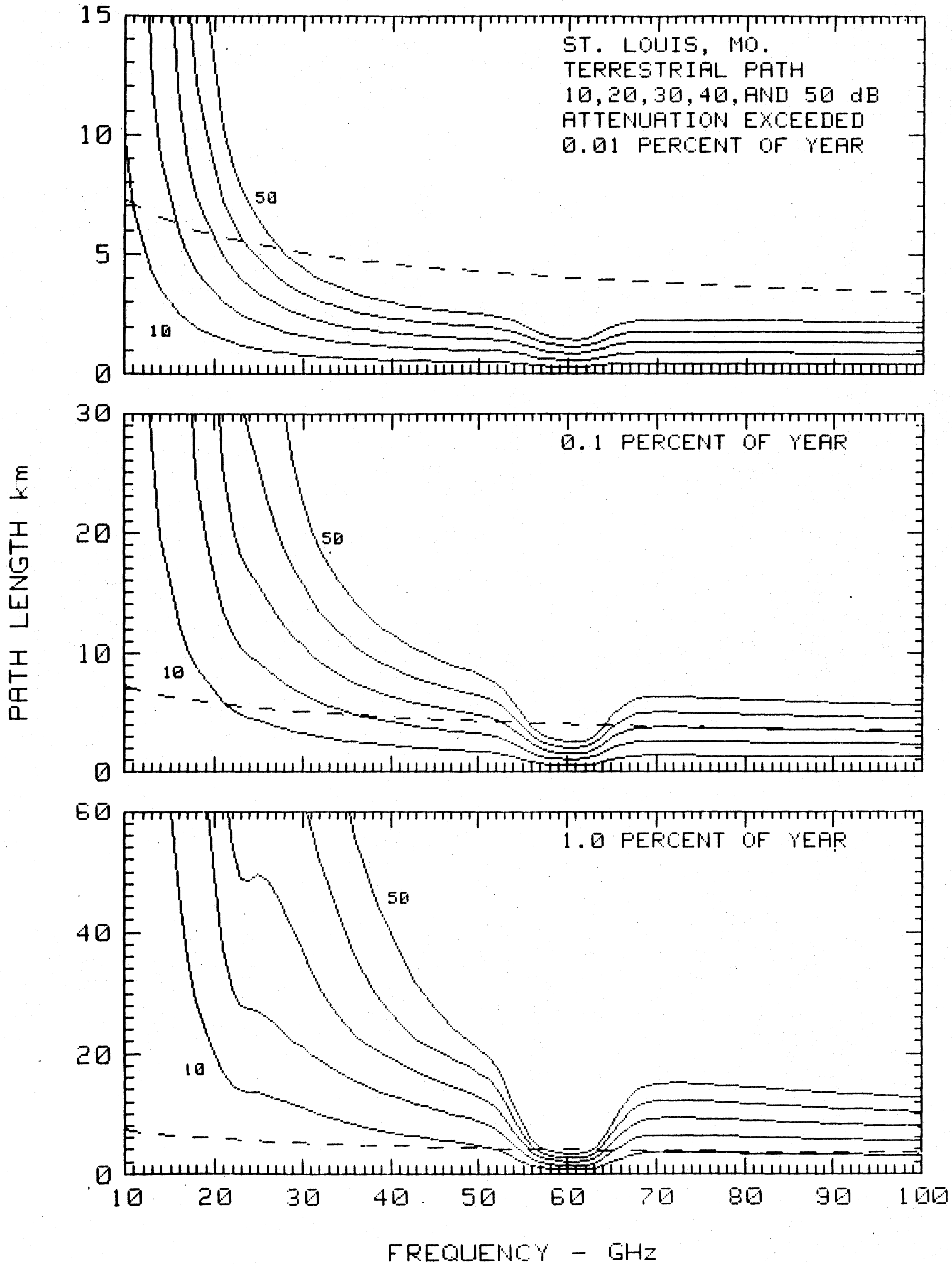

Figure A-33. St. Louis, Mo., terrestrial path.

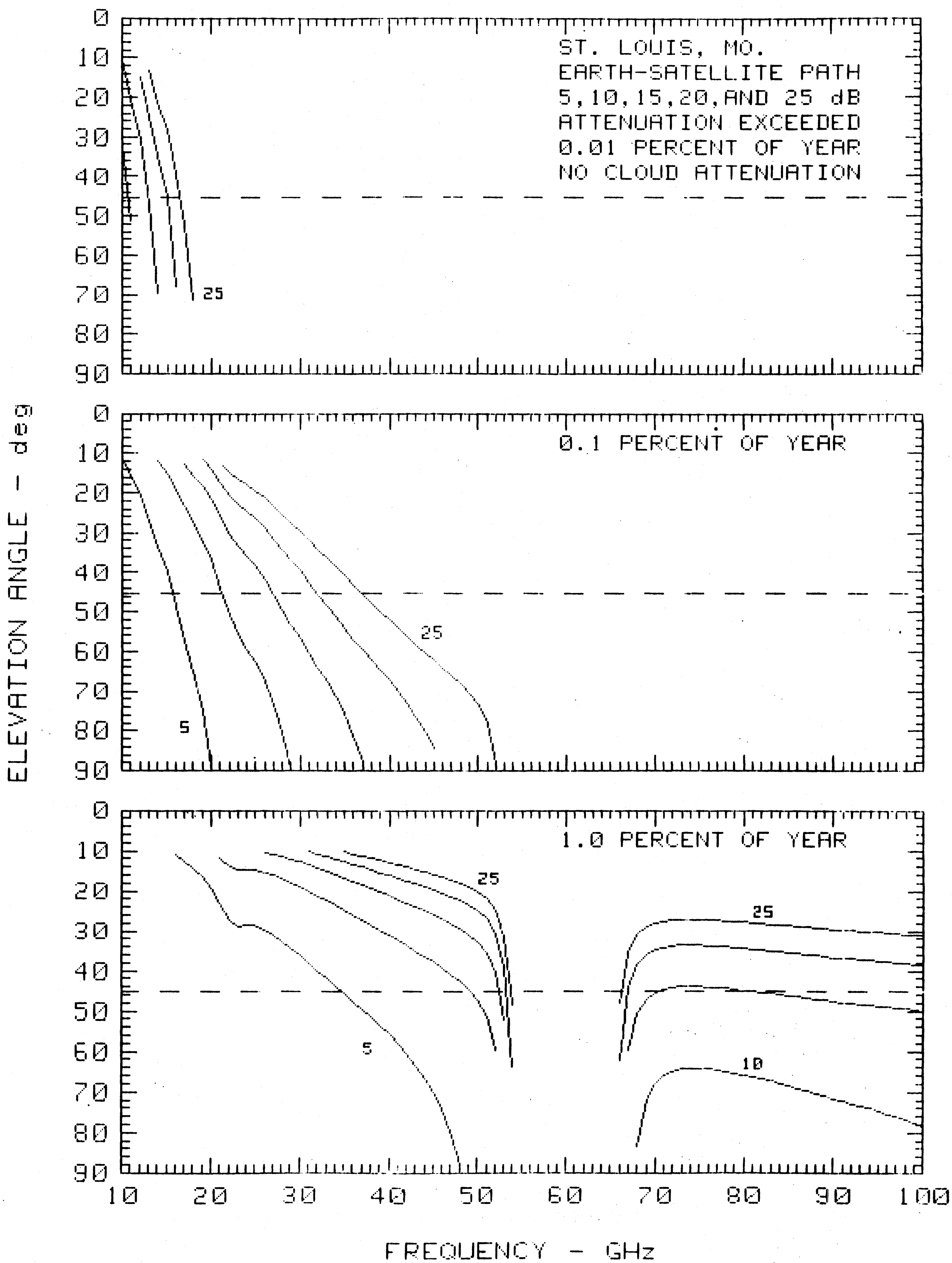

Figure A-34. St. Louis, Mo., earth-satellite path.

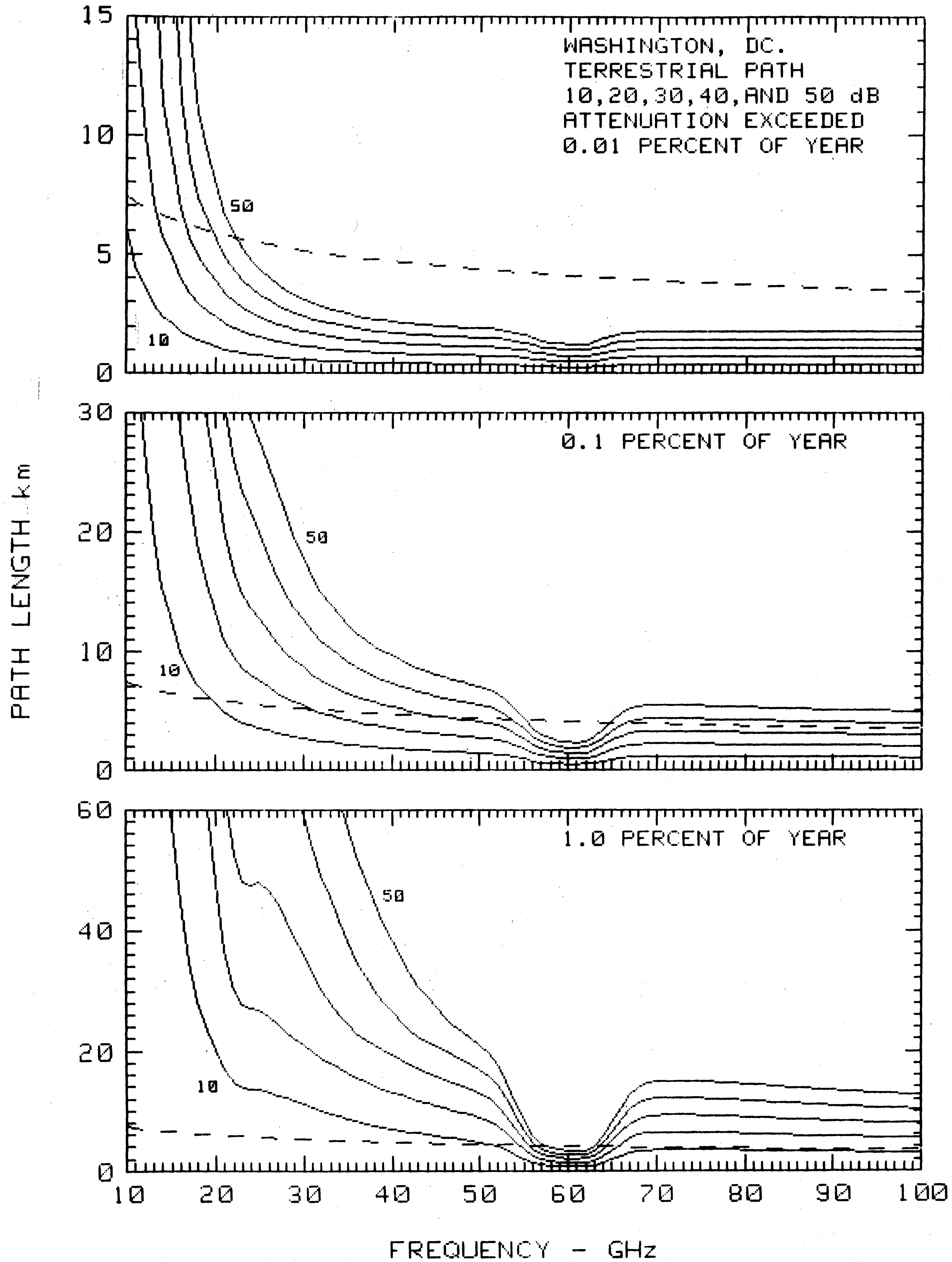

Figure A-35. Washington, DC., terrestrial path.

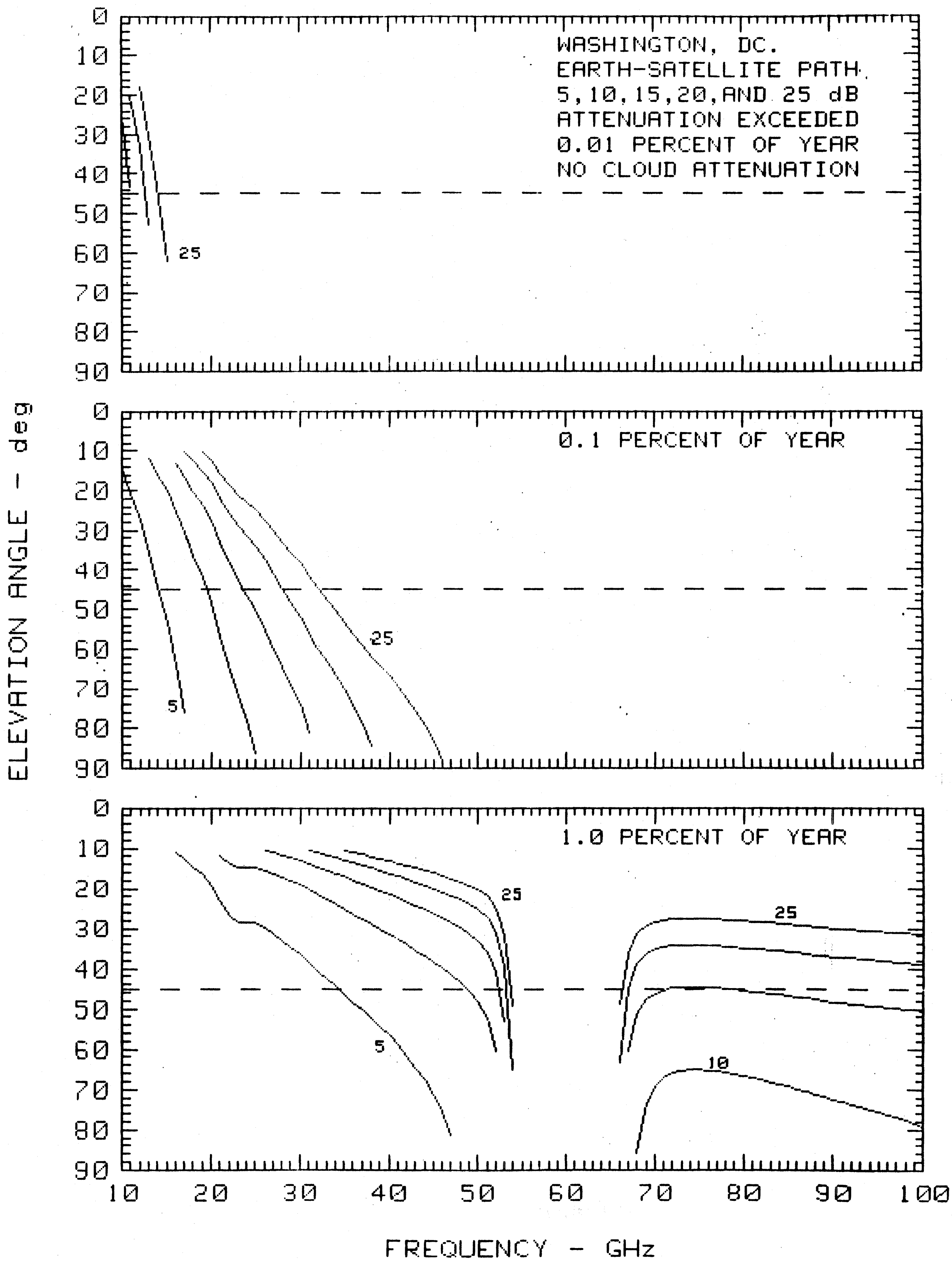

Figure A-36. Washington, DC., earth-satellite path.

APPENDIX B. MODELS AND METEOROLOGICAL DATA

B.1 Meteorological Data

Most of the surface meteorological data were taken from the work of Bryson and Hare (1974). The data for Honolulu were taken from Dutton (1977). The data are presented in Table B-1 where the following notation is used:

p - monthly mean station pressure in kilopascals (kPa) for month with greatest mean partial water vapor pressure. (Annual mean is given for Honolulu. Pressures for Atlanta, Dallas, and Seattle are from standard atmosphere table (Rex, 1969).

t - monthly mean temperature in degrees Celsius for same month as used for the mean pressure

e - greatest monthly mean partial water vapor pressure in kPa

$\bar{e}$ - average monthly mean partial water vapor pressure for May through September

M - mean annual precipitation in mm

Mm - maximum precipitation in one month in mm over 30-year period (NOAA, 1980c)

U - mean number of days per year with thunderstorms

D - mean number of days per year with more than 0.25 mm precipitation.

When only mean relative humidity data were available, the partial water vapor pressure was found by using a table of saturation pressure over water (List, 1951) and the mean temperature.

Most of the upper air meteorological data are taken from Ratner (1945, 1957). Data for the month of July were chosen and were taken from tables where possible; otherwise, they were read from charts (Ratner, 1957). The data for Honolulu were found by averaging three years of measurements for Hilo (NOAA, 1979, 1980b; WMO, 1981).

The profiles included pressure, height, temperature, and relative humidity to 30 km in height in approximately 25 height increments. When data were only available for wide height increments, values were interpolated for intermediate heights. Where the data did not extend to 30 km, the profiles were extended to that height using values from standard atmosphere tables (Rex, 1969). The relative humidity data were extended in height to the tropopause by approximations (usually assuming nearly constant relative humidity from the last datum). Above the tropopause to 30 km, the relative humidity was assumed to be 3 percent (Ellsaesser et al., 1980).

Table B-1. Surface Meteorological Data

CITY	p (kPa)	t (c)	e (kPa)	$\bar{e}$ (kPa)	M (mm)	Mm (mm)	u (days)	D (days)
Atlanta	97.7*	26.0	2.3	2.08	1197	399	51	117
Boston	99.2	21.6	1.9	1.56	1206	434	20	137
Chicago	98.9	24.3	2.0	1.64	843	360	37	120
Dallas	99.6*	29.4	2.4	2.16	879	391	43	81
Denver	84.0	23.0	0.9	0.78	380	186	42	86
El Paso	88.6	26.6	1.5	1.14	201	170	36	44
Fairbanks	99.6	15.4	1.2	0.95	287	157	8	112
Honolulu	101.3	24.8	2.16	2.16	582	528	8	102
Miami	101.6	27.9	2.9	2.72	1520	620	80	128
New Orleans	101.6	28.6	2.8	2.58	1613	485	73	119
New York	100.5	23.9	2.0	1.70	1076	428	30	121
Phoenix	97.1	31.7	1.7	1.18	184	141	22	34
Omaha	98.5	24.6	2.0	1.66	700	349	49	95
San Diego	101.0	21.5	1.7	1.44	264	193	3	43
San Francisco	101.0	14.9	1.4	1.32	529	312	2	67
Seattle	101.3*	16.2	1.2	1.16	866	328	6	151
St. Louis	99.5	25.4	2.2	1.86	897	231	51	110
Washington, DC.	101.2	25.7	2.2	1.84	1036	462	32	115

* From a standard atmosphere.

B.2 Clear Air Absorption Model

The atmospheric absorption model of Liebe (1981) was used to compute the attenuation due to atmospheric gases. Variations in atmospheric attenuation were assumed to be primarily due to variations in the water vapor content of the atmosphere (Bussey, 1950). Therefore, the month with the greatest mean partial water vapor pressure was assumed to be the month with the greatest mean atmospheric attenuation. Most often July has the greatest mean water vapor pressure (in U.S.) and although sometimes another month has a greater mean, it is not significantly larger than the July value. Therefore, the attenuation levels computed for the month of July can be assumed to be close to the attenuation levels for the worst month of the year. The distribution of attenuation during July was estimated by using the constant mean temperature and pressure for July and the water vapor distribution model of Bean and Cahoon (1957). Although this model is restricted to the atmosphere near ground level, it was applied to the upper air profiles by scaling down the change in water vapor density proportionately with the decrease in mean water vapor density with height. When computing the attenuation exceedance distributions, the level of water vapor exceeded the same percentage of the year was used at each level along the profile. Because the variations of water vapor at different heights in the atmosphere are partially statistically independent, the above method overestimates the variance of absorption on an earth-satellite path. The levels of attenuation exceeded for different percentages of the year should be closer to the average attenuation than this method predicts.

Because the level of water vapor absorption exceeded during one month does not increase significantly as the percentage of time decreases below a few percent (Bean and Cahoon, 1957), the absorption predicted to be exceeded 5 percent of July was used as the amount of water vapor absorption expected during rain. This absorption was added to the attenuation due to rain in order to compute the attenuation given in the figures of Appendix A.

B.3 Rain Attenuation Model

The rain attenuation model of Crane (1980), with some modification as described below, was used to predict the rain attenuation to be expected in the selected cities. The Crane (1980) model was chosen because its simplicity lends itself to the many iterative computations required in carrying out this analysis. Its accuracy is sufficient for the purposes of this report. The a and b parameters given by Olsen et al. (1978) for a low rain rate, 0 degree Celsius, Laws and Parsons drop-size distribution were used instead of those given by Crane. The Rice-Holmberg (1973) model was used to compute rain rate distributions for each of the cities.

The equation

$$P = M \{.03 \exp(-.03R) + .2(1 - \beta)[\exp(-.258R) + 1.86 \exp(-1.63R)]\}/87.64 \qquad \text{(B-1)}$$

giving the percentage of the year, P, that the rain rate, R, in mm/hr is exceeded was solved iteratively for R. The variable, M, is the mean annual precipitation in millimeters and is given in Table B-1. The variable, β, is the fraction of the annual precipitation due to thunderstorms and was found using

$$\beta_o = .03 + .97 \exp[-5 \exp(-.004Mm)] \qquad \text{(B-2)}$$

and

$$\beta = \beta_o \{.25 + 2 \exp[-.35(1 + .125M)/U]\} \qquad \text{(B-3)}$$

where Mm is the maximum precipitation in one month in mm, and U is the mean number of days per year with thunderstorms, and they are given in Table B-1.

B.4 Multipath Model

It has been assumed that there is a critical path length given in km by

$$L_o = C_o \lambda^{1/3} \qquad \text{(B-4)}$$

where λ is the wavelength in centimeters and C_o is a constant determined by geographic location. This formulation was derived by Ruthroff (1971) by assuming that there was a maximum ducting gradient which was seldom, if ever, exceeded for each geographic location. Then for a horizontal ducting layer, the maximum difference in delay during multipath is determined by this maximum duct gradient and is proportional to the cube of the path length. If this maximum delay is set to 3/8 λ and the corresponding path length found, the maximum fade would only be 3 dB. Equation (B-4) gives this path length.

Ruthroff gave the value of C_o based on observations on a path in New Jersey as 4.8. Allen et al. (1982) gave the value of C_o as 9.2 for a path in Colorado. Because the major cause of changes in refractive index gradients in the troposphere are variations in water vapor content, it seems plausible that the occurrence of ducting gradient may be predicted based on the average water vapor content,

it seems plausible that the occurrence of ducting gradient may be predicted based on the average water vapor content of the atmosphere. The monthly average absolute humidity during the months when the multipath events occurred which determined the values of C_o given above was 13.9 grams per cubic meter for the New Jersey path (NOAA, 1950) and 5.25 grams per cubic meter for the Colorado path (NOAA, 1980a). These values are very close to the 30-year May through September average values of absolute humidity for the path locations. Assuming a straight line dependence of C_o on average absolute humidity yields
humidity yields

$$C_o = -.52\overline{e} + 12 \tag{B-5}$$

where $\overline{e}$ is the 30-year, May through September average absolute humidity as given in Table B-1.

The above model is at best limited. It has been based on only two observations of C_o. While the occurrence of multipath is more common in more humid climates, it also depends on the local geography and terrain of the path including such features as smoothness of terrain, surrounding mountains, large bodies of water, wind conditions, etc. Therefore, the model should only be used as an indicator of approximate frequency and climatic dependence of atmospheric multipath.

B.5 Cloud Attenuation Model

The cloud attenuation model described in Section 3.3 is based upon the Rayleigh absorption approximation and assuming a uniform cloud temperature of 2 degrees Celsius, attenuation can be approximated by

$$A = 13Wf^2/(14100 + f^2) \tag{B-6}$$

where f is the frequency in GHz and W is the total liquid water, which is traversed, in millimeters (of thickness). The total liquid water along a vertical path in the cloud models presented by Reeves (1975) that were developed by Gaut and Reifenstein (1971) can be approximated by

$$W = 0.5R \tag{B-7}$$

where R is the rain rate being produced by a stratus cloud in mm/hr. Combining Equations (B-6) and B-7) gives the attenuation in dB due to suspended cloud particles as

$$7.5Rf^2/(14100 + f^2) \tag{B-8}$$

where elevation angle dependence is ignored. Equation (B-8) may be used as an approximation of the additional attenuation due to the cloud itself by adding it to the rain attenuation predicted by most models.

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15. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)*

Attenuation by the atmosphere can severely limit the use of the radio spectrum above 10 GHz for telecommunication purposes. In this report brief discussions of three mechanisms that attenuate millimeter waves in the atmosphere are presented: rain attenuation, clear air absorption, and atmospheric multipath. Propagation models developed by personnel at the Institute for Telecommunication Sciences and by others were combined with meteorological statistics to obtain estimates of average year attenuation distributions for 18 cities in the United States. The estimates are presented in such a way to elucidate the restrictions on system parameters required for reliable operation, i.e. frequency, path length for terrestrial paths, and path elevation angle for earth-satellite paths. The variation imposed by the diverse climates within the United States is demonstrated. Generally, in regions that have humid climates, millimeter wave systems perform less favorably than in areas where arid or semi-arid conditions prevail.

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