6.3.1.2 Procedures for Calculating Cumulative Rain Attenuation Statistics. The system designer needs reliable cumulative attenuation statistics to realistically trade off link margins, availability, siting and other factors. Needless to say, applicable millimeter-wave attenuation measurements spanning many years seldom exist. It is therefore necessary to estimate statistics, using whatever information is available.

An estimate of the rain attenuation cumulative statistics may be determined in several ways. The optimum way depends on the amount of rain and/or attenuation data available, and on the level of sophistication desired. However, it is recommended that the simplest calculations be carried out first to provide an approximation for the statistics and also to act as a check on the results of more sophisticated calculations.

The flow charts in Figures 6.3-1, 6.3-7 and 6.3-13 will assist in applying selected calculation procedures. The steps are numbered sequentially to allow easy reference with the accompanying discussions in Sections 6.3.2, 6.3.3 and 6.3.4. These are the procedures given:

- Analytical Estimates using the Global Model (Section 6.3.2, Figure 6.3-1). Requires only Earth station location, elevation angle, and frequency.

- Analytical Estimates using the CCIR Model (Section 6.3.2, Figure 6.3-7). Requires only Earth station location, elevation angle, and frequency.

- Estimates Given Rain Rate Statistics (Section 6.3.3, Figure 6.3-1). Requires cumulative rain rate exceedance statistics for vicinity of the Earth station location, elevation angle, and frequency.

- Estimates Given Rain Rate and Attenuation Statistics (Section 6.3.4, Figure 6.3-13). Requires attenuation statistics which

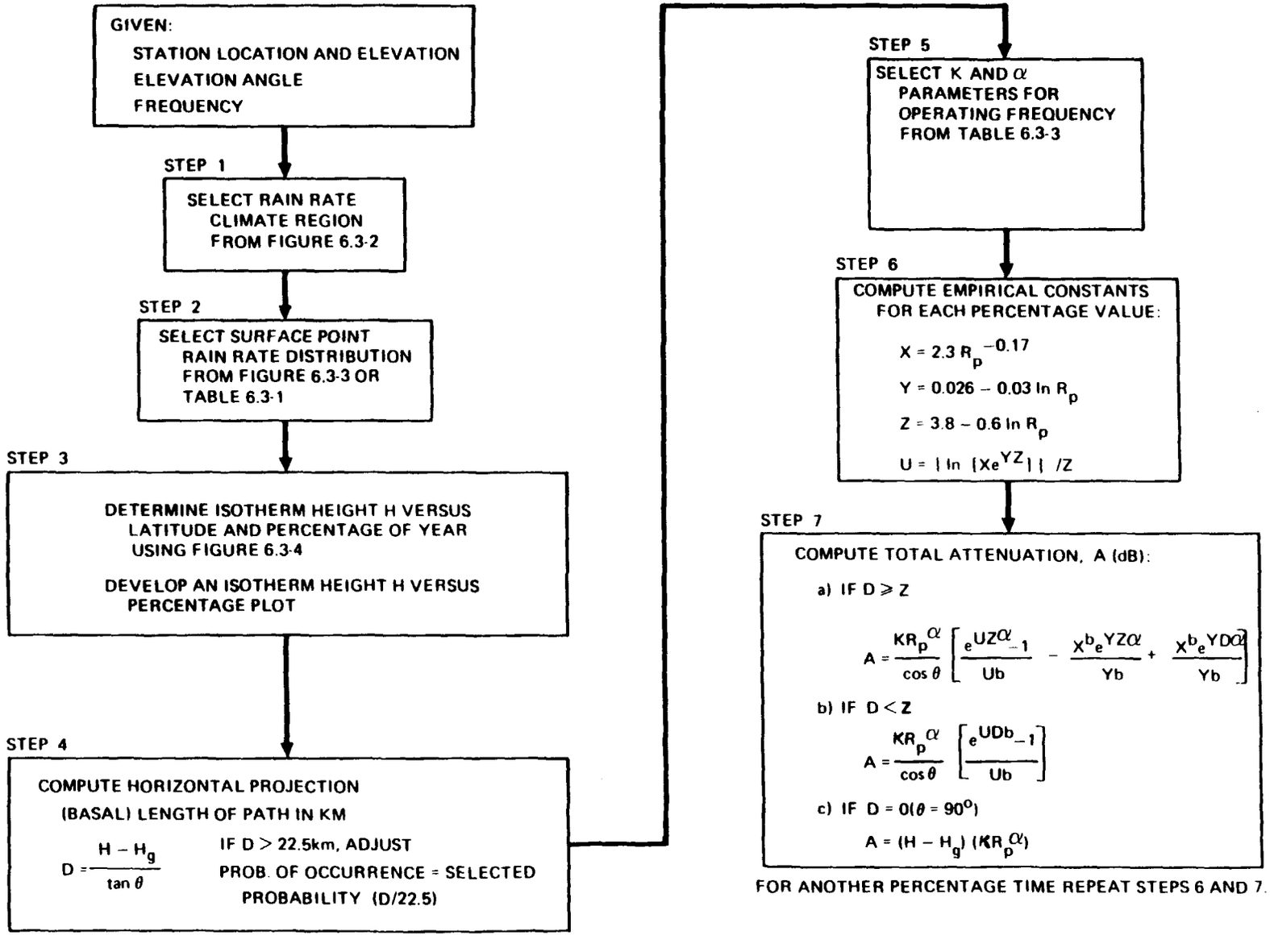


Figure 6.3-1. Analytic Estimate Procedure for Cumulative Rain Rate and Attenuation Statistics Using the Global Model

may be for frequency and elevation angle different from those needed.

6.3.1.3 Other Considerations. Generally the yearly cumulative statistics are desired. The worst-month or 30-day statistics are sometimes also needed, but are not derivable from the data presented here. Worst 30-day statistics are discussed in Section 6.3.7.

The attenuation events due to liquid rain only are considered here. Liquid rain is the dominate attenuation-producing precipitation because its specific attenuation is considerably higher than snow, ice, fog, etc. The contribution of these other hydrometeors is estimated in later sections.

The cumulative statistics are appropriate for earth-space paths for geostationary or near-geostationary satellites with relatively stable orbital positions. The modifications required to develop statistics for low-orbiting satellites is unclear because of the possibly nonuniform spatial distribution of rain events arising from local topography (lakes, mountains, etc.). However, if one assumes these effects are of second-order, low orbiting satellites may simply be considered to have time-dependent elevation angles.

6.3.2 Analytic Estimates of Rain Attenuation from Location and Link Parameters

The following analytic estimation techniques provide reasonably precise estimates of rain attenuation statistics. The first technique is based on the modified Global Prediction Model (Crane and Blood- 1979, Crane- 1980, 1980a). Only parts of the model relevant to the contiguous US and Canada, and elevation angles greater than 10°, are presented here. The second technique uses the CCIR Model and is perhaps the simplest prediction approach. Example applications of both techniques are given. The analytical developments for the global model and the CCIR model are presented in Sections 3.4 and 3.6, respectively.

The models require the following inputs:

a) Ground station latitude, longitude and height above mean sea level

b) The earth-space path elevation angle

c) The operating frequency

6.3.2.1 Global Model Rain Attenuation Prediction Technique. Figure 6.3-1 gives the step-by-step procedure for applying the Global Model. The steps are described in detail below.

Step 1 - At the Earth terminal's geographic latitude and longitude, obtain the appropriate climate region using Figure 6.3-2. For locations outside the Continental U.S. and Canada, see Section 3.4.1. If long term rain rate statistics are available for the location of the ground terminal, they should be used instead of the model distribution functions and the procedure of Section 6.3.3 should be employed.

Step 2 - Select probabilities of exceedance (P) covering the range of interest (e.g., .01, .1 or 1%). Obtain the terminal point rain rate R (mm/hour) corresponding to the selected values of P using Figure 6.3.3, Table 6.3-1 or long term measured values if available.

Step 3 - For an Earth-to-space link through the entire atmosphere, obtain the rain layer height from the height of the 0° isotherm (melting layer) H_o at the path latitude (Figure 6.3-4). The heights will vary correspondingly with the probabilities of exceedance, P. To interpolate for values of P not given, plot H_o (P) vs Log P and sketch a best-fit curve.

Step 4 - Obtain the horizontal path projection D of the oblique path through the rain volume:

$$D = \frac{H_o - H_g}{\tan\theta} \; ; \; \theta \geq 10^o \qquad (6.3\text{-}1)$$

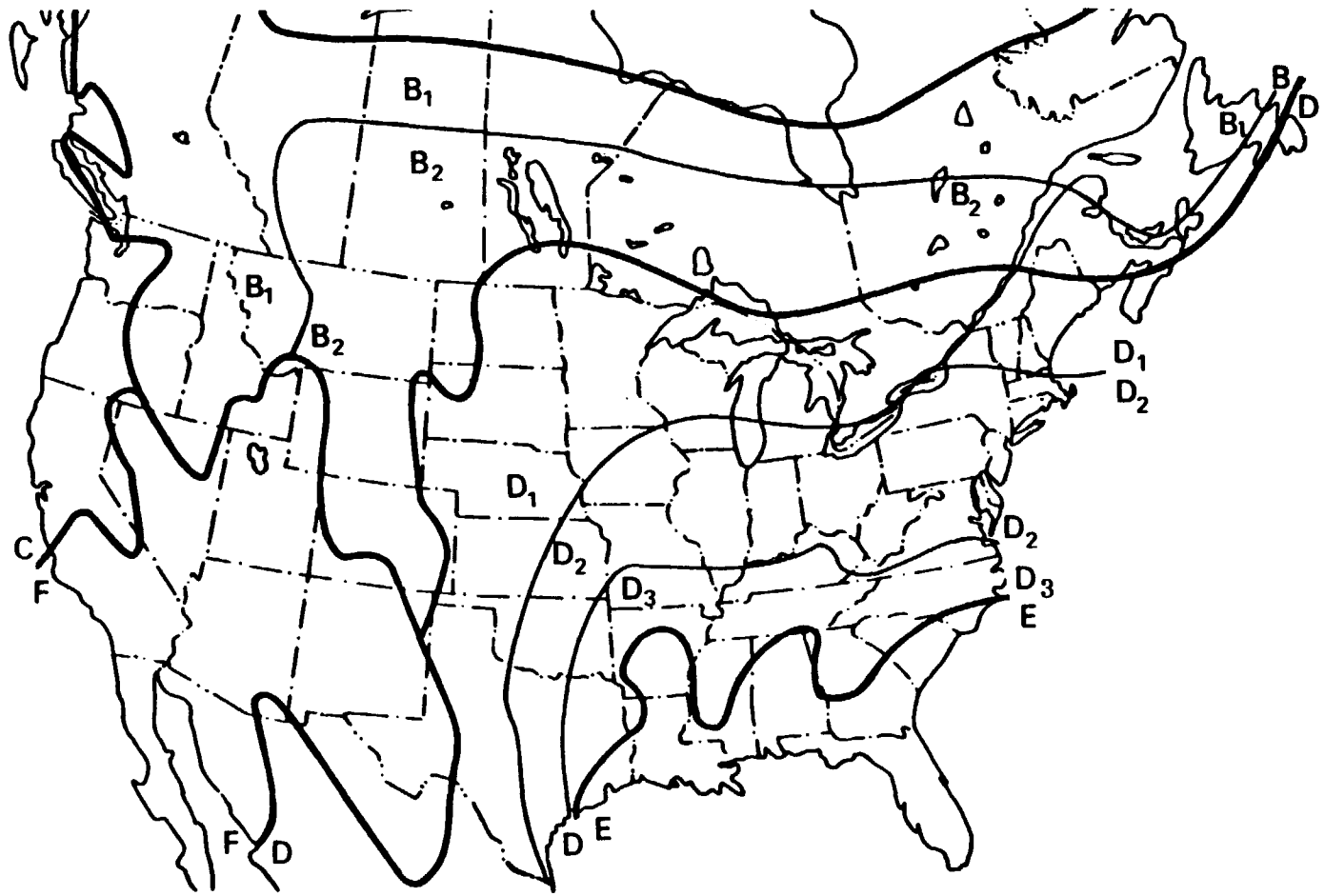
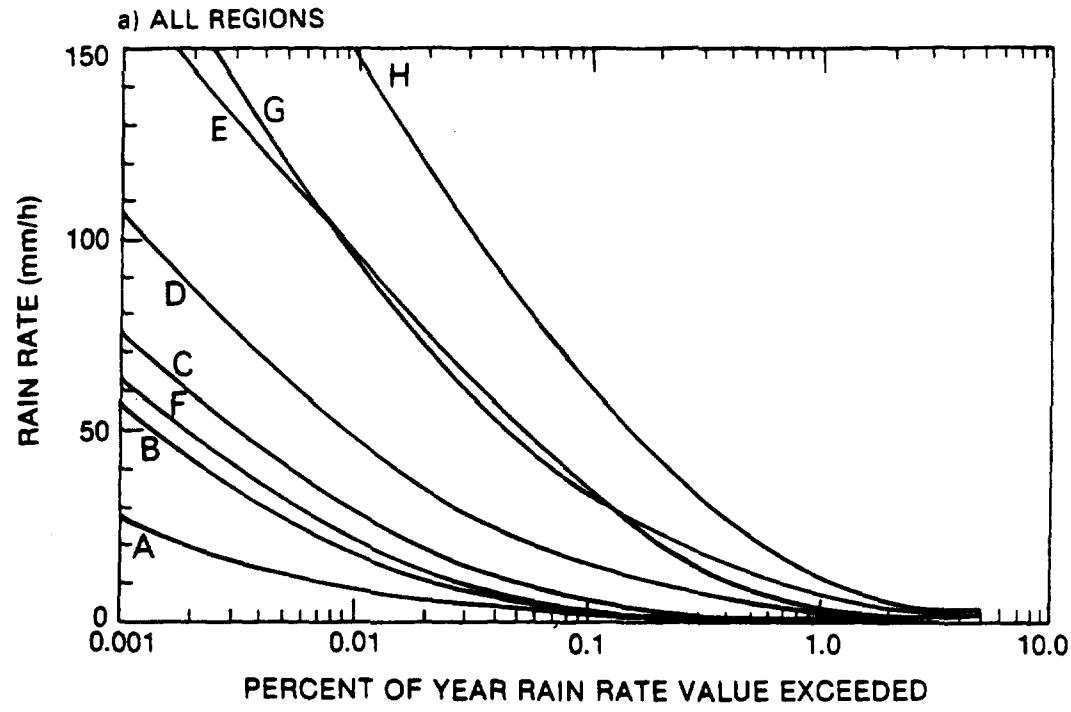


Figure 6.3-2. Rain Rate Climate Regions for the Continental U.S. and Southern Canada



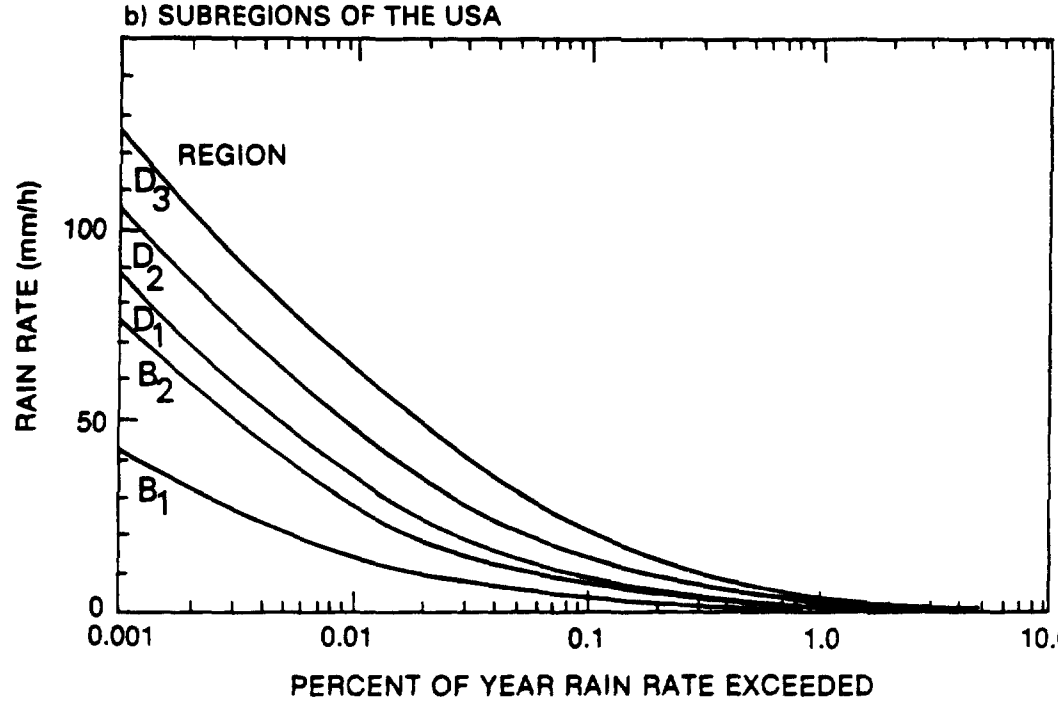


Figure 6.3-3. Point Rain Rate Distributions as a Function of Percent of Year Exceeded

Table 6.3-1. Point Rain Rate Distribution Values (mm/hr) Versus Percent of Year Rain Rate is Exceeded

Percent of Year	RAIN CLIMATE REGION												Minutes per Year	Hours per Year
	A	B_1	B	B_2	C	D_1	$D=D_2$	D_3	E	F	G	H		
0.001	28.5	45	57.5	70	78	90	108	126	165	66	185	253	5.26	0.09
0.002	21	34	44	54	62	72	89	106	144	51	157	220.5	10.5	0.18
0.005	13.5	22	28.5	35	41	50	64.5	80.5	118	34	120.5	178	26.3	0.44
0.01	10.0	15.5	19.5	23.5	28	35.5	49	63	98	23	94	147	52.6	0.88
0.02	7.0	11.0	13.5	16	18	24	35	48	78	15	72	119	105	1.75
0.05	4.0	6.4	8.0	9.5	11	14.5	22	32	52	8.3	47	86.5	263	4.38
0.1	2.5	4.2	5.2	6.1	7.2	9.8	14.5	22	35	5.2	32	64	526	8.77
0.2	1.5	2.8	3.4	4.0	4.8	6.4	9.5	14.5	21	3.1	21.8	43.5	1052	17.5
0.5	0.7	1.5	1.9	2.3	2.7	3.6	5.2	7.8	10.6	1.4	12.2	22.5	2630	43.8
1.0	0.4	1.0	1.3	1.5	1.8	2.2	3.0	4.7	6.0	0.7	8.0	12.0	5260	87.7
2.0	0.1	0.5	0.7	0.8	1.1	1.2	1.5	1.9	2.9	0.2	5.0	5.2	10520	175
5.0	0.0	0.2	0.3	0.3	0.5	0.0	0.0	0.0	0.5	0.0	1.8	1.2	26298	438

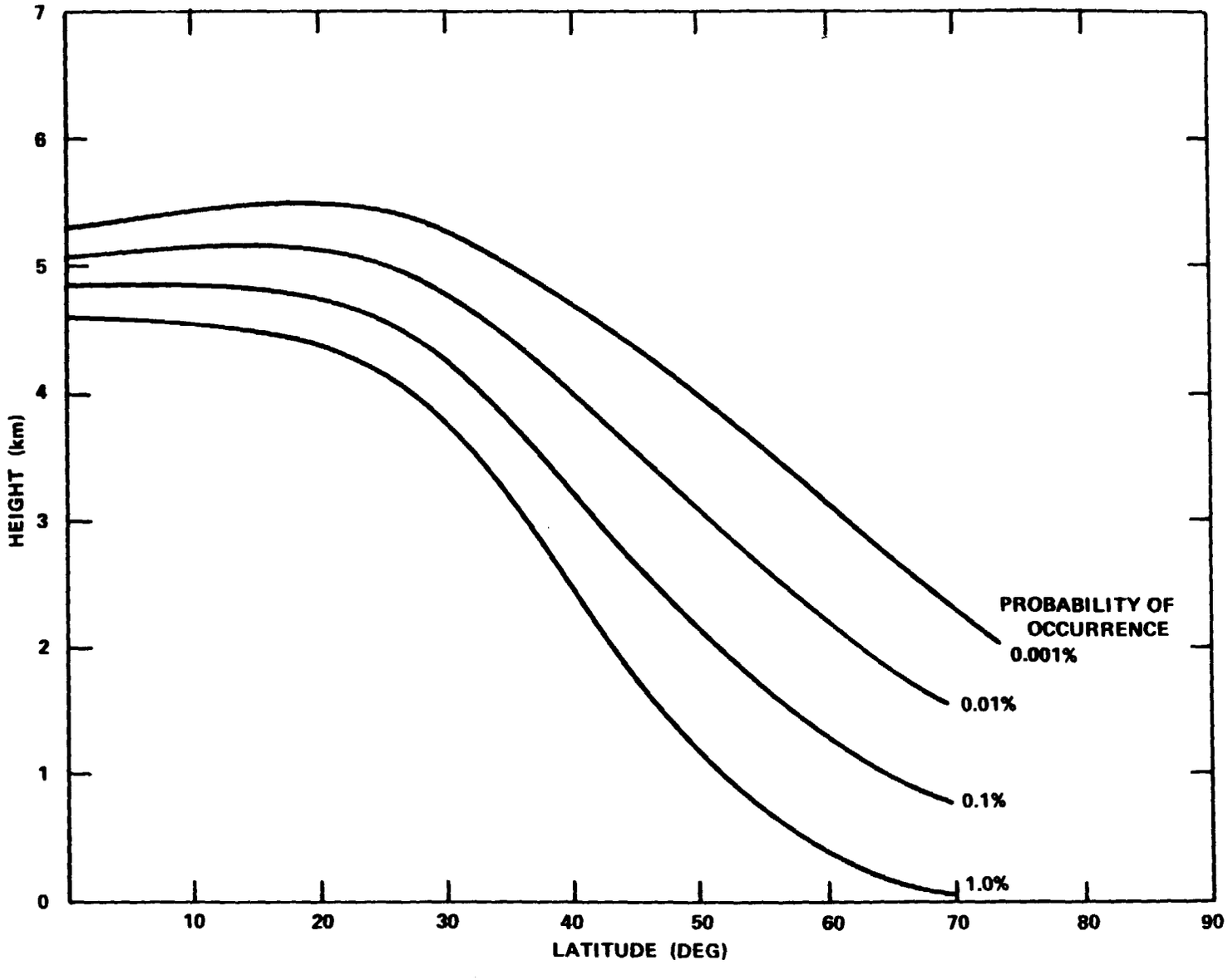


Figure 6.3-4. Latitude Dependence of the Rain Layer 0°C Isoltherm Height (H) as a Function of Probability of Occurrence

$H_o = H_o(P)$ = height (km) of isotherm for pbobability P

H_g = height of ground terminal (km)

θ = path elevation angle

Test $D \leq 22.5$ km; if true, proceed to the next step. If $D \geq 22.5$ km, the path is assumed to have the same attenuation value as for a 22.5 km path but the probability of exceedance is adjusted by the ratio of 22.5 km to the path length:

$$\text{New probability of exceedance, } P' = P \left(\frac{22.5 \text{ km}}{D} \right) \tag{6.3-2}$$

where D = path length projected on surface. This correction accounts for the effects of traversing multiple rain cells at low elevation angles.

<u>Step 5</u> - Obtain the specific attenuation coefficients, k and α, at the frequency and polarization angle of interest, from Table 6.3-3. For frequencies not in the table, use logarithmic interpolation for K and linear interpolation for α. The subscript H columns are for horizontal linear polarization, and the subscript V columns are for vertical linear polarization. [For polarization tilt angles other than horizontal or vertical, use the relationships on Figure 6.3-6, Step 4, to obtain K and α].

<u>Step 6</u> - Using the R_p values corresponding to each exceedance probability of interest, calculate the empirical constants X, Y, Z and U using

$$X = 2.3\ R_p^{-0.17} \tag{6.3-4}$$

$$Y = 0.026 - 0.03 \ln R_p \tag{6.3-5}$$

$$Z = 3.8 - 0.7 \ln R_p \tag{6.3-6}$$

$$U = [\ln(Xe^{YZ})]/z \tag{6.3-7}$$

Step 7 - If $Z \leq D$, compute the total attenuation due to rain exceeded for P % of the time using

$$A = \frac{k R_p^{\alpha}}{\cos\theta}\left[\frac{e^{UZ\alpha}-1}{U\alpha} - \frac{X^{\alpha}e^{YZ\alpha}}{Y\alpha} + \frac{X^{\alpha}e^{YD\alpha}}{Y\alpha}\right]; \theta \geqslant 10^{\circ} \qquad (6.3\text{-}8)$$

where A = Total path attenuation due to rain (dB)

k, α = parameters relating the specific attenuation to rain rate (from Step 5).

R_p = point rain rate

θ = elevation angle of path

D = horizontal path projection length (from step 4)

If D< Z,

$$A = \frac{k R_p^{\alpha}}{\cos\theta}\left[\frac{e^{U\alpha D}-1}{U\alpha}\right] \qquad (6.3\text{-}9)$$

If $D = 0, \theta = 90^{\circ}$,

$$A = (H - H_g)(K R_p^{\alpha}) \qquad (6.3\text{-}10)$$

This procedure results in an analytical estimate for the attenuation, A, exceeded for P percent of an average year. The use of a programmable calculator or computer for performihg these calculations is highly recommended.

6.3.2.2 A Sample Calculation for the Global Model. The following information is given for the Rosman, NC Earth Station operating with the ATS-6 satellite.

Earth station latitude :.	35°N
Earth station longitude:	277°E.
Earth station elevation:	0.9 km

Antenna elevation Angle: 47°

Operating frequency: 20 GHz

We wish to find an analytic estimate for the cumulative attenuation statistics using the procedure of Figure 6.3-1.

1. Select rain rate climate region for Rosman, NC:
   From Figure 6.3-2, Rosman is located in region D_3.

2. Select surface point rain rate distribution:
   From Table 6.3-1, region D_3 has the following distribution:

%	R_p
0.01	63
0.02	48
0.05	32
0.10	22
0.20	14.5
0.50	7.8
1.0	4.7

3. Determine isotherm height H:

   From Figure 6.3-4, the following isotherm height estimates apply at 35° latitude.

%	H
0.01	4.4 km
0.1	3.75
1.0	3.2

   By plotting these, the following additional points may be interpolated

0.02	4.2
0.05	3.95
0.2	3.55
0.5	3.3

4. Compute D:

Using $\theta = 47^{\circ}$ and $H_g = 0.9$ km, we obtain

%	D
0.01	3.25 km
0.02	3.1
0.05	2.85
0.1	2.65
0.2	2.45
0.5	2.25
1.0	2.15

5. Select K and α:

The specific attenuation coefficients, K and α are selected from Table 6.3-3 at 20 GHz, horizontal polarization.

$K = 0.0751$

$\alpha = 1.10$

6. Compute empirical constants:

For example,

%	X	Y	Z	U
0.1	1.36	-0.067	1.95	0.091
0.2	1.46	-0.054	2.20	0.118

0.5	1.62	-0.036	2.57	0.153

7. Compute attenuation, A:

We note from step 6 that at 0.2%, D is greater than Z. This also holds for percentages less than 0.1%. Thus the formula of Step 7 (a) is used to find the attenuation for % ≤ 0.1.

For % ≥ 0.5, D is less than Z, so the formula of Step 7 (b) applies. The attenuation values found in this way are plotted versus percentage exceedance in Figure 6.3-5. The figure includes statistics derived from 20 GHz attenuation measurements made at Rosman with the ATS-6 over a 6-month period.

6.3.2.3 CCIR Model Rain Attenuation Prediction Technique

This section presents the step by step procedure for application of the CCIR rain attenuation prediction model, described in detail in Section 3.6. The procedure is outlined in Figure 6.3-6.

Step 1 Obtain the rain rate, $R_{0.01}$, exceeded for 0.01% of an average year for the ground terminal location of interest. If this information is not available from local data sources, an estimate can be obtained by selecting the climate zone of the ground terminal location from Figure 6.3-7, and the corresponding rain rate value for that climate zone from Table 6.3-2. (For locations not found on Figure 6.3-7, see Figures 3.6-1 and 3.6-2).

[Important Note: The CCIR rain climate zones are not the same as the climate regions of the Global Model described earlier.]

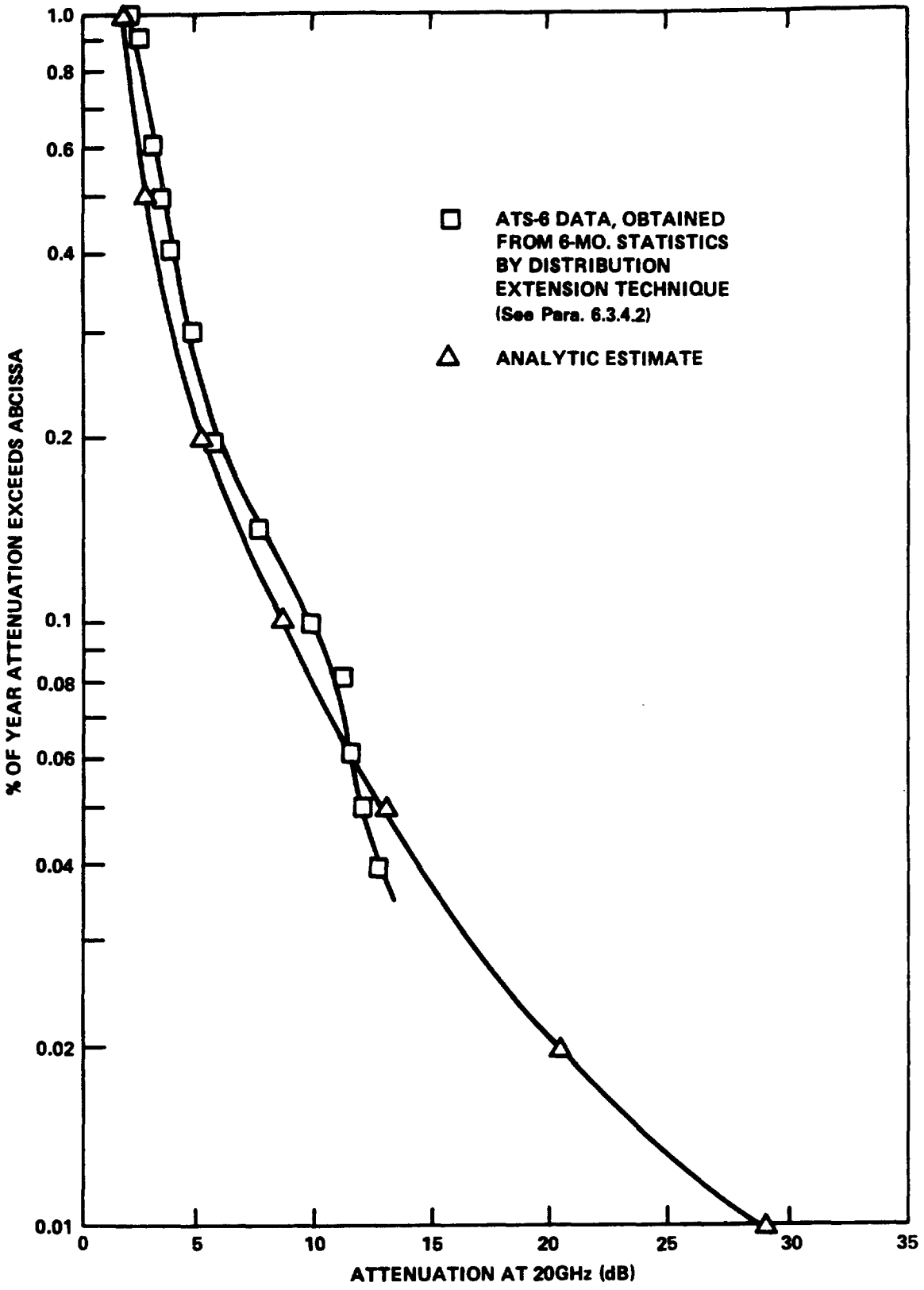


Figure 6.3-5. Analytic Attenuation Estimate and Actual Measurements

Table 6.3-2. Rain Rates Exceeded for 0.01% of the Time

Climate	A	B	C	D	E	F	G	H	J	K	L	M	N	P
Rate	8	12	15	19	22	28	30	32	35	42	60	63	95	145

Step 2 Determine the effective rain height, h_r, from;

$$h_r = 4.0 \qquad 0 < \phi < 36^\circ$$
$$= 4.0 - 0.075\,(\phi - 36) \qquad \phi \geq 36^\circ \qquad (6.3\text{-}11)$$

where ϕ is the latitude of the ground station, in degrees N or S.

Step 3 Calculate the slant path length, L_s, horizontal projection, L_G, and reduction factor, r_p, from:

For $\Theta \geq 5°$,

$$L_s = (h_r - h_o)/\sin(\Theta) \qquad (6.3\text{-}12)$$

$$L_G = L_s \cos(\Theta) \qquad (6.3\text{-}13)$$

$$r_p \quad \frac{1}{1 + 0.045 L_G} \qquad (6.3\text{-}14)$$

where Θ is the elevation angle to the satellite, in degrees, and h_o is the height above mean sea level of the ground terminal location, in km. (For elevation angles less then 5°, see Section 3.6).

Step 4 Obtain the specific attenuation coefficients, K and α, at the frequency and polarization angle of interest from Table 6.3-3. For frequencies not on the table, use logarithmic interpolation for K and linear interpolation for α. For polarization tilt angles other than linear horizontal or vertical, use the relationships on Figure 6.3-6, Step 4, to obtain K and α.

Step 5 Calculate the attenuation exceeded for 0.01% of an average year from;

$$A_{0.01} = K\, R_{0.01}{}^{\alpha}\, L_s\, r_p \qquad (6.3\text{-}15)$$

Step 6 Calculate the attenuation exceeded for other percentage values of an average year from:

$$A_p = 0.12\ A_{0.01}\ p^{-(0.546 + 0.043 \log p)} \qquad (6.3\text{-}16)$$

This relationship is valid for annual percentages from 0.001% to 1.0%.

6.3.2.4 Sample Calculation for the CCIR Model

In this section the CCIR model is applied to a specific ground terminal case. Consider a terminal located at Greenbelt, MD., at a latitude of 38°N, and elevation above sea level of 0.2 km. The characteristics of the link are as follows:

Frequency: 11.7 GHz

Elevation Angle: 29°

Polarization: Circular

Step 1 Figure 6.3-7 indicates that the terminal is in climate zone K, with a corresponding $R_{0.01}$ f 42 mm/h (Table 6.3-2).

Step 2 The effective rain height, from Eq (6.3-11), is

$$h_r = 4.0 - 0.075(38 - 36) = 3.85$$

Step 3 The slant path length, horizontal projection, and reduction factor are determined from Eq.'s (6.3-12, -13, -14) respectively;

$$L_S = (3.85 - 0.2)(/\sin(29°) = 7.53$$

$$L_G = (7.53)\cos(29°) = 6.58$$

$$r_p = 1/[1 + (0.045)(6.58)] = 0.771$$

Step 4 The specific attenuation coefficients are determined by interpolation from Table 6.3-3, with a polarizaiton tilt angle of 45° (circular polarization);

$$K = 0.0163, \quad \alpha = 1.2175$$

Step 5 The attenuation exceeded for 0.01% of an average year, from Eq. (6.3-15), is;

$$A_{0.01} = (0.0163)(42)^{1.2175}(7.53)(0.771)$$
$$= 8.96 \text{ dB}$$

Step 6 The attenuation exceeded for other percentages is then determined from Eq. (3.6-16);

%	Attenuation (dB)
1.0	1.08
0.5	1.56
0.3	2.02
0.1	3.42
0.05	4.67
0.03	5.80
0.01	8.96
0.005	11.48
0.003	13.65
0.001	19.16

Figure 6.3-8 shows a plot of the resulting attenuation prediction distribution, compared with three years of measured distributions obtained with the CTS satellite (Ippolito 1979). The CCIR prediction is seen to over-predict slightly for higher percentage values, and to vastly under-predict for percentages below about 0.01%.

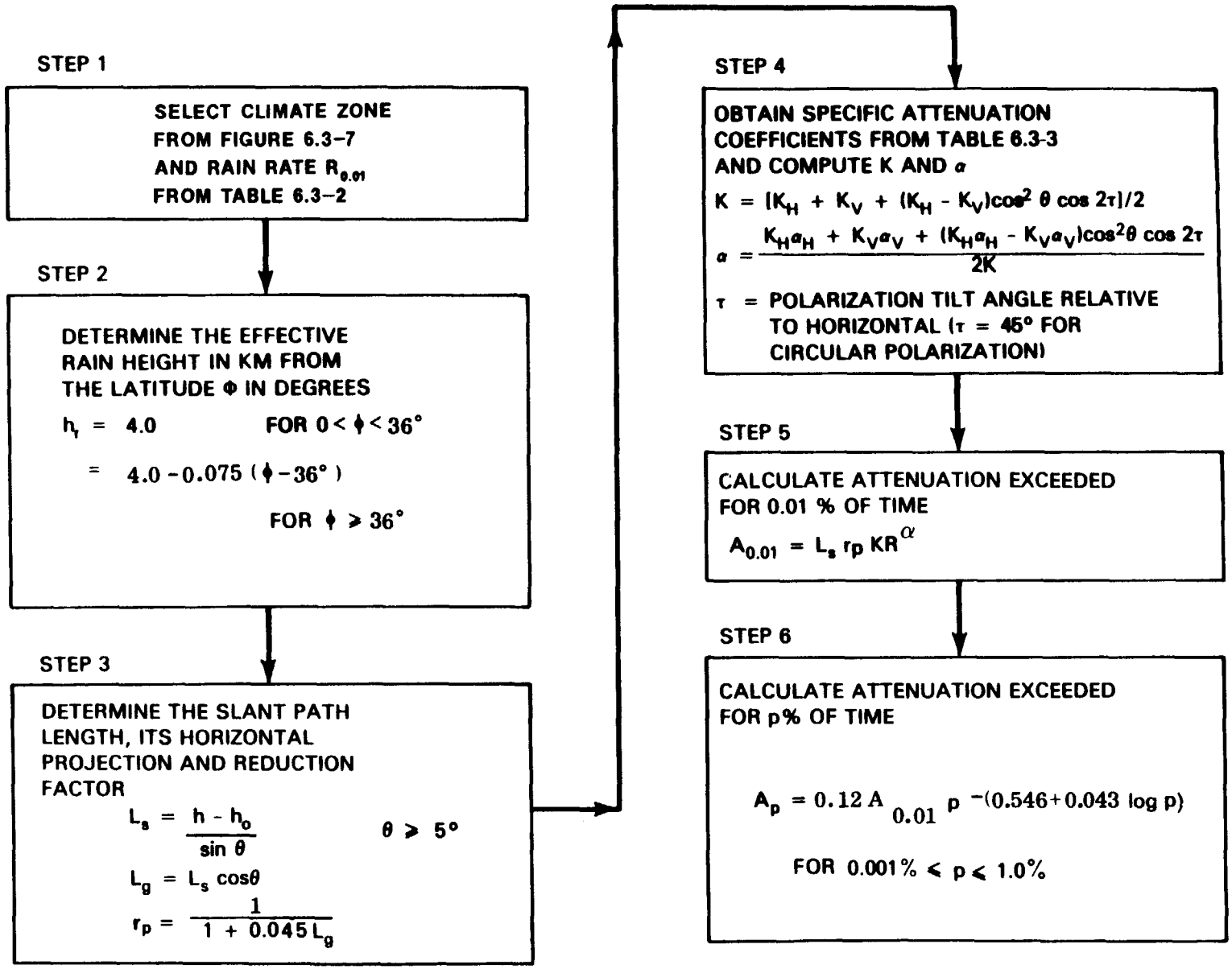


Figure 6.3-6. Analytical Estimate Procedure for Cumulative Rain Rate and Attenuation Statistics Using the CCIR Model

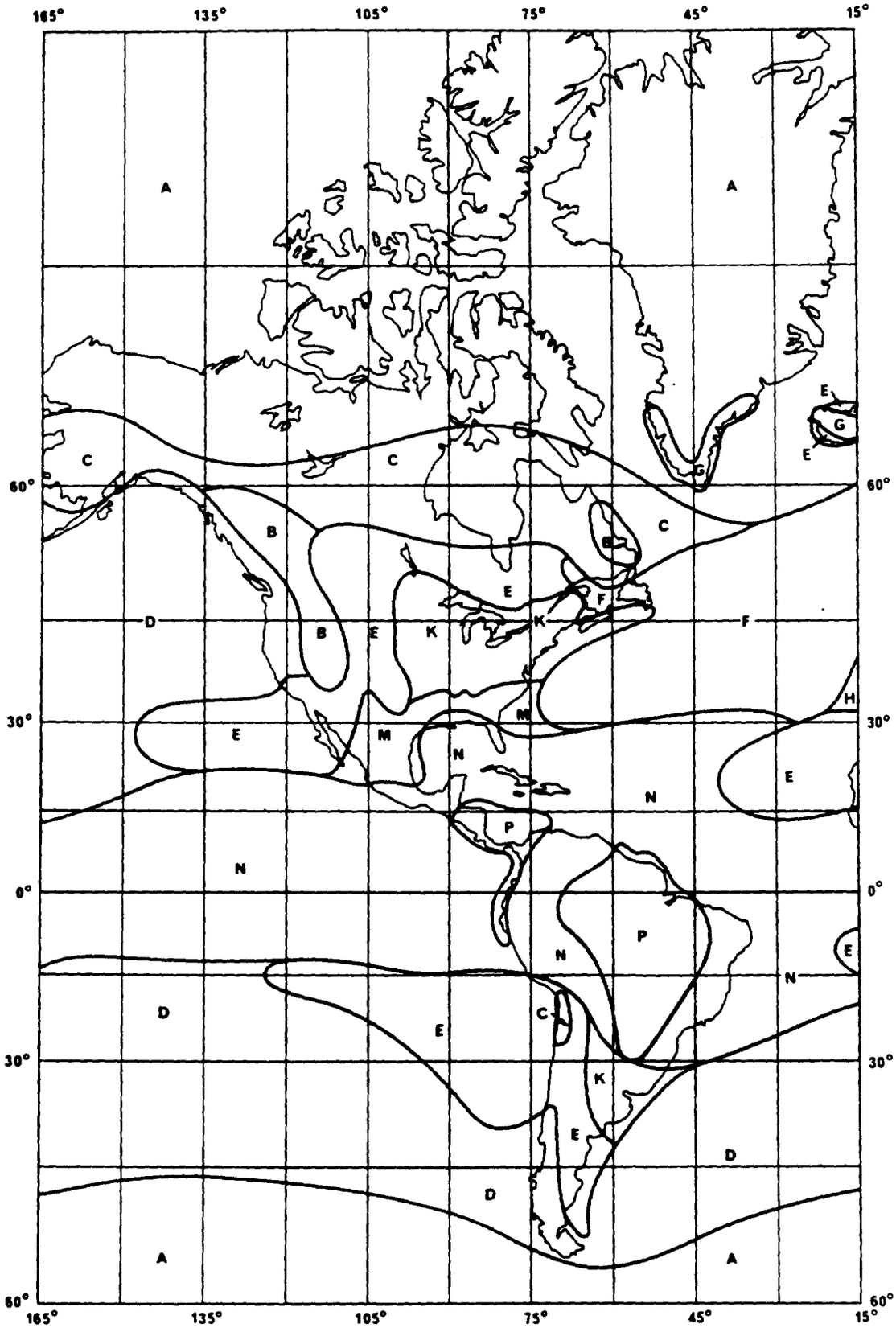


Figure 6.3-7. CCIR Rain Climate Zones for ITU Region 2

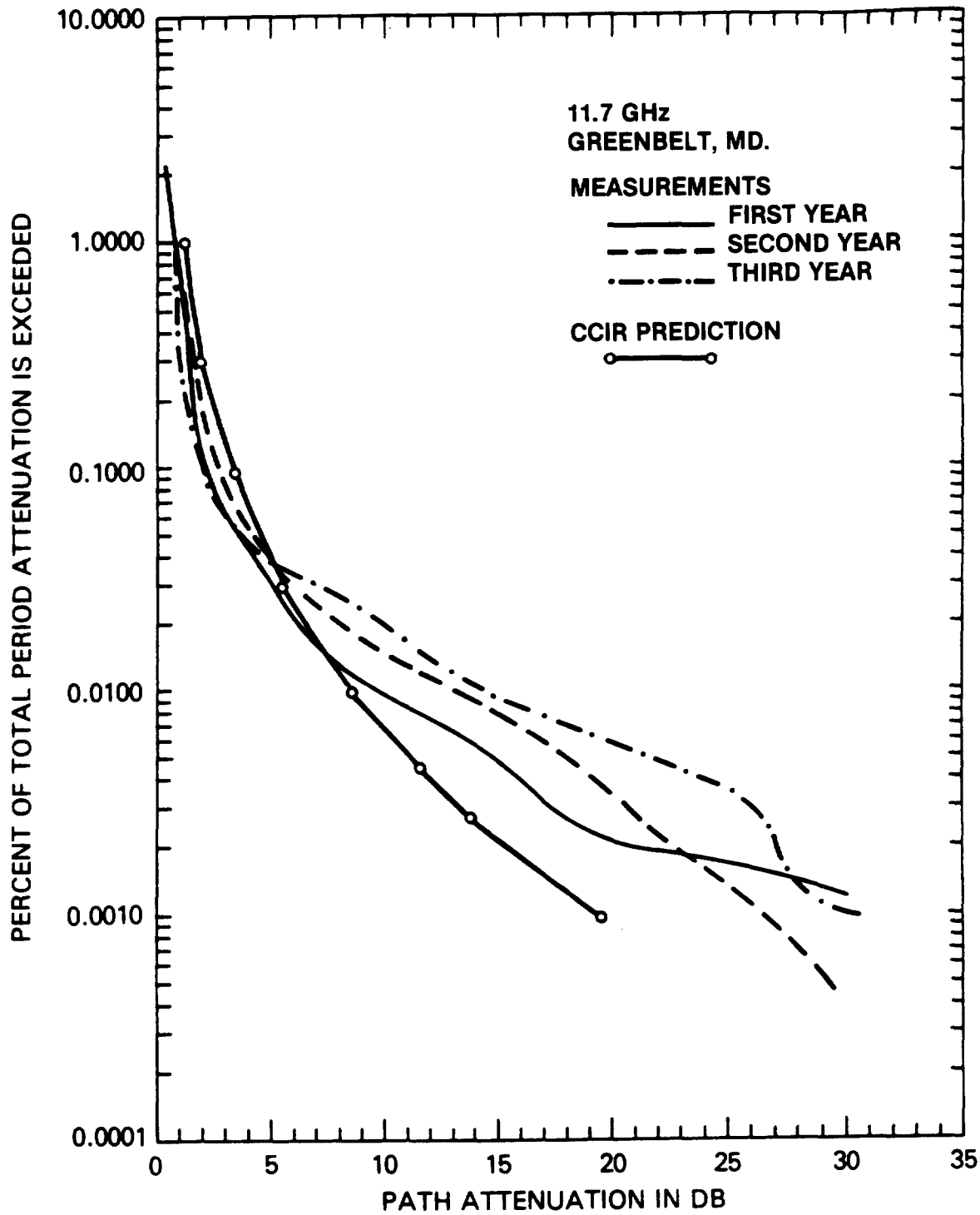


Figure 6.3-8. Comparison of CCIR Prediction with Measured Data, Greenbelt, MD. 11.7 GHz

Table 6.3-3. Regression Coefficients for Estimating Specific Attenuation in Step 4 of Figure 6.3-6

Frequency (GHz)	k_H	k_V	α_H	α_V
1	0.0000387	0.0000352	0.912	0.880
2	0.000154	0.000138	0.963	0.923
4	0.000650	0.000591	1.12	1.07
6	0.00175	0.00155	1.31	1.27
8	0.00454	0.00395	1.33	1.31
10	0.0101	0.00887	1.28	1.26
12	0.0188	0.0168	1.22	1.20
15	0.0367	0.0347	1.15	1.13
20	0.0751	0.0691	1.10	1.07
25	0.124	0.113	1.06	1.03
30	0.187	0.167	1.02	1.00
35	0.263	0.233	0.979	0.963
40	0.350	0.310	0.939	0.929
45	0.442	0.393	0.903	0.897
50	0.536	0.479	0.873	0.868
60	0.707	0.642	0.826	0.824
70	0.851	0.784	0.793	0.793
80	0.975	0.906	0.769	0.769
90	1.06	0.999	0.753	0.754
100	1.12	1.06	0.743	0.744
120	1.18	1.13	0.731	0.732
150	1.31	1.27	0.710	0.711
200	1.45	1.42	0.689	0.690
300	1.36	1.35	0.688	0.689
400	1.32	1.31	0.683	0.684

* Values for k and α at other frequencies can be obtained by interpolation using a logarithmic scale for k and frequency and a linear scale for α

6.3.3 Estimates of Attenuation Given Rain Rate Statistics

6.3.3.1 Discussion and Procedures. If the rainfall statistics can be reconstructed from Weather Service data or actual site measurements exist for a period of at least 10 years near the ground station site, these may be utilized to provide R_p versus percentage exceedance. The temporal resolution required of these measurements is dependent on the smallest percentage resolution required. For example, if 0.001% of a year (5.3 minutes) statistics are desired, it is recommended that the rain rate be resolved to increments of no more than 1-minute to provide sufficient accuracy. This can be done utilizing techniques described in Chapter 2 of this handbook, but 5-minute data is more easily obtained.

The cumulative statistics measured near the ground station site replaces Steps 1 and 2 of Figure 6.3-1. The attenuation statistics are generated using the procedures in Steps 3 through 7 of Figure 6.3-1.

6.3.3.2 Example. Again we take the case of the 20 GHz ATS-6 link to Rosman, NC. We have cumulative rain rate statistics for Rosman for a six-month period as shown in Figure 6.3-9. (Data spanning such a short period should not be used to estimate long-term statistics. The use here is for demonstration purposes only.) We first select values of rain rate R corresponding to several values of percentage exceedance.:

%	R_p
0.01	66
0.02	55
0.05	34
0.10	16.5
0.20	10.5
0.50	4.5
1.0	2.3

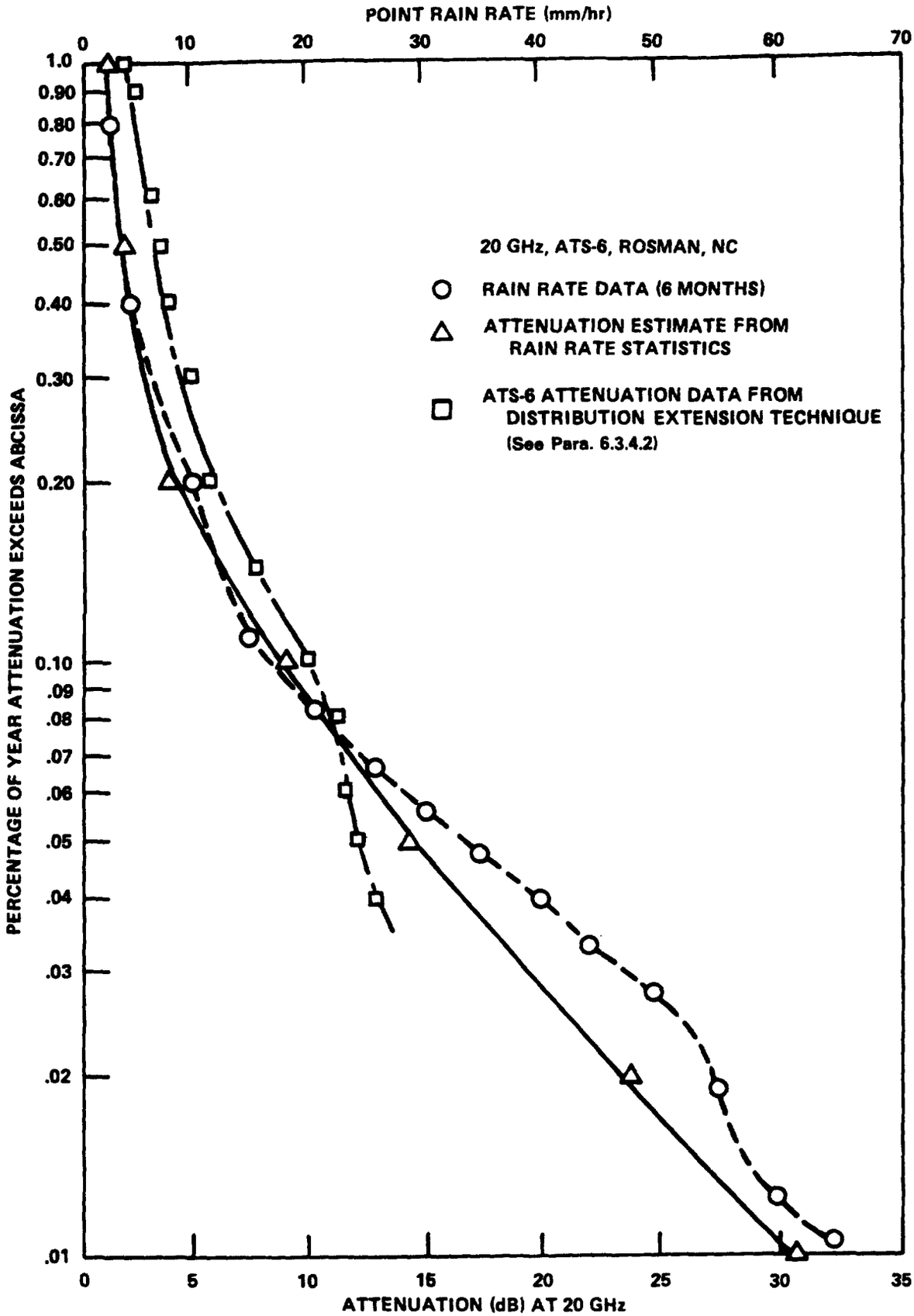


Figure 6.3-9. :tenuation Statistics Estimate Based on Measured Rainfall Statistics

We now proceed exactly as in the Global Model application example (Section 6.3.2.2), using these values of R_p instead of those in Table 6.3-1 or Figure 6.3-3.

The results of these calculations are shown in Figure 6.3-9, along with the measured attenuation statistics. This data is presented to demonstrate the technique. More accurate data, covering a longer period, is presented in Chapter 5.

6.3.4 Attenuation Estimates Given Limited Rain Rate and Attenuation Statistics

6.3.4.1 Discussion and Procedures. The system designer will virtually never find attenuation statistics spanning a number of years for his desired location, operating frequency and elevation angle. But by applying distribution extension and scaling procedures to the limited statistics available, the designer may make useful estimates of the statistics for the situation at hand.

Distribution extension allows one to take concurrent rain rate and attenuation measurements intermittently over a limited period of time, then convert the data into cumulative attenuation statistics covering the entire year. The conversion requires stable cumulative rain rate statistics for the site or a nearby weather station, and measurements taken over a statistically significant fraction of the year. Distribution extension is required in practice because it is often costly to make continuous attenuation measurements over extended periods. Rather, data are taken only during rainy periods.

Scaling is required to account for differences between the frequency and elevation angle applying to the available statistics, and those applying to the actual system under consideration. This scaling is based on empirical formulas which, to the first order approximation, depend only on the frequencies or the elevation angle and apply equally to all attenuation values. To a better approximation, however, the rain rate corresponding to the attenuation and other factors must be considered as well.

Figure 6.3-10 shows a generalized procedure for applying the distribution extension and scaling techniques described in this section.

6.3.4.2 Attenuation Distribution Extension. The technique is illustrated in Figure 6.3-11. The upper two curves represent cumulative rain rate and attenuation statistics derived from measurements taken over some limited period of time. The measurement time may consist for example, of only the rainy periods from April through September. The exceedence curves are plotted as functions of the percentage of the total measurement time. The lower solid curve represents the cumulative rain rate statistics, measured over an extended period at the same location as the attenuation measurements, or derived from multi-year rainfall records from a nearby weather station.

A curve approximating the long-term cumulative attenuation distribution (the bottom curve in Figure 6.3-11) is derived from the three upper curves by the following graphical procedure:

1. Select a percent exceedance value, E_1, and draw a horizontal line at that value intersecting the limited-time rain rate and attenuation distribution curves at points a and b, respectively.

2. At the rain rate value R corresponding to E_1, project a line down to intersect (at point c) the long-term rain rate curve at the exceedance value E_2.

3. At the attenuation value A corresponding to E_1, project a line down to the exceedance value E_2. This (point d) is a point on the long-term attenuation curve.