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Attenuation of Millimeter Waves on Earth-Space Paths by Rain Clouds

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ATTENUATION OF MILLIMETER WAVES
ON EARTH-SPACE PATHS BY RAIN CLOUDS

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A simple model of the attenuation of millimeter waves by precipitating liquid water clouds is presented. As frequency increases from the microwave band into the millimeter wave band, the model indicates a significant increase in the relative importance of the attenuation due to the suspended liquid water of cumulus clouds in comparison with that due to the rain produced by the clouds. For the upper portion of the millimeter wave band, the cumulative distribution of attenuation due to rain is overshadowed by the attenuation due to clouds. The need for an adequate cloud model for the accurate prediction of earth-space millimeter wave link performance is indicated. A short review of measurements of attenuation by clouds is presented for comparison with model predictions.

Key words: attenuation; attenuation distribution; cloud attenuation; clouds; millimeter wave propagation; millimeter waves

1. INTRODUCTION

Many measurements of the cumulative distribution of attenuation on earth-space paths have been made at frequencies below 30 GHz. These measurements have shown that the higher attenuation values exceeded small percentages of the year, say one percent and less, are due to rain on the path. As a result, a number of empirical and theoretical models (Crane, 1980; Dutton, 1977; Dutton et al., 1982; Lin, 1979; Stutzman and Dishman, 1982) have been developed to predict the cumulative distribution of attenuation due to rain. Comparison with the data has shown that many of these models are good predictors.

Because of the current increase of interest in millimeter waves, models are needed that are valid above 30 GHz. It is natural to try to extend these models to millimeter wave frequencies and, indeed, some modelers have provided parameters for frequencies well into the millimeter wave band. However, the extension of existing models to frequencies above 30 GHz, without any treatment of the attenuation due to clouds, needs to be questioned.

Although the attenuation by clouds was found to be unimportant for frequencies below 30 GHz, it is widely accepted that at millimeter wave frequencies

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clouds are capable of siqnificant attenuation. Of course, clouds occur very often in the atmosphere over most of the earth, so that cloud attenuation would be expected much more often than rain attenuation for most locations. Some work has already been done in modeling cloud attenuation (Slobin, 1982), most of which has been concerned with nonprecipitating clouds. It seems implicit in the cloud attenuation studies to date, and in some of the rain attenuation models (Stutzman and Dishman, 1982) that rain attenuation is still expected to dominate the cumulative distribution of attenuation at small percentages of the year even for millimeter wave frequencies. If this were so, then the fade margin requirements for high reliability millimeter wave earth-space links would be determined by the rain attenuation statistics and there would be no need to incorporate cloud attenuation effects into existing models.

The preliminary investigation described in this report was designed to study the contribution of clouds to the attenuation distribution at small percentages of the year. To do this, a simple model of the cumulative distribution of attenuation by precipitating clouds and a method of combining the attenuation distributions due to clouds and rain were developed. The results indicate that, for the upper portion of the millimeter wave band, cloud attenuation dominates at small percentages of the year.

2. BACKGROUND

Although ice clouds have depolarization effects, they are weak attenuators at frequencies below 300 GHz in comparison with liquid water clouds. For this reason, only liquid water clouds will be discussed. Clouds will be classified according to whether or not they produce rain, and according to whether they are of the convective type, e.g. cumulus, or the more stable layer type, stratus.

The attenuation of an electromagnetic wave in a cloud depends on how much water it must travel through. The total integrated liquid water along the path is often given as an equivalent depth. That is, one gram per cubic meter of liquid water content along a one kilometer length becomes one millimeter. The liquid water content, and therefore the attenuation, of rain-producing and cumulus cloud types is greater than that of nonprecipitating and nonconvective cloud types.

Nonprecipitating clouds would occur on earth-space paths a large percentage of the time at many geographic locations. However, they have vertical path integrated liquid water contents typically of less than one millimeter. For example, stratus and high altitude cloud types have integrated water contents on the order of one- to two-tenths of a millimeter. The total integrated liquid water content through fair weather cumulus is about one millimeter and through cumulus congestus is only slightly higher.

Rain clouds would attenuate an earth-space path about the same percentage of time that rain does, and often simultaneously. Therefore, the attenuation by the clouds themselves would only contribute significantly to the attenuation distribution if it approached the levels of attenuation due to the rain they produce. Stratus rain clouds have total vertically integrated liquid water contents of as high as several millimeters. Cumulus rain clouds--i.e. cumulonimbi (thunderstorms)--typically have the largest liquid water content of all clouds, which for a vertical path can integrate to tens of millimeters. For this reason, they are capable of the greatest attenuation, and as will be shown later, they may contribute importantly to the attenuation distribution of millimeter waves on earth-space paths.

Not only are cumulonimbi capable of the greatest liquid water content, they also have the most complex structure of all clouds. They contain one or more updraft regions, which drive the storm during its developing and mature stages. The greatest attenuation by cloud particles would be expected in these updraft regions where the maximum cloud liquid water content occurs as the water condenses out of the rapidly rising and cooling air. However, drier air may be pulled into the updraft from the outside at various heights, lowering the liquid water content and temperature. This is called entrainment and is not understood well enough for accurate prediction of liquid water content at this time. It is generally thought that there may not be enough time for entrainment in very high velocity updrafts. The location of the updraft within the storm is not always the same; e.g., it may occur at the front or the back of the storm (Sinclair, 1982) and may even twist around the the downdraft rain cell.

The prediction of attenuation is further complicated by the climatological dependence of liquid water content and storm structure. Cloud bases are lower in the more humid climate of the southern United States where large amounts of surface water vapor also make greater cloud water content possible. In addition, the freezing level is higher in the storm. Together, these effects may result in a significant geographical variation in path integrated liquid water content. Typical path integrated cloud water in Florida may be four times as great as in Colorado for storms producing similar rain rates. Thunderstorms may occur as isolated single updraft-downdraft systems, they may break up into several systems, or they may occur as a complex aggregate along frontal systems. In the southern United States, where up to 70 percent of the rain comes from thunderstorms, they sometimes occur as isolated systems. In the western United States, only about 5 to 30 percent of the precipitation comes from thunderstorms which usually form along weather fronts, often stretching out in a northeast to southwest direction.

Additional information on clouds may be found in the classic works of Fletcher (1962) and Mason (1971). A recent and complete work is available on thunderstorms (NOAA, 1982).

3. ATTENUATION MODEL

Since the purpose of this model is to determine whether or not attenuation by clouds contribute to the attenuation distribution at small percentages of the year, for which rain dominates at microwave frequencies, and there is insufficient experimental data or theoretical understanding for a rigorous model, a model involving simplifying approximations is used.

The specfic attenuation, α in dB/km, of liquid water cloud droplets (radii smaller than 100 μm) can be estimated using the Rayleigh approximation.

To further simplify the model, it is assumed that the temperature of the liquid water is constant within the cloud. Since the temperature of liquid water droplets in clouds may range roughly from +20 to -20° C and there is some reason to believe that the highest liquid water content occurs around the freezing level, an average droplet temperature could be around 2° C. In Figure 1, it can be seen that the Rayleigh approximation of attenuation for -20° C and +20° C are within about 50 percent of the attenuation at +2° C for millimeter waves. Since the average temperature of the liquid water in the cloud would be nearer to +2° C than -20° C or +20° C, the error introduced by the constant temperature assumption should be much less than 50 percent. The specific attenuation is then given (at 2° C) by the simple expression

$$\alpha = 12.9\, wf^2/(14000 + f^2) \qquad (1)$$

where w is the liquid water content in g/m^3 and f is the frequency in GHz.

The total attenuation in dB through a cloud is given by the integration of the specific attenuation along the path. Because of the constant temperature assumption, (1) gives α as the product of w and a factor dependent only on frequency, so that the integration need only be performed on w, resulting in the total liquid water W along the path. That is, the total attenuation in dB is given by (1) when w is replaced by W in mm.

With equation (1) the cumulative distribution of cloud attenuation can be estimated from the cumulative distribution of the total suspended cloud liquid

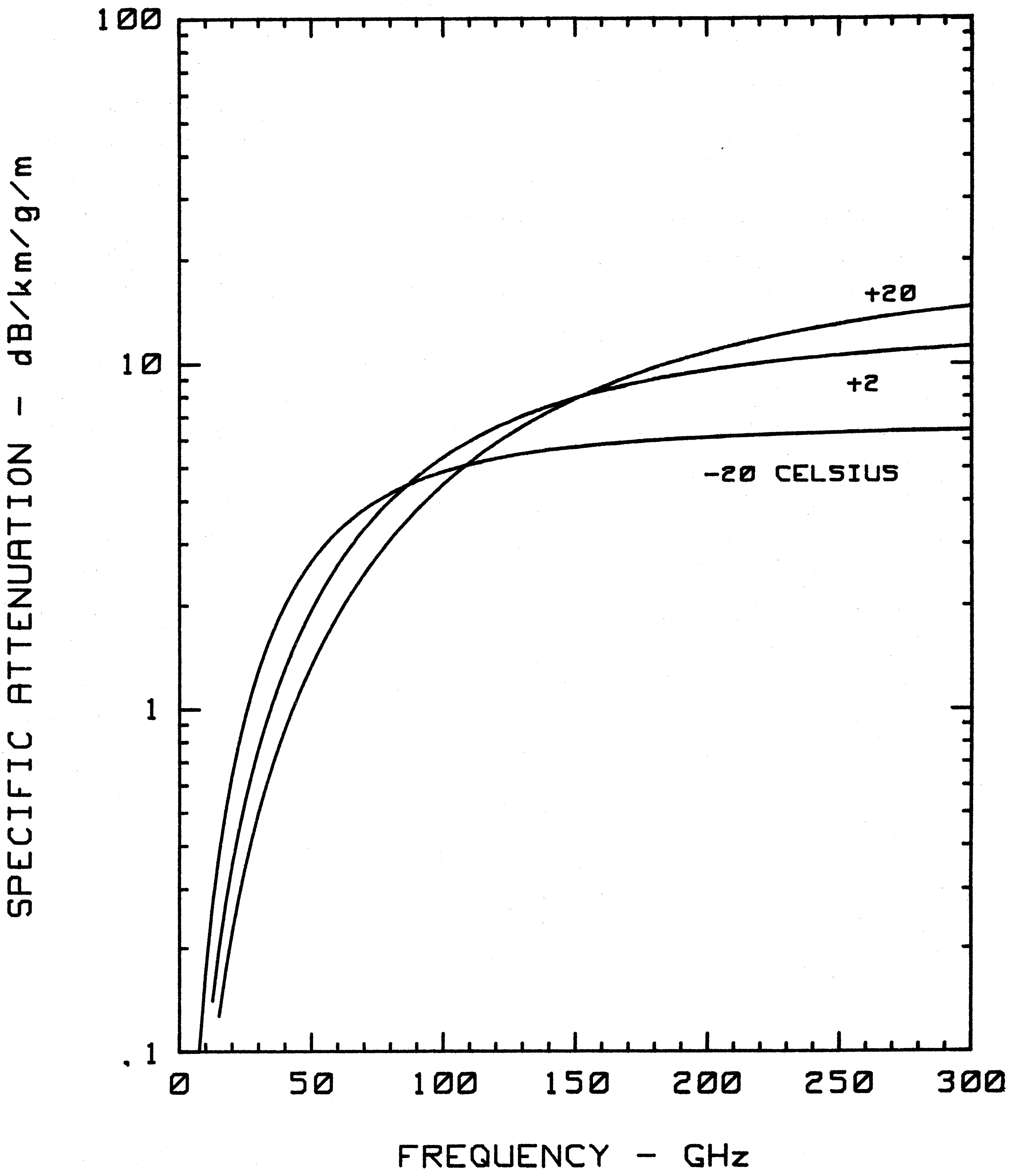

Figure 1. The specific attenuation of 1 g/m^3 cloud water content at 20, 2, and -20 Celsius.

water integrated along the path. However, these statistics are not available and must be estimated. To do this, the plausible assumption is made that high rain rates tend to be associated with large and intense storms, and that there is, therefore, at least a statistical relationship between rain rate and suspended cloud liquid water. Thus, models of typical clouds associated with various rain rates will be used to estimate the amount of cloud liquid water which may on average be associated with certain rain rates. The cumulative distribution of rain rate then gives a cumulative distribution of path integrated liquid water.

A high degree of correlation between cloud liquid water and rain rate is speculative and has not been supported by measurements (R. K. Crane, 1983, private correspondence). However, the distribution for cloud liquid water derived in this manner seems reasonable and needs only to approximate the true distribution.

To estimate the relationship, the Gaut and Reifenstein (1971) cloud models were used as models of typical or average cloud liquid water content for clouds corresponding to various rain rates. The integrated cloud liquid water (radii$<100\mu m$) over a vertical path was computed for two stratus cloud models corresponding to rain rates of 3 and 15 mm/hr and three cumulus cloud models corresponding to rain rates of 2.4, 12, and 150 mm/hr. A curve of the form $W=xR^y$ was then least squares fit to these data. Of course, an exact fit resulted for the two parameter curve fit to the two data points for stratus clouds while the root-mean-square-error for the cumulus data was 9 percent in liquid water content. The resulting approximation for stratus clouds producing a rain rate R in mm/hr is

$$W = 0.66\ R^{0.94} \tag{2}$$

while the approximation for cumulus or cumulonimbus clouds is

$$W = 3.0\ R^{0.54}\ . \tag{3}$$

Combining these equations with equation (1) gives

$$A_s = 8.5\ R^{0.94}\ f^2/(14000+\ f^2) \tag{4}$$

and

$$A_c = 39\ R^{0.54}\ f^2/(14000\ +\ f^2) \tag{5}$$

where A_s and A_c are the total attenuation in dB due to suspended liquid water cloud droplets along a vertical path through stratus and cumulus clouds, respectively.

The attenuation of stratus clouds, which have a limited vertical extent but a large horizontal extent, should display a cosecant dependence on path elevation angle. Dutton (1968) assumed such a dependence to predict the temporal distribution of attenuation (10 GHz) due to clouds from radiosonde data.

Convective clouds have the greatest potential for attenuation and their horizontal structure is very irregular. Since their horizontal extent is roughly the same as their vertical extent, very little elevation angle dependence would be expected. This was found to be so by Lo et al. (1975). Because of the greater possibility of a convective cloud (or more than one) occurring along a path with an extremely low elevation angle, there would be some increase in the temporal occurrence of a given attenuation level with lower elevation angle.

Equation (5) gives much larger values of attenuation than expected or have been measured. This is because nearly all measurements of liquid water content in convective clouds are less than one or two g/m^3. These measurements are a statistically biased sample since measurements within the updraft of violent thunderstorms are rare. Most measurements of cloud attenuation have been made through nonprecipitating clouds. Such clouds would be expected to have lower liquid water content than clouds which have developed fully to the rain producing stage. If large values of attenuation are measured, they are normally attributed to rain contaminating the measurement. On the other hand, the actual geometry may be such that only a short portion of any straight-line path would intersect the updraft. In this case, equation (5) would overestimate attenuation.

Equations (4) and (5) can be used to make a rough correction to attenuation prediction models which do not include cloud attenuation on earth-space paths. If the Rice-Holmberg (1973) model is used for the point rain rate distribution, then the point rain rate distribution of thunderstorm rain can be separated from that of wide spread rain. The attenuation distribution of precipitating stratus clouds can be estimated from the point rain rate distribution of wide spread rain via (4). Then a combined cloud and rain attenuation distribution for stratus systems can be approximated by adding the cloud and rain attenuations exceeded each fixed percentage of time, since stratus cloud attenuation and stratus rain attenuation are simultaneous. Similarly, a precipitating cumulus cloud attenuation distribution can be estimated from the point rain rate distribution of thunderstorm rain via (5). The attenuation distribution due to precipitating convective clouds should be added to the attenuation distribution due to thunderstorm rain. Since the updraft and downdraft (rain) regions are in separate locations, the attenuation due to clouds and rain would be expected to occur at different times (i.e., independently). Therefore, the percentages of time a fixed level of attenuation is exceeded can be added together. Then the total attenuation distribution can be found by recombining the attenuations due to widespread rain systems with that due to thunderstorms (percentage of time added for each exceedence level).

The distribution of liquid water in the updraft of thunderstorms was not studied in the development of this attenuation model. Instead, cloud models giving a single vertical profile of liquid water content for several fixed rain rates were used to relate total integrated liquid water content to rain rate. However, clouds do not produce a constant rain rate in space or time. It has been implicitly assumed in the development of the model that the spatial and temporal distribution of cloud liquid water and rain rate are related in such a way that (3) can be used to estimate the distribution of total integrated liquid water content of cumulus rain clouds from the surface point rain rate distribution of convective rain--i.e., the spatial and temporal distribution of cloud liquid water and rain rate are statistically quite similar.

4. PREDICTIONS AND MEASUREMENTS

In Figure 2, zenith cloud attenuation according to equation (5) is presented for several rain rates. Also presented in Figure 2 for comparison, is the rain attenuation for a zenith path (Washington, D.C.) at the same rain rates according to Crane's model (1980) using parameters tabulated by Olsen et al. (1978) for a Laws and Parsons (low rain rate) raindrop-size distribution at 0° C. It can be seen that for frequencies below 30 GHz the attenuation due to clouds only exceeds that due to rain at low rain rates where only fractions of a dB are involved. At higher rain rates, the attenuation due to clouds is small enough to be masked by the uncertainties in the rain attenuation.

Above 30 GHz, the attenuation due to rain begins to flatten out. However, because of the smaller sizes of cloud particles, the attenuation due to clouds begins to flatten out more slowly. As frequency increases, cloud attenuation increases not only in absolute terms, but also relative to rain attenuation.

Attenuation distributions for precipitating stratus and cumulus rain clouds and for rain were computed using the Rice and Holmberg (1973) rain rate model and the models mentioned above for Washington, D.C. A zenith path was chosen so that point-to-path conversion of the rain rate would not be necessary. The distributions are shown in Figures 3, 4, and 5 for the frequencies of 10, 30, and 90 GHz, respectively. As can be seen in the figures, the attenuation due to the clouds

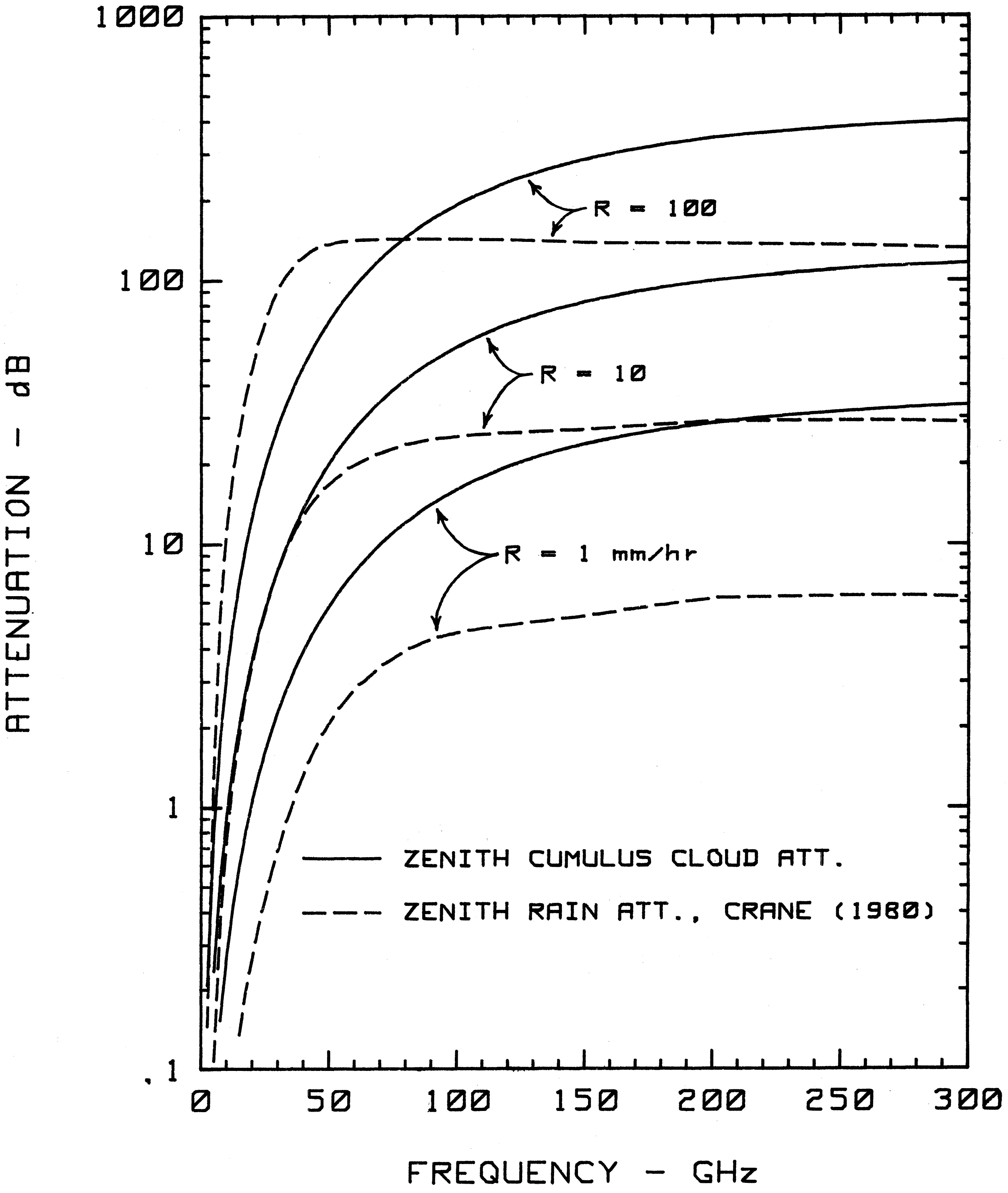

Figure 2. The zenith attenuation of rain and rain producing cumulonimbus clouds for rain rates of 1, 10, and 100 mm/hr.

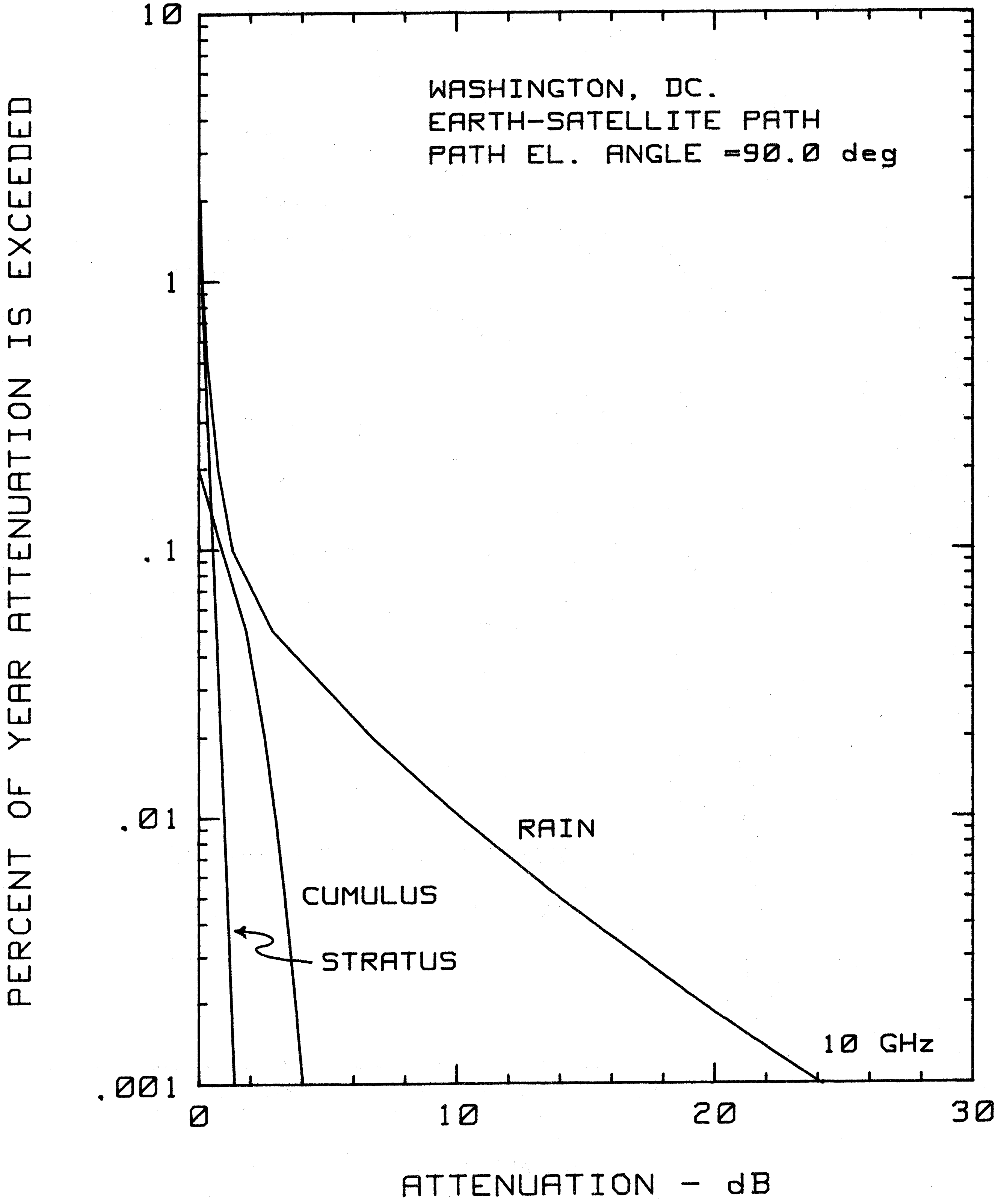

Figure 3. Predicted attenuation distributions for 10 GHz due to rain and precipitating stratus and cumulus clouds for a zenith path at Washington, D. C.

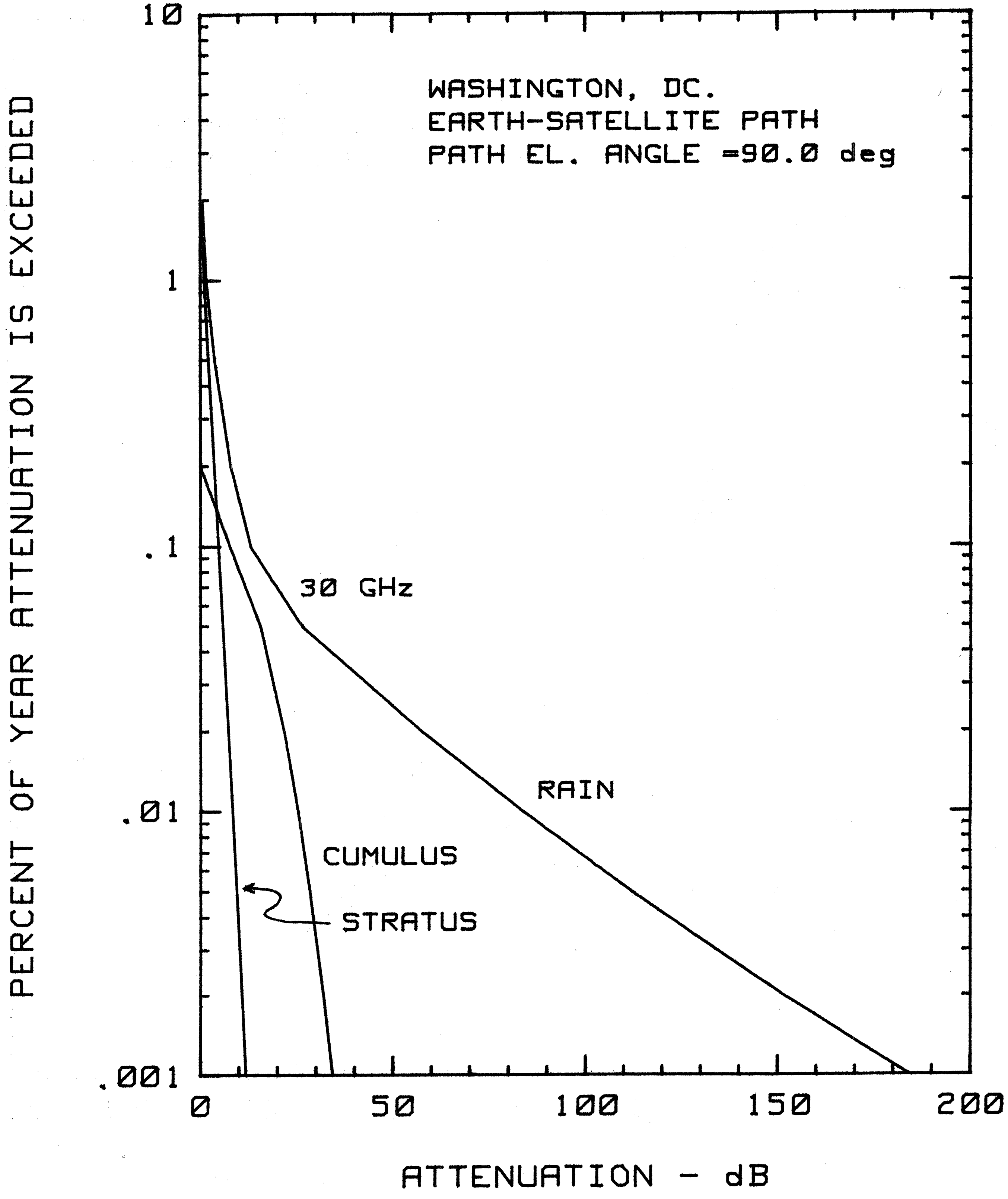

Figure 4. Predicted attenuation distributions for 30 GHz due to rain and precipitating stratus and cumulus clouds for a zenith path at Washington, D. C.

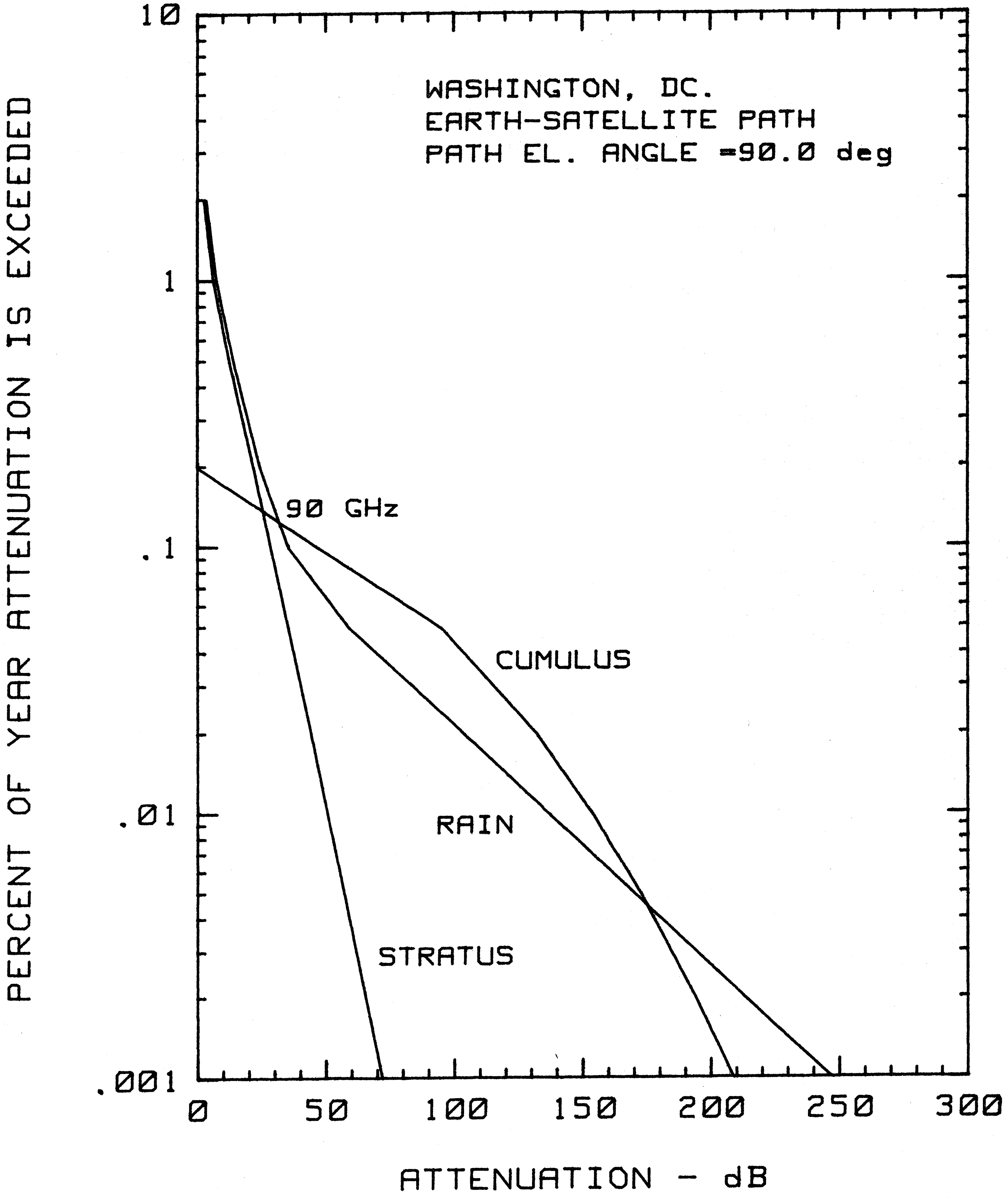

Figure 5. Predicted attenuation distributions for 90 GHz due to rain and precipitating stratus and cumulus clouds for a zenith path at Washington, D. C.

associated with the rain does not appear to be significant at 10 GHz, or even at 30 GHz. However, at 90 GHz the attenuation due to the clouds is comparable to the attenuation due to rain.

Total attenuation distributions based on the combined attenuation of clouds and rain, in addition to the attenuation distributions based solely on rain were computed for Washington, D.C., using the methods mentioned above. A zenith path was again chosen. The ratio of the total attenuation distribution to the distribution based solely on rain was computed. The results are presented in Figure 6 for frequencies up to 300 GHz. It can be seen that below 30 GHz, cloud attenuation only contributes significantly to the attenuation distribution for percentages of the year greater than .1 percent where attenuation levels are a few decibels at most. However, the portion of the total attenuation due to clouds increases with frequency above 30 GHz, especially at the smaller percentages of the year (.01 and .001 percent).

This result depends on the cloud models chosen. There is a wide range in the predicted liquid water content of cumulonimbus clouds and few data are available. Any errors in the estimate of path integrated liquid water content derived from the cloud models used here are probably not large enough to invalidate the conclusion that cloud attenuation must be considered for accurate prediction of earth-space millimeter wave attenuation distributions. However, the frequency at which cloud attenuation must be included remains uncertain. This model indicates that it may be below 100 GHz.

The measurement of cloud attenuation by rain producing clouds is extremely difficult because the rain within the cloud contaminates the measurements. A few measurements of attenuation by nonprecipitating clouds are available in the literature. Haroules and Brown (1969) described atmospheric attenuation measurements made simultaneously at 8, 15, 19, and 35 GHz. The average attenuation through cumulus clouds was 0.5 dB at 35 GHz. Wixon (1971) has reported on measurements made at 90 and 16 GHz of cloud, fog, and rain attenuation using a sun tracker. The maximum attenuation without rain of 7.2 dB at 90 GHz occurred during a heavy overcast between rains. The ratio of cloud attenuation at 90 and 16 GHz was usually in the range of 23 to 27. Lo et al. (1975) have reported on six months of cloud attenuation data at 35 and 95 GHz observed in Texas. They report maximum cloud attenuations of 2.3 dB at 35 GHz and 10 dB at 95 GHz. Their data indicated that there was little path elevation angle dependence of attenuation down to an elevation angle of 16 degrees. Sokolov et al. (1974) reported that nonprecipitating cloud attenuation of millimeter and submillimeter waves was large

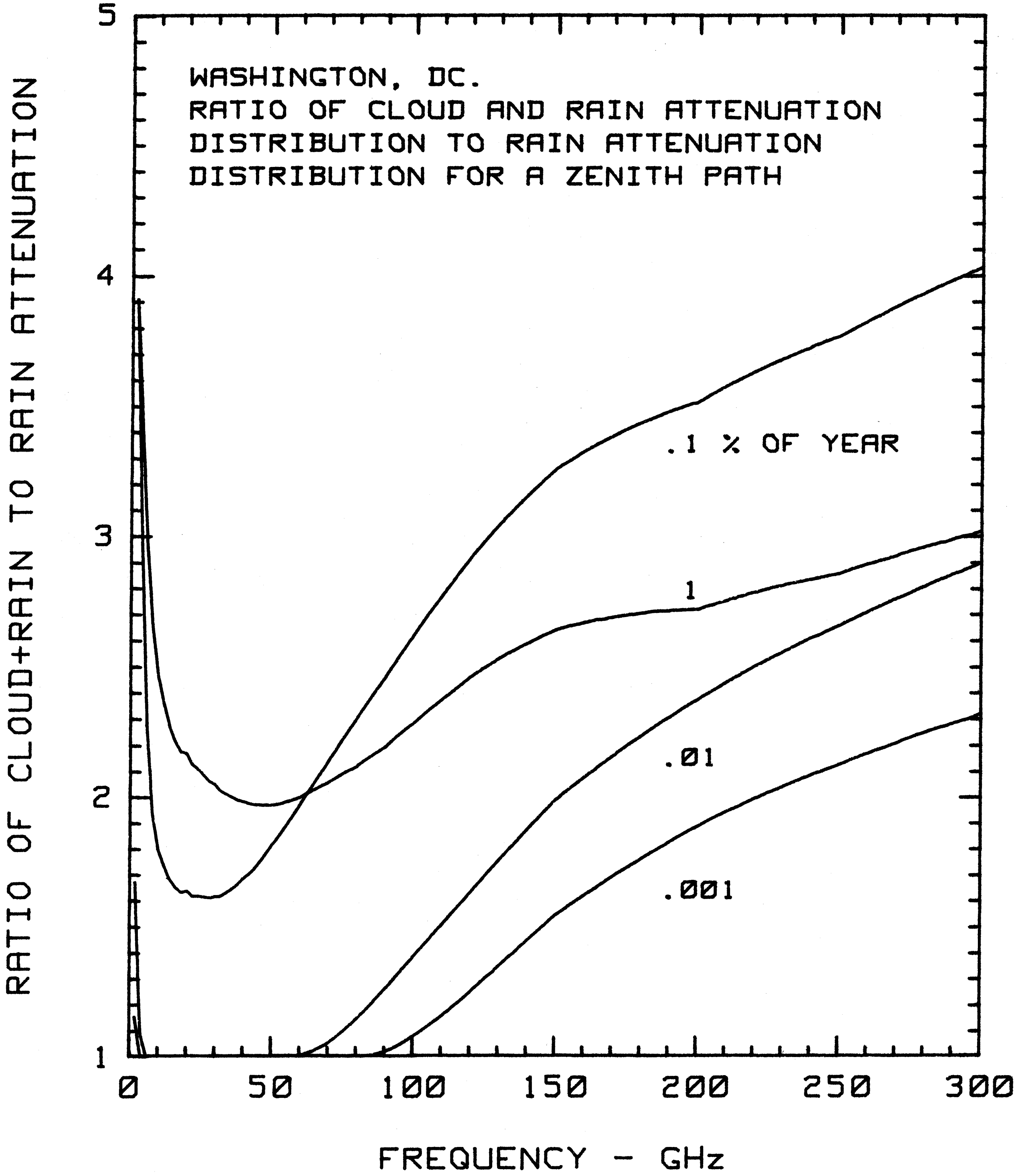

Figure 6 The ratios of the predicted attenuation distribution due to rain and rain producing clouds to the predicted attenuation distribution due to just rain at 1, .1, .01, and .001 percent of the year for a zenith path in Washington, D. C.

only in cumulus and cumulus congestus clouds where it varied from 10 to 50 dB. These same data with additional measurements were reported in more detail by Zabolotniy et al. (1978). They give mean values of zenith attenuation for nonprecipitating cumulus congestus clouds measured in the summer of 19 and 9 dB for 240 and 150 GHz, respectively. Snider and Hogg (1981) and Snider et al. (1980) reported on radiometric measurements of cloud liquid at path elevation angles near 30 and 40 degrees. The attenuation rarely exceeded 2 dB in nonprecipitating clouds at 28.56 GHz, and the greatest attenuation measured was 5.5 dB during the passage of a cumulonimbus. The measured integrated liquid water reached a maximum of 4.8 mm. Total liquid water greater than 6 mm was nearly always associated with heavy rainfall.

Data from the above reports are summarized in Table 1. Some of the measurements are also presented in Figure 7 for comparison with the model. Three curves from the model are presented in Figure 7. They are the cloud attenuation predicted for path integrated total liquid water of 1 mm, and the cloud attenuation predicted for vertical paths through a stratus cloud and through a cumulus cloud, both producing rain rates of 1 mm/hr. As can be seen, the measurements of attenuation by nonprecipitating clouds agrees reasonably well with the attenuation predicted for these low rain rate clouds.

5. SUMMARY

The preliminary work reported here indicates that millimeter wave attenuation by precipitating clouds is large enough to contribute to the attenuation distribution at percentages of the year where rain attenuation would be expected to dominate based on experience at microwave frequencies. This is the result of attenuation by clouds increasing relative to attenuation by rain as frequency increases. For convective, precipitating clouds, the expected attenuation by the suspended liquid water of the cloud may exceed the attenuation due to the associated rain for the upper portion of the millimeter wave band. Models predicting attenuation distributions for earth-space paths at frequencies above 30 GHz should include cloud attenuation. Cloud attenuation, because of the spatial distribution of clouds around rain cells, is even more important in models for path diversity applications (Evans, 1971).

The model presented, while suitable to indicate that cloud attenuation should be modeled in order to predict millimeter wave attenuation distributions for earth-space paths, is not adequate in itself. The model of liquid water content does not have any geographic dependence, although the average integrated liquid

TABLE 1

Summary of Cloud Attenuation Measurements

Author	Cloud Description	Frequency GHz	Typical or Mean Attenuation, dB	Maximum Observed Attenuation, dB	Symbol in Figure 4
Haroules and Brown (1969)	Cumulus	19	.5	---	○
		35	.5	---	○
Wixon (1971)	Cumulus	90	2.1	3.7	
	overcast, no rain	90	---	1.6	
	Heavy overcast between periods of rain	90	5.2	7.2	●
Lai-Iun Lo et al. (1975)	---	35	---	2.3	■
		92/95	---	10.0	■
	Strato cumulus	35	.18	---	
		95	.61	---	
	Cumulus	35	.12	---	□
		95	.34	---	□
Zabolotniy et al. (1978)	Ac	150	.16	---	
		240	.36	---	
	Cu	150	---	---	
		240	1.6	---	
	Cu cong	150	9.0	---	△
		240	19.0	---	△
Snider et al. (1980)	Cumulonimbus	28.56	---	5.5	▲
	---	28.56	---	rarely exceeded 2	

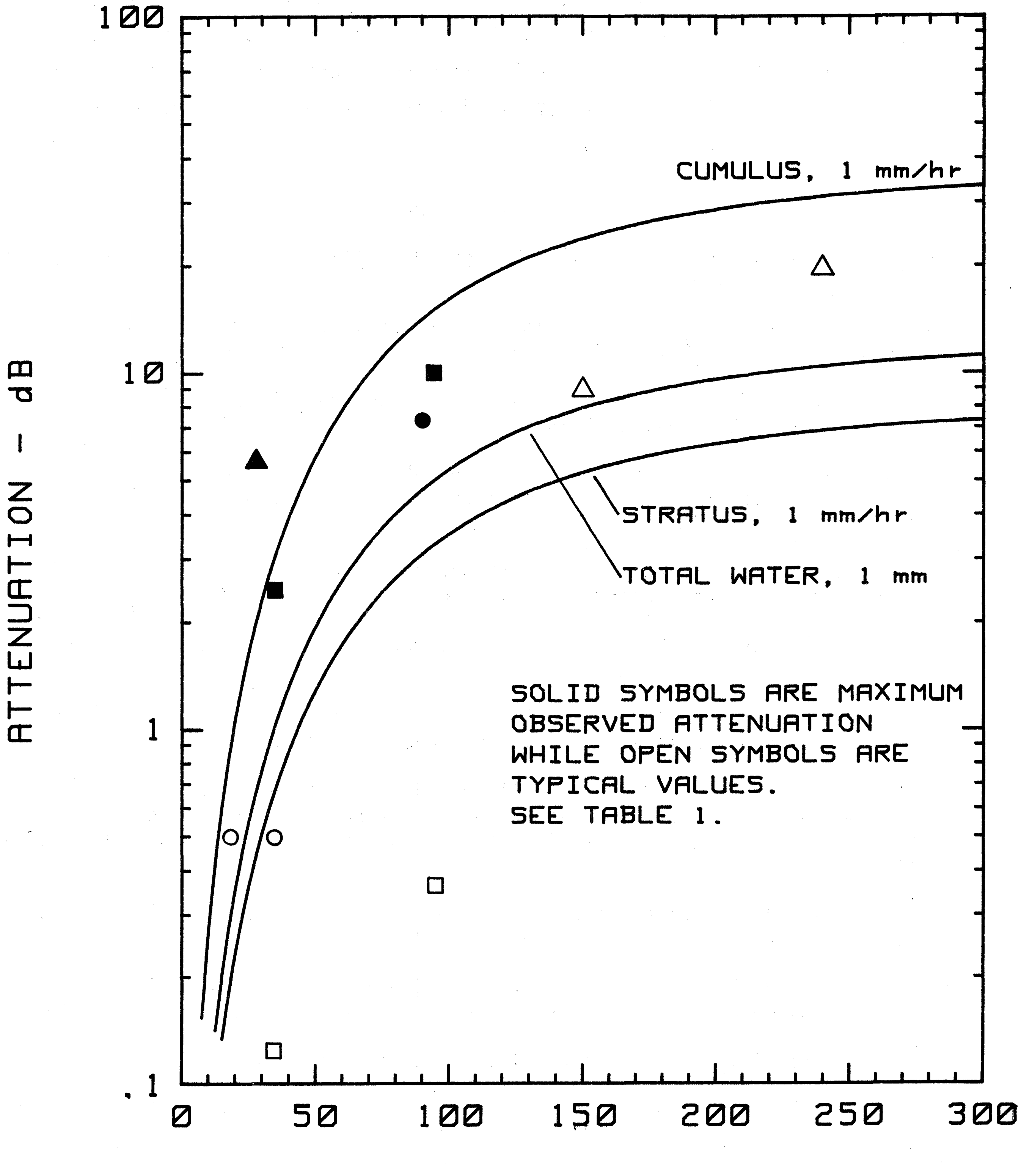

Figure 7. Measured attenuation through nonprecipitating clouds and predicted zenith attenuation for 1 mm total path integrated liquid water content and for stratus and cumulus clouds producing a 1 mm/hr rain rate.

water content of cumulonimbus clouds producing the same rain rate is expected to vary by as much as a factor of four within the United States. There remain large uncertainties in the amount of cloud liquid water content and its spacial distribution. A more detailed analysis of cloud structure and climate dependence is necessary for accurate prediction.

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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.)*

A simple model of the attenuation of millimeter waves by precipitating liquid water clouds is presented. As frequency increases from the microwave band into the millimeter wave band, the model indicates a significant increase in the relative importance of the attenuation due to the suspended liquid water of cumulus clouds in comparison with that due to the rain produced by the clouds. For the upper portion of millimeter wave band, the cumulative distribution of attenuation due to rain is overshadowed by the attenuation due to clouds. The need for an adequate cloud model for the accurate prediction of earth-space millimeter wave link performance is indicated. A short review of measurements of attenuation by clouds is presented for comparison with model predictions.

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

attenuation; attenuation distribution; cloud attenuation; clouds; millimeter wave propagation; millimeter waves

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