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3G10 Tactical Technology

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March 1974

# Atmospheric Effects on Terrestrial Millimeter-Wave Communications

S. J. Dudzinsky, Jr.

A Report prepared for

DEFENSE ADVANCED RESEARCH PROJECTS AGENCY

Rand
SANTA MONICA, CA. 90406

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## PREFACE

This report, prepared as a contribution to the Defense Advanced Research Projects Agency's study on Millimeter Wave Technology, combines the most current information on the transmission properties of millimeter waves with currently available meteorological data to derive a methodology that may be used by the design engineer in estimating the performance of millimeter-wave systems in the atmosphere and in the presence of rainfall. An understanding of atmospheric transmission losses, especially losses due to rainfall attenuation, is required to properly design reliable millimeter-wave communication links and other millimeter-wave systems that rely on propagation through the atmosphere. The emphasis here is on high-reliability communications in which outages are 0.1 percent (530 min of outage per year) or less, but the methodology described applies to higher outage systems as well.

## SUMMARY

The advantages, as well as the disadvantages, of millimeter waves for communications through the atmosphere have been well known for some time. The inherent capability for providing extremely wide system bandwidths, the ability of antennas of modest size to produce sharply collimated beams, and the fact that other system components may be small at millimeter wavelengths are important advantages indeed. These advantages make millimeter waves very attractive for many applications, particularly when the problem of crowding in the lower portions of the spectrum is considered. These advantages are reduced only by the disadvantages of substantial atmospheric attenuation (compared with longer wavelengths) and by the severe attenuation of millimeter-wave transmissions caused by heavy rainfall on a radio path. Consequently, the attenuation of millimeter-wave transmissions through the atmosphere, particularly in the presence of rainfall, is a matter of prime concern.

The present report assembles in convenient form the most current information on the transmission properties of millimeter waves as well as currently available meteorological data. This information is then combined to provide the design engineer with a methodology for quantitatively estimating the performance of millimeter-wave systems in the atmosphere and in the presence of rainfall. This report describes how to use the available propagation and rainfall data for a given climatic region to derive curves such as those given in Figs. 11a-c, which give rainfall attenuation versus path length for various frequencies. Each of these figures corresponds to a given probability of occurrence. For a particular climatic region, a set of such curves for different probabilities of occurrence completely describes the margins necessary for operation during rain. In conjunction with a set of universal curves of attenuation versus path length in a clear atmosphere (such as those given in Fig. 12 for sea level), they provide all the information the system designer needs, not only to estimate the performance of millimeter-wave systems in the atmosphere and

in the presence of rainfall, but also to design around the propagation problems which such systems inevitably encounter.

To demonstrate the use of the methodology developed here, an example using a set of assumed system characteristics is given which shows how to determine the absolute transmitter power required to achieve a given reliability on various path lengths in a climate such as that in the Washington, D.C. area, and also how to determine the system performance given a specified amount of transmitter power.

## ACKNOWLEDGMENTS

The critical review of the original draft and the helpful suggestions by N. E. Feldman of The Rand Corporation and E. C. Park of R & D Associates are gratefully acknowledged.

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# I. INTRODUCTION

Millimeter waves include that part of the electromagnetic-wave spectrum between 10 millimeters (frequency = 30 GHz) and 1 millimeter (frequency = 300 GHz), but the term is sometimes used loosely to also include the region between 10 and 30 GHz. As power sources with adequate output for a variety of applications have become available, these wavelengths have begun to attract attention for use in communications and other applications.

At these shorter wavelengths, it is possible (and in some cases necessary) to reduce the size of most system components. For example, high-gain, narrow-beam antennas are of modest size at millimeter wavelengths and hence are more practical at these frequencies than at lower frequencies. On the other hand, most transmission losses increase with increasing frequency and this can create problems, especially when millimeter waves are to be propagated through the earth's atmosphere.[1]

In a clear atmosphere, the atmospheric propagation loss and noise are relatively small for frequencies below about 10 GHz but increase rapidly for higher frequencies primarily because of attenuation by water vapor and oxygen. Although these effects are significant, the attenuation through a typical atmosphere does not rule out the use of the spectrum above 10 GHz for terrestrial (line-of-sight) communications or other terrestrial applications.

Of more significance is attenuation by precipitation, primarily rain,* as a restriction on the use of these higher frequencies in the atmosphere. Attenuation by rain is a complex process involving both absorption and scattering, and at frequencies above 10 GHz, heavy rainfall on a radio path causes severe fading of received signals. In

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*For frequencies below about 100 GHz, attenuation caused by snow, hail, and fog can generally be expected to be significantly less than rainfall attenuation for most regions of the earth. Under this circumstance, design considerations for fading margins required for precipitation attenuation can be based on rainfall statistics alone.[2]

spite of the complexity of the process, the attenuation caused by rain can be calculated for a specified density and size distribution of drops, and the principal practical problem in radio path design at frequencies above 10 GHz is to determine the expected spatial distribution of rain and its statistics for any locality in order to design a system with sufficient margin and/or other characteristics to give the desired performance.

If millimeter waves are considered for terrestrial communications and other terrestrial applications, the challenge is to design around the problems in such a way as to produce a new communications system (or other type of system) which provides either a new service or performs an old task with reduced cost. In spite of the problems caused by atmospheric and precipitation attenuation at frequencies above 10 GHz, the spectrum up to 40 GHz has been allocated on an international basis since 1959, and during the summer of 1971, the World Administrative Radio Conference on Space Telecommunications met in Geneva and allocated the spectrum from 40 GHz all the way up to 275 GHz.*(3)

The purpose of this report is to discuss the propagation factors affecting the performance of terrestrial millimeter-wave communications links operating through the atmosphere, and to develop a methodology, based on propagation and meteorological data in the literature, which can be used to estimate the performance of such communications links.

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*Of the 12 services allocated portions of the spectrum from 30 to 300 GHz, half are communications services; a little over half the band (52.6 percent or 142 GHz) has been allocated to communications, almost all of it to satellite systems. 32.5 percent or 88 GHz remains unallocated.

## II. PROPAGATION FACTORS

### ATTENUATION BY RAIN

In attenuation by rain, power loss occurs both by absorption and by scattering, with the relative importance of these two factors dependent on the size of the raindrops compared to the carrier wavelength. Calculations of attenuation by rain using the Mie[4] theory of single scattering and the drop-size distribution determined by Laws and Parsons[5] have been carried out by several authors.[6-11] Medhurst[10] made such calculations for frequencies in the range of 2 to 100 GHz, and Setzer[11] later extended these calculations to include frequencies up to 300 GHz.

The values of attenuation by rain calculated by Setzer for frequencies between 3 and 300 GHz and for rainfall rates of 2.5 to 150 mm per hour are shown in Figs. 1 and 2. Figure 1 is a three-cycle logarithmic plot of attenuation in dB/km which emphasizes the rapid increase with frequency in the attenuation caused by rain for frequencies up to about 100 GHz; Fig. 2 is a linear plot of attenuation in dB/km which shows that the attenuation due to rain levels off around 100 GHz and even tapers off slightly with increasing frequency. This latter circumstance is a fortunate one for those contemplating the use of frequencies above 100 GHz for transmission through the atmosphere.

Several investigators have also made experimental measurements of the attenuation due to rainfall in the range from 8 GHz (37.5 mm) to 70 GHz (4.3 mm), and other measurements are now under way to extend the experimental results up to 300 GHz (1 mm).[1] Although the theoretical predictions of rainfall attenuation are in qualitative agreement with the measurements, the quantitative agreement is not always satisfactory. Unfortunately, there is also disagreement among the average measured values of attenuation presented in the literature by various authors. This should not be too surprising in view of the difficulties involved in measuring the meteorological parameters in the experiments. The lack of good quantitative agreement between theory and experiment is even less surprising because of the difficulty

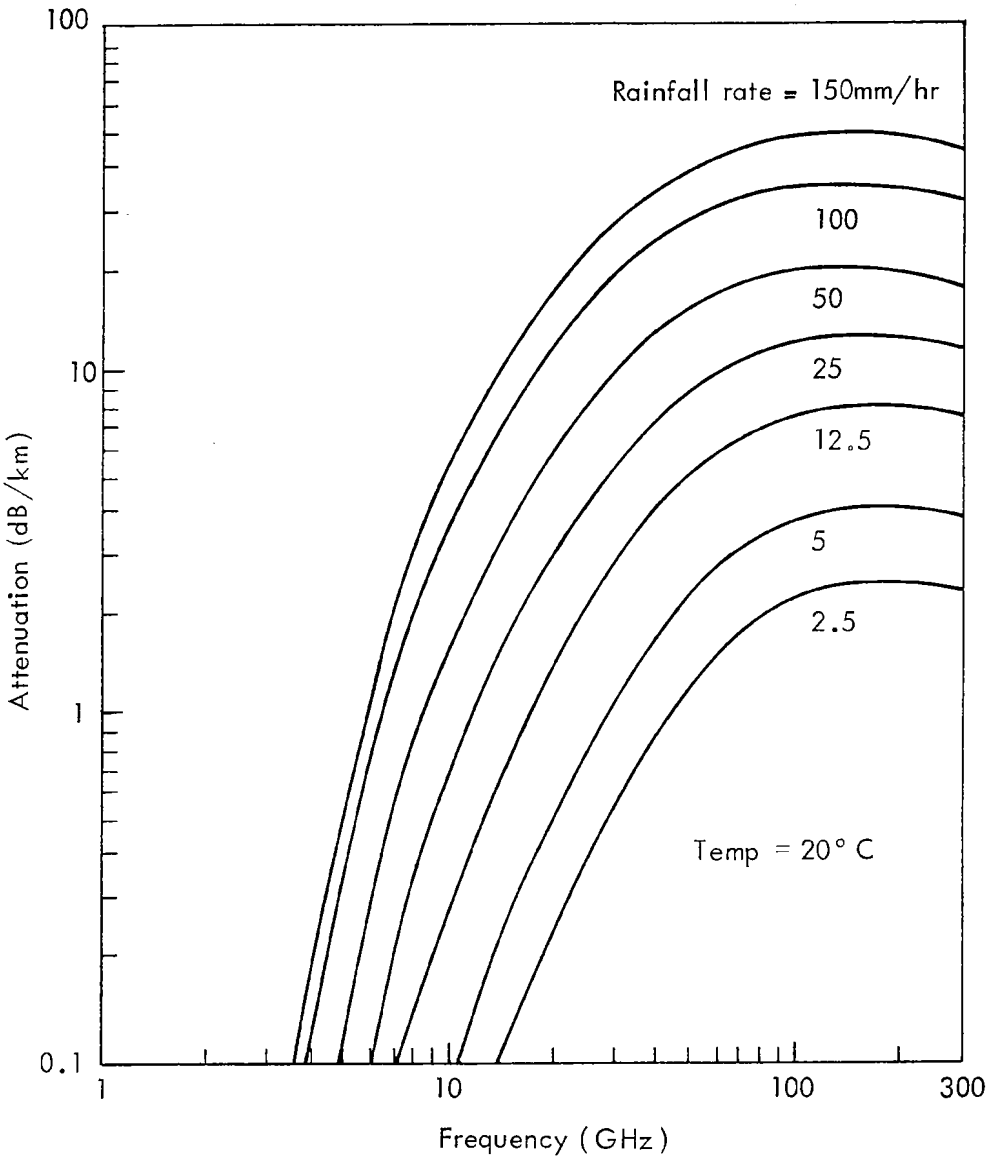


Fig.1 — Logarithmic plot of calculated values of attenuation by rain in dB/km

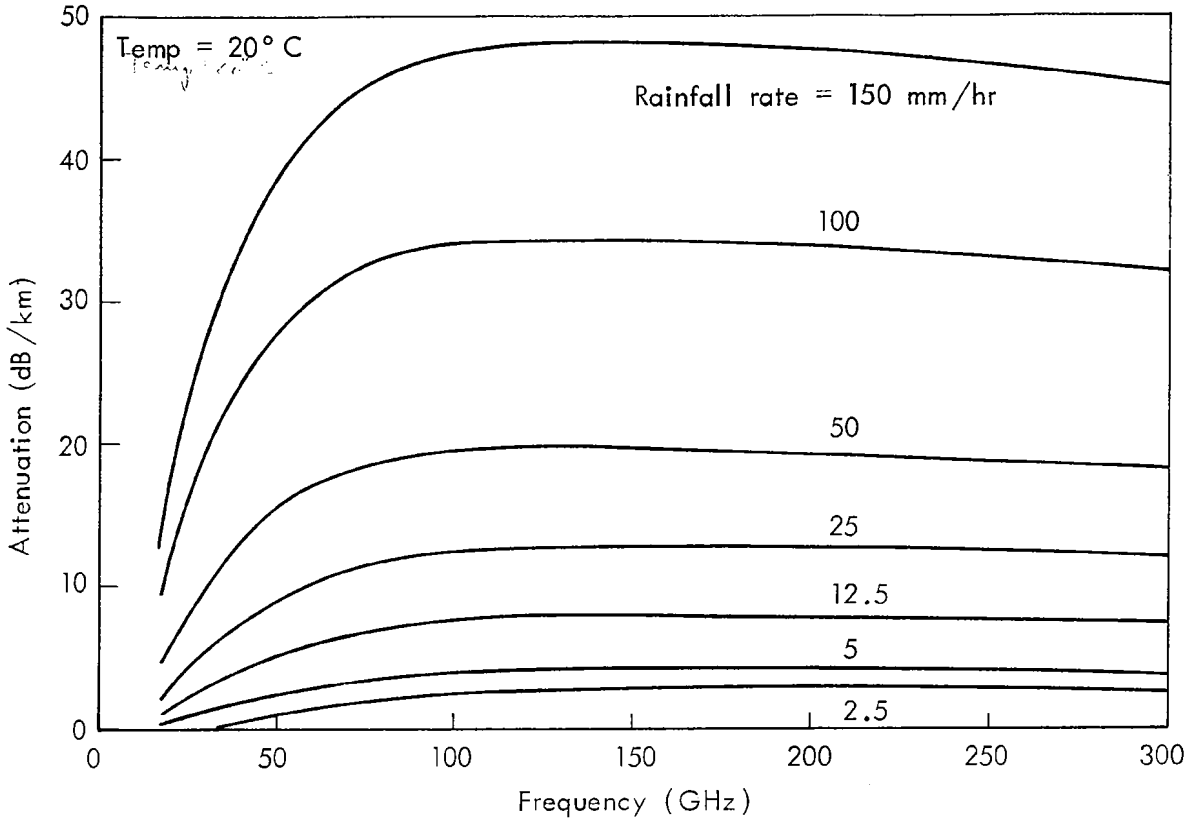


Fig.2 — Linear plot of calculated values of attenuation by rain in dB/km

in applying the theory, which contains many simplifying assumptions to the practical case. For example, the theory assumes uniform rain, whereas in reality the rain on a transmission path is seldom uniform.

In his 1965 paper, Medhurst[10] collected most of the published experimental measurements on microwave attenuation by rain throughout the world and summarized them in a graph showing the upper and lower limits and the mean of rainfall attenuation as a function of frequency. This graph is reproduced in Fig. 3. The "mean" curve in Fig. 3 reflects heavy weighting of the data by Medhurst to account for the considerable faith he had in the results of Anderson, et al.[12]

Also shown in Fig. 3 is a curve of the attenuation measured during a rainfall rate of 100 mm/hr (averaged over a 1-km path). The

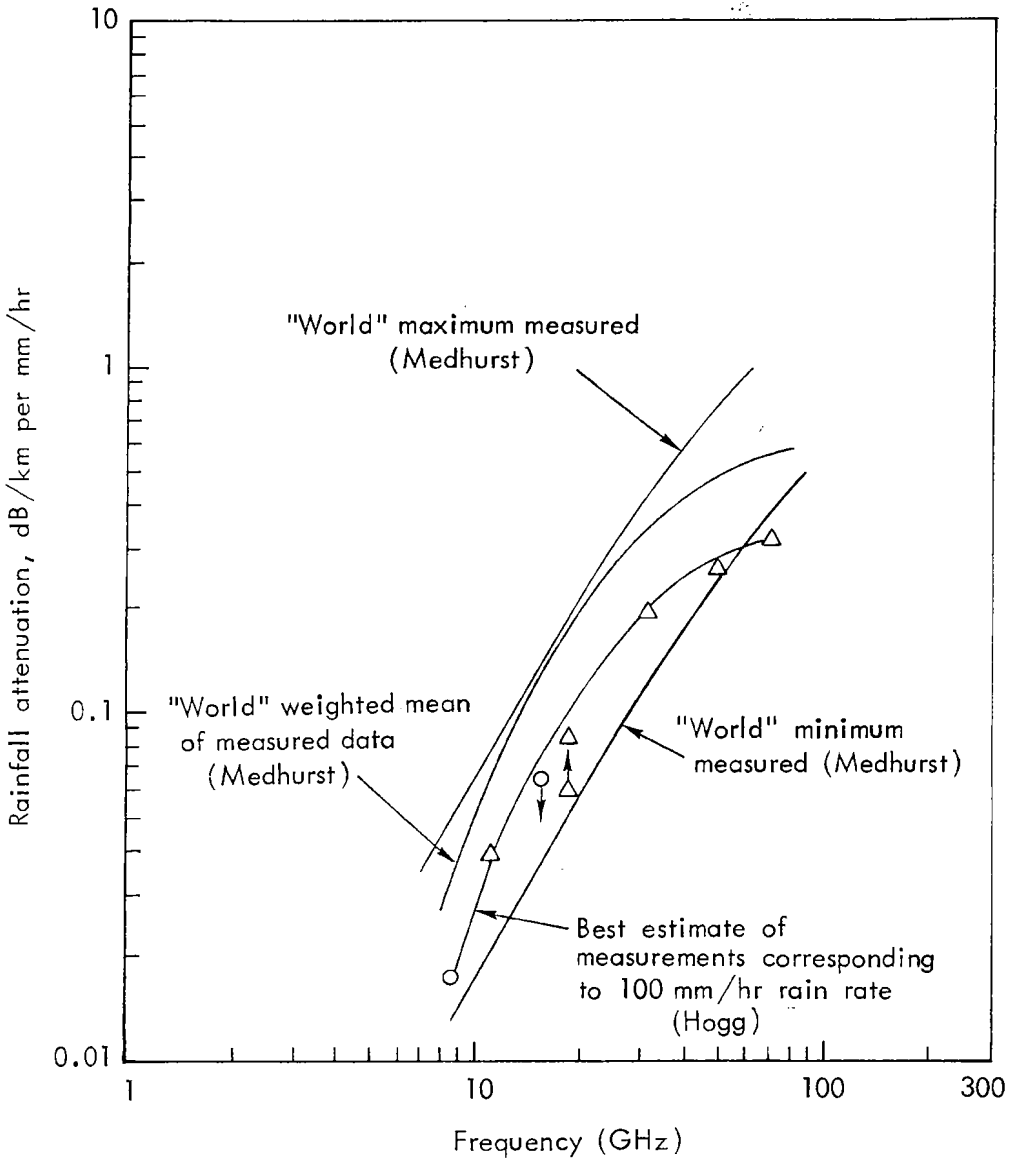


Fig. 3 — Upper and lower limits and mean of rainfall attenuation (Medhurst) and attenuation measured during rain rate of 100 mm/hr (averaged over a 1 km-path) (Hogg)

measurements used to plot this curve, which was taken from Hogg,[13] were made at 8, 11, 15, 18, 30, 50, and 70 GHz, and they are believed to represent the best experimental data currently available. The curve of Hogg lies well below that of the "world" weighted mean plotted by Medhurst over the same band. This discrepancy is at least partly due to the distortion of Medhurst's curve caused by his heavy weighting of Anderson's results, and it is now believed that the values given by the "world" weighted mean curve of Medhurst are too high and that for all practical purposes the best values of attenuation coefficients, even for rainfall rates much less than 100 mm/hr, are obtained from Hogg's curve by taking the attenuations to be directly proportional to the path-average rainfall rates.*

This is, of course, an approximation since the drop-size distribution, and thus the attenuation, are functions of rainfall rate as well as of rainfall types; there is clearly a need for more and better measurements and better interpretation of the experimental results in the region between 8 and 70 GHz as well as at higher frequencies. (The two questions that most need to be answered concerning this approximation are whether Hogg's data, which correspond to 100 mm/hr of rainfall, accurately represent significantly different rainfall rates, and whether the variation from that average is so great that one must have separate curves for each climatological area.) Nevertheless, until there are more and better data and better interpretation of the experimental results, this is felt to be the best approximation available and it is used in developing the methodology and the quantitative results presented in this report.

## ATTENUATION BY SNOW AND HAIL

The dielectric constant of ice is much smaller than that of water, and therefore the scattering cross sections of snowflakes, ice needles, and hailstones are considerably smaller than those of liquid water drops of comparable physical cross section. At the same time, an ice

*Private communication from D. C. Hogg, Bell Telephone Laboratories.

particle absorbs much less power than a comparable raindrop. Thus, for equivalent rates of precipitation, measured as melted ice equivalent in mm/hr, the attenuation due to snow and hail is expected to be much less than that produced by an equivalent rainfall.

Although there is a dearth of research and publications in this area, the results available[2,14-16] do indicate that the above is true for wavelengths in the centimeter region of the spectrum and probably also for the lower portion of the millimeter-wave region. It appears that it is only at shorter wavelengths in the millimeter-wave region that the attenuation by snow and hail might be expected to be comparable to that produced by rainfall of equivalent precipitation rate. Thus, at least for frequencies below about 100 GHz, the attenuation caused by snow and hail can generally be expected to be significantly less than the rainfall attenuation for most regions of the earth.

## ATTENUATION BY FOG

Fog (very small, condensed water droplets suspended in the air) is, of course, expected to introduce noticeable path losses at millimeter wavelengths because drop sizes are of the order of the wavelengths. However, since typical fogs and stratus clouds have water contents on the order of 0.25 $g/m^3$ or less,[17] signal attenuation due to fog encountered in practice is usually modest compared with the attenuation rates for rain.

On rare occasions, the liquid water content can become as high as 0.5 to 1.0 $g/m^3$ in very dense radiation (or inland) fogs.[17] Such fogs can be expected to produce attenuation rates comparable to those caused by rain with an intensity of about 2.5 to 5 mm/hr in the frequency range below 100 GHz. This is shown in Fig. 4 in which the solid curves show rain attenuation as calculated by Setzer[11] and the dashed curves show the attenuation due to fog calculated using Rayleigh scattering theory.[17] From this, the path losses produced by rain with an intensity of perhaps 10 mm/hr should equal, if not exceed, the path losses ordinarily encountered with other forms of precipitation in the presence of fog.

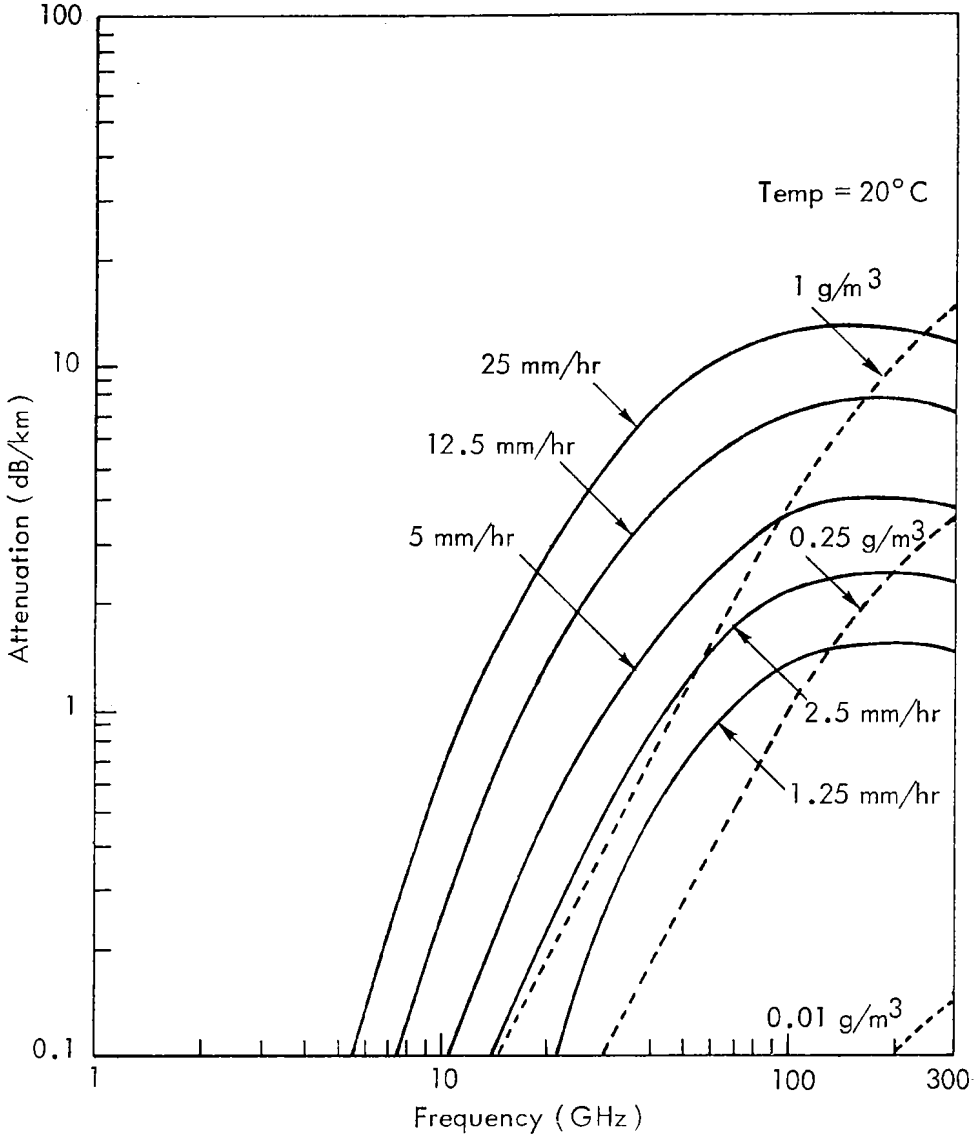


Fig. 4 — Comparison of theoretical values of attenuation by rain and fog.

## ATTENUATION BY OXYGEN AND WATER VAPOR ABSORPTION

Precipitation and fog are not the only absorbers at millimeter wavelengths; transmission of millimeter waves through the atmosphere is also subject to attenuation caused by resonances of oxygen and water vapor molecules. The attenuation caused by resonances of the oxygen molecule in the vicinity of 60 and 119 GHz is dependent on ambient pressure and temperature, and for a given altitude may vary by as much as a factor of two from place to place and time to time.[18] Resonances of water vapor molecules result in absorption peaks in the vicinity of 22 and 183 GHz. The absorption caused by water vapor is less well understood than that of oxygen, and the losses measured at frequencies well removed from the water vapor resonance peaks are often 2 to 4 times as many dB/km as predicted by theory. Also, of course, the water vapor content of the atmosphere varies over a wide range with time and location.

Curves of the atmospheric absorption at two altitudes, as produced from the data of Straiton,[19] are given in Fig. 5.[20] It is seen from these curves that there are several so-called atmospheric windows in the millimeter-wave region, and that the transparency of these windows decreases with increasing frequency.

## TOTAL ATTENUATION ON PATHS THROUGH THE ATMOSPHERE

In addition to the propagation factors already discussed, one must account for the attenuation due to "free space" or spreading loss $(4\pi r/\lambda)^2$, where r is the path length and $\lambda$ is the wavelength, as well as the attenuation due to other processes along the path such as reflection, refraction, cross-polarization, and antenna misalignment. The total attenuation on paths through the atmosphere is then found by adding the attenuation due to these factors to the attenuation due to precipitation and/or fog and the attenuation due to oxygen and water vapor absorption.

To give an idea of the relative contributions of precipitation attenuation and attenuation due to atmospheric absorption, the calculations of Setzer[11] showing the total attenuation caused by 100 mm of rain per hour and the oxygen and water vapor content of the

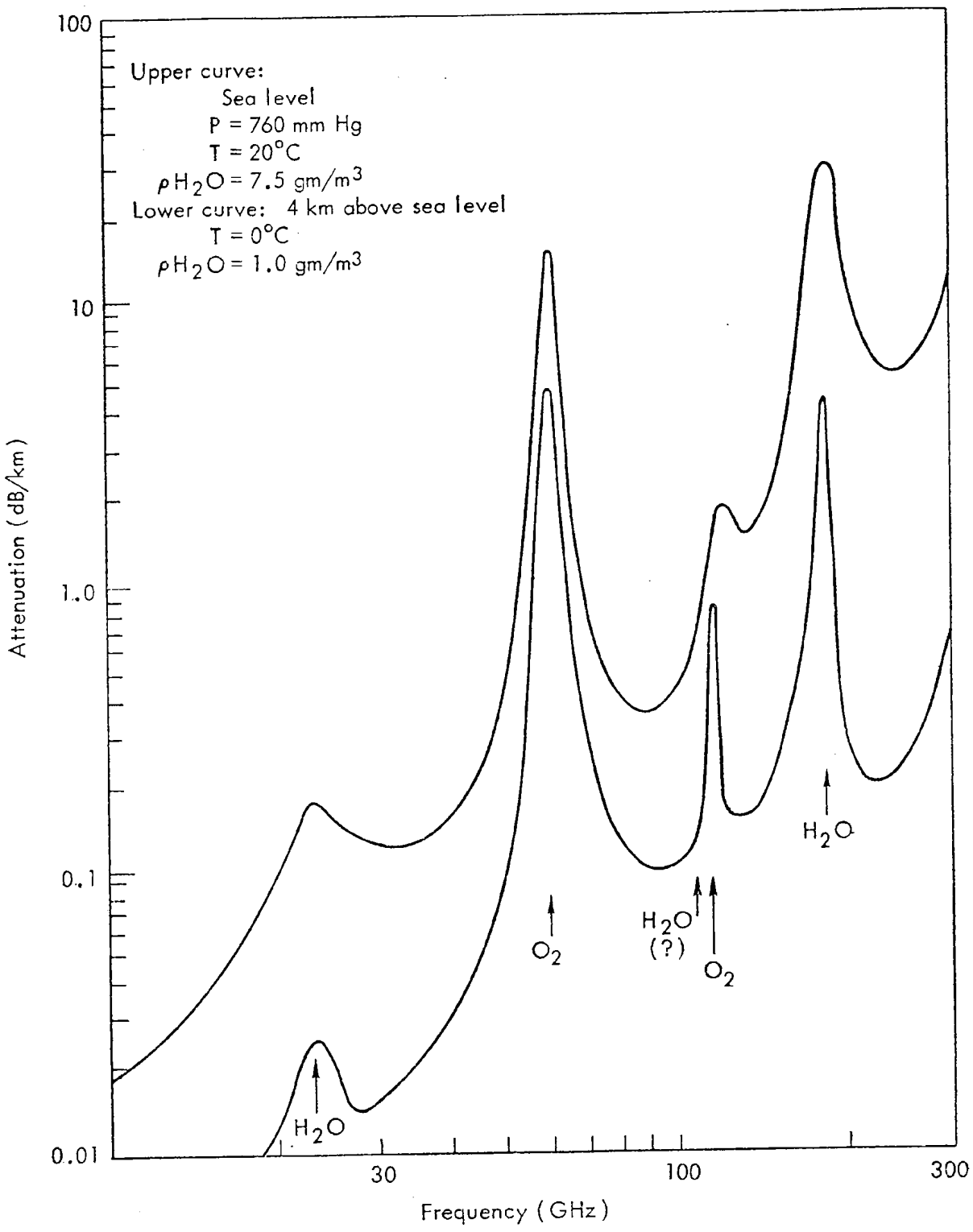


Fig. 5 — Horizontal attenuation due to oxygen and water vapor

atmosphere for two values of water vapor are shown in Fig. 6 (from Ref. 1). Also shown separately is the loss caused by a dense fog (1.0 gram of water per cubic meter).

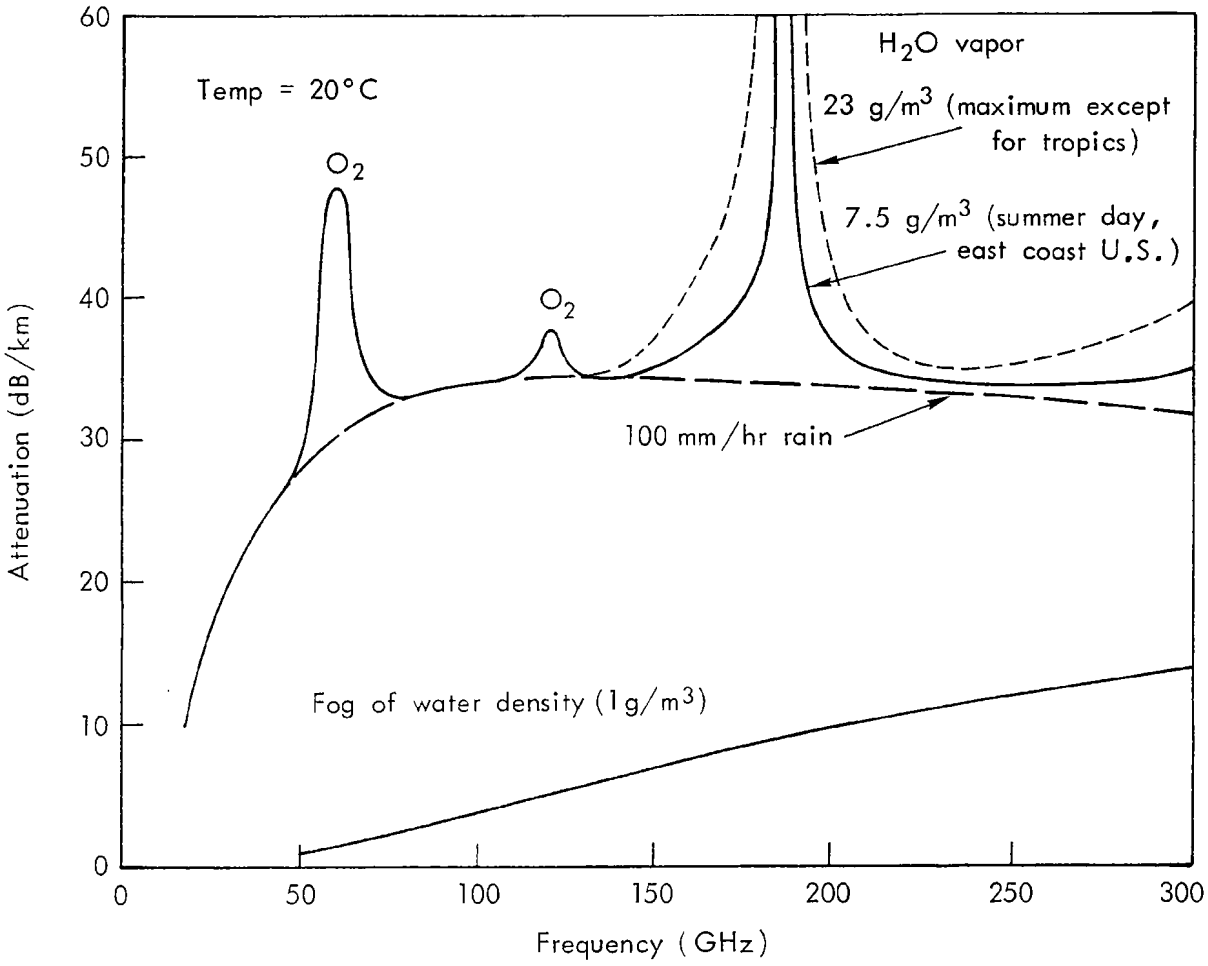


Fig.6 — Calculated values of total attenuation by the earth's atmosphere during a rain of 100 mm/hr

## III. DEPENDENCE OF ATTENUATION ON PATH LENGTH

### DOMINANCE OF ATTENUATION BY RAIN

With the background on propagation factors at millimeter wavelengths described in Sec. II, the attenuation over a given path can be calculated provided that the composition of the atmosphere is known in exact detail. However, because of the wide variability in the density and extent of water in all of its forms in the earth's atmosphere, it is not feasible to predict by calculation the attenuation to be expected on a given path at a particular time.

Fortunately, in most cases the attenuation as a function of time is not required for the design of radio links; for radio link design, the fraction of the time that the path attenuation exceeds the fading margin is the important parameter. For highly reliable operations at millimeter wavelengths, attenuation by rain is the dominant factor in determining the reliability of transmission through the atmosphere; with our present knowledge of the earth's atmosphere, the best way to obtain information relating path attenuation to rainfall rate is from experiments at the frequencies of interest made on typical propagation paths located in the climates of interest, with detailed simultaneous meteorological observations.

Indeed, in an experiment properly designed to relate attenuation to rainfall, as many carefully designed rain gauges as possible should be placed along the propagation path. Bell Telephone Laboratory personnel have recently made such experiments in Alabama and New Jersey.[21-24] A sample of data taken in New Jersey for use in the design of radio systems operating near 20 GHz is shown in Fig. 7.[23] These data were made at a frequency of 18.5 GHz on a 6.4-km path, with four rain gauges along the path. Depicted in Fig. 7a is the percentage of time during which a given path rainfall rate was exceeded during the summer period extending from June 23, 1967, to October 31, 1967 (3144 hours).* (A path rainfall rate is defined as the space average of the

*Also depicted here are three dashed curves for point rainfall rate distributions from one gauge on the propagation path. These curves will be discussed later.

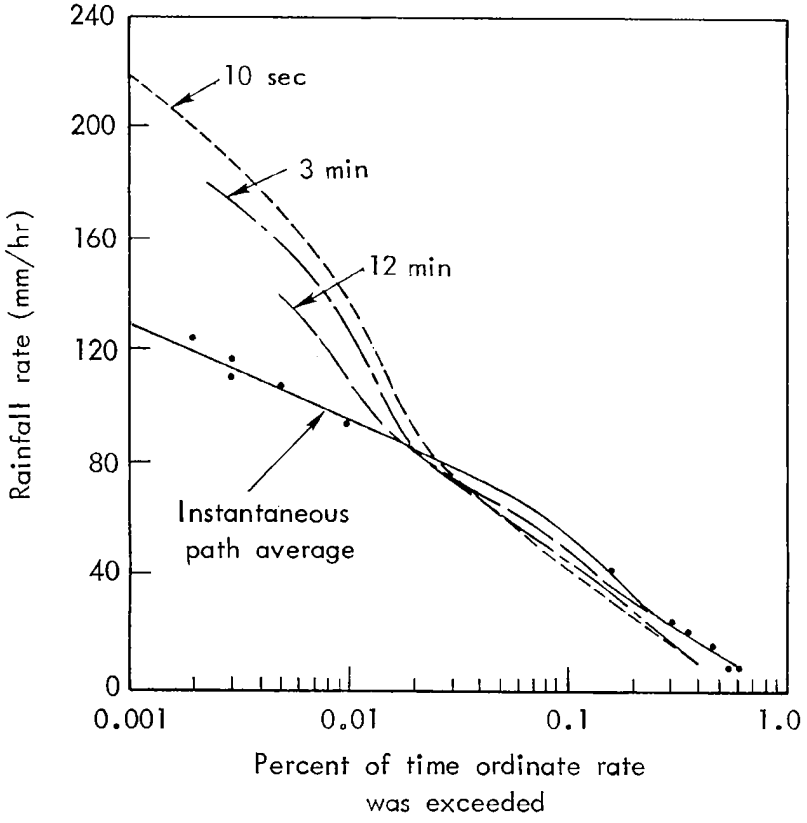


Fig.7a — Percent of time the path average rainfall rate exceeded the ordinate for a total period of 3144 hours (summer)

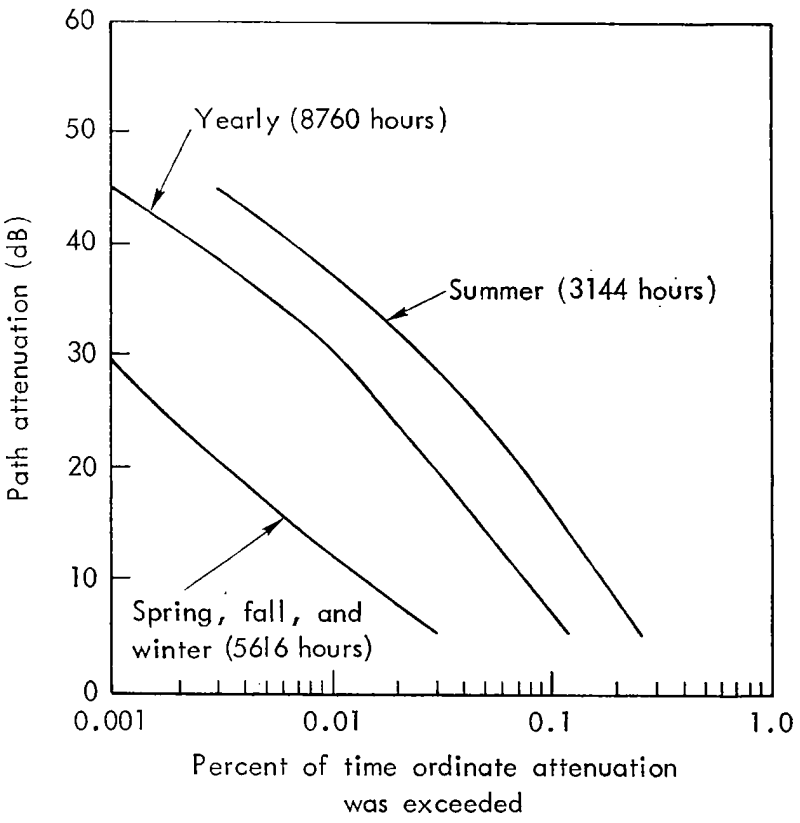


Fig.7b — Percent of time the attenuation at 18.5 GHz exceeded the ordinate for three different measurement periods

point rates along a path.) Depicted in Fig. 7b is the percentage of time during which a given level of attenuation was equaled or exceeded during the same summer period of 3144 hours. In addition, distributions are shown for the period covering spring, fall, and winter (5616 hours) and for the full year extending from April 1, 1967, to March 31, 1968 (8760 hours).

Because other rainfall environments have very different characteristics, it would be desirable to have similar data (at the frequencies of interest) for other climates for which it is desired to use millimeter-wave communication links. Although many studies have been conducted[1,10,13,21-24] and many data have already been obtained, still more are needed. In particular, from the designer's point of view it would be desirable to have data similar to those illustrated in Fig. 7 gathered over the specific paths on which it is proposed to operate the system, with emphasis on data for the wet season since this is the period of greatest path attenuation (Fig. 7b).

In practice, however, it is not economically feasible to measure rain attenuation in the manner described above in all parts of the world in which it may be desired to use millimeter-wave communication links. Hence, it is necessary to use what rainfall data are available and to couple these through reasonable assumptions to empirical (when available) or theoretical relationships between rainfall and attenuation. Since theoretical and empirical attenuation coefficients are available for uniform average path rain rates, as given in Figs. 2 and 3, the rain statistic we would like to have is the distribution of percentage of time that specific average rain rates are exceeded along a particular path.

Thus, in predicting the rainfall attenuation for terrestrial radio links, we are interested not in point rainfall rates but rather in the average rate along a particular propagation path. In fact, however, very few data are available on path rainfall rates, whereas there is an abundance of point rainfall data for locations throughout the world. Furthermore, most rainfall data are in terms of fairly long discrete time intervals, such as 30 minutes or one hour, and the relationship between hourly and instantaneous rates of fall is not perfectly known.

In order to utilize the available point rainfall data in radio link design, it is necessary to postulate a relationship between point and path-averaged rainfall rates.

## DEPENDENCE OF PATH-AVERAGE RAINFALL RATE ON PATH LENGTH

Bussey[25] first proposed such a relationship in 1950, and since then his results have been used in the design of radio systems. First, Bussey assumed that point rainfall rates are identical with path rates if the path is short enough (1 km). Then, using point rainfall data from the Washington, D.C. area, he plotted the annual cumulative distribution curves for different time intervals given in Fig. 8. The one-hour curve in Fig. 8 is based upon observed long-time data. The other three curves are not based on observed data, but were computed or derived from the one-hour curve by Bussey using data tabulated by the U.S. Department of Agriculture's Soil Conservation Service.

Bussey next analyzed rainfall data for one year from the Muskingum, Ohio area, and on the basis of these data found that the annual distribution of one-hour point rainfall rates is approximately the same as the annual distribution of instantaneous 50-km path rates in Ohio. If this approximation extends to locations outside of Ohio, then it is indeed a convenient one, for one-hour point data have been observed for many years in various parts of the world.

Bussey further suggested that two-hour point data apply to a 100-km path, 30-min data to a 25-km path, 10-min data to an 8-km path, and so forth. The curves of Fig. 8 may then be used to draw another set of curves such as those presented in Fig. 9, which shows the path-average rainfall rate as a function of path length for various probability levels. From this figure we can see, for example, that for a 1-km path in the Washington, D.C. area, there is a 0.01 percent probability that the path-average rain rate will equal or exceed 61 mm/hr, i.e., the rain rate will equal or exceed 61 mm/hr for 53 min per year; whereas for a 10-km path, the path-average rain rate will equal or exceed only 47.4 mm/hr 0.01 percent of the time.

For a climatological region for which point rainfall data are available for various time intervals such as, say, 1 min, 30 min, and

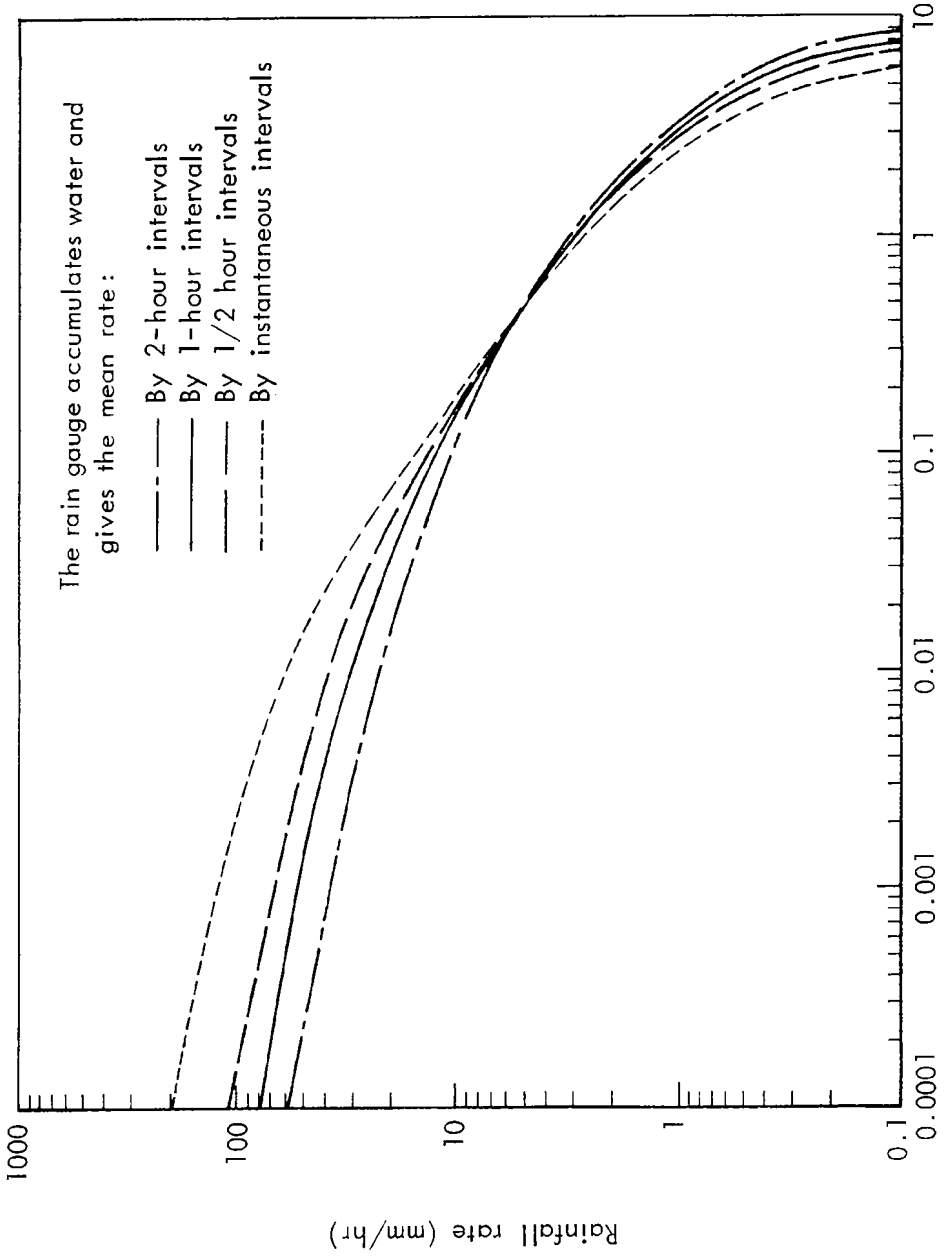


Fig. 8 — Cumulative distributions for point rainfall rates at Washington, D. C. The 1-hour curve is based upon observed long-time data. The other curves are derived from the 1-hour curve (from Ref. 25)

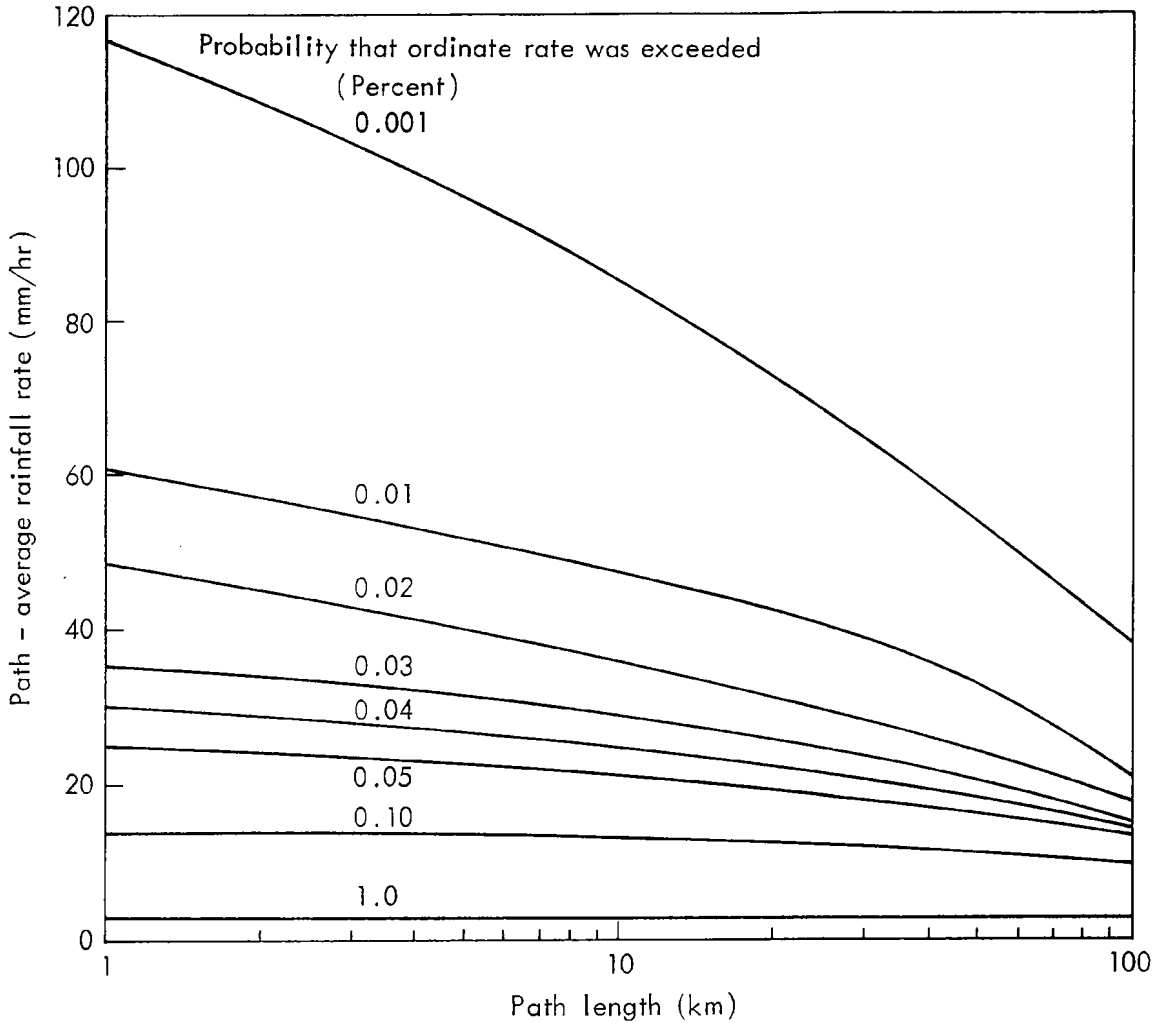


Fig.9 — Path-average rainfall rate in Washington, D.C. versus path length

1 hr, or for which they can be derived in the fashion of Bussey, it is a simple matter to plot curves such as those of Fig. 8 directly, and then to use these curves together with Bussey's approximation to determine the dependence of path-average rainfall rate on path length, as has been done in Fig. 9. Although these data are not abundant at present, some are available[26,27] (including some data on path-average rain rates given directly in the form of the curves of Fig. 9[27]). It is likely that such data will become more abundant in the future in view of their usefulness in selecting frequencies and power levels in radio systems and in the design of supersonic vehicles, as well as in more mundane applications such as sewer design and soil-erosion investigations.

For climatological regions in which point rainfall data are not available for intervals other than one hour, the point rates for other intervals may roughly be inferred from the available one-hour rates by assuming that Fig. 8 portrays a general relation between these rates. In other words, the percentage differences between the curve for a one-hour interval and the curve for other measurement intervals are the same as in Fig. 8.[25]* The resulting curves again may be used with Bussey's approximation to determine the dependence of path-average rainfall rate on path length.

Sufficient detailed experimental point and path rain-rate distributions are not available for confirmation of Bussey's theory. The limited experimental data available, however, give reason for optimism. For example, a comparison of point and path-averaged distributions measured in New Jersey is shown in Fig. 7a. The three dashed curves are for point rainfall rate distributions from one gauge on a 6.4-km propagation path. As indicated on the curves, measuring intervals of 10 sec, 3 min, and 12 min were used. One sees that as the time of the measuring interval is increased, the tail of the distribution obtained from the point gauge approaches that obtained for the instantaneous

*Since the Washington, D.C. area is subject to the gamut of rainfall types, this approximation is considered reliable at least in the region where the distribution for instantaneous intervals is not too different from that for hourly intervals.[28]

path-average distribution (the solid curve). These dashed curves cross over, as do those of Bussey (Fig. 8), since the total depth of rainfall is constant regardless of the observing interval used. For rain rates less than about 100 mm/hr, the equivalence between the point and path-average distribution is fairly good. For higher rainfall rates, however, the point distribution, even for a 12-min averaging interval, indicates higher percentage times than the true path-average distribution. (Bussey's theory predicts that a 7.7-min measuring interval should give the correct path distribution for a 6.4-km path. This does not check exactly with the values of Fig. 7a, but it is certainly close enough to be useful for rain rates less than about 100 mm/hr.)

Another example of agreement between point rainfall rate and path-averaged rainfall distributions is that for a 3-km path given in Fig. 10.[22] These data, which were taken by the British Meteorological

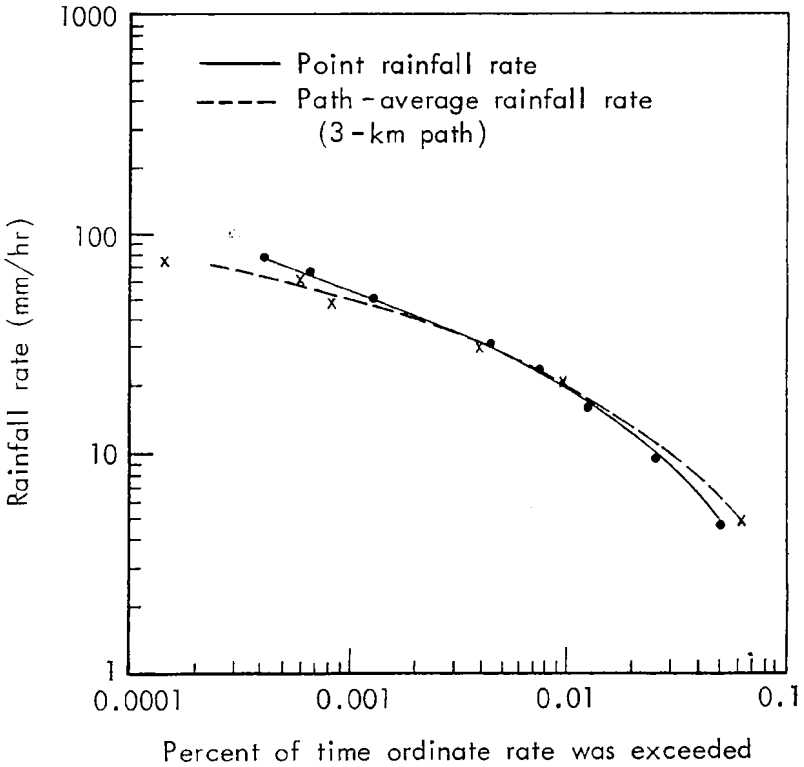


Fig. 10 — An example of agreement between point and path-average rainfall rate distributions

Office, represent four years of rainfall collected along a 3-km path in Bedfordshire, England by four rain gauges spaced 1-km apart. The gauges had a time resolution of about 2 min. The distribution of rainfall rate at a point is represented by the dots and solid line in Fig. 10, and the distribution of the average rainfall rate over the 3-km path is given by the crosses and dashed lines. Clearly, for this path length (and presumably for lesser ones), the point distribution represents the path average reasonably well.

Thus it appears that if certain, not yet fully defined, restrictions are placed on the length of the path over which the average is taken, the space-time ergodicity proposed by Bussey is valid, and that (in the absence of path-average rates) point rainfall rates can be used to predict path-average rainfall rates. Using these arguments, the performance of millimeter-wave links in the presence of rainfall can be estimated, as demonstrated in the following section.

## DEPENDENCE OF RAINFALL ATTENUATION ON PATH LENGTH

On the basis of presently available data, the best estimate of the relationship between attenuation and path-average rainfall at various frequencies for intense rainfall rates of the order of 100 mm/hr is given by the Hogg curve of Fig. 3. As mentioned earlier, it is now believed that the values given by Medhurst's curve are too high, primarily because of the heavy weighting he gave to the data of Anderson, et al.,[12] and that the best values of attenuation coefficients, even for rainfall rates much lower than 100 mm/hr, are obtained from Hogg's curve by taking attenuation to be directly proportional to the path-average rainfall rate.

The Hogg relationship between attenuation and path-average rainfall rate at various frequencies, as given in Fig. 3, and the probability of occurrence of rainfall rates for different path lengths, as given in Fig. 9 for the Washington, D.C. area, have been used to produce Figs. 11a, 11b, and 11c. For a given probability of occurrence, these plots give computed attenuation as a function of path length. Note that there is curvature in the plots. As one would expect from Fig. 9, the attenuation obtained (for a low probability of occurrence)

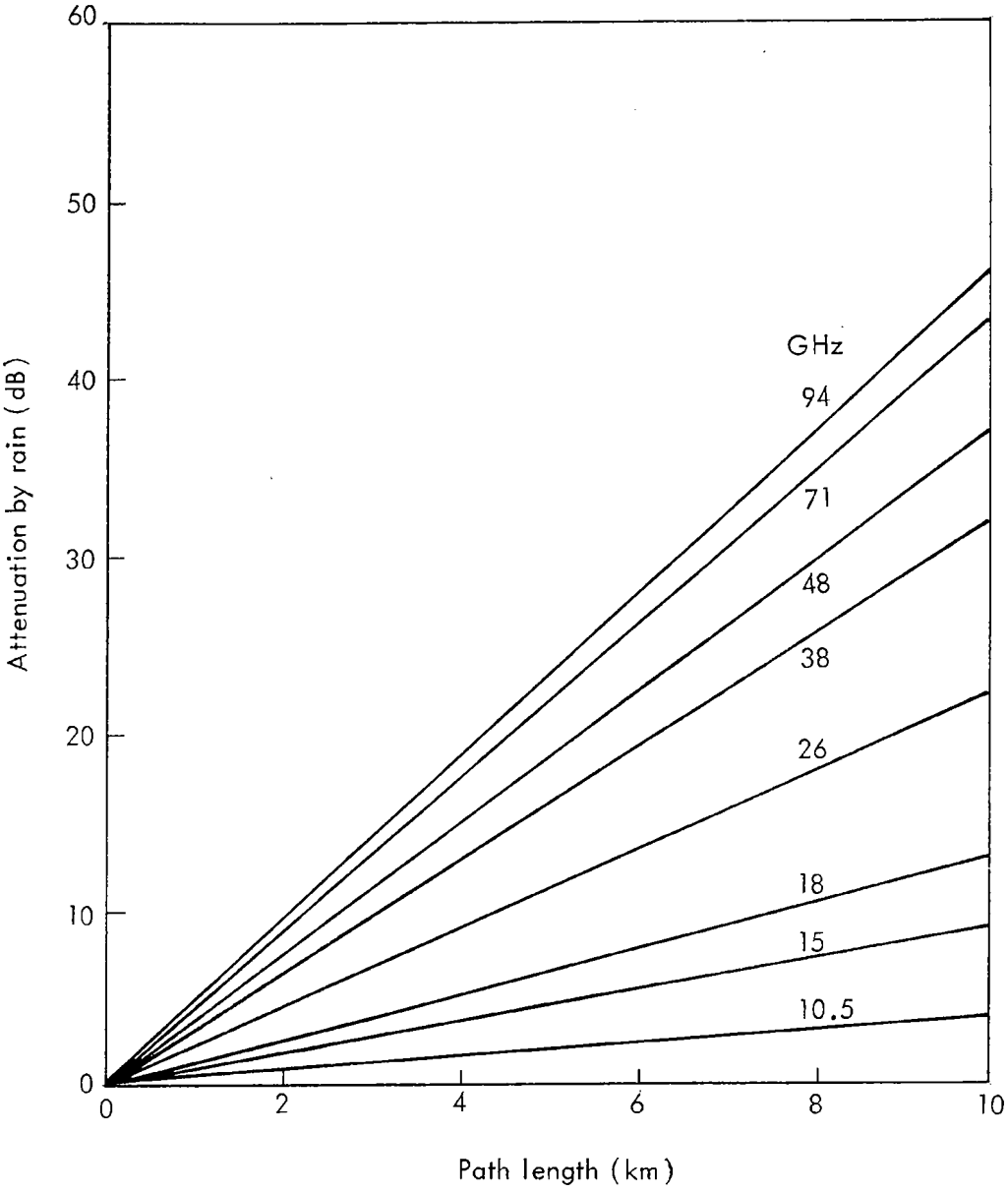


Fig. 11a — Attenuation by rain as a function of path length in the Washington, D.C. area for 0.1 percent probability of occurrence

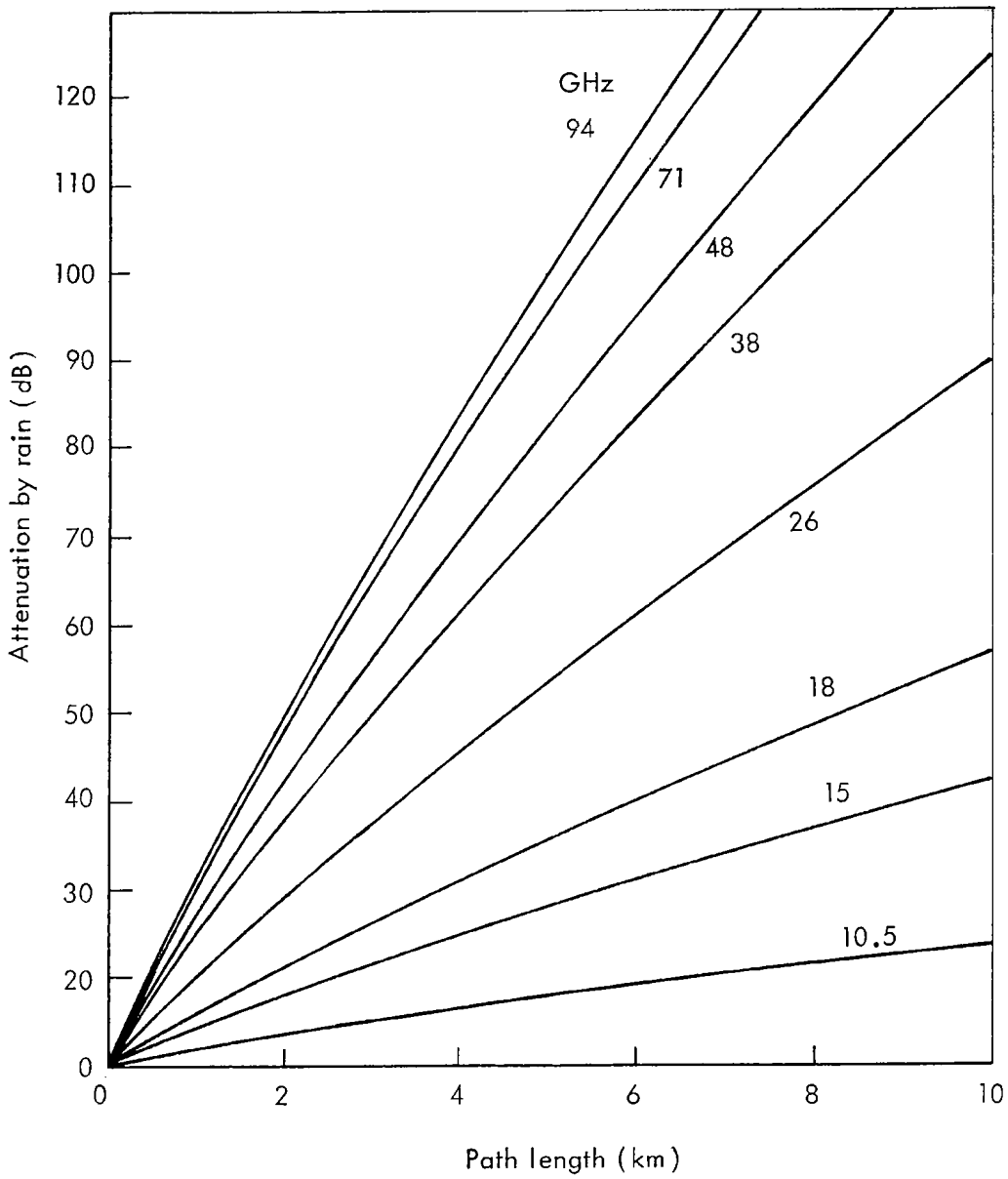


Fig. 11b — Attenuation by rain as a function of path length in the Washington, D.C. area for 0.01 percent probability of occurrence

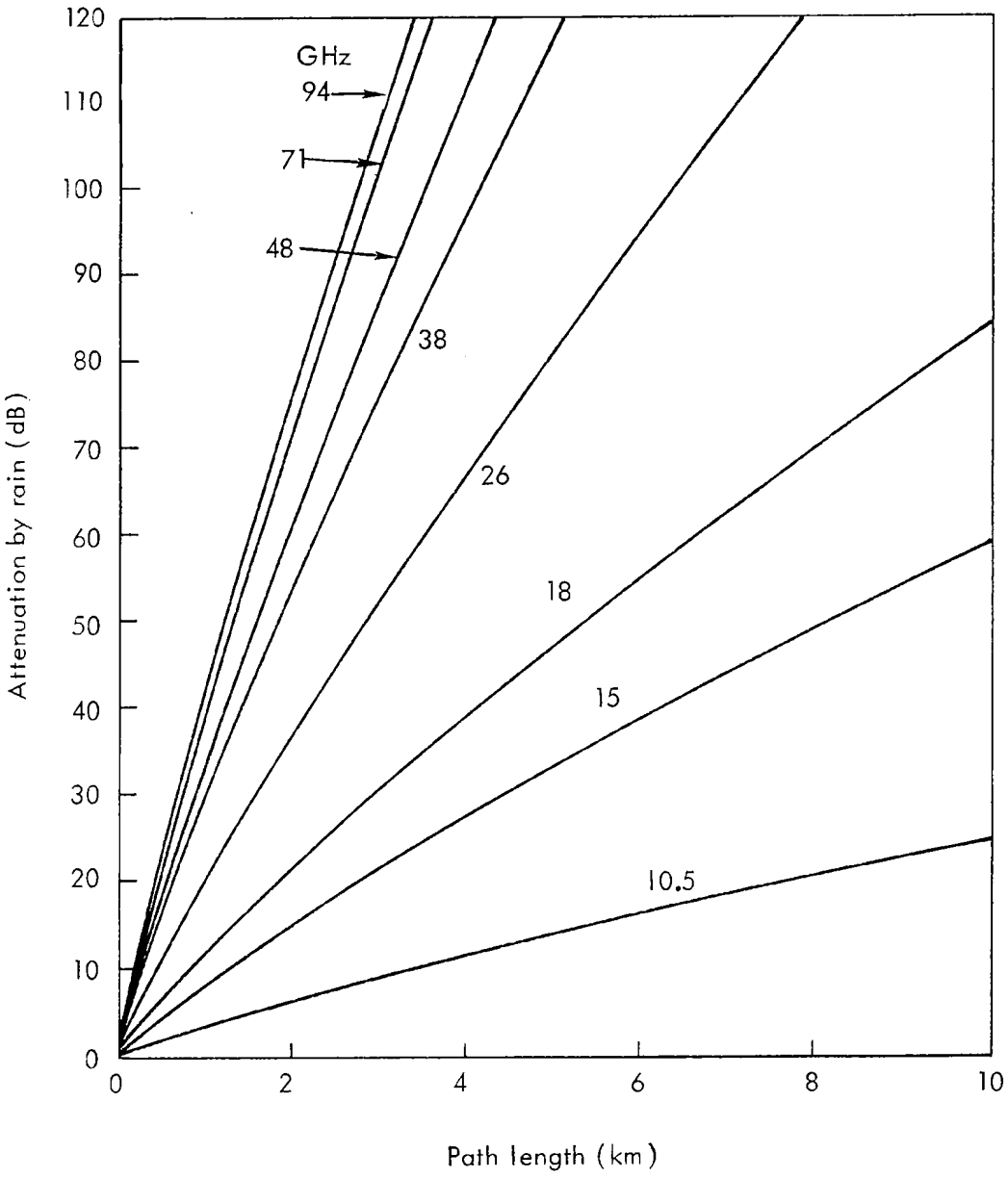


Fig. 11c — Attenuation by rain as a function of path length in the Washington, D.C. area for 0.001 percent probability of occurrence

on a 10-km path is less than one would expect by linearly extrapolating from the attenuation on a 1-km path. However, the curves become nearly linear for probabilities of 0.1 percent and above, and for these cases the attenuation can be estimated fairly accurately by a linear approximation.

The three probability levels (0.1 percent or 530 min/yr, 0.01 percent or 53 min/yr, and 0.001 percent or 5.3 min/yr) were chosen as representative of reliability levels traditionally used in discussions and designs of radio links for commercial telephone service. Taking into account all sources of equipment failures as well as the vagaries of weather, the total outage time in practice from end user to end user in long-haul microwave communication systems is usually in the range of 0.1 to 1 percent.* Therefore, for some applications of single-hop communications links, it may be acceptable to design the link so that the expected outage due to rainfall alone is on the order of 0.1 to 1 percent. Such designs would relax the design margins on millimeter-wave systems so that the use of these frequencies would not be penalized excessively by rainfall attenuation. Such systems may even be considered well-matched in the sense that the percentage of outages due to rainfall and that due to equipment failure would be of the same order of magnitude. The performance of such systems can be estimated by using Figs. 3 and 9 to plot curves similar to those of Figs. 11a-c for any desired probability levels.

The curves of Figs. 11a-c can be used to estimate the performance of communications links in the Washington, D.C. area and in other areas with similar climatological environments. For example, Fig. 11a indicates that with a communications system designed for a 30-dB fading margin, a single transmission path should not exceed 27 km (extrapolated), 9.3 km, and 6.5 km for frequencies of 15, 38, and 94 GHz, respectively, if the system is to operate with 99.9 percent reliability (0.1 percent or 530 min outage per year due to rainfall). Similarly, Fig. 11b tells us that if the reliability requirements are increased

*Private communication from Nathaniel Feldman, The Rand Corporation.

to 99.99 percent, then the permitted lengths of a single transmission path decrease to 9.1 km, 2.2 km, and 1.5 km for 15, 38, and 94 GHz, respectively, if the system is designed for a 30-dB fading margin.

Thus, in the 10- to 100-GHz region of the spectrum, the maximum path length for a given fading margin and a specified reliability decreases with increased frequency and, for communications links designed to operate above 10 GHz, the transmission path lengths in general must be short compared with the path lengths used at lower frequencies. Furthermore, since the rain attenuation increases by 10 dB per kilometer or more at high rainfall rates, the path length cannot practically be extended many kilometers by the brute force method of increasing the transmitter power for reliabilities of 99.99 percent or better. For example, consider a 38-GHz system designed to work over a 2-km path with 99.999 percent reliability (Fig. 11c). A doubling of the path length to 4 km would require twenty thousand times the transmitter power to account for rainfall attenuation alone.

The curves for 71 and 94 GHz in Figs. 11a-c are based upon a small extrapolation of the Hogg curve of Fig. 3, but curves have not been plotted for frequencies above 94 GHz because there are no experimental data for this region. However, theory indicates that the attenuation due to rain levels off at around 100 GHz and even tapers off slightly with increasing frequency (Fig. 2). Thus it is expected that for frequencies between 100 and 300 GHz, curves such as those of Figs. 11a-c would differ very little from the 94-GHz curve, and that the maximum path length for a specified fading margin for rainfall attenuation would be more or less independent of frequency.

## DEPENDENCE OF CLEAR-AIR ATTENUATION ON PATH LENGTH

The atmospheric attenuation over a path through a clear atmosphere is simply the sum of the spreading loss $(4\pi r/\lambda)^2$ and the loss due to oxygen and water vapor absorption. The dependence of this attenuation on path length can be represented by curves such as those of Fig. 12, which have been plotted using the atmospheric attenuation coefficients at sea level as given in Fig. 5. Curves such as these can, of course, be plotted for any given altitude by using appropriate

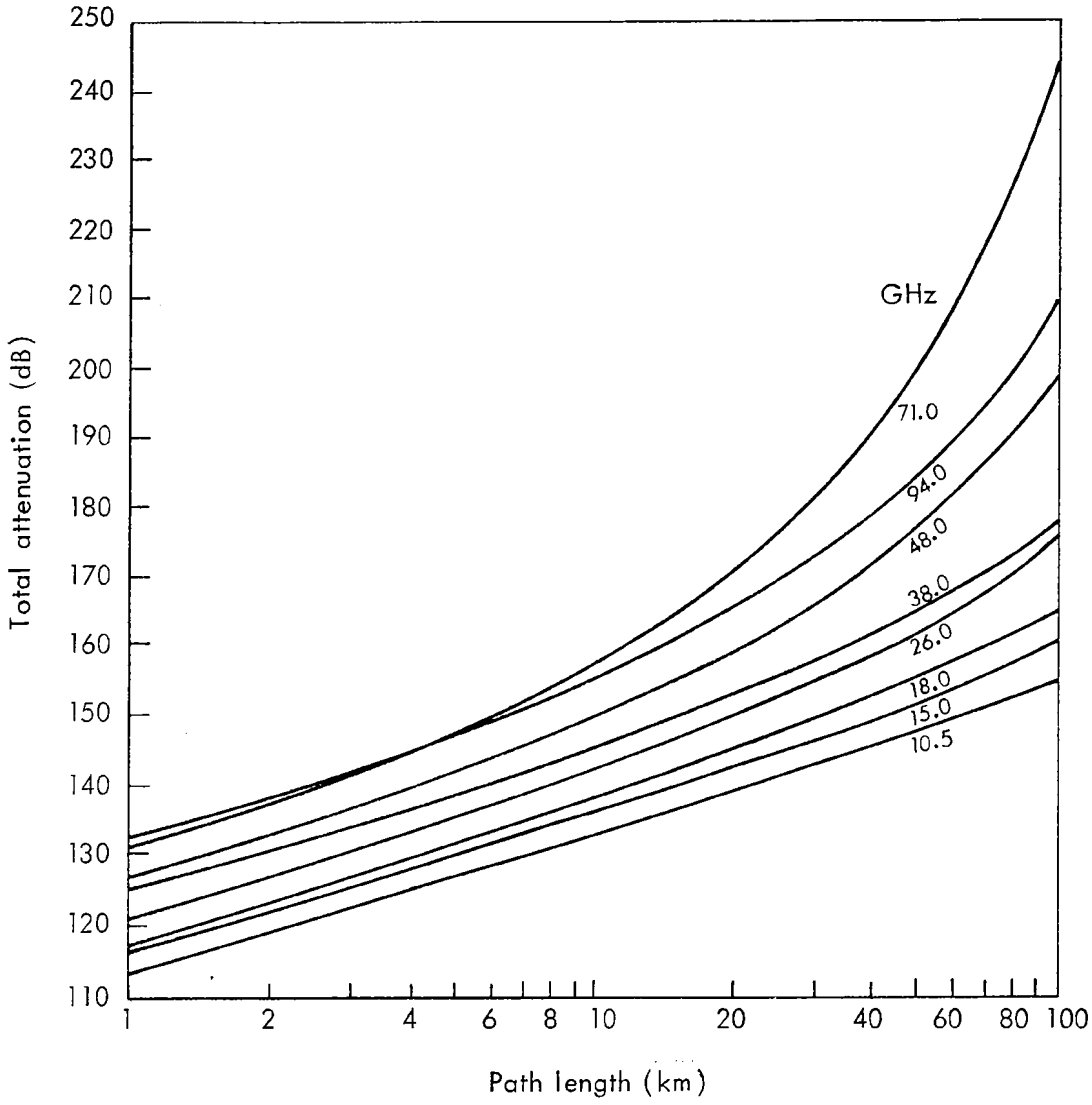


Fig. 12 — Total attenuation through a clear atmosphere at sea level

values of attenuation coefficients. It is worthwhile to note, however, that for the shorter path lengths required for highly reliable millimeter-wave links, most of path attenuation through a clear atmosphere is due to spreading loss (unless the transmission is at a frequency near one of the oxygen or water vapor absorption peaks). For the frequencies plotted in Fig. 12, this is true for the regions where the curves are fairly linear. Thus, not much error would be incurred by using the curves at sea level for estimating the clear air attenuation at higher elevations on the earth, and in any case the error that is incurred would result in a conservative estimate of attenuation.

Curves such as those of Fig. 12 can now be used together with curves such as those of Figs. 11a-c to estimate the performance of millimeter-wave communications links operating through the atmosphere and in the presence of rainfall.

## IV. TERRESTRIAL MILLIMETER-WAVE LINKS: AN EXAMPLE

We now consider an example of a terrestrial millimeter-wave communications link using analog modulation. In this case, the link equation, which expresses the fact that the ratio of signal-to-total-noise power at the terminal receiver input must be at least equal to the value which yields the specified output message quality, is[2]

$$\frac{P_T G_T G_R / L}{k T_o B_{rf} F_s} \geq \left(\frac{S}{N}\right)_{min}$$

where $P_T$ = transmitter output power (watts)

$G_T$ = transmitting antenna gain

$G_R$ = receiving antenna gain

$L$ = overall transmission loss

$k$ = Boltzmann's constant ($1.38 \times 10^{-23}$ joule/°K)

$T_o$ = reference noise temperature (290°K)

$B_{rf}$ = r-f bandwidth of receiver (Hz)*

$F_s$ = system noise figure

$(S/N)_{min}$ = signal-to-noise ratio at receiver input corresponding to minimum acceptable message quality.

The overall transmission loss L is defined implicitly in the above equation as the ratio $P_T G_T G_R / P_R$, where $P_R$ is the power of the received signal at the receiver input. In this example, it is convenient to factor L into several contributing terms

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*Strictly speaking, $B_{rf}$ should be replaced by $B_n$, the noise bandwidth of the receiver, defined as the width of the rectangular filter, which has the same center frequency gain and passes the same white noise power as does the receiver. However, the frequency-response characteristics of many practical receivers are such that the 3-dB r-f bandwidth and i-f bandwidth do not differ appreciably from the noise bandwidth of the receiver. Thus the 3-dB r-f bandwidth is widely used since it is easy to measure, whereas the measurement of the noise bandwidth requires a complete knowledge of the receiver response characteristics.

$$L = \left(\frac{4\pi r}{\lambda}\right)^2 \cdot L_{O_2-H_2O} \cdot L_{rain} \cdot L_T \cdot L_R \cdot L_P$$

where $(4\pi r/\lambda)^2$ is the spreading loss, $L_{O_2-H_2O}$ is the loss due to oxygen and water vapor absorption, $L_{rain}$ is the loss due to rainfall attenuation, $L_T$ and $L_R$, respectively, are the losses associated with the transmitting station and the receiving station (ohmic and mismatch losses), and $L_P$ includes all other transmission losses such as those due to reflection, refraction, cross-polarization, and antenna misalignment.

The following convenient set of reference values for systems characteristics are assumed: receiver bandwidth, 10 MHz; signal-to-noise ratio, 10 dB; system noise figure, 15 dB; and hardware losses ($L_TL_R$), 3 dB. We also assume that the link uses a directive antenna system consisting of identical parabolic transmit and receive antennas with a 2 × 2 deg beamwidth* ($G_TG_R \cong 75$ dB). (Such a system might find application in several areas, some of which include: (1) secure or interference-free communications links for video, or multichannel facsimile and voice, (2) communications relay from a master receiving antenna to a forward command post, (3) a rapidly setup battlefield link, (4) a link for remote closed-circuit television monitoring and surveillance, and (5) ship-to-ship and ship-to-shore communications.) Assuming further that $L_P = 1$, the link equation can be written

$$P_T(\text{dBW}) = -181 + \left[\left(\frac{4\pi r}{\lambda}\right)^2 \cdot L_{O_2-H_2O}\right](\text{dB}) + L_{rain}(\text{dB})$$

Now, suppose that we want to operate over a given path with a specified reliability in a climatological area such as Washington, D.C.

*This represents a practical lower limit on beamwidth that does not require extreme care in alignment and is fairly tolerant of wind loading effects on tower supporting structures. Omnidirectional antennas, if appropriate, should have the beam limited in the vertical plane. An omnidirectional antenna with a vertical beamwidth of 2 deg, for example, would provide a gain of about 15 dB.

By substituting the appropriate values from the curves of Figs. 11a-c and 12 into the above equation, we can determine the transmitter power requirements for any of the frequencies plotted. For example, operation over a 3-km path with only 0.01 percent outage time (53 min/yr) due to rainfall requires about 18.4 dBW (69 watts) of transmitter power at 94 GHz, and 14.2 dBW (26 watts) at 71 GHz.

If, however, the required reliability is only 99.9 percent (0.1 percent or 530 min of outage per year), then the transmitter power requirements for this same link are only about 3.6 mW and 2.2 mW at 94 GHz and 71 GHz, respectively. Thus, if the transmitter in such a link were equipped with automatic power-level switching (between low-level and high-level output), then the required power level would be only a few milliwatts at these frequencies for about 99.9 percent of the time (rainfall rate < 14 mm/hr), and would only need to be switched to the higher level during the 0.1 percent of the time that it rains harder than 14 mm/hr in order to maintain a 99.99 percent reliability.*

If, on the other hand, it is desired to operate this same system over a 5-km path, about 480 kW of transmitter power would be required at 94 GHz and 135 kW at 71 GHz to provide 99.99 percent reliability, but only about 0.1 watt would be required at 94 GHz and 0.07 watt at 71 GHz to provide 99.9 percent reliability. This emphasizes the point, made at the end of the previous section, that the use of millimeter waves, especially over longer paths, is penalized excessively by rainfall attenuation only in the face of very high reliability requirements.

The link equation can, of course, also be used together with curves like those of Figs. 11a-c and 12 to estimate system performance for cases in which a given amount of transmitter power is available. For example, continuing with the systems parameters given above, we see that if we have 10 watts of transmitter power available, then the maximum total path loss our system can support is 191 dB. If we desire to operate at 94 GHz with 99.9 percent reliability, then we see

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*Other diversity techniques such as path or frequency diversity could also be used to increase the reliability of millimeter-wave communications links, but this subject has been discussed thoroughly in the literature[13,29,30] and is not addressed further here.

from Figs. 11b and 12 that the maximum path length for a single hop will be about 8 km, allowing about a 37-dB fading margin. If, on the other hand, we want to operate over a longer path, say 10 km, at the same reliability level with the same amount of transmitter power, then it will be necessary to operate at a lower frequency, in the near vicinity of 48 GHz.

The examples given here are intended only to be illustrative, and really apply only to the Washington, D.C. area since the curves of Figs. 11a-c and 12 are based on data from the Washington area and at sea level, respectively. However, by using Bussey's approximation together with meteorological data from any region of interest, curves similar to those of Fig. 9 can be generated. Such a figure combined with Hogg's curve on attenuation coefficients contains all the essential information for computing the additional link power requirements in the presence of rain. It is only necessary to combine them as has been done here to generate Figs. 11a-c. Each of these figures corresponds to a given probability of occurrence. For a particular climatic region, a set of such curves for different probabilities of occurrence completely describes the margins necessary for operation during rain. In conjunction with curves for fair weather, such as those of Fig. 12, they provide all the information the system designer needs.

## V. SUMMARY AND CONCLUSIONS

From the viewpoint of reliability, the major atmospheric effect influencing the design and implementation of millimeter-wave radio systems is attenuation due to rainfall. Thus, users of radio frequencies above 10 GHz who require reliable terrestrial communications must face up to the vagaries of millimeter-wave transmission during inclement weather. The principal result, from which other parameters are determined, is that the transmission paths (between transmitter and receiver in the case of a single transmission path, or between repeaters for paths in tandem) must be made short (compared with lower frequency systems) in order to maintain the same reliability. The link design is, thus, strongly determined by the choice of two basic parameters: path distance between transmitter and receiver and the required reliability of transmission. In most instances, provision of 99.99 to 99.999 percent reliable communications at millimeter wavelengths is not an insurmountable problem if the path lengths between terminals or repeaters are short enough (between about 1 and 10 km, with the exact distance dependent on the frequency and required reliability).

On the other hand, users of millimeter-wave frequencies who are content with a communication channel that is available *most* of the time can employ these frequencies with much longer paths, limited primarily by line-of-sight requirements. Such a compromise might be desirable in some instances, for example, if the lower reliability channel were much less expensive than other competing channels; it is only when very high reliability is mandatory that communications links over these longer paths could not provide a useful service. In any case, sufficient understanding of the basic propagation mechanism and of the limitations imposed by rainfall attenuation will make possible the design of systems with the degree of reliability required for specific applications.

Even though frequencies above 10 GHz suffer the disadvantage of attenuation caused by rain, which becomes a basic limitation in system

design, the wide bandwidths available and the small high-gain (narrow-beamwidth) antennas that are feasible at these short wavelengths are important advantages. Above 35 GHz, antennas less than one foot in aperture provide 2-deg beams with gains of about 40 dB. Thus, a transmitter or repeater package of modest size can provide high-gain narrow beams, and if the antennas are designed to have low sidelobe levels, then they make possible the design of systems which provide security and good protection against interference and jamming. Wide system bandwidths are inherently available at millimeter wavelengths and can also be used to provide protection against interference and jamming through the use of spread spectrum techniques.

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