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Millimeter-Wave Communication through the Atmosphere

The known and unknown features in propagation of short radio waves are discussed.

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In spite of the fact that we have had coherent radio sources with significant amounts of millimeter-wave power for many years, these wavelengths have not been used for communication. Why do millimeter-length waves lie idle, and what is being done to make them more useful?

Additional frequency space is needed, and regulatory bodies throughout the world charged with optimum allocation of radio frequencies for communication are increasingly concerned with this problem. The centimeter-wavelength bands, used so successfully in radio relay for wide-band communication, are now exhausted in some heavily populated areas. For satellite communication, it has been necessary to reuse the centimeter-wave bands used by earth-based microwave radio relay for transmission of audio and video information and data. This parsimony requires caution, for although the electromagnetic spectrum is a global resource, and technical problems concerning compatibility still must be solved to bring about its most efficient utilization, interference between systems operating on the same frequency can badly degrade performance.

There has been no slackening in invention and development of electronic components for utilization of the millimeter-wave band. Steadily, over the past two decades, invention and improvement have given us equipment equal in quality to that used in the first centimeter-wave radio systems. We have solid-state devices, tubes, wave guides, and antennas of good quality. Moreover, the past few years have brought such increased understanding of the solid state that many millimeter-wave devices are now superior to their centimeter-wave counterparts of the 1940's, the decade when centimeter-wave communication began to flourish.

With all this technology and with such an urgent need for more frequency space, why does the millimeter-wave band lie idle? The answer is that it lies idle because of our environment and the inadequacy of our knowledge concerning that environment. The atmosphere can exhibit severe absorption at these short wavelengths.

Alternatively, then, why not guide the waves in a protected medium similar to a suitably pressurized cable or pipe buried beneath the surface of the earth? This method of guided transmission has been studied diligently over the past two decades, and a pilot system has been successfully demonstrated *(1)*. Guided transmission of millimeter waves may well come into widespread use. But this does not preclude the use of millimeter waves in the open atmosphere. My present intent, then, is to reexamine the problems of transmission through the atmosphere. Much is known, but we do not yet know, or do not know surely, some things necessary for the engineering design of reliable, useful millimeter-wave systems.

Absorption by the Clear Atmosphere

Transmission of waves along the earth's surface through a clear atmosphere is subject to attenuation due to absorption by oxygen and water vapor. This attenuation is ordinarily plotted in decibels per kilometer, as shown in Fig. 1. The theoretical curve *(2)* agrees satisfactorily with the measured data *(3)*, provided suitable values are taken for the pressure broadening constants —namely, the frequency widths—of the oxygen and water-vapor lines *(4)*. There are many thousands of megahertz of frequency space available in this frequency range. The only serious restrictions are those imposed by the oxygen absorption surrounding frequency of 60 gigahertz and by water vapor, which exhibits strong absorption at frequencies above about 150 gigahertz. Given a choice, one would prefer to use frequencies in the neighborhood of 15, 35, and 90 gigahertz.

For satellite communication, or for any proposed use of millimeter waves to communicate with space probes, the same general arguments hold. Figure 2 shows the one-way attenuation for a zenith-oriented signal traversing a clear atmosphere and for a signal traversing a path having an elevation angle of 30 degrees. In comparing Fig. 2 with Fig. 1, it is interesting to note that, for standard atmosphere and frequency of, say, 32 gigahertz, the attenuation for a zenith-oriented signal is only about twice the attenuation for a signal traversing a 1-kilometer path along the earth's surface (Fig. 1). Therein lies an advantage in using these bands for satellite communication. In satellite communication, propagation through the atmosphere occurs only twice, as opposed to earth-based sys-

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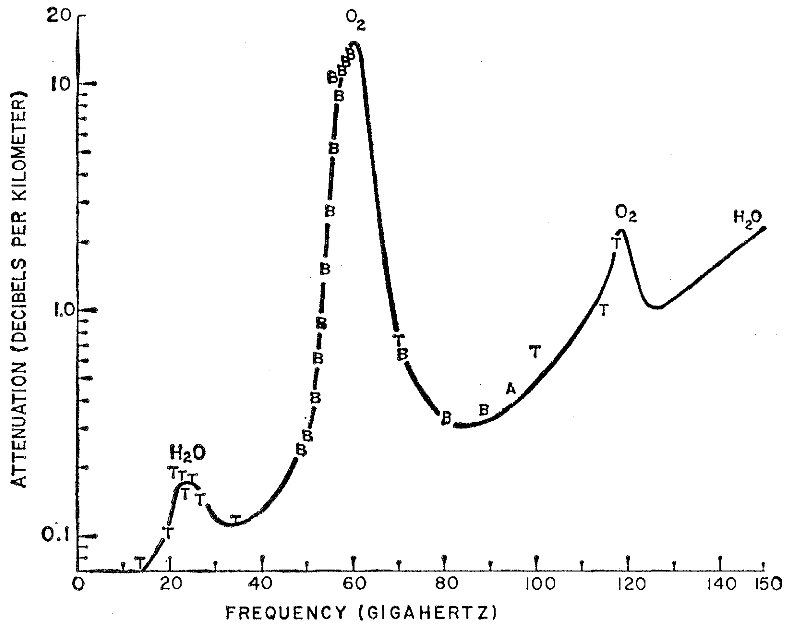


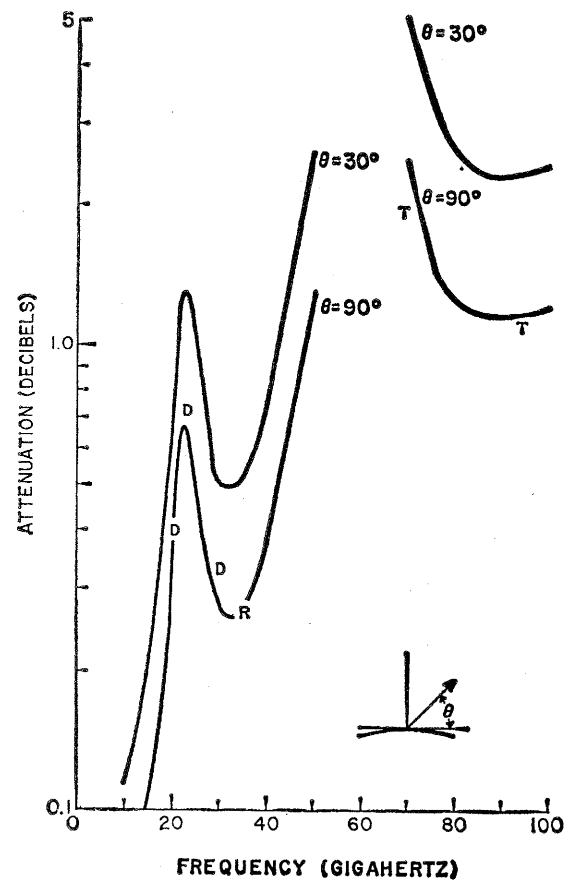


Fig. 1 (above). Measurements, by the University of Texas (*T*), the Aerospace Corporation (*A*), and the Bell Telephone Laboratories (*B*), of attenuation at frequencies in the millimeter-wave band for a sea-level atmosphere with a water-vapor content of 7.5 grams per cubic meter, and (solid curve) corresponding calculated values. Fig. 2 (right). Zenith (elevation angle θ, 90 degrees) measurements, R. H. Dicke (*D*), A. W. Straiton and C. W. Tolbert (*T*), and D. H. Ring (*R*), of attenuation at frequencies in the millimeter-wave band for a standard atmosphere, and calculated values (solid curves) for a zenith path and for a path with an elevation angle of 30 degrees.

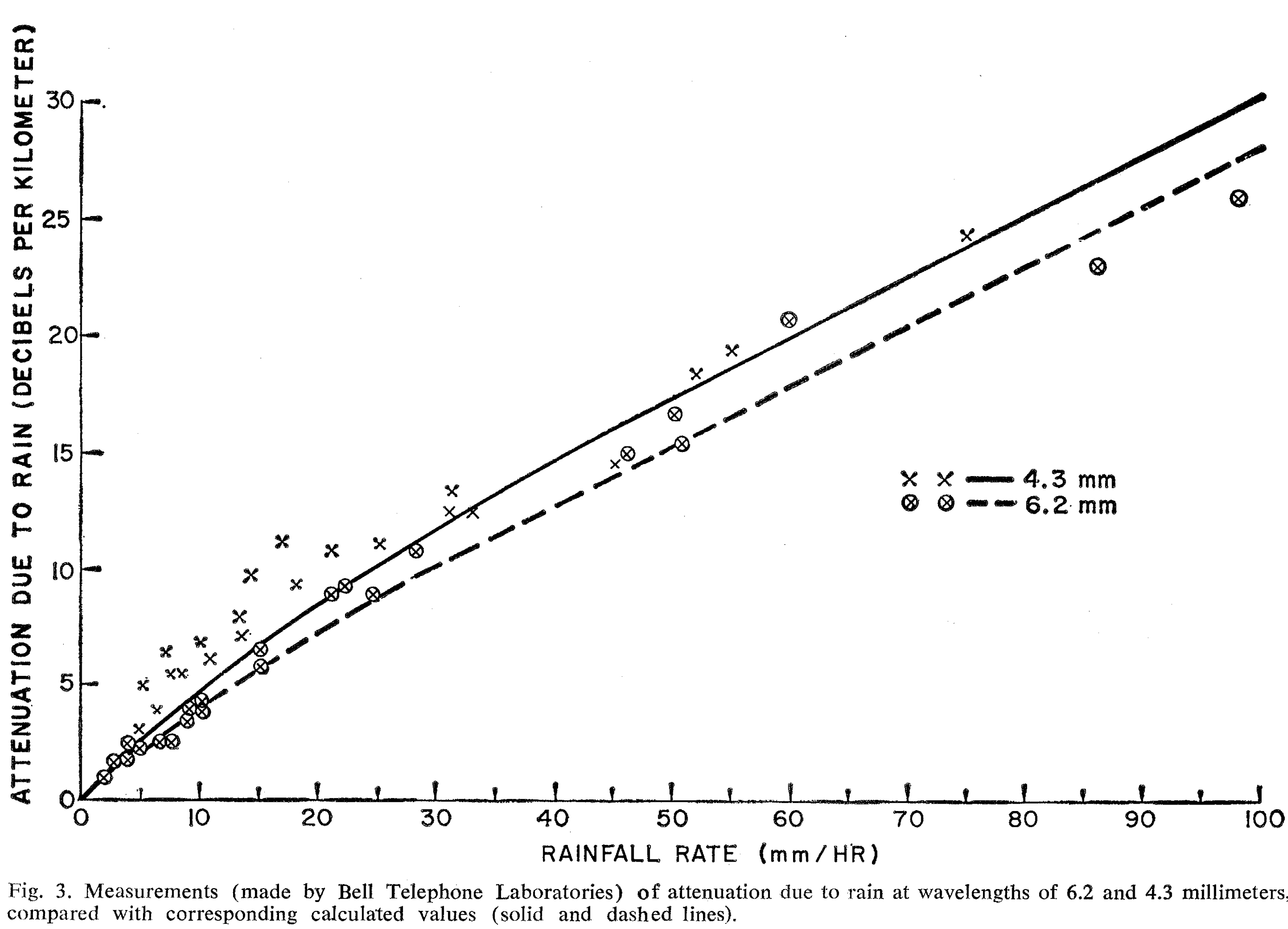


Fig. 3. Measurements (made by Bell Telephone Laboratories) of attenuation due to rain at wavelengths of 6.2 and 4.3 millimeters, compared with corresponding calculated values (solid and dashed lines).

tems in which many tandem paths through the atmosphere may be involved. In Fig. 2 one again sees that the measured data *(5)* are adequately described by theory and that great spans of usable frequency space are available.

Scintillation

The clear atmosphere, in addition to introducing molecular absorption, gives rise to certain refractive effects. A millimeter-wave signal that has gone a few kilometers through a typical atmosphere fluctuates. This effect is called scintillation; it is much like the twinkling of lights or stars at visible wavelengths. However, the magnitude of the scintillation at millimeter wavelengths is small compared with that of an equivalent optical system.

There are two deleterious effects that the ever-present refractive-index inhomogeneities in the atmosphere (which produce the scintillation) could have on transmission of broad-band information. One is that the phase front of the wave reaching a receiver would be so perturbed that the receiving antenna, which is designed to accept a uniform phase front, would not function efficiently *(6)*. This would be evidenced by an apparent decrease in antenna gain, together with an apparent broadening of the antenna beam (major lobe of the radiation pattern). However, in transmission on the earth *(7)* and in radio astronomy measurements *(8)* in which very large narrow-beam antennas are utilized, no significant beam broadening has been observed. In fact, certain wide-base interferometers have obtained resolutions of fractions of 1 second of arc.

The second effect associated with scintillation would be that of limiting the usable signal bandwidth, because of time delays introduced by scattering from the refractive-index inhomogeneities in the air. This effect is intimately related to the beam-broadening, since both are produced by the same mechanism. However, since the beam-broadening effect is insignificant, it follows that relative delays on the path are very short, and there will be no degradation of bandwidth to any marked degree. Anomalous propagation may sometimes occur and give rise to a fading signal, as it does at centimeter wavelengths.

So far we have found no effects which rule out the use of millimeter wavelengths for radio-relay purposes.

Attenuation by Precipitation

It is attenuation by precipitation, mainly rain, that has restricted the use of millimeter waves in the atmosphere. Liquid water exhibits strong absorption, which steadily increases as the wavelength decreases from 1 centimeter to 1 millimeter. Ice and dry snow, on the other hand, have negligible absorption in this band. Thus, our problem in utilizing millimeter waves for radio relay and satellite communication is that of knowing the nature of liquid precipitation at the earth's surface and the liquid content of cloud *(9)*. A first-order approximation shows that attenuation by a medium composed of drops whose diameter is small relative to the wavelength is proportional to the density of liquid water along the radio path. Rain, rather than fog, is the most restrictive propagation medium simply because the liquid-water content is so high when it rains.

Attenuation by Rain

The basic features of attenuation of millimeter waves by rainfall of a given rate are known, though some details are not. When a microwave is incident upon a drop of water, part of it is absorbed and dissipated as heat and the remainder is scattered. At centimeter wavelengths, dissipation is predominant for the drop sizes characteristic of fog and rain (the opposite is true at optical wavelengths, for example). Thus, the attenuation is roughly proportional to the liquid-water content. However, millimeter wavelengths are of the same order as the diameter of the larger raindrops, and this complicates the behavior of the attenuation as a function of frequency. Nevertheless, the problem has been solved exactly for drops of arbitrary size with given dielectric and loss coefficients.

The power remaining in a wave that has passed a distance L through a homogeneous medium comprising drops of given radius a is $P = P_0 \exp(-\gamma_a L)$. Here γ_a is the power-attenuation coefficient appropriate to drops of radius a and is given by $\gamma_a = N\pi a^2 Q$, where N is the number of drops per unit volume, Q is a measure of the efficiency of the drop in extinction, and πa^2 is the projected area of the drop. But rainfall comprises drops of various sizes. Moreover, the extinction efficiency is a function of wavelength, because the loss and the refractive index of water change with wavelength and because the drop diameters are of the same order as the wavelength. Thus, the attenuation coefficient must be written

$$\gamma = \int_0^\infty N(a)\, \pi a^2 Q(a)\, da$$

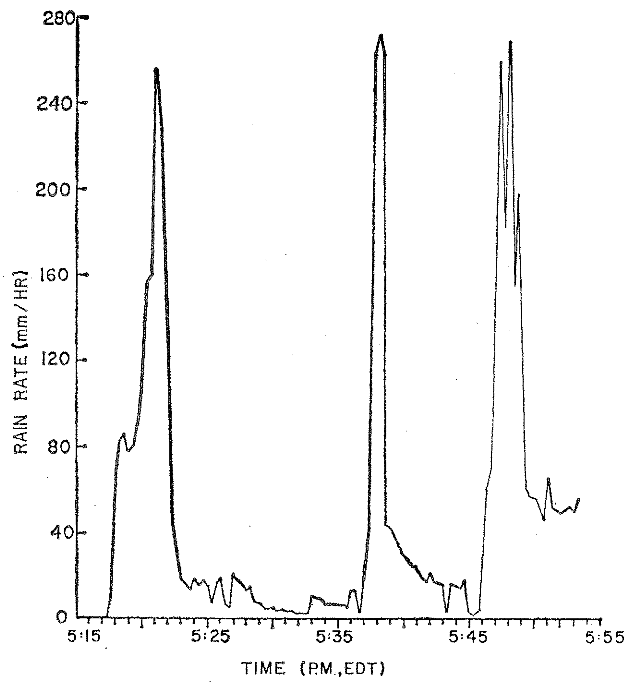
where the integration is carried out over all drop sizes. The refractive index and the loss of water have been measured to good accuracy; therefore $Q(a)$ is known with a fair degree of confidence. The drop-size distribution, $N(a)$, near the earth's surface is also known with considerable confidence, although its form depends on the rainfall rate (the heavier the rain is, the more water exists in the form of large drops) and to some extent on geography.

It is not surprising, then, that there is reasonable agreement between measured and calculated attenuation due to rain. Such agreement, at least, is found for rains in New Jersey, as we see from Fig. 3. Two sets of measured data are shown, one set obtained at wavelength 6.2 millimeters [by Mueller *(10)* in 1946] and the other at wavelength 4.3 millimeter *(11)*. In both cases the results are compared with calculated attenuation based on measured rainfall rates and the drop-size distribution of Laws and Parsons *(12)*. Most radio-relay systems are designed to accommodate fading of the order of 30 decibels. We see from Fig. 3 that, at millimeter wavelengths, the spacing between repeating stations should not exceed about 1 kilometer if the system is to operate (that is, be reliable) during heavy rain. However, this spacing depends on the characteristics of the rainfall at the place under consideration.

Fine-Grain Time Statistics for Rainfall

Traditionally, rate of rainfall has been measured with gauges which collect water and eventually indicate that a given amount has fallen. Such devices measure average rainfall over a considerable period. If we wish to evaluate the reliability of a communication system on the basis of rainfall data, those data must be resolved in time down to minutes and seconds per year *(13)*.

Recently a high-speed rain gauge *(14)* with an output readily adaptable for computer analysis has been designed.



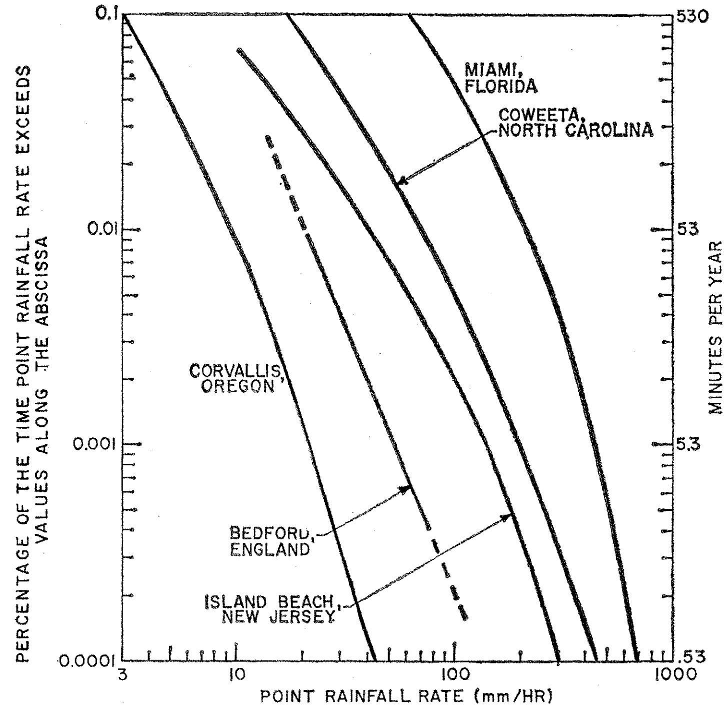
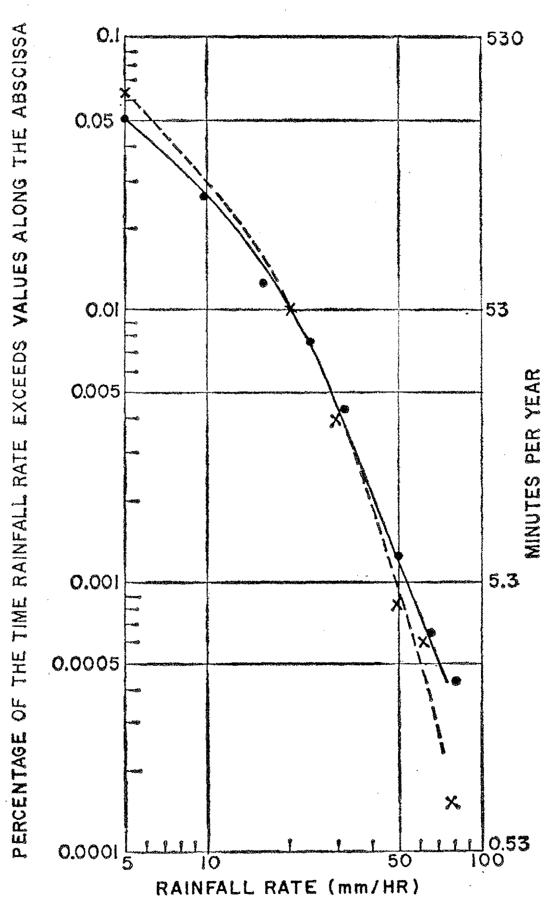


Fig. 4 (left). Rainfall rate at a point, as measured by a rain gauge with a time resolution of about 1 second. Fig. 5 (right). Yearly distributions, in percentage of time and in minutes per year, of point rainfall rates for various places in the United States and for Bedford, England. [Based on a 1-year data sample made available through the courtesy of the Illinois State Water Survey]



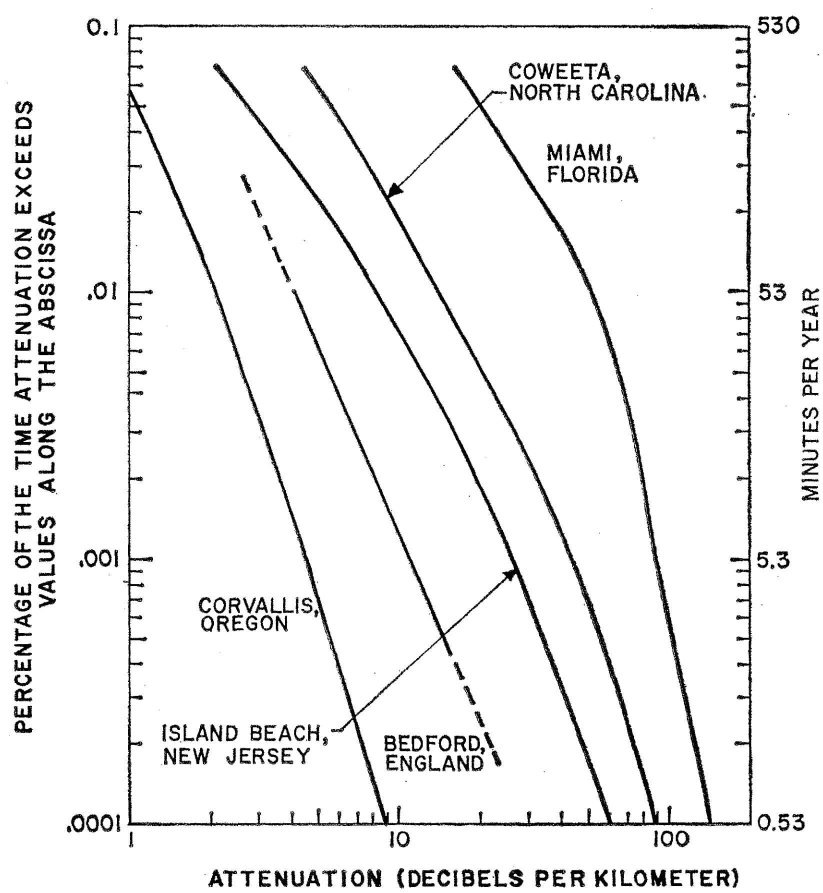


Fig. 6 (left). An example of the equivalence of the time-wise distribution of rainfall rate at a point (dots and solid line) and the average rate along a 3-kilometer path (crosses and dashed line). [Based on a 4-year data sample made available through the courtesy of Her Majesty's Meteorological Office] Fig. 7 (right). Yearly distribution, in percentage of time and minutes per year, of attenuation at frequency of 30 gigahertz over a 1-kilometer path for various places in the United States and for Bedford, England.

Figure 4 shows measurements of rain rate made by such a gauge during a brief, intense summer shower in New Jersey. Within seconds, the rain rate at a given point changes by a factor as great as 10. Long-term statistics obtained with such devices are necessary for the design of millimeter-wave radio systems.

Another method *(15)* of obtaining highly resolved rain rates is that of photographing, counting, and measuring the drops in a given volume of rain. This technique has been successfully instrumented by the Illinois State Water Survey, and was used for about 1 year in making measurements at various locations in the United States. The data obtained from the Survey study, reduced to percentage-of-time distributions of rainfall rate, are given in Fig. 5. Note that the measurements extend to 0.0001 percent of the time, which is about 30 seconds per year. Perhaps it is not surprising that, as Fig. 5 shows, heavy showers in Miami have maximum rain rates about 20 times greater than those of heavy showers in Oregon. But it is surprising that, for a short time interval, the point rainfall rate (the rate at a given point) in Miami can exceed 700 millimeters per hour (28 inches per hour). The distribution from Bedford, England, also shown in Fig. 5, was obtained by methods discussed later.

Space-Averaged Rain Rates

In calculating attenuation for earth-based radio-relay systems, one is interested not in point rainfall rates per se but, rather, in the average rate along a particular propagation path. Indeed, in an experiment properly designed to relate attenuation to rainfall, as many rain gauges as possible should be placed along the path. In the absence of multigauge data, if we try to use point rainfall data (such as those of Fig. 5) in designing systems for reliable operation in various parts of the country, we must ask: Is there any relationship between point and space-averaged rainfall rates? This question was posed by Bussey *(16)* several years ago. Provided certain restrictions (not yet fully defined) are placed on the length of path over which the average is taken, such space-time ergodicity is valid.

An example of agreement between point-rainfall-rate and space-averaged-rainfall-rate distributions is given in Fig. 6 *(17)*. These data, provided by the British Meteorological Office, represent 4 years of rainfall collected along a 3-kilometer path in Bedfordshire, England, by four rain gauges, with intergauge spacing of 1 kilometer. The gauges had a time resolution of 2 minutes. The solid curve is the distribution at a point; the dashed curve is the distribution of the average over the 3-kilometer path. Clearly, for this path length (and presumably for lesser ones), the point distribution represents the space average reasonably well. To the extent that this is true, we can proceed to utilize the data in Fig. 5 and the attenuation relationships discussed above to obtain percentage-of-time distributions for millimeter-wave attenuation in various parts of the United States, and from these data we can compute system reliability.

An example of this procedure is given in Fig. 7. Here distributions of attenuation at frequency of 30 gigahertz are plotted for the various locations represented in Fig. 5. At 30 gigahertz, the attenuation is, to a good approximation, directly proportional to the rain rate R ($\gamma = 0.2R$ decibels per kilometer where R is in millimeters per hour). Therefore, the distributions of Fig. 5 have merely been multiplied by a constant to obtain those of Fig. 7. Although 30 gigahertz has been used in this example, the procedure also applies to some other frequencies in the microwave band.

Using the above arguments, we have armed ourselves with enough information to estimate the reliability of a hypothetical system having a repeater spacing of 1 kilometer. For example, if the signal-level margin appropriate to the system in question is 30 decibels, one finds from Fig. 7 that, for each transmitter-receiver pair, the signal will fall below the desired level for 140 minutes per year in Miami, Florida; 13 minutes in Coweeta, North Carolina; 4 minutes in Island Beach, New Jersey; 0.5 minute in Bedford, England; and < 0.5 minute in Corvallis, Oregon. If these outages are judged to be unacceptable, they can be reduced through design of the radio system to provide more margin or through the use of diversity, as discussed below.

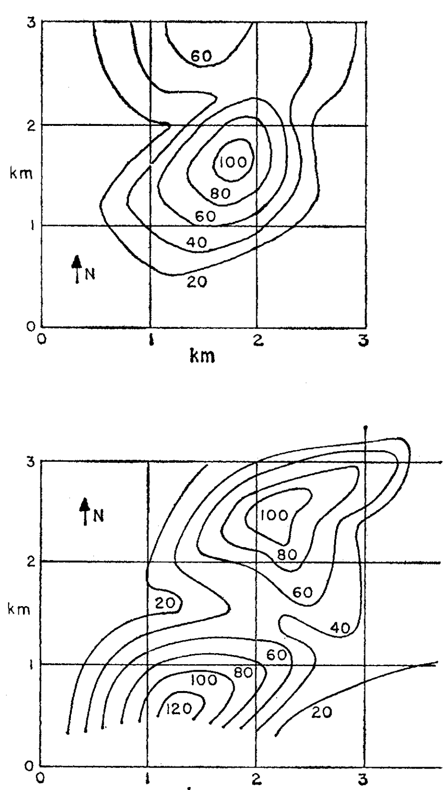


Fig. 8 (left). (Top) Plot of rainfall-rate contours (in millimeters per hour), showing two rain cells on the Bedfordshire rain-gauge network; (bottom) contours 2 minutes later.

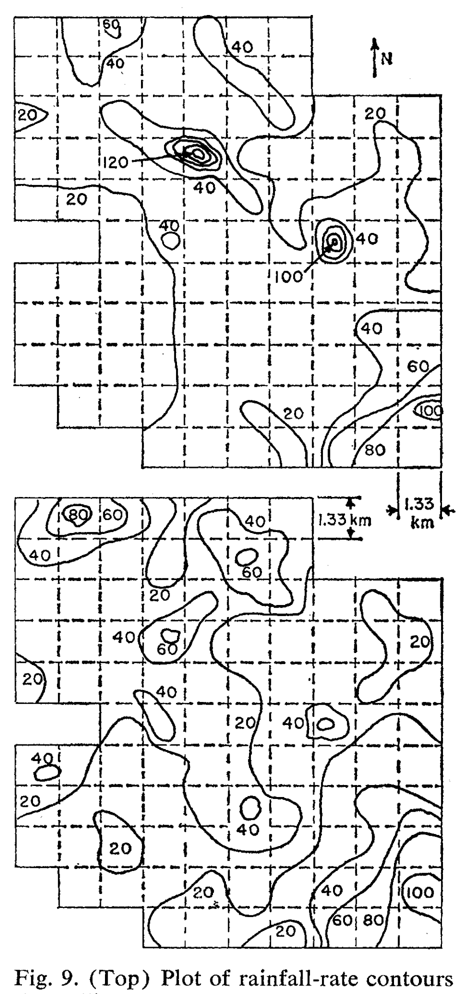


Fig. 9. (Top) Plot of rainfall-rate contours (in millimeters per hour) showing several rain cells on the Holmdel, New Jersey, rain-gauge network; (bottom) contours 10 seconds later.

Fine-Grain Spatial Distribution of Rainfall

Up to this point, the discussion has been centered mainly on the temporal rather than the spatial variability of rainfall. However, it is known from our everyday experience, to some extent from measurements by weather radar, and from dense rain-gauge networks that storms, and particularly heavy showers, have rather fine-grain spatial characteristics. How fine-grain these characteristics of heavy showers are is still a matter for research.

Let me give examples of data taken on two rain-gauge networks of rather high resolutions, one in Bedfordshire, the other in New Jersey, to demonstrate spatial variability.

The Bedford network covers an area about 3 kilometers square and has an intergauge spacing of about 1 kilometer. We can take the reading of rainfall rate for the system at a chosen instant and linearly interpolate between a given gauge and its nearest neighbors. In this way we can plot a contour map. The result of such a procedure *(17)* is shown in Fig. 8, top. In Fig. 8, top, there is evidence of two rather discrete cells, the center of the northern one being somewhat beyond the perimeter of the network. Figure 8, bottom, shows conditions 2 minutes later. The two cells have moved about 1 kilometer toward the south during the 2-minute interval; This movement is equivalent to a translational velocity of about 20 miles (32 kilometers) per hour. The detail of the rain structure is fairly clear in Fig. 8, bottom. However, because there is only one gauge per square kilometer we are not sure that the maximum rates given at the centers of the cells in Fig. 8 are actually the maximum rates. That is to say, the true centers of the cells may not have passed over the points where the gauges are located. As for the shape and size of the cells, we do not know that linear interpolation between gauges is an optimum procedure for determining this.

The Holmdel, New Jersey, network covers an area about 13 kilometers square and has an intergauge spacing of 1.3 kilometers. It consists of 96 rain gauges of the type discussed in connection with Fig. 4. Because of the fast response of such gauges, successive contour maps can represent conditions separated by an interval of as little as 10 seconds; this is the case in Fig. 9. In Fig. 9, top, there is evidence of four fairly discrete cells; the most intense of these is located in the upper central portion of the network and has a maximum rainfall rate of 120 millimeters per hour. Conditions 10 seconds later are shown in Fig. 9, bottom. The intensity of the cell in the upper central section has decreased to 60 millimeters per hour in this short interval, and a similar decrease in intensity has occurred in the cell in the central eastern section.

Apparently Figs. 8 and 9 represent two different types of rainfall dynamics. In Fig. 8 the intensity of the cells is well preserved over the 2-minute interval, and the cells appear merely to undergo a translation. But in Fig. 9 the position of the two central cells appears to be stationary whereas their intensity decreased significantly during the 10-second interval. Figure 9 represents the "on-off" character of rainfall intensity (since no translation is evident).

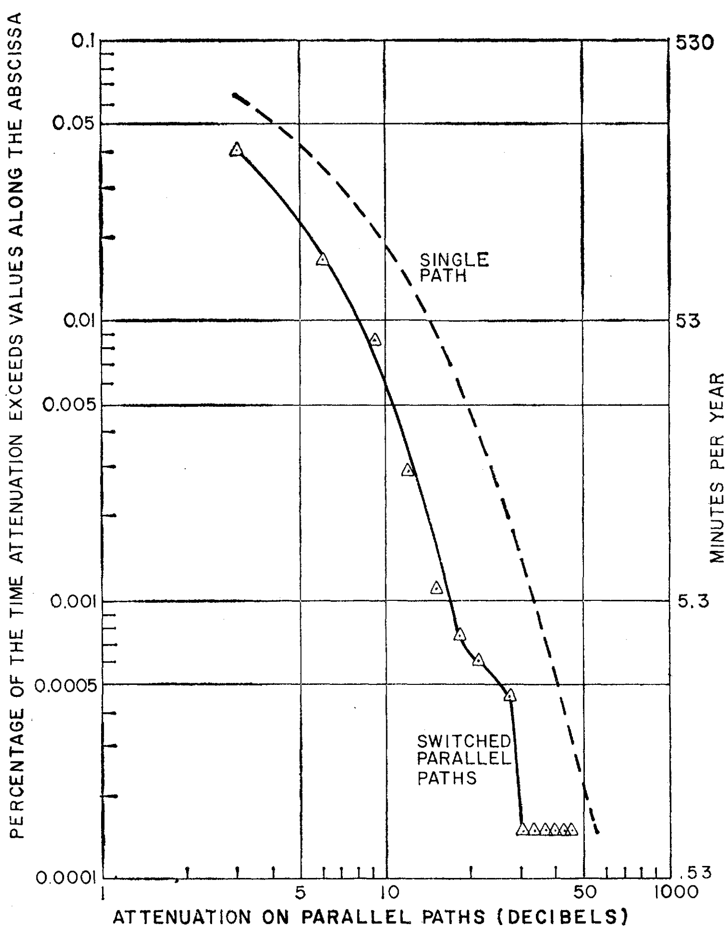
In light of these spatial characteristics, it is of interest to ask how well the average rain rate along one path is correlated with that along another path which is, say, parallel to the first but at a given distance from it. If the attenuation on one path exceeds that on the other, we can switch the communication system to the second path, and vice versa. This alternating type of operation is called switched-path diversity. Through such switching the reliability might be increased for a given spacing between stations, or, conversely, the spacing could be increased over that of a conventional tandem arrangement for a given reliability.

The increase in reliability attainable with a switched-path diversity system has been evaluated; for this purpose, the same 4-year sample of rainfall data from the Bedford network that was discussed in connection with Fig. 8 was used. The paths considered were both 3 kilometers long; they were parallel to each other and separated by a distance of 2 kilometers. The distribution of (effective) attenuation for this "switched-path" case is plotted in Fig. 10, along with distribution of attenuation for the case of a single path. If we again choose the 30-decibel level as a reference value, it is seen that the reliability is improved by a factor of 10 through use of path diversity (outage time is reduced from 10 minutes to 1 minute per year). On the other hand, if we choose a reliability factor of 10 minutes per year per link (about 0.002 on the percentage-of-time scale in Fig. 10), the (effective) attenuation is only 14 decibels for the diversity distribution as compared with 28 decibels for the single path. Thus longer path lengths may be used in the diversity system.

Attenuation by Rain in Space Communication

In evaluating the use of millimeter waves for space communication, what is needed is a set of attenuation distributions similar to the set of distributions of Fig. 7, but with the propagation path extending through the atmosphere at a fairly high angle of elevation rather than along the surface of the earth. No such experimental distributions exist, but, of course, it is known that both falling rain and rain-bearing clouds introduce high attenuations at these wavelengths. Nor are we able to calculate with any certainty what these attenuations would be, because the liquid-water content and the distributions of drop size are unknown for such nearly vertical paths. It has been proposed that measurements made by weather radar be used for calculating the attenuation, but this is a risky business at best, since (i) the radar signal is proportional to the sixth power of the diameter of the raindrop, but the attenuation is roughly proportional to the third power of the diameter, and (ii) the distributions of drop size, except at the earth's surface, are relatively unknown. Also, radar responds to ice particles, which do not play a significant role in attenuation.

At centimeter wavelengths it is possible to estimate attenuation due to rain by measuring the black-body radiation (that is, microwave noise) generated by the rain. Measurements of this type have been made at a frequency of 6 gigahertz *(18)* over a period of about 5 months. While the validity of the result is somewhat uncertain, the data from this limited sample have been transformed, through use of the best estimate for the dependence of attenuation on wavelength, to produce a distribution of attenuation for frequency of 30 gigahertz. The result, given in Fig. 11, applies to a zenith path above central New Jersey. Again using the 30-decibel criterion as one that provides a suitable margin, one sees from Fig. 11 that the appropriate outage time



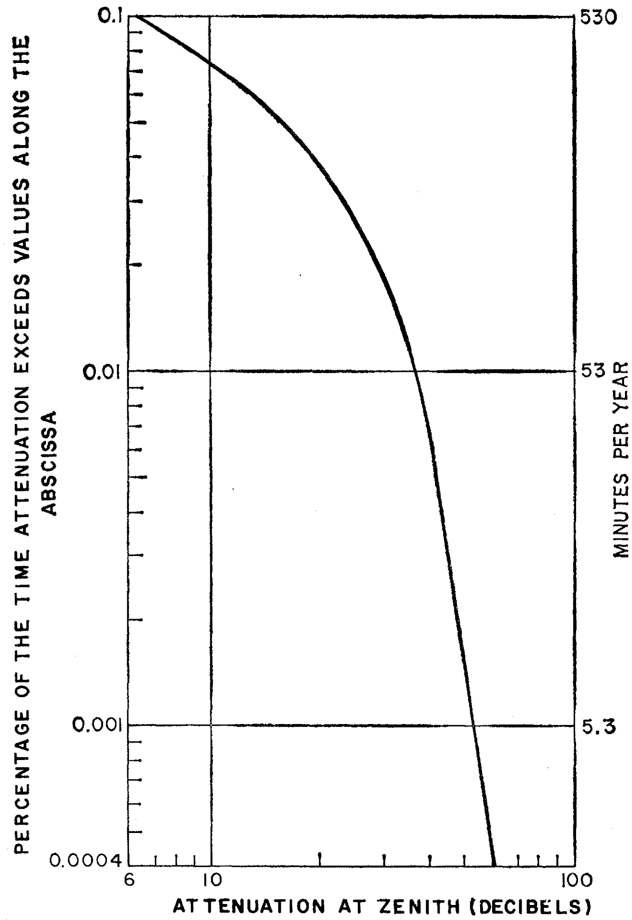


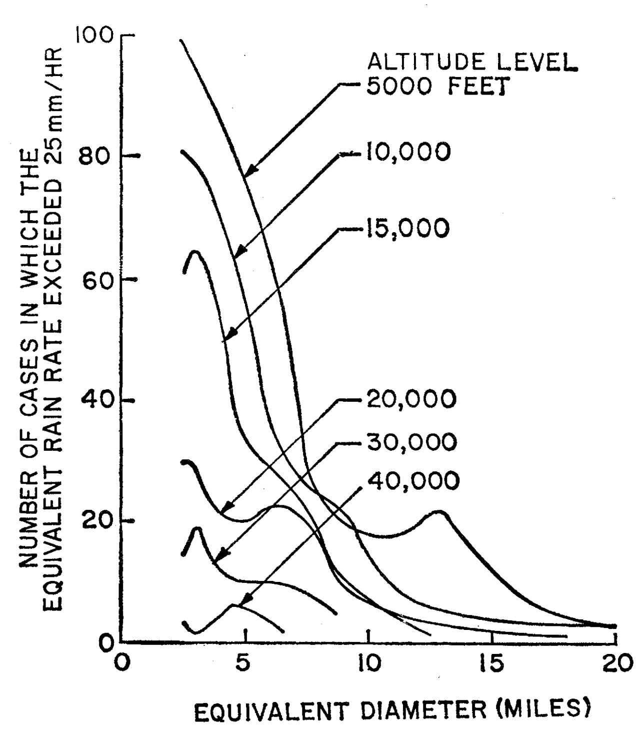
Fig. 10 (left). Distribution, in percentage of time and minutes per year, of attenuation at frequency of 30 gigahertz, calculated (i) for two parallel paths separated by a distance of 2 kilometers and operated as a switched-path communication system, and (ii) for a single path. [Based on 4-year data sample made available through the courtesy of Her Majesty's Meteorological Office] Fig. 11 (right). An estimated distribution, in percentage of time and minutes per year, of attenuation at frequency of 30 gigahertz for a zenith-oriented antenna beam at Holmdel, New Jersey; the data were extrapolated from a limited sample at frequency of 6 gigahertz.

is about 2 hours per year. Of course the distribution of Fig. 11 is speculative, and knowledge of the true state of affairs must await further measurement. But this does give an idea of the problem that is faced *(19)*. However, I now discuss a way of circumventing the problem.

Path Diversity in Space Communication

Just as in earth-based systems, in space communication the fact that very heavy rains are usually quite localized can be used to advantage. Thus, one pictures communication by way of, say, a synchronous satellite to be accomplished by locating two or more stations at a given terminal on the earth. The question then is: How far apart must these terminal stations be placed in order to obtain diversity—that is, in order for the path from one station

Fig. 12. Frequency of occurrence of rain cells as a function of cell diameter for various altitudes. [Based on half-year sample made available through the courtesy of McGill University, Montreal]



toward the satellite to be out of range of a heavy storm that is obscuring the path from the other station? In this case, data obtained by weather radars help resolve the question.

Weather-radar data taken over a 5-month period in a study at McGill University (Montreal, Canada) have been analyzed *(20)* in an effort to identify the areas of storms of various intensities at various altitudes. It is true, of course, that not all storms are circular patches; some may be considerably elongated, as in the case of a frontal storm. Nevertheless, the needed inter-station spacing referred to above can be estimated by taking the square root of these areas. This is what has been done in Fig. 12. These plots show the number of storms of a given diameter whose intensity exceeded an equivalent rainfall rate of 25 millimeters per hour. Curves are given for several altitudes between 5000 and 40,000 feet (1500 and 12,000 meters). One immediately notes that the storm size does not depend strongly on altitude—that is, most of the curves fall to rather low values when the equivalent diameter exceeds 10 miles (16 kilometers). Taken at face value, this means that good path diversity should be attainable in a space communication system with terminal-station spacings of 10 miles or more. However, nothing has been said here about correlation of storms over the earth's surface; degradation in diversity due to this effect is a subject for future study.

Remarks

In investigating the possibility of using millimeter waves for satellite communication and earth-based radio relay, we find that attenuation by rain is the chief cause of unreliability. But much is yet to be learned about the spatial and temporal behavior of rainfall. How large is a rain cell with intensity of several hundred millimeters per hour? Is there an optimum class of showers for which the diameter decreases as the intensity increases, the total amount of water remaining constant? What must be the spacing between two propagation paths such that correlation between their average rainfall rates is below a prescribed value? For what length of path are the statistics of average rainfall rate well described by the statistics obtained at a point on the path? Questions such as these will be answered through establishment of rain-gauge networks of high temporal and spatial resolution, through study of the small-scale dynamics of the rain cells, and through appropriate design of attenuation experiments at millimeter wavelengths.

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