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Rain Attenuation on Earth-Satellite Paths—Summary of 10-Year Experiments and Studies

By S. H. LIN, H. J. BERGMANN, and M. V. PURSLEY

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Since 1969, the Bell System has been conducting continuous rain attenuation experiments on earth-satellite paths. The experiments were carried out at four New Jersey sites by the radio basic research group of the Crawford Hill Laboratory, and at three Georgia sites, two Illinois sites, and two Colorado sites by the radio system engineering group of the Holmdel Laboratory. The measurement frequencies include 11.7, 13.6, 15.5, 17.8, 19, and 28.5 GHz. Interim results of the 10-year (1969–1978) experiments have been published in various technical journals and conference proceedings. For the convenience of system engineers, this paper summarizes the new results and the previously published results and discusses the implications of these data to the design of satellite radio communication systems. The summary includes the geographic dependence, the frequency dependence, the diurnal, monthly, and yearly variations of rain attenuation statistics, the diversity improvement factors, the fade duration distributions, the dynamic rain attenuation behavior, the long-term (20 years) rain rate distribution for U.S. locations, and a simple empirical model for rain attenuation.

I. INTRODUCTION

In 1967 and 1968, the Bell System used a suntracker during the day and a radiometer during the night to measure rain attenuation statistics on earth-space paths because there were no strong signal sources in space available for measurement of large rain attenuation on earth-space paths, except the sun.[1] These pioneer experiments[1–4] have contributed significantly to the understanding of rain attenuation phenomena on earth-space paths. An excellent review of these early experiments can be found in Ref. 5.

However, the antenna elevation angle of the suntracker is not constant. For direct application to satellite communication systems, it is desirable to measure rain attenuation statistics with fixed antenna elevation angle. The radiometer technique can fulfill this need by measuring rain-originated thermal noise with a constant antenna elevation angle.[6,7] In other words, the radiometer technique does not require any active signal source in space such as the sun or satellite beacons. The dynamic range of the radiometer technique for rain attenuation measurement is approximately 10 dB. By simultaneous measurements at Holmdel, New Jersey, using a 16-GHz radiometer and a 15.3 GHz receiver for the NASA ATS-5 beacon signal, A. A. Penzias[8] first verified the accuracy of the radiometer technique in 1969.

Since 1969, the Bell System has been conducting continuous rain attenuation experiments at microwave frequencies on earth-satellite paths with constant antenna elevation angle in New Jersey, Georgia, Illinois, and Colorado. Both radiometers and radio receivers for satellite beacon signal reception have been employed. The measurement frequencies include 11.7, 13.6, 15.5, 17.8, 19, and 28.5 GHz. The effects of site-diversity protection with site separation ranging from 3 to 47 kilometers were an integral part of these experiments.

All rain attenuation data presented and discussed in this paper are measured with constant antenna elevation angle using either radiometers or satellite beacon receivers. Tables I, II, and III summarize the important parameters of these experiments. Figures 1 and 2 depict the locations and the configuration of the site-diversity experiments. All measurements listed in Tables I, II, and III were performed over continuous, long-term ($\geq$ 1 year) periods.* Experimental details and some of the results of this extensive measurement program have been published in Refs. 5 to 32, 41 to 44, and 101.

In parallel with these wave propagation experiments, long-term (20 to 70 years) distributions of 5-minute point rain rates for U.S. locations have been obtained by computer processing of rainfall data published by the National Climatic Center.[33–37]

Based on the large amount of rain attenuation data on earth-satellite paths and the surface point rain-rate distributions, a simple empirical model has been deduced for prediction of the long-term distribution of rain attenuation from the long-term distribution of 5-minute point rain rates at the location of interest.

Publication of the interim results of the 10-year (1969 to 1978) experiments and studies was scattered among many different technical journals, conference proceedings, and meeting digests (see Refs. 5 to 44). For convenience of system engineering and planning, this paper summarizes the new results and the previously published results which are important to the design of earth-satellite radio communication

* Reference 6 describes a four-month experiment not covered in this paper, with short baselines of 3 and 11 km.

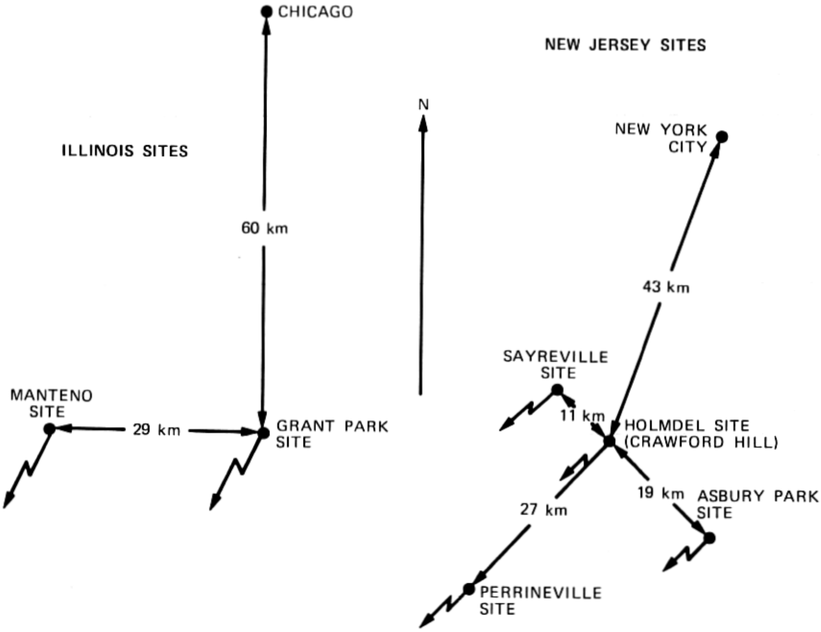

Fig. 1—Configurations of radiometer site-diversity experiments in New Jersey and Illinois.

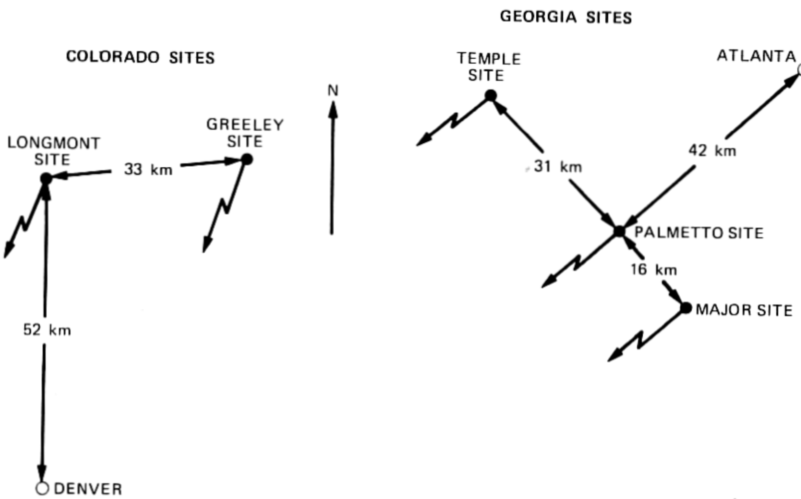

Fig. 2—Configurations of radiometer site-diversity experiments in Georgia and Colorado.

systems. The implications of these results to system engineering are also discussed.

All the New Jersey-based experiments were carried out by the radio research group of the Crawford Hill Laboratory including H. W.

Table I—Rain attenuation experiments on earth-space paths using radiometer

Location	Freq. (GHz)	Elev. Angle (Degr.)	No. of Sites	Site Separation (Km)	Operation Period: No. of Yrs.	Operation Period	Ground Elevation H (Km)
Holmdel, N.J.	15.5	32	3	11, 19, 30	2	9/15/69–9/14/71	0.15
Holmdel, N.J.	15.5	32	3	19, 27, 33	1	11/1/71–11/1/72	0.15
Palmetto, Ga.	17.8	38.2	3	16, 31, 47	2	6/73–6/75	0.29
Palmetto, Ga.	17.8	29.9	2	31	1	6/76–7/77	0.29
Palmetto, Ga.	13.6	38.2	1	—	2	6/73–6/75	0.29
Palmetto, Ga.	13.6	29.9	1	—	1	6/76–7/77	0.29
Palmetto, Ga.	13.6	49.5	1	—	1	8/77–8/78	0.29
Grant Park, Ill.	13.6	27.3	2	29	1	7/76–6/77	0.20
Grant Park, Ill.	13.6	41.8	2	29	1	8/77–8/78	0.20
Longmont, Colo.	17.8	42.6	2	33	2	6/73–6/75	1.50
Longmont, Colo.	13.6	42.6	1	—	2	6/73–6/75	1.50

Table II—Rain attenuation experiments on earth-satellite paths using satellite beacon

Location	Freq. (GHz)	Elev. Angle (Degr.)	Satellite	Operation Period		Groun Elevation H (Km)
				No. of Yrs.		
Holmdel, N.J.	11.7	27	CTS	>3	4/76–Continuing	0.15
Holmdel, N.J.	19	18.5	COMSTAR, D1	>2	6/76–9/78	0.15
Holmdel, N.J.	19	38.6	COMSTAR, D2	1½	1/77–9/78	0.15
Holmdel, N.J.	28.5	38.6	COMSTAR, D2	1½	1/77–9/78	0.15
Holmdel, N.J.	19	41.5	COMSTAR, D3	1	9/78–Continuing	0.15
Holmdel, N.J.	28	41.5	COMSTAR, D3	1	9/78–Continuing	0.15
Palmetto, Ga.	19	29.9	COMSTAR, D1	1	6/76–7/77	0.29
Palmetto, Ga.	28.5	29.9	COMSTAR, D1	1	6/76–7/77	0.29
Palmetto, Ga.	19	49.5	COMSTAR, D2	1	8/77–8/78	0.29
Palmetto, Ga.	28.5	49.5	COMSTAR, D2	1	8/77–8/78	0.29
Palmetto, Ga.	19	51.0	COMSTAR, D3	1	9/78–Continuing	0.29
Palmetto, Ga.	28.5	51.0	COMSTAR, D3	1	9/78–Continuing	0.29
Grant Park, Ill.	19	27.3	COMSTAR, D1	1	7/76–6/77	0.20
Grant Park, Ill.	28.5	27.3	COMSTAR, D1	1	7/76–7/77	0.20
Grant Park, Ill.	19	41.8	COMSTAR, D2	1	8/77–8/78	0.20
Grant Park, Ill.	28.5	41.8	COMSTAR, D2	1	8/77–8/78	0.20

Table III—Locations and beacon frequencies of geostationary satellites

	Satellite Location (Longitude)	Beacon Frequency (GHz)
COMSTAR(D1)	128° W	19 and 28.5
COMSTAR(D2)	95° W	19 and 28.5
COMSTAR(D3)	87° W	19 and 28.5
Communication Technology Satellite (CTS)	116° W	11.7

Arnold, D. C. Cox, D. A. Gray, D. C. Hogg, H. H. Hoffman, R. P. Leck, A. W. Norris, A. A. Penzias, A. J. Rustako, and R. W. Wilson. The other experiments were carried out by H. J. Bergmann, E. E. Muller, and G. Zimmerman.

Precipitation-induced microwave depolarization on earth-satellite paths is addressed in Refs. 5, 10, 15–17, 21–32, 41–44, 99, and 100 and are not discussed in this paper.

II. SUMMARY AND CONCLUSION

The data indicate that the 28.5-GHz earth-satellite radio link, assuming 20-dB fade margin, will require site-diversity protection for most U.S. locations to meet the conventional long-haul reliability objective. Operation in this or higher frequency bands would therefore probably require new network operation procedures.

On the other hand, the site-diversity protection may be avoided if the frequency is at or below 14 GHz and if the antenna elevation angle is above 43 degrees for eastern U.S. locations (assuming 20-dB fade margin). The antenna elevation angle can be lower than 43 degrees for earth stations in the relatively dry western U.S.A. Consequently, the frequency bands below 14 GHz and the eastern satellite orbital positions should be considered as very precious national resources and should be utilized accordingly.

The 19-GHz earth-satellite link may or may not require site-diversity protection, depending on earth-station location and satellite orbital position. Other major findings are:

(*i*) Rain-induced outages on earth-satellite radio have higher service impact than multipath-fading-induced outages on terrestrial (4/6 GHz) radio relays even if the two systems are engineered for equal total outage time. This is because multipath fading occurs mostly during the early morning hours of low telephone activity. Furthermore, multipath fading is frequency selective and interrupts only a fraction of the frequency band at a time. By contrast, about 35 percent of rain outages will occur during telephone busy hours, and the outage will interrupt all traffic on an earth-satellite radio link at the same time

(*ii*) Site diversity protection can reduce the rain outage time by at least one order of magnitude if site separation exceeds 20 km. Orbital diversity protection, although effective against sun-transit outages, reduces rain outage time by less than 20 percent.

(*iii*) The measured temporal variations of rain attenuation indicate that the rate of change (i.e., the absolute value of time derivative) of attenuation tends to increase with attenuation in decibels. It is demonstrated that this proportionate behavior is another manifestation of lognormality of the rain attenuation process.

(*iv*) The distribution of the duration of rain attenuation, exceeding a given threshold, is approximately lognormal. The average duration of rain fades exceeding a 25-dB threshold on the 19-GHz COMSTAR(D2)-to-Palmetto path is 3 minutes. About 23 percent of the outages are longer than the average outage duration. The probability of an outage duration lasting longer than 10 times its average duration is about one percent (i.e., one out of 100 outages).

(*v*) From the large amount of rain rate and rain attenuation data, we have deduced a simple empirical model for prediction of a rain attenuation distribution from a point rain rate distribution. The model, consisting of three simple equations, has the virtue of easy application in system engineering studies.

III. GEOGRAPHIC AND FREQUENCY VARIATIONS OF RAIN ATTENUATION DISTRIBUTION

The cumulative distributions of rain attenuation measured in Georgia, New Jersey, Illinois, and Colorado are displayed in Figs. 3 to 15. They include attenuation data for single site and simultaneous fades of multiple sites in site diversity configuration.

One purpose of these experiments was to determine the rain outage probability of an earth-satellite radio link as functions of frequency and geographic location. The available long-term rain-rate data indicate that heavy-rain probability is relatively high in the southeastern U.S.A., decreases toward the northeast, and further decreases in the western U.S.A. (see Fig. 38). One would expect that the rain attenuation distribution follows this general pattern. However, the rain attenuation distribution on an earth-satellite path depends not only on the local rain-rate distribution but also on the antenna elevation angle and the ground elevation.

3.1 North-south variation

Figure 14 shows that the one-year rain attenuation distributions measured on the three paths, COMSTAR(D1)-to-Palmetto (Ga.), COMSTAR(D1)-to-Holmdel (N.J.), and COMSTAR(D1)-to-Grant Park (Ill.), are almost identical. Contrary to expectations, the lack of north-south variation is due to the effect of antenna elevation angle. When pointing to a given geostationary satellite, the northern location uses a lower

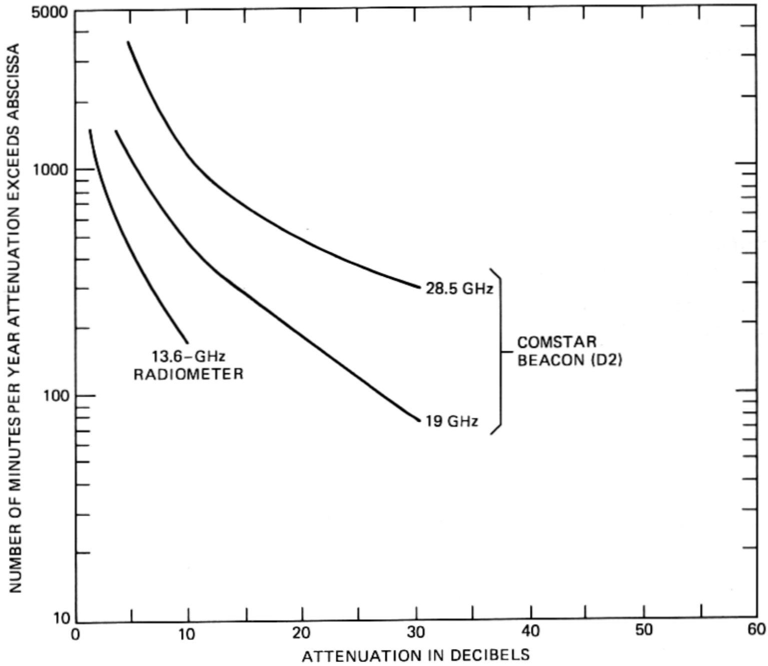

Fig. 3—One-year (August 1977 to August 1978) cumulative distributions of 13.6-, 19-, and 28.5-GHz rain attenuations measured from the COMSTAR(D2)-to-Palmetto path with 49.5-degree elevation angle.

antenna elevation angle, which corresponds to a longer rainfall intercepting path. The effect of antenna elevation angle variation partially compensates for the north-south variation of rain-rate distribution. However, these one-year data must be viewed with some caution because of the year-to-year variation discussed in Section IV. The year-to-year variations at widely separated sites may not be correlated.

3.2 East-west variation

The two-year radiometer data on Fig. 15 show that the probability of 17.8-GHz attenuation exceeding the 10-dB threshold in Colorado is lower than that in Georgia by a factor of 60. Three important factors contribute to such a large difference in outage probabilities:* (*i*) rain-rate distributions in Colorado are lower than those in Georgia by a factor of 10 (see Fig. 38), (*ii*) the ground elevation at Longmont, Colorado is about 1.5 km above sea level, which leads to a shorter length of the earth-satellite path which may intercept heavy rain, and (*iii*) the antenna elevation angle at Longmont, Colorado is 42.6 degrees,

* The rain attenuation data measured by suntrackers in New Jersey (Refs. 1–3) and in California (Ref. 4) also indicate difference in attenuation probabilities by more than one order of magnitude.

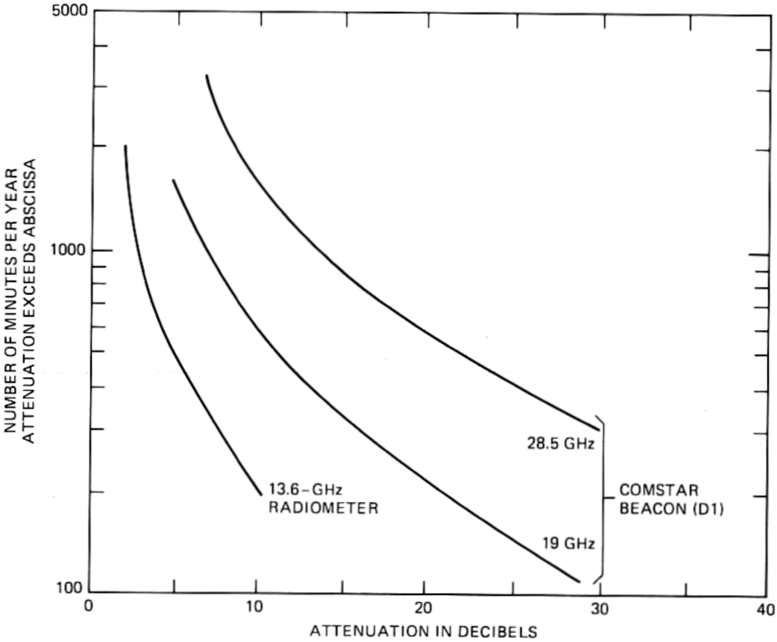

Fig. 4—One-year (June 1976 to July 1977) cumulative distributions of 13.6-, 19-, and 28.5-GHz rain attenuations measured from the COMSTAR(D1)-to-Palmetto path with 29.9-degree elevation angle.

which is higher than 38.2 degrees at Palmetto, Georgia.* These data indicate that an eastern satellite orbital position is highly desirable to reduce the rain outage probabilities for earth-stations in the relatively wet, eastern U.S.A.

The present consensus is that a feasible and practical fade margin for earth-satellite radio link is 20 dB or less. Figure 13 indicates that in Colorado the probability of 17.8 GHz attenuation exceeding the 10-dB threshold is less than 15 minutes per year per link. The measured ratio of attenuations at 28.5 and 19 GHz is approximately 2 to 1† within the dynamic range of the experiment. Therefore, in Colorado the probability of 28.5 GHz attenuation exceeding 20 dB is expected to be less than 15 minutes per year per link. This is comfortably less than the conventional outage objective of 0.02 percent of the time (i.e., 105 minutes per year) for a long-haul radio transmission system.[45–50] Since the rain rate distributions in western U.S.A. are generally lower than those in Colorado, 19-GHz earth stations in the western U.S.A. can meet the conventional reliability objective without site diversity protection.

* The antennas of these radiometer experiments were all pointed to an assumed geostationary satellite position at 116 degrees west.

† The theory indicates that this ratio decreases slightly as the rain rate increases.

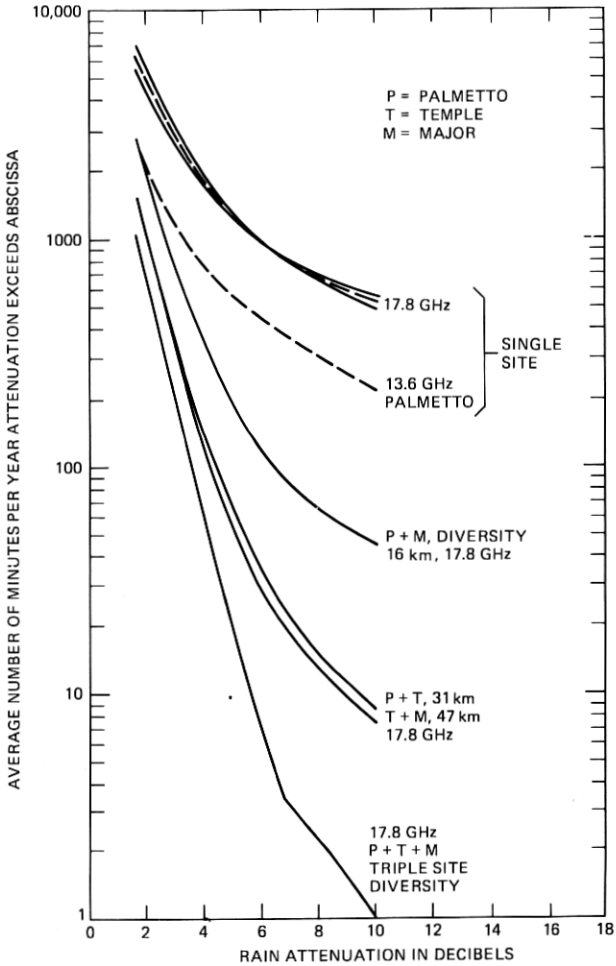

Fig. 5—Two-year (June 1973 to June 1975) cumulative distributions of rain attenuation measured by a 13.6-GHz and a 17.8-GHz radiometer at Palmetto (P) and by 17.8-GHz radiometers at Major (M) and Temple (T), Georgia. The elevation angle is 38.2 degrees. The simultaneous fades on diversity sites are all measured at 17.8 GHz.

The results for the eastern U.S.A. indicate that diversity protection is required for frequency bands above 18 GHz. Figures 3 to 10 indicate the probability of 28.5-GHz attenuation exceeding the 20-dB level ranges from 300 to 600 minutes per year per link, depending on the location and the antenna elevation angle. The 19-GHz outage time is lower than the 28.5-GHz outage time by a factor of 2 for the same fade margin. (Of course, the outage time will be even higher if the achieved fade margin is less than 20 dB.) Therefore, earth stations in most eastern locations operating at 19 GHz or higher frequencies will require site-diversity protection if the conventional outage objective is to be observed.

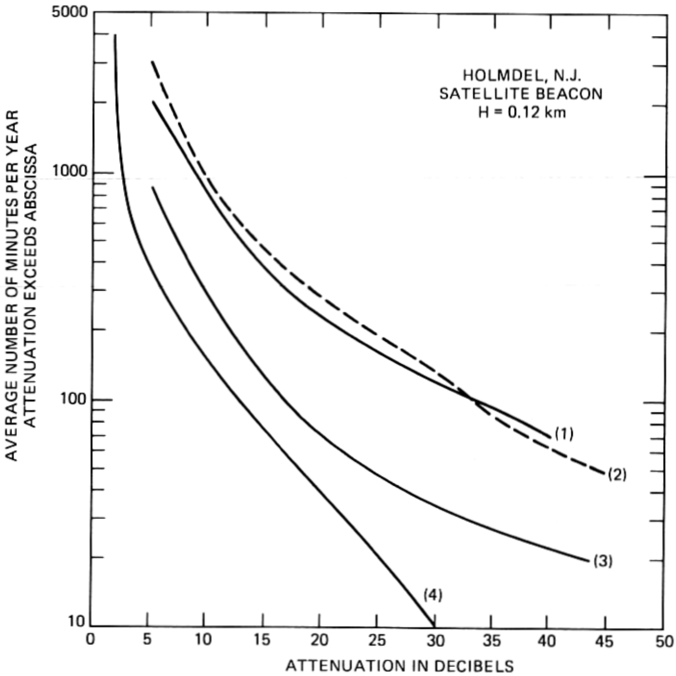

Fig. 6—One-year cumulative distributions of rain attenuation on earth-satellite paths measured at Crawford Hill (Holmdel), New Jersey. (1) 19-GHz COMSTAR(D1)-to-Holmdel path with 18.5-degree elevation angle. One year (June 1976 to June 1977). (2) 28.5-GHz COMSTAR(D2)-to-Holmdel path with 38.6-degree elevation angle. One year (May 18, 1977 to May 18, 1978). (3) 19-GHz COMSTAR(D2)-to-Homdel path with 38.6-degree elevation angle. One year (May 18, 1977 to May 18, 1978). (4) 11.7-GHz CTS satellite-to-Holmdel path with 27-degree elevation angle. One year (April 1976 to April 1977).

Notice that the measured rain attenuation decreases rapidly with frequency. Site-diversity protection may be avoided if the operating frequency is below 14 GHz and if an eastern satellite orbital position is chosen to maximize the antenna elevation angle for earth stations in the heavy-rain, eastern U.S.A. For this reason, the frequency bands below 14 GHz and the eastern satellite orbital positions should be considered very precious national resources and should be utilized accordingly.

Other aspects and implications of these attenuation data are discussed in the following sections.

IV. DIURNAL, MONTHLY AND YEARLY VARIATIONS OF RAIN ATTENUATION STATISTICS

Radio outages occurring during periods of low telephone activity are more tolerable than those occurring during busy hours. The information on diurnal variation of rain-induced radio outages is, therefore, useful to radio engineering. One-year (June 1976 to July 1977) rain attenuation data measured from the 19-GHz COMSTAR(D1)-to-Palmetto path has been processed to determine the diurnal dependence. The results are shown in Fig. 16. Substantial percentages (30 to 40 percent) of rain outage occurs during the telephone busy hours (08:00–12:00, 13:00–17:00, 19:00–20:00). By contrast, multipath fading-induced outages on 4- and 6-GHz terrestrial radio relays occur mostly during the night, especially the early morning hours of low telephone activity.[51–54] Furthermore, multipath fading, being an interference phenomenon, is frequency-selective and interrupts only a small fraction of the radio frequency band at a time. For this reason, 1 by N frequency diversity protection is effective against multipath fading. On the other hand, rain attenuation will interrupt all the traffic on the radio link at the same time. Therefore, rain outages of satellite radio system will be more noticeable and more annoying than multipath outages of terrestrial radio relays even if both systems are engineered for equal total outage time.

Figures 17 and 18 show monthly and seasonal variations of rain

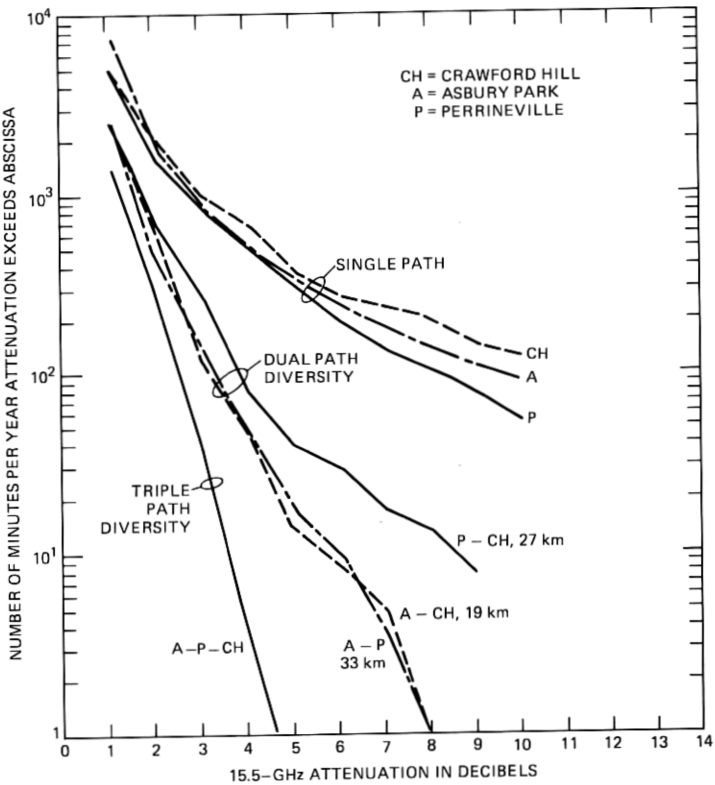

Fig. 7—One-year (November 1, 1971 to November 1, 1972) cumulative distributions of rain attenuation measured by 15.5-GHz radiometers at Crawford Hill (CH), Asbury Park (A), and Perrineville (P), New Jersey, with 32-degree elevation angle.

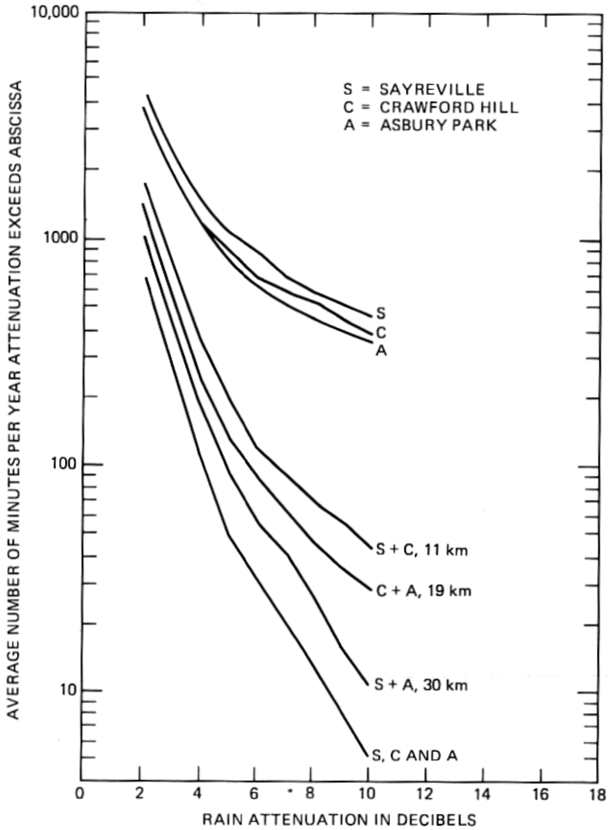

Fig. 8—Two-year (September 15, 1969 to September 14, 1971) cumulative distributions of rain attenuation measured by 15.5-GHz radiometers at Crawford Hill (CH), Asbury Park (A), and Sayreville (S), New Jersey, with 32-degree elevation angle.

attenuation statistics without diversity protection. Figure 18 shows that the rain outage probability in the winter season is lower than the annual average, as expected. With site diversity protection, the remaining outages become significantly more concentrated in the worst month. The fraction of annual outage contained in the worst month is shown in Fig. 19. In other words, site-diversity protection eliminates most of the outage events which typically occur over 4 to 5 months, leaving only a few severe rain storm outages occurring in the one or two "worst" months.

Figures 20 and 21 show the variation of measured yearly distribution of rain attenuation. The measured probability of attenuation exceeding 10 dB can vary by a factor of 4 from one year to another. Such a large variation highlights the need for continuous measurement for more than one year.

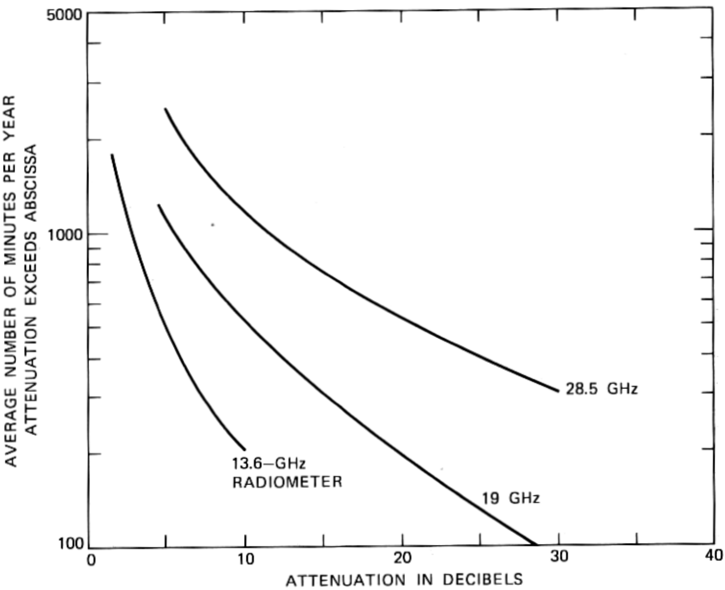

Fig. 9—One-year (August 1977 to August 1978) cumulative distributions of 13.6-, 19-, and 28.5-GHz rain attenuation measured from the COMSTAR(D2)-to-Grant Park path with 41.8-degree elevation angle.

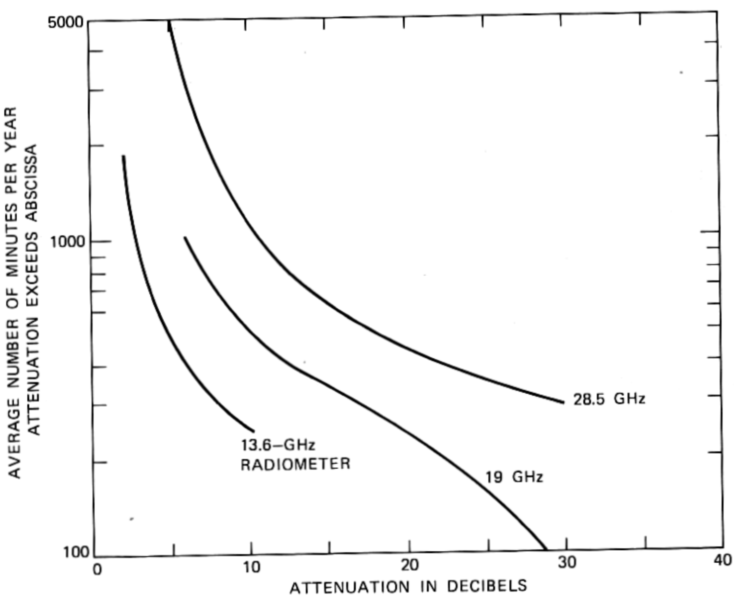

Fig. 10—One-year (July 1976 to June 1977) cumulative distributions of 13.6-, 19-, and 28.5-GHz rain attenuation measured from the COMSTAR(D1)-to-Grant Park path with 27.3-degree elevation angle.

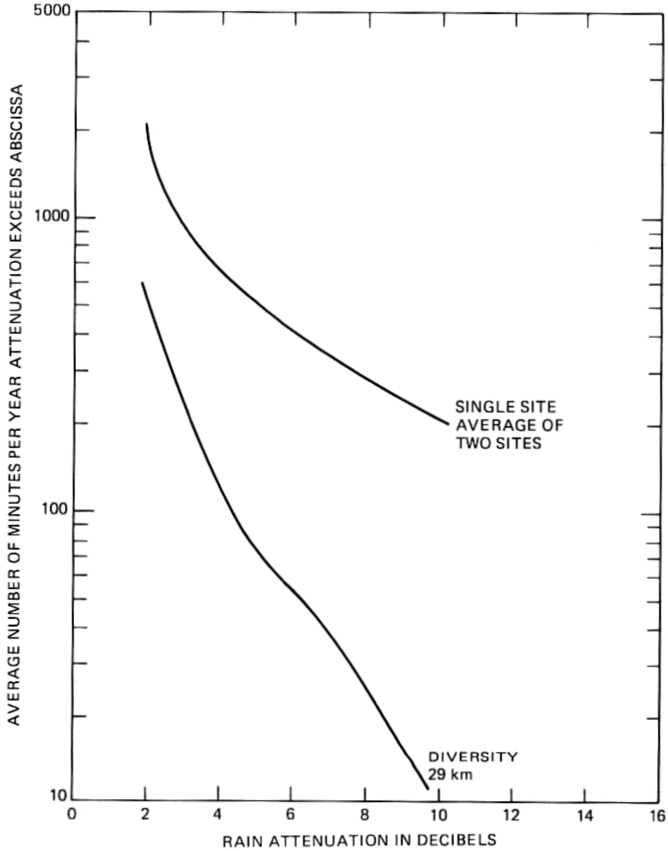

Fig. 11—One-year (August 1977 to August 1978) cumulative distributions of rain attenuation measured by 13.6-GHz radiometers at Grant Park and Manteno, Illinois, with 41.8-degree elevation angle.

V. EFFECTS OF SITE DIVERSITY AND ORBITAL DIVERSITY PROTECTIONS

Another purpose of these experiments was to determine the effectiveness of diversity protection for rain outage limited radio systems. Figures 5, 7, 8, 11, 12, and 13 show that site diversity indeed provides ample reduction factors of rain outage time to meet the conventional outage objective. For convenience, we define the diversity improvement factor as the ratio of nondiversity fade time to diversity fade time at the same attenuation threshold. The measured diversity improvement factor versus site separation are displayed on Figs. 22 and 23. In general, an improvement factor of 10 can be achieved if the site separation exceeds 20 km and if fade margin is at least 10 dB.

The data also indicate that the baseline of multiple sites normal to

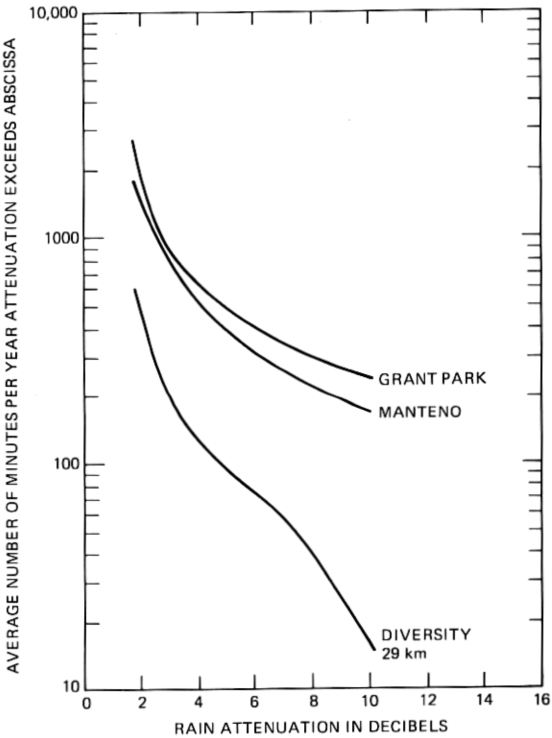

Fig. 12—One-year (July 1976 to June 1977) cumulative distributions of rain attenuation measured by 13.6-GHz radiometers at Grant Park and Manteno, Illinois, with 27.3-degree elevation angle.

the radio path and, secondarily, normal to the direction of the convective weather fronts, are most desirable for large improvement factors. More detailed discussion of the effects of baseline orientation can be found in Refs. 5 and 9.

Figures 24 and 25 show that the measured diversity improvement factor varies considerably from year to year. The reason for this instability is the small number of extreme rain storms per year which cause simultaneous deep fades on the diversity sites. Many years of continuous measurement are required to experience sufficient number of extreme rain storms for stable, representative statistics of simultaneous fades on multiple sites.

Another form of diversity referred to as orbital diversity is illustrated in Fig. 26. It protects the system against sun transit outages and equipment failures of the main satellite. The question is whether this form of diversity protection is effective against rain outages. The measured data on Fig. 27 indicates that the rain attenuations on the two converging paths are highly correlated and the diversity improvement factor is trivially small (≤ 1.2). Therefore, orbital diversity is *not* effective against rain outages.

VI. PROPORTIONATE EFFECT AND LOGNORMAL DISTRIBUTION

Many sets of measured rain rate and rain attenuation data indicate that long-term distributions of rain rate and rain attenuation are approximately lognormal.[55–67] In the following, we present two sets of data to show that the temporal variation of rain attenuation obeys the proportionate effect described by Aitchison and Brown.[68] The proportionate variation of rain attenuation is another manifestation of the lognormality of rain attenuation statistics.

The rainfall and microwave rain attenuation processes are influenced by many environment parameters. An important question is whether the environmental parameters affect the rain attenuation in a proportional fashion or in an additive fashion. It is well known that

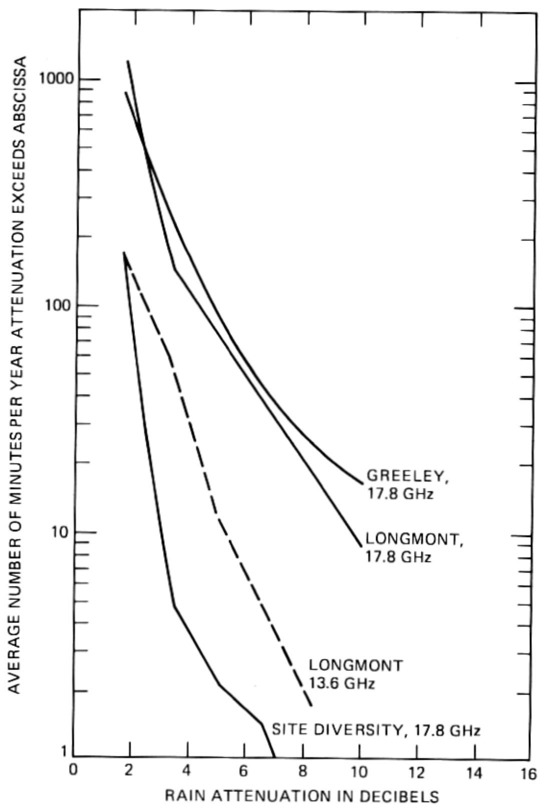

Fig. 13—Two-year (June 1973 to June 1975) cumulative distributions of rain attenuation measured by a 13.6-GHz and a 17.8-GHz radiometer at Longmont and by a 17.8-GHz radiometer at Greeley, Colorado, with 42.6-degree elevation angle.

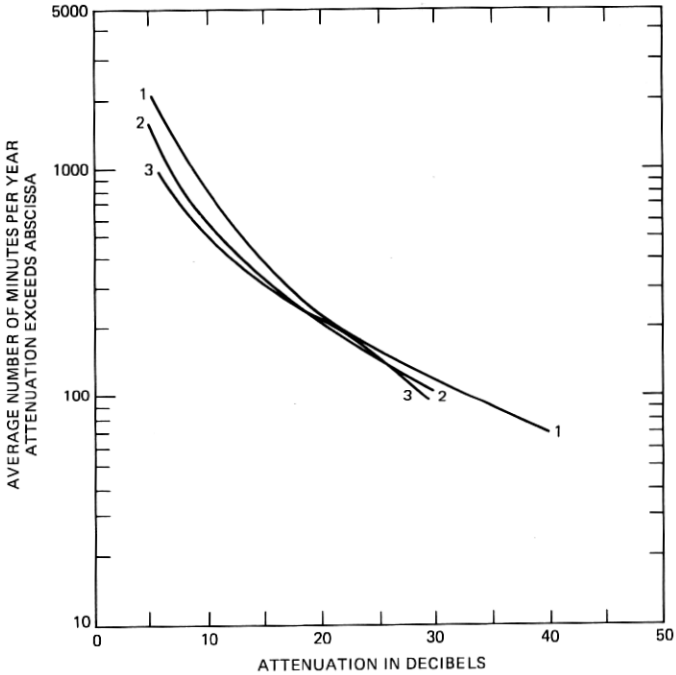

Fig. 14—Almost identical distributions of 19-GHz rain attenuation measured from the three paths: (1) COMSTAR(D1)-to-Holmdel, New Jersey; (2) COMSTAR(D1)-to-Palmetto, Georgia; and (3) COMSTAR(D1)-to-Grant Park, Illinois. One-year data from June 1976 to June 1977.

a proportional fashion leads to a lognormal distribution, whereas an additive fashion leads to a normal distribution. The following rain attenuation data demonstrate that the rate of change (i.e., the absolute value of the time derivate) of rain attenuation tends to increase with the attenuation.

Figure 28 displays a 32-minute sample of temporal variation of rain attenuation measured from the 19-GHz COMSTAR(D2)-to-Palmetto path. It is seen that the rate of change of attenuation (i.e., slope) tends to increase with the attenuation level. The scatter plot on Fig. 29 shows the correlation between the slope* and the attenuation in this 32-minute sample period. One month (April to May 1978) of rain attenuation data on this path was processed in this fashion, and the result is shown in Fig. 30. It is seen that the average† slope at a given attenuation level indeed increases with the attenuation. Figure 31

* The slope is calculated as $\Delta\alpha/\Delta t = |\alpha(t + \Delta t) - \alpha(t)|/\Delta t$, where $\Delta t = 0.17$ minute (or 10 seconds) and $\alpha(t)$ is the rain attenuation in decibels at time t.

† Average over the one-month period of the randomly varying slope at a given attenuation level.

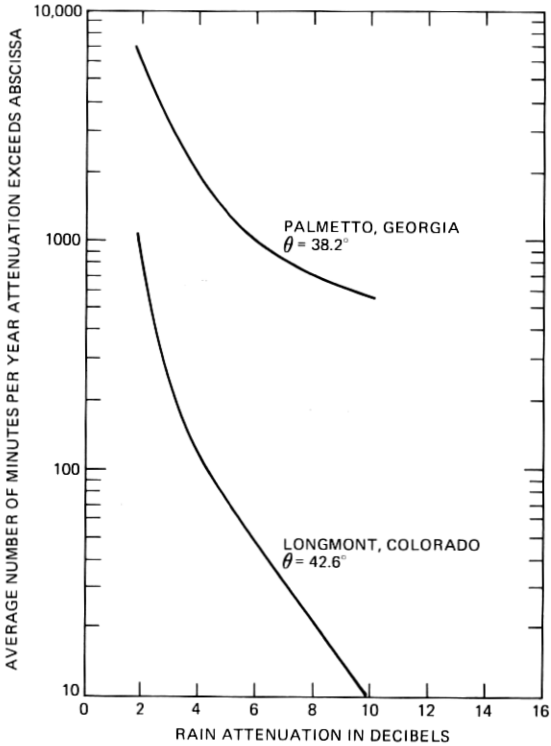

Fig. 15—Large difference in distributions of 17.8-GHz rain attenuations measured by radiometers at Palmetto, Georgia, and Longmont, Colorado. Two-year data from June 1973 to June 1975.

displays the similar correlation obtained from 8-month measurement on an 18-GHz, 3.2-mile terrestrial radio path at Palmetto, Georgia.

These data indicate that the increment, $\Delta\alpha$, of attenuation, α, in decibels is approximately linearly proportional to α, i.e.,

$$\Delta\alpha = h \cdot \alpha, \tag{1}$$

where h is a proportional parameter. The scattering of the data on Fig. 29 and the random variation of $\Delta\alpha$ on Fig. 28 indicate that the proportional parameter, h, is not a constant, but is a time-varying random variable. Equation (1) can be interpreted in that the change, $\Delta\alpha$, in attenuation is proportional to the product of the attenuation and the intensity of the cause h. In other words, the environmental parameters affect the rain attenuation in a *proportional fashion*. Therefore, the data on Figs. 28 to 31 are another manifestation of the lognormal rain attenuation process. Readers interested in the derivation of the lognormal distribution from the proportionate relationship (1) are referred to Refs. 68 and 69. Figure 32 provides three sets of

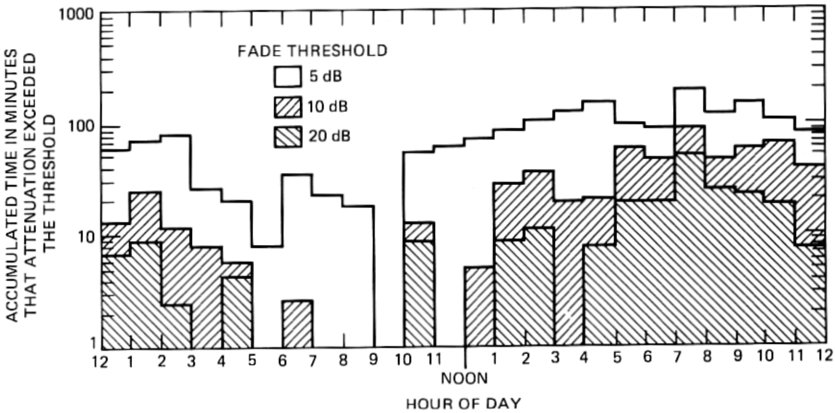

Fig. 16—One-year (June 1976 to July 1977) data showing diurnal variation of 19-GHz rain attenuation statistics measured from the COMSTAR(D1)-to-Palmetto path.

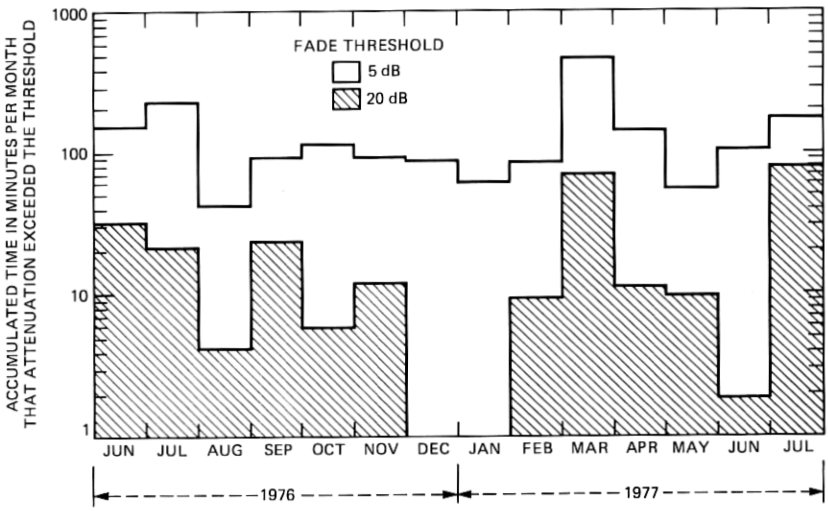

Fig. 17—One-year (June 1976 to July 1977) data showing monthly variation of 19-GHz rain attenuation statistics measured from the COMSTAR(D1)-to-Palmetto path.

data to show that the measured rain attenuation distributions are indeed approximately lognormal. The equation describing the lognormal distribution of rain attenuation α is[55,56]

$$P[\alpha \geq A] \simeq P_0 \cdot \frac{1}{2} \operatorname{erfc}\left[\frac{\ln A - \ln \alpha_m}{\sqrt{2}\, S_\alpha}\right], \tag{2}$$

where erfc (~) denotes the complementary error function, ln (~) denotes natural logarithm, α_m and S_α are median value of α and standard deviation of $\ln \alpha$, respectively, during raining time, A is a

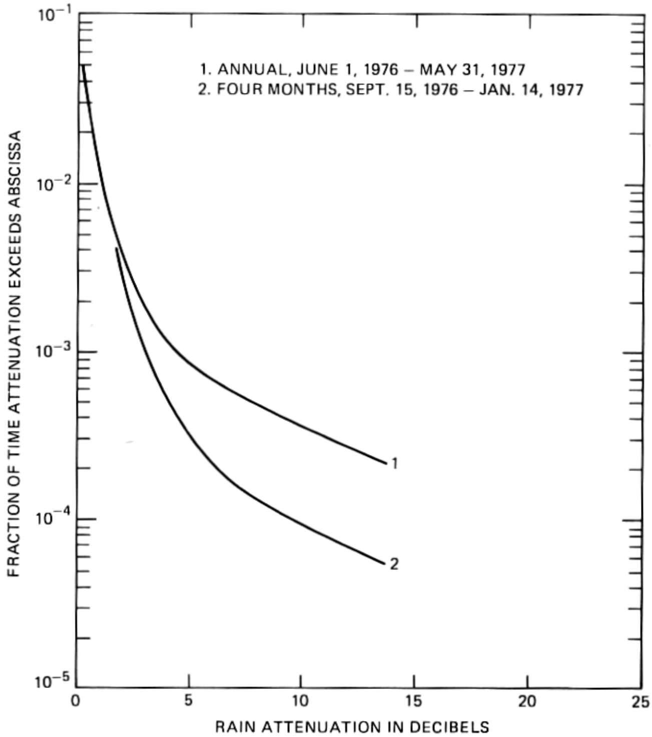

Fig. 18—One-year (June 1976 to June 1977) data showing seasonal variation of 13.6-GHz rain attenuation measured at Palmetto, Georgia with 29.9-degree elevation angle.

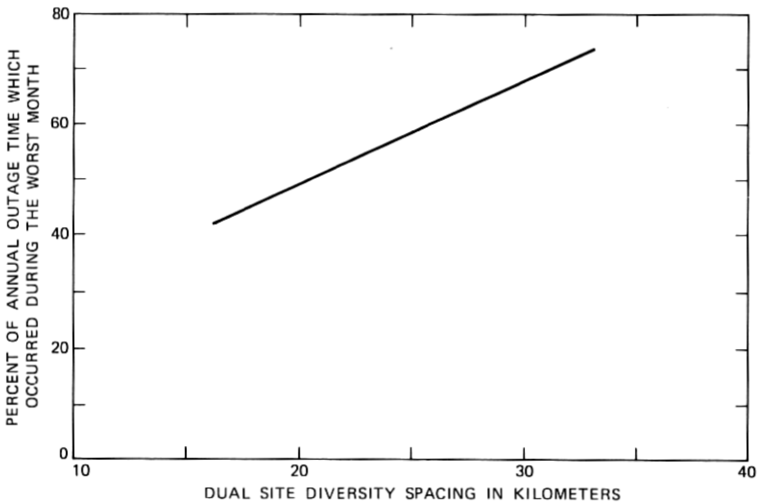

Fig. 19—Effect of site-diversity protection on percent concentration of annual outage time occurred during the worst month.

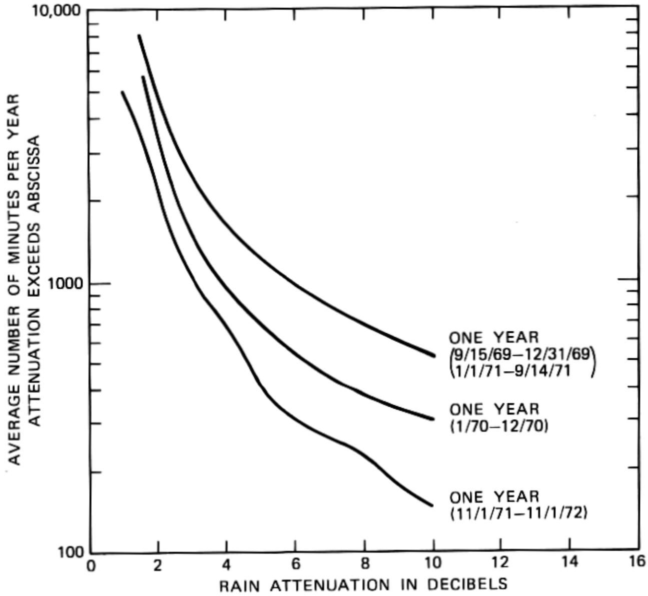

Fig. 20—Variation of annual distribution of rain attenuation measured by a 15.5-GHz radiometer at Holmdel (Crawford Hill), New Jersey with 32-degree elevation angle.

given attenuation threshold at which the probability is of interest, and P_0 is the probability that rain will fall on the earth-satellite radio path. For the three sets of data measured at Holmdel, New Jersey,

$$P_0 \simeq 0.05 \qquad \text{(i.e., 5 percent).} \tag{3}$$

The values of α_m and S_α are:*

	α_m (dB)	S_α (nepers)	θ (degrees)
28.5-GHz COMSTAR(D2)	0.94	1.33	38.6
19-GHz COMSTAR(D2)	0.27	1.57	38.6
11.7-GHz CTS	0.3	1.39	27.0

The instability of annual distribution of rain attenuation noted on Figs. 20 and 21 implies that these estimated values of α_m and S_α may also vary somewhat from one year to another.

Figure 33 displays another form of proportionate rain attenuation behavior. It shows the relationship between 19- and 28.5-GHz rain attenuations on the same path from COMSTAR(D2) to Holmdel, New Jersey.[16] Due to the random variations of many rainfall parameters

* These values pf α_m and S_α are estimated by a least-squares fit of the lognormal distribution (2) to the data on Fig. 32, assuming $P_0 = 0.05$.

(e.g., the sizes, shapes and canting angles of rain drops, rain temperature and nonuniform spatial distribution of rain density), the ratio between 19- and 28.5-GHz rain attenuations fluctuates in a random fashion. The vertical bars on Fig. 33 represent the middle 80-percent range of fluctuation. The data indicate that the fluctuation range increases with attenuation level. To examine this relationship more closely, let us define

$$z = \ln(\alpha), \tag{4}$$

where α is the rain attenuation in decibels. The 1-year data on Fig. 33 are replotted on Fig. 34 on the z-scale (i.e., the logarithmic scale). It is seen that the fluctuation range on the logarithmic scale does not increase with the value of z. This means that the environmental factors affect the rain attenuation in a proportional fashion on the decibel scale and in an additive fashion on the z-scale, implying the proportionate effect and the lognormal process for α.

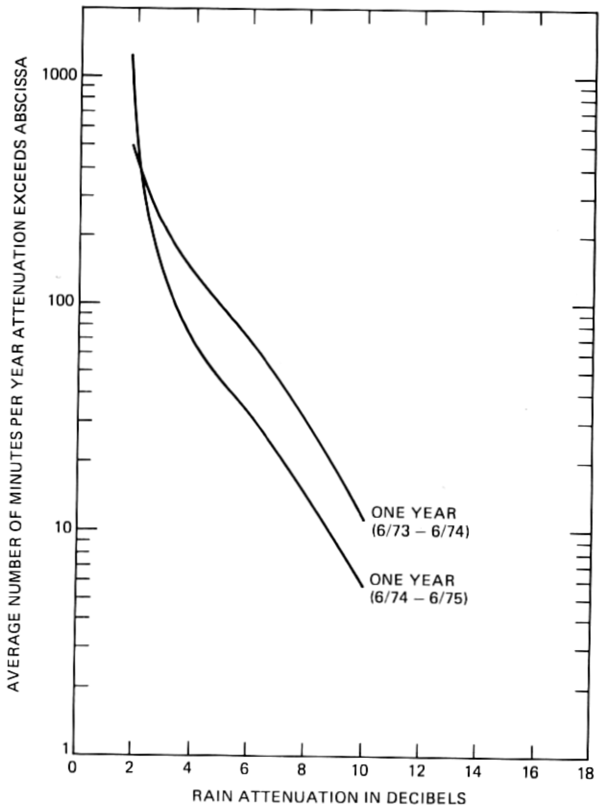

Fig. 21—Variation of annual distribution of rain attenuation measured by a 17.8-GHz radiometer at Longmont, Colorado, with 42.6-degree elevation angle.

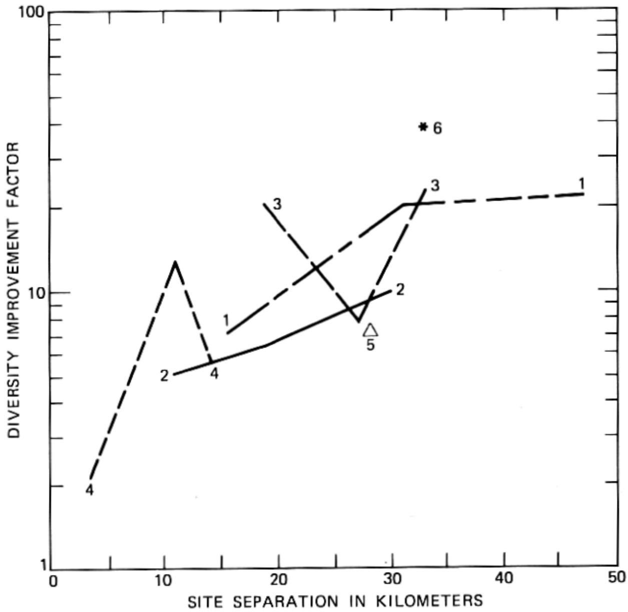

Fig. 22—Dependence of diversity improvement factor at 5-dB fade threshold on site separation. (1) Two-year (June 1973 to June 1975), 17.8-GHz data measured in Georgia; $\theta = 38.2$ degrees. (2) Two-year (September 15, 1969 to September 14, 1971), 15.5-GHz data measured in New Jersey; $\theta = 32$ degrees. (3) One-year (November 1, 1971 to November 1, 1972), 15.5-GHz data measured in New Jersey; $\theta = 32$ degrees. (4) Four-month (April 1, 1969 to August 7, 1969), 15.5-GHz data measured in New Jersey; $\theta = 32$ degrees. (5) One-year (August 1977 to August 1978), 13.6-GHz data measured in Illinois; $\theta = 41.8$ degrees. (6) Two-year (June 1973 to June 1975), 17.8-GHz data measured in Colorado; $\theta = 42.6$ degrees.

Several sets of rain rate data measured in Illinois, New Jersey, Georgia, and Canada indicate the randomly varying rain-rate process also obeys the proportionate effect and support the lognormal model.[37]

VII. LOGNORMAL DISTRIBUTION OF FADE DURATION

In the design of a satellite communication system, maintaining a fixed, large fade margin to combat occasional, deep rain fades may result in a severe reduction in communication capacity or an excessively large solar power system on the satellite which would otherwise not be required for a large percentage (e.g., 99 percent) of time. An effective method to overcome this problem is the dynamic power control technique.[70-73] In this approach, the small fade margin of the radio link is increased during heavy rain periods by increasing the transmitter power. The increased transmitter power on the satellite during rain is supported by batteries usually provided to cover the eclipse periods. However, a prolonged heavy rain period may exhaust the battery capacity and result in an outage. The statistics of durations

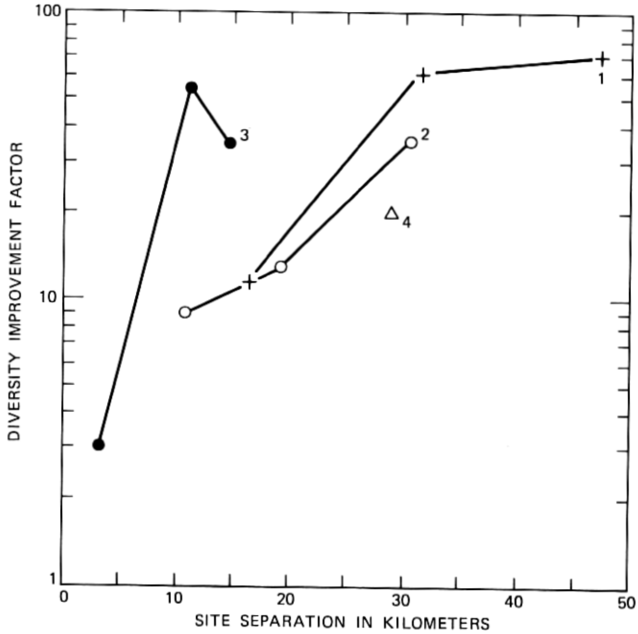

Fig. 23—Dependence of diversity improvement factor at 10-dB fade threshold on site separation. (1) Two-year (June 1973 to June 1975), 17.8-GHz data measured in Georgia; θ = 38.2 degrees. (2) Two-year (September 15, 1969 to September 14, 1971), 15.5-GHz data measured in New Jersey; θ = 32 degrees. (3) Four-month (April 1, 1969 to August 7, 1969), 15.5-GHz data measured in New Jersey; θ = 32 degrees. (4) One-year (August 1977 to August 1978), 13.6-GHz data measured in Illinois; θ = 41.8 degrees.

of rain attenuation fades is, therefore, important in an optimal design of dynamic power control system involving tradeoffs among battery size, fade margin, transmission capacity, satellite cost, etc.

The experimental data on Figs. 35* and 37 and those in Refs. 7, 56, 67, and 71 consistently indicate that the distribution of duration, τ, of rain attenuation exceeding a given threshold is approximately lognormal and can be written as:[56]

$$P(x \geq X) \simeq \frac{1}{2}\,\mathrm{erfc}\left[\frac{\ln X + \frac{1}{2}\sigma^2}{\sqrt{2}\sigma}\right] \tag{5}$$

where

$$x = \frac{\tau}{\bar{\tau}} \tag{6}$$

* These fade duration data contain only fades with durations longer than 15 seconds. Rapid fluctuations with durations shorter than 15 seconds are considered as scintillations. The solid line on Fig. 35 is obtained by a least-squares fit of Eq. (5) to the data points with one adjustable parameter σ.

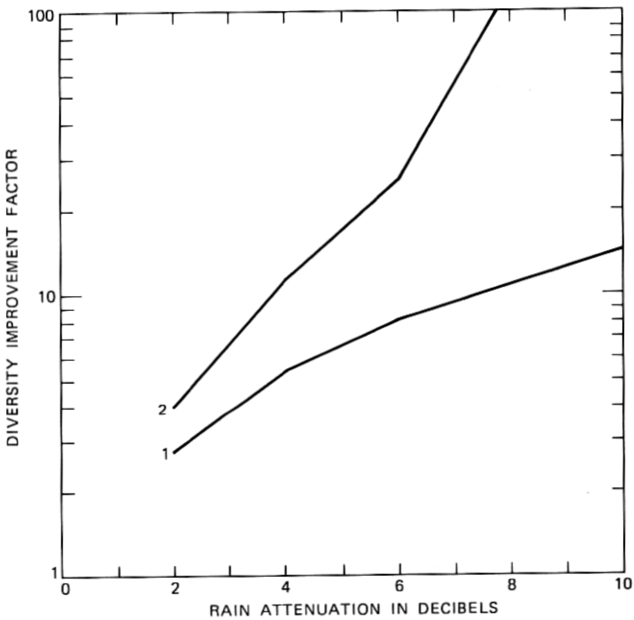

Fig. 24—Variation of diversity improvement factor with fade threshold and time base measured by 15.5-GHz radiometers at Crawford Hill and Asbury Park, New Jersey, with 32-degree elevation angle and 19-Km site separation. (1) Two-year (September 15, 1969 to September 14, 1971) data. (2) One-year (November 1, 1971 to November 1, 1972) data.

is the normalized fade duration, $\bar{\tau}$ is the average duration of attenuation exceeding the given threshold, σ is the standard deviation of $\ln(\tau/\bar{\tau})$ and X is a given value of normalized duration at which the probability is of interest. The average fade duration depends on frequency and fade threshold as shown on Fig. 36. For the 19-GHz COMSTAR(D2)-to-Palmetto link, the average fade duration decreases from 5 minutes to 3 minutes as the fade threshold increases from 5 to 25 dB.

Notice that the lognormal distribution (5) of normalized fade duration, $\tau/\bar{\tau}$, is uniquely determined by one parameter σ. The mean value of $\ln(\tau/\bar{\tau})$ is equal to $-\sigma^2/2$ because of the definition (6).[56] The experimental data on Fig. 35 indicate that

$$\sigma \simeq 1.47 \text{ nepers.} \tag{7}$$

The 19-GHz COMSTAR(D2)-to-Palmetto link experienced 50 events per year of rain attenuation exceeding the 20-dB threshold. This is obtained by dividing the total fade time of 180 minutes/year on Fig. 3 by the 3.6 minutes average fade duration on Fig. 36 at the 20-dB threshold. The lognormal distribution on Fig. 35 indicates that 2 percent of the outages will be longer than $7 \times \bar{\tau}$. This means one of the 50 outages per year can be expected to last longer than 25 minutes (i.e., 7×3.6).

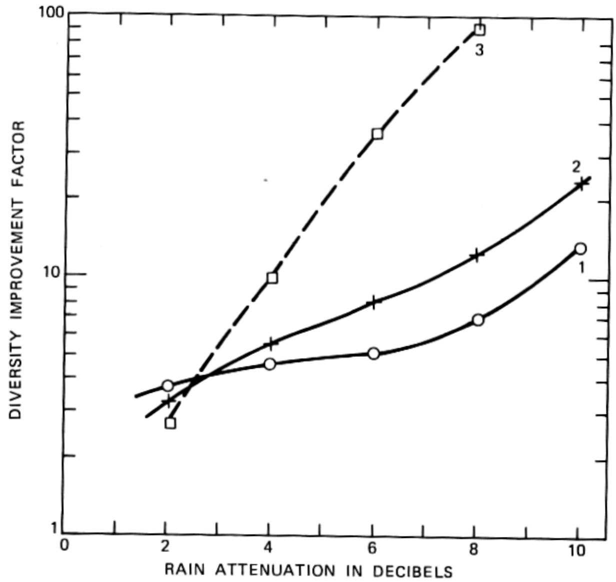

Fig. 25—Variation of diversity improvement factor with fade threshold and time base measured by 13.6-GHz radiometers at Grant Park and Manteno, Illinois, with 29-km site separation. (1) One-year (July 1976 to June 1977) data; $\theta = 27.3$ degrees. (2) One-year (August 1977 to August 1978) data; $\theta = 41.8$ degrees. (3) Six-month (September 18, 1975 to March 31, 1976) data; $\theta = 32.8$ degrees.

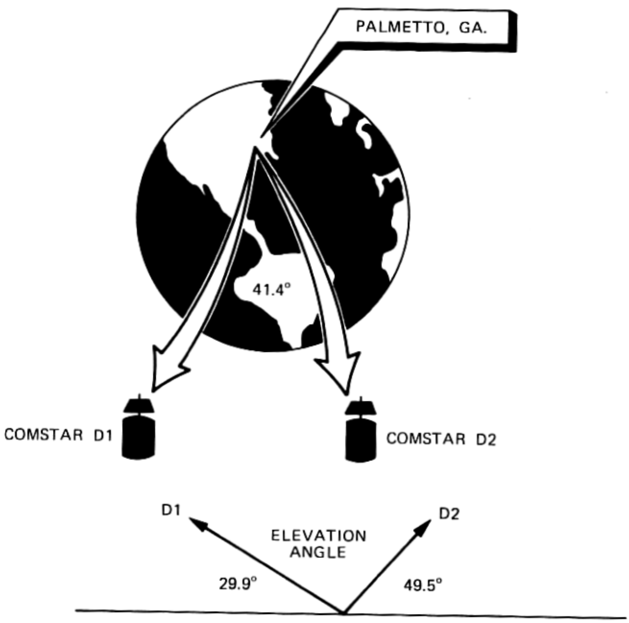

Fig. 26—Configuration of orbital diversity experiment with reception at Palmetto, Georgia. One antenna is pointed toward COMSTAR(D1) and the other antenna is pointed toward COMSTAR(D2).

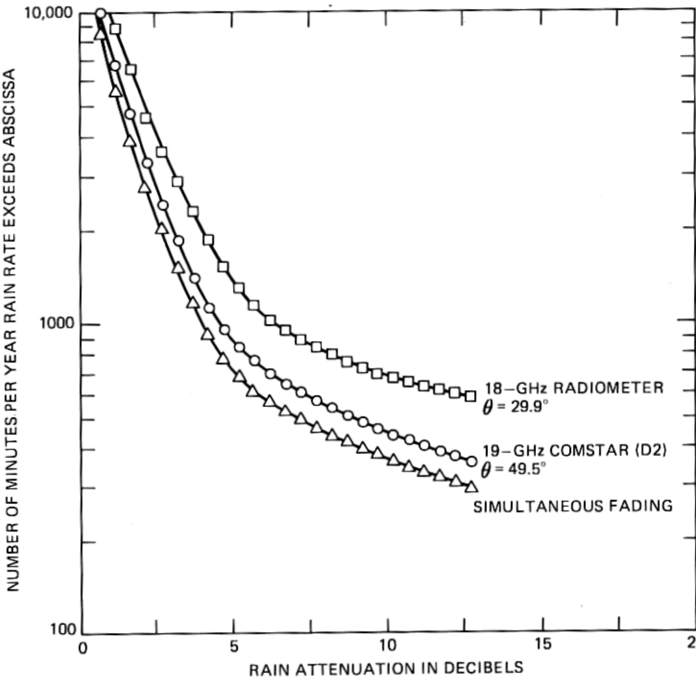

Fig. 27—One-year (July 16, 1977 to August 31, 1978) data measured at Palmetto, Georgia, indicating that the orbital diversity protection is practically ineffective against rain outages.

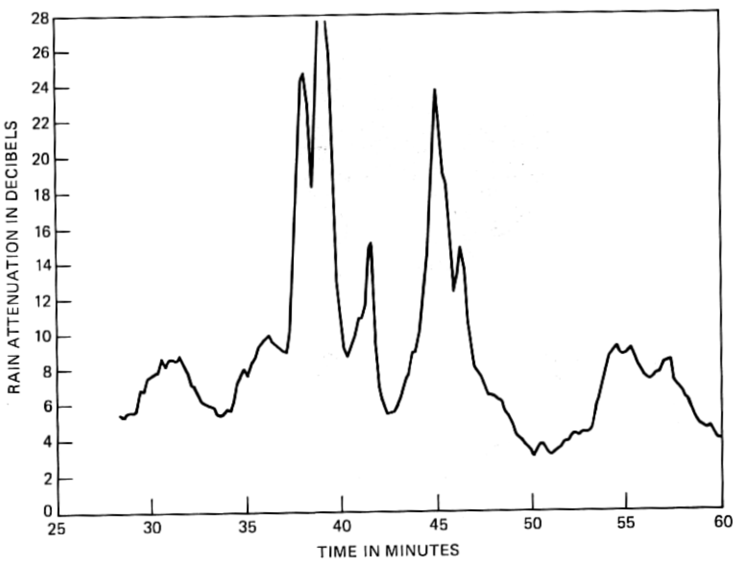

Fig. 28—Temporal variation of rain attenuation measured from the 19-GHz COMSTAR(D2)-to-Palmetto path with 49.5-degree elevation angle. Thirty-two-minute sample from 07:28 to 08:00 a.m. on April 18, 1978.

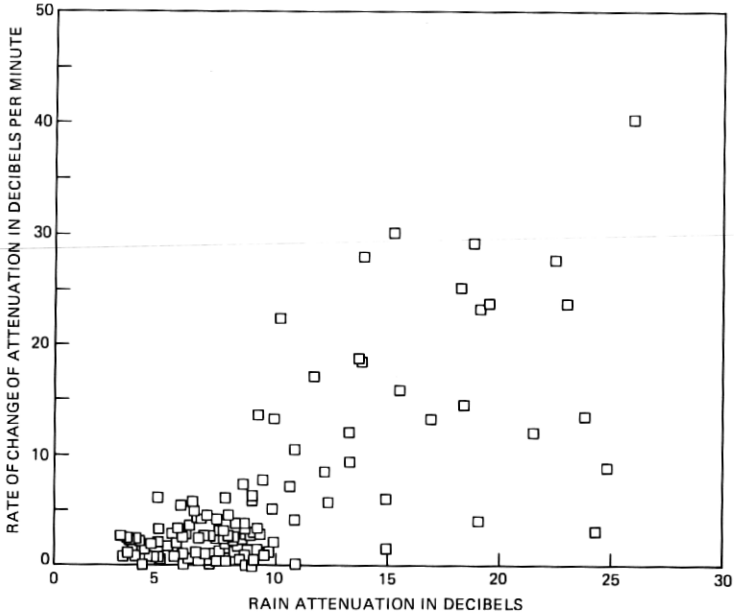

Fig. 29—A scatter plot showing the correlation between rain attenuation and its rate of change (i.e., absolute value of time derivative) measured from the 19-GHz COMSTAR(D2)-to-Palmetto path with 49.5-degree elevation angle. Thirty-two-minute sample from 07:28 to 08:00 a.m. on April 18. 1978. The slope is estimated as $|\Delta\alpha|/\Delta t$ with $\Delta t = 0.17$ minute, or 10 seconds.

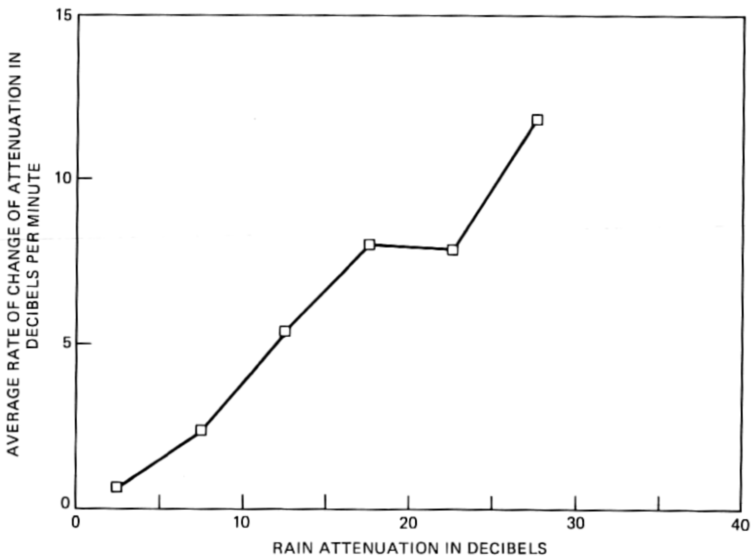

Fig. 30—One-month (April 11, 1978 to May 10, 1978) data showing correlation between rain attenuation and its rate of change (i.e., absolute value of time derivative) measured from the 19-GHz COMSTAR(D2)-to-Palmetto path with 49.5-degree elevation angle. The slope is estimated as $|\Delta\alpha|/\Delta t$ with $\Delta t = 0.17$ minute. Each data point represents the average value of the slope given that attenuation equals abscissa.

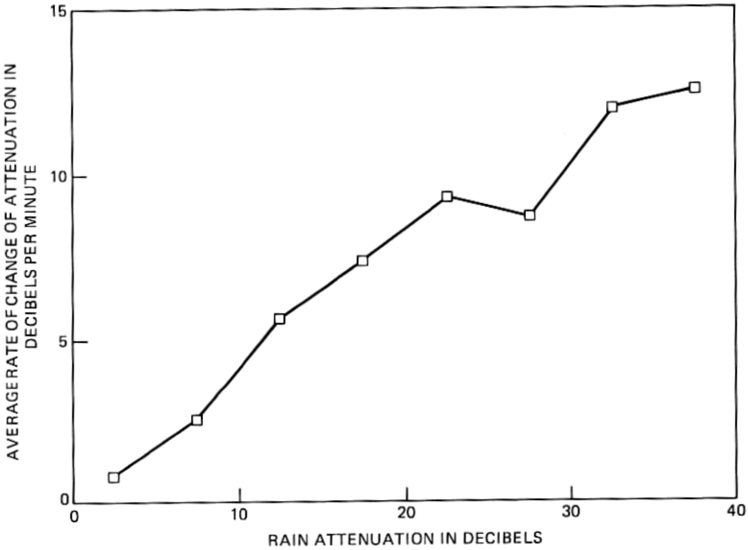

Fig. 31—Eight-month (November 1973 to July 1974) data showing correlation between rain attenuation and its rate of change measured from a 17.7-GHz, 3.2 mile terrestrial radio path at Palmetto, Georgia. The slope is estimated as $|\Delta\alpha|/\Delta t$ with $\Delta t = 0.17$ minute. Each data point represents the average value of the slope given that attenuation equals abscissa.

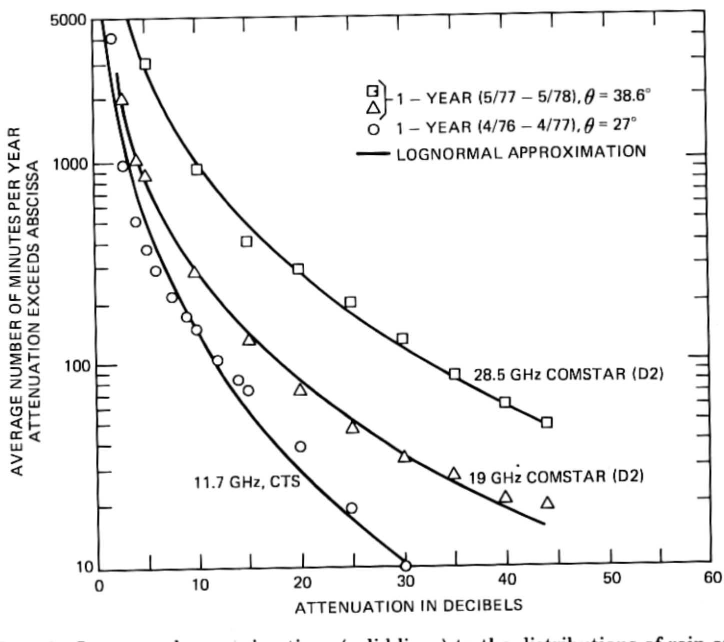

Fig. 32—Lognormal approximations (solid lines) to the distributions of rain attenuation measured from the COMSTAR-to-Holmdel paths and the CTS-to-Holmdel path.

Figure 37 shows similar statistics measured by 15.5-GHz radiometers in New Jersey.

VIII. NATIONWIDE LONG-TERM RAIN RATE DISTRIBUTIONS

The long-term, continuous rain attenuation experiments described in previous sections are costly, time-consuming, and tedious. It is impractical to carry out such measurements at all potential locations of future earth stations. On the other hand, the Weather Bureau has been accumulating rain statistics at numerous locations (≥300) in the U.S.A. for more than a hundred years. It is, therefore, desirable to apply these available rain rate statistics to engineering of rain-outage limited radio systems. This section describes the long-term (≥20 years) distributions of 5-minute point rain rates for U.S. locations. Section IX describes a simple method of predicting rain attenuation distribution from point rain-rate distribution.

The data sources suitable for this radio engineering application are:

(*i*) "Excessive Short Duration Rainfall Data" in *Climatological Data, National Summary*, annual issues prior to 1973.[74]

(*ii*) "Rainfall Intensity Duration Frequency Curves," Weather Bureau Technical Paper No. 25.[75]

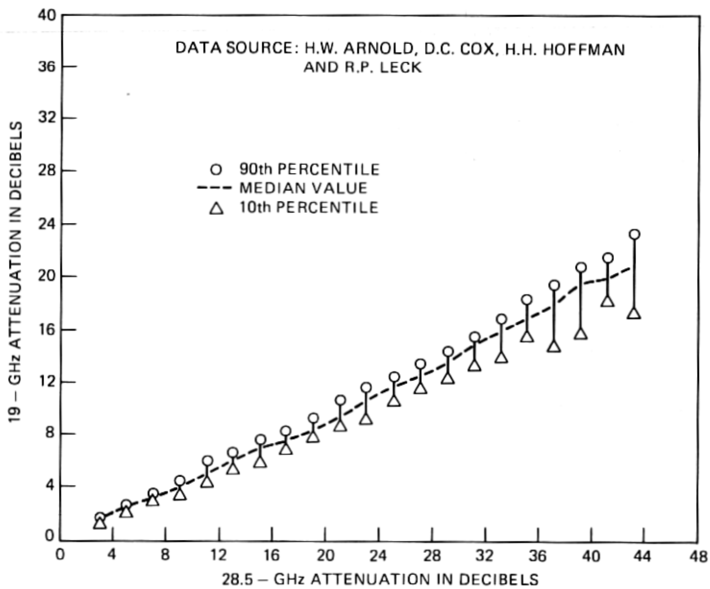

Fig. 33—One-year (May 18, 1977 to May 18, 1978) data on relation between 19- and 28.5-GHz rain attenuations measured from the COMSTAR(D2)-to-Holmdel path with 38.6-degree elevation angle. The increase of the middle 80-percent range of fluctuation with attenuation indicates that environmental parameters affect rain attenuation in a proportional fashion.

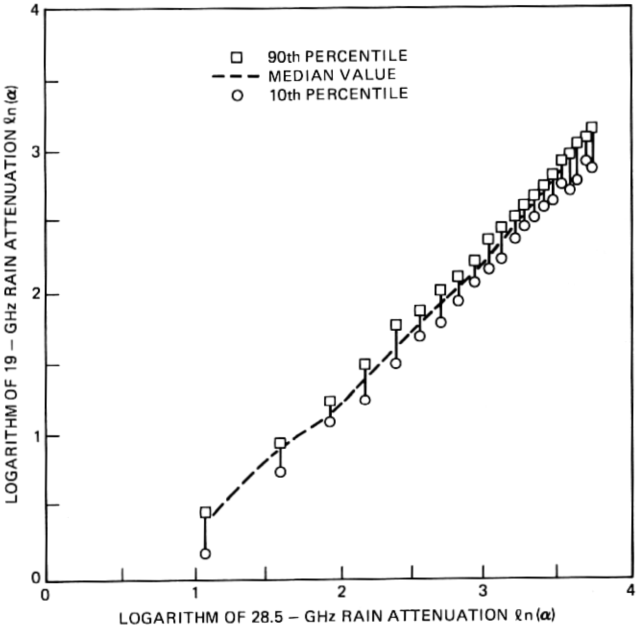

Fig. 34—One-year (May 18, 1977 to May 18, 1978) data on relation between logarithms of 19- and 28.5-GHz rain attenuation measured from the COMSTAR(D2)-to-Holmdel path with 38.6-degree elevation angle. The middle 80-percent range of fluctuation is independent of the value of $\ln(\alpha)$, where α is the rain attenuation in decibels. It implies that the environmental parameters affect $\ln(\alpha)$ in an additive fashion.

(*iii*) "Climatography of the United States. No. 82, Decennial Census of United States Climate—Summary of Hourly Observations (1951–1960)."[76]

References 33 to 37 have described the methods for converting these rain-rate data into the rain-rate distributions required for radio engineering. Figure 38 shows examples of 20-year distributions of 5-minute point rain rates at Miami, Atlanta, New York, Boston, Denver, and San Francisco. More examples are given in Refs. 33 to 37.*

Prior to 1973, the "Excessive Short Duration Rainfall Data" in document (*i*) contain sufficiently detailed information on all heavy rainstorms to obtain rain-rate distributions by application of the "Finite Difference Method" described in Refs. 33 to 35. However, beginning with 1973, only the maximum amounts of rainfall accumulations in 12 selected durations (from 5 to 180 minutes) in each month have been published. The title of the data was also changed to "The Maximum Short Duration Precipitation." Therefore, the "Finite Dif-

* Ruthroff and Bodtmann (Ref. 77) have also published 5-year rain rate distributions for 20 locations in the U.S.A.

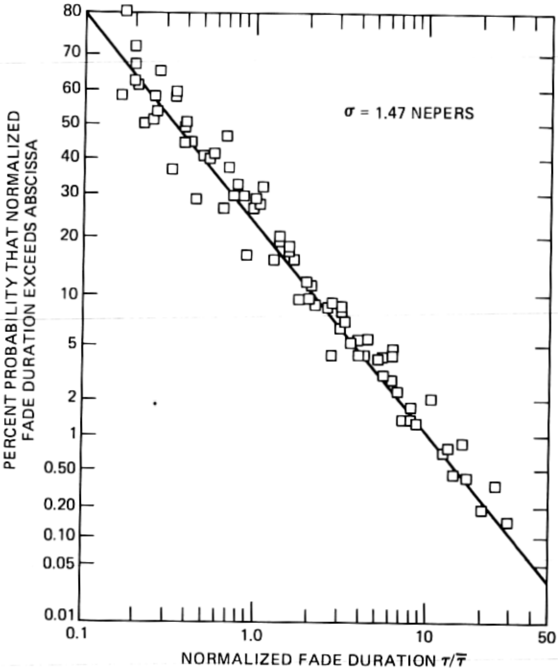

Fig. 35—Lognormal distribution of normalized fade duration $\tau/\bar{\tau}$ measured on the 19- and 28.5-GHz COMSTAR(D2)-to-Palmetto path with 49.5 degree elevation angle. One-year data from July 16, 1977 to August 31, 1978. Fade thresholds range from 5 to 25 dB.

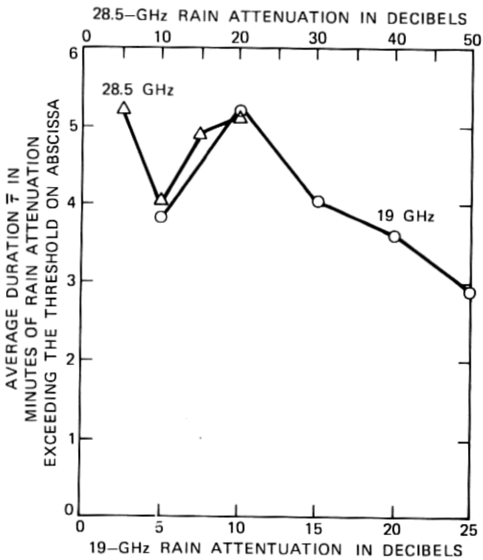

Fig. 36—Average duration of rain fades as a function of fade threshold and frequency measured on the 19- and 28.5-GHz COMSTAR(D2)-to-Palmetto path with 49.5-degree elevation angle. One-year data from July 16, 1977 to August 31, 1978.

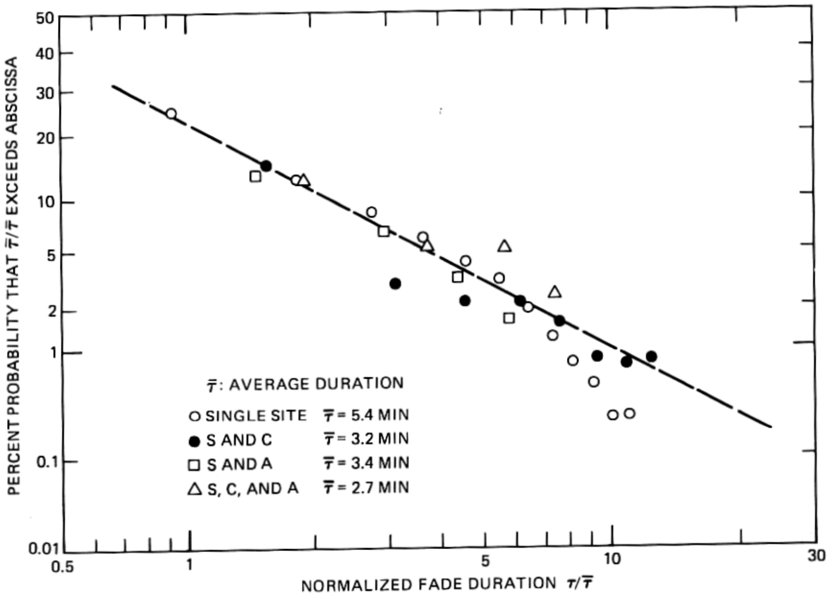

Fig. 37—Lognormal distribution of normalized fade duration $\tau/\bar{\tau}$ measured by 15.5-GHz radiometers at Holmdel, New Jersey, with 32-degree elevation angle. Two-year data from September 16, 1969 to September 14, 1971.

ference Method" is applicable only to the more detailed data published prior to 1973. Alternatively, it is possible to apply the "Extreme Value Statistics Method"[36,37] to the new "Maximum Short Duration Precipitation Data" to obtain rain rate distributions, given sufficient number of years (e.g., 20 years) of such data.

Rain-rate data measured at many locations[35,38,39,62,64,77–87] consistently indicate that the probability distribution of point rain rate varies considerably with rain gauge integration time, τ. The reason for this sensitivity is that a long integration time (e.g., 30 minutes) will smooth out and reduce the magnitudes of many peaked, short bursts of high rain rates. The probability distribution of τ-minute average rain rate in the tail region of high rain rate will, therefore, decrease as the integration time τ increases. Figure 39 shows the dependence of rain-rate distribution on the integration time measured in Georgia. Consequently, the probability distribution of point rain rate at any given geographic location is *not* unique unless the rain gauge integration time is specified.*

* Strictly speaking, the so-called "instantaneous point rain rate" with zero integration time may not be meaningful in the conventional sense because rainfall consists of discrete raindrops. As the rain gauge integration time approaches zero, the measured rain rate, theoretically, approaches a time sequence of short pulses representing the successive entries of discrete raindrops into the gauge. In other words, the so-called "instantaneous point rain rate" will behave like that of impulse noise instead of a smooth continuous function of time.

The two reasons for using 5-minute integration time in these long-term rain rate distributions are:

(*i*) The Weather Bureau rain gauges and the associated strip chart recorders were designed to measure rainfall accumulations in 5-minute intervals or longer. Attempting to estimate high rain rates in durations much shorter than 5 minutes from these strip charts will encounter significant uncertainty. For this reason, the 5-minute interval is the shortest integration time in the Weather Bureau publications.

(*ii*) Our experience[33,38,39] indicates that the distribution of 5-minute point rain rates is fairly close to the distributions of "effective path average rain rates" for a wide range of radio path lengths of interest. The slight differences between the distributions of 5-minute point rain rate and of path average rain rate can be compensated for by a mild correction factor, as discussed in the next section.

IX. SIMPLE EMPIRICAL RAIN ATTENUATION MODEL

The large amount of data indicate that the long-term distribution of rain attenuation on a radio path can be predicted from the long-term

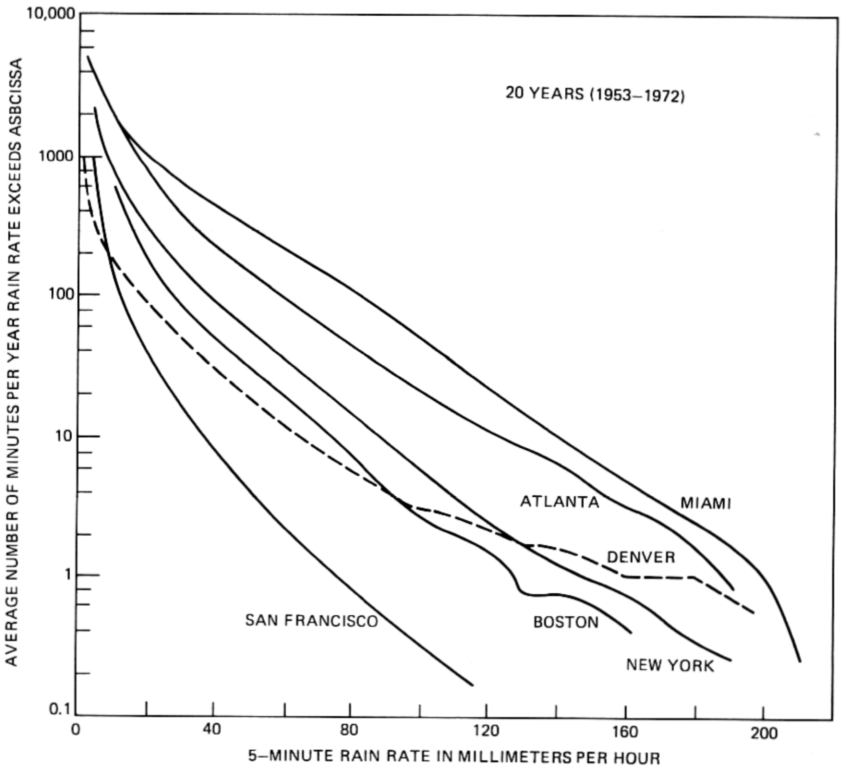

Fig. 38—Twenty-year distributions of 5-minute point rain rates at Miami, Atlanta, New York, Boston, Denver, and San Francisco.

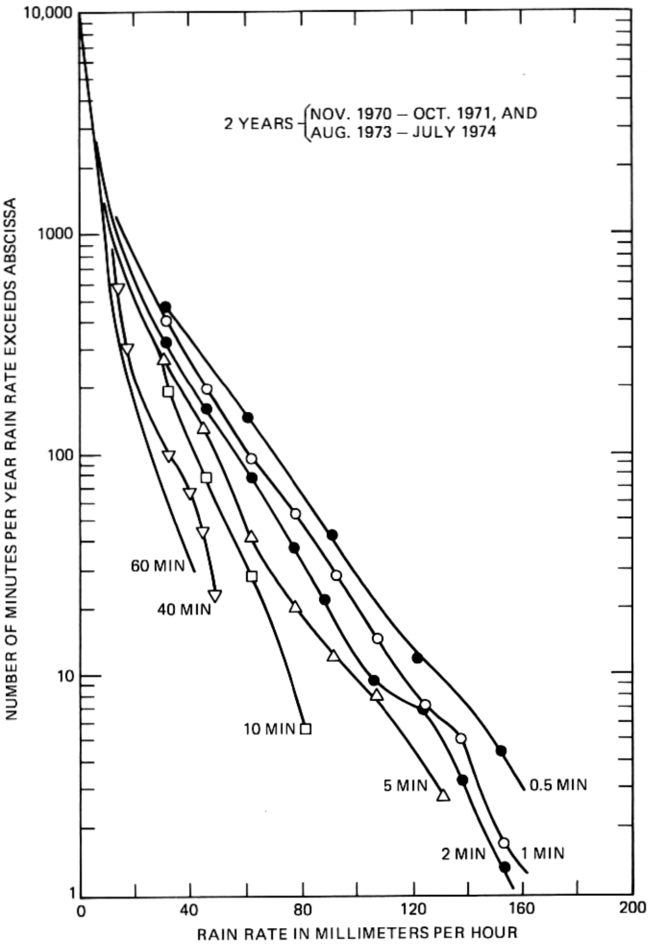

Fig. 39—Dependence of rain rate distribution on rain gauge integration time from two years of measurement at Palmetto, Georgia.

distribution of 5-minute point rain rate at the same location by three simple empirical formulas:

$$\beta(R) = a \times R^b \text{ dB/Km}, \tag{8}$$

$$\alpha(R, L) = \beta(R) \times L \times \frac{1}{1 + ((L/\bar{L}(R))} \text{dB}, \tag{9}$$

and

$$L = (H - G)/\sin\theta \qquad \text{Km}, \tag{10}$$

where R is the 5-minute point rain rate in mm/hr, $\alpha(R, L)$ is the path rain attenuation in decibels at the same probability level as that of R, the parameters a and b are functions[40,88–91] of radio frequency, as shown in Table IV and in Fig. 40, θ is the satellite elevation angle as viewed from the earth station, G is the ground elevation in kilometers measured from sea level,

$$H \simeq 4 \text{ Km} \tag{11}$$

is the long-term average height of the (water) freezing level in the atmosphere measured relative to the sea level,[93–95] and

$$\bar{L}(R) \simeq \frac{2636}{R - 6.2} \text{ Km} \tag{12}$$

is simply an empirical parameter to yield the proper path length correction factor (13) discussed in the following. Figure 41 depicts the geometry of this simple empirical model. References 38 and 39 present

Table IV—The parameters a and b in eq. $\beta = a \cdot R^b$
(From A. A. M. Saleh)

	Frequency in GHz						
	6.0	11.0	16.0	18.5	30.0	60.0	100.0
a	0.001968	0.01545	0.04726	0.06769	0.1961	0.6860	1.138
b	1.239	1.220	1.115	1.089	1.002	0.8310	0.7382

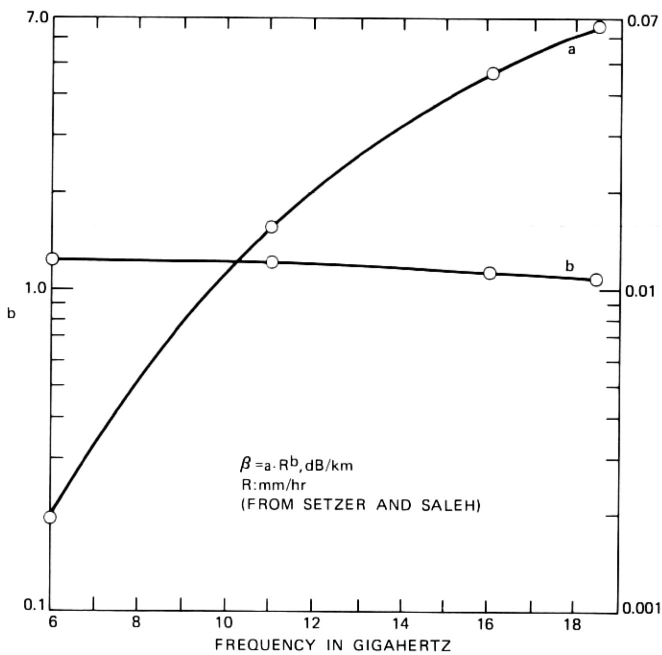

Fig. 40—Dependence of parameters a and b on radio frequency.

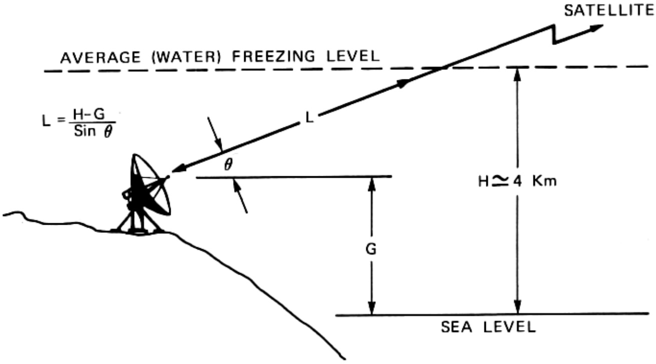

Fig. 41—Empirical model for effective average length L of earth-satellite path affected by rain.

eight sets of measured rain attenuation and rain rate data supporting the simple model.

This simple model is developed for pediction of attenuation probability distribution and is valid only in terms of a long-term average. It is *not* to be used for prediction of path attenuation from point rain rate at any particular instant of time. The short-term relationship between the point rain rate and the radio path rain attenuation is erratic and difficult to predict.

The heights of precipitation clouds, including snow, hail, etc., in the frozen state, can be much higher than 4 Km with variations from storm to storm. The average freezing level below which the precipitation is in liquid state is a function of season and latitude. The 4-Km value for the average freezing level in this model is a long-term average value applicable to the eastern U.S.A., where most of our rain attenuation data are gathered.

The parameter L in this model (see Fig. 41) represents the effective average length of the earth-satellite path affected by rain. This parameter L should *not* be confused with the average extent of rain cells often discussed in the literature.[5,96–98] Heavy rain cells are of very limited spatial extent and usually intercept only a fraction of the effective path length L. The effects of radio path averaging of nonuniform rain rates are accounted for in this model by the use of the nonlinear path length correction factor

$$\frac{1}{1 + (L/\bar{L}(R))} \tag{13}$$

in eq. (9), and by the use of *5-minute* average of point rain rates. The 5-minute averaging of short bursts of high rain rates is similar to radio path averaging of small cells of heavy rains. Therefore, the parameter L for paths with low elevation angles can be much longer than the

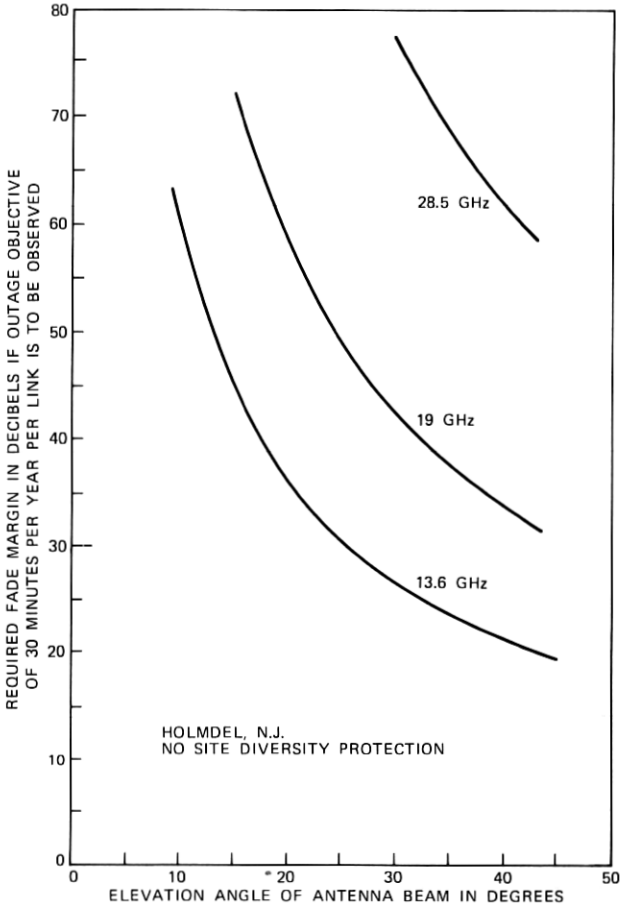

Fig. 42—Dependences of required fade margin on elevation angle and frequency for an earth station at Holmdel, New Jersey, if an outage objective of 30 minutes per year per link is to be observed.

average extent of heavy rain cells.* The average extent of rain cells in Refs. 5 and 96–98 represents the parameter L reduced by the factor given in eq. (13) and by the 5-minute average effect.

We emphasize that these formulas are applicable only to 5-minute rain rate distribution since they are deduced empirically based upon the 5-minute rain rate data and the attenuation data. Some authors have ignored the effect of rain gauge integration time entirely and applied the formulas to whatever rain-rate data happen to be available. Figure 39 shows that applying these formulas to the 0.5-minute rain-

* This model is also applicable to engineering of terrestrial radio path (Ref. 33). In the case of terrestrial radio, the parameter L represents the hop length in kilometers between the adjacent radio repeater stations.

rate distribution may overestimate the attenuation probability by at least a factor of 2, and that applying them to the 60-minute rain rate distribution may underestimate the attenuation probability by at least a factor of 4.

As an example of the application of the empirical model, Figs. 42 and 43 show the calculated, required fade margin for an earth station at Holmdel, New Jersey, and San Francisco, California, respectively, if an outage objective of 30 minutes per year per link is to be observed. Since the practical feasible fade margin is believed to be 20 dB or less, Fig. 42 indicates that a 13.6-GHz radio link for Holmdel, New Jersey, can meet the objective if the elevation angle is above 43 degrees. On the other hand, 19- and 28.5-GHz radio links definitely require site diversity protection if the 30-minute outage objective is to be observed.

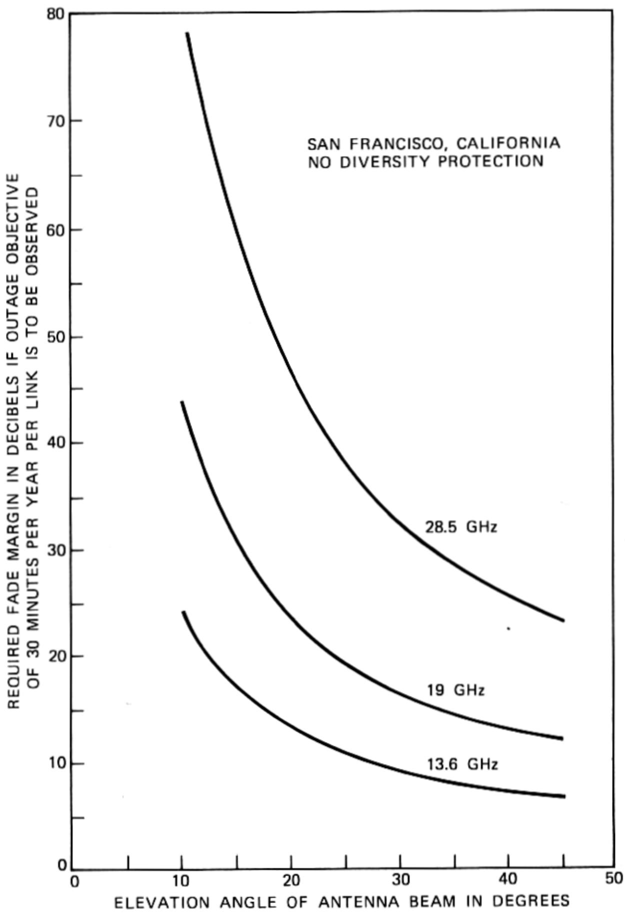

Fig. 43—Dependences of required fade margin on elevation angle and frequency for an earth station at San Francisco, California, if an outage objective of 30 minutes per year per link is to be observed.

If an eastern satellite orbital position is chosen to minimize rain outage time for earth stations in heavy-rain eastern U.S.A., then the antenna elevation angles for western earth stations probably will be below 40 degrees. The calculated results for San Francisco in Fig. 43 indicate that the 13.6- and 19-GHz links can meet the objective without diversity protection if the elevation angle is above 25 degrees. However, the 28.5-GHz link will require site-diversity protection. Therefore, the frequency band above 28 GHz should be considered as a relatively "expensive band" in which to operate.

X. CONCLUDING REMARKS

Interim results of 10-year experiments and studies on rain attenuation on earth-satellite paths have been published in Refs. 5 to 44. The scattering of the results in many different journals, conference proceedings, and meeting digests is inconvenient for applications by system engineers in the planning and the design of new satellite radio systems. This paper summarizes the new results and the previously published results. The major findings, conclusion, and implications to system engineering are summarized in Section II.

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