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11-GHz Radio:

Nationwide Long-Term Rain Rate Statistics and Empirical Calculation of 11-GHz Microwave Rain Attenuation

By S. H. LIN

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Two methods are described to obtain long-term (≥20 years) distributions of 5-minute point rain rates from data published by the National Climatic Center for U.S. locations. A set of simple empirical formulas for converting the distribution of 5-minute rain rates into rain attenuation distributions on 11-GHz radio paths has been deduced from data measured in Georgia. Additional data measured in several other locations also support this empirical formulation. These simple formulas and 5-minute point rain rate distributions are useful for path engineering of 11-GHz radio. The work on rain rate distributions discussed in the paper derives from approaches suggested by the late W. Y. S. Chen.[5,9,16]

I. INTRODUCTION

An important problem in designing terrestrial and earth-satellite radio systems at frequencies above 10 GHz is the added path attenuation caused by rain. Long term (≥20 years) rain rate statistics are needed to engineer radio paths for various geographic locations to meet reliability objectives. Section II describes a method to obtain 20-year distributions of 5-minute point rain rates from the excessive short duration rainfall data[1,2] for locations in the relatively wet eastern and midwestern U.S.A. Section III describes another method, employing the theory of extreme value statistics, to obtain 50-year distributions of 5-minute point rain rates from rainfall-intensity-duration-frequency curves[3] for locations in relatively dry locations such as western U.S.A. Section IV discusses the variability of rain rate distributions with observation time base.

Table I — Thresholds* of excessive short-duration rainfalls

Duration τ, minutes	Minimum depth of recorded rainfall, inches	Threshold (τ minute average rain rate), mm/hr
5	0.25	76.2
10	0.30	45.7
15	0.35	35.6
20	0.40	30.5
30	0.50	25.4
45	0.65	22.0
60	0.80	20.3
80	1.00	19.1
100	1.20	18.3
120	1.40	17.8
150	1.70	17.3
180	2.00	16.9

* Exceeding any one of these 12 thresholds is sufficient to qualify a rainstorm as an excessive rainfall. Therefore, this definition does not require that an excessive rainfall exceeds all the 12 thresholds.

In this paper, a "5-minute rain rate" corresponds to the average value of the randomly varying rain rate in a 5-minute interval and is calculated as $\Delta H/\tau$ where ΔH is the 5-minute accumulated depth of rainfall and $\tau = 5$ minutes $= 1/12$ hour is the rain gauge integration time. Similarly, a "τ-minute rain rate" is the average rain rate in a τ-minute interval.

Sections V to VII describe a set of simple empirical formulas deduced from experimental data in Georgia for converting the distribution of 5-minute point rain rates into distributions of rain attenuation on 11-GHz radio paths. Section VIII compares the calculated results with additional data from other locations.

II. 20-YEAR DISTRIBUTIONS OF 5-MINUTE RAIN RATES

The excessive short duration rainfall data[1] record details of those heavy rainfalls which exceed one or more thresholds; these thresholds are dependent upon the rain integration times τ as shown in Table I. For example, the thresholds are 76 and 20 mm/hr for $\tau = 5$ and 60 minutes, respectively. The data, published in tabular form, consist of a storm-by-storm compilation of accumulated depth of rainfall in the most intense 5, 10, 15, 20, 30, 45, 60, 80, 100, 150, and 180 minute periods. For example, Table II shows such data for Newark, New Jersey in 1972. Only three rainstorms exceeded the excessive rainfall thresholds at Newark during 1972. More detailed discussions on the excessive short duration rainfall data can be found in Refs. 1, 5 and 6.

The method for obtaining 5-minute rain rates from this data source is illustrated in Table III for the storm of August 26, 1972 at Newark. In essence, for each storm, the most intense 5-minute accumulation gives

Table II — Excessive short-duration rainfall, year 1972

Station and Date	5	10	15	20	30	45	60	80	100	120	150	180
⋮												
New Jersey												
⋮												
Newark												
Jul 13	0.26	0.37	0.48	0.57	0.74	0.86	1.06	1.48	1.65	1.80	2.10	2.37
Jul 17	0.31	0.48	0.49	0.52	0.61	0.70	0.74	0.74	0.74	0.74	0.74	0.74
Aug 26	0.64	1.08	1.54	1.68	1.80	1.87	1.93	1.98	2.02	2.03	2.05	2.06
Trenton												
⋮												

Duration in minutes

Accumulated depth of rainfall in inches

Table III — Obtaining 5-minute rain rates from excessive short-duration rainfall data, year 1972

	5	10	15	20	30	45	60	80	100	120	150	180	Minutes
Newark													
⋮													
Aug 26	0.64	1.08	1.54	1.68	1.80	1.87	1.93	1.98	2.02	2.03	2.05	2.06	

$$\frac{0.64 \text{ inch}}{5 \text{ minutes}} = 195 \text{ mm/hr}$$

$$\frac{(1.08 - 0.64) \text{ inch}}{(10 - 5) \text{ minutes}} = \frac{0.44 \text{ inch}}{5 \text{ minutes}} = 134 \text{ mm/hr}$$

$$\frac{(1.68 - 1.54) \text{ inch}}{(20 - 15) \text{ minutes}} = 43 \text{ mm/hr}$$

one sample of 5-minute rain rate; the difference between the 10-minute and 5-minute greatest accumulations gives the second sample of 5-minute rain rate; and so on. By applying this single operation to 20 years (1953 to 1972) of such data for Newark, New Jersey, we obtain a 20-year distribution of 5-minute rain rates in the range above the 76 mm/hr threshold as shown in Fig. 1. The results of this method were tested[5] using the reports of the 20 storms which were available in more detailed form[6] and excellent agreement was found.[5]

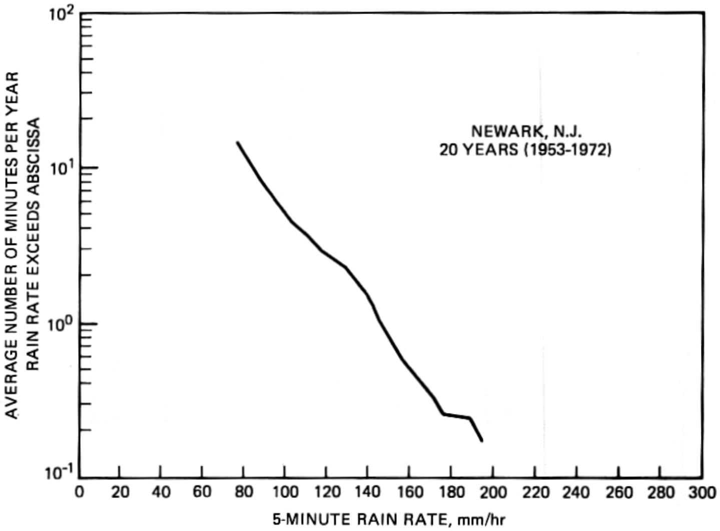

Fig. 1—Twenty-year distribution of 5-minute rain rates above the 76-mm/hr threshold at Newark, New Jersey.

As observed in Table I, the published 5-minute rain rates are given only for those storms which exceed the thresholds in Table I. These data are, therefore, incomplete with respect to 5-minute rain rates of less than 76 mm/hr. However, in the same publication, progressively lower thresholds (see Table I) are used for longer durations; for example, the threshold at 60-minute duration is 20 mm/hr. The method developed to extend the distributions of 5-minute rain rate to very low rain rate employs measured distributions of 1-hour rain rates as the basic data, since these are readily available.[1,2,7] By using long-term (≥10 years) data from New York City, Miami, and McGill Observatory in Canada, a simple empirical formula was deduced for converting the 1-hour rain rate distribution into the 5-minute rain rate distribution in the low rain rate region.[8] A normalizing procedure is used in this conversion formula to account for the difference in rain characteristics between geographic areas. Twenty-year distributions of 5-minute rain rates for locations in the eastern and midwestern U.S.A. have been obtained by this process. Some results are given in Refs. 8 and 9.

In low rain rate areas such as Oregon and Washington, however, few rainfalls exceed the criterial thresholds, and hence few are included in the excessive short duration rainfall data. For example, at Spokane, Washington, the 5-minute rain rate exceeded the 76 mm/hr threshold only once in the 20-year interval from 1953 to 1972. In such areas, a different data source and a method using statistics of extremes, discussed in the next section, is more suitable.

III. 50-YEAR RAIN RATE DISTRIBUTIONS AND EXTREME VALUE STATISTICS

The statistical behavior of the extremes of a random variable has been extensively investigated.[10–15] In an unpublished work, W. Y. S. Chen and R. L. Lahlum[16] have applied the theoretical distribution of yearly maximum 5-minute rain rates and an empirical extrapolation to obtain the rain rate distribution in the range of interest to radio path engineering. We extend Chen and Lahlum's method by incorporating the theoretical distributions of the yearly K largest 5-minute rain rates for K ranging from 1 to 12. The application of the higher-order statistics of extremes eliminates the need for empirical extrapolation.

Briefly, the average time per year that a rain rate r, measured by a gauge with integration time τ, is exceeded, is given by[9]

$$T(R \geq r) \simeq \tau \sum_{K=1}^{12} \left\{ 1 - e^{-e^{-y}} \sum_{N=0}^{K-1} \frac{e^{-Ny}}{N!} \right\} \tag{1}$$

for the range $T(R \geq r) \leq 50$ minutes/year, where

$$y = \alpha[(\ln r) - U] \tag{2}$$

is called the reduced variate, and α and U are scale and location parameters, respectively. Notice that $T(R \geq r)$ in eq. (1) is uniquely determined by the two parameters α and U. These two parameters can be calculated from the rainfall-intensity-duration-frequency curves[3] which are available for U.S. locations. These rainfall-intensity-duration-frequency curves are derived by the Gumbel method[11,12] using the theory of extreme value statistics and are based on approximately 50 years (1900 to 1950) of rainfall data.

From this data source, we need only the following three numbers for a given location to calculate the long-term distribution of 5-minute rain rates:

M = the number of years of rainfall data from which rainfall-intensity-duration-frequency curves are derived,

r_a = the extreme rain rate with 2-year return period, i.e., the rain rate which is exceeded once in 2 years, on average, by the yearly maximum 5-minute rain rates,

r_b = the extreme rain rate with 10-year return period, i.e., the rain rate which is exceeded once in 10 years, on average, by the yearly maximum 5-minute rain rates.

The formulas for calculating α and U are:[9]

$$\alpha = \alpha_\infty \sigma_z \frac{\sqrt{6}}{\pi} \tag{3}$$

$$U = U_\infty + \frac{1}{\alpha_\infty}\left[\gamma - \frac{\overline{Z}}{\sigma_Z} \cdot \frac{\pi}{\sqrt{6}}\right] \tag{4}$$

where

$$\alpha_\infty = \frac{A_a - A_b}{\ln r_a - \ln r_b} \tag{5}$$

$$U_\infty = \frac{A_a \ln r_b - A_b \ln r_a}{A_a - A_b} \tag{6}$$

$$A_a = -\ln\left(\ln \frac{10 \text{ years}}{2 \text{ years} - 1 \text{ year}}\right) \approx 0.3665 \tag{7}$$

$$A_b = -\ln\left(\ln \frac{10 \text{ years}}{10 \text{ years} - 1 \text{ year}}\right) \approx 2.25 \tag{8}$$

$$\gamma = \text{Euler's Constant} \approx 0.5772 \tag{9}$$

$$Z(j) = -\ln\left(-\ln \frac{j}{M+1}\right) \tag{10}$$

$$\overline{Z} = \frac{1}{M}\sum_{j=1}^{M} Z(j) \tag{11}$$

$$\overline{Z^2} = \frac{1}{M}\sum_{j=1}^{M} [Z(j)]^2 \tag{12}$$

and

$$\sigma_z = \sqrt{\overline{Z^2} - \overline{Z}^2} \tag{13}$$

For example, Fig. 2 shows a portion* of the rainfall-intensity-duration-frequency curves for New York City. The required three numbers read from Fig. 2 are

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* The source curves in Ref. 3 cover a wider range for duration τ from 5 to 1440 minutes and return period from 2 to 100 years.

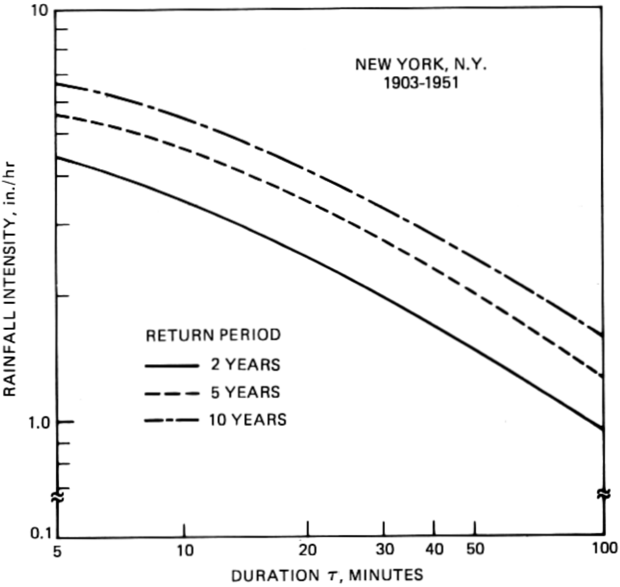

Fig. 2—Rainfall intensity-duration-frequency curve by method of extreme values (after Gumbel) for New York City based on 49 years (1903–1951) of rainfall data.

M = 49 years (1903 to 1951)
r_a = 4.4 inches/hr = 111.8 mm/hr
r_b = 6.5 inches/hr = 165 mm/hr

By substituting these three values into eqs. (3) to (13), we obtain

$$\alpha = 4.363$$

$$U = 4.63$$

Substituting this α, U pair into eqs. (1) and (2) yields the 49-year distribution (dashed line) of 5-minute rain rates as shown in Fig. 3. The 49-year (1903 to 1951) distribution obtained agrees well with the 20-year (1953 to 1972) distribution obtained by the method based on excessive short-duration rainfall data.

Long-term distributions of 5-minute rain rates for U.S. locations can therefore easily be obtained by the extreme value method.

IV. VARIABILITY OF SHORT-TERM DISTRIBUTIONS OF 5-MINUTE RAIN RATES

Figure 4 shows that the 20-year distributions of 5-minute rain rates at Central Park,* La Guardia Airport,* and Newark Airport* agree

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* All within the New York Metropolitan area.

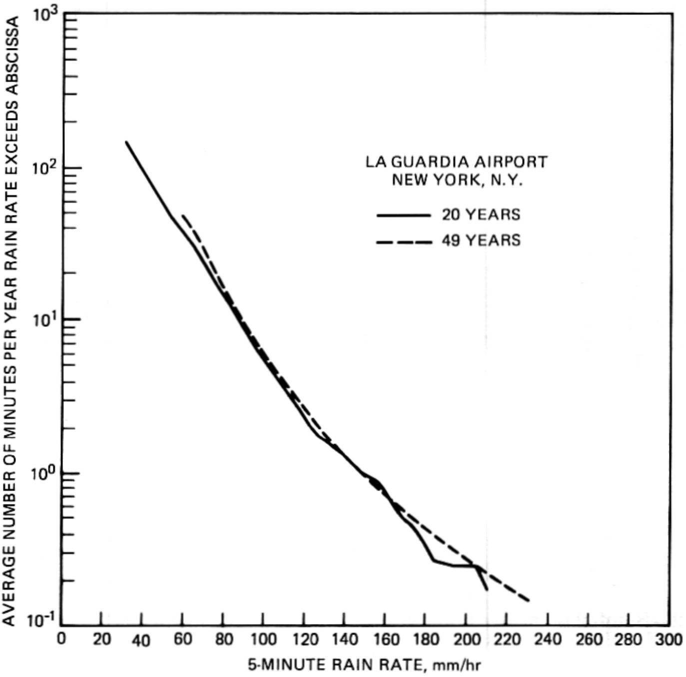

Fig. 3—Comparison of 49-year (1903–1951) distribution of 5-minute rain rates calculated by extreme statistics method with measured 20-year (1953–1972) data at La Guardia Airport, New York City.

closely. On the other hand, Figs. 5 and 6 show that 4-year (1969 to 1972) and 1-year (1972) distributions at these three locations differed significantly. Figure 7 displays the convergence of the rain rate distributions at Newark as the time base is increased from 1 to 20 years. Figure 8 indicates that with a single rain gauge measurement, even a 20-year time base may still be insufficient to provide stable statistics of extremely high rain rates (beyond 160 mm/hr).

Table IV lists the intervals, in minutes per year, that the rain rate exceeded 140 mm/hr at Newark, La Guardia Airport, and Central Park during the 20-year observation period. The last column contains the three-site summation for each year. The last three rows in Table IV indicate the 20-year average $\bar{t}$, the difference Δt, between the worst year and the best year, and the ratio $\Delta t/\bar{t}$ respectively. Figure 9 shows that the normalized range of variations, $\Delta t/\bar{t}$, increases rapidly as the rain rate increases from 80 to 160 mm/hr. This behavior is consistent with the divergence between the upper and lower envelopes in Fig. 7. In Fig. 9, notice that the normalized range of variation, $\Delta t/\bar{t}$, of individual sites are significantly greater than that of three-site summation for high rain rates. Since point rain rate statistics may be representative of a short

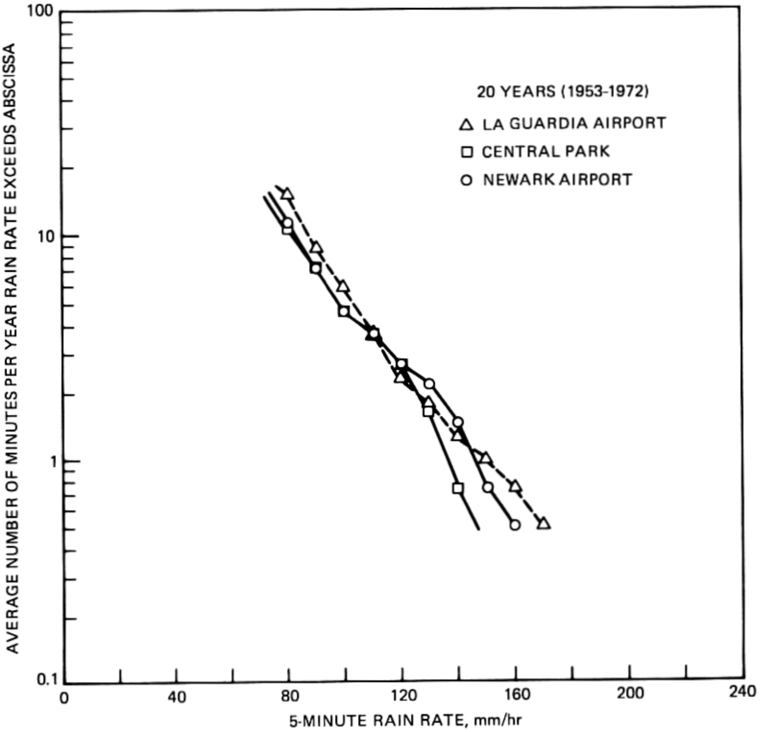

Fig. 4—Twenty-year (1953–1972) distributions of 5-minute rain rates at three locations: La Guardia Airport, Central Park, and Newark Airport, in the New York Metropolitan area.

radio hop, but three-site summation statistics are more representative for a multihop radio route, then, as shown in Fig. 9, the normalized range of variations, $\Delta t/\bar{t}$, of annual outage time of a radio route can be expected to be much smaller than that of a short radio hop. In other words, the annual outage time of a radio route is statistically more stable than that of a short radio hop. Intuitively, the statistical stability of the accumulated outage time of a radio route stems from the partial compensation effect of the incoherent, random variations of individual-hop outage times as displayed in Figs. 5 and 6.

The three-site, 20-year measurements yield 60 samples of annual accumulated time that rain rates exceed 140 mm/hr as listed in Table IV. The average value of these 60 samples is 0.97 minutes per year. Notice that 51 out of these 60 samples are less than the average value. Such nonsymmetric deviations of small sample data from long-term, large-sample average have already been observed and discussed in Ref. 17.

These data indicate that rain rate statistics gathered from a single rain gauge measurement require a very long time base to yield stable statistics

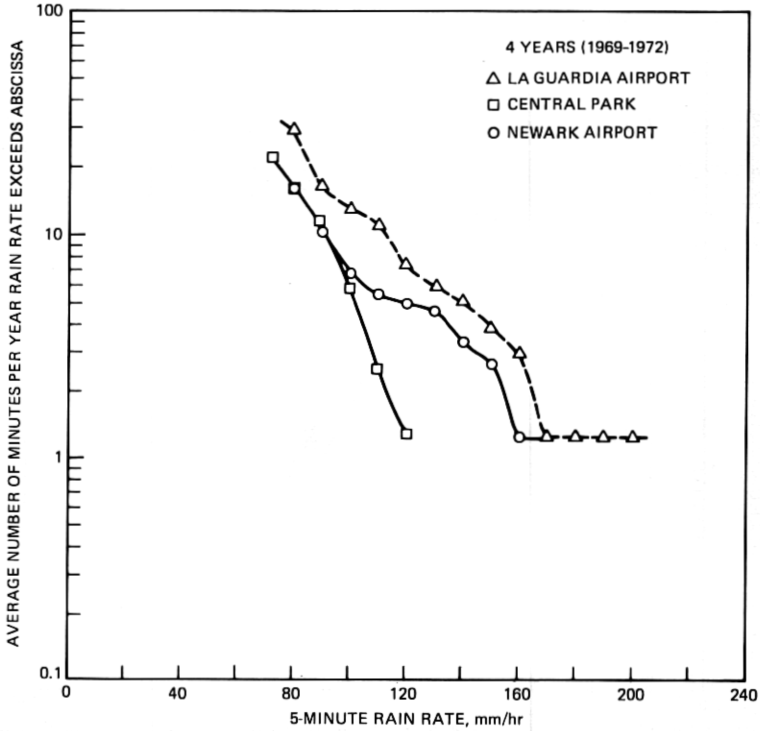

Fig. 5—Four-year (1969–1972) distributions of 5-minute rain rates at three locations: La Guardia Airport, Central Park, and Newark Airport, in the New York Metropolitan area.

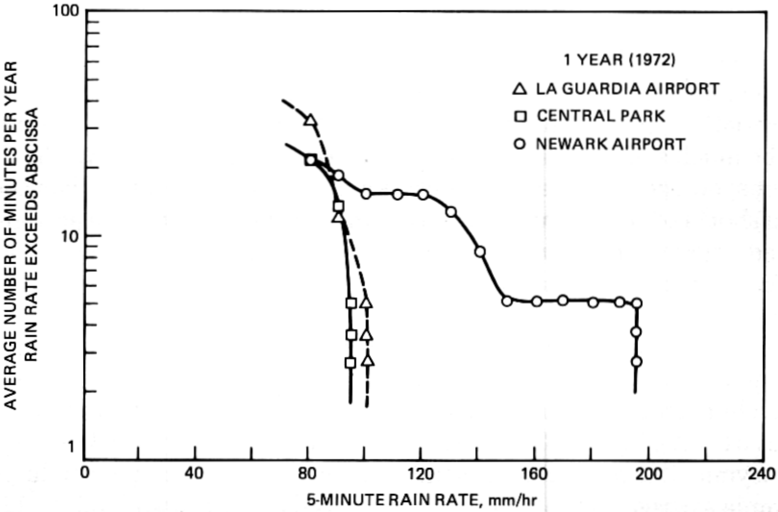

Fig. 6—One-year (1972) distributions of 5-minute rain rates at three locations: La Guardia Airport, Central Park, and Newark Airport, in the New York Metropolitan area.

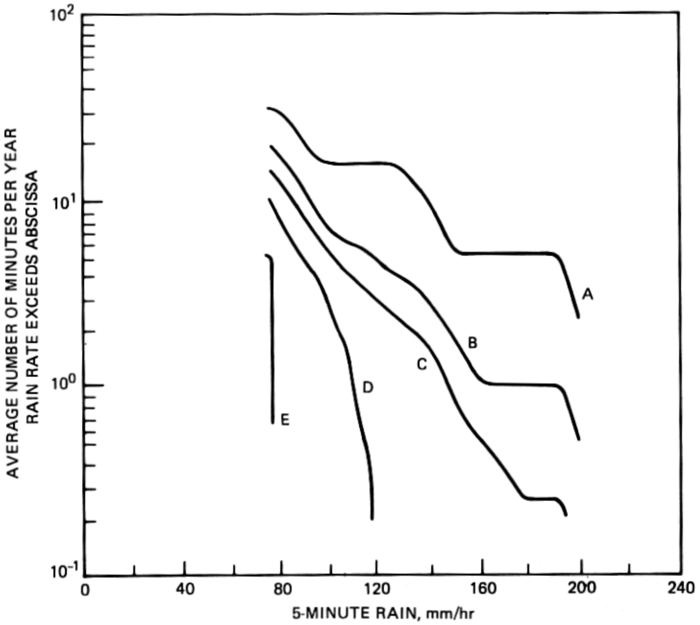

Fig. 7—Variations of yearly distributions of 5-minute rain rates at Newark, New Jersey; A: 1-year upper envelope, B: 5-year upper envelope, C: 20-year average, D: 5-year lower envelope, E: 1-year lower envelope.

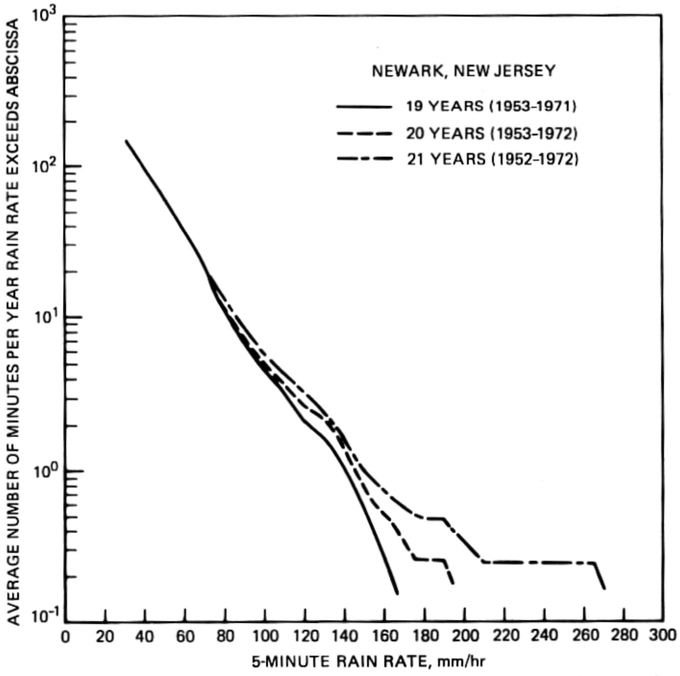

Fig. 8—Comparison of 19-, 20-, and 21-year distributions of 5-minute rain rates at Newark, New Jersey, showing the instability in the extremely high rain rate region.

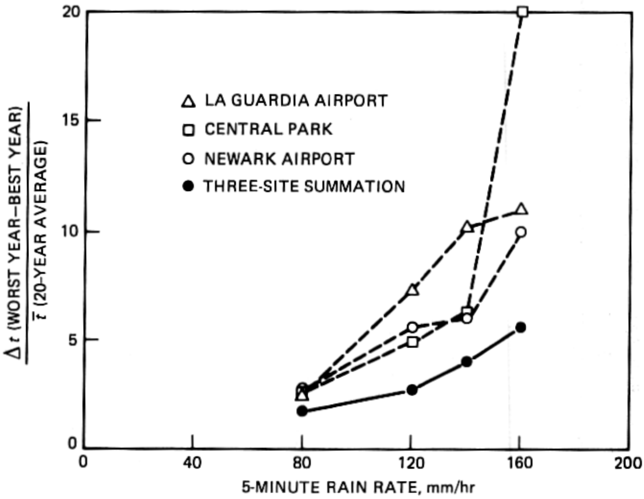

Fig. 9—The effect of three-site summation on the normalized range of variations of annual distributions of 5-minute rain rate. Δt is the difference between the worst year and the best year in number of minutes per year rain rate exceeds abscissa during the 20-year period (1953–1972), and $\bar{t}$ is the number of minutes per year rain rate exceeds abscissa averaged over the 20-year period (see Table IV).

Table IV — Number of minutes per year rain rate exceeds 140 mm/hr

Time base	Newark	La Guardia Airport	Central Park	Three-site summation
1953	0.0	0.0	0.0	0.0
1954	0.0	0.0	0.0	0.0
1955	0.0	0.0	0.0	0.0
1956	0.0	0.0	0.0	0.0
1957	0.0	0.0	0.0	0.0
1958	0.0	0.0	0.0	0.0
1959	0.0	0.0	0.0	0.0
1960	0.0	0.0	5.0	5.0
1961	5.0	0.0	0.0	5.0
1962	0.0	0.0	0.0	0.0
1963	0.0	0.0	0.0	0.0
1964	0.0	0.0	0.0	0.0
1965	5.0	0.0	0.0	5.0
1966	0.0	5.0	0.0	5.0
1967	0.0	0.0	0.0	0.0
1968	0.0	0.0	5.0	5.0
1969	0.0	13.3	0.0	13.3
1970	5.0	0.0	0.0	5.0
1971	0.0	6.7	0.0	6.7
1972	8.3	0.0	0.0	8.3
$\bar{t}$ (20-year average)	1.2	1.3	0.5	2.9
Δt (worst year-best year)	8.3	13.3	5.0	13.3
$\frac{\Delta t}{\bar{t}}$	6.9	10.2	10.0	4.6

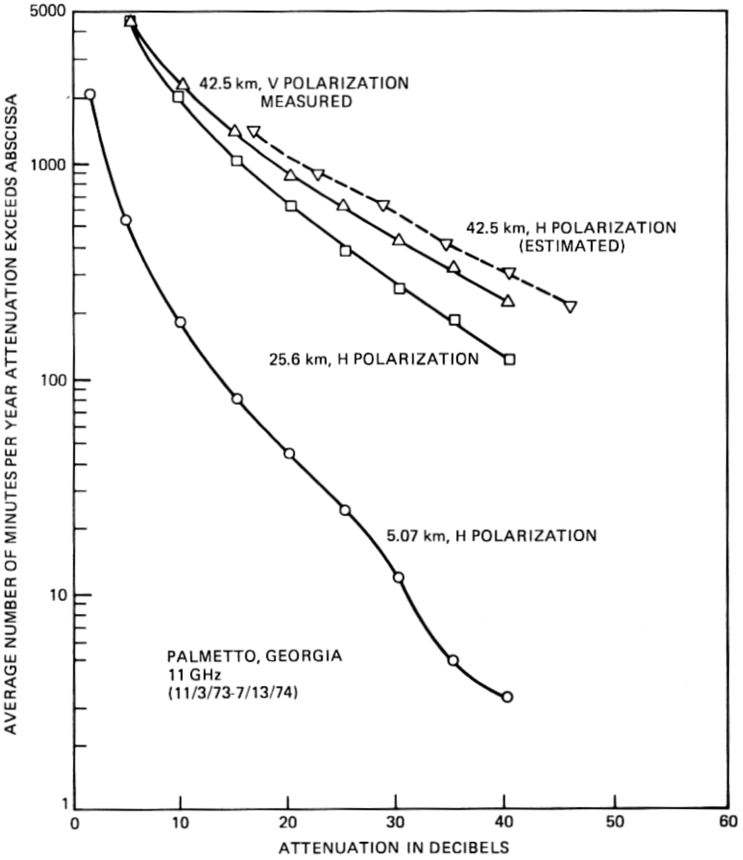

Fig. 10—Distributions of 11-GHz rain attenuation measured on three paths near Atlanta, Georgia.

for engineering a radio route. On the other hand, if the time base is not sufficiently long, the short term results tend to underestimate the long-term, large-sample average.

V. ANALYSES OF MICROWAVE RAIN ATTENUATION

For radio path engineering applications, a procedure is needed to calculate the rain attenuation distributions on microwave radio paths from the available rain rate distributions. Several independent theoretical analyses relating rain attenuation distributions to radio path length have been developed.[18,23,30] One analysis is based upon the approximate log-normality of long-term distributions of rain attenuation and of point rain rates.[17–22] These two distributions are related by suitably derived parameters. Since existing theory for converting rain rate into rain attenuation applies to spatially inform rain rates, whereas actual rainfalls are almost never uniform over a radio path, the hop is divided into incremental volumes in each of which the rain rate is uniform; the total attenuation is then obtained by integrating over the path. Since the rain rates at various positions along the radio path only partially correlated, the increase of attenuation with radio path length is nonlinear.

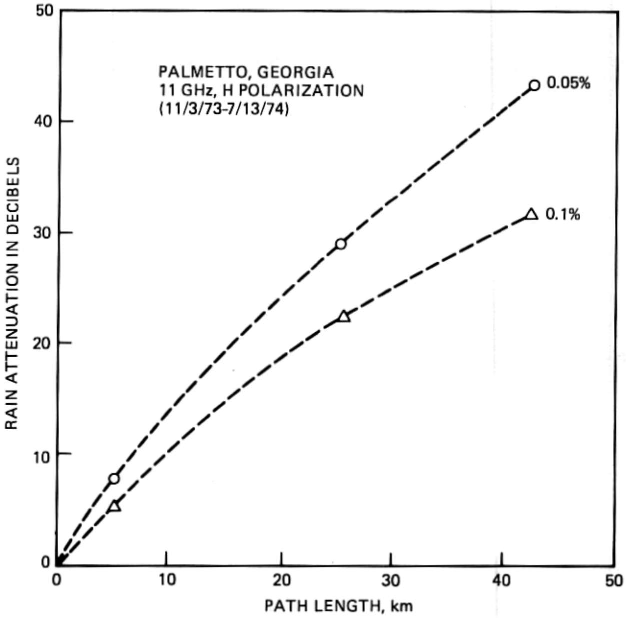

Fig. 11—Nonlinear dependence of 11-GHz rain attenuation on path length measured at Palmetto, Georgia.

In another analysis,[23] rain cells of circular cross section are assumed, allowing calculation of the probable length of path on which rain will fall from the probability of rain occurring at a point. It is found that the increase of attenuation with hop length is nonlinear because of the finite diameter of rain cells. In the limit, for hop lengths smaller than the cell diameter, the attenuation is almost proportional to path length, but for hops much larger than the cell diameter, it is almost independent of path length.

Both analyses indicate that the nonlinearity of the path length dependence is a function of rain rate and rigorous derivations are fairly complex. For path engineering applications, it is desirable to have a simple empirical formula to describe this nonlinear behavior. The following two sections describe the empirical formulas deduced from the available 11-GHz rain attenuation data.

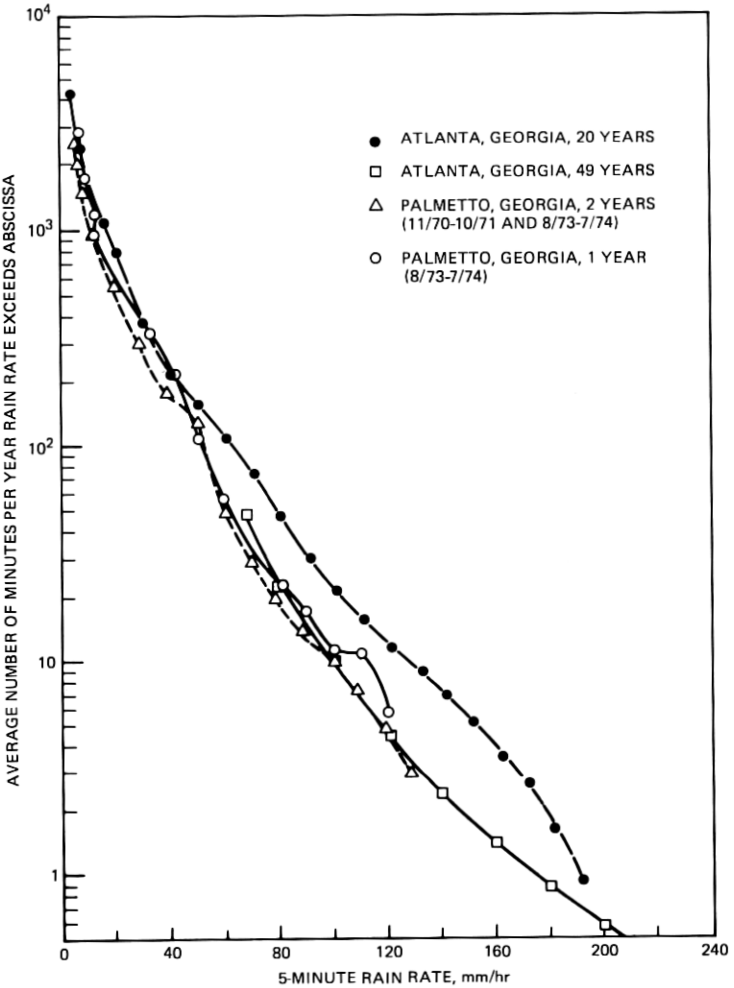

Fig. 12—Rain rate distributions measured at Atlanta and Palmetto, Georgia.

VI. RAIN ATTENUATION AND RAIN RATE DATA AT ATLANTA

The 11-GHz rain attenuation distributions obtained by simultaneous measurement on three paths (5.07, 25.6, and 42.5 km) near Atlanta[24] from November, 1973 to July, 1974 are shown for illustration in Fig. 10. The path-length dependence derived from these data is indicated in Fig. 11 which is a cross-plot relating attenuation observed to path length traversed, for fixed levels of probability. These data demonstrate that, for probability levels of 0.05 and 0.1 percent, rain attenuation increases nonlinearly with increased path length.

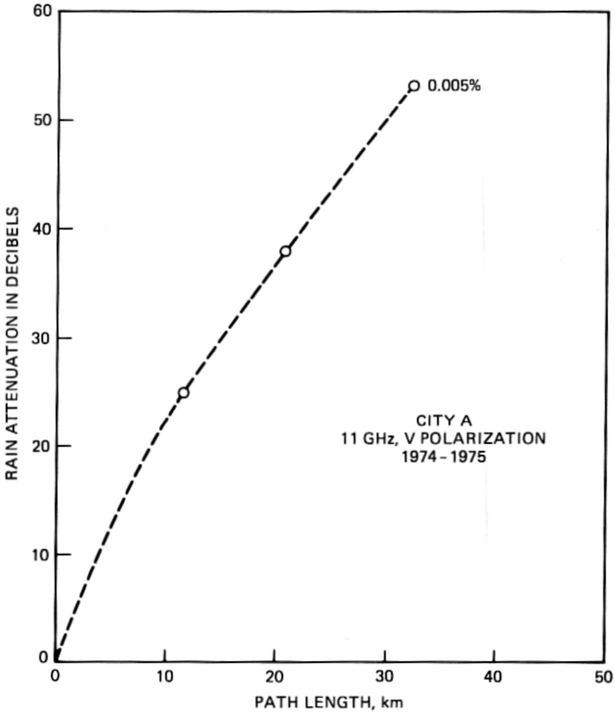

Fig. 13—Nonlinear dependence of 11-GHz rain attenuation on path length measured at another location.

Rain rate data for the above measuring interval are available from a tipping-bucket rain gauge at a common path terminal (Palmetto, Georgia) and from a Weather Bureau rain gauge at Atlanta Airport.[1,2,3] Figure 12 shows the distributions of 5-minute point rain rates obtained from these two rain gauges, as well as long-term results from the same Atlanta station.

Figure 13 shows another example of nonlinear increase of rain attenuation with path length measured at another location. The data in Figs. 13 and 15 are from the same city.

VII. EMPIRICAL PATH-LENGTH DEPENDENCE

Many authors[26–35] have pointed out that the relationship between the rain attenuation gradient, β in dB/km, and the point rain rate, R in mm/hr, can be approximately described by

$$\beta(R) = \rho R^{\eta} \tag{14}$$

where the coefficient ρ and the exponent η depend on the radio fre-

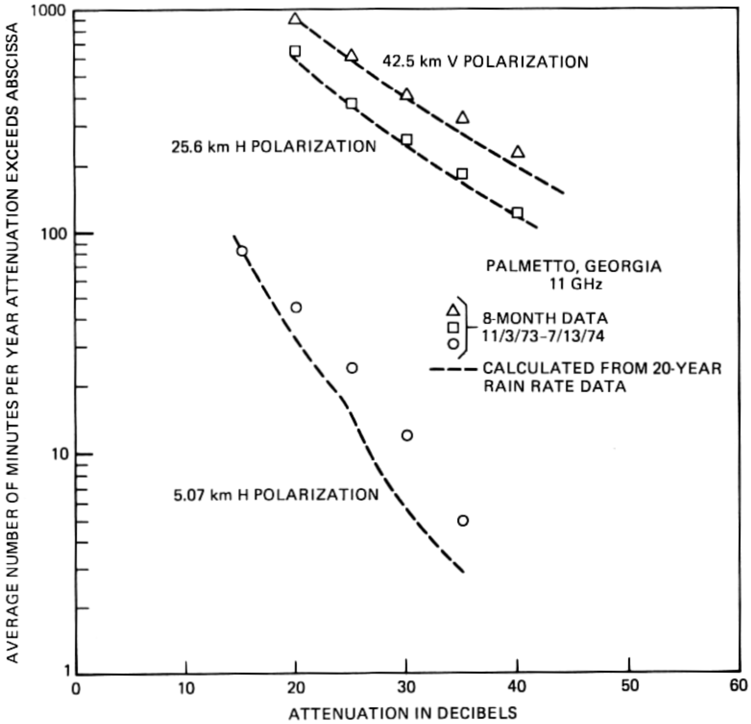

Fig. 14—Comparison of calculated (dashed lines) versus measured 11-GHz rain attenuation distributions on 5.07, 25.6, and 42.5 km paths at Palmetto, Georgia. The calculations are based on 20-year distribution of 5-minute point rain rates at Atlanta, Georgia.

quency, the polarization of the radio signal, and the canting angles of the oblate raindrops. Based on T. S. Chu's theoretical calculation[36] and the experimental data on the polarization dependence of rain attenuation in Refs. 37 and 38, the empirical formula for 11-GHz rain attenuation gradient is

$$\beta_V(R) = 0.0153R^{1.1909} \quad \text{dB/km} \tag{15}$$

for vertically polarized signals and

$$\beta_H(R) = 0.0170R^{1.2012} \quad \text{dB/km} \tag{16}$$

for horizontally polarized signals.

If the rain rates were uniform over a radio path of length L (km), the path rain attenuation $\mu(R,L)$ would be simply $\beta(R)L$, but since actual rainfalls are not uniform, the increase of $\mu(R,L)$ with L is nonlinear. In Ref. 39, a two-parameter empirical formula was shown to describe this nonlinear behavior. A single parameter variation also provides satis-

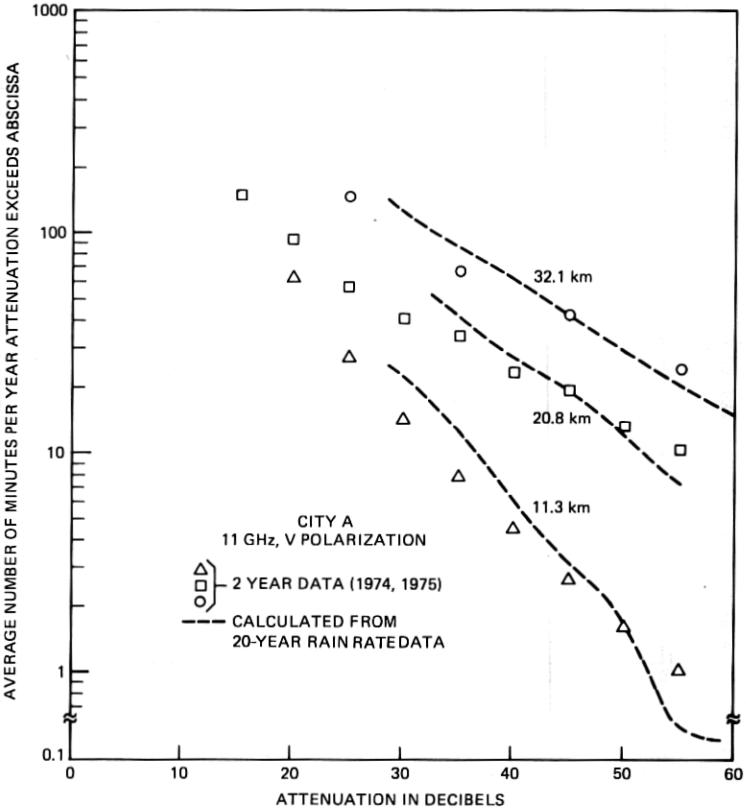

Fig. 15—Comparison of calculated (dashed lines) versus measured 11-GHz rain attenuation distributions on 11.3, 20.8, and 32.1 km paths at City A. The calculations are based on 20-year distribution of 5-minute point rain rates at City A.

factory agreement:

$$\mu(R,L) = \beta(R)L\frac{1}{1+\dfrac{L}{\overline{L}(R)}} \tag{17}$$

where the factor

$$\frac{1}{1+\dfrac{L}{\overline{L}(R)}} \tag{18}$$

accounts for the partially correlated rain rate variations along the path, and $\overline{L}(R)$ is a characteristic path length such that the nonlinear factor (18) equals one-half when $L = \overline{L}$. $\overline{L}$ is related to the diameter of the rain cell.

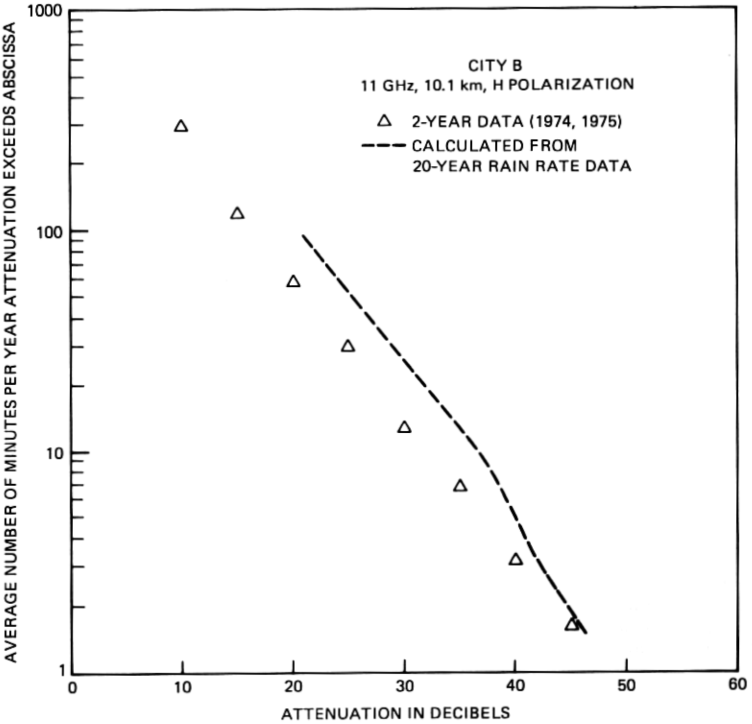

Fig. 16—Comparison of calculated (dashed line) versus measured 11-GHz rain attenuation distribution on a 10.1-km path at City B. The calculation is based on 20-year distribution of 5-minute point rain rate at City B.

By fitting eq. (17) to concurrently measured (August 1973 to July 1974) distributions of 5-minute point rain rates and 11-GHz rain attenuation on the 42.5 km path at Palmetto, Georgia, it is found that $\overline{L}(R)$ can be approximately described by

$$\overline{L}(R) \approx \frac{2636}{R - 6.2} \text{ km} \qquad \text{for} \qquad R > 10 \text{ mm/hr} \qquad (19)$$

VIII. COMPARISON OF PREDICTED AND MEASURED 11-GHZ ATTENUATIONS

Measured rain attenuation data on nine 11-GHz paths, listed in Table V, are available for comparison with the calculated results. Figures 14 to 18 show such comparisons. The calculated results (dashed lines) are based on 20-year distributions of 5-minute point rain rates and include path rain attenuation and assumed wet radome loss listed in Table V. It is assumed that, on the average, a wet, flat radome introduces 2 dB loss and a wet, hemispheric radomes introduces 4-dB loss.[18,40,41] Figures

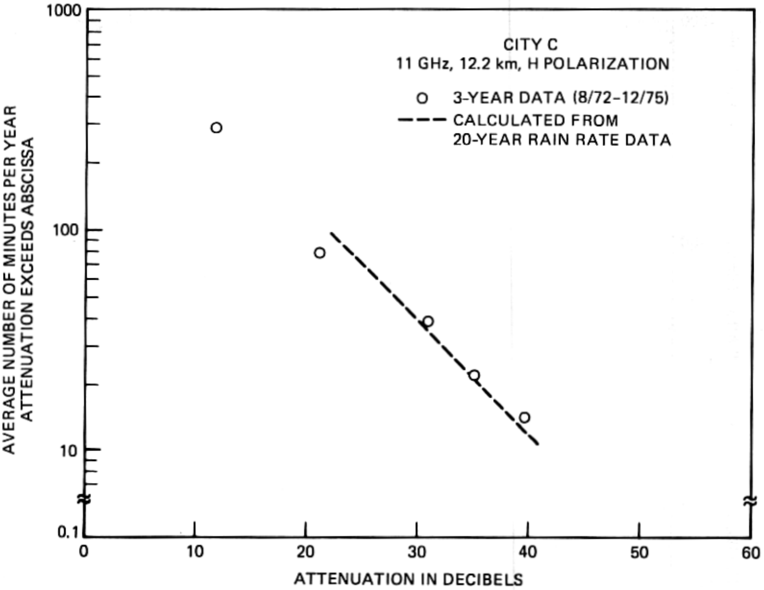

Fig. 17—Comparison of calculated (dashed line) versus measured 11-GHz rain attenuation distribution on a 12.2-km path at City C. The calculation is based on 20-year distribution of 5-minute point rain rates at City C.

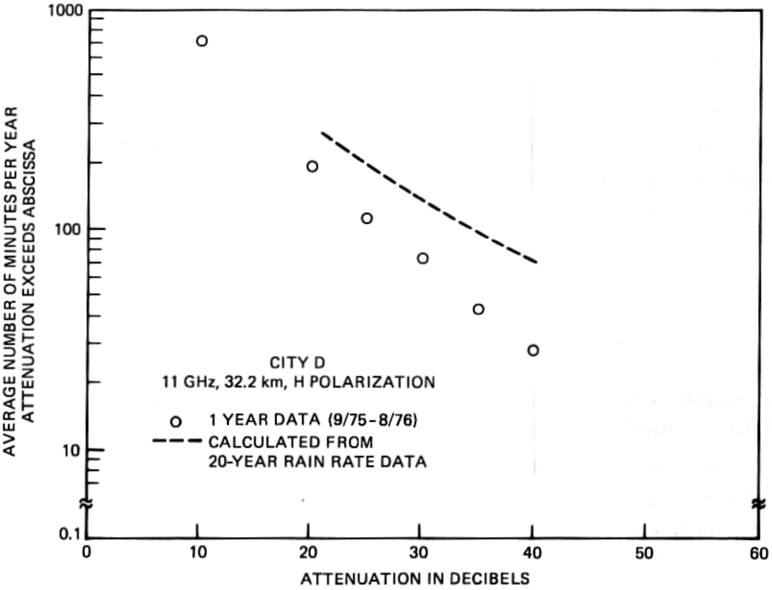

Fig. 18—Comparison of calculated (dashed line) versus measured 11-GHz rain attenuation distribution on a 32.3-km path at City D. The calculation is based on 20-year distribution of 5-minute point rain rates at City D.

Table V — Measured rain attenuation data on 11-GHz paths

Location	Path length, km	Time base	Radomes	Polar-ization	Assumed attenuation (dB) due to two wet radomes for calculations
Palmetto, Ga.	42.5	8/73–7/74	2 flat radomes	V	4
Palmetto, Ga.	25.6	8/73–7/74	2 flat radomes	H	4
Palmetto, Ga.	5.1	8/73–7/74	2 dishes without radome	H	4
City A	32.1	74–75	2 flat radomes	V	4
City A	20.8	74–75	2 flat radomes	V	4
City A	11.3	74–75	2 flat radomes	V	4
City B	10.1	74–75	1 flat; 1 hemispheric	H	6
City C	12.2	8/72–12/75	2 hemispheric radomes	H	8
City D	32.2	9/75–8/76	2 flat radomes	H	4

14 to 18 indicate that the measured results are comparable with the predicted curves.

IX. CONCLUSION

Two methods have been described to obtain long term (≥20 years) distributions of 5-minute rain rates from data published by the National Climatic Center for U.S. locations. Some typical results are given in Refs. 8 and 9. The variability of distributions based on shorter terms is discussed in Section IV.

A set of simple empirical formulas, for converting the distributions of 5-minute rain rates into the distributions of 11-GHz rain attenuation on any path length, has been deduced from experimental data gathered near Atlanta, Georgia. These formulas are supported by further experimental data from other locations.

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The author is grateful to the late W. Y. S. Chen for valuable discussions on rain rate statistics and the theory of extreme value statistics. W. C. Y. Lee,[42] R. A. Semplak,[44] P. L. Rice and N. R. Holmberg[43] have separately described three different approximate methods for obtaining rain rate distributions from rainfall data published by the National Climatic Center. The method described in Ref. 5 by W. Y. S. Chen and in Section II of this paper is inspired from this work. The author would also like to thank C. A. Maxon, P. L. Dirner, and E. E. Sorrentino for their assistance in the computer processing of the large volume of rainfall data.

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