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Some Further Aspects of the Influence of Raindrop-Size Distributions on Millimeter-Wave Propagation

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PREFACE

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TABLE OF CONTENTS

LIST OF FIGURES AND TABLE

SOME FURTHER ASPECTS OF THE INFLUENCE OF RAINDROP-SIZE DISTRIBUTIONS ON MILLIMETER-WAVE PROPAGATION

E. J. Dutton and F. K. Steele*

In the presence of rain, millimeter-wave propagation is acutely sensitive to the distribution of raindrop sizes along a given propagation link. This report analyzes the variability of rain attenuation prediction at microwave/millimeter wave frequencies caused from the variation of measured raindrop-size distribution data. The results show a considerable need for better and more extensive dropsize distribution data, both in time and geography.

After searching for potential solutions, the report discusses the historical development of raindrop distribution measurement methodology, including direct measurement techniques, but with emphasis on indirect, or remote sensing, multiple frequency techniques. These latter techniques are carefully scrutinized, with the conclusion that some information derived separately from the techniques is usually necessary to successful usage of the techniques. Some concluding observations are then made for the selection of an appropriate remote-sensing technique for the improved determination of path-averaged raindrop-size distributions.

Key words: annual variability; attenuation coefficients; millimeter waves; multiple frequency techniques; prediction variability; raindrop-size distributions

1. INTRODUCTION AND BACKGROUND

The distribution of raindrop sizes in a given volume of the atmosphere is not an easy quantity to measure or determine. This is primarily because this distribution is representative of a highly dynamic, nonstationary process. Raindrops pass in and out of the volume rapidly, some growing, some colliding with and absorbing other drops, and some breaking into many smaller drops because they are physically too large to withstand atmospheric stresses. In this scenario it is difficult to imagine the ability to obtain exact knowledge of the raindrop-size distribution per unit volume at any given time as ever being realizable. Atmospheric scientists have resorted to various dropsize counting schemes (Dutton et al., 1983) to obtain raindrop-size distributions with, as might be expected, a potpourri of results. Like almost everything else in atmospheric processes, raindrop-size distributions exhibit a general deterministic trend, but with a large random component.

Raindrop-size distributions have been of concern to varied groups for a long time. Early in the century, dropsizes were of interest to meteorologists and

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agriculturists. Later, Ryde (1946) identified the significance of raindrops in the attenuation and backscatter of radar waves. It is now known (Kobayashi, 1980) that rain is of primary importance in millimeter or microwave propagation. Figure 1 shows the relative attenuating characteristics of rain as it impacted a 30.3 GHz, 27.2 km-link bit error rate (BER) measured by Espeland et al. (1984). Figure 1 clearly indicates the dominance of the rain effect when it occurred. At frequencies below 10 GHz or so, large drops tend to be responsible for absorption, scattering, and depolarization. At the higher frequencies, drop sizes are more comparable to wavelengths and the small drops increase in significance. There has been a recent increase in the use of millimeter waves and a resulting greater need for specific information about rain rates, drop sizes and effects on telecommunication.

Notwithstanding all the difficulties in determining raindrop-size distributions is the fact that much of the developed theory of rain attenuation is directly dependent upon knowledge of raindrop-size distributions. This creates a very inauspicious situation with respect to the need for valid drop-size distributions vis-à-vis the existing information on such drop-size distributions. Complicating matters even further is the high degree of sensitivity to drop-size distribution of rain attenuation evaluated from theory at millimeter wave frequencies (Dutton et al., 1983). Now the need for valid drop-size distribution material becomes even more acute, but, alas, the information base remains the same. In Dutton et al. (1983) an attempt was made to glean rain attenuation prediction coefficients, a_z and b_z, by the use of linear and nonlinear least-squares techniques, in four general worldwide climatic zone types. This procedure subdivided 226 worldwide-measured drop-size distributions into four distinct climatological zones; whence, four relationships of the form

$$\left\langle \log_{10}\alpha_z(f,R) \right\rangle = b_z(f)\log_{10}R + \log_{10}a_z(f) \tag{1}$$

were predicted by least-squares techniques. In (1), $\left\langle \log_{10}\alpha_z(f,R) \right\rangle$ gives a value, $\alpha_z(f,R)$ for specific attenuation (attenuation in decibels per kilometer), R is the rain rate in millimeters per hour, and $a_z(f)$ and $b_z(f)$ are frequency, f, dependent coefficients for the zone, z. The analysis of prediction errors associated with this process may be partially representative of unknown measurement errors of the individual drop-size distributions. This analysis will be considered in Section 2 of this report.

As will be seen in Section 2, inclusion of prediction errors gives such a broad range of possibilities for rain attenuation along a terrestrial link that it in no way clarifies the critical situation at millimeter-wave frequencies. Thus,

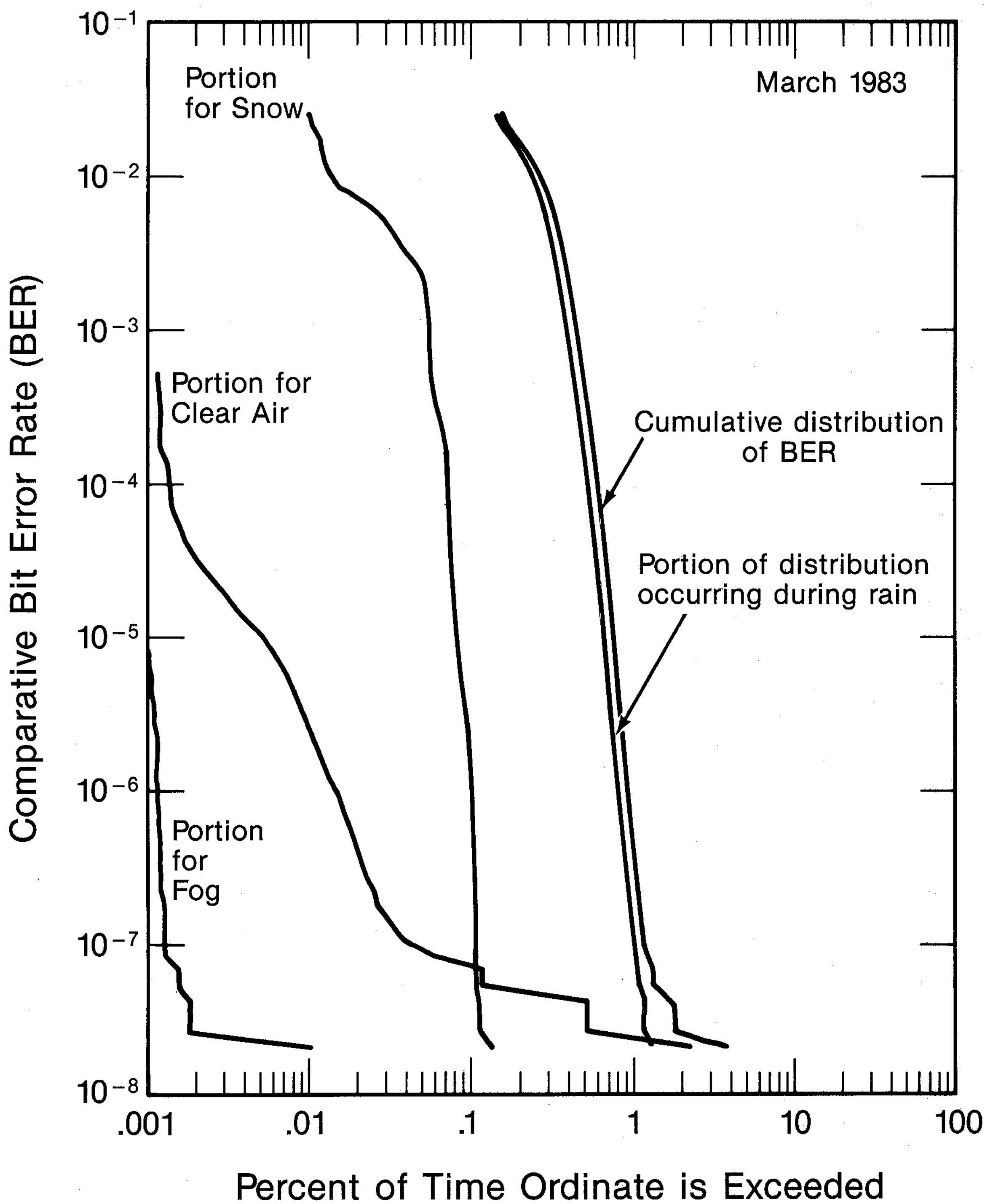

Figure 1. Cumulative distribution of BER and the portion of the distribution contributed under each meteorological classification as recorded during March 1983 on a 30.3 GHz 27.2 km path.

we must seek other means of determining raindrop-size distributions, most likely involving new experimental procedures. The leading candidate in new experimental procedures for determining drop-size distribution is the "passive probe" approach; i.e., indirectly measuring path-averaged raindrop-size distributions by measuring path attenuation at a number of desired frequencies. This has the advantage over direct measurements in that it covers an entire path and places the emphasis on measuring the desired output phenomenon (attenuation) rather than on the intermediate phenomenon (drop-size distribution). As will be seen in Section 5 of this report, however, these indirect measurement procedures are prone to ambiguities just as were the direct measurement procedures.

2. COMBINED YEAR-TO-YEAR AND PREDICTION VARIABILITIES

In every least-squares fitting procedure, there is a deviation, δ, of the true value from the estimated value. This deviation can be expressed as

$$\delta = \zeta + \varepsilon, \tag{2}$$

where ζ represents contributions to δ because of the difference between the expected population fit and the sample regression fit, and ε represents the difference between an actual value and the population fit. If we use a sample regression fit of the form of (1), which is essentially a linear regression, we can use the basic concept (2), which leads to the formulations on page 163 of Crow et al. (1960), to arrive at a prediction variability, s_δ^2, for the model

$$\log_{10}\alpha_z(f,R) = \left\langle \log_{10}\alpha_z(f,R) \right\rangle + \delta = b_z(f)\log_{10}R + \log_{10}a_z(f) + \delta. \tag{3}$$

Now, $\alpha_z(f,R)$ represents a "true" value of specific attenuation for any given f and R. Expression (3) obtains <u>specific</u> attenuation, which must be combined with an "effective path length," L_e, to give the total path attenuation $\tau_p'(f)$ at percentile, p. In an attenuation distribution, the percentile, p, will correspond to a particular rain rate, R. However, $\tau_p'(f)$ has a year-to-year variability that has been modeled for both terrestrial links (Dutton, 1984) and earth-space paths (Dutton et al., 1982). In that modeling, we essentially use an expression of the form

$$\tau_p'(f) = c(f)L_e \quad , \tag{4}$$

where c(f) is for convenience treated here as a nonrandom function* of frequency (only) for specific attenuation that, when multiplied by the random variable, L_e (i.e., variable on a yearly basis at percentile, p) produces the random variable $\tau_p'(f)$, which is also variable on a yearly-basis only. This permits us to develop a reasonable, yet tractable, analysis. Now, with the application of (3), we have introduced statistical variability into the specific attenuation, so that

$$\tau_p(f) = \alpha_z(f,R)L_e \quad , \tag{5}$$

a product of two random variables. Using (4), (5) can be rewritten as

$$\tau_p(f) = \alpha_z(f,R)\frac{\tau_p'(f)}{c(f)} \tag{6}$$

If we take logarithms in (6), we will have the expression

$$\log_{10}\tau_p(f) = \log_{10}\alpha_z(f,R) + \log_{10}\tau_p'(f) - \log_{10}c(f) \quad , \tag{7}$$

that can be more readily manipulated. This is because we now have the sum of two random variables rather than the product of them. However, it also implies that as well as knowing the distribution functions of the random variables we will have to ascertain the distributions of the logarithms of these variables. Probably the most straightforward and manageable approach to this is to use normal distributions for the logarithms, which implies lognormal distribution of the individual variables themselves.

How feasible is this approach? The basic variance analysis procedures associated with linear regression of the form of (3) requires the assumption of normality; thus, for $\log_{10}\alpha_z(f)$, use of normality is a consistent procedure (Crow et al., 1960,

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* c(f) is a function of the random variable, R, and is thus in reality a random function. However, the variability of $\tau_p'(f)$ must be at least as large as the variability of c(f), as can be noted from (4), so that the overall effect of including it would be at most to add an additional variance of the order of s_{vp}^2 to (15). In other words, the dominance of s_u^2 in (15) would remain intact. It should also be noted that predicted values of rain attenuation in the rightmost three columns of Table 1 should be slightly larger.

page 150). The lognormal distribution is probably a valid distribution to use in connection with the modeling of the year-to-year variability of $\tau'_p(f)$, although we have preferred the use of a truncated normal distribution (Dutton, 1977). In the development that follows, we shall make use of the fact that a lognormal distribution represents the total year-to-year distribution of $\tau'_p(f)$ reasonably well, and the fact that a normal distribution represents the upper 50% portion of the year-to-year distribution of $\tau'_p(f)$ very well. This apparent inconsistency can be resolved via the truncated normal distribution.

It is known that (Beckmann, 1967, page 415) if the ratio of the year-to-year standard deviation, s_{yp}, of $\tau'_p(f)$, to the mean value of $\tau'_p(f)$, $\langle \tau'(f) \rangle$, is sufficiently small, i.e.,

$$\frac{s_{yp}}{\langle \tau'_p(f) \rangle} << 1 \quad , \tag{8}$$

then the truncated normal distribution can be approximated by the normal distribution, itself. This, as is indicated in Dutton (1977), is almost always the case for $\tau'_p(f)$. This also means that

$$\langle \tau'_p(f) \rangle \approx \tau'_{p,50}(f) \quad , \tag{9}$$

where $\tau'_{p,50}(f)$ is the median value of $\tau'_p(f)$. If we now let

$$v = \log_{10}\tau'_p(f) - \log_{10}c(f) \quad , \tag{10}$$

then the variance of v at percentile, p, s^2_{vp} is given by

$$s^2_{vp} \approx 0.18861 \left[\frac{s_{yp}}{\tau'_{p,50}(f)} \right]^2 \quad , \tag{11}$$

(Crow et al., 1960, page 69) so long as the condition (8) holds. However, Panter (1972, page 354) notes that if $\tau'_p(f)$ is lognormally distributed, then

$$s^2_{vp} = 0.18661 \ln \left\{ \left[\frac{s_{yp}}{\tau'_{p,50}(f)} \right]^2 + 1 \right\} \quad . \tag{12}$$

Again, if the condition (8) applies, (12) becomes

$$s_{vp}^2 \approx 0.18861 \left[\frac{s_{yp}}{\tau'_{p,50}(f)} \right]^2 , \tag{13}$$

which is identical to (11). While this, as the mathematicians say, may not be "sufficient" rationale for the dual use of a normal and a lognormal distribution of the year-to-year variability of $\tau'_p(f)$, it turns out to be inconsequential, anyway. This is because, as will be shown, the variability due to the regression procedures to obtain $\alpha_z(f)$ is by far the dominant variability effect in the following analysis. Any assumption for the year-to-year variability of $\tau'_p(f)$ vis-à-vis the regression variability of $\alpha_z(f)$ appears to have little impact on the final results.

At any rate, we now have some justification for assuming $\log_{10}\alpha_z(f)$ and $\log_{10}\tau'_p(f)$ to be normally distributed. If we let the random variable U represent $u = \log_{10}\alpha_z(f)$, V_p represent $v_p = \log_{10}\tau'_p(f) - \log_{10}c(f)$, and W represent $w = \log_{10}\tau_p(f)$, then

$$W = U + V_p \tag{14}$$

from (7), where W, because it is the sum of two normally distributed random variables, is also normally distributed (Beckmann, 1967, page 79). Also, the variance of W, s_w^2, is given by

$$s_w^2 = s_u^2 + s_{vp}^2 \quad . \tag{15}$$

In (15), s_{vp}^2 is the variance of v at percentile, p, and is given by (12). Further in (15), s_u^2 is the variance of u, which, from (3) becomes

$$s_u^2 = E(\delta^2) \quad , \tag{16}$$

where E represents the "expected value" operator. As a consequence of the result (16), it can be shown that

$$s_u^2 = (S.E.)^2 \left[1 + \frac{1}{n} + \frac{(\log_{10}R - \langle \log_{10}R \rangle)^2}{(n-1)s_{\log_{10}R}^2} \right] \tag{17}$$

in the case of a linear regression such as (3). In (17), S. E. is the "standard error of estimate" (Crow et al., 1960, page 163) of the linear regression, n is the number of data pairs used in the regression analysis (in this case, $\log_{10}\alpha(f,R)$, and $\log_{10}R$), $\langle \log_{10}R \rangle$ is the mean value of $\log_{10}R$, and $s^2_{\log_{10}R}$ is the sample variance of $\log_{10}R$.

On the basis that W is normally distributed, we can write, with z_p the standard normal deviate value of interest,

$$w = \hat{w} + z_p s_w \quad , \tag{18}$$

where $\hat{w}$ is the expected value of w. It is known that (Beckmann, 1967, page 82)

$$\hat{w} = \hat{u} + \hat{v}_p \quad , \tag{19}$$

where $\hat{u}$ and $\hat{v}_p$ are expected values of u and v_p, respectively. On the basis of the relationships between lognormal and normal distributions and their respective parameters, we can obtain

$$\hat{v}_p = 0.4343 \left[\ln \tau'_{p,50}(f) - \frac{s^2_{vp}}{0.37722} \right] - \log_{10}c(f) \quad , \tag{20}$$

where s^2_{vp} was given by (12). The expression (20) requires the implicit assumption of (9), as well. Since

$$\hat{u} = \langle \log_{10}\alpha_z(f,R) \rangle \quad , \tag{21}$$

where the brackets indicate the expected value; thus

$$\hat{u} = \log_{10}a_z(f) + b_z(f)\log_{10}R \tag{22}$$

using (1). Since we now know all the parameters in (18), we can obtain $\tau_p(f)$ as

$$\tau_p(f) = 10^{\hat{u} + \hat{v}_p + z_p s_w} \tag{23}$$

Let us now undertake a sample computation using (23) to determine its usefulness and meaning. For this purpose we choose Washington, D. C., as the sample location, with an 11 GHz, 25 km link. Although not shown here, a millimeter wave link in the same area, assumed operating at 50 GHz over 2 km gave even more divergent results than those about to be presented. What is meant by the slightly ominous "even more divergent" is shown in Table 1. Table 1 results are divided basically into two parts. The first part represents the results of expression (4), with year to year variability, s_{yp}, yielding results at p = 0.001, 0.01, and 0.1 percent of a year. The median (average annual) distribution is given, along with the extreme 99.5 percent upper limit distribution. Results have been calculated using six models as described in Dutton (1984). The second part represents the results of (5), via (23), for the same conditions as in the first part of Table 1. The salient feature of Table 1 is the tremendous differential between the 50 percent and the 99.5 percent confidence levels at corresponding exceedance percentiles in the second part of the table. For example, at the 0.001 percent exceedance level, the difference is 1303.8 dB. This is clearly an overwhelming number that devoids the entire prediction process under these circumstances of any meaning, whatsoever. We must now examine the source of these unacceptably large numbers.

Without going into detail, a sample hand calculation revealed that the primary source of this aberration in values was in the standard error of estimate, S.E., in (17) associated with the zonal linear regressions (3). The dispersion of the points in all four of the zones analyzed in Dutton et al. (1983) is so great, apparently, that it completely masks the more modest year-to-year variability effect (12). Thus, when the variances are combined as in (15),

$$s_w^2 \approx s_u^2 \quad , \tag{24}$$

and the combination of variances process is "reductio ad absurdum." Once again, then, this strongly suggests the need for more and improved data from which to analyze the behavior of millimeter-wave specific attenuation and/or raindrop distributions, before the ability to proceed with any kind of meaningful variability analysis will exist.

3. DIRECT RAINDROP-SIZE DISTRIBUTION MEASUREMENTS

Early on, raindrop sizes were directly measured with absorbent paper and water soluble dye by Weisner (1895), or with a flour/powder method by Bentley (1904). Later Jones and Dean (1953) developed a camera that could photograph and size raindrops from 0.4 to 8.0 mm in diameter. Probably the most common direct drop-size measurement device in use today is the impact distrometer introduced by Joss and

Table 1
Prediction Comparison Results
for Washington, D.C., on an 11 GHz, 25 km Link*

Model	Rain Attenuation Computations for Unvarying Specific Attenuation; i.e., Equation (4)						Rain Attenuation Computations for Variable Specific Attenuation; i.e., Equation (23)					
	Median (50%)			(99.5%)			Median (50%)			(99.5%)		
	Percentile level			Percentile level			Percentile level			Percentile level		
	.001	.01	.1	.001	.01	.1	.001	.01	.1	.001	.01	.1
PROMOD (Dutton, 1984)	66.9	30.6	10.2	95.4	43.0	17.9	60.4	24.1	5.6	1369.2	535.4	129.5
Barsis et al. (1973)	44.1	24.0	6.7	60.2	35.9	10.5	20.7	12.0	3.0	466.9	270.5	86.4
Battesti et al. (1971)	106.2	42.6	6.3	186.8	78.2	17.3	48.5	20.6	3.1	1165.0	496.5	96.3
Global (Crane, 1980)	27.3	6.1	6.9	64.4	37.9	16.4	11.9	7.2	3.2	337.7	199.4	87.8
Two-Component (Crane, 1982)	26.1	15.0	7.1	50.3	28.9	13.9	12.1	7.1	3.5	302.8	174.2	84.3
Lin (1977)	66.5	40.5	8.5	84.2	56.6	18.7	40.8	24.5	4.6	908.0	543.5	119.27

*Note that year-to-year variability has been added to some of these models in the manner prescribed in Dutton (1984).

Waldvogel (1967). This device measures the momenta of falling raindrops, then with the terminal velocities of raindrops as established by Gunn and Kinzer (1949), drop masses and diameters can be ascertained. Ugai (1977) used a water-soluble dye and castor oil technique for drop-size measurement.

The various methods of direct drop-size measurement tend to yield consistent results for drops of diameter 1 mm or greater. The drop density, N(D), of the mode diameter ($\sim$1 mm) is typically a few hundred per cubic meter per millimeter of diametric range ($m^{-3}mm^{-1}$) for moderate rain rates. Laws and Parsons (1943), and Marshall and Palmer (1948), established an empirical relationship for drop density in rain of the form,

$$N(D) = N_0 \exp[-\Lambda(R)D] \quad . \tag{25}$$

Here N_0 is a constant, Λ is a function of rain rate R and D is drop diameter. The expression is represented by a straight line on a logarithmetic versus linear plot, and its slope is observed to be related to rain rate. The model (25) has been used for a long time and is satisfactory for the larger drops. Unfortunately, the model predicts more (typically thousands) very small drops ($D \ll 1$ mm) than are commonly observed. For example, Ajayi and Olsen (1983) found only a few (<100) drops of very small diameter with an impact disdrometer. However, it should be noted that Ugai (1977) found hundreds of thousands of very small drops ($m^{-3}mm^{-1}$) in moderate rainfall. These disparities in directly measured densities of small drops are perplexing, and with increasing use of millimeter waves will be of growing practical concern.

4. INDIRECT RAINDROP-SIZE DISTRIBUTION MEASUREMENTS

Raindrop-size distributions can be inferred indirectly from measurements of microwave or millimeter-wave attenuations and phase variations in propagation through rain cells. Sophisticated solutions to the mathematical problem of inversion have been discussed by Furuhama and Ihara (1981), and Bebbington (1983).

The indirect radio wave measurement method is implicitly based on the Lambert-Bouguer law of basic optics. It is assumed that a plane wave (source effectively at infinity) propagates in the parallel beam through a homogeneous slab that is transverse to the direction of propagation. Under these assumptions, the intensity, I, ($watts/m^2$) can be expressed as

$$I = I_0 \exp(-\alpha L) \quad , \tag{26}$$

where I_o is the initial intensity, L is the distance of penetration, and α is an attenuation coefficient. It is generally taken that α represents loss of intensity by absorption and scattering. The absorption and scattering due to water droplets are usually treated in the manner of Mie (1908). Each spherical raindrop has an absorbing cross-sectional area c_a and a scattering cross-sectional area c_s, which are functions of both D and frequency, as will be noted later. Rain typically contains drops of various sizes. So, if there are n(D)dD particles per unit volume having diameters, D, in the range from D to D + dD then the total number of drops, N, per unit volume is

$$N = \int_0^\infty n(D)dD, \tag{27}$$

and the total absorption cross section, K_a, is

$$K_a = \int_0^\infty n(D)c_a dD \; . \tag{28}$$

Similarly, then

$$K_s = \int_0^\infty n(D)c_s dD, \tag{29}$$

and the total attenuation or extinction cross section, K_e, is

$$K_e = K_a + K_s \; . \tag{30}$$

Finally then

$$I = I_o \exp(-\int_0^L K_e d\ell) \; . \tag{31}$$

The extinction cross section may be calculated as described by Mie (1908), Van de Hulst (1957), or Wickramasinghe (1973), from raindrop size, incident wavelength, and index of refraction of the raindrops as modeled by Ray (1972). With the calculated extinction cross sections, the measured propagation parameters of attenuation and phase, and the inversion methods mentioned, it is then possible to infer raindrop-size distributions.

The indirect methods of drop-size measurements are mathematically elegant and have produced some interesting, consistent results. A prudent experimentalist, however, may choose to be a bit circumspect in his measurement approach, assumptions in the inversion method, and interpretation of results.

Propagation path geometry should be chosen so that measurements are made when the rain cell does not approach the receiver too closely. The technique used by Furuhama and Ihara (1981), for example, utilizes a result obtained by Van de Hulst (1957). This result that describes the amplitude of an electromagnetic wave received through a scattering-absorbing slab, is predicated on small-angle forward scattering that may not be the case when a rain cell is close to the receiver.

Expression (30) has been derived on the assumption that there is no multiple scattering within the propagation medium. Whether or not this is so is not entirely clear. Respected workers have published disparate views concerning the significance of multiple scattering of millimeter waves and microwaves in rain cells. Uzunoglu and Evans (1978) found insignificant multiple scattering in rain for frequencies to 100 GHz, while Ishimaru and Cheung (1980) found that multiple scattering may be significant at frequencies above 30 GHz in moderate rain, or at lower frequencies in heavy rain when drop sizes are more likely to be more comparable in size to a wavelength. Bayvel and Jones (1981) found that multiple scattering may be significant if $K_e L \gtrsim 0.01$. Further, it has been suggested by Capsoni et al. (1977) that total attenuation of millimeter waves in a rain cell is nonlinear with distance and is related to multiple scattering.

The indirect raindrop-size measurement methods of Furuhama and Ihara (1981) and Bebbington (1983) are similar. Each method presupposes Mie (1908) scattering by spherical raindrops. The assumption of sphericity is certainly an appropriate first trial approach to use, particularly if it is assumed that nearly 32 percent (Jones, 1959) of the observed drops are spherical and the prolate and oblate ellipsoidal drops are about equal in number.

The two indirect methods discussed here differ primarily in that Furuhama and Ihara (1981) assume a known form (25) of drop-size distribution, while Bebbington (1983) states that no particular form of drop-size distribution (maximum entropy method) is assumed. It is interesting to note, as discussed in Section 3.3, that Bebbington (1983) does have to assume a value of N_o from Marshall and Palmer (1948) as part of the inversion process. The final results of both methods are similar distributions that are reminiscent of expression (25) where N_o ranges from about 10,000 to 20,000 ($m^{-3}mm^{-1}$) at maxima. It is disappointing that these indirectly inferred raindrop-size distributions do not confirm either the low drop densities of small drops as reported for by Ajayi and Olsen (1983), or the large, high-drop densities observed by Ugai (1977).

5. USES OF MULTIPLE FREQUENCIES TO DETERMINE PATH-AVERAGED DROPSIZE DISTRIBUTIONS

Instantaneous or nearly instantaneous "snapshots" of the atmosphere often give the best information about it. The use of multiple frequencies along a given propagation path is a widely used tool for attempting to discern such properties of the atmosphere. This is one of the techniques of the process known as "remote sensing." This approach may also hold some hope for the eventual determination of path-averaged raindrop distributions during stormy conditions to help evaluate millimeter-wave specific attenuations. As discussed in Section 2, these specific attenuation results are desperately needed at this stage of millimeter-wave model development. While the use of multiple-frequency techniques may provide a means of obtaining such specific attenuation information, it is nevertheless uncertain regarding the extent of the information that will be realized from such techniques.

Goldhirsh and Katz (1974) appear to have been among the earliest to examine a multiple-frequency technique. They hoped to use radars operating at 1, 3, and 10 cm to obtain results but stated that

> ". . .one needs combined 2-radar accuracies of 1 dB to get even marginal drop distribution accuracies. Such accuracies are considered impractical at present. . . ."

In other words, Goldhirsh and Katz (1974) decided that the use of multiple-frequency techniques via radar for determining raindrop-size distributions was not feasible.

This hardly exhausts the set of multiple-frequency technique (MFT's), however, although it provides considerable discouragement for any radar-MFT combination. Furuhama and Ihara (1981) investigated several potential applications of MFT's in connection with an experimental microwave/millimeter-wave link of 1.3 km length in Japan. In order to isolate the path-average drop-size distribution in the presence of rain, they considered three different MFT's:

(1) the method of a trial function

(2) the Phillips-Twomey method

(3) the Backus-Gilbert method.

These methods fall under the general heading of "inversion techniques" (Westwater and Strand, 1972), and, as such, they all suffer from a common deficiency. As Westwater and Strand (1972) reiterate, solutions using inversion techniques suffer instability (i.e., are equivocal) unless some preconditions about the behavior of the solutions are assumed. This situation appears to apply regardless of the method, and implies that no results that deviate much from some preconceived notion (or prejudice) are going to occur, whether they actually occur or not. However, in the particular instance of determining path-averaged raindrop-size distributions, the path averaging may limit some of the deviation from preconceived notions, so that such "initial guesses" may not be as restrictive as they might be in some other applications.

Furuhama and Ihara (1981) intercompare methods (1) through (3) above and show results that lead to the conclusion that only method (1) produces any feasible results. In connection with method (1), the trial-function method, Furuhama and Ihara (1981) use an exponential trial function

$$\overline{n(D)} = N_0 \exp(-\Lambda D) \tag{32}$$

to initially represent the path-average drop-size distribution density function, $\overline{n(D)}$. In (32), which is the classical representation of Marshall and Palmer (1948), N_0 and Λ are the unknown parameters of the distribution that are obtained from method (1), and D is raindrop diameter, assuming spherical drops. Furuhama and Ihara (1981) then proceed to determine some "representative" N_0's and Λ's using three frequencies at 11.5, 34.5, and 81.8 GHz. For the determination of accurate drop-size distributions for use at millimeter-wave frequencies, the choice of analysis frequencies could be critical. This is because the electromagnetic effect of small drop sizes is greatly magnified in the millimeter-wave region vis-à-vis the microwave region. Hence the choice of two frequencies such as 11.5 GHz and 34.5 GHz, rather than some higher values that might bias resultant distributions toward larger drop sizes. The more frequencies used, the better the results, of course, but the addition of frequencies could prove prohibitively expensive to an operational experimental scheme.

As a final MFT to be discussed here, let us examine what is known as a "maximum entropy method." The basic concept of the maximum entropy method is conveyance of as much information about an unknown quantity as possible to a user through its application. However, certain appropriate relationships must exist in order to apply the maximum entropy method, and this appears to be almost the case in the raindrop-size distribution situation. The reason that it is not quite clear that it is entirely applicable is the fact that a drop-size distribution is not a strict probability distribution, and the maximum entropy method has been developed for true probability distributions. In order to make a true probability distribution out of a drop-size distribution, one must normalize the drop-size distribution by the total number of drops, N, in a given volume of atmosphere. This, as we shall see, causes a problem in the straightforward application of the maximum entropy method.

To our knowledge, the first attempt to apply the maximum entropy method, as developed by Jaynes (1957), to the raindrop-size distribution problem was made by Bebbington (1983). Let us now discuss the maximum entropy procedure as applied to the determination of raindrop-size distributions.

The maximum entropy method procedure as developed by Jaynes (1957) is evolved from Lagrange's method of multipliers, which we shall briefly review. If we have a function $F = F(x_1, x_2, \ldots x_m)$ of m variables that are not independent, but are constrained by M conditions ($M < m$),

$$\left.\begin{aligned} \phi_1 &= \phi_1(x_1, x_2, \ldots, x_m) \\ \phi_2 &= \phi_2(x_1, x_2, \ldots, x_m) \\ &\vdots \\ \phi_M &= \phi_M(x_1, x_2, \ldots, x_m) \end{aligned}\right\} = 0 \quad , \tag{33}$$

then we can construct a function $W = W(x_1, x_2, \ldots, x_m)$ where

$$W = F + \lambda_1\phi_1 + \lambda_2\phi_2 + \ldots + \lambda_M\phi_M \quad . \tag{34}$$

In (34), $\lambda_1, \lambda_2, \ldots, \lambda_M$ are the so-called "Lagrangian multipliers" (not to be confused with wavelength). The function W can then be maximized via setting

$$\frac{\partial W}{\partial x_1} = \frac{\partial W}{\partial x_2} = \ldots = \frac{\partial W}{\partial x_m} = 0 \quad , \tag{35}$$

and solving the m + M equations in (33) and (35) for $x_1, x_2, \ldots, x_m$, and $\lambda_1, \lambda_2, \ldots, \lambda_M$. In order to obtain a probability density function $\rho(x_i)$ at any x_i, i = 1 to m, using the Jaynes (1957) procedure, we must introduce a function, $f(x_i)$, such that

$$\left\langle f(x_i) \right\rangle = \sum_{i=1}^{m} \rho(x_i) f(x_i) \quad , \tag{36}$$

where $\left\langle f(x_i) \right\rangle$ represents the expected value of the function $f(x_i)$. Then Jaynes (1957) obtains

$$\rho(x_i) = \exp\,[-\lambda_1 - \lambda_2 f_1(x_i) - \lambda_3 f_2(x_i) - \ldots - \lambda_M f_{M-1}(x_i)], \quad (37)$$

for several functions $f_{j-1}(x_i)$, $j = 2$ to M. If we were to apply this result to raindrop distributions, let $n(D_i)$ be the [path-averaged, with the overbar in (32) dropped] number of drops per cubic meter of diameter, D_i between $D_i - \Delta D_i/2$ and $D_i + \Delta D_i/2$ where ΔD_i represents some diameter region around D_i. Then if the attenuation A_ν, in decibels, were to be used at frequency ν_j, $j = 1$ to $M - 1$, as the measured quantity on a path of length L kilometers, we can work with the specific attenuation, α_{ν_j}, where

$$\alpha_{\nu_j} = \frac{A_{\nu_j}}{L}\,, \quad (\mathrm{dB/km}) \quad (38)$$

to obtain a suitable F and ϕ_j's. The F's and ϕ_j's can be constructed as follows:

$$F = -\sum_{i=1}^{m} \frac{n(D_i)}{N} \ln \frac{n(D_i)}{N}\,, \quad (39)$$

$$\phi_1 = N - \sum_{i=1}^{m} n(D_i) = 0\,, \quad (40)$$

and

$$\phi_j = \alpha_{\nu_{j-1}} - 4.343 \times 10^3 \sum_{i=1}^{m} Q(D_i,\nu_{j-1})\,n(D_i)\Delta D_i = 0\,, \quad j = 2,M. \quad (41)$$

In (41), $Q(D_i,\nu_{j-1})$ represents the attenuation cross section <u>in square meters</u> of a spherical raindrop as evaluated from Mie theory, with $n(D_i)$ the number of drops per cubic meter per millimeter of drop diameter, and the width ΔD_i in millimeters. Equations (39) and (40) are essentially required formulations for the maximum entropy condition, assuming

$$\rho(x_i) = \rho(D_i) = \frac{n(D_i)}{N}\,, \quad (42)$$

where N is the (path averaged) total number of drops per cubic meter of air given by (27). We can also generate the $f_{j-1}(x_i) = f_{j-1}(D_i)$ in (36) as

$$f_{j-1}(D_i) = 4.343 \times 10^3 NQ(D_i, \nu_{j-1}) \ , \ j = 2,M. \tag{43}$$

Then, using (37) and (42),

$$n(D_i) = N \exp\left[- \lambda_1 - \sum_{j=2}^{M} \lambda_j f_{j-1}(D_i)\right] \tag{44}$$

The results (43) and (44) indicate the problem discussed earlier; namely, one needs an independent assessment of N in addition to other parameters in order to evaluate $n(D_i)$. This is not helpful because one would hope to obtain N from the maximum entropy method itself, via (27), and thereby minimize biasing in the procedure by keeping it self-contained. Now, however, one must resort to methodology additional to the maximum entropy analysis to obtain N. Bebbington (1983) leaves one with the impression that N can somehow be gleaned from the maximum entropy procedure by what he calls a "shooting method." There is not sufficient elucidation in Bebbington's (1983) paper to ascertain whether this is so, but in view of the preceding analysis it would seem unlikely. Of course,there are a variety of additional procedures for estimating N along a path, but the potential of the maximum entropy method seems somehow tarnished as a method for obtaining $n(D_i)$ as a result. Now, when applied to the drop-size distribution problem, the maximum entropy method requires some kind of additional information, or "initial guess" just as did the inversion techniques.

There is another aspect of the maximum entropy method that is somewhat bothersome, as well. This concern stems from the fact that the elementary application of maximum entropy implies a flat, or uniform, density function $\rho(x_i)$. Clearly this cannot be so for $n(D_i)$, since there can be no drops with negative diameters, or at infinity. Nevertheless, one wonders if there is not an implicit tendency of $n(D_i)$ toward uniformity (i.e., flatness) in the application of the maximum entropy method. Unless it can be shown that this is not the case, this would seem to be yet another reason to be circumspect about the interpretation of results derived from the maximum entropy method, especially with only a few data points, or constraints, available.

There is a means by which the path-average drop-size distribution can be bounded using the basic conditions (40) and (41) assuming N is somehow known, although the accuracy of the approximation remains uncertain. This procedure requires some separate procedure to estimate the total number of drops, N, per unit volume, not attempted here. Estimation of the exact distribution itself does not seem very likely because of a host of problems and assumptions associated with the essential problem of integral inversion discussed earlier.

A restatement of (41) in precise (integral) format yields

$$\alpha_{\nu_{j-1}} = 4.343 \times 10^3 \int_0^{D_{max}} Q(D,\nu_{j-1})n(D)dD \quad , \tag{45}$$

where D_{max} is the maximum drop diameter occurring in a given volume of air, and D is any drop diameter. Using (42) and (43), (45) can be rewritten as

$$\alpha_{\nu_{j-1}} = \int_0^{D_{max}} f_{j-1}(D)\rho(D)dD \quad . \tag{46}$$

However, since the $\alpha_{\nu_{j-1}}$'s are measured, and the f_{j-1}'s are theoretical, assuming spherical droplets, etc., more than likely (46) should read

$$\alpha_{\nu_{j-1}} = \int_0^{D_{max}} f_{j-1}(D)\rho(D)dD \pm \varepsilon \ , \tag{47}$$

where ε is an error resulting from the attempt to predict $\alpha_{\nu_{j-1}}$ using $f_{j-1}(D)$. In view of (47), it is unlikely that any very precise determination of $\rho(D)$ via integral inversion will result. Therefore, we shall take the approach of trying to determine reasonable bounds for $\rho(D)$ or $n(D)$.

If we break the integral in (46) into m intervals of width ΔD, then we can write

$$\alpha_{\nu_{j-1}} = \int_0^{\Delta D} f_{j-1}(D)\rho(D)dD + \int_{\Delta D}^{2\Delta D} f_{j-1}(D)\rho(D)dD + \ldots + \int_{(m-1)\Delta D}^{m\Delta D} f_{j-1}(D)\rho(D)dD. \tag{48}$$

By the mean value theorem for integrals, then, we can write (48) as

$$\alpha_{\nu_{j-1}} = \rho(\xi_1) \int_0^{\Delta D} f_{j-1}(D)dD + \rho(\xi_2) \int_{\Delta D}^{2\Delta D} f_{j-1}(D)dD + \ldots + \rho(\xi_m)\int_{(m-1)\Delta D}^{m\Delta D} f_{j-1}(D)dD \tag{49}$$

where $(i-1)\Delta D \le \xi_i \le i\Delta D$ for $i=1$ to m. Thus we have the array

$$\begin{aligned} a_{11}x_1 + a_{12}x_2 + \ldots + a_{1m}x_m &= 1 \\ a_{21}x_1 + a_{22}x_2 + \ldots + a_{2m}x_m &= \alpha_{\nu_1} \quad , \\ \vdots \qquad \vdots \qquad & \\ a_{M1}x_1 + a_{M2}x_2 + \ldots + a_{Mm}x_m &= \alpha_{\nu_{M-1}} \quad , \end{aligned} \tag{50}$$

where $a_{ji} = \int_{(i-1)\Delta D}^{i\Delta D} f_{j-1}(D)dD$ in rows $j=2$ through M of (50). Row 1 of (50) is a restatement of the condition (40), where $a_{1i} = \Delta D$. Further, in (50) $x_i = \rho_i(\xi_i)$, where the reader is cautioned that these x_i's are not the same x_i's used earlier. If we now set $m = M$ (i.e., determine M^2 values of a_{ji}) then we have

$$\underline{a}\ \underline{X} = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1M} \\ a_{21} & a_{22} & \cdots & a_{2M} \\ \vdots & \vdots & & \\ a_{M1} & a_{M2} & \cdots & a_{MM} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_M \end{bmatrix} = \begin{bmatrix} 1 \\ \alpha_{\nu_1} \\ \vdots \\ \alpha_{\nu_{M-1}} \end{bmatrix} = \underline{\alpha} \tag{51}$$

which can be solved for $\underline{X}$; i.e.,

$$\underline{X} = \underline{a}^{-1}\underline{\alpha} \ . \tag{52}$$

The solution of (52), however, hardly solves the problem. First of all, we still have no idea of exactly what ξ_i should be. Second, the error term in (47) causes instability in the $\underline{X}$ matrix, with the result that we can possibly obtain some negative x_i's in a solution--a result that seems to occur as often as not. However, a negative x_i is a clear violation of the definition (42). Although the problems above are not conducive to precise solutions for the x_i's, there are various "ad hocisms" we can initiate to obtain bounds on the drop-size distribution.

At a given frequency, $f_{j-1}(D)$ increases rapidly with diameter D, if that frequency is between 10 and 100 GHz. Thus the last column of the $\underline{a}$ matrix, a_{jM}, is often much larger than the preceding column values, especially if M is not very large (say M = 4 or 5). Quite often a_{jM} is numerically larger than $\alpha_{\nu_{j-1}}$, requiring a very small x_M to offset it. If the maximum drop diameter, D_{max}, is on the order of 0.6 cm, then this is understandable, since there are few drops of that size ever observed in a given volume of air. Often x_M, when obtained from (52), is one of the negative x_i's mentioned earlier. The fact that x_M is negative, either alone or along with other x_i's, and usually small, caused us to set the value of D_{max} much lower, so that the range of D covered by x_M is essentially ignored. This was only done when either x_M or some other x_i (or both) were negative. Proceeding to diminish D_{max} in a systematic way seems to eventually produce* all positive x_i's. When this occurs, the resultant all-positive set of x_i's is used to obtain a drop-size distribution. There is no real justification for this approach other than that just given, and thereby represents one of the arbitrary "ad hocisms" we used.

If we desire to plot the dropsize distribution, Nx_i, versus diameter, we have no way of exactly locating the unknown diameters, ξ_i, along the abscissa. Hence, we have no way of exactly locating the distribution. However, if we assume that the distribution is monotonically decreasing with increasing drop diameter, then we can approximately bound the distribution by plotting two distributions at the end points of ξ_i; i.e., at diameters of $(i-1)\Delta D$ and $i\Delta D$.

To demonstrate the foregoing procedures, let us consider an example drawn from the data of Furuhama and Ihara (1981). The observed attenuations were made at three frequencies of 11.5, 34.5, and 81.8 GHz over a 1.3-km link during rain. If we use the same test case as they did in their paper, we obtain $\alpha_{\nu_{j-1}}$'s of 3.23, 14.69, and 25.85 dB/km at 11.5, 34.5, and 81.8 GHz, respectively. Thus M = 4, and if we initially choose D_{max} = 0.6 cm and solve (52) for $\underline{X}$, we find that x_4 is negative, as is x_2. We then decrease D_{max} until D_{max} = 0.46 cm; whence, all four x_i's are positive results. Having chosen four equal increments between diameters of 0 and 0.46 cm, ΔD = 0.115 cm.

*Although continued diminution of D_{max} can again result in some negative x_i's again.

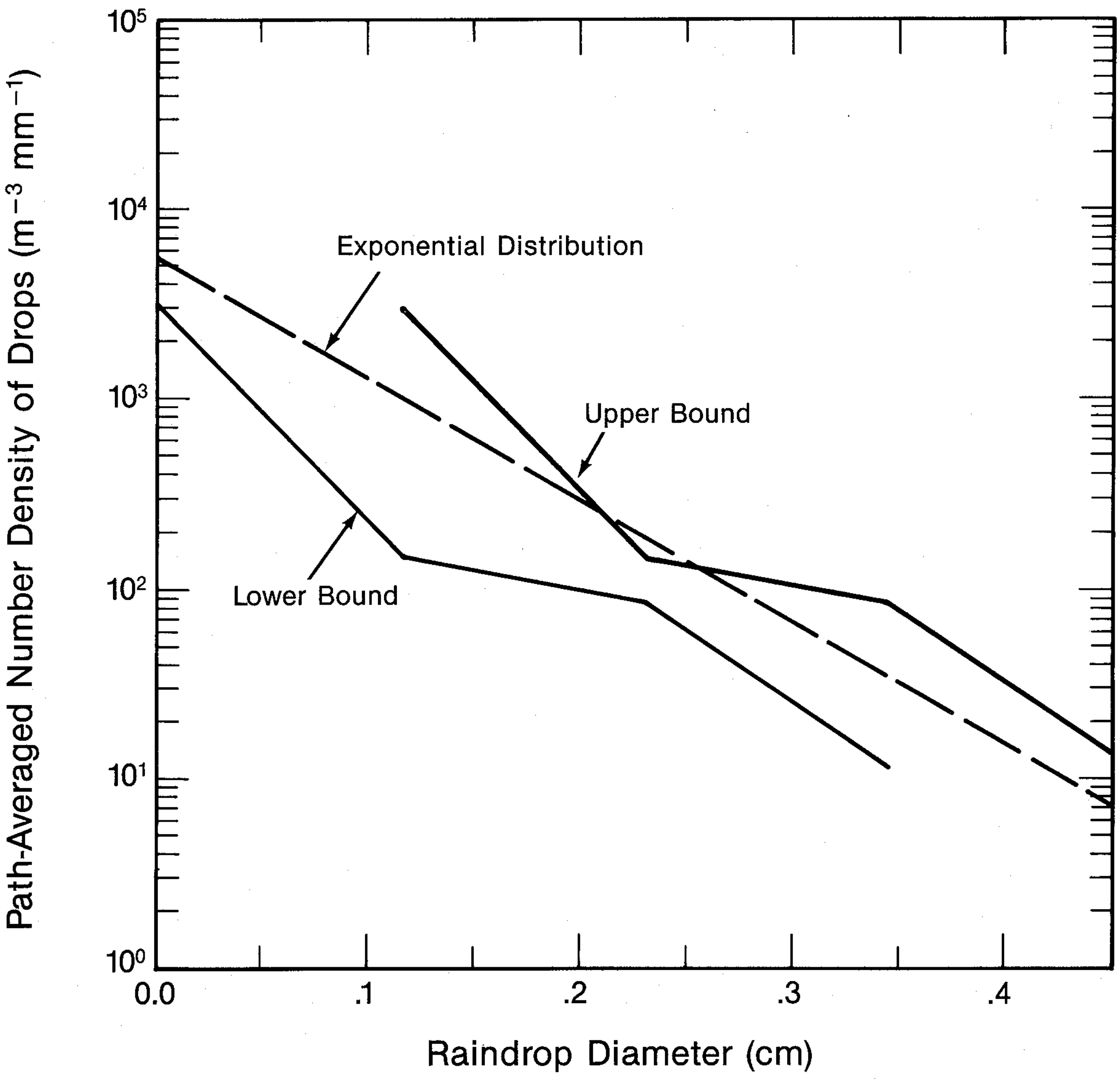

Figure 2. Calculated bounds on a drop-size distribution resulting from the data of Furuhama and Ihara (1981), and their resultant exponential distribution.

Figure 2 shows the two bounds thusly obtained on the drop-size distribution. The four points obtained via (52) are plotted at the lower limits of ξ_i to constitute the lower bound, and at the upper limits of ξ_i to constitute the upper bound. Each set of four points has then been joined by solid straight line segments in Figure 2. For comparison, the exponential drop-size distribution, of the form of (32), that Furuhama and Ihara (1981) obtained from this data set is shown as a dashed straight line on the semilogarithmic plot of Figure 2. In Figure 2, we used the value of N that results from the distribution (32) for these data to obtain the bound values.

6. CONCLUSION

Throughout the earlier part of this report, the need for and importance of raindrop-size distribution information at millimeter-wave frequencies in addition to that already available was demonstrated. The latter part of the report indicated, however, that this need was not likely to be entirely fulfilled by the use of existing electromagnetic remote-sensing techniques. The authors do not really feel comfortable recommending any of the afore-discussed multiple-frequency techniques for the determination of representative path-averaged raindrop-size distributions for the eventual use in establishing a data base for use in rain attenuation prediction. One method, the trial function method of Furuhama and Ihara (1981), has the redeeming features of directness and apparent relative simplicity. The method explicitly assumes a functional form for the drop-size distribution, whereas the other MFT's, including the maximum entropy method, appear to have to make the same assumption, or an analogous one, implicitly at some point, anyhow. Because the trial function method "knows" it has to make an initial assumption about the drop-size distribution, this could make the method more meaningfully applicable than the other MFT's. Any particular use of the trial function method may have to be slightly different from that presented by Furuhama and Ihara (1981) because their usage was tailored to their particular application. Based on an initial analysis, we harbor some confusion as to the application of a least-squares procedure to an exponential drop-size distribution to obtain the parameters Λ and N_0 in (32) in exactly the manner as prescribed by Furuhama and Ihara (1981). Therefore, we are withholding complete approbation of this method until we have contacted the authors and resolved the confusion. Until that time, however, we do not feel that we can really recommend any of the methods discussed herein above any of the other methods as preferable.

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15. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)*

In the presence of rain, millimeter-wave propagation is acutely sensitive to the distribution of raindrop sizes along a given propagation link. This report analyzes the variability of rain attenuation prediction at microwave/millimeter wave frequencies caused from the variation of measured raindrop-size distribution data. The results show a considerable need for better and more extensive dropsize distribution data. The results show a considerable need for better and more extensive dropsize distribution data, both in time and geography.
After searching for potential solutions, the report discusses the historical development of raindrop distribution measurement methodology, including direct measurement techniques, but with emphasis on indirect, or remote sensing, multiple frequency techniques. These latter techniques are carefully scrutinized, with the conclusion that some information derived separately from the techniques is usually necessary to successful usage of the techniques. Some concluding observations are then made for the improved determination of path-averaged raindrop-size distributions..

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

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