ILLINOIS STATE WATER SURVEY
Meteorologic Laboratory
at the
University of Illinois
Urbana, Illinois

INVESTIGATION
OP THE QUANTITATIVE DETERMINATION OF POINT AND AREAL PRECIPITATION BY RADAR ECHO MEASUREMENTS

Ninth Technical Report

1 October 1963 - 31 March 1964

Sponsored by
U. S. Army Electronics Research and Development Laboratory
Port Monmouth, New Jersey

CONTRACT NO. DA-36-039 SC-87280
DA Task 3A99-07-001-01

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The proposal for measuring radar attenuation and reflectivity to determine rainfall rate is investigated and found to yield no significant gain in estimate reliability

A method for attenuation correction is proposed and evaluated It appears to be useful for a majority of storms

The 1963 drop-size data from East Central Illinois Network are presented in brief Generally no differences in the R-Z relationship for a 2-mile separation of sampling points was found

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NINTH TECHNICAL REPORT

1 October 1963 - 31 March 1964

Signal Corps Contracts DA-36-039 SC-87280

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To record and analyze data on raindrop-size distribution in various parts of the world. These data will be correlated with appropriate radar parameters in order to improve the capability of radar in measuring surface rainfall intensities for Army applications such as radioactive rainout prediction, trafficability, and communications.

Prepared by

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PURPOSE

The object of this research is to study the utility of radar equipment in measuring surface precipitation and to improve radar techniques in measuring precipitation for application by the Army to radioactive rainout prediction, trafficability, and communications. Considerable effort is being directed toward determining the correlation between radar variables and actual rainfall quantities by means of raindrop-size distribution.

ABSTRACT

The operational programs for the radars and raindrop cameras are proceeding normally. The M-33 acquisition radar is being used with step gain, at present. The drop cameras have been installed but are not yet ready for data collection.

The proposal for measuring radar attenuation and reflectivity to determine rainfall rate is investigated and found to yield no significant gain in estimate reliability.

A method for attenuation correction is proposed and evaluated. It appears to be useful for a majority of storms.

The 1963 drop-size data from the East Central Illinois Network are presented in brief. Generally no differences in the R-Z relationship for a 2-mile separation of sampling points was found.

PUBLICATIONS, LECTURES, REPORTS, AND CONFERENCES

Dr. H. Weickmann visited the Meteorological Laboratory at Champaign, Illinois, on October 23-24, 1963. During his visit the results of the analysis to date were discussed, as well as the results of the summer's operation in Flagstaff, Arizona.

On November 21, 1963, A. L. Sims and E. A. Mueller visited Evans Laboratory to confer with technical personnel from the Evans Laboratory and Dr. P. Austin from Massachusetts Institute of Technology. The discussion centered around the problems in measuring rainfall intensity by radar. Most of the discussion was directed toward the problem of precipitation attenuation at the shorter wave lengths.

One paper was presented by G. E. Stout at the Fifth Conference on Applied Meteorology: Atmospheric Problems of Aerospace Vehicles at Atlantic City, New Jersey, on March 2-6, 1964. This paper, by E. A. Mueller and A. L. Sims, was entitled, "Liquid Water Content of Rain." It is included in this semiannual report as Appendix A.

All scientific project personnel attended the Severe Storms Conference held at the University of Illinois on November 12-14, 1963. A paper by E. A. Mueller, entitled, "Digital Computer as an Aid in Radar Data Reduction" was presented. E. A. Mueller and A. L. Sims attended the Conference on Physics and Dynamics of Clouds at the University of Chicago on March 24-26, 1964.

RADAR OPERATIONAL PROGRAM

CPS-9

The CPS-9 has been operated for 274 hours during the period. Operation of this radar has been excellent since the overhaul of the slip-ring assembly on the antenna last fall. No changes have been made in the procedures of collecting data with the CPS-9, and it will be used in the same manner for the remainder of this thunderstorm season.

TPS-10

The TPS-10 has been used for collecting data during the period. Some difficulties have been experienced with its transmitter section. The data-collection system has been changed to include two 16-mm cameras. A switch can select between the two cameras to allow either to photograph the RHI scope, and the film can be changed without interrupting data collection. Both cameras have worked satisfactorily and the pictures obtained are of high quality.

M-33

The M-33 acquisition radar has been installed and is used for collecting data. The M-33 antenna has been located on a 35-foot tower to allow a good exposure to the surrounding areas. No modification of the antenna assembly was necessary for installing it except to provide a means of anchoring the tripod legs securely to the tower. Holes were drilled for 3/4-inch bolts which fasten the tripod assembly to the tower. The antenna has a switch that triggers once per antenna revolution, and is used as control circuitry for the camera,

A 35-mm, 0-15 camera has been mounted in front of the tactical control console PPI scope for recording data. This camera mount was made detachable so that if the tracking radar is used for tracking balloons, the camera can be removed and there will be no obstruction to the plotting boards. A control circuit was designed and built which allows gain-step reduction for the M-33. This reduction is the type of gain reduction normally applied to the pre-intermediate frequency amplifier in the M-33. A total range of about 40 decibels (db) can be calibrated. The receiver can be reduced even more in sensitivity, but present calibration techniques do not allow calibration of the reduced sensitivity. The receiver sensitivity is measured at -95 dbm and the transmitter power at 500 kilowatts peak and 800 watts average.

Minor modifications to the presentation system have been made to allow the track azimuth mark to be shown as a radial line from the center to the edge of the scope, and the track range mark as a continuous one around the scope. Therefore, instead of having an electronic cross, as originally designed, another azimuth line and another range mark are available. In this manner two range marks and two azimuth marks can be preset by the operator at known locations to help in the data reduction.

A number of minor difficulties were encountered with the M-33, most of which were due to high humidity or high moisture conditions. It was noted frequently that when the radar was turned on in the morning, the negative 270 volt supply was as much as negative 350 volts because of moisture in the power supply units. Leaving an electric heater on all night has solved this problem.

Plans have been made to install a pulse integrator on the M-33, using the gating circuits for the track radar, and an operational amplifier which is already part of the M-33 computer. These modifications will be primarily to reconnect some of the coaxial cables, so that the video into the track-range gate control is from the acquisition radar rather than the track radar. The gated acquisition video will be sent to an operational amplifier with a condenser feedback to perform integration. The analog computer is reset automatically ten times a second under its present operating conditions. No changes are contemplated in the resetting of the operational amplifier. A peak response amplifier will be placed at the output of the operational amplifier feeding an Esterline Angus strip recorder. At present there is no means of stopping the acquisition antenna and holding the antenna fixed against the wind. For a few selected cases when the drop cameras are running, the antenna will be stopped, and an attempt will be made to hold it in the appropriate direction with guy wires. This is not feasible if more than just a few selected cases are required, however. The pulse integrator operation during antenna scanning is less desirable since the scan rate of the antenna is too rapid to permit a sufficient number of "hits" in a given radar volume at the range of the drop cameras.

A study has been begun to find out whether the quartz-delay line already incorporated in the M-33 moving target indicator (MTI) circuit can be used as a quartz-delay-line integrator. The quartz-delay line may integrate radar echoes if some auxiliary circuits are built. If this appears feasible after further evaluation, some means of contouring and recording the output from the integrator will be devised. During the 1964 summer, pulse integration will be used since time does not permit the final design, construction, and testing of the quartz-delay-line integrator.

RAINDROP CAMERAS

All three raindrop cameras are scheduled for installation on the East Central Illinois Network for the spring and summer of 1964. Two cameras will be located close together in the vicinity of camera A from the previous year. Figure 1 shows a diagram of the location of these two cameras and the surrounding areas. Both cameras have been installed on the west side of the Swigart School. The sampling volumes are approximately 100 feet apart. There are no obstructions to deflect or sort raindrop size distributions from the south through the northwest, but there are obstructions east and north of the drop cameras. Probably these will not greatly influence most of the rains where the wind is from other quadrants.

The southernmost of these two cameras has been installed on a flat-bed trailer which originally held the acquisition antenna of the M-33. This will permit the camera to be moved relatively easily and set up at another location and should eliminate some of the difficulties of realignment and refocusing. The camera and mirror are mounted on H-beams tied to the frame of the flat-bed trailer. The drop-camera shelters are separately supported by 4" x 4" wooden posts so that the wind loading on the shelters will not be transmitted directly to the optical elements. However, the wind loading will be transmitted to the bed of the trailer and then to the optical elements. For this reason, the trailer has been put up on blocks which should reduce the amount of the trailer motion with wind loading.

At present, no test pictures have been taken from this location, but both cameras and electronics have been installed and alignment is in progress. The spare parts van from the M-33 has been towed to the network to serve as field headquarters for maintenance, and as shelter for personnel. The two cameras at the northern end of the network have been modified to permit continuous exposures at 2-second intervals. Some modifications were made in the camera-triggering circuits which will differentiate the camera pulses and permit a longer time for the film to advance between pulses. It was found also that the shutter overheated under continuous operation with the original pulse-length. Shortening the pulse-length by means of a differentiation relay has made the cameras operate more satisfactorily.

Both cameras will be synchronized by the same microswitch and timer, so that flashes will occur simultaneously, greatly facilitating frame-by-frame comparison. A synchronizing light will be operated manually, or by a five-minute timer located in the repair van.

The southernmost camera has been reinstalled and is operating in the same place where it was in previous years. Both of the mirrors for the two northern cameras have been resurfaced with a stainless surface coating which is resistant to weather contaminants, and the two cameras will be in use by April.

ATTENUATION CALCULATIONS

Recent discussions with personnel from Evans Laboratory and the Massachusetts Institute of Technology have led to a reconsideration of some of the problems of measuring rainfall rate because of the rainfall attenuation problem. Data on drop size have been reevaluated to obtain better measures of the actual attenuation expected for various values of Z, as well as a regression of the attenuation versus the rainfall rate. The data selected was obtained at Miami, Florida. A number of different approaches to the problem have been suggested and are reviewed in detail within this report.

Multiple regression analysis of R, Z, and Q

It has been suggested that an independent measurement be made of radar attenuation through a storm. If this were done, it would be possible to have independent measurements of the attenuation and also of the back-scattering cross-section. Whether better estimates of rainfall rate might be obtained in this manner was Investigated by means of the multiple correlation between radar reflectivity, Z, rainfall rate, R, and the attenuation cross-section, Q, with R the dependent variable and Z and Q the independent variables. The analysis was performed using the logarithms of the variables rather than the variables themselves. The results of this multiple correlation was that either Z or Q was very well correlated with R, and adding of the second variable did not decrease the residual sum of squares significantly. The best value of R given Q and Z based on logarithmic analysis is

$$R = \frac{1.11\,Q^{0.89}}{Z^{0.097}}$$

The multiple correlation coefficient for these data was 0.97. This compares with a simple correlation coefficient of each of the variables of 0.96 for Z-R relationship and 0.97 for the R-Q relationship. It is apparent that the relationship between the Q and the R Is a better relationship than the relationship between the Z and R. This is reasonable for drops that are in the Rayleigh scattering region since the rainfall rate Is roughly proportional to $D^{3\frac{1}{2}}$, and Q is proportional to D^3, while Z is proportional to D^6 of the drop size diameter. Thus, it seems reasonable that the attenuation might be more closely related to the rainfall rate than Is the back-scattered cross-section. The result of these calculations is that no gain in confidence in estimation of R is possible by independently measuring the Q and Z. If a single measurement could be chosen without regard to other considerations, the measurement of Q would be a better measure of R than would Z„ Obviously the measurement of attenuation at restricted Intervals is a much more difficult procedure and also removes the real advantage of the radar set to observe rainfall rates at a distance.

From the same data a regression of Q on R is obtained as

$$Q = 2.45\ R^{1.2}$$

with the correlation coefficient of 0.97, Figure 2 shows this regression line along with some average data points. If instead of using logarithms to determine the regression line, no variable transformation is used, the regression of Q = 7.2R - 22.62 with a correlation coefficient of 0.84 is obtained. This is also plotted on Figure 2. The linear relationship fails to match the low rates points but does fit the large rates well. On this figure there are limits that were drawn around the scattered data of Robertson and King[1]. All of this attenuation is calculated at a frequency of λ =3.2 cm.

The variable Q Is related to the attenuation in db per mile by a relationship

$$\alpha = 7 \times 10^{-3}\ Q$$

where Q is measured in mm^2/m^3 and α Is in db/stat mi. The parameter Q instead of the attenuation per mile is usually calculated because it Is a somewhat simpler parameter to handle In the computer.

Since such a simple relationship connects the two, it does not seem to be a great disadvantage to continue operation in total cross-section, Q, rather than attenuation in db per mile.

A second multiple regression analysis was performed using the actual numbers rather than transforming to the logarithms of the actual numbers. The nontransformed regression shows somewhat lower correlation coefficients but again shows no significant improvement by using both Z and Q to estimate R. The simple correlation coefficients of the untransformed data to the rainfall rate yielded correlation coefficients of 0.85 and 0.84 for R-Z and R-Q, respectively.

Attenuation versus Reflectivity Regressions

The attenuation cross-section was estimated from Z parameters in a method comparable to that reported in the Eighth Quarterly Technical Report on Z and R comparisons. In this method the summary cards are fed into the computer and Z intervals of 1 db are chosen. In each 1-db interval of Z all of the values of the attenuation cross-section are ranked to find a minimum and maximum attenuation and also an average attenuation. A second variable, denoted best estimate of attenuation and symbolized as Q* is determined by minimizing the function

$$S = \sum_i \left| Q_i (Q_i - Q^*) \right|$$

Figure 3 shows the table of these Q's obtained in this manner and also graphs for the three locations: Miami, Majuro, and Alaska. Data from Oregon have not been included because the maximum rainfall rate and therefore the maximum Z's are quite small. Although for convenience these are plotted on log-log scale, it is evident that the slope is nearly one to one and that they could have been plotted easily on linear paper and still result in a straight line relationship.

A logarithmic regression of Z and Q from the Miami data yields

$$Q = 1.15 \times 10^{-2} Z^{0.91}$$

with a correlation coefficient of 0.98. If it is reasoned that the attenuation below a $Z = 10^3$ is of little consequence (less than 0.05 db/mi) a fit to the data for Z in excess of 10^3 yields a linear regression of the form

$$Q = 6.75 \times 10^{-3} Z$$

This yields results for Q that are always slightly larger than the value obtained from the logarithmic regression. For example, at $Z = 10^3$, Q is overestimated by 0.3 db, and at $Z \times 10^5$, by 2 db. A better overall estimate might be obtained by reducing the coefficient of Z, but it is felt that consistent overestimation is a better choice. The reduction of these relationships to linear relationships is admittedly forced to some extent. However, the scatter of the data does not preclude this possibility. The linear line always falls well within the scatter of points for values of $Z > 10^3$. It does tend to underestimate the attenuation for very low values of Z, but the total attenuation obtained in a storm from these small Z values is so low that normal measurements would not detect the differences.

The significance of a straight line on linear paper is understood in terms of. equations derived by Hitschfeld and Bordan[2] and later analysis in this report. In their analysis for the errors in the measurement of rainfall at attenuation wavelengths, they derive equations of the form

$$\frac{R'}{R} = \left[1 - \left\{ \left(1 - \frac{\Delta a}{a'}\right)^{\alpha} - 1 \right\} \exp \left\{ \frac{C\alpha}{A} \int_0^r R^{\alpha} \, dr \right\} \right]^{-\frac{1}{\alpha}}$$

equation (3.6) from Hitschfeld. Their assumptions can be modified somewhat by removing the step of calculating the rainfall rate from Z and then correcting ib for attenuation by making a direct relationship from Z to the attenuation. When this is done, the value of alpha in equation 3.6 is the exponent between Q and Z, and in view of the foregoing data can be considered unity. From equation 3.6 Hitschfeld and Bordan have plotted two figures, 3.1 and 3.2, which illustrate the differences when alpha is equal to 1.0 and alpha is equal to 1.3. These figures show the rain calibration error as a function of the true attenuation. They consider alpha to be 1 for 10-cm wavelength, approximately 1 for the 5.6 cm, and 1.3 for the 3-cm wavelength. It is contended here that the alpha should be 1.0 for a 3-cm as well as for the 10-cm if instead of making the correction from Z to R and R to attenuation the correction is made in one step from Z to attenuation and the value of Z is determined instead of R.

Certainly it still remains true that in general if one wishes to measure rainfall rate and has a free choice of wavelength the choice should be made to a non-attenuating wavelength. However, If an attenuating wavelength Is chosen, some correction may reduce the total amount of error in the system. Considering Figure 3.1 from Hitschfeld and Bordan we find for instance that if there is a true attenuation of 10 db and the calibration of the radar is known to within the certainty of +1 to -2 db error, the rainfall rate can be kept within a factor of four. This may be a rather wide range, but it is still less than there would be if no correction were used. Since 10 db error in a measurement of Z would yield a rainfall rate error of 5 times, some gain can be accomplished in attenuation correction with approximately 10 db of total attenuation.

Attenuation Correction

There may be another method for correcting attenuation so that some of the difficulties pointed out by Hitschfeld are not encountered. This method consists in purposefully undercorrecting, or not correcting for the correction. The correct method of estimating Z at a point is to correct the power returned at the point by the attenuation at all nearer points. The attenuation in turn should be estimated from the corrected Z values. If, instead, the Z at a point is estimated from the power returned at the point corrected by the attenuation from the uncorrected Z's for all previous times, the equations are less likely to mushroom or increase without bound. Admittedly, this technique is not a completely correct estimate of the attenuation. The forced undercorrection will still provide better values of Z than no correction.

A method of correcting for attenuation is proposed which purposefully underestimates the effect of attenuation. Suppose that the dependent variable desired is Z instead of R, as Hitschfeld and Bordan do. The basic radar equation is

$$\overline{P}_{ro} = \frac{P_o h A_e}{8\pi r^2} \sum \sigma = \frac{AZ}{r^2} \qquad (1)$$

where:

$\overline{P}_{ro}$ = average received power
P_o = peak transmitted power
h = pulse length
r = range to target
$\Sigma\sigma$ = back-scattering cross-section
$Z = \Sigma D^6$ over unit volume
A = radar calibration constant and constants relating Z to σ

The attenuation can be expressed properly as

$$10 \log \frac{P_r}{P_o} = -2 \int_0^r \Lambda \, dr \qquad (2)$$

where Λ is the one-way attenuation in db per unit length. P_r is the return power with the attenuation and P_{ro} is the power which would be returned in the absence of attenuation. Λ can be related to Q and empirically to Z by means of drop-size data. From the definition of total scattering and absorption cross-section,

$$dP = -PQ\,dr \qquad (3)$$

where:

P is a power density and r a length.

and $$\int_{P(r=0)}^{P(r=r)} \frac{dP}{P} = -\int_0^r Q\,dr$$

or $$10 \log \frac{P_r}{P_{ro}} = -4.343 \int_0^r Q\,dr \qquad (4)$$

where the unite of Q and r must be consistent.

So (2) becomes $$10 \log \frac{P_r}{P_{ro}} = -8.68 \int_0^r Q\,dr$$

$$= -8.68 \int_0^r 6.75 \times 10^{-9}\, Z\,dr \qquad (5)$$

where 10^{-6} has been added to change Q units to per meter.

Then (1) can be written as

$$\log \frac{r^2 P_r}{AZ} = -b \int_0^r Z\,dr \qquad (6)$$

$$\log P_r = \log A + \log Z - b \int_0^r Z\,dr - 2 \log r \qquad (7)$$

where:

$b = 8.68(6.75 \text{ x } 10^{-10}) = 5.86 \text{ x } 10''^{9}$

This equation is in a form equivalent to equation (2.14) of Hitschfeld with α = 1.0. Using Hitschfeld's solution we obtain

$$Z = \frac{r^2 e^{2.3y}}{A_1 - 1.35 \times 10^{-8} \int_0^r r^2 e^{2.3y}\,dr} \qquad (8)$$

where:

$y = 10 \log P_r$

A_1 = a constant of integration and may be considered as a form of the calibration constant of the radar.

This equation exhibits all of the errors in correction mentioned by Hitschfeld with the exception that Hitschfeld's α should be considered equal to one. Large errors result when the second term in the denominator becomes large (when attenuation is large). To reduce this it is suggested that partial correction be applied according to the following schemes

Consider the attenuation which would be calculated on the basis of an independent measure of Z from a non-attenuated radar. If the P_r is corrected by this attenuation, a true value of P_r would be available for use in calculating Z. Since, in general, two radars are not available, one approximation would be to use the uncorrected P_r to obtain at any point an attenuation which would be added to the P_r as an approximation to the appropriate amount.

Let the attenuation at r be approximated by

$$-b\int_0^r Z_u \, dr = -b\int_0^r \frac{r^2 P_{ru}}{A} \, dr \tag{9}$$

where%

Z_u = the uncorrected Z or the value of Z obtained directly from (1) and measured P_r

P_{ru} = the uncorrected P_r

then $\log \frac{P_{ru}}{P_{rc}} = -b\int_0^r Z_u \, dr$

$$\log P_{rc} = \log P_{ru} + b\int_0^r Z_u \, dr \tag{10}$$

but

$$\log Z_u = \log P_{ru} + 2 \log r - \log A$$

and

$$\log Z_c = \log P_{rc} + 2 \log r - \log A \qquad (11)$$

so substituting (11) into (10) yields

$$\log Z_c = \log Z_u + b\int_0^r Z_u \, dr$$

$$Z_c = \frac{r^2 P_{ru}}{A} \exp\left(b\int_0^r \frac{r^2 P_{ru}}{A} \, dr \right) \qquad (12)$$

Equation (12) certainly does not exhibit the same type of gross error that might be obtained from (8) since there are no differences in the denominator to vanish.

However, admittedly (12) does not properly account for the attenuation,, At best it reduces the effect. As an example, a storm whose Z profile with r varies linearly, Z - ar, will be calculated and the amount of error in the correction deduced.

$$P_{ru} = \frac{aA}{r} \exp -b\int_0^r a r \, dr$$

and

$$Z_c = ar\left\{-b\int_0^r a r \, dr\right\} \exp\left\{b\int_0^r ar \exp\left(-b\int_0^r ax \, dx\right) dr\right\}$$

which becomes after simplification

$$Z_c = ar \exp \frac{1}{2}\left(1 - abr^2 - e^{-abr^2}\right)$$

The error in Z_C in db is then

$$10 \log \frac{Z_c}{Z} = 2.171\left(1 - abr^2 - e^{-abr^2}\right)$$

The error in Z is just the total attenuation which is

$$= 4.343\left(-abr^2\right)$$

Figure 4 shows the error made with this correction. The abscissa represents the total attenuation in the storm and the ordinate represents the error remaining after the correction. For example, a storm where $Z= 10^5$ at 2×10^3 meters and $Z = 0$ at 0 meters and with proper regard for units would yield an error of 1.0 db where the total attenuation is 5 db. This should be only a justification of considering this type of correction since the error is definitely influenced by the form of the Z profile in the storm. A second profile is easily calculated assuming Z is constant with range. Only the results are presented:

$$10 \log \frac{Z_c}{Z} = 4.34\left(1 - bcr - e^{-bcr}\right)$$

and

$$10 \log \frac{Z_u}{Z} = 4.34\left(-bcr\right)$$

Figure 4 shows the errors from a correction through this type of Z profile. Thus, a storm with a high and constant rate of attenuation will be less satisfactorily compensated than a storm with linearly changing Z profile. More important is the effect or error in the calibration constant of the radar. Equation (12) indicates that the calibration constant A appears twice. Equation (12) can be written as:

$$Z_c = \frac{K}{A} \exp \frac{L}{A}$$

where K and L are independent of A.

$$\frac{dZ_c}{dA} = \frac{KL}{A^2} \exp \frac{L}{A} - \frac{K}{A^2} \exp \frac{K}{A}$$

$$= Z_c\left(\frac{L-1}{A}\right)$$

$$\frac{dZ_c}{Z_c} = (L-1)\frac{dA}{A}$$

so that the logarithmic inaccuracy in Z is equal to a constant times the logarithmic inaccuracy in A. That is to say, the inaccuracy of the calibration in db of the radar is directly related to the inaccuracy of the Z measurement. This is of considerable importance since the main objection to the full correction method is that errors in the calibration become highly magnified in the corrected Z.

DATA ANALYSIS

Raindrop Data Reduction

A total of 26 rolls of raindrop data was measured. Twenty rolls were from the 1963 Illinois operation. The Illinois measurement program was completed in January 1964; at that time, measurement of the Island Beach, New Jersey, film was resumed. Five rolls from New Jersey have been measured during this period, and it is expected that measurement of these data will be completed in April 1964. The Coweeta, North Carolina, film data then will be measured until Illinois 1964 data are available.

Only one roll of the Flagstaff, Arizona, film was measured, and its data were not of sufficient quality to be reliably analyzed. Since other film showed very little rain, none of the remaining Arizona data will be reduced.

Data from Illinois 1964 should be ready for measurement by early May.

1963 Illinois Data

Measurement of these data has been completed. The drop images on the film rolls from camera B were not sharp, perhaps because the mirror surfaces had deteriorated slightly. Therefore, in most of these analyses, only the films from cameras A and C were considered. All of these were of excellent quality except one which had been overexposed.

These cameras were two miles apart. Eight cases with satisfactory data from two cameras are available for comprehensive analyses. Four of these are showers and thundershowers, three are continuous rain, and one is a combination of showers and continuous rain.

A plot of Z versus R for one of the continuous rain cases, 15 May 1963, is shown in Figure 5. The radar for this date shows stratified echoes completely without cellular structure. Logarithmic least square analysis was performed and the resulting lines are quite similar. It does not appear that any significant differences exist which could be accounted for by the 2-mile separation of the cameras. The other cases of this type indicate similar conclusions.

In the case of showers, it has also been noticed that the R-Z relationships are usually quite similar for the two cameras. A typical case is shown in Figure 6. The error introduced by using either relationship for the whole storm would be less than would be indicated by the scatter of points for either camera. It has not been possible to define an R-Z relationship for various portions of a cell,, The cells generally moved too rapidly to get a sufficient sample for each portion of the cell. Also, considerable difficulty was encountered in determining the cell positions due to attenuation of the 3-cm radar by nearer storms.

The situation of 31 July 1963 does not fit well with either the continuous rain cases or with the shower cases. A line of showers formed in the warm sector of a wave which had developed a day earlier on a stationary front. This line moved over the cameras from the west and was followed by an extensive area of continuous rain. The full extent of this rain area was not apparent on the radar until the showers had passed the station. Rain began at the cameras at 0920 GST and continued to about 1115.

The photographs obtained cover the last portion of the showers and about an hour of the continuous rain. Figure 7 shows the R-Z plot for this case. The points for camera C lie well along a single line. The points for camera A were much more widely scattered. In examining the time variation of these points, and the distributions associated with them, it appeared to be appropriate to derive two lines for these data. During the early part of the sample (0925 to 0946), the points lie along line A_2 except for three minutes (0938-0940) when the points are along line A_1. The rainfall rate generally decreased during this period. At 0949 the rate increased but now the points were along line A, . The points were all clustered at the low rate end of the lines after 1000. On the figure, some sample average distributions of the observations encircled by the curves are shown. These are smoothed slightly. The distributions representing points along line A_1 are broad, straight-line types. However, along the other line, the distributions are more narrow and are similar to the theoretical coalescence curves.

These differences were evident in the individual distributions before averaging, as well as in the averages. An average was used as a means of reducing the statistical sampling noise. Unlike most continuous rain distributions, curve A_1 contains some large drops. It is possible that the camera was on the edge of convective activity and large drops were being generated at this edge. Unfortunately, the radar was too badly attenuated to allow confirmation or disproval of this hypothesis.

The types of distributions associated with the lines tend to suggest that A_1 is continuous rain and A_2 is showery rain. The timing also indicates this. However, the R-Z relationship for line A_1 has a higher coefficient and exponent than line A_2, indicating that for the same R, the Z is greater for the continuous rain, line A_1. This is the opposite of what has been generally observed, and as published by Jones[3], and the only explanation is that this case is an unusual one and does not conform to the average.

This storm shows that it is possible to have within the same air mass and the same storm system two very different types of raindrop spectra producing quite different R-Z relationships.

Also, on this occasion camera C, only two miles away, showed none of this duality.

SUMMARY AND CONCLUSIONS

Measurement of the higher rainfall rate by means of radar is greatly simplified and improved by using wavelengths longer than 5 cm. However, if other design criteria require the use of the 3-cm radar, some means for compensating for attenuation should be considered. The method proposed in this report is not a unique solution to prohibit correction from becoming excessive. This method does not correct well when there are large amounts of attenuation, but for moderate amounts, it provides an acceptable correction. It does minimize the possibility of radar calibration error strongly influencing the amount of error or correction applied.

Results of analysis of the 1963 raindrop data have pointed out the insufficiency of detailed work with attenuating radar wavelengths. This will be corrected during the 1964 season with use of the acquisition radar of the M-33. For the July 31 storm it would appear that sometimes there are considerable differences in the type of raindrop distributions and in the resulting R-Z relationships for points 2 miles apart. Usually, either because of no real differences or because of the sampling and averaging effects, no variability within 2 miles could be noted.

There is no statistical justification for measuring both the attenuation and the reflectivity to estimate the rainfall rate. Considering the added complexity of obtaining an attenuation measurement, this approach does not warrant further effort.

PROGRAM FOR NEXT INTERVAL

The three drop cameras will be operated in East Central Illinois during the summer. Two of these cameras will be in close proximity and will be operated at the maximum possible sampling rate. Analysis of these data will be initiated. The main objective of this study will be to determine what sample size can be considered sufficient to represent the rain in the radar volume. Also, the study of areal variations in raindrop-size distributions will be continued.

It is expected that the distributions from Oregon and Majuro will be published during this interval. Analysis of data from Island Beach, New Jersey, will be continued.

The M-33 radar will be modified to provide pulse integration. A feasibility study on developing delay-line integration will be made.

Three papers for the Weather Radar Conference at Boulder, Colorado, will be prepared and submitted to the Army for approval.

REFERENCES

1. Robertson, S. D. and King, A. P.: The Effect of Rain upon the Propagation of Waves in the 1- and 3-Centimeter Regions. Proc. of IRE, April 1946.

2. Hitschfeld, W. and Bordan, J.: Errors Inherent in the Radar Measurement of Rainfall at Attenuating Wavelengths. Scientific Report MW - 12, McGill Univ., May 1953.

3= Jones, D. M. A.: Rainfall Drop-Size Distributions and Radar Reflectivity. Research Report No. 6, Illinois State Water Survey, April 1956.

PERSONNEL

The following personnel were engaged in the research during the period of this reports

Name and Title	Starting Date	Hours Worked	Terminated
G. E. Stout Project Director	10/1/61	102	
Eugene A. Mueller Electronic Engineer	10/1/61	850	
Arthur L. Sims Research Assistant	5/13/63	1020	
Stanley G. Peery Electronics Technician II	3/1/63	1020	
Robert D. Vogt Scientific Assistant	8/12/63	403	

Name and Title	Starting Date	Hour3 Worked	Terminated
Marian E. Adair Meteorological Aide I	9/24/62	510	
Edna M. Anderson Meteorological Aide I	10/1/61	1020	
Ileah W. Trover Meteorological Aide I	9/10/62		9/30/63
Gerald W. Swanson Statistical Clerk	9/19/63	160	1/27/64
Karen Sue Adair Laboratory Helper	6/17/63	122	
Gustav A. Berquist Laboratory Assistant	2/18/64	43	
Michael R. Goodale Laboratory Assistant	2/3/64	125	
Doris M. Kaberline Card Punch Operator	2/10/64	127	

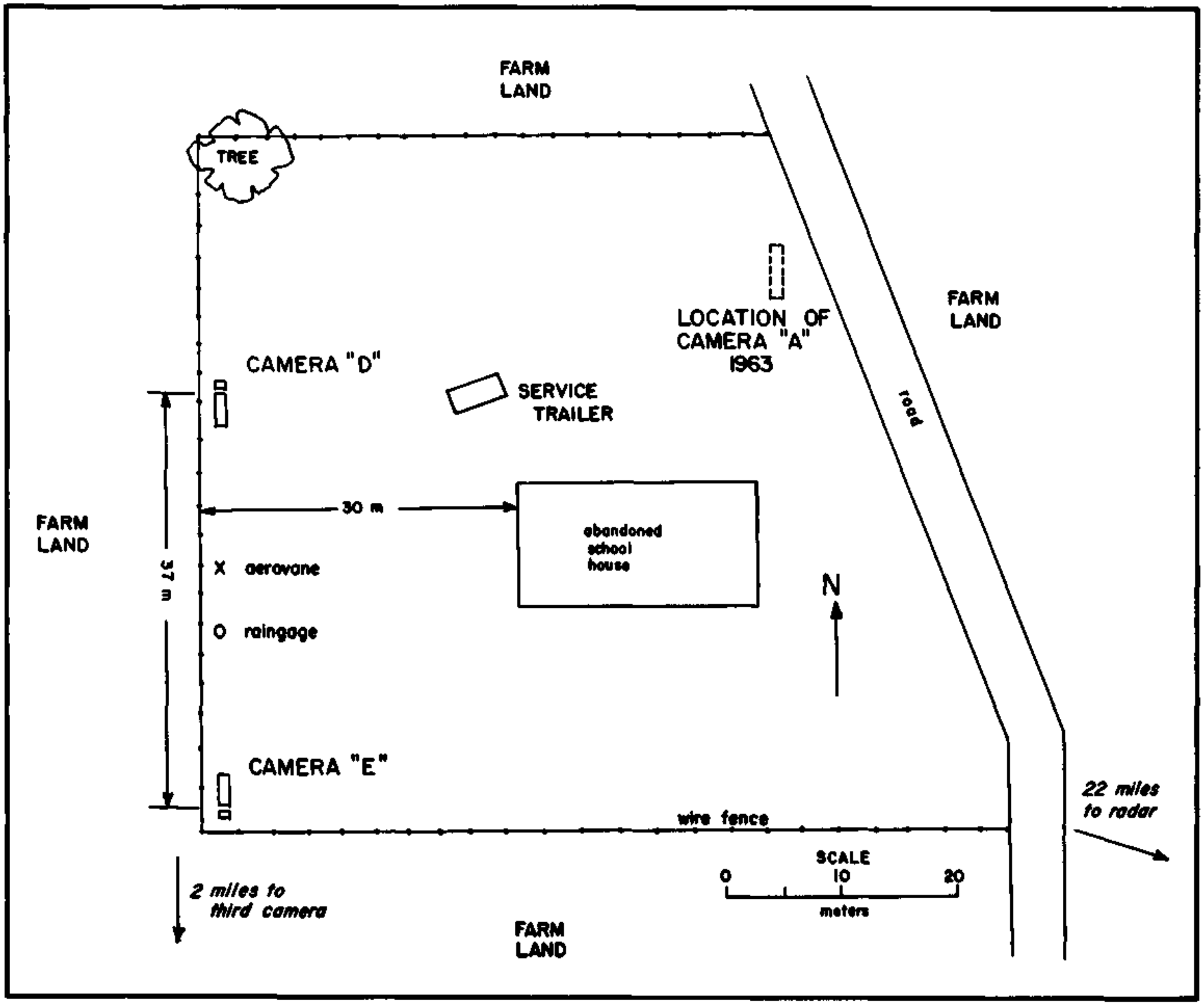

FIG. 1 LOCATION OF DROP CAMERAS 1964.

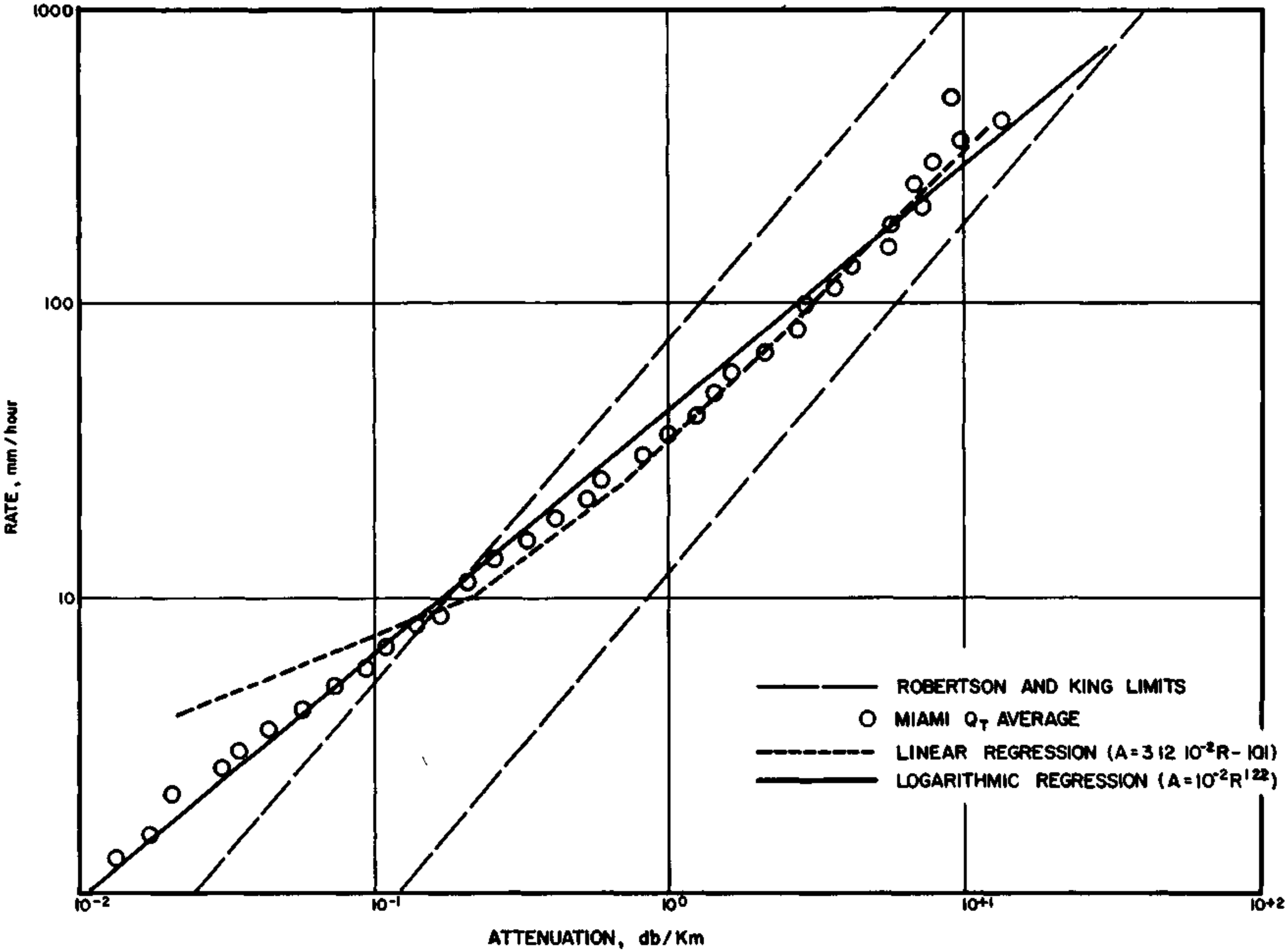

FIG. 2 ATTENUATION VERSUS RAINFALL RATE FROM MIAMI DROP SIZE DATA.

MIAMI

Z	Q*	Q MIN	Q AVE	Q MAX	N
11.2	1	1	1	2	10
14.1					
17.8					
22.4	2	1	1	2	41
28.2	2	0	2	3	65
35.5					
44.7	3	2	3	6	104
56.2	4	3	4	30	55
70.8	4	3	4	6	43
89.1	5	3	5	8	85
112.2	7	4	7	10	96
141.3	8	5	8	11	61
177.8	10	7	10	28	105
223.9	13	10	13	44	134
281.8	16	14	17	54	90
354.8	21	15	21	49	125
446.7	26	13	25	31	139
562.3	32	3	32	36	116
707.9	39	7	39	45	128
891.3	49	6	48	78	115
1122.0	60	15	59	92	111
1412.5	77	55	76	88	72
1778.3	97	44	95	150	90
2238.7	122	27	120	456	72
2818.4	149	30	136	173	76
3548.1	194	61	185	715	69
4466.8	246	55	224	372	59
5623.4	298	86	284	346	61
7079.4	361	116	327	472	50
8912.5	448	122	386	590	60
11220.2	551	56	492	1561	34
14125.4	666	367	637	878	36
17782.8	783	131	656	951	32
22387.2	947	148	852	1247	33
28183.8	1197	123	973	1579	36
35481.3	1496	356	1303	1765	28
44668.3	1469	260	1372	2185	24
56234.0	1751	376	1651	2286	9
70794.5	1687	679	1600	2737	8
89124.9	2445	584	1838	3092	4
112201.7	2890	836	2267	3279	4
141253.5	4242	917	3089	4783	5
177827.6	2084	2084	2084	2084	1

ALASKA

Z	Q*	Q MIN	Q AVE	Q MAX	N
5.6	1	0	0	1	103
7.1	1	0	0	1	71
8.9	1	1	1	1	119
11.2	1	1	1	1	187
14.1	1	1	1	2	131
17.8	2	1	1	2	164
22.4	2	1	2	3	177
28.2	2	2	2	4	149
35.5	3	2	3	4	150
44.7	3	2	3	5	156
56.2	4	3	4	6	142
70.8	5	4	5	6	117
89.1	5	4	6	8	114
112.2	7	5	7	12	111
141.3	9	7	9	13	64
177.8	11	8	11	16	62
223.9	13	11	13	15	36
281.8	16	13	16	20	32
354.8	20	17	20	24	28
446.7	25	14	23	28	9
562.3	32	17	31	39	12
707.9	38	28	37	40	7
891.3	48	19	41	51	4
1122.0	64	32	52	67	5
1412.5	73	45	69	78	6
1778.3	86	25	71	99	4
2238.7	113	96	115	135	3
2818.4	112	112	112	112	1
3548.1	63	63	63	63	1
4466.8					
5623.4					
7079.4					
8912.5					
11220.2	130	130	130	130	1

MAJURO

Z	Q*	Q MIN	Q AVE	Q MAX	N
8.9					
11.2	1	1	1	2	118
14.1					
17.8					
22.4	2	1	2	3	185
28.2	2	1	2	4	138
35.5					
44.7	4	2	4	37	204
56.2	5	3	5	8	75
70.8	5	4	5	8	67
89.1	6	4	6	9	118
112.2	8	5	8	12	155
141.3	10	7	10	14	127
177.8	12	9	12	18	126
223.9	14	11	14	20	146
281.8	18	14	18	26	102
354.8	22	14	22	29	111
446.7	28	20	28	56	118
562.3	35	27	34	43	107
707.9	43	19	42	53	93
891.3	53	33	53	64	76
1122.0	55	35	64	75	87
1412.5	82	36	80	91	62
1778.3	99	26	96	126	64
2238.7	126	52	123	142	54
2818.4	151	63	147	171	42
3548.1	197	95	195	289	48
4466.8	242	76	230	226	34
5623.4	356	115	266	349	24
7079.4	387	80	359	432	25
8912.5	456	340	447	526	14
11220.2	544	419	525	649	8
14125.4	741	534	705	808	10
17782.8	880	419	816	1010	8
22387.2	957	917	937	957	2
28183.8	1387	1309	1348	1387	2
35481.3					
44668.3	2003	1341	1672	2003	2

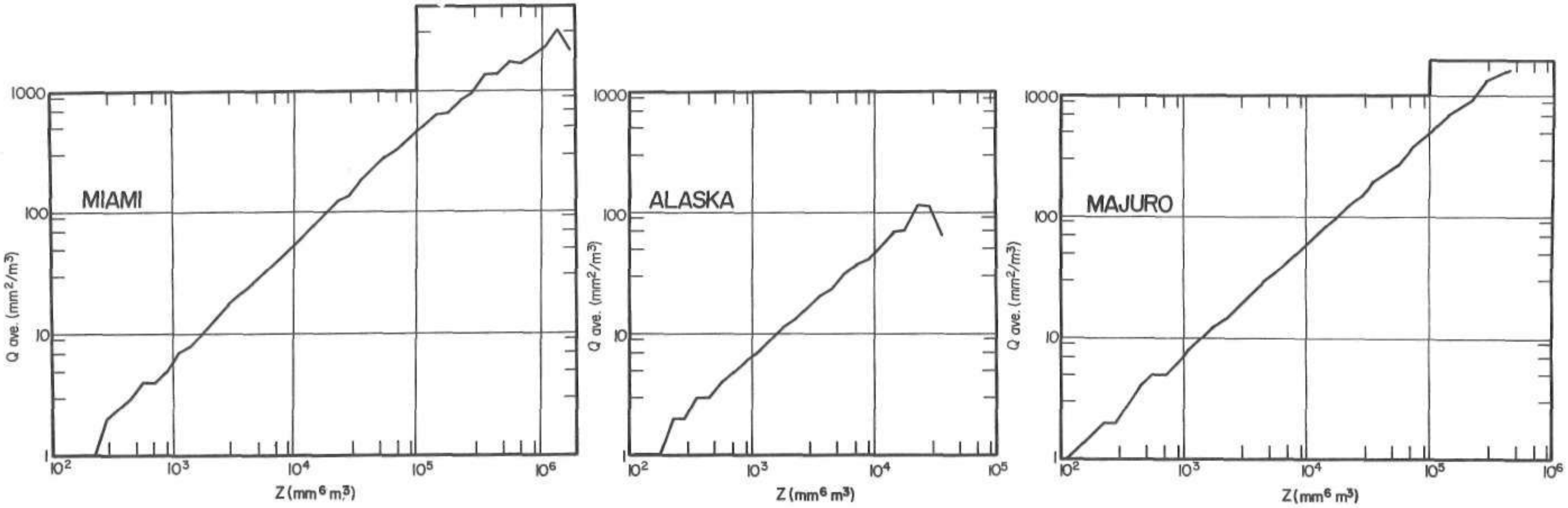

FIG. 3 ATTENUATION VERSUS REFLECTIVITY FOR MIAMI, ALASKA, AND MAJURO.

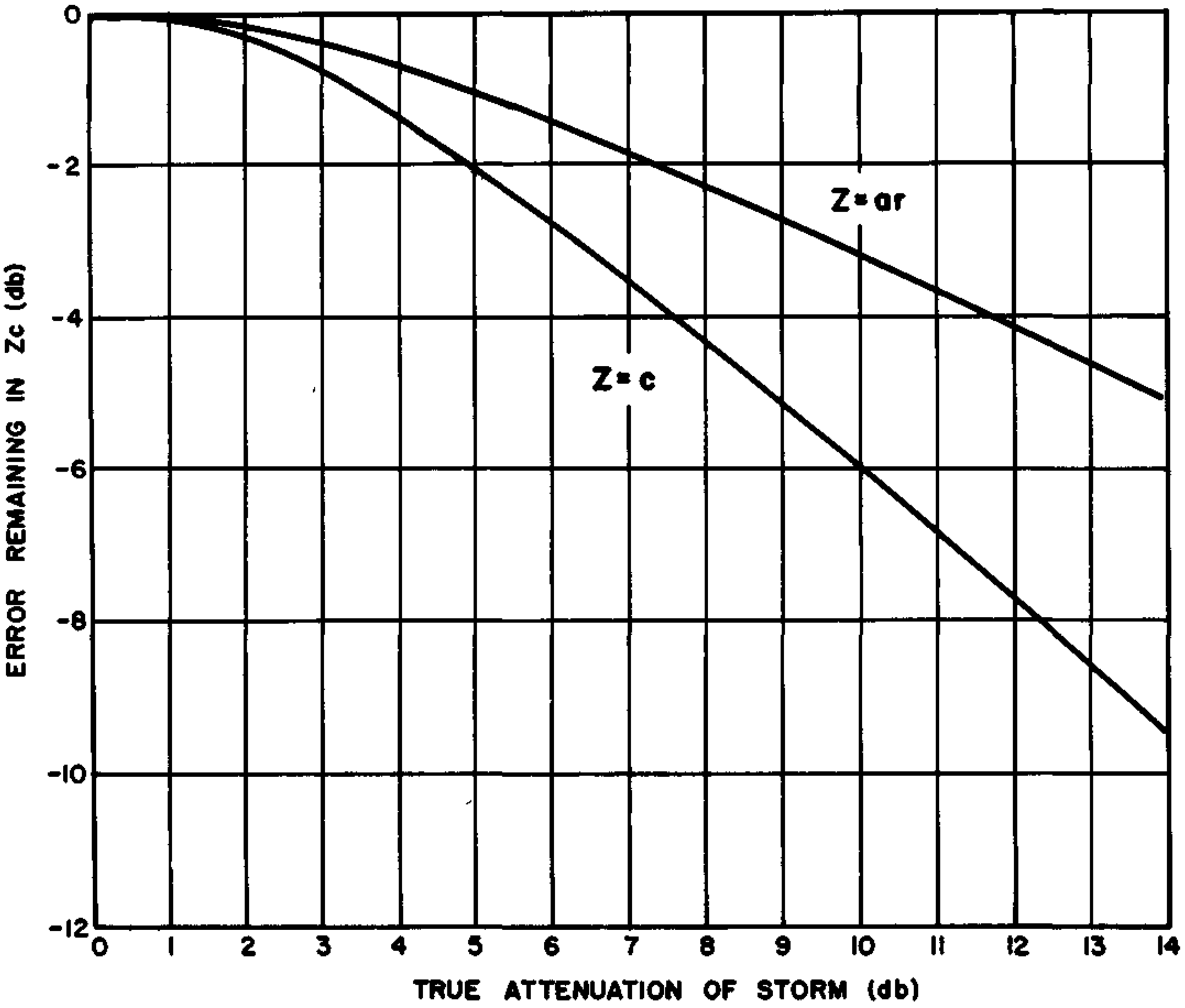

FIG. 4 ERROR IN PROPOSED METHOD OF UNDERCORRECTION OF ATTENUATION FOR TWO ASSUMED Z PROFILES.

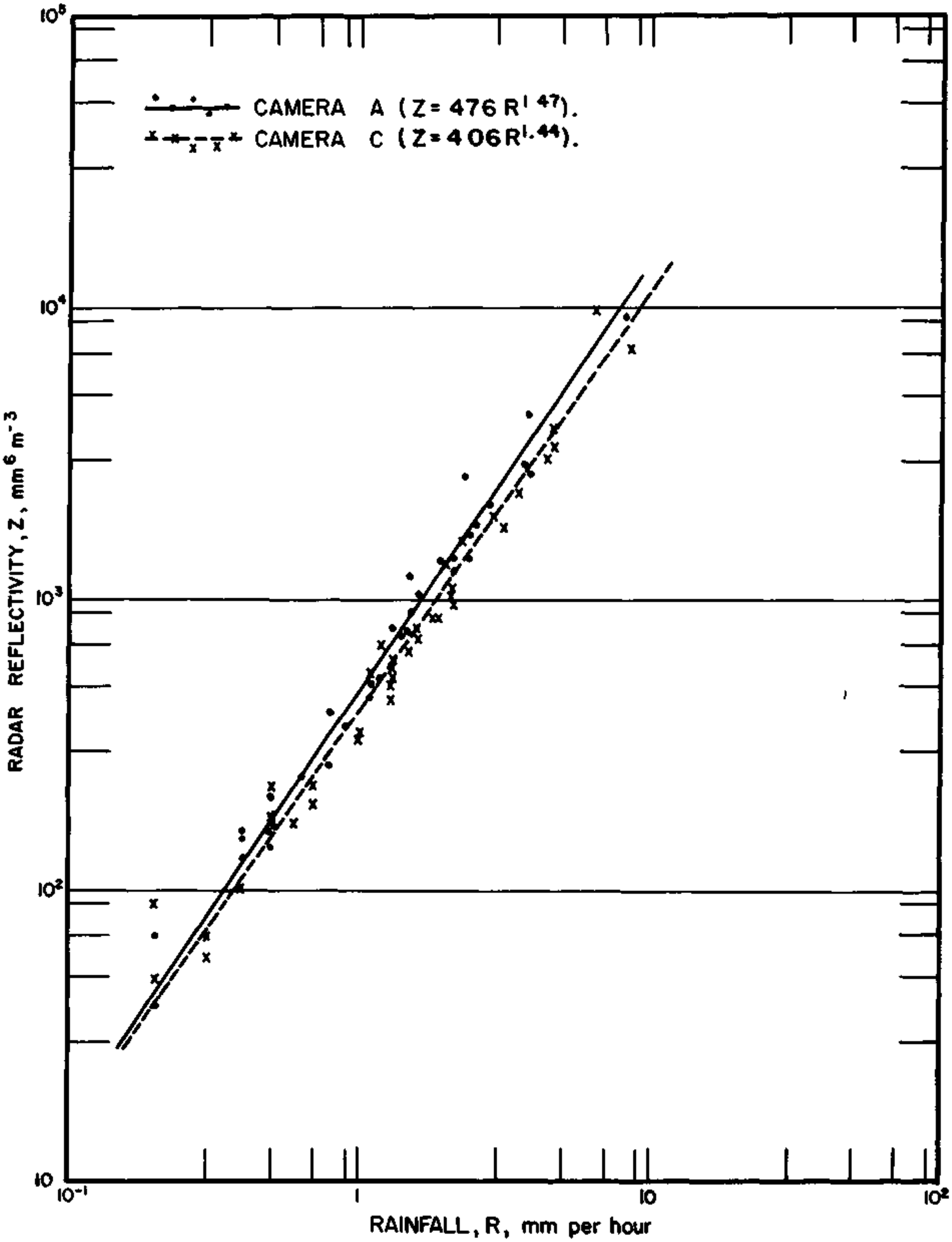

FIG. 5 R-Z PLOT FOR CAMERAS "A" AND "C" FOR 15 MAY 1963, A CONTINUOUS RAIN CASE.

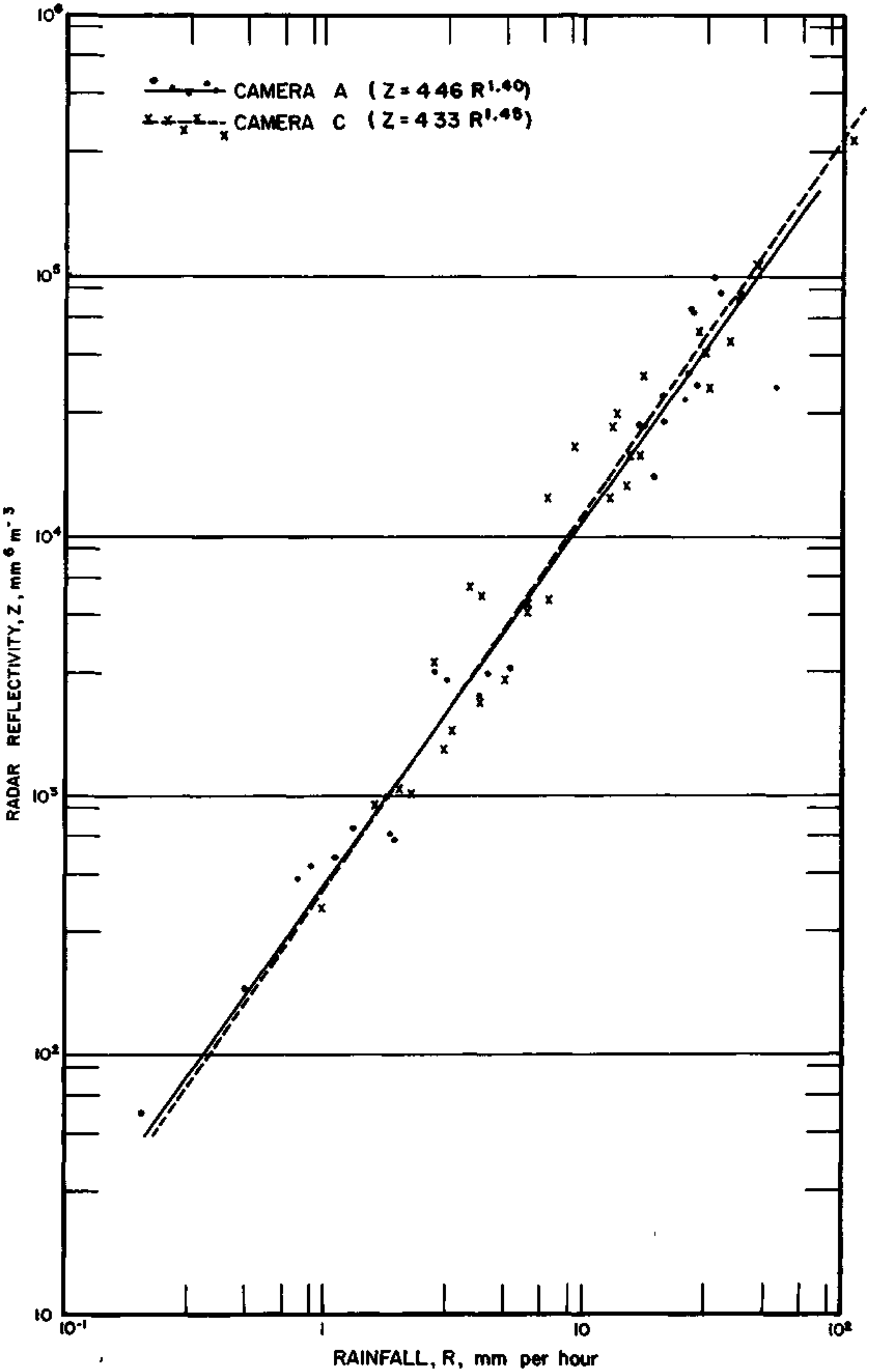

FIG 6 R-Z PLOT FOR CAMERAS "A" AND "c" FOR 7 JUNE 1963, A THUNDERSTORM CASE.

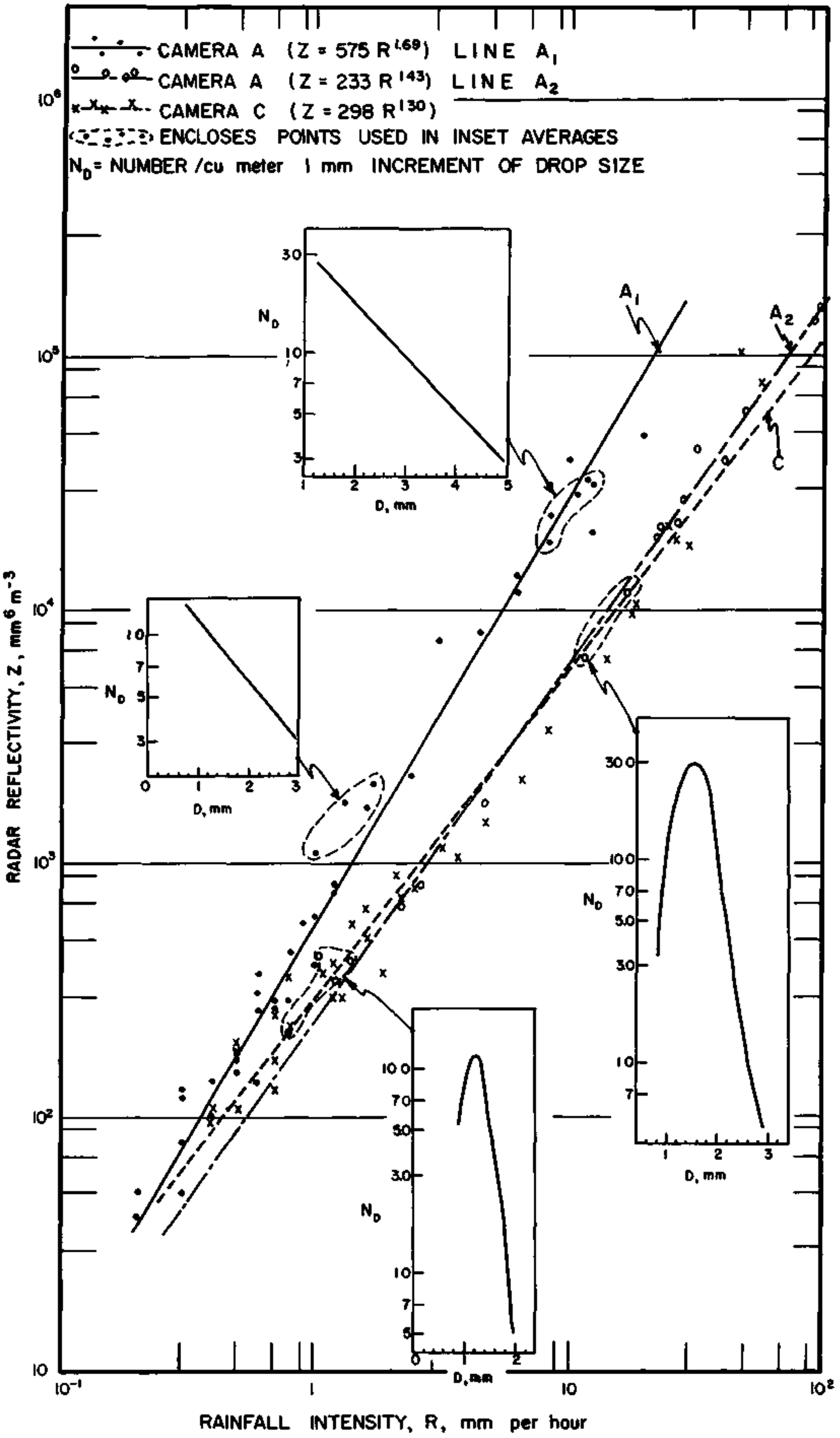

FIG 7 R-Z PLOTS FOR CAMERAS "A" AND "C" FOR 31 JULY 1963. INSETS SHOW AVERAGE DISTRIBUTION FOR SELECTED "A" POINTS

Appendix A

LIQUID WATER CONTENT OP RAIN*

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Illinois State Water Survey**

ABSTRACT

One-minute raindrop size spectra for rains at Miami, Florida; Corvallis, Oregon; Woody Island, Alaska; Majuro, Marshall Islands; Coweeta, North Carolina; Champaign, Illinois; Island Beach, New Jersey; and Bogor, Indonesia, have been obtained. Approximately one year of rainfall at each location has been sampled. This amounts in most cases to about 40 hours of rain or 70 percent of the annual rainfall. The liquid water content has been calculated for each minute of rainfall. The largest single observation was obtained at Miami where 29 gm m^{-3} was noted. Frequency of occurrences of liquid water contents for each location is reported.

Data Collection and Processing

The data reported in this paper were obtained primarily for determination of radar rainfall relationships. These data were reduced from measurements of photographs of raindrops taken by a raindrop camera. The camera system consists of a telecentric optical system using a thirty-inch parabolic mirror as its first element, and a 70-mm camera. The sampling volume is a right circular cylinder, thirty inches in diameter and about fourteen inches high, so approximately 1/7 of a cubic meter is photographed on each frame. This volume is back-lighted by four FT 503 flash tubes, each delivering approximately 125-watt-seconds in 10 microseconds. A normal sample taken with this camera system consists of seven frames exposed 1-1/2 seconds apart, so that a volume of about one cubic meter is observed in 10.5 seconds. These samples are obtained once each minute and are referred to in this paper as one-minute samples.

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*As presented at the Fifth Conference on Applied Meteorology of the American Meteorological Society on March 2-6, 1964, in Atlantic City, New Jersey.

**This research supported by the U. S. Army Signal Corps under Contracts SC-75055 and SC-87280.

The film is then projected to double the original object size, and since the camera system has a theoretical circle of confusion of 0.15 millimeter diameter in object space, the size of the drops can be measured quite accurately. Two measurements of each individual drop image are made; one of the shorter axis, and one of the longer. Calipers which read out directly into IBM cards are used for these measurements. All drops of 0.5 millimeter diameter and greater are measured to the nearest 0.1 millimeter. Smaller drops can be seen but are not usually measured, since the radar relationships are relatively insensitive to very small drops.

The IBM cards are processed by IBM 1401 and 7094 computers. The computers calculate the drop size distribution for each one-minute sample, and from this distribution calculate various radar parameters as well as the liquid water content and the rainfall rate. For the rainfall rate, the assumption is made that the drops are falling at terminal velocity. For both the rainfall rate and liquid water calculations, it is assumed that the geometrical mean of the two measurements of the raindrop is the diameter of an equivalent sphere. This introduces a very small error when the drops are not spherical; however, the calculation of the liquid water content for the one-minute sample is not greatly affected.

Data has been obtained at eight different locations, and these data are summarized in Table 1. It can be seen that there are always more than 1100 one-minute samples at each of the locations. In general, the raindrop cameras were located at each of these stations for approximately one year. In all cases, at least one year of data was obtained. The data from Coweeta, North Carolina, and Island Beach, New Jersey, have not been completely analyzed and the results here represent only a portion of the entire year sampled. The Champaign, Illinois, data was obtained with a prototype raindrop camera on 35-millimeter film and represents data collected primarily during summertime. The Indonesia data is incomplete during summer months. The Corvallis, Oregon, data has no summer observations since no rainfall occurred during the summer operation. Table 2 shows the distribution of the number of days on which samples were obtained in each of the months of the year as well as the number of samples in each of the months of the year. It can be seen that, with the exceptions already noted, the samples are all distributed well within the various months of the year.

In general, the one-year sample represented between 60 percent and 85 percent of all the total rainfall time that was occurring at the location. At Miami, where detailed records were kept of the raindrop camera, 65 percent of the total rain time was captured. This Installation was the first remote installation of a raindrop camera and suffered somewhat more from equipment and operational difficulties than did the other installations. For some of the other installations, particularly Indonesia, no reasonable estimate of the total time of rainfall can be obtained.

As an attempt to justify the usefulness of a single year's data, the data from Miami, Florida, was compared with the rainfall frequencies as obtained by the U. S. Weather Bureau[1]. The rainfall rate, as determined from the drop camera, should be properly ascribed to 10-second rainfall rates. A comparison was made between the Weather Bureau 5-minute maximum rate at Miami and the 5-minute maximum rate in Illinois. From this, it appears that the maximum rate in Miami is about 1.1 times the maximum in Illinois. Illinois data, as published by Huff and Neill[2], indicate that the maximum one-minute rate should be 350 millimeters per hour for Illinois from longer records. The maximum 10-second rate at Miami for our drop camera sample is 722 millimeters per hour, which is higher than the 385 millimeters per hour one-minute rate which might be expected by comparison with Illinois data and the 5-minute rainfall rates. No data are available at this time as to how maximum 10-second rates should compare with maximum one-minute rates. However, it would seem that the difference between 722 millimeters per hour and 385 millimeters per hour might be accounted for by these time differences. Although this does not prove the adequacy or representativeness of the one-year sample, it does tend to indicate that this sample was not extremely abnormal.

Cumulative Liquid Water Content

Figures 1 and 2 show the cumulative frequency of liquid water content based on the drop camera samples at various locations. The abscissa represents the liquid water measured In grams per cubic meter of air space. The ordinate represents the fraction of the time the liquid water content is greater than the particular value represented on the abscissa. This method of representation of the liquid water content frequency distributions was chosen because it tended to produce the smoothest and most easily read curve.

On inspection, it can be noted that there are groups of data that appear to be very similar. The frequency distributions from Woody Island, Alaska, and Corvallis, Oregon, are nearly duplicates of each other. They both represent very light rainfall. The maximum rainfall experienced in Alaska and Oregon together was only 26 mm per hour. The liquid water contents were quite low. Most of this rain was light, continuous rain. Majuro and Indonesia, both representative of tropical conditions, also appear to be very similar. They both appear to be nearly straight on these plots and there is less than a half gram per cubic meter spread between them at any point except at the highest liquid water content points. These points are subject to large sampling error since only a few samples were obtained at these values,, Likewise, New Jersey and North Carolina seem to be very similar, again, differing primarily in the higher values of liquid water content. Both New Jersey and North Carolina exhibit a curvature in the low liquid water content region. The data from Majuro are all shower type rainfall. The Indonesian data are thunderstorms and showers. Therefore, it would appear that showers and thunderstorms can be characterized by a straight line with low slope on these distributions. If it is noted that the curves for Alaska and Oregon represent, primarily, continuous rains and that they represent very high values of the ordinate for low liquid water content, 1-1/2 grams per cubic meter and below, an explanation for the curvature in the New Jersey and North Carolina data might be obtained. It is proposed that a portion of the New Jersey and North Carolina rain were of a light continuous nature, similar to the light continuous rains found at Alaska and Oregon. Thus, when these are added to the showery rainfalls as represented by the data from Majuro and Indonesia, a curve such as those for New Jersey and North Carolina is obtained. The data from New Jersey shows a second bit of curvature appearing at about 6-1/2 grams per cubic meter dropping down quite rapidly to the largest value of liquid water content plotted of 7.1 grams per cubic meter. This curvature may be eliminated by the inclusion of the last of the New Jersey data, which will primarily be of showery nature. These points will increase the sample size of the larger liquid water content points. The curve from Miami, Florida, is different from any of those previously described. It does have some curvature at the small end which might be attributed to light continuous rain, but it has a much higher percentage of the rains occurring with large liquid water content than either Majuro or Indonesia.

Since it is felt that Majuro, Indonesia, and Miami all have an adequate sample, it is believed that this difference in the curve has meaning. It is suggested that one possible explanation might be that both Majuro and Indonesia, in a tropical climate, do not experience as great an instability condition as Miami. Perhaps the updraft velocities in the showers and thunderstorms In Miami may be of greater magnitude which would allow larger amounts of liquid water to be suspended during the storm's growing period. If there is suspended liquid water content aloft when the updraft system breaks down and this water is allowed to fall, it is not surprising that higher liquid water content may be found at the ground. The highest liquid water content which was experienced at Miami was 29.18 grams per cubic meter. This point does not show on the figure since the probability of higher amounts is extremely low. (This sample also had the hignest rainfall rate measured at any location: 722 millimeters per hour. The observation was made at 1426 EST, 13 May 1958. The cubic meter sample contained 4782 drops.) The portion of the curve beyond 15 grams per cubic meter was represented by a number of samples and it is not believed that this could have been a sampling problem in the raindrop cameras. This represents a higher liquid water content than was obtained at any other location. It is believed that Miami has a unique position in that a plentiful moisture supply is available along with high instability, due to cooler, drier air aloft.

Liquid Water Content vs. Rainfall Rate

Figure 3 shows liquid water content plotted against rainfall rate for Miami, Florida; Champaign, Illinois; and Woody Island, Alaska. Each point on these plots shows the average liquid water content for each one millimeter per hour increment of rainfall rate up to about 100 mm per hour. Above this rate, larger increments are used. The relationship of these parameters does not vary greatly from one location to another. The logarithmic least squares fit to the Miami, Florida, data produces the equation

$$W = .0528R^{0.95}$$

where W is liquid water content in grams per m^3 and R is rainfall rate in mm per hour. The data from the other locations do not vary greatly from this. The graph for Miami also has plotted the highest and lowest value of liquid water content associated with each rainfall rate up to about 100 mm per hour. Above this rate, the scatter about the points becomes so small on logarithmic paper that it has not been plotted. The value of the exponent of R being near unity in the regression equation is an indication that a linear relationship between these parameters would be as good a fit of the data as the logarithmic fit. A linear by eye fit of the data yields an equation of

$$W = .0425R$$

Conclusions

There is a systematic difference in the frequency distributions of liquid water content in rain. It is believed that the area most likely to have high values of liquid water is an area where there is a plentiful supply of moisture and a high instability in the atmosphere. The lowest values of liquid water were obtained from the areas of light continuous rains such as the Northwestern section of the United States.

No difference in the relationship between the liquid water content and the rainfall rate could be noted at any of the eight locations. Therefore, the frequency distributions of liquid water are directly related to the frequency distributions of short duration rainfall rates.

References

1. Yarnell, D. L., 1935: Rainfall intensity-frequency data. U. S. Dept. Agr. Misc. Pub. 204, 67 pp.
2. Huff, F. A. and J. C. Neill, 1956s Frequency of point and areal mean rainfall rates. Trans. Amer. Geophys. Union, 37, 679-681.

TABLE 1

SUMMARY OF DATA COLLECTION FOR EACH LOCATION

Locatxon	Days of Sample	Samples	Liquid Water Content gm m^{-3}		Rainfall Rate mm hr^{-1}	
			Mm.	Max.	Min.*	Max.
Woody Island, Alaska	74	2688	0.01	1.39	0.1	26
Miami, Florida	79	2506	0.03	29.18	1.0	722
Majuro, Marshall Islands	93	2552	0.03	11.35	1.0	270
Corvallis, Oregon	59	1706	0.01	1.24	0.1	26
Bogar, Indonesia	76	1879	0.01	13.47	0.1	282
Champaign, Illinois	36	1126	0.01	5.56	0.1	130
Island Beach, New Jersey	78	2354	0.01	8.13	0.1	155
Coweeta, North Carolina	85	3369	0.01	13.49	0.1	310

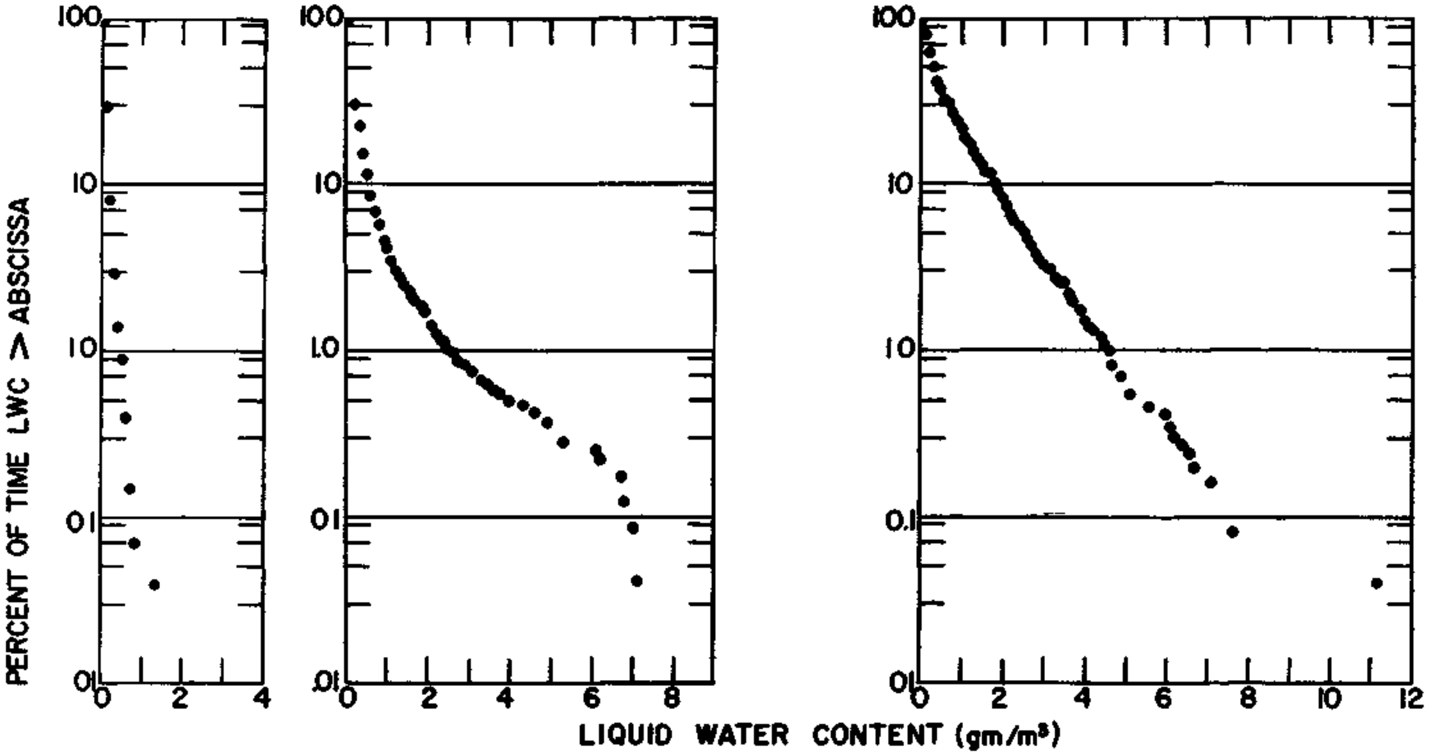
*Arbitrary lower limit applied to rainfall rate of 0.1 or 1.0 mm/hr depending on location.

TABLE 2

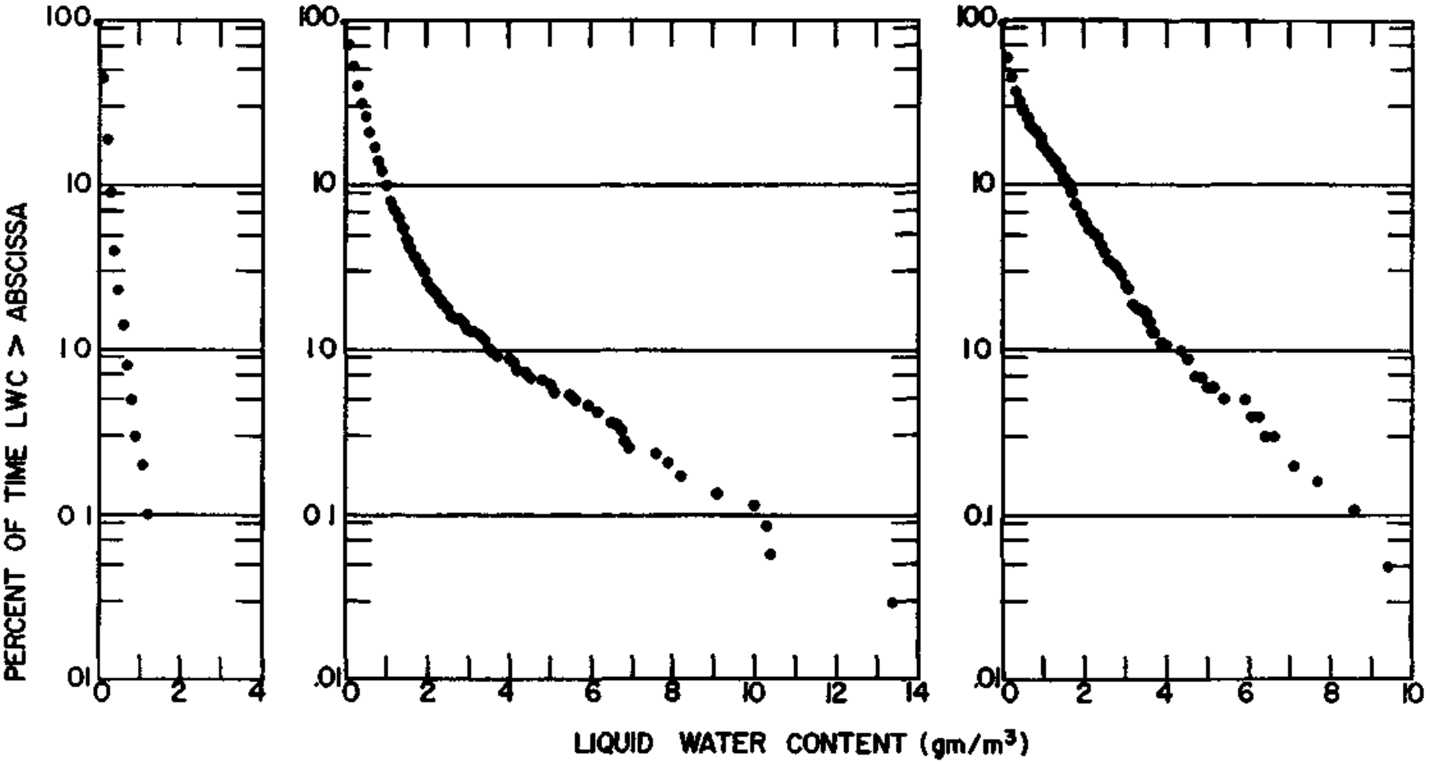
DISTRIBUTION OF DATA COLLECTION BT MONTHS

Location	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
Woody Island, Alaska	6 225	5 133	3 33	6 216	9 351	8 442	7 343	10 391	5 56	3 94	10 326	2 Days 78 Samples
Miami, Florida	7 394	1 66	9 306	4 46	7 448	3 82	8 207	12 250	9 128	6 189	6 184	7 Days 206 Samples
Majuro, Marshall Islands	4 81	1 44	7 67	20 445	11 215	12 524	7 271	11 457	7 208	4 96	5 63	6 Days 81 Samples
Corvallis, Oregon	12 501	1 8	10 198	16 358	-- ---	9 203	-- ---	-- ---	-- ---	-- ---	-- ---	11 Days 435 Samples
Bogar, Indonesia	14 426	4 55	15 333	13 253	5 63	1 16	-- ---	-- ---	-- ---	-- ---	12 239	12 Days 494 Samples
Champaign, Illinoxs	1 17	-- ---	1 20	1 14	4 68	2 41	6 208	13 343	3 152	5 256	-- ---	-- Days --- Samples
Island Beach, New Jersey	6 165	5 225	8 35	1* 67	--* ---	14 487	10 293	9 125	5 92	8 287	8 326	4 Days 187 Samples
Coweeta, North Carolina	2 128	6 276	14 489	9 410	7 283	14 661	15 553	11 384	6 157	--* ---	--* ---	1 Days 38 Samples

*Data measurement incomplete for these months.



a ALASKA b. NEW JERSEY c. MAJURO



d OREGON e. COWEETA f INDONESIA

FIG 1 LIQUID WATER CONTENT FREQUENCY DISTRIBUTIONS

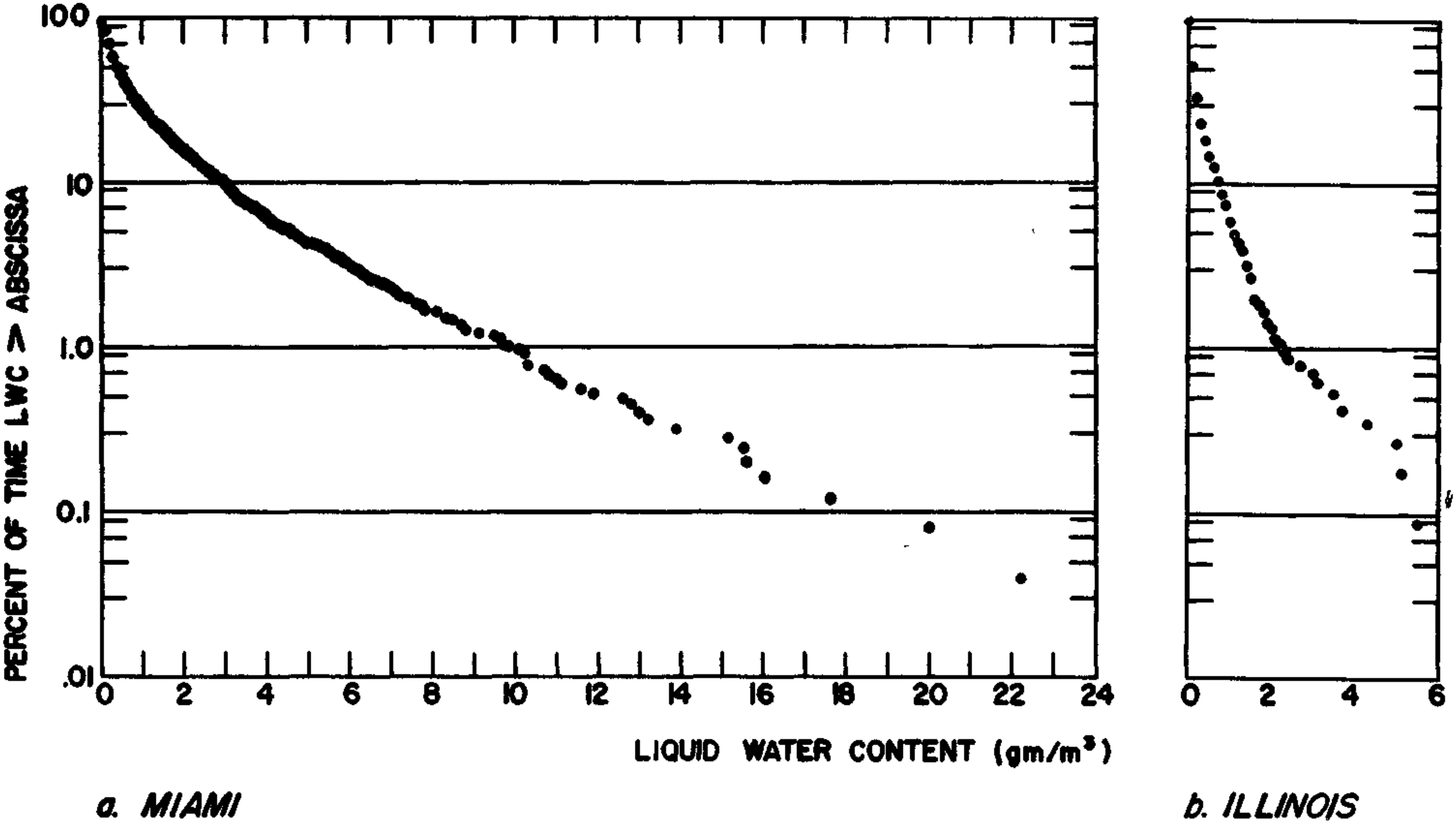
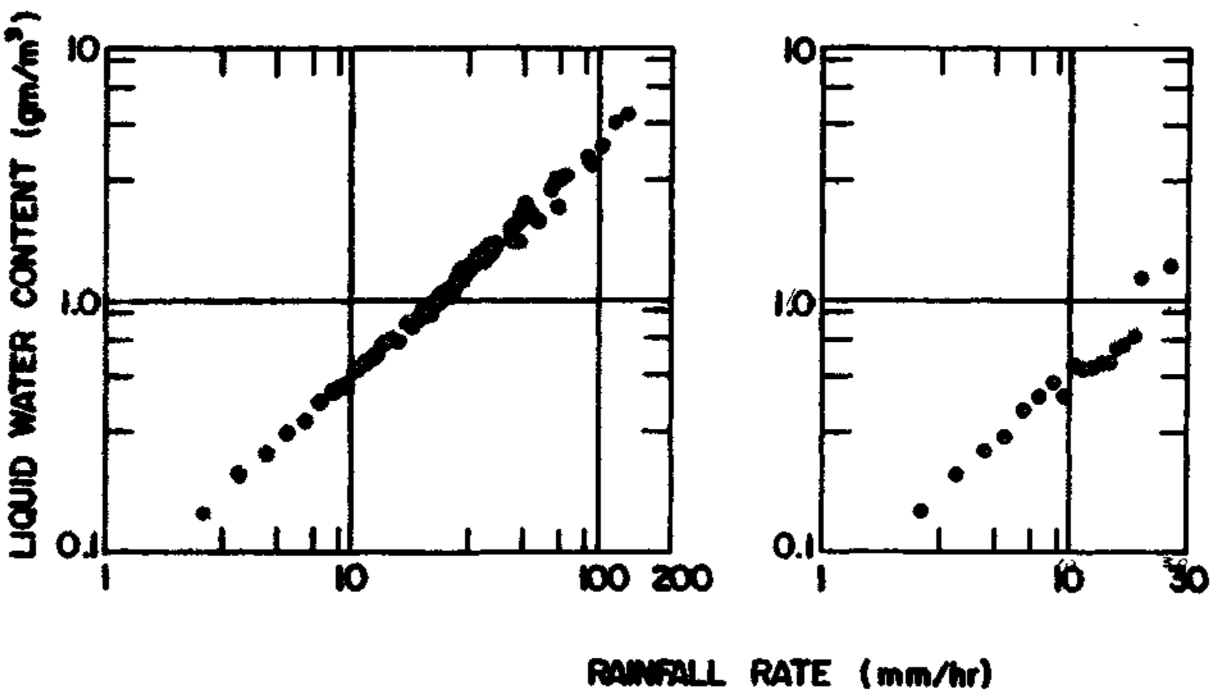
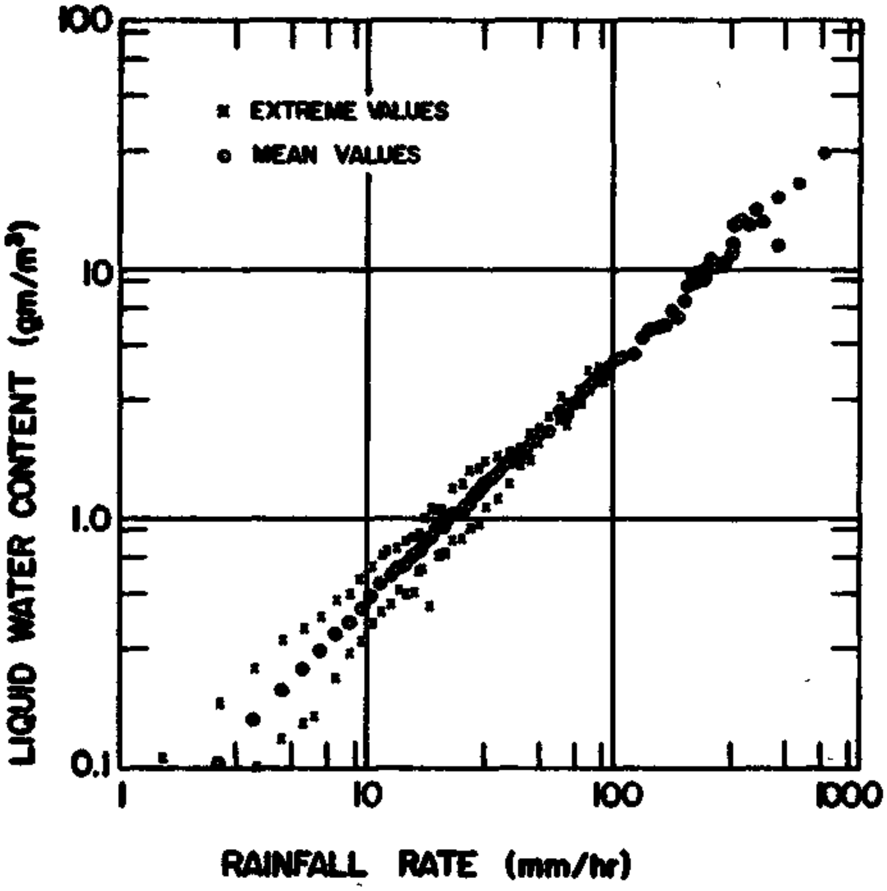


FIG. 2 LIQUID WATER CONTENT FREQUENCY DISTRIBUTIONS



a ILLINOIS

b. ALASKA



c. MIAMI

FIG. 3 LIQUID WATER CONTENT VERSUS RAINFALL RATE FROM FLORIDA, ILLINOIS & ALASKA.

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