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Research and Development Technical Report
ECOM-02071-3

SUMMARY OF RADAR-RAINFALL RESEARCH
1952-1968

INTERIM REPORT NO. 3

by

G. E. Stout - E. A. Mueller - A. L. Sims
R. Cataneo - F. A. Huff

October 1968

ECOM

UNITED STATES ARMY ELECTRONICS COMMAND - FORT MONMOUTH, N J
ATMOSPHERIC SCIENCES LABORATORY

Contract DA-28-043 AMC-02071(E)
ILLINOIS STATE WATER SURVEY
at the
University of Illinois
Urbana, Illinois

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TECHNICAL REPORT ECOM-02071-3 October 1968

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INTERIM REPORT NO. 3

Contract No. DA-28-043 AMC-0207l(E)

DA Project No. 1TO-14501-B-53A-07

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G. E. Stout - E. A. Mueller - A. L. Sims
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ABSTRACT

A summary of research activities and their highlights during the past 16 years through a series of individual contracts has been prepared in order to focus on the state of knowledge concerning the measurement of rainfall with 3-cm radar. Much effort has been expended on determining the raindrop size distributions for many climatic areas. In order to evaluate the radar, dense networks of raingages were employed. The availability of the radar and a dense network of raingages has resulted in numerous applications of these facilities for related studies in hydrometeorology, cloud physics, and weather modification experiments. In summary, a well-calibrated radar is capable of measuring rainfall which is equivalent to about 1 gage in 60 mi^2, and of detecting severe storms and short range forecasts of precipitation; however, its utilization is limited because of the lack of instrumentation to properly process the large amount of data that becomes available to the user and because of the meteorological variance between storms.

HISTORY

The research, through a series of contracts which started on 1 June 1952, was primarily directed towards the measurement of precipitation by use of a radar. The ability to measure rainfall remotely was considered to be important to the Army, since it was anticipated that the density and areal distribution of precipitation would play a pertinent part in the planning and execution of military operations. At the time this work was begun, very little was known about the methods required for proper use of a radar to measure precipitation, and there was not available a dense raingage network with which the radar could be compared. The original contract with the Army provided an installation of 50 raingages in an area of approximately 96 mi^2. The initial radar used for this work was an AN/APS-15, a low power 3-cm radar which was purchased from war surplus. At that time, it was known that radar detected rainshowers, but very little quantitative data had been obtained. The low-powered radar was replaced in 1954 with the high-powered CPS-9 radar. The radars have been operated now for 16 years, and the quality of radar data has improved considerably.

Equipment Developments

Initially, procedures had to be determined for collecting data in a quantitative manner, for calibrating the radar so that values of return signal could be correlated with precipitation rates, and for properly assessing the total rainfall that had fallen. One of the early and important discoveries on this contract was the concept of "step-gain pictures." This concept is discussed in greater detail in a later section. This technique is now widely used by a number of research and operational groups. In recent years, the step-gain technique has not been considered adequate to allow maximum usage of the radar. Furthermore, this procedure is extremely time-consuming and laborious. Nonetheless, it was a result of the early work and is considered an important contribution to the overall science of the measurement of precipitation by radar.

Very early, it was recognized that a more appropriate method for collecting and analyzing the data would have to be determined if the radar were to be useful to the Army. In pursuit of this, the area integrator was developed. This device is also considered a very important step in the overall advancement of the use of weather radar and is discussed in a later section. Briefly, the area integrator performed satisfactorily within the realm of the state of electronics of 1954. Its most serious drawback was that improper signal averaging was preformed. This meant that the theoretical value of average power return from a rainstorm would not be obtained, but only a set of instantaneous readings. This basic difficulty has also been noted in all other automatic data processors. Within the last few years, advances in electronics have permitted better averaging techniques, providing a feasible means of obtaining automatic radar data processing.

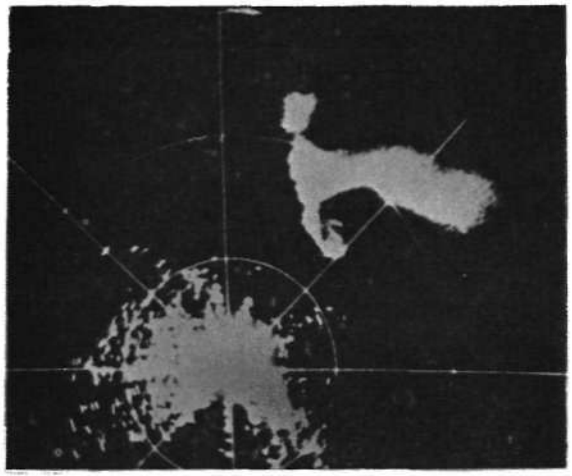
During the early investigations, it was recognized that the relationships between rainfall rate and radar reflectivity were neither well understood nor well defined. In an attempt to define better the relationships between rainfall rate and radar reflectivity, a raindrop camera was designed and built to provide measurements of the raindrop size spectrum. This photographic technique has proven to be extremely successful, and a large amount of data in the United States and at points outside of the United States has been obtained. These data have been used not only by the Army and the Illinois State Water Survey in determining better relationships, but by several other groups within the Department of Defense, and by various agencies as outlined under the raindrop camera section of this report. This raindrop camera spectrograph is still the only working method of obtaining drop-size spectra in extremely high rainfall rates where the most interest generally lies. Other devices which obtain drop-size distributions are not capable of sampling the very high rainfall rates that the drop camera does.

Supplementary Applications of Radar-Rainfall Data

The raingage networks, also referred to later in this report, have provided a great deal of information not only for correlation with radar-measured precipitation but in the development of rainfall relations needed for the design of hydraulic structures and useful in the design of weather modification experiments. Information gained from the original dense network has permitted numerous other dense networks to he designed in recent years with gage spacings which are more nearly optimal.

Another use for the radar, although not an original objective of this project, was the first observation, Figure 1, in April of 1953 of a hook-shaped echo on the radar associated with a confirmed sighting of a tornado. This observation provided the original impetus for the U. S. Weather Bureau to install a network of APS-2 radars in the Texas-Oklahoma area for severe storm warnings. This eventually resulted in the present network of the U. S. Weather Bureau, consisting of a number of WSR-57 radars and modified military equipment. The hooked echo has remained to this time the only means of identifying tornadoes on an operational radar set. Eventually, it is believed, a more positive identification of tornadoes should be possible by the use of a coherent Doppler radar. However, the military and the Weather Bureau are still operating with the hooked-echo criterion.

In the areas of severe storms, the radars supplied by the U. S. Army have been helpful in determining the ability to recognize hail on the ground by virtue of radar echoes aloft. This work was originally sponsored by the Air Force Cambridge Research Laboratories. Along with other AFCRL investigators, Illinois researchers observed that hail echoes tended to have a higher radar reflectivity aloft than at the ground. This is commonly referred to as a "nose" in the reflectivity profile. This work has resulted in a means of detecting hail which has been used successfully by the Russians in hail suppression experiments. Currently, the radars are being used in a study supported by the National Science Foundation to develop further knowledge of the use of radar in hail suppression projects.



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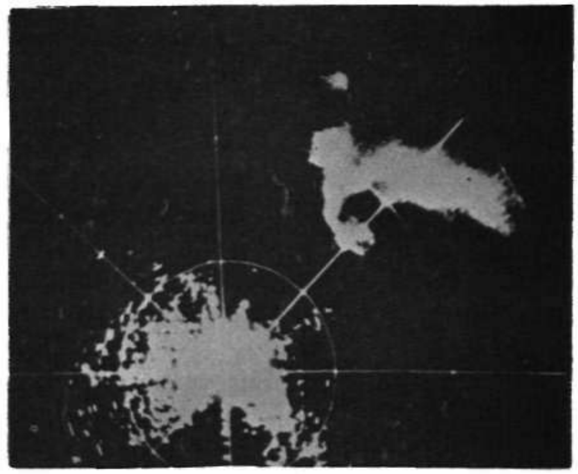

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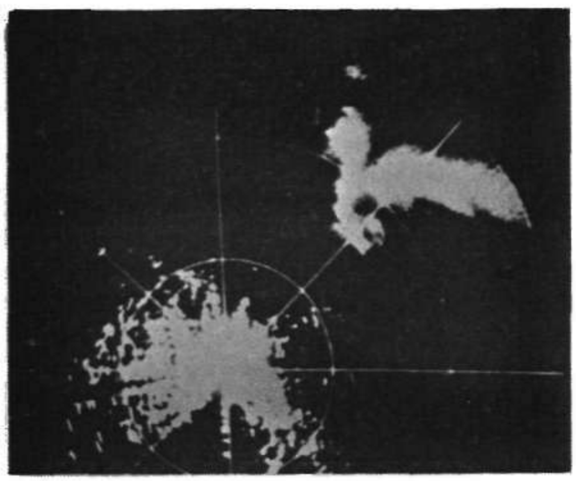

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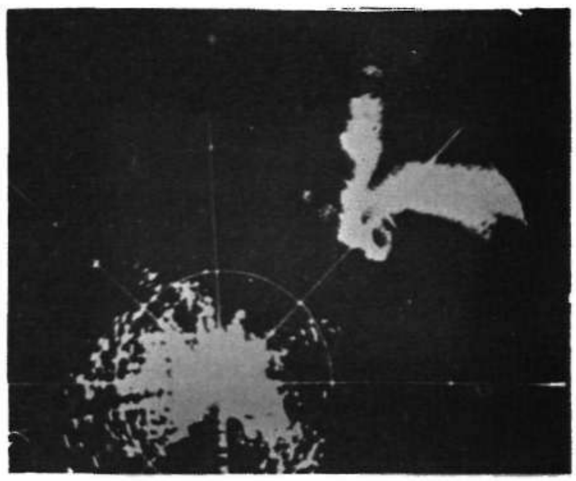

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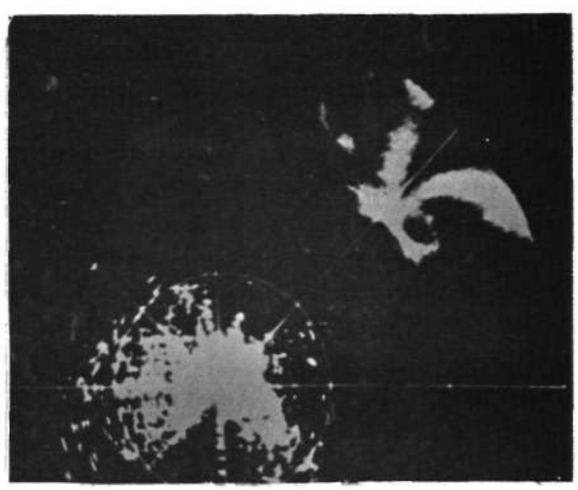

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Figure 1. PPI photographs on 9 April 1953, reduced gain, 10-mile markers

Other areas of research with respect to sever weather have been pursued using the radar. For example, attempts have been made to determine points of high wind damage by observing the morphology of the echoes on the radar. Most of these investigations have proven to be fruitless.

Outstanding Contributions

Delineation of the most important findings under the contracts for research extending from 1952 to 1968 is a very difficult job. A large number of the tasks and studies have been completed and are described in detail in numerous quarterly technical reports, special reports, or papers (see Appendix). These publications and the work of the investigators are well known throughout the scientific community. Nonetheless, an attempt has been made to set forth what we consider some of the important results of this contractual work.

One of the most important contributions is the establishment of rainfall rate-radar reflectivity relationships in the U. S. and in various locations around the world. These relationships have proven to be of great value. For example, we have furnished the Air Force with values which are estimates of the type of rainfall-radar reflectivity relationships that probably exist in South Vietnam. Furthermore, the data generated by these relationships from the various locations have been used profitably in attempting to delineate the types of rainfall and the cloud physics of rainfall at these locations. Also, these data have been and are being used extensively to improve our capability to estimate the loss of signal from satellite communication transmitters and to estimate the attenuation between ground link radio communications. This latter area has proven to be one of great interest for a number of agencies. In particular, the Air Force Cambridge Research Laboratories, as well as the Army, have been interested in the data from the standpoint of attenuation in radio links. Furthermore, a portion of these data has been used by Bell Laboratories in evaluating the attenuation by rainfall at various localities. A large catalog of drop-size data is now available on magnetic tape and can be reanalyzed in any of a number of ways for other problems.

The data from the drop camera have indicated the ultimate limit in accuracy which can be expected from a measurement of precipitation by radar. It has not been possible, however, to achieve this accuracy in using a radar set. There are a number of reasons for this discrepancy. With the radars available to our group, the problem of precipitation attenuation reduces the certainty with which one can measure rainfall rates, and thus the integrated rainfall amount is in error. However, more important than this problem, we feel, is the problem of improper signal processing. One of the contributions of this contract has been pointing the way towards better radar data processing. The concept of step-gain pictures, which originated in this group, has served its purpose and is no longer an appropriate manner in which to collect data with the modern radar. The area integrator was the first automatic data processor for a radar set which considered an area greater than a single radar volume at a time. This device was a forerunner of the Air Force Cambridge Research Laboratories STRADAP data processor, which appeared some years later and depended in large measure upon the design parameters of the original area integrator developed for the Army. Stanford Research Institute utilized our experience in designing an automatic radar processor for the National Severe Storms Laboratories. There is still a great deal to be desired in the area of radar data processing, and recently the Army has permitted us to investigate the properties of a contiguous range interval analog integrator with a digitizer on the output. It would appear that modern electronics will permit rapid and accurate radar data processing. It has not been possible in the past to perform both accurate and rapid processing by virtue of the tremendous cost required.

The values of liquid water content calculated from the raindrop data have been found useful by the Naval Air Turbine Test Center in relation to problems of rainwater ingestion into turbine engines. These data are unique with respect to giving the liquid water content in the air for any particular rainfall rate, and a reasonable estimate of the probability of encountering various values of liquid water content.

The application of radar in the detection of tornadoes, hail, severe rainstorms, and other forms of precipitation has increased the knowledge of these phenomena considerably.

RADAR RESEARCH

The major portion of the radar research at the University of Illinois, State Water Survey, has been in the area of radar meteorology. A large variety of work has been accomplished with the aid of Army support. This work has consisted of the development of special instrumentation, such as the area integrator and the step-gain procedure for evaluation of radar quantitative amounts, and various meteorological investigations. During the course of the contracts, at least five different radars have been operated with Army sponsorship, including an APS-15, a TPL-1, a CPS-9, an M-33, and a TPS-10.

The main purpose of our research has been to develop and evaluate techniques for the quantitative measurement of precipitation by 3-cm radar, since this has been a prime requirement for tactical Army use. However, as in all research, the principle of serendipity has operated and a number of useful side findings have been obtained. In particular, the identification of the first tornado on radar was made using the AN/APS-15.

Quantitative Measurement of Rainfall

Restricting ourselves first to an examination of the quantitative measurement of precipitation by means of radar, we find that during the past 16 years some improvements have been made. However, overall the techniques for the measurement of precipitation still leaves much to be desired. In the final report on the first contract with the Army (DA-36-O39 SC-42446), it was stated that the 1951-1954 data indicate that the APS-15 generally has an average accuracy equivalent to less than 1 raingage per 100 mi^2 in moderate to heavy rainfall. Prom the 1967 Kankakee network data, it is estimated that the radar is producing an average estimate which is equivalent to about 1 gage in 60 mi . Thus, some improvement has been shown. Since the method of analysis and the radar calibration procedure have not changed, the improvement has been due to the use of better radar equations and better radar-rainfall relationships. The 1967 data do exhibit a number of storms in which the average gage density would have been much poorer than 1 in 60. For instance, the radar data for the storm on 7 June 1967 indicated 6 times as much rain than the raingage data. This and several other storms of the same nature were unique in the sense that large radar echoes were apparent over the network for relatively long periods of time during which the raingages exhibited no rain.

It is felt that these analyses indicated a serious drawback in the procedural methods for obtaining radar quantitative amounts, and better averaging and processing methods must be obtained if the radar is to be used for quantitative precipitation amounts.

Step-Gain Development

In the early part of these studies, the step-gain procedure was developed to measure the reflectivity of precipitation with the radar. In this procedure, photographs are made of the radar scope, while for each successive revolution of the radar antenna, the gain of the receiver is reduced by a calibrated amount. Since the power of the transmitter and the total gain of the receiver are known, it is then possible to measure the ratio of the returned signal to the transmitted signal by observing which gain-step photograph shows the echo to be extinguished. This P_r/P_v ratio can then be converted to an equivalent Z or to rainfall rate through the use of equations relating Z to R. This procedure has been used for most of the radar-rainfall studies.

Area Integrator

As early as 1952, the Army recognized the need for automatic reduction of radar data. Research resulted in the production of a special-purpose hybrid computer, known as the area integrator. The first integrator used as an operating signal the instantaneous power return from the radar. Theoretically, this is not the best signal for determining the rainfall from radar. The proper control signal should have been a time-averaged signal from a point in space. A second model was built in 1955 for use with the CPS-9 radar. This model had some improvement in the signal-averaging capabilities by using a specially-formulated low pass filter for range integration. Nonetheless, the appropriate signal averaging was not performed.

The area integrator operated over a single selected watershed which was determined by masking a slave plan-position-indicator. By means of special digital circuity, the area within the selected watershed at which the instantaneous power was greater than a threshold level was measured. The rainfall rate corresponding to this threshold was used to evaluate the radar-measured rainfall amount. This was summed for the period of the storm.

In summary, the area integrator was the first radar data processor for operation in radar meteorology which was directed towards obtaining quantitative rainfall over an area. Prior to the area integrator, work had been accomplished at Massachusetts Institute of Technology on the pulse integrator technique, which obtained rainfall rate at one point. The work that has been done since the design of the original area integrator has to some extent been influenced by it. In particular, the AFCRL STRADAP is similar in characteristics to the area integrator and suffers from the same major drawbacks in respect to improper signal averaging.

The area integrator was physically large and inconvenient to use. Modern technology in electronics would permit a much smaller and more useful integrator to be built today. Furthermore, modern techniques permit excellent averaging techniques to be performed in analog fashion, rapidly and inexpensively.

Maser Equipped Radar

An MPS-34 equipped with a maser was evaluated for its usefulness in meteorological work under contract DA 28-043 AMC-01257(E). This radar had much greater receiver detection capability than the conventional set, and it was hoped that a number of advantages could be obtained by using this type of receiver for meteorological work. During the summers of 1965 and 1966, this radar was operated in Arizona and in New Mexico for evaluation of cloud physics experiments. At other times, the set was operated in Illinois. During 1965, the prime objective was to attempt to make an early determination of echo occurrence in clouds. It was hoped that the radar would be capable of detecting the clouds well before the rain stage had been reached. Unfortunately, the experiment was in general unsuccessful because the side lobes of the radar antenna were receiving echoes from the surrounding mountains which overrode the echoes from the clouds.

The major use of the radar during the 1966 season was in support of the Army USAECOM cloud physics project in the Flagstaff area. The radar operated properly, and considerable data on the movement and location of showers in the Flagstaff area were obtained. Again, the radar was not capable of detecting clouds much before the precipitation stage of the clouds, even though it should have theoretically. This is a departure from theory which has since been noted by others and requires further examination. It would appear that the cloud droplet densities are so high that the normal prediction of backscattering cross sections from the ensemble of drops does not hold. The discrepancy between measurements and first order theory is at least 10 db, and perhaps as much as the 20 to 25 db, as reported theoretically recently by Naito and Atlas[1] and by Smith[2].

One of the major difficulties with the maser as installed on the MPS-34 was its lack of stability. The gain of the maser itself varied widely from hour to hour, and frequent calibrations and retuning were necessary. At times, the sensitivity variations were on the order of 15 to 20 db, which amounted to the entire gain of the maser. Thus, at times even though the maser was on, its effective gain was 1. This lack of stability could undoubtedly be eliminated by design changes in future masers. However, one conclusion of this operation is that the use of the ultra-sensitive maser receiver does not aid in radar measurement of precipitation. The added sensitivity is not required for detection or measurement of any reasonable precipitation amounts. However, it would be very useful in certain cloud physics experiments.

There were several observations with the maser radar which would be unique to a high-gain receiver. These included the detection of a thin line echo in the Flagstaff operations in 1966. This thin line resulted from a cold outflow of a large cumulonimbus echo about 10 miles east of the radar. The line passed over the radar and produced no apparent rainfall or change in sky conditions. This was strictly a clear air anomaly. The thin line had an average length of 9 miles and an average width of 3/4-mile, extending to about 6500 feet above the radar. On the passage of the line over the radar, the temperature at the surface dropped 6°F, while the humidity rose from 28% to 42% during its passage.

The use of maser on a radar greatly facilitates the capability of the radar in detecting clouds. Despite the negative results in cloud studies in Flagstaff, good correlation with cloud echo detection was obtained in Illinois with this radar, in fact, clouds were noted on one occasion which were so thin that the only visual observation was a slight obscuration of the moon as the cloud passed in front of it. Stars could be seen through the cloud bank, and yet it was still detectable on the MPS-34 with maser. As mentioned earlier, there seems to be a discrepancy between measurement of cloud droplet size and number and the radar reflectivity from clouds. This should be further investigated by radar and direct measurement of cloud droplet distributions.

In conclusion, the maser amplifier was found to add 10 to 13 db additional gain to the radar receiver under optimum operating conditions. This device could be most effectively used with a radar that has less normal receiver gain than the MPS-34, since the added sensitivity with the MPS-34 causes the radar to display thermal noise at low elevation angles. Furthermore, needs for specialized antennas with low side lobes are indicated whenever such sensitive radar receivers are to be used.

DROP CAMERA RESEARCH

Radar-rainfall studies were initiated by the Illinois State Water Survey in 1948. It soon became evident that the errors in the quantitative measurements of rainfall by radar were greater than had been anticipated. One of several factors recognized as contributing to these errors was the variability of the drop-size distributions in rain. The data available at that time demonstrated that rates of 0.48 to 2.30 mm/hr could be indicated by radar for an actual rate of 1.0 mm/hr, even if it were assumed that the drop-size variablility was the only factor limiting the accuracy of the measurement. Therefore, in 1951, investigations were begun of methods of measuring raindrop sizes. It was thought that each type of rainfall might have its own particular drop-size distribution and that a separate radar-rainfall equation could be applied to each type. Also, there was a possibility that the drop-size distributions might be more uniform at a given rate than the data then available indicated.

After considerable study and experimentation, it was decided that a photographic method would be the best way to measure drop-size distributions. This method could obtain larger samples more accurately than the other methods that were investigated.

The First Drop Camera

Although some preliminary design work was done in 1951, the construction of the first drop camera was made possible by the Army under Contract DA-36-039 SC-42446 in June 1952.

This first drop camera used a 12-3/4 inch diameter parabolic mirror as the first element in a telecentric optical system which eliminated perspective effects. This system required that the iris of the camera lens be placed at the mirror's focal length (4581.5 mm) from the mirror. A small, flat, first surface mirror was placed in the system to reflect the converging rays of light from the parabolic mirror to the camera.

The camera used In the apparatus was a modified 35-mm motion picture camera equipped with a Bausch and Lomb Tessar f/4.5, 210-mm focal length lens.

The drops falling through the sampling volume were back-lighted by a flash tube behind a translucent screen. The flash unit provided an exposure of 10 microseconds.

Each photograph represented a volume of 0.033 m^3. Normally, the camera was operated by electrical controls to take a series of 36 photographs at a spacing of 1/3 second, once each minute. Thus, a 1-m^3 sample was recorded during a 12-second period, and this cycle was repeated at 1-minute intervals.

This camera system was operated in Illinois from July 1953 until January 1955. During this period, 1211 samples were obtained. Separate R-Z relationships were derived from these data for thundershowers, rainshowers, and for continuous rain. These are discussed more fully in another section of this report.

This system was later used on other projects. In 1955, tne system along with a similar system was used to obtain drop pictures from two viewing directions. These data were used to study the shape of raindrops3. This work was sponsored by the Office of Naval Research, Contract N0NR-l834(04).

From 1960 to 1964, the original camera unit was used by the Agricultural Research Service station at Urbana in connection with a study of soil erosion .

The 70-mm Drop Camera

In 1956, the Army proposed that drop-size data be gathered in various climatic regions around the world. For this purpose, additional drop cameras were needed. Rather than reproduce the original camera, it was decided to improve the design by increasing the film size and by using a larger mirror to increase the sampling volume per frame.

The new design used a 29-inch parabolic mirror with a focal length of 4100 mm as the first element in the telecentric optical system. The second element was the 300-mm Schneider-Kreuznach Xenar camera lens. A Beatty-Coleman electrically-operated camera using 70-mm film was substituted for the previously used 35-mm motion picture camera. To light the 29-inch diameter object space, four PT-503 flash tubes were used behind a translucent screen. Figure 2 shows one of the camera installations.

The sample volume with the larger system is a right circular cylinder, 29 inches in diameter and 14 inches deep. After corrections due to the obstructions of the light path by the diagonal flat mirror and necessary mirror mounts are made, the usable sampling volume is about 1/7 or 0.143 m . over four times that of the earlier systems. The diameter of this volume on the film is about 55 cm.

The normal mode of operation for these cameras was to photograph seven frames in a 10.5-second period, once each minute, thereby providing a sample of 1 m^3 during each minute.

Between August 1957 and May 1962, these 70-mm cameras were operated in seven different locations. Over 19,000 m^3 of natural rains were sampled. Additional data concerning these remote sampling programs are shown in Table 1. In this table, only samples having rainfall rates of 0.1 mm/hr or greater are indicated. Approximately one year of raindrop data was collected in Miami, Florida, Corvallis, Oregon, Majuro Atoll, Marshall Islands; Woody Island, Alaska; Bogor, Indonesia; Island Beach, New Jersey; and Franklin, North Carolina.

During two summers, multiple camera operations were conducted in Illinois. In 1963, two cameras were operated in Illinois spaced a distance of 2 miles apart. For the early part of the season, another camera was located between these two, l/2-mile from one of the other cameras. These cameras were set up in this fashion to examine whether or not the R-Z relationship was dependent upon the portion of the storm sampled. The relationships

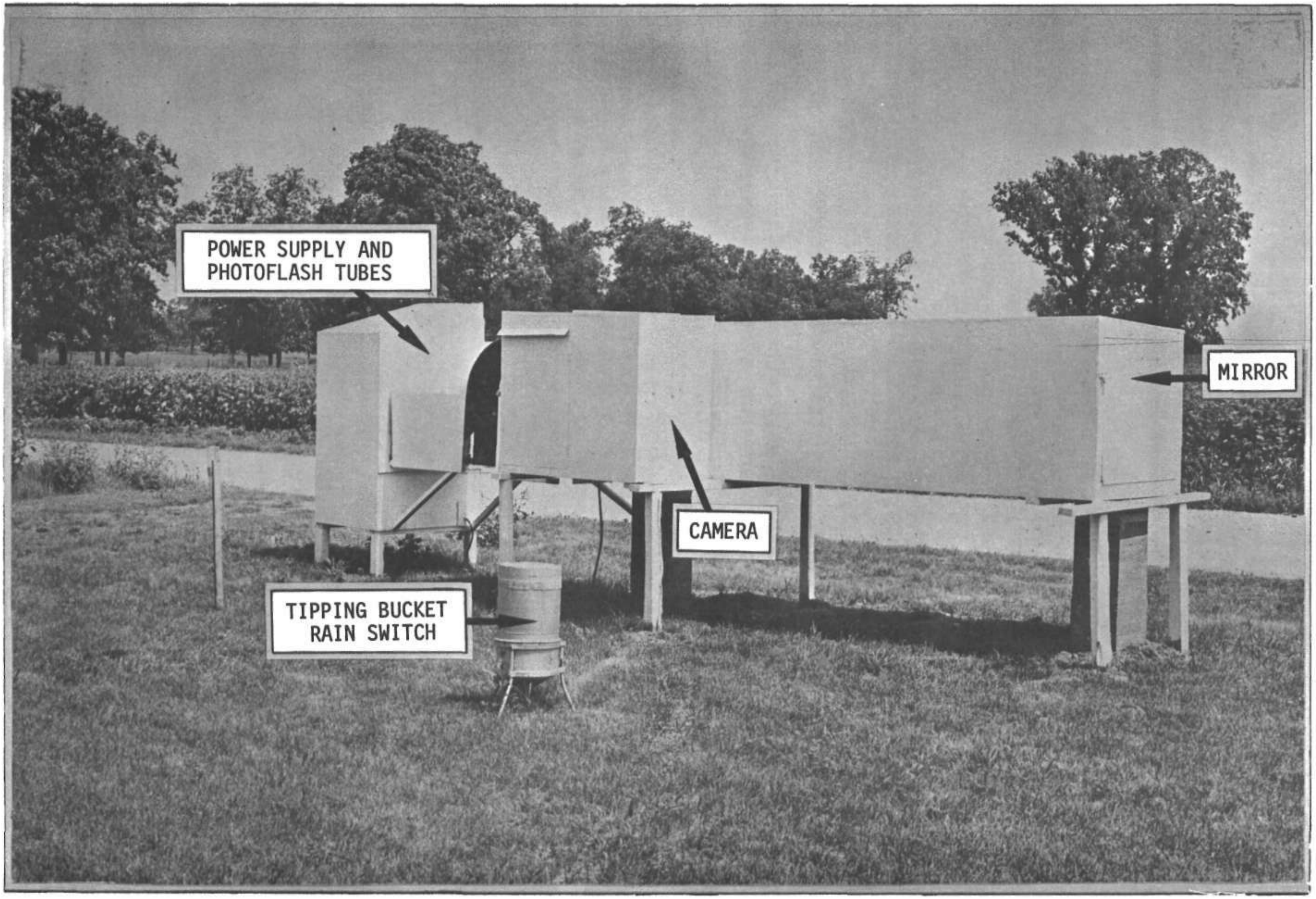

Figure 2. East Central Illinois drop camera installation

calculated from each camera's data were generally very similar for a given storm. The variation from storm to storm was much greater than the variation within the storm.

Another experiment was conducted in the summer of 1964. Two cameras were operated in close proximity, photographing at the maximum possible rate. Twenty-eight frames per minute were taken by each camera, giving a total sample of 8 nP each minute. Statistical analyses were made of these data to determine the size of sample necessary to describe adequately the drop-size distribution and to determine the uncertainty inherent in the R-Z relationships derived from the 1-m^3 samples previously taken. The results of this study showed that although 44 m^3 would be required to determine rainfall rate within 10% accuracy with a 95$ confidence, the size of sample needed to estimate the R-Z relationships reliably is much smaller. The variances of a 1-m^3 sample amount to less than 12% of the total variance around the relationship. After correcting for the effects of a 1-m^3 sample, on the average, 90% confidence limits range from 43$ below the mean to 73$ above the mean.

On three occasions, a drop camera was taken to Flagstaff, Arizona, to collect drop-size data during the summer rainy season. In 1963, the camera was operated from mid-July to mid-August however, very little rain occurred at the camera site that year, and because of camera problems, the data collected were not usable.

The 1966 Flagstaff operations were more successful. Data were collected during July and August through the support of Contract DA-28-043 AMC-02376. The drop-size distributions observed fell into distinctive groups, one having a much higher concentration of drops than the others. There was some suspicion that this difference might have been caused by the cloud-seeding experiments being conducted in the area. In order to further investigate this possibility, a drop camera was returned to Flagstaff during the summer of 1967 under Grant DA-AR0-D-31-124-G937. The data obtained are still being measured and analyzed, and no conclusions are possible at this time.

Table 1. Summary of Drop Camera Data Collection

Location	Days of Sample	No. of 1-m^3 Samples	Maximum Rainfall Rate mm/hr	Maximum Z mm^6/mm^3	Max. Liqurd Water Concent g/m^3
Miami, Florida	79	2506	722	1.9×10^6	29.18
Corvallis, Oregon	59	1703	26	5.6×10^4	1.24
Majuro Atoll, Marshall Islands	93	2660	270	4.5×10^5	11.35
Woody Island, Alaska	74	2682	26	2.6×10^4	1.39
Bogor, Indonesia	76	1872	282	1.1×10^6	13.47
Island Beach, New Jersey	78	3135	155	3.4×10^5	8.13
Franklin, North Carolina	85	4741	310	7.2×10^5	13.49

During the summer of 1968, raindrop data were collected for 30 days in Panama at the request of Frankford Arsenal, Philadelphia, under Contract DAAG11-68-C-1342. These data are needed in support of the testing of new nose cones for artillery shells.

Other Users of the 70-mm Cameras

After the Flagstaff operations of 1967, the drop camera was loaned to the University of Arizona for use in connection with cloud physics studies under the direction of Dr. Louis J. Battan. This was done at no cost to the Army. It has been learned that few data were obtained because of the lack of significant rainfall during the period of operations.

Since June 1966, another set of drop camera components has been on loan to a group at the Lincoln Laboratories of the Massachusetts Institute of Technology under the supervision of Mr. Robert K. Crane. This camera is being used to measure some natural rains and also to measure the drop spectra produced by a sprayer device used in connection with a study of signal attenuation by rain. This work is supported by the Air Force.

Data Processing

For measurement, the film was projected onto a ground-glass screen, magnified so that the drop images were double the size of the actual drops. Two measurements of each drop were made, one of the longest and one of the shortest diameter. These two measurements were then combined to approximate the equivalent spherical diameter.

The earliest data were measured entirely by hand, and calculations performed with a desk calculator. A caliper rule was used to make the measurement, which was then written on paper. In 1954, this method was improved upon by connecting the calipers via a flexible shaft to a machine which printed the measurements on a roll of paper tape. Since 1958, a system has been used by which the calipers are electrically connected to a card punch machine. When the calipers are adjusted to the size of a drop image, a foot switch is pressed which causes the size to be punched into a punch card. The rest of the analysis is accomplished by a computer.

Several different computers have been used as they have become available at the University of Illinois. The Illiac I was designed and built at the University and was one of the earliest computers. Later, use has been made of an IBM 650, an IBM 1401, and an IBM 7090. The 7090 was updated to a 7094 and is still in use. Recently, an IBM 360/75 has been installed and used in some recent projects.

Uses of the Drop Data

The major use of the raindrop-size data obtained by the cameras has been to calculate radar-rainfall relationships for several locations and to determine the effects of various synoptic classifications, rain types, atmospheric stability, and other meteorological factors on the relationship. This area of research is treated more thoroughly in another section of this report.

Much has also been learned about the general shape of raindrop spectra. Figure 3 shows a set of average distributions, and illustrates the change in the distributions with rainfall rate. Although these curves are for the data taken in North Carolina, the general features are similar at other locations.

It has been found that the spectra are usually monomodal, with the mode between 0.7 and 2.0 mm. Above the mode, the curve on a semi-logarithmic plot is nearly straight. The slope of this portion of the curve decreases slightly with rate, although not sufficiently to produce convergence at a single point on the zero drop diameter axis, were it extended to this axis. The mode has a somewhat systematic variation with rate. The modal diameter is generally small at low rates, increases with rate, then decreases again at high rates.

Probably the most generally used equation to describe drop-size distributions is that of Marshall and Palmer:

$$N_D = N_o \exp(-\lambda D) \qquad (1)$$

where $N_D dD$ is the number of drops per cubic meter of diameters between D and D + dD mm, and N is the value of N_D for D = 0. N_o was considered constant with a value of 0.08 cm^{-4}. The parameter λ was related to rainfall rate by the equation:

$$\lambda = 41R^{-0.21}cm^{-1} \qquad (2)$$

where R is the rainfall rate in mm/hr. The drop distributions obtained by the drop cameras are not fitted well by these equations, since the number of small drops is overestimated quite severely. Even if the drops below the mode are ignored, it has been found that much of the raindrop camera data is not fitted well by these equations using a constant N_o and with λ determined by Equation 2.

Types of Distributions

One of the fitting equations used by the Illinois State Water Survey was the one developed by Fujiwara[5] while he was on the staff. He proposed the equation:

$$N_D = \alpha(D-D_o)^2 \exp - \beta(D-D_o)^3 \qquad (3)$$

where α, β, and D_o are empirical parameters. This equation fits the small drop portion of the distribution much better than does Equation 1. The major disadvantage of this fitting equation is the difficulty of determining the three parameters from the drop distribution.

The log-normal distribution was examined as to its applicability to the drop camera drop-size distributions. The use of this distribution has been suggested by Levine[6]. Also, Matvejev[7] references the work of Kolmogoroff on this equation. Irani and Callis use the log-normal distribution for particle size

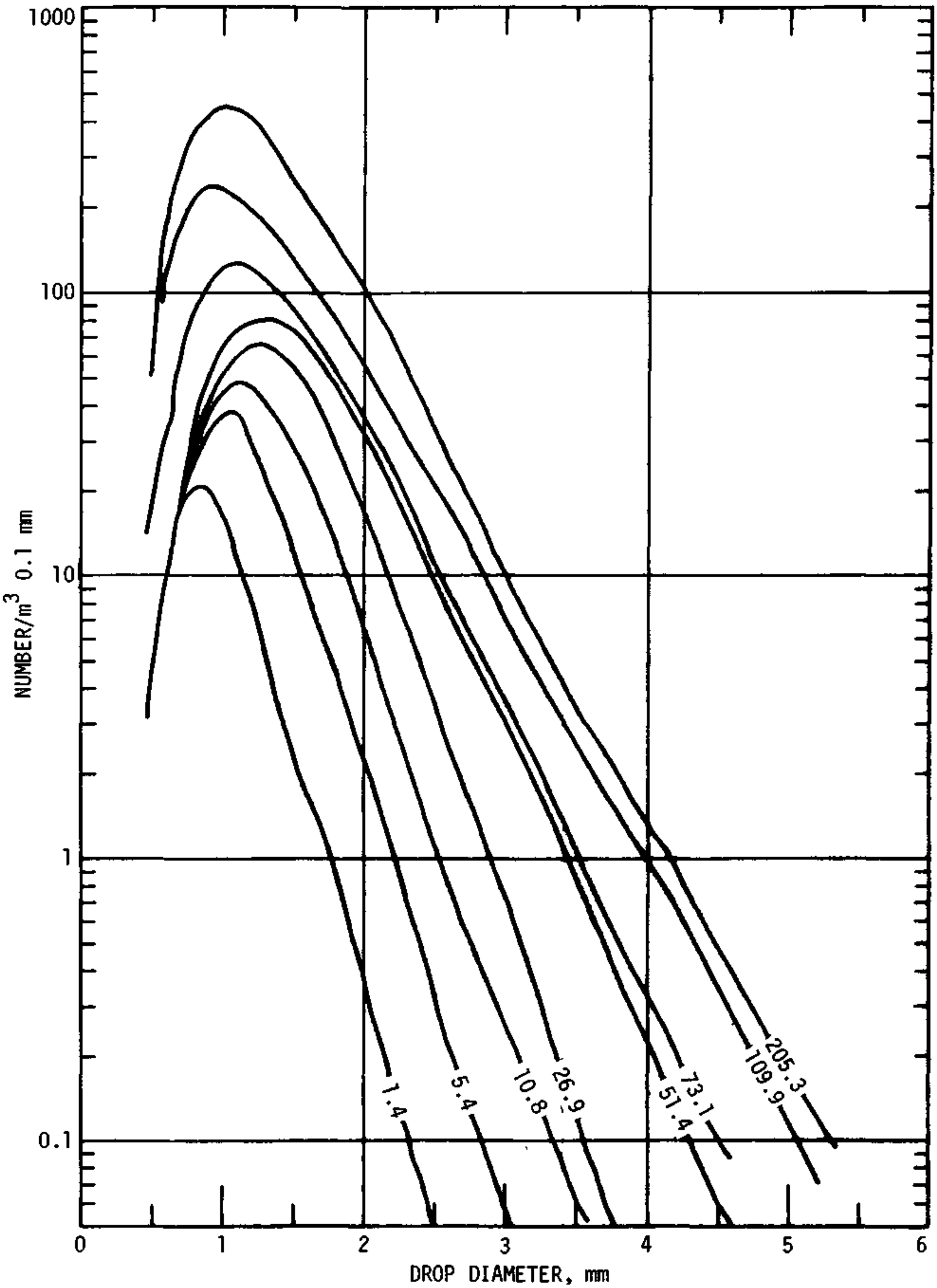

Figure 3. Average drop size distributions from North Carolina for various rainfall rates, mm/hr.

distributions, in general, and the form of the equation used here is largely attributable to them. This distribution has the appearance of a Gaussian normal distribution if the frequency of occurrence is plotted against the logarithm of the drop diameter.

The log-normal distribution can be expressed in the following form for use with drop-size distributions:

$$N_D dD = \frac{N_T}{D\sqrt{2\pi}\ln\sigma} \exp - 1/2 \left(\frac{\ln D/D_G}{\ln\sigma}\right)^2 dD \qquad (4)$$

where $N_D dD$ is the number of drops per cubic meter of diameter between D and D + dD, and N_T is the total number cf drops per cubic meter in the distribution. D_G is the geometric mean diameter of the distribution and is readily computed from drop-size data by the equation-

$$\ln D_G = \frac{1}{N_T} \sum_{i=0.5}^{i=7.9} N_i \ln D_i \qquad (5)$$

The geometric standard deviation, σ, is then given by:

$$(\ln\sigma)^2 = \frac{1}{N_T} \sum_{i=0.5}^{i=7.9} n_i (\ln D_i - \ln D_G)^2 \qquad (6)$$

Average distributions have been fitted with these equations better than by any other distribution tested. The fit is also quite satisfactory on the individual 1-m^3 distributions in most cases. The calculations of the parameters of this fitting equation are done easily on a digital computer.

Attenuation

Attenuation was calculated routinely for each drop sample. Correlations between the radar reflectivity factor, Z, and the attenuation cross section, Q_t, have been calculated. Some results of these studies were reported in the Proceedings of the 11th Weather Radar Conference[9]. The logarithmic regression of Z and Q_t for the Miami data was found to be-

$$Q_t = 1.15 \times 10^{-2} Z^{0.91} \qquad (7)$$

where Q_t is the 3-cm attenuation cross section in mm^2/m^3 and Z is in mm^6/m^3. The data for other locations were similar. The attenuation coefficient, A, in db/km can be related to Q_t by the equation.

$$A = 4.34.10^{-3} \; Q_t \tag{8}$$

Work is now under way which will relate backscattering cross section to attenuation (and other parameters) for all locations sampled and for a wide range of radiation wavelengths.

The frequency of occurrence of liquid water contents as determined from the drop-size data has been studied and was reported in a paper presented at the Fifth Conference on Applied Meteorology[10]. This information was found to be of considerable interest to the jet engine designers present. This paper also showed the relationship of liquid water content to rainfall rate for several locations. Typical of the logarithmic least squares fit to the data is the equation for Miami, Florida

$$W = .0528 \; R^{0.95} \tag{9}$$

where W is the liquid water content in g/m^3 and R is rainfall rate in mm/hr.

Other Users of the Drop-Size Data

Many other researchers across the country have found uses for the drop-size data. Some of these have received the data on magnetic tape, others have received copies of certain tabulations, and still others have used the information as published in the various contract reports and other media.

Data for Majuro and Miami, which were supplied as tables of average distributions, have been used extensively by Novella S. Billions of the Physical Sciences Laboratory at the Redstone Arsenal. Her calculations from these data are the basis of an Army report

Some average distributions were also supplied by personal communication to Dr. Rudolph J. Engelmann of the Batelle-Northwest Laboratories. He has used the data in fallout calculations sponsored by the Atomic Energy Commission[12]

David C. Hogg of Bell Telephone Laboratories has used drop-size data recorded on tapes supplied by him. These data were used in the investigation of the frequencies of occurrence of various levels of attenuation of microwave signals[13].

Melvin Stone of the Massachusetts Institute of Technology and Robert K. Crane of the Lincoln Laboratories at MIT have received taped distributions which were used on studies related to satellite communications. Mr. Crane has also calculated the scattering parameters of the distributions at a variety of wavelengths[14]

RAINFALL RATE-RADAR REFLECTIVITY RELATIONSHIPS

One of the more important contributions made possible by Army support has been the collection of large amounts of drop-size data. These data, in turn, have made possible the calculation of the relationships between the radar parameter of back-scattering cross section and rainfall rate. These relationships represent by far the most comprehensive and concerted analysis that has been performed. Included is information for locations in all of the major wet climates of the world. In most locations, sufficient data have been collected to permit stratifications by local conditions to improve the reliability of the estimates. The data are extensive enough that an estimate of the best relationship to use in South Vietnam has been furnished to the U. S. Air Force. This estimate was based largely on data from Bogor, Indonesia, which is in a similar climate.

In order to obtain a measure of rainfall rate or total rainfall amount for a storm at some location with radar, the relationship between rainfall rate (R) and backscattering cross section (σ) must be known. The σ value of a spherical particle of diameter D which is small compared with λ, the wavelength of the radar signal, is given by:

$$\sigma = \pi^5 \left(\frac{\varepsilon - 1}{\varepsilon + 2}\right)^2 \frac{D^6}{\lambda^4} \tag{10}$$

where £ is the complex dielectric constant of the material of which the particle is composed. This equation is valid for values of $D/\lambda<0.2$. This type of scattering is termed Rayleigh scattering; for greater values of D/λ, the expression for σ becomes more complex (Mie scattering). For particles of raindrop size, D/λ is less than 0.2 for $\lambda \geq 3$ cm, since raindrops very seldom exceed 6 mm in diameter. Equation 10 is therefore appropriate for precipitation echoes. Since the total σ or total reflectivity for a particular radar is directly proportional to $\sum n_D D^6$, where n_D is the number of drops of diameter D, the rainfall rate is directly related to $\sum n_D D^6$, commonly called Z, the radar reflectivity factor. It is this parameter (z) that is used when relationships between rainfall and radar reflectivity are discussed.

When R-Z points are plotted on log R, log Z coordinates, the resulting plot is best fitted by a straight line of the form log Z = log A + b log R. This equation becomes Z = AR when antilogs are taken. This form is widely used to describe the relationship between rainfall rate and radar reflectivity. In the following discussion, Z is assumed to be the independent variable, since R values are to be determined from measures of Z.

Since the project was begun, many R-Z relationships have been determined using the drop camera. The procedure was as follows. Prom each drop-size distribution, representing 1 m^3, the rainfall rate and radar reflectivity were determined. The analysis of all samples collected at a particular location resulted in a general R-Z relationship for the area. A log-least-squares fitting procedure was used to determine the parameters of the R-Z equation.

A study was made concerning the possibility of fitting the R-Z points with a second order logarithmic equation, rather than linear[15]. However, it was found that the improvement was not significant enough to warrant changing the fitting equation from the simple linear relationship to the more cumbersome second order equation. R-Z relationships have been determined with the drop camera for a total of nine locations. The locations and the combined relationships are indicated in Table 2.

This extensive list of relationships rivals any other in existence today. Dr. M. Diem (also with Army support through the European Research Office) has collected the second most extensive set of drop-size data for which radar-rainfall relationships have been calculated. Diem has sampled rainfall in the European and African continents and has obtained some high latitude data from Axel Heiberg. Much of Diem's data is limited to low rainfall rates, since the filter paper technique has numerous limitations in moderate or high rainfall rates.

Sources of Error in Determining Rainfall Rates and Amounts with Radar

When the R-Z data points for a location are plotted and a regression line determined, a considerable amount of scatter of points around the line is observed. This means that for a particular Z there may exist several R values, making an R estimate subject to considerable error. One of the major factors contributing to this error is the variability of raindrop distributions, since it is possible for several different distributions to produce a particular Z value.

Table 2. R-Z Relationships for Drop Camera Locations

Location	R-Z Equation	No. of Cubic Meter Samples Analyzed
Miami, Florida	$Z = 286R^{1.43}$	2506
Island Beach, New Jersey	$Z = 256R^{1.41}$	3135
Franklin, North Carolina	$Z = 234R^{1.39}$	4742
Champaign, Illinois	$Z = 372R^{1.47}$	1211
Corvallis, Oregon	$Z = 301R^{1.64}$	1703
Woody Island, Alaska	$Z = 267R^{1.54}$	2686
Majuro Atoll, Marshall Islands	$Z = 221R^{1.32}$	2660
Bogor, Indonesia	$Z = 305R^{1.44}$	1872
Flagstaff, Arizona	$Z = 593R^{1.61}$	442

If the data could be separated into nearly constant drop-size spectra, then the scatter around the regression line would be considerably reduced. During the early period of the study, it was thought that the variations in drop-size distributions were related to different rain types such as rainshowers, thundershowers, and steady rain. If this were correct, then the R-Z regression line for each rain type would be unique and would have less scatter of points about the line. In 1953 and 1954, 1211-m^3 samples were collected with the drop camera in Illinois, the rain type associated with the precipitation was also noted. The R-Z relationships that resulted are as follows:

All Storms	$Z = 372\ R^{1.47}$	1211 obs.
Thundershowers	$Z = 435\ R^{1.48}$	515 obs.
Rainshowers	$Z = 370\ R^{1.31}$	314 obs.
Rain	$Z = 311\ R^{1.43}$	382 obs.

These were the first relationships determined for different rain types. Since 1954, several other groups in other countries have basically substantiated the differences in relationships for different rain types, although the magnitude of the differences vary considerably. The variability of the rainfall rate of the ungrouped data at $Z = 4 \times 10^2\ mm^6/m^3$ is from 0.5 to 2.1 mm/hr, and at $Z = 2 \times 10^5\ mm^6/m^3$ it is from 17 to 140 mm/hr.

Other means of stratifying the cubic meter samples were also attempted. Two that were found to be effective were synoptic stratification and thermodynamic instability. Thermodynamic instability was measured by the parcel method, which yielded a relative measure of the instability from radiosonde data. The synoptic stratification was accomplished by separating the samples according to the synoptic condition that produced the rain, as deduced from synoptic surface analysis. At Island Beach, New Jersey, and Coweeta, North Carolina, this means was found to be the most effective, while at Miami, Florida, the instability method was the most appropriate. Table 3 illustrates this.

Table 3. Comparison of Synoptic and Thermodynamic Instability Stratifications for Three Drop Camera Locations

Location	Standard Error of Estimate for All Synoptic Stratifications Combined	Standard Error of Estimate for All PASI Data Combined	Standard Error of Estimate for All Data, No Stratification
Island Beach, New Jersey	.153	.155	.163
Coweeta, North Carolina	.162	.165	.170
Miami, Florida	.171	.157	.198

Although these three means of stratification have succeeded in varying degrees in reducing the scatter around the regression line, the remaining amount of variability still leaves much to be desired. There may be considerably better separating criteria, but the amount and type of data taken in association with the drop data do not allow other criteria to be tested. For example, if some measure of the amount of coalescence occurring during precipitation were available, this might be a good predictor of changes in the drop-size distributions. However, microscale observations of this nature do not exist. It appears that one solution to the problem may be to have a continuous reading of the drop spectra during the storm, using Doppler radar concurrently with the reflectivity measurements of the echoes.

Extension of R-Z Relationships to New Areas

Since the locations chosen for the drop cameras included several general climates, an extrapolation of the R-Z relationships determined for these regions to other areas of the world with similar raindrop climates was possible. The basic problem in tnis undertaking was to identify the variables that were responsible for changes in the overall R-Z equations. Two parameters are found to be highly correlated with changes in the coefficient A and exponent b in the nine average R-Z equations determined with the drop camera[16]. These were: the mean annual percent of rain days that are thunderstorm days (TD), and the mean annual relative humidity at 0.5 km above the ground (RH). The regression equations for A and b are:

$$A = 1.3716\ (TD) - 4.7015\ (RH) + 571$$
$$b = -0.0002580\ (TD) - 0.004437\ (RH) + 1.7759$$

Therefore, in order to estimate the A and b values for a given location, the data for TD and RH must be obtained.

The standard error of estimate of A was found to be 55.3, and for b it was O.O87. The observed sample multiple correlation on A is 0.906, which is significant at the 99% significance level, while the observed sample multiple correlation on b is 0.700, which is significant at the 90% significance level. A comparison is made in Table 4 between R-Z relationships established by others at three locations with the filter paper technique, and the equations that are estimated with the method described above; the last five equations are estimates for the other locations where R-Z relationships have not been established as yet. Since the estimation procedure was derived from R-Z data taken with the drop camera, it is not completely valid to compare results with relationships obtained with another method. Tne two procedures (raindrop camera vs. filter paper) have not been compared in a field test situation as yet. It is hoped that additional raindrop data will be collected and R-Z equations determined for other areas so that an extensive evaluation of the prediction method may be made.

In summary, the major contributions have been to:

1. Establish average R-Z relationships for nine locations around the world.

2. Establish R-Z relationships for synoptic rain and thermodynamic instability types for most of the locations where drop data were collected.

3. Develop a method for estimating R-Z relationships for similar climatic areas of the world.

Table 4. Comparison of Existing and Predicted R-Z Equations for Three Sampled Locations

Location	Mean Annual Percent of Rain Days that are Thunderstorm Days	Mean Annual Relative Humidity at 0.5 km Above Ground	Measured R-Z Equation	Predicted R-Z Equation
Karlsruhe, Germany	16	78	$Z = 184R^{1.26}$	$Z = 225R^{1.43}$
Entebbe, British East Africa	100	73	$Z = 278R^{1.30}$	$Z = 360R^{1.42}$
Tucson, Arizona	74	38	$Z = 520R^{1.81}$	$Z = 494R^{1.59}$
Cristobal, Panama	34	80	---	$Z = 240R^{1.41}$
Montreal, Canada	22	68	---	$Z = 281R^{1.47}$
Saigon, South Vietnam	32	76	---	$Z = 257R^{1.43}$
Da Nang, South Vietnam	22	77	---	$Z = 239R^{1.43}$
Dong Hoi, North Vietnam	20	77	---	$Z = 237R^{1.43}$

RAINGAGE NETWORKS

Goose Creek and East Central Illinois Networks

The first ralngage network, consisting of 33 recording gages in 60 mi^2, was installed in 1951. The network was centered on the Goose Creek watershed, approximately 20 mi WNW of the radar site. All gages were equipped with 12.648-inch diameter collectors and chart drums making one revolution every 6 hours to facilitate making rainfall readings at 1-minute intervals. These rainfall data were used as a standard in correlation studies between surface rainfall observations and the precipitation echo presentations photographed on the 3-cm PPI.

In 1952, the Goose Creek Network was enlarged to include 50 gages in 100 mi (Figure 4). It remained so through 1953. Although reorganized somewhat in 1954, the area and gage density remained essentially the same. In order to obtain data over an area larger than 100 mi^2, the Goose Creek Network was reorganized and expanded north and west during the spring of 1955. The new network, known as the East Central Illinois, included an area of 400 mi^2 with 49 recording gages arranged in a nearly uniform grid pattern (Figure 5). This network remained in existence through 1967 with no major changes in gage locations. In 1968, the network was reorganized and enlarged to include 196 recording raingages over an area of 1760 mi^2.

Extensive studies to evaluate radar for the quantitative measurement of precipitation were carried out during the 1951-1954 period. Detailed results of these studies have been presented in several research reports[17,18,19]. Essentially, it was concluded that short wavelengths, such as 3-cm, are unsatisfactory for accurate point measurements of rainfall, principally because of attenuation effects. However, it was also evident that much more knowledge was needed with respect to the size distribution of raindrops in storms before routine utilization of any wavelength radar for rainfall measurements could become effective.

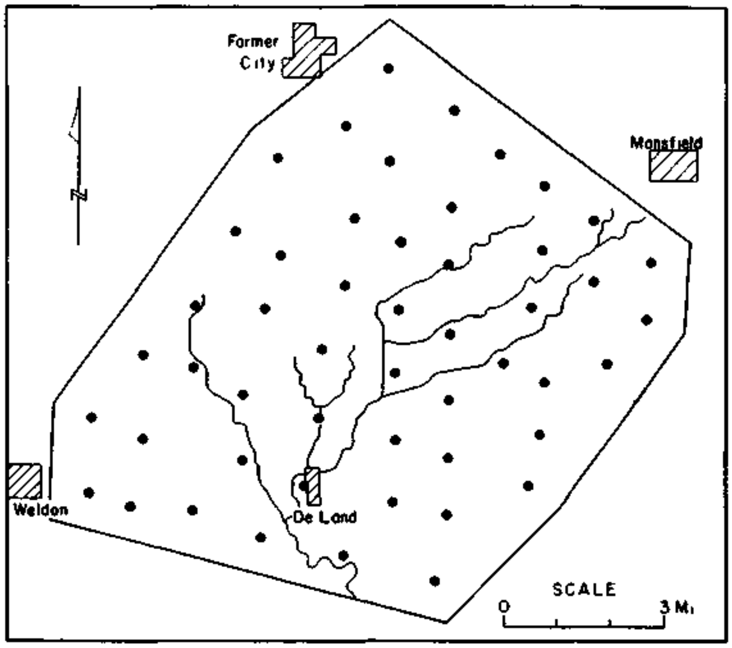

Figure 4. Goose Creek Network, 100 square miles, 1952

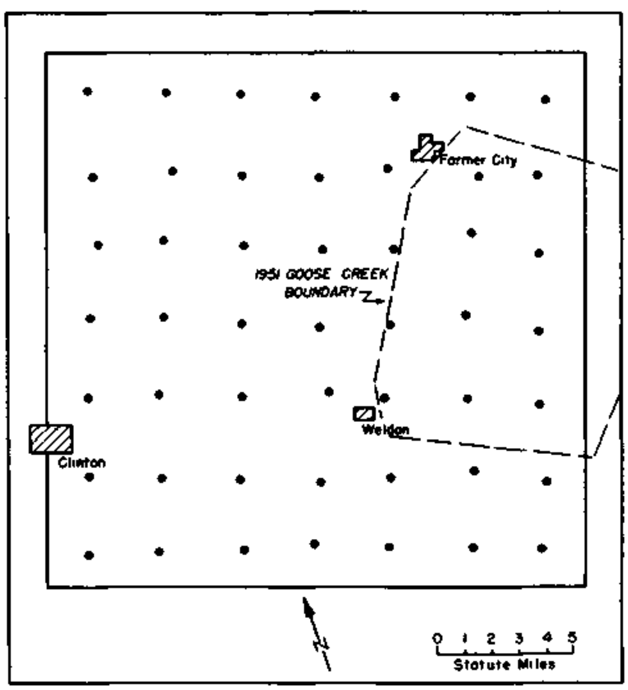

Figure 5. East Central Illinois Network, 400 square miles, 1955

As a result, an extensive study of raindrop distributions on a worldwide scale was undertaken.

Kankakee Network Study

In order to evaluate the usefulness of radar to measure rainfall at more distant ranges, the Kankakee Raingage Network was established near Kankakee, Illinois, in the spring of 1966 and was operated during the spring and summer seasons of 1966 and 1967. This network was located at a mean range of 64 nautical miles from the CPS-9 radar near Champaign. It consisted of 16 recording gages arranged in a nearly square grid of four rows, with gages spaced five miles apart to enclose an area of approximately 400 square statute miles.

The CPS-9 radar was operated both years to obtain step-gain photographs of precipitation echoes over the network. These photographs were traced and planimetered to obtain a radar measurement of the mean rainfall on the network area. Rainfall amounts for 30-minute periods were calculated. For the same time period, the network mean rainfall as measured by the raingages was tabulated.

The analysis of 33 rainstorms during the two seasons revealed that although many of the problems of measurement are accentuated, the overall results were not significantly different from the earlier measurements over the East Central Illinois Network at a mean range of 30 miles.

Other Applications of Network Data

The data from the Goose Creek and East Central Illinois networks have had widespread application in hydrometeorology and other types of meteorological research. Huff and Neill[20] used the data in a number of storm rainfall studies undertaken to provide information needed by the hydrologist in various applications, particularly the design of hydraulic structures such as dams, reservoirs, and drainage systems. These include total storm area-depth relations on areas up to 400 mi , the areal representativeness of point rainfall measurements, the variation of point rainfall with distance, and the evaluation of mean rainfall sampling errors based upon gage density, sampling area, and storm rainfall magnitude. This publication is required reading for students in hydrology. Recent installation of dense raingage networks for agricultural, hydrological, and weather modification studies depended heavily on Huff and Neill's results in the design of the networks and in the evaluation of their data. The East Central Illinois data were also used in a study of the frequency distribution of point and areal mean rainfall rates in convective storms[21]. This information is pertinent to both the hydrologist and the radar meteorologist or others concerned with precipitation attenuation.

Rainfall data from the networks were used in precipitation physics research on cloud electrification during the period 1960-1962[22]. Wilk[23] used the network facilities in a study of severe storms utilizing radar to determine radar's capability of recognizing such storms so that they could be avoided by aircraft. Network data were utilized by Changnon and Huff[24] in a study of radar-depicted precipitation lines that provided definitive information on their space and time characteristics. Changnon and Neill[25] have used the network data in conjunction with research on the relationship of corn and soybean yields with weather factors and have shown the comparative and interrelated effects of temperature and rainfall on yield. During the period 1962-1965, the network facilities were used in a study of the rainout of radioactivity in convective storms . This AEC project was concerned with the space and time characteristics of the rainout and with the sampling requirements to define storm rainout accurately. The results are the only available data of this nature in the literature.

More recently, the East Central Illinois data have been used in comprehensive studies of the time distribution of rainfall in heavy storms[27] and the spatial distribution of heavy storm rainfall[28]. These studies yielded much information pertinent to hydrologic design problems, as well as providing meteorological knowledge on the distribution characteristics of such storms. The East Central Illinois data, along with those from other Illinois networks, have been employed by Huff[29] in a study of the effect of natural rainfall variability in the verification of rain modification experiments and have provided valuable information on sampling needs in such studies. At the present time, the East Central Illinois Network data and facilities are being employed in two research projects sponsored by the National Science Foundation to evaluate the natural properties of hail and rainfall for application in the design, operation, and verification of weather modification experiments.

REFERENCES

1. Naito, Keikichi, and David Atlas. 1966. On microwave scatter by partially coherent clouds. Proceedings of the Twelfth Conference on Radar Meteorology, Norman, Oklahoma, 7-12.
2. Smith, Paul L., Jr. 1966. Interpretation of the fluctuating echo from randomly distributed scatteres: Part 3. Proceedings of the Twelfth Conference on Radar Meteorology, Norman, Oklahoma, 1-6.
3. Jones, D. M. A. 1959. The shape of raindrops. Journal of Meteorology v. 16(5):504-510.
4. Rogers, J. S., L. C. Johnson, D. M. A. Jones, and B. A. Jones, Jr. 1967. Sources of error in calculating the kinetic energy of rainfall. Journal of Soil and Water Conservation v. 22(4).
5. Fujiwara, M. 196l. Raindrop size distributions with rainfall types and weather conditions. Contract DA-36-039 SC-87280, 67 pp.
6. Levin, L. M. 1954. Size distribution function for cloud droplets and raindrops. Doklady Akad. Nauk. SSSR v. 94(6): 1045-1048. (Translated by Assoc. Tech. Services, Inc., East Orange, N. J.)
7. Matvejev, L. T. 1964. On the formation and development of layer clouds. Tellus v. l6(2):l46.
8. Irani, R. R., and C. F. Callis. 1963. Particle size: measurement, interpretation, and application. John Wiley and Sons, New York, 39-4l.
9. Mueller, E. A. 1964. A study of the radar precipitation attenuation as deduced from drop-size distributions. Proceedings of 1964 World Conference on Radio Meteorology incorporating Eleventh Weather Radar Conference, Boulder, Colorado, 194-197. (also Appendix B, Ill. State Water Survey Final Rept. to U. S. Army, Contract DA-36-039 SC-87280).

10. Mueller, E. A., and A. L. Sims. 1966. The influence of sampling volume on raindrop size spectra. Proceedings of Twelfth Conference on Radar Meteorology, Norman, Oklahoma, 135-138.

11. Billions, N. S. 1965. A study of raindrop size distributions and probability of occurrence. U. S. Army Missile Command, Redstone Arsenal, Report RR-TR-65-1.

12. Engelmann, R. J., R. W. Perkins, D. I. Hagen, and ¥. A. Haller. 1966. Washout coefficients for selected gases and particulates. Battelle Memorial Institute, Pacific Northwest Laboratories, Richland, Washington. Report BNWL-SA-657 to U. S. Atomic Energy Commission, Contract AT(45-l)-l830.

13. Hogg, D. C. 1968. Millimeter-wave communication through the atmosphere. Science v. 159(3810):39-46.

14. Crane, R. K. 1966. Microwave scattering parameters for New England rain. M. I. T. Lincoln Laboratory Tech. Rept. 426 to U. S. Air Force, Contract AP 19(628)-1567, 72 pp.

15. Jones, D. M. A. 1956. Rainfall drop size distribution and radar reflectivity. Ill. State Water Survey Research Rept. 6 to U. S. Army, Contract DA-36-039 SC-64723, 10-12.

16. Mueller, E. A., A. L. Sims, and R. Cataneo. 1967. Investigation of the quantitative determination of precipitation by radar. Ill. State Water Survey Interim Rept. 2 to U. S. Army, Contract DA-28-043 AMC-0207l(E), 10-17.

17. Stout, G. E., J. C. Neill, and G. W. Farnsworth. 1953. Rainfall-radar studies of 1951. Rept. of Investigation 19, Ill. State Water Survey.

18. Neill, J. C. 1953. Analysis of 1952 radar and raingage data. Rept. of Investigation 21, Ill. State Water Survey.

19. Huff, P. A., J. C. Neill, and M. Spock, Jr. 1956. Evaluation of a low-powered 3-cm radar for quantitative precipitation measurements. Research Rept. 4, U. S. Army Signal Corps Engineering Lab., Contract DA-36-039 SC-64723, Ill. State Water Survey.

20. Huff, F. A., and J. C. Neill. 1957. Rainfall relations on small areas in Illinois. Bulletin 44, Ill. State Water Survey.

21. Huff, F. A., and J. C. Neill. 1956. Frequency of points and areal mean rainfall rates. Trans. Am. Geophys. Union v. 37 (6).679-681.

22. Semonin, R. G., D. W. Staggs, and G. E. Stout. 1964. Cloud electrification studies in Illinois. Final Rept. to NSF under G-17038, Ill. State Water Survey.

23. Wilk, K. E. 1961. Radar investigations of Illinois hail-storms. Scientific Rept. 1, Contract AF 19(604)-4940, Ill. State Water Survey.

24. Changnon, S. A., Jr., and F. A. Huff. 1961. Studies of radar-depicted precipitation lines. Scientific Rept. 2, Contract AF 19(604)-4940, Ill. State Water Survey.

25. Changnon, S. A., Jr., and J. C. Neill. 1967. Areal variations in corn-weather relations in Illinois. Trans. Ill. Acad. Sci., v 60:221-230.

26. Huff, F. A., and G. E. Stout. 1964. Distribution of radioactive rainout in convective rainfall. Journal of Applied Meteorology v. 3(6):717.

27. Huff, F. A. 1967. Time distribution of rainfall in heavy storms. Water Resources Research v. 3(4):1007-1019.

28. Huff, F. A. 1968. Spatial distribution of heavy storm rainfalls in Illinois. Water Resources Research v. 4(1):47-54.

29. Huff, F. A. 1966. The effect of natural rainfall variability in verification of rain modification experiments. Water Resources Research v. 2(4):791-801.

APPENDIX A

PAPERS AND PUBLICATIONS

Journal Publications

Stout, G. E., and J. C. Neill. 1953. Utility of radar in measuring areal rainfall. Bull. Am. Met. Soc. v. 34(1):21-27.

Stout, G. E., and P. A. Huff. 1953. Radar records Illinois tornadogenesis. Bull. Am. Met. Soc. v. 34(6):281-284. (In greater detail as Ill. State Water Survey Rept. of Investigation 22, 1954).

Buswell, A. M., G. E. Stout, and J. C. Neill. 1954. Quantitative measurement of rainfall by radar. J. Am. Water Wks. Assoc. v. 46(9):837-852.

Stout, G. E., and H. W. Hiser. 1955. Radar scope interpretation of wind, hail, and heavy rain storms between May 27 and June 8, 1954. Bull. Am. Met. Soc. v. 36(10):519-527.

Mather, P. N., and E. A. Mueller. 1956. Radar back-scattering cross section for nonspherical targets. Trans. IRE Prop. Group, January.

Schuetz, J., and G. E. Stout. 1957. RHI radar observations of a tornado. Bull. Am. Met. Soc. v. 38(10):591-595.

Jones, D. M. A. 1959. The shape of raindrops. J. Met. v. 16 (5):504-510.

Stout, G. E. 1959. Radar for rainfall measurements and storm tracking. Proc. ASCE v. 85(HY l):l-l6.

Stout, G. E., R. H. Blackmer, and K. E. Wilk. 1960. Hail studies in Illinois relating to cloud physics. Monograph 5, AGU, Physics of Precipitation. pp. 369-383.

Stout, G. E., and K. E. Wilk. 1962. Influence of Lake Michigan on squall line rainfall. Univ. of Michigan. Inst. of Sci. and Tech., Great Lakes Res. Div. Pub. 9.

Fujiwara, M. 1965. Raindrop-size distribution from individual storms. J. At. Sci. v. 22(5):585-591.

Huff, P. A., and S. A. Changnon, Jr. 1966. Development and utilization of Illinois precipitation networks. IASH extract of pub. 67:97-125.

Huff, P. A. 1967. The adjustment of radar estimates of storm mean rainfall with rain gage data. J. Ap. Met. v. 6(l): 52-56.

Stout, G. E., and E. A. Mueller. 1968. Survey of relationships between rainfall rate and radar reflectivity in the measurement of precipitation. J. Ap. Met. v. 7(3):465-474.

Cataneo, R., and G. E. Stout. Raindrop-size distributions in humid continental climates, and associated rainfall rate-radar reflectivity relationships. Accepted for publication in the September 1968 J. Ap. Met.

Technical Papers

Presented at the 1952 Weather Radar Conference:

Jones, D. M. A. A raindrop camera and some preliminary results.

Stout, G. E., and J. C. Neill. Rainfall measurements by radar.

Stout, G. E. Raingage network observations.

Presented at the 1953 Weather Radar Conference:

Parnsworth, G. W., and E. A. Mueller. Radar-rainfall area integrator.

Jones, D. M. A., and L. A. Dean. Some observations from photographs of falling raindrops.

Neill, J. C. Variance of areal-mean thunderstorm rainfall.

Stout, G. E. Radar in single station analysis.

Presented at the 1955 Weather Radar Conference:

Stout, G. E., and M. Spock. A verified observation of angel-type echoes.

Huff, F. A., and G. E. Stout. Precipitation and cloud detection with CPS-9.

Mather, P. M., and E. A. Mueller. Radar back-scattering cross-section from non-spherical raindrops.

Jones, D. M. A. 3.2 cm and 10.7 cm wavelength radiation back-scatter from rain.

<u>Presented at the Sixth Weather Radar Conference, 1957</u>:

Schuetz, J. The relationship between maximum echo top and stability.

Mueller, E. A. Attenuation calculations from drop-size distributions.

Semonin, R. G. Radar-indicated rainfall estimates corrected for precipitation attenuation.

<u>Presented at the Seventh Weather Radar Conference, 1958</u>:

Mueller, E. A. Climatic variations in raindrop distributions.

Mueller, E. A. Recent observations of unusual echoes.

<u>Presented at the Eighth Weather Radar Conference, 1960</u>:

Jones, D. M. A., and E. A. Mueller. Drop size distributions in Florida.

Jones, D. M. A., and E. A. Mueller. Z-R relationships from drop size data.

Fujiwara, M. An analytical investigation of the variability of size distributions of raindrops in convective storms.

<u>Presented at the Ninth Weather Radar Conference, 1961</u>:

Pujiwara, M., and E. A. Mueller. Attractive forces between charged drops and their effect on the coalescence process.

Mueller, E. A. Uncertainty in rainfall measurements due to drop size distributions.

Johnson, R. M. Effects of stability on drop size distributions.

<u>Presented at the 1964 World Conference on Radio Meteorology Incorporating the Eleventh Weather Radar Conference</u>:

Mueller, E. A. A study of the radar precipitation attenuation as deduced from drop size distributions.

Sims, A. L. Case studies of the areal variations in raindrop size distributions.

<u>Presented at the Twelfth Conference on Radar Meteorology, 1966</u>:

Mueller, E. A., and A. L. Sims. The influence of sampling volume on raindrop size spectra.

<u>To Be Presented at the Thirteenth Radar Meteorology Conference, 1968</u>:

Cataneo, R. A method for estimating rainfall rate-radar reflectivity relationships.

Other Technical Papers

Stout, G. E., and P. A. Huff. CPS-9 radar observation of record rain storm in northern Illinois. Presented at the National Meeting, Am. Met. Soc, Washington, D. C, May 1953. (In detail as Ill. State Water Survey Rept. of Investigation 27, 1955).

Mueller, E. A., and G. E. Stout. Drop size distributions in Oregon. Presented at 187th National Meeting, Am. Met. Soc, Eugene, Oregon. (Appendix A, 9th Quarterly Tech. Rept., Contract DA-36-039 SC-75055). 1960.

Mueller, E. A. Digital computer as an aid in radar data reduction. Presented to and in the Proceedings of 3rd Conference on Severe Local Storms, Urbana, Illinois, November 1963.

Mueller, E. A., and A. L. Sims. Liquid water content of rain. Presented at the 5th Conference on Applied Meteorology, Atlantic City, New Jersey, March 1964, and at the 4th Annual National Conference on Environmental Effects on Aircraft and Propulsion Systems, Trenton, New Jersey, September 1964. (Appendix A, 9th Tech. Rept., Contract DA-36-039 SC-87280).

Cataneo, R. A comparison of raindrop spectra between Miami, Florida, and Corvallis, Oregon. Presented at the 60th Annual Meeting of the Illinois State Academy of Science, Charleston, Illinois, April 1967. (Appendix, Interim Rept. 1, Contract DA-28-043 AMC-0207l(E)).

Cataneo, R. A method for estimating rainfall rate-radar reflectivity relationships. Presented at the 6lst Annual Meeting of the Illinois Academy of Science, Edwardsville, Illinois, April 1968.

Contract Research Reports

No.

1. Stout, G. E., J. C. Neill, and G. W. Parnsworth. Rainfall-radar studies of 1951. Contract DA-36-039 SC-42446. 4l pp. May 1953.

2. Neill, J. C. Analysis of 1952 radar and raingage data. Contract DA-36-039 SC-42446. 22 pp. July 1953.

No.

3. Jones, D. M. A., and L. A. Dean. A raindrop camera. Contract DA-36-039 SC-42446. 19 pp. Dec. 1953.

4. Huff, P. A., J. C. Neill, and M. Spock, Jr. Evaluation of a low-powered 3-cm radar for quantitative rainfall measurements. Contract DA-36-039 SC-64723. 35 pp. 1956. (Same as Rept. of Investigation 29)

5. Farnsworth, G. W., and E. A. Mueller. The theory and operations of the area integrator. Contract DA-36-039 SC-64723. 31 pp. Jan. 1956.

6. Jones, D. M. A. Rainfall drop size-distribution and radar reflectivity. Contract DA-36-039 SC-64723. 20 pp. Apr. 1956.

7. Mueller, E. A. An evaluation of the area integrator. Contract DA-36-039 SC-75055. 34 pp. Dec. 1958.

8. Fujiwara, M. Raindrop size distributions with rainfall types and weather conditions. Contract DA-36-039 SC-87280. 67 pp. 1961.

9b. Mueller, E. A. Raindrop distributions at Miami, Florida. Contract DA-36-039 SC-87280. 28l pp. June 1962.

RR1. Mueller, E. A., and A. L. Sims. Raindrop distributions at Majuro Atoll, Marshall Islands. Contract DA-28-043 AMC-02071(E). 93 pp. March 1967.

RR2. Mueller, E. A., and A. L. Sims. Raindrop distributions at Island Beach, New Jersey. Contract DA-28-043 AMC-0207l(E). 108 pp. Sept. 1967.

RR3. Mueller, E. A., and A. L. Sims. Raindrop distributions at Franklin, North Carolina. Contract DA-28-043 AMC-0207l(E). 157 pp. Sept. 1967.

RR4. Mueller, E. A., and A. L. Sims. Raindrop distributions at Woody Island, Alaska. Contract DA-28-043 AMC-0207l(E). 93 PP. Nov. 1967.

RR5. Mueller, E. A., and A. L. Sims. Raindrop distributions at Bogor, Indonesia. Contract DA-043 AMC-0207l(E). 72 pp. Jan. 1968.

RR6. Mueller, E. A., and A. L. Sims. Raindrop distributions at Corvallis, Oregon. Contract DA-043 AMC-0207l(E). 69 pp. Feb. 1968.

Reports Which Utilized Army-Supplied Facilities But Were Supported By Other Agencies

Hudson, H. E., Jr., G. E. Stout, and P. A. Huff. Studies of thunderstorm rainfall with dense rain-gage networks and radar. Ill. State Water Survey Rept. of Investigation 13. 30 pp. 1952.

Hiser, H. W., and S. G. Bigler. Wind data from radar echoes. Tech. Rept. 1. Contract Nl89s-88l64. 18 pp. Mar. 1953.

Kurtyka, J. C. Precipitation measurements study, bibliography. Under Contract DA-36-039 SC-794C-0. 178 pp. 1953.

Huff, P. A., H. W. Hiser, and S. G. Bigler. Study of an Illinois tornado using radar, synoptic weather and field survey data. 73 PP. 1954.

Huff, P. A., H. W. Hiser, and G. E. Stout. The October 1954 storm in northern Illinois. 23 pp. 1955.

Mathur, P., and E. A. Mueller. Radar back-scattering from non-spherical scatterers. 85 pp. 1955.

Huff, P. A., and J. C. Neill. Rainfall relations on small areas in Illinois. Ill. State Water Survey Bulletin 46. 54 pp. 1957.

Pearson, J. E., and G. E. Martin. An evaluation of raindrop sizing and counting techniques. Scientific Rept. 1. Contract AP19(604)-1900. 116 pp. Nov. 1957.

Wilk, K. E. Evaluation of the AN/APQ-39(XA-3) cloud detector radar. Pinal Rept. Contract AF19(604)-1395. 39 pp. Mar. 1955-Mar. 1958.

Wilk, K. E. Radar investigations of Illinois hailstorms. Scientific Rept. 1. Contract AP19(604)-4940. 42 pp. Jan. 1961.

Changnon, S. A., Jr., and P. A. Huff. Studies of radar-depicted precipitation lines. Scientific Rept. 2. Contract AP 19(604)-4940. 63 pp. 15 Feb. 1961.

Wilk, K. E. Research concerning analysis of severe thunderstorms. Pinal Rept. Contract AF19(604)-4940. 68 pp. Dec. 1961.

Semonin, R. G., D. W. Staggs, and G. E. Stout. Cloud electrification studies in Illinois. Pinal Rept. National Science Foundation G-17038. 76 pp. 1964.

Changnon, S. A., Jr., and P. A. Huff. Feasibility study of quantitative radar measurement of precipitation on Lake Michigan. Pinal Rept. Univ. of Ill. Water Resources Center. Contract 6666-04G (26-84). 18 pp. June 20, 1966.

Mueller, E. A. Radar cross sections from drop size spectra. Thesis for Ph.D. degree in Electrical Engineering, Univ. of Ill., 1966.

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1 ORIGINATING ACTIVITY (Corporate author) Illinois State Water Survey University of Illinois Urbana, Illinois 6l802	2a. REPORT SECURITY CLASSIFICATION UNCLASSIFIED 2b GROUP N/A

3 REPORT TITLE

Summary of Radar-Rainfall Research 1952-1968

4 DESCRIPTIVE NOTES (Type of report and inclusive dates)

Interim Report No. 3

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6 REPORT DATE	7a TOTAL NO OF PAGES	7b NO OF REFS
October 1968	47	29

8a CONTRACT OR GRANT NO DA-28-043 AMC-0207l(E) b PROJECT NO ITO-14501-B-53A-07 c d	9a ORIGINATOR'S REPORT NUMBER(S) 9b OTHER REPORT NO(S) (Any other numbers that may be assigned this report) ECOM-02071-3

10 DISTRIBUTION STATEMENT

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11 SUPPLEMENTARY NOTES	12 SPONSORING MILITARY ACTIVITY
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13 ABSTRACT

A summary of research activities and their highlights during the past sixteen years has been prepared in order to focus on the state of knowledge concerning the measurement of rainfall with 3-cm radar. Much effort has been expended on determining the raindrop size distributions for many climatic areas. In order to evaluate the radar, dense networks of rain gages were employed. The availability of the radar and a dense network of raingages has resulted in numerous applications of these facilities for related studies in hydrometeorology, cloud physics and weather modification experiments. In summary, a well calibrated radar is capable of measuring rainfall which is equivalent to about one gage in 60 square miles, detects severe stroms, etc., but its utilization is limited due to lack of instrumentation to properly process the large amount of data that becomes available to the user and to the meteorological variance between storms.

14 KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Meteorology- Weather radar precipitation raindrop size distribution rainfall rate radar-rainfall water shed						