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Illinois State Water Survey

Meteorologic Laboratory

at the

University of Illinois

Urbana, Illinois

RAINFALL-RADAR STUDIES OF 1951

by

G. E. Stout, J. C. Neill and G. W. Farnsworth

(This report is being reprinted as
the Illinois State Water Survey
Report of Investigation No. 19)

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Fort Monmouth, New Jersey

Department of the Army Project: 3-99-07-022
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May 1953

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SUMMARY

This report has been divided into the following principal parts: (1) Equipment and Methods, (2) Analysis of Data and Discussion, (3) Limiting-Factors, and (4) Rainfall Summary. Each of these parts is summarized briefly in order.

1. Equipment and Methods. Two radar sets, an AN/APS-15A (3-cm) and a TPL-1 (10-cm) were used to obtain observations of precipitation echoes on their PPI (plan position indicator). Effort was directed chiefly toward observations of thunderstorm type rainfall.

An automatic receiver-sensitivity control system was developed for use on the 3-cm radar set. A movie camera was installed to photograph the PPI and to work in synchronization with the receiver-sensitivity control mechanism. This technique has proven to be a satisfactory method of obtaining a record of rain. rain-intensity contours and it can be adapted to almost any radar equipment. Resolution of 35-mm cameras and film has proven better than 16-mm, making the 35-mm more desirable where fine detail of the storm is desired.

Close observation of the PPI on the 3-cm set indicated that apparent attenuation was being introduced by the radar circuits. Tests indicated that the reduction in sensitivity was occurring within the video circuits. Increasing all the video coupling condensers from .01 to 0.1 mfd, almost completely eliminated the sensitivity reduction.

A dense network of 33 recording rain gages was installed on a watershed between 15 and 22 nautical miles west-northwest of the radar site. All recording rain gages were equipped with 12.648-inch diameter collectors and chart drums making one revolution every six hours to facilitate making rainfall readings at one-minute intervals. Rainfall data collected by the network was used as a standard in correlation studies between surface rainfall observations and the precipitation echo presentations photographed on the PPI.

2. Analysis* of Data and Discussion. One-minute isohyetal maps were prepared from the recording raingage data. Areal rainfall patterns were compared with the corresponding isoecho contour patterns prepared from the PPI film records. In the absence of severe attenuation these short-interval precipitation distribution patterns were very similar.

Comparisons between rainfall rates measured by

*All comparisons between radar and raingage data are based on 3-cm radar data.

rain gages at a point and rates computed from radar data were made. The computed rates deviated considerably from the raingage measured rates. Several factors are instrumental in producing the magnitude of these deviations. Drift of the raindrops while falling from the volume observed by the radar in the atmosphere, attenuation due to intervening raindrops, and variation in raindrop-size distribution are among the most important factors.

Total storm rainfall amounts were computed for raingage locations from radar data which was observed directly over the raingage positions during one storm. Many of the differences between the radar point rainfall amounts and the raingage rainfall amounts were large. However, the average of each set of rainfall amounts were almost the same, i.e., the radar estimated the mean rainfall for the network as accurately as the rain gages for the storm studied.

A total storm isohyetal map was prepared from the radar point rainfall totals. This areal rainfall distribution pattern was similar to the isohyetal map prepared from raingage data. This is an indication that observations by a calibrated radar may be an aid in preparing isohyetal maps for areas where rain gages are widely spaced.

Because of the difficulties in correlating point rainfall measurements with point radar observations, an areal comparison between rainfall amounts computed from radar and raingage data was tried. Mean storm rainfall for the raingage network was computed from both radar and raingage data for four storm periods. For this study the measurement of areal thunderstorm rainfall by radar was, in the least satisfactory case, as accurate as normally expected from one rain gage per 300 square miles, while in the other cases, it was considerably more accurate.

Movement of precipitation echoes during one storm period were studied in relation to corresponding rainfall cores on the network. In most cases the movement of echo cores in the atmosphere could be traced on the ground by drawing isohyetal patterns. Evidence was found which indicated that precipitation echo cores moved approximately in accordance with the resultant of two vectors; the frontal movement and the wind from 6000 to 8000 feet in altitude ahead of the front.

3. Limiting factors. Some factors limiting the utility of the present radar equipment for quantitative rainfall measurements are discussed. These include the effect of beam width, attenuation due to intervening rainfall, the effect of drop-size distribution upon reflectivity, and instability of the radar with re-

spect to transmitted power and receiver sensitivity. Very accurate measurement of the electrical characteristics of a radar set are needed. One decibel change in either transmitter power or receiver sensitivity will produce approximately a 12 percent change in calculated rainfall intensity. Some computations were made to determine the magnitude of attenuation due to intervening rainfall. Two-way attenuation greater than 5 decibels per mile occurred frequently. Computations using Hood's, and Laws and Parsons' drop-size data indicate that, for an actual rainfall

rate of 1-mm/hr, an accurately calibrated radar could indicate rainfall intensities from 0.48 to 2.30 mm/hr.

4. Rainfall Summary. A rainfall summary is tabulated for May through October 1951 over Goose Creek network. This summary includes storm, monthly, and seasonal totals for each gage; maximum, minimum, and average rainfall for each storm period; and a detailed tabulation of high rainfall rates for four storm periods.

ACKNOWLEDGMENTS

The authors wish to acknowledge the efforts of Homer Hiser and D. M. A. Jones who assisted with collection of the data and carried out much of the area depth work which was originally published in the 1951 Radar Weather Conference Proceedings, Bulletin No. 41, Illinois State Water Survey, 1952. The work covered by this report was performed under the supervision of A. M. Buswell, Chief, and directed by H. E. Hudson, Jr., Head of the Engineering Sub Division. Floyd A. Huff assisted with the final editing. Principal research assistants who have assisted in the collection of the data and in the analysis were James A. West, Jack C. Fatz, George D. Hack, Kenneth Faulk, Donald Whitnah and Ann J. Hallman. Drafting was done by Stanley A. Changnon, Jr.

Consultants in this program were Dr. H. R. Byers, Head of the Department of Meteorology, University of Chicago and W. A. Albright, Assistant Professor of Electrical Engineering, University of Illinois.

The Water Survey is happy to acknowledge very material assistance in the analysis and organization of the 1951 data through support from the Signal Corps Engineering Laboratories under Contract No. DA-36-039 SC 42446. Credit is also due to Dr. Donald M. Swingle of the above Laboratory who reviewed the entire manuscript and made several helpful suggestions.

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Introduction

The measurement of precipitation is an important phase of any water resources program. Present rain-gaging techniques do not provide the accuracy needed by engineers and meteorologists in determining the intensity and areal distribution of storm rainfall. This is especially true for the highly variable shower-type precipitation which accounts for a major portion of the annual rainfall in Illinois and is responsible for flash floods on small watersheds.

According to Braham (1), the average area of a thunderstorm cell is approximately 8 square miles. This corresponds to a diameter of about 3 miles for a circular cell. Because of the small areal size of these cells, the present Illinois climatological network of approximately one rain gage every 225 square miles does not accurately sample thunderstorm rainfall. This is illustrated in Figure 1, which shows a comparison of the rainfall pattern obtained from a dense network having one gage per 2.4 square miles with that indicated by the Illinois climatological network. The patterns show the resultant or total storm rainfall distribution for a 24-hour period, during which at least 12 thunderstorm cells contributed to the total at many of the gages in the 95-square-mile area under consideration.

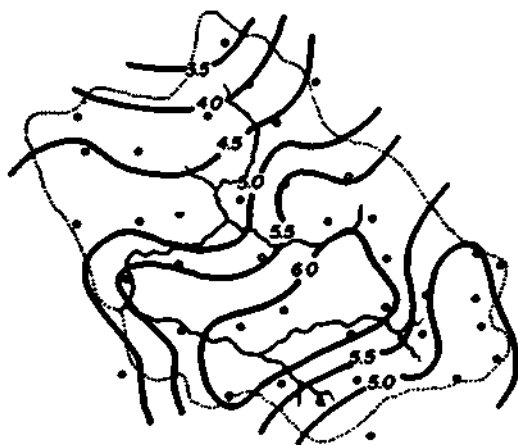
During World War II, it was established that radar equipment could be used to locate and track areas of precipitation. This discovery led to investigations to determine the ability of radar to ascertain rainfall distribution over an area.

Realizing the inability of ordinary climatological networks to provide sufficiently detailed information on the distribution of thunderstorm rainfall, and the pro-

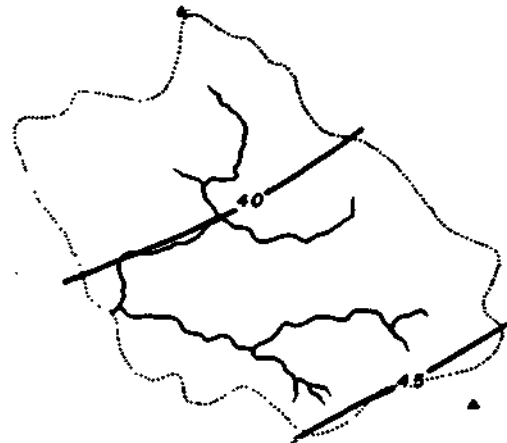
hibitive costs involved in establishing satisfactory rain-gage networks for this purpose over large areas, the Illinois State Water Survey initiated an investigation in 1948 to determine the ability of radar to provide quantitative rainfall measurements needed by engineers and hydro-meteorologists in the accomplishment of water resource programs. Initial emphasis was to be placed on determining radar's ability to accurately detect, track, and indicate the areal extent of shower-type precipitation. Subsequent efforts were to be concentrated on developing methods for quantitatively measuring rainfall by radar if the preliminary phase of the investigation proved successful. This report briefly summarizes radar-rainfall studies through early 1952, but is chiefly concerned with progress made in 1951 in the use of radar for quantitative measurement of rainfall.

HISTORICAL BACKGROUND

During the spring of 1948, the Illinois State Water Survey began an investigation in cooperation with the Pfister Hybrid Corn Company, El Paso, Illinois, to determine the utility of radar in detecting, tracking, and measuring the areal extent of shower-type rainfall. A war surplus AN/APS-15A, 3-cm radar set, was purchased, and a network of 35 stick and 12 recording rain gages was installed over an area of approximately 280 square miles in the vicinity of El Paso. The radar set and raingage network were also to be utilized in evaluating induced-precipitation on experiments contemplated by the Pfister Hybrid Corn Company. Due to the abundance of the natural rainfall occurring during



2.4 sq. mi. per gage



U. S. Weather Bureau Climatological Network, 225 sq. mi. per gage

FIG. 1 EFFECT OF GAGE DENSITY ON ISOHYETAL PATTERN, STORM OF JULY 16-17, 1950

the growing season these experiments did not materialize. Details of this study are discussed in Report of Investigation No. 3 Illinois State Water Survey, 1949.

Operations during the thunderstorm seasons of 1948 and 1949 emphasized the inability of ordinary climatological networks to accurately measure shower-type rainfall. Radar, however, had proven successful in detecting, tracking, and indicating the areal extent of precipitation in showers and thunderstorms during this period. Since investigation by agencies of the Armed Forces and others indicated that radar could be adapted to the quantitative measurement of rainfall, it was decided to continue the radar program and concentrate efforts on the development of methods and techniques for quantitative determinations of rainfall.

With the advent of the 1950 thunderstorm season, the investigation of the utility of radar for the quantitative measurement of rainfall was initiated. A concentrated network of 31 recording rain gages was installed over an area of approximately 70 square miles in the vicinity of the Farm Creek watershed between 15 and 22 nautical miles west of El Paso. Most of these rain gages had collectors of 12.648-inch diameter and were provided with six-hour charts so that detailed rainfall data could be obtained. Another rain-gage network consisting of 25 recording and 17 stick gages was maintained in conjunction with a detailed hydrologic study on the 95-square-mile Panther Creek watershed to the north and east of El Paso. A second radar set (AN/TPL-1, 10-cm) was obtained from the University of Illinois to supplement observations with the AN/APS-15 A, * 3-cm set, and to determine whether 3-cm or 10-cm radar was best suited for quantitative rainfall measurements.

Operational results during the summer of the 1950 were encouraging although data collection was limited due to necessary modifications of the radar equipment for quantitative analysis and to late delivery of the rain gages equipped with large collectors and six-hour

*In the remainder of this report the AN/APS-15A and the AN/TPL-1 will be referred to as APS-15 and TPL-1, respectively.

charts. Data from the Panther Creek hydrologic network were only occasionally applicable since standard recording rain gages were used and most of the watershed was in the "ground clutter" region of the radar sets. A complete summary of the 1948, 1949, and 1950 studies have been published in Report of Investigation No. 13, Illinois State Water Survey, 1952.

During the spring of 1951, radar equipment was installed at the University of Illinois Airport near Champaign-Urbana to improve and facilitate operations. A concentrated network of 34 recording rain-gages with 12.648-inch diameter openings and six-hour charts was installed over an area of 50 square miles on the Goose Creek watershed in the vicinity of DeLand. The center of this network was approximately 18 nautical miles from the radar installation. A network of 25 recording rain gages was maintained in the Panther Creek area in conjunction with the detailed hydrologic study and to supplement radar observations from the Goose Creek network.

CONCLUSIONS

1. Photographing the PPI presentations with a 35-mm movie camera operating in synchronization with an automatic receiver sensitivity control has proven to be a reliable technique for obtaining a record of radar-rain intensity contours.
2. The technique of obtaining radar-rain intensity contours can be adapted to almost any radar equipment.
3. In the absence of severe attenuation, areal precipitation distribution patterns displayed by isoechoand isohyetal maps were very similar.
4. Results indicated that point storm rainfall amounts computed from radar data may be expected to deviate considerably from corresponding raingage measurements. On the other hand, radar measurement of areal mean rainfall, in thunderstorms was in all cases as accurate as that normally expected from one rain gage per 300 square miles, while in most cases it was considerably more accurate.
5. Further investigation of the size distribution of falling raindrops is needed to improve the accuracy of radar-rainfall intensity measurements.

Equipment and Methods

Raingage Measurement of Rainfall

Raingage Network

The raingage network of 34 Bendix-Friez Dual Traverse Model 775-BS rain gages was located on the Goose Creek watershed between 15 and 22 nautical miles west-northwest of the airport radar station, Figure 2. The gages were installed on radials which were $3 \frac{1}{2}$ degrees apart with their origin at the radar station. A stream-gaging station was installed on Goose Creek in order to utilize the raingage records in runoff studies.

Rain Gages

Thirty-two of the rain gages were equipped with 12.648-inch diameter collectors and with chart drums making one revolution every six hours. One gage was equipped with a 24-hour chart in order to orient those rains recorded by the other gages, with respect to time. The 24-hour chart was an aid in determining the time of a rainfall period since a six-hour chart often revolved several times before and after each rain. After the pen had traced completely around the chart at the same level more than once, it became difficult, if not impossible, to determine how many six-hour periods had elapsed, and therefore difficult to determine the time rain occurred. On 31 July 1951, a second gage was installed at Station 31 near the center of the network. This gage had an extra sheet-metal collector

with a diameter of 17.87 inches placed on top of its regular collector. This top increased the rain collecting area of the gage to twice that of the 12.648-inch collector and to five times that of the standard 8-inch collector. The increased area allowed a direct reading of 0.01 inch of rainfall for each vertical division of the raingage chart. Records from this gage were not used in the analysis as discussed later.

An example of a raingage trace as recorded at gage location No. 4 on the Goose Creek network during the storm of 12 September 1951, is shown in Figure 3. This trace for a 12.648-inch collector was made on a chart drive making one revolution every six hours. On this chart each space between horizontal lines represents 0.02 inch of rain and each space between lines on the time scale represents five minutes. Thus, 0.98-inch of rain fell in 2 hours and 35 minutes. The rainfall trace shown by gage No. 3, Figure 4, is an example from a storm of short duration and high rainfall rate. The largest amount of rain which fell over a one-minute period was 0.09 inch. This amount is equivalent to a rainfall rate of 5.4 inches per hour. Both of these raingage observations show considerable variability in the rainfall rates within storms.

The characteristics and performance of the Model 775-BS raingage have been studied on a preliminary basis by R. E. Roberts (2), who reported that the instrument's charts may be trusted to report rainfall rates with an accuracy of 0.05 inch per hour if the rate is

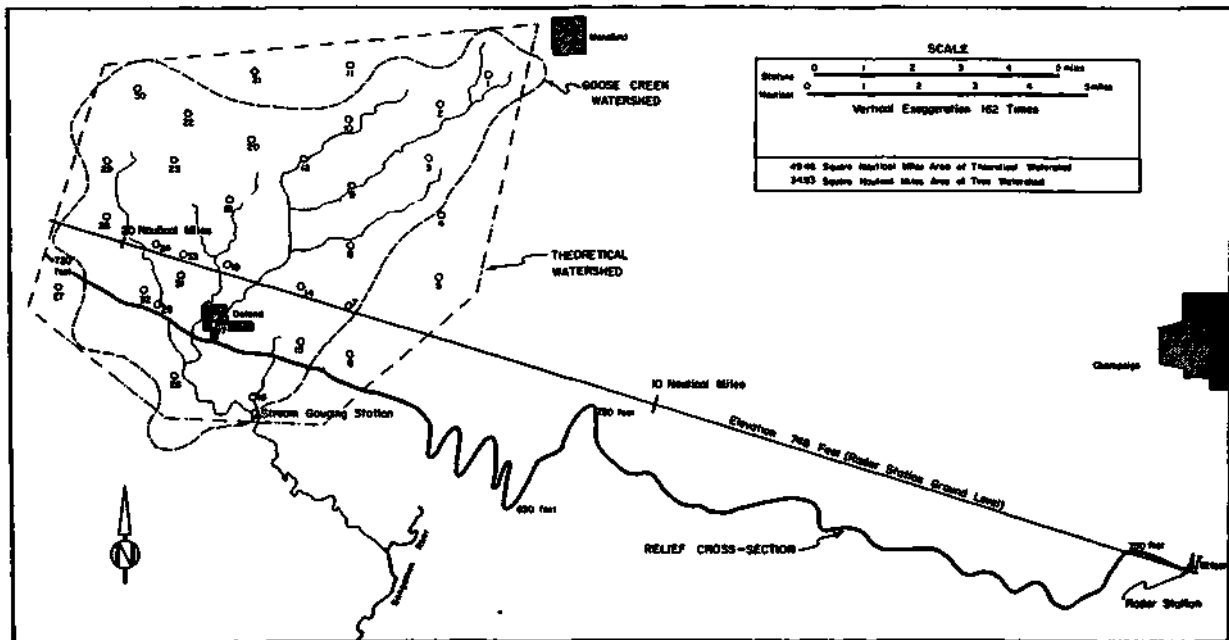


FIG. 2 MAP SHOWING AIRPORT RADAR STATION AND GOOSE CREEK RAIN GAGE NETWORK

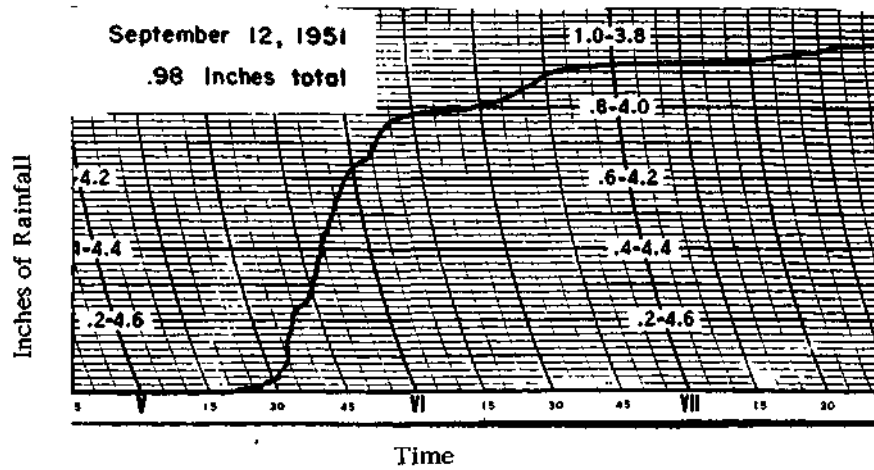


FIG. 3 RAINGAGE RAINFALL RECORD AT STATION 4 ON GOOSE CREEK NETWORK DURING STORM OF 12 SEPTEMBER 1951

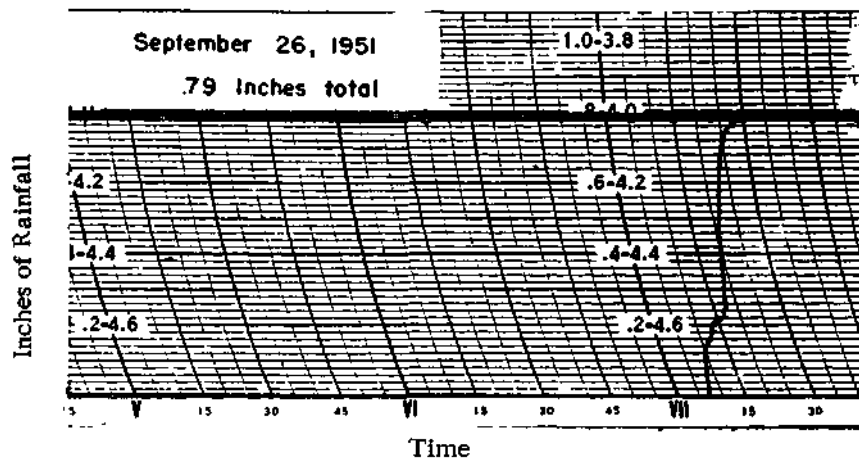


FIG. 4 RAINGAGE RAINFALL RECORD AT STATION 3 ON GOOSE CREEK NETWORK DURING STORM OF 26 SEPTEMBER 1951

constant for five minutes or longer. The lag in time for recording the beginning and ending of rainfall and for a change of rate during rainfall was checked. It was found that for the beginning of rainfall the lag varied from two minutes at about 0.23 inch per hour to nearly zero for rates of about one inch per hour. Lag at the end of a rainfall was determined to vary from nearly zero at low rates to two minutes for rates over one inch per hour. Lag between changes of rate during a rain was found to be hidden by the thickness of the trace line.

In the region of maximum sensitivity of the rain-gage spring, it was noticed that drops which struck the bottom of the rain-gage bucket produced a slight bounce of the pen arm. This slight movement caused a pronounced broadening of the trace line. In many cases, this broadening of the trace line was associated with the beginning of a rain before a sufficient quantity had fallen to register as a rising trace on the chart.

Radar Observations of Rainfall

Radar Equipment

During the 1951 thunderstorm season the Water Survey had three radar sets available; a TPL-1, 10-cm searchlight-tracking radar, and two APS-15, 3-cm, airborne radar sets. These radar sets were modified to fit the particular needs of the project. The TPL-1 and one APS-15 were located on the eastern edge of the University of Illinois Airport with the radiator of the TPL-1 seven feet from the ground as shown in Figure 5. Power requirements for the radar plus the proximity of the radars to the airport runways limited the heights to which the antenna could be elevated. Although the TPL-1 radiator was very close to the ground, it was located on the west side of the building at the radar station (Figure 5), and there were no serious obstructions which prevented scanning in the direction of the Goose Creek network to the north and west (Figure 2).

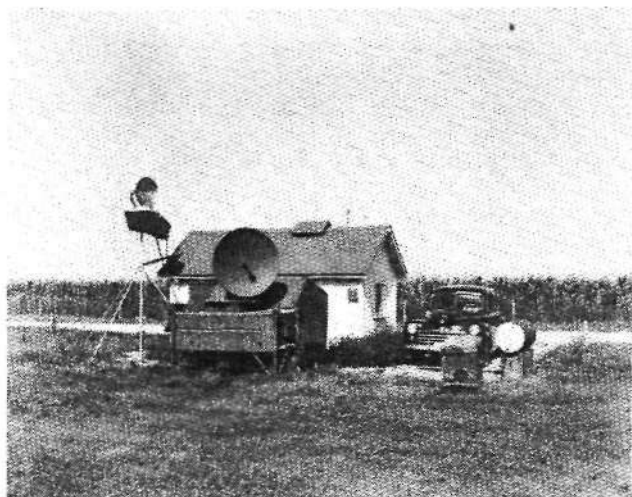


FIG. 5 RADAR STATION AT THE UNIVERSITY OF ILLINOIS AIRPORT, 1951

The other APS-15 was mounted with its antenna under a radome 70 feet above the ground on the roof of the Pfister Hybrid Corn Company factory building in El Paso, Illinois, 53 nautical miles northwest of the airport radar station. It had been hoped that a well defined storm could be detected from both radar locations at a time when the storm was over the Goose Creek raingage network, but limited personnel curtailed operation of the El Paso equipment.

Modification of Video Circuits

The use of the APS-15 for quantitative rainfall measurements has been greatly improved by modification of its video circuits. Close observation of the PPI (plan position indicator) scope disclosed that apparent attenuation was being introduced by the radar circuits. This action may be characteristic of war surplus radar sets other than the APS-15.

Figure 6 is a picture of the Water Survey APS-15 scope on 8 July 1951, with the original circuits. The range is 100 miles. The "grass" level on the upper half of the scope is considerably reduced, particularly in the area immediately to the rear of the storm. The small echo, 17 nautical miles southwest (toward lower left corner) has introduced a very pronounced shadow and dimming of the 20 and 30 mile markers. Figure 7 is the same scope on 30-mile range. The range markers are the third and fourth circles, the other three being signals from a 3-cm signal generator. Both the test signal and range markers are almost invisible where rain is intervening.

Tests carried out indicated that the reduction in sensitivity was occurring entirely within the video circuits. The main reduction occurred in the input to the first video amplifier. The high amplitude, long-duration signals, caused some grid current to flow, which charged the coupling condenser. The discharge drove the grid toward cut-off, causing a temporary loss of low-amplitude signals. Increasing all the video coupling condensers from .01 to 0.1 mfd, almost complete -

ly eliminated the sensitivity reduction. Inserting a germanium diode has also been recommended. Figure 8 is a picture of the scope taken on 28 July with the modified circuit. Isolated storms caused no reduction in the "grass" level. A solid line of rain from the station out to 30 miles to the southwest caused a slight reduction in "grass" level. Increasing the value of the coupling condensers even more would probably reduce this effect.

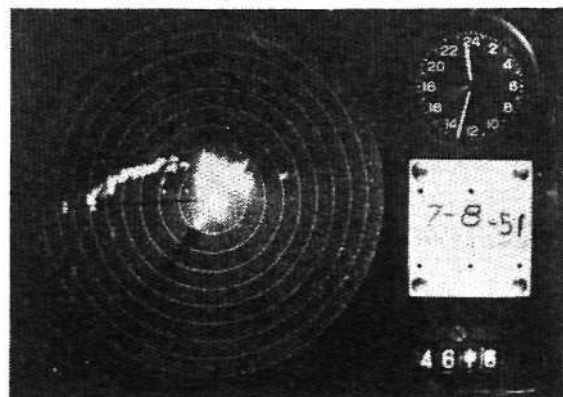


FIG. 6 PHOTOGRAPH OF THE APS-15 PPI SCOPE ON 8 JULY 1951 ON 100 MILE RANGE WITH THE ORIGINAL CIRCUITS



FIG. 7 PHOTOGRAPH OF THE APS-15 PPI SCOPE ON 8 JULY 1951 ON 30 MILE RANGE WITH THE ORIGINAL CIRCUITS

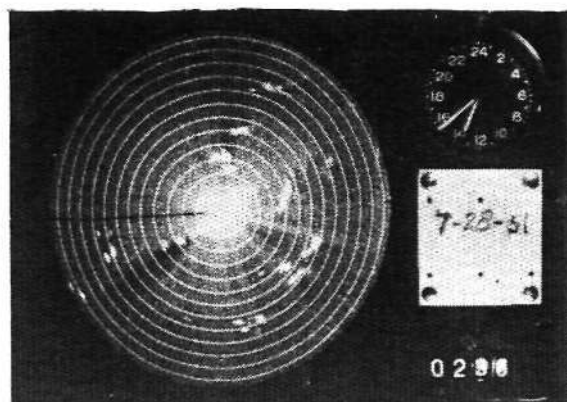


FIG. 8 PHOTOGRAPH OF APS-15 PPI SCOPE ON 28 JULY 1951 AFTER MODIFICATION OF THE CIRCUITS

Radar Rain-Intensity Contour Recorder

Each of the three radar sets was equipped with an automatic system for changing the receiver sensitivity in a stepwise fashion. An automatic film recording system was synchronized with the receiver sensitivity control. When used with a radar plan position indicator, a continuous, detailed record of storms within range of the radar was obtained. The film record provided information on storm development or dissipation, movement, duration, maximum rainfall intensities, and total rainfall amounts.

Radar-Rainfall Relations

Raindrops act as scatterers of the radar beam. Each individual drop reflects a portion, of the radiated pulse back to the radar (3) (4). Rainfall is a function of the size and number of drops. It has been shown that subject to a number of restrictions and assumptions, the received power (P_r) is directly proportional to the rain intensity (I) to the n th power and inversely proportional to the distance (R) squared (8) (9) (10) (11) (12) (13).

$$P_r = f(I^n ; R^{-2})$$

The equation for the relationship between rainfall intensities and radar parameters is given in the section on Radar Calibration.

The relationship of received power to rainfall intensity is illustrated in Figure 9-a, which represents a hypothetical storm five miles in diameter with the nearest edge 15 miles from a radar. Each oval represents a contour of rain intensity, with the core of heaviest rain in the center. When the radar antenna is directed toward the center of the storm, Figure 9-b is the representative wave form of received power. The horizontal axis represents distance and the vertical axis indicates received power (neglecting the effect of range). This wave form would be observed on the "A" scope.

When operating a radar set, it is necessary to maintain the receiver sensitivity at a high level so that light rain can be detected. The receiver i-f and video amplifier stages are driven to saturation, obscuring the relative rain intensities and cores of heavy rain. Additional distortion is introduced on the plan-position-indicator (PPI) because of the narrow range of brilliance between threshold of visibility and maximum brilliance (saturation). As shown in Figure 9-c, only the base of the received-power wave form is observed on the PPI with the receiver gain set for maximum sensitivity. The area of the storm is seen on the PPI when the receiver is set for maximum sensitivity (step 1). The core of heaviest rain cannot be distinguished on the PPI since the power returned from the heavy rain intensities saturate the circuits. When the receiver sensitivity is reduced to the next fixed setting (step 2), greater received power is necessary to reach the threshold of visibility. Therefore, it is necessary for the rain intensity to be greater to produce a detectable signal. The extent of the storm as seen on the PPI at receiver gain step 2 represents rain-intensity contour 2 (Figure 9-c). Reducing the receiver gain by further

steps reduces the sensitivity until only the received power from the core of heaviest rain produces a visible image. If the region of the storm on the PPI is recorded at each gain setting, superimposing the outlines of the regions will produce radar rain-intensity contours similar to the actual rain-intensity contours.

A series of pictures taken on 28 July 1951, (Figure 10) illustrates the effect that reducing the receiver gain by steps will have upon the PPI pattern. These were obtained with the automatic recording and gain stepping circuit. The entire series was taken in a period of one minute and five seconds. The first picture, step 1, was taken with maximum receiver sensitivity. The circles are range markers at 10 and 20 nautical miles. Most of the white dots and irregular

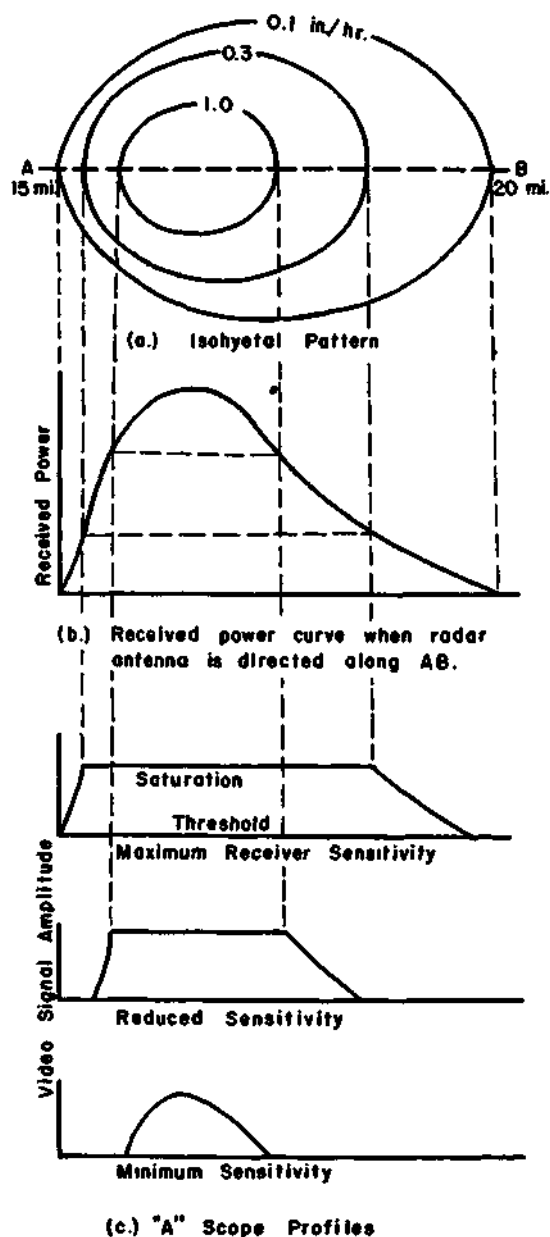
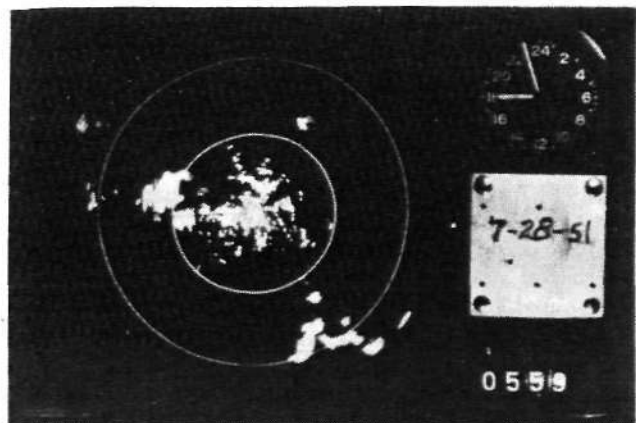
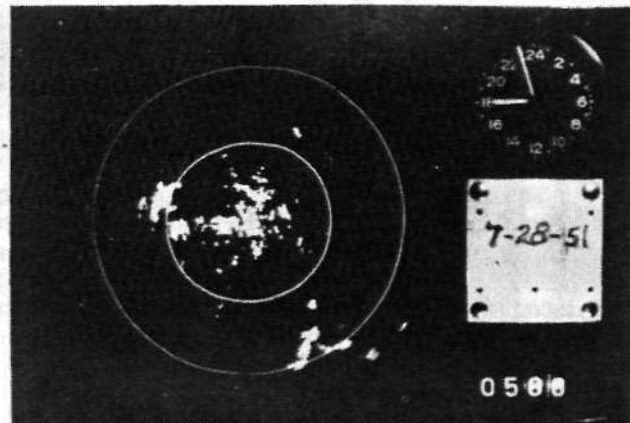


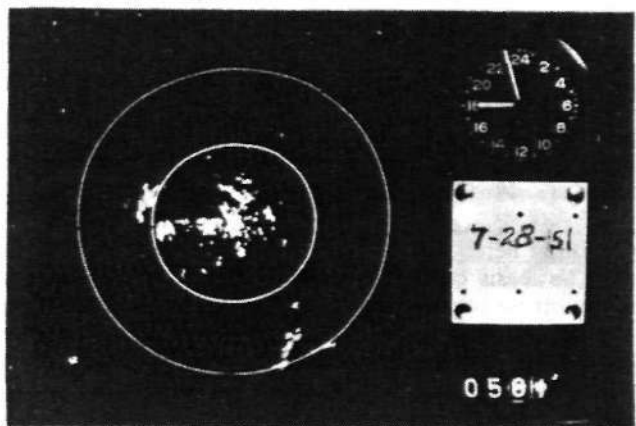
FIG. 9 RECEIVED POWER PROFILES (No Attenuation)



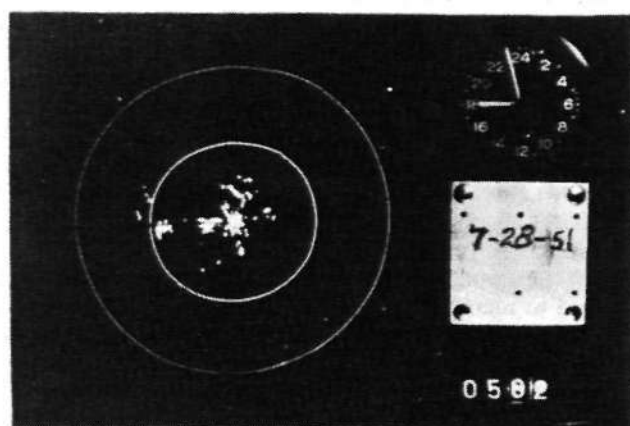
STEP 1



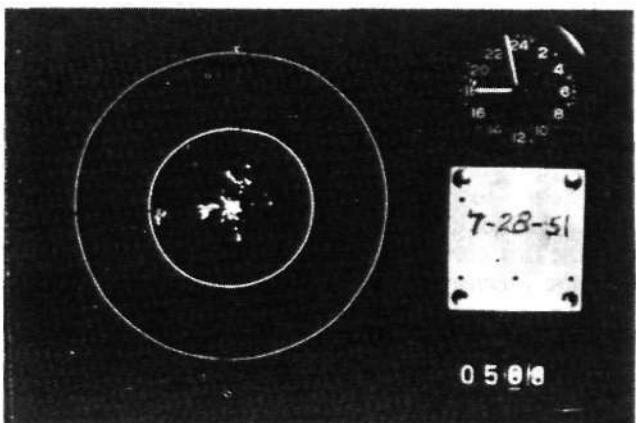
STEP 2



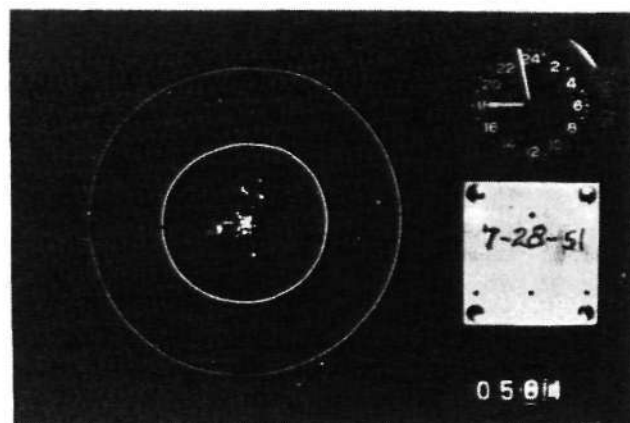
STEP 3



STEP 4



STEP 5



STEP 6

FIG. 10 RAIN INTENSITY PATTERNS AS PRESENTED ON THE PPI SCOPE WITH THE AUTOMATIC SENSITIVITY CONTROL

areas within the 10-mile range marker are ground return. Two relatively large areas within the 10-mile range marker and due west of the radar set represent precipitation. All white areas beyond the 10-mile circle also represent rainstorms. A 24-hour clock, a date card, and the frame number of the film strip are shown in the right hand section of each photo.

The second photo, step 2, was taken with reduced receiver sensitivity. All precipitation areas are considerably smaller than in the first photo and represent areas of heavier rainfall. The sensitivity was further reduced in the photos for steps 3, 4, 5, and 6. The heavier cores of precipitation were further defined with each reduction in receiver sensitivity.

Automatic Film Recording System

It is relatively simple to use a camera to record the PPI image on film, although some special techniques must be used. The PPI tube face has two phosphors; one delivers a very short duration blue flash and the other a persistent yellow glow that, with a color filter, enables the operator to observe all echoes and determine their location. The yellow glow is not of sufficient brilliance to record on the film but the blue flash has high brilliance, and, when the color filter is removed, a good photographic image can be obtained. The camera shutter must be held open for at least one complete revolution of the antenna so that the flash of every echo can be recorded (6).

Originally a war-surplus GSAP 16-mm camera was used to record the PPI image, the antenna making about two revolutions during each exposure. The pictures obtained were good, but the camera magazines were continually jamming. A 35-mm still camera was also used, but the radar operator had to hold the shutter open for each exposure and then advance the film by hand. With this method a picture was taken every 15 minutes, but even during this short interval of time, new storm developments were often missed.

A Bolex H-16 (16-mm) movie camera was then obtained and a circuit built to hold the shutter open during a complete revolution of the antenna. A cam on the antenna momentarily closed a microswitch once each revolution. The pulses from the switch operated an impulse relay (Advance Relay Company, Type 904). This relay acted as an "on-off" switch; one impulse closed the contacts and the next impulse opened the contacts. Closing the contacts energized the solenoid which was mechanically linked to the camera shutter slide. When the solenoid was energized, the shutter was held open, making an exposure of the PPI every other revolution of the antenna. One winding of the camera spring operated the camera for 2 1/2 hours at an exposure rate of one frame every 10 seconds.

Receiver Sensitivity Control.

Only two methods of obtaining radar-rain-intensity contours were known to be in general use at the time of development of the automatic receiver sensitivity control. A manually-controlled calibrated gain dial was one method. Video-inversion circuits were used in the other method (5) (7).

The calibrated-receiver gain-dial method only required replacing the regular sensitivity control knob with a calibrated dial, so the receiver-sensitivity control potentiometer could be accurately controlled. The dial was calibrated in echo power necessary for threshold of visibility on the PPI. The radar operator changed the gain to various settings while taking a photograph of the PPI image on each setting. The operator entered the receiver gain setting for each picture in a log.

The video inversion method presented the storm structure as alternate bright and dark bands. The light rain around the outside of the storm appeared bright, while the heavier rain appeared as a bright area in the center of the storm.

It was concluded that neither method filled all the immediate requirements. Several contours were desired, so additional tubes and associated circuits would have been necessary for video inversion. Also, the steep rainfall gradients in a thunderstorm would have produced very closely-spaced contours and made it difficult to separate them. Keeping an accurately written record of gain settings would have become quite a task if several pictures were taken every minute, so this method was also rejected. Since an automatic system of film recording was desired, the automatic system of receiver sensitivity control operating in synchronism with the camera was developed.

Automatic Sensitivity Control

The basis of the sensitivity control circuit is a multiposition stepping switch that changes the receiver gain by fixed steps. The antenna switch used to control the camera also controls the stepping switch.

Figure 11 is a block diagram of the APS-15 and modifications for automatic film recording and receiver gain control. The receiver gain control establishes the bias voltage on the first three i-f stages and thus controls the receiver sensitivity level. In the modified circuit a voltage divider network with 10 taps provides fixed gain steps. The receiver gain dial is used to establish the level of the voltage divider network.

The impulse from the antenna microswitch operates both the stepping switch rotator and impulse relay in synchronism. The stepping switch contacts are connected in pairs so two impulses are required to change taps on the voltage divider. Likewise, two impulses are required to complete the operation cycle of the camera control circuit. Assume the stepping switch is on the first contact and the solenoid is de-energized. The first impulse from the antenna microswitch will advance the stepping switch to contact No. 2 and at the same time switch the impulse relay to "on" position, energizing the solenoid. The solenoid holds the camera shutter open for the period "T" between pulses, providing an exposure time of one complete antenna revolution. The second impulse will advance the stepping switch to contact No. 3 and also switch the impulse relay to "off" position. This process is carried through the desired number of steps and then repeated.

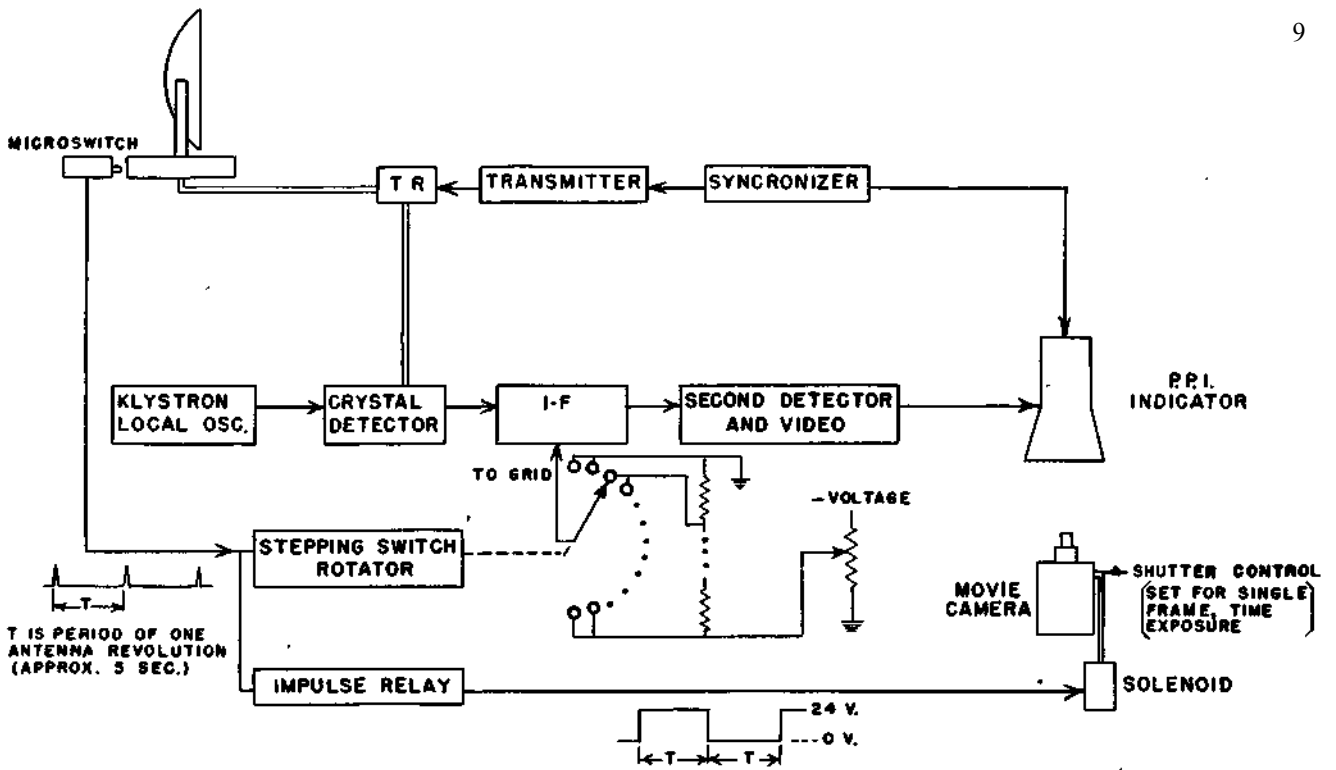


FIG. 11 RADAR WITH AUTOMATIC RECEIVER SENSITIVITY AND CAMERA CONTROL

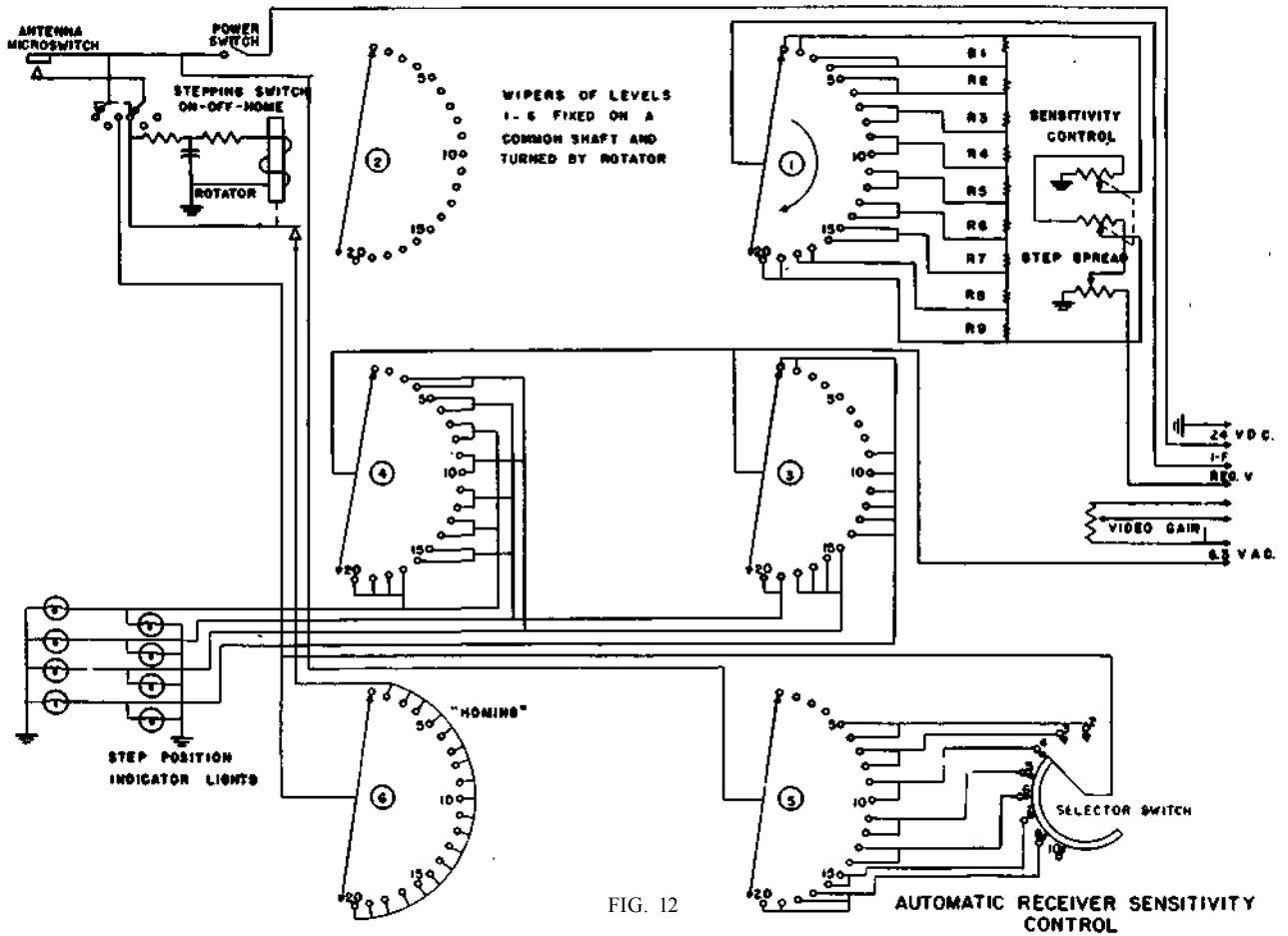


FIG. 12

Figure 12 is the schematic of the stepping switch circuit. The particular stepping switch used is spring-driven with six contact levels and 20 contacts on each level. Level No. 1 is the receiver gain control circuit, No. 2 is not used; levels No. 3 and No. 4 are used as an indicator circuit to show the position of the switch. Levels No. 5 and No. 6 provide a selector circuit which will advance the switch to the normal or home position (on contact No. 1) from any of the intermediate positions.

The double-ended wipers are mounted on a shaft together with a ratchet wheel, and can only rotate in a clockwise direction. The 20 contacts are arranged in a semicircle so that one end of the wiper will traverse the 20 contacts in a half-revolution. As one end is leaving the contact 20, the other end is approaching the first contact. The receiver gain divider network is made up of resistors R-1 through R-9. They are of low value, ranging from 220 ohms to 550 ohms. The values desired may vary with receivers and desired sensitivity distribution. An approximately logarithmic change in receiver sensitivity between steps was desired for this particular application.

The sensitivity control is a dual potentiometer with linear taper which is controlled with a calibrated dial mounted on the control panel. It is used to compensate for changes in over-all radar sensitivity that occur due to aging of tubes and components. The dual potentiometer maintains a constant voltage across the resistor network but changes the voltage with reference to ground. This maintains a constant voltage between steps. The step spread potentiometer changes the ratio between steps. Raising the tap above ground increases the voltage across the divider network, thus increasing the change in sensitivity between steps. Changing the step-spread control will change the receiver sensitivity and necessitate resetting of the sensitivity control. This is not important because the step-spread control is a screw-driver adjustment and is seldom changed.

The receiver sensitivity calibration curve is shown in Figure 13. The step position is roughly a function of the logarithm of the received power. This makes the step position a semi-logarithmic function of the rainfall intensity. This is explained more fully later in this report. The step-level control will shift the entire curve up and down. The maximum sensitivity on step 1 is dependent on the signal-to-noise ratio. For the APS-15 radar, the threshold signal that can be observed in the noise is about 0.4 micro-microwatts.

The selector circuit enables the radar operator to return the switch to the start or home position and to select the number of steps the circuit will automatically scan. If the rain is a light shower, the third or fourth step will reduce the sensitivity to a point where the rain will no longer be visible on the PPI. If the rain is intense, the sensitivity may have to be reduced to step 7 or more before the signal is reduced to the threshold of visibility. The stepping circuit provides a maximum of 10 steps. Since, with a light rain, the PPI will be blank from step 3 or 4 through 10, it is desirable to return the circuit to the "home" position

after the first four steps are completed.

The spring-driven stepping switch has provisions for rotating the wipers to the "home" (contact No. 1) position. A set of normally-closed, interrupted contacts are connected to the rotator coil circuit. These normally-closed contacts are opened each time the rotator coil is energized. Applying a D. C. voltage between the contacts and ground causes the switch to rotate in a self-interrupted or buzzer type manner.

The selector switch and level No. 5 automatically "home" the stepping switch after it has advanced the desired number of steps. In the circuit diagram the selector switch is set so the stepping switch will return to the "home" position after advancing through three receiver gain steps. The 24 V.D.C. is applied to the wiper of level No. 5. Contacts No. 9 through No. 20 are all shorted together by the selector switch. When the wiper reaches No. 9, the circuit is completed through the selector switch to the normally-closed, interrupted contacts, causing the switch to rotate the

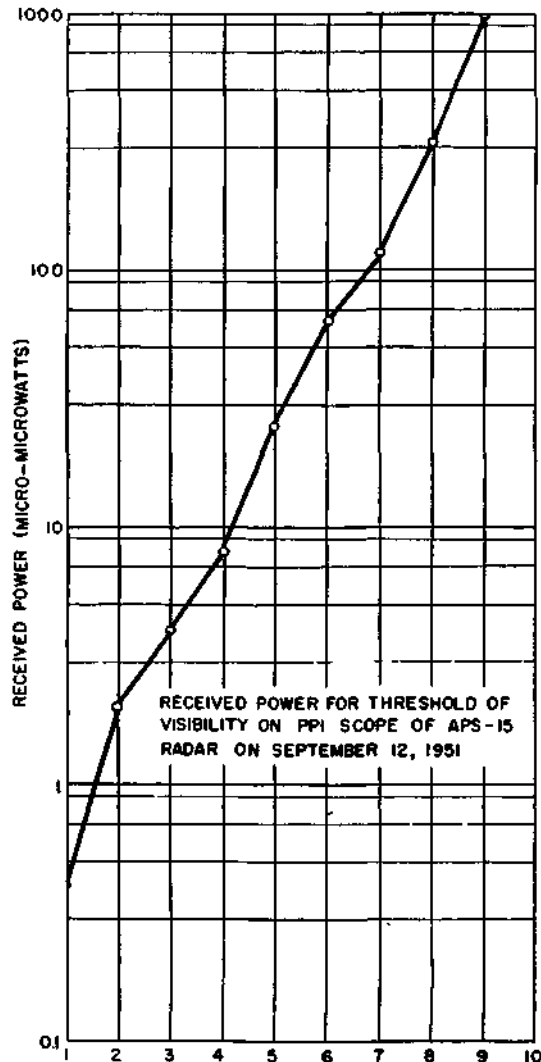


FIG. 13 RECEIVER SENSITIVITY STEP POSITION

wipers until "home" position, contact No. 1, is reached. If seven receiver-gain steps are desired, the selector switch is set at position 7 so the switch will not "home" until contact No. 15 is reached. The operator can "home" the stepping switch by moving the 3-position control switch to the "home" position. This applies the 24 V.D.C. to the wipers of level 6, and the stepping switch will rotate until contact No. 1 is reached.

For analysis purposes the receiver gain step should be recorded on each frame of film. Also, the radar operator often wishes to know the position of the stepping switch. Two sets of step position indicator lights are connected to levels 3 and 4 and indicate the receiver gain step position. On step 1 (contact No. 1 or No. 2) light number 1 will be on. Step 2 (contact No. 3 or No. 4) will light number 2. By using combinations, only four indicator lights are needed to show the 10 steps. One set of lights is mounted in the camera box for recording on the film, while the other set is mounted on the operator's panel.

Fairchild Type-A Recording Camera

A Fairchild, Type-A, PPI recording camera was obtained in June 1951. This camera is especially designed for PPI photography and mounts directly in the front of the APS-15 radar indicator. Adichroic mirror reflects the blue flash from the P7 phosphor, but transmits the long persistent yellow light to the observer's eye. A second optical system records the clock, data card, and frame counter. Six small indicator lights shine through holes in the data card (Figure 14). Four of these are used to record the step number. The other two are not used.

Figure 14 is a series of pictures taken with the Fairchild camera on September 12, 1951. The radar scope is on 28-mile range with 10-mile markers showing. The APS-15 radar, with which these photos were taken, operates on 3.2 cm wave length and has a 2.7° beam width and a 2 micro-second pulse length. The narrow antenna beam width and excellent resolution of the 35 mm image presents the fine, intricate detail of variable rainfall intensities within the storm. The receiver sensitivity values of received power (in db below one milliwatt) for threshold of visibility on the PPI are indicated below each photo.

This particular storm was a squall line associated with a cold front, traveling from the west at 20 mph. The first picture shows the area of rainfall within 28 miles of the radar. A solid, irregular line of rain extends from the southwestern edge of the scope to 20 miles north. There is a 3-mile break and then a circular cluster about four miles in diameter off the edge of the scope to the north. The shaded segment on the clock face from four minutes to nine minutes is the movement of the second hand while the 5-second exposure was made. Five black dots are showing on the data card. The light is on in the sixth position in the upper right hand corner, indicating the stepping switch in on step number 1. The frame counter is visible at the very bottom. The second picture is on step 2. The area of rainfall is only slightly reduced. Note the mid-

dle light of the upper row on the data card is on. An appreciable change in echo area can be seen in step 3. The areas of lighter rainfall are no longer visible. In step 5 the cores of heavier rainfall are readily discernible. The isolated cluster 25 miles north has only one very small echo showing. The storm area is progressively reduced until in step 8 only a few of the heaviest cores are discernible, the echo nine miles due west being most prominent. On step 9 this is the only echo showing, and on step 10 it is eliminated.

A continuous series of scope pictures such as these for the duration of a storm over a small watershed provides a complete, detailed, and continuous record of the rainfall distribution and intensities.

Radar Calibration

Figure 15 is the theoretical radar-rainfall intensity calibration for the APS-15 on 12 September 1951. This calibration is based upon the relationship developed by Marshall, Langille, and Palmer (8).

$$\text{Log } \frac{P_r R^2}{C H P_t} = 1.72 \text{ Log } I - 17.527$$

Where: P_r = Received power—watts
 R = Range—meters
 C = Summation of various radar parameters which remain constant for the particular radar set used
 H = Pulse length—Meters
 P_t = Power transmitted—watts
 I = Rainfall intensity—mm/hr

The radar constants for the APS-15 and conversion factors were inserted to obtain:

$$\text{Log } \frac{P_r R^2}{P_t} = 1.72 \text{ Log } I - 12.538$$

Where: P_r = Received power—watts
 R = Range—nautical miles
 P_t = Power transmitted—watts
 I = Rainfall intensity—in/hr

The calibration curve indicates the importance of the range. A contour of step 2 at 12 miles would be the same rainfall intensity as step 1 contour at 30 miles.

When the calibration curve was applied to the isoecho patterns (outline of equal received power from a storm) of Figure 14, very high rates of rainfall were indicated. Step No. 5 at 10 miles is a rate of 0.6 inch per hour and at 20 miles is 2.0 inches per hour. In picture No. 5, a considerable portion of the storm area is showing, the echoes at 10 miles having rainfall rates over 0.6 inch per hour and those at 25 to 30 miles having a rate over 1.5 inches per hour. The calibration curve indicated the cell 9 miles west had an intensity of over five inches per hour. The network of 33 recording rain gages located between 15 and 22 miles west northwest of the radar station recorded a maximum intensity of seven inches per hour.

Discussion of Intensity Contour Recorder

This method of obtaining radar-rainfall intensity contours has proven to be a relatively simple and re-

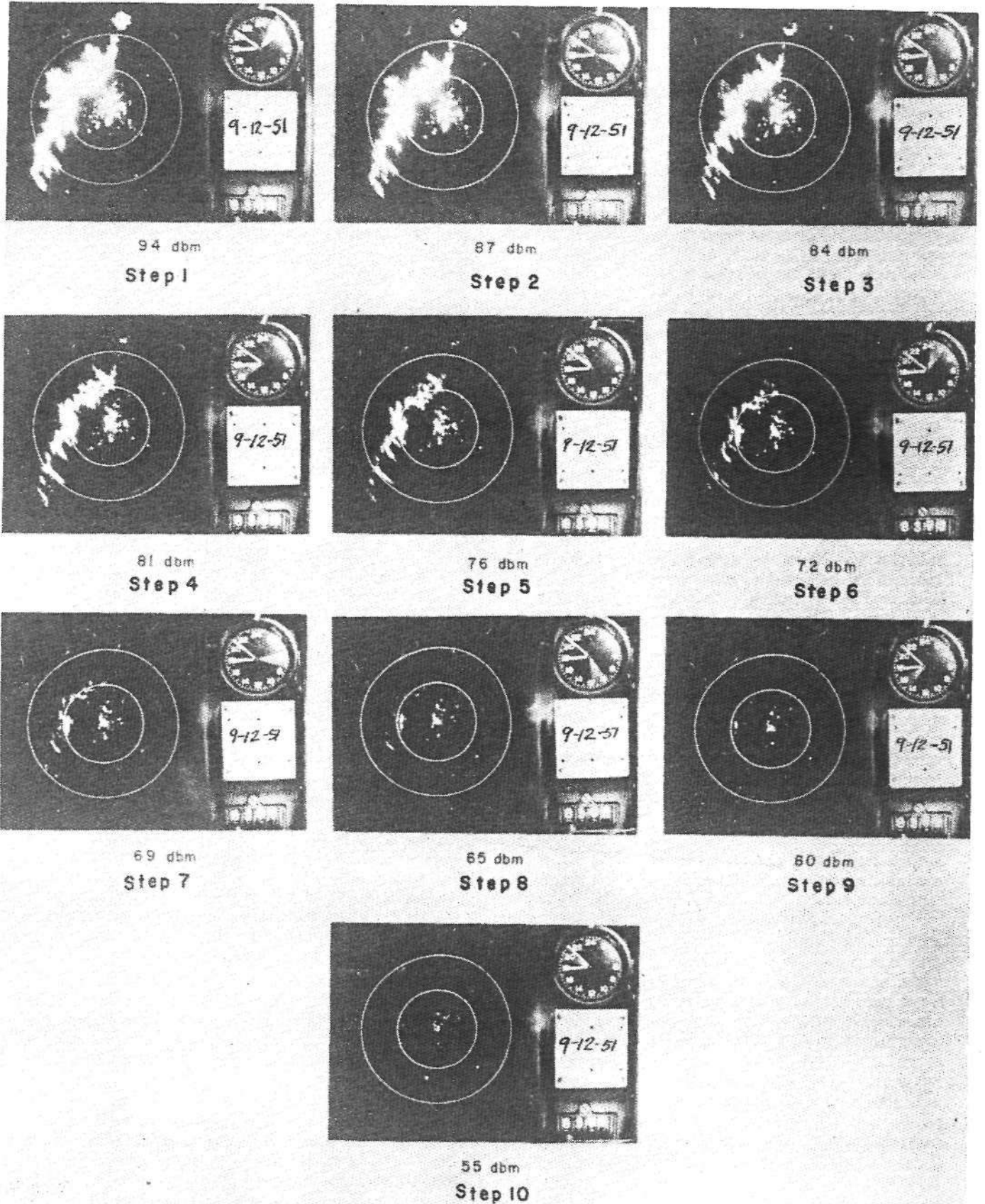


FIG. 14 A SERIES OF PICTURES OF THE 12 SEPTEMBER 1951 STORM AS SHOWN ON THE APS-15 PPI ON 28-MILE RANGE

liable method. The stepping switch and Bolex H-16 camera were used during the entire summer of 1950 and in the spring of 1951. The equipment operated without any trouble except for routine replacements and maintenance. Over 4,000 feet of 16-mm film was exposed with the Bolex camera over a year's period.

About 2,500 feet of 35-mm film record for 1951 summer rainfall was obtained with the Fairchild camera with almost no trouble. The resolution of the 35-mm camera and film was better than the 16-mm camera, making the 35-mm more desirable where the fine detail of the storm was desired.

This technique of obtaining radar rain-intensity contours can be adapted to almost any radar equipment. A number of circuit arrangements can be easily made to fit the stepping switch operation with the particular camera. The Fairchild camera transports the film quite rapidly so an exposure can be made for every revolution of the antenna. The stepping switch will operate in synchronism with the Fairchild camera if each individual contact of the bank is used, rather than binding them together in pairs as is shown in the schematic.

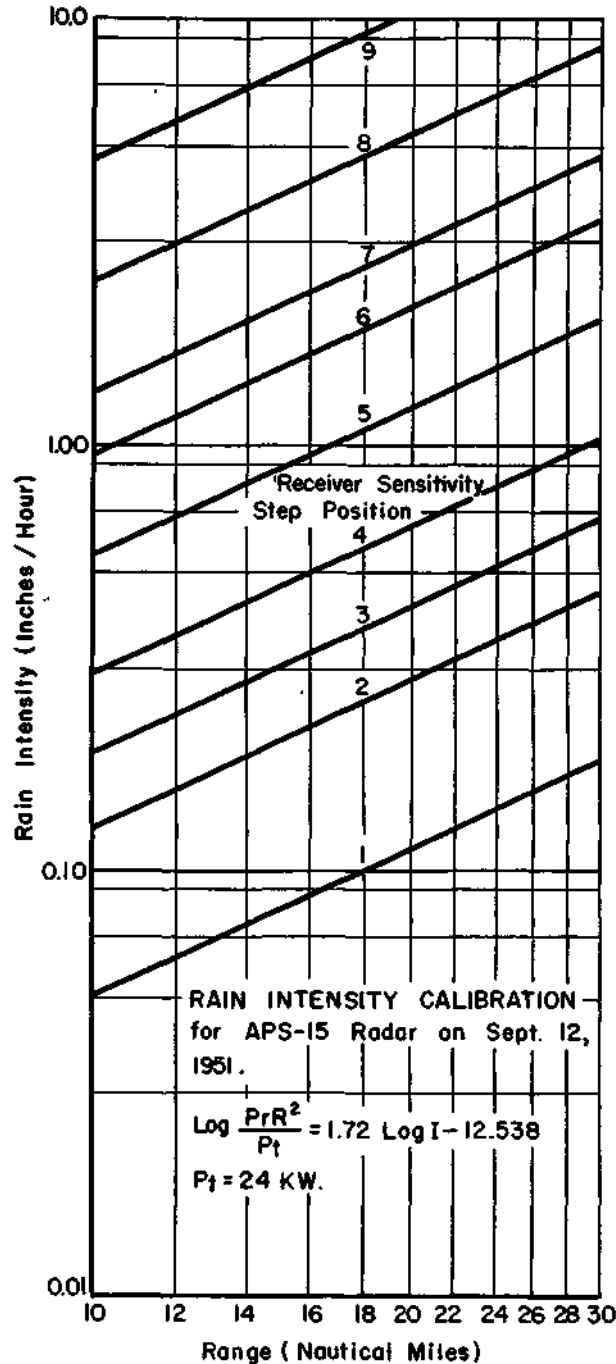


FIG. 15 THEORETICAL RADAR-RAINFALL INTENSITY CALIBRATION

Analysis of Data and Discussion

Correlation of Radar Data* With Raingage Data

Rainfall Distribution Patterns

Radar-Rainfall Pattern

Using the automatic sensitivity control and camera while rain was falling over the Goose Creek network, resulted in a film record consisting of a series of pictures taken over approximately one-minute intervals during a storm. The number of pictures (steps photographed) in each series was dependent upon the rainfall intensity. Each picture or frame of a series was enlarged approximately 50 diameters and projected onto a base map of Goose Creek network. The portion of the echo pattern which fell within and just outside the network boundary was outlined on the base map. The echo outlines obtained for each step in a series were superimposed one on the other to obtain an echo-intensity contour map of the rain shower (Isoecho patterns, Figures 16, 17, 18, 19, and 20.)

Raingage-Rainfall Pattern

The raingage charts from the 33 recording rain gages on the Goose Creek network were each enlarged eight diameters by projection so that rainfall accumulative amounts could be read from them at one-minute intervals. These readings could be made quite accurately to 0.005 inch. One-minute rainfall amounts were then obtained from subtractions between the successive accumulative one-minute readings.

One-minute rainfall values were plotted on base maps of the Goose Creek network and one-minute isohyetal maps were drawn. These isohyetal patterns are illustrated in Figures 16 to 20 inclusive, where they are shown with corresponding isoecho maps. A time lapse between the isoecho map and the isohyetal map was necessary to permit raindrops viewed by the radar beam at an altitude of several thousand feet to reach the rain gages. The matching of isohyetal and isoecho maps was done by comparing the over-all pattern between the two maps. Generally the leading edges of both maps were the best criteria for matching the maps.

The question will no doubt arise as to why such short intervals as one minute were used for the radar and rainfall correlation maps. Large variations in rainfall rates and radar and rainfall patterns from minute to minute may be expected, especially from rapidly moving squall lines. Figure 16 is an example of this and shows 3 one-minute maps for a five-minute period during the 26 September 1951 storm. Note the rapid build up in the cell and the rapid movement during the five-minute period. In Figure 17 the storm

continues to move rapidly across the network. Note the changing isohyetal and isoecho pattern as cells move onto the network and merge with the leading cell. After numerous trials with five-minute maps and other intervals it was decided that the best similarity of patterns was obtained by using the shortest practicable time period, one minute. For light rains of the warm front type which show only slight intensity variations with time, (Figure 18) longer intervals could no doubt be used with a considerable degree of confidence. Most of the data are from thundershowers that display many short-period intensity fluctuations on the raingage charts (Figures 3 and 4) and radar photos as well as high rates of rainfall as illustrated by Figures 16, 17, 19, and 20.

Point Comparison

Precipitation Echo Intensity and Rainfall Rate at a Point

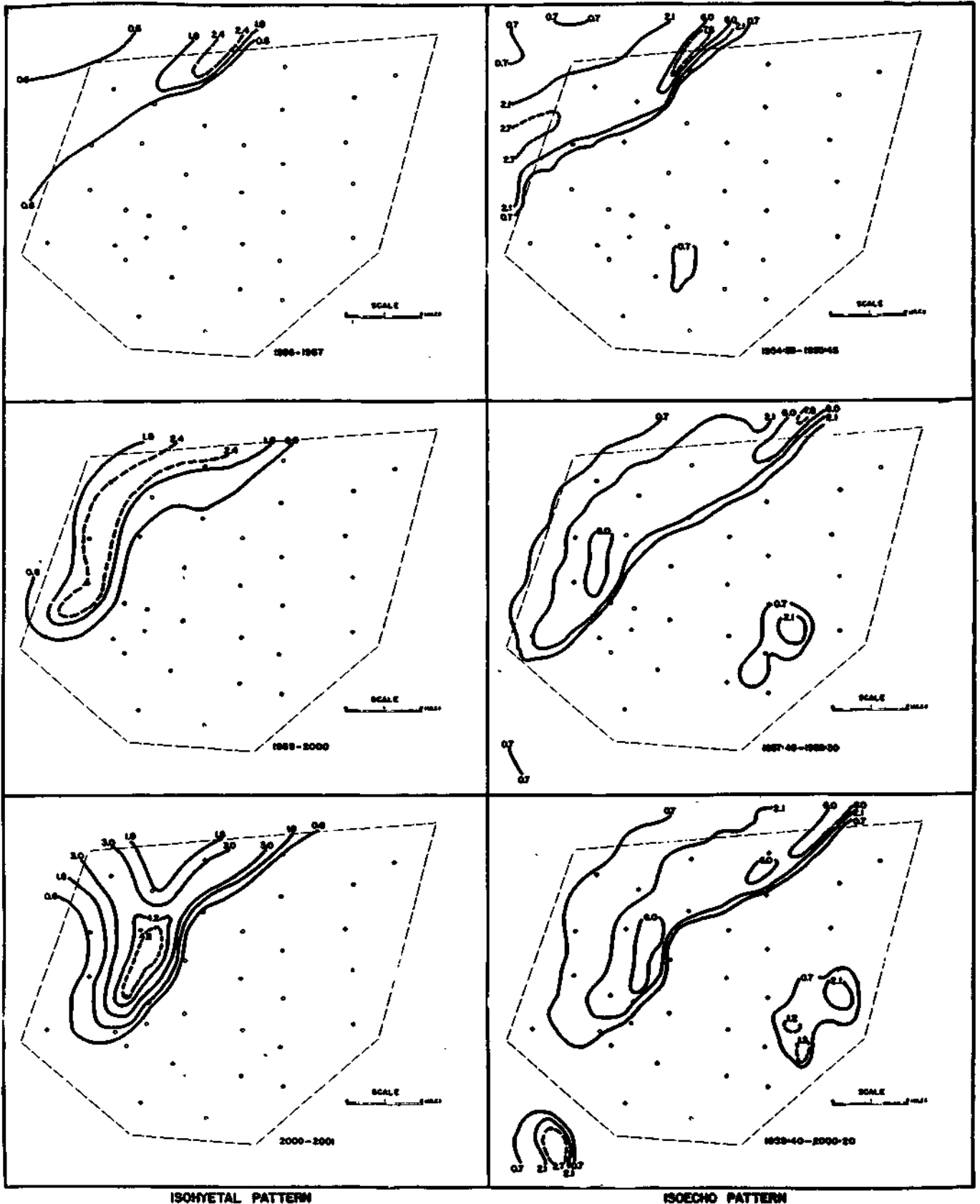
One objective in this investigation is to determine the ability of radar to measure quantitative rainfall rates at a point on the ground. The relationship between rainfall rate at a point on the ground and the rate computed from radar observations above the same point can be shown by time profiles for each of the 33 Goose Creek gage locations for the storm of 26 September 1951. Radar observations and corresponding point rainfall data at several gage locations are illustrated in Figures 21 to 24 inclusive. Raingage rate curves are based on one-minute amounts. Corresponding radar-rate curves are based on rates computed by substituting radar received-power measurements and the characteristics of the APS-15 set in the equation,

$$P_r = K \frac{I^{1.72}}{R^2}$$

P_r equals power received from the rain drops in watts, I is the rainfall rate in inches per hour, R is distance from the radar set in nautical miles, and K is a constant, which includes the characteristics of the radar set.

Each comparison indicates that a rain echo occurred directly over the gage location before rain was recorded at the gage. This result may be explained by the fact that the radar observations represent raindrops which occupy a depth of 5,000 feet (vertical cross section) above the Goose Creek network at a range of 20 nautical miles from the radar set. Consequently, the lag between the radar observation and the ground observation is due to the time that is required for rain to fall from the radar observed volume to the ground level. The time required for a raindrop to fall from a given height will vary with the diameter of the drop and with the speed and direction of vertical wind movement. Free falling drops, 1 mm and 5 mm

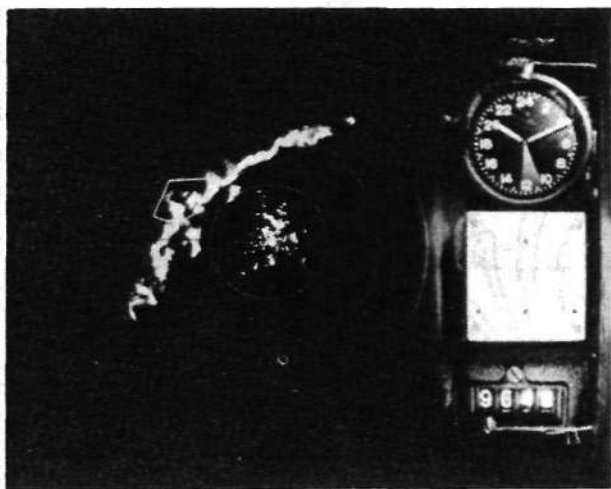
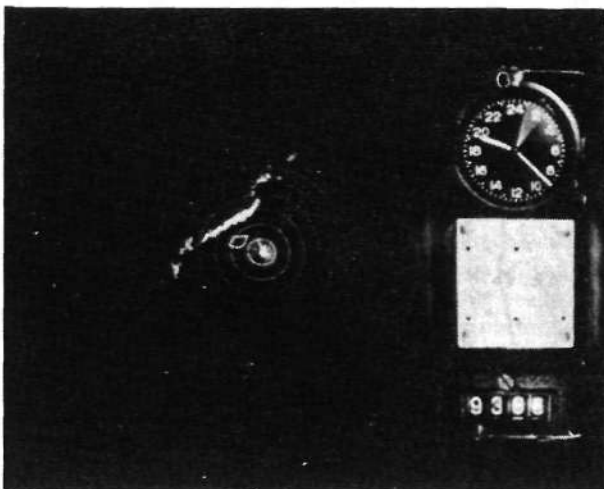
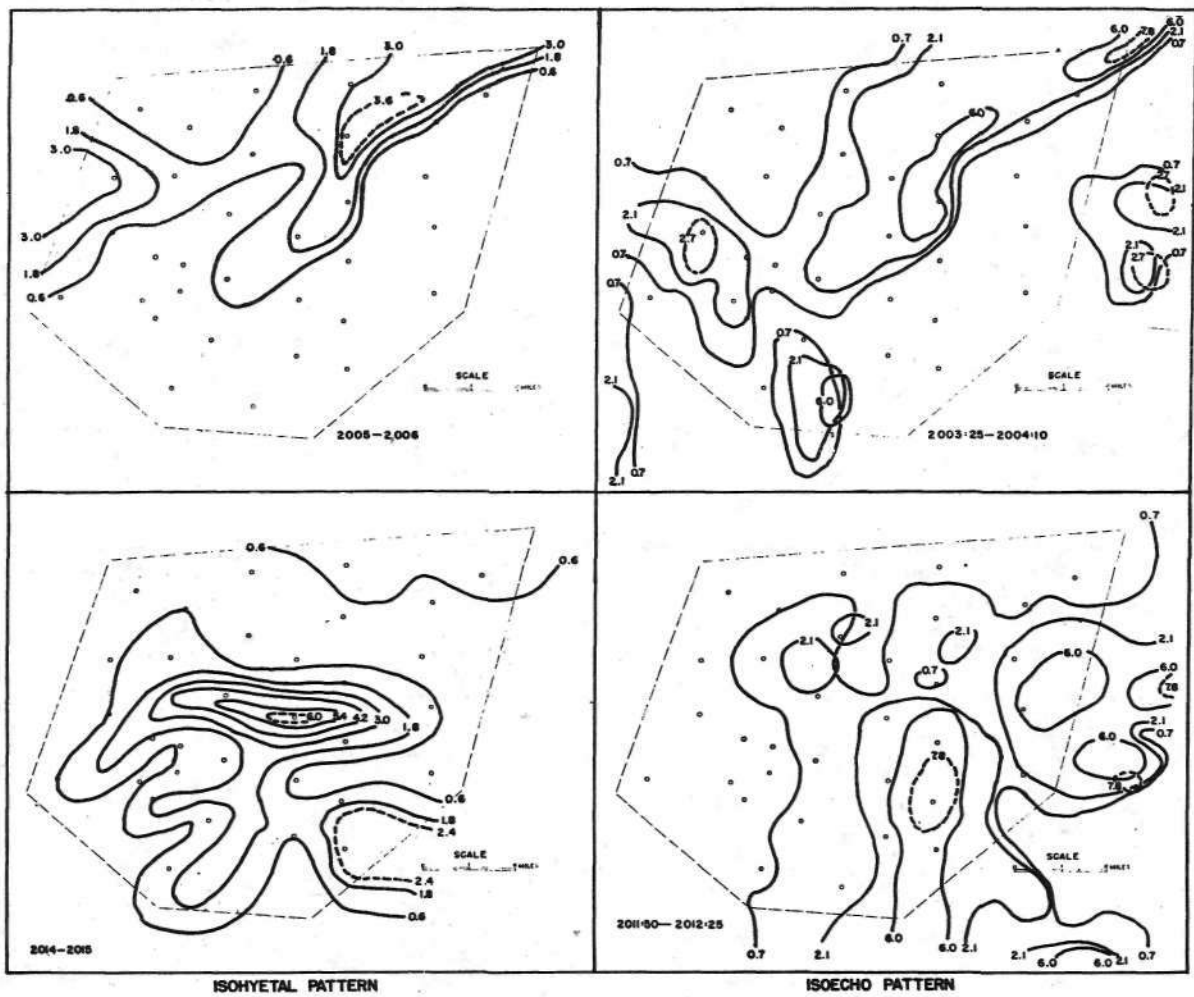
*All analysis based on APS-15 radar data.



ISOHYETAL PATTERN

ISOECHO PATTERN

FIG. 16 COMPARATIVE RAINFALL MAPS
Rainfall in inches per hour for 26 September, 1951.



RADAR SCOPE PICTURE AT 1922:05 WITH 10 MILE RANGE MARKERS.

RADAR SCOPE PICTURE AT 2010:30 WITH 10 MILE RANGE MARKERS.

FIG. 17 COMPARATIVE RAINFALL MAPS AND SCOPE PICTURES

Rainfall in inches per hour for 26 September, 1951

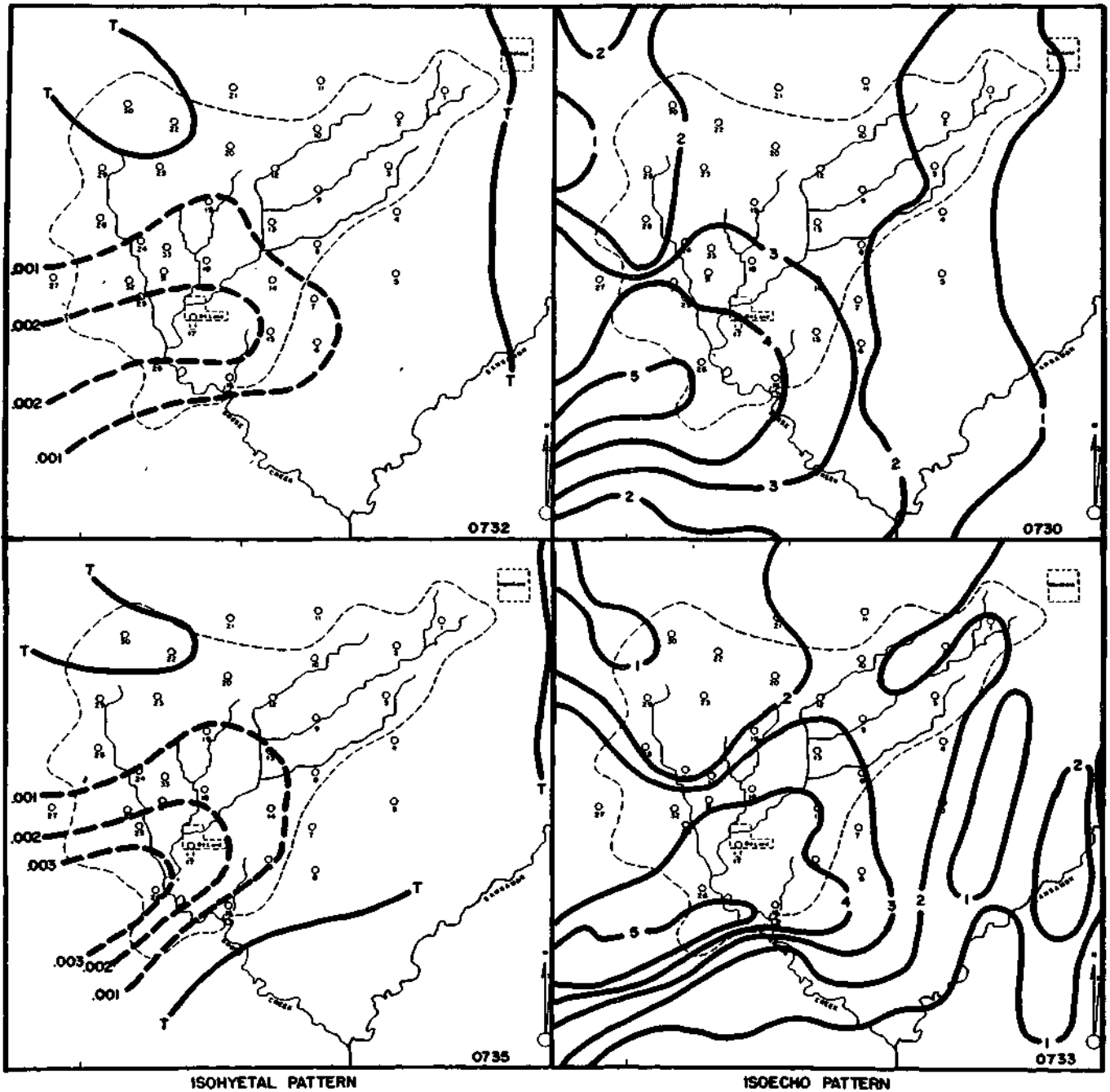


FIG. 18 ONE MINUTE MAP, JULY 22, 1951

in diameter, will require about 3.2 and 1.4 minutes, respectively, to reach the ground from an altitude of 2,500 feet. Drops would require less time to reach ground level if they were falling in adwraft region of the rain cloud, longer if contained in an updraft region.

Another prominent difference between the appearance of the comparative curves in Figures 21 to 24 is the short duration of the radar-rate curve in comparison with that of the rainfall-rate curve. This dif-

ference was due to attenuation of the radar beam by precipitation occurring between the rain gage and the radar set. Roberts and King (9) determine the attenuation coefficient to be 0.05 db/mi/mm/hr (one-way transmission) for 3-cm radar. Converting this attenuation coefficient to nautical miles and inches/hr gives an attenuation rate of 1.46 db/nauticalmi/in/hr. Raingage measurements along radials for the 26 September storm indicated that an average rainfall rate of 1.2 inches per hour occurred quite frequently in a

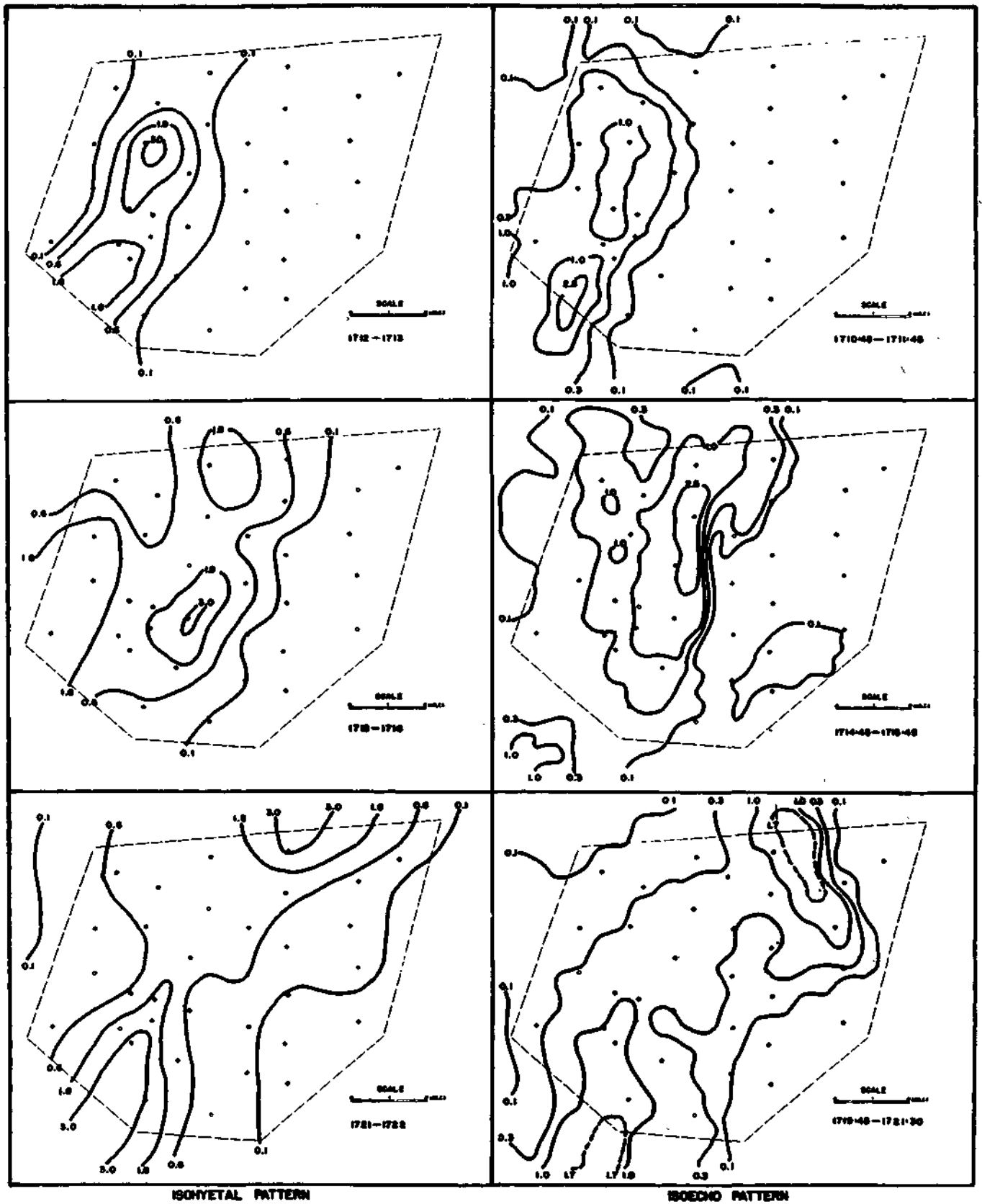
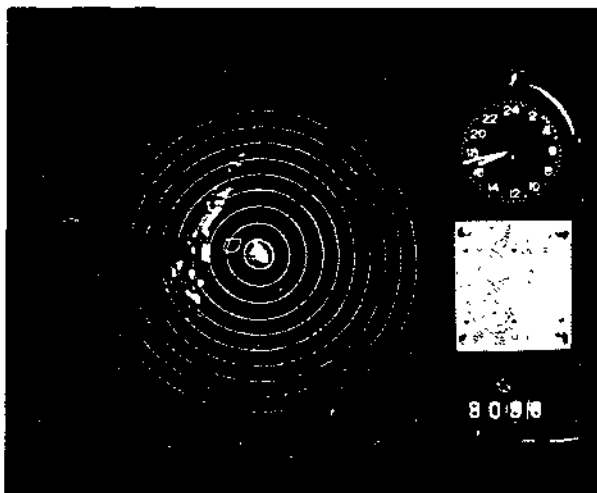
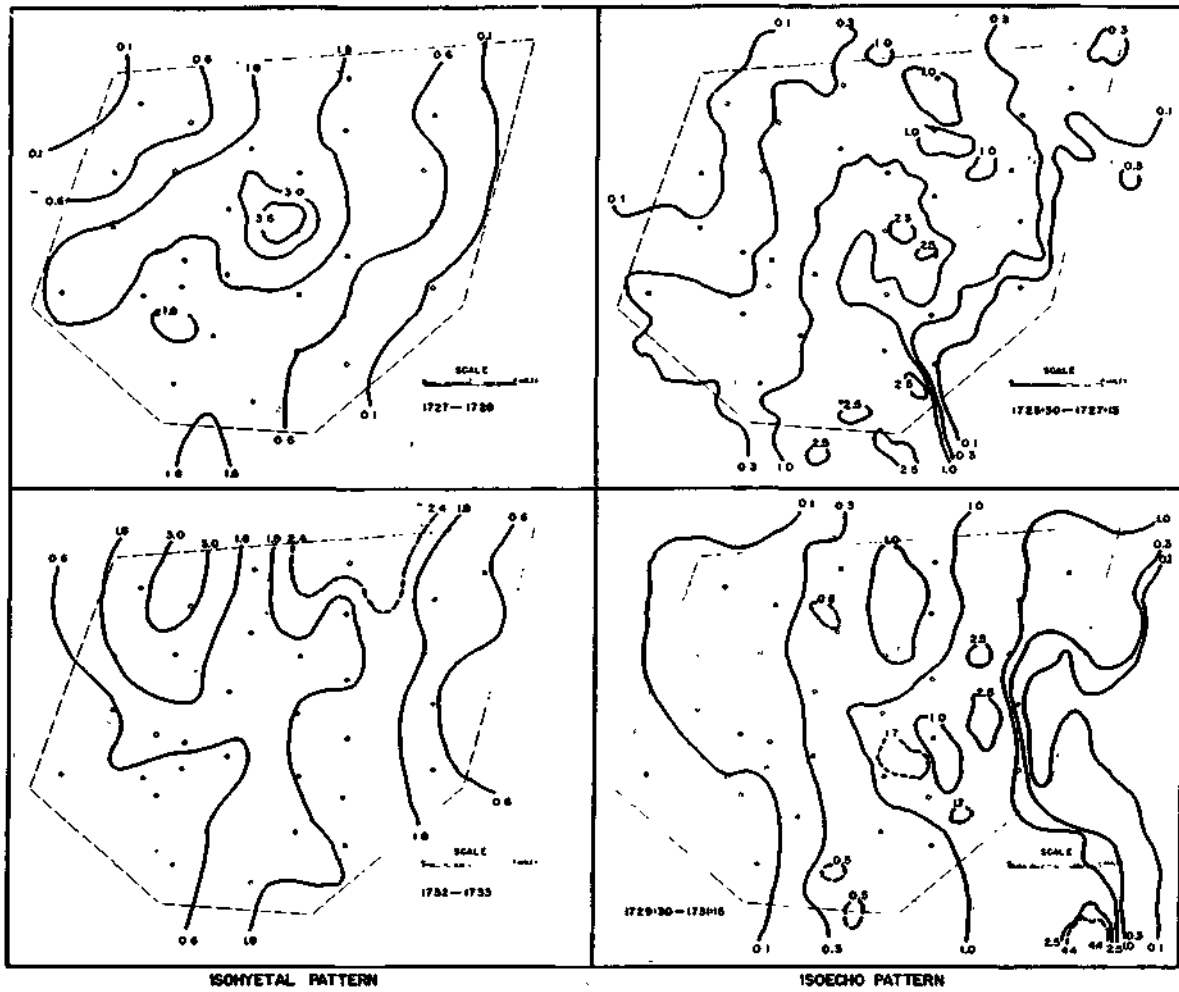
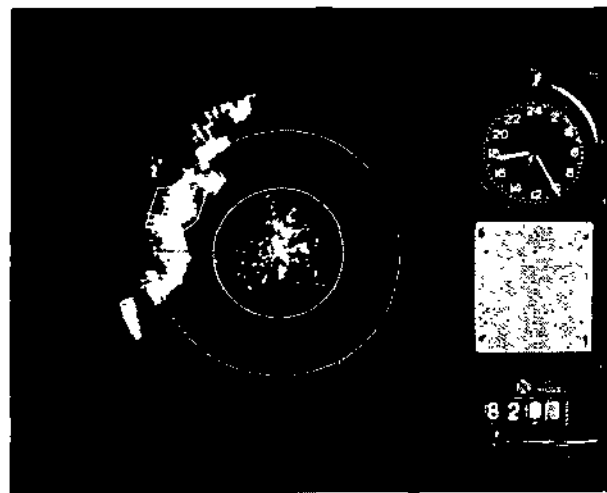


FIG. 19 COMPARATIVE RAINFALL MAPS
 Rainfall in inches per hour for 12 September, 1951



RADAR SCOPE PICTURE AT 1643:30 WITH 10 MILE RANGE MARKERS.



RADAR SCOPE PICTURE AT 1725:30 WITH 10 MILE RANGE MARKERS.

FIG. 20 COMPARATIVE RAINFALL MAPS AND SCOPE PICTURES

Rainfall in inches per hour for 12 September, 1951

precipitation zone five miles in depth. An average rainfall rate of this magnitude would cause a loss of 8.8 db as the transmitted signal penetrated the storm to a depth of five miles. The same loss would occur as the echo returned, causing a total loss of 17.6 db. This loss is equivalent to a loss of the first four sensitivity steps on the automatic receiver-sensitivity control. At a range of 20 nautical miles, a rainfall rate of approximately 0.1 inch per hour is necessary to reach the threshold of visibility on step 1 without attenuation. At the same range and with a 15 db attenuation loss, a rainfall rate of approximately 1.2 inches per hour would be necessary to produce an echo of sufficient intensity to reach the threshold of visibility on step 1. An attenuation loss of the order of magnitude discussed would be sufficient to cause a large part of the back side of the 5-mile-wide storm of 26 September to be beyond detection by the radar beam.

Differences in the quantitative rates of the comparative curves (Figures 21 to 24) are partially due to horizontal drift of the raindrops while falling from the radar volume to the ground level. A constant horizontal wind component of 20 miles-per-hour would carry a raindrop 1/3 mile in one minute of fall time. The horizontal distance on the ground over which the drops in a radar beam cross section may be distributed were estimated within the limits of five conditions: (1) The vertical width of the radar beam over the center of the raingage network (20 miles from the radar set) extends from 200 feet above ground level to 5,000 feet above ground level; (2) Raindrops are assumed to be randomly distributed throughout a beam cross-section; (3) Raindrops falling through the cross-section range from 0.1 mm to 4.0 mm in diameter; (4) The vertical velocities due to updrafts and/or downdrafts are assumed to be zero; (5) The horizontal component of motion is taken to be constant at 20 mph between the surface and 5,000 feet. Using these conditions, drift computations were made for drops in the top and bottom of the beam. It was found that raindrops which produce the echo over a point on the ground under the given conditions may be distributed horizontally between .04 mile and 33.5 miles downwind from that point. However, since drops less than 1 mm in diameter contribute very little to the rainfall rate and comparatively little to the intensity of the radar echo in thunderstorm rainfall, it is more practical to consider a range of drops from 1 mm to 4 mm in diameter. The distribution would then be within a horizontal distance of .04 mile to 2.08 miles downwind from the radar observation point. This horizontal distribution of raindrops on the surface is considerably greater than the width of the radar beam itself.

The above results would be altered considerably by other factors which were omitted from the assumptions. For example, the velocity of fall of a raindrop is often influenced by vertical components of velocity due to updrafts and downdrafts in the cloud. The effect of upward and downward air movement within the rain cloud would be a function of the intensity of the meteorological factors causing them at different stages of development of a thunderstorm. Byers and Braham (10) have reported that updrafts dominate the vertical

motion in a thunderstorm cloud during the early stage of development with a change to a downdraft motion as the storm progresses and finally to a very weak downdraft motion as the storm dissipates. During the course of these changes in stage of development, Byers and Braham (10) have reported that vertical drafts, both upward and downward, up to 20 feet per second may exist at an altitude of 5,000 feet. Updraft and downdraft motion was not measured below this level, but horizontal convergence and divergence at the surface under a thunderstorm cell indicated that vertical wind motion existed between the surface and 5,000 feet.

The horizontal wind field between the surface and the height at which the raindrops are detected by the radar beam is seldom uniform in speed and direction as indicated by upper wind observations. Byers and Braham (10) have shown that the normal, smooth pattern of the wind field in which the thunderstorm cell is embedded is destroyed in the vicinity of the cell. These factors make the assumption of a constant, horizontal-wind component between the surface and 5,000 feet a very rough approximation.

From the above discussion, it is certain that the intensity of a radar echo observed over an observation point should not be expected to correlate well with the intensity of the precipitation at that point and at that instant. Point rainfall rates on the ground must, therefore, be limited in comparisons with radar rate observations to those cases where relatively large homogeneous-echo-intensity volumes move across a gage position.

An estimation of the minimum areal extent of equal-echo-intensity needed for successful correlation between a one-minute raingage amount and echo intensity over that rain gage may be determined within the limits of the following conditions: (1) radar-beam height extends from 200 feet above ground to 5,000 feet above ground; (2) no distortion of radar observation due to beam width; (3) free-falling raindrops; (4) a uniform horizontal drift component of 20 mph from the surface to 5,000 feet; (5) let the raingage one-minute sample be considered only for the time when drops of 1 mm to 4 mm in diameter from the top and bottom of the beam are being collected.

In Figure 25, let it be assumed that the line AB represents an instantaneous radar observation. Drops of 1 mm to 4 mm in diameter from point A will fall between points A_4 and A_1 , respectively. Let A_1 be a raingage location also. Then, in order to get drops of size 1 mm to 4 mm from the top of the beam to fall into the gage at the same time, the width of the echo must be extended forward from AB to CD which represents an echo of 1.15 miles in length. In addition, in order to have drops of size 1 mm to 4 mm arriving at A_1 from the base of the beam at the same time drops of size 1 mm to 4 mm are arriving from 5,000 feet, the echo must be extended past CD to EF, producing an echo 2.04 miles long. To maintain this situation for one minute, the echo would have to be extended back from AB to GH by an amount equal to 1/3 mile to allow for the 20 mph forward movement. The echo passing over the gage would have a minimum length of

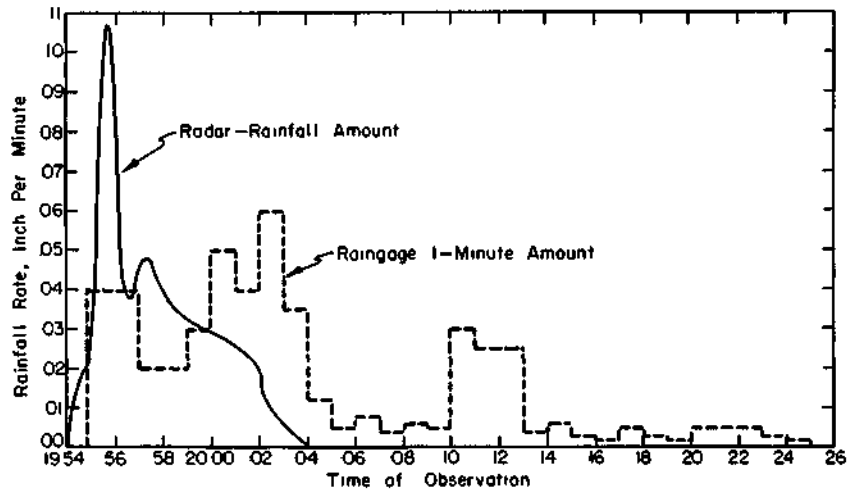


FIG. 21 RADAR AND RAINGAGE RAINFALL RATE OBSERVATIONS AT GAGE LOCATION 21 DURING 26 SEPTEMBER 1951 STORM.

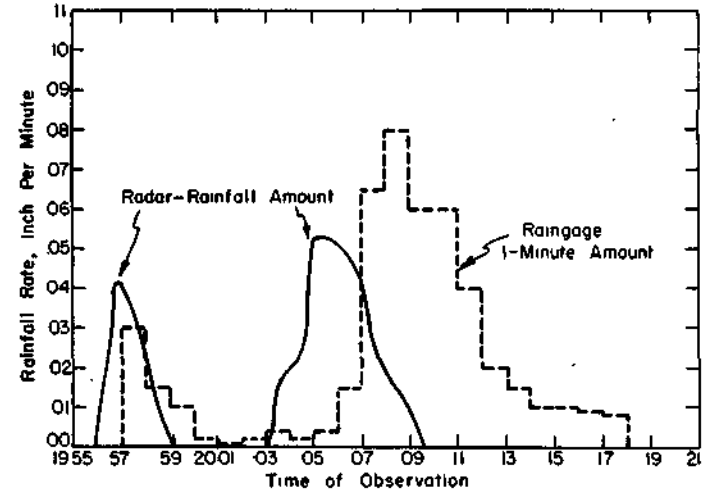


FIG. 22 RADAR AND RAINGAGE RAINFALL RATE OBSERVATIONS AT GAGE LOCATION 27 DURING 26 SEPTEMBER 1951 STORM

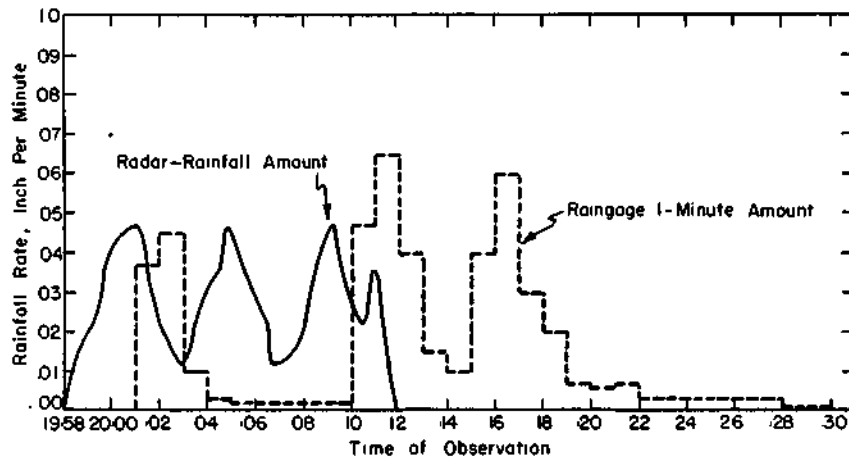


FIG. 23 RADAR AND RAINGAGE RAINFALL RATE OBSERVATIONS AT GAGE LOCATION 33 DURING 26 SEPTEMBER 1951 STORM.

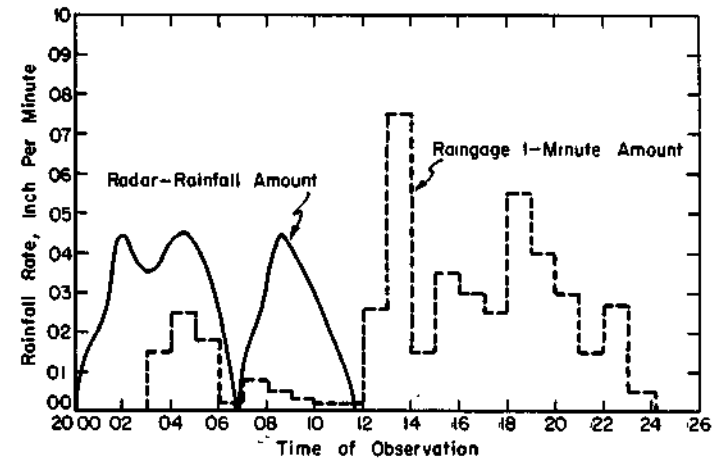
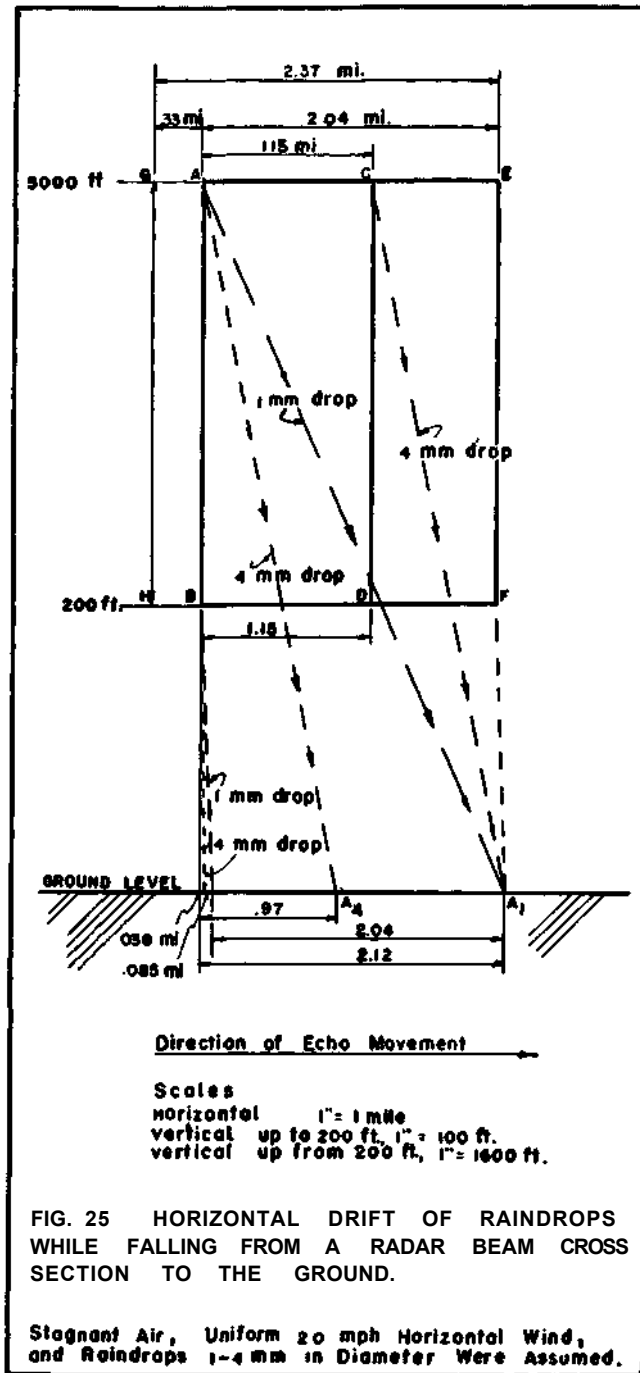


FIG. 24 RADAR AND RAINGAGE RAINFALL RATE OBSERVATIONS AT GAGE LOCATION 18 DURING 26 SEPTEMBER 1951 STORM



2.37 miles. This example indicated the difficulty in correlating raingage and radar point-rainfall observations unless the radar echo is relatively homogeneous over a considerable area.

Point Rainfall Amounts Computed from Radar Data

For the 26 September 1951 storm, point radar-rainfall calculations were made for each of the 33 raingage locations. Each point value is the product of the amount of time which each step (receiver-sensitivity setting) was over each gage location and the "apparent" rate of rainfall as determined from the

equation by Marshall, Langille and Palmer (8). Total rainfall patterns as determined from raingage and radar observations are shown in Figure 26. The individual values varied from a minimum of 0.18 inch to a maximum of 0.75 inch. These compare with a low of 0.26 inch and a 0.79 inch maximum as determined from the raingage records. The average rainfall as determined by the point method was 0.43 inch. The mean of the raingage values was 0.44 inch. The percentage difference between these two point-rainfall averages was 2 per cent.

The difference of 0.01 inch or 2 per cent error between the raingages and radar rainfall averages was not large enough to be statistically significant. This is evidence that the radar estimated the true network mean rainfall as accurately as the network of 33 gages. However, it is evident from Figure 26 that many of the individual radar-rainfall values at the gage locations are significantly different from the raingage amounts. According to the discussion in the previous section (Precipitation Echo Intensity and Rainfall at a Point) rather large differences in point comparisons may be expected from drift and attenuation. The difference in location of the center of highest rainfall on the isohetal and isoecho maps is approximately two miles which is of the same order of magnitude as reported for drift in the preceding section. The displacement was also in the direction of cell movement for this storm. However, the algebraic sum of these point differences is very small, which accounts for the small deviation between the raingage and radar mean rainfall amounts.

From the above discussion, it may be concluded that the average of the radar point observations estimated the mean rainfall very accurately. A reasonably accurate, areal-distribution pattern was also obtained from the radar-point values, although the differences between radar and raingage observations at specific points were often considerable. This is evidence that observations with a calibrated radar can be used as an aid in preparing isohetal maps over areas of widely-spaced raingage observations.

Area-Depth Method

Because of the evident difficulties with correlating point rainfall measurements with radar observations, it was felt that an areal comparison between rainfall amounts computed from the radar and raingage networks might be more satisfactory than a point analysis. The areal analysis offered a possibility of minimizing the difficulty arising from the drift of raindrops away from any particular raingage location while falling from the height of the radar observation. The areal method used was somewhat similar to that suggested by Byers and collaborators (11), in which horizontal, cross-sectional areas of different echo intensities were considered representative of different precipitation echo volumes.

In assembling the data for areal studies, values were used only for radar cores of rainfall located at least one mile within the boundaries of a theoretical watershed. This theoretical watershed is outlined by

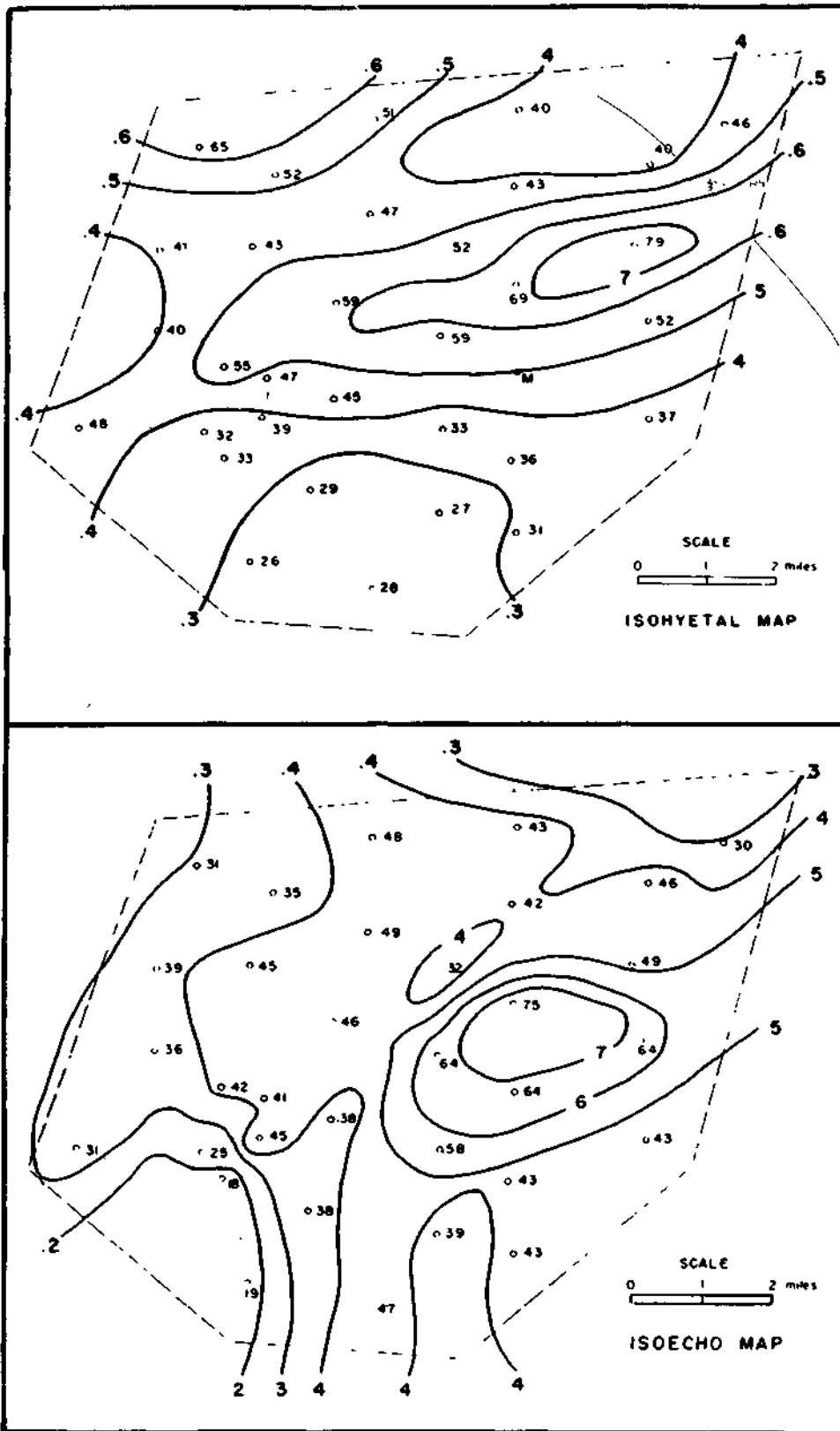


FIG. 26 TOTAL 40-MINUTE RAINFALL FOR THE 26TH OF SEPTEMBER 1951, AS DETERMINED BY RAINGAGES AND BY RADAR

the dashed polygon in Figure 2. Isoecho maps enclosing areas within each gain step were drawn from the PPI photographs for each one-minute interval. Similarly, one-minute isohyetal maps were drawn from the raingage-network data. A correction for the time lag between observations of the rain aloft by the radar and recording of it by the rain gages at the surface was made by superimposing isohyetal maps for several consecutive minutes upon a given isoecho map. The isohyetal map most closely matching the isoecho pattern was then used for comparison purposes. No correction for drift was made. By selecting storm cores well within the watershed boundaries, it was assumed that the rain observed by the radar would reach the ground within the watershed boundaries.

The area enclosed by consecutive isoecho and isohyetal lines were planimeted on corresponding one-minute radar and raingage rainfall maps. Curves of area vs. step for the isoecho map and area vs. rainfall for the isohyetal map were then drawn. Figure 27 is an example which shows the area-step and area-rainfall curves for the isoecho and isohyetal patterns at the bottom of Figure 16. The area corresponding to a given step was then determined from the radar "area-depth" curve to obtain the actual rainfall corresponding to this area within the watershed. This procedure was repeated for each step and for each one-minute interval under consideration. The calculated rainfall step values obtained for each step in this manner were averaged to obtain a mean value for the entire storm.

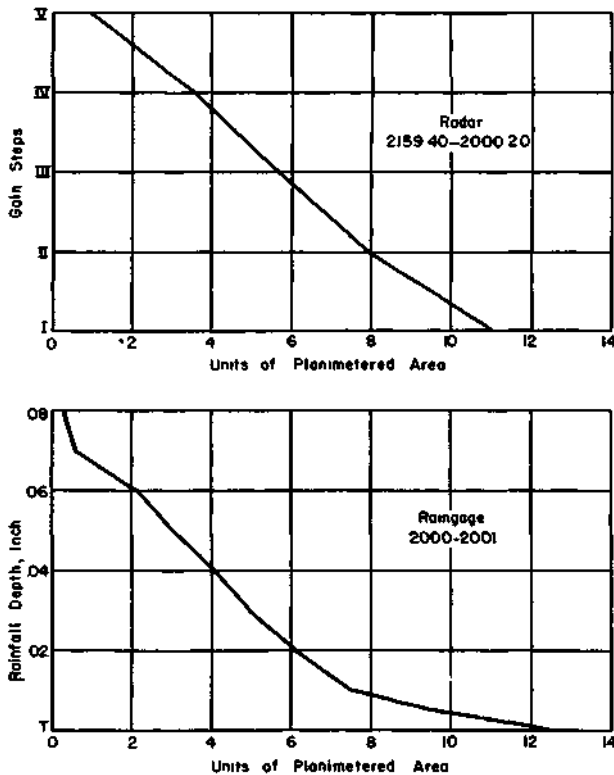


FIG. 27 ONE-MINUTE AREA DEPTH CURVES PREPARED FROM RADAR AND RAINGAGE DATA FOR THE STORM OF 26 SEPTEMBER 1951 OVER GOOSE CREEK NETWORK

The mean values were then plotted against the corresponding gain steps for various storms to produce the curves shown in Figure 28. The small number beside each point on the curves indicates the gain step. The power range factor was used as an ordinate since the calculated intensity of radar-observed rainfall is a function of power transmitted, power received, and the square of the range.

Results

Four curves correlating the radar-received power with the rainfall rate measured by the concentrated raingage network are shown in Figure 28. Also included is a curve obtained by applying the radar equation of Marshall, Langille, and Palmer (8) to the average for the computed power return to be expected for the radar used in 1951, and a curve developed by Atlas (12) in 1948.

Curves I, II, and III were all derived from one storm day, 22 July 1951. Reference to the recorded gain-steps shows that, for a given rainfall rate, these three curves included the greatest power received, the least power received, and the approximate average of the logarithms of the powers received. These curves indicate that one or both of two processes was taking place. One possibility is that the transmitted power was decreasing, or the sensitivity of the radar was changing to a less sensitive value during the day; and the other possibility is that a significant change occurred in the mean drop diameter or reflectivity for a given rain intensity. It seems possible that the radar parameters changed during the day. No power measurements were made on 22 July. A power measurement was made on 17 July when the peak-transmitted power was found to be 27 kw and the receiver threshold of visibility 85 dbm (db below 1 milliwatt). Another power measurement was made on 24 July when the peak-transmitted power was found to be 21.5 kw and the receiver threshold of visibility 93 dbm. It will be noted that Curves I and II change in slope at approximately 1.5 x 10¹³ square miles and it is conceivable that Curve III would have changed slope at the same value had the power received reached that value.

The data determining Curve IV were collected before the radar video strip was modified to correct for the presence of attenuation in the circuitry. This curve included raingage rainfall rates as high as 1.64 inches per hour which would also cause appreciable attenuation of the reflected signal. It would appear that the attenuation from these two sources caused the radar to indicate exceptionally low values of power received for a given rate. It is thought that the apparent attenuation in the video strip was a major factor.

Curve V tends to follow a slope similar to that of the Atlas curve between 0.2 and 0.4 inch per hour, then decreases in slope. Its shape is thought to be partly due to attenuation resulting from a small core of very heavy rain, which was located near the forward edge of a relatively large area having a rainfall

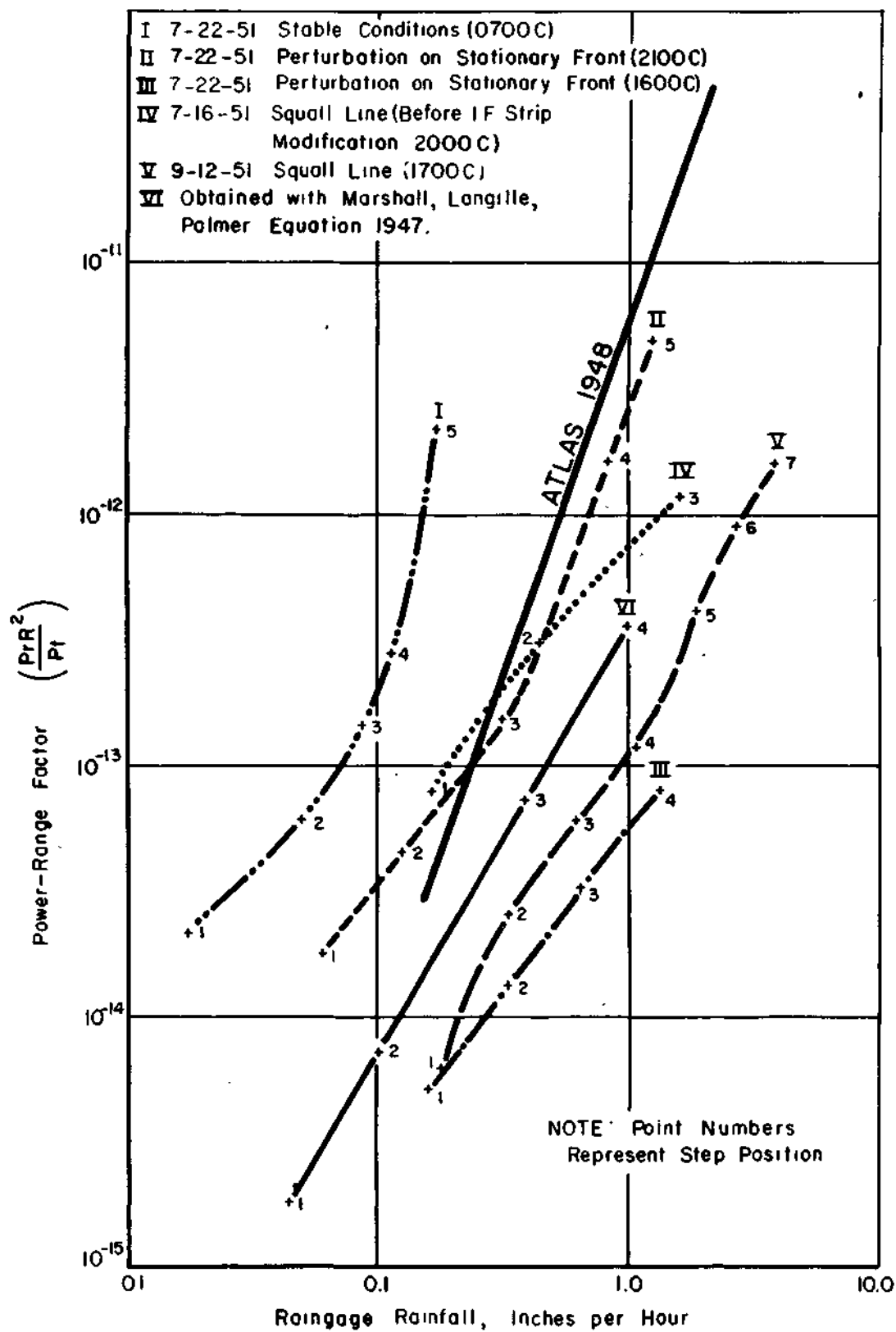


FIG. 28 POWER-RANGE FACTOR VERSUS RAINFALL INTENSITY

rate of about one inch per hour. This would have caused a considerable portion of the rainfall in the larger area located to the rear of the small intense core to be obscured from the radar through attenuation. A much smaller echo area than actually existed would therefore have appeared on the radar scope. In making comparisons with the Atlas curve, it should be remembered that the Water Survey curves were drawn through points obtained by averaging all rainfall rates in a given storm for each gain step intensity; while the Atlas curve is a regression line based upon observations from a number of storms.

Another possible explanation for the peculiar shape of Curve V is the deviation from Rayleigh scattering at 3.2-cm wave-length as suggested by Wexler (13). Changes in slope, which occur in several of the curves in Figure 28, may be associated with changes in reflectivity due to changes in the drop-size distribution with increasing rainfall rate. This does not apply very well to curves III and IV. However, these two curves were obtained from observations under a certain synoptic weather condition, a perturbation on a stationary front. This suggests that there may also be a significant shift in drop-size distribution between various synoptic situations.

Network Mean Rainfall Computed from Radar Data

Quantitative rainfall comparisons were made between raingage and radar observations of four storms. Data from other storms observed during the 1951 season were eliminated, several due to severe attenuation by rainfall at the radar station while rain was occurring over the network. Other storms either produced very light rainfall or passed along the edge of the network. In a few cases, mechanical difficulties and human errors prevented obtaining a complete record of precipitation echoes over the network from the beginning to the end of the storms.

In order to determine the total volume of rainfall represented by an individual isoecho map, it was assumed that the areas enclosed by isoecho contours were representative samples of precipitation-echo areas during the period from the starting time of one series of gain steps to the starting time of the next series. The volume of rainfall over the network was obtained from the products of the areas between adjacent isoecho lines, the duration of the step series, and the "apparent rainfall rates", summed over all series of the rainfall period. The rainfall rates used in this summation were computed for an average range of 18 nautical miles by substituting the proper values for the radar characteristics in the formula presented by Marshall, Langille, and Palmer (8) which was noted previously.

Results of this study are summarized in Table 1. The 22 July storm presented some interesting data. A single thunderstorm cell passed over the center of the network. The isoecho contour lines were not tightly packed. The thunderstorm cell moved rapidly across the network. Rain did not fall at all stations. The maximum point-rainfall value observed was 0.32 inch. The radar indicated that 29 per cent less rain fell than

Table 1 -- Radar Raingage Summary of Four Storms Over Goose Creek Network 1951

Date	Time	Depth of Rainfall (in.)				% Radar, Rain-Gage Difference*	Equivalent Raingage Density
		Min. Rain Gage	Max. Rain Gage	Average Rain Gage	Radar		
7-22	21:28-55	0.00	0.32	0.07	0.05	-29	35 sq. mi. / gage
8-20	17:15-40	0.09	0.24	0.12	0.19	+58	125 sq. mi. / gage
9-12	17:10-54	0.17	0.79	0.44	0.18	-59	300 sq. mi. / gage
9-26	20:10-50	0.26	0.79	0.44	0.40	-9	20 sq. mi. / gage

* + greater than raingage average, - less than raingage average.

was actually observed by the gages. By extrapolating in Figure 29, it was possible to express percentage difference between the raingage and radar values in terms of accuracies that might be expected from networks of varying raingage densities. It was concluded for this storm that the radar was as accurate as one rain gage per 35 square miles.

The 20 August storm was one in which wide-spread rain fell over the entire area and rainfall rates were fairly low. In this case the radar indicated 58 per cent more rain than was actually observed by the rain gages. The radar was as accurate as one rain gage per 125 square miles.

For the 12 September storm in which a rapidly moving squall line passed over the network, rainfall rates as high as 5.4 inches per hour were experienced.

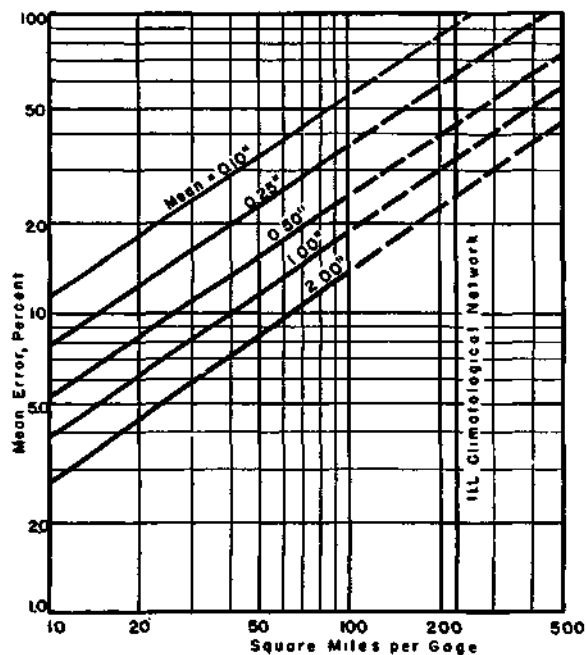


FIG. 29 EFFECT OF GAGE DENSITY ON PERCENT ERROR FOR VARIOUS STORM RAINFALLS. 95 SQ. MI. AREA, 1948-1950 ASSUMING 4.75 SQ. MI. GAGE GAVE TRUE MEAN FOR AREA. (This graph was prepared from data obtained on the Panther Creek Network)

Total rainfall as measured by radar was 59 per cent less than the actual precipitation. This was exceedingly disappointing since the isoecho maps and isohyetal maps corresponded closely. In spite of the large differences between the radar-rainfall and raingage-rainfall which may have been due to attenuation, the radar appeared to give results in measuring areal rainfall equivalent to one rain gage per 300 square miles.

Rainfall which occurred over the network on 26 September came from a portion of a long, narrow, cold-front squall line which moved rapidly. Total storm average rainfall was computed from radar data to be 0.40 inch, which was 9 per cent less than the raingage value. For the storm the radar observation was as accurate as a raingage density of 20 square miles per gage.

From this study, it may be concluded that the measurement of areal thunderstorm rainfall by radar was, in the least satisfactory case, as accurate as that obtained by a raingage network of one gage per 300 square miles, while in other cases, it was considerably more accurate.

Movement of Precipitation Echoes

A study of the direction of thunderstorm cell movement was undertaken to determine the most probable direction of movement in the vicinity of the Goose Creek raingage network. Movement of thunderstorm-type rainfall was determined for 11 storms in 1951. Positions of two or three cells in each storm were plotted at approximately one-minute intervals for several minutes.

Although successive positions of a cell did not fall exactly on a straight line, the general direction of movement was well represented by a straight line. Arrows representing direction of storm cell movement are shown in Figure 30. The double arrow represents the average or the most probable direction based on the sample of 11 storms. The range in direction of cell movement was from 215 degrees to 320 degrees with an average direction of 265 degrees. The average speed of each precipitation-echo cell during the period of observation was also calculated.

Speed and direction of corresponding rainfall cells on the isohyetal maps were determined in a similar manner for several cases where rainfall cells on the network could be identified with precipitation echo cells. The path of an isoecho cell and the apparent corresponding rainfall cell are shown in Figure 31. The plotted paths give the impression that the movement of the echo center was much more uniform in speed and direction than the isohyetal record. However, the true path of the rainfall cell is believed to be more uniform than is indicated. The major difference between the two indicated paths between time 20:04 and 20:08 can be attributed to the merging of the cell in question with a cell of rather indefinite location to the north. During the four-minute period, it was practically impossible to identify the rainfall cell in question. Another cause of difference in the plotted paths was the fact that the echo center is an observation in the atmosphere and is thus subject to some change in apparent location and shape on the ground due to attenuation and drift of the raindrops while falling. Further difficulty was experienced in

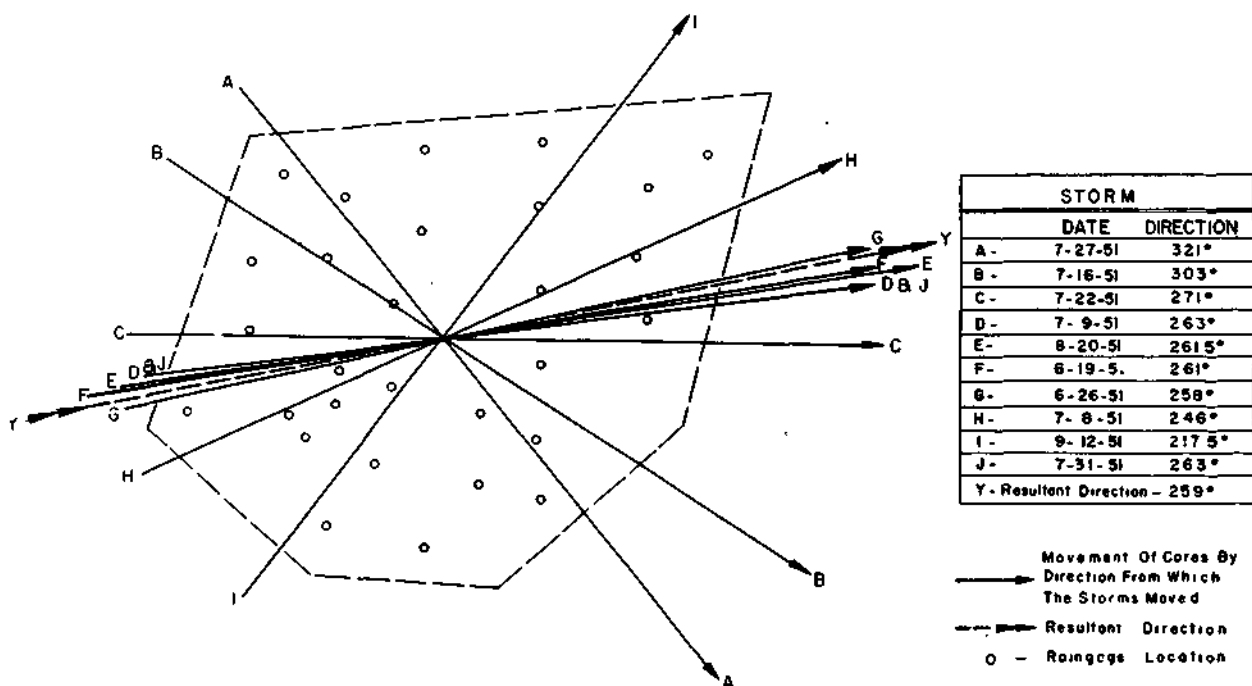


FIG. 30 DIRECTION OF STORM CELL MOVEMENT IN THE VICINITY OF GOOSE CREEK NETWORK DURING TEN 1951 STORMS

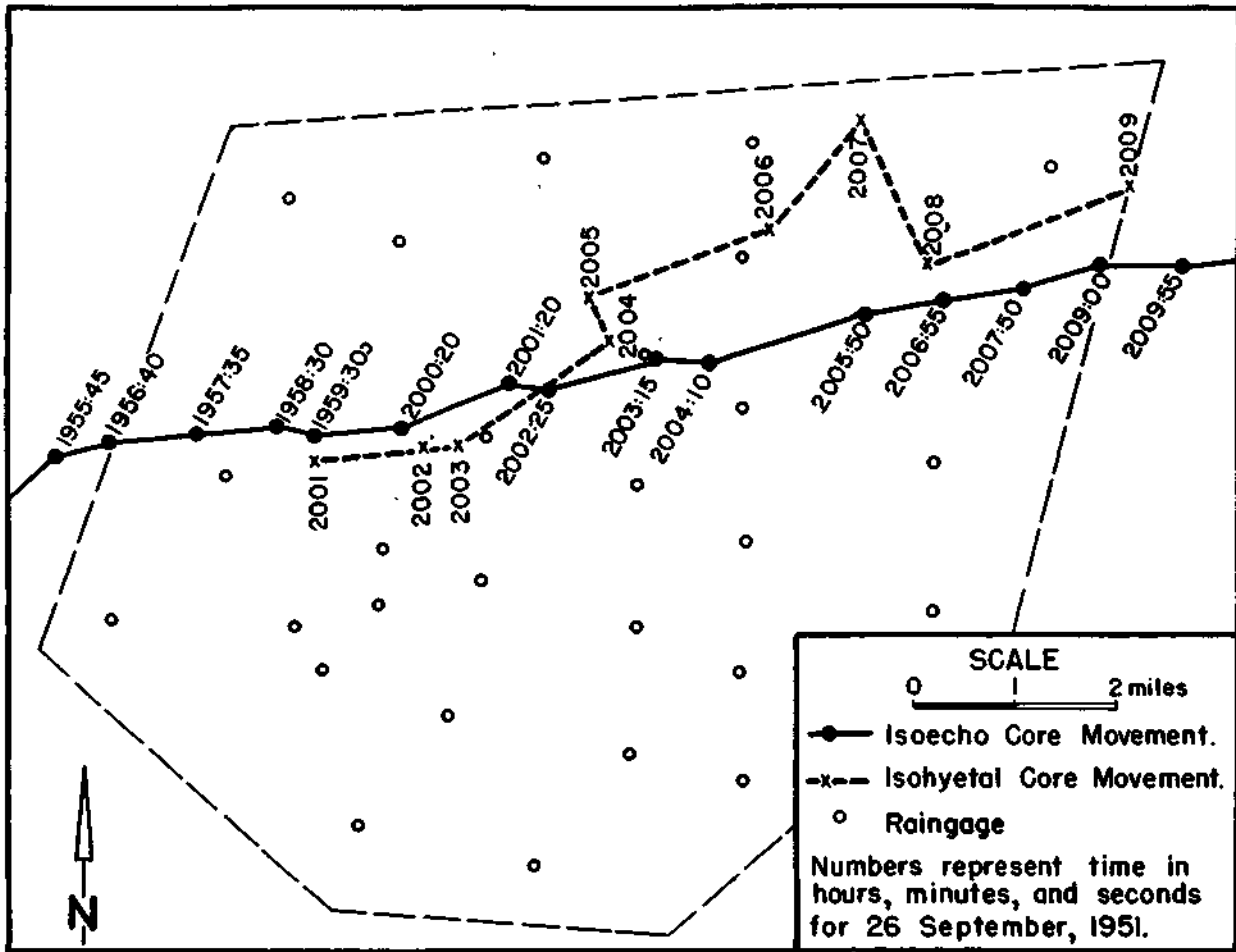


FIG. 31 PATH OF AN ISOECHO CELL AND THE APPARENT CORRESPONDING RAINFALL CELL

locating the true rainfall cell center because the rain-gage network was not dense enough to accurately and consistently determine the true location of precipitation-echo cores of the order of 2 miles in diameter from minute to minute as shown by the radar.

Speed and direction of the general movement of the fronts or squall lines with which the cells were associated were studied. The leading edge of the precipitation echo was assumed to represent the forward movement of the front or squall line. Isochrones of successive positions of the leading edge of precipitation zones on isoecho maps gave the direction of frontal movement and data for computing the speed of movement.

It was noted that the precipitation echo cells did not move in the same direction as the front or squall line with which they were associated. For the 26 September storm, individual cells moved along the frontal zones as indicated in Figure 32. Positions of isochrones representing the forward movement of the precipitation zone are numbered in succession. The numbered circles correspond to the successive positions of two cells. Direction of cell movement was

approximately from 245 degrees, while the movement of the squall line was approximately from 315 degrees. This difference of 70 degrees in direction indicated that another component of motion was directing the cell movement in addition to that of the frontal movement, i.e., the speed and direction of cell movement was probable the resultant of two main components, winds aloft and frontal movement. Cell and frontal movements of other storms are presented in Table 2. Those cases where echoes were not in the immediate vicinity of a front or a squall line were classified as scattered thunderstorms and are not included in Table 2.

Some investigating was done to determine if the wind aloft at some level ahead of the front or squall line was a major directional component for cell movement. Vector diagrams were prepared by using a vector representing the movement of the front with vectors representing the upper wind at various levels. It was felt that the resultant of these two vectors at some altitude might approximate the movement of the cell. The best-fitting wind levels for each case are tabulated in Table 2. Wind vectors for 6000 to 8000 feet usually

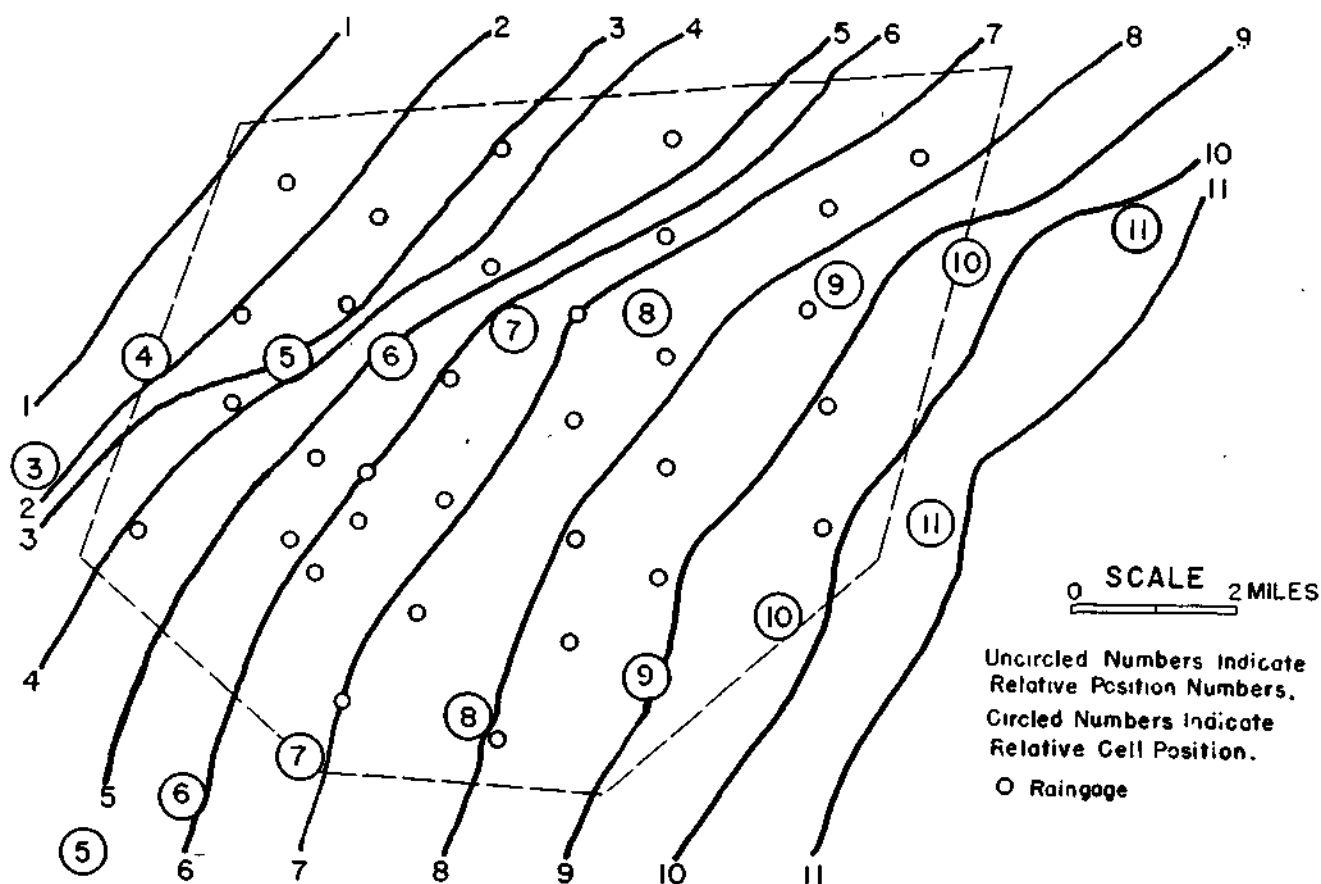


FIG. 32 RELATIVE MOVEMENT OF INDIVIDUAL ISOECHO CELLS AND THE PRECIPITATION ZONE

Table 2. Comparison of Actual Cell Movement with Resultant of Vector Diagram.

Storm date 1951	Wind level*	Resultant of Vector diagram		Cell Movement	
		Direction in degrees	Speed in nautical miles	Direction in degrees	Speed in nautical miles
6-26	6000	265	43	260	32
7- 8	**4000	230	40	245	42
7-22	8000	275	32	270	27
7-31	4000	270	24	265	24
8-20	8000	260	42	260	41
9-12	**6000	215	46	215	42
9-26	8000	245	39	250	45

* Rantoul winds aloft, except Johet wind aloft for 9-12 storm

**No winds available above this level.

produced a resultant that gave the best approximation to the cell movement with the exception of the 4,000 feet reported for the 8 July and 31 July storms.

If wind data above 4,000 feet had been available on 8 July, a better resultant vector might have been found with the 6,000-ft. or 8,000-ft. wind vectors. Wind data to 8,000 feet was available on 31 July. On this date the wind observation was taken when a cold front was apparently very near the observation station

according to the synoptic weather map. The wind veered abruptly from 240 degrees at 4,000 to 290 degrees at 6,000 feet and to 300 degrees at 8,000 feet. The wind at 6,000 to 8,000 feet may have been in the air mass behind the front and consequently not a representative wind vector for wind ahead of the front. This point was verified by an examination of wind aloft data at Indianapolis, Indiana, which was definitely ahead of the front. The wind from 6,000 to 8,000 feet was from 250 degrees.

It should be pointed out that using the forward vector movement of fronts and squall lines with wind vectors at different levels as the two main components which determine the movement of a cell is only a rough approximation. However, the evidence indicated that a relationship existed, either direct or indirect, between winds from 6,000 to 8,000 feet and cell movement. It is perhaps more logical to expect the winds aloft, in a layer to exert a greater influence on cell movement than the wind at one level. A wind vector at one altitude, however, may very well reflect the resultant or mean vector for a layer.

Some Factors Limiting the Utility of Radar for Quantitative Rainfall Measurements

Radar Performance Measurements

The electrical characteristics of a radar set must be accurately measured when it is used in determining rainfall intensities. The two parameters that seem to be most unstable are transmitter power output and receiver sensitivity. Transmitter pulse length and beam width may vary in special cases but generally can be assumed as constant. A one decibel change in either transmitter power or receiver sensitivity will produce approximately a 12 per cent change in calculated rainfall intensity. Thus it is important to know the absolute value of transmitted power and receiver sensitivity accurately.

The Water Survey has had war surplus equipment available for checking transmitted power and receiver sensitivity. The TS-13 and TS-263 operate in the 3 cm range, and the TS-155 operates in the 10 cm range. These sets are somewhat unsatisfactory. It is doubtful that the absolute accuracies are better than plus or minus three decibels, although relative accuracies of a few tenths of a decibel can be obtained. The calibrated attenuator dials are not finely divided, so interpolation is necessary to make readings closer than one decibel. Even if the dials did have fine divisions, accuracy would be poor, for the calibration will vary with the frequency. The specifications for a 9,000 mc f-m test set built by Sperry, the commercial equivalent of the TS-147, specifies a wattmeter accuracy of $\pm 1.5\text{db}$, using the calibration curve supplied with the instrument.

The same difficulties are found in receiver sensitivity measurements. The technique used in obtaining data required that the received power to produce a barely visible signal on the PPI be known. This "threshold of visibility" method introduced another important radar factor, the PPI brilliance setting. The brilliance must remain constant, or the received power will vary for threshold of visibility.

The manner in which the signal generator is connected to the wave guide directional coupler is also important. Experiments were conducted to determine how RG-8U and RG-9U flexible coaxial cable functioned at 9,000 mc. The attenuation of RG-8U was much greater than for RG-9U, but even more important was the change in attenuation introduced when the cable was bent or twisted. As much as 0.3 db/ft change was noted with RG-9U cable. The RG-8U had even greater change. If flexible coaxial cable is used with the test set, it should be kept to very short lengths. It would be much more desirable to use flexible waveguide.

Effect of Beam Width

The antenna beam width is quite important in quantitative measurements. The simplest relationship of received power to rain intensity is based upon the assumption that the rainstorm completely fills the beam to the half-power points. Corrections can be made if the beam is not completely filled but they are complicated and may introduce considerable error (14). The useful range of the radar is limited to that in which its beam is completely filled, unless extensive corrections are made.

The Thunderstorm Project (10) found that the initial radar echo usually had a height close to the freezing level although the thunderstorms grew to heights of over 25,000 feet. Therefore, it is assumed that the useful range of the radar for quantitative rainfall measurement is reached when the upper half-power point of the beam reaches the freezing level. Figure 33 is a graph showing how the freezing levels and beam widths will effect the useful range. An earth's effective radius of $4/3$ actual radius has been used. During summertime thunderstorms the freezing level is in the vicinity of 15,000 feet. With the 3-degree beam width of the APS-15, a 3-cm radar, the useful range is 50 miles. The TPL, a 10-cm set, with a beam width of seven degrees has a useful range of about 24 miles. However, other radar sets with a one degree beam width extend this useful range greater than 100 miles.

During late fall and early spring warm front rains, the freezing level is considerably lower, 10,000 feet or less. This would greatly reduce the useful ranges. Even with a 10,000-foot level the useful ranges are reduced to 35 miles for the 3-degree beam width and 18 miles for a 7-degree beam width.

These same limitations will apply to storms of small diameter. The Thunderstorm Project obtained a mean horizontal crosssectional area of about 10 square miles from 115 thunderstorms. Assuming the storms were circular, the mean diameter would be 3.5 miles. This would impose about the same range restrictions as the summertime freezing level.

Attenuation By Rainfall

During thunderstorms, rainfall of sufficient intensity to produce considerable attenuation often exists. No actual measurements of attenuation were taken, but attenuation values were calculated from rainfall rates along radials through the core of heaviest rain of several storms on the 50-square-mile GooseCreek network. These attenuation values are tabulated in Table

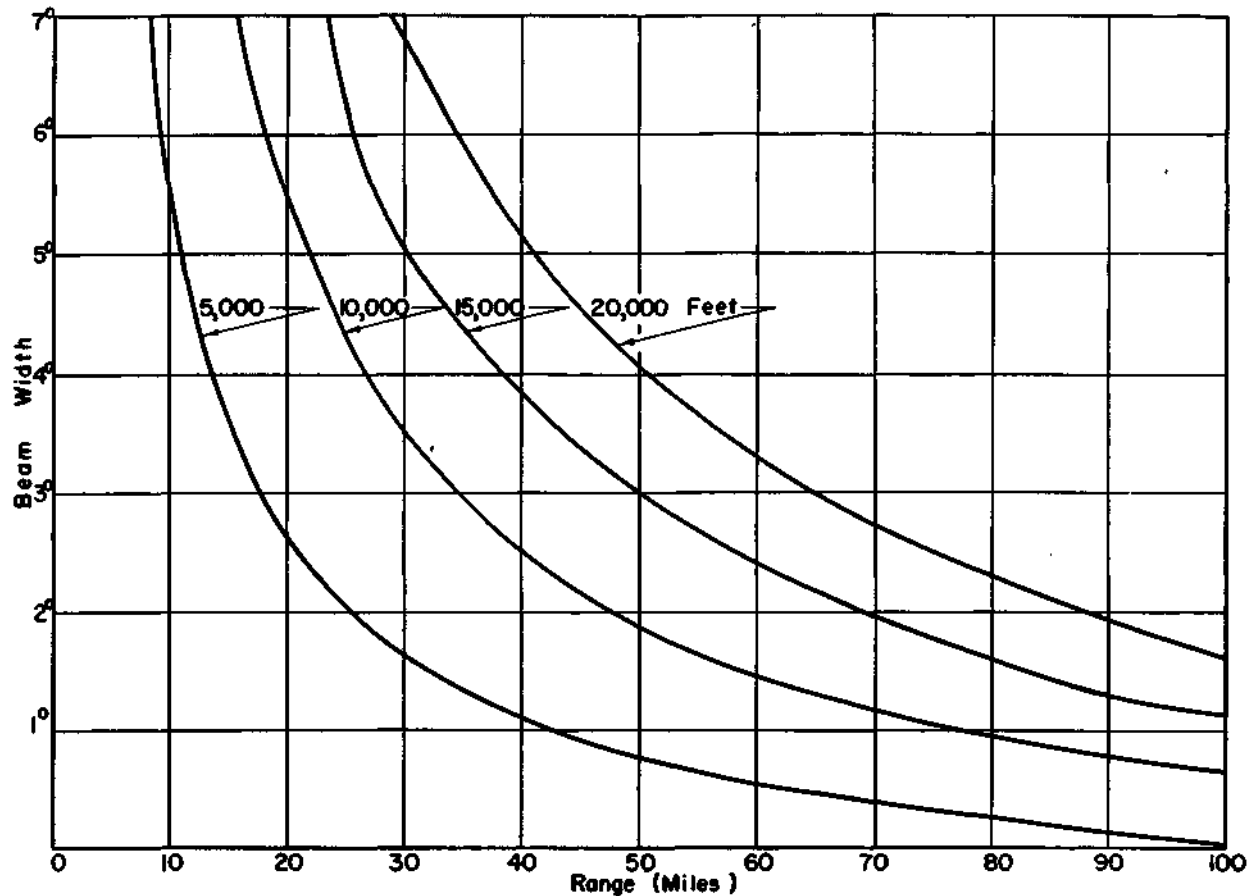


FIG. 33 UPPER HALF-POWER POINT OF BEAM AS A FUNCTION OF BEAM WIDTH AND RANGE

Table 3. Attenuation Introduced by Rainfall

Date	Time	Distance nautical miles	Rainfall Rate		Attenuation two way db
			Weighted average rainfall rate in/hr/nautical mile	Maximum In/hr	
6-8-51	0055-0056	3	2.63	3.60	23.0
6-19-51	1134-1135	3 3/4	1.01	3.60	11.1
6-26-51	0620-0621	6 1/2	3.22	6.00	61.1
6-26-51	0621-0622	6 1/2	2.86	6.12	54.3
6-27-51	2053-2054	6 1/2	1.56	2.40	29.6
6-27-51	2058-2059	6 1/2	2.07	3.60	39.3
7-9-51	0012-0013	4 1/2	1.34	1.80	17.6
7-9-51	0015-0016	6 1/2	1.92	3.60	36.4
7-22-51	1631-1632	3 3/4	1.78	2.58	19.5
7-22-51	2130-2137	4	2.15	3.00	25.1
9-12-51	1717-1718	4	1.63	4.80	19.0
9-12-51	1717-1718	5	3.05	4.50	44.5
9-26-51	2016-2017	5 1/2	1.80	3.00	28.9
9-26-51	2017-2018	6	2.88	6.00	50.5
9-26-51	2009-2010	6	1.20	2.10	21.0

3. One-minute amounts of rainfall from the raingage charts were used as rates. Attenuation values are equal to the product of a weighted average rainfall rate per mile along a radial through the rainfall core, the distance along the radial, and an attenuation coefficient. The attenuation coefficient used was .05 db/mi/mm/hr (9). Converting this coefficient to miles and inches gives an attenuation rate of 1.46 db/nautical mile/inch/hr.

The values of attenuation cover a range from a minimum of 11.1 db on 19 June to a maximum of 61.1 db on 26 June. The maximum rates do not necessarily give the greatest total attenuation. High average rainfall rates along a relatively long radial distance will produce the greater total attenuating effect on a radar beam.

These high values of attenuation should be compensated for when making point or areal rainfall studies with radar. Often the rear of the storm is blocked out, as well as isolated storms at greater ranges. Also attenuation will cause the core, as observed on the radar scope, to appear to be shifted toward the center of the scope from its actual location as shown on the raingage records.

Effect of Drop Size Distribution

Theory indicates that when the raindrop diameter is small compared to the wave length, the power reflected is proportional to Nd^6 ; where N is the number of drops in a given volume, and d is the radius of the drop. Various organizations working independently have arrived at similar relationships of Nd^6 to rainfall intensity. Their data also indicated that there may be considerable variation in the mean drop diameter for any particular rainfall rate. The effect of maximum and minimum mean drop diameter for a given rainfall intensity on the intensity computed from the return power has been calculated. Two sources of data have been used: Hood, (15), and Laws & Parsons (16).

Assume the radar is very accurately calibrated and the relationship $Nd^6 = 190 I^{1.72}$ (8) to be accurate, d is drop diameter in mm and I is rainfall intensity in mm/hr. At a rainfall rate of 1.0 mm/hr, $Nd^6 = 190$. However, for rainfall intensities of 1.0 mm/hr the outer limits of Hood's data give values as high as $Nd^6 = 800$. The maximum and minimum limits of drop diameters for a 1 mm rate measured by Laws & Parsons, applied to the same equation, resulted in in-

dicated rates from a maximum of 1.45 mm/hr. to a minimum of 0.48 mm/hr. The relative spread in drop size at higher intensities is about the same as for the rate of 1.0 mm/hr, so narrower limits at higher rates would not be expected. Thus, even though the radar is very accurately calibrated, it could indicate rainfall rates from 0.48 to 2.30 mm/hr for an actual rate of 1.0 mm/hr.

These limits indicate the accuracy that can be expected using radar to determine rainfall intensities, unless each type of rainfall has its own particular drop-size distribution and a separate radar-rainfall equation is applied to each type; or the drop sizes are more uniform at a given rate than present data indicate. With these points in mind the Water Survey decided to build a photographic sampling instrument to further investigate the shape and size-distribution of falling raindrops. A preliminary report entitled "A Raindrop Camera and Some Preliminary Results" By D. M. A. Jones, Meteorologist, Illinois State Water Survey has been published in "Proceedings of the Third Radar Weather Conference", 15-17 September 1952, McGill University, Montreal. A complete Technical Report on the instrument, including construction, operation, and results will be published in the future.

RAINFALL SUMMARY OF 1951 OVER GOOSE
CREEK NETWORK

Brief Discussion of Rainfall Data in Tables 4 to 15

A rainfall summary from May to October inclusive has been prepared in tabular form. The raingage network was not in operation during the other months of 1951. This summary includes storm, monthly, and seasonal totals for each gage. Maximum, minimum, and average rainfall for the gage network have been determined for each storm period. High rates for four storm periods have been tabulated in detail.

A storm period as used in this discussion has been arbitrarily defined on the basis of a time lapse without rainfall. A period of approximately six hours or longer between ending and beginning of rain was chosen as a sufficient time lapse to separate one storm period from another. Periods of less than six hours during which a major synoptic change might have been used as a basis for separating storms were not found.

Table 4 was prepared for the purpose of summarizing all rainfall periods for the 1951 thunderstorm season. The approximate duration of each rainfall period and the corresponding maximum, minimum, and average gage depths are presented in this table. An interesting comparison can be made by reviewing the data in this table for the whole network and for gage number 13. The records from gage number 13 give the results at a single observation station located near the center of the 59 square -mile network. As would be expected, there is often considerable error involved when a single gage observation is used as a sample even for an area as small as 59 square miles.

Another interesting comparison can be made between the maximum rate data recorded in Table 4. For the 13 storms for which maximum rate data were recorded, the single gage observation at gage 13 exceeded the highest rate for all gages only once and equaled it once. These data point out the much greater possibility of observing the higher rates by increasing the number of observations within a storm. All rates are based on one-minute amounts. One-minute amounts were only available for those storms for which the one-minute amounts had been prepared for comparisons between radar and raingage observations.

More detailed rate data for four of the 13 storms has been recorded in Tables 5 to 8 inclusive. Of the 13 storms for which one-minute amounts were available, these four represent those with the highest rainfall rates. This type of data was prepared chiefly to determine the magnitude, variability, and persistence of the higher rainfall rates within different storms over the network.

Total storm rainfall over Goose Creek network for the months of May to October inclusive is tabulated in Tables 9 to 15 inclusive.

Two gages (31a and 31b) were operated approximately six feet apart at station 31 (Figure 2) during 10 storms in August and September. Gage 31a and 17.78-inch diameter collector and 31b had a 12.648-

inch diameter collector. Simultaneous recordings by these gages are presented in Tables 12 and 13. The gage with the larger diameter collector recorded higher total amounts in 8 out of 10 cases. Except for two storms the difference in total rainfall recorded was relatively small. Two rather large differences of 0.12 inch and 0.14 inch occurred when the total rainfall exceeded one inch.

Table 4 Summary of 1951 Thunderstorm Rainfall by Storm Periods

Storm date		Duration of Storm Period			Comparison of gage 13 with network					
		No. Gages	Hours	Minutes	Min. Depth	Max. Depth	Ave. Depth	Depth Gage 13*	Max. Rate* in/hr. Gage	Max. Rate* in/hr. All gages
May	3 & 4	19		45"	.02	.37	.07	0		
"	5 & 6	17	11'		.18	.87	.31	0		
"	10 & 11	21	19'		.79	1.28	1.05	1.04		
"	20	27		30"	.04	.98	.34	.10		
"	22	26		45"	.09	.27	.17	.16		
"	26 & 27	30	17'		.68	1.38	.91	.89		
June	3	30	1'		.15	.30	.21	.19		
"	7 & 8	29	2'	30"	.38	1.43	.87	.72	2.7	5.34
"	12	31	5'		.18	.28	.23	.20		
"	16	30	6'		.30	1.06	.63	1.01		
"	17	31		15"	0	.24	.01	.03		
"	19	29	1'		0	1.15	.20	.03	1.08	5.4
"	22 & 23	31	3'	30"	.27	.63	.41	.48	3.54	3.54
"	26	31	1'		.11	.67	.38	.63	6.12	7.2
"	27	30	2'		.13	.40	.21	.24		
"	27	30	2'		.45	1.22	.82	.62	3.9	5.34
"	28	30	12'		.28	.43	.34	.32	.3	1.02
"	29	31		30"	0	.05	.01	.02		
"	30	31		30"	0	.02	.01	0		
July	3	30	1'		.21	1.32	.67	.56		
"	30	4'			2.22	3.39	2.82	2.92	3.78	6.0
"	11	31	7'		.19	.42	.25	.33		
"	17	30	5'		.04	1.50	.67	.60	5.1	6.06
"	22	29	1'		.26	.77	.53	.57	2.1	4.5
"	23	29	1'		.15	.51	.21	.23		
"	27	33		15"	0	.44	.12	.12		
"	31	33	1'	30"	.06	.61	.29	.21		
Aug.	6	34	4'		.69	1.16	.86	.89		
"	8	32	4'		0	.13	.06	T		
"	9	32		30"	0	.12	.04	.04		
"	15	33		30"	0	.06	.04	.03		
"	17	33		30"	0	.10	.04	.05	.3	1.86
"	20	33	6'		.40	.86	.57	.59	1.2	3.6
"	25	31	3'		.08	.20	.13	.12		
"	26	31	2'		0	.24	.11	.10		
"	27	32	1'		0	.10	.04	.06		
"	28 & 29	33	9'		.72	1.66	1.12	1.18		
Sept.	1	34	2'		.08	.48	.27	.26		
"	9	31	2'		.04	.20	.10	.17		
"	10	31	12'		.17	.33	.25	.26		
"	12 & 13	33	10'		.72	1.34	1.12	1.20	3.6	5.4
"	22	33	2'		.23	.66	.45	.50		
"	23	30	2'		0	.10	.08	.08		
"	24	30	1'		0	.06	.005	0		
"	25	30	7'		0	.16	.08	.16		
"	26	33		30"	.26	.79	.44	.59	4.8	7.02
"	30	33	1'		.04	.11	.07	.05		
Oct.	6 & 7	32	26'		.56	1.00	.85	.61		
"	22 & 23	28	24'		1.38	2.38	2.06	2.14		
"	27	11	2'		.07	.16	.10	M		
"	28	12	1'		.02	.05	.03	M		
"	29	33	1'		.02	.02	.02	.02		

* Based on one-minute amounts

** Gage 13 is near center of the network

M - Missing data

T - Trace

TABLE 5
Goose Creek Rainfall Rates
(June 26, 1951).

Gage No.	Storm Duration (Minutes)	Five Highest Rates (In/hr)					Storm Average (In/hr)
		Max.	2nd	3rd	4th	5th	
1	67	3.30	3.00	2.70a	1.92	1.68	0.03
2	67	3.60	3.12	2.88	2.40a	1.38	0.03
3	63	6.00	5.40a	3.60	3.30	2.70	0.05
4	62	5.10	4.92	4.80	3.30b	2.88	0.07
5	64	3.12	3.00	2.70	2.40	2.28	0.04
6	61	1.80b	1.68	1.62	1.32	1.26	0.03
7	59	3.60	3.00	2.76	2.28	1.62	0.05
8	59	6.00	5.70	4.50	3.90	3.30	0.06
9	63	7.20	5.40	4.80	3.30	2.70	0.05
10	61	2.04	1.56	1.38	1.08	1.02	0.02
11	59	1.20	1.08	.90	.72	.30a	0.01
12	62	2.28	2.04a	1.68	1.14	1.08	0.02
13	55	6.12	4.74a	4.68	4.56	2.52	0.07
14	62	2.58	.90	.78	.72	.66	0.01
15	59	2.10	1.98	1.50	1.20a	1.14	0.03
16	66	3.30	2.88	2.82	1.80	1.32	0.03
17	61	3.48	2.82	1.80a	1.50	1.20	0.04
18	64	4.20	4.02	2.70	2.40	1.68	0.04
19	65	2.80	2.22	1.86	1.44	1.26	0.02
20							
21	53	.72	.48	.36	.30	.24	0.01
22	55	.90	.78	.72a	.42a	.36	0.01
23	69	2.10	1.68	1.62	1.32	1.08	0.02
24	63	2.52	2.34	2.10	1.74	1.44	0.03
25	64	3.30	2.70	2.64	1.50	1.38	0.03
26	66	2.28	1.86	1.74	1.68	1.50	0.02
27	52	3.36	3.36	2.88	1.98	1.92	0.04
28	67	2.64	2.34a	1.86	1.74	1.50a	0.03
29	57	1.86	1.36	1.26	1.14	1.08	0.02
30	66	1.92	1.86	1.68	1.62	.78	0.02
	Min. rate	0.72	0.48	0.36	0.30	0.24	0.01
	Max. rate	7.20	5.70	4.80	4.56	2.88	0.07

*Based on one-minute amounts.

a - rate occurred 2 times

b - rate occurred 3 times

TABLE 6
Goose Creek Rainfall Rates*
(August 17, 1951).

Gage No.	Storm Duration (Minutes)	Max. rate (In/hr)	Storm Average (In/hr)
2	0		
3	63	.30	.06
4	0		
5	63	.12	.02
6	0		
7	M		
8	10	.42	.36
9	69	.06	.01
10	5	.06	.06
11	0		
12	35	.24	.03
13	32	.30	.05
14	36	1.26	.12
15	0		
16	0		
17	0		
18	18	.24	.06
19	17	.24	.12
20	54	.36	.04
21	34	.18	.04
22	40	.66	.12
23	20	.30	.06
24	13	.60	.12
25	0		
26	8	1.02	.24
27	0		
28	13	.60	.24
29	M		
30	37	.90	.18
31	19	.66	.06
32	M		
33	9	.42	.18
34	16	.12	.06

*Based on one-minute amounts.

1. Gage 31 had a 17.78 - inch diameter collector; other gages had 12.65 - inch diameter collectors.

M - Missing data

TABLE 7
Goose Creek Rainfall Rates*
(September 12, 1951)

Gage No.	Storm Duration (Minutes)	Five highest rates (In/hr)					Storm Average (In/hr)
		Max.	2nd	3rd	4th	5th	
1	26	2.10	1.80a	1.68a	1.62	1.50a	.84
2	26	2.40	2.16	1.98	1.92	1.32	.84
3	27	2.22	1.98	1.80a	1.62	1.50a	.84
4	30	2.40	1.92	1.80	1.62a	1.50a	.78
5	28	2.28	2.10	1.98	1.92	1.98	.84
6	28	2.10	2.04	1.80	1.68	1.50c	.90
7	M						
8	32	2.40	1.80a	1.68	1.50	1.32a	.78
9	48	2.-10b	1.80a	1.50c	1.20c	0.90c	.60
10	37	3.60	2.40	1.98a	1.80a	1.44	.90
11	33	3.30	3.00	2.70	2.40	2.10	.96
12	33	3.60	3.30	3.18	3.00	1.80a	1.14
13	32	3.60	3.30	2.60	1.80c	1.62a	1.20
14	34	2.82	2.70	2.40	2.10	1.80a	1.02
15	33	3.00	2.70	2.28	2.10a	1.92	1.08
16	31	3.00	2.40a	2.28	1.80d	1.68	1.08
17	36	2.40	2.22	2.10	1.80b	1.68	1.02
18	41	3.60	2.10d	1.92	1.44	1.38	.90
19	37	4.80	4.50	2.70	2.52	2.40	1.20
20	35	3.90	3.30	3.12	2.58	2.52	1.26
21	37	4.80	4.20a	3.00a	2.40b	2.28	1.26
22	36	4.80	3.60a	3.00a	2.10	2.04	1.14
23	36	5.34	4.20	3.66	3.00c	2.10	1.26
24	37	4.80	4.50	3.60	3.30	2.28	1.38
25	39	4.20	3.90	3.00a	2.40	1.98	1.26
26	35	3.00	2.40a	2.10a	1.80e	1.50	1.14
27	34	4.20a	3.00	2.40b	2.10a	1.44	.96
28	35	3.60	3.30	2.82	2.40	2.10	.84
29	44	3.00	2.70	2.40	2.10	1.92	.54
30	44	3.00	2.70	2.40	2.10	1.98	.66
31	39	5.40a	3.18	3.00a	2.10	2.04	.66
32	40	2.82	2.28	2.16b	1.98	1.68	1.02
33	38	3.60	3.00b	1.92	1.50a	1.38	1.02
34	39	3.30a	3.00a	2.22	2.10	1.62	1.08
35							

*Based on one-minute amounts

a - rate occurred 2 times

b - rate occurred 3 times

c - rate occurred 4 times

d - rate occurred 5 times

e - rate occurred 6 times

1. Gage 31 had a 17.78 - inch diameter collector; other gages had 12.65 - inch diameter collectors.

M - Missing data

TABLE 8
GOOSE CREEK RAINFALL RATES*
(September 26, 1951).

Gage No.	Storm Duration (Minutes)	Ten highest rates (In/hr)										Storm Average (In/hr)
		Max.	2nd.	3rd.	4th.	5th.	6th.	7th.	8th.	9th.	10th.	
1	50	4.80	3.48	3.00	1.68	1.32	1.20	1.02	.96a	.78a	.72	.54
2	46	3.00	2.58	2.40	1.50	1.26	1.20	1.02b	.96	.90a	.84	.48
3	49	5.40	4.80	3.60b	3.00a	2.70a	2.40	1.92	1.68a	1.20a	.90	.96
4	32	5.10	2.70	2.40	2.28	2.10	2.04	1.38	1.32	1.26	1.20a	.96
5	42	2.70	2.40a	2.28	1.80	1.50	1.20	.90	.60b	.30a	.24	.54
6	27	3.18	2.70	2.40	1.80	1.32	1.14	1.08	.90a	.78	.48	.72
7	32	3.30	3.24	1.98	1.92	1.80	1.38	1.32	.96	.84	.78	.84
8	30	2.40	2.10	1.80a	1.50	.90c	.78	.60a	.42	.30d	.18	.60
9	33	4.80	4.20	3.60	3.30	3.00	2.70a	2.40a	2.10a	1.80	1.50	1.26
10	38	4.20	2.22	1.98	1.80	1.50	1.38	1.26b	.96	.90a	.84	.66
11	41	3.60	2.70	2.10	1.80	1.32	1.20	1.08	1.02	.90	.78	.60
12	37	4.50a	4.20	3.90	1.92	1.50	1.38	1.20b	.90	.60	.54	.84
13	33	6.60	4.80	3.00	2.70	2.10a	1.80	1.50a	1.38	1.20	1.08	1.08
14	28	3.90	2.70	2.40	1.50	1.20	1.08	.90a	.78	.72	.60	.72
15	28	3.60	3.00	1.20	1.02a	.78	.60d	.30a	.24	.18a	.12	.54
16	28	1.98	1.62	1.50	1.38	1.20b	.90a	.72	.60a	.36	.30	.60
17	21	3.60	3.00	1.80	1.50	1.20	1.02	.90a	.60	.48a	.48	.84
18	30	3.90	3.30	2.70	2.40a	2.10	1.50a	1.20	.90a	.60	.48a	.90
19	33	6.00	5.52	5.10	3.60a	2.40	1.50	1.20	.90	.78	.60	1.08
20	35	3.90	3.60a	1.92	1.80a	1.50	1.20a	.90	.78	.72	.60a	.78
21	41	4.20	3.00a	2.58	2.28	1.80	1.50b	1.20a	1.02	.90	.60	.72
22	40	3.60	3.30	2.70	2.10	1.80	1.68	1.50a	1.32a	.78	.60b	.78
23	30	7.02	2.10	1.80a	1.50	1.44	1.20a	1.02	.96	.66	.60c	.90
24	32	4.20	3.72	3.48	2.82	2.70	2.40	1.98	1.80	1.20a	.60a	1.02
25	27	4.20	3.30	3.00	2.40	1.20a	.78	.60	.54a	.42	.24	.78
26	25	2.40	1.80	1.50b	1.20	.90a	.60b	.30	.06			.66
27	33	5.10	3.60	3.30	3.00a	1.80	1.50	1.20	.90	.72	.60b	.90
28	35	3.30	2.40a	1.80	1.50	1.20b	.90b	.72	.54a	.48	.42	.66
29	35	4.20	2.70	2.40	2.10	1.80	1.50a	1.08	.90	.78	.72	.72
30	40	4.80	3.60a	3.30	3.18	3.00a	2.70	2.40	1.50	1.20	1.02	.96
31 ¹	32	3.60a	3.00	2.28	2.10	1.80	1.32	.90	.72	.66	.48	.72
33	32	3.30	3.00a	2.70	2.40a	2.04	1.62	1.32	1.14	1.08	.66	.90
Min. rate		1.98	1.62	1.20	1.02	0.78	0.60	0.30	0.06	0.00	0.00	0.54
Max. rate		7.02	5.52	5.10	3.60	3.00	2.70	2.40	1.80	1.80	1.50	1.26

*Based on one-minute amounts.

a - rate occurred 2' times; b - rate occurred 3 times; c - rate occurred 4 times; d - rate occurred 5 times.

1. Gage 31 had a 17.78 - inch diameter collector; other gages had 12.65 - inch diameter collectors.

Table 9 Total Storm Rainfall

Goose Creek Network

May 1951

Gage No.	Day of Month						Total
	<u>3 & 4</u>	<u>5 & 6</u>	<u>10 & 11</u>	<u>20</u>	<u>22</u>	<u>26 & 27</u>	
1	.08	.23	1.10	.34	.14	.94	2.83
2	.13	.26	1.21	.34	.15	.86	2.95
3	.26	.26	1.16	.14	.17	.89	2.88
4	.37	.18	1.13	.09	.21	.87	2.85
5	.06	.23	1.08	.06	.22	1.06	2.71
6	.11	.33	1.12	.58	.22	1.38	3.74
7	.05	M	M	---.44---		.86	Inc.
8	M	M	M	.04	.16	.82	Inc.
9	.18	.23	1.09	.10	.16	.70	2.46
10	.15	-----1.45-----		.22	.15	.91	2.88
11	-----1.36*-----			.36	.13	.68	2.53
12	.00	.28	1.28	.20	.17	.78	2.71
13	M	M	1.04	.10	.16	.89	Inc.
14	.00	.23	.88	.15	.20	1.06	2.52
15	-----1.47*-----			.53	.24	1.30	3.54
16	.00	.87	1.10	.73	.20	1.17	4.07
17	.00	.56	1.12	.49	.21	1.26	3.64
18	.00	.28	1.02	.42	.16	1.10	2.98
19	.00	.22	1.27	.23	.15	.80	2.67
20	-----1.31*-----			.15	.15	.75	2.42
21	.00	.21	.90	.26	M	.68	2.05
22	.00	.28	.90	.27	.14	.74	2.33
23	.00	.28	.91	.38	.14	.72	2.43
24	-----1.48*-----			.98	.15	.72	3.33
25	.00	.43	1.09	---28---		1.02	Inc.
26	.02	M	M	.42	.22	1.09	Inc.
27	-----1.15*-----			.70	.27	1.00	3.12
28	M	M	.98	.68	.16	.86	Inc.
29	M	M	.85	M	M	.75	Inc.
30	M	M	.79	.33	.09	.78	Inc.
Average	.07	.32	1.05	.34	.17	.91	2.86

*Total

M Missing data

Inc - Incomplete

T - Trace

TABLE 10
TOTAL STORM RAINFALL
GOOSE CREEK NETWORK
June 1951

Gage No.	Day of Month													Total	
	3	7 & 8	12	16	12	12	22 & 23	26	27	28	29	30			
				0100-11300			2000-.2200			0900-1100					
1	.15	1.08	.19	.47	.00	M	.36	.38	.32	.45	1.39	.42	.00	.00	Inc.
2	.16	1.24	.18	.60	.00	.20	.36	.38	.27	.47	1.45	.43	.00	.00	5.74
3	.19	.96	.20	.58	.00	.22	.40	.58	.24	.50	1.68	.32	.00	.01	5.88
4	.20	.62	.20	.59	.00	.10	.37	.67	.20	.82	1.51	.28	.00	.02	5.58
5	.24	.55	.24	.63	.00	.17	.35	.50	.19	1.12	1.32	.36	.00	.02	5.70
6	.26	.54	.26	.47	.00	.27	.34	.37	.17	1.14	1.29	.32	.00	.01	5.44
7	M	.48	.24	.45	.00	.00	.36	.43	.22	1.22	1.38	.39	.00	.02	Inc.
8	.15	M	.18	M	.00	M	.32	.62	.14	.75	1.40	.28	.00	.01	Inc.
9	.20	.85	.22	.51	.00	.05	.39	.56	.24	.48	1.61	.33	.00	.00	5.44
10	.18	1.18	.21	.84	.00	.04	.39	.35	.28	.50	1.80	.40	.00	.00	6.17
11	.15	1.43	.21	.87	.00	.08	.39	.14	.36	.52	1.41	.36	.00	.02	5.94
12	.16	1.37	.19	1.06	.00	.05	.43	.28	.23	.56	1.92	.38	.03	.00	6.67
13	.19	.72	.20	1.01	.03	.03	.48	.63	.24	.62	1.76	.32	.02	.00	6.25
14	.22	.42	.25	.75	.00	.00	.35	.50	.17	.86	1.55	.28	.00	.02	5.43
15	.23	.42	.27	.64	.00	.12	.31	.31	.19	1.20	1.31	.31	.02	.02	5.41
16	.24	.52	.28	.60	.00	.11	.36	.37	.13	1.24	1.40	.34	.00	.01	5.60
17	.24	.42	.26	.67	.00	.04	.36	.41	.18	.83	1.48	.30	.00	.02	5.21
18	.19	.55	.20	.68	.00	.00	.50	.45	.17	.67	1.70	.28	.03	.00	5.42
19	.18	1.21	.21	.96	.04	.08	.44	.32	.22	.76	1.89	.31	.00	.00	6.62
20	.16	1.30	.20	.54	.00	.08	.42	.20	.22	.65	1.87	.35	.03	.00	6.02
21	.26	1.20	.25	.70	.00	.20	.35	.11	.40	.78	1.62	.41	.02	.02	6.33
22	.30	1.50	.24	.46	.08	.46	.44	.13	.23	.84	1.68	.39	.03	.01	6.30
23	.24	1.26	.23	.41	.24	.31	.43	.25	.23	.92	1.82	.33	.03	.00	6.70
24	.29	.75	.20	.30	.04	.22	.48	.35	.18	.99	1.74	.36	.00	.00	5.90
25	.23	.55	.22	.44	.00	.12	.50	.40	.16	.93	1.48	.32	.00	.01	5.42
26	.26	.38	.28	.71	.00	.06	.37	.32	.13	1.00	1.38	.31	.00	.02	5.22
27	.24	.83	.25	.58	.00	.22	.46	.40	.16	.96	1.54	.29	.00	.01	5.94
28	.22	M	.22	.41	.00	.40	.44	.41	.21	.92	M	M	.00	.01	Inc.
29	.19	.94	.22	.59	.00	.73	.50	.25	.20	.86	1.77	.36	.05	.01	6.67
30	.24	1.36	.27	.61	.00	1.15	.47	.22	.31	1.03	1.65	.41	.02	.02	7.76
31	.27	.59	.23	.70	.00	.11	.61	.37	.18	.96	1.75	.28	.00	.00	6.05
Average.	.21	.87	.23	.63	.01	.20	.41	.38	.21	.82	1.59	.34	.01	.01	5.92

M - Missing data
Inc. - Incomplete

TABLE 11
TOTAL STORM RAINFALL
GOOSE CREEK NETWORK
July 1951

Gage No.	Day of Month								Total
	3	9	11	17	22	23	27	31	
1	.47	2.25	.42	.72	.40	.20	.11	.06	4.63
2	.38	2.31	.23	.38	.58	.25	.13	.10	4.36
3	.23	2.49	.27	.50	.63	.24	.30	.23	4.89
4	.42	2.64	.34	.88	.64	.23	.19	.22	5.56
5	.53	3.31	.33	.64	.39	.21	.22	.31	5.94
6	.21	3.00	.26	.75	---54*-----		.44	.16	5.36
7	.49	3.39	.31	.57	.49	.21	.29	.26	6.01
8	.30	2.84	.23	.53	.39	.51	.09	.21	5.10
9	.41	2.69	.25	.65	.57	.20	.14	.23	5.14
10	.64	2.42	.19	1.10	.58	.31	.35	.21	5.80
11	.51	2.22	.19	.36	.41	.15	.29	.11	4.24
12	.76	2.69	.25	.36	---.90*-----		.20	.28	5.44
13	.56	2.92	.33	.60	.57	.23	.12	.21	5.52
14	.63	3.16	.24	.79	.71	.21	.08	.17	5.99
15	.31	3.18	.19	.82	.36	.19	.00	.22	5.27
16	.23	2.96	.22	.78	.26	.21	.00	.20	4.86
17	.44	3.16	.23	1.00	.58	.22	.00	.25	5.88
18	.86	2.96	.28	.54	.69	.24	.00	.22	5.79
19	.98	2.86	.32	.33	.50	.22	.04	.34	5.59
20	M	2.80	.28	.30	.53	.24	.10	.35	Inc.
21	.61	2.30	.24	.86	.40	.16	.32	.20	5.09
22	1.08	2.55	.25	.31	.43	.18	.19	.36	5.35
23	.98	2.68	.31	.04	.49	.23	.02	.48	5.23
24	1.20	3.02	.30	.64	.77	.20	.04	.42	6.59
25	.87	3.37	.34	1.03	.60	.20	.04	.34	6.79
26	.22	2.82	.20	1.04	.50	.22	.07	.24	5.31
27	.77	3.33	.26	1.50	.57	.16	.19	.56	7.34
28	1.27	3.01	.30	.93	.45	.18	.01	.61	6.75
29	1.23	3.05	.37	M	.44	.22	.03	.58	Inc.
30	1.32	2.60	.30	.16	.34	.17	.02	.40	5.29
31	1.09	over- flowed	.30	.98	.67	.21	.01	.33	6.59 (3.59)+
32							.05	.36	Inc.
33				installed 7/26/51			.00	.33	Inc.
Average	.67	2.83	.27	.67	.52	.22	.12	.29	5.56

*Total

M - Missing data

+ -3.00 inches added to monthly total of 3.59 inches as an approximation of the July 9th overflow.

Inc. - Incomplete

TABLE 12
TOTAL STORM RAINFALL
GOOSE CREEK NETWORK
August 1951

Gage No.	Day of Month										TOTAL
	6	8	9	15	17	20	25	26	27	28 & 29	
1	1.12	.04	T	.02	.06	.52	.20	.05	.00	.76	2.77
2	1.11	.07	.03	.02	.02	.54	.15	.06	.00	.90	2.90
3	1.16	.03	.03	.02	.04	.51	.13	.07	.03	1.21	3.23
4	1.02	.02	.02	.03	.02	.45	.09	.09	.04	1.42	3.20
5	1.00	.02	T	.02	.03	.56	.11	.15	.03	1.28	3.20
6	.77	T	.00	.02	.00	.79	.12	.15	.02	1.10	2.97
7	.78	.03	.03	.02	.08	.58	.12	.22	.01	1.08	2.95
8	.88	T	M	.04	.06	.40	.08	.10	.02	1.17	Inc.
9	.91	.03	.03	.06	.04	.54	.11	.06	.04	1.13	2.95
10	1.02	.13	.03	.02	.04	.54	.14	.07	.02	1.03	3.04
11	1.08	.03	.02	.02	.08	.51	.17	.05	.00	.75	2.71
12	.94	.13	.02	.03	.04	.50	.11	.06	.03	1.04	2.90
13	.89	T	.04	.03	.05	.59	.12	.10	.06	1.18	3.06
14	.87	T	.01	.04	.09	.45	.08	.24	.04	1.16	2.98
15	.75	.00	.04	.04	.00	.64	.12	.21	.02	1.09	2.91
16	.82	T	.05	.03	.00	.86	.18	.10	.04	1.04	3.12
17	.76	T	.02	.04	.00	.56	.13	.10	.09	1.21	2.91
18	.77	T	.02	.02	.04	.57	.12	.13	.10	1.15	2.92
19	.81	.07	.03	-.04	.04	.45	---24*---		.04	1.02	2.74
20	.80	.10	.02	.00	.06	.48	M	M	M	1.03	Inc.
21	.95	M	.07	.04	.03	.60	.14	.00	.01	.93	Inc.
22	.82	T	.12	.05	.08	.62	.12	.04	.00	.86	2.71
23	.75	T	.10	.05	.04	.44	.12	.04	.00	.91	2.45
24	.80	T	.07	.05	.06	.59	.15	.15	.08	1.24	3.19
25	.77	.00	.04	.05	.00	.71	.18	.15	.10	1.66	3.66
26	.85	T	.06	.05	.05	.75	.14	.10	.04	1.13	3.17
27	.71	T	.02	.04	.00	.51	.18	.11	.02	1.58	3.17
28	.69	T	.03	.06	.04	.60	---36*---		.00	1.11	2.89
29	.74	.00	.00	.04	.09	.64	.13	.04	.00	1.03	2.71
30	.85	.03	.03	.05	.10	.62	.13	.07	.00	.76	2.64
31a	.83	T	.07	.05	.02	.59	.16	.15	.09	1.40	3.36
32	.78	.00	.05	.06	.02	.59	.17	.18	.10	1.36	3.31
33	.76	T	.02	.06	.06	.57	.14	.15	.07	1.21	3.04
31b	.82	.00	.02	.04	.03	.57	M	M	M	1.28	Inc.
Average.	.86	.06	.04	.04	.04	.57	.13	.11	.04	1.12	2.97

*Total

M - Missing data

T - Trace

Inc. - Incomplete

Gage 31a had a 17.78 inch diameter collector.

Gage 31 b and other gages had 12.65 - inch diameter collectors.

TABLE 13
TOTAL STORM RAINFALL
GOOSE CREEK NETWORK
September 1951

Gage	Day of Month								TOTAL
	1	°	& 10	12 & 13	22	23	24 & 25	26	
1	.08	.36	1.20	.42	.08	.07	.46	.09	2.76
2	.11	.33	1.07	.36	.09	.13	.40	.08	2.57
3	.21	.39	1.16	.36	.07	.13	.79	.06	3.17
4	.23	.35	1.23	.37	.07	.11	.52	.06	2.94
5	.24	.38	1.34	.28	.06	.02	.37	.08	2.77
6	.34	.43	1.29	.23	-.06*	---	.31	.06	2.72
7	.27	.28	M	.30	--M--	---	.36	.05	Inc.
8	.16	.29	1.05	.36	.06	.05	.32	.04	2.33
9	.30	.32	1.10	.47	.08	.08	.69	.08	3.12
10	.15	.32	1.15	.47	.08	.14	.43	.09	2.83
11	.09	.32	1.10	.47	.09	.10	.40	.08	2.65
12	.24	.34	1.22	.47	.10	.11	.52	.08	3.08
13	.26	.43	1.20	.50	.08	.16	.59	.05	3.29
14	.34	.38	1.17	.43	.08	.03	.33	.08	2.84
15	.32	.34	1.23	.29	-.08*	---	.27	.07	2.60
16	.36	.36	1.17	.32	.02	.06	.28	.05	2.62
17	.35	.38	1.08	.45	.00	.09	.29	.06	2.70
18	.35	.31	1.08	.44	.08	.03	.46	.06	2.81
19	.27	.37	1.20	.59	.08	.15	.59	.09	3.34
20	.18	.38	1.28	.59	.09	.10	.47	.08	3.17
21	.11	.32	1.21	.66	.07	.15	.51	.08	3.11
22	.25	.33	1.03	.63	.10	.14	.52	.09	3.09
23	.17	.33	1.24	.60	.10	.11	.43	.10	3.08
24	.39	.33	1.26	.52	.10	.09	.55	.08	3.32
25	.40	.43	1.27	.60	.08	.03	.33	.07	3.21
26	.48	.35	1.03	.26	.08	.00	.26	.05	2.51
27	.42	.25	.88	.46	.10	.03	.48	.06	2.69
28	.35	.33	.83	.50	.10	.15	.40	.08	2.74
29	.22	.28	.72	.46	.10	.07	.41	.08	2.34
30	.16	.28	.81	.41	.09	.12	.65	.11	2.63
31a	.41	.40	1.22	.53	.08	.03	.39	.07	3.13
32	.36	.34	1.05	.62	.08	.03	.32	.06	2.86
33	.37	.37	1.04	.58	.06	.06	.47	.07	3.02
31b	.39	.41	1.08	M	M	M	M	M	Inc.
Average	.27	.35	1.12	.45	.08	.08	.45	.07	2.86

* [F.]
i otai
M-Missing data
T - Trace
Inc. - Incomplete
Gage 31E had a 17.78 - Inch diameter collector.
Gage 31 b and other gages had 12.65 - inch diameter collectors.

TOTAL 14
TOTAL STORM RAINFALL
GOOSE CREEK NETWORK
October 1951

Gage No.	Day of Month					TOTAL
	6 & 7	22 & 23	27	28	29	
1	.94	2.28	M	M	.02	Inc.
2	.92	2.20	.08	.05	.02	3.47
3	.96	2.10	.10	.02	.02	3.20
4	.88	1.95	---.09*	---	.02	2.94
5	.95	2.38	.08	.04	.02	3.47
6	.80	2.14	---.20*	---	.02	3.16
7	1.00	1.38	.16	.02	.02	2.58
8	.76	1.90	.07	.03	.02	2.78
9	.86	2.19	.10	.05	.02	3.22
10	.93	2.31	---.11*	---	.02	3.37
11	.86	2.35	M	M	.02	Inc.
12	.90	2.26	---.10*	---	.02	3.28
13	.61	2.14	---.12*	---	.02	2.89
14	.84	2.00	---.13*	---	.02	2.99
15	.79	1.92	.10	.02	.02	2.85
16	.74	1.92	---.20*	---	.02	2.88
17	.83	2.19	M	M	.02	Inc.
18	.82	2.10	---.05*	---	.02	2.99
19	.88	2.16	---.09*	---	.02	3.15
20	1.02	2.16	---.08*	---	.02	3.28
21	M	M	M	M	.02	Inc.
22	.85	2.14	---.13*	---	.02	3.14
23	.83	2.04	.09	.02	.02	2.99
24	.99	2.22	---.16*	---	.02	3.39
25	.81	2.10	---.16*	---	.02	3.09
26	.75	1.96	---.13*	---	.02	2.86
27	.81	2.06	---.28*	---	.02	3.17
28	.85	2.16	---.12*	---	.02	3.15
29	.77	2.05	.10	.02	.02	2.96
30	.86	2.05	M	M	.02	Inc.
31	.98	2.32	.11	.02	.02	3.45
32	.90	2.12	.09	.03	.02	3.16
33	.56	2.10	.09	.02	.02	2.79
Average	.85	2.10	.11	.03	.02	3.11

* Total
M - Missing data
Inc. - Incomplete

Table 15. Goose Creek Network Total Rainfall
1951

Gage No.	May	June	July	Aug.	Sept.	Oct.	Total
1	2.83	*5.70	4.63	2.77	2.76	3.24	21.93
2	2.95	5.75	4.36	2.90	2.57	3.47	22.00
3	2.88	5.87	4.89	3.23	3.17	3.20	23.24
4	2.85	5.58	5.56	3.20	2.94	2.94	23.07
5	2.71	5.70	5.94	3.20	2.77	3.47	23.79
6	3.74	5.44	5.36	2.97	2.72	3.16	23.39
7	*3.05	*5.45	6.01	2.95	*2.55	2.58	*22.59
8	*2.35	*5.50	5.10	2.75	2.32	2.78	*20.80
9	2.46	5.44	5.14	2.95	3.12	3.22	22.33
10	2.88	6.16	5.80	3.04	2.83	3.37	24.08
11	2.53	5.93	4.24	2.71	2.65	3.23	21.29
12	2.71	6.66	5.44	2.90	3.08	3.28	24.07
13	*2.30	6.45	5.52	3.06	3.27	2.89	*23.49
14	2.52	5.44	5.99	2.98	2.84	2.99	22.76
15	3.54	5.41	5.27	2.91	2.60	2.85	22.58
16	4.07	5.63	4.86	3.12	2.62	2.88	23.18
17	3.63	5.21	5.88	2.91	2.70	3.04	23.38
18	2.98	5.41	5.79	2.92	2.81	2.99	22.90
19	2.67	6.62	5.59	2.74	3.34	3.15	24.11
20	2.42	6.02	*5.30	*2.70	3.17	3.28	*22.89
21	2.05	6.35	5.09	2.77	3.11	*3.20	*22.57
22	2.33	6.30	5.35	2.71	3.09	3.14	22.92
23	2.43	6.70	5.23	2.45	3.08	2.99	22.88
24	3.33	5.92	6.59	3.19	3.32	3.39	25.74
25	*3.60	5.36	6.79	3.66	3.21	3.09	*25.71
26	*3.80	5.22	5.31	3.17	2.51	2.86	*22.87
27	3.12	6.14	7.34	3.17	2.69	3.17	25.63
28	2.68	*6.35	6.75	2.89	2.74	3.15	*24.56
29	*2.48	6.65	*6.30	2.71	2.34	2.96	*23.44
30	1.99	7.75	5.29	2.64	2.63	2.93	23.23
31	*3.40	6.10	6.59	3.36	3.13	3.45	*26.03
32	*3.45	*5.55	*6.80	3.31	2.86	3.16	*25.13
33	*3.20	*5.95	*6.35	3.04	3.02	2.79	*24.35

* Estimated Values

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