A QUANTITATIVE STUDY OF RAINFALL MEASUREMENT BY RADAR

By

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To my wife, Janet, and four children, Sharon, Diane, John, and Joe, in recognition of their inspiration and encouragement, this thesis is dedicated.

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CHAPTER I

INTRODUCTION

The measurement of rainfall has been a problem facing man for hundreds of years. At best, this measurement is only an estimate of the rainfall that covers the earth during a storm or any other continuous interval of time. As early as 400 B.C., man has attempted to record rainfall with small catchment basins (Kurtyka, 1953). Measurement of the water collected in these containers gave him knowledge of the amount of rainfall in the vicinity of his abode. This crude sampling process combined with careful record keeping was the method of measuring rainfall then and it is essentially the same method used today.

Technological advances of man have helped solve this problem. However, there still exists the need for a better estimate of rainfall. The meteorologists, hydrologists, engineers, and scientists are usually never satisfied with the rainfall data available to them for use in studies concerning water usage. The sampling process for collecting these data and the instruments used have always been a subject of criticism. With the sparse spacing of rain gages and the inherent errors in their operation, the need for a better method of measuring rainfall is recognized as a major field for weather research. Investigators working in this field are constantly searching for new devices and techniques to aid in the solution of this problem.

During World War II radar was developed for detecting enemy air craft and naval surface vessels. It was also noted that radar would detect the occurrence of rainfall in the range of its beam. At the time, this hindered the intended use of radar. However, it was hypothesized that it might have possibilities as a tool for studying rainfall characteristics.

After the war, work started in developing radar to measure rainfall. A relationship was needed to relate the measurements made by radar to actual rainfall on the surface of the earth. To develop this relationship, two facilities are necessary: (1) A dense network of recording rain gages, and (2) a weather radar. For various reasons these two facilities have never been available in close proximity for the study necessary to derive the relationship.

These two facilities now exist in central Oklahoma, close enough to each other to allow a detailed study of measurement of rainfall by radar. This thesis presents results of a study to develop a relationship for converting radar measurements to surface rainfall. This study is intended to provide data and analyses which will improve the method of estimating rainfall.

CHAPTER II

REVIEW OF LITERATURE

Radar Theory

The theory of radar must be thoroughly understood before good use can be made of it in studying meteorological phenomena. The application of radar to this study relies on the parameters of the radar used. Pulse length, pulse interval, wave length, receiver sensitivity, beam width, peak power transmitted, and antenna gain are parameters that will either limit the application or influence the presentations on the radar scopes. Therefore, the effect of these parameters upon the limitations and interpretations must be understood before analyses of data can be made.

At least two good text books are available that deal with the use of radar as a meteorological tool. These books by Hiser (1) and Battan (2) give the theory of weather radar and its applications. A review of these or similar references is essential to anyone working in the field of radar meteorology.

In general, there are two types of radar, the continuous wave and the pulsed wave. The pulsed wave is the type commonly used in meteorological work, although there are applications for the continuous wave type. The pulsed wave radar usually consists of eight major components. These are as follows:

1. The trigger generator or timer. This is the most important part of a radar because it controls the pulse and timed intervals of the radar system.
2. The modulator, which forms the pulsating DC signal from the input AC electrical current that is taken from the power source.
3. The transmitter. This component takes the pulsating DC signal from the modulator, transforms it to radio frequency and transmits it to the antenna.
4. The duplexer or TR switch which regulates the transmission of the outgoing signal to the antenna and the returning signal from the target.
5. The antenna forms and reflects the outgoing signal into a beam and catches the returning signal from the target.
6. The scanner, which rotates the antenna at a given speed in the direction or plane desired.
7. The receiver. This component accepts the returning signal through the duplexer, then transforms and amplifies it to a video signal.
8. The indicator unit, which transforms the video signal and portrays it in such a manner as to show range, height, area density, thickenss, and bearing to the target.

These common major components of pulsed radar are generally connected in a manner as shown in the line diagram of Figure 1. The pulsed wave radar sends out one pulse and then waits for a period of time equal to that necessary for the pulse to reach the maximum range

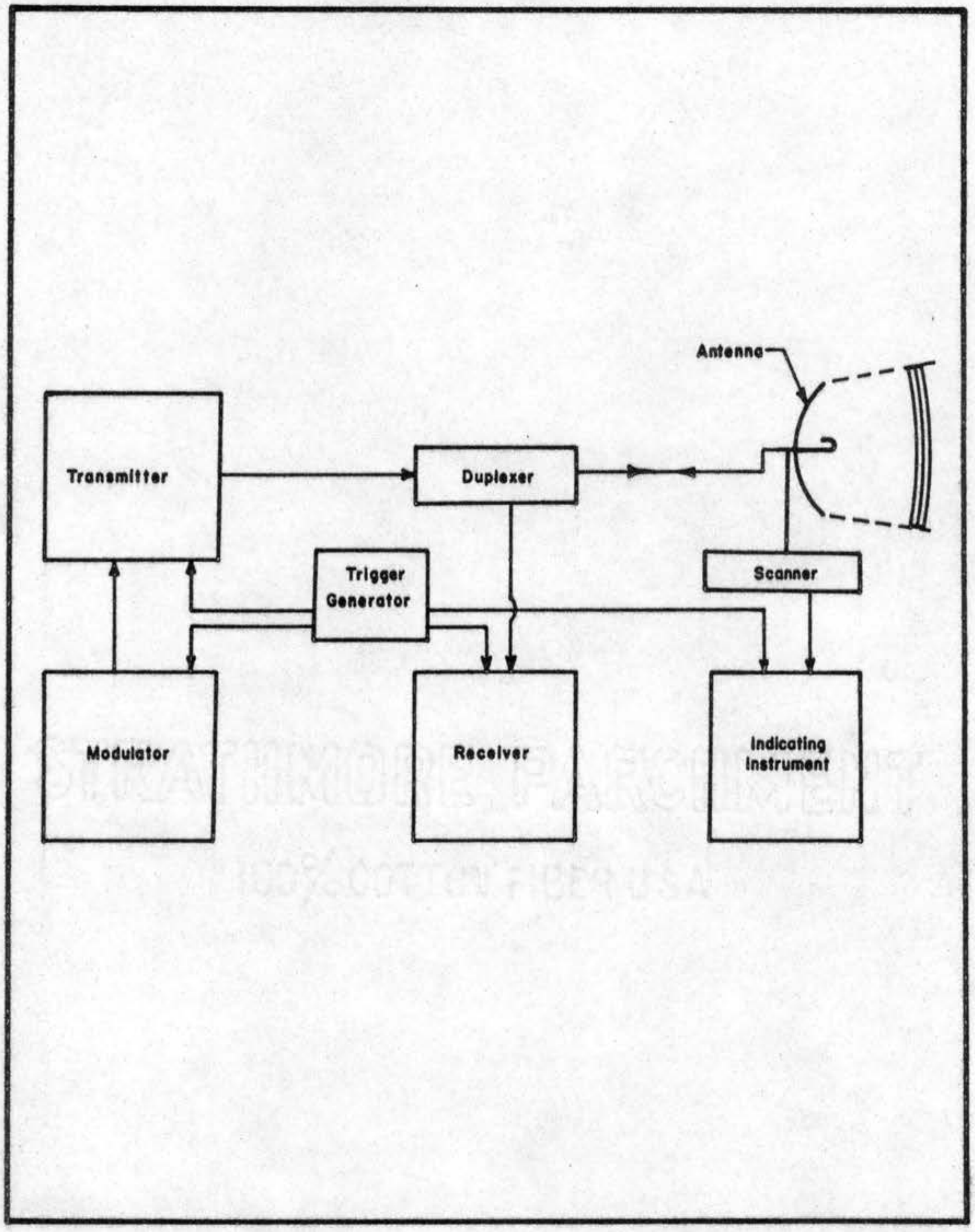


Figure 1. Line diagram of typical pulsed wave radar showing major components.

of the radar and return before it sends out another pulse. If the pulse strikes a target, some of the pulse is reflected back to the radar, where it is presented on the indicator units or scopes. This entire process is repeated several hundred times each second. The radar, in effect, senses the speed of propagation, the direction the antenna is pointed and its elevation, and can by appropriate indicating devices, give the range to the target, the azimuth, and the height of the target above the radar. The strength of the returning signal, that is, amount of pulse reflected back to the radar from the cross-section of the target intercepted by the beam, will give the intensity of the target.

The height of the target is the height of the sample volume that the radar sees. In Figure 2, an example is shown of how a radar samples a storm. The height of the cross-section of the storm intercepted by the radar beam is dependent upon the elevation of the radar antenna and range of the target from the radar site. For meteorological targets, it is very important that the height of the storm be known. The storm at 10-mile range in the example (Figure 2) is being sampled in the area where rain is falling from the storm. The storm at 100-mile range is being sampled at a greater height due to the curvature of the radar beam with respect to the curvature of the earth's surface. Because the presentations or echos seen on the radar scopes are representative of the sample volume taken by the radar beam, the beam should be within the portion of the storm where fallout of rain particles is occurring. This fact makes comparison of radar observations with surface observations very difficult, but these comparisons can be made within limits when all the pertinent conditions are known.

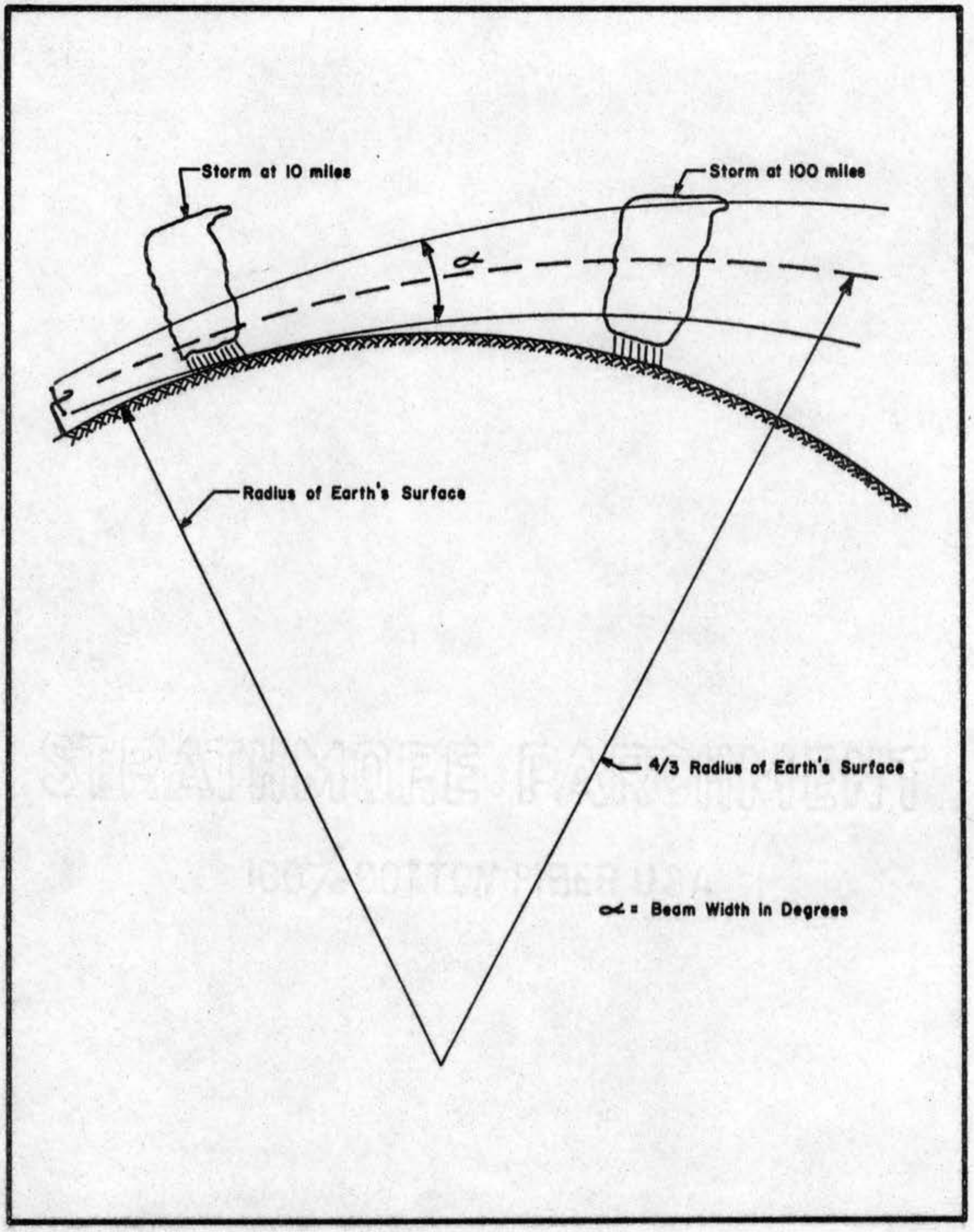


Figure 2. Diagram showing the radar sampling of storms. Storm at 10-mile range is sampled at a lower height than storm at 100 miles.

Another important factor influencing radar is the propagation of the transmitted radio frequency wave through the atmosphere. Here again, a good knowledge of the theories that apply must be had in order to interpret the data given by radar. It is usually assumed that a standard atmosphere is present when using radars theoretical equations. This, as it turns out, is the exception instead of the rule. Departures from the standard atmosphere produce different types of abnormal propagation, depending upon the nature of the conditions that exist. Radar will give presentations that may be interpreted erroneously by the untrained observer. Persons working with film of radar scopes must be able to qualify each observation as to the nature of the echo. To do this, he must have a knowledge of the conditions that produce the erroneous presentations. Also, experience gained from working with radar and radar film data is helpful in interpreting radar scope presentations.

Radar Equation

The evolution of radar as an instrument for the measurement of precipitation started during the latter part of World War II. It was noted that rainfall had a definite effect upon the propagation of microwaves emitted from the radar. This effect, echo presentation on the radar scope, was investigated later to obtain the spatial distribution of precipitation. Later investigations have been conducted to develop techniques to make quantitative measurements of precipitation, and to detect and track severe storms.

The theory supporting measurement of precipitation by radar has been developed by early investigators in this field, such as Marshall, Langille, and Palmer (3). These men reported in their study that the power reflected from rain was proportional to Z, the sum of the sixth power of the diameters of raindrops contained in a representative volume. They also derived mathematically a relationship for the power received by the radar which was given as follows:

$$P_r = \frac{P_t \pi^4 A\, h\, (n^2 - 1)^2}{8\, R^2\, L^4\, (n^2 + 2)^2}\, Z \qquad [1]$$

Where,

P_r = Power received by the radar from the target

P_t = Power transmitted by the radar

A = Area of the antenna

n = Indices of refraction for water

L = Wave length of transmitted radar beam

h = Pulse length of radar

R = Range to target

Z = Reflectivity - Summation of the sixth power of the diameters of raindrops divided by a specific volume

Reflectivity - Rainfall Relationship

The Z term (reflectivity) was related to rainfall intensity by Marshall (3). Several hundred samples of raindrops caught on filter paper were used to determine relationship between Z and the rainfall intensity I. This relationship was stated as

$$Z = aI^b \qquad [2]$$

Where, Z = Reflectivity

I = Rainfall intensity

a = Intercept on a log-log plot

b = Slope of the line on a log-log plot

The values of a and b reported by the Marshall et. al. study were:

$a = 190$

$b = 1.72$

If the above relationship for Z is substituted in the theoretical equation developed for the power received by the radar, the following equation results:

$$P_r = \frac{K\ P_t\ a\ I^b}{R^2} \qquad [3]$$

In this equation, K is a constant formed by the evaluation of the parameters of the radar and the refraction indices of water. It was hypothesized that this equation could be used to make radar rainfall measurements. Other investigations were conducted to relate Z to I for other climatic areas.

Perrie (4) conducted a study in Ontario, Canada in 1945 to investigate radar echoes from rain. Filter paper was used to collect data on rain drop size and distribution. Values of Z were determined at ranges of 14.5 to 55.5 kilometers from the radar. Rainfall intensity was also related to range from the radar. The principal contribution of this study was determination of amounts of rainfall necessary to produce an echo at a given range from the radar site. Results of the investigation showed that rainfall occurred at a value of $Z > 0.8\ R^2$ and $I > 10^{-3}\ R^2$.

It was concluded that when the radar beam was filled with rain, the power received from the echo was inversely proportional to R^2 and directly proportional to Z. These findings confirmed the earlier theoretical equations proposed by Marshall.

Other investigations have been conducted to determine the relationship between Z and I. Many techniques and methods of collecting data have been tried. Jones (5) in Illinois, used a photographic technique to determine distribution of drop size in a specific volume of rainfall. Laws and Parsons (6) developed a technique of using trays of flour exposed to rain to collect drop size distribution data for natural rainfall. Russian investigators have reported the use of a photoelectric device to determine the number of drops and their size in a sampled volume of rain. Mikrov (7) reported the use of an instrument taken aloft in an aircraft to sample rainstorms at heights of 300 to 1,000 meters. Regardless of the methods, devices, or techniques used for the measurement of drop size and distribution for various rainfall intensities, the process is very time consuming, tedious, and difficult to accomplish. Stout (8), reporting on work done by the Illinois State Water Survey, stated the seriousness of the problem by the following example. Two years of work done in sampling of rainfall for drop size determination had produced data from a volume of approximately 1,100 cubic feet of rainfall. Over 500 million cubic feet of rainfall is sampled in a volume of rainfall at a range of 30 miles from the radar by a single pulse of the beam.

A closer look at the results of investigations in this field of research shows large discrepancies in the values that relate Z to I. Hiser (1) lists a table that summarizes the findings of seven researchers working on this problem in various parts of the world. The values of a and b derived from the findings for these various climatic zones vary from 127 to 505 for a and 1.41 to 2.29 for b. Hiser used the following relationship given by Gunn and East (10) as the mean of the closest ten grouped Z-I relationships given:

$$Z = 353\ I^{1.52}\ \mathrm{mm}^6/\mathrm{m}^3 \qquad [4]$$

Dimaksyan, Zotimov, and Zykov (12) list a summary of work done in the Soviet Union. The values of a and b varied approximately the same as those conducted elsewhere in the world depending on the climatological characteristics of the area in which the investigations were conducted. The values of a and b reported ranged from 207 to 405 for a and 1.39 to 1.70 for b.

Not all studies using radar to measure precipitation have relied upon the knowledge of an appropriate Z-I relationship. Byers (9) reported a study made in Florida using a radar and a dense network of rain gages covering a 50-square-mile area. The object of this study was to calibrate the radar with data from the rain gage network. The radar could then be used to measure rainfall over the area covered by its beam. The results of this study showed that the area of the echo and the area of rainfall were related. Also, the height and volume of the echo were related to the amount of rainfall measured on the surface of the earth. Conclusions from the results of this early work stated that radar has the potential for measuring rainfall over a small area in a manner many times more accurate than is possible by existing rain gage distributions. However, this goal has yet to be accomplished.

Photographic Integration

Another method of relating the rain echo presented on a radar scope with surface rainfall, was reported by Hiser, Senn, and Conover (1). This method was described as a photographic integration of the radar scope presentation. The radar scope was photographed continuously by multiple exposure for periods of one to two hours. The resulting photographs were then analyzed with a photo-densitometer at points corresponding to recording rain gage locations. A network of 71 recording rain gages was used for surface rainfall measurements. The results of this study indicated that carefully controlled photographic procedures and film processing must be maintained for the successful calibration of the radar to the rain gage data. It was concluded that a method had been devised to measure rainfall by radar. It was also implied that a better radar was needed for operational use in rainfall measurement.

A similar study conducted in Texas by Ligda, Bigler, Tarble, and Truppi (13), used the multiple exposure technique of photography to relate radar echos to surface rainfall. One feature of this study was the use of existing data and facilities for research purposes. This noteworthy report of investigations into the use of radar as a tool for hydrological and climatological work was a significant contribution to the state of the art. Recommendations and conclusions set forth in this report were used as guide lines by later investigators.

Many other investigations have been made regarding radar rainfall measurements. Studies made by Austin (14), Tarble (15), Ryde (17), Wallace (16), Hitschfield (18), and Ackerman (19), have contributed to the knowledge of the application of radar to measurement of rainfall. Although findings reported from these studies did not always agree, they did add information about the characteristics of the radars, the techniques, and the approaches used to solve the problems involved.

Integrating Devices

Another problem associated with radar data is the difficulty in collecting and reducing it to a meaningful form. The film techniques developed by various people are adequate as a record of the radar operation. However, the volume of data collected does present a problem to the research analyst. The conversion of film data to a quantitative form is a tedious, time consuming process, as anyone who has worked with radar film data will testify. This fact has been recognized and attempts have been made to remedy it by developing devices to automatically present digital output from the radar.

One study reported by Muller (20) described a device called an area integrater, which was developed to compute areal rainfall from information supplied by radar. This was accomplished by electronically converting the echo return from a rainstorm to a mean rainfall value for the area of the study. The integrater was evaluated with surface measurements of rainfall from a recording rain gage network consisting of 55 stations. It was concluded from this evaluation that the accuracy of the integrater was limited by the radar available and the lack of knowledge of a Z-I relationship. Further investigations of the Z-I relationships would be necessary before the integrater could be developed.

Work is continuing in the development of integrating devices for radar data. Also, an adequate weather surveillance radar, the WSR-57 has been developed by the Weather Bureau. Flanders (21), gave a summary of work being done throughout the United States, where the WSR-57 radars were installed. Included in this summary was a description of an integrating device that provides hydrologists and meteorologists with instantaneous values of rainfall necessary for accurate flood forecasting. The Z-I relationship used by this integrating device was reported to be inadequate by a factor of two to measure rainfall accurately.

CHAPTER III

THE STUDY

Objectives

The present study was undertaken to determine a relationship between radar film data of rainstorms and surface rainfall measurements. This study was conducted using data from a weather surveillance radar and a dense network of recording rain gages. Although the data provided by these facilities are more detailed than those normally recorded, the relationship derived from this study could be used with routinely collected data from a weather radar station. This routine data would be that available in most instances.

Specific objectives are:

1. To determine the frequency of observation of the radar signal necessary to give the best correlation with surface rainfall measurements.
2. To relate radar signal strength with quantitative estimates of surface rainfall.

Assumptions

Several assumptions were made concerning the data used in this study. It was assumed that no atmospheric abnormalities were present to influence the radar data collection at those intervals selected for study. It was assumed that the radar used in this study was in calibration during the periods of time that the data were being collected. Data was available from periodic calibration tests of the radar. These are shown in Table 1. Operating characteristics for the radar used in this study are shown in Table 2.

It was assumed that the individual rain gages of the rain gage network were in adequate calibration and that the data from these gages were within the range of justifiable tolerances. The maps used to locate the rain gages in respect to the radar were assumed to be accurate enough for this study. Figure 3 is a map of the study area and shows the radar location.

Radar Data

The radar data necessary for this study consisted of 35 mm film of the radar PPI scope (Plan Position Indicator scope). This data was collected by personnel of the Weather Bureau at Oklahoma City Airport Station and by personnel of the National Severe Storms Projects conducted in Central Oklahoma. During the spring and early summer months of each year, these two groups of Weather Bureau personnel make a detailed study of thunderstorms occurring within range of the WSR-57 radar located at Will Rogers Field. In 1962, step-gain pictures of the PPI scope were made of several storms. Copies of these film data were obtained from the National Weather Records Center at Ashville, North Carolina.

Some explanation of commonly used radar terms that will appear in this thesis should be given before continuing. Such terms as PPI scope,

TABLE I

CALIBRATION DATA FOR THE WSR-57 RADAR
OKLAHOMA CITY, OKLAHOMA 1962

Minimum Detectable Signal (dbm)*

	Meter Reading		
Date	20	30	40
April 18	107	103	97
May 1	110	105	99
May 15	111	106	100
May 25	110	107	99
June 1	112	109	102
June 20	112	110	102

Peak Power Transmitted (Long Pulse) 400 kw.

Peak Power Transmitted (Short Pulse) 500 kw.

*Decibel below a milliwatt.

TABLE II

OPERATING CHARACTERISTICS OF THE WEATHER BUREAU WSR-57 WEATHER SURVEILLANCE RADAR, OKLAHOMA CITY, OKLAHOMA

Peak Power Output	500 kw.
Wave Length	10 cm.
Pulse Length	
Long	4 micro. sec.
Short	0.5 micro. sec.
Minimum Detectable Signal	
Long Pulse	103 dbm.
Short Pulse	93 dbm.
Pulse Repetition Frequency	
Long Pulse	164 per sec.
Short Pulse	656 per sec.
Antenna (Parabolic bowl)	12 ft. dia.
Beam Width	
Horizontal	2.2 degrees
Vertical	2.2 degrees

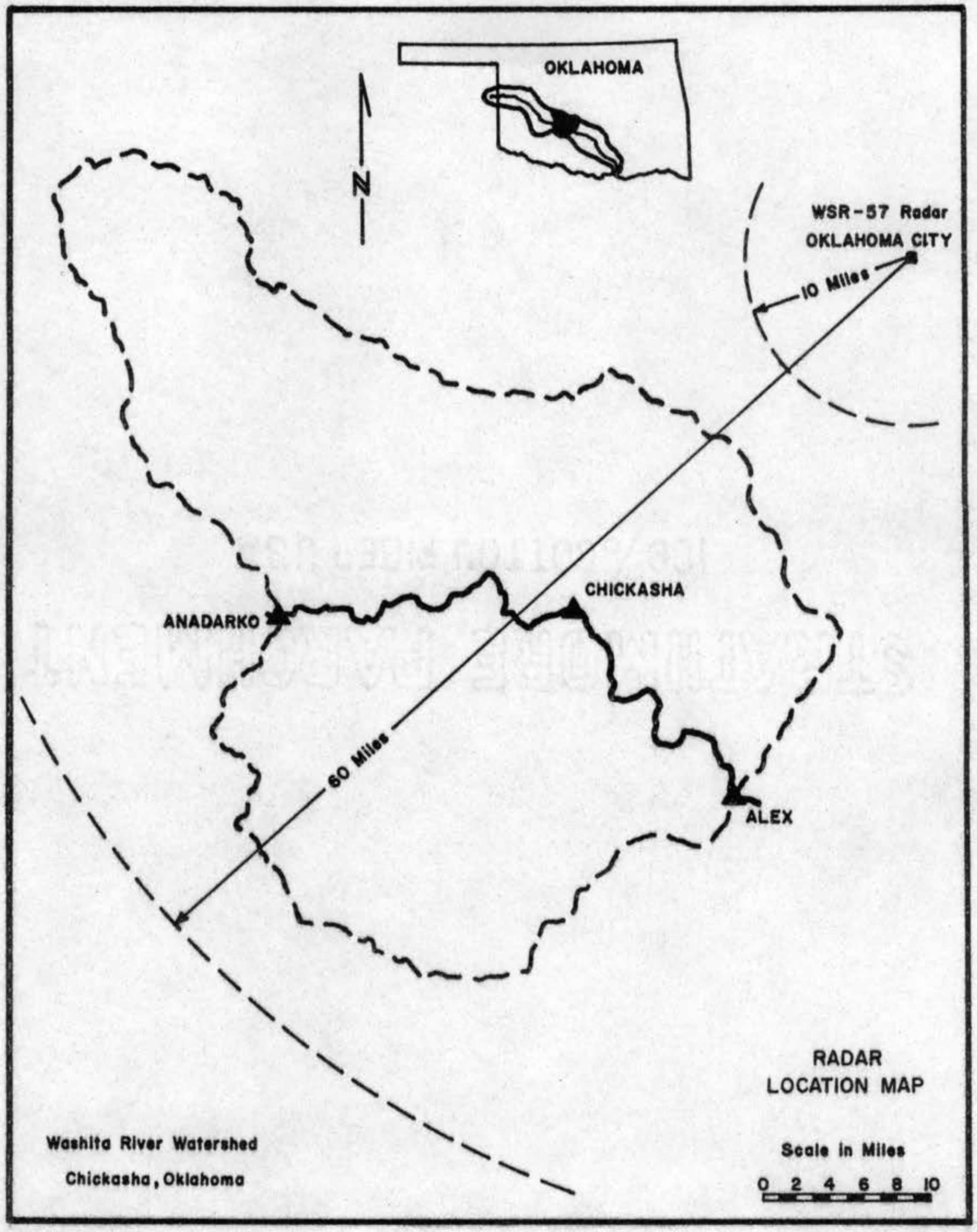


Figure 3. Map showing location of rain gage network in relation to radar site.

step-gain photography, and attenuation, have specific definitions which apply to radar meteorology. They should be discussed to give the reader a better understanding of their intended use.

PPI Scope

The Plan Position Indicator, or as it is more commonly known, the PPI scope, portrays the plan cross-section of the radar beam. In the case of a precipitation echo, the scope shows the area of the echo, the range from the radar, and its position relative to the radar site. This is accomplished by appropriate circuitry of the radar. The sweep of a cathode ray tube is synchronized with the rotation of the radar antenna. When the antenna rotates, the targets or echoes encountered by the beam of the radar are painted upon the face of the cathode ray tube. Thus, a visual representation of what the radar beam encounters is shown. Figure 4 is a diagram of a photograph of the PPI scope presentation used in this study.

Attenuation

Attenuation, as used in this thesis, refers to the electronically controlled level of the radar receiver's sensitivity. The WSR-57 radar receiver has the capability of receiving a signal of approximately 10^{-14} watts. Instead of using this small value in referring to the power of the receiver, a more common power ratio is used, the decibel (db). The decibel, as used with radar, is given as:

$$\text{db} = 10 \log \frac{P_t}{P_r} \qquad [5]$$

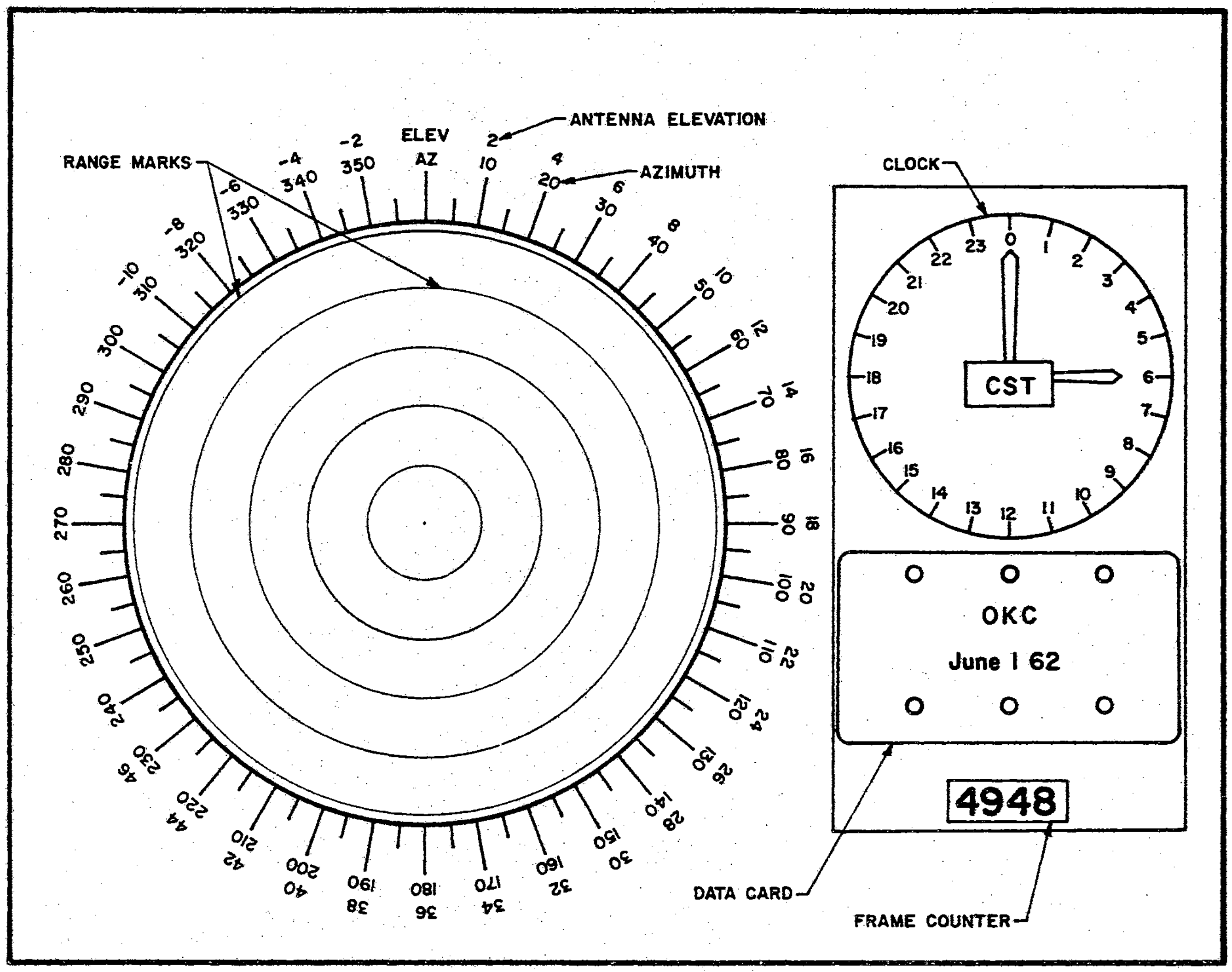


Figure 4. Diagram of Plan Position Indicator scope and data card as seen on the film data.

Where, P_t = Power transmitted (watts).

P_r = Power received (watts).

The receiver lever of the WSR-57 radar can be increased by three decibel increments, thus, the minimum detectable signal can be increased. Increasing the minimum detectable signal has the effect of blocking out all or a portion of the echo. Therefore, only those echoes of a given intensity, depending upon the attenuation set into the receiver, will be displayed on the scope. Increasing the attenuation of the radar receiver has the effect of blocking out the weaker portion of a precipitation echo.

Step-Gain Photography

The step-gain photographic process used in collecting the film data used in this study, consists of time lapse exposures of the PPI scope for each sweep of the radar antenna. An automatic 35 mm camera and attenuation stepping device was used to accomplish the photographic process. Predetermined values of attenuation were set into the receiver for each frame of film. The result of this process is a reduction of the echo shown on the scope. Most of the data available for this study had six to seven steps in a series of as many pictures. Figures 5 - 10 show the reduction of the echo as increasing values of attenuation are applied to the receiver. If these echo images were superimposed one upon the other, and the outline of each one traced, then in effect a contour map of the echo intensity would result.

In normal operation, the radar antenna is rotated at three revolutions per minute. It takes approximately two minutes for the

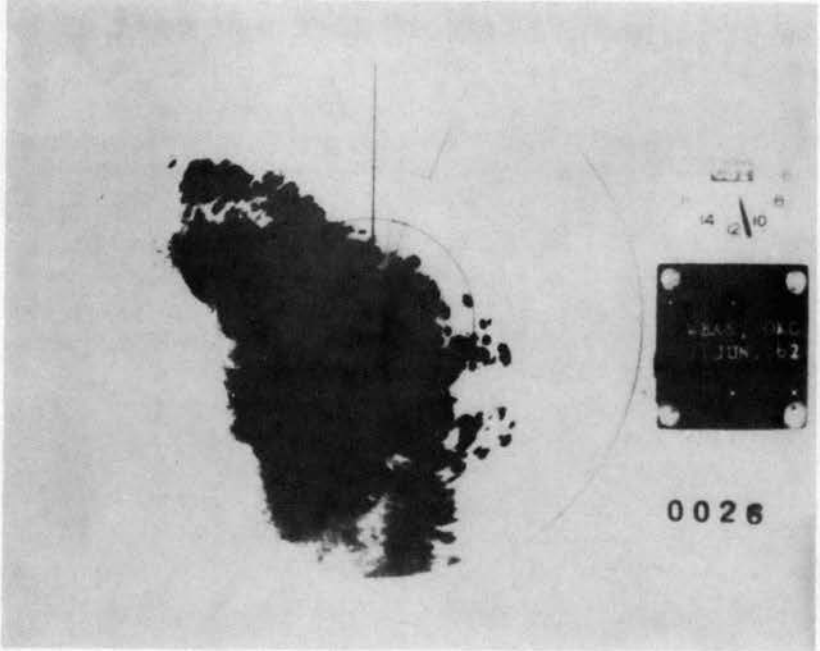


Figure 5. Step gain at zero attenuation

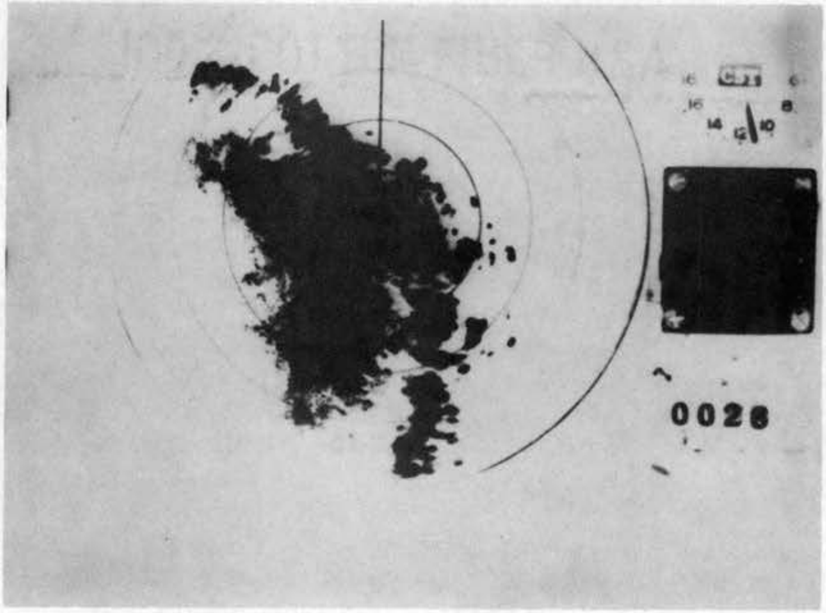


Figure 6. Step gain at step 1 (12 db attenuation).

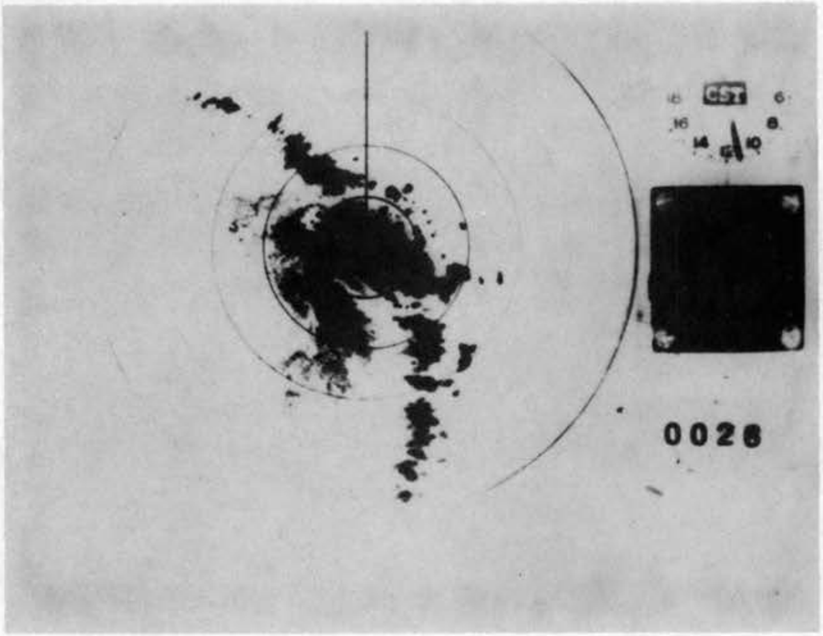


Figure 7. Step gain at step 2 (21 db attenuation).

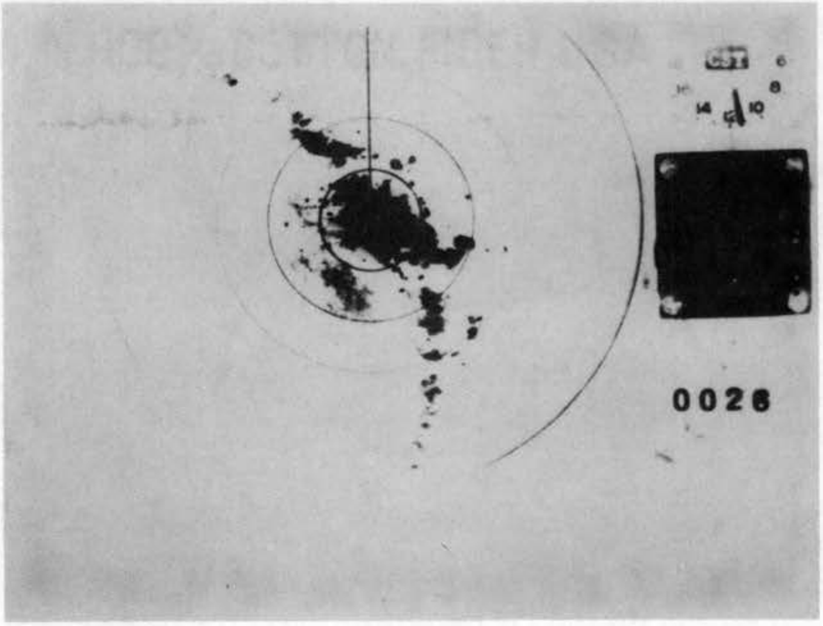


Figure 8. Step gain at step 3 (27 db attenuation).

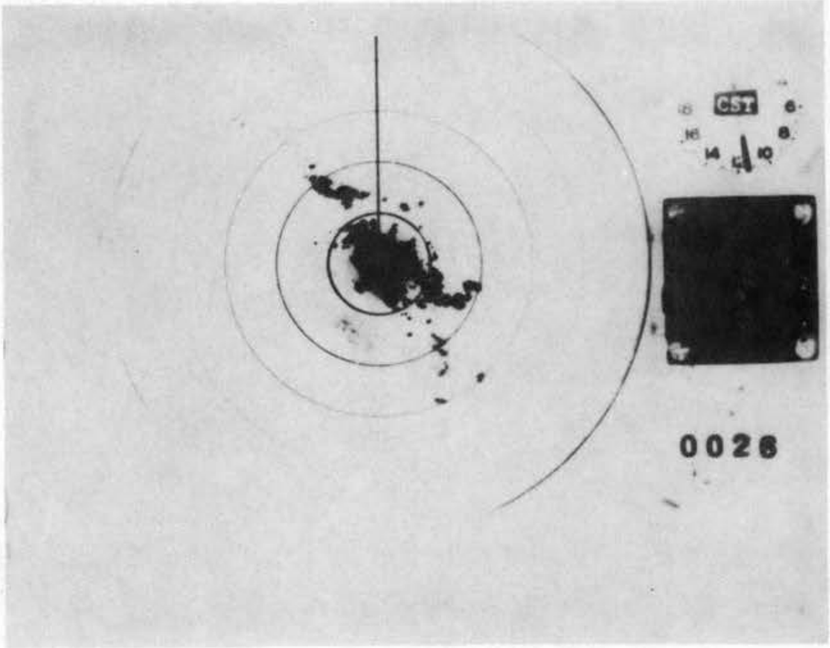


Figure 9. Step gain at step 4 (33 db attenuation).

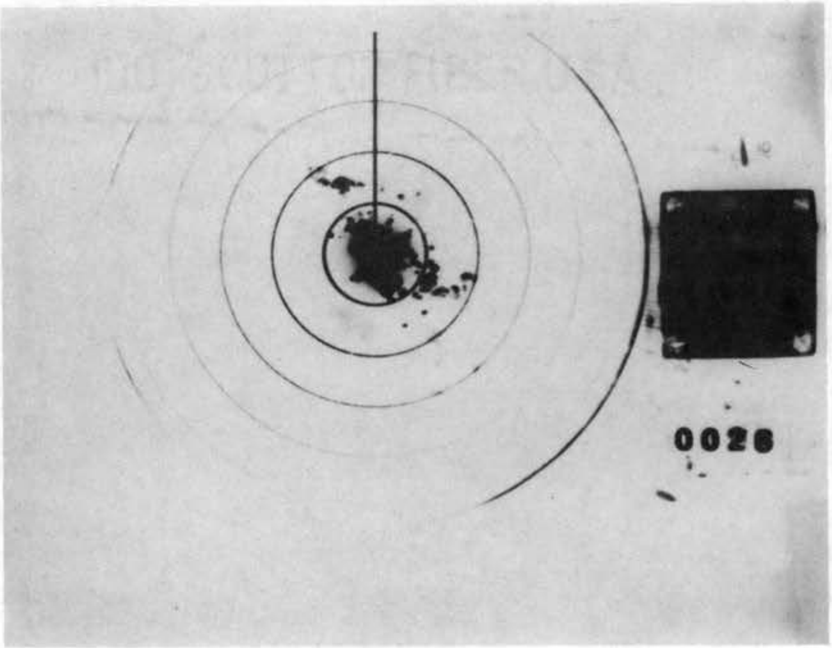


Figure 10. Step gain at step 6 (45 db attenuation)

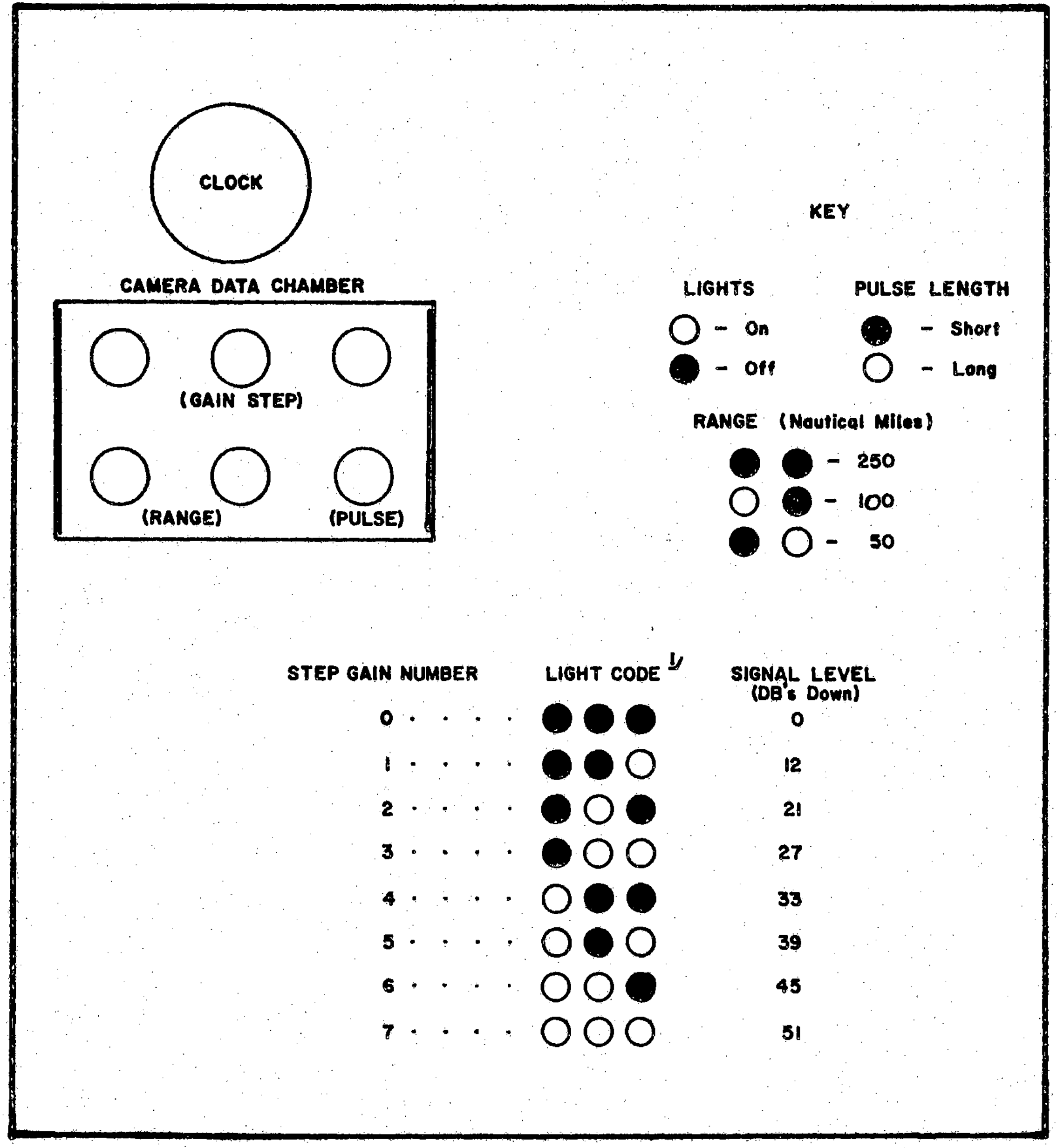
complete series of echo contours to be photographed. This filming process was followed during the operation of the radar data collection.

Figure 11 gives a detailed explanation of the data card indicator lights shown on the radar film. This coded technique of recording the attenuation, range, and pulse length data provided the essential radar record pertinent to this study.

Rainfall Data

The surface rainfall data used in this study were collected from a network of 168 recording rain gages. This network is operated as a part of a research project conducted by the Agricultural Research Service of the Department of Agriculture. Locations of the stations of this network are shown in Figure 12. The network covers an 1,130-square-mile study reach of the Washita River Basin in Caddo and Grady counties of Oklahoma. Spacing of the gages of this network is on a 3- by 3-mile-square grid system. A typical rain gage station is shown in Figure 13.

Data collected from the rain gages of this network is in chart form. Rainfall recorded on these charts is shown as a tracing of the accumulated amount of water caught in the collector of the gage. Figure 14 is an example of a storm recorded on these charts. Intensities of rainfall calculated from these charts are the rainfall measurements necessary for this study. The intensity values were derived from charts with 24-hour time scales such as is shown.



LIGHTS
○ - On
● - Off

PULSE LENGTH
● - Short
○ - Long

RANGE (Nautical Miles)
● ● - 250
○ ● - 100
● ○ - 50

STEP GAIN NUMBER	LIGHT CODE [1/]	SIGNAL LEVEL (DB's Down)
0	● ● ●	0
1	● ● ○	12
2	● ○ ●	21
3	● ○ ○	27
4	○ ● ●	33
5	○ ● ○	39
6	○ ○ ●	45
7	○ ○ ○	51

Figure 11. Radar film lighting code. Reading from left to right, lights have values, one, two, and four respectively. Step number is determined by the sum of the values of lights on.

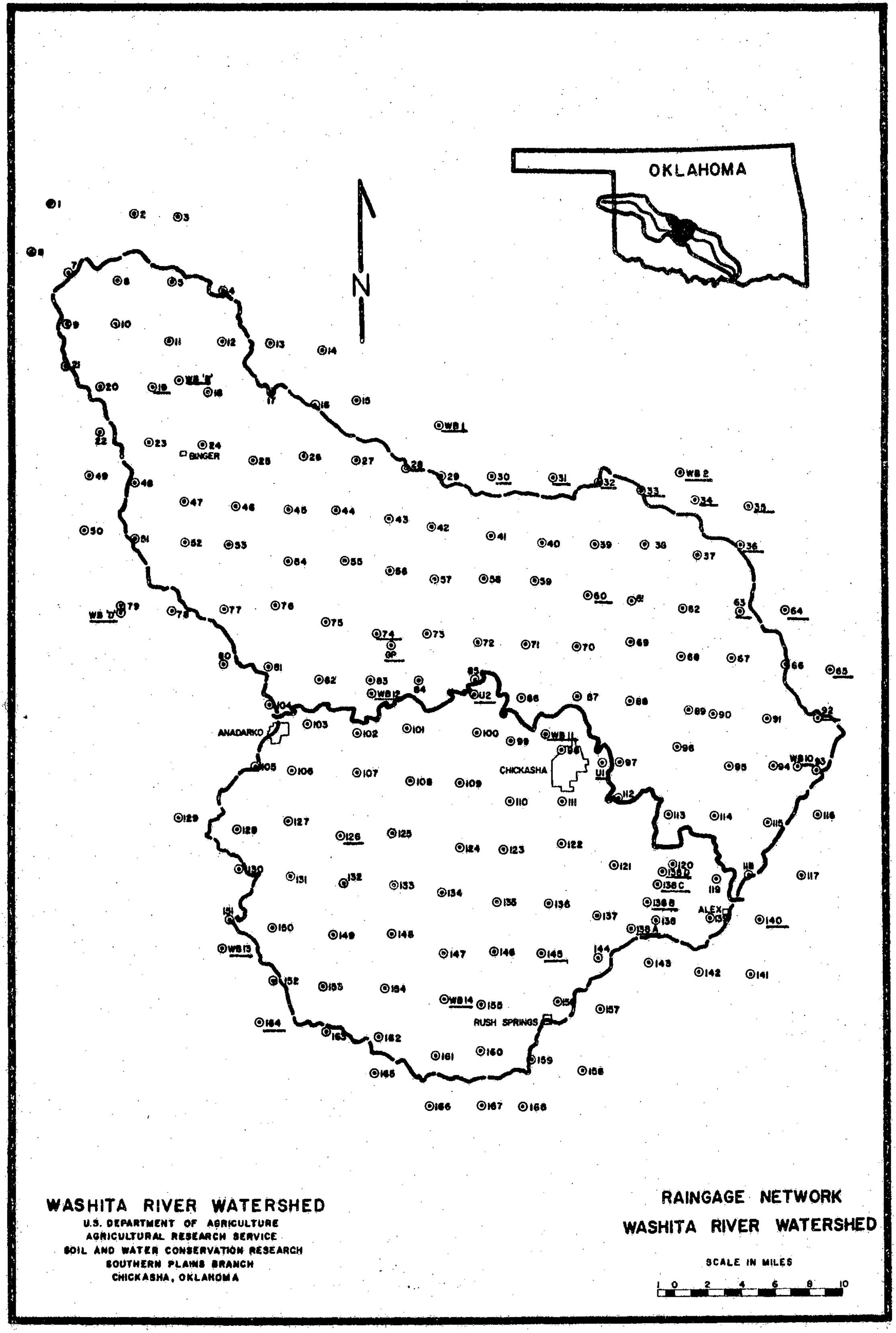


Figure 12. Raingage location map showing stations used in the study. Gages that are underlined were deleted.

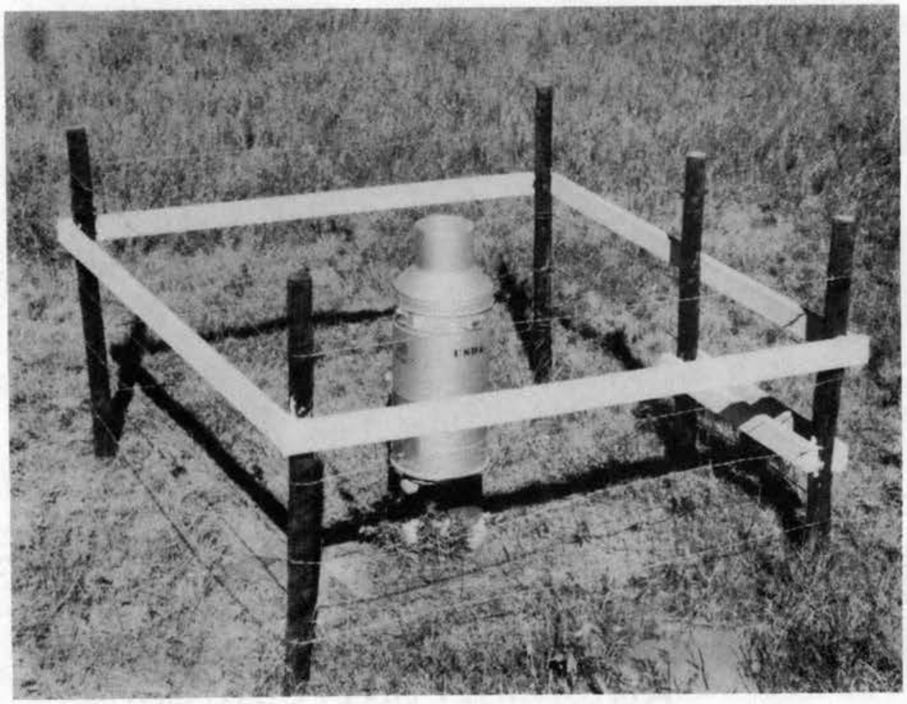


Figure 13. Typical recording rain gage station. Data from 150 stations such as this were used for comparison with radar echoes.

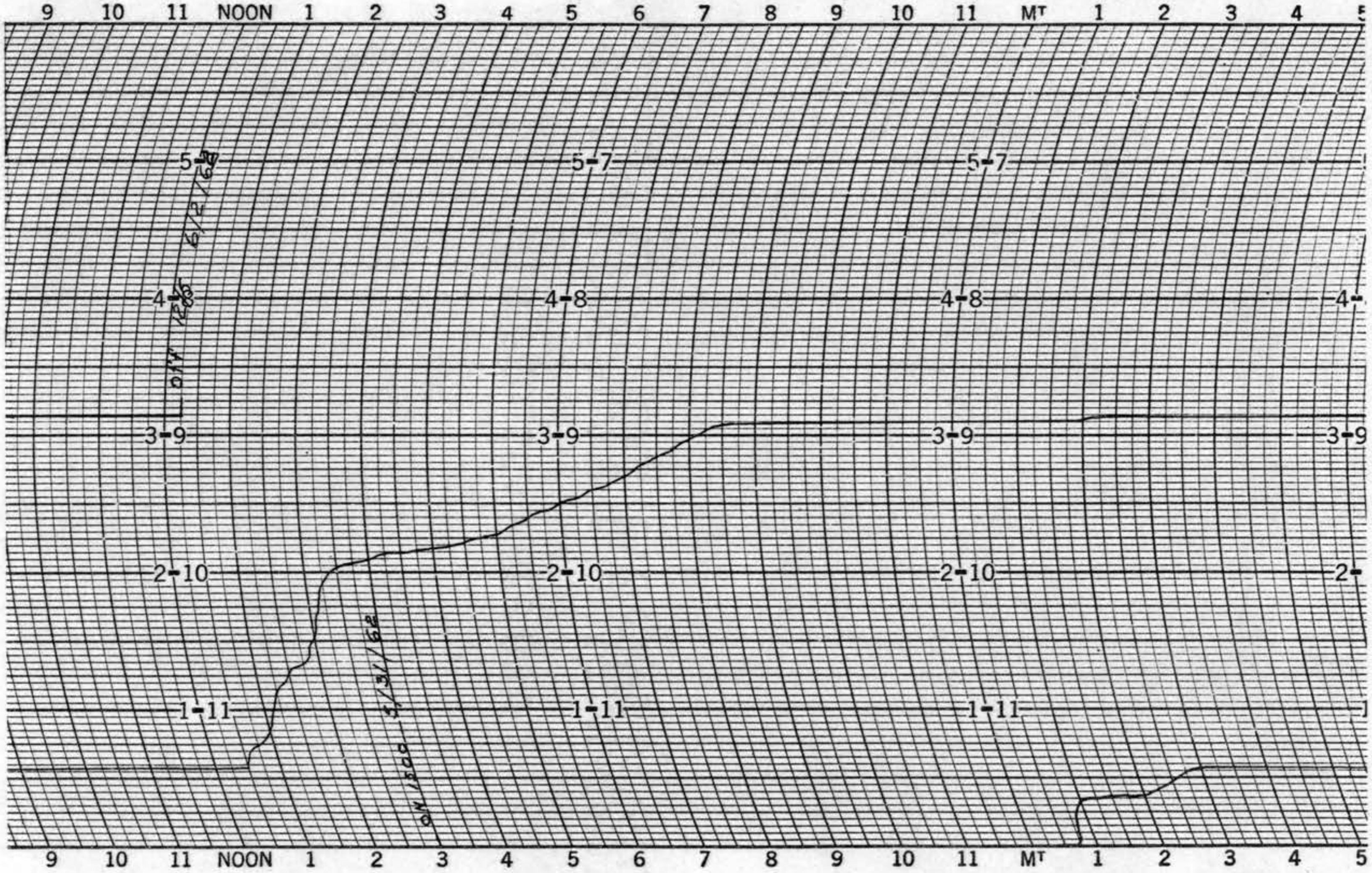


Figure 14. An example of the chart data from one of the 150 rain gages used in the study.

CHAPTER IV

PROCEDURE

A unique feature of this study is the amount of surface rainfall data available for use in the analysis. Of the 168 rain gage stations of the network, 150 were selected for use in this study. These stations provided a large volume of data to be handled. It was therefore imperative that techniques for processing these data be developed - techniques that would allow machine processing to be done with a minimum of manual labor.

Rainfall Data Processing

It was necessary to convert the rainfall chart data to digital form. This was accomplished with the aid of an analog to digital converter system. The decimal converter system consisted of three components: (1) The chart reader head, (2) the decimal converter, and (3) a keypunch. Components of this system are shown in Figure 15.

The most important part of this system is the decimal converter. It electronically scales and converts the electrical impulses fed to it from the chart reader head. Then it sends controlled impulses to the keypunch where the conversion is completed in the form of a punch card. The punch cards from the decimal converter system are then used

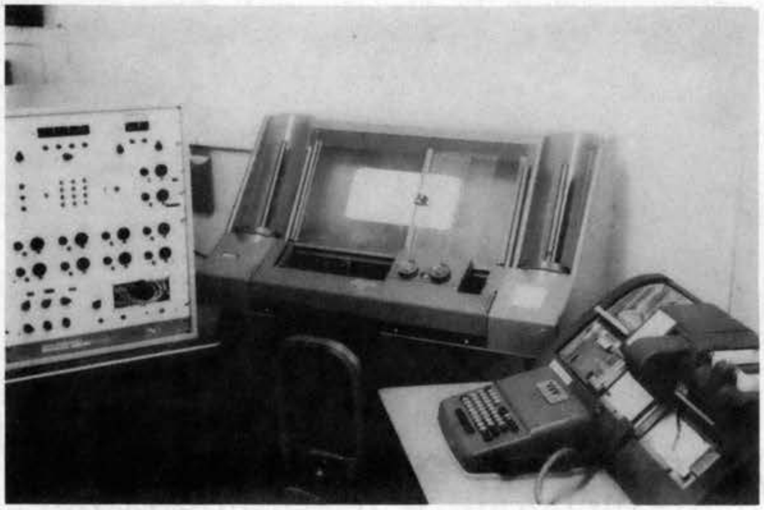


Figure 15. Analog to digital chart reader system was used to process rainfall data. The three components of the system are shown left to right: Digital converter, reader head, and keypunch.

as input to an electronic computer. Here, the final processing is completed in the form of output cards with the pertinent data on them. A flow chart of this process is shown in Figure 16.

The method used to tabulate the rainfall data on punch cards by the decimal converter system was the "break point" method. Points on the rain gage chart trace were selected where there was a change in slope. The time and gage height at these points were the data punched on cards. A program was written to calculate intensity (rate of rainfall) for the intervals between break points. Since these intervals were of unequal length, it was desirable to convert the data to equal time intervals. This was easily done by the computer program. The output data from the computer consisted of both fixed and unequal time intervals. The length of the fixed intervals was a variable which could be selected at the discretion of the analyst.

The variables contained in the output data were:

1. Rain gage number.
2. Date of storm.
3. Time at the end of the interval (hours and minutes).
4. Accumulated time from the beginning of the storm (minutes).
5. Length of the interval (minutes).
6. Accumulated gage height from the beginning of the storm (inches).
7. Incremental gage height for the interval (inches).
8. Intensity for the interval (inches per hour).

When the input data was processed by the computer, the output was ready for further processing by sorting and combining with the radar data.

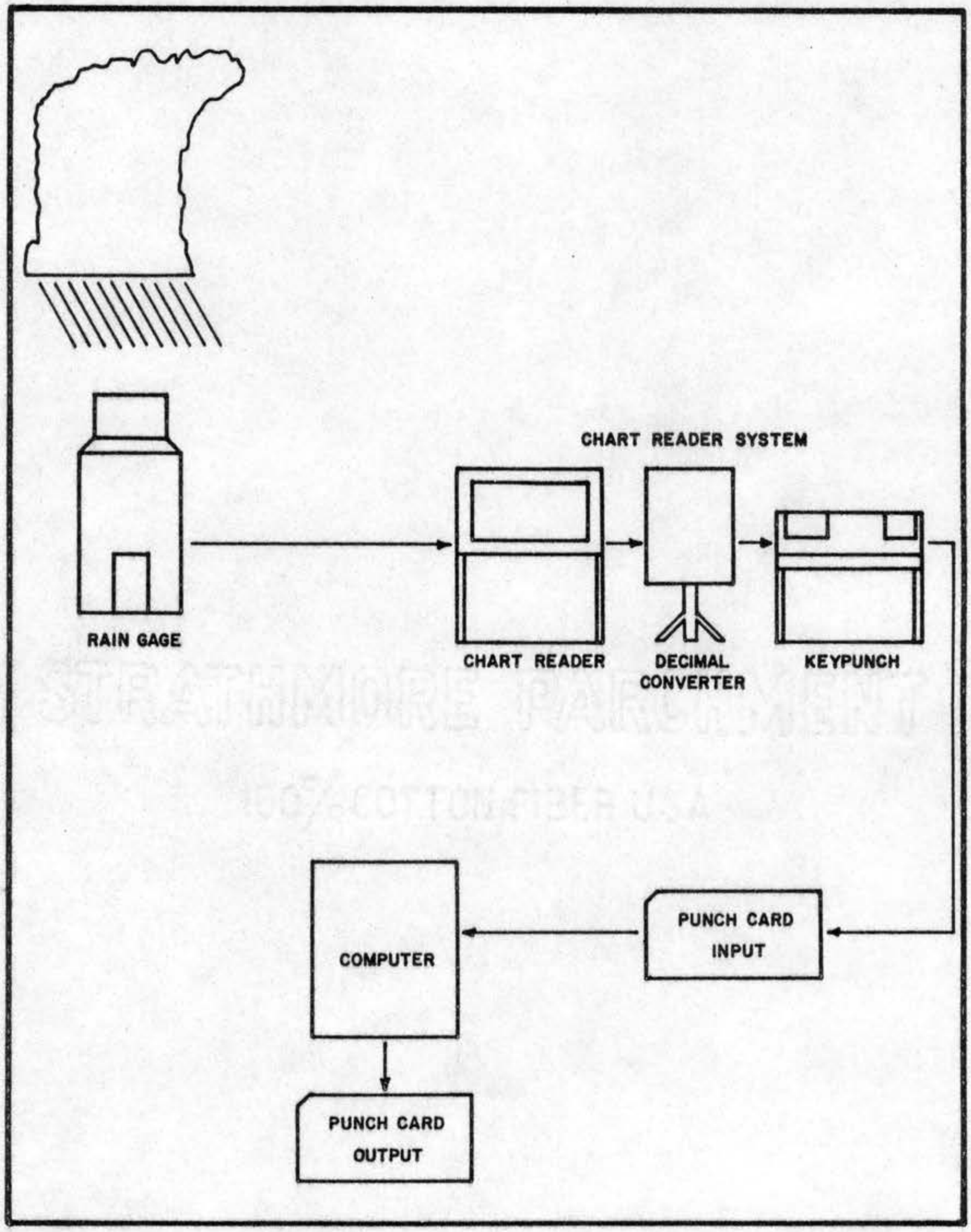


Figure 16. Rainfall data processing flow chart.

Radar Data Processing

Readings of echo strength at each rain gage location was accomplished with the aid of a film reader and a scaled transparent overlay of the rain gage network. The overlay was constructed from maps of the study area and reduced to the scale of the radar scope as viewed on the film reader screen.

The film reader used in the processing of radar data is specifically designed for reading 35 mm film one frame at a time. This reader, shown in Figure 17, has the capability for aligning each frame of film at the same location on the reader screen. Alignment is done manually by the handle on the side of the viewer. The overlay is attached to the face of the viewer and the film image positioned to fit it by use of the handle.

The procedure used in processing the radar film data for this study was as follows: The first frame of a series was positioned under the overlay and an observation was made at each rain gage location. If an echo was present, the numeral one was punched in an appropriate column of a punch card. If an echo was not present, a zero was punched in that gage's column on the card. Three punch cards were necessary to list the data from one frame of film. The film was then advanced to the next frame and the procedure repeated. This continued until the frame of the last step of gain was processed and then the next series was started. The step number of each frame was punched on the first card of each series. Since six to seven frames had to be analyzed to determine a maximum attenuation value at each gage location, 18 to 21 cards were necessary to contain this

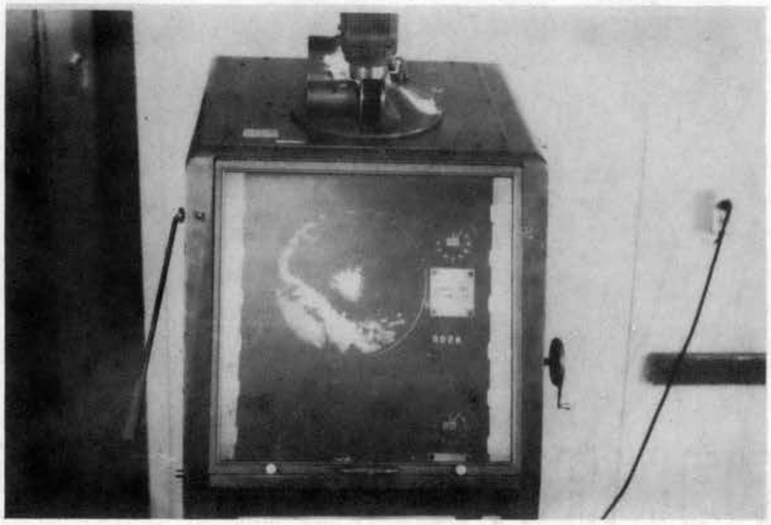


Figure 17. A library microfilm reader was used to analyze the radar data. A frame of radar film is shown projected on the viewer screen.

data. Approximately 3 to 10 series were punched for a 15-minute interval. In no case were fewer than three series used to define the radar signal for an interval, and a maximum for a 15-minute interval was 10 series.

Once the information was on punched cards, the attenuation values necessary to obliterate the echo for a given series or group of series could be determined by the computer. In effect, this attenuation value is the intensity level of the echo. The length of the time interval for which the level can be determined by the computer is fixed. However, if several of this series are evaluated and combined, an average intensity level for the time interval can be computed. In this study the interval used was 15 minutes. Figure 18 shows the flow chart for the processing of the radar film data.

The data output from the computer contained the following variables:

1. Date.
2. Numbers of series in an interval.
3. Time of interval (hours and minutes).
4. Rain gage location number.
5. Average attenuation for the interval (db).

After the radar film data was processed by the computer, it was combined with rainfall and other pertinent data for further processing and analysis.

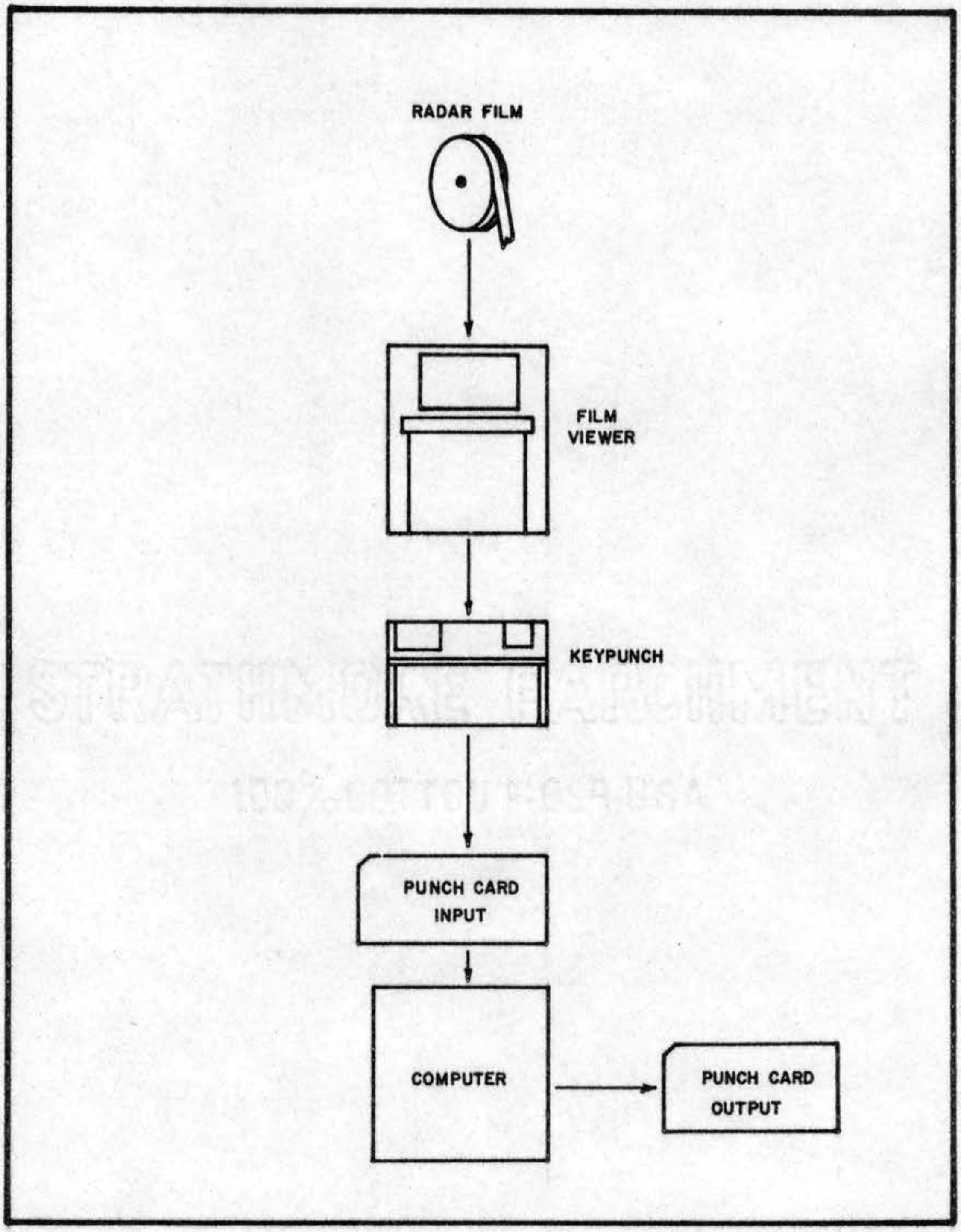


Figure 18. Radar film data processing flow chart.

Combination of Data

Combination of the pertinent quantities of this study was done by computer and supporting machines such as a sorter and printer. Rainfall, range, and radar data were combined on one card for each rain gage location and time interval. This allowed for more convenient handling of the data in the analysis to follow. The resulting data contained the following variables:

1. Rain gage number.
2. Date.
3. Time at the end of the interval (hours and minutes).
4. Rainfall intensity for the interval (inches per hour).
5. Average attenuation for the interval (db).
6. Range of the rain gage from the radar (nautical miles).
7. Number of series of film data used in determining average attenuation for the time interval.

CHAPTER V

ANALYSIS OF DATA

Selection of Analytical Procedure

In the past, analyses associated with radar-rainfall relationships have been centered around the use of a Z - I (radar reflectivity-rainfall rate) relation that could be used with the theoretical radar equation developed by Marshall et. al. (3). During the past 15 years a multitude of such relations have been developed and have produced results that varied with climatic zones and the type of radar used. This approach of relating radar signal strength to rainfall was excluded from the analysis in this study in favor of a strictly empirical procedure.

Excluding the semi-empirical approach used by previous investigators led to the selection of empirical analysis that would present: 1) Some knowledge about the correlation of combined independent variables with the dependent variable, and 2) a prediction equation between a measure of radar signal strength and rainfall rate at a given range from the radar station. The selection of the type of analysis was also based upon the objectives set forth in Chapter III.

Multivariable Functional Relationship

The type of analysis selected for this study was the multivariable functional relationship of the form

$$Y = B_0X_0 + B_1X_1 + B_2X_2 + \cdots + B_{k-1}X_{k-1} \qquad [5]$$

where B_0, B_1, $\cdots$, B_{k-1} are coefficients of the combined independent variables X_0, X_1, $\cdots$, X_2, and Y is the dependent variable to be predicted.

If it is assumed that the true functional form of a relationship is

$$Y = f(X_1, X_2, X_3) \qquad [6]$$

then equation [5] can be used to approximate it. Evaluation of the coefficients B_0, B_1, $\cdots$, B_{k-1} by methods of least squares and multiple regression gives a resulting prediction equation of a response surface. The prediction equation is an approximation of the functional relationship within a given probability. Analytical methods for evaluation of the coefficients in equation [5] are given in the works of Natrella (24) and Anderson (25).

Transformation of Raw Variables

Four variables were used in the analysis. These were:

1. A = Average attenuation for a given time interval (15 minutes).
2. R = Range of the rain gage from the radar station.
3. T = Number of series of film frames used in determining the average attenuation for a given time interval.
4. I = Rainfall rate for the time interval at the rain gage site.

The first three in this list are raw independent variables which were combined in various forms and entered into the regression analysis. Table III lists the combinations of the transformed variables that were used.

The variables in Table III were formed for the purpose of determining the approximate functional relationship which would give the best estimate of the rainfall rate, I. Although the true relationship between rainfall rate and the parameters of the radar were not known, the theoretical equation of the form given in equation [3] was used to obtain a first approximation. Other combinations of variables listed in Table III were formed as a step-wise build up of the raw variables.

After the variables of Table III were formed, their correlation with the dependent variable ($Y = I$) was calculated. Prediction equations were then formed by introducing these variables into equation [5] one at a time and evaluating the regression coefficients.

Use of Computers

The value of electronic computers in this study should not be understated. From the processing of the raw data, both rainfall and radar, to the foregoing analysis, electronic digital computers were used whenever possible to handle the mass of data. A study of this type would be nearly prohibitive without electronic computers and computing techniques. Computer programs have been developed to perform the analysis outlined in this Chapter. These programs are available

TABLE III

LIST OF TRANSFORMED VARIABLES

Transformed Variable	Combination of Raw Variable	Transformed Variable	Combination of Raw Variable
X_1	A	X_{16}	A^2T
X_2	A^2	X_{17}	RT^2
X_3	A^3	X_{18}	R^2T
X_4	R	X_{19}	ART
X_5	R^2	X_{20}	e^A
X_6	R^3	X_{21}	$\text{Log}_e A$
X_7	T	X_{22}	e^A/R
X_8	T^2	X_{23}	e^A/R^2
X_9	T^3	X_{24}	e^A/R^3
X_{10}	AR	X_{25}	$\text{Log}_e A/R$
X_{11}	AT	X_{26}	$\text{Log}_e A/R^2$
X_{12}	RT	X_{27}	$\text{Log}_e A/R^3$
X_{13}	AR^2	X_{28}	A/R^2
X_{14}	AT^2	X_{29}	A/R^3
X_{15}	A^2R		

in various forms in most computer center libraries. The author's indebtedness for the advice and use of such programs is given in the acknowledgment section of this thesis.

Data Available for Analysis

The amount of data available for analysis was limited to the radar film taken during the spring storm season of 1962. Twenty rolls of 35 mm film were purchased from the National Weather Records Center, Ashville, North Carolina. Of these 20 rolls, 14 were deleted from the study due to: 1) Poor photography, 2) no rainfall on the network, and 3) no step-gain photography for the period of rainfall on the network. The remaining 6 rolls were edited to determine the portion of the film that could be used. From these rolls, data for 6 separate storms were found to meet the requirements for the study. The list of storms included two storms on April 27, and one storm on each of the dates, May 5, May 24, May 25, and June 1, 1962. Summaries of the radar and rainfall data for these storms are given in Table IV and Table V.

The amount of data included in the analysis consisted of 700 observations of radar receiver attenuation and rainfall rate from the six storms. Tables VI and VII list the frequency of these observations with respect to class interval. The 700 observations were combined from punch card output of the radar and rainfall processing computer programs. Examples of the computer output of these programs are presented in Appendices A and B. Range data for rain gage location from the radar site are given in Appendix C.

TABLE IV

SUMMARY OF RADAR DATA

Date of Storm	Time Interval Sampled	Number of Radar Observations	Range of Attenuation Values (db)
4/27/62	0000-0015	43	2.40-48.60
4/27/62	0015-0030	47	2.40-48.60
4/27/62	1630-1645	15	2.00-39.00
4/27/62	1645-1700	6	4.00-37.00
4/27/62	1700-1715	11	4.00-43.00
4/27/62	1715-1730	35	4.00-39.00
5/ 4/62	0330-0345	105	4.00-37.00
5/24/62	2000-2015	19	4.00-20.00
5/25/62	1930-1945	77	4.00-37.00
6/ 1/62	0000-0015	62	1.20-39.60
6/ 1/62	0015-0030	85	1.50-40.50
6/ 1/62	0030-0045	97	1.20-39.60
6/ 1/62	0045-0100	98	1.20-42.00

TABLE V

SUMMARY OF RAINFALL DATA

Date of Storm	Number of Rain Gages	Time Interval	Range of Intensity (in/hr)
4/27/62	43	0000-0015	0.00-1.88
4/27/62	47	0015-0030	0.00-1.72
4/27/62	15	1630-1645	0.00-0.88
4/27/62	6	1645-1700	0.00-1.12
4/27/62	11	1700-1715	0.00-0.60
4/27/62	35	1715-1730	.04-1.40
5/ 4/62	105	0330-0345	0.00-0.88
5/24/62	19	2000-2015	0.00-0.20
5/25/62	17	1930-1945	0.00-1.60
6/ 1/62	62	0000-0015	0.00-0.84
6/ 1/62	85	0015-0030	0.00-1.92
6/ 1/62	97	0030-0045	0.00-1.53
6/ 1/62	98	0045-0100	0.01-2.1

TABLE VI

FREQUENCY OF RAINFALL OBSERVATIONS BY CLASS INTERVAL

Intensity Class Interval (in/hr)	Number of Observations
0.00-0.25	492
0.26-0.50	84
0.51-0.75	36
0.76-1.00	41
1.01-1.25	23
1.26-1.50	10
1.51-1.75	7
1.76-2.00	5
> 2.01	2

TABLE VII

FREQUENCY OF RADAR OBSERVATIONS BY CLASS INTERVAL

Attenuation Class Interval (db)	Number of Observations
0-5	220
6-10	101
11-15	80
16-20	53
21-25	58
26-30	85
31-35	50
36-40	38
41-45	9
> 45	6

CHAPTER VI

RESULTS

Simple Correlation of Variables

The simple correlation coefficients of the 29 transformed variables listed in Table III were calculated. The results of these calculations, listed in Table VIII, reveal that no single raw independent variable or transform of the independent variables is closely correlated with rainfall rate. In no case did the simple correlation exceed 0.54. The variables with the better correlation coefficients were those that contained radar attenuation, A, or some combination of A with other variables. In general, the logarithmic or exponential transforms of variables shown in the latter portion of Table VIII were not closely correlated with rainfall rate.

Prediction Equations

A stepwise linear regression computer program from the library of the Oklahoma State University Computer Center was used to formulate prediction equations from the list of 29 variables. This program is in two phases. The first phase will make 20 transforms of the input variables, calculate the sums, sums of squares, corrected sums of squares, cross products, and simple correlation coefficients between the dependent and independent variables. The second phase enters the

TABLE VIII

SIMPLE CORRELATION OF TRANSFORMED VARIABLES WITH Y (RAINFALL RATE)

Transformed Variable	Combination of Raw Variable	Simple Correlation Coefficient (r)
X_1	A	.5380
X_2	A^2	.5359
X_3	A^3	.5076
X_4	R	-.0088
X_5	R^2	-.0271
X_6	R^3	-.0418
X_7	T	.0931
X_8	T^2	.0764
X_9	T^3	.0669
X_{10}	AR	.5037
X_{11}	AT	.4363
X_{12}	RT	.0622
X_{13}	AR^2	.4266
X_{14}	AT^2	.3310
X_{15}	A^2R	.5263
X_{16}	A^2T	.4756
X_{17}	RT^2	.0543
X_{18}	R^2T	.0285
X_{19}	ART	.4020
X_{20}	e^A	.1424
X_{21}	Log_eA	.4700
X_{22}	e^A/R	.1405
X_{23}	E^A/R^2	.1382
X_{24}	e^A/R^3	.1356
X_{25}	Log_eA/R	.3858
X_{26}	Log_eA/R^2	.2312
X_{27}	Log_eA/R^3	.1146
X_{28}	A/R^2	.4224
X_{29}	A/R^3	.0000

transformed variables into a linear regression at specific levels of significance and calculates the regression coefficients. Variables are included or rejected from the regression depending on the level of significance specified. The second phase of this program also calculates the predicted value and the deviation of the predicted value from the observed. The program was run on the IBM 1410 computer at the Oklahoma State University Computer Center.

Machine storage requirements limited the number of variables that could be used in this program to 19. Therefore, variables X_1 through X_{19} were entered into the regression in the first run. A significance level of 5 percent ($F = 3.84$) was used for including or rejecting variables into or from the regression. Results of this first attempt at forming a prediction equation revealed that only 2 of the 19 variables were retained in the regression at the 5 percent level. These variables, A and A^2, were the one most closely correlated with Y, as shown in Table VIII. The resulting equation was of the form:

$$Y = B_0 + B_1X_1 + B_2X_2 \qquad [7]$$

With the exclusion of all variables except the first two, X_1 and X_2, it was apparent that the significance level chosen was too stringent to allow entering or retaining more value into the regression. To reduce the restriction place on the significance level of variables to be entered and retained into the regression, an F level of 0.00 was chosen.

The 19 variables were run again with the following equation resulting:

$$Y = B_0 + B_1X_1 + B_2X_2 + B_8X_8 + B_{10}X_{10} + B_{11}X_{11} + B_{12}X_{12} + B_{13}X_{13} + B_{17}X_{17} \qquad [8]$$

Nineteen variables of the original list of 29 had been included in the regression at this point in the analysis. The remaining 10 variables (X_{20} through X_{29}) which were combinations of logarithmic or exponential transforms of A, R, and T were introduced into the regression with the first 9 variables in Table VIII. As in the previous run, an F value of 0.00 was used to enter or reject variables into or from the regression. The results of this run was the same as the first. All variables except X_1 and X_2 were excluded from the regression and the equation that was formed was the same as equation [7].

Another approach was attempted that would include some additional variables regardless of their significance level. A program that would include up to 12 variables into the regression was available. When the first 12 variables of Table VIII were used in this program, the following equation was formed:

$$Y = B_0 + B_1X_1 + B_2X_2 + B_3X_3 + B_4X_4 + B_5X_5 + B_6X_6 + B_7X_7 + B_8X_8 + B_9X_9 + B_{10}X_{10} + B_{11}X_{11} + B_{12}X_{12} \qquad [9]$$

The regression coefficients for the three prediction equations are given in Table IX. Samples of calculated values using each equation are listed in Appendix D with the observed values and deviations from the observed values. Multiple correlation coefficients and the standard errors of the predicted Y values for each equation are given in Table X.

TABLE IX

VALUES OF REGRESSION COEFFICIENTS FOR THE PREDICTION EQUATIONS

B_i	Equation [7]	Equation [8]	Equation [9]
B_0	.00899	-.18585	-1.637040
B_1	.01041	-.01960	.008863
B_2	.00019	.00013	.000728
B_3			.000009
B_4			- .083450
B_5			.003207
B_6			- .000036
B_7			1.245200
B_8		-.00286	- .200323
B_9			.009829
B_{10}		.00192	- .000275
B_{11}		.00239	.000161
B_{12}		.00153	.000019
B_{13}		-.00002	
B_{14}			
B_{15}			
B_{16}			
B_{17}		-.00002	

TABLE X

COEFFICIENTS OF MULTIPLE CORRELATION

	Multiple Correlation Coefficients (R)	Fraction of Explained Variation (R^2)	Standard Error	Number of Variables
Equation [7]	.5422	.294	.3383	2
Equation [8]	.5558	.309	.3365	8
Equation [9]	.5585	.312	.3280	12

Discussion of Results

From the results presented in the previous sections, it was revealed that only two variables of the 29 were significant in predicting rainfall rate by radar. The equations developed depended upon A and A^2 to predict rainfall rate. While attenuation was thought to be one of the most important factors influencing the prediction, it was not expected that other variables would be excluded as indicated by the results. It is also interesting to note that the amount of explained variation was not improved by forcing additional variables into the regression.

The addition of 6 and 10 variables in equations [8] and [9], respectively, did not improve the multiple correlation coefficient exhibited by equation [7], nor were the standard errors of the predicted value reduced appreciably.

There are several possible reasons why such a low value of the multiple correlation coefficient was obtained for the prediction equations. One possibility is the measurement of the raw variables used in the analysis, particularly the measurement of A, radar receiver attenuation.

Attenuation values used in the study were derived solely from the film of the PPI scope presentation. Starting from the recording of the data on film and continuing to the processing of the film data, inconsistencies, errors, and mistakes could have influenced the determination of attenuation values of the storm echoes at the rain gage locations. Exposure setting of the camera and processing of the film are sources of error which could only be controlled in the study to the extent of rejecting or accepting the film as the best that was available.

Sources of error that could be controlled, such as the construction of rain gage location overlays and positioning of the storm echo image on the overlay, were believed to be controlled within the limits of the film resolution and scale of existing maps of the rain gage network.

Another possibility for the poor multiple correlation coefficients shown in Table X concerns unmeasured variables that were not included in the analysis. Only measurements of the independent variables, A, R, and T were available for the study. These three variables do not exhaust the possible variables that would influence the measurement of rainfall by radar. Such variables as storm height, speed, direction, or measurements of other atmospheric variables may be pertinent in such a radar-rainfall relationship.

The distribution of data available for the analysis could be another factor that influenced the results. Tables VI and VII show that most observations of rainfall and radar data were obtained at low values. Approximately 54 percent of the radar observations were less than 20 db and 82 percent of the rainfall observations were below 0.50 inch per hour. Equation [7] and [9] appear to be fitted to these lower values. Equation [8] however, tends to predict the higher values of rainfall rate. The skewed distribution of the data may have influenced these results.

The effect of the number of observations of attenuation, T, that were averaged to obtain a value of attenuation for a time interval is shown in Figures 19 through 22. These figures showing response surfaces from Equation [9] were constructed by holding T constant at values of 3, 5, 8, and 10 observations and then varying A and R from 5 to 25 db at ranges of 20 to 40 miles. These limits on A and R were chosen to insure construction of the response surfaces within the limits of the experimental data. Equation [9] was selected because of its higher multiple correlation coefficient.

Figures 19 through 22 indicate that a better definition of the response surface is achieved when a greater number of attenuation observations are taken within a time interval. A desirable type of prediction equation would be one that yields positive values of rainfall rate at the minimum range and signal strength of a radar. Such a prediction equation is shown by the response surface in Figure 22 where T = 10. The response surfaces at T = 3 and T = 8 do not meet these requirements. The response surface shown in Figure 21 at T = 5, appears to overestimate rainfall rates at the lower limits of range and attenuation, and is also unacceptable.

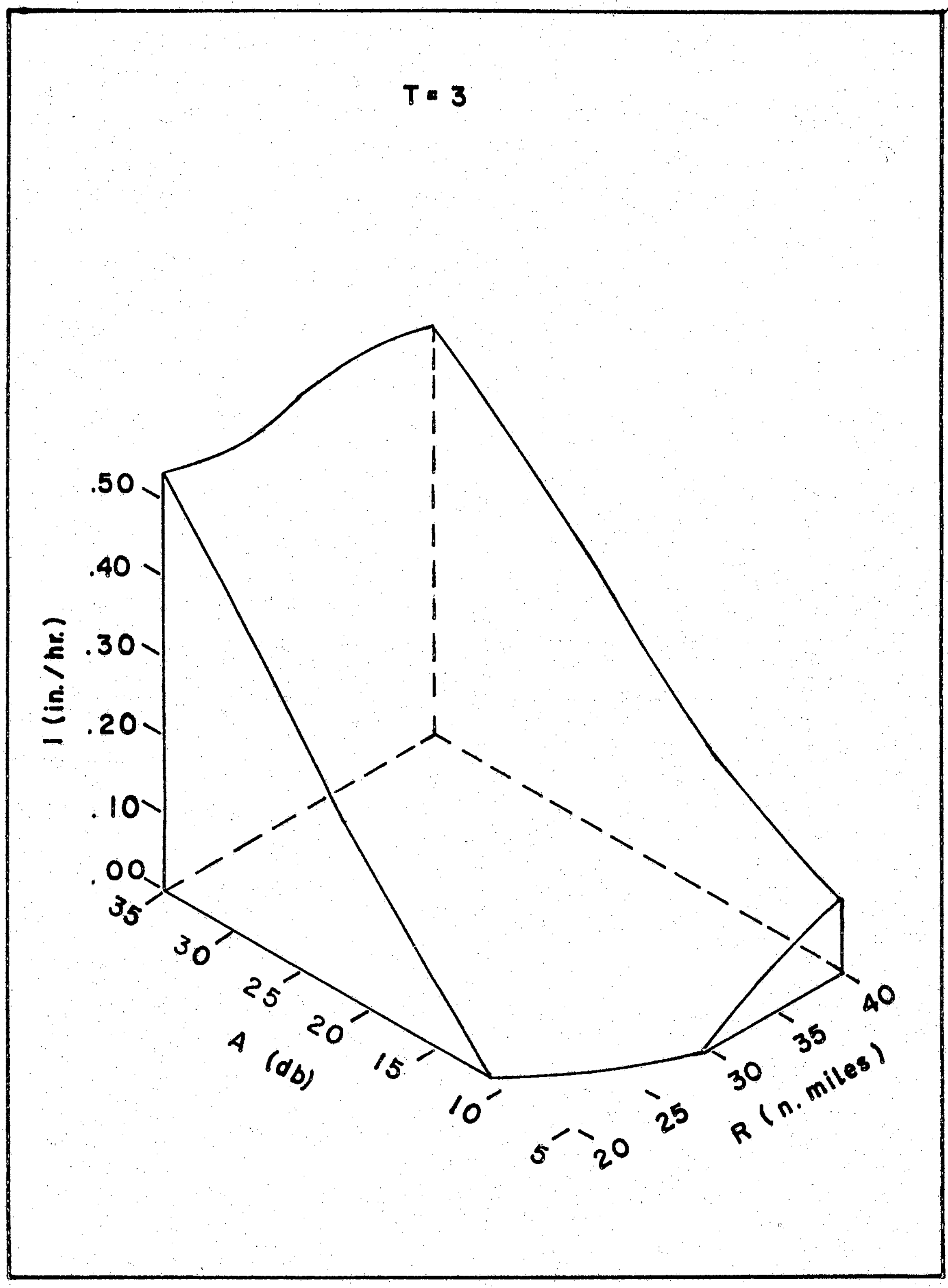


Figure 19. Response surface of the radar-rainfall relation generated by equation [9] at T = 3.

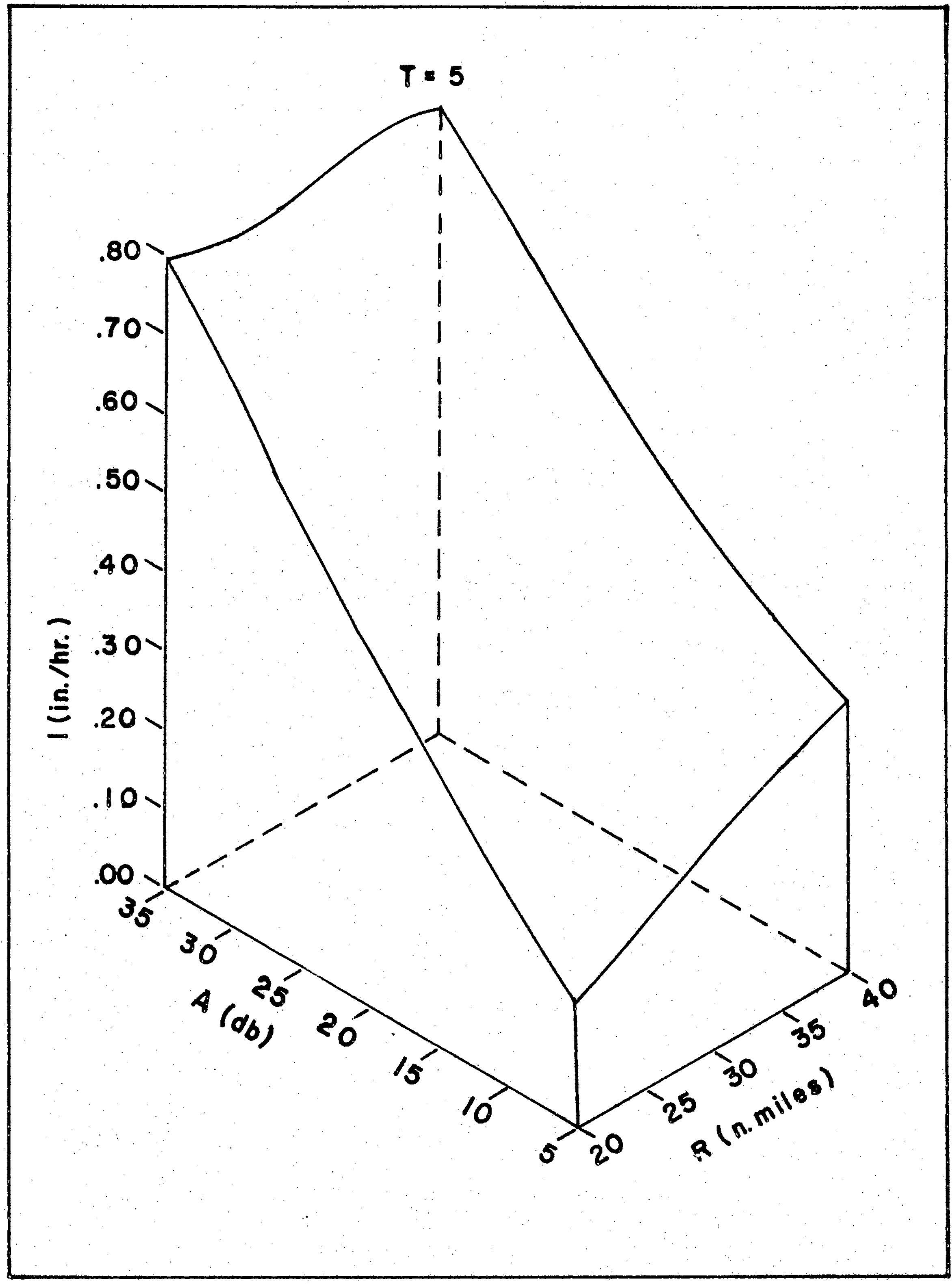


Figure 20. Response surface of the radar-rainfall relation generated by equation [9] at T = 5.

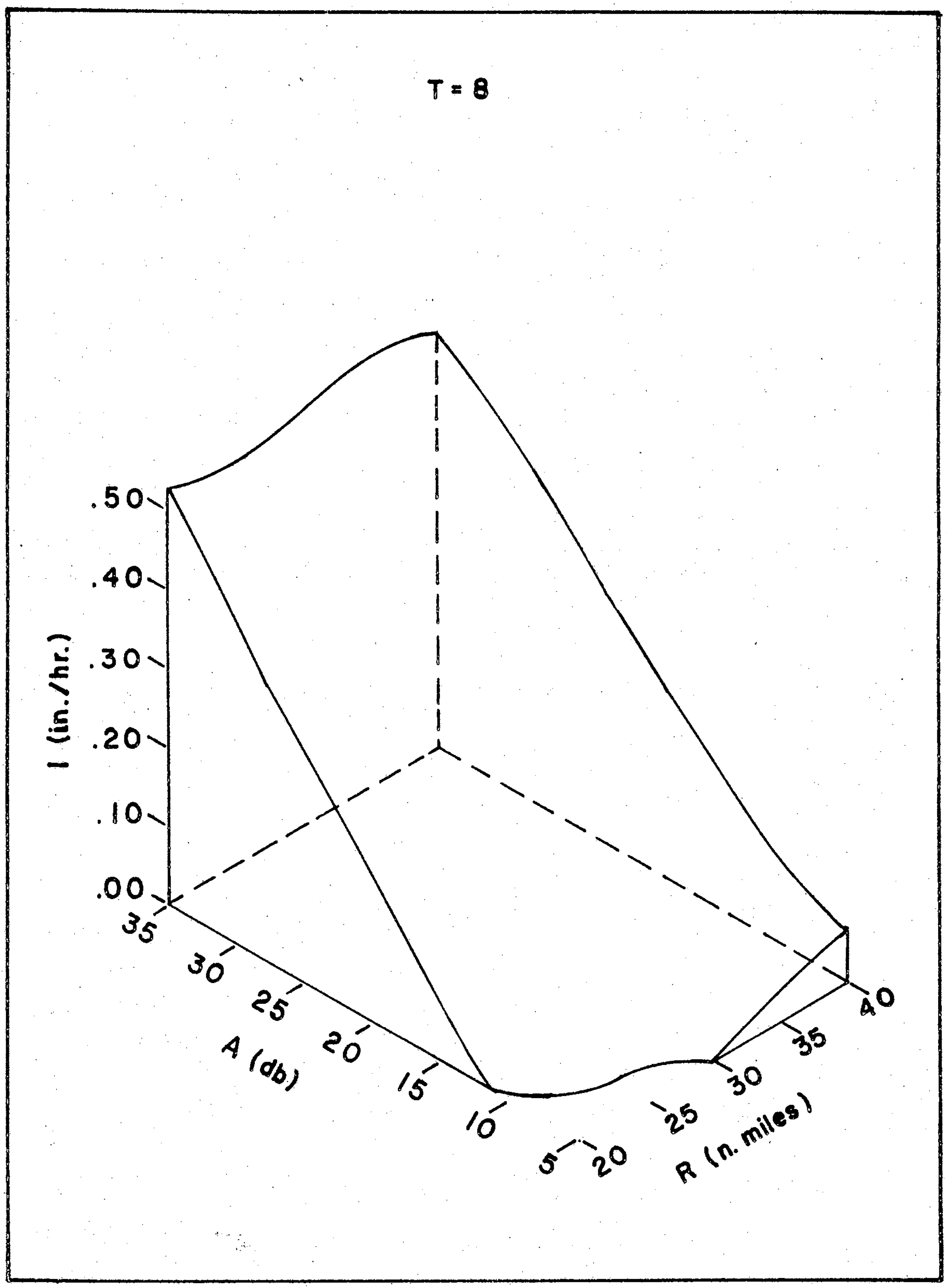


Figure 21. Response surface of the radar-rainfall relation generated by equation [9] at T = 8.

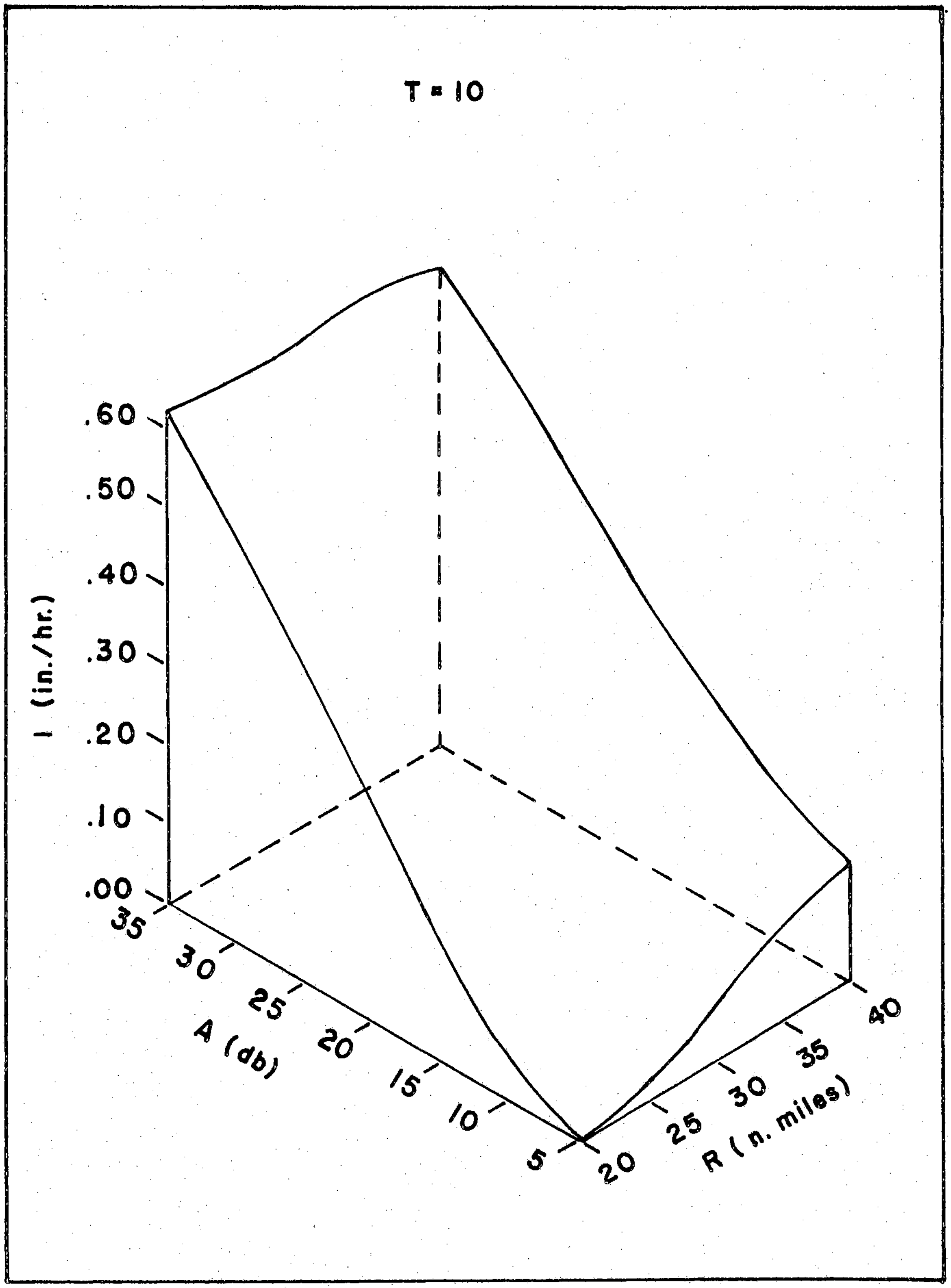


Figure 22. Response surface of the radar-rainfall relation generated by equation [9] at T = 10.

CHAPTER VII

SUMMARY AND CONCLUSIONS

Summary

Radar echoes from six storms occurring in the spring of 1962 on a network of 175 recording rain gages were analyzed quantitatively to obtain a measure of the radar signal strength of the echoes at points corresponding to rain gage locations. Images of the echoes recorded on 35 mm film at the Oklahoma City Weather Bureau radar location were reduced to punch cards for computer processing. Charts from 150 recording rain gages of the network were processed to give rainfall intensities for 15-minute intervals. The rainfall and radar data were combined and used in a multiple regression analysis to relate radar signal strength to surface rainfall rate at distances of 20 to 40 nautical miles from the radar. Seven hundred observations of radar signal strength, rainfall rate, and range were available for the analysis. These variables ranged in value from 0.00 to 2.01 inches per hour for rainfall rate and 0 to 45 db for attenuation.

Conclusions

The best definitions of the response surface of the prediction equation at low values of attenuation and range were obtained when the value of T was a maximum. It was concluded that as many observations of attenuation as possible should be made during a time interval when radar data is recorded on film.

A multiple functional relationship was used to develop a prediction equation. Three independent variables, A (attenuation of the radar receiver), R (range to the rain gage location), and T (number of radar observations within a time interval), were transformed into 29 variables and entered into the regression analysis. All except two of these independent variables were eliminated from the regression at the 5 percent level. These two variables, A and A^2, explained 30 percent of the variation in rainfall rate given by the regression. Forcing additional variables into the regression did not improve the standard error of .383 inch per hour or increase the multiple correlation coefficient. It was concluded that other pertinent quantities not being measured should be included in the regression analysis.

Three prediction equations developed will predict rainfall rate with a standard error of .33 inch per hour.

Suggestions for Future Study

One of the major problems encountered in this study was the processing of radar film data. Suggestions for future study pertain to the measurement and recording of pertinent variables of the radar that would allow easy access to data for research. Some suggestions that would aid in relating radar signal strength to rainfall rate are:

1. Improvements in measurement techniques of radar signal strength and recording of instantaneious values in a digital form compatible with computer input requirements.
2. Investigation of other pertinent measurable quantities that may influence radar-rainfall relationships such as storm speed, cloud height, and atmospheric conditions in the vicinity of the radar and the storm.

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APPENDICES

APPENDIX A

SAMPLE OF COMPUTER OUTPUT

RAINFALL DATA

APPENDIX A

SAMPLE OF COMPUTER OUTPUT-RAINFALL DATA

Watershed No.	Raingage No.	Month	Day	Year	End of Interval	Accumulative Time	Accumulative Gage Height	Interval Time	Interval Gage Height	Interval Intensity	Code
0121	002	05	25	62	1945	0015.0	00.04	0015.0	00.04	00.160	7
0121	003	05	25	62	1945	0015.0	00.01	0015.0	00.01	00.040	7
0121	005	05	25	62	1945	0015.0	00.01	0015.0	00.01	00.040	7
0121	006	05	25	62	1945	0030.0	00.16	0015.0	00.14	00.560	7
0121	007	05	25	62	1945	0030.0	00.37	0015.0	00.35	01.400	7
0121	008	05	25	62	1945	0030.0	00.14	0015.0	00.10	00.400	7
0121	009	05	25	62	1945	0015.0	00.37	0015.0	00.37	01.480	7
0121	010	05	25	62	1945	0015.0	00.08	0015.0	00.08	00.320	7
0121	012	05	25	62	1945	0015.0	00.01	0015.0	00.01	00.040	7
0141	014	05	25	62	1945	0015.0	00.01	0015.0	00.01	00.040	7
0141	016	05	25	62	1945	0015.0	00.02	0015.0	00.02	00.080	7
0121	017	05	25	62	1945	0015.0	00.03	0015.0	00.03	00.120	7
0121	018	05	25	62	1945	0015.0	00.03	0015.0	00.03	00.120	7
0121	020	05	25	62	1945	0030.0	00.05	0015.0	00.03	00.120	7
0121	021	05	25	62	1945	0030.0	00.23	0015.0	00.08	00.320	7
0121	022	05	25	62	1945	0015.0	00.11	0015.0	00.11	00.440	7
0121	023	05	25	62	1945	0015.0	00.07	0015.0	00.07	00.280	7
0121	025	05	25	62	1945	0015.0	00.01	0015.0	00.01	00.040	7
0121	026	05	25	62	1945	0015.0	00.01	0015.0	00.01	00.040	7
0141	027	05	25	62	1945	0015.0	00.01	0015.0	00.01	00.040	7
0141	028	05	25	62	1945	0015.0	00.01	0015.0	00.01	00.040	7
0211	029	05	25	62	1945	0015.0	00.03	0015.0	00.03	00.120	7
0512	037	05	25	62	1945	0015.0	00.18	0015.0	00.18	00.720	7
0141	043	05	25	62	1945	0015.0	00.03	0015.0	00.03	00.120	7
0141	045	05	25	62	1945	0015.0	00.05	0015.0	00.05	00.200	7
0121	046	05	25	62	1945	0030.0	00.10	0015.0	00.07	00.280	7
0121	047	05	25	62	1945	0015.0	00.06	0015.0	00.06	00.240	7
0121	048	05	25	62	1945	0015.0	00.25	0015.0	00.25	01.000	7
0121	049	05	25	62	1945	0015.0	00.06	0015.0	00.06	00.240	7
0121	050	05	25	62	1945	0030.0	00.45	0015.0	00.40	01.600	7
0121	051	05	25	62	1945	0030.0	00.41	0015.0	00.27	01.080	7
0121	052	05	25	62	1945	0030.0	00.13	0015.0	00.09	00.360	7
0121	053	05	25	62	1945	0015.0	00.07	0015.0	00.07	00.280	7
0141	054	05	25	62	1945	0030.0	00.14	0015.0	00.12	00.480	7
0141	055	05	25	62	1945	0030.0	00.17	0015.0	00.12	00.480	7
0211	058	05	24	62	1945	0075.0	00.05	0015.0	00.03	00.120	7
0512	067	05	25	62	1945	0015.0	00.01	0015.0	00.01	00.040	7
0311	070	05	25	62	1945	0015.0	00.01	0015.0	00.01	00.040	7
0311	071	05	25	62	1945	0015.0	00.03	0015.0	00.03	00.120	7
0141	075	05	25	62	1945	0015.0	00.13	0015.0	00.13	00.520	7

APPENDIX B

SAMPLE OF COMPUTER OUTPUT

RADAR DATA

APPENDIX B

SAMPLE OF COMPUTER OUTPUT-RADAR DATA

Month	Day	Year	No.of Observation within Interval	End Time of Interval	Readout No.	Raingage No.	Attenuation for interval
05	25	62	03.00	1945	001	001	22.00
05	25	62	03.00	1945	002	002	19.00
05	25	62	03.00	1945	003	003	20.00
05	25	62	03.00	1945	004	004	29.00
05	25	62	03.00	1945	005	005	31.00
05	25	62	03.00	1945	006	006	19.00
05	25	62	03.00	1945	007	007	15.00
05	25	62	03.00	1945	008	008	18.00
05	25	62	03.00	1945	009	009	18.00
05	25	62	03.00	1945	010	010	29.00
05	25	62	03.00	1945	011	011	28.00
05	25	62	03.00	1945	012	012	29.00
05	25	62	03.00	1945	013	013	24.00
05	25	62	03.00	1945	014	014	22.00
05	25	62	03.00	1945	015	015	16.00
05	25	62	03.00	1945	016	016	24.00
05	25	62	03.00	1945	017	017	23.00
05	25	62	03.00	1945	018	018	17.00
05	25	62	03.00	1945	019	020	22.00
05	25	62	03.00	1945	020	021	20.00
05	25	62	03.00	1945	021	022	19.00
05	25	62	03.00	1945	022	023	18.00
05	25	62	03.00	1945	023	024	29.00
05	25	62	03.00	1945	024	025	29.00
05	25	62	03.00	1945	025	026	29.00
05	25	62	03.00	1945	026	027	24.00
05	25	62	03.00	1945	027	028	15.00
05	25	62	03.00	1945	028	029	24.00
05	25	62	03.00	1945	029	037	04.00
05	25	62	03.00	1945	030	038	08.00
05	25	62	03.00	1945	031	039	11.00
05	25	62	03.00	1945	032	040	07.00
05	25	62	03.00	1945	033	041	23.00
05	25	62	03.00	1945	034	042	31.00
05	25	62	03.00	1945	035	043	24.00
05	25	62	03.00	1945	036	044	27.00
05	25	62	03.00	1945	037	045	29.00
05	25	62	03.00	1945	038	046	33.00
05	25	62	03.00	1945	039	047	31.00
05	25	62	03.00	1945	040	048	24.00
05	25	62	03.00	1945	041	049	24.00

APPENDIX C

RANGE DATA

DISTANCE OF RAIN GAGES FROM THE RADAR SITE

APPENDIX C

RANGE DATA
DISTANCE OF RAIN GAGES FROM THE RADAR SITE

Rain Gage No.	Range (N.Mi.)	Rain Gage No.	Range (N.Mi.)	Rain Gage No.	Range (N.Mi.)
1	43.32	61	18.69	117	26.86
2	41.21	63	15.59	118	27.80
3	36.95	66	17.05	119	28.47
4	34.18	67	17.84	120	28.47
5	36.78	68	19.11	121	29.86
6	39.63	69	20.11	122	30.27
7	42.00	70	22.25	123	32.29
8	43.98	71	23.97	124	33.60
9	41.96	72	25.95	125	35.39
10	39.48	73	27.86	126	37.43
11	36.80	75	32.13	127	39.09
12	34.20	76	34.04	128	41.25
13	31.69	77	36.45	129	43.42
14	29.11	78	39.03	130	42.42
15	27.51	79	41.25	131	40.63
16	29.71	80	37.64	132	39.09
17	31.81	81	35.70	133	37.22
18	35.00	82	33.68	134	35.91
20	40.34	83	31.52	135	34.60
21	41.96	84	29.57	136	33.23
22	40.50	85	27.18	137	32.58
23	38.05	86	26.05	138	31.46
24	35.45	87	23.93	139	30.48
25	33.12	88	22.46	141	32.60
26	30.50	89	21.17	142	33.19
27	28.01	90	23.75	143	33.58
28	25.72	91	19.92	144	34.43
29	24.02	93	21.79	146	36.72
37	14.64	94	22.10	147	38.26
38	16.32	95	22.85	148	39.15
39	18.36	96	23.16	149	41.09
40	20.58	97	25.26	150	43.00
41	22.66	98	26.57	151	44.37
42	25.30	99	27.86	152	44.95
43	27.18	100	28.88	153	43.35
44	29.57	101	31.36	154	41.36
45	31.96	102	33.52	155	41.40
46	34.41	103	35.35	156	37.30
47	36.87	104	36.51	157	36.68
48	39.09	105	38.67	158	39.92
49	41.38	106	37.38	159	40.55
50	42.02	107	34.72	160	41.27
51	39.71	108	32.94	161	42.63
52	36.74	109	31.25	162	43.54
53	35.31	110	30.25	163	45.00
54	32.64	111	28.61	165	45.14
55	29.94	112	26.97	166	45.06
56	28.05	113	26.39	167	43.66
57	26.20	114	25.45	168	42.89
58	23.18	115	24.83		
59	21.62	116	23.91		

APPENDIX D

COMPUTER OUTPUT
OF
PREDICTION EQUATIONS

APPENDIX D

COMPUTER OUTPUT OF PREDICTION EQUATION [7]

$$Y = .00899 + .01041A + .00019A^2$$

Y (Observed)	Y (Calculated)	Deviation $Y_o - Y_c$
.23300	.68722	-.45422
.35500	.66446	-.30946
.36000	.66446	-.30446
.48000	.47412	.00587
.24000	.55548	-.31548
1.56000	.67201	.88798
.96000	.74949	.21050
1.19400	.68722	.50677
1.11200	.58376	.52823
.19300	.24531	-.05231
.26300	.08251	.18048
.00900	.30433	-.29533
.51200	.48732	.02467
.56600	.54156	.02443
1.02000	.79771	.22228
2.02600	.78149	1.24450
1.32700	.73371	.59328
1.73000	.64202	1.08797
1.40000	.54156	.85843
1.28000	.32117	.95882
.18500	.20512	-.02212
.03200	.12732	-.09532
.08400	.04906	.03493
.05100	.12732	-.07632
.02600	.12732	-.10132
.01800	.12732	-.10932
.04100	.12732	-.08632
.05800	.14470	-.08670
.06500	.17648	-.11148
.75500	.19064	.56435
.21400	.21495	-.00095
.18500	.11885	.06614
.32000	.15360	.16639
.34700	.13594	.21105
.15800	.12307	.03492
.06100	.12732	-.06632
.04600	.09430	-.04830
.06200	.02177	.04022
.12400	.06357	.06042
.09000	.09033	-.00033

APPENDIX D

COMPUTER OUTPUT OF PREDICTION EQUATION [8]

$$Y = -.18585 - .01960A + .00013A^2 - .00286T^2 + .00192AR + .00239AT + .00153RT - .00002AR^2 - .00002RT^2$$

Y (Observed)	Y (Calculated)	Deviation $Y_o - Y_c$
.36000	1.36790	-1.00790
.48000	.98074	-.50074
.24000	1.17771	-.93771
1.56000	1.42224	.13775
.96000	1.58135	-.62135
1.19400	1.50260	-.30860
1.11200	1.31523	-.20323
.19300	.63890	-.44590
.26300	.22449	.03850
.00900	.79423	-.78523
.51200	1.17607	-.66407
.56600	1.27596	-.70996
1.02000	1.73982	-.71982
2.02600	1.68921	.33678
1.32700	1.64530	-.31830
1.73000	1.48291	.24708
1.40000	1.29195	.10804
1.28000	.83118	.44881
.18300	.57657	-.39357
.03200	.38393	-.35193
.08400	.17987	-.09587
.05100	.42957	-.37857
.02600	.44055	-.41455
.01800	.44490	-.42690
.04100	.43247	-.39147
.05800	.46269	-.40469
.06500	.54719	-.48219
.75500	.54544	.20955
.21400	.60128	-.38728
.18500	.37735	-.19235
.32000	.47944	-.15944
.34700	.43804	-.09104
.15800	.41474	-.25674
.06100	.43401	-.37301
.04600	.35516	-.30916
.06200	.13821	-.07621
.12400	.26717	-.14317
.09000	.33187	-.24187

APPENDIX D

COMPUTER OUTPUT OF PREDICTION EQUATION [9]

$$Y = -1.637040 + .008863A + .000728A^2 + .00009A^3 - .083450R + .003207R^2 - .00036R^3 + 1.2452T - .200323T^2 + .009829T^3 - .000275AR + .000161AT + .000019RT$$

$Y_{Obs.}$	$Y_{Cal.}$	Dev. $Y_o - Y_c$
.480	.471	.008
.240	.555	-.315
1.560	.657	.902
.960	.713	.246
1.194	.673	.520
1.112	.593	.518
.193	.274	-.081
.263	.140	.122
.009	.342	-.333
.512	.519	-.007
.566	.565	.000
1.020	.747	.272
2.026	.736	1.289
1.327	.711	.615
1.730	.649	1.080
1.400	.569	.830
1.280	.359	.920
.183	.251	-.068
.032	.187	-.155
.084	.143	-.059
.051	.179	-.128
.026	.166	-.140
.018	.159	-.141
.041	.176	-.135
.058	.201	-.143
.065	.227	-.162
.755	.240	.514
.214	.261	-.047
.185	.183	.001
.320	.210	.109
.347	.194	.152
.158	.179	-.021
.061	.175	-.114
.046	.138	-.092
.062	.115	-.053
.124	.123	.000
.090	.150	-.060
.154	.200	-.046
.640	.544	.095
.480	.570	-.090
.120	.501	-.381
.240	.467	-.227
.280	.459	-.179

VITA

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