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ILLINOIS STATE WATER SURVEY

METEOROLOGY LABORATORY

at the

University of Illinois

Urbana, Illinois

RADAR INVESTIGATIONS OF ILLINOIS HAILSTORMS

by

KENNETH E. WILK

Scientific Report No. 1

Contract No. AF 19(6041-4940

15 January 1961

Prepared for

GEOPHYSICS RESEARCH DIRECTORATE

AIR FORCE CAMBRIDGE RESEARCH LABORATORIES

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TABLE OF CONTENTS

FOREWORD

This report is the first of a series which will summarize the results of an investigation directed toward the determination of the utility of the AN/CPS-9 radar in the detection and identification of severe local thunderstorms.

The quantitative radar measurements in this report are relative values and subject to revision when more accurate measurements of the radar parameters become available.

The values of radar reflectivity were computed using the characteristics of a specific CPS-9 radar except for the antenna gain value. The antenna gain value used was 44 db.

Recent antenna gain measurements made by Austin and Geotes at M. I. T. indicate that the calculated value is probably too large. Use of the M. I. T. value (42 db) requires that <u>all</u> Z values in this report be multiplied by a factor of 2.5.

The data collection, processing, and analysis summarized in this report was supported by the Geophysics Research Directorate under Contract AF 19(604)-4940.

ABSTRACT

This report discusses research concerning the use of radar in the detection and identification of severe thunderstorms. Methods used in the collection of radar and meteorological data for severe local hailstorms are discussed. Results are shown of a comparison between surface hail observations and radar echo intensity measurements for various altitudes. It is suggested that identification of hail-producing thunderstorms is possible in the Midwest by examining the radar echo intensity between 20,000 and 25,000 feet for a radar reflectivity factor (Z) exceeding $1 \times 10^5 mm^6 m^{-3}$.

ACKNOWLEDGEMENTS

This report was written under the direction of William C. Ackermann, Chief of the Illinois State Water Survey. Research was accomplished under the general guidance of the Project Director, Glenn E. Stout, Head, Meteorology Section.

The author wishes to express appreciation to Irene Koch and August H. Krueger for their assistance in data processing and analyses, and the final preparation of this report. Special credit is due Eugene A. Mueller and Donald H. Summers for the origination of the radar antenna control circuit modifications on the AN/CPS-9 radar.

Credit is due also to the many cooperative weather observers who have volunteered their services to the project. These observers were contacted through the Agricultural Extension Service at the University of Illinois. The crop insurance data were provided by the Crop-Hail Insurance Actuarial Association.

The author wishes to thank Ralph J. Donaldson, Jr. and Dr. David Atlas, Geophysics Research Directorate, Air Force Cambridge Research Laboratories, for their critical review and comments of the report.

INTRODUCTION

The advent of the AN/CPS-9 radar in 1953 provided the first X-band weather radar system capable of long range examination of thunderstorm activity. The adoption of this system by Air Weather Service, United States Air Force has prompted the search for the radar echo characteristics which are indicative of severe weather occurrence. It is the purpose of this report to suggest certain criteria, both objective and subjective, which may be used in conjunction with the AN/CPS-9 radar to detect and identify the severe local thunderstorms.

Prior to 1953, a multitude of government surplus radars was placed in service at various research and operational organizations to aid in meteorological projects. Although much of the research work was concerned with quantitative determination of rainfall, it soon became evident that the precipitation echo configuration on the plan position indicator (PPI) could be of great significance as an indicator of severe weather. The first example of the detection of a tornado-producing thunderstorm to be documented by scope photography occurred in 1953 at the Illinois State Water Survey, when, using an APS-15 radar, meteorologists recorded the figure "6-shaped" or "hooked echo" associated with a tornado.[1] Since that time, many similar cases have been recorded, including another observation made by the Illinois State Water Survey using the AN/CPS-9 radar in 1956.[2] Continued research of the characteristics of severe weather echoes disclosed possible anomalies in echo velocity and intensity. Convergence, rapid development, attenuation notches, and lack of a bright band were a few of the characteristics noted as being indicators of severity. However, little or no quantitative evaluation was attempted, with the exception of the work by Atlas[3] concerning the use of gain-step reduction.

In 1957, Cook[4] as shown in figure 1, presented data from United States Weather Bureau APS-2 radars which showed a surprisingly high correlation between echo range of detection and the occurrence of hail. The wide beam width of this radar (4 degrees) guaranteed a great vertical extent of sampling at the ranges considered. It would appear that the radar sensitivity was such that the critical values of Z for hail could be detected by changes in range attenuation. It is of special interest to estimate the Z values at the 50, 75, and 100 per cent verification points (corresponding approximately to ranges of 135, 185, and 245 miles) in Cook's graph, figure 1. The Z values were calculated using the known APS-2 radar characteristics and assuming an average receiver sensitivity for the 17 Weather Bureau radars of -94 dbm. The calculations were made assuming the average cross sectional area of the core of the storm was 8 square miles. At 135 mile range, or 50 per cent hail verification, a Z of 2.6×10^5 mm^6m^{-3} was required for threshold detection. At a range of 185 miles (75 per cent hail verification), a Z of 9.0×10^5 mm^6m^{-3} was needed. Extrapolation of the range to 245 miles (100 per cent hail verification) suggested a critical Z value of 2o9 x $10^6 mm^6m^{-3}$. Thus, a review of Cook's radar analysis indicated a close association of hail with medium to high values of radar reflectivity. It is of great significance, however, that the 4-degree beam width of this PPI radar resulted in a vertical integration of the majority of the thunderstorm depth.

The importance of the vertical profile of the radar reflectivity was first noted by Donaldson[5] in research of thunderstorms in New England, with the discovery of a reflectivity maximum above 10,000 feet in thunderstorms. This development in severe storm identification prompted the intensification of severe local storm research programs in various climatic areas, such as Illinois, Texas, and Alberta, Canada.

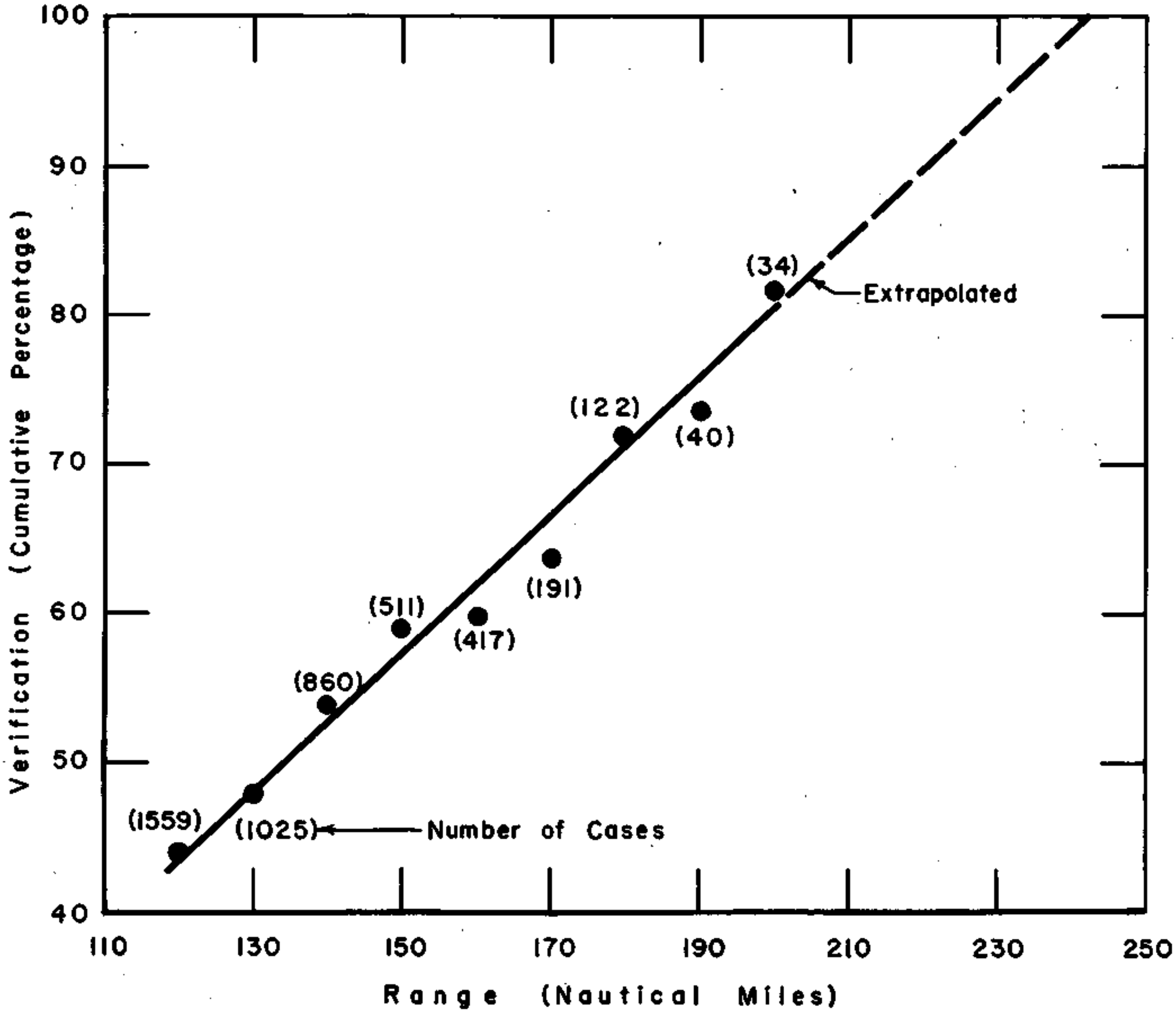


Fig. 1 Verification of hail occurrences vs. radar echo range (after Cook).

DATA COLLECTION METHODS

The establishment of the Illinois Severe local storm research program under Geophysics Research Directorate sponsorship began in May 1958. The initial task was the design and operation of the data collection systems to provide detailed radar and surface observations of severe local storms and the associated severe wind and hail occurrences.

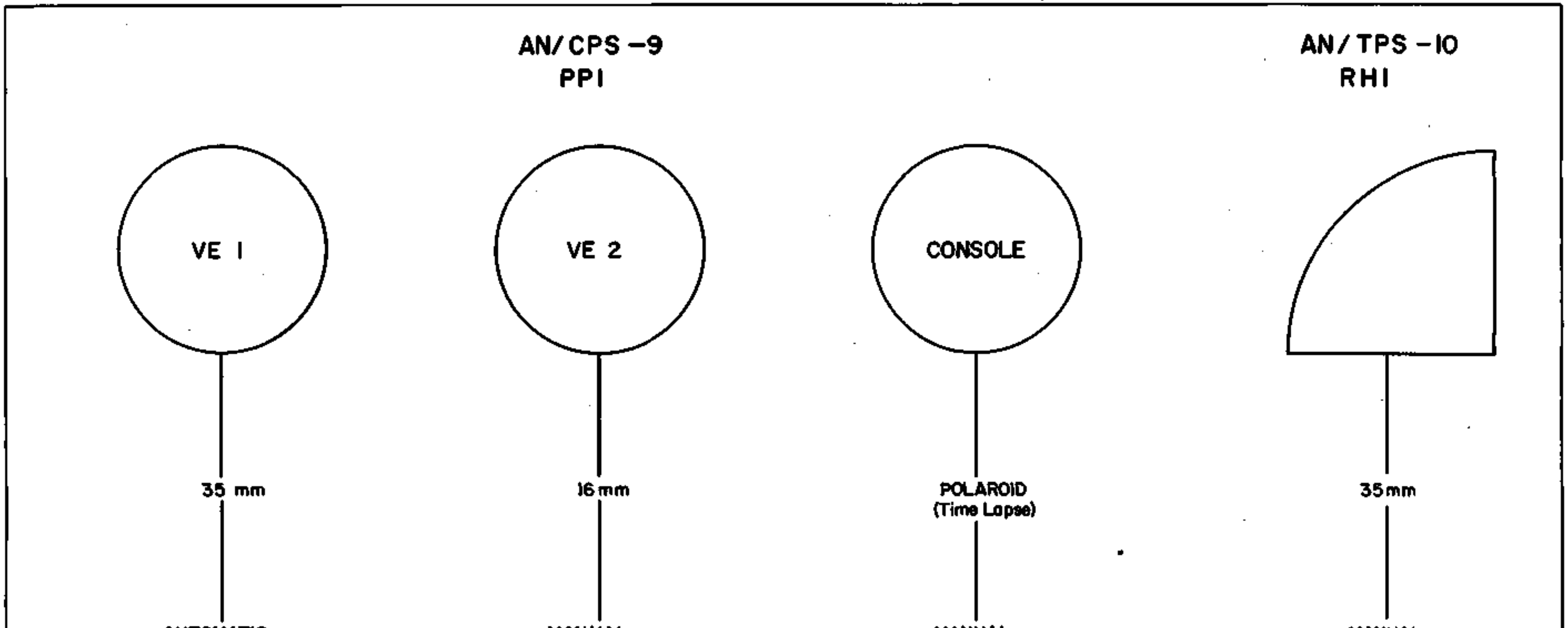
The radar equipment available for the project consisted of a modified AN/CPS-9, PPI radar and a TPS-10, RHI radar. Since the initial objective of the project was concerned with the ability of radar to distinguish between severe and nonsevere storms, analysis was on a comparative basis and integration of the intensity data from both radars was not necessary. The great advantage in relying on the TPS-10 radar to obtain echo-height measurements was that the CPS-9 radar could then be used simultaneously to sample echo intensities through a more restricted vertical range and that the time between CPS-9 echo measurements could be decreased.

Of primary importance in establishing the radar operating procedure was the determination of the atmospheric volume to be sampled and the frequency of observations required to permit satisfactory analysis of the data. Obviously, the volume constitutes a cylinder of a radius equal to the practical range of the TPS-10 radar, which, for acceptable height resolution, is approximately 50 miles. At that range, the CPS-9 and TPS-10 radars have vertical resolution of approximately 5000 feet and 3500 feet, respectively. Since the TPS-10 radar was used to measure echo tops, it was decided to limit the vertical scan of the CPS-9 radar to a maximum of 30,000 feet. At a range of 50 to 100 miles, the entire interval from 5000 feet to 30,000 feet was sampled by an antenna tilt range from 0 to 5 degrees on the CPS-9. At ranges less than 50 miles, the antenna tilt range necessary to cover the desired height interval increased, reaching 15 degrees at a range of 20 miles. Considering the antenna horizontal scan rate of 6 rpm and the 8 gain-reduction steps required for intensity measurements to be fixed, the volume sampled becomes a function only of the desired frequency of observations.

Therefore, a decision had to be made as to the maximum acceptable time between samples which was congruous with the minimum acceptable number of vertical intensity observations.

Although the durations of thunderstorms vary widely, from a few minutes to several hours, the average time of development of radar echo cells 1 to 2 miles in diameter has been established to be at least 10 minutes. Thus, selecting a radar observation repetition time of 10 minutes and a receiver gain reduction of 8 steps, a limit of 6 antenna tilt angles was imposed upon the CPS-9 radar operation procedure. The choice of the 6 antenna tilt angles was made from consideration of Donaldson's data for New England which show that the peak in severe storm reflectivity is near 20,000 feet. Assuming that the echo intensity increases with height in the lower half of the cloud, the first 2 gain-reduction steps could be eliminated on antenna tilts above 1 degree. The bypassing of steps 1 and 2 provided 2 additional scans which were utilized in obtaining a different scope range presentation. Both 250-mile and 100-mile scope range photographs at 0-degree tilt were required to maintain continuity with past data which is used for echo climatological studies.

The complete radar data recording procedure is illustrated in the schematic in figure 2. This system underwent certain modifications after the analysis of the first year of data. In the second year, 1960, another tilt angle was added and the 50-mile range, 0-degree tilt pictures and the intermediate 100-mile range, 0-degree tilt pictures were eliminated.



AN/CPS-9 PPI — VE 1 — 35 mm — AUTOMATIC

PHOTO TIME INTERVAL	SCOPE RANGE (MILES)	ANTENNA TILT ANGLE	RECEIVER GAIN STEP
↑	100	0°	1 - 8
	250	0°	1 - 8
Nine	50	0°	1 - 8
Minute	50 or 100	1,2,3 or 6	1 - 8
Cycle	50 or 100	2,4,8 or 10	3 - 8
	100	0°	1 - 2
	50 or 100	3,6,8 or 12	3 - 8
↓	50 or 100	4,7,10 or 15	3 - 8

AN/CPS-9 PPI — VE 2 — 16 mm — MANUAL

PHOTO TIME INTERVAL	SCOPE RANGE (MILES)	ANTENNA TILT ANGLE	RECEIVER GAIN STEP
20 sec	20	0°	Normal
	or		(Max)
20 sec	80	0°	Normal
	or		(Max)
20 sec	200	0°	Normal
			(Max)

AN/CPS-9 PPI — CONSOLE — POLAROID (Time Lapse) — MANUAL

PHOTO TIME INTERVAL	SCOPE RANGE (MILES)	ANTENNA TILT ANGLE	RECEIVER GAIN STEP
1 – 6	200	0°	4,5,6,7, or 8
hour			

AN/TPS-10 RHI — 35 mm — MANUAL

PHOTO TIME INTERVAL	SCOPE RANGE (MILES)	RECEIVER GAIN STEP
5 min	40	1 - 3
	or	
5 min	80	Normal

Fig. 2 Radar data recording schematic.

The selection of the 5 (in 1959) or 6 (in 1960) antenna tilt angles was based on the selection of the standard pressure levels (850, 700, 500, and 300 mb) as the echo reference heights (5000, 10,000, 18,000, and 30,000 feet) for echo intensity measurements. Observations were also made at the 15,000 and/or 25,000 foot levels. By varying the sequence of antenna tilt angles according to the median echo range, a pseudo-CAPPI system provided data for three-dimensional echo analyses with emphasis on the vertical reflectivity profiles. The system furnished constant altitude displays which could be composed manually from the film data. However, no range-gating circuitry was used so the system was not a true CAPPI as originated by McGill University.(7)

The TPS-10 operating procedure, although not as complicated as the CPS-9, was also based on echo duration,, The principal objective was the measurement of the range and height of the apex of each discernible echo turret. Assuming a mean echo growth rate of 900 feet per minute, observations were required at 5-minute intervals to provide echo top data in increments of 5000 feet. Therefore, the frequency of the TPS-10 RHI observations was fixed at twice that of the CPS-9 PPI data.

The two principal radar scope cameras provided 35-mm single scan exposures. Two additional cameras were installed on the CPS-9 repeater scopes. A 16-mm camera recorded maximum receiver gain, 0-degree antenna tilt presentations of the 250-mile range pattern. A 4- x 5-inch camera, mounted on the main console PPI scope, provided a 3-hour multiple exposure of a reduced gain presentation. Although choices of 4 gain steps and tilt angles were available for the multiple exposure, the majority of the data were recorded at approximately a 30-db gain reduction on 1-degree antenna tilt. These radar photographic recordings provided data on scales adequate for thunderstorm cell, thunderstorm complex, squall line, and frontal system analyses.

The controlling factor in the severe storm investigation was the identification of the severity of the individual storms. Severity was defined in terms of wind gust velocity, hail size, lightning, rainfall, and cloud formations (funnels). In order to obtain these observations, it was necessary to establish a severe storm reporting network with a high areal density of observers with reporting reliability. The largest group of potential observers in Illinois consisted of 2400 Farm Bureau-Farm Management cooperators under the guidance of the Agricultural Extension Service at the University of Illinois. Another group of approximately 2000 farmers were part of the State Crop Reporting Service in Illinois. Supplementary volunteers from urban and rural areas were recruited through local television, radio, and newspaper appeals. Approximately 1000 farmers volunteered for the project and immediately provided information concerning their exact location, type of rain gage, et cetera. The resulting severe storm observer network is shown in figure 3° The original federal land survey based on townships, range, and section divisions aided greatly in creating a grid of 1-mile squares for geographical reference of storm occurrence. Actually, for the majority of surface hail and radar intensity comparisons, 618 townships, (6- x 6-mile squares), rather than 1-mile squares, were used for reference.

The reports of the severe weather occurrences were recorded by the observers on specially designed post cards as shown in figure 4. A letter of instructions to the observers followed by periodic reports concerning the preliminary analysis of specific storms was used to stress the importance of the observers' contributions. Special emphasis was placed on the accuracy required in reporting exact time of hail and wind occurrences.

Although the average observer density exceeded 1 observer per 20 square miles, the severe storm observer reports did not adequately describe the areal

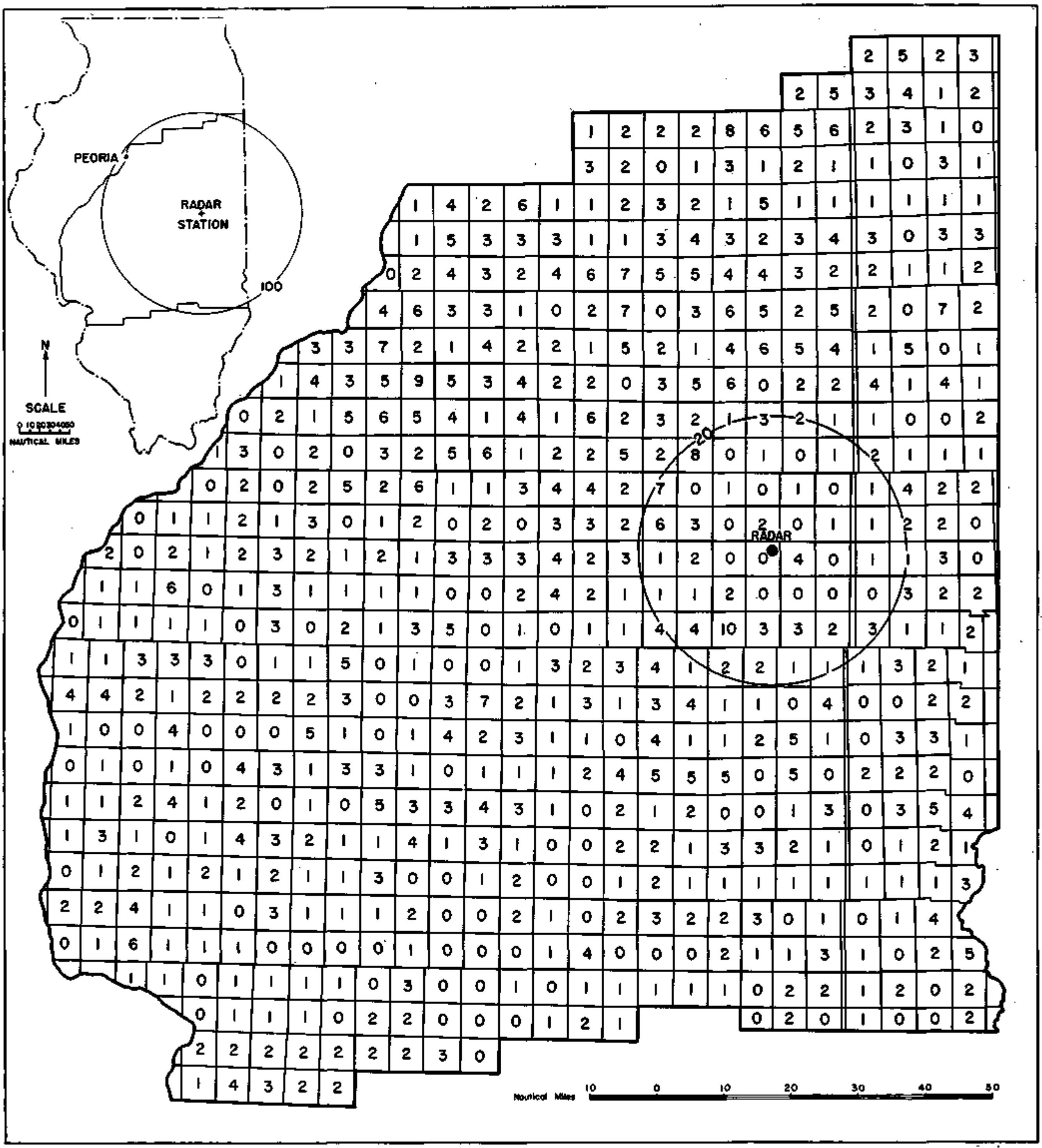


Fig. 3 Severe local storm reporting network, number of observers per township (1960).

Name of Observer:____________________

Mail Address:____________________

Location of storm: County__________Twnshp.__________Range__________Sect__________
-or-other description
of location:____________________

Date:____________________Time of day: AM___PM___Daylight (fast)___Standard___

<u>HAIL</u>: Time began__________ended__________

Size (diam.) of largest stones: ______¼,___½,_____¾,___1, or ____________ inches

Average size (diam.) of stones:_____¼,_____½,_____¾,_____1. or ____________ inches

No. of stones per sq. ft:__________

Color of stones: Clear__________, White__________, Layers clear & white__________

Shape: Round__________Flat__________Triangle__________Other__________

<u>DAMAGING WINDS</u>: Time began__________ended__________

Direction from which damaging winds blew_______________

Damage to trees_______property_______or crops_______; Little_______or much_______

<u>LIGHTNING WITHIN 1 MILE</u> (5 seconds or less between flash, thunder)

Time began__________ended__________

Direction of most lightning: N_______E_______S_____W_______Overhead_______

Type of lightning: Cloud to cloud_______________Cloud to ground_______________

<u>HEAVY RAIN</u>: Time first rain began____________Heavy rain began_______________

Heavy rain ended____________all rain ended____________Total__________inches

<u>COMMENTS ON SKY CONDITION</u>: (color of sky, unusual cloud formations, etc.) or COMMENTS ON ANY OF THE ABOVE ITEMS:

____

____

____

5M—3-60—70743

Fig. 4 Severe storm reporting card.

extent of the storms. A more accurate areal description was obtained from data provided by the Crop-Hail Insurance Actuarial Association, which afforded excellent coverage in the northern two-thirds of the network area, illustrated in figure 5. The application of these data, by a method previously described by Blackmer,[8] was dependent upon the susceptibility of crops to damage. Fortunately, only the two crops, soybeans and corn, are prevalent in central Illinois. The two crops have parallel growing seasons as well as comparable susceptibility to hail damage. The most descriptive crop-damage parameter to be used in estimating hail distribution was the number of sections (square miles) reporting damage. By normalizing this figure with the number of sections insured in a given area (townships), a corrected areal distribution of the number of sections affected was obtained.

A preliminary analysis was made of the time and space distribution of the crop-hail reports of hail damage between 1952 and 1957. The purpose of this analysis was to determine the mean duration and sector width of damaging hailstorms within the volunteer observer network. The results of the analysis were used to determine the expected duration of damaging storms within the network and, to determine if the CPS-9 could be sector-scanned, thereby reducing the scanning time to allow more frequent observations. Generally, the total hail damage reports could be classified according to one of three basic patterns. The most frequent pattern (42 per cent) was composed of scattered reports with little semblance of direction or time continuity. However, many of the storm damage patterns (31 per cent) exhibited swaths with well marked beginning and ending times. The remainder of the storms examined (27 per cent) contained both swaths and scattered reports and were classified as such.

The times of the first and last reports of hail damage for the three patterns were used to determine the duration of the damaging storms. Table la

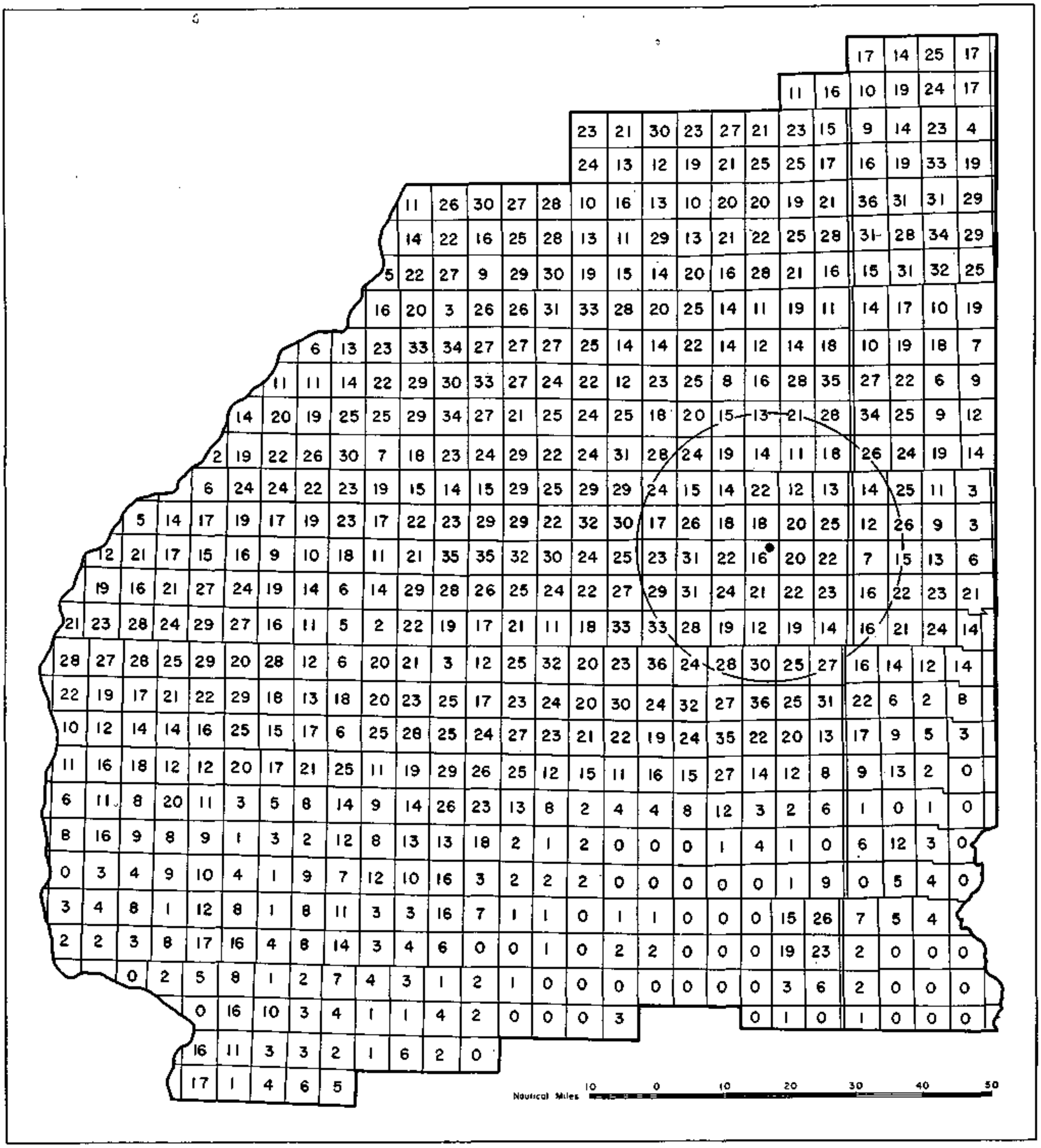


Fig. 5 Distribution of crop-hail insurance, number of insured sections per township (1954).

lists the durations of the storms by 6-hour intervals. The mean durations of the three patterns, determined to the nearest hour, were 6 hours for swaths, 6 hours for the scattered, and 10 hours for the swath and scattered patterns.

TABLE la

DURATION OF DAMAGING HAILSTORMS

Duration (hours)	Pattern (number of cases)		
	Swaths	Scattered	Swaths and Scattered
0 - 6	35	49	15
7 - 12	16	13	20
13 - 18	3	8	8
19 - 24	1	4	4

The radar scan sector width which would be necessary to cover the geographical area of the hail damage pattern was recorded for each case and grouped, as shown in table lb, in 45 degree intervals. The mean sector widths of the three patterns were 91 degrees for the swaths, 77 degrees for the scattered, and 107 degrees for the swaths and scattered patterns. Since more than 70 per cent of the patterns exceed 45 degrees, the use of a sector scan on the radar did not appear practical considering the frequent readjustments of the sector which would be required.

TABLE 1b

SECTOR WIDTH OF DAMAGING HAILSTORMS

	Pattern (number of cases)		
Sector Width (degrees)	Swaths	Scattered	Swaths and Scattered
0 - 45	14	22	4
46 - 90	13	23	18
91 - 135	15	19	11
136 - 180	13	10	14

For investigation of individual thunderstorms, special instrumentation was installed in an Illinois State Water Survey network of 50 recording rain gages evenly distributed in a grid pattern within a 400-square-mile area. Hail indicators (figure 6), which were constructed of styrofoam covered with aluminum foil, were placed adjacent to each rain gage. Two anemometers and 12 microbarographs were located in the network during the 1960 data-collection season.

The data collection phase described in this section resulted in 1605 detailed thunderstorm observations during 1958, 1959, and 1960. These observations were supported by radar observations, crop-hail damage reports, and a limited number of wind, pressure, and rainfall observations from the special raingage network. These data were then analyzed to determine the characteristics of the individual storms.

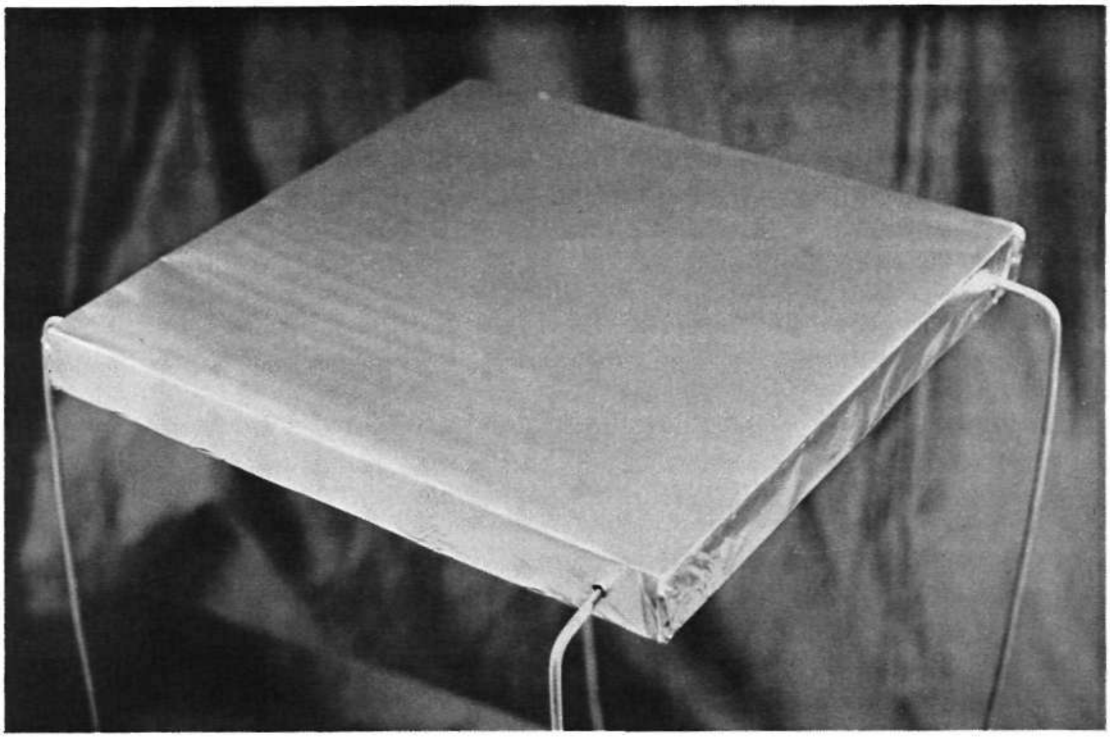


Fig. 6a Hail indicator.

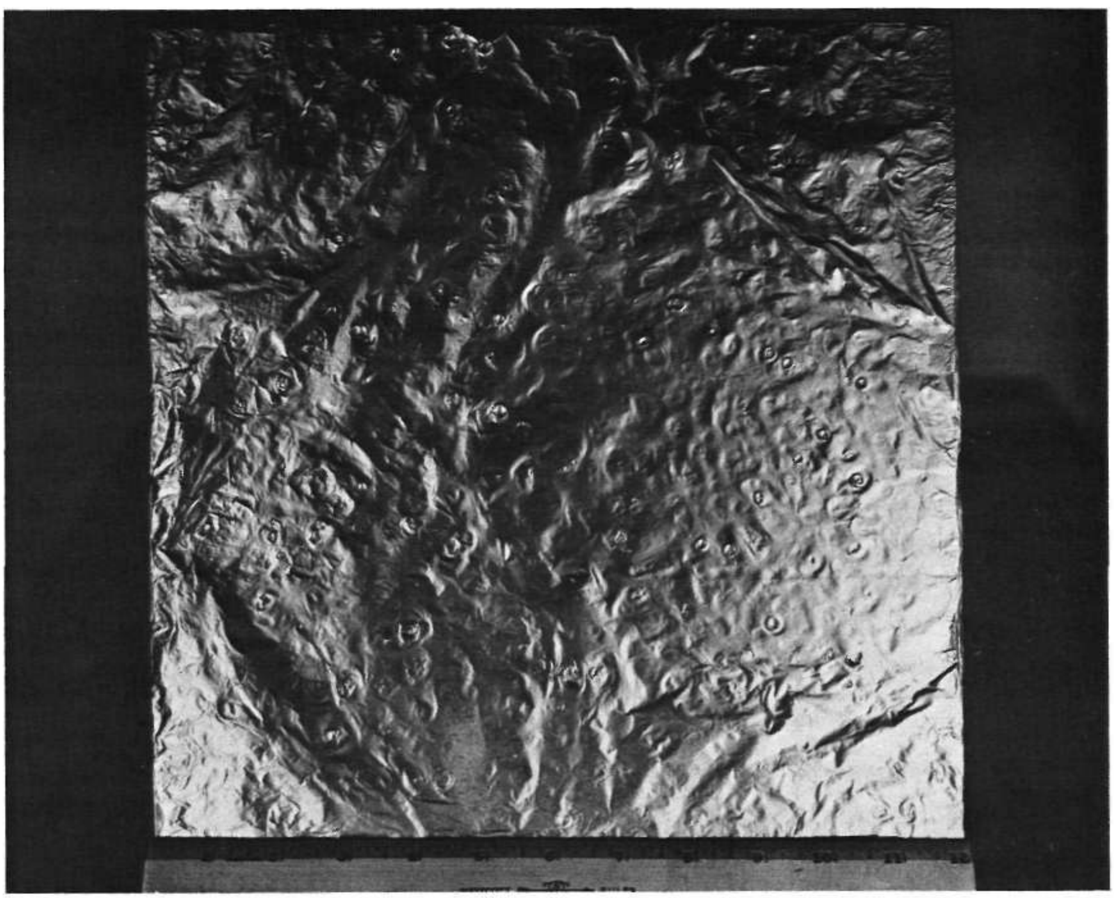


Fig. 6b Imprint of clear, hard hail registered after long term (8 day) exposure of indicator.

RADAR (CPS-9) IDENTIFICATION OF HAILSTORMS AND WINDSTORMS

The comparative analyses of radar data with severe local storm observations were performed utilizing two independent procedures. First, case studies were made of specific radar echoes known to be associated with severe weather. Second, a numerical study for a selected area was made of all echoes occurring within designated grid squares in the area to determine echo frequencies at various intensity and height levels. These measurements were related to severe weather occurring in these squares.

The initial study undertaken was the examination of line-echo configurations associated with squall lines. As reported previously,[9] one of the simplest and most obvious identifying features on the PPI which is indicative of hail and damaging wind is the marked acceleration in the solid squall line. Figure 7 shows a case of line distortion which occurred in the severe local storm reporting network. The time lapse sequence of the May 25, 1960 storm is an excellent example of the acceleration of a line segment. The May 24, 1960 storm, figure 8, illustrates a case with cell velocity remaining fairly constant throughout the length of the line and with no major distortion development. The hail and wind damage indicated on figures 7 and 8 reveal the comparative severity of the two cases.

Unfortunately, many of the major hailstorms are not associated with a single echo line but are accompanied by more than one convective system which produces a complex radar scope pattern on normal receiver gain and on 0-degree antenna tilt. Therefore, the development of a line distortion can only be recognized in a relatively small percentage of the hail-producing storms. A solution to the problem of scope complexity with hail-producing storms was suggested by Donaldson[5] by his discovery of a reflectivity maximum above 10,000

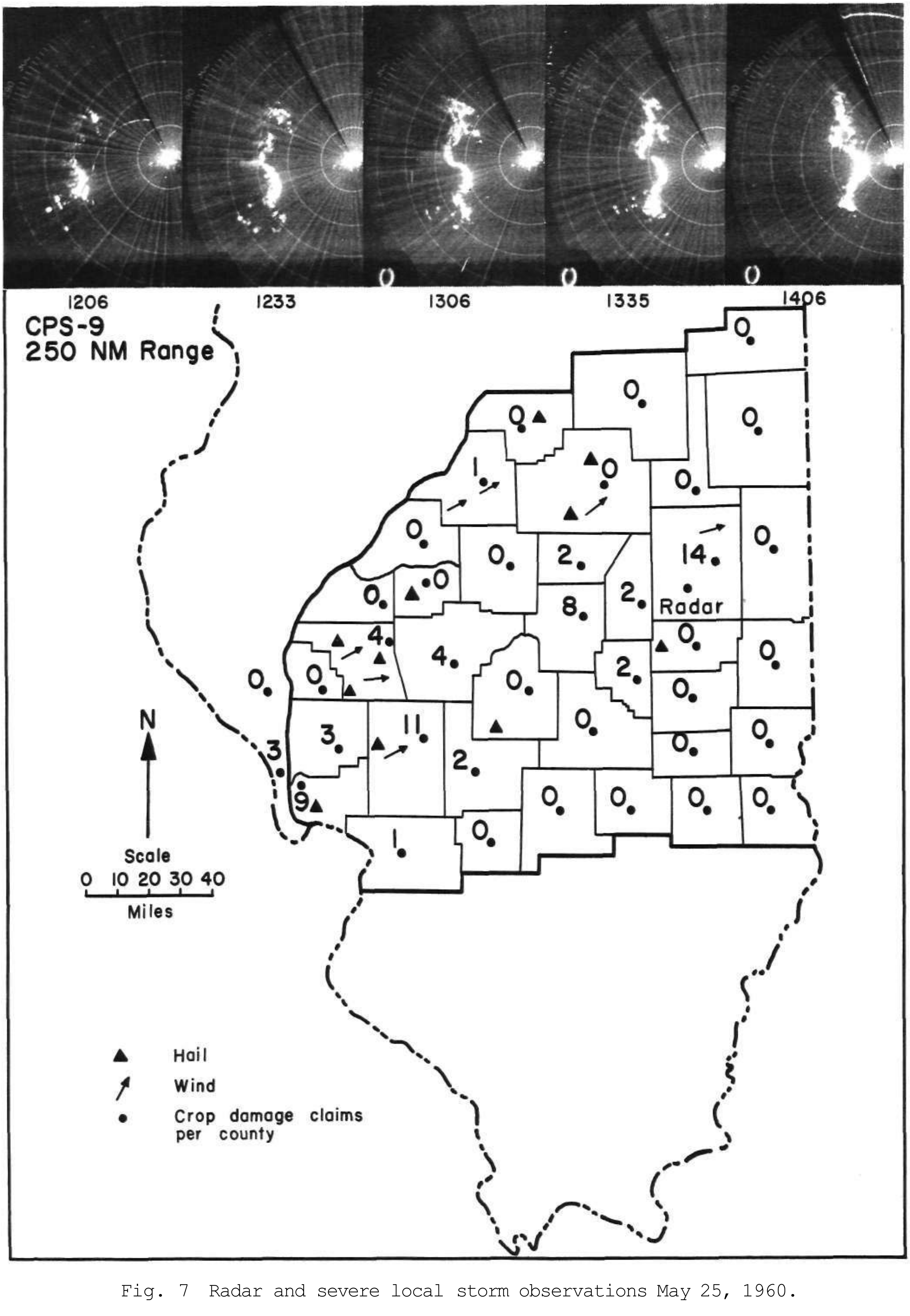


Fig. 7 Radar and severe local storm observations May 25, 1960.

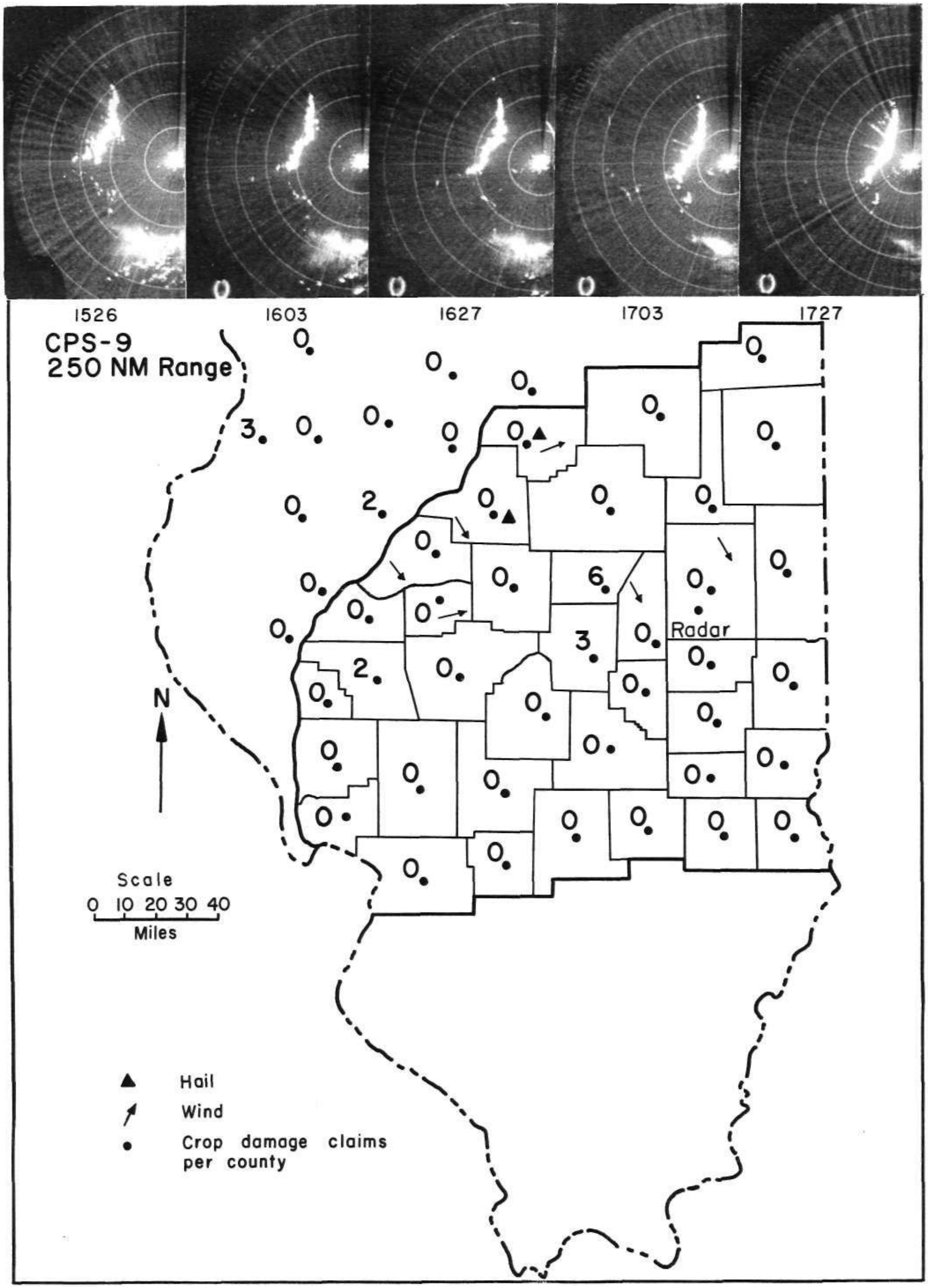


Fig. 8 Radar and severe local storm observations May 24, 1960.

feet in severe thunderstorms in New England.

Analysis of the Illinois radar data collected during the hailstorm on September 28, 1959 supported Donaldson's findings and provided additional information concerning echo height and radar reflectivity relationships. In this case analysis, the CPS-9 PPI photographs taken at various antenna tilts were used to construct five constant altitude intensity cross sections of all echoes that occurred during the storm period. The altitudes chosen corresponded to the approximate heights of the standard pressure surfaces (1000, 850, 700, 500, and 300 mb). The repetition time of the antenna program permitted the cross sections to be drawn at 9-minute intervals. The TPS-10 radar was used primarily for obtaining maximum echo heights. Using the two radars, there were 395 measurements of echo height and/or intensity made during the storm period which extended from 1400 to 2000 CST. Of these 395 measurements, 75 were of echoes associated with hail-producing storms.

The CPS-9 PPI patterns and the surface hail damage configurations associated with the most severe thunderstorms are shown in figure 9° The primary cell tracks of echoes A_2, as marked at the 500 mb level, and B agreed closely in time and space with the crop damage and observer reports. Two adjacent cells, A_1 and C, were not correlated to specific hail areas and were assumed not to have produced hail of significant size and intensity to be observed at the surface. The echo configurations shown were acquired at a receiver gain setting of 30 db below maximum sensitivity, or, at a mean equivalent radar reflectivity (Z) value exceeding 1 to 2 x $10^3 mm^6 m^{-3}$. The best areal agreement between echo and surface hail damage greater than 20 per cent was associated with a mean Z value exceeding 6 x $10^3 mm^6 m^{-3}$, at an altitude between 16,000 and 20,000 feet. The surface storm cores, or areas of damage greater than 80 per cent, were best

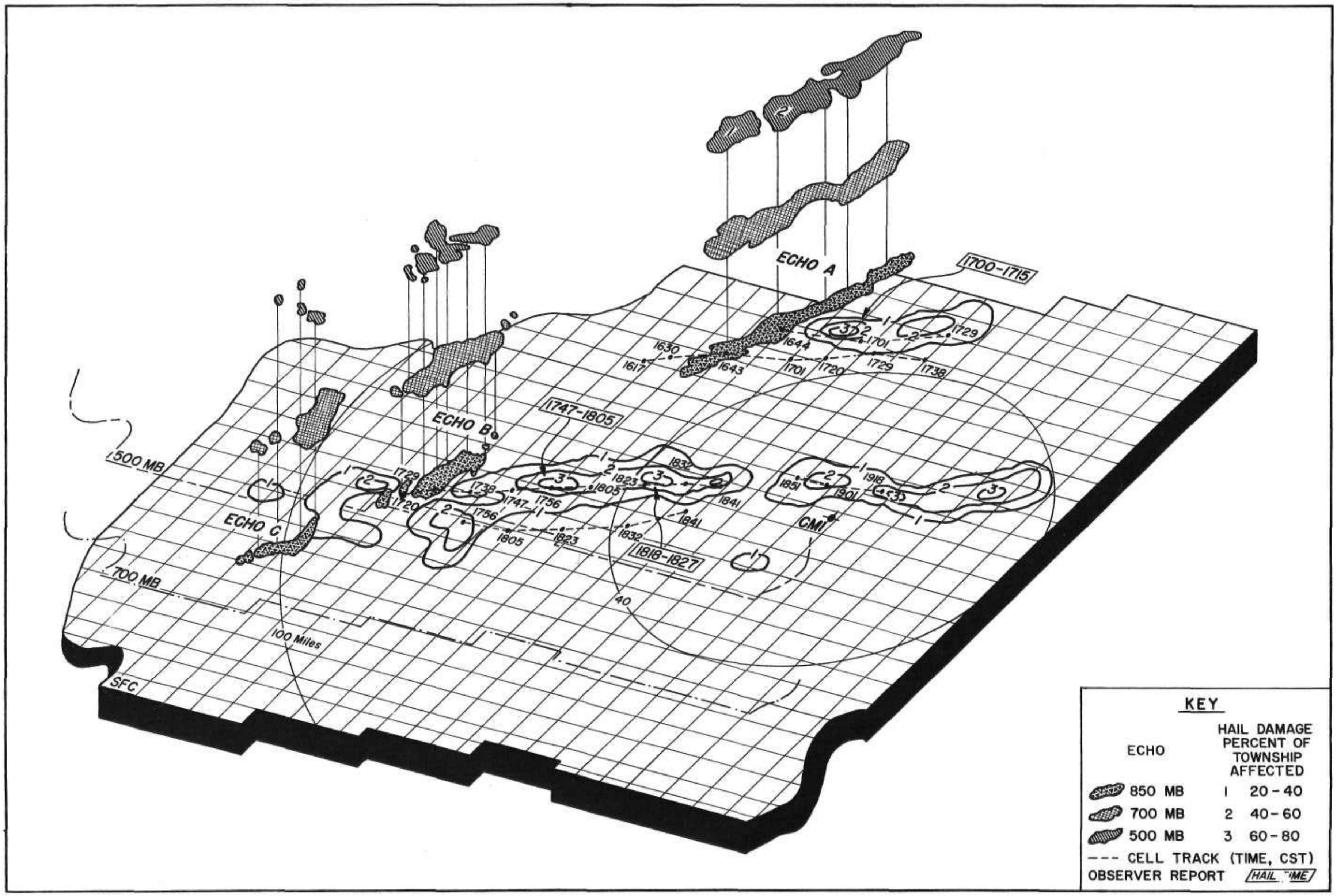


Fig. 9 Composite radar echo, surface hail damage and cell track, 1600-1900 CST, September 28, 1959.

related to a Z in excess of 1 to 2 x $10^5 mm^6 m^{-3}$ at an altitude between 20,000 and 25,000 feet.

The vertical intensity profiles of the individual cells were analyzed for consecutive 9-minute observations. In figure 10, the Z-H relations are shown for the four individual echoes A_1, A_2, B, and C. The available TPS-10 echo measurements are included to describe the associated maximum echo tops. The initial growth rate of echo A_1 between 35,000 and 45,000 feet was 900 ft min^{-1}.

The rate of intensification of echo A_1 (no associated hail) was congruent with the radar sampling time, which resulted in the orderly change depicted in figure 10. The average height of the reflectivity maximum is well defined near 15,000 feet. The radar observations of echo A_2 were limited to the dissipation stage. However, it was apparent that the highest Z-value region was above 20,000 feet, significantly higher than the maximum observed in echo A_1. Echo B, which was associated with the most intense hail occurrences, had a high level intensity peak similar to echo A_2 but had a deeper maximum Z region.

The time of maximum echo height was in agreement with the observed hail time, with a tendency for the maximum echo intensity to occur slightly before the surface hail report. It was not possible to obtain an absolute value of this delay time because of the time lag between radar observations and because of slight inaccuracies in surface time reports. The Z profiles of echo C show little time continuity. The highest intensity value was obtained when echo C merged with echo B.

Since individual echo tracking was not accomplished with the CPS-9 radar, the number of cases showing time variations of the Z profiles was limited. However, the antenna tilt program provided a large sample of point measurements which represented all stages of echo growth and dissipation. The 395 observations

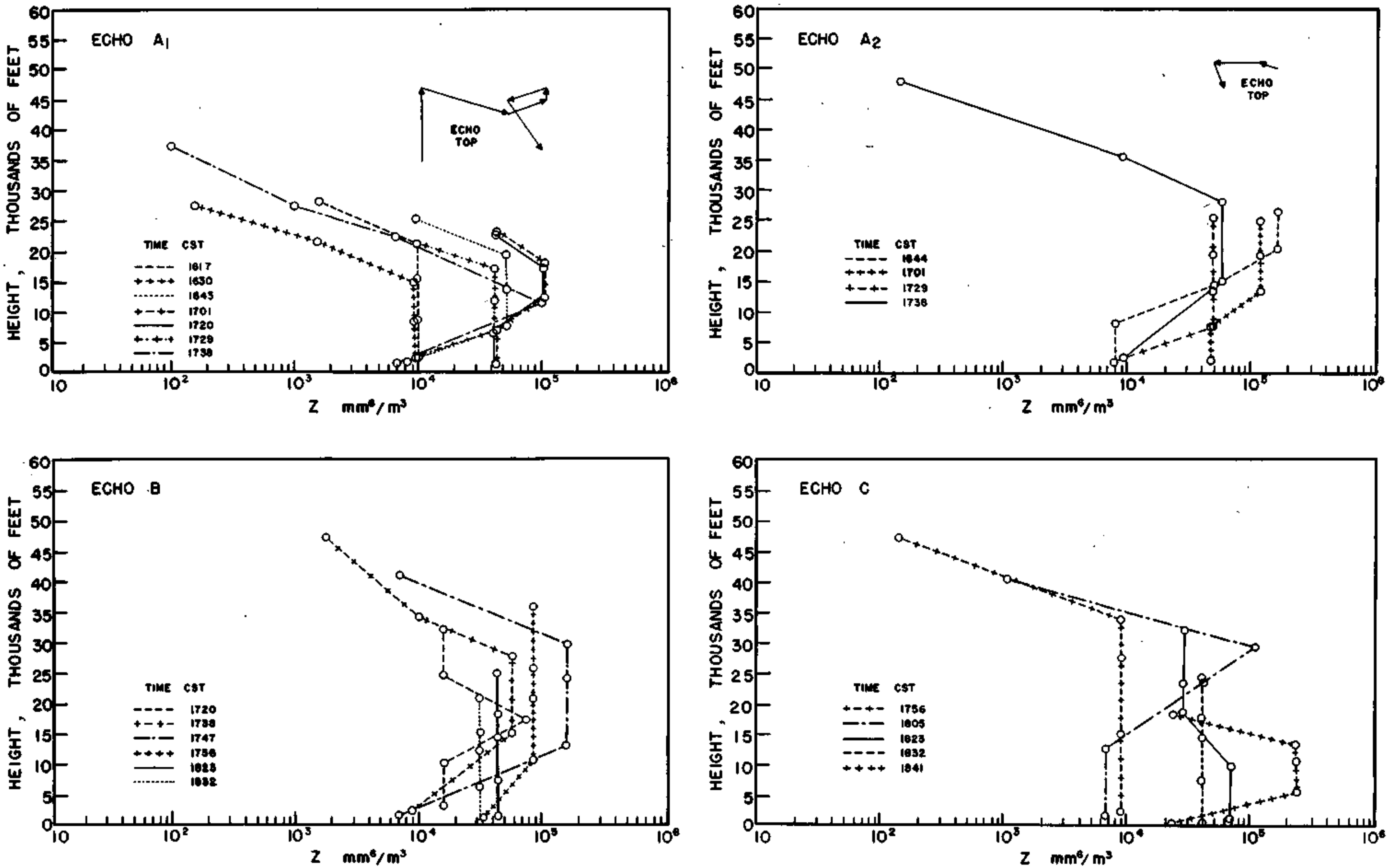


Fig. 10 Radar reflectivity (Z) profiles, September 28, 1959.

were used to obtain the mean Z profiles for the echo-top height intervals as shown in figure 11a. With the exception of the echoes with tops in the interval of 36,000 to 40,000 feet, there was a uniform rise of the maximum Z region with increasing echo height. The relation of the maximum Z values to the heights of the echo tops is shown in figure 11c. The greater range of Z values with the lower echo tops was caused by obtaining data during all stages of thunderstorm development. Obviously, as the echo height increases and since the Z observations are made near the peak of the growth stage, the range of maximum Z values must decrease. The range of Z values for a particular echo height is less for the hail associated echoes, as shown in figure 11b. However, the Z-H relation is obviously still too weak to be used for prediction purposes.

The variability of the Z-H relationship caused by the growth stage of each echo can be further examined for the echoes associated with hail. In figure 11d, the data were sorted according to five stages of the echo life cycle. The stages were defined by equally dividing the total range observed for the individual echo height and intensity measurements. The change in slope of the Z-H regression lines between the development and dissipation stages emphasizes the variability which can be expected with single measurements of thunderstorm echoes.

The results of the single storm analysis indicated the radar reflectivity maximum in the vicinity of 20,000 feet in thunderstorms to be a measure of the hail productivity of a storm. The maximum Z value acquired from most Illinois hailstorms exceeded $10^5 mm^6 m^{-3}$.

In order to make a reliable test of the Z-hail relationship, a large sample of radar echo intensity measurements was required over the severe local storm reporting network. The tremendous volume of radar data to be processed necessitated that the information be digitized. This was accomplished by transferring

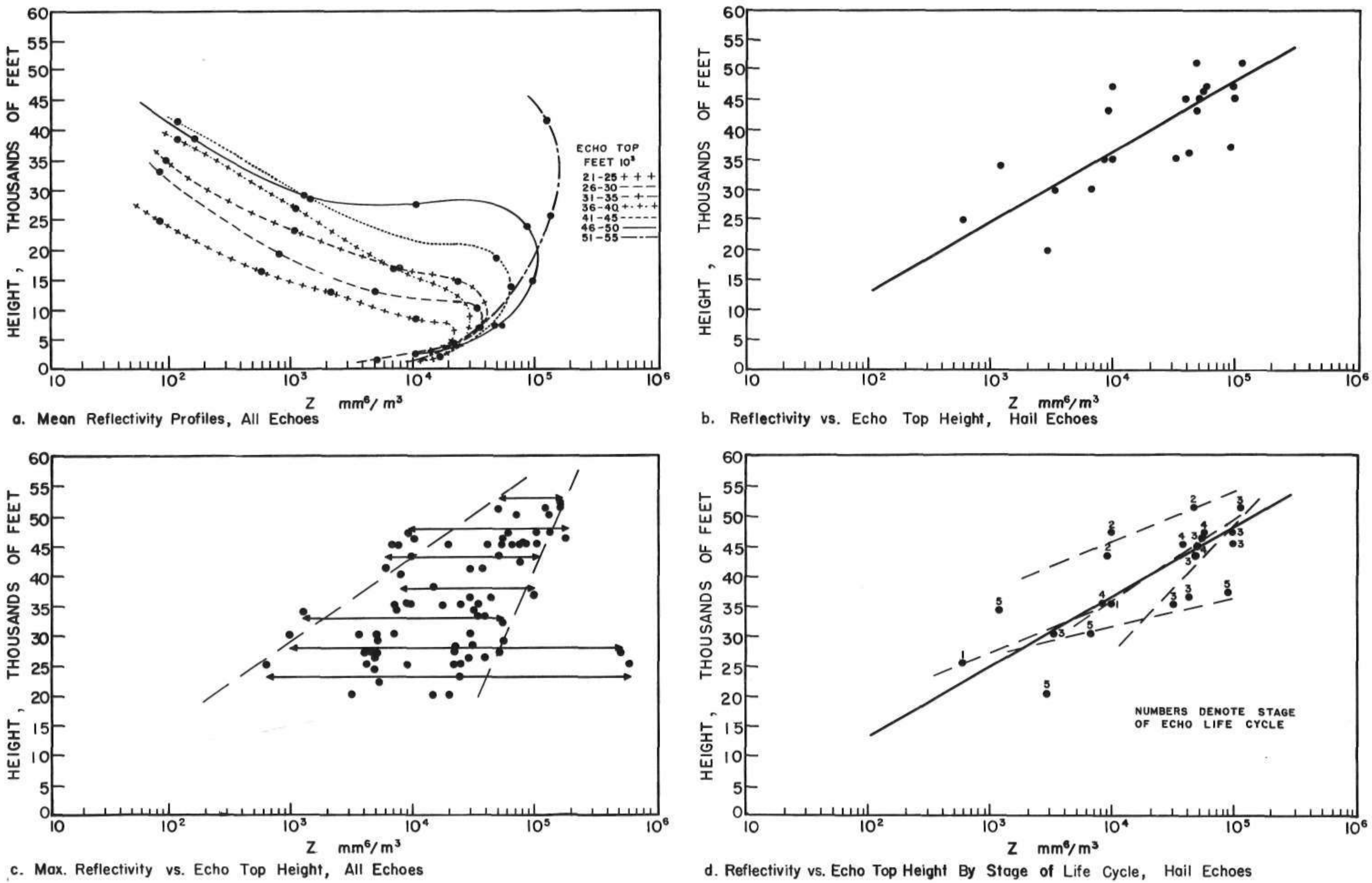


Fig. 11 Radar reflectivity (Z) vs. height, September 28, 1959.

the CPS-9 data to IBM cards by referencing echo occurrence at 9-minute intervals to a grid composed of 618 6- x 6-mile squares as shown in figure 3° The date, time, tilt, and gain-step identification were punched initially on each IBM card. Then the squares (townships) that contained echoes were punched in order across the card.

No limitation was placed on the percentage of square covered by echo because of the area variability of convective storms and almost point targets obtained from individual cell cores. Also, no differentiation was made by the key punch operator between precipitation and coherent targets.

The echo data were sorted and consolidated on summary cards containing echo frequency counts for all squares for all given antenna tilt angles and receiver gain-reduction steps. The network observer cards provided times of severe weather occurrences for the initial card sort. After the echo frequency counts were completed, Z values were calculated for the total storm sample of 9-minute observations for each grid square. The range attenuation correction (R^2) was referenced to the center of each square.

The township radar reflectivity factor totals were analyzed according to height and compared to the surface hail reports. Since the initial sort of the data was according to time, the first comparison made was between the total echo frequencies based on 9-minute observations for the hail periods and the no-hail periods. As can be seen in figures 12 and 13, the average normal-gain echo (0-degree tilt) frequency for the no-hail period was approximately two times that for the hail period.

The numerical pattern comparison between total Z's indicated the most significant difference between the hail and no-hail periods was near the 20,000 foot level. A plot of the total "hail" Z's equal to or greater than 1×10^4 mm^6m^{-3} is shown in figure 14. Figure 15 shows the corresponding township plot

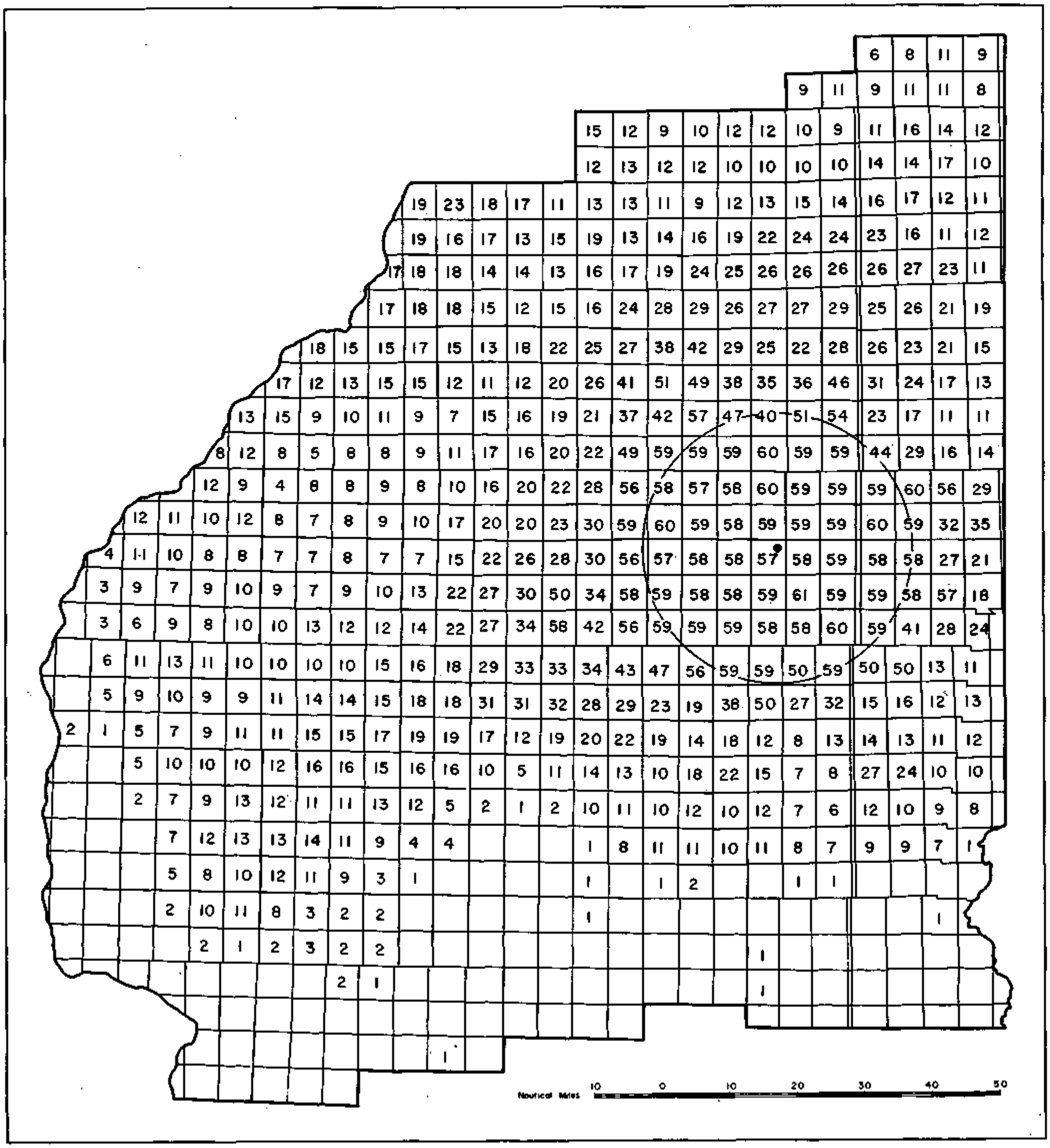


Fig. 12 Echo frequency count based on 9-minute observations for periods of no hail occurrence 0° tilt maximum gain, September 28, 1959.

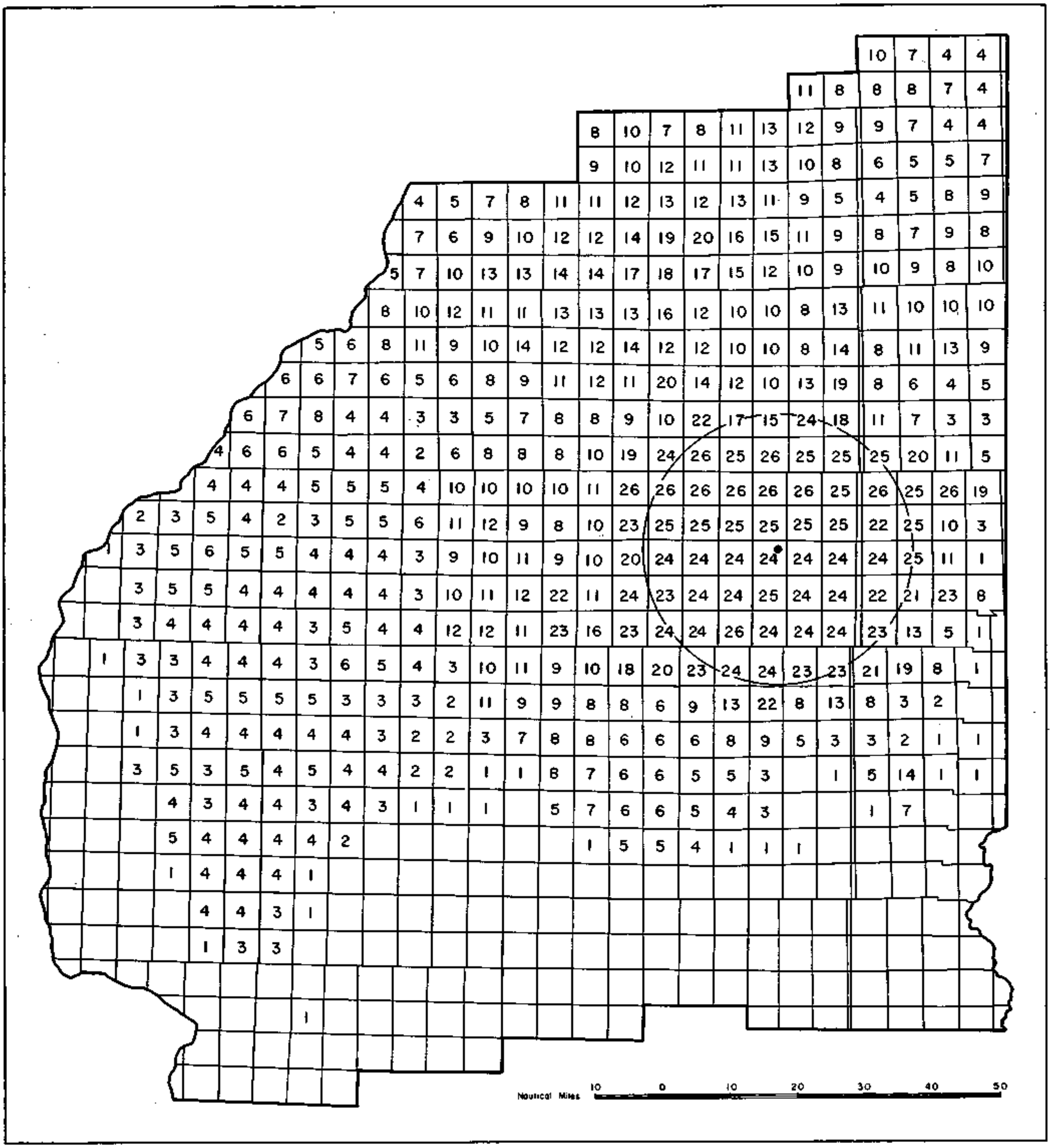


Fig. 13 Echo frequency count based on 9-minute observations for periods of hail occurrence 0° tilt maximum gain, September 28, 1959.

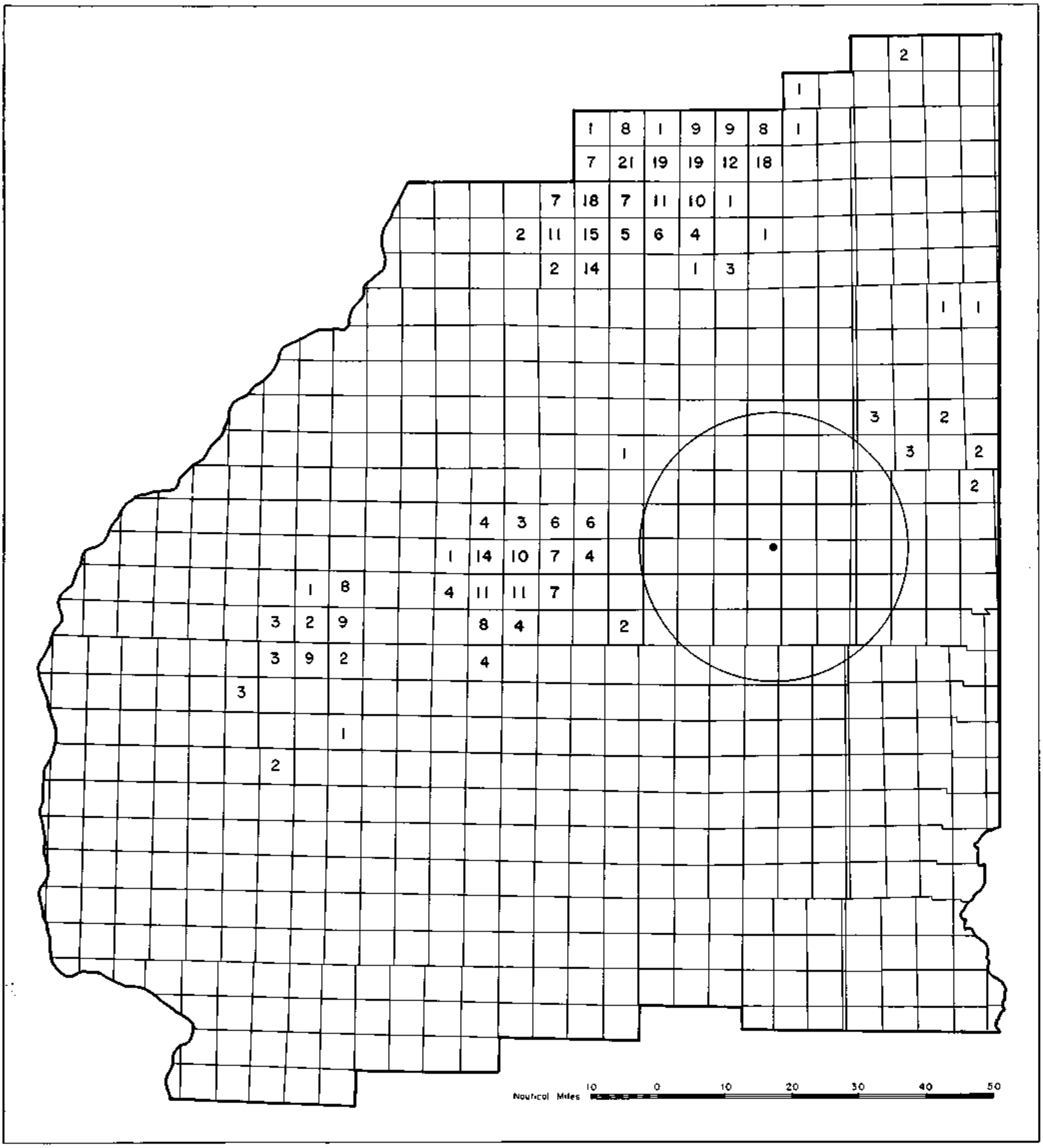


Fig. 14 Total radar reflectivity factor (Z) x $10^4 mm^6 m^{-3}$ at 20,000 feet based on 9-minute observations for hail period, September 28, 1959.

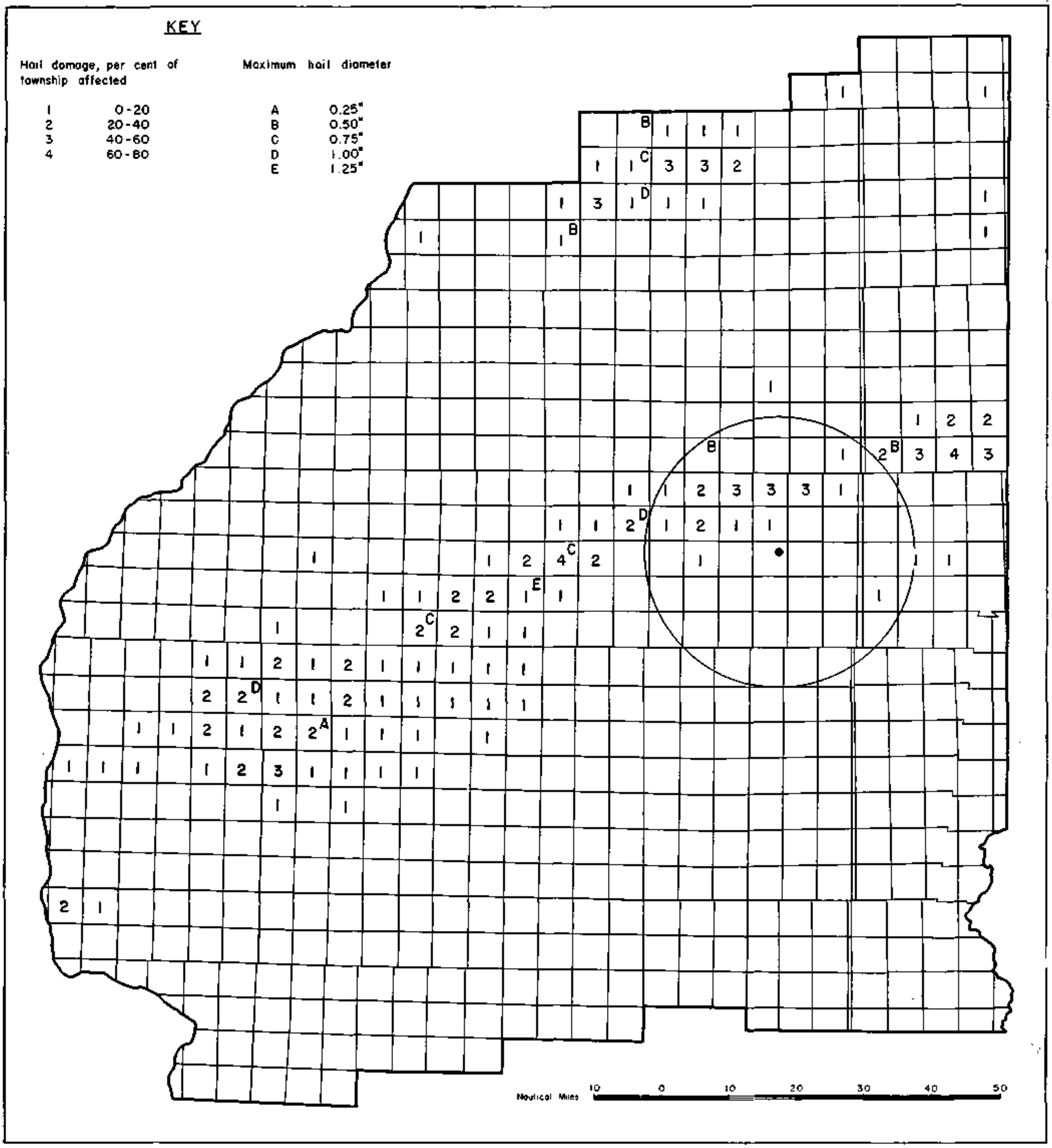


Fig. 15 Crop-hail damage and hail observations, September 28, 1959.

of crop damage and reports of hailstone size. The total "no-hail" Z's equal to or greater than $1 \times 10^4 mm^6 m^{-3}$ are shown in figure 16. In general, the comparison of the hail damage and stone size with the average Z total indicated that hail damage greater than 50 per cent and hailstone diameter of 2 to 3 cm corresponded to a Z exceeding 1 to $2 \times 10^5 mm^6 m^{-3}$. Hail damage between 20 and 50 per cent and a stone diameter of 1 to 2 cm corresponded to a Z exceeding 5×10^4 to $1 \times 10^5 mm^6 m^{-3}$. Hail damage less than 20 per cent and hailstones less than 1 cm in diameter were associated with a Z less than $5 \times 10^4 mm^6 m^{-3}$.

For a specific areal comparison of the individual townships where both hail damage and echo were present, the Z's were analyzed for various altitudes from 5000 to 25,000 feet. Only the townships where echo and hail damage both occurred were considered. No townships were considered where no echo was found since the absence of echo may have been tabulating error or reporting time error. The first cases examined were those where the total storm (based on 9-minute observations) Z was equal to or greater than $1 \times 10^4 mm^6 m^{-3}$ for all townships that reported hail damage. Next, a threshold of $5 \times 10^4 mm^6 m^{-3}$ was placed on Z and damage was required to equal or exceed 20 per cent. Finally, Z's of $1 \times 10^5 mm^6 m^{-3}$ were compared to damage equal to or greater than 40 per cento The results are shown in table 2.

The first section of table 2 lists: the number of townships affected by hail damage (column 2), the number of townships identified by Z's equal to or greater than $10^4 mm^6 m^{-3}$ (column 3), and the per cent of the affected townships which were identified (column 5). The maximum Z was apparent aloft with 57 per cent of the townships with hail damage identified at 20,000 feet as compared to only 31 Per cent at 5000 feet. A change in the Z and damage thresholds to $5 \times 10^4 mm^6 m^{-3}$ and 20 per cent, respectively, decreased the percentage identified, but the optimum altitude for identification again was 20,000

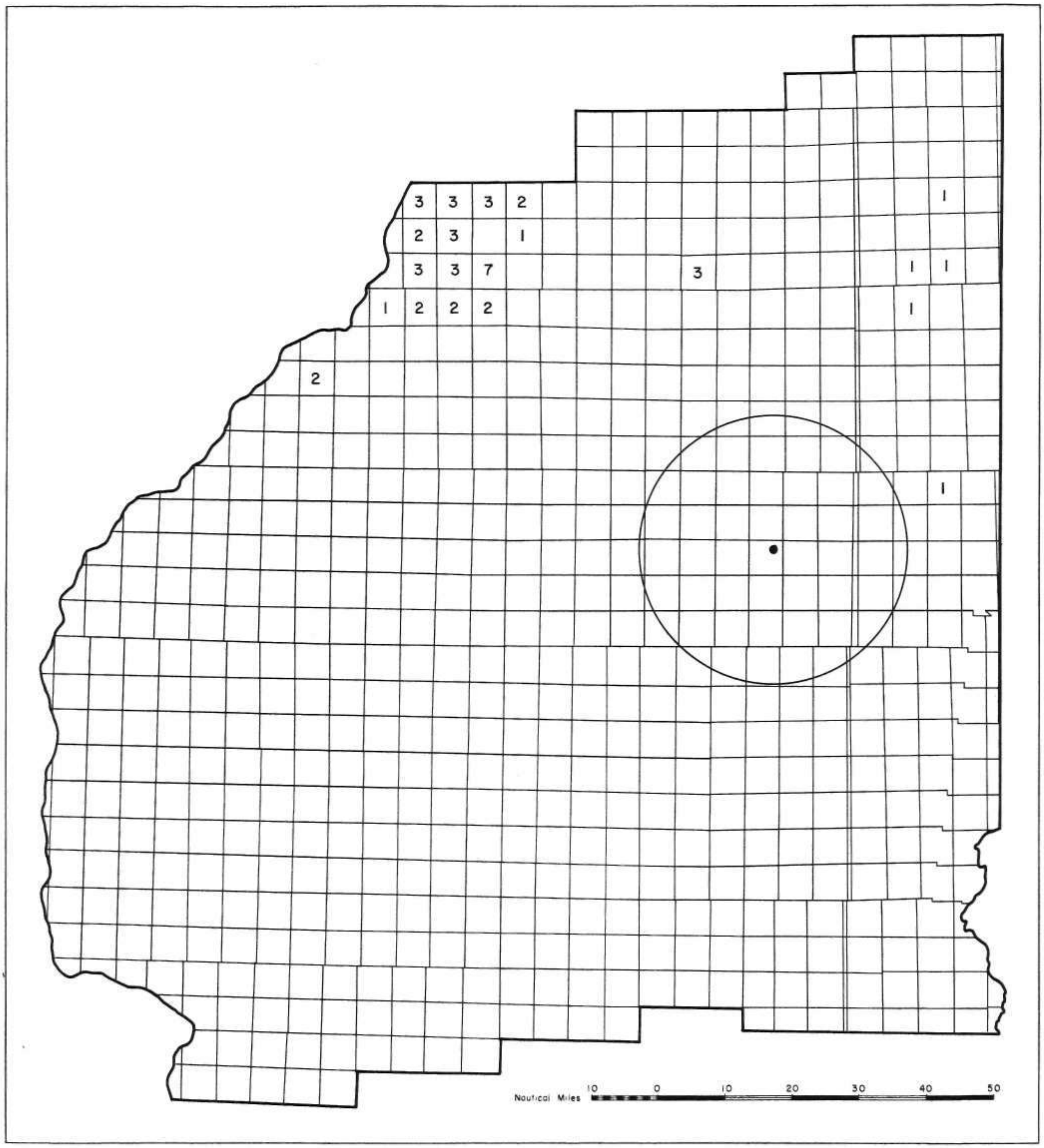


Fig. 16 Total radar reflectivity factor (Z) x $10^4 mm^6 m^{-3}$ at 20,000 feet based on 9-minute observations for no hail period, September 28, 1959.

TABLE 2

ASSOCIATION OF RADAR REFLECTIVITY (Z) WITH HAIL DAMAGE FOR VARIOUS ECHO ALTITUDES (based on 9-minute radar observations)

TOTAL STORM

for $Z \geq 1 \times 10^4 mm^6 m^{-3}$ and all damage:

Altitude (feet)	Townships Affected	Number of Townships Identified	Number of Townships Missed	Per cent Identified
5,000	71	22	49	31
10,000	72	36	36	50
15,000	72	35	37	49
20,000	65	37	28	57
25,000	70	36	34	51
30,000	54	21	33	39

for $Z \geq 5 \times 10^4 mm^6 m^{-3}$ and damage $\geq$ 20 per cent:

Altitude (feet)	Townships Affected	Number of Townships Identified	Number of Townships Missed	Per cent Identified
5,000	23	0	23	0
10,000	28	3	25	11
15,000	24	6	18	25
20,000	25	7	18	28
25,000	25	7	18	28
30,000	20	3	17	15

for $Z \geq 1 \times 10^5 mm^6 m^{-3}$ and damage $\geq$ 40 per cent:

Altitude (feet)	Townships Affected	Number of Townships Identified	Number of Townships Missed	Per cent Identified
5,000	5	0	5	0
10,000	7	0	7	0
15,000	6	0	6	0
20,000	8	3	5	38
25,000	8	2	6	25
30,000	6	1	5	17

to 25,000 feet. Similar results were obtained for the comparison of heights for Z equal to or greater than $1 \times 10^5 mm^6m^{-3}$, and damage equal to or exceeding 40 per cent.

The low percentage of townships which were identified was disappointing; however, a comparison of the Z and damage cores suggested that the Z cores occurred slightly upwind. As can be seen in figure 14, there were several townships with Z equal to or greater than 1×10^4 where no hail was reported. This discrepancy may be due to missed hail occurrences, real horizontal displacement of echo cores aloft from hail at the surface, and/or errors in overlay alignment during data extraction. It is expected that the tilt of echoes reduces the point agreement although no attempt was made to correct it. It is hoped that future examination of several cases will suggest an answer to this problem.

The alignment of the primary hail damage track was parallel to the southwest radial from the radar (figure 15). Since the northern damage area, shown in the extreme upper portion of figure 15, was aligned normal to the north radial, the attenuation may have been less than that with the primary area. The two areas were separated for comparison. The summaries for the north and south storm segments are shown in tables 3 and 4, respectively. The contrast in percentage identified was immediately obvious with the north segment having a very respectable 93 per cent at 25,000 feet compared to only 40 per cent at the same level in the south segment. The contrast in per cent identified persisted through the remaining levels and was assumed to be caused primarily by attenuation.

The attenuation associated with the individual echo cell is certainly an immediate problem in the use of intensity measurements. Obviously, the loss of data is a function of the frequency of echo alignment. In the case of squall

TABLE 3

ASSOCIATION OF RADAR REFLECTIVITY (Z) WITH
HAIL DAMAGE FOR VARIOUS ECHO ALTITUDES
(based on 9-minute radar observations

NORTH SEGMENT

for $Z \geq 1 \times 10^4 mm^6 m^{-3}$ and all damage:

Altitude (feet)	Townships Affected	Number of Townships Identified	Number of Townships Missed	Per cent Identified
5,000	17	13	4	76
10,000	16	11	5	69
15,000	16	14	2	88
20,000	17	14	3	82
25,000	15	14	1	93
30,000	14	9	5	64

for $Z \geq 5 \times 10^4 mm^6 m^{-3}$ and damage ≥ 20 per cent:

Altitude (feet)	Townships Affected	Number of Townships Identified	Number of Townships Missed	Per-cent Identified
5,000	4	0	4	0
10,000	4	1	3	25
15,000	4	4	0	100
20,000	4	4	0	100
25,000	4	4	0	100
30.000	3	2	1	67

for $Z \geq 1 \times 10^5 mm^6 m^{-3}$ and damage ≥ 40 per cent:

Altitude (feet)	Townships Affected	Number of Townships Identified	Number of Townships Missed	Per cent Identified
5,000	3	0	3	0
10,000	3	0	3	0
15,000	3	0	3	0
20,000	3	3	0	100
25,000	3	2	1	67
30.000	2	1	1	50

TABLE 4

ASSOCIATION OF RADAR REFLECTIVITY (Z) WITH
HAIL DAMAGE FOR VARIOUS ECHO ALTITUDES
(based on 9-minute radar observations)

SOUTH SEGMENT

for $Z \geq 1 \times 10^4 mm^6 m^{-3}$ and all damage:

Altitude (feet)	Townships Affected	Number of Townships Identified	Number of Townships Missed	Per cent Identified
5,000	54	9	45	17
10,000	56	25	31	45
15,000	57	21	36	37
20,000	48	23	25	48
25,000	55	22	33	40
30,000	40	12	28	30

for $Z \geq 5 \times 10^4 mm^6 m^{-3}$ and damage ≥ 20 per cent:

Altitude (feet)	Townships Affected	Number of Townships Identified	Number of Townships Missed	Per cent Identified
5,000	19	0	19	0
10,000	24	2	22	17
15,000	20	2	18	10
20,000	21	3	18	14
25,000	21	3	18	14
30,000	20	1	16	5

for $Z \geq 1 \times 10^5 mm^6 m^{-3}$ and damage ≥ 40 per cent:

Altitude (feet)	Townships Affected	Number of Townships Identified	Number of Townships Missed	Per cent Identified
5,000	2	0	2	0
10,000	4	0	4	0
15,000	3	0	3	0
20,000	5	0	5	0
25,000	5	0	5	0
30,000	4	0	4	0

lines, the loss of echo would maximize when the line orientation is along a radial from the radar. Attenuation may also be important when thunderstorm echoes become so numerous that radial alignment between individual cells frequently occurs. The most troublesome echoes are those which approach the radar site along the radial since they block the same sector for a considerable period of time.

An example of the effect of attenuation on severe storm detection was afforded by the extensive hailstorm on June 10, 1958. On this date, hail occurred in the reporting network area during a 16-hour period of which 11 hours were covered by CPS-9 radar operation. A total of 142 hail reports were received within 100-mile range. The observations, grouped in 30-minute intervals are listed in table 5a. By assuming echo core dimensions of 1 and 5 miles, the number of points (square miles) obscured could be determined for each 30-minute period.

The point totals indicate that a loss of 7 and 31 per cent of the hail occurrences could be expected with the 1-mile and 5-mile diameter echoes, respectively. Admittedly, the 30-minute grouping of the data probably is excessive when normal storm velocity is considered. However, a 10-minute grouping made of the peak 30-minute period from 1100 to 1130 CST (shown in table 5b) indicated that the cumulative 10-minute period losses total 16 and 37 per cent for the 30 minutes. Thus, it would appear that with the extremely intense and widespread storms, meaningful intensity measurements can be made on only approximately 65 per cent of echoes associated with hail.

Neglecting the storms which are lost because of attenuation, the identification of the hail-producing storms can be accomplished by monitoring the radar echo at 20,000 to 25,000 feet at an intensity level equivalent to a radar reflectivity factor (Z) value of approximately $5 \times 10^4 mm^6 m^{-3}$.

TABLE 5a

ECHO BLOCKING ASSOCIATED WITH SURFACE HAIL OCCURRENCES
(grouped by 30 minute intervals)

Time CST	Total Points Hail Occurrences	PBO* 1 Mi. Dia. Echo	PBO* 5 Mi. Dia. Echo
0830-0900	3	0	0
0930-1000	5	0	2
1000-1030	6	0	1
1030-1100	8	0	2
1100-1130	19	3	12
1130-1200	12	0	4
1200-1230	8	1	2
1230-1300	8	2	4
1300-1330	9	0	1
1330-1400	1	0	0
1400-1430	3	0	1
1430-1500	4	0	1
1500-1530	16	3	7
1530-1600	11	1	4
1600-1630	8	0	2
1630-1700	4	0	0
1700-1730	2	0	0
1730-1800	1	0	0
1800-1830	6	0	0
1830-1900	5	0	0
1900-1930	3	0	1
TOTAL	142	10	44

TABLE 5b

ECHO BLOCKING ASSOCIATED WITH SURFACE HAIL OCCURRENCES
(grouped by 10 minute intervals)

Time CST	Total Points Hail Occurrences	PBO* 1 Mi. Dia. Echo	PBO* 5 Mi. Dia. Echo
1100-1110	8	2	4
1110-1120	4	0	1
1120-1130	7	1	2
TOTAL	19	3	7

*Points blocked out assuming average effective diameters of 1-mile and 5-miles for the blocking cells.

One means of integrating the radar echo obtained under specific antenna tilt and receiver-gain-reduction settings is with a long-term time lapse PPI exposure. Several storms were sampled during 1960 by exposing 4- x 5-inch contrast process film for a 3-hour period. Since the antenna program cycle time is approximately 9 minutes, the 3-hour echo sample represents only 20 exposures at the designated tilt and receiver gain-reduction setting. The main problem of long-term integration was the selection of the antenna tilt angle which determined the altitude of the storm sample. This selection required the radar operator to choose the echo or echoes to be integrated. Normally, the selection was made in conjunction with the choice of the antenna tilt sequence. The tilt sequence, as described previously, was chosen by determination of the median range of all echoes appearing on step 2 and 0-degree tilt. The time lapse was exposed for the range selected and for only the antenna tilt which approximated 20,000 feet.

Two examples of radar echoes recorded on time lapses are shown in figures 17 and 18. The hail, wind, and crop damage reports are included for comparison with the echo. The echoes near Vandalia (VLA) in figure 17 represent a range-corrected average Z value exceeding approximately 6 x $10^4 mm^6 m^{-3}$ at a mean altitude of 21,000 feet. The echo 40 miles south of the radar corresponds to a Z value exceeding approximately 1 x $10^4 mm^6 m^{-3}$ at 10,000 feet. The lack of hail reports with the near echo suggested that the critical Z value for hail detection was above $10^4 mm^6 m^{-3}$. In the June 28, 1960 example, in figure 18, the most prominent echo streak was 95 miles north of the radar site. This echo corresponded to a Z value exceeding 9 x $10^4 mm^6 m^{-3}$ at a mean altitude of 25,000 feet. The hail associated with this storm exceeded 2 inches in diameter and caused heavy damage in DeKalb and LaSalle counties. The DeKalb hail occurred

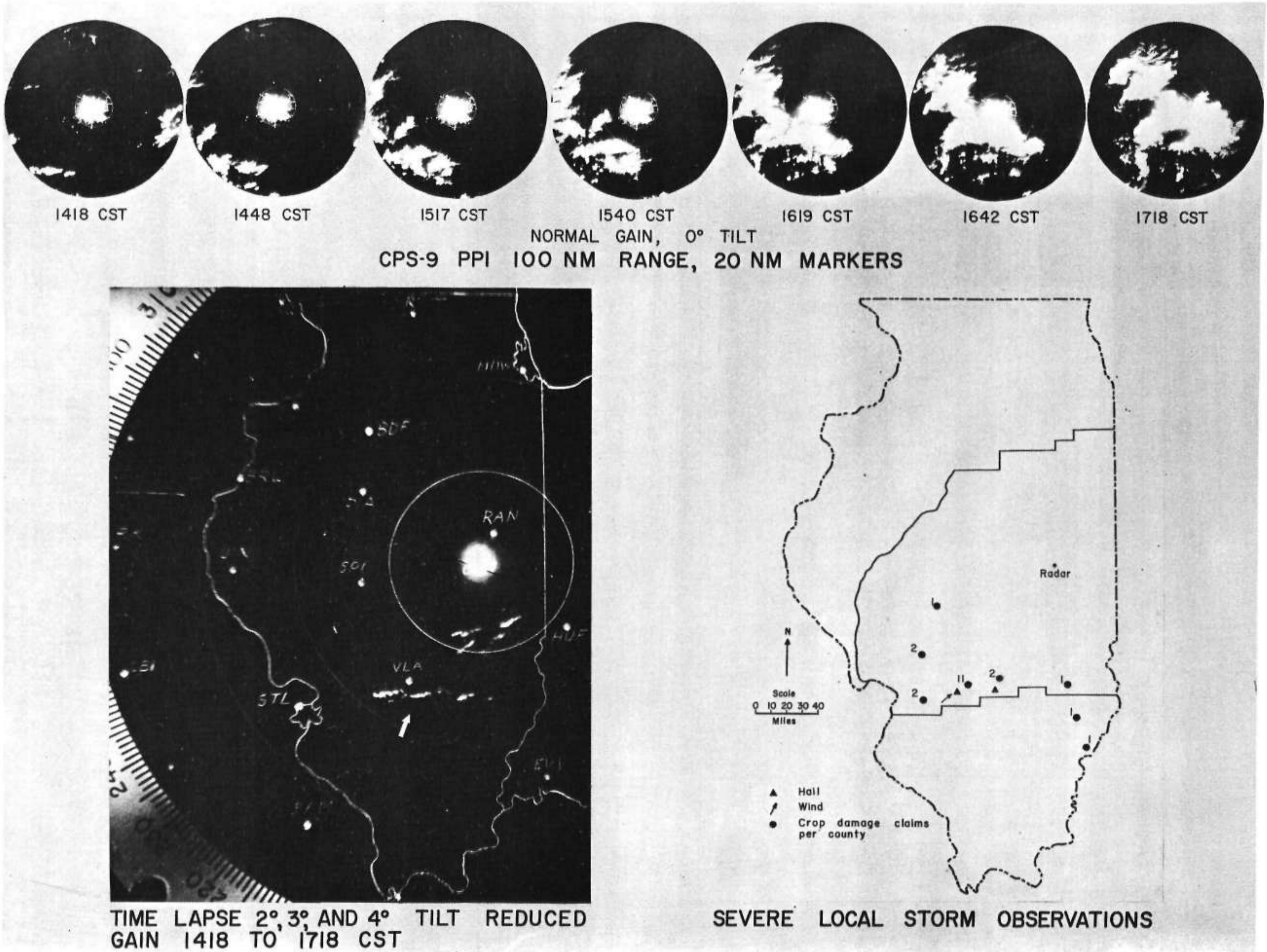


Fig. 17 Radar and severe local storm observations, June 12, 1960.

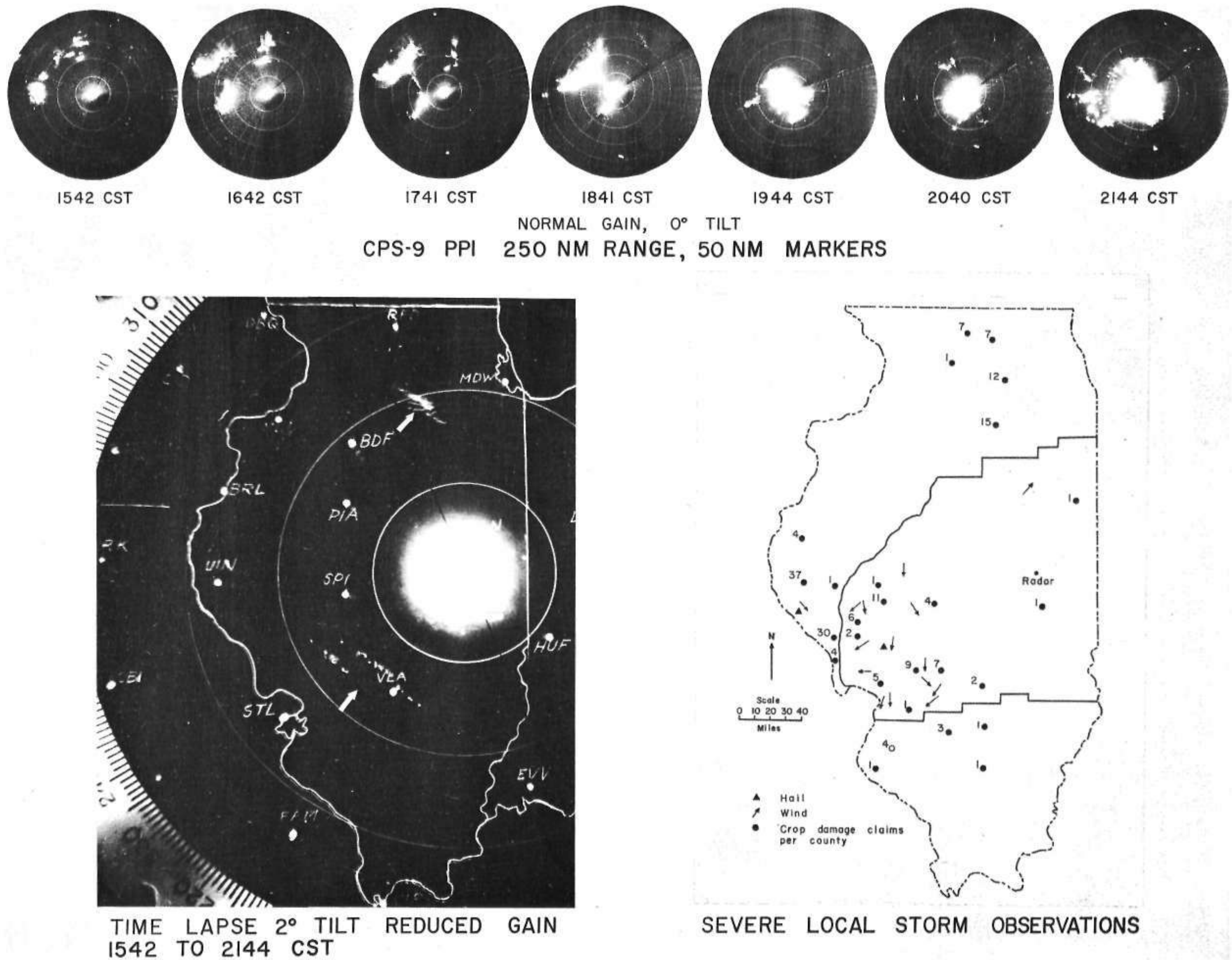


Fig. 18 Radar and severe local storm observations, June 28, 1960.

prior to the start of radar operations. The echo near Vandalia was associated with a severe hail and wind storm which developed near Ottumwa, Iowa, (OTM) and moved southeastward through Quincy (UIN). The disappearance of the echo approximately 30 miles southwest of Springfield (SPI) occurred at a Z value exceeding approximately $7 \times 10^4 mm^6 m^{-3}$. However, this measurement was made at a mean altitude of 35,000 feet. It is assumed that a lower measurement in the region of 25,000 feet would have shown echo along the entire track from Quincy to Vandalia.

SUMMARY

1. The most important criterion for identifying hail-producing thunderstorms with the CPS-9 radar is the intensity of the echo between 20,000 and 25,000 feet. Radar reflectivity factor (Z) values in this height interval which are in excess of $10^4 mm^6 m^{-3}$ are indicative of hail. Z values in excess of $10^5 mm^6 m^{-3}$ are indicative of hail of a size large enough to constitute a hazard to air craft and crops.

2. The maximum Z value appears to occur a few minutes before and slightly upstream of the surface hail observations. This delay time is of special interest in studying the physical aspects of the hail development. However, operationally, the Z maximum is not a forecast but is an indicator of conditions already in existence.

3. It may be possible to anticipate thunderstorm (and echo) intensification by careful analysis of the wind structure. In many of the severe local hailstorms investigated, a mid-tropospheric jetstream was detected below 20,000 feet.

4. Precipitation attenuation can seriously restrict the utility of a single CPS-9 radar in examining hailstorms which cover a large geographical area. In

at least one case considered, meaningful intensity measurements could be made on only 65 per cent of echoes associated with hail.

Future investigations are necessary to determine the significance of the radar reflectivity maximum in terms of cloud liquid water content, temperature, and drop size distributions in the hailstorm.

Considerable effort must be devoted to the investigation of damaging wind and lightning associated with severe thunderstorms. It is hoped that criteria can be found for the identification of these phenomena using the CPS-9 radar.

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