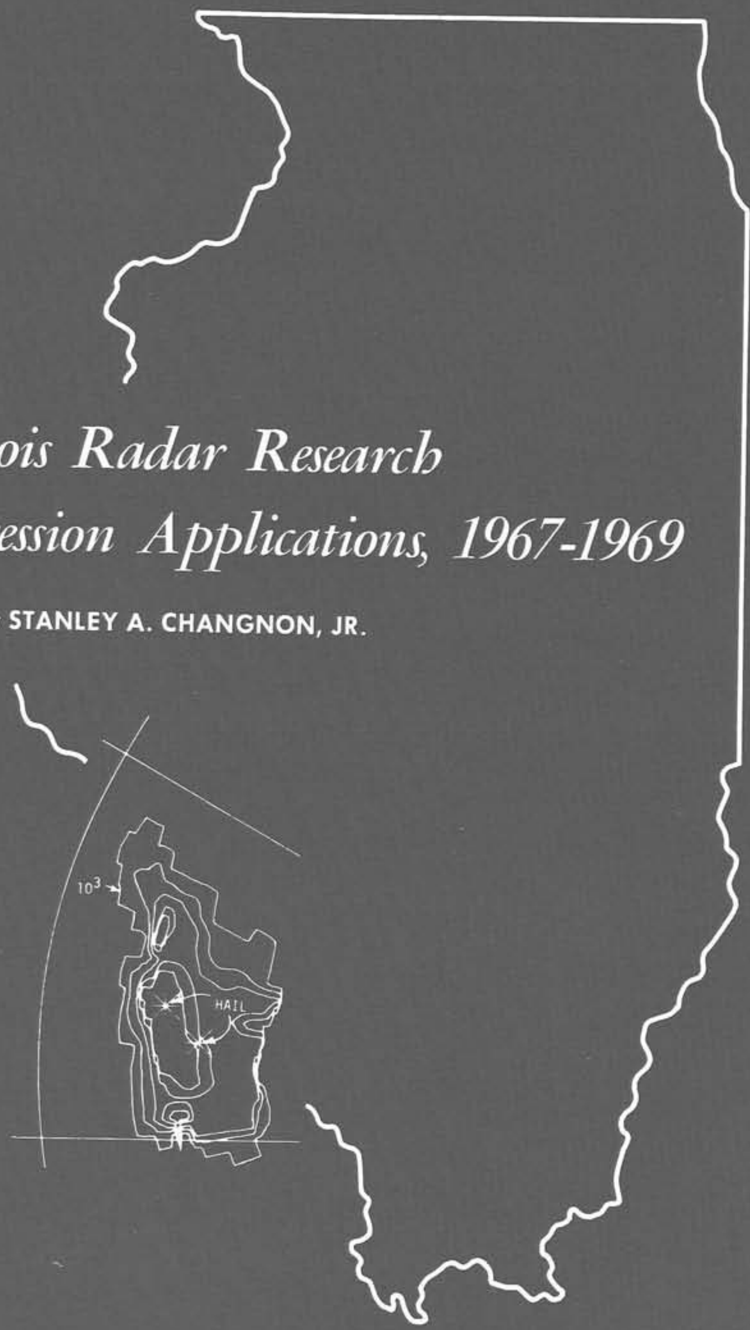
REPORT OF INVESTIGATION 71

STATE OF ILLINOIS

DEPARTMENT OF REGISTRATION AND EDUCATION

Illinois Radar Research for Hail Suppression Applications, 1967-1969

by STANLEY A. CHANGNON, JR.



ILLINOIS STATE WATER SURVEY

URBANA

1972

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Abstract: Studies with two 3-cm radars and dense surface hail networks showed that the areal extent of hail during a given precipitation period can be estimated in a study area from the areal extent of the highest half-order of reflectivity for the day. However, only 20 percent of the high reflectivities ($>10^5$ mm^{6}m^{-8}), surface or aloft, were associated with point hailfalls In-storm hail volumes could not be detected by magnitude of reflectivity, reflectivity gradients, or echo volumes. However, hail echoes showed large volume increases above the —5C level in the 5 minutes prior to hail A hail-producing echo could be identified by three or more of five criteria relative to a given day: 1) echoes were in the taller half of the first echoes; 2) had above average first echo depths, top to base, 3) had above average reflectivities at first echo; 4) grew more than 3000 feet, and 5) existed more than 20 minutes. Conditions leading to hailstorm development are rooted often in the initial phases of a cloud (echo) development. Complete 3-dimensional radar reflectivity scanning must be accomplished over a study area in 2 minutes or less to identify hailstorms and to measure surface hail areas with 3-cm radar.
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ABSTRACT

Two 3-cm radars, a CPS-9 operated during 1967 in a pseudo-CAPPI fashion and a TPS-10 (RHI) operated in 1967-1969, were used with very dense surface hail networks in Illinois to investigate a variety of radar applications to potential hail suppression activities.

The areal extent of hail during a given precipitation period can be estimated in a study area from the areal extent of the highest half-order of reflectivity for the day. However, only 20 percent of the reflectivities of 10^5 to 10^7 mm^6m^{-3} at the surface or aloft were associated with point hailfalls. In-storm hail volumes could not be detected by the magnitude of reflectivity, by reflectivity gradients, or by echo volumes. However, all hail echoes exhibited large volumetric increases ($Z \geq 10^{4.5}$) above the —5C level during the 5 minutes prior to hail.

Hail-producing echoes could be identified on a given day if the echoes fulfilled three or more of five criteria, relative to the echo characteristics on a given day. The criteria were that the echoes 1) were in the taller half of the first echoes; 2) had above average first echo depths, top to base; 3) had above average reflectivities at first echo; 4) grew more than 3000 feet; and 5) existed more than 20 minutes.

The relationship of first echo characteristics with eventual hailstorms indicates that conditions leading to hailstorm development are rooted often in the initial phases of a cloud development. Complete 3-dimensional radar reflectivity scanning must be accomplished over a study area in 2 minutes or less to identify hailstorms and to measure surface hail areas with 3-cm radar.

INTRODUCTION

In the United States the use of radar to detect hail has generally been related to three applications. The first was detection of hail-bearing storms for airways forecasting and specifically for aircraft avoidance of hail. The second concerned studies of hailstone formation and hailstorm mechanics and dynamics. The third and more recent application, which is the primary subject of this report, has been the detection and study of hailstorms and hail volumes for hail suppression activities.

Early Research

Hailstorm detection for aircraft avoidance and forecasting was pursued initially by private industry in the 1947-1954 period. Their intention was to identify hail-echo configurations depicted by 3- and 5-cm wavelength airborne radars with visual observations or airborne encounters to verify hail (American Airlines, 1949; Harrison and Post, 1954). This work was followed by a series of more specific radar-hail studies sponsored by the U.S. Air Force during the 1956-1961 period in New England (Donaldson, 1959), in Illinois (Wilk, 1961), and in Texas (Sanford, 1961). This later hail research was based largely on 1) high-powered 3-cm (CPS-9) radars operating in a PPI, gain-reduction, antenna-tilt mode to develop pseudo-CAPPI presentations of echo data, and 2) networks of volunteer hail observers to supply surface hail data.

Basically, these studies all concluded that echoes with high reflectivities aloft (15,000 to 30,000 feet) and/or very tall echoes were often associated with hail occurrences at the surface. These high reflectivity results were supported by theoretical calculations done by Ryde (1946), Atlas and Donaldson (1955), Gehrhart et al. (1960), Herman and Battan (1960), and subsequently by experimental research done by Atlas et al. (1961), all of which indicated that hail should have a greater reflectivity than raindrops.

In retrospect, the high reflectivity aloft ('Z-nose') and maximum echo height climatic-type results of these important studies are useful, but certain inadequacies in the data did not allow establishment of the cause and effect, nor a direct radar-hail relationship. This was the result of 1) inadequate surface hail data, both in temporal accuracy and areal density, and 2) the long sampling interval involved in 3-dimensional measurements of an entire storm (10 to 30 minutes) forced by the modes of operation. These two critical factors led to acceptance of the maximum echo height or maximum reflectivity values found anywhere in an extensive storm-echo volume around the hail report. Hence, it is not surprising that research projects were able to find with surface hail some large height and/or reflectivity values since both are commonly found somewhere in major thunderstorm complexes that typically produce hail.

Even so, the 1958-1961 results in Illinois for high reflectivity-hail relationships were not spectacular. The best identification that could be obtained at any height was at the 20,000-foot level where 56 percent of the crop-damaging hail reports were associated with high reflectivities ($Z > 10^4$ mm^6nr^3). Subsequent forecast-avoidance studies of organized lines of echoes in Illinois showed that relatively large, long-lived, and rotating lines generally contained several hail-producing echoes (Changnon and Huff, 1961).

The second major radar application to hail was for individual storm studies. These studies attempted to explain hailstone growth and/or hailstorm mechanics, and usually concerned unusual or severe hailstorms. For instance, several hailstorms in Illinois were studied during 1954-1964 using radar data, mesosynoptic analyses, and intensive field surveys to gather surface hail data (Stout and Hiser, 1955; Stout et al., 1960; Changnon, 1964; and Changnon and Stout, 1964). These studies dealt largely with hail-echo configurations, and the major results showed that: 1) some individual hail echoes were wedge-shaped, some had a 'donut' appearance, and some had finger-like protuberances; 2) hailstorms in some organized lines of storms frequently occurred in the echo areas with distorted forward motion; 3) hailstorms occasionally developed rapidly from unusually high-level first echoes; and 4) hailfalls frequently occurred after the merger of two major echoes. Essentially, these studies revealed no common hail-echo characteristic, the only common aspect being the variety of echo behaviors and unusual shapes. Such a conclusion may be indicative of a wide variety of mechanisms and types of hail-producing storms.

Recent Research and Plan of This Report

The third application, use of radar in hail suppression research and operations, received a major thrust from the rapidly growing national interest in hail suppression that began in 1965-1966 (Schleusener, 1966). Interest in using radar to detect hail-bearing storms was renewed, along with the hope that the hail volume and hailstone sizes within a storm could be defined, as had been claimed by the Russians (Sulakvelidze, 1966).

There are several ways that radar could be employed in weather modification experiments and operations. These include 1) delineating developing hailstorms for directing seeding activities; 2) counting hailstorms in seeded and nonseeded areas, as part of an evaluation approach; 3) measuring hailstone sizes to decide on seeding; 4) monitoring various physical changes in storms before and after seeding; 5) determining the surface area covered by hail for evaluation and post-storm surveys (Changnon, 1969a); and 6) ascertaining the in-echo volumes containing hail for direction of in-cloud seeding techniques.

In Illinois, a 3-year hail project involving further radar-hail studies was initiated in 1967 (Changnon, 1969b). This was oriented to the application of radar to hail suppression projects, in contrast to earlier Illinois research dealing with individual storms or gross hailstorm detection. This report summarizes the primary results of the recent research, with interpretation in respect to other research needs including the development of radar-hail operational techniques and adequate radar-hail systems.

Two forms of 3-cm radars, a CPS-9 (PPI) and a TPS-10(RHI), were employed along with dense surface hail networks to make more sophisticated radar-hail studies than had been accomplished in the 1954-1964 period. Attenuation problems with both radars were resolved by collecting a large quantity of data, and by studying only those storms over the network that were not attenuated by intervening echoes. The 3-year program actually involved four different radar operational-analytical approaches. These were interrelated because the findings from each were used successively in radar operational decisions, in the surface hail network installations and operations, and in analytical techniques.

These four operational-analytical efforts included: 1) 1967 operations of the CPS-9 and studies of the PPI data, 2) analysis of historical RHI data, 3) 1967 TPS-10 operations and analysis of ensuing RHI data, and 4) 1968-1969 modified TPS-10 operations and analysis of RHI data.

The first section of this report describes the various interrelationships of the four 1967-1969 studies and gives details of the operations and the data base for each. The next four sections present separately the results of the four studies. The next section brings together interpretations of the major findings, and a final section gives conclusions and recommendations concerning future research.

Acknowledgments

This research has been pursued under the general direction of Dr. William C. Ackermann, Chief of the Illinois State Water Survey. Special credit is due Donald W. Staggs, Neil G. Towery, and Ronald E. Rinehart of the Survey staff for their extensive analyses and assistance. Much of the difficult routine data processing was accomplished by Susan Ting, Eberhard Brieschke, Phyllis Stone, Ruth Braham, Edna Anderson, Donald Crum, and Timothy Lewis. Advice and suggestions of Eugene A. Mueller and Griffith M. Morgan, Jr., are appreciated. Mrs. J. Loreena Ivens and Mrs. Patricia A. Motherway edited the manuscript, and John W. Brother, Jr., and William Motherway, Jr., prepared the illustrations. This research was supported largely by the National Science Foundation under grants GA-482 and GA-4618, and surface hail loss data were supplied by the Crop-Hail Insurance Actuarial Association of Chicago.

1967 CPS-9 Studies

Major activities in 1967 involved the CPS-9, operated during April-September in a PPI psuedo-CAPPI mode, and a denser hail network (figure 1) than existed in prior Illinois programs. The very dense observational East-Central Illinois Network was 30 miles west of the radar. In a 400-square-mile area, 49 raingage-hailpad sites were installed, 72 cooperative hail observers were secured, and crop-hail insurance data were gleaned from all losses (75 percent of the area covered by liability). A larger area of 18,000 square miles with 1308 cooperative hail observers within 80 nautical miles of the radar in central Illinois was also utilized in 1967 (figure 1). More selective operational choices of gain steps and antenna tilt angles were made to improve the data rate which varied from 7 to 15 minutes according to echo extent.

The scope photographs from this 6-month period were used to analyze 1) characteristics of 103 hail echoes and 50 no-hail echoes (Towery and Changnon, 1970); 2) the capability of the radar to measure the areas of hailfall on the surface (Rinehart and Staggs, 1968); and 3) the relationship of echo reflectivity (surface and aloft) with hail (Rinehart et al., 1968). Certain results in 1967 showed a need for a larger dense sampling area and for more rapid radar sampling of a given storm, particularly in the vertical, than could be obtained with the psuedo-CAPPI. These results also indicated that an adequate sample of the CPS-9 hail data had been collected during the 1967 operations.

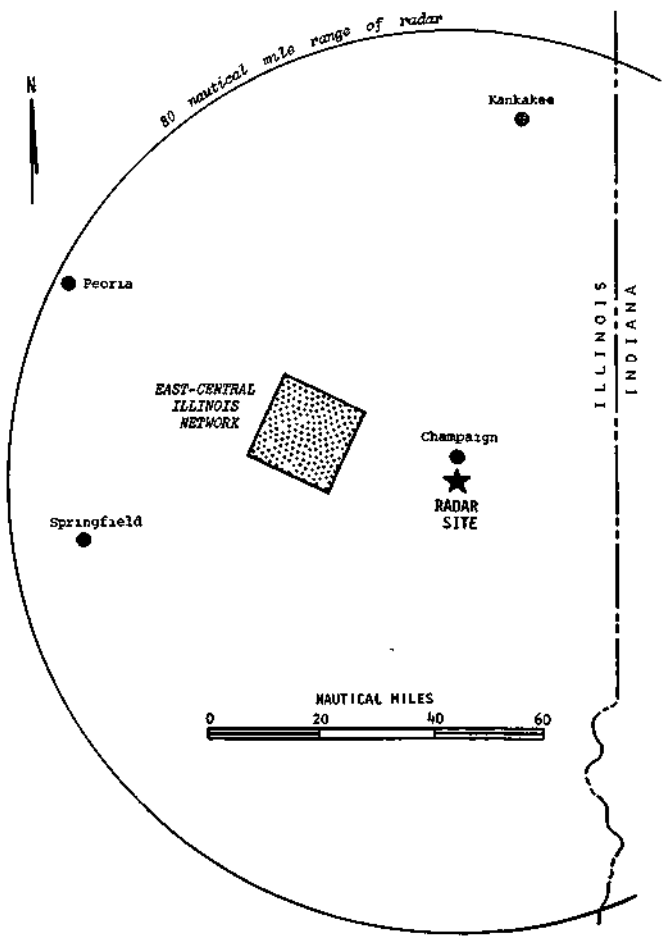

Figure 1. Areas from which 1967 hail data were collected

1967 Analysis of Historical RHI Data

Historical RHI (TPS-10) film records collected during radar operations of 1953-1965 were studied in 1967 to investigate echo characteristics of hail-producing storms. The search of the film records unfortunately did not provide a very large sample of echoes (33 echoes on 15 dates), but it was adequate to indicate important differences in sizes and configurations between spring and summer hailstorms (Changnon, 1969b). These and certain other results from the historical RHI data affected decisions made for subsequent radar-hail operations in 1968 and 1969.

1967 TPS-10 Operations

The operation of the TPS-10 (RHI) radar during September 1967 resulted in data for 1 day with hailstorms on the network. These operations and the historical RHI film data indicated that this type of radar presentation would provide data more useful to radar-hail detection analysis than the CAPPI format. However, a more rapid RHI data rate than employed in 1967 appeared necessary because complete storm sampling on a 2- to 4-minute frequency was not always adequate to monitor the higher reflectivity variations in the hailstorms (Staggs, 1968).

These results, plus those gained from detailed study of surface hailstreaks (Changnon, 1970), led to modifications of the TPS-10 radar to utilize sector scanning, iso-echo contouring, and dual scope photography to increase the rate of data collection in 1968 and 1969. The extensive effort to analyze these 1967 data manually and the shift to more rapid data rates also pointed to a need for digitization of the 1968-1969 RHI data and their computer analysis.

1968-1969 TPS-10 Operations

The various results of the 1967 studies led to the enlargement of the hail-rain network to 1000 square miles with 100 raingage-hailpad sites, 13 recording hailgages, and 96 hailpads in a 100-square-mile dense internal network (figure 2). Crop-hail insurance data also were collected from within this larger network.

The TPS-10 modifications using different iso-echo displays on 2 scopes resulted in a complete sample of all echoes over the network in 8 reflectivity levels in 100 seconds. The modified TPS-10 operations in 1968-1969 unfortunately occurred in a period of low hail frequency over the larger

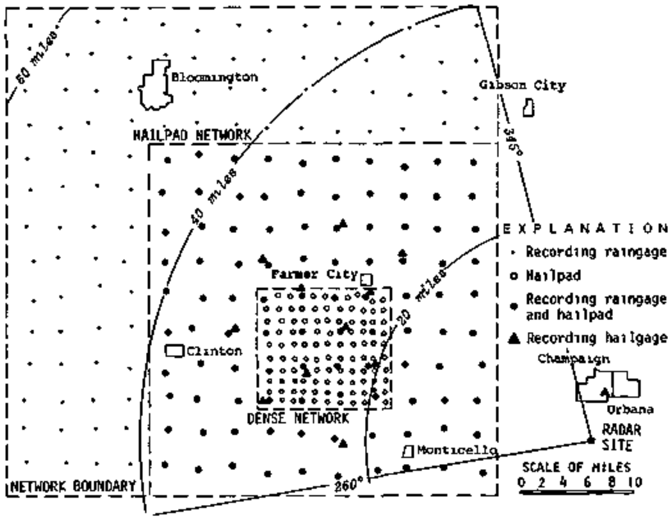

Figure **2. Radar** site **and** hail network in central Illinois

dense network. The 2-scope radar photographs were digitized by a Benson-Lehner Oscar mated to a card punch to enable a more thorough, comprehensive (and hopefully more rapid) investigation of the echo characteristics. Because of the larger volume of echo data resulting from digitization of data, time and funds permitted extensive analysis of data from only 3 hailstorm days (Staggs and Lonnquist, 1970). Yet, this data reduction approach required only 2 percent of the time that manual analysis would have required.

Analysis of these 1968-1969 radar-hail data concerned the placement of the surface hail occurrences in time and space with respect 1) to the reflectivity maximums at hail time and earlier, 2) to their spatially related reflectivity gradients, and 3) to their echo core volumes. Hail-producing echoes and no-hail echoes from 2 hail days were compared (Towery et al., 1970). A secondary study of echo top-base characteristics from 1 day with many severe hailstorms in 1969 was pursued using the RHI data (Changnon and Staggs, 1970).

Efforts to utilize radar in the various American hail studies of the 1946-1965 period generally had the goal of identification of echo entities that were either producing hail or were potential hailstorms. This goal differs markedly from the more sophisticated goal of determining the specific hail volume *within* the storm echo.

The Illinois radar-hail research of 1967-1969 had both goals. The primary goal was detection of the in-storm hail volume. This was a very ambitious goal fraught with the difficulties and limitations inherent in 3-cm wavelength radars, but every effort was made to optimize the research through detailed echo analyses and the best possible surface hail data. The other goal, hail-echo identification, was secondary. Its goal was to define the 'common denominators' in echo characteristics, useful on a given storm day. The earlier Illinois hail research had been unable to discern these characteristics other than in a gross sense where the median reflectivity values of all studied hailstorms were greater than the median values of rain-only storms.

Z_e is the equivalent radar reflectivity factor (hereafter called *reflectivity)* as measured by the radar and has units of mm^6m^{-3} hereafter in this report.

The basic analytical approach employed in the radar-hail volume detection research of 1967-1969 centered on comparisons of hail with reflectivity measurements. This assumed that higher reflectivities or reflectivity gradients in the storm echo were hail, or very directly related to the hail. The evaluation of the characteristics of echoes at or prior to surface hail times primarily concerned the analysis on a storm-day basis of echo heights, growth rates, and echo dimensions as factors that would uniquely identify the hailstorms. Results have been summarized according to those derived from the four operational-analytical studies previously outlined.

1967 CPS-9 STUDIES

The analysis of the 1967 pseudo-CAPPI data was oriented to detection and/or measurement of the hail volume at the surface and aloft, and secondly to the study of hail-echo characteristics. Six individual substudies were performed relating to the CPS-9 data. Four of these revolved around two sets of 1967 data: the hailstorms on the 400-square-mile dense East-Central Illinois Network in 15 storm periods (12 days), and the hailstorms on the 18,000-square-mile observer network in 5 days with widespread damaging hail (figure 1).

Surface Reflectivity-Hail Relations in Dense Network

One study concerned the relationship between various surface echo reflectivity parameters and the areal extent of hailstreaks measured in the dense network. Surface echo reflectivity tracks or envelopes for each half-order of Z_e (as illustrated in figure 3) were constructed and planimetered for the 61 echoes that produced 83 hailstreaks (average size was 0.9 by 5.8 miles) in 15 different hailstorm periods on the 400-square-mile area containing 121 hail reporting sites.

For each storm period the one or more individual hailstreak areas and associated echo areas were grouped and summed. The area of the highest half-order of magnitude samples per storm period had the best relationship with hail area. For instance, on 21 April when the area of maximum Z_e was $10^{7.2}$, 13.6 square miles were enveloped in the $10^{7.0}$ to $10^{7.5}$ class interval, and the hail area was 15.4 square miles. On 18 September when the maximum Z_e was $10^{5.2}$, the area in the $10^{5.0}$ to $10^{5.5}$ interval was 7.8 square miles, and the hail area was 1.5 square miles.

The results for the 15 storm periods are shown in figure 4,

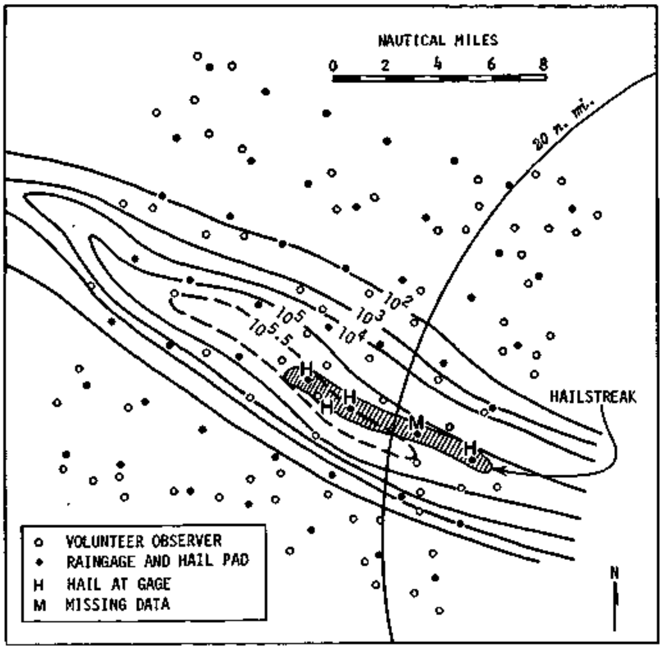

Figure 3. Hailstreak and reflectivity tracks at the surface for an echo that crossed hail-rain network in 1967

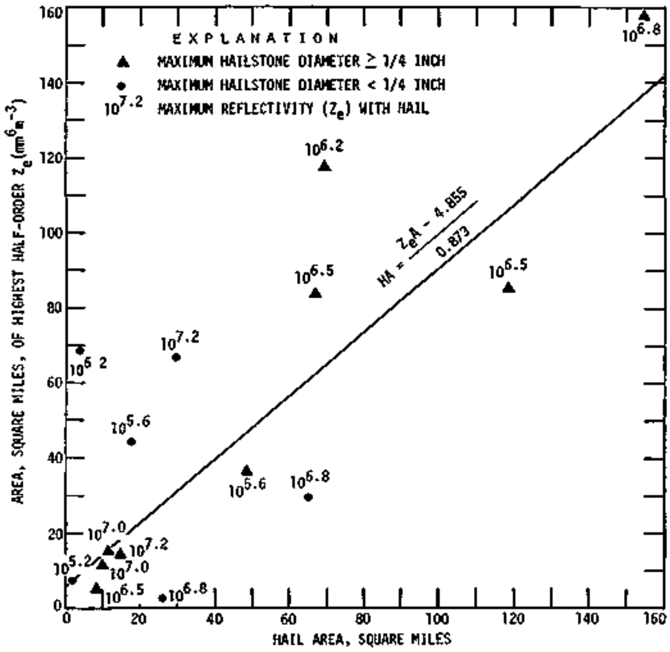

Figure 4. Relationship of hail area and surface area of the highest half-order of reflectivity samples in each of the 15 hailstorm periods

and the correlation coefficient for the Z_e areas and hail areas was +0.80. The maximum Z_e values sampled in the 15 storm periods are also indicated on figure 4, and these range from $10^{5.6}$ to $10^{7.2}$, indicating the need to study the relationships for Z_e area and hail area on a given storm day or storm system basis. Interestingly, the poorer reflectivity-hail area relationships were derived from the 6 storm periods with small hail (the maximum stone size in the network was less than ¼-inch diameter), and these are indicated on figure 4. The correlation coefficient for the 9 storm periods where the maximum stone sizes were ¼ inch or larger was +0.91, and the hail area predictive equation was $HA = (Z_eA - 4.855) / 0.873$, with a standard error of estimate of ±23 square miles.

The ratio of the areas enveloped by the 2 highest half-orders of magnitude of Z_e also was determined for each storm period. For example, when $10^{6.5}$ was the maximum Z_e, the area of $10^{6.0}$ to $10^{6.5}$ was divided by the area of $10^{5.5}$ to $10^{6.0}$. These Z_e-area ratios were also compared with the hail areas of each storm day. The resulting correlation coefficient of −0.63 (significant at 5 percent level) indicated that strong gradients of reflectivity along the echo tracks were associated with large areas of hail.

Another analysis was made of the surface reflectivity data to examine the utility of its specific magnitude to describe the occurrence of hail. The echo tracks were used to count the number of times various surface reflectivity values occurred over each of the 49 raingage-hailpad stations when hail occurred and when hail was not occurring. The results for the 12 storm days appear in table 1. There were 945 occurrences of Z_e of 10^4 and greater, and only 17 percent

Table 1. Number of Echoes at the Surface within Each Reflectivity Interval, with and without Hail, for 12 Hail Periods in 1967

Date (1967)	$<10^{4.0}$ W	$10^{4.0}$–$10^{4.5}$ W	W/O	$10^{4.5}$–$10^{5.0}$ W	W/O	$10^{5.0}$–$10^{5.5}$ W	W/O	$10^{5.5}$–$10^{6.0}$ W	W/O	$10^{6.0}$–$10^{6.5}$ W	W/O	$10^{6.5}$–$10^{7.0}$ W	W/O	$10^{7.5}$ W	W/O	Total $\geq 10^{4.0}$ W	W/O	Daily total
21 April				9	2	21	76	3	8	24	30	1	2	2	1	60	119	179
30 April			5		7		9			2	10		6			2	37	39
8 May (AM)		1	3	1	6	7	10	2	2							11	21	32
8 May (PM)			13		13	2	11	4	1							6	38	44
18 May			17	3	20		4	8	22	2	22	1	17			14	102	116
28 May		2	18	1	7	9	41		4	1	9		1			13	80	93
8 June			3	1	5	2	2	2	2		1					5	13	18
9 June			5	5	15	2	29	2	7	3	10	15	16		1	27	83	110
12 June			2	1	7		9	1	9		2		1			2	30	32
18 July	3	1	1		1	1	3									2	5	7
18 August							11	3	23	1	8		3			4	45	49
18 September			2					1	1							1	3	4
26 September			13	2	76	2	31	4	30	2	50	1	11			11	211	222
Subtotals	3	4	82	23	159	46	236	30	109	35	142	18	57	2	2	158	787	945
Interval totals	3	86		182		282		139		177		75		4		945		
Percent of totals with hail		5		13		16		21		20		24		50		17		

Note: *W = with hail; W/O = without hail.*

occurred with hail. At all classes of reflectivity between 10^4 and 10^7, there were more no-hail occurrences than hail. However, the percentages increased with reflectivity, reaching 50 percent for the $> 10^7$ class.

Reflectivities Aloft over Dense Network

The reflectivities over each of the 49 raingage-hailpad sites during the periods of hail *somewhere* in the network also were determined and studied. The resultant 2893 values were grouped into 2000-foot height intervals (relative to the freezing level in the cloud) and into half-order of magnitude reflectivity classes. The data were further normalized for each Z_e-height combination because of the unequal chance of obtaining each reflectivity height combination.

Figure 5a shows the relative number of occurrences of $10^n < Z_e < 10^{n+0.5}$ for each 2000-foot height interval based on all (hail plus no-hail) data. One way of interpreting the curves on figure 5a is to follow a line of constant height across and determine the relative number of occurrences of each reflectivity. For example, the value of 60 for 10* at 8000 feet above the freezing level indicates there were 6 times as many occurrences of this Z_e as there were for $10^{6.0}$ to $10^{6.5}$ at this height (a value of 10). A reflectivity maximum exists near the freezing level, as shown by the enclosed 40 value at $10^{5.0}$ to $10^{5.5}$, but none occurs above it. Only 343, or 12 percent, of the values used in this graph were obtained near the time of hail, and the remaining values were obtained above stations which had no hail.

A similar analysis was made using only the 343 echo values obtained above a station either at the time of hail or in the radar cycle immediately preceding the hail (approximately 10 minutes). These results (figure 5b) clearly reveal a maximum number of occurrences of echoes at about 10,000 feet above the freezing level in the $10^{4.5}$ to $10^{5.5}$ range. The occurrence of this maximum with hail is likely a strong feature of several individual hailstorm echoes.

The study of reflectivities aloft with the dense network indicated that high reflectivities did not conclusively imply hail at the surface. In most cases it was possible to find a strong echo near or above a report of hail. However, there were 4 times as many cases of strong echoes (that is, $Z_e > 10^5$) not associated with hail at the surface.

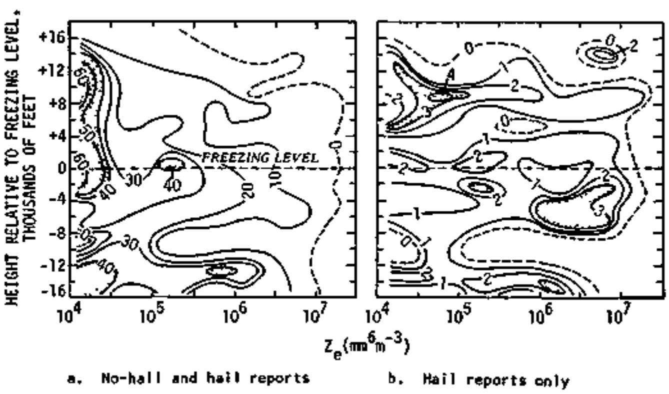

Figure 5. Relative number of reflectivity occurrences for given intervals, 1967 season

Reflectivities Aloft on Severe Hailstorm Days in Observer Network

Since much of the hail on the dense hail network was small (<½ inch) and frequently non-damaging (and thus below a level of potential significance), data from the 18,000-square-mile observer network were used to study further the reflectivity relationships aloft with large, damaging surface hail. The 5 major crop-damaging hailstorm days of 1967 were incorporated in this study, and vertical profiles of reflectivity associated with 196 hail occurrences were analyzed to determine the reflectivity at each height at hail time and at other times without hail but with an echo above the hail report locations. Again, the Z_e values were grouped into half-orders of magnitude and by 2000-foot intervals.

Since the radar operations did not sample each height-reflectivity combination equally, the number of such occurrences obtained were corrected for the likelihood of their being measured over the 196 hail points on the 5 days (Rinehart et al., 1968). The total number of each height-reflectivity combination at hail time for these days was then expressed as a percent of the height-reflectivity values with no hail falling at the hail location. These percentages were used to construct figure 6.

The primary maximum, or where 2 percent or more of the values at any height-reflectivity combination occurred, exists between 5000 and 20,000 feet above the freezing level and is bounded by Z_e of 10^5 and 10^6. However, the hail-

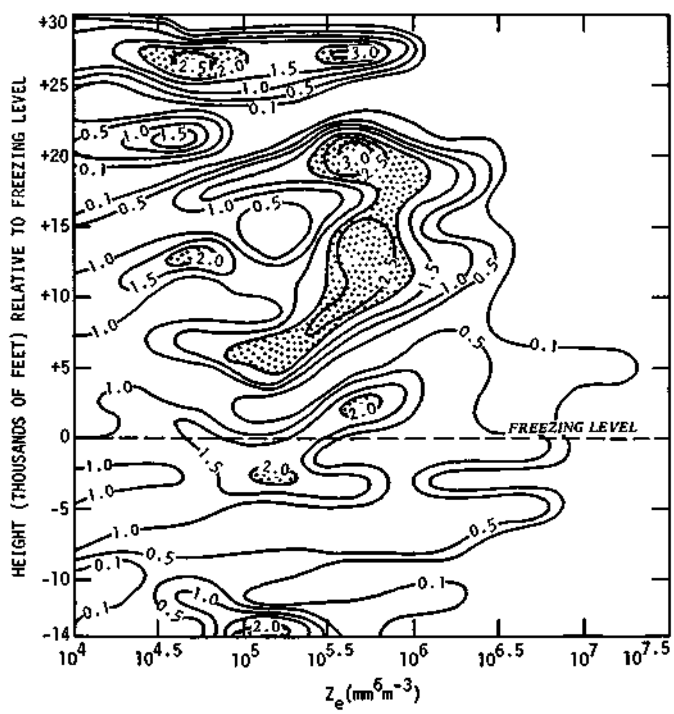

Figure 6. Number of each height-reflectivity combination associated with hail expressed as a percent of all reflectivity values above hail reports

from 5 storms

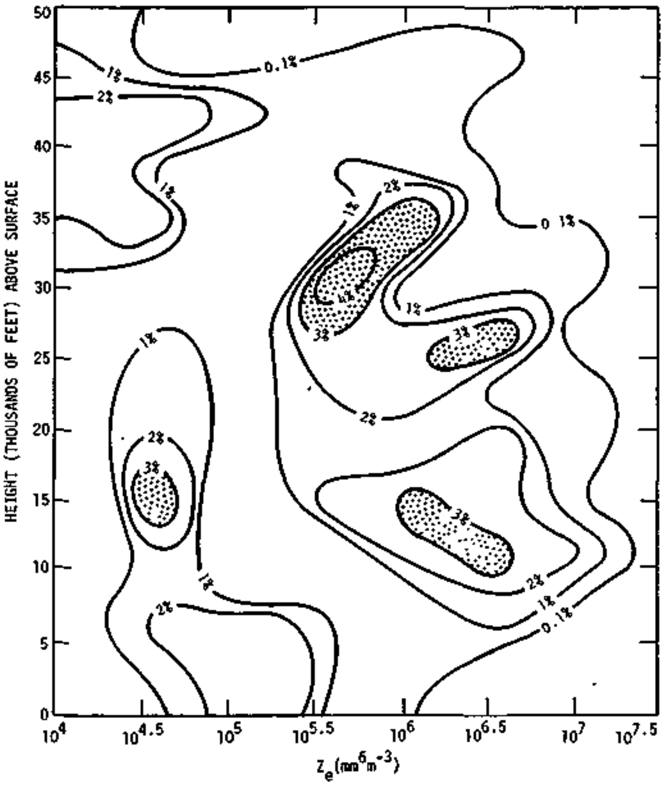

Figure 7. Percent of number of each hail-reflectivity combination for reflectivities in the core nearest to hail reported

related high reflectivities ($>10^5$) did not account for more than 3 percent of the total number of such reflectivities.

In the earlier Illinois hail-reflectivity studies of the 1958-1961 period (Wilk, 1961), the vertical distributions of reflectivity values were chosen from the 'core' nearest to the hail because of the slow radar scanning rate and the qualitative hail-time data. To measure the possible differences in this procedure, the 1967 data were also analyzed on the basis of the reflectivity determined from the nearest core to a hail report, unless the report was already in a core, and the results appear in figure 7. In the $10^{6.0}$ to $10^{7\ 0}$ range there are maxima at the 10-15,000- and 25-27,000-foot levels so that they correspond to the 'reflectivity nose' derived from the earlier studies. These results and the differences between figures 6 and 7 are indicative of the biasing introduced by using the nearest radar core reflectivity data rather than that overhead.

Potential errors involved in using the reflectivity profiles of the nearest core to a hail report were further assessed by measuring the distance and direction to the nearest core from the 196 hail reports. Analysis of the positioning of the core was performed for definable iso-echo cores anywhere below the freezing level and anywhere above it. If the core had considerable vertical development and was sloping, the vertical mid-point of the core was measured.

As shown in table 2, almost all of the 196 hail occurrences had relatable cores somewhere below the freezing level. Only 5 percent were within 2 miles, whereas 10 percent were more than 10 miles away. The preferred directions of the cores

Table 2. Geographical Relations between Surface Hail and Nearest Echo Cores

	Cores below freezing level			*Cores above freezing level*		
Direction of core from hail	Percent of total hail reports	Average horizontal distance (*miles*)	Maximum distance (*miles*)	Percent of total hail reports	Average horizontal distance (*miles*)	Maximum distance (*miles*)
North	11	6 5	12.1	8	6.5	16.3
Northeast	13	4.7	7 7	16	6 9	25.0
East	21	4 3	11 7	9	7 7	26 5
Southeast	9	45	95	9	40	10 0
South	9	21	75	9	17	38
Southwest	14	3.1	8 0	13	3 5	10 6
West	8	6 3	14.5	8	4 2	12 0
Northwest	11	12 2	27.0	11	9 7	22 8
No Core	4			17		

below the freezing level away from the hail were east and southwest suggesting that if the hail were relatable to echo cores, it was frequently falling from either the front or rear of the core. Five of the average distances below the freezing level vary from 2.1 to 4.7 miles which are within reasonable time limits based on average speeds of 5 storms (5 miles per 10 minutes) and the time required (10 minutes) to go through the entire radar step-tilt sequence.

Above the freezing level, 17 percent of the 196 hail reports had no cores within 30 miles of the hail, but 34 percent were within 2 miles and 16 percent were more than 10 miles distant. The directional preferences shown by the percentages in table 2 also reveal frequent positioning to the northeast and southwest, generally upwind and downwind with respect to the prevalent echo motions. If the 5-mile distance between a core and hail at the surface is considered to represent the upper limit of their physical relationship, which seems reasonable, 41 percent of the nearest cores below the freezing level and 32 percent of those above the freezing level were too distant to be associated with the hailfalls.

Reflectivities Aloft in No-Hail Thunderstorms

Thunderstorms were reported by several observers on 12 radar operational days in 1967 when there were no observer reports of hail and no crop-hail damage claims. Data from 3 of these dates were chosen for a reflectivity analysis because 1) these dates were temporally close to severe hail days, and 2) they were in July, the month when Illinois crops are most susceptible to hail damage and any hailfalls are most likely to be detected (Ghangnon, 1967).

Profiles based on the maximum reflectivities plus the maximum echo top measured with the 6 thunderstorms on these 3 dates are shown in figure 8. The greatest reflectivity for each 5000-foot level was chosen from those measured during the period (20-35 minutes) when the thunderstorm was occurring at the surface plus the 10 minutes prior to the initial report of thunder. The widely different reflectivity profiles indicate interesting results. For instance, 3 of the 6 storms have reflectivities between 15,000 and 25,000 feet that are sufficiently great to have predicted damaging surface hail

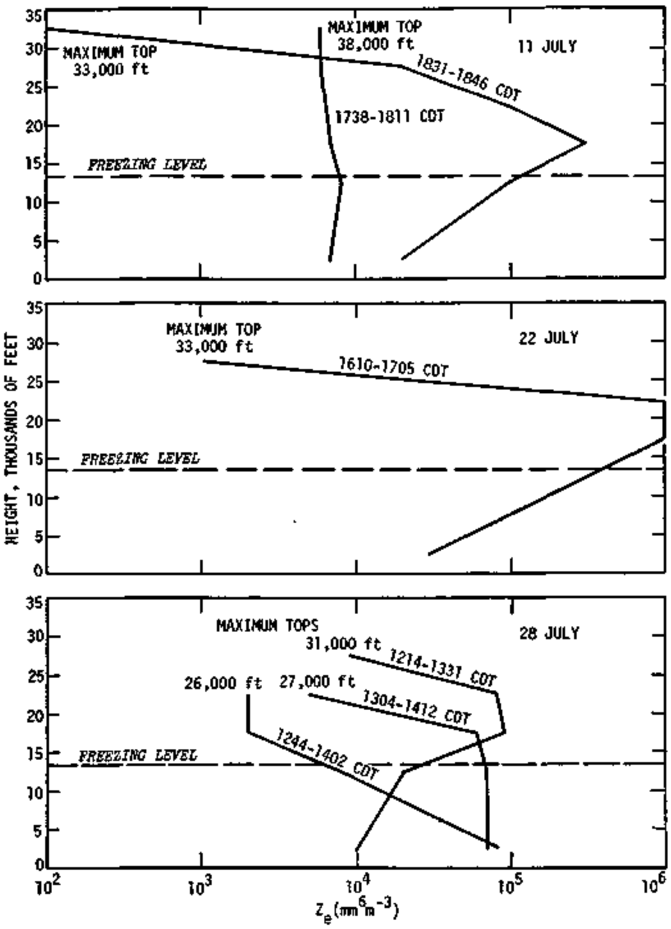

Figure 8. Reflectivity profiles for no-hail thunderstorms based on maximum observed reflectivities during periods of thunderstorm occurrence, as noted for each echo

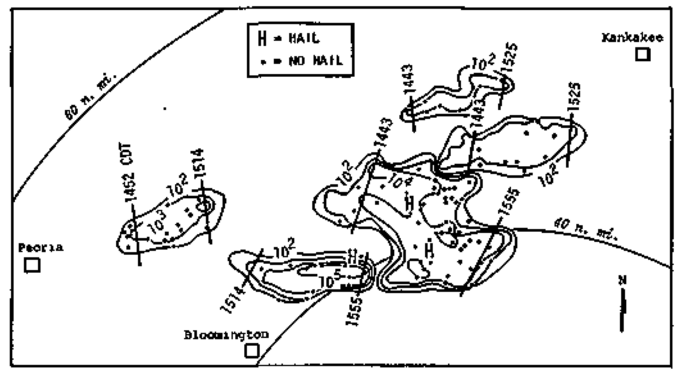

Figure 9. Reflectivity envelopes at the freezing level for 5 echoes on 18 July 1967 showing associated hail and no-hail reports

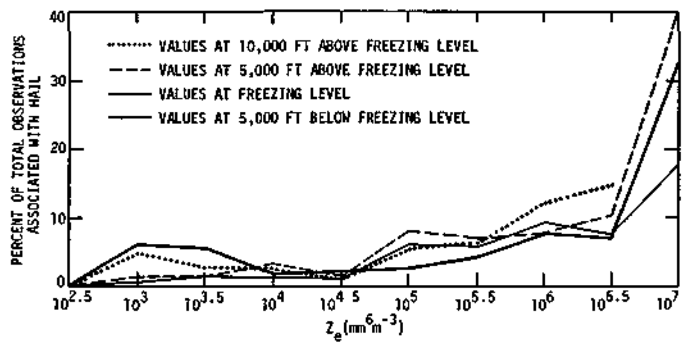

Figure 10. Number of given reflectivities with hail above observers, expressed as a percent of total reflectivities sampled above observers, on 5 major hailstorm days in 1967

(Wilk, 1961). Also, the profile for the 22 July storm was not different from those for 2 severe hailstorms that had occurred on the previous day. The vertical extent of 4 of the echoes above the freezing level was sufficient to allow hail development, and the presence of a distinct 'nose' of high reflectivity on 3 of these profiles suggests they fit previously established models of hail-producing storms. However, the great difference in Z_e profiles between these 3 days, as well as between profiles of storms on the same day, suggests that there is not a 'typical' profile for no-hail or rain-only thunderstorms, and further points up the problems inherent in establishing a useful reflectivity-hailstorm relationship.

Relations between Reflectivity Envelopes Aloft and Hail

The fifth study of the 1967 CPS-9 data was considered the most relevant for evaluating the relationship between echo reflectivities aloft and hail occurrences. Data from the 5 days of damaging hail were employed to track all echoes with $Z_e > 10^2$ throughout their duration for four levels: 5000 feet below the freezing level, the freezing level, and 5000 and 10,000 feet above the freezing level. Iso-echo contours for each gain step defined for each time and height were used to construct 'envelopes' of each echo for its entire lifetime.

Figure 9 shows an example of these echo envelopes. Dots indicate the hail observers who did not have hail with these echoes and an H indicates those reporting hail. Results on figure 9 indicate that surface hail on this day occurred with relatively low reflectivities at the freezing level, but that the high reflectivities at this height ($Z_e > 10^5$) did not often associate with surface hail.

Table 3 presents the number of observers experiencing various reflectivities from the reflectivity echo tracks on these

Table 3. Number of Observers Experiencing Each Reflectivity at 4 Levels on 5 Major Hail Days in 1967

	Number of observers for given reflectivity									
	10^{25}	10^{30}	10^{35}	$10^{4\ 0}$	$10^{4\ 5}$	10^{50}	$10^{5\ 5}$	10^{60}	10^{65}	10^{70}
10,000 feet above freezing level										
No hail	25	105	474	319	287	303	200	87	42	0
Hail (any size)	0	5	13	12	5	18	16	12	7	0
Hail >½ inch diam	0	1	1	4	5	8	4	5	5	0
5000 feet above freezing level										
No hail	21	81	268	300	248	216	249	107	54	6
Hail (any size)	0	1	3	10	5	19	16	9	5	4
Hall >½ inch diam	0	0	1	6	4	7	6	7	3	2
Freezing level										
No hail	29	113	332	218	332	217	264	146	50	9
Hail (any size)	0	1	5	13	3	14	17	15	4	2
Hail >½ inch diam	0	1	2	5	3	5	7	8	3	2
5000 feet below freezing level										
No hail	27	61	91	55	123	156	228	148	47	14
Hail (any size)	0	4	5	1	2	4	10	18	3	7
Hail > ½ inch diam	0	0	0	0	1	2	2	11	2	3

5 days, classified according to whether or not the observer had no hail, any size of hail, or large hail. The number of observers having hail is very small for all reflectivities up to $10^{4.5}$, after which there is a slight increase up to $Z_e > 10^7$. However, the essentially low frequencies of hail reports below $Z_e = 10^7$ points out the difficulty of using reflectivity alone as an indicator for hail.

Figure 10 presents the frequencies of hail (any size) for each height-reflectivity class expressed as a percent of the total number experienced in each class. Only 40 percent of the observers experiencing a reflectivity of 10^7 at 5000 feet above the freezing level (the level of best relationship) had hail, and for most height-reflectivity classes the percentages were 10 percent or less.

Characteristics of Hail-Producing Echoes

Data from 103 hail echoes on 24 days in 1967 and 50 no-hail echoes randomly chosen from the same days were analyzed to describe hailstorm echo characteristics and to provide information useful in operational detection and forecasting of hail-producing storms (Towery and Changnon, 1970). Echo characteristics investigated included locations of echo formation and dissipation, echo reflectivities, echo-top heights, echo duration, direction of motion, speed, time of occurrence, and associated synoptic weather conditions.

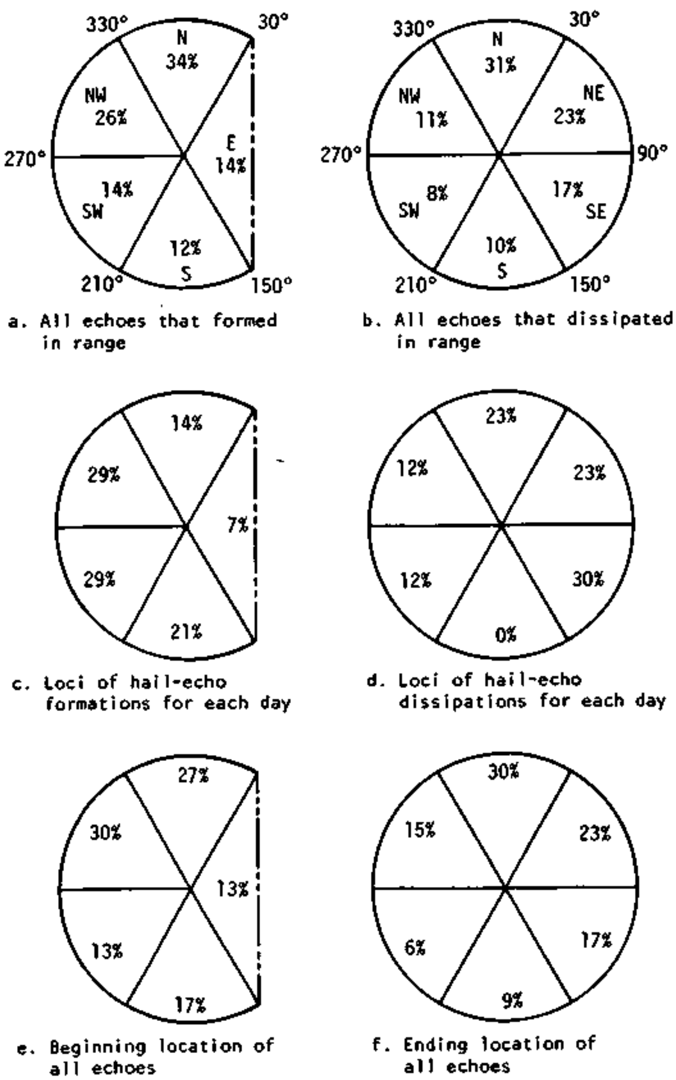

Figure 11. Percent of occurrence of hail-echo locations in the indicated sectors of formation (a, c), and dissipation (b, d), and at the beginning (e) and ending (f) of all echo tracks

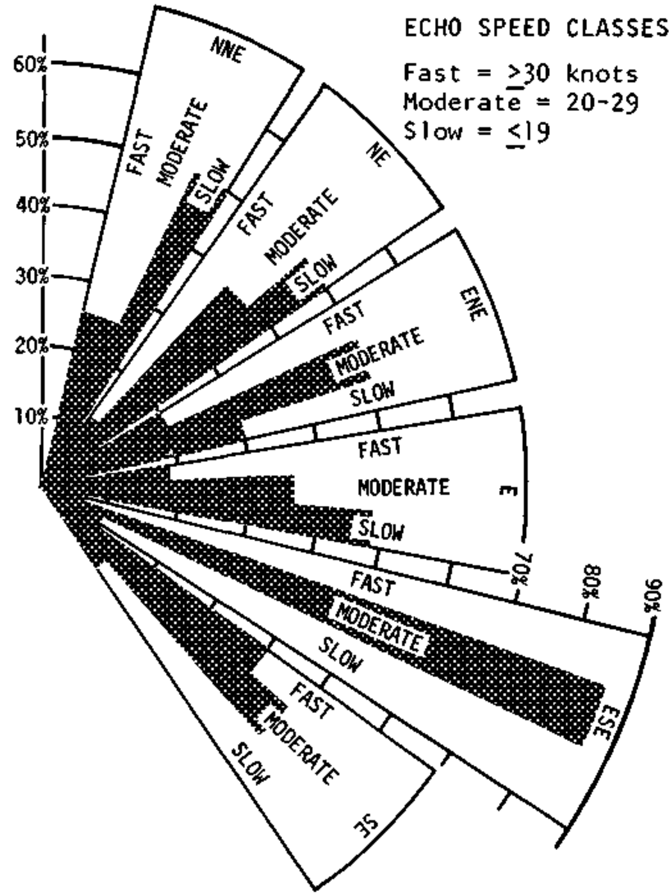

Figure 12. Percent of occurrence of the 3 echo speeds (as averaged over whole echo life) for each direction of motion of all hail echoes

Figure 11 depicts the frequency (in percentages) of echo formation and dissipation for equal sized areas, and a distinct preference for both events exists in the northwest and north sectors where hail is normally most frequent. The speed of motion of the 103 hail echoes were sorted into classes (figure 12) according to direction of motion. Echoes moving to the north-northeast and northeast tend to be slow, those going to the east-northeast and east-southeast tend to be moderate (faster speeds), and echoes going southeast more often than not are fast moving.

Comparisons of these characteristics of hail echoes and no-hail echoes revealed little difference between many values (table 4). However, the hail echoes had moderately higher reflectivities at average time of hail (7.3×10^4 versus 1.6×10^4), and the average heights of the hail echoes were higher than those of no-hail echoes throughout their durations (figure 13).

Figure 14 shows the results of a frequency analysis of the

Table 4. Comparison of Characteristics of Hail Echoes and No-Hail Echoes

Echo characteristic*	Hail	No-hail
Preferred time of occurrence (CST)	1200—1800	1200—1800
Average direction of movement *(degrees)*	81.9	85.9
Average speed *(knots)*	23.8	24.2
Average reflectivity at formation *(mm^6m^{-3})*	6.1 x 10^2	5 5 x 10^2
Average reflectivity at hail time (mm^6m^{-3}) **	7 3 x 10^4	1.6 x 10^4
Average height at formation *(feet)*	25,300	22,000
Average height at hail time *(feet)***	26,900	21,700
Average height at dissipation *(feet)*	25,000	18,500

** All values based on the 50 no-had echoes and on the 50 hail echoes that formed m range, except the height values which are based on the 35 hail echoes that formed and dissipated in range*
*** Average hail time was 44 minutes after formation*

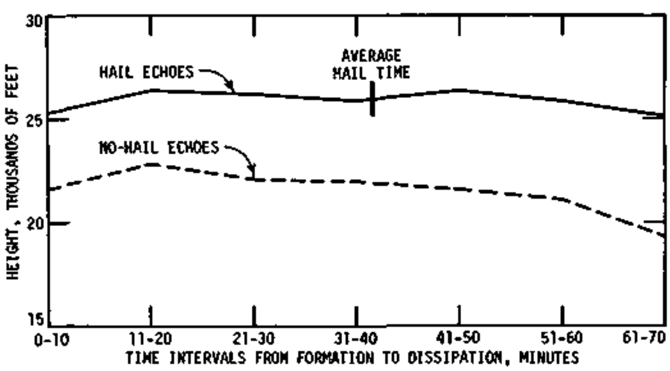

Figure 13. Height curves for all hail and no-hail echoes that formed and dissipated in range

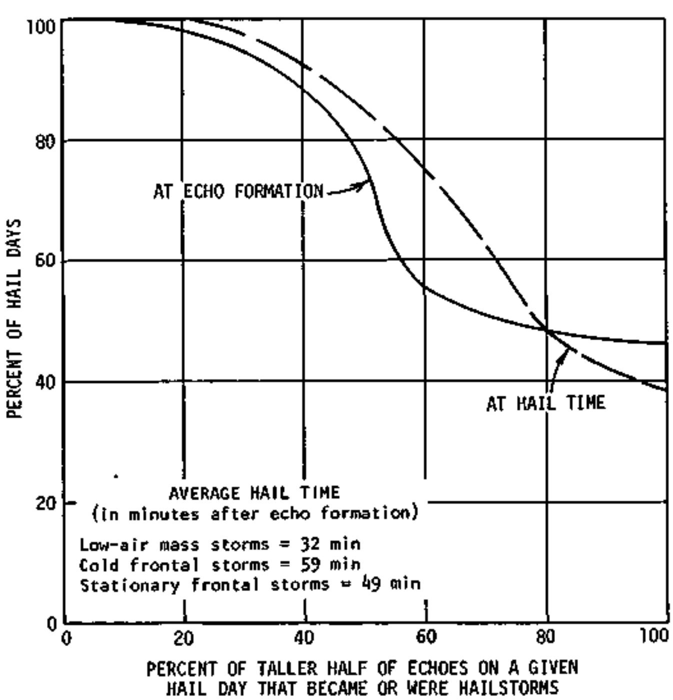

Figure 14. Frequency per hail day of taller half of echoes (at formation and at hail time) that became hailstorms

taller hail-producing echoes on each hail day, as based on echo-top heights at echo formation time and those at hail time. Heights defined for no-hail echoes at 'hail time' were those existing at the average time of hail, as defined for each synoptic class and shown on figure 14. The curves (figure 14) indicate that 100 percent of the taller echoes at formation became hailstorms on 46 percent of the hail days, and 56 percent of the taller echoes at formation became hailstorms on 60 percent of the days. The general similarity in the frequency curves at formation time and at hail time indicates that the echo-top height at formation is as good as height at storm maturity (hail time) in defining hailstorms. Since the first echo height is relatively important in ascertaining whether a storm will produce hail, it suggests that the 'roots' of a hailstorm are tied to the initial strength of the convection in a developing cloud. The results are sufficiently good to suggest that useful operational decisions on hail-producing storms could be made from monitoring the relative heights of first echoes on a given day.

Analysis of the echo characteristics, when sorted and grouped for the 3 basic synoptic weather categories associated with hail, revealed distinctly different models (table 5). The 3 weather categories were cold frontal storms, stationary frontal storms, and storms associated with either low centers or disorganized random air mass convection (these 2 were grouped because they were non-frontal). These synoptic echo models also are useful guides for operational decisions on potential hail-producing echoes. Their differences as reflected in direction of motion, echo turning, and top heights are depicted on figures 15, 16, and 17.

The hail-echo model for cold fronts is faster moving, as would be expected, than are the other echo models. The cold frontal model is also the longest lived, has a wide variety of motions (figure 15), is the tallest storm (over its

Table 5. Summary of Echo Characteristics for Each Synoptic Classification

Echo characteristic	Cold front	Stationary front	Low-air mass
Average speed *(knots)*	30	21	25
Average duration prior to hail *(minutes)*	59	49	32
Average total duration *(minutes)*	90	83	75
Preferred direction of motion	NE	NE	ESE
Preferred direction of turn	Left	Right	No turn
Average number of degrees turn (when turning) in preferred direction	12	17	0
Preferred time of day (CST)	1200—2400	1200—1800	0000—1800
Average reflectivity at formation *($mm^em\sim^3$)*	5.6x10*	5.1x10*	46x10*
Average reflectivity at hail time *($mm'm^{-3}$)*	2.6 xlO^5	4.6x10*	5.2 xlO^4
Average top height for echo duration *(thousands of feet)*	38	36	19
Average top height at hail time *(thousands offeet)*	37	38	20

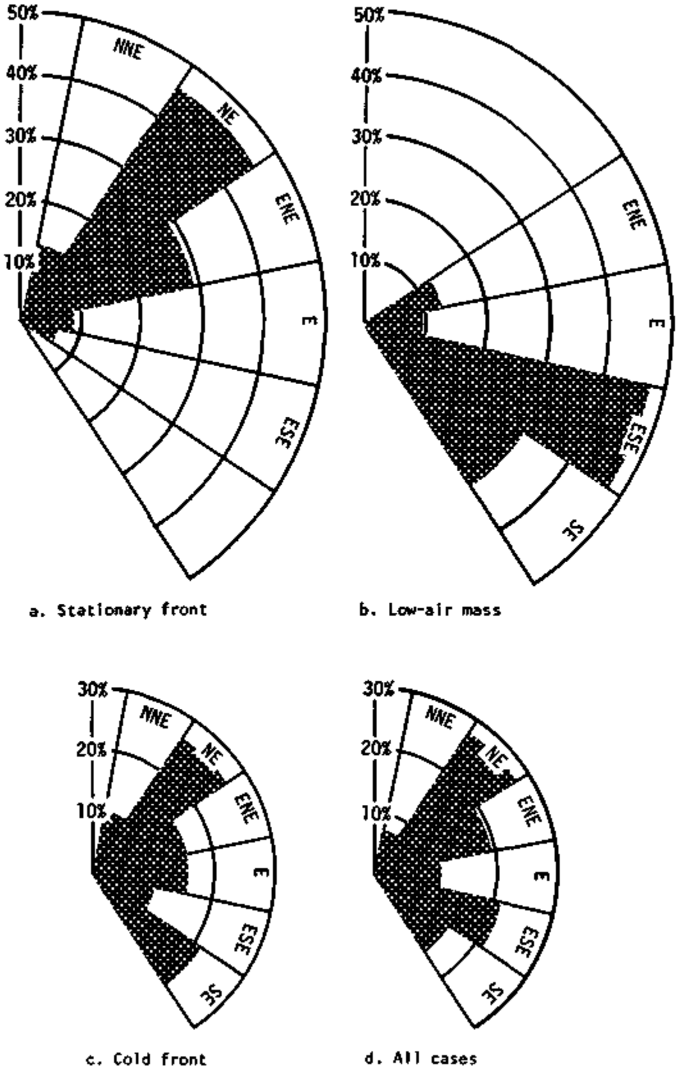

Figure 15. Percent of occurrence of hail-echo motion (toward which the echoes were moving) for each synoptic weather category and for all cases

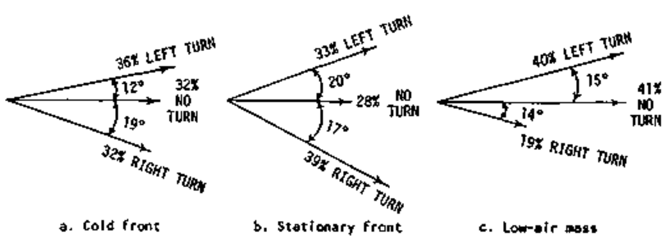

Figure 16. Percent of occurrence of hail echoes turning and not turning and average degrees of turns for each synoptic weather category

entire duration), and has relatively high reflectivities at formation.

The stationary frontal model of Illinois hail echoes indicates a preference for a right turn prior to the development of hail (figure 16), reflecting new echo growth along the right flank. Preference for afternoon echo development in this model further reflects the importance of low-level local heating on the development of hail echoes. This model (table 5) also is shown by its reflectivity and height values

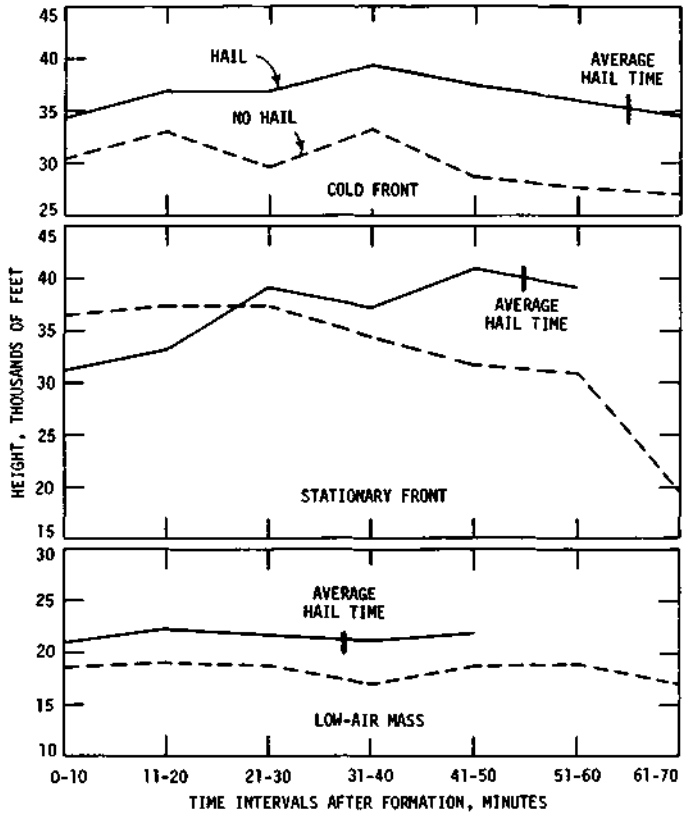

Figure 17. Height curves of hail and no-hail echoes for three synoptic weather categories for time after echo formation

to be a strong, vigorous storm, and one that grows more vigorously than 1) its no-hail echoes or 2) the typical cold front hail echo (figure 17).

The typical hailstorm produced by low-air mass conditions is the weakest and shortest lived of the three synoptic models. These storms exhibit a capability of producing hail quickly after echo formation but, in turn, echo life is considerably shorter than with the other models (figure 17). They make relatively few right turns (figure 16) and frequently have an east-southeast overall motion (figure 15).

The most striking finding from this hail-echo study was the great *variability* in all echo characteristics. Hail-prodrcing echoes had maximum tops ranging anywhere between 9000 and 54,000 feet at the time of hail, durations from 30 to 197 minutes, average speeds of 5 to 50 knots, reflectivities at hail time ranging from $10^{3.5}$ to $10^{8.0}$, and were produced by all types of synoptic weather classifications that produce summer precipitation in Illinois. Consequently, the establishment of a single model of a hail-producing echo would be difficult and relatively meaningless.

However, development of models based on synoptic weather conditions provides useful information. Comparison of the characteristics of hail-producing echoes with those of no-hail echoes to discern forecasting guides reveals great similarities in all aspects except echo height and reflectivities. The average hail-echo tops ranged between 2000 and 5000 feet higher than the average of no-hail echoes. Two-thirds of the hail echoes turned either to the right or left prior to hail production, but there was no marked preference for either direction. Echo speeds at time of hail were not markedly different from that prior to and after hail. Thus, changes in echo speed cannot be used to indicate hail-producing echoes.

The similarity in the behavior of the average echo tops with time for the hail echo and for the no-hail echo indicates a similar evolution of growth and dissipation of convection. Importantly, the greater height of the average hail echo at formation indicates stronger early convection prior to echo development as well as sustenance of greater convection throughout its duration. Thus, the likelihood of hail in an Illinois echo on a day with convective clouds is directly related to the degree of the echo's early vertical development.

STUDY OF HISTORICAL RHI DATA

Before launching an RHI-hail data collection effort using the TPS-10, historical film and hail files were searched for possible hail-echo data. This analysis was to discern characteristics of echoes that produced hail and to provide guidance for future TPS-10 operations and studies. The RHI presentation allows more accurate 3-dimensional measurements of echoes than can be obtained from the CPS-9 CAPPI data.

Hailfall dates and times had to be identified from crop-hail insurance records and U. S. Weather Bureau (National Weather Service) hail records. Attempts were made to identify only echoes known to have been hail-producers and then to obtain their vertical and horizontal measurements and shape at hailfall times. Only 33 hail-echo cases that occurred on 15 days could be discerned from the 13 years of record, and no gain-reduction data were included in this sample. From 1956 through 1963 there were only limited TPS-10 radar operations, and when operating, the TPS-10 was usually scanning in a complete circle, which required 3 minutes to complete. Thus, the frequency of radar observations of echoes of interest was seriously reduced. Only 3 of the 33 hail echoes could be traced for their duration.

An example of results from the analysis of RHI echoes on 25 April 1954 is shown in figure 18. The echo that produced hail appeared initially at a much higher altitude than did 2 other storms in the same area, and hail fell 16 minutes after the storm echo first appeared. All 3 echoes had approximately equal lifetimes, but the tops of the non-hailstorms exhibited less initial growth than did the hailstorm echo. As with the other studies using this type of data, effects of rain and range attenuation were considered in a qualitative fashion. This usually consisted of selecting echoes which were not at extreme ranges, and those that had no intervening echoes.

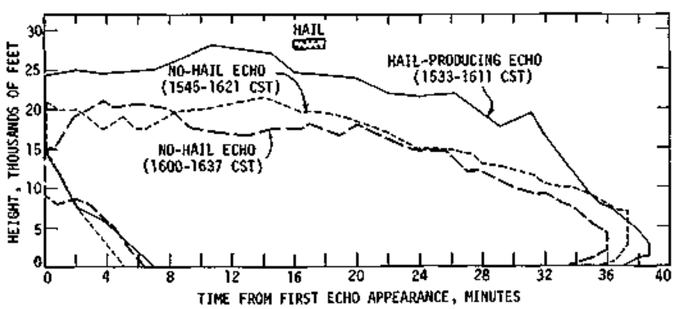

Figure 18. Echo lop-base profiles versus time for 3 adjacent echoes on 25 April 1954

Echo characteristics during the hailfall periods of each echo are summarized in table 6. The echo characteristics of spring hailstorms differed considerably from those of the summer (June-September), and thus echoes were separated on a seasonal basis. In general, the spring echoes at the time of hail production were smaller, both horizontally and vertically, than the summer echoes. The maximum tops of summer storms also were much higher above the average main echo top (as determined for the main echo mass below any isolated turrets).

Various features of the echo shapes also were investigated. Only 5 of the 33 echoes were sloping, or indicating pronounced shear with height, and thus most were generally 'upright' storms at hail time. One summer echo had a vault, and 8 had notable 'fingers' (new cells) hanging below the large echo volume usually existing in the 15,000- to 30,000-foot level and located adjacent to the rain-hail shaft. All but 2 of the 18 spring hail echoes were solitary echoes, and 15 had no radar-indicated anvil. Ten of the 15 summer echoes had horizontal dimensions larger than the average of the spring echoes. The configuration of the summer hail-echo storms was typified by 3 or more turrets, fingers below its large volume, and an anvil, and thus it was notably more irregular than the simple 'tear-drop shape' of the spring echoes at time of hail.

Table 6. Characteristics of RHI Hail Echoes during 1954-1963

	Number of days	Number of echoes	Average maximum echo height at hail time* (thousands of feet) Mean	Max	Min	Average distance of maximum echo top above average height (feet)	Echo length (miles)** Mean	Max	Min	Echo width (miles)** Mean	Max	Min
Spring	6	18	24.7	31.0	15.0	2000	4.5	8 7	2 4	3 9	7 0	2.0
Summer	9	15	34.5	46.0	19.0	6500	10 8	35 0	4 0	5.4	10 0	10

** Average of the top of all echo turrets*
*** Computed by averaging the values along the profile from the surface to 15,000 feet of the widest (length) and narrowest (width) dimensions of the echo*

RHI-HAIL STUDY OF 1967

Three of the major conclusions from the extensive 1967 CPS-9 studies were that 1) the Illinois dense hail network indeed had alleviated one of the radar-hail research problems—obtaining more explicit surface hail-time data; 2) the step-gain, antenna-tilt sampling sequence of 7 to 12 minutes was apparently too long to follow inner-echo reflectivity variations potentially related to hail; and 3) RHI data rather than PPI data were needed to describe better the important vertical size and configurations of hail echoes and their cores. The historical RHI-hail studies had indicated a need for step-gain RHI data and for rapid scanning of echoes.

The TPS-10 operations on a September 1967 day with 6 small hailstorms that produced small hail (<½-inch diameter) in the dense network provided an opportunity to make a thorough RHI-hail case study to ascertain whether the hailfall volumes were detectable. The radar was sector-scanned over the network using 4 gain reduction levels, 1 per sector scan, and an entire sequence of echo sampling was obtained every 3 to 4 minutes. The analysis consisted of tracing the scope photographs and developing constant-level presentations. This manual analysis of 62 minutes of RHI data required 0.5 man year.

Results for this single day (Staggs, 1968) showed that the hailfalls occurred during the early portion of the high reflectivity development and before high reflectivity cores began systematic movements that were trackable within the operating cycle of the radar. No systematic hail growth areas were observed. Interestingly, the cross-sectional areas of hail echoes (at both low and high reflectivities) were larger at hail times than before or after hail occurrences. The high reflectivity zones aloft showed considerable variability in their height and space locations during short periods of time, generally less than 3 minutes.

This last finding on variability of high reflectivity volumes aloft, which often appeared to be present for 5 to 10 minutes and then not present 3 minutes later, is of interest in resolving the problem of hail volume identification. This possibility has considerable bearing on the 1967 and 1958-1961 CPS-9 reflectivity results which were based on a time cycle of echo sampling of about once every 10 minutes. Essentially, the September 1967 storm results raised the question, "Does the high reflectivity zone aloft that is presumed to be hail and/or associated hydrometeors appear only for short periods of 10 minutes or less?" To help answer this question, available surface data were analyzed to derive some approximations of the residence times of radar-detectable hail volumes aloft (Changnon, 1970), and these results revealed that sampling times of 10 minutes or more could be critical in missing hail aloft.

RHI-HAIL STUDIES OF 1968-1969

To obtain the rapid sampling desired for more nearly instantaneous echo descriptions through several reflectivity levels, the TPS-10 was modified considerably. Also to get a greater sample of hailstorm data, the Central Illinois dense network was enlarged from 400 to 1000 square miles.

The two major goals of the 1968-1969 RHI-hail research were: 1) to study further the detection of in-storm hail volumes by using the specially modified TPS-10 operated in a mode to present 3-dimensional and 8 reflectivity-level portrayals of all echoes over and around the 1000-square-mile hail network, and 2) to develop an analytical system involving echo digitization and computer processing to handle and reduce the immense volume of radar data generated by this system and its mode of operation. A secondary goal was to investigate echo top behavior of hail and no-hail echoes.

Hail-Volume Defection

The best potential radar-hail research of the 1967-1969 period for a means of detecting hail volumes involved the excellent rapid-scan RHI radar data of 1968-1969 plus the excellent surface hail network data. Both data sources finally permitted an opportunity to truly ascertain whether 3-cm wavelength radar could identify uniquely the hail volumes within an echo. However, the lack of hail during radar operational periods in 1968 and 1969 resulted in the collection of useful data on only 3 hail days (2 in September and 1 in June) involving 221 minutes of radar echo data which were digitized and analyzed. Echo data on all periods of hailfall on each of these days were digitized, as were 10 to 30 minutes of echo data prior to the first surface hail.

The data sample available for analysis included complete data on 6 hail-producing echoes and on 3 no-hail producing echoes, and several of the hail-producing echoes produced more than one hailstreak. The computer-produced echo-data tapes could define for a 100-second or shorter sampling period, 3-dimensional echoes with a range-corrected reflectivity computed for each 1000-cubic-foot element of echo volume. To aid the study of in-echo hail volumes, plan-position maps of reflectivity contours were machine-drawn as shown in figures 19 and 20. Such maps were plotted with a Z_e contour for each half-order of magnitude and at each 2000-foot elevation level. The locations of hailfall are shown in the three 2-minute sampling periods represented in figure 20, as are those 4 hailfalls on 23 September (figure 19).

The three principal areas of hail-volume investigation were based on the results of the CPS-9 operations and those of the 1967 TPS-10 study which indicated 1) a good rela-

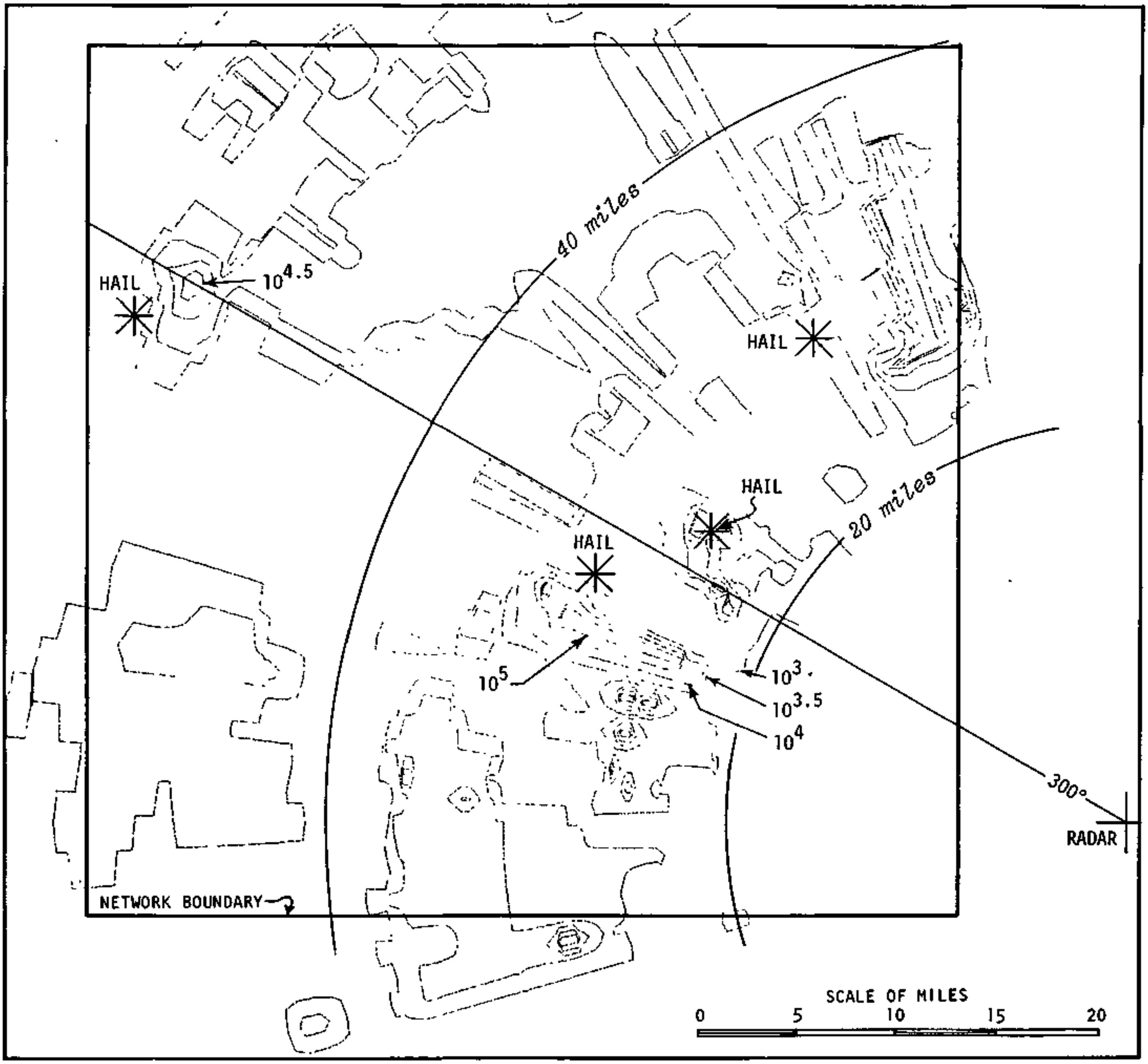

Figure 19. Computer plotted PPI from digitized RHI data for 23 September 1968 at 11:52:59-11:54:42 CDT (The echo altitude is 2000 feet, and the hail indicated is at the surface)

tion of areal extent of reflectivity with hail area, 2) good relation of hail area with steep reflectivity gradients, and 3) changes in echo volume at hail time. The primary goal was to define one or more internal echo parameters that would uniquely define the existence and position of hail volumes. Thus, for each echo that produced hail at the ground, and for the three selected no-hail echoes, the computer data were used to derive tables for each 100-second radar sampling cycle for 1) the area of Z_e for each 2000-foot level, 2) volumes of Z_e for each half-order of magnitude, 3) the value and location of the maximum reflectivity of each echo, and 4) the centroid of the maximum reflectivity contour at each 2000-foot level in hail echoes. The change of reflectivity was calculated outward from this centroid along 8 radials, as shown at the 12,000-foot level for 1710:38 in figure 20. The extensive analytical techniques, computer processing, and computer programs employed are described in detail elsewhere (Staggs and Lonnquist, 1970).

Figure 20 demonstrates the considerable variability of echo characteristics that occurred with time and altitude during a 6.7-minute period. For example, the areas enclosed by the 10^3 contour at 1710:38 vary greatly with height (~ 2 square miles at 12,000 feet compared with ~ 20 square miles at 24,000 feet). Hail was not falling at 1707:29, but hail

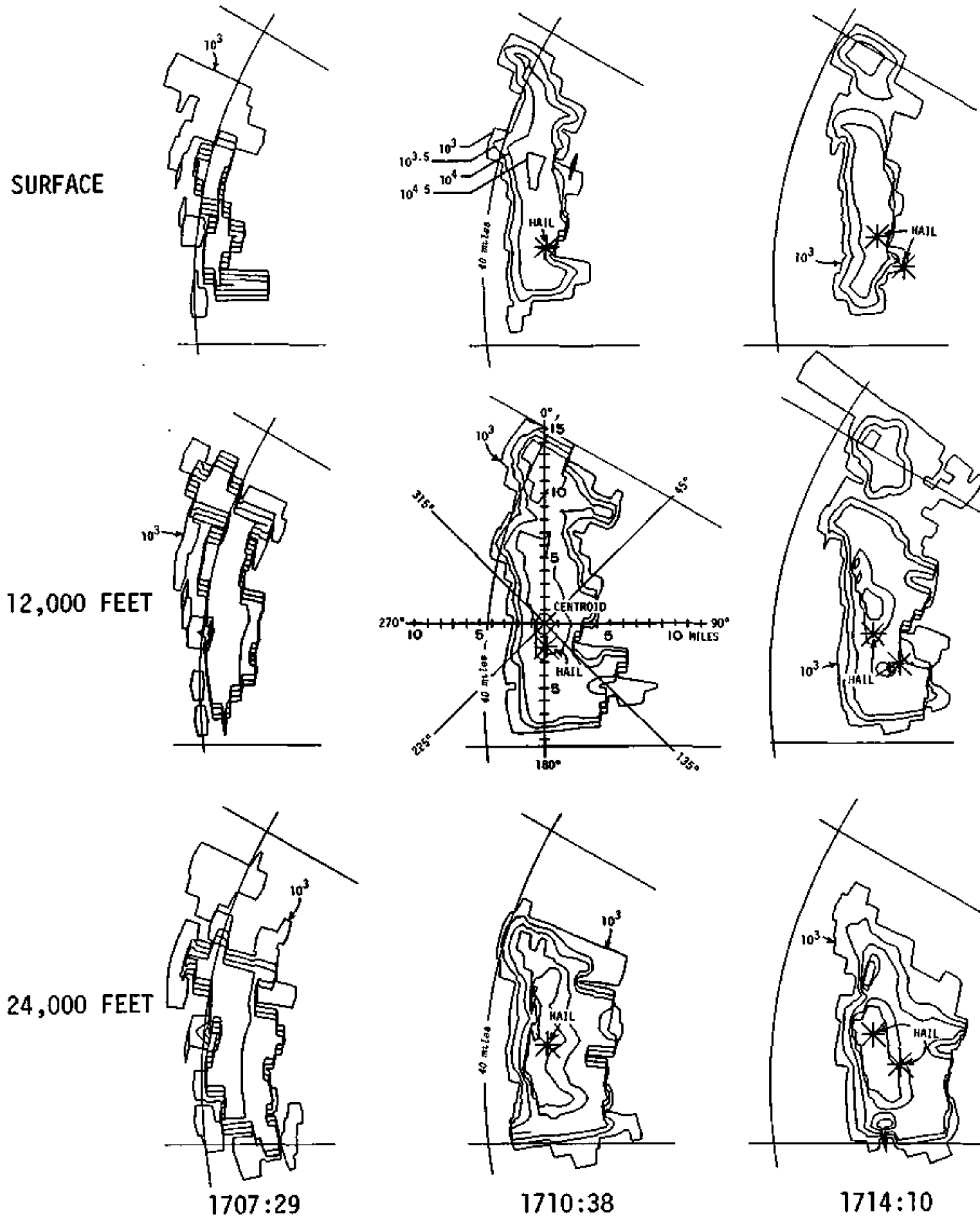

Figure 20. Computer generated CAPPI plots of reflectivity for 22 June 1969

was occurring at 1710:38, and a second hailfall area had appeared 3 miles southeast of the first by 1714:10. Comparison of the hailfall locations with their reflectivity plots at the different levels reveals that the surface hail areas are both near the forward edge where Z_e gradients were sharp, and that at both 1710:38 and 1714:10 the surface hailfall areas were positioned in or very close to the highest reflectivities shown at 12,000 and 24,000 feet. However, as also illustrated in figures 19 and 20, hailfalls occurred outside the areas of highest reflectivity.

The reflectivity gradients out to 6 miles along each 45-degree radial from the calculated centroid of the highest Z_e contour level at 12,000 feet (1710:38) appear in table 7. Those for the 0-degree, 135-degree, and 180-degree radials of this echo reveal the echo extended beyond 6 miles. This illustrates the gradient data made available for each echo

Table 7. Reflectivity at Half-Mile Locations on the Radials Plotted on Center Diagram of Figure 20*

Distance from centroid *(miles)*	0°	45°	90°	135°	180°	225°	270°	315°
	Ze in the form log10 Ze for given azimuths							
0	5 469	5 469	5 469	5 469	5 469	5 469	5 469	5 469
0 5	5 139	5 065	5 110	5 122	5 237	5 247	5 383	5 276
1 0	4 809	4 752	4 816	4 859	5 001	4 773	4 486	4 616
1 5	4 647	4 547	4 610	4 680	4 808	4 452	4 266	4 514
2 0	4 671	4 502	4 484	4 554	4 653	4 334	3 815	4 479
2 5	4 706	4 469	4 420	4 452	4 505	4 146	1 306	4 279
3 0	4 701	4 436	1 614	2 696	4 499	3 937		3 919
3 5	4 706	4 199	1 782	3 268	4 494	3 652		3 438
4.0	4 695	3 675	1 022	3 673	4 486	3 336		0 156
4 5	4 621	2 990		3 800	4 476	0 649		
5 0	4 530	1 616		4 077	4 467			
5 5	4 503	0 376		4 334	4 473			
6 0	4 505			4 039	4 480			

* *The origin of the radials is located at the centroid of the 10^5 contour*

Table 8. Volumes of Specified Reflectivities of a Hail Echo on 23 September 1968 for Selected Times

Time (CDT)	Number of hailfalls in progress	Volume *(cubic miles)* for given reflectivity ≥ 10^{30}	> 10^{35}	> 10^{40}	> 10^{45}	> 10^{50}	> 10^{55}
1148:16	1	302.08	48.81				
1150:21	2	425.77	71 24	8.08	1.64		
1151:53	3	423.35	93.00	21.32	2.99	0.40	
1153:51	2	421.35	118.34	46.60	14 42	13.76	0.08
1155:47	2	431.15	66.74	15.28			
1157:49	2	408 36	6.97				
1200:10	1	313.24	1.83				

Table 9. Volumes of Specified Reflectivities of a Hail Echo on 22 June 1969 for Selected Times

Time (CDT)	Number of hailfalls in progress	Volume *(cubic miles)* for given reflectivity > 10^{30}	> 10^{35}	> 10^{40}	> 10^{45}	> 10^{50}	> 10^{55}
1707:29	0	637.71	363.20	345.38	266.70	0.20	0.20
1709:05	1	977.02	715.85	541.28	271.07	50.02	27.83
1710:38	1	921.93	671.11	526.12	199.75	47.61	1.57
1712:17	2	1,005 96	696.61	535.74	179.30	62 88	
1714:10	2	953.05	618.19	482.76	116.28	51.36	
1715:55	1	1,038.71	720.56	57815	137.21	77.94	

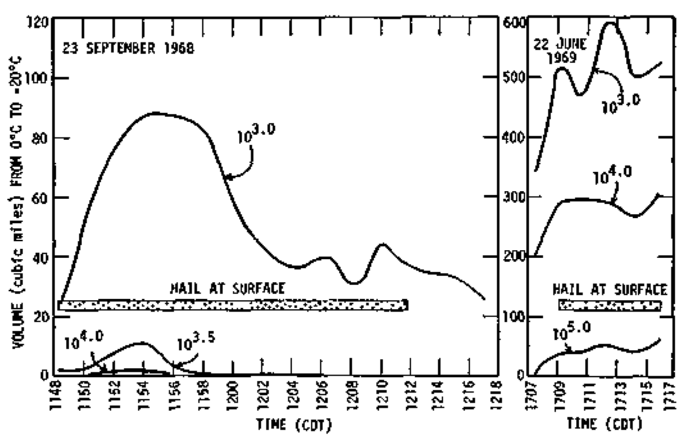

Figure 21. Echo volume of selected reflectivities plotted against time for 23 September 1968 and 22 June 1969

at each 2000-foot level and for each 100-second sampling interval.

Selected echo volume results for 2 of the 6 hail echoes studied are presented in tables 8 and 9 and in figure 21 to illustrate the dramatic differences in Illinois hailstorms when

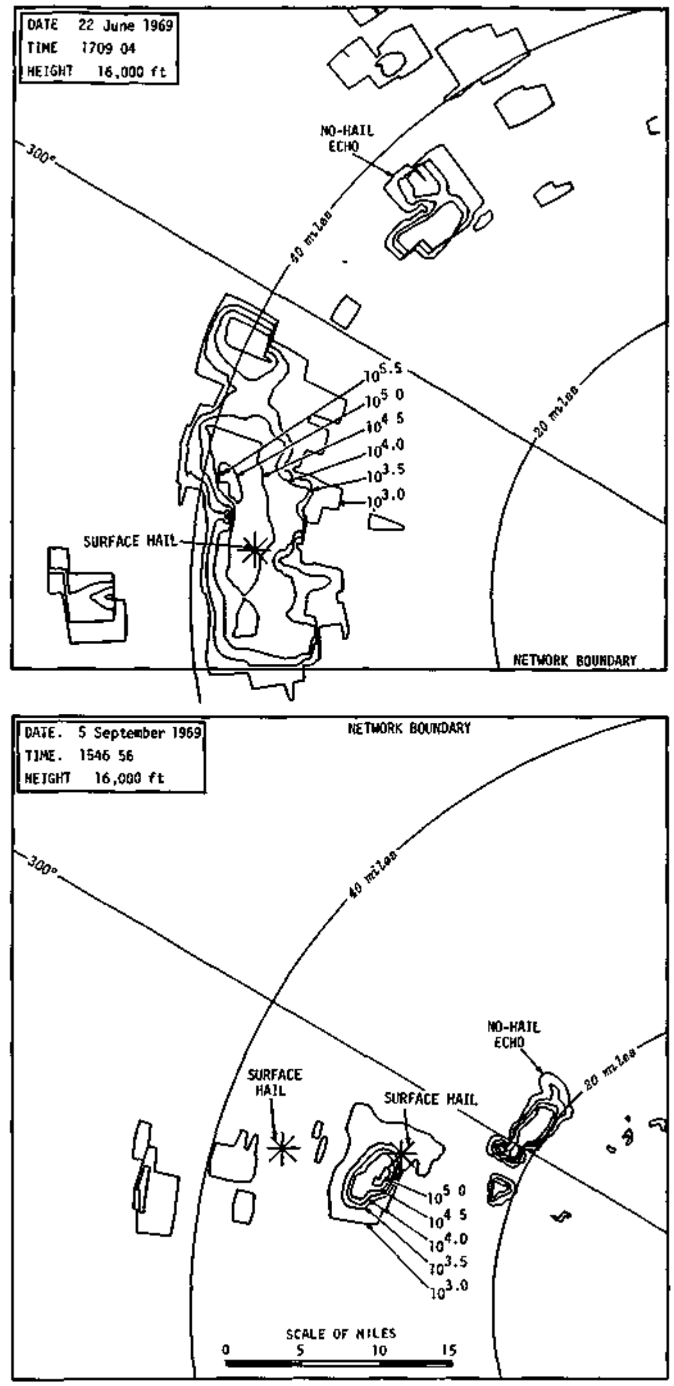

Figure 22. Computer plotted reflectivity patterns from digitized RHI data on 22 June and 5 September 1969 showing the hail and no-hail echoes

they are radar-described in great detail. One echo was one of a series of isolated small hailstorms on 23 September 1968 (Changnon, 1970), and the other was a large prefrontal echo that produced major hailstreaks on 22 June 1969. The hail echo of 23 September was small in vertical extent (maximum top of 18,000 feet) and produced sparse hail ranging from 1/8 to ½ inch in diameter and 3 hailstreaks ranging in length from 2 to 6 miles. In contrast, the hail echo on 22 June (figure 20) was large in vertical extent (tops to 44,000 feet) and produced 2 hailstreaks (lengths of 3 and 20 miles) with many stones ranging from ½ to 1 inch in diameter. Tables 8 and 9 are data for only short periods of time during the lifetime of these echoes, but they illustrate the form of the data and differences between 2 hail-producing echoes. The maximum volume for the echo on 22 June (table 9) was more than 1000 cubic miles whereas the maximum volume on 23 September (table 8) was approximately 430 cubic miles. Investigation of a higher reflectivity (> 10^{40}) reveals that the maximum volume was 46 cubic miles on 23 September 1968 and almost 580 cubic miles on 22 June 1969.

The hail-echo volume analysis was based on a comparison of volume characteristics of hail and no-hail echoes. Examples of the computer-drawn reflectivity maps for the hail echoes on 22 June and 5 September 1969 and for the 2 no-hail echoes (chosen for having a maximum reflectivity during lifetime comparable to that of the hailstorms) appear on figure 22. Hail and no-hail echoes on both days were prefrontal echoes. The echoes on 22 June had eastward movements of 40 miles per hour and those on 5 September moved southeastward at approximately 20 miles per hour. The maximum hail-echo tops both days were 44,000 feet, whereas the maximum no-hail echo tops for both days were 28,000 feet.

The echo volume analysis was accomplished by hail-orders of magnitude for the total echo and for the volume above the —5C level, the area of expected hail growth. Figure 23 is a plot of the echo volumes above —5C plotted against time for the indicated reflectivities of these 4 echoes. The hail echoes exhibited sizeable rapid increases in echo volume in the 5-minute period prior to first hail production at the ground, whereas the no-hail echoes above —5C indicated no comparable quantitative changes. It must be noted that the no-hail echoes chosen were those having, at the time of the hail, maximum reflectivities comparable to those of the hail echoes.

On both dates (figure 23) the no-hail echo volumes above —5C were much smaller than those for the hail echoes. The volumes above —5C were expressed as a percent of the total echo volumes, and these percentages for the 2 hail and 2 no-hail echoes appear in table 10. The percentages were referenced to the time of initiation of hail at the surface. A large portion of the total echo in the $10^{4.5}$ reflectivity class was above —5C in the hail echoes, but relatively smaller portions of the no-hail echoes (50 percent or less) were above —5C. Thus, much more of the high reflectivity areas in the no-hail echoes were at lower levels and below regions of hail formation.

The general positioning of the surface hailfalls with respect to reflectivity values, and particularly to reflectivity gradients above hail at hail time and in the 5 minutes prior to hail, was subjectively examined. A most promising result

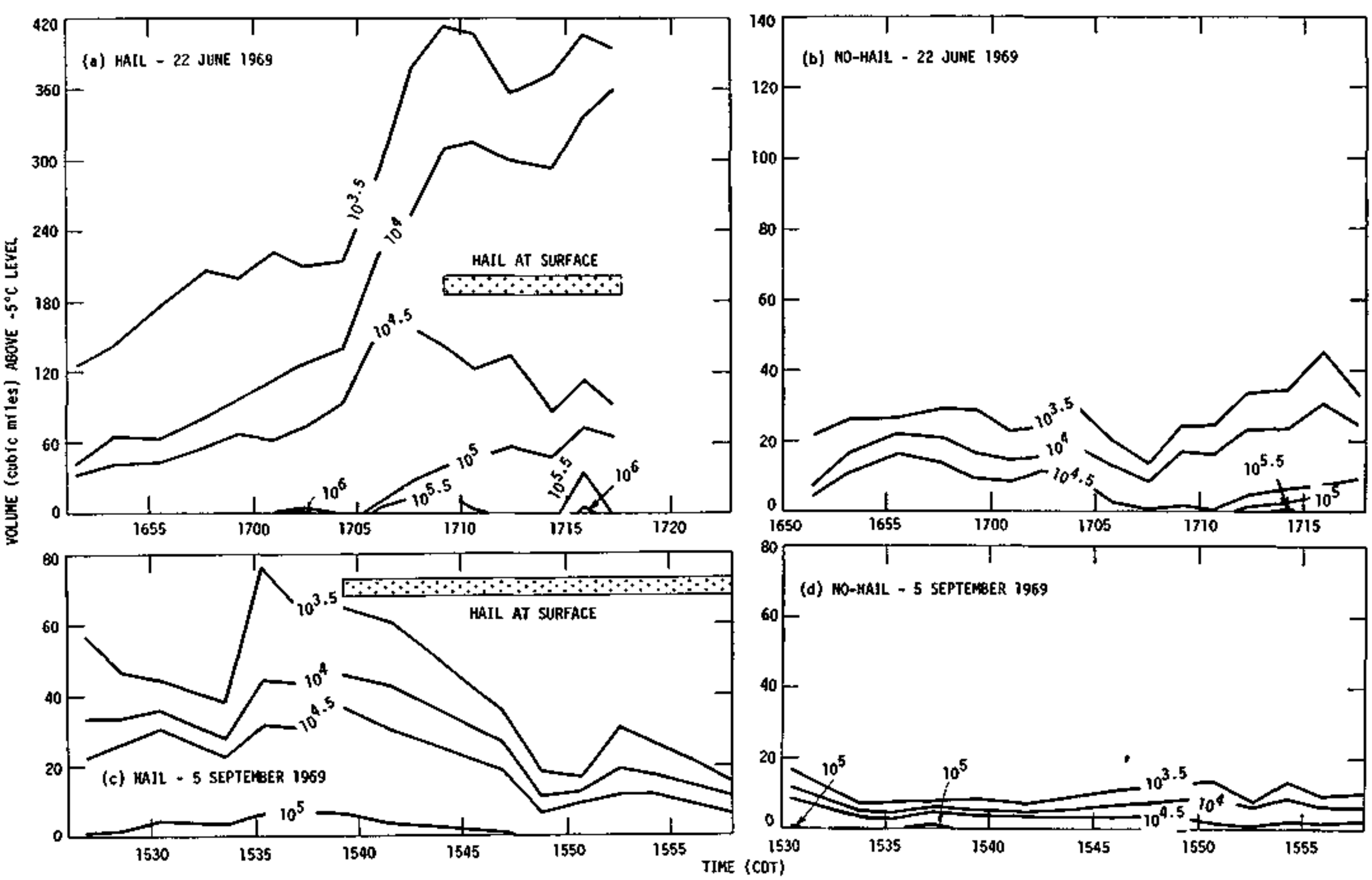

Figure 23. Echo volume above —5C for selected reflectivities for hail and no-hail echoes on 22 June and 5 September 1969

Table 10. Percent of Total Echo Volume above — 5C Level
(Volume defined by $Z_e > 10^{45}$)

	Minutes before hail start				Time of hail start	Minutes after hail start	
	20	15	10	5		5	10
Hail echoes							
22 June	72	75	68	66	69	87	M
5 September	M	80	96	91	90	86	77
Average		77	82	78	79	86	
No-hail echoes							
22 June	50	50	34	30	33	50	M
5 September	M	60	33	27	27	22	25
Average		55	34	29	30	36	

Note: *M — missing data*

was that 8 of the 12 hailfalls produced by the 6 hail echoes were in or within 1000 feet of very high reflectivity gradients (more than one order of magnitude in 0.5 mile). These gradients existed 1) at the surface and extended upward to 4000 feet and 2) along the forward edge of the echoes (see figure 20). Three hailfalls were inside high reflectivity cores (and these were the largest cores existing in the echo at hailfall start), and one hailfall was behind an echo core in an area being obviously attenuated (see 5 September, figure 22).

Echo Top and Base Characteristics

The 1967 CPS-9 results based on comparisons of hail and no-hail echoes (as described by pseudo CAPPI) indicated that the single most important identifier of an echo that was to become a hailstorm was the height of the first echo. The higher quality, more definitive echo top and base data from the RHI (TPS-10) were used to study further these relationships. The numerous (51) echoes that occurred on the hail network during a 2-hour period on 22 June 1969 were selected for a detailed temporal study of their bases and tops. Three of the echoes produced hail and the other 48 did not.

The bases and tops of each echo, as indicated on maximum radar sensitivity, were measured at the time of first echo. The first detection of particles sufficient in size and number to produce an echo was limited by the radar sampling frequency of 100 seconds or less. Thus it is possible that some echoes had been in existence for as much as 90 seconds before the radar scan sampled them. The bases and tops of each echo were measured on every radar sweep interval (10 to 100 seconds) from formation until the echo dissipated or moved too close to the radar for the top to be indicated. The echo top measured was the highest point indicated; however, for echoes that had two or more turrets, the top value was determined by averaging the heights of all turrets. The echo base value was the lowest point measured at the echo base (bottom).

First echo tops occurred over a wide range, 13,500 to 28,000 feet. Four 5000-foot echo top classes, beginning with the 10,000-15,000-foot interval, were developed. The number of no-hail echoes found in each first echo class is shown on table 11, and average values for various echo charac-

Table 11. Average Values for Four Classes
of No-Hail Echoes on 22 June 1969

	Values for given echo class based on height of first echo top *(thousands o/ feet)*			
	10-15	15-20	20-25	25-30
Number of echoes	3	14	23	8
First echo dimensions *(thousands of feet)*				
Top	14 0	17.9	22.6	26.2
Base	9 0	10.7	14 2	17.4
Depth	5.0	7 2	8 4	8 8
Time first echo base to ground *(minutes)*	*	*	8 5	6 5
Maxium echo stage				
Height *(thousands of feet)*	16 0	20 3	23 0	26 2
Time after first echo *(minutes)*	2 0	4 5	6 0	0 0
Dissipation stage				
Height *(thousands of feet)*				
Top	13 7	18 0	15 0	20 0
Base	8 0	6.0	0 0	0 0
Time after first echo *(minutes)*	5 0	8 0	28 0	23 0

* *Did not reach ground*

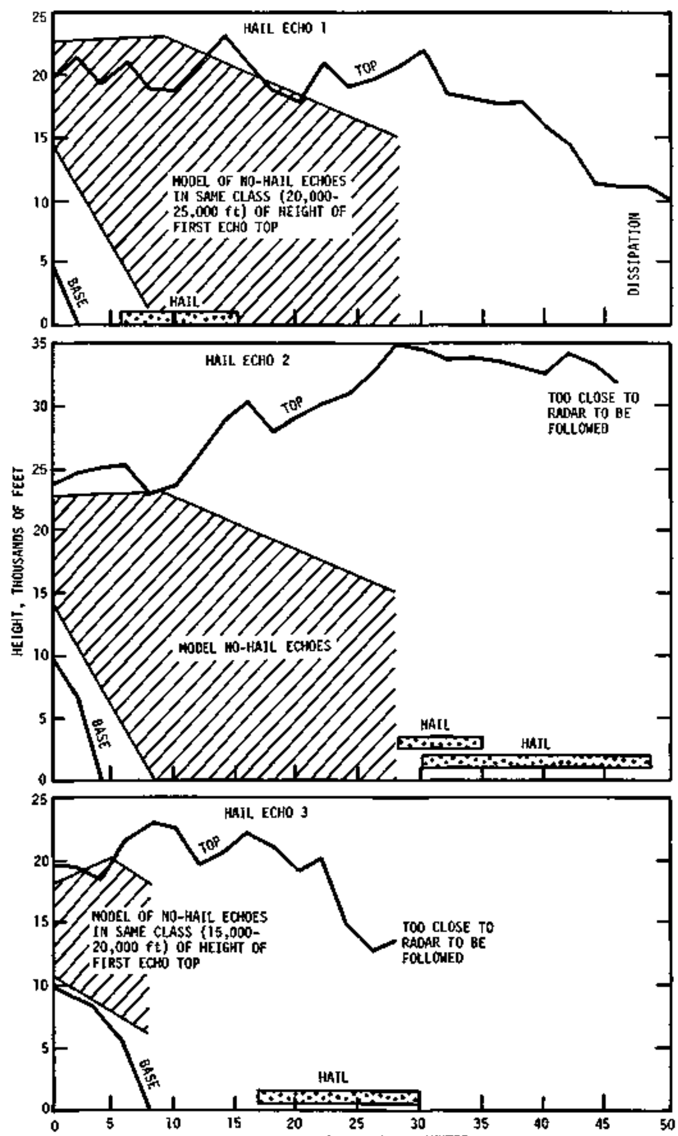

Figure 24. Profiles of three hail-producing echoes on 22 June 1969

teristics are listed. Study of the growth of tops revealed that only 15 of the 48 no-hail echoes had any upward motion after formation, and all other tops were either stationary then downward, or just downward. The averages in table 11 essentially describe 4 echo types. The two lower formation echo types were short lived, 5 and 8 minutes, from the first echo to dissipation, although most had a short period of echo top growth. However, radar detectable particles never reached the ground in any of these 17 echoes.

There were 23 echoes with first echo tops between 20,000 and 25,000 feet. These echoes exhibited very little or no vertical growth, but persisted longer (28 minutes) than any other class. Echo bases in this class reached the ground in 6 to 18 minutes after formation. Interestingly, the average echo depths (top to base) of the first echoes increased with increasing height of echo class. For instance, the average depth of the first echo in the lowest height class was 5000 feet, whereas that for the first echo tops above 25,000 feet was 8800 feet. Although the top and base characteristics of the 8 tallest first echoes differed somewhat, very few exhibited any growth after formation. As can be noted in table 11, most of the no-hail echoes had durations of much less than 30 minutes. In fact, only 3 persisted for 40 minutes.

The profiles of the tops and bases of the 3 hail-producing echoes on 22 June appear in figure 24. No-hail echo profiles, based on the averages in table 11, that are appropriate to the first echo top heights of the 3 hail echoes are also shown. First echo height on 22 June 1969 alone was not a hail-echo distinguishing factor since 17 no-hail echoes had higher tops than that of hail echo 2, the highest of the 3 hail echoes. Only 2, or less than 10 percent, of the tallest half (25 echoes) of the 51 echoes on 22 June became hailstorms, and comparison of this with the echo summation curve of figure 14 reveals that this was a very low and infrequent number of tall echoes to become hailers.

The second conclusion from figure 24 is that the 3 hail echoes were not alike in echo top behavior, duration, or stage when hail fell. Indeed, the 3 hail echoes aptly illustrate the considerable variability that exists in hail-producing storm echoes within a restricted time and area. Echo 2, which is also illustrated in figures 20 and 22, was a major storm of great vertical development, areal size, and duration. Hail echo 1 had only a slightly lower top at formation, but never evidenced any great vertical growth. Hail from it began at the surface 6 minutes after the first echo, rather than 28 minutes later as with echo 2.

The 3 hail-producing echoes did exhibit certain top-base characteristics that were not apparent in the 48 no-hail echoes. All 3 hail echoes had exceptionally greater depth (top to base) at first detection than did the no-hail echoes (see figure 24), indicating a much greater volume of detectable particles to lower elevations within the cloud than was present with no-hail echoes with similar echo top heights. Consequently, the bases of the hail-producing echoes reached the ground much sooner than those of no-hail types. Although hail echoes 1 and 3 did not exhibit exceptional vertical growth after formation, their maximum tops were 3000 feet higher than their first echo. This increase is considerably more than that achieved by any no-hail echoes in their size classes which tended either not to grow or to grow only very slightly (table 11). Finally, the hail-producing echoes on 22 June all had durations much greater than their associated no-hail types.

INTERPRETATION OF FINDINGS

Hail-Volume Detection

A goal of the recent Illinois hail-radar research that evolved as the primary goal was a difficult one — the detection of in-cloud hail volumes. This was approached chiefly through study of the magnitude of reflectivity, gradients of the reflectivity, and reflectivity volumes. The more promising results concerned hail-echo volumes above —5C and hail in gradients of high reflectivity, whereas the least promising results came from the magnitude of reflectivity.

Echoes that produced hail were relatively large above —5C (>65 percent of total $10^{4\ 5}$ volume), and they also exhibited sudden sizeable volumetric increases above —5C during the 5 minutes before first hail. Conversely, no-hail echoes had low volumes above —5C and no large increases. In general, the volumetric increases just prior to hail were >15 cubic miles for Z_e of $>10^5$, and >5 cubic miles for Z^e of $>10^5$, although this finding is relative to the echo dimensions of a given day.

Nearly 70 percent of all hailfalls occurred in the forward edge of storms in high reflectivity gradients at or near the surface. Studies of reflectivity cores near hailfalls showed that the cores were most frequently southwest or northeast of the hail (along the primary orientation of storm motion), further suggesting that hail was produced out of the backside or frontside of reflectivity cores. However, many steep reflectivity gradients in radar cores did not contain hail, and thus a near-surface, steep reflectivity gradient was not a unique detector of a hail volume.

Extremely high reflectivities ($>10^7$) at the surface had the best relation to hail with 50 percent of all areas of 10^7 at the surface being hail, and 40 percent of all 10^7 values at 5000 feet above the freezing level being associated with surface hail. Although reflectivities of 10^7 were moderately well related to hail, 10^6 and lower reflectivities were not. About 20 percent of the reflectivities in 10^{50} to $10^{6.5}$ range measured at the surface were related to hail. A high reflectivity ($>10^5$) always existed somewhere aloft above a hail report, but 5 times more reflectivities of this magnitude occurred aloft with no hail ever occurring at the ground. In general, surface hail reports (big or small hail, damaging or non-damaging) had their relative maximum frequencies of higher reflectivities (10^{45} to 10^{60}) in the area from 5000 to 20,000 feet above the freezing level, but only 2 to 3 percent of the high reflectivities at any 2000-foot level in this 15,000-foot segment occurred with hail at the surface.

The earlier 1958-1961 conclusion that a high reflectivity nose aloft was an indication of hail, as based on psuedo-CAPPI data, was partially substantiated. When the reflectivities of the cores nearest to the 1967 point hail occurrences were summed, they showed the 'Z-nose' found earlier. However, 41 percent of the hail reports did not have a reflectivity core sufficiently close to have been associated with hailfall. Furthermore, when the reflectivity values above a hailfall at the time of hail and during the 5 minutes prior to hail were summed, no comparable reflectivity nose existed. Studies of known no-hail (surface) thunderstorms also revealed that many had reflectivity profiles and maximum echo tops that earlier findings would have indicated to be hail-producing storms. These results show that the mean (climatological) hailstorm reflectivity profiles developed in the earlier work in Illinois, Texas, and New England are meaningless when used alone as an indicator of a hailstorm on a given storm day.

Thus, the magnitude of reflectivity alone is a poor indicator of a hail volume or hailstorm; hail frequently occurs in steep reflectivity gradients in the frontside of storms, but many gradients do not contain hail; and although growth in echo volume above —5C is a good indicator of the onset of hail in a storm, it does not indicate the in-storm position of hail.

Hailstorm Echo Detection

The second major research effort of the 1967-1969 radar-hail studies in Illinois concerned the detection of existing hailstorms before or during hailfalls. This is useful in hail suppression techniques that depend only upon the seeding of total storms, not the specific hail volumes within storms, and in inventorying hailstorm frequencies over a given area.

Studies oriented toward hailstorm identification revealed that characteristics of first echoes should be carefully monitored because they are frequently important in the identification of echoes that will produce hail. Comparisons of hail and no-hail echoes on 27 days in 1967-1969 revealed that potential hailstorms at first echo (formation) frequently had greater heights of the echo tops, a greater depth between top and base, and markedly higher reflectivities than no-hail echoes. Echo duration was not a useful indicator of a hail echo, but all hail echoes persisted more than 20 minutes, and many no-hail echoes did not. On the average, the height of hail echoes is greater than that of no-hail echoes at all times of their life. All hail-echo tops grew at least 3000 feet after the first formation, and many no-hail echoes exhibited no vertical growth after formation. The amount of echo turning, by either direction or amount, was shown to be not important in defining hail echoes, nor was duration if it persisted longer than 20 minutes. Time of formation and location of echo formations in Illinois also were not useful in identifying hail echoes.

On an operational basis, one should monitor (as based on real-time monitoring of the echoes on a given day) the heights of first echo tops, first echo depths, the first echo reflectivities, the amount of echo top growth, and durations. All echoes on a given hail day became hailstorms if they fulfilled 3 or more of the following criteria: 1) were in the taller half of the first echo top heights, 2) had greater than average (for the day) first echo depths, 3) had above average (for the day) first echo maximum reflectivities, 4) grew more than 3000 feet in the first 15 minutes of life, and 5) existed more than 20 minutes. Synoptic modeling of hail echo characteristics revealed distinctly different hail echo types between those produced by cold fronts, stationary fronts, and low-air mass conditions. Employment of these average or model characteristics for a given hail day will aid in the real-time classification of echo characteristics on a given day.

Measurement of Surface Hail Area

Another potential application of radar data to hail suppression activities concerned possible measurement of the areal extent of hail within a study area. Although the studies indicated that knowledge of specific hail occurrences at a point could not be obtained with confidence from reflectivity data, they did indicate that the areal extent of hail at the surface for a given storm period (1-6 hours) could be estimated from the area of surface reflectivity described by the highest half-order of magnitude in the storm period. However, use of this measure requires knowing that hail has occurred in the study region. A fair relationship was shown between areas of high reflectivity gradient and hail area, indicating that steep reflectivity gradients were associated with large areas of hail.

Seasonal Radar Models of Hailstorms

One way to summarize the results of these 1967-1969 radar-hail studies in light of hailstorm mechanics and storm types is to discuss the typical storms on a seasonal basis. The typical Illinois hailstorm in spring (March-May) and in fall (September-October) is small (<5 miles in diameter, tops 25,000 feet or lower) with a simple configuration (tear-drop shape) and not sheared. Yet a spring storm often produces crop-damaging hail because of crop susceptibility to damage (Changnon, 1967). The maximum reflectivities aloft are short lived (10 minutes or less) and have little time-space continuity. The maximum reflectivity values in these hail echoes vary considerably between days, with 10^5 possible on one day and $10^{7.5}$ on other days. Hail volumes in spring storms generally exist in the reflectivity cores, but the infrequency of surface hail with many cores indicates that hail volumes are just not reliably detectable with 3-cm radar. Echo heights from formation through maturity are the best indicators of hailstorms in the spring and fall seasons, being generally higher for hailstorms, and the hail echoes also frequently undergo echo volumetric increases 5 minutes before hail time in the level above —5C.

The typical summer hailstorm in Illinois is much larger (>10 miles in diameter and maximum tops exceeding 30,000 feet). It also is multi-turreted and weirdly configured at maturity. At times of hail, the maximum reflectivities somewhere in the echo are generally 10^6 or higher, and the mature echo has more than one maximum reflectivity core. However, many high reflectivities occur in summer storms near and at the surface without hail. Most summer hail occurs in the steep reflectivity gradients near the front of the echoes at the surface, but such steep reflectivity gradients exist frequently without hail in them, and cannot be used to specifically identify hail volumes in summer storms. Five minutes prior to hail, summer hail echoes begin sizeable increases in the echo volume above —5C, and in general throughout maturity (30 minutes) they have much more echo volume above —5C than do no-hail echoes. Large summer hail echoes differ from no-hail echoes on a given day basically in their first echo heights and in their sustained higher echo tops and durations. However, maximum echo reflectivities as determined anytime throughout storm life, the echo speed and motion, and the echo duration are not useful predictors or identifiers of summer hailstorms in Illinois.

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

The relevant conclusions from the 1967-1969 radar-hail detection research in Illinois indicated, first, that there is a high reflectivity-hail relationship but that high reflectivities are not unique to hail. A reflectivity core relatable in space and time to hail at the surface is not present 41 percent of the time. Eighty percent of the high reflectivities ($>10^5$) found anywhere in an echo on a given hail day occur without surface hail. Secondly, hailfalls are frequently associated with steep reflectivity gradients near the surface, but many steep gradients do not contain hail. Thirdly, a relatively large increase in the echo volume above —5C is a good predictor of the onset of hail. The recent Illinois results do not indicate a useful (reliable) radar capability of detecting hail volumes aloft or at the surface.

However, monitoring of 5 echo characteristics when sorted by relative echo characteristics per day, can lead to the identification of all hail-producing echoes that have occurred on a given day. In general, the taller and more vigorous storms, both at first echo and throughout maturity, are hailstorms. Other characteristics such as speed, echo direction, and duration (beyond 20 minutes) are not useful in identifying hailstorms.

These Illinois results based on 3-cm radars indicate that a rapid rate of radar search over a given study area (sampling various reflectivities in a 2-minute or shorter period) is required to obtain information on echo characteristics that will allow hail-echo identification.

Future Research Considerations

It appears that the exhaustive radar-hail studies of 1967-1969 have defined adequately the capabilities, limitations, and applications of 3-cm radar in Midwestern hail research. Hail echoes can be detected, storm-period hailfall areas can be estimated, but in-storm hail volumes cannot be detected. In many respects the results of the concentrated Illinois research efforts to identify the hail volume within a storm unfortunately resemble those from the first preliminary radar-hail observations accomplished 25 years ago in the Midwest. Miller (1947) using airborne radar data on two storms concluded that "hail was associated with intense appearing echoes and [hail] could not be particularly distinguished within the main [echo] area of high return." Failure in the Illinois 3-cm studies of hail volumes was not totally unexpected, but since it is important, both for hail physics studies and for certain hail suppression approaches, to detect in-echo hail volumes, other more complex means of hail volume detection by radar must be considered.

The possibility of using paired radars of different wavelengths to detect hail was first offered by Atlas and Donaldson (1955), and although the idea was kept alive largely in theoretical fashion (Atlas and Ludlam, 1961; Cartmill, 1963), the Russians (Sulakvelidze, 1966) were the first to claim utilization of such systems in hail suppression projects. Another potential means of detecting hail volumes was offered by Atlas et al. (1953) and this technique involves a polarization diversity antenna and receiving system to detect hailstones. Another potential means of hail detection, including measurement of hailstone sizes aloft in certain circumstances, has been offered by Battan and Theiss (1966). This method utilizes the vertical velocity and reflectivity data from a pulsed-doppler radar, plus assumptions as to stone shapes and density, to develop calculations of the sizes of hailstones that correspond to a particular doppler spectrum.

Efforts to detect hail volumes using the depolarization and dual-wavelength techniques have recently found new impetus. The depolarization technique is considered to have hail detection potential because 1) depolarization exists when the polarized energy is back-scattered from targets which are not spherical, and 2) hailstones, as opposed to raindrops, are generally not spherical. The Alberta hail research program has developed a 10-cm wavelength radar that has such a polarization capability, and a recent investigation of a single severe hailstorm (Barge, 1970) indicated that the polarization measurements did relate well with the occurrence and type of hailstones surveyed at two ground locations. If one assumes that the polarization is a good detector of non-spherical hailstones, then the only remaining questions concern the frequency of non-spherical stones. The amount of back-scatter depolarization, or depolarization component, from hailstones with axial ratios (minimum diameter divided by maximum diameter) of 0.5 or less is considered 'small' (Atlas and Donaldson, 1955).

Data collected from hail observers in Illinois during the 1967-1969 period were analyzed for the shapes listed in 960 different hailfall reports. These observers reported, for a given hailfall, the hailstone shapes to be: all round, all flat, all irregular (triangular, elongated, or unusual), or combinations thereof. Admittedly, the observers' classifications of stone shapes are subjective, but 70 percent of the hailfall reports indicated only round stones. The minimum and maximum dimensions of 9486 hailstones measured on Illinois hailpads in 1968 were analyzed to determine their axial ratios, and the results sorted by stone size are shown in table 12. Seventy-seven percent of all hailstones had axial ratios of 0.51 or greater which agrees favorably with the frequency of round stones reported by the observers. These data suggest that the use of radar depolarization to detect hail volumes aloft in Illinois would not be a particularly successful technique. However, as shown by Battan and Theiss (1971), a radar combining a depolarization capability with doppler capability (to furnish information on terminal velocities of particles) could provide greater confidence in detecting hail.

Table 12. Axial Ratios for 9486 Hailstones Measured on Illinois Hailpads in 1968

	Hailstone diameter *(inches)*						
	1/8	1/4	3/8	1/2	3/4	>1	Total
Total stones	3966	4304	908	216	66	26	9486
Axial ratio* *(width/length)*	Percent of total in each size class						
< 0 25	1	1	0	0	0	0	1 -
0 26-0 50	34	12	13	10	24	23	22
0 51-0 75	55	46	50	46	48	46	50
> 0 76	10	41	37	44	28	31	27

** Width is defined as narrowest dimension, and is considered to be the diameter; length is the longest dimension*

Recently, a new method of hail detection which depends upon the range derivative of the ratio of average echo powers, as observed by two synchronized and slaved radars of different wavelengths, has been offered by Eccles and Atlas (1969). The method requires that the average of the echo power of both radar sets be sufficiently accurate that the range derivative in rain alone is always positive and proportional to the increasing differences in attenuation at the smaller (3-cm) wavelength. In the presence of hailstones of any type (wet or dry) or shape with diameters > 1 cm, the derivative of the radar signals becomes negative on the far side of a hail shaft. The derivative will behave thusly because the wavelength dependence of the equivalent reflectivity factor of hail is quite different from that of rain, and the hail reflectivity for 10-cm is much greater than that for 3-cm. A radar system designed to test this unique method is under joint development in Illinois by the Illinois State Water Survey and the Laboratory for Atmospheric Probing at the University of Chicago.

Operations during 1972 in central Illinois using this dual-wavelength system in conjunction with an 800-square-mile dense hail-rain network comprising 81 recording raingages, 250 hailpads, 15 recording hailgages, and 350 hail observers should provide data to evaluate the capability of this system to uniquely detect hail volumes.

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RI 71, SAC

Found difc. to predict hail by refl. aloft

While hail assoc. w/ high refl. aloft (5000-20000 ft abv. freezing level for instance), 4 to 5 times more often these refl. appear w/out hail at surface

1967 CPS 9

→ ~~[illegible] SAC (1970)~~ ; Rinehart, et. al (1968)

CPS-9 also 1967

103 hail echoes 24 days

50 randomly chosen no hail echoes

table 4 & 5 page 10 *

hail echoes - moderately higher refl. at time of average time of hail (7.3×10^4 v.s. 1.6×10^4)

avg. heights higher thruout lifetime

refl. somewhat higher at start (6.1 vs. 5.5×10^2)

avg. height	Formation	25.3×10^3 ft	22.0
	hail time	26.9	21.7
	dissipation	25.0	18.5

echoes - hail nohail by synoptic class

cold front ;	Stationary front ;	low or airmass
30	21	25

with out stratification - great variability in echo characteristics

max tops	9 - 54,000 ft at time of hail
durations	30 - 197 min.
speeds	5 - 50 knots
refl.	$10^{3.5}$ - $10^{8.0}$ at time of hail

see other reports for freq. of hail w/
various synoptic classes

TPS-10 RHI 3cm.

▽ historical 1954-1963 15 days; 33 ~~storm~~ echoes

no gain reduction data

Spring April- May
Summer June-Sept.

only 5 indicated pronounced shear
1 vault
8 fingers
16/18 spring solitary 15 no-radar indicated anvil
10/15 summer had horz. dim. > avg. of spring echoes

▽ 1968-1969
3 days
2 sept; 1 June

6 hail prod. echoes
3 non-hail

FE no-hail cases p18

not a good predictor

in general - not large enfough sample to
account for great variability in hail &
no-hail echoes

might give some implications - but none statistically
significant