PRELIMINARY STUDY OF THE RELATIONS BETWEEN HAIL AND THUNDERSTORM REFLECTIVITY STRUCTURE

by

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TABLE OF CONTENTS

I. INTRODUCTION

This is a report of preliminary findings from a study of the relations between hail and thunderstorm reflectivity structure. Basic data for the study were obtained during the summer of 1962, as a part of the hail studies which were conducted under the direction of the author at Colorado State University. Arrangements were made with Air Weather Service for a radar operator from Colorado State University to obtain data on thunderstorm reflectivity structure from the CPS-9 at Lowry Air Force Base. These data were correlated with information on rain and hail obtained from an observational network in northeastern Colorado.

In addition to data from the CPS-9 at Lowry AFB, data on echo tops and low level reflectivity were analyzed from a 3-cm radar set operated by Atmospherics, Inc. at New Raymer, Colorado from 11 June - 31 July 1962.

The results presented in this report are limited to a preliminary study of the data available as of 4 September 1962 and were limited by the total time available for analysis during the 15 day active duty tour. Additional analyses will be performed when all of the available data have been reduced. These additional analyses will permit either confirmation or revision of the preliminary results presented in this report.

II. OBJECTIVES

The objective of the study reported herein was to develop criteria for operational interpretation of quantitative reflectivity data from the CPS-9.

The specific objectives of the study were:

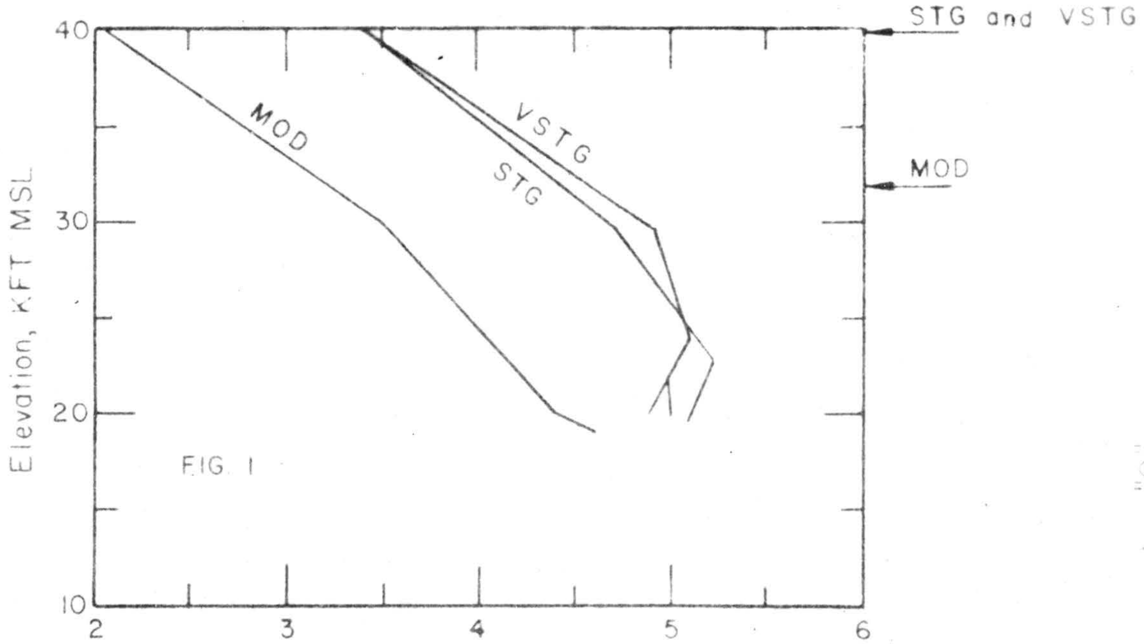
1. To determine the relation between convective severe weather and reflectivity structure.

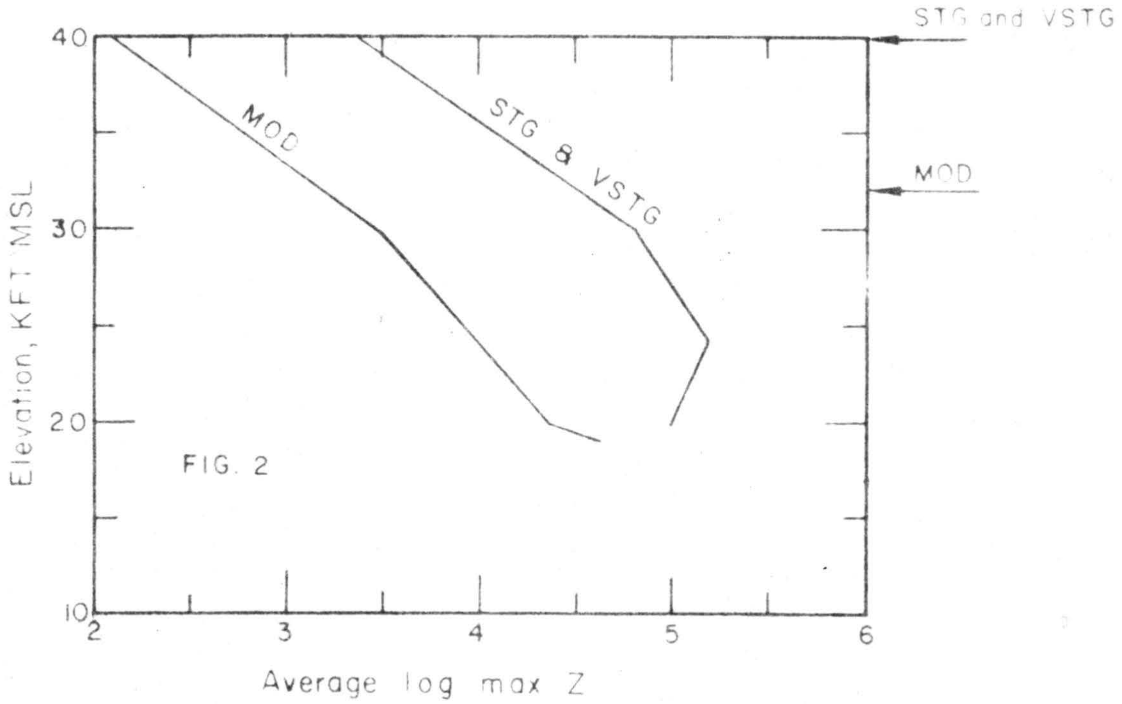
2. To determine if the relation obtained from Lowry AFB might reasonably be extended to another location (specifically, for example, to Ellsworth AFB, South Dakota.)

III. PROCEDURE

A. Radar Data

The Lowry CPS-9 was modified in the spring of 1961, with the addition of a "stepped-gain" device to reduce the receiver gain automatically through a series of eight(8) steps (0 through 7).





Arrows show elevation of avrage RHI tops - step "O"

AVERAGE LOG MAX Z FROM CPS-9 FOR REFLECTIVITY PROFILES CORRESPONDING WITH LOCATIONS FOR WHICH FIELD DAMAGE SURVEY DATA ARE AVAILABLE FOR MOD, STG AND VSTG CATEGORIES

The gain steps were calibrated to the following values:

Step	Power Received (-dbm)
0	95
1	85
2	75
3	65
4	60
5	55
6	50
7	42

For a given gain step and range, the reflectivity "Z" was determined from Luckenbach's echo intensity graph. (1, fig 8)*

The radar was operated 31 days between 15 May and 31 July 1962, to obtain the following information on thunderstorms that occurred within 100 statute miles of Lowry.

1. Elevation (ft msl) of echo top at gain step "O" (Obtained by viewing the RHI scope.)

2. Elevation of the maximum reflectivity, (ft msl).

3. Maximum reflectivity, Z_{max}.

4. Reflectivity at 20,000 ft msl, Z_{20}.

5. Reflectivity at 30,000 ft msl, Z_{30}.

6. Reflectivity at 40,000 ft msl, Z_{40}.

(Echo intensities were determined for items 2-6 by viewing the A/R scope.)

In addition to these measurements, a photographic record of echoes was made by photographing the off-center PPI scope with a 16 mm 0-22 camera.

Priority was given to measurements of thunderstorms occurring in the northeast quadrant, since this was the region in which the Colorado State University hail network was located. (2)

* Numbers refer to appended references.

The 3-cm set of Atmospherics, Inc. was operated to give the location and elevation of echo tops, and the corresponding location of maximum reflectivity near the ground surface. The strength of the signal returned from the low-level reflectivity maximum was estimated by noting the gain setting at which the echo was lost (just before it disappeared) on the PPI scope. Estimates of reflectivity were made from these data from a calibration procedure as described by Atlas and Mossop (3).

Measurements of echo tops were made by noting the range and elevation angle at which the echo disappeared on the PPI scope. Measurements of tops were made at full gain.

B. Field Verification

Verification of hail and severe weather was accomplished by assigning one man full-time to the task of making field surveys of storm damage in those regions in which the radar operator believed hail damage might have occurred. This field survey gave information on location, time, duration, size and depth of hail, as well as information on the motion of the storm path.

C. Classification of Hail Intensity

The information on hail occurrence as determined from field surveys was used to select corresponding reflectivity data to coincide in time and space with the hail event. Each of the events for which there was corresponding reflectivity data was classified according to each of the following criteria:

1. Air Weather Service intensity (1)

   VSTG - Heavy hail, probable tornado, funnel aloft, etc.

   STG - Heavy rain, scattered hail $\geq$ 3/4 inch, winds $\geq$ 50 knots.

   MOD - Moderate rain, sctd hail $<$ 3/4 inch, wind $<$ 50 knots.

   WK - Light to moderate precipitation, angels, etc.

2. Maximum stone size, inches.

3. Most common stone size, inches.

4. Computed $Z = \Sigma nd^6$, mm^6/m^3, computed for the most common stone size for the depth and duration of the storm as reported from the field survey.

5. Impact energy, E, ft-lbs per ft^2, estimated from the reports of most common hailstone size, depth, and attendant wind.

In addition to the information obtained from the field surveys, reports of hail and rain were obtained from a variety of sources in the CSU hail network. However, since all of these data were not completely reduced at the time of making this study, the verifications in this preliminary study confined to the data were obtained from the field surveys.

IV. RESULTS

A. Hail Intensity and Areal Extent of $Z > 10^3$, 10^4...

The areal extent of $Z \geq 10^3$, 10^4, 10^5, and 10^6 at 20, 30 and 40,000 ft msl was determined for cells corresponding to the position of the field surveys. The area covered (in square miles) was then plotted as a function of the intensity of hail for each intensity category described above.

The results (not reproduced here) do not indicate any clear relationship between the areal extent of $Z > 10^3$, 10^4... (as measured at a particular instant in time) and hail intensity as estimated by any of these parameters. (It is possible that a time-integration of the area covered over a larger period of time might be better related to hail intensity, but with the data collecting procedure used, sufficient photographic data were not available to permit such in integration.)

The results do indicate that higher values of reflectivity at any elevation are usually associated with more intense storms.

B. Reflectivity Profiles and Hail Intensity

Figure 1 shows the average log maximum Z values as a function of elevation for AWS category VSTG, STG, and MOD for reflectivity profiles corresponding with locations for which field damage survey data were available.

Figure 2 shows the same data as figure 1, except that the STG and VSTG categories were combined. These figures show little difference in log maximum Z value for 20 KFT, and greater difference for 30 and 40 KFT.

The average elevation of maximum reflectivity was at 18 KFT for the MOD category, and at 24 KFT for the STC and VSTG categories.

The average elevation of echo tops as measured on the RHI scope at step "0" was 40 KFT for STG and VSTG categories, and at 32 KFT for the MOD category.

There appears to be little difference between the reflectivity profiles of the STG and VSTG categories.

The significance of the difference in the average log maximum Z was tested with a "Students t" test (4, p 66-67). The results of the test are given in Table 1, page 8.

Table 1 shows no significant difference in sample means between STG vs VSTG cases. However, significant differences do exist between MOD and the other categories STG and VSTG (either singly or in combination) for echo tops at step "0" or for log Z_{30}.

Table 1 may be interpreted to indicate that it should be possible to differentiate between MOD vs strong cases of severe weather either from the RHI measurements of top at step "0", or from reflectivity measurements at 30 KFT.

The non-significance of log Z_{40} for all categories is probably due to the higher variability of reflectivity measurements at that level as noted by a high coefficient of variation, C_V, in Table 2, page 8. Table 2 gives the mean, standard deviation and coefficient of variation for the various parameters considered in the analysis.

C. Mean Reflectivity Profiles for all Storms

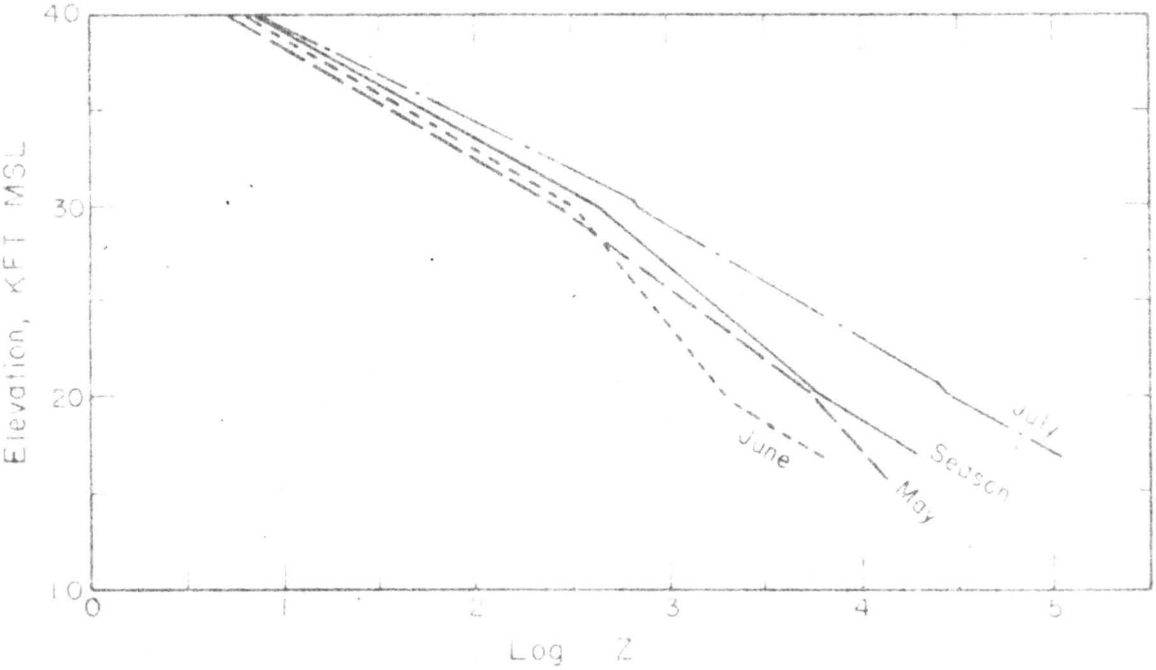
The mean reflectivity profiles for all storms for which reflectivity measurements were made are shown in Fig 3. (Reflectivity measurements taken on 26, 30 and 31 July were excluded, since weather modification experiments were conducted on these days.)

It should be noted that Fig 3 gives mean values for all thunderstorms, whereas Fig 1 and 2 are only for the maximum values observed concurrent with the times of hail occurrence, as determined from the field surveys.

D. Extending Results to Another Location (North or South)

Tests were made to determine whether or not a significant difference existed in the intensity of thunderstorms as a function of N-S distance. To accomplish these tests, data were used from the 3-cm set located at New Raymer, Colorado. (Location: 40° 36' N, 103° 51' W).

Echo tops (normal gain) and (relative) log Z values were classified on a function of (North-South) distance from the observing site at New Raymer, and the significance of differences in their frequency was tested, using a "students t" test (4, p 67). The results are shown in Table 3, page 9.



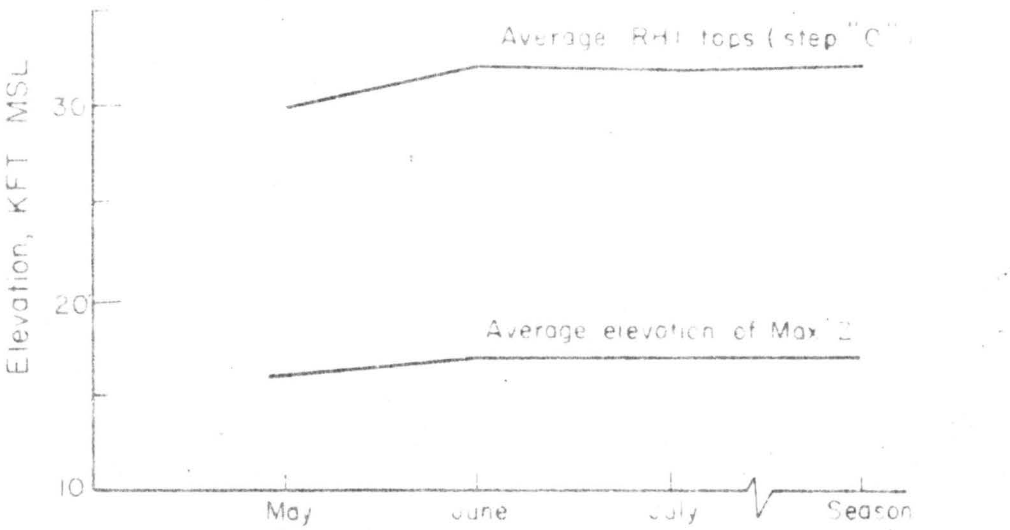


FIG. 3 MEAN REFLECTIVITY PROFILES FOR ALL STORMS
(26, 30, and 31 July excluded)

TABLE 1

Probability, P, in percent, of having larger "t" values by chance for degrees of freedom (D.F.) indicated

ITEM	VSTG vs STG		VSTG vs MOD		STG vs MOD		VSTG + STG vs MOD	
	P	DF	P	DF	P	DF	P	DF
RHI Echo Tops at Step "0", KFT	>90	10	1-2*	9	2-5*	9	<1**	15
Elev max Z, KFT	70-80	10	10-20	9	20-30	9	2-5*	15
Log Z max	80-90	10	40-50	9	40-50	9	20-30	15
Log Z_{20}	70-80	10	40-50	8	30-40	8	30-40	14
Log Z_{30}	60-70	10	2-5*	8	5-10	8	1-2*	14
Log Z_{40}	>90	10	30-40	7	40-50	7	30-40	13

* = Significant at 5% level
** = Significant at 01% level

TABLE 2

Mean, (M) number of cases (N), standard deviation (σ), and percent coefficient of variation (C_v) for various measures of thunderstorm reflectivity for storm categories indicated.

	RHI TOPS @STEP "0" KFT	Max Z ELEV KFT	Log Z_{max}	Log Z_{20}	Log Z_{30}	Log Z_{40}
VSTG						
M	40	24	5.1	4.9	4.9	3.4
N	6	6	6	6	6	6
σ	3.6	5.5	1.0	.8	.9	1.8
C_v	9	23	19	16	19	52
STG						
M	40	23	5.2	5.1	4.7	3.4
N	6	6	6	6	6	6
σ	1.8	4.6	1.1	1.0	.9	2.1
C_v	5	20	21	20	18	62
STG+ VSTG						
M	40	24	5.2	5.0	4.8	3.4
N	12	12	12	12	12	12
σ	4.6	4.9	1.0	.9	.9	1.9
C_v	12	20	19	18	18	56
MOD						
M	32	19	4.6	4.4	3.5	2.1
N	5	5	5	4	4	3
σ	4.7	5.7	1.2	1.4	.8	2.4
C_v	15	30	40	31	24	114

TABLE 3

Summary of results of "t" test for significance of differences in Log Z and echo tops for cells which occurred in various range categories (North vs South) from New Raymer, Colorado:

RANGE, N. M.	ITEM	PERIOD	PROB %	DF
20 - 40	Log Z	Season	70-80	70
40 - 80	Log Z	Season	80-90	38
> 80	Log Z	Season	40-50	3
All > 20	Log Z	Season	30-40	115
All > 40	Log Z	June	5-10	32
All > 40	Log Z	July	5-10	9
20 - 40	Echo Tops	Season	70-80	73
40 - 80	Echo Tops	Season	20-30	39
> 80	Echo Tops	Season	10-20	2
All > 20	Echo Tops	Season	30-40	118
All > 40	Echo Tops	June	50-60	32
All > 40	Echo Tops	July	10-20	9

From the data of Table 3 it may be concluded that there is no significant difference in the intensity of thunderstorms as a function North-South distance from the observing site, up to at least about 80 nautical miles.

V. DISCUSSION OF RESULTS

The lack of a clear relationship between areal extent of reflectivity $\geq 10^3$, 10^4... and hail intensity suggests that the size of precipitation cells of a given intensity is not necessarily related to the intensity of hail. A better relation between hail intensity and areal extent of reflectivity $> 10^3$, 10^4... was noted for July than for May and June. One possible explanation for this might be that cells tend to be more isolated in July than earlier in the season, and hence attenuation would be less of a problem in July than earlier.

Figures 1 and 2 indicate larger differences in reflectivity at 30 and 40 KFT than at 20 KFT. However, the significance tests summarized in Table 1 indicate that the differences are significant only at the 30 KFT level. Since the elevation of maximum reflectivity is at about 20 KFT, it would seem reasonable to adopt an operational procedure whereby a scan is made for echoes at 20KFT, and once an echo was observed at that level, to categorize the intensity of the storm by measurements of reflectivity at 30 KFT and measurements of echo top (RHI, Step "O"). This is the recommended operational procedure, as given in the appendix.

The mean reflectivity profiles shown in Figure 3 are for all storms, regardless of intensity. Further study will be made to categorize these by hail intensity, and to determine whether significant difference in reflectivity profiles exist for the various categories.

From the tests summarized in Table 3, it would appear reasonable to use data from Colorado as a first approximation for stations within several hundred miles north or south of 40^0 N latitude.

VI. SUMMARY

No clear relationship was found between hail intensity and areal extent of $Z \geq 10^3$, 10^4... A better relationship was observed for July than for May or June, which suggests that attenuation may be a problem early in the thunderstorm season.

The best parameters for differentiating between moderate hail intensity and more severe hail appear to be the echo top (at step "O" as measured on the RHI scope), and reflectivity at 30 KFT.

These results are considered applicable, within at least 80 nautical miles and probably within several hundred miles north or south of Denver.

The thunderstorm is a complex mechanism and it should not be anticipated that the intensity of a given storm can be described with complete accuracy by any single parameter. For this reason, operational procedures should be based on appropriate limits above which severe weather can possibly be expected (an "alert" level) and appropriate limits above which severe weather can probably be expected (an "alarm" level).

VII. RECOMMENDATIONS

It is recommended that Air Weather Service adopt the following procedure for reporting reflectivity data:

1. Use units of log Z in reporting data - under this system $Z = 10^3$ would be equivalent to a log Z of 3, $Z = 10^5 = 5$, etc.

2. Adopt the procedure recommended by Donaldson (5) for "alert" and "alarm" thresholds, using $\log Z > 3$ and $\log Z > 5$ at 30 KFT, respectively for summer thunderstorms.

3. "Alert" and "alarm" limits may also be defined by RHI echo tops of 30 and 40 KFT respectively at gain step "0" in the vicinity of Colorado.

VIII. REFERENCES

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IX. ACKNOWLEDGEMENTS

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The 0-22 camera used on the CPS-9 was loaned to Colorado State University from the U. S. Weather Bureau.

RECOMMENDED TENTATIVE PROCEDURE FOR USE OF STEP-GAIN SYSTEM FOR CLASSIFYING THE PROBABLE INTENSITY OF THUNDERSTORMS.

A. Determine range of cell (statute miles) and select appropriate elevation angle to scan at 20,000 ft msl.

ELEVATION ANGLE REQUIRED TO GIVE VARIOUS HEIGHTS.

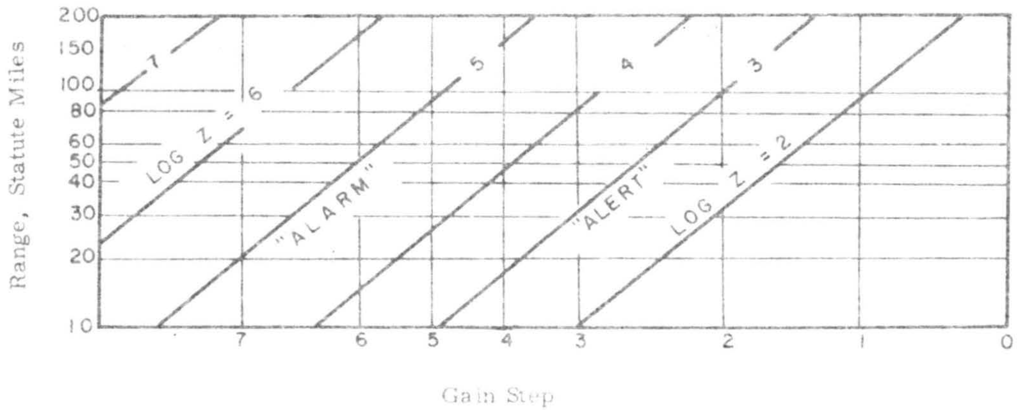
Height ft msl	RANGE, STATUTE MILES.																						
	20	30	40	50	60	70	80	90	100	110	120	130	140	150	160	170	180	190	200	210	220	230	240	25
20,000	8.0	5.1	3.8	2.8	2.3	1.9	1.6	1.3	1.1	0.8	0.7	0.5	0.4	0.3	0.2									
30,000	13.5	8.7	6.5	5.0	4.2	3.4	2.9	2.5	2.2	1.8	1.6	1.3	1.2	0.9	0.8	0.7	0.5	0.4	0.3	0.2	0.1			

Valid for Lowry A. F. B. only (Elev. 5500 ft. msl)

B. Stop antenna rotation at the appropriate azimuth to give maximum return from cell on A/R scope.

C. Step through gain-reduction steps and note the step at which the echo disappears on the A/R scope.

D. From the graph below, determine log Z. If > 3, adjust elevation angle to scan cell at 30,000 ft msl and repeat steps B and C above.



E. Make an RHI scan through the azimuth of maximum return at 30,000 ft msl at gain step "O" and note the echo top.

F. Interpret as follows:

Log Z (and/or)	RHI top (KFT msl)	Condition	Probable Weather
3	30	"Alert"	Hail Possible
5	40	"Alarm"	Hail and/or damaging wind probable.