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(10) Carlton L. Bjerkaas
Ralph J. Donaldson, Jr.

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In April to June 1977, an operational test was conducted in Oklahoma utilizing Doppler radar as the basis for real-time warning of severe weather. The Air Force Geophysics Laboratory color display was mated to the 10 cm Cimarron Doppler radar and used as warning back-up capability to the operations center at Norman. Experiences in real-time identification of mesocyclone signatures which are characteristic of severe weather are discussed. A detailed analysis of parameters associated with one tornadic →

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mesocyclone is presented. A comparison is made between parameter values determined from the color display and from fine resolution digitized data.

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REAL TIME TORNADO WARNING UTILIZING DOPPLER VELOCITIES FROM A COLOR DISPLAY

Carlton L. Bjerkaas and Ralph J. Donaldson, Jr.
Air Force Geophysics Laboratory
Hanscom AFB, MA 01731

1. INTRODUCTION

Flow fields inside severe convective storms have been examined for several years by the meteorological research community utilizing Doppler radar (e.g. Donaldson et al., 1969, Brown et al., 1971). Doppler velocities in tornadic storms have always indicated a mesocyclone vortex signature. In spite of the inability of a single Doppler radar to provide sufficient information for the unambiguous identification of such a vortex, Donaldson (1970) set forth a set of criteria for the elimination of the likelihood of alternate interpretations. These vortex recognition rules have been verified by dual-Doppler measurements by Brown et al. (1975) and have been refined and operationally organized by Burgess (1976).

Burgess identified 37 mesocyclones in post-analysis of a five-year period of Doppler radar observations at the National Severe Storms Laboratory (NSSL). All but two were associated with damaging wind or hail and 23 (62%) with reported tornadoes. No verified tornado occurred during the five-year period unless preceded by a mesocyclone signature. The signature was identified on an average of 36 minutes before tornado occurrence. Brown and Lemon (1976) identified a special subset of mesocyclone vortices, the tornadic vortex signature (TVS), having a horizontal scale on the order of 1 km and measured shear near 0.1 sec^{-1}. Of the 9 instances of TVS observed with NSSL radars through 1975, 7 were associated with tornadoes or funnel clouds.

2. AN OPERATIONAL TEST AND PRELIMINARY RESULTS

Doppler radar, on the basis of current research results, has earned a recommendation as a significant tool for improvement of severe storm and tornado warning. Both the Air Weather Service (AWS) and the National Weather Service (NWS) are planning replacement and upgrade of their current operational radars and both services are aware of the excellent reputation of Doppler radar techniques. However, Doppler capability and the data processing suggested by velocity measurement has higher financial costs than the conventional radar techniques which deal only with reflectivity. Consequently, the two weather services, in cooperation with NSSL and AFGL, are sponsoring an operational test to determine the usefulness of Doppler radar in real-time warning of severe thunderstorm hazards.

The first phase of the two year test was conducted during the spring of 1977 at Norman, Oklahoma, using NSSL's 10 cm Doppler radar. AFGL's observations were made from the second NSSL Doppler radar located near Cimarron Airport, about 40 km northwest of Norman. We connected our pulse pair processor, analog tape-recording system and color display (described by Jagodnik et al., 1975) to the data output stream of the Cimarron radar. In addition to archiving data for subsequent analysis, it was our mission to provide back-up warning capability during the test for the Norman radar when storms were lost in its ground clutter and during the times when the Norman radar was engaged in other missions.

Preliminary test results (Burgess et al., 1977) indicate that Doppler radar technology convincingly proved its worth in meeting the challenge of the real-time warning environment. Over 30 mesocyclone signatures were detected including several in Texas. Of those detected in Oklahoma during the time when the warning team had operational control of the radar, there was an average tornado warning time of 23 minutes versus less than a minute lead time for warnings put out by WSFO, Oklahoma City with no Doppler data input. As an illustration of the Doppler radar capability, we provide a discussion of one of the mesocyclones observed during a tornado outbreak.

3. THE NORMAN MESOCYCLONE

During the afternoon and evening hours of 20 May 1977, tornado reports were numerous in central and southwestern Oklahoma and adjacent areas of Texas. Many separate occurrences of severe wind damage, hail, flash floods and extremely active lightning accompanied the tornado outbreak. The earliest of the Oklahoma tornadoes inflicted multimillion dollar damage to Altus Air Force Base. Twenty-four minutes prior to the damage, the AWS-NWS Doppler Forecasting Team (Capt. Dave Bonewitz, AWS and Don DeVore, NWS) identified a mesocyclone approaching the Altus area and initiated a warning to the Base weather station.

One of the more interesting events of the day was a mesocyclone which passed over Norman, with a rotating cloud base and funnel cloud in clear view of several NSSL personnel. The mesocyclone threatened Tinker Air Force Base with the initial tornadic damage occurring just a few kilometers west of the Base. The mesocyclone exhibited several interesting features, one of which was the splitting of the mesocyclone into two parts which co-existed for a few minutes. The two parts produced two simultaneous tornadoes, before the old part died as its tornado dissipated. The new part of the mesocyclone continued to exist for several minutes. The event was very photogenically portrayed on our color display. Four photographs of the color display are exhibited as examples.

Plate 1 shows the reflectivity (top) and mean velocity (bottom) displays for 1844 CST. The small mesocyclone is located at 106° azimuth and 35 km. Each range ring on the display represents 32 km. The elevation angle was 1.8°. Velocities can be converted to m s^{-1} by noting that black, the center color, represents +2 m s^{-1} to -2 m s^{-1} with each color block representing 5 m s^{-1} increments. The maximum unambiguous velocity is 35 m s^{-1}. Positive velocities are to the top of the display. Reflectivity values can be converted to dbZ by subtracting 57.2 from the color display values. Each color block here represents a 5 dbZ interval. Reflectivity values less than 50 on the display are really wraparound values so 100 must be added to give the correct values, e.g. yellow represents values of 120 to 150 (63 to 93 dbZ), not 20 to 50 (-37 to -7 dbZ). The reflectivity values are range normalized. The hook echo appears at a high reflectivity level. It was noted during the test that the reflectivity value delineating the hook echo varied with time. Thus the incremental reflectivity value display was mandatory for easy identification of the hook echo. Note the location of the hook echo relative to the mesocyclone location.

Plate 2 shows the mean velocity displays during later stages of mesocyclone development. Phenomena shown in these photographs will be discussed later.

The process for mesocyclone vortex recognition involves several steps as summarized below. These were used in our analysis scheme as well as in real time during the test.

1. A velocity couplet had to be identified by closed constant velocity contours (isodops) with adjacent maxima of different signs (positive velocity is outbound radial velocity) with the maximum at the more clockwise azimuth angle.

2. The angle between the two velocity extrema needed to be less than 45° with a zero degree angle meaning the extrema was at the same range and representing zero divergence. If the positive velocity center was at a further range than the negative velocity center, a divergence component would be indicated. The opposite case would represent a convergence component. Examples of divergent and convergent structures are shown in Plate 2.

3. A vertical continuity was required which was at least equal to 50% of the horizontal separation of the velocity extrema with an absolute minimum vertical extent of 3 km.

4. The final step was a time persistence scale equal to half the period required for vortex revolution, i.e. $\tau p = \frac{\pi D}{\Delta V}$, where D is the distance between the velocity maxima and ΔV is the velocity difference between the velocity peaks. For example, if the diameter of the mesocyclone was 4 km and ΔV was 40 m s^{-1}, τp would be 5.2 minutes. For a TVS, with a diameter of 1 km and a ΔV of 70 m s^{-1}, τp would be 45 seconds. Generally this step was satisfied by the time the vertical extent of the mesocyclone was sampled in sector mode.

For our analysis based on color display data (discussed by Kraus <u>et</u> <u>al</u>., 1977) we measured distances to the nearest kilometer and the velocity to the nearest 5 m s^{-1}, which was the approximate interval between velocity contours of the Cimarron radar (wavelength, 10.9 cm and PRF, 1302) used in these measurements. From every elevation tilt sequence (1° elevation steps) in which a vortex signature could be identified, the following information was extracted: (1) the velocity difference across the vortex couplet (ΔV), (2) the minimum vortex diameter (D), which was the distance between the velocity extrema, (3) the level of zero divergence (LZD) and (4) the altitude of all these features. After data extraction, the maximum tangential shear in the region of zero divergence was calculated. For a symmetrical vortex this value was approximately half the vorticity. In the computer analysis scheme the same parameters were identified. However, the velocities were measured to the nearest m s^{-1}, the range distances to the nearest 150 m (1 μs) and the azimuthal distances to the nearest 0.1° (200 m at the maximum range of 115 km).

4. COMPARISON OF COLOR DISPLAY AND DIGITAL DATA

The following table lists the comparisons of the results of the two analyses--color display versus digital data. The digital data is indicated by parentheses and is shown only when it differs from color display values. The differences in velocity are what one would expect. Since color display velocity could be read to the nearest 5 m s^{-1} and since ΔV involves two such values the errors could be up to ±10 m s^{-1}. However, most of the values should be considerably less. The values ranged from -11 to +10 with an average difference of 0.2 m s^{-1}.

The largest variation in comparing color display and digital values was in determining the minimum diameter which directly affected the maximum shear values. The most notable variation occurred when the diameter was near 1 km as seen by the color display. As discussed earlier the digital distance values could be read to the nearest tenth of a km versus the nearest kilometer for the color display. For small values of D this resulted in a 50 to 60% decrease in D and, combined with a slight increase in ΔV, produced doubling or tripling of the shear values.

5. DISCUSSION

A comparison of the tornado occurrence times with the tabular values of the <u>minimum</u> height above ground of the parameters ΔV, D, LZD was made. Values of ΔV max varied over a narrow range of values 35-60 m s^{-1}. However, the maximum velocity difference (ΔV_{max}) was located nearly always within a kilometer of the ground while a tornado was occurring, having descended from altitudes of 3-5 kilometers in the initial stages of mesocyclone

Table: Low-Altitude Features of the "Norman" Mesocyclone. The data are from the color display, except those in parenthesis which are extracted from digital maps. Digital results are shown only when they differ from color display values.

Time CST	Av.(max) m s^{-1}	Min Height km	D(min) km	Min Height km	Div = 0 Min Height km	Shear (max) s^{-1} x 10^{-2}
Old part: tornado 1840 - 1907						
1756	45(39)	3.0	5(3.6)	3.0	0.9	0.5(0.6)
1804	40	4.9	3	1.7	0.9	1.2
1811	45(44)	2.6	4	2.1	2.6	1.1
1818	35	0.8	4(3.6)	0.8	2.0	0.8(1.0)
1826	35(38)	0.8	6(5.0)	0.8	1.6	~0.6(0.8)
1832	55(45)	1.3	3(4.8)	1.3	1.3	1.8(0.9)
1838	50(52)	0.7	4	1.3	1.9	1.0(1.1)
1844	55	1.3	1	0.1	0.1	4.5
1850	60(59)	0.7	2(1.6)	0.7	0.1	3.0(3.7)
1855*	50(52)	0.1	2(1.6)	0.1(0.7)	0.1	2.5(3.2)
1858	50(61)	0.8	1(0.4)	0.8	0.8	5.0(15.5)
1904*	40(46)	0.1	1(0.5)	0.1	0.1	4.0(10.1)
1909	40	0.1	<1	0.1	0.1	>4.0
New part: tornado 1911 - 1926						
1855*	60	0.1	4	0.1	>2	<1.5
1858	50(45)	2.0	2(1.5)	2.9	1.5	1.5(1.8)
1908*	55	1.9	2.5	1.9	1.9	2.2
1909	55(47)	0.9	<1(0.6)	0.2	0.2	>4.5(7.2)
1918	50(57)	0.2	4(2.9)	0.2	1.2	1.1(2.0)
1926	60	0.3	4	0.3	0.3	1.5
1934	50	0.3	4	3.9	1.6	0.7
1942	40(38)	0.4	4(1.5)	3.0(1.7)	>1 (0.4)	0.8(2.3)

*incomplete tilt sequence

development. The minimum vortex diameter, D, showed good correspondence with tornado occurrence, especially in the first tornado. Shear values increased basically in response to the shrinking of the vortex diameter. Vortex diameters of 1 km or less had shears and dimensions identical to the TVS discussed by Brown and Lemon (1976).

Tornado occurrence was also well correlated with the minimum height above ground of the smallest vortex diameter. The smallest vortex diameter was never near the ground except during and within two minutes of tornadoes. At higher altitudes the mesocyclone had a larger diameter, which was consistent with the concept of the term "funnel cloud." The approach of the level of zero divergence height to the ground was also an excellent indication of a tornado in progress. Before tornado occurrence the pattern of velocities suggested low-level convergence and strong upper-level divergence with the level of zero divergence near 3-5 km.

Forecasters will be interested to note that the earliest recognizable mesocyclone signature occurred 44 minutes prior to the touchdown of the tornado. From the first appearance of the new part of the mesocyclone until its tornado touchdown there was only 16 minutes. Also, the first tornado took a 30° turn to the left with the new part of the mesocyclone appeared on its right.

Comparison of data values extracted from the color display and digital data shows no unexpected results. The color display data permits identification of the mesocyclone vortex within sufficient accuracy for real-time warning purposes. However, if the velocity data is to be used for straight line wind warning or wind shear warning in an operational scenario, the finer resolution of the digital data is vital for the reduction of false alarms and the elimination of possible missed mission successes. The need to digest the enormous amounts of data available from the Doppler radar requires a processing device (mini-computer) dedicated to this purpose. Even with the resultant processed data, a forecaster needs a concisely summarized parameter list to adequately utilize the information for warning purposes. As Doppler radars approach the stage of operational deployment, the need for new procedures and methods of summarizing and using the data becomes of paramount importance and provides exciting opportunities for applying new and innovative ideas.

6. ACKNOWLEDGEMENTS

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20 May. We also thank June Queijo for typing our manuscript in spite of the penmanship. However, most of all, we wish to acknowledge the truly outstanding performance of our technician colleague, Bill Smith, who kept the AFGL equipment operational in spite of minor flooding, power surges and lightning strikes. Without Bill's dedication none of this spectacular data could have been gathered for analysis--a job well done.

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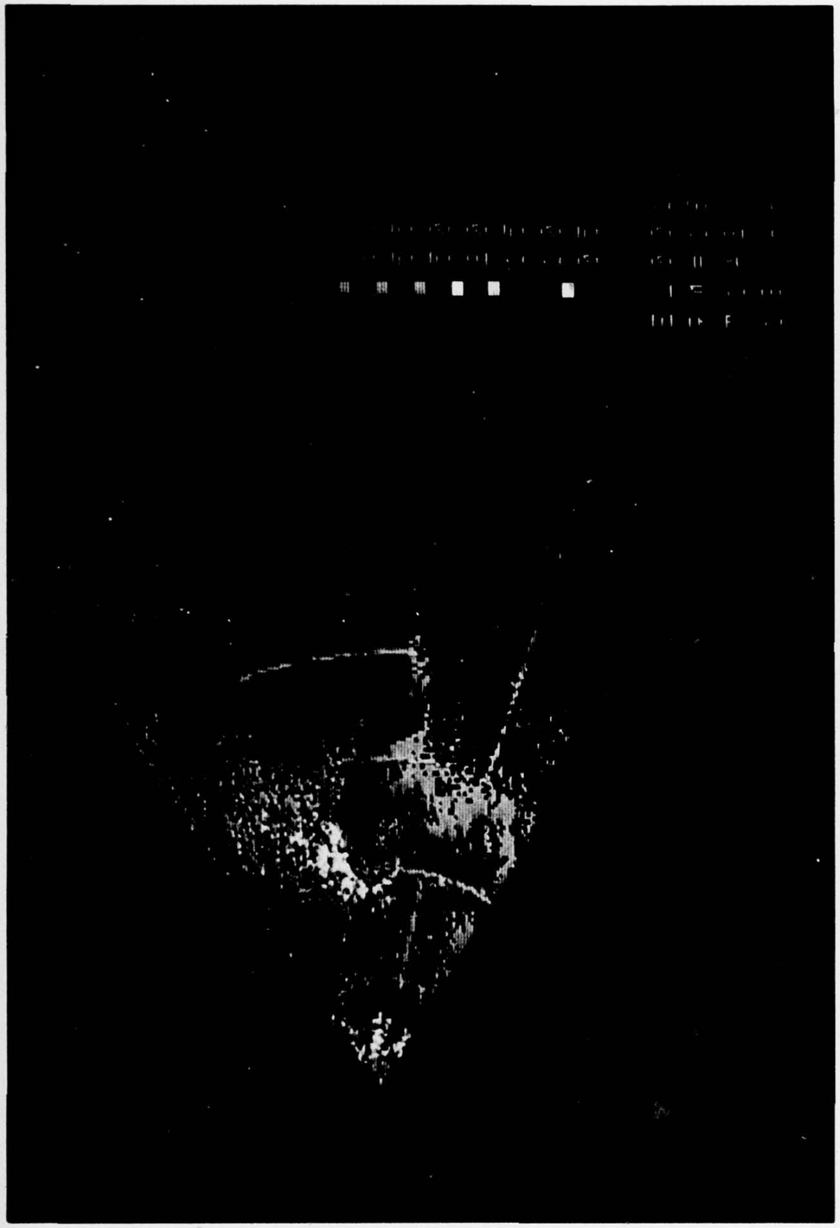

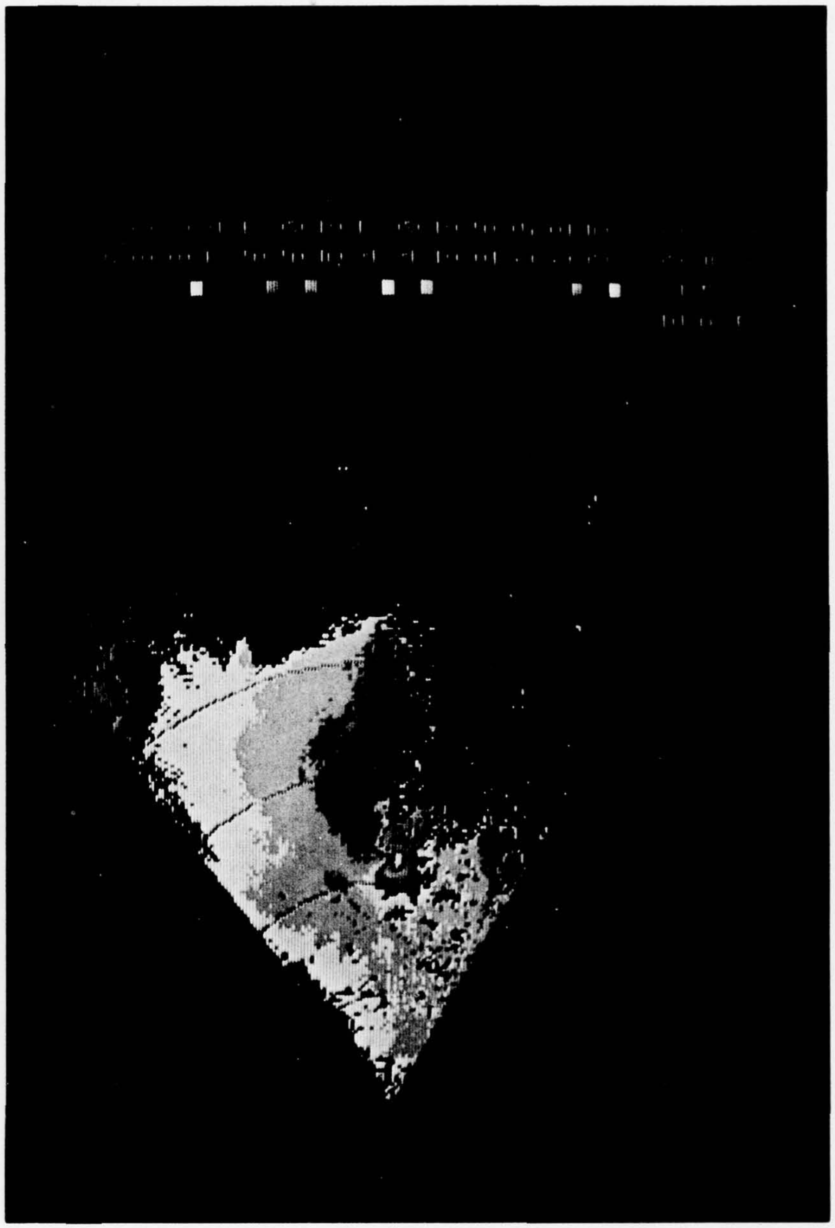

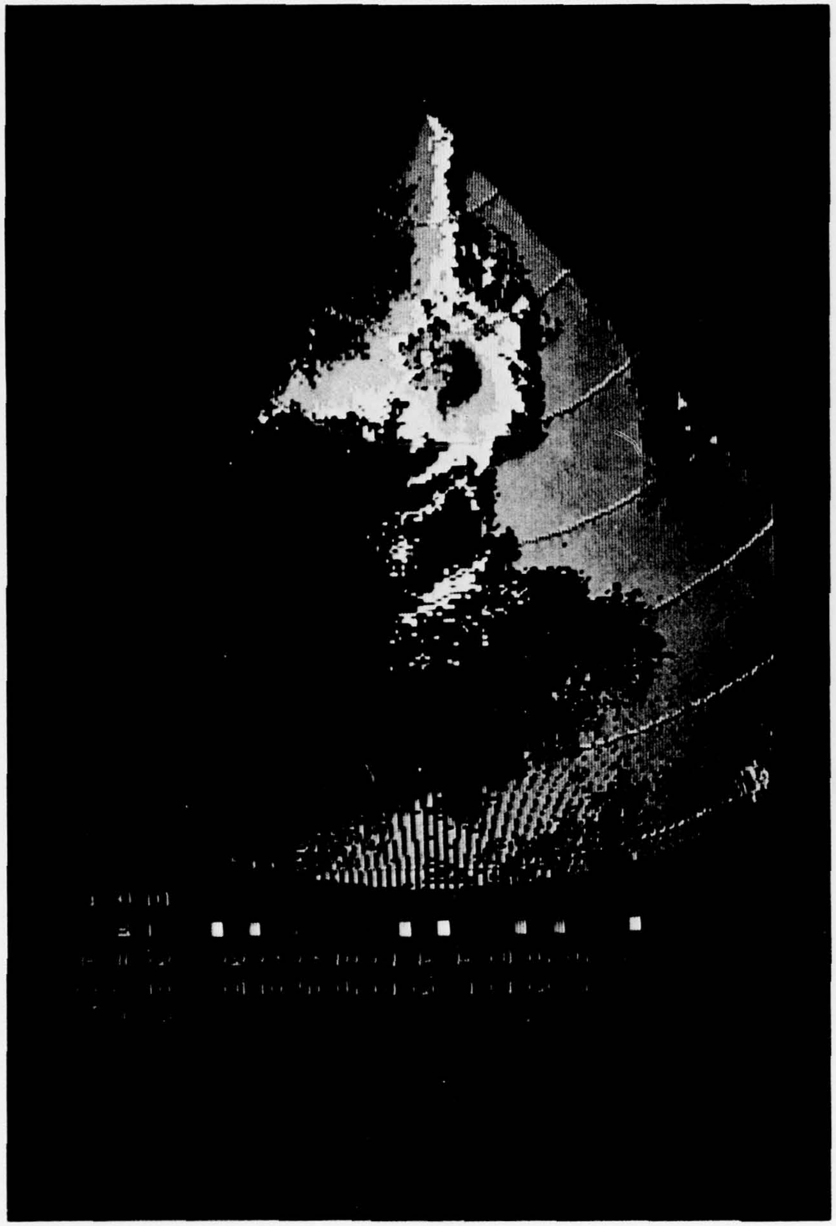

USE OF MANUALLY DIGITIZED RADAR DATA IN FORECASTING PRECIPITATION AND FLASH FLOODS

Frank Lewis

Management and Technical Services Company/G.E.
Beltsville, Maryland 20705

Paul L. Moore

Southern Region Headquarters
National Weather Service, NOAA
Fort Worth, Texas 76102

Dale A. Lowry

Techniques Development Laboratory
National Weather Service, NOAA
Silver Spring, Maryland 20910

1. INTRODUCTION

The National Weather Service's (NWS's) system for Automation of Field Operations and Services (AFOS) will speed up the receipt and handling of weather data at forecast offices. It will also permit automatic processing of data that is not feasible at present. We have conducted several sets of experiments to test proposed uses of Manually Digitized Radar (MDR) data in the AFOS mini-computers at forecast offices. The first application would use the latest MDR data to update Probability-of-Precipitation (PoP) forecasts; the second would alert forecasters to threats of flash floods.

2. UPDATING POP FORECASTS

In a paper, "Updating of Numerical Precipitation Guidance," Paul L. Moore and Daniel L. Smith (1972) presented equations that improved the PoP forecasts for Atlanta, Jackson and Birmingham. The predictors they used were the Model Output Statistics (MOS) PoP forecasts based on the 00Z (and 12Z) NMC model outputs and subsequent 09Z (and 21Z) MDR values. The equations they obtained, each applicable to all three stations, contained combined predictors representing MDR values at 1, 9 and 25 squares with the same displacements from each of the three stations respectively.

We attempted to extend the work to five stations scheduled for early introduction into the AFOS system. These are Philadelphia, Washington, Richmond, Norfolk and Roanoke. We developed several sets of predictors covering a large vicinity of the stations, using combinations of squares as well as individual squares. We submitted the data for the period October 1973 through September 1975 to regression programs, stratifying variously by:

- Warm season and cold season
- Daytime and Nighttime
- Individual Stations
- Combinations of Stations

From the large number of regressions obtained the best were selected (on the basis of reductions of variance) and tested on independent data. These data were from the period October 1975 through May 1976. Although the test sample was small, the results were clear enough. Most of the equations failed to improve on the MOS PoP forecasts on the test data. The improvements obtained could not be considered reliable.

Moore and Smith had proposed in their paper, mentioned above, that projected positions of echo patterns be used as predictors and Dan Smith had written a pattern-tracking program to develop these predictors. However, the MDR-data archive contained too many missing values to permit the development of an even marginally adequate data set for such an application.

Was our procedure at fault in failing to obtain acceptable regressions for our five stations, considering the success of Moore and Smith at Atlanta, Jackson and Birmingham? To resolve this question we first tested the Moore-Smith equations on our archive (at the Techniques Development Laboratory of NWS), using data from November 1, 1973 through March 15, 1976. The results showed that their equations do indeed improve the MOS PoP forecasts for Atlanta and Jackson but not for Birmingham, at least on that sample.

We, therefore, developed and tested three pairs of regression equations. Each equation applied to all three of the cities and each pair comprised one equation for the daytime forecast period and one for the nighttime forecast period. In each case the MOS PoP forecast was forced to