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AN OPERATIONAL DIFFERENTIAL REFLECTIVITY PRODUCT FOR HAIL IDENTIFICATION AT PROFS

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1. INTRODUCTION

During the 1985 convective season, the Program for Regional Observing and Forecasting Services (PROFS) conducted a real-time mesoscale forecasting exercise using an integrated weather information processing and display system (Haugen, 1986). One goal of this exercise was to evaluate the utility of numerous meteorological data products and display techniques in mesoscale nowcasting and short-term (0-2 hour) convective forecasting. Among the new products developed for this system was a Precipitation Type/Intensity (PTI) product, intended to differentiate hail from rain and to estimate rainfall intensity and hail size. This product is derived from a combinination of differential reflectivity (Z_{DR}) and reflectivity factor data collected by an S-band (10-cm) radar.

While numerous studies have dealt with the relationship between conventional radar reflectivity factor and precipitation intensity (Doviak and Zrnic', 1984), single scan reflectivity factor data alone are insufficient to differentiate hail from rain (Dye and Martner, 1978; Richardson et al., 1983). One approach to identifying precipitation type with radar is to infer hail probability from storm structure characteristics computed from volume scan reflectivity factor data (Petrocchi, 1982; Smart and Alberty, 1984). This method is being implemented in the NEXRAD system. Another volume scan technique is based on calculations of vertically integrated liquid water (VIL), from which climatological estimates of severe weather probability (SWP) are derived (Saffle and Elvander, 1981). A third, more direct method, which has received much attention in recent years, uses so-called differential reflectivity, computed from the returns from pairs of vertically and horizontally polarized pulses (Seliga and Bringi, 1976).

The basis of the differential reflectivity method is the fact that raindrops fall as flattened, or oblate, spheroids, while hailstones are more irregularly shaped and tumble as they fall. Because reflectivity is related to the diameter of the particle in the direction of polarization, at low radar elevation angles, rain will exhibit relatively larger effective radar reflectivities for horizontally polarized radar waves than for vertically polarized. Distributed hail targets, on the other hand, will show little reflectivity difference between the two polarizations. In decibels, this difference in the signals is expressed as

$$Z_{DR} = 10 \operatorname{Log}_{10} (Z_H / Z_V) \qquad (1)$$

where Z_H and Z_V are the effective radar reflectivity factors for horizontally and vertically polarized pulses, respectively. For rain, Z_{DR} is positive and relatively large (1 to 4 dB), while for hail Z_{DR} is normally near zero (Bringi et al., 1984).

The PTI product presented in this paper uses Z_{DR} to differentiate hail from rain, and Z_H to qualitatively characterize the rain intensity or hail size. In the first part of this paper we describe the formulation of the PTI product. In the remainder, we describe three cases, collected during the 1985 exercise, in which PTI produced correct hail indications. In addition to illustrating the use of PTI for identifying hailstorms, this latter portion of the paper describes the mesoscale characteristics of these cases, as observed by PROFS forecasters and storm chase teams.

2. RADAR CHARACTERISTICS

The CP-2 Doppler radar, operated by the National Center for Atmospheric Research (NCAR), was available to PROFS for the 1985 convective season. CP-2 is a dual-polarization, dual-wavelength (S- and X-band) Doppler radar with a 1° beam width (Carbone et al., 1982). For the PROFS exercise, the radar was operated with a gate spacing of 300 m and a maximum range of about 150 km. During periods of convective activity, a twelve-tilt volume scan sequence covered elevation angles between 0.2° and 13° every five minutes. To observe hail signatures as close to the ground as possible, the lowest scan (0.2°) was set up for the S-band differential reflec-

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tivity measurements from which the PTI images were generated. (At a range of 150 km, a 0.2° elevation beam is about 1.8 km above the ground.

3. THE PRECIPITATION TYPE/INTENSITY PRODUCT

As indicated earlier, Z_{DR} is dependent on hydrometeor shape and orientation. While distributed hail targets have no preferred shape or orientation, raindrops do fall with a preferred orientation, and their shape is dependent on size. Thus, a strong correlation between Z_{DR} an Z_H for rain can be expected. By plotting Z_{DR} against Z_H for numerous rain cases, Leitao and Watson (1984) identified a well-defined region in the Z_{DR} - Z_H plane in which rain data were found The boundary of this region is indicated by the solid curve in Figure 1; observations outside the rain area are most likely to be from hail. A similar Z_{DR} - Z_H pattern was reported by Aydin et al. (1985), shown by the dashed line in Figure 1. In that study, Z_{DR} and Z_H were estimated from drop size distributions obtained from disdrometer data, rather than from direct radar measurements.

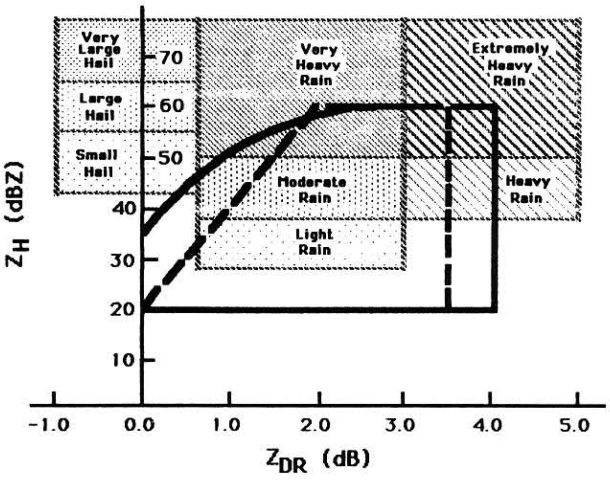

Figure 1. The eight precipitation type/intensity categories for PROFS PTI product as a function of Z_{DR} and Z_H. Solid curve is rain/hail boundary given by Leitao and Watson (1984); dashed, by Aydin et al. (1985).

For the PROFS PTI product, Z_{DR} and Z_H information are merged into a single PPI-format image with eight qualitative precipitation categories: "light" to "extremely heavy" rain, and "small", "large", and "very large" hail, as shown in Figure 1. The images are quite clean since ground clutter returns, out-of-bounds Z_{DR} values and data below a minimum precipitation signal threshold do not appear.

While our intention was to approximate the rain/hail boundary curves shown in Figure 1, limitations in the processing system forced us to use a constant Z_{DR} threshold (0.6 dB) to discriminate hail. The hail size categories were then created with the simplifying assumption that larger hail is associated with higher reflectivity. When Z_{DR} is less than 0.6 dB, PTI indicates "small" hail if Z_H is 43 to 54 dBZ; "large" hail, 55 to 66 dBZ and "very large" hail, 67 to 78 dBZ. These categories were selected heuristically, but with the intent that the "large" category be an indicator of severe weather (>3/4" hail). The choice of 55 dBZ as the reflectivity factor threshold for the "large" category is supported by the study of Colorado hailstorms by Dye and Martner (1978).

The rain categories were also chosen qualitatively. Although, as Seliga and Bringi (1976) have shown, the combination of Z_{DR} and Z_H can be used to achieve better quantitative estimates of rainfall rate than the traditional Z-R relations, such quantitative techniques were not possible in our 1985 system. Hence, the five rain categories we defined simply progress in intensity for increasing Z_{DR} (bigger drops) and increasing Z_H (more and/or bigger drops).

4. ILLUSTRATIVE CASES

On most storm days during the 1985 exercise, PROFS chase team vehicles were vectored to intense storms to gather forecast verification data. Numerous cases in which PTI correctly indicated hail were thereby documented. In this section, we describe one of these cases (14 July 1985) in detail, including observations of the chase teams and the PROFS workstation forecasters. We also present the highlights of two other cases.

4.1 <u>14 July 1985</u>

Analysis of the morning data found features common to high plains, severe thunderstorm episodes (Doswell, 1982). Chief among these features was the passage of a cool front through the northern half of Colorado during the morning. The frontal passage left the PROFS region in low-level easterly flow which, in northeast Colorado, is upslope and tends to advect moist air westward to the Front Range of the Rocky Mountains.

The 1200 GMT Denver sounding (Fig. 2) was taken before frontal passage. However, the front did not affect the troposphere above the boundary layer, and upper level thermodynamic parameters were not expected to change appreciably throughout the day since the flow aloft was weak.

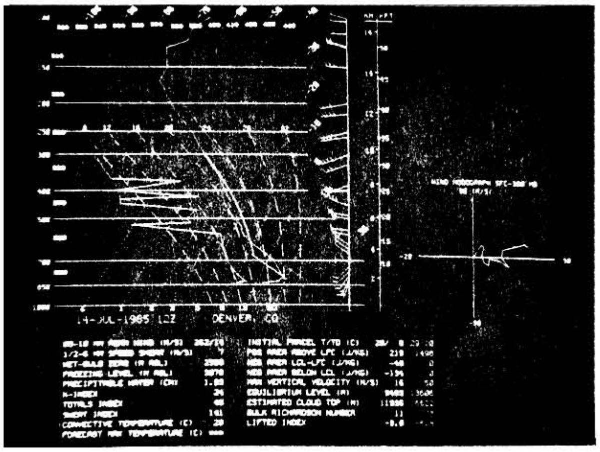

Figure 2. Plot and analysis of Denver rawinsonde data for 1200 GMT, 14 July 1985. See text for pertinent features.

As shown in Figure 2, PROFS' interactive sounding analysis routine predicted a very unstable airmass, with a Lifted Index of -6.4 and positive buoyancy of 1498 Jkg^{-1}, based on an expected afternoon temperature of 29°C and a mixed dewpoint of 10°C. In their 1830 GMT convective outlook, the exercise forecasters mentioned the front, the airmass instability, and the weak upper tropospheric dynamics.

Throughout the early afternoon convective storms were of a short-lived, multicellular character. However, about 2100 GMT a cell which formed in Larimer County grew steadily in both size and reflectivity. By 2140 GMT it was clear that the cell was more organized and stronger than earlier storms. A chase team positioned about 75 km to the southeast in southern Weld County was sent to intercept the storm.

As the chase team traveled north, both the reflectivity and PTI images were monitored closely for any signs of change in storm intensity. By 2230 GMT, the storm had reflectivity approaching 60 dBZ and had the first indications of "large" hail in the PTI data (cell A, Fig. 3).

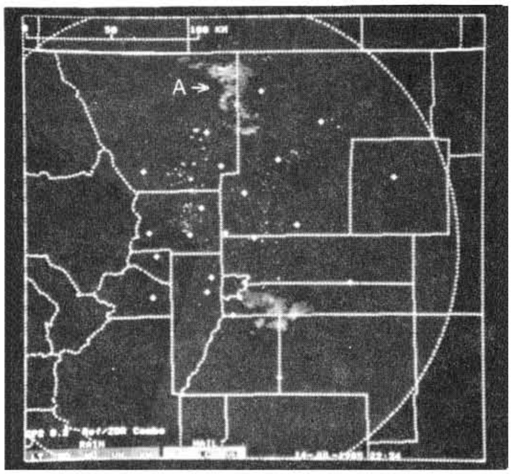

Figure 3. PTI for 2234 GMT, 14 July 1985. Radius of coverage is 150 km; Denver is small county near center. Storm "A" contains first indications of hail at this time.

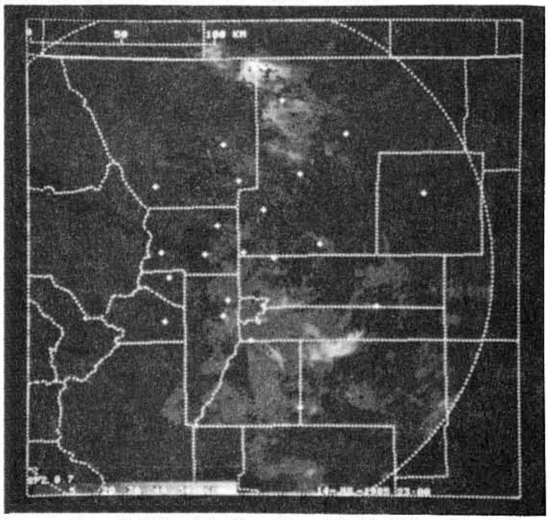

Figure 4. Reflectivity for 2300 GMT, 14 July 1985.

Shortly thereafter the team caught first sight of the storm. The following is from the chase team debriefing transcript:

> "We neared the cloud from the south... The precipitation shaft was concentrated in one mass with a solid delineation to the front and rear edges. The lightning activity was quite frequent, with numerous cloud to ground strikes... A classic flanking line became apparent. It contained large towers and was shearing into the storm from the southwest... The convective base was uniform and extended about 2 km AGL. The flank was lowering slowly as it moved east."

The 2300 GMT reflectivity and PTI data are given in Figures 4 and 5. Reflectivity at this time showed a storm core exceeding 60 dBZ and PTI was now consistently indicating "large" and "very large" hail. While verification forecasters were becoming quite interested in learning what the core actually contained, the chase team was still some 30 km south of the storm ...

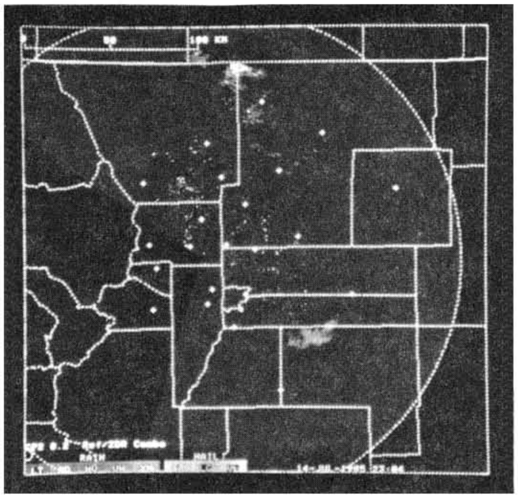

Figure 5. PTI for 2304 GMT, 14 July 1985. Bright area, top-center, contains "large" and "very large" hail indications.

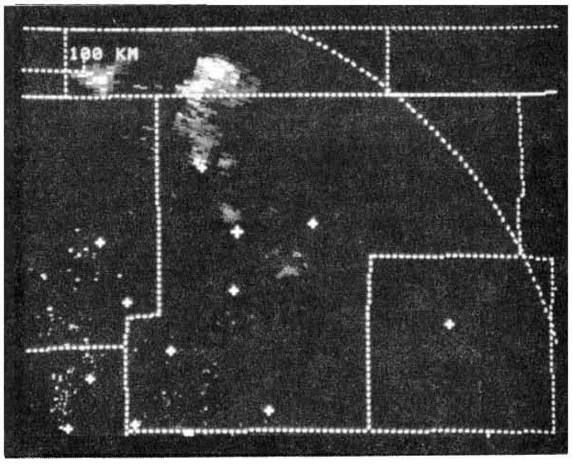

Figure 6. Zoomed PTI for 2349 GMT, 14 July 1985, showing "large" hail indication in storm.

> "Another updraft area became visible at this time. It was located on the east quadrant of the storm (and) consisted of low, dark bands feeding into the storm from the east-northeast. The base was about 1 km AGL. Just in advance of the updraft, skies had cleared somewhat. A large field of cumulus and towering cumulus was forming in the path of the storm."

After examination of the Doppler velocity data and considerable dialogue with the chase team, forecasters became convinced that no organized circulations were present in the storm. The team was asked to move north and penetrate the core.

A small band of precipitation was developing on the southeastern edge of the storm as the chase team drove into the area. They experienced a brief period of rain and 1/2" hail before driving out of the precipitation. They then reported that a broad, 200-m diameter circulation was developing in the scud on the east side of the cell, and that the region to their immediate northwest was "extremely dark." After making sure that the circulation was well east of the road, they advanced north into the core. Over the next 45 minutes the storm remained very intense, as indicated by a well-defined area of "large" hail in PTI at 2349 GMT (Fig. 6), and the chase team was able to observe the precipitation under a large portion of the core. Their observations included very heavy rain, a broad swath of 1/2" hail to a depth of 4" on the ground, regions with 3/4" hail (and at least one stone measured at 0.9"), as well as 55 kt winds. These observations confirm that the PTI product, showing a high degree of spatial and temporal continuity, correctly identified this storm as a severe hailstorm.

4.2 15 July 1985

The 15th of July was also a post-frontal, upslope case. There were two important differences between it and the 14th. First, the boundary layer moisture was greater by about 5°C due to 24 hours of upslope. Secondly, a low-level, cyclonic circulation, the Denver cyclone (Szoke et al., 1984), had developed northeast of Denver. Severe weather seemed likely, and once again several chase teams were dispatched.

There were many reports of significant weather throughout the afternoon, including frequent lightning, 40 kt winds, funnel clouds and 1/2" hail. The most interesting storm of the day formed when a cell on the northern end of a squall line east of Denver split away from the line and moved off toward the north-northeast. The reflectivity of the storm increased to 65 dBZ and developed a "very large" hail signature on PTI at a range of about 145 km (Fig. 7). The signature covered a large area and maintained itself over a period of about 30 minutes before the storm weakened and moved out of radar range.

Two chase teams were in the vicinity of the storm. Radio conversations between the forecasters and the chase teams established that important differences existed in the visual appearance of this storm versus that of the previous day. First, the inflow which had earlier been described as a rotating, bell-shaped wall cloud with rapidly rising scud on the south side of the storm was, at that point, weakening. Secondly, the precipitation shaft was observed to be "very light", and "almost transparent." It was clear that chase team members felt that the storm core appeared too weak to contain hail (or even heavy rain). However, large hail can produce high reflectivity with only a relatively few stones, so it was decided to investigate anyway. The team to the south was in a better position to observe the potentially tornadic inflow region, so the northern team agreed to go in. Almost immediately they encountered 1.5-2.0" hail, and verified the "very large" hail indication of the PTI output. In fact, the team found a 19 km-long path of hail on the ground which verified an even greater segment of the lengthy indication.

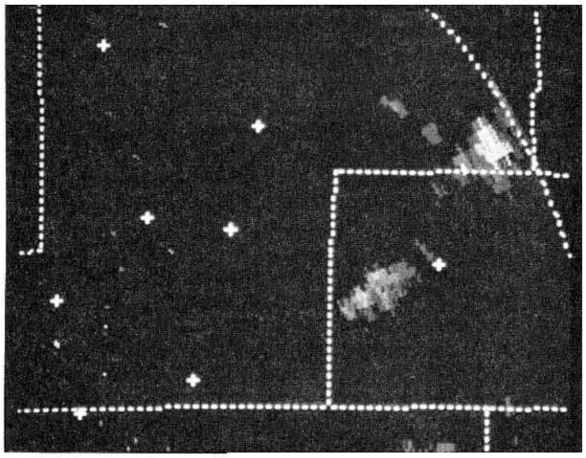

Figure 7. Zoomed PTI for 2304 GMT, 15 July 1985, with "large" and "very large" hail indications near edge of radar range. Beam height is about 1.8 km AGL.

4.3 23 July 1985

A fairly intense low-level trough (below 700 mb) was situated along the eastern slopes of the Rockies. To the west of the trough the winds were from the northwest; to the east the flow was south to southeast, and moist. At upper levels (seen best at 500 mb) a shortwave trough was approaching the state, and was forecast to arrive in north-central Colorado by early afternoon. These factors, combined with a moderately unstable airmass, suggested a chance for early thunderstorms.

Storms of moderate intensity formed early in the afternoon and similar development continued through the rest of the day. Chase teams were in place to observe much of the activity. Their reports included heavy rain, lightning, and small hail. In one storm under observation by a chase team, PTI showed only a few range gates of "large hail", and these only at intermittent times. Since the signature was ambiguous, and the range was approximately 140 km, the chase team was asked to carefully document hail of any size.

Their observations were extremely interesting. In the southern portion of the storm, where the "large hail" signal appeared, the team found small hail covering the ground (albeit not very deep). However, to the north they encountered very heavy rain over a very broad region, but saw no indications of frozen precipitation; the nature of the precipitation was quite different in the two core regions. We conclude that the PTI product effectively identified the frozen precipitation, although the size determination in this case was not handled adequately with our simple scheme.

5. CONCLUDING REMARKS

An operational nowcasting product which qualitatively indicates precipitation type and intensity was described, and its use illustrated with data for three cases. The PTI product, presented in PPI image format, was derived from a combination of differential reflectivity and conventional reflectivity factor data. In the cases presented, PTI gave correct, and quite useful, indications of hail. The two larger and more severe storms described were identified with very coherent "large hail" signatures which persisted over time; the hail indication for the less severe storm was much less coherent and did not properly represent the hail size, but it did correctly identify the presence of hail. In general, the feeling among forecasters at PROFS was that PTI provided a valuable level of confidence about the presence or absence of hail in convective storms.

While this PTI product, developed for PROFS' 1985 exercise, shows considerable promise as a real-time nowcasting tool, much development work remains. First, as part of an evaluation of several operational hail diagnosis techniques, we are conducting a thorough evaluation of PTI performance for 1985 (Winston and Lipschutz, 1986). We then hope to model more quantitatively the various precipitation categories by closely following the empirical curves shown in Figure 1 and by incorporating more rigorous methods of estimating rainfall rate from Z_{DR} and Z_H.

6. ACKNOWLEDGMENTS

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