6.7 Aviation Weather Hazard Detection with Polarimetric Radar

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1. INTRODUCTION

Plans are proceeding to upgrade the national network of WSR-88Ds for polarimetric measurements. The radars will transmit electromagnetic energy at 45^o (slant) polarization and receive returned signals at horizontal and vertical polarization. Because hydrometeors are not spherical, their radar backscattering cross sections are not the same for the two polarizations. Signal properties change continuously as the radar waves propagate yielding information that can be used to determine hydrometeor type (rain, snow, or mixed-phase), size, shape, and orientation. The added measurements of differential reflectivity, differential propagation phase, and correlation coefficient provide far more information regarding scatterers than is obtained from radar reflectivity alone. The measurements readily discriminate among ground targets, biological scatterers (insects and birds), and precipitation. Consistency among the measurements can be used to verify radar hardware calibration.

Demonstrated capabilities with polarimetric radar include improved rain-snow discrimination, hail detection, estimation of heavy rainfall rates, and freezing-level designation. Other benefits, likely to be developed long term, are improved quantification of winter (frozen) precipitation, detection of some icing conditions (especially situations involving embedded convection), estimation of precipitation-impacted visibility, detection of lightning precursors, and improved microphysical parameterization in numerical forecast models. Importantly, polarimetric measurements should also be useful for eliminating regions of the atmosphere where particular hazards are not likely. The net result will be better detection and quantification of weather hazards. Here we describe the polarimetric measurements and summarize potential benefits for aviation.

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2. POLARIMETRIC MEASUREMENTS

The radar reflectivity factor Z at horizontal H and vertical polarization V for a unit volume can be expressed as

$$Z_{H,V} = \frac{\lambda^4}{\pi^5 |K_w|^2} \int_0^{D_{\max}} \sigma_{H,V}(D) N(D) dD \ ,$$

where λ is the radar wavelength (mm), K_w is the dielectric factor for water, $\sigma_{H,V}(D)$ are the particle radar backscattering cross sections at horizontal and vertical polarization (mm^2), $N(D)$ is the particle distribution (mm^{-1} m^{-3}), and D is the particle equivalent volume diameter (mm). Reflectivity is generally computed in units of mm^6 m^{-3} but expressed in dBZ (10×log Z_H).

Differential reflectivity (Z_{DR}, in dB) is defined as

$$Z_{DR} = 10 \times \log(Z_H / Z_V)$$

with Z_H and Z_V in linear units. Differential reflectivity is positive (negative) for particles whose major axes are close to horizontal (vertical) in the mean. Raindrops tend to flatten and orient themselves with their major axes close to horizontal, giving Z_{DR} values typically between 0.3 to 3 dB. Hailstones tend to tumble as they fall creating a random distribution of orientations; Z_H and Z_V are similar in magnitude causing Z_{DR} to be small (< 0.5 dB). Dry snow aggregates tend to be more spherical than raindrops and have a lower dielectric constant. Consequently, Z_{DR} for snow tends to be small (< 1 dB). Z_{DR} for pristine ice crystals is typically larger than that for aggregates and may be 2 dB or more.

Another useful parameter is the correlation coefficient ρ_{HV} between horizontally and vertically polarized returns. This parameter is sensitive to the distribution of particle axis ratios, particularly for partly-melted hydrometeors and mixtures of hydrometeor types. Theoretical values are ~0.99 for raindrops, ice crystals, and dry aggregates. For hail and melting aggregates ρ_{HV} is typically less than 0.95.

The above parameters are derived from power measurements that depend upon backscattering properties of illuminated particles. Radar waves are also subject to propagation effects such as attenuation and phase shifts. The differential phase shift Φ_{DP} between horizontally and vertically propagating polarized waves at a distance r is given by

$$\Phi_{DP}(r) = \Phi_0 + \delta(r) + \int_0^r K_{DP}(r)dr \quad ,$$

where Φ_0 is the radar hardware offset between signals at the two polarizations, $\delta(r)$ is the backscatter differential phase shift, and K_{DP} is the two-way specific differential phase due to propagation. For an anisotropic medium like rain or pristine ice crystals, propagation constants for horizontally and vertically polarized waves differ. Horizontally polarized waves "see" a larger particle cross-section and propagate more slowly than vertically polarized waves. Signals returned to the receiver for the two polarizations exhibit different accumulative phase (time) shifts depending on hydrometeor size, shape, orientation, quantity, and distance from the radar. In the absence of backscatter phase shifts, Φ_{DP} increases monotonically with range. Hail that tumbles or is near spherical in shape makes little contribution to K_{DP}. Large oriented hail will have little impact if it is dry because of its smaller dielectric constant. However, large wetted oriented hail and aggregates in the Mie scattering region can produce a backscatter differential phase shift that is manifest as a temporary decrease in Φ_{DP}.

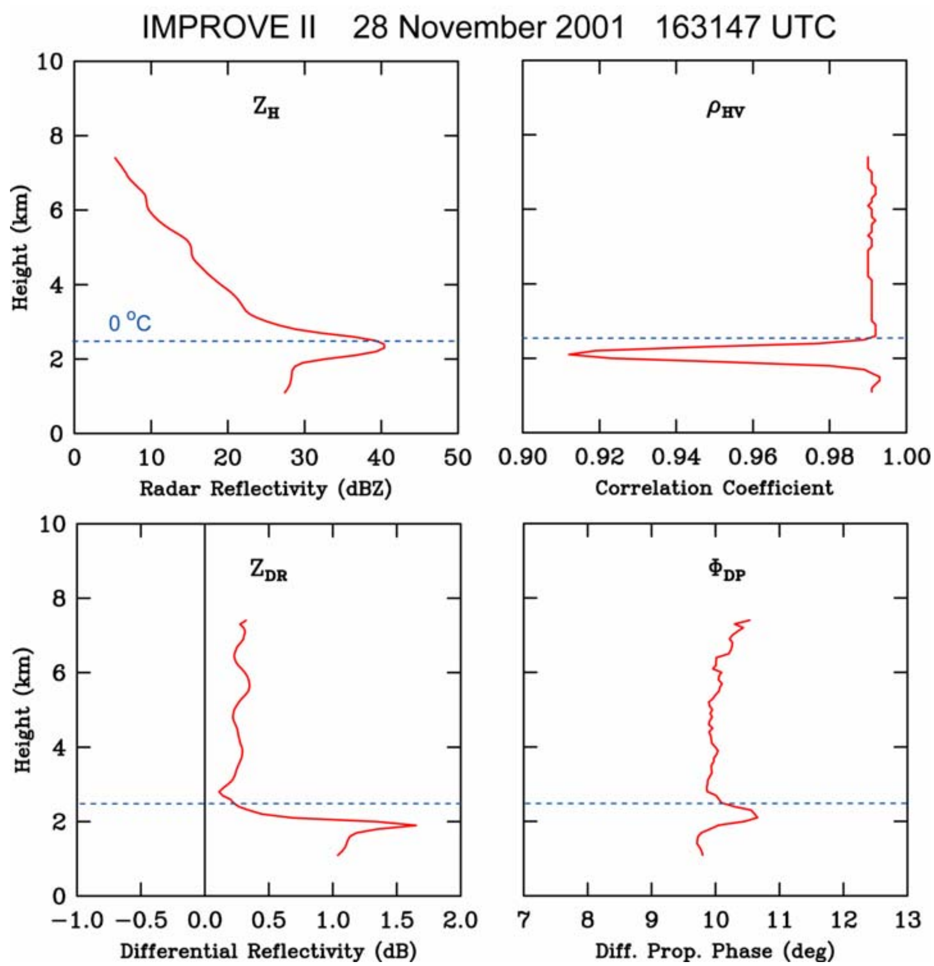

Fig. 1: Vertical profiles of polarimetric measurements constructed from vertical cross-sections. The freezing level is indicated by a horizontal line. Heights are above mean sea level.

Many properties of polarimetric measurements are exemplified by vertical profiles that pass through the melting layer (Fig. 1). The radar reflectivity bright band between 1.8 and 3 km responds to increased snowflake aggregation as temperatures warm to 0°C and to changes in dielectric factor as the hydrometeors melt. High reflectivity is also a sign of large particles. The layer of mixed-phase precipitation is characterized by a sharp decrease in ρ_{HV} as the distribution of particle shapes and types broadens. Correlation coefficients in the surface rain layer and upper snow layer are uniformly high. Differential reflectivity is relatively low in the snow layer and high in the rain layer. This observation is the foundation of rain−snow discrimination. The spike in Z_{DR} at ~2 km is a consequence of the melting process. The trace for Φ_{DP} shows a temporary increase due to the presence of Mie scatterers in the melting layer and the monotonic increase, in this case with height, as the signals propagate. For additional discussion of these measurements and the signatures for various hydrometeor types readers should consult Doviak and Zrnić (1993).

Z_H and Z_{DR} measurement pairs for rain and snow are compared in Fig. 2. For rain Z_H and Z_{DR} are positively correlated. High reflectivity normally associates with high rain rates and larger, more flattened drops. Z_H and Z_{DR} are usually negatively correlated for snow. Radar returns from light frozen precipitation often exhibit characteristics of dense pristine hydrometeors with elongated horizontal axes, whereas heavy snow rates typically involve low density aggregates of pristine forms with shapes that are less flattened.

The distribution of Z_H and Z_{DR} measurement pairs in a hail-producing thunderstorm is shown in Fig. 3. The large size of the hail (¾ in) causes the reflectivity to be high, but the random hail

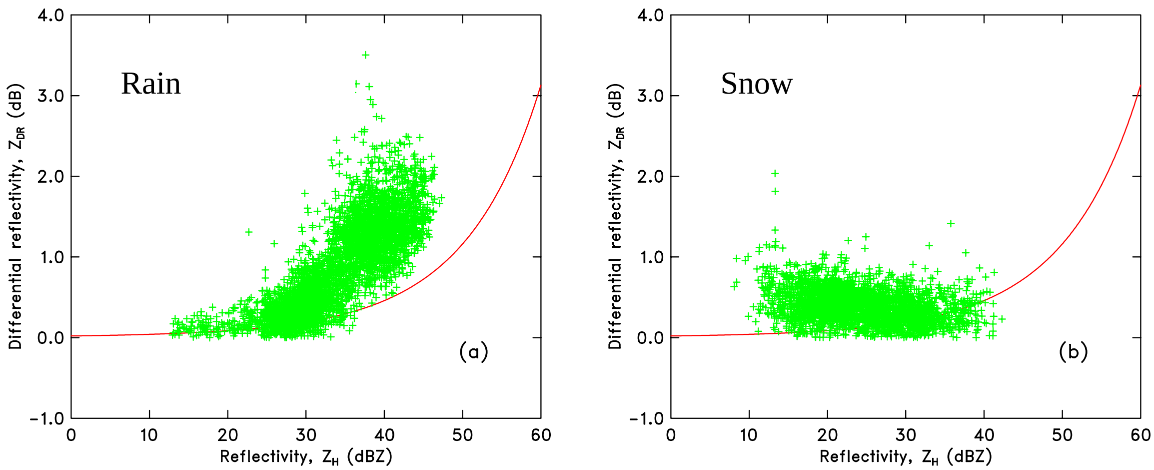

Fig. 2: Z_H and Z_{DR} measurements for freezing rain and snow regions in a storm that occurred in Oklahoma on 5 January 2005 (1311 UTC).

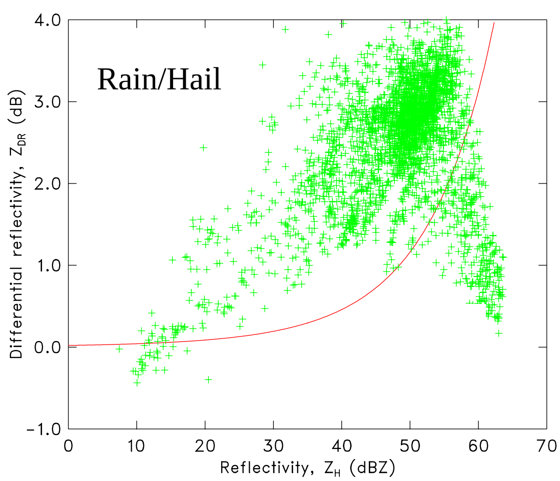

Fig. 3: As in Fig. 2, except for a hailstorm in Oklahoma on 13 June 2002 (0055 UTC).

orientation reduces the differential reflectivity, creating a negative correlation between Z_H and Z_{DR} at high reflectivity. Data points with $Z_H > 60$ dBZ and $Z_{DR} < \sim 2$ dB are clearly contaminated by hail. Further, their separation from data points associated with heavy rain (Z_H = 50 dBZ and Z_{DR} = 3 dB) is an indication of hail size.

3. IMPACTS ON DATA QUALITY

Polarimetric measurements allow consistency checks among variables that can be used to verify the hardware calibration. For example, the differential propagation phase can be computed from the Z_H and Z_{DR} measurements (Vivekanandan et al. 2003). Comparison with the radar-measured value can then be used to validate the radar calibration for reflectivity, assuming Z_{DR} (a difference quantity) is known. Experience suggests bias in Z_H can be reduced to about 0.5 dB by this procedure.

Insects have a large Z_{DR} signature (often 5 dB and more) but a ρ_{HV} of about 0.8 (Zrnić and Ryzhkov 1998). The number density of insects is usually small so that their reflectivity is low. Differential phase is usually small and, if the insects are large, may exhibit a backscatter component δ. Migrating birds are distinguished by low Z_H (< 20 dBZ), a Z_{DR} of 3−4 dB, and large δ (100^o and more). An ability to detect and perhaps remove biological scatterers should lead to improvements in winds derived from velocity-azimuth displays (VADs) and radar-based precipitation estimates.

Scattering from ground targets causes large random differential phase shifts, reduces the correlation coefficient to 0.8 and less, and creates high spatial variance in Z_{DR} measurements. Consequently, additional pattern texture parameters are available for discriminating between precipitation and ground echoes.

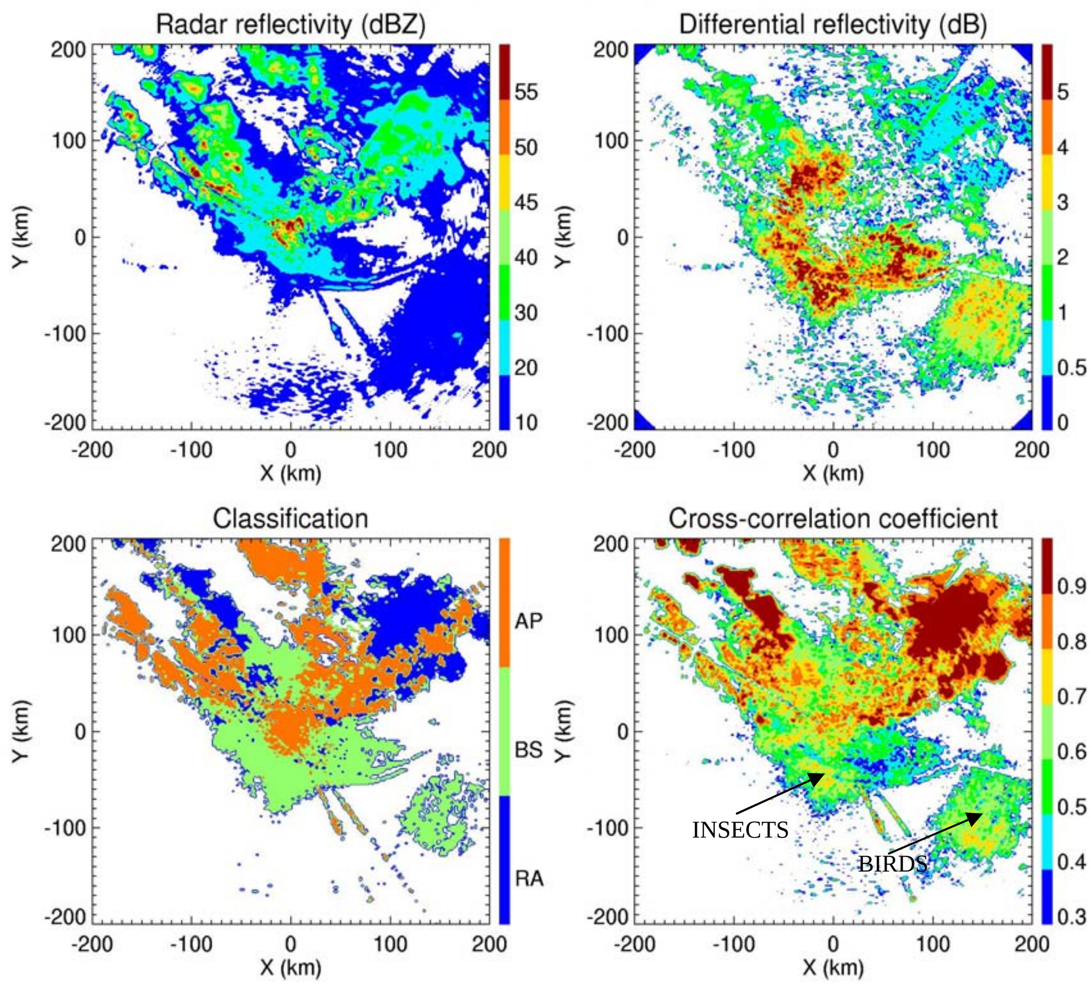

Fig. 4: An example of radar echo designations made with a version of the NSSL HCA. Classifications are made for ground clutter and anomalous propagation echoes (AP), biological scatterers (BS, insects and birds), and rain echoes (RA).

4. POTENTIAL NEW PRODUCTS

As suggested in Section 2, polarimetric measurements should lead to improved rain−snow discrimination and hail detection. As research progresses, there will be better quantification of frozen precipitation as well. An ability to retrieve raindrop-size distributions in precipitation (e.g., Brandes et al. 2004) is increasing the understanding of precipitation processes and will result in improved microphysics parameterization in numerical forecast models. The raindrop retrieval capability will support better estimates of precipitation-impacted visibility at airports than is currently available from radar reflectivity measurements alone.

An example of a Hydrometeor Classification Algorithm (HCA) product being developed at the National Severe Storms Laboratory is presented in Fig. 4. Radar echoes from precipitation (rain), ground targets, and biological scatterers are indicated. An example of a prototype research HCA under development at the National Center for Atmospheric Research is shown in Fig. 5. Designations are made for several precipitation types, insects, ground clutter, and range folded echoes. An attempt is made to identify regions of potential icing conditions (super-cooled liquid water). Research suggests that icing hazards associated with large super-cooled drops is possible—provided the radar returns from drops dominate that of frozen particles that may be present.

Knowing the vertical distribution of radar measurements, e.g., Fig. 1, and the statistical relationship that exists between the height of melting layer signature extremes and the 0^{o}C level, it is possible to estimate the freezing-level height with an accuracy of 100−200 m (Brandes and Ikeda 2004). Such information is needed by HCAs for discriminating between liquid and frozen precipitation types, can be used to nudge numerical forecasts in models that ingest observations, and aids in the isolation of precipitation layers with potential icing hazard. The power to designate precipitation as rain or drizzle when sub-freezing temperatures exist should reduce occurrences of this icing hazard.

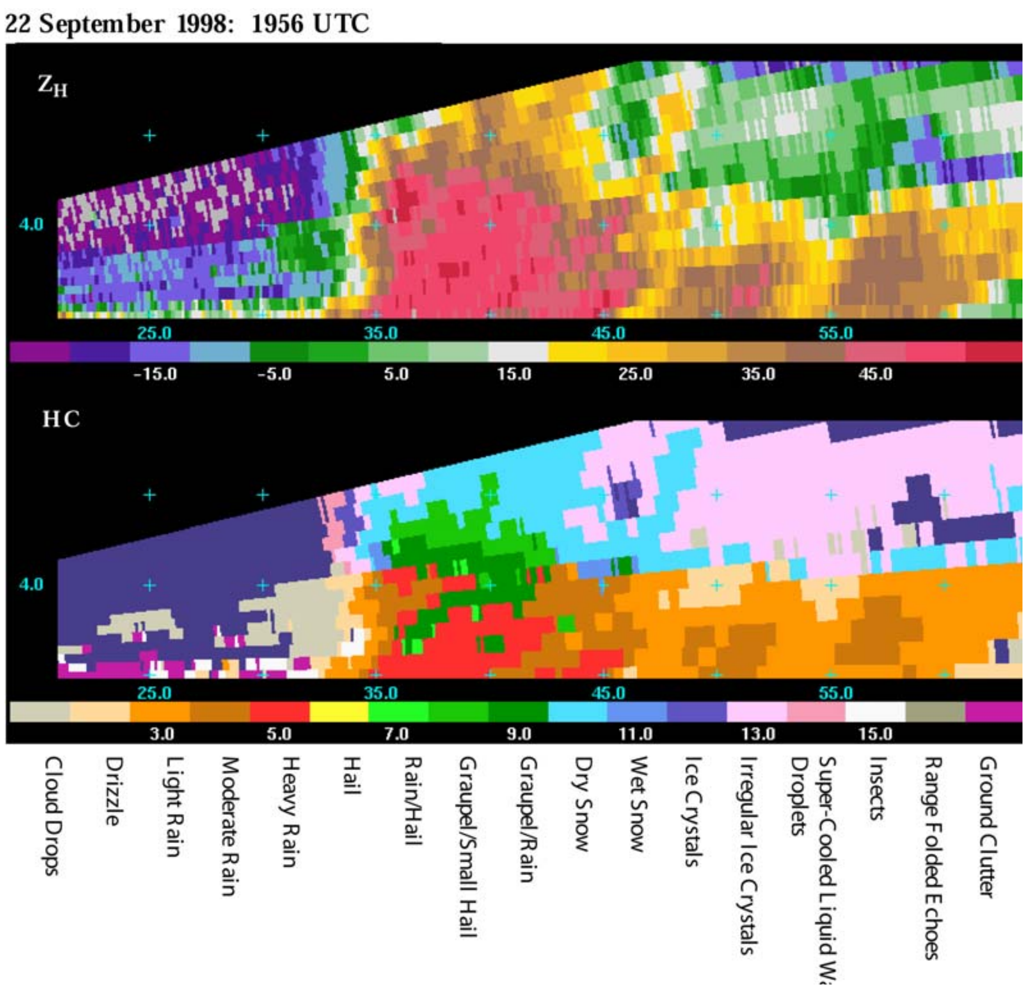

Fig. 5: Radar echo designations made with the NCAR HCA.

5. SUMMARY AND CONCLUSIONS

The impact of polarimetric measurements on aircraft operations and severe weather warning should rival the Doppler capability that became available with the installation of the WSR-88D network. New capabilities for the designation of potential icing hazards exist that simply aren't possible with radar reflectivity measurements alone. Existing radar-based algorithms being developed for the aviation community will benefit from an overall improvement in radar data quality. Other expected benefits include enhanced skill in detecting hail, tornadoes (Ryzhkov et al. 2005), some icing conditions, and rain−snow discrimination. The latter ability could help determine when deicing fluids are needed and the type required. A capacity to designate freezing levels and hydrometeor types should lead to improved numerical forecasts. The net effect will be improved safety and situation awareness.

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