P11.4 HAIL CHARACTERIZATION VIA THE JOINT UTILIZATION OF REFLECTIVITY, DIFFERENTIAL REFLECTIVITY, AND LINEAR DEPOLARIZATION RATIO DATA

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1. INTRODUCTION

It has been shown that dual polarization radars can differentiate between the return signals from hail stones and rain drops based on the fundamental differences between the cross sectional shapes and fall modes of these two forms of precipitation. One of the polarimetric radar measurements that is sensitive to these precipitation characteristics is differential reflectivity (Z_{dr}):

$$Z_{dr} = 10\,log\left(\frac{Z_{hh}}{Z_{vv}}\right) \qquad (1)$$

where Z_{hh} is the reflectivity obtained using horizontally polarized reception and transmission, and Z_{vv} is the corresponding reflectivity when vertical polarization used. Rain drops larger than ~1.0 mm tend to become flattened by aerodynamic and gravitational forces as they fall (Pruppacher and Beard, 1970). Furthermore, the orientation of the falling raindrop's long axis generally remains within ± 10-15 ^{o} of the horizontal, causing positive Z_{dr} values (typically 2-4 dB) to be observed in rain. In contrast, the ice structure of hailstones makes them resistant to deformation during free fall. Hailstones also typically tumble as they fall (Knight and Knight, 1970). This lack of a preferred orientation tends to equalize the Z_{hh} and Z_{vv} return signals, producing Z_{dr} values of ~0 dB.

Using disdrometer-observed rain drop size spectra, Aydin et al. (1986) defined a rain boundary in Z_{hh} vs. Z_{dr} space. Deviations away from the rain side of this boundary were quantified by the Hail Differential Reflectivity (HDR) parameter, where:

$$HDR = Z_{hh} - f(Z_{dr}) \qquad (2)$$

$$f(Z_{dr}) \equiv \left\{ \begin{bmatrix} 27 \quad (if\ Z_{dr} < 0) \\ 19 * Z_{dr} + 27 \\ 60 \quad (if\ Z_{dr} > 1.74) \end{bmatrix} \right\}$$

HDR represents the displacement of a given Z_{hh}, Z_{dr} pair from the limit of the pure rain regime; i.e., large positive HDR values (indicative of hail) will occur when relatively high Z_{hh} values are associated with Z_{dr} near 0 dB.

A second polarimetric quantity useful for the detection of hail is the Linear Depolarization Ratio (LDR):

$$LDR = 10\,log\left(\frac{Z_{vh}}{Z_{hh}}\right) \qquad (3)$$

Qualitatively, the cross-polar return signal component (Z_{vh}) strengthens when the major axis of nonspherical scatterers becomes increasingly canted (up to 45°) with respect to the polarization plane of the incident radar pulse. The degree of shape departure from spherical (as expressed by the axis ratio), and, in the case of frozen scatterers, the magnitude of the particle's bulk refractive index, also strongly affect the cross polar return signal level. Due to their nonspherical shapes and tumbling fall mode, hailstones generally develop appreciable (> ~-25 dB) S-Band LDR values. This paper describes a hail parameter that combines HDR and LDR measurements, which is expected to be a more reliable detector of damaging hail.

2. A COMBINED HDR – LDR HAIL PARAMETER

For the purpose of this technique, HDR and LDR are considered quadrature components of a Hail "Quadrature" Parameter (HQP, Fig. 1). The HQP is defined as the length of a vector whose orthogonal components are HDR and LDR (both in dB). The vector domain is offset to contain just the HDR, LDR values typically expected from hail observed at S-Band (5 < HDR < 50 dB; -25 < LDR < -10 dB). The axes in this vector domain are scaled from 0 to 1 such that the HQP is the square root of 2 at the point HDR=50 dB, LDR=-10 dB.

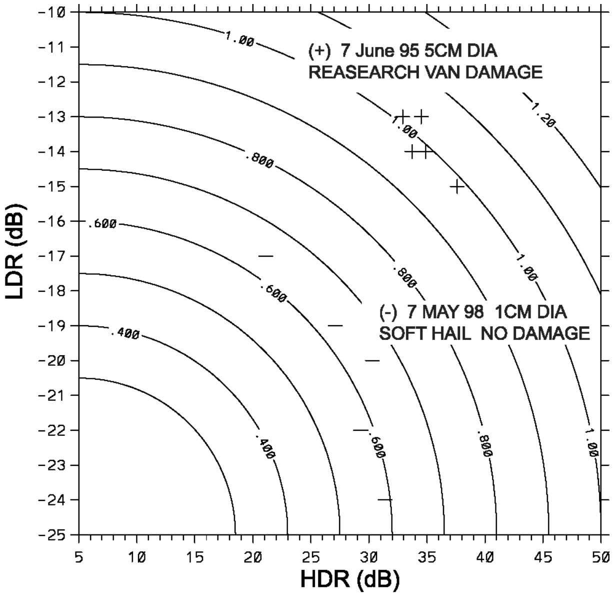

Figure 1. Selected HQP gate values for two hail events.

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The working hypothesis of this paper is that LDR augments the hail detection information that has traditionally been provided by HDR. Theoretical support for this idea comes from the LDR approximation of Bringi and Chandrasekar (2001):

$$LDR = \frac{1}{4}\left[1 - exp\left(-8\sigma_\beta^2\right)\right]\left[g^2 D_Z^2 + var\left(r_Z\right)\right] \quad (4)$$

Where σ_β is the standard deviation of the canting angle (assuming a Gaussian distribution with a mean of zero), g is the slope of the mean axis ratio vs. diameter curve, D_z is proportional to reflectivity-weighted mean diameter of the particle size spectrum, and $var(r_z)$ is the variance of axis ratio for a given diameter (D). The evaluation of this expression is carried out over prescribed distributions of particle size, canting angle, and axis ratio. Figure 2 is a plot of LDR calculated from Eq. 4 vs. the associated HDR values. The modeled precipitation includes an unvarying exponential raindrop distribution with D_o=2.5 mm, N_o=3000, and a rain rate of 50 mm hr $^{-1}$. The basic hail distribution is from Cheng and English (1983). The slope of the mean axis ratio vs. D of oblate hail and the variance of the axis ratio were both obtained from Knight (1986). The specific points along the curve in Fig. 2 were generated by adjusting the slope parameter in the Cheng and English (1983) exponential hail size distribution and integrating through a diameter range of 1-40 mm. The steepening curve shows the increasing occurrence of high depolarization levels as the population of large diameter hailstones increases. Much of this LDR enhancement is due to the general tendency for the hail axis ratios to decrease with increasing diameter (Knight, 1986). The HQP parameter magnitude vs. hail rate from these same rain and hail mixtures is plotted in Figure 3. HQP values above ~0.7 are associated with rapidly increasing hail rates.

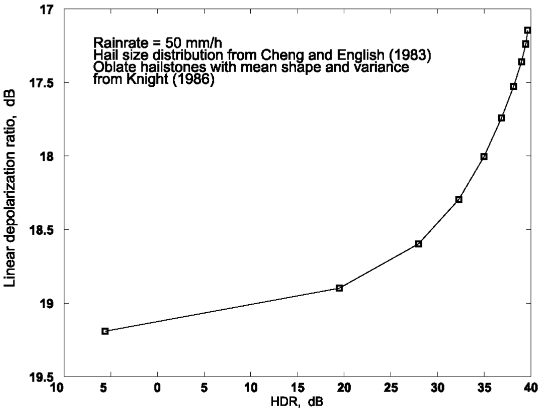

Figure 2. Calculated LDR vs. HDR.

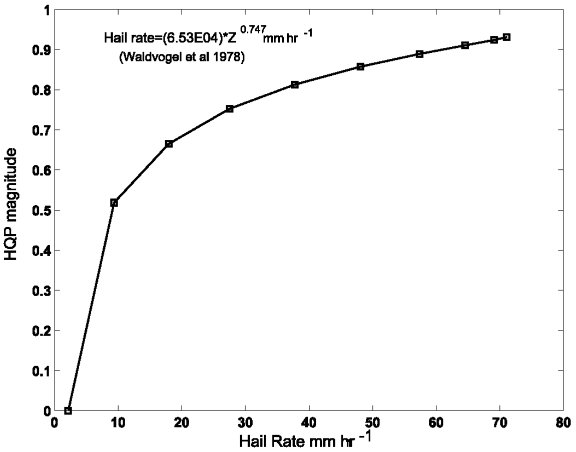

Figure 3. Calculated HQP vs. Hail Rate.

3. VERIFICATION OBSERVATIONS

The correlation between the HQP magnitude and ground truth hail observations has been examined using data recorded in northeastern Colorado by the 11 cm wavelength CSU-CHILL radar. The radar data consist of individual range gate values extracted from the lowest elevation angle PPI sweep (nominally 0.5^o). Thresholds are imposed to exclude gates suspected of containing ground clutter. The HQP magnitude is computed for all gates within a specified radius (~0.75 km) of a surface hail observation point. The average of the five largest HQP magnitudes is taken to be the polarimetric radar representation of the maximum hail severity at the ground truth location (see Fig. 1). Table 1 summarizes the verification observations:

HQP	Top 5 HDR Average(dB)	Remarks
1.01	36.7	Torn hailpad foil, broken windows
0.97	37.2	Research van windshield cracked
0.75	35.4	Severe crop destruction
0.61	30.4	Cherry size soft hail, no damage
0.58	30.7	METAR: small hail (GS)
0.41	23.0	Hailpad: 6.4mm max diameter
0.34	19.0	Hailpad: pea size stones

Table 1. HQP, HDR verification Results

Damaging hail was observed as the HQP magnitudes increased above ~0.7. Also, as noted in Brandes and Vivekanandan (1998), hail diameters >~20 mm tend to be associated with HDR values > 30 dB.

Hail maps can be made by applying the above gate data extraction technique at the grid points within a Cartesian network. Each grid point is assigned the average of the five largest hail parameter magnitudes that were recorded in the immediate vicinity. A contour analysis is then done on the resultant two-dimensional array of HQP magnitudes. Figure 4 shows the hail map generated from NCAR SPOL radar data collected in western Kansas on 29 June 2000 during the early lifetime of a severe thunderstorm during the STEPS project. Larger diameter hail was generally reported near the higher values of HQP hail parameter. The data from the Bird City spotter fell outside of the HQP contours. However, the exact location from which this spotter made his observations could not be verified.

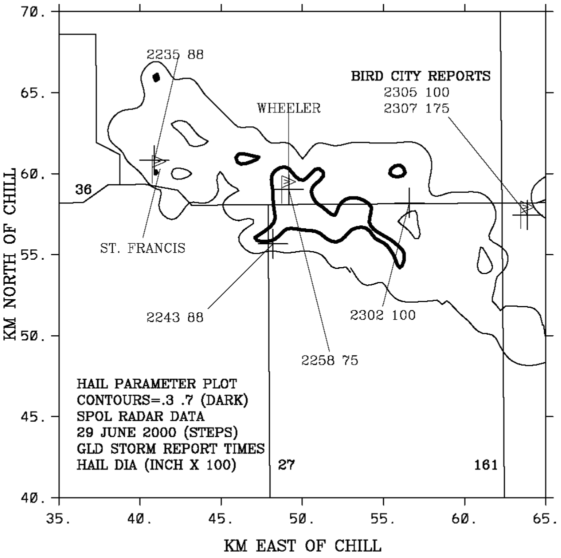

Figure 4. Hailmap based on HQP.

4. CONCLUSIONS

HDR has a demonstrated capability to identify hail near the surface in mid-latitude, continental convective precipitation. However, as Z_{dr} values approach 0 dB, the polarimetric contribution to HDR goes a constant ($f(Z_{dr})=27$), and HDR becomes a simple offset from Z_{hh}. The additional consideration of LDR permits particle shape inferences to be made when no preferential particle orientation exists (i.e., when Z_{dr} = 0 dB). Observational evidence suggests that there is some tendency for larger diameter hailstones to have smaller axis ratios (Knight, 1986). Appreciably sized surface protuberances may also become more common at larger hail diameters (List, 1985). Relatively large LDR levels would be expected from tumbling hail exhibiting these shape characteristics. Also, radar observations made with circular polarization have found a positive correlation between depolarization levels and hail sizes (Barge, 1970). Thus, it appears that augmenting HDR with LDR information may improve polarimetric radar's ability to characterize hail.

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