Estimating Hail Size Using Polarimetric Radar
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1. Introduction

The National Weather Service (NWS) completed installation of the current national network of Weather-Surveillance Radar-1988 Dopplers (WSR-88Ds) in 1997 (Doviak et al. 2000). An upgrade of the entire WSR-88D national network to include dual-polarimetric capabilities is expected by about 2010. This upgrade is motivated by significant improvements in rainfall estimation, separation of meteorological echoes from nonmeteorological echoes, and hail classification demonstrated by the quantitative analysis of polarimetric data collected during the Joint Polarization Experiment (JPOLE; Ryzhkov et al. 2005) at the National Severe Storms Laboratory (NSSL). During JPOLE, polarimetric data were attained by NSSL's WSR-88D research radar (KOUN), which was modified to transmit simultaneously pulses of horizontally and vertically polarized waves (Doviak et al. 2000).

Through the simultaneous transmission of horizontally and vertically polarized waves, dual-polarization radar provides additional information regarding the size, shape, orientation, phase, and distribution of hydrometeors within a resolution volume. The availability of these hydrometeor properties instigated the development of new approaches to hail classification. Aydin et al. (1986) capitalized on differences in the size and shape of rain and hail, measured by horizontal reflectivity factor Z and differential reflectivity factor Z_{DR}, respectively, to define a hail signal parameter, H_{DR}. More recently, Depue and Rutledge (2003) introduced the hail quadrature parameter (HQP), which was developed by combining H_{DR} with information found in the linear depolarization ratio (LDR). Because LDR can measure the greater irregularity of shape and variety of canting angles that differentiate hail from rain (e.g., Doviak and Zrnic 1993), Depue and Rutledge (2003) hypothesized that HPQ would provide hail detection superior to H_{DR} alone. However, validation of these parameters found no advantage to using HPQ in place of H_{DR} (Depue and Rutledge 2003).

Other approaches to hail classification using polarimetric variables include fuzzy logic (e.g., Vivekanandan et al. 1999; Zrnic and Ryzhkov 1999; Straka et al. 2000, Lim et al. 2005; Ryzhkov et al. 2005) and a combination of fuzzy logic and neuro-fuzzy systems (Liu and Chandrasekar 2000). NSSL's Hydrometeor Classification Algorithm (HCA) employs fuzzy-logic to identify the

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location of different hydrometeor types in a storm (Ryzhkov et al. 2005). In terms of overall accuracy and skill, HCA outperforms the current HDA (Heinselman and Ryzhkov 2004). From an operational perspective, HCA is a more effective hail classifier because it identifies regions where hail is falling to the ground, rather than providing a probability of hail anywhere within a storm.

Dual-polarization radar not only supplies information for hydrometeor classification, but may also prove useful for gauging hail size within the storm. Past research indicates relationships between polarimetric variables that might allow for hail size to be categorized (e.g., Balakrishnan and Zrnić 1990). Investigating the relation of polarimetric variables to hail size can be beneficial in improving warnings for hail producing storms, understanding the physical processes that lead to hail formation, and determining possible precursive signatures associated with hail formation and growth.

The goal of this study is to investigate the use of polarimetric variables to estimate maximum hail size within a storm. This will be achieved through interpretation of polarimetric KOUN radar data during 17 hail-producing events. These variables and their application for gauging hail size are discussed further in section 2. The methods used to analyze the polarimetric data are presented in section 3, and section 4 reveals the results. The summary and concluding remarks are provided in section 5.

2. Polarimetric variables used for investigating hail size

Previous studies indicate that the variables of interest for gauging hail size include reflectivity at horizontal polarization (Z_H), Z_{DR}, correlation coefficient ρ_{hv}, and specific differential phase K_{DP} (e.g., Balakrishnan and Zrnić 1990; Zrnić et al. 1993; Straka et al. 2000; Depue and Rutledge 2003). A brief review of these variables is given below.

Z_H is proportional to the cross section of a hydrometeor and is weighted heavily by hydrometeors of largest diameter within the volume. Therefore, in regions of hail, Z_H generally increases with respect to rain regions (Aydin et al. 1986). Combined with other polarimetric variables, Z_H may be useful for estimating the maximum hail size within the storm.

Z_{DR} is obtained from the ratio of the returned power in the horizontal (Z_H) to the returned power in the vertical (Z_V) as follows:

$$Z_{DR} = 10 \log (Z_H/Z_V) \qquad (1)$$

Because Z_{DR} is a logarithmic function, the sign of Z_{DR} provides information concerning the orientation of the hydrometeors within the volume. In general, positive values of Z_{DR} represent horizontally oriented hydrometeors (i.e., rain), values near 0 indicate either spherical hydrometeors (i.e., hail) or tumbling hail, and values less than 0 indicate vertically oriented hydrometeors (i.e., graupel or hail with a conical shape). Aydin et al. (1986) introduced a new hail signal (H_{DR}) that accounted for the negative correlation between Z_{DR} and Z_H. For the two hail-producing storms investigated by Aydin et al.

(1986), H_{DR} increased as hail size increased.

Irregularly shaped hydrometeors and wobbling, tumbling, or oscillating particles cause a decrease in the correlation coefficient. Meteorological scatterers typically have ρ_{hv} values higher than 0.7. For rain, ρ_{hv} is usually higher than 0.95, whereas for hail, ρ_{hv} is usually lower than 0.95. Because ρ_{hv} decreases with increasing size of hailstones in both a mixture of hail and rain and within a mixture of hail sizes, Balakrishnan and Zrnić (1990) hypothesized that ρ_{hv} might be used to infer maximum hail diameters.

K_{DP} is a range derivative of the differential phase shift. The presence of hydrometeors within a volume causes the electromagnetic waves to propagate at different speeds in the horizontal and vertical directions, producing a noticeable phase shift. This allows discrimination of hydrometeors based on their shape and number concentration. Values of K_{DP} range from -1° km^{-1} to 6° km^{-1}, such that higher values indicate higher rain rates. Unlike Z_H, K_{DP} is fairly insensitive to hail (i.e., K_{DP} ~0), allowing for a more accurate rain rate to be determined. The specific differential phase may also be useful for looking at processes within a hail-producing storm. In a study of two hail-producing events, Balakrishnan and Zrnić (1990) observed an increase in K_{DP} from the top of the melting layer to the ground during the event that produced larger hail. This result indicated that melting was the dominant process within the column, as opposed to breakup and coalescence. The possible implications for using K_{DP} to gauge hail size will be discussed in later sections.

Balakrishnan and Zrnić (1990) attempted also to categorize hail size by investigating the effects of various hail models on Z_{DR} and ρ_{hv}. In their modeling studies, larger hail produced negative Z_{DR}. Results of Balakrishnan and Zrnić (1990) also revealed a significant difference in Z_{DR} and ρ_{hv} signatures for hail larger than 5 cm (1.97") compared to signatures for hail smaller than 5 cm. Specifically, Z_{DR} of dry, oblate hailstones became negative at a diameter of 5 cm, and a significant decrease in ρ_{hv} occurred for wet, oblate hail when the size of the hailstone reached 5 cm.

In this study, Z_H, Z_{DR}, K_{DP}, and ρ_{hv} are the primary variables investigated to estimate hail size. Seventeen hail-producing events are used to obtain a larger data set of hail reports for comparison with the two cases observed by Balakrishnan and Zrnić (1990). Details about these events and the methods for investigating the polarimetric data are discussed further in the next section.

3. Data collection and analysis

In this study, KOUN polarimetric data are investigated for seventeen hail-producing events in Oklahoma, all located within 10−100 km of KOUN (Table 1). Of the seventeen events, ten occurred during the spring of 2003 and seven occurred mostly during the spring of 2004 (Table 1). The dataset represents a variety of storm types: seven supercells, four squall lines, and six convective cell events. A total of 106 hail-size observations, ranging from 0.64 cm (0.25") to 6.99 cm (2.75"), were

Table 1. List of event dates, storm type, and number of hail reports.

Date	Storm Type	Number of Hail Reports
04192003	Convective Cells	3
04242003	Supercell & Bow echo	13
05082003	Supercell	2
05102003	Supercell & Convective Line	10
05142003	Scattered Convective Cells	12
05192003	Scattered Convective Cells	16
05242003	Squall Line	2
06022003	Convective Line	3
06102003	Squall Line	2
06122003	Squall Line	9
04242004	Supercell	3
05132004	Convective Line	5
05242004	Supercell	9
05262004	Supercell	1
05292004	Supercell	7
06022004	Squall Line	8
07012004	Isolate Cell	1
Sum of Hail Reports		106

verified during these storms (Fig. 1). The probability density function of these hail reports indicates that the majority of observations had hail sizes between 1.9 cm (0.75 in) and 2.5 cm (1.0 in) —sizes depicting the threshold considered "severe" by the NWS. The distribution shows also that the most commonly reported "large" hail size was 4.5 cm (1.75 in). These hail observations were attained from Storm Data [reference] and special spotter reports during JPOLE.

Prior to analysis, storm reports are validated against radar reflectivity at the 0.5° elevation using a -15 min to +5 min time window. Additionally, polarimetric data are corrected for errors and bias. First, KOUN reflectivity data are compared to reflectivity data from a nearby WSR-88D (KTLX), located 20 km NE of KOUN. KOUN reflectivity

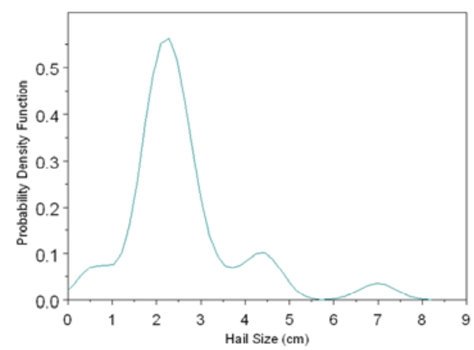

Figure 1. Probability density function of hail size distribution.

data are "corrected" based on the average difference between reflectivity values at overlapping gates. Second, the correlation coefficient is adjusted for the different cases because it is noticeably biased for signal-to-noise ratios (SNR) less than 20 dB (Schuur et al. 2003). The SNR is a function of reflectivity, range, and the radar constant. Using an Interactive Data Language (IDL) program, the ρ_{hv} values are plotted against the SNR. For each report, the value of the radar constant used for computing SNR is adjusted so that the plot is flat (i.e., there is no dependence of ρ_{hv} on SNR for SNR > 5dB) (Schuur et al. 2003). Third, values of Z_{DR} are also examined and corrected using criteria of Giangrande et al. (2004).

After the polarimetric variables are corrected, IDL programs are used to attain a set of polarmetric variables associated with each hail report, including Z_H, Z_{DR}, K_{DP}, and ρ_{hv}. For each hail report, these variables are attained by 1) finding the range gate located closest to the hail report, 2) attaining the polarimetric values within ± 1° azimuth and ±250-km, and 3) retaining the maximum Z_H and minimum Z_{DR}, K_{DP}, and ρ_{hv} values within this defined region. Note that prior to this procedure a 3-pt (Z_H) or 5-pt (Z_{DR} and ρ_{hv}) smoother was applied to most fields. To assess the relation of polarimetric data to hail size, all possible pairs of polarimetric variables were plotted for each hail size category. Primary findings of this analysis are presented in the following section.

4. Relation of polarimetric data to hail size

An examination of the distribution of polarimetric variables associated with various hail sizes reveals that polarimetric variables at the 0.5° elevation are generally poor discriminators of hail size. Of the four polarimetric variables investigated, ρ_{hv} and K_{DP} and ρ_{hv} and Z_{DR} appear to discern hail size best (Figs. 2 and 3). Figures 2 and 3 show that hail sizes smaller than 2.5 cm usually have higher values of ρ_{hv}, K_{DP}, and Z_{DR} than hail sizes larger than 2.5 cm. Interestingly, characteristics of 2.5-cm hail reports are about evenly split between these two groups (Figs. 2 and 3). Given data quality issues associated with Storm Data (Witt et al. 1998), the bimodal distribution of 2.5-cm hail within ρ_{hv}–K_{DP} and ρ_{hv}–Z_{DR} space results most likely from poor hail-size estimates rather than from differences in the microphysics of the hail itself.

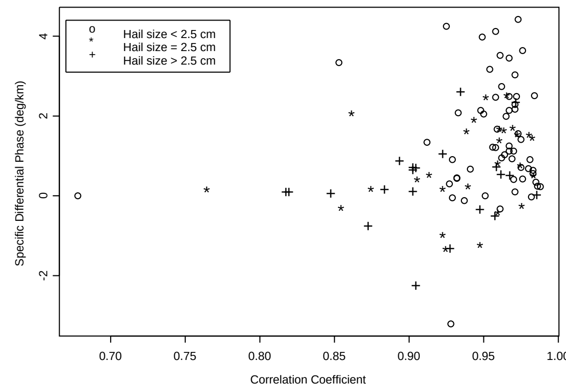

Figure 2. Scatterplot of specific differential phase (K_{DP}) and correlation coefficient (ρ_{hv}) for hail sizes < 2.5 cm (circle), 2.5 cm (asterisk), and > 2.5 cm (plus sign).

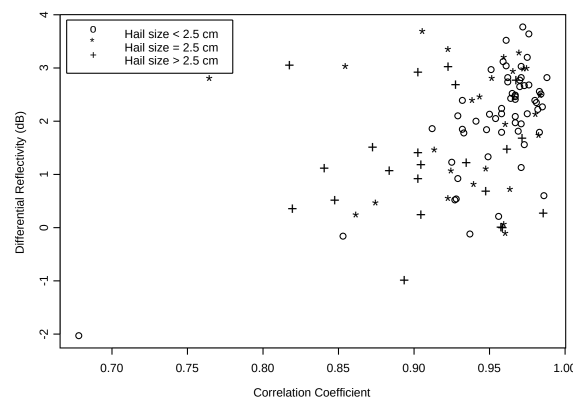

Figure 3. Scatterplot of differential reflectivity (Z_{DR}) and correlation coefficient (ρ_{hv}) for hail sizes < 2.5 cm (circle), 2.5 cm (asterisk), and > 2.5 cm (plus sign).

To investigate the relationship between ρ_{hv}, K_{DP}, and Z_{DR} further, the data are analyzed using discriminant analysis. This is a statistical method used to determine which variables are best for discriminating between different groups. A quadratic discriminant function is developed for ρ_{hv} versus K_{DP} (Fig. 4) and a linear discriminant function is developed for ρ_{hv} versus Z_{DR} (Fig. 5), which provides details about the division line for the three categories. The purpose of this function is to allow future observations to accurately be classified into the different groups

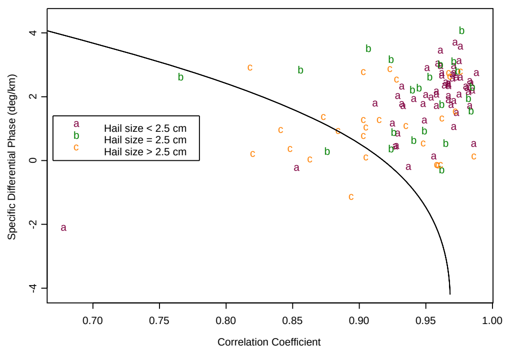

Figure 4. Quadratic discriminant analysis of correlation coefficient and specific differential phase associated with hail sizes less than 2.5 cm ("a"), equal to 2.5 cm ("b"), and greater than 2.5 cm ("c").

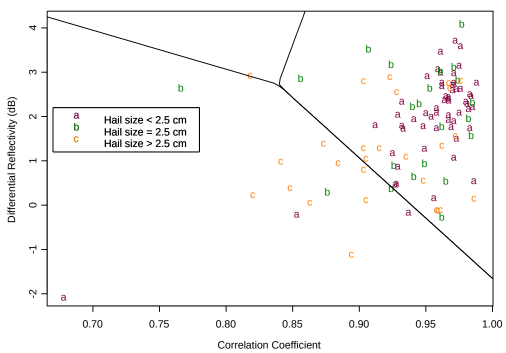

Figure 5. Linear discriminant analysis of correlation coefficient and differential reflectivity associated with hail sizes less than 2.5 cm ("a"), equal to 2.5 cm ("b"), and greater than 2.5 cm ("c").

(Wilks 1995). For both plots, most of the reports for category 1 (hail size < 2.5 cm) and category 2 (hail size = 2.5 cm) are grouped together to the right of the line, whereas only 22% (41%) of category 3 reports (hail size > 2.5 cm) are grouped together on the other side (Figs. 4 and 5, respectively). This shows that, overall, the best discriminant function between the categories (1 and 2 vs 3) arises from ρ_{hv} and K_{DP}. This result indicates that additional research of hail-producing storms is required to improve the understanding of the affects of the water content and shape on the polarimetric variables.

5. Summary and concluding remarks

This study investigates the use of polarimetric variables (Z_H, Z_{DR}, ρ_{hv}, and K_{DP}) for estimating hail size. A total of 106 hail reports from 17 hail-producing storms that occurred mostly during the spring of 2003 and 2004 are used for this study. The location of each hail report was matched to the closest polar coordinate and used to find associated polarimetric measures. Scatterplots of Z_H, Z_{DR}, ρ_{hv}, and K_{DP} indicate that K_{DP} and Z_{DR} vs ρ_{hv} showed the best clustering of hail sizes less than and greater than 2.5 cm. However, discriminant analysis of the data reveals that the pairing of Z_{DR} with ρ_{hv} distinguishes hail sizes best.

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References

Aydin, K., T. A. Seliga, and V. Balaji, 1986: Remote sensing of hail with a dual linear polarization radar. *J. Climate Appl. Meteor.*, **25,** 1475−1484.

Balakrishnan, N., and D. S. Zrnić, 1990: Use of polarization to characterize precipitation and discriminate large hail. *J. Atmos. Sci.,* **47,** 1525−1540.

Depue, T. K., and S. A. Rutledge, 2003: Ground truth and modeling verification of the hail quadrature parameter. M. S. Thesis, Colorado State University, Fort Collins, CO, 154 pp. [Available from Department of Atmospheric Science, Colorado State University, Fort Collins, CO 80523]

Doviak, R. J., V. Bringi, A. Ryzhkov, A. Zahrai, and D. Zrnić, 2000: Considerations for polarimetric upgrades to operational WSR-88D radars. *J. Atmos. Oceanic Technol.,* **17,** 257−278.

Doviak, R., and D. Zrnić, 1993: *Doppler Radar and Weather Observations*, Academic Press, 562 pp.

Giangrande, S.E.**,** A.V. Ryzhkov**,** V.M. Melnikov**,** and J. Krause**,** 2004: Calibration of the polarimetric NEXRAD radar using meteorological signals. Preprints, *11th Conf. on Aviation, Range, and Aerospace Meteorology*, Hyannis, MA, Amer. Meteor. Soc., CD-ROM, P5.15.

Heinselman, P. L., and A. V. Ryzhkov, 2004: Validation of polarimetric hail detection. Preprints, *22nd Conference on Severe Local Storms*, Hyannis, MA, Amer. Meteor. Soc., CD-ROM, J1.3.

Lim, S., V. Chandrasekar, and V.N. Bringi, 2005: Hydrometeor classification system using dual-polarization radar measurements: model improvements and in situ verification. *IEEE Trans. Geosci. Rem. Sens*., **43**, 792 – 801.

Liu, H., and V. Chandrasekar, 2000: Classification of hydrometeors based on polarimetric radar measurements: Development of fuzzy logic and neuro-fuzzy systems, and in situ verification. *J. Atmos. Oceanic Techno,* **17**, 140–164.

NCDC, 2003: *Storm Data*. Vol 45, No. 4–6.

NCDC, 2004: *Storm Data*. Vol 46, No. 4–7.

Ryzhkov, A. V., Schuur, T. J., Burgess, D. W., Heinselman, P. L., Giangrande, S. E., and Zrnic, D. S., 2005: The Joint Polarization Experiment: Polarimetric rainfall measurements and hydrometeor classification. *Bull. Amer. Meteor. Soc.,***86**, 809–824.

Schuur, T. J., A. Ryzhkov, P. Heinselman, D. Zrnić, D. Burgess, and K. Scharfenberg, 2003b: Observations and classification of echoes with the Polarimetric WSR-88D Radar, Report of the National Severe Storms Laboratory, Norman, OK, 46 pp. [Available from the NSSL, 1313 Halley Circle, Norman, OK 73069]

Straka, J. M., D. S. Zrnić, and A. V. Ryzhkov, 2000: Bulk hydrometeor classification and quantification using polarimetric radar data: synthesis of relations. *J. Appl. Meteor.,* **39,** 1341−1372.

Vivekanandan, J., G. Zhang, S. M. Ellis, D. Rajopadhyaya, and S. K. Avery, 2003: Radar reflectivity calibration using differential propagation phase measurement. *Radio Sci.,* **38,** 381–388.

Wilks, D.S., 1995: *Statistical Methods in the Atmospheric Sciences*. Academic Press, 408−419.

Witt, A., M. D., Eilts, G. J. Stumpf, E. D. Mitchell, J. T. Johnson and K. W. Thomas, 1998: Evaluating the performance of WSR-88D severe storm detection algorithms. *Wea. Forecasting,***13**, 513–518.

Zrnić, D.S. and A. V. Ryzhkov, 1999: Polarimetry for weather surveillance radars. *Bull. Amer. Meteor. Soc.,* **80,** 389−406.