Comparison of polarimetric radar signatures in hailstorms simultaneously observed by C-band and S-band radars.

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1. Introduction

Direct comparisons of polarimetric signatures in hailstorms simultaneously observed by C-band and S-band radars in Oklahoma reveal numerous differences. Vertical profiles of radar reflectivity $Z_{HH}$, differential reflectivity $Z_{DR}$, and cross-correlation coefficient $\rho_{hv}$ in the major downdraft cores of hailstorms at S and C bands reflect fundamental differences in backscattering by melting hailstones and large raindrops at the two wavelengths (e.g. Kaltenboeck and Ryzhkov 2012).

The focus of this study is to examine the signatures at the periphery of the major reflectivity cores which are affected by strong size sorting (Kumjian and Ryzhkov 2009), three-body scattering (TBSS, Lemon 1998), attenuation (Borowska et al. 2011), updrafts (e.g., Straka et al. 2000), side lobe contamination, nonuniform beam filling and reflectivity gradients across the beam (Ryzhkov 2007), depolarization (Ryzhkov and Zrnić 2007), low signal to noise ratio (SNR), and range dependency which manifest themselves very differently at S and C bands. Some of these factors are closely associated with hail itself and its size and their comparative analysis may provide additional insight into the microphysics of hail generation and fallout.

2. Data

Over a period of 3 years, different SPC hail size reports were analyzed in association with data from two polarimetric weather radars closely located in Norman, Oklahoma. One of them is the polarimetric prototype of the WSR-88D S-band radar (KOUN) operated by NOAA (NSSL/ROC) and another one is the C-band OU-PRIME radar operated and maintained by ARRC / University of Oklahoma.

3. Vertical profiles of radar variables in hail.

Typical vertical profiles of radar variables observed in hail are shown in Fig.1.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig1.png}
\caption{Vertical profiles of polarimetric variables ($Z_{HH} \geq 55$ dBZ) in hail bearing cell. Reported hail size is 2.5 cm. Upper panel shows C-band data and lower panel shows S-band data respectively. From left to right: $Z_{HH}$, $Z_{DR}$, $\rho_{hv}$, $\phi_{DP}$ and counts per level. Vertical profiles reveal stronger scattering of $Z_{DR}/\rho_{hv}$ data at C band at different levels. Median vertical profiles are plotted in black.}
\end{figure}
Below freezing level, stronger increase of positive $Z_{\text{DR}}$ and decrease of $\rho_{hv}$ at C band indicate melting hail with resonance sizes. The secondary $\rho_{hv}$ minimum is observed in the wet growth region aloft which is more pronounced at C band for large or giant hail. Polarimetric variables such as $Z_{\text{DR}}$, $\rho_{hv}$ and $\phi_{\text{DP}}$ (differential phase) are more scattered at C band than at S band which is caused by resonance effects and strong differential attenuation. Subsequently, the standard deviations (STD) of polarimetric moments within high reflectivity cell cores are much larger at C than at S band. Larger STD below freezing level for $Z_{\text{DR}}/\rho_{hv}$ and for $\rho_{hv}$ aloft at the wet growth regime can be possibly used for hail size discrimination (Kaltenboeck and Ryzhkov 2012).


The following section presents a collection of secondary polarimetric attributes of hail which can affect hail detection, determination of its size, and vertical profiles of polarimetric variables within or close to the convective core containing hail. These effects are more pronounced at C band due to stronger effects of resonance scattering and attenuation. Most of these effects depend on relative positions of the storm and the radar. These secondary signatures can be both beneficial and detrimental for appropriate hail identification. These signatures were identified in the process of visual inspection of radar data collected over 3 year period of observations.

4.1 Hail spike and side lobe effects

Fig. 2a illustrates the TBSS and side lobe effects for the storm producing 2.5 cm hail at C and S bands at two PPI elevations. The three-body scattering signature (TBSS) is indicated by a radial spike of moderate $Z_H$ behind cell core. The spike is characterized by positive $Z_{\text{DR}}$ close to core followed by negative $Z_{\text{DR}}$ further away from the core and low values of $\rho_{hv}$. The three-body scattering is more apparent in terms of polarimetric variables and the $Z_{\text{DR}}$ dependence on range is explained in Picca and Ryzhkov (2012). At elevation 6°, the TBSS signature is more pronounced at C band which might indicate stronger contributions of resonant scatterers.

Additional RHI (Fig.2b) for C-band data are shown to reveal differences in vertical structure of radar variables. The $Z_{\text{DR}}$ depression (marked by arrow) appears tilted due to the geometry of TBSS. Longer propagation path of radiation reflected from the ground projects into larger apparent TBSS distances from the radar at higher elevations. Note the $Z_{\text{DR}}$-hole with values close to 0 dB which indicates large hail aloft. Weak echo at the periphery of the cell core is attributed to side lobe effects (marked by an arrow) associated with low $\rho_{hv}$ and noisy, mostly positive $Z_{\text{DR}}$. 
4.2 ZDR column

Cross section in Fig.3 shows ZDR column associated with updraft in the bounded weak echo region (BWER) next to precipitation core with high values of ZH. The ZDR column develops when large raindrops are lifted above the freezing level. It usually precedes subsequent development of hail. In this example, the ZDR columns are well developed at C and S band and ZDR values as high as 2.5 dBZ are observed at 6 km height (about -20 °C) and accompanied by the decrease of ρhv. Notable are negative values of ZDR at the base of the ZDR column at C band which is a result of strong differential attenuation in the main precipitation core.

![Cross section from NW-SE through 10.8 cm hail-bearing supercell from 14th April 2011 2132+2130UTC showing ZDR column (marked) which indicates the updraft position within BWER. Large melting hail causing high ZDR (low ρhv) values close to the surface marked as white (black) ellipse. Wet bulb freezing level for that day was 2520 m msl.](image)

4.3 ZDR arc and strong C-band attenuation

Fig. 4 illustrates ZDR arc which is very visible in the southern part of the rear-flank downdraft at S band but is not detectable at C band due to strong differential attenuation. As expected, in the part of the storm facing the radar, ZDR(C) > ZDR(S) due to resonance scattering. In the shadow of the storm (with respect to the radar), differential attenuation at C band is overwhelming and the C-band cross-correlation coefficient is significantly reduced due to stronger impact of nonuniform beam filling at C band.

![CAPPI at 1.5 km height from 14th April 2011 2205+2200 UTC (4.4 cm hail report) for ZH, ZDR, ΦDP and ρhv. C-band polarimetric variables are strongly affected by attenuation and nonuniform beam filling. S-band data show more clearly ZDR arc (black arrow) and ZDR column (marked by white dashed arrow).](image)

4.4 Low SNR and C-band attenuation

Effects of nonuniform beam filling are demonstrated in Fig.5 and 6 which show strong gradients of ZH, ZDR (negative C-band ZDR values behind the core), and ΦDP. The latter causes strong reduction of ρhv. The SNR dropped down at the outer edge of the storm. White arrow in Fig.5 marks the ZDR-circle structure NE of cell core which is pronounced in C- and S-band data (up to 4 dB). Below freezing level (wet bulb freezing level at 2760 m msl), this might be a graupel belt wrapping around the storm core as an embryo corridor including entrainment and melting. This curved structure also might indicate mesoscale rotation.
Fig. 5: Strong $Z_H$ and $Z_{DR}$ gradients (negative $Z_{DR}(C)$ due to differential attenuation marked by black arrow) resulting low $\rho_{hv}$ and strong decrease of SNR behind cell core seen at lowest CAPPI level 1.5 km GND from 27th March 2009 16:47+45 UTC for 2.5cm hail report. Left (right) panel show C (S) band including subplots of $Z_H$, $Z_{DR}$ and $\Phi_{DP}$, $\rho_{hv}$. White filled arrow denotes the decrease of $\rho_{hv}$ due to low SNR at southern flank, while white arrow mark the $Z_{DR}$-circ at C band.

4.5 Nonuniform beam filling / $\Phi_{DP}$ gradient.

Fig. 6: As Fig. 4 except cross section from SW-NE through 2.5 cm hail bearing cell along ray from 14th April 2011 21:56 UTC and negative $Z_{DR}(C)$ behind cell core. $\Phi_{DP}$ gradient results in low $\rho_{hv}$.

4.6 $Z_{DR}$-circle

Same $Z_{DR}$-circle pattern as in Fig.5 (northeast of cell core) was observed at the western flank of the storm (Fig.7). The feature is more pronounced at C than at S band. The position of the $Z_{DR}$-circle might be related to low level inflow and development of flanking line updraft turrets. Soundings from Oklahoma for these days reveal low level winds from NE for Fig.5 (northern flank $Z_{DR}$-circle) and from SE-SW for Fig.7 (western flank $Z_{DR}$-circle). More pronounced $Z_{DR}$-circle (at C band) occurs for the 4.4 cm than for the 10.8 cm hail case.
4.7 Depolarization

Last example shows depolarization pattern which appear as closely located radials of negative and positive $Z_{DR}$ at higher elevations (Fig. 8).

Fig. 8a: $Z_{DR}$, $Z_{H}$, $\Phi_{DP}$ and $\rho_{hv}$ are shown at PPI elevation 6 and 6.2° at C/S band from 27\textsuperscript{th} March 2009 1658/1656 UTC. Depolarization streaks are marked by the arrows. All plots show overlaid 30 dBZ contour.

Fig. 8b: Upper (lower) panel show RHI of $Z_{H}$, $Z_{DR}$, $\Phi_{DP}$, and $\rho_{hv}$ for azimuths 80 and 84° at C band from 27\textsuperscript{th} March 2009 1658 UTC. Depolarization (marked by dashed circle) on top of cell core is seen in the $Z_{DR}$ and $\Phi_{DP}$ panels. Starting point of depolarization is marked by arrow.
**S band**

Fig. 8c: as Fig. 8b except for azimuths 84 and 89° at S band.

Those features start on the top of the updraft and are caused by oriented ice crystals due to the electric field within thunderstorm. The PPI and RHI in Fig. 8 show sectors of positive and negative $Z_{DR}$ behind storm tops and center (even with high $Z_{H}$) which vary in the range of -2 to +3 dB at both wavelengths. The $Z_{DR}$ depolarization streaks are accompanied by negative $\Phi_{DR}$ (more pronounced at C band).

5. Conclusion

The polarimetric signatures at the periphery of the major reflectivity hail cores have been examined for 3 years of simultaneously collected C- and S-band data in Oklahoma. These signatures include size sorting manifested as $Z_{DR}$-arc/rings, TBSS, attenuation, updrafts ($Z_{DR}$-columns), side lobe contamination, nonuniform beam filling associated with reflectivity gradients across the beam, and depolarization streaks. These secondary polarimetric signatures should be taken into account in the interpretation of radar data and hail detection. Some of them, such as TBSS can be viewed as additional attributes of large hail. Several associated $Z_{DR}$ features (columns, arcs, rings) may indicate imminent development of hail. Enhanced effects of attenuation and nonuniform beam filling at C band may mask the key attributes of hail and can be erroneously qualified as indicators of hail outside of real hail cores.

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References


