# 8B.3 POLARIMETRIC RADAR OBSERVATIONS OF TORNADIC DEBRIS SIGNATURES

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## 1. Introduction

In recent years, polarimetric radars have been shown to provide improved discrimination between meteorological and nonmeteorological radar echoes (Zrnic and Ryzhkov 1999, Vivekanandan et al. 1999). As demonstrated by Ryzhkov et al. (2002), this can include the detection of tornadic debris signatures. It is natural to assume that tornadic debris is composed of more or less randomly oriented particles with very irregular shapes and a refractive index different from that of hydrometeors, thereby producing much different signatures than hydrometeors. Randomly oriented scatterers are characterized by differential reflectivity $Z_{DR}$ equal to zero. If large debris scatterers are not chaotically oriented and possess some degree of common orientation, then their $Z_{DR}$ might be both positive and negative depending on their size and the mean canting angle. Linear depolarization ratio LDR and cross-correlation coefficient $\rho_{hv}$ of tornadic debris should also be quite different from signatures associated with hydrometeors. Similar to other nonmeteorological scatterers such as natural ground cover (trees, grass, etc.) and biological scatterers (insects, birds, and bats), tornadic debris is expected to have significantly higher LDR and lower $\rho_{hv}$ than typical for liquid or frozen hydrometeors.

In this paper, we present polarimetric analyses of the three tornadic supercell storms that occurred in central Oklahoma on 3 May 1999, 8 May 2003, and 9 May 2003.

## 2. 3 May 1999

On 3 May 1999, multiple tornadoes occurred in close proximity to the Oklahoma City metropolitan area (Burgess et al. 2002). Polarimetric data from the Cimarron radar are available on that day for the period from 2145 UTC to 2322 UTC, after which the radar went down when an intense storm passed over the radar site. As a result, the radar missed the most violent stage of the F5 tornado that eventually struck the Oklahoma City metropolitan area. However, 15 volume scans that document the early stages of several storms were collected, including data on a less destructive tornado, rated as F3 in the Fujita scale, at a location west of Chickasha, OK. This tornado produced an approximately 900 m wide damage swath and lasted from 2246 until 2310 UTC. The tornado track was at the ranges 45 – 60 km from the radar.

The 10-cm Cimarron radar measured radar reflectivity factor Z at horizontal polarization, mean Doppler velocity V, Doppler spectrum width $\sigma_v$, differential reflectivity $Z_{DR}$, differential phase $\Phi_{DP}$, and cross-correlation coefficient $\rho_{hv}$ between radar returns at two orthogonal polarizations (Zahrai and Zrnic 1993). The data were collected at elevations of 0.0º, 0.5º, 1.5º, 2.5º, 4.0º, and 6.0º with an update time of approximately 6 min. All radar variables were measured with a radial resolution of 0.24 km and an azimuthal resolution of about 1.9º (although the radar beam has a 0.9º width).

To obtain observations as close to ground level as possible, we use radar data collected at 0.0º elevation. At such a low elevation, the radar beam is inevitably partially blocked and the power-related radar variables such as Z and $Z_{DR}$ are biased. Partial blockage, however, does not affect phase-related variables - Doppler velocity and differential phase. Moreover, it is possible to restore correct values of Z and $Z_{DR}$ using specific differential phase $K_{DP}$ and the concept of self-consistency between Z, $Z_{DR}$, and $K_{DP}$ in rain (Gorgucci et al. 1999). The self-consistency technique proves to work well even in the presence of severe beam blockage (Ryzhkov et al. 2002). The Z and $Z_{DR}$ data collected at 0.0º and 0.5º elevations have been corrected according to such methodology.

A volume at 2305 UTC is used to illustrate tornadic polarimetric signatures. At that time, the F3 tornado was still observed on the ground and the storm was relatively close (within 55 km) to the radar. Therefore, small-scale features can be more easily resolved. A combined plot of Z, V, $Z_{DR}$, and $\rho_{hv}$ at the lowest CAPPI level (approximately 200 m above ground) is shown in Fig. 1. At that moment, a hook echo was well developed and the area of intense hail mixed with rain was located north of the hook. The latter is marked with Z exceeding 60 dBZ near ground and 65 dBZ aloft. Maximal radar reflectivity within the hook is slightly below 50 dBZ. Very intense cyclonic rotation at the tip of the hook is evident in the Doppler velocity image. Relatively poor azimuthal resolution of the radar data in this particular dataset (about 2°) does not allow us to distinguish fine structure of velocity field in Fig. 1c. Nevertheless, analysis of individual adjacent radials shows that the azimuthal change in Doppler velocity is about 39 m $s^{-1}$ across a distance of 2 – 3 km in the hook area.

As expected, differential reflectivity and cross-correlation coefficient are anomalously low in the part

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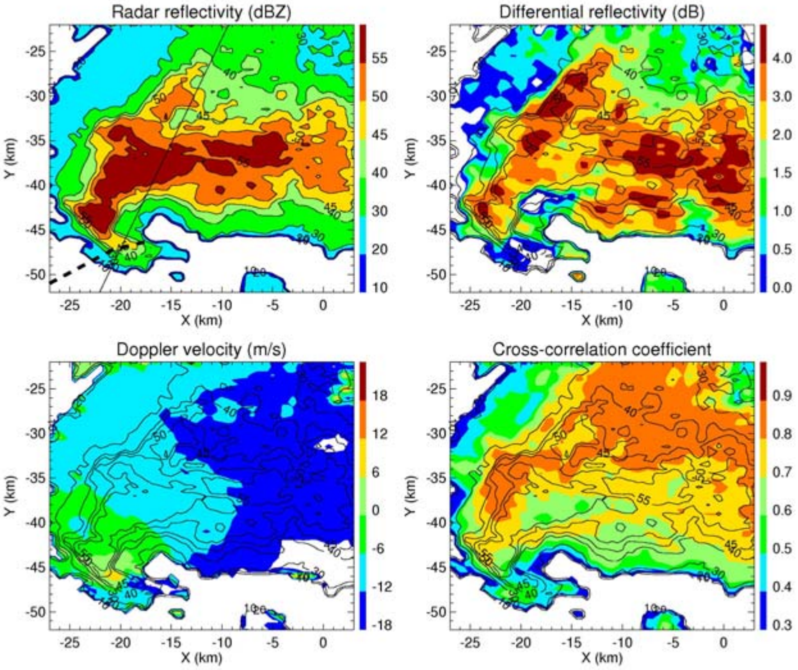

**Fig. 1.** Fields of Z, $Z_{DR}$, V, and $\rho_{hv}$ at the lowest CAPPI level (~ 200 m) at 2304 UTC on 3 May 1999. Solid line in the Z panel indicates azimuthal direction 203°, dashed line depicts tornado track from the ground observations.

of the hook where the tornado was detected (according to a ground survey, the tornado track is depicted by a thick dashed line in Fig. 1a). $Z_{DR}$ values (in dB) are slightly positive or even negative at the tip of the hook. Such low $Z_{DR}$ values can be explained by the presence of lofted debris in the radar resolution volume, and to some extent by enhanced differential attenuation along propagation path that intersects hail-bearing region NE of the hook. Normally, $Z_{DR}$ is corrected for differential attenuation using empirical relation $\Delta Z_{DR}$ (dB) = 0.004 $\Phi_{DP}$ (deg) which is valid at S band for rain in Oklahoma (Ryzhkov and Zrnic 1995). Note high $Z_{DR}$ (more than 4 dB) in the area ahead of forward-flank downdraft (FFD). Analysis of the vertical structure of $Z_{DR}$ shows that the region of high $Z_{DR}$ stretches above freezing level in the updraft region (the "$Z_{DR}$ column") and is very shallow (confined to a 1-km-depth layer) in the FFD area. The enhanced $Z_{DR}$ in updraft has been referred to as "$Z_{DR}$ column" (Conway and Zrnic 1993, Hubbert et al. 1998, Loney et al. 2002).

Cross-correlation coefficient drops below 0.4 at the inner side of the hook in the vicinity of the tornado track. In pure rain or dry snow, $\rho_{hv}$ usually varies between 0.980 and 0.997 if a dual-polarization radar is well designed. Because of quantization noise in the Cimarron data processor, the measured values of $\rho_{hv}$ are negatively biased and those high values have never been attained. This should be taken into account in interpretation of the Cimarron polarimetric data. Although absolute values of $\rho_{hv}$ are not reliable, its relative changes are more trustworthy. Notable are the lower $\rho_{hv}$ values (less than 0.7) that are located within the 55 dBZ contour of Z (indicative of rain / hail mixture) and at weaker reflectivities in the southern part of the storm associated with the updraft. The latter signature is very repetitive in the supercell storms and might indicate a mixture of raindrops and light debris (leaves, grass, etc.) being advected into the cloud by strong inflow.

## 3. 8 May 2003

In the spring of 2003, polarimetric radar data were collected with the KOUN WSR-88D radar - a prototype of a future polarimetric WSR-88D. The KOUN radar experiences much less blockage at lower elevations than the Cimarron radar and surpasses the latter in the quality of polarimetric data. Values of $\rho_{hv}$ measured by KOUN reach theoretical limits for rain (0.997 – 0.998) and confirm the high quality of the radar engineering design and radar data processor. Higher values of $\rho_{hv}$ ensure lower statistical errors in the estimates of all polarimetric variables: $Z_{DR}$, $\rho_{hv}$, $\Phi_{DP}$, and $K_{DP}$ for the same dwell time (Bringi and Chandrasekar 2001). Most data during the spring of 2003 were collected following the VCP-11 scanning strategy, which includes 14 elevation sweeps from 0.5° to 19.5° and a volume update time of about 6 min.

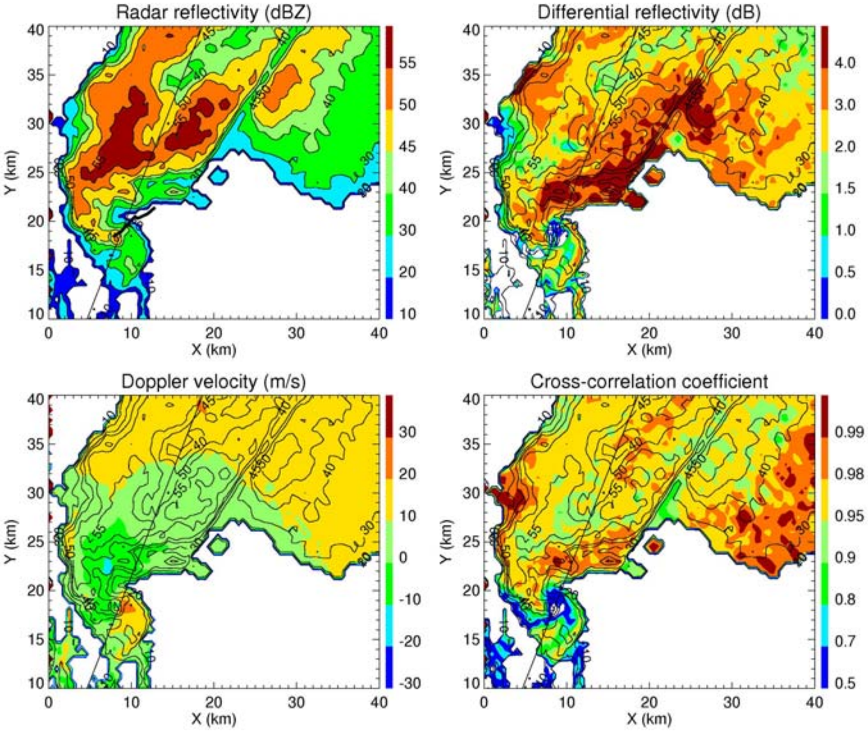

**Fig. 2.** Fields of Z, $Z_{DR}$, V, and $\rho_{hv}$ at the PPI scan (1.5°) at 2229 UTC on 8 May 2003. Thin solid line in the Z panel indicates azimuthal direction 25°, thick solid line depicts a part of tornado track from the ground observations

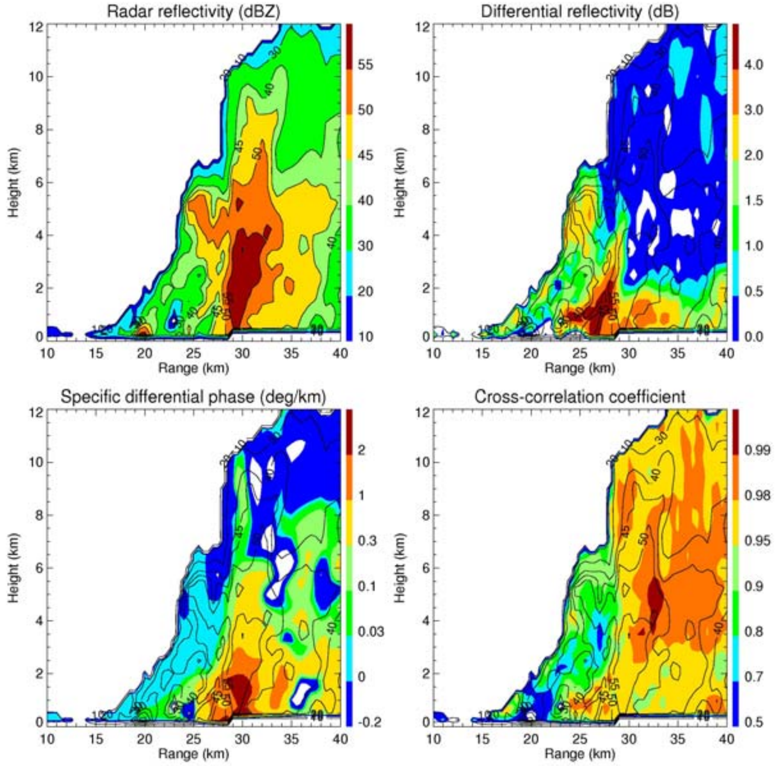

**Fig. 3.** Vertical cross-section of Z, $Z_{DR}$, $K_{DP}$, and $\rho_{hv}$ corresponding to azimuthal direction 25° (shown in Fig. 2) at 2229 UTC on 8 May 2003. A debris signature is centered at about 20 km from the radar.

On 8 May 2003, a destructive F4 tornado hit Moore, Southeast Oklahoma City, Midwest City, and Choctaw, OK creating a 27 km damage path. The tornado was spotted on the ground from 2210 to 2238 UTC. Fig. 2 presents a composite plot of Z, V, $Z_{DR}$, and $\rho_{hv}$ at 1.5° elevation at 2229 UTC, when the tornado was about 20 km from the radar. A tornadic signature at the tip of the hook is marked by Z exceeding 50 dBZ, an obvious presence of a vortex in the Doppler velocity field, $Z_{DR}$ close to zero, and anomalously low $\rho_{hv}$ (less than 0.5). These components of the tornado signature are very similar to what was observed by the Cimarron radar on 3 May 1999. Outside the hook, the highest values of $Z_{DR}$ are associated with low to moderate values of Z in the inflow region, which is an indication of pronounced drop sorting.

The vertical extension of the debris signature in the hook is about 500 m, as the composite RHI at Az = 25° demonstrates (Fig. 3, 19 – 20 km from the radar). Among other notable features in a vertical cross-section is the $Z_{DR}$ column at the periphery of a hail core and extensive region of lower values of $\rho_{hv}$ (less than 0.90 - 0.95) stretching up from the tornado on the ground to the height of 7 km in the updraft portion of the storm. We don't exclude the possibility that this unusually low $\rho_{hv}$ might be attributed to a mixture of meteorological particles and light debris that were lofted to a midlevel height in the storm by a strong updraft. A vertical column of specific differential phase $K_{DP}$ (Fig. 3c) at the distances 29 – 31 km from the radar is associated with a major precipitation shaft loaded primarily with raindrops and possibly some hail, as can be concluded from vertical distribution of Z and $Z_{DR}$ (Loney et al. 2002).

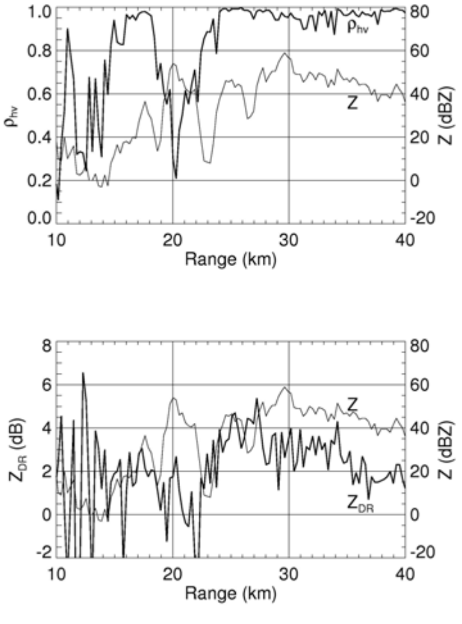

**Fig. 4.** Radial profiles of raw (unprocessed) Z, $Z_{DR}$, and $\rho_{hv}$ along the beam through tornado at 2229 UTC on 8 May 2003. El = 1.5°, Az =25°.

A tornadic vortex is a very localized feature. Because of spatial smoothing of radar data as part of data processing and conversion of the data from polar to Cartesian grid, the corresponding values of radar variables may therefore not be correctly represented in the PPI and RHI composite images presented in Figs. 2 and 3. Radial profiles of raw (unprocessed) data, although more affected by measurement noise, better represent extreme values of radar variables associated with tornadic touchdown. An example of such profiles of Z, $Z_{DR}$, and $\rho_{hv}$ is presented in Fig. 4. The tornadic signature at the distance of 20 km from the radar is characterized by a local reflectivity maximum of 53 dBZ combined with an unprecedented drop of the cross-correlation coefficient to a level of 0.2! Because of extremely low $\rho_{hv}$, the corresponding differential reflectivity is quite noisy, but it is definitely lower than in surrounding areas.

## 4. 9 May 2003

On 9 May 2003, a strong tornado struck northeast Oklahoma City, Witcher, and rural parts of Jones and Luther, OK over a 29 km damage path. According to ground information, the tornado started at 2229 CST and ended at about 2306 CST (0329 – 0406 UTC on 10 May 2003). During this time interval, the tornado was at distances 35 – 55 km from the radar. The KOUN radar provided uninterrupted flow of polarimetric data throughout the entire lifetime of the tornado. A tornadic signature was identified during successive volume scans, updated every 6 minutes from 0334 UTC to 0358 UTC.

The tornado was relatively far from the radar, thus the data at the lowest elevation tilt of 0.5° were not contaminated by a ground clutter. The fields of Z, V, $Z_{DR}$, and $\rho_{hv}$ at the lowest radar scan at 0346 UTC are displayed in Fig. 5. At that moment, a strong classical hook echo had developed with all indications of tornado occurrence at the tip of the hook (X = 6.5 km, Y = 38.5 km): increased Z, Doppler vortex, anomalously low $\rho_{hv}$, and negative $Z_{DR}$.

A remarkable tornadic signature at distances 39 – 40 km from the radar is evident in the vertical cross-section through the hook echo (Fig. 6). The columns of negative $Z_{DR}$, negative $K_{DP}$, and low $\rho_{hv}$ extend vertically from the ground up to a height of 4 km. The corresponding Z is between 50 and 55 dBZ. There is no doubt that the radar echo in this region is dominated by nonmeteorological scatterers, i.e., debris. Negative values of $Z_{DR}$ and $K_{DP}$ might be attributed either to a certain degree of vertical common orientation of the scatterers (if they are relatively small) or to their large size (provided that their orientation is not totally chaotic).

As can be seen from Fig. 6, two distinct columns of enhanced Z closely connected aloft and separated by a "vault" at altitudes below 7.5 km have strikingly different polarimetric attributes. The left column is associated with the RFD and exhibits an impressive tilted column of high positive $K_{DP}$, low values of $\rho_{hv}$ (compared to its right counterpart), and

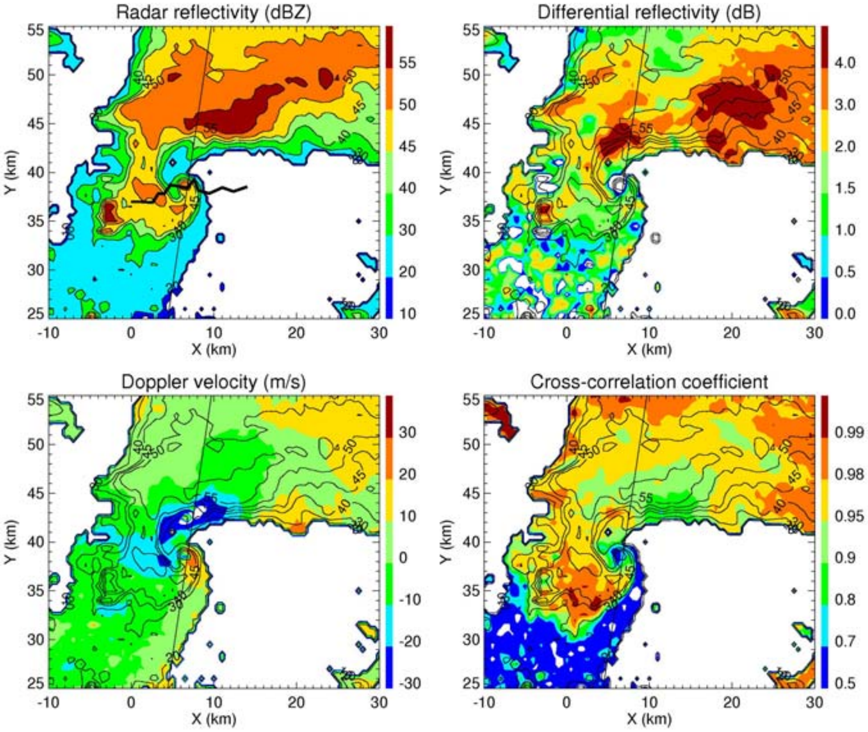

**Fig. 5.** Fields of Z, $Z_{DR}$, V, and $\rho_{hv}$ at the PPI scan (0.5°) at 0346 UTC on 10 May 2003. Thin solid line in the Z panel indicates azimuthal direction 10°, thick solid line depicts a part of tornado track from the ground observations.

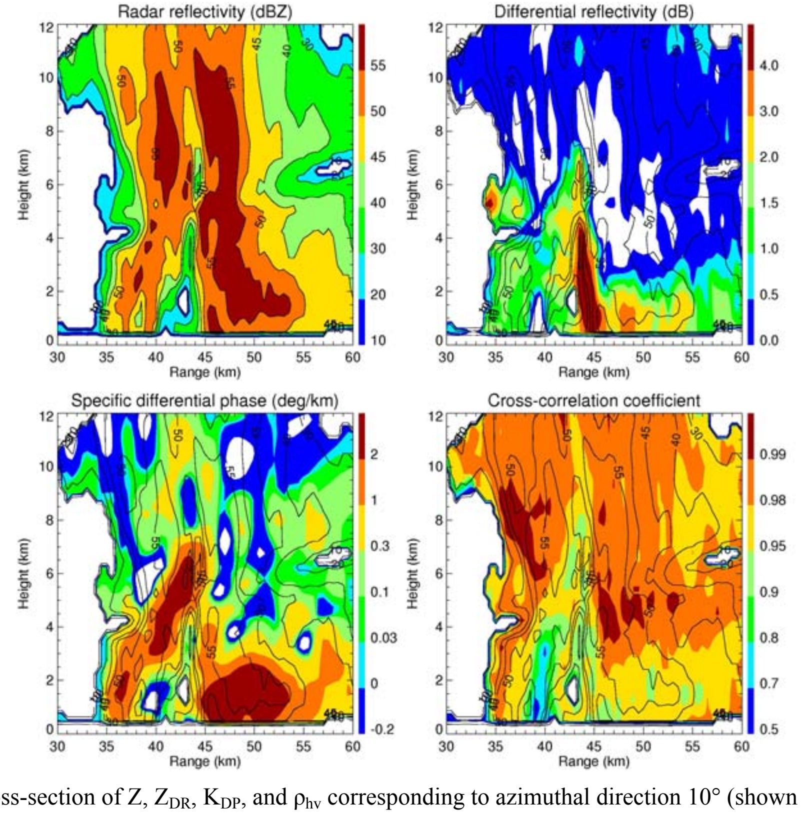

**Fig. 6.** Vertical cross-section of Z, $Z_{DR}$, $K_{DP}$, and $\rho_{hv}$ corresponding to azimuthal direction 10° (shown in Fig. 5) at 0346 UTC on 10 May 2003. A debris signature is centered at about 39.5 km from the radar.

highly variable low-to-moderate $Z_{DR}$. The right column represents the main precipitation core, consisting of rain below 2 – 2.5 km and hail above as can be inferred from $Z_{DR}$, $K_{DP}$, and $\rho_{hv}$. A spectacular $Z_{DR}$ column with maximal $Z_{DR}$ values approaching 6.5 dB is observed in the weak echo region associated with the storm updraft.

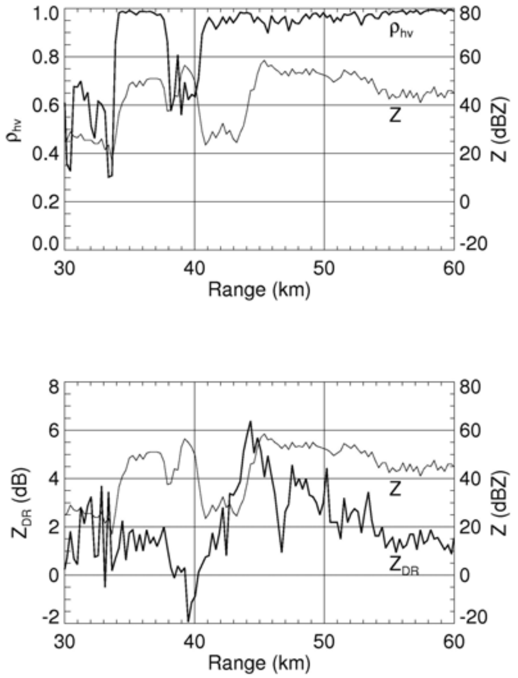

**Fig. 7.** Radial profiles of raw (unprocessed) Z, $Z_{DR}$, and $\rho_{hv}$ along the beam through tornado at 0346 UTC on 10 May 2003. El = 0.5°, Az =10°.

Analysis of raw data along the radial through the tip of the hook at El = 0.5° shows that Z varies between 50 and 57 dBZ, $\rho_{hv}$ drops to approximately 0.60 – 0.65 and, $Z_{DR}$ to -2 – 0 dB in the tornado location at 39 – 40 km from the radar (Fig. 7). Notable is a tremendous change of $Z_{DR}$ from -2 dB in the hook echo to 6.4 dB at the edge of the main precipitation core (44 – 45 km).

## 5. Discussion

Analysis of the three tornadic cases presented in this study shows that the polarimetric debris signature is a repeatable feature. The signature exists throughout tornado lifetime provided that the tornado has an intensity of at least F3. A cursory analysis of other tornadic storms indicates that the majority of the weak tornadoes did not produce definable signatures. One possible reason for this is that wind speeds in weak tornadoes are not sufficient to significantly damage structures and loft debris. Another feasible explanation is that some of the weaker tornadoes may be too short-lived. Therefore, a debris signature might have been missed due to coarse temporal sampling. On the other hand, our study of all significant nontornadic supercell storms observed during JPOLE doesn't reveal such a signature. Although $Z_{DR}$ and $\rho_{hv}$ can drop considerably in the middle of hail cores, it is almost impossible to confuse hail and tornado designations because of their location in the storm and the depth of the $\rho_{hv}$ dip. In hail, $\rho_{hv}$ usually doesn't drop below 0.85 even if hail is large. The only exception in our dataset is an extreme hail event that occurred on 14 May 2003 where the measured $\rho_{hv}$ in the center of the hail core dropped to as low as 0.75. But that was an exceptional hailstorm that produced hail of 13 cm size!

If we summarize our observations of these three events, we can tentatively formulate the following five criteria for polarimetric tornado detection: (1) hook echo, (2) Z > 40 dBZ, (3) pronounced vortex signature in the Doppler velocity field, (4) $Z_{DR} < 0.5$ dB, (5) $\rho_{hv} < 0.7$. If conditions 2 – 5 are satisfied in the hook area, then it is very likely that a tornado is on the ground. Among criteria 2 – 5, the last one probably has the best discriminating power. The cross-correlation coefficient is the most attractive variable because, unlike $Z_{DR}$, it is not affected by radar miscalibration, attenuation in precipitation, and partial radar beam blockage, provided that signal-to-noise ratio is sufficiently high. Linear depolarization ratio LDR, considered as a proxy for $\rho_{hv}$, is vulnerable to all these conditions.

One reservation regarding the use of $\rho_{hv}$ is that the magnitude of the cross-correlation coefficient is affected by the variability of differential phase within the radar resolution volume. If a gradient of $\Phi_{DP}$ across the radar beam is high and the radar sampling volume is too large, then $\rho_{hv}$ noticeably decreases. This factor explains an observed general decrease of $\rho_{hv}$ with distance, especially if a propagation path contains large amount of precipitation. Hence, the $\rho_{hv}$ threshold in criteria (5) might depend on range and $\Phi_{DP}$.

We also comment on other debris signatures associated with tornadic storms. Once light debris is lofted to higher levels in a tornadic storm, it takes some time (tens of minutes) for debris to sediment to the ground (Magzig and Snow 1998). Suspended light debris is the most reasonable explanation of the supercell storm "wake" signature that is usually observed in the wake of the strong low-level wind field behind the storm (see Fig. 5). It is characterized by low Z (less than 30 dBZ), low $\rho_{hv}$ (less than 0.7), and mean $Z_{DR}$ varying between 1 and 2 dB. Low values of $\rho_{hv}$ point to nonmeteorological scatterers as a source of echo. Ground clutter is excluded because the Doppler velocity is far from zero, and $Z_{DR}$ is mainly positive, whereas it is usually slightly negative for ground targets. Biological scatterers like insects and birds have much higher $Z_{DR}$ and quite different differential phase upon scattering $\delta$. The observed $\delta$ in the "wake" echo is about 50 – 60° which is different from the one typical for insects (10 - 40°) and birds (70 - 100°) (Zrnic and Ryzhkov 1998, Schuur et al. 2003). Hence, lofted light debris with certain degree of common alignment (probably leaves and grass) remains the only feasible explanation for such an echo.

## 6. Conclusions

All previous observational studies of tornadoes that were made with Doppler radars emphasized the kinematic properties of storms (see for example a review by Markowski (2002)). For the first time we have obtained strong evidence that a dual-polarizaton radar can effectively complement Doppler information and provide additional tornado detection capabilities. Three major tornadic storms that hit the Oklahoma City metropolitan area in recent years all exhibit well defined polarimetric debris signatures characterized by an unprecedented drop in the cross-correlation coefficient $\rho_{hv}$ and differential reflectivity $Z_{DR}$ in the hook echo. Such signatures are less pronounced for weaker tornadoes but reliably identify tornadoes rated as F3 in the Fujita scale.

The debris signature associated with tornadic touchdown is quite small with horizontal size of about 1 km and vertical extent of 1 – 3 km. Doppler measurements require good spatial resolution in order to resolve a small tornado vortex, whereas identification of polarimetric signatures can be accomplished with a coarser resolution. Moreover, these signatures are "isotropic" in their nature. That is, as opposed to Doppler velocities, they do not depend on a viewing angle.

Although a very small tornado signature might not be well resolved at long distances from the radar, larger-scale polarimetric signatures associated with light debris (leaves, grass, etc.) lofted in the cloud by a strong updraft as well as intense size sorting of hydrometeors might be helpful to diagnose the current state of the supercell storm and its potential ability to produce a tornado. Light debris in the inflow region of the storm and in its wake is associated with low values of $\rho_{hv}$ and sizeable differential phase upon scattering, whereas size sorting is manifested by very high values of $Z_{DR}$. Both larger-scale polarimetric signatures provide indirect estimates of the strength of vertical flows and circulation within the cloud.

In cases where traditional Doppler tornado-warning signatures are absent or overlooked by forecasters, the polarization tornado signature might be very valuable in preventing what otherwise might have been a missed warning. This signature might also be very helpful in issuing accurate severe weather warning updates to pinpoint current tornado location and confirm occurrence of damage (based on debris).

The debris signatures can be very useful to confirm tornado warnings, tornado damage, and to pinpoint current tornado location. Although tornado detection is important, its prediction and early warning are even more important. A cursory look into evolution of the 3D pattern of polarimetric variables in a tornadic supercell reveals quite unusual and intriguing polarimetric signatures aloft and in the near proximity of the storm that might be related to tornado development. Similar to the debris signature, these polarimetric patterns are also repetitive and require microphysical interpretation.

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