Dual-Wavelength Polarimetric Radar Analyses of Tornadic Debris Signatures

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(Manuscript received 5 June 2013, in final form 6 October 2013)

ABSTRACT

Statistical properties of tornado debris signatures (TDSs) are investigated using S- and C-band polarimetric radar data with comparisons to damage surveys and satellite imagery. Close proximity of the radars to the 10 May 2010 Moore–Oklahoma City, Oklahoma, tornado that was rated as a 4 on the enhanced Fujita scale (EF4) provides a large number of resolution volumes, and good temporal and spatial matching for dual-wavelength comparisons. These comparisons reveal that S-band TDSs exhibit a higher radar reflectivity factor ($Z_{HH}$) and copolar cross-correlation coefficient ($r_{hv}$) than do C-band TDSs. Higher S-band $r_{hv}$ may result from a smaller ratio of non-Rayleigh scatterers to total scatterers due to the smaller electrical sizes of debris and, consequently, reduced resonance effects. A negative $Z_{DR}$ signature is observed at 350 m AGL at both the S and C bands as the tornado passes over a vegetated area near a large body of water. Another interesting signature is a positive (negative) shift in propagation differential phase ($\Phi_{DP}$) at S band (C band), which could result from increased phase folding at C band. With increasing height above 350 m AGL, the S- and C-band $Z_{HH}$ decreases and $r_{hv}$ increases, indicating a decrease in debris size. To investigate relationships between polarimetric variables and tornado wind fields, range profiles of radial and tangential wind speeds are obtained using two radars. Velocity profiles reveal radial divergence within vortex core flow through 700 m AGL collocated with the TDS. Formation of a weak-echo hole and higher $r_{hv}$ in the vortex center aloft suggests debris centrifuging, outward motion of scatterers due to radial divergence (i.e., two-cell vortex flow), or both.

1. Introduction

Polarimetric radar signatures of tornadoes have received much attention from the scientific community, and promising applications have emerged from this research, including tornado detection and damage severity estimation. Lofted debris possesses distinct scattering characteristics as a result of its random orientations, nonspherical shapes, and varied compositions (Ryzhkov et al. 2002, 2005). This signature, called the tornadic debris signature (TDS; Ryzhkov et al. 2005; Bluestein et al. 2007; Kumjian and Ryzhkov 2008; Snyder et al. 2010; Palmer et al. 2011; Schultz et al. 2012a,b; Bodine et al. 2013), exhibits a large range of radar reflectivity factors ($Z_{HH}$), low copolar cross-correlation coefficients ($r_{hv} < 0.8$), near-zero differential reflectivities ($Z_{DR}$), and is collocated with a tornadic vortex signature (TVS; Brown et al. 1978). National Weather Service (NWS) forecast offices have used TDSs to confirm tornadoes (Scharfenberg et al. 2005; Schultz et al. 2012a). For tornado detection, $r_{hv}$ provides a better indicator of tornadic debris than does $Z_{DR}$ because $Z_{DR}$ exhibits a positive bias when rain is present (Bluestein et al. 2007; Bodine et al. 2011) and a negative bias when differential attenuation occurs (Schultz et al. 2012a).

Recent studies have suggested that TDS parameters could help estimate near-real-time tornado damage severity (Ryzhkov et al. 2005; Schultz et al. 2012a; Bodine et al. 2013). Ryzhkov et al. (2005) found that maxima in areal extent, and minima in $r_{hv}$ and $Z_{DR}$ occurred during peak tornado damage severity for three tornadoes with enhanced Fujita (EF) scale ratings (McDonald et al. 2004; WSEC 2006) of 3 or higher. Schultz et al. (2012a) observed a general trend of increasing TDS diameter and height for higher EF ratings for 19 tornado cases. Bodine et al. (2013) compared damage surveys from two EF4 tornadoes and found that the along-path EF rating tended to be correlated with 90th percentile $Z_{HH}$, as well as TDS height and volume. The 10th percentile $Z_{DR}$ and $r_{hv}$ values, however, exhibited a lower correlation with along-path EF rating. Although a general relationship appears...
to exist between TDS characteristics and damage severity, this relationship remains unclear because debris-scattering characteristics are poorly understood and the relationship between the amount of lofted debris and tornado dynamics (e.g., wind speed) has not been investigated.

Polarimetric radar observations have revealed some interesting characteristics of tornadic debris. Tornadic debris is generally thought to be randomly oriented in tornadoes (e.g., tumbling debris in tornado videos); however, polarimetric radar observations have revealed negative Z_{DR} in TDSs at the S, C, and X bands (Ryzhkov et al. 2005; Bluestein et al. 2007; Bodine et al. 2011, 2013). Two explanations have been proposed for negative Z_{DR} in TDSs: Mie scattering and common debris alignment. Mie scattering could cause negative Z_{DR} values, even without vertically oriented debris (Ryzhkov et al. 2005). For example, 50-mm-diameter dry hail produces negative Z_{DR} at S, C, and X bands (Snyder et al. 2010). Bluestein et al. (2007) suggested an alternative explanation that some degree of common alignment existed among scatterers, resulting in negative Z_{DR}.

In this study, statistical analyses of TDSs are presented using dual-wavelength polarimetric radar observations. Although TDSs have been documented at different wavelengths, dual-wavelength comparisons of TDSs have not yet been presented. Moreover, statistical properties of TDSs have not been thoroughly investigated, particularly as a function of height. A better characterization of the statistical properties of TDSs could improve tornado detection and damage severity estimates. This study also relates statistical analyses to surface damage characteristics to ascertain relationships between debris characteristics and polarimetric variables. Finally, polarimetric radar observations are compared to axisymmetric velocity retrievals to investigate the relationships between three-dimensional TDS structure and tornado dynamics.

The close proximity of an EF4 tornado on 10 May 2010 to the University of Oklahoma Polarimetric Radar for Innovations in Meteorology and Engineering (OU-PRIME; Palmer et al. 2011) and a polarimetric S-band Weather Surveillance Radar-1988 Doppler (WSR-88D; Doviak et al. 2000) radar in Norman, Oklahoma (KOUN), provides unique opportunities for close-range, dual-wavelength comparisons. Exploiting the large number of resolution volumes due to the tornado’s large diameter and close range, statistical analyses are performed to examine how polarimetric variables change as a function of height, and illuminate similarities and differences between S- and C-band TDSs.

Section 2 describes OU-PRIME and KOUN, permutation tests used in statistical radar comparisons, and T-matrix calculations for simplified debris. Dual-wavelength polarimetric radar analyses of TDSs are presented in section 3. Finally, conclusions from the study are presented in section 4.

2. Data and methods

This study investigates TDS statistics using OU-PRIME and KOUN polarimetric radar data. Detailed comparisons of the radars’ specifications, as well as an overview of the 10 May 2010 tornado outbreak, can be found in Palmer et al. (2011). OU-PRIME is a C-band, polarimetric radar with a 0.45° 3-dB beamwidth and a peak transmit power of 1 MW. On 10 May 2010, OU-PRIME operated a pulse length and range resolution of 125 m and maximum unambiguous velocity of 16 m s⁻¹. KOUN has a 0.9° 3-dB beamwidth, range resolution of 250 m, and a peak transmit power of 750 kW, and operated a maximum unambiguous velocity of 27.5 m s⁻¹. KOUN and OU-PRIME data are gridded and plotted in Cartesian coordinates, and dual-wavelength comparison plots are shown using zonal and meridional distances from KOUN. Radial velocity data were edited and dealiased using SOLOII software (Oye et al. 1995).

On 10 May 2010, OU-PRIME operated volumetric sector scans with update times between 2 min 20 s and 2 min 40 s. Volumetric sector scans included the following elevation angles: 1.0°, 2.0°, 3.0°, 4.0°, 5.0°, 6.5°, and 9.0°. KOUN operated volume coverage pattern (VCP) 12 (Brown et al. 2005b) for the volume scans presented in this study. The VCP 12 requires 4 min 18 s to complete, and includes the following elevation angles: 0.5°, 0.9°, 1.3°, 1.8°, 2.4°, 3.1°, 4.0°, 5.1°, 6.4°, 8.0°, 10.0°, 12.5°, 15.6°, and 19.5°. KOUN data at the lowest three elevation angles are oversampled at 0.5° resolution (Brown et al. 2005a).

KOUN and OU-PRIME scans exhibited serendipitously close temporal and spatial matching from 2230 to 2232 UTC. Table 1 shows beam heights at the center of the TVS, as well as scan times for the three comparisons of KOUN and OU-PRIME data. Differences in beam center heights for KOUN and OU-PRIME range from ±20 to 90 m, and scan times are nearly synchronous at the lowest-level comparison and differences in scan times approach 55 s at the highest tilt comparison. A notable difference is that KOUN’s resolution volumes are 2–2.5 times larger than OU-PRIME. Consequently, KOUN’s larger beamwidth illuminates debris at higher and lower altitudes compared to OU-PRIME. While some differences in resolution volumes exist, close temporal and spatial matching suggest that debris types within the tornado at a given height are likely similar. It is therefore assumed that statistical, dual-wavelength comparisons represent similar debris distributions.
A basic thresholding procedure is implemented to identify the debris field of the tornado. Some S-band resolution volumes within the tornado exhibit relatively high $p_{hv}$ (0.8–0.95) while C-band $p_{hv}$ is much lower. If thresholds imposed by previous studies are used to identify TDSs (e.g., Ryzhkov et al. 2005; Bodine et al. 2013), these high-$p_{hv}$ regions would be excluded from the analysis. Another issue arises from using high-$Z_{HH}$ thresholds, which remove resolution volumes with small or low concentrations of debris (e.g., within the weak-echo hole). To avoid removing high-$p_{hv}$ or low-$Z_{HH}$ resolution volumes at S band, all resolution volumes within the radius of maximum wind (RMW) of the tornado or low-level mesocyclone are included in the analysis. Between the RMW and 1.5 × RMW, the $p_{hv}$ threshold of 0.82 used by Bodine et al. (2013) is imposed but no threshold on $Z_{HH}$ is enforced. The extended region allows centrifuged debris outside of the RMW to be included in analyses, while excluding resolution volumes where hydrometeors are the dominant scatterers.

Nonparametric resampling techniques, such as the bootstrap or permutation tests, resample data without assumptions about the type of distribution that fits the data (Efron and Tibshirani 1993). Because underlying distributions of polarimetric variables in TDSs are unknown, nonparametric tests are applicable to this study. Permutation tests are used to determine the statistical significance of two samples with a null hypothesis that the two samples have the same parent distributions. The T-matrix calculation, polarimetric radar variables can be obtained for different types of hydrometeors (e.g., Vivekanandan et al. 1991; Zhang et al. 2001).

In this study, T-matrix calculations are presented for elongated debris to develop a basic understanding of polarimetric variables for two simplified debris types. Variations in debris sizes, irregularities in debris shapes, and varied compositions likely limit the applicability of these T-matrix calculations to other debris types. T-matrix calculations are performed using an axis ratio of 0.2 and 5 (i.e., oblate and prolate spheroids) for dry and wet debris. Wet debris is given a fractional water content of 50%, and complex dielectric factors for dry and wet debris are $1.9 + 0.01i$ and $15.9 + 4.6i$, respectively. The effective dielectric factor for wet debris is computed using the Maxwell-Garnett formula with water as the background. Figures 1 and 2 show $Z_{HH}$, $Z_{DR}$, and $\delta_{DP}$ for dry and wet elongated debris with axis ratios of 0.2 and 5. The value of $Z_{HH}$ is computed for a monodispersed size distribution with a debris concentration of 0.01 m$^{-3}$.

### 3. Statistical analysis of TDSs

#### a. 2229 UTC KOUN low-altitude TDSs

During the 2229:51 UTC volume scan, KOUN collected three levels of polarimetric radar data in the lowest 350 m of the tornado. Using these data, changes in polarimetric variables with height are investigated. The 0.5°-elevation KOUN velocity data indicate that the tornado was located southwest of the intersection of 119th Street and Douglas Boulevard. Satellite imagery indicates that the tornado passed through a densely wooded area west of Lake Stanley Draper with a low population density and a small number of man-made structures (Fig. 3). An interesting observation is that the 2229 UTC TVS is offset from the center of the damage path by 590 m. One explanation for the offset is that the most severe damage occurred on the southeast side of the tornado where storm motion increased ground-relative wind speeds. Vortex tilt can also cause separation.
between the TVS and the damage path. Given the low beam height of 110 m, however, an offset of 590 m would require a vortex tilt of about 80°.

Low-altitude KOUN scans show distinct TDSs with concentric regions of high \( Z_{HH} \) collocated with the TVSs and low \( r_{hv} \) (Fig. 4). Thirteen percent of the \( Z_{HH} \) values inside the TDS exceed 60 dBZ at 0.5° elevation compared to only 1% at 1.4° elevation (Fig. 5). The 90th percentile \( Z_{HH} \) exhibits a statistically significant decrease between the 0.5° and 1.4° elevations with a permutation test p value of 0.001 (Table 2). Decreasing \( Z_{HH} \) with height occurs frequently in tornadoes (e.g., Wurman et al. 1996; Wurman and Gill 2000; Bluestein et al. 2004; Dowell et al. 2005) as a consequence of debris centrifuging and fallout (Snow 1984; Dowell et al. 2005).

An increase in \( r_{hv} \) is evident between the 0.5° and 1.4°-elevation angles. The 1.4° \( r_{hv} \) histogram reveals a higher frequency of \( r_{hv} > 0.85 \) compared to the 0.5° \( r_{hv} \) histogram (Fig. 5). Median \( r_{hv} \) exhibits a statistically significant increase in \( r_{hv} \) with a permutation test p value of 0.014. The increase in \( r_{hv} \) with height may be attributed to a reduction in non-Rayleigh scattering as debris size decreases with height. Because debris distributions likely exhibit a range of debris sizes and shapes, some Rayleigh and non-Rayleigh scatterers contribute to the TDS. As larger debris are centrifuged and fall out, concentrations of non-Rayleigh scatterers will decrease, increasing \( r_{hv} \). Moreover, given the strong \( Z_{HH} \) dependence on size, decreasing debris size increases the relative power-weighted contributions of Rayleigh scatterers (e.g., raindrops or smaller debris) compared to non-Rayleigh scatterers, which also increases \( r_{hv} \).

Studies have discussed negative \( Z_{DR} \) in tornadoes, indicating some common degree of debris alignment and/or non-Rayleigh scattering. At 0.5° and 1.4° elevations, the median \( Z_{DR} \) are -0.1 and -0.3 dB, respectively. Permutation tests yield a p value of 0.206, indicating that a statistically significant change in median \( Z_{DR} \) is not likely. The 90th percentile \( Z_{DR} \) indicates a statistically significant reduction in large positive values of \( Z_{DR} \) at 1.4° compared to 0.5° (Table 2). Figure 4 shows this reduction in positive \( Z_{DR} \) values and a higher frequency of negative \( Z_{DR} \) at 1.4° elevation compared to the 0.5° elevation. A discussion of possible causes of negative
$Z_{DR}$ and decreasing $Z_{DR}$ with height is presented later.

High spatial $Z_{DR}$ variability is evident within the TDS (Fig. 4). The 0.5°-elevation $Z_{DR}$ histogram (Fig. 5) indicates a roughly symmetric distribution centered near 0 dB with some positive and negative $Z_{DR}$ values. Spatial variability of $Z_{DR}$ may depend on several factors. Errors in $Z_{DR}$ estimates and other polarimetric variables increase as $\rho_{hv}$ and signal-to-noise ratio (SNR) decrease (Bringi and Chandrasekar 2001). Thus, greater $Z_{DR}$ variability in TDSs may occur due to low $\rho_{hv}$, although high SNR in tornadoes containing large or numerous debris may mitigate this effect. Many debris exhibit large aspect ratios and may possess inherently large ranges of $Z_{DR}$ depending on their orientation. Random orientations of large debris, however, could cause near-zero $Z_{DR}$ if numerous debris are present. As the number of scatterers decrease, the large-magnitude $Z_{DR}$ of a few scatterers may contribute to higher variability of $Z_{DR}$.

b. 2230–2232 UTC dual-wavelength analyses

Dual-wavelength analyses of OU-PRIME and KOUN data are presented in this section, exploiting close temporal and spatial matching of radar scans between 2230 and 2232 UTC. For clarity, pairs of elevation angles at the approximately matching heights and times are abbreviated using C and S to refer to C and S band, as follows:

- comparison level 1—$C_1$ and $S_1$ for 1.0° OU-PRIME and 1.4° KOUN data,
- comparison level 2—$C_2$ and $S_2$ for 2.0° OU-PRIME and 2.4° KOUN data, and
- comparison level 3—$C_3$ and $S_3$ for 3.0° OU-PRIME and 4.0° KOUN data.

1) RADAR REFLECTIVITY FACTOR

The S-band $Z_{HH}$ exceeds C-band $Z_{HH}$ within the TDS. The 90th percentile $Z_{HH}$ at S band is 9.0–11.0 dB higher than at C band at each comparison height, and median $Z_{HH}$ at S band is 4.8–7.2 dB higher than at C band (Tables 3–5). Higher $Z_{HH}$ at S band has been observed for hail compared to X band (Atlas and Ludlam 1961; Snyder et al. 2010) and C band (Picca and Ryzhkov 2012) due to resonance effects. Likewise, resonance effects in TDSs may contribute to large $Z_{HH}$ differences at S and C bands. Given that the 90th percentile $Z_{HH}$ represents the highest radar reflectivity factors in the

![Fig. 2. As in Fig. 1, but for an axis ratio of 5.](image-url)
FIG. 3. Satellite imagery with an overlay of the NWS damage path (white lines) and locations of the 0.5°-elevation TVS (yellow pins) at (top) 2229:51 and (bottom) 2238:27 UTC. Images were created using Google Earth and satellite imagery from 8 Apr 2010.
Fig. 4. (top to bottom) KOUN $Z_{HH}$ (dBZ), radial velocity (m s$^{-1}$), $\rho_{HV}$, and $Z_{DR}$ (dB) at (left) 0.5° (2229:51 UTC) and (right) 1.4° (2230:24 UTC) elevations. TDSs are evident with high $Z_{HH}$ and low $\rho_{HV}$ collocated with the TVS.
TDS, these resolution volumes would be expected to contain the largest debris. Accordingly, larger dual-wavelength $Z_{HH}$ differences are observed for 90th percentile $Z_{HH}$ compared to median $Z_{HH}$, which may indicate larger debris sizes.

The T-matrix calculations reveal that S-band $Z_{HH}$ is often higher than C-band $Z_{HH}$. Dual-wavelength $Z_{HH}$ differences exhibit significant differences depending on the debris aspect ratio or wetness (Figs. 1 and 2). With the exception of wet, prolate spheroids, S-band $Z_{HH}$ is generally greater than or equal to C-band $Z_{HH}$. Several diameter ranges of dry and wet oblate spheroids and dry prolate spheroids could produce a TDS with 10-dB differences in S- and C-band $Z_{HH}$, such as dry, oblate spheroids with diameters between 22 and 32 mm.

2) COPOLAR CROSS-CORRELATION COEFFICIENT

Comparisons of OU-PRIME and KOUN data from 2230 to 2232 UTC reveal differences in $\rho_{hv}$. Figure 6

**TABLE 2.** The 90th percentile $Z_{HH}$ (dBZ), median $\rho_{hv}$, median $Z_{DR}$ (dB), and 90th percentile $Z_{DR}$ (dB) for the 0.5° and 1.4° KOUN elevation scans at 2229:51 UTC. The $p$ values are determined through hypothesis testing using a permutation test with 5000 permutations.

<table>
<thead>
<tr>
<th>Statistic</th>
<th>KOUN 0.5°</th>
<th>KOUN 1.4°</th>
<th>Difference</th>
<th>$p$ value</th>
</tr>
</thead>
<tbody>
<tr>
<td>90th percentile</td>
<td>60.8</td>
<td>56.5</td>
<td>4.3</td>
<td>0.001</td>
</tr>
<tr>
<td>$Z_{HH}$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Median $\rho_{hv}$</td>
<td>0.70</td>
<td>0.75</td>
<td>-0.05</td>
<td>0.014</td>
</tr>
<tr>
<td>Median $Z_{DR}$</td>
<td>-0.1</td>
<td>-0.3</td>
<td>0.2</td>
<td>0.206</td>
</tr>
<tr>
<td>90th percentile</td>
<td>2.7</td>
<td>2.0</td>
<td>0.7</td>
<td>0.020</td>
</tr>
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</table>
Table 3. Median and 90th percentile $Z_{HH}$ (dBZ), median $\rho_{hv}$, median $Z_{DR}$ (dB), 90th percentile $Z_{DR}$ (dB), and median $\Phi_{DP}$ (°) in the TDS and surrounding areas of rain, for the 1.0° OU-PRIME and 1.4° KOUN elevations. Center beam heights for OU-PRIME and KOUN are 360 and 340 m AGL, respectively. OU-PRIME and KOUN scan times are 2230:59–2231:14 and 2230:56–2231:13 UTC, respectively. For median $\Phi_{DP}$ in the TDS and rain, $p$ values are only calculated for $\Phi_{DP}$ differences between the TDS and rain, so the dual-wavelength differences are not calculated (NC).

<table>
<thead>
<tr>
<th>Statistic</th>
<th>OU-PRIME 1.0°</th>
<th>KOUN 1.4°</th>
<th>Difference</th>
<th>$p$ value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Median $Z_{HH}$</td>
<td>42.0</td>
<td>47.0</td>
<td>-5.0</td>
<td>0</td>
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<tr>
<td>90th percentile $Z_{HH}$</td>
<td>47.5</td>
<td>56.5</td>
<td>-9.0</td>
<td>0</td>
</tr>
<tr>
<td>Median $\rho_{hv}$</td>
<td>0.60</td>
<td>0.75</td>
<td>-0.15</td>
<td>0</td>
</tr>
<tr>
<td>Median $Z_{DR}$</td>
<td>0.2</td>
<td>-0.3</td>
<td>0.5</td>
<td>0.005</td>
</tr>
<tr>
<td>90th percentile $Z_{DR}$</td>
<td>3.5</td>
<td>2.0</td>
<td>1.5</td>
<td>0.001</td>
</tr>
<tr>
<td>$Z_{DR}$ MAD</td>
<td>1.1</td>
<td>1.5</td>
<td>-0.4</td>
<td>0.199</td>
</tr>
<tr>
<td>Median $\Phi_{DP}$ (TDS)</td>
<td>-8.2</td>
<td>9.6</td>
<td>-17.8</td>
<td>NC</td>
</tr>
<tr>
<td>Median $\Phi_{DP}$ (rain)</td>
<td>4.4</td>
<td>3.9</td>
<td>0.5</td>
<td>NC</td>
</tr>
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</table>

Table 4. As in Table 3, but for the 2.0° OU-PRIME and 2.4° KOUN elevations. Center beam heights for OU-PRIME and KOUN are 720 and 630 m AGL, respectively. OU-PRIME and KOUN scan times are 2231:14–2231:31 and 2231:44–2231:57 UTC, respectively.

<table>
<thead>
<tr>
<th>Statistic</th>
<th>OU-PRIME 2.0°</th>
<th>KOUN 2.4°</th>
<th>Difference</th>
<th>$p$ value</th>
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<tbody>
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<td>Median $Z_{HH}$</td>
<td>41.5</td>
<td>46.3</td>
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<tr>
<td>Median $\rho_{hv}$</td>
<td>0.61</td>
<td>0.76</td>
<td>-0.15</td>
<td>0.011</td>
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<tr>
<td>Median $Z_{DR}$</td>
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<td>-0.7</td>
<td>0.5</td>
<td>0.194</td>
</tr>
<tr>
<td>90th percentile $Z_{DR}$</td>
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<td>2.2</td>
<td>-0.3</td>
<td>0.194</td>
</tr>
<tr>
<td>$Z_{DR}$ MAD</td>
<td>1.1</td>
<td>1.5</td>
<td>-0.4</td>
<td>0.199</td>
</tr>
<tr>
<td>Median $\Phi_{DP}$ (TDS)</td>
<td>-7.2</td>
<td>11.8</td>
<td>-19.0</td>
<td>NC</td>
</tr>
<tr>
<td>Median $\Phi_{DP}$ (rain)</td>
<td>6.2</td>
<td>4.6</td>
<td>1.6</td>
<td>NC</td>
</tr>
</tbody>
</table>

shapes, sizes, and orientations may be a contributing factor to the large variability of $\rho_{hv}$ in TDSs. The increase in $\rho_{hv}$ with height at both S and C bands may result from a smaller ratio of non-Rayleigh scatterers to total scatterers due to debris fallout and centrifuging.

3) Differential Reflectivity

OU-PRIME and KOUN data exhibit similarities and differences in $Z_{DR}$. Contiguous regions of negative $Z_{DR}$ are observed at both $S_1$ and $C_1$, respectively (Fig. 6). Mean values of $S_1$ and $C_1$ median $Z_{DR}$ are $-0.3$ and $0.2$ dB, respectively, indicating lower $Z_{DR}$ at S band (Table 3). Higher 90th percentile $Z_{DR}$ is observed at C band, with a greater dual-wavelength difference in the 90th percentile $Z_{DR}$ compared to median $Z_{DR}$.

An intriguing observation of TDS studies is that coherent regions of negative $Z_{DR}$ are observed while positive $Z_{DR}$ regions are only observed in regions of higher $\rho_{hv}$, where precipitation entrainment is suspected. If no common debris alignment occurs, individual debris would produce both large positive and negative $Z_{DR}$, which could average to near-zero values for a resolution.

Table 5. As in Table 3, but for the 3.0° OU-PRIME and 4.0° KOUN elevations. Center beam heights for OU-PRIME and KOUN are 1110 and 1090 m AGL, respectively. OU-PRIME and KOUN scan times are 2231:31–2231:47 and 2232:13–2232:26 UTC, respectively.

<table>
<thead>
<tr>
<th>Statistic</th>
<th>OU-PRIME 3.0°</th>
<th>KOUN 4.0°</th>
<th>Difference</th>
<th>$p$ value</th>
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</thead>
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<tr>
<td>Median $Z_{HH}$</td>
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<td>47.0</td>
<td>-7.2</td>
<td>0</td>
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<tr>
<td>90th percentile $Z_{HH}$</td>
<td>43.5</td>
<td>54.5</td>
<td>-11.0</td>
<td>0</td>
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<tr>
<td>Median $\rho_{hv}$</td>
<td>0.66</td>
<td>0.80</td>
<td>-0.14</td>
<td>0.2</td>
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<tr>
<td>Median $Z_{DR}$</td>
<td>0.1</td>
<td>-0.1</td>
<td>0.2</td>
<td>0.325</td>
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<tr>
<td>90th percentile $Z_{DR}$</td>
<td>1.8</td>
<td>2.5</td>
<td>-0.7</td>
<td>0.006</td>
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<tr>
<td>$Z_{DR}$ MAD</td>
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<td>1.8</td>
<td>-0.8</td>
<td>0.200</td>
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<tr>
<td>Median $\Phi_{DP}$ (TDS)</td>
<td>2.0</td>
<td>13.1</td>
<td>-11.1</td>
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<tr>
<td>Median $\Phi_{DP}$ (rain)</td>
<td>11.4</td>
<td>6.7</td>
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</tbody>
</table>
FIG. 6. (left) The 1.4° KOUN (2230:56 UTC) and (right) 1° OU-PRIME (2230:59 UTC) for (top to bottom) $Z_{HH}$ (dBZ), $\rho_{HV}$, $Z_{DR}$ (dB), and $\Phi_{DP}$ (°). The x and y coordinates show the distance from KOUN (km). Generally, $\rho_{HV}$ is higher at S band compared to C band. Within the TDS, $\rho_{HV}$ at C band is typically $<0.7$ while S-band $\rho_{HV}$ is $>0.7$ in the same regions. Both KOUN and OU-PRIME exhibit considerable variability in $Z_{DR}$ and regions of negative $Z_{DR}$. The S-band (C band) $\Phi_{DP}$ exhibits a positive (negative) shift within the TDS.
Bluestein et al. (2007) suggest that a small amount of commonly aligned debris in a resolution volume could cause negative $Z_{DR}$. In such cases, distinct peaks in the Doppler spectra would likely be evident. In the present case, C-band Doppler spectra in negative $Z_{DR}$ regions are generally flat or exhibit broad peaks, suggesting that a large amount of debris contributes to negative $Z_{DR}$ measurements.

The negative $Z_{DR}$ signature occurs when the tornado is passing over a heavily vegetated area with few man-made structures near Lake Stanley Draper (Fig. 3), and the NWS damage survey notes extensive tree damage in this area. Although some larger debris from structures could be lofted, numerical modeling simulations have shown that most of the large, dense debris falls out in the lowest 300 m AGL (Snow 1984; Dowell et al. 2005). Based on satellite imagery and the damage survey, it is speculated that vegetation, such as leaves or small tree branches, are the dominant scatterers in the TDS during this dual-wavelength comparison at 340–360 m AGL. A second explanation is that a small concentration of large debris remains above 300 m AGL, and produces negative $Z_{DR}$.

The presence of both very low $\rho_{HV}$ and negative $Z_{DR}$ creates an interesting conundrum. Given low $\rho_{HV}$ collocated with the negative $Z_{DR}$ signature, scatterers likely exhibit non-Rayleigh scattering and/or a low common degree of scatterer alignment. Balakrishnan and Zrnić (1990) found that as the degree of common alignment of wet hail decreases, $\rho_{HV}$ decreases. Hence, very low $\rho_{HV}$ may suggest a low degree of common alignment. However, given that debris-scattering characteristics are complex.

FIG. 7. Histograms of (left) OU-PRIME and (right) KOUN $\rho_{HV}$ at comparable beam heights. As height increases, $\rho_{HV}$ increases at both S and C bands.
due to their unusual shapes, sizes, and compositions, we speculate that the wide range of scatterer characteristics within a resolution volume could still produce very low $\rho_{hv}$ even if some degree of common scatterer alignment exists. Given the large intrinsic $Z_{DR}$ values of debris (Figs. 1c,f), even a small degree of common alignment could produce the slightly negative $Z_{DR}$ values observed herein. We speculate that observations of increasingly negative $Z_{DR}$ with height could result from a greater tendency of smaller, less-dense debris to exhibit a greater degree of common alignment whereas larger debris near the surface are exhibit a lower degree of common alignment.

Within the TDS at both S and C bands, $Z_{DR}$ exhibits large spatial variability (Fig. 6). Errors in $Z_{DR}$ measurements increase as $\rho_{hv}$ decreases (Bringi and Chandrasekar 2001), which may account for some variability in $Z_{DR}$. Histograms of $Z_{DR}$ at each comparison level (Fig. 8) also reveal the high variability of $Z_{DR}$ at each elevation angle. Although S-band $Z_{DR}$ MAD is higher at each elevation angle compared to C band, the permutation test $p$ value is 0.198–0.200. Thus, the permutation test does not yield statistical significance for dual-wavelength $Z_{DR}$ MAD differences.

4) DIFFERENTIAL PROPAGATION PHASE

Within the TDS, the differential propagation phase $\delta_{DP}$ exhibits high variability and different offsets at S and C bands compared to surrounding areas of rain (Fig. 6). Non-Rayleigh scattering effects by numerous debris within resolution volumes, likely contribute to the high variability of $\delta_{DP}$, leading to the high variability

Fig. 8. As in Fig. 7, but for $Z_{DR}$ (dB). Higher variability of $Z_{DR}$ is observed at S band compared to C band, although statistically significant differences are not observed.
of \( \Phi_{DP} \). An interesting observation is that \( \Phi_{DP} \) exhibits an offset from \( \Phi_{DP} \) values outside of the TDS. To investigate these differences, median \( \Phi_{DP} \) values inside and outside of the TDS are calculated to illuminate the differences in \( \Phi_{DP} \). The same thresholding procedure discussed in section 2 is used to identify the TDS. To provide a comparison in areas of rain, resolution volumes with \( \rho_{hv} \) above 0.98 and 0.93 at S and C bands, respectively, are identified within an annulus between the radius of maximum wind and a 4-km radius from the vortex center.

Higher (lower) median \( \Phi_{DP} \) is observed within the TDS at S band (C band) compared to surrounding areas of rain. Tables 3–5 present median S- and C-band TDS at S band (C band) compared to surrounding areas of rain. The \( \rho_{hv} \) values for \( S_1 - S_3 \) and \( C_1 - C_3 \) are 0, indicating a statistically significant offset in median \( \Phi_{DP} \) within the TDS at both S and C bands.

The \( \delta_{DP} \) folding may account for the observations of a slightly positive (negative) shift in \( \Phi_{DP} \) at S band (C band). The \( \delta_{DP} \) folding occurs where \( \delta_{DP} \) changes from \(-180^\circ\) to \(180^\circ\), or from \(180^\circ\) to \(-180^\circ\) (Figs. 1 and 2). Because of the larger electrical sizes of scatterers at C band compared to S band, the first \( \delta_{DP} \) fold at C band occurs at a smaller diameter compared to S band. For example, in the case of wet, oblate debris (Fig. 11), the first \( \delta_{DP} \) folds at S and C bands occur at 47 and 23 mm, respectively. Based on KOUN and OU-PRIME observations, positive (negative) \( \delta_{DP} \) at S band (C band) could result for diameter ranges of 24–41 or 62–72 mm.

Based on T-matrix calculations, if a large range of scatterer diameters are present, an offset is less likely because multiple folds average out large positive and negative \( \delta_{DP} \). On the other hand, if a small range of scatterer diameters are present, or a few similarly sized debris dominate the backscattered radar signal, then a distinct \( \delta_{DP} \) offset is more likely. Hence, \( \delta_{DP} \) offsets could provide some qualitative information about debris size distributions. However, using \( \delta_{DP} \) to estimate debris size might not be feasible because \( \delta_{DP} \) depends on poorly known variables such as debris composition, orientation, and water coating.

c. 2237–2238 UTC volume scans

The 2238 UTC KOUN volume scan encompasses the period of most severe tornado damage. At 2238 UTC, 0.5° KOUN velocity data reveal that the tornado had just passed over Interstate 40 (I-40) near Choctaw Road (Fig. 3). An NWS damage survey found EF4 tornado damage to houses in the Deerfield West subdivision just west of I-40, and a gas station and restaurant sustained up to EF3 damage as the tornado passed over I-40 (NOAA/National Climatic Data Center 2013).

Decreasing \( Z_{HH} \) with height is observed at 2238 UTC (Fig. 9), indicating a decrease in debris size or concentration with height. The 90th percentile \( Z_{HH} \) exhibits a statistically significant decrease in height with a permutation test \( p \) value of 0.001 (Table 6). Given differences in damage severity and terrain characteristics between the 2229 and 2238 UTC volume scans, polarimetric variables might be expected to exhibit some differences. To compare similar altitudes between the 2229 and 2238 UTC scans, 0.9° KOUN data at 2229 UTC (\( z = 210 \) m) and 0.5° KOUN data at 2238 UTC (\( z = 200 \) m AGL) are selected. The 2238 UTC 0.5°-elevation median and 90th percentile \( Z_{HH} \) are 7.3 and 3.0 dB higher, respectively, compared to the 2229 UTC 0.5°-elevation KOUN data. Permutation tests yield \( p \) values of 0 for both statistics, indicating statistically significant differences.

Higher \( \rho_{hv} \) is observed in the TDS at 2238 UTC compared to 2229 UTC. The 2238 UTC 0.5° median \( \rho_{hv} \) is 0.04 higher than the 2229 UTC 0.9° \( \rho_{hv} \). Permutation tests indicate that the median \( \rho_{hv} \) difference is statistically significant at a \( p \) value of 0.029. A possible cause of higher \( \rho_{hv} \) in tornadoes is precipitation entrainment. \( \rho_{hv} \) increases and increases in \( Z_{DR} \) have been observed when rainbands wrap around tornadoes (Schwarz and Burgess 2011; Bodine et al. 2011). In the present case, permutation tests indicate that changes in median and 90th percentile \( Z_{DR} \) are not statistically significant, for this case.

Similarities are observed in the 2238–2239 UTC dual-wavelength analyses to the earlier dual-wavelength analyses. For the 1.4° KOUN and 1° OU-PRIME elevation angles, the S-band median and 90th percentile \( Z_{HH} \) are higher compared to C-band \( Z_{HH} \) (Table 7) with \( p \) values of 0 for median and 90th percentile \( Z_{HH} \), indicating statistically significant differences in \( Z_{HH} \). Figure 10 reveals that \( \rho_{hv} \) is higher in the TDS at S band compared to C band, with a difference of \(-0.12\). The permutation test \( p \) value of 0 indicates a statistically significant difference in median \( \rho_{hv} \) at S and C bands.

Some interesting differences are observed during the 2238–2239 UTC dual-wavelength comparison compared to the earlier dual-wavelength analyses. Median and 90th percentile \( Z_{HH} \) are 9.8 and 9.7 dB higher at S band compared to C band. In contrast to the 2231 UTC dual-wavelength comparison, median \( Z_{HH} \) does not exhibit a smaller dual-wavelength difference compared to the 90th percentile \( Z_{HH} \). This result indicates a greater number of resolution volumes containing large dual-wavelength \( Z_{HH} \) differences during the 2238–2239 UTC comparison, and may suggest greater amounts of large debris lofted compared to the 2230–2232 UTC comparison. Given the increased damage severity at 2238 UTC indicated by the damage survey and the higher
density of man-made structures (Fig. 3), an increase in lofted debris size is consistent with the damage survey. Differences are also noted in $\Phi_{DP}$ compared to the earlier dual-wavelength comparison. For median $\Phi_{DP}$, a negative shift is observed at C band while a statistically significant shift in S-band $\Phi_{DP}$ is not observed in the TDS.

d. Range profiles of polarimetric radar data and axisymmetric velocity

Axisymmetric velocity retrieval techniques have been applied to high-resolution radar data to retrieve three-dimensional tornado wind fields (e.g., Lee et al. 1999; Lee and Wurman 2005; Dowell et al. 2005). Range profiles of axisymmetric radial and tangential velocities, $u_p(r)$ and $v_p(r)$, are retrieved using a method developed by Dowell et al. (2005), which uses a least squares fit for Doppler radial velocity data. To avoid confusion between axisymmetric radial velocities and Doppler radial velocity, the latter will be referred to as Doppler velocity hereafter. For KOUN and OU-PRIME, $u_p(r)$ and $v_p(r)$ are computed for 250-m-wide annuli, at 125-m intervals, respectively. Velocity retrievals are obtained for the 2229 UTC KOUN and 2230 UTC OU-PRIME volume scans at low elevation angles.

A comparison of KOUN and OU-PRIME at similar altitudes shows the close agreement between retrieved velocity profiles from the two radars. Figures 11a–d show range profiles of radial and tangential winds, and Figs. 11e–h show range profiles of $Z_{HH}$ and $\rho_{HV}$. The maximum tangential wind speeds from 1.4° KOUN and 1.0° OU-PRIME are 46 and 50 m s$^{-1}$, respectively (Fig. 11b). Although the radar comparison yields relatively
Table 6. 90th percentile $Z_{HH}$ (dBZ), median $\rho_{HV}$, and median and 90th percentile $Z_{DR}$ (dB) for the 0.5° and 1.4° KOUN elevation scans at 2238:27 UTC. The $p$ values are determined through hypothesis testing using a permutation test with 5000 permutations.

<table>
<thead>
<tr>
<th>Statistic</th>
<th>KOUN 0.5°</th>
<th>KOUN 1.4°</th>
<th>Difference</th>
<th>$p$ value</th>
</tr>
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<tr>
<td>$Z_{HH}$</td>
<td>62.5</td>
<td>58.2</td>
<td>4.3</td>
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<tr>
<td>Median $\rho_{HV}$</td>
<td>0.78</td>
<td>0.79</td>
<td>-0.01</td>
<td>0.435</td>
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<tr>
<td>Median $Z_{DR}$</td>
<td>0.5</td>
<td>0.0</td>
<td>0.5</td>
<td>0.165</td>
</tr>
<tr>
<td>90th percentile $Z_{DR}$</td>
<td>2.5</td>
<td>3.4</td>
<td>-0.9</td>
<td>0.130</td>
</tr>
</tbody>
</table>

Table 7. The 90th percentile and median $Z_{HH}$ (dBZ), median $\rho_{HV}$, median $Z_{DR}$ (dB), 90th percentile $Z_{DR}$ (dB), $Z_{DR}$ MAD (dB), and median $\Phi_{DP}$ (°) in the TDS and surrounding areas of rain, for 1.0° OU-PRIME and 1.4° KOUN elevation scans. Center beam heights for OU-PRIME and KOUN are 484 and 595 m AGL, respectively, and resolution volume sizes for OU-PRIME and KOUN are 0.014 and 0.059 km$^3$, respectively. OU-PRIME and KOUN scan times are 2238:13–2238:31 and 2239:31–2239:48 UTC, respectively.

<table>
<thead>
<tr>
<th>Statistic</th>
<th>OU-PRIME</th>
<th>KOUN</th>
<th>Difference</th>
<th>$p$ value</th>
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<tr>
<td>Median $Z_{HH}$</td>
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<td>90th percentile $Z_{HH}$</td>
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<td>58.2</td>
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<tr>
<td>Median $\rho_{HV}$</td>
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<td>0.79</td>
<td>-0.12</td>
<td>0.001</td>
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<tr>
<td>Median $Z_{DR}$</td>
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<td>0.2</td>
<td>0.37</td>
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<tr>
<td>90th percentile $Z_{DR}$</td>
<td>1.1</td>
<td>3.8</td>
<td>-2.7</td>
<td>0.001</td>
</tr>
<tr>
<td>$Z_{DR}$ MAD</td>
<td>0.7</td>
<td>1.5</td>
<td>0.8</td>
<td>0.200</td>
</tr>
<tr>
<td>Median $\Phi_{DP}$ (TDS)</td>
<td>1.8</td>
<td>7.6</td>
<td>-5.8</td>
<td>NC</td>
</tr>
<tr>
<td>Median $\Phi_{DP}$ (rain)</td>
<td>13.9</td>
<td>7.8</td>
<td>6.1</td>
<td>NC</td>
</tr>
</tbody>
</table>

close agreement, some differences may result from different resolution volume geometries and spatial resolutions. Larger resolution volume sizes from KOUN may not fully sample the azimuthal Doppler velocity profile, which may result in an underestimate of the maximum tangential wind speed (e.g., Carbone et al. 1985). Errors in KOUN least squares fit velocity estimates may also be higher because fewer resolution volumes are available within each annulus.

Comparisons of polarimetric variables and the wind retrievals suggest possible effects of debris centrifuging on retrieved velocity profiles. A consistent trend in range profiles of radial velocity from 100 to 720 m AGL (Figs. 11a–d) is radial divergence ($du_p/dr > 0$) from the vortex center to radii of 0.5–0.75 km, with radial convergence ($du_p/dr < 0$) beyond these radii. If air–scatterer velocity differences are neglected, integration of the continuity equation would reveal a two-cell vortex with a central downdraft surrounded by an annulus of updraft. In the region of largest $u_p$, median $Z_{HH}$ exceeds 45 dBZ and median $\rho_{HV}$ is below 0.8 (Figs. 11e–h). Thus, dominant scatterers in the region of radial divergence and positive $u_p$ are torndbris. Because scatterer properties, such as size or density, must be known to estimate debris centrifuging effects, contributions of debris centrifuging to the radial wind component cannot be accurately determined.

Range profiles near the surface exhibit decreasing $Z_{HH}$ as a function of range. The 0.5° KOUN $Z_{HH}$ profile (Fig. 11a; $z = 110$ m) reveals a maximum in $Z_{HH}$ at the center of the tornado, suggesting that the vortex center contains the largest debris, the highest concentration of debris, or both. One explanation for this observation is that inflow may inhibit debris centrifuging at low levels. Range profiles of radial winds indicate inflow at $r > 1$ km, with maximum inflow velocities of $-15$ m s$^{-1}$. At closer radii, debris centrifuging or debris falling into the inflow layer may mask inflow winds (e.g., Dowell et al. 2005). A second explanation is that a smaller-scale vortex is present within the 1-km-scale vortex, which could enhance debris generation and lofting. The 0.5° Doppler velocity data indicate that a smaller-scale vortex may be embedded within the 1-km-scale radius vortex. However, the smaller-scale vortex is not adequately resolved by KOUN, so the maximum tangential wind speed within the smaller-scale vortex is unknown.

At 350 m AGL, $Z_{HH}$ remains approximately constant with range inside the TDS (Fig. 11f). The highest value of $u_p$ within the tornado of 15.7 m s$^{-1}$ is observed at a range of 750 m AGL. Positive $u_p$ values at 0.21 and 0.34 km indicate the outward motion of scatterers from $r = 0$ to 750 m. Compared to 0.5° elevation ($z = 110$ m), lower $Z_{HH}$ at 1.4° elevation is observed near the center of the tornado, and higher $Z_{HH}$ is observed closer to the maximum $u_p$ (Fig. 11f). The shift of higher $Z_{HH}$ toward greater ranges likely arises from debris centrifuging, radially outward debris motion caused by a two-cell vortex (divergence within core flow), or both. At 2° elevation ($z = 720$ m AGL), OU-PRIME data reveal a weak-echo hole (WEH; Fujita 1981; Wurman et al. 1996; Wurman and Gill 2000; Bluestein et al. 2004; Dowell et al. 2005). Within the WEH, the median $\rho_{HV}$ exhibits a relative maximum within the RMW even though a minimum in $Z_{HH}$ is observed. The increase in $\rho_{HV}$ in the center of the tornado may result from a decrease in the mean size of scatterers due to centrifuging, and therefore reduce the proportion of scatterers exhibiting non-Rayleigh scattering (Fig. 11c; $z = 720$ m).

4. Conclusions

Statistical analyses of dual-wavelength polarimetric TDSs are presented with comparisons to damage surveys. Low-altitude KOUN radar measurements are examined to investigate changes in polarimetric TDSs with height.
FIG. 10. As in Fig. 6, KOUN (2239:31 UTC) and OU-PRIME (2238:13 UTC). TDSs are evident at both S and C bands and the TDS is farther east for the KOUN scan due to the time difference between scans. As observed during the earlier dual-wavelength comparison, $\rho_{HV}$ is higher at S band compared to C band.
While the tornado passed through a region of dense vegetation, KOUN data reveal that $Z_{HH}$ decreases with height, $r_{hv}$ increases with height, and $Z_{DR}$ became increasing negative. Debris centrifuging and fallout likely results in a reduction in larger scatterers, which decreases $Z_{HH}$. If a large number of non-Rayleigh scatterers fall out, an increase in $r_{hv}$ should occur with height.

As the tornado passed through an urban area where EF3 and EF4 damage was observed, KOUN data reveal that $Z_{HH}$ decreases with height while statistically significant changes in other polarimetric variable statistics are not observed. Higher 90th percentile $Z_{HH}$ dual-wavelength differences of 10 dB are observed. A larger dual-wavelength difference in median $Z_{HH}$ occurs while the tornado caused greater amounts of damage, which suggests a greater amount of lofted large debris. Dual-wavelength comparisons reveal that S-band median $r_{hv}$ is 0.12–0.15 higher than C-band $r_{hv}$. Non-Rayleigh scattering effects may account for lower $r_{hv}$ at C band as a consequence of a larger proportion of non-Rayleigh scatterers and

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**Fig. 11.** (left) Range profiles of radial (solid lines) and tangential (dashed lines) velocity from the 2229 UTC KOUN (red) and 2230 UTC OU-PRIME (blue) volume scans showing (a) 2.0° OU-PRIME ($z = 0.72$ km), (b) 1.0° OU-PRIME ($z = 0.36$ km) and 1.4° KOUN ($z = 0.34$ km), (c) 0.9° KOUN ($z = 0.21$ km), and (d) 0.5° KOUN ($z = 0.11$ km). (e)–(h) As in (a)–(d), but for $Z_{HH}$ (dBZ, left $y$-axis, solid lines) and $r_{hv}$ (right $y$-axis, dashed lines). Beam heights at the center of the tornado are labeled in (a)–(d).
greater sensitivity to deviations from spherical shapes at C band. Increasing $\rho_{hv}$ is observed with increasing height above 350 m AGL, which could indicate a smaller proportion of non-Rayleigh scatterers resulting from the fallout of larger debris.

A conceptual diagram of the polarimetric TDS at different altitudes is presented in Fig. 12. At lower altitudes, a $Z_{HH}$ maximum occurs in the center of the vortex and low $\rho_{hv}$ is observed throughout the TDS. At 350 m, relatively uniform $Z_{HH}$ and low $\rho_{hv}$ are observed, indicating an outward centrifuging of debris from the vortex center compared to lower altitudes. At 720 m, a weak-echo hole and a $\rho_{hv}$ maximum are observed in the vortex center, implying lower concentrations of non-Rayleigh scatterers, reduced concentrations of debris, or both.

Range profiles of polarimetric variables and axisymmetric velocity retrievals suggest debris-centrifuging effects on velocity retrievals. Higher $Z_{HH}$ and low $\rho_{hv}$ are observed in regions of positive $u_p$, indicating an outward motion of scatterers within the TDS. Using range profiles, polarimetric radar observations, and velocity retrievals may help identify areas where debris centrifuging may contaminate Doppler velocity measurements. Unfortunately, contributions of debris centrifuging to velocity retrievals cannot be determined without substantial speculation about debris-scattering characteristics.

This study addresses the need for statistical analyses of TDSs and dual-wavelength polarimetric radar comparisons of TDSs with good spatial and temporal matching. Dual-wavelength comparisons of TDSs illuminate some general characteristics of debris scattering.
which may help interpret TDSs. Although dual-wavelength polarimetric radar measurements are uncommon in an operational setting, dual-wavelength $Z_{HV}$ observations of TDSs are possible using the WSR-88D network with C-band Terminal Doppler Weather Radars or television station radars. Moreover, future radar networks could include polarimetric radars with different operating frequencies, including closely spaced X-band radars (McLaughlin et al. 2009).

Some intriguing differences are noted in TDS structure with height and at different wavelengths, indicating some potential for debris-size estimation using polarimetric radar. A debris-size-estimation technique could help estimate and correct debris-centrifuging effects on Doppler radial velocity fields and three-dimensional wind field retrievals. Wakimoto et al. (2012) proposed a method of correcting debris-centrifuging effects using the radar reflectivity factor under the assumption that scatterers within the tornado were similar to raindrops, and estimated centrifuging effects based on drop diameters retrieved from a Marshall–Palmer drop size distribution. They noted large differences in ground-based velocity tracking display (GBVTD; Lee et al. 1999) vertical velocity fields for corrected and uncorrected radial velocities. Common observations of low $\rho_{HV}$ in tornadoes suggest that tornadic debris exhibit resonance effects and are larger than raindrops. Accordingly, applying this method may result in an underestimation of debris diameter and centrifuging effects. To correct the radial velocity for debris centrifuging, a quantitative retrieval of debris distribution characteristics (e.g., size, concentration, type) would be needed, and would require a fundamental investigation of debris-scattering characteristics to understand the relationship between debris characteristics and polarimetric radar variables.

Acknowledgments. This research effort was partially supported by NSF Grant AGS-1303685. The authors thank Boon Leng Cheong for his assistance operating OU-PRIME on 10 May 2010. Discussions with Kim Elmore and Jim Kurdzo helped improve the manuscript. The authors greatly appreciate detailed damage surveys provided by Doug Speheger and others who contributed to the 10 May 2010 damage surveys. Comments from two anonymous reviewers also helped improve the quality of the manuscript.

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