Observations of Polarimetric Signatures in Supercells by an X-Band Mobile Doppler Radar

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ABSTRACT

Polarimetric weather radars significantly enhance the capability to infer the properties of scatterers within a resolution volume. Previous studies have identified several consistently seen polarimetric signatures in supercells observed in the central United States. Nearly all of these studies used data collected by fixed-site S- and C-band radars. Because there are few polarimetric mobile radars, relatively little has been documented in high-resolution polarimetric data from mobile radars. Compared to S and C bands, there has been very limited examination of polarimetric signatures at X band.

The primary focus of this paper is on one signature that has not been documented previously and one that has had little documentation at X band. The first signature, seen in at least seven supercell datasets collected by a mobile, X-band, polarimetric radar, consists of a narrow band of locally reduced reflectivity factor $Z_H$ and differential reflectivity, typically near the location where the hook echo “attaches” to the main body of the storm echo. No consistent pattern is seen in radial velocity $V_R$ or copolar cross correlation $r_{HV}$. The small size of this feature suggests a significant heterogeneity in precipitation microphysics, the cause and impact of which are unknown. The greater resolution and the scattering differences at X band compared to other frequencies may make this feature more apparent. The second signature consists of anomalously low $r_{HV}$ in areas of high $Z_H$ along the left section (relative to storm motion) of the bounded weak-echo region. Examples of other polarimetric signatures at X band are provided.

1. Introduction

Weather radars have been used for decades as a remote sensing tool to collect data on scales many times larger than is available from in situ observation platforms. Indeed, radars have been a valuable tool for examining the structure and dynamics of supercells (e.g., Browning and Donaldson 1963; Browning 1964; Marwitz 1972; Brandes 1978, 1984, 1993; Lemon and Doswell 1979), and many of the early studies using radar data primarily focused on power-based (e.g., radar reflectivity factor) and radial velocity measurements. Radars have been used at fixed-site locations, on airborne platforms (e.g., Wakimoto et al. 1996; Bluestein and Gaddy 2001), and on mobile platforms (e.g., Bluestein and Unruh 1989; Bluestein et al. 1995; Wurman et al. 1997; Bluestein and Pazmany 2000; Biggerstaff et al. 2005; Bluestein et al. 2010a,b; Weiss et al. 2011). More recently, there has been a significant increase in the number of polarimetric radars; there are now more polarimetric mobile radars (Bluestein et al. 2007a,b; Burgess et al. 2010; Asefi-Najafabady et al. 2010; Pazmany and Bluestein 2011; Wurman et al. 2011; M. I. Biggerstaff 2010, personal communication) and polarimetric fixed-site radars (Hubbert et al. 1998; Doviak et al. 2000; Petersen et al. 2007; McLaughlin et al. 2009; Palmer et al. 2011) than ever before.

As the number of polarimetric weather radar datasets collected in supercells has increased, numerous polarimetric signatures have been observed and described [e.g., Kumjian and Ryzhkov 2008 (KR08); Romine et al. 2008 (R08), among others]. Zrnić and Ryzhkov (1999) and Straka et al. (2000) extensively discuss the polarimetric characteristics of different hydrometeors, though their discussions are focused primarily on S-band radar systems. Hydrometeor classification schemes using fuzzy logic have
have been developed at S band (e.g., Vivekanandan et al. 1999; Liu and Chandrasekar 2000; Zrnić et al. 2001; Ryzhkov et al. 2005b; Park et al. 2009), C band (e.g., Keenan 2003; Lim et al. 2005; Marzano et al. 2006), and, more recently, X band (Iwanami et al. 2007; Dolan and Rutledge 2009; Snyder et al. 2010b). Polarimetric data have also been used in quantitative precipitation estimation (e.g., Sutchilli et al. 1993; Ryzhkov and Zrnić 1995, 1996; Matrosov et al. 1999, 2002; Brandes et al. 2002; Le Bouar et al. 2002; Ryzhkov et al. 2005a; Giangrande et al. 2008) and in drop size distribution (DSD) retrievals (e.g., Zhang et al. 2001; Gorgucci et al. 2002; Brugi et al. 2002; Brandes et al. 2004a, b; Vivekanandan et al. 2004; Caio et al. 2008).

Although previous papers—such as Conway and Zrnić (1993), KR08, and R08—provide conceptual models of some often-seen signatures within supercells, there are important differences between those previous studies and this current study. As a result of being mounted on a truck, the UMass X-Pol (details of which are provided in the next section) has been able to collect data at much higher spatial and temporal resolutions than fixed-site radar systems that have broader scanning strategies; because mobile radars can be relocated to minimize the distance to the target, spatial resolution can be maximized. In addition, the scanning strategies employed to collect data of supercells examined in this paper often provide the flexibility to designate sectors and/or elevation angles that result in enhanced temporal resolution. The added benefits of mobile radars are the reason why they served as a major facet of the second Verification of the Origins of Rotation in Tornadoes Experiment (VORTEX 2; Wurman et al. 2012).

In addition to differences in spatial resolution, much of the past work examining the polarimetric structure of supercells has been done using S-band and C-band data (e.g., Van Den Broeke et al. 2008; KR08; R08, among many others); the availability of X-band polarimetric radar data of severe convective storms has been rather limited until the past few years (e.g., Bluestein et al. 2007a, b). Scattering simulations of rain and hail (Fig. 1), for example, indicate that the often-used polarimetric radar variables can vary significantly with radar frequency (Bringi et al. 1990; Vivekanandan et al. 1990; Feré et al. 2003; Ryzhkov and Zrnić 2005; Kumjian et al. 2010; Anderson et al. 2011; Borowska et al. 2011; Ryzhkov et al. 2011; Picca and Ryzhkov 2012). For example, whereas one may be accustomed to associating very high $Z_H$ (e.g., $Z_H > 65$ dBZ$_H$) with large hail when using S-band data, such large hail may have $Z_H < 50$ dBZ$_H$ at X band. As such, the polarimetric signature of large hail is likely to be different at X band than it is at S band. It is important that one keep these differences in mind as more data are collected with emerging X-band polarimetric fixed-site radar networks, such as the X-band polarimetric radar network (X-NET) in Japan (Maki et al. 2010) and the Collaborative Adaptive Sensing of the Atmosphere network (CASA) in the United States (McLaughlin et al. 2009), and X-band polarimetric mobile radars, such as the rapid-scanning X-band polarimetric Doppler radar (RaXPoL; Pazmany and Bluestein 2011), the National Oceanic and Atmospheric Administration (NOAA) X-band polarimetric radar (NOXP; Burgess et al. 2010), the Mobile Alabama X-band radar (MAX; Asefi-Najafabady et al. 2010), and the Doppler-on-Wheels (DOW; J. Wurman 2010, personal communication).

In datasets collected by the UMass X-Pol throughout the central United States, a signature has been identified that has yet to receive discussion in the formal literature, and another signature has been observed that has not yet been documented in high-resolution X-band data. The first signature, recently observed in Snyder et al. (2010a), Wurman et al. (2010), and Kosiba et al. (2011), is primarily seen in the lowest 3 km of the supercell and is characterized by a narrow, winding zone of locally reduced reflectivity factor at horizontal polarization $Z_H$ and differential reflectivity $Z_{DR}$ and characterized by a narrow, winding zone of locally reduced reflectivity factor at horizontal polarization $Z_H$ and differential reflectivity $Z_{DR}$ (Seliga and Bringi 1976). This feature is located along the very rear portion of the forward-flank downdraft (FFD) near the hook echo. The second signature that serves as the primary focus of this paper is characterized by a band of very low copolar cross-correlation coefficients $\rho_{HV}$ located along the left side (where “forward” is aligned along the storm’s motion vector) of the middle- to lower-level weak-echo region (BWER; Chisholm 1973).

The purpose of this paper is to document these and other polarimetric signatures seen by a high-resolution, X-band mobile Doppler radar in supercells in the central United States. As a result of greater spatial resolution and the different scattering properties at X band, the polarimetric representation of supercells in which we have collected data can vary from that which would be seen by a fixed-site radar operating at a lower frequency. A brief explanation of the radar and details about data processing and collection are given in section 2. Section 3 provides a limited discussion of several previously observed polarimetric signatures in supercell thunderstorms, along with examples of one lesser-documented and one currently undocumented signature. A review and discussion of the observed signatures conclude the paper.

2. Instrument and data processing

a. Instrument overview

The observational data used in this study were collected by the UMass X-Pol (Fig. 2), a mobile, truck-mounted,
dual-polarization (linearly polarized in the horizontal and vertical), X-band Doppler weather radar, built and maintained by the Microwave Remote Sensing Laboratory (MIRSL) at the University of Massachusetts—Amherst. Between 2002 and 2010, graduate students and faculty at the University of Oklahoma (OU), in collaboration with MIRSL, used the UMass X-Pol [Table 1; see Junyent-Lopez (2003) and Pazmany et al. (2003) for more technical details] throughout the central United States to collect data in severe convective storms. In a typical deployment focused on supercell meso-cyclones and tornadoes, the personnel operating the radar attempted to begin data collection approximately 20–25 km downstream of the particular “feature of

Fig. 1. A comparison of equivalent $Z_{H}$ in (a) rain, (b) hail with 0% fractional water ($f_w$; “dry hail”), and (c) hail with 10% $f_w$ (“wet hail”); $Z_{DR}$ in (d) rain, (e) dry hail, and (f) wet hail; $K_{DP}$ in (g) rain, (h) dry hail, and (i) wet hail as a function of particle diameter in monodispersed distributions. Wavelengths of 10.7, 5, and 3.2 cm are shown as solid, long dashed, and short dashed curves. Scattering matrices were calculated by the $T$-matrix method (Waterman 1969), with the effective dielectric constant for wet hail calculated using the Maxwell–Garnett mixing formula with water as the background and ice as the inclusion. The values for rain were calculated at 10°C, with mean canting angle and canting angle standard deviation $\sigma$ of 0°, using the size–shape relationship of Brandes et al. (2002) and LWC of 10 g m$^{-3}$. Hail is treated similar to Jung et al. (2008), where $\sigma = 60^\circ (1-0.8f_w)$, yielding $\sigma$ of 60° and 55.2° for dry and wet hail. The monodispersed distributions for hail are calculated using a mass concentration of 2 g m$^{-3}$, and the axis ratio is fixed at 0.75 at a temperature of 0°C (from Snyder et al. 2010b).
interest” (often, for the cases examined in this paper, this was a tornado, wall cloud, or mesocyclone), usually to the right of the expected track of the feature. Deployments were often stopped when the feature moved beyond the radar’s location, though specific deployment strategies varied on a case-by-case basis depending upon the expected future evolution of the storm of interest and the availability of subsequent deployment locations. In many situations, 8–12 elevation angles separated by $2^\circ–3^\circ$ were collected in a $120^\circ–150^\circ$ sector; resultant “volume” update times were typically 80–120 s. This deployment technique often prevented the collection of uninterrupted data for more than 20–30 km of a given storm’s path. If the scanned storm was moving quickly, deployments may have lasted only 10–20 min, significantly reducing the ability to examine storm evolution. In addition, in nearly all datasets, the high elevation angle used is not great enough for the beam height to exceed storm height. Considering the relatively close distance between the radar and the storm that was often desired to maximize spatial resolution, scanning to storm top would have required elevation angles of $45^\circ–70^\circ$, angles at which a new set of complexities arise (e.g., the apparent aspect ratio of particles tends to approach unity assuming $\sim 0^\circ$ mean canting angles, thereby biasing $K_{DP}$ and $Z_{DR}$ and reducing the polarimetric discriminating powers of these quantities; the observed $V_R$ tends to have an increasing vertical component and decreasing quasi-horizontal component). As such, in nearly all UMass X-Pol datasets, the top of the radar scanning volume is often considerably below storm top.

b. Polarimetric data processing

One of the most significant benefits of operating a mobile radar at X band is that the antenna can be smaller than that required for the same half-power beamwidth for a radar operating at a lower frequency. X-band radars, however, suffer from much more significant attenuation than radars at C and S bands (Fig. 3). Also, as a result of resonance effects, the scattering properties of hydrometeors, particularly hail, at X band can differ significantly from those at S band (Fig. 1). With the increasing popularity of X-band radar systems, it is important that users of such data be aware of the expected differences.

Radar signal attenuation through rain is nearly an order of magnitude greater at X band than at S band. In data collected by the UMass X-Pol, total signal extinction has been observed to occur over as short a path-length as $\sim 10$ km in heavy precipitation. In general, polarimetric-based attenuation-correction methods [see Park et al. (2005a,b) and Snyder et al. (2010b) for a brief review of several techniques used with X-band data] make use of the propagation component of the total measured differential phase $\phi_{DP}$:

$$\phi_{DP} = \arg\left\{nf_{vv}f_{hh}^*\right\} + 2 \int_0^K_{DP}(r')dr' = \delta + \phi_{DP}.$$  

where $n$ is a proxy for the drop size distribution, $f_{vv}$ and $f_{hh}$ are the amplitudes of the copolar terms of the backscattering matrix, $K_{DP}$ is the specific propagation differential phase ($^\circ$ km$^{-1}$), and $\delta$ is differential phase upon backscatter ($^\circ$). In many situations, particularly at lower radar frequencies, the effects of $\delta$ tend to be ignored. At higher frequencies, such as at X band, appreciable $\delta$ may be present.

Where applicable in this paper, estimates of attenuation are retrieved using the ZPHI technique (Testud et al. 2000); differential attenuation is estimated from an attenuation–differential attenuation relationship. As noted in Snyder et al. (2010b), the ZPHI technique has some logistical advantages that simplify the attenuation correction of X-band convective storm data. Unfortunately, as a practical result of the nature of $K_{DP}$-based attenuation...
attenuation correction, attenuation-corrected data may contain significant “streakiness,” and because reliable calculations of $K_{DP}$ can be difficult around the edge of precipitation echoes, it is often difficult to estimate attenuation near the edges of echoes and within narrow echoes. In addition, there are datasets for which the previously published parameters for attenuation and differential attenuation correction perform very poorly.

Because hail can be thought of as being statistically isotropic as a result of tumbling and because of the reduced dielectric constant of ice compared to liquid water, the phase lag that accrues along the H and V planes can be very small; $K_{DP}$ tends to be near $0^\circ \text{ km}^{-1}$ in dry hail, although water-coated (i.e., “wet”) hail has more complicated dielectric and physical structures that can yield larger $K_{DP}$. Consequently, the constants chosen for attenuation correction may be significantly different in hail than in rain. Attempts to account for the effects of attenuation from hail have recently appeared (Ryzhkov et al. 2007, 2009; Borowska et al. 2011; Gu et al. 2011), and the initial results indicate that attenuation through hail may be appreciable. The poor performance of $K_{DP}$-based attenuation estimates examined in Snyder et al. (2010b) in some UMass X-Pol datasets may be the result of anomalous attenuation through water-coated hail. In UMass X-Pol data, $K_{DP}$ is calculated by the linear

![Image](image_url)
3. Polarimetric signatures in convective storms

Analyses of polarimetric radar data have indicated the presence of columns of relatively high $Z_{\text{DR}}$ above the "ambient" freezing level in thunderstorms (e.g., Hall et al. 1984; Tuttle et al. 1989; Meischner et al. 1991; Conway and Zrnić 1993; Brandes et al. 1995; Zrnić and Ryzhkov 1999; Loney et al. 2002). The part of a convective storm's updraft between the level of free convection and the equilibrium level possesses positive thermal buoyancy and is characterized by a warm temperature perturbation relative to the surrounding environment. As a result, assuming the updraft extends through the environmental freezing level, the local freezing level is perturbed upward by the updraft and perturbed downward by the downdraft. The warm updraft carries liquid water drops to an altitude above that of the environmental freezing level. Of more consequence from a microphysical perspective is that, even above the perturbed freezing level, supercooled water drops exist (as a result of noninstantaneous freezing of liquid hydrometeors as they are advected upward) and act as a source for positive $Z_{\text{DR}}$. Similarly enhanced $Z_{\text{DR}}$ was found by Höller et al. (1994) to be the result of melted graupel brought back above the freezing level by the updraft. In a dual-Doppler, polarimetric analysis of a hailstorm, Conway and Zrnić (1993) noted that the $Z_{\text{DR}}$ column was located just west of the updraft and consisted of raindrops and wet hydrometeors. In the presence of a convective updraft, smaller drops tend to be advected upward much more quickly than the larger drops; the effect of size sorting in an updraft preferentially leaves larger rain drops lower in the updraft as the smaller drops advect more quickly to higher altitudes. The region of $Z_{\text{DR}} > 0$ dB often extends to a maximum height in an updraft, resulting in what is termed the $Z_{\text{DR}}$ column. In situ observations support the notion that the $Z_{\text{DR}}$ column is nearly coincident with the updraft (e.g., Brini et al. 1991; Brandes et al. 1995; Loney et al. 2002).

As in the $Z_{\text{DR}}$ column, positive values of $K_{\text{DP}}$ have also been observed to extend to a greater height in the relatively warm updraft compared to surrounding areas (e.g., Hubbert et al. 1998; Zrnić and Ryzhkov 1999; Loney et al. 2002). The $K_{\text{DP}}$ column is a region of locally enhanced $K_{\text{DP}}$ that extends well above the ambient freezing level. Loney et al. (2002) observed that the $K_{\text{DP}}$ and $Z_{\text{DR}}$ columns were not collocated in observations of a supercell in Oklahoma, and Zrnić and Ryzhkov (1999) observed a separation as well. KR08 suggests that environmental vertical shear affects the relative locations of the columns. In cases in which there is an offset, the $K_{\text{DP}}$ column is often located on the left flank of the updraft to the left of the $Z_{\text{DR}}$ column, and it is often, though not always, associated with the maximum in $Z_{\text{HH}}$. In the in situ observations examined by Loney et al. (2002), the highest $K_{\text{DP}}$ was located east of the peak in $Z_{\text{HH}}$ along the $Z_{\text{HH}}$ gradient. Hubbert et al. (1998) suggested that the significant liquid water content that makes up the $K_{\text{DP}}$ column may be the result of drops shed from hail falling at the periphery of the updraft, although the observations in Loney et al. (2002) of primarily mixed-phase hydrometeors and large drops within the $K_{\text{DP}}$ column suggest that shedding may not be significantly occurring in or responsible for the $K_{\text{DP}}$ column (at least in that case). Scatterers located outside the updraft above the ambient freezing level are likely to be of the frozen variety, with $K_{\text{DP}}$ typically quite small in magnitude (i.e., near 0° km$^{-1}$).

Circular or semicircular structures in the $Z_{\text{DR}}$ and $\rho_{\text{HV}}$ data near the freezing level have been observed by polarimetric radars. The features, referred to as $Z_{\text{DR}}$ and $\rho_{\text{HV}}$ rings (KR08), may be full rings encircling an updraft or only partial rings. When not a complete ring, $Z_{\text{DR}}$ half-rings are always positioned on the inflow side of the updraft (KR08). As a result of the mixture of liquid and ice hydrometeors near the freezing level, $\rho_{\text{HV}}$ tends to be reduced and $Z_{\text{HH}}$ tends to be enhanced (the so-called bright band; Zrnić et al. 1993; Zrnić and Ryzhkov 1999; Brandes and Ikeda 2004; Giangrande et al. 2008). A similar reduction in $\rho_{\text{HV}}$ has been observed in S-band and C-band data around convective updrafts (e.g., KR08; Payne et al. 2010). KR08 speculates that the $\rho_{\text{HV}}$ ring marks an area where significant mixed-phase hydrometeors exist, perhaps the result of frozen particles outside the updraft falling into the relatively warm updraft and partially melting. Payne et al. (2010) observed that a $\rho_{\text{HV}}$ ring in a supercell was primarily centered upon the vertical vorticity maximum within the updraft and postulated that the location of the vertical velocity maximum relative to the vertical velocity maximum affects the appearance of the $\rho_{\text{HV}}$ ring. The melting of previously frozen hydrometeors can also explain the observed local maxima in $Z_{\text{DR}}$ that have also been noted to occur in similar ringlike structures, although the $Z_{\text{DR}}$ ring is not always collocated with the $\rho_{\text{HV}}$ ring (KR08). Several of these polarimetric signatures have been simulated using polarimetric emulators in high-resolution numerical models with multimoment bulk (e.g., Jung et al. 2010; Snyder et al. 2010a) and spectral bin microphysics (Ryzhkov et al. 2011). In Jung et al. (2010), a $\rho_{\text{HV}}$ ring observed in a simulated supercell was associated with a peak in the mixture of rain and hail.

For completeness, it is worth mentioning the tornado debris signature (Ryzhkov et al. 2005c), characterized by...
a strong couplet in radial velocity $V_R$, a local minimum in $Z_H$, low $Z_{DR}$, and very low $\rho_{HV}$. Since the study of Ryzhkov et al. (2005c), tornado debris signatures have been observed at C band (e.g., KR08; Petersen et al. 2008; Palmer et al. 2011; Schultz et al. 2012) and, to a more limited extent, X band (Bluestein et al. 2007a,b, 2010, 2012; Tanamachi et al. 2012).

Most of the previous work examining the polarimetric structure of supercells (e.g., KR08; R08) used data collected at S and C bands, owing to the relatively limited observations of convective storms from polarimetric X-band radars. Considering that resonance effects are much more prominent at X band than at S band, the impacts of resonance scattering effects at C band can vary significantly from those at X band, and that there are large resolution differences that exist between most of the polarimetric radars used in previous studies and many mobile radars, one should expect that some of the polarimetric signatures presented previously in the literature may differ from what has been collected by the UMass X-Pol and other X-band radars.

a. Low-reflectivity ribbon (LRR)

A narrow band of locally reduced $Z_H$ extending from near where the hook echo “attaches” to the main body of the storm near the rear of the forward-flank downdraft has been observed in at least seven supercells on which UMass X-Pol has collected data (Table 2). This feature is most evident in $Z_H$ and $Z_{DR}$ data collected in the lower troposphere, typically within 3 km of the ground. Because this feature is essentially a “texture” feature and is observed as a local minimum in $Z_H$ and $Z_{DR}$, and given that attenuation estimation can introduce streakiness and other aesthetic unpleasantries that can complicate analysis (even assuming that the attenuation estimates are accurate), the observed (attenuated) $Z_H$ and $Z_{DR}$ tend to highlight the signature well and will be used to highlight this feature in most of the cases presented.

In data collected from a tornadic supercell in southeastern Wyoming on 5 June 2009 (Fig. 4), a narrow zone of locally reduced $Z_H$ extends northeastward from near the area where the hook echo appears to attach to the main body of the storm on the upshear (southwest) side of the FFD. Values of $Z_H$ within this local minimum are 6–10 dBZ lower than in immediately adjacent areas, and the reduction in $Z_H$ is approximately 500–700 m in width. This is most evident from the lowest elevation angle [at a height of approximately 1.25 km above radar location (ARL)] to approximately 3.3 km ARL. At the time of these data, a strong tornado was occurring (Fig. 4c), evidence of which is seen in $Z_H$ (Fig. 4a) and as a Doppler velocity couplet (Fig. 4c).

Nearly collocated with this narrow, arcing band of reduced $Z_H$ is an area of $Z_{DR}$ that is 3–5 dB lower than surrounding areas (Fig. 4b); $Z_{DR}$ near 0 dB in this band is flanked on either side by $Z_{DR}$ of 3–5 dB. The minimum in $Z_{DR}$ is located slightly west of the minimum in $Z_H$. The east side of the $Z_H$ reduction is characterized by $Z_{DR}$ of 4–5 dB; the west side (and approximately 300 m west of the lowest $Z_H$) has values of 0 dB. The low $Z_{DR}$ band is approximately 700–800 m in width. Little evidence of this signature in $\rho_{HV}$ is noted (Fig. 4d), although there occasionally is reduced $\rho_{HV}$ in the same area, and only minor radial convergence ($\sim 2.5 \times 10^{-3} \text{s}^{-1}$) is observed in $V_R$ (Fig. 4c). The minima are evident from the time of deployment (2209 UTC) until approximately 2225 UTC, though they are most prominent in the first few minutes after the start of data collection. This signature, hereafter referred to as the low-reflectivity ribbon, is characterized by a narrow, sometimes “winding” band of locally reduced $Z_H$, typically nearly collocated with locally reduced $Z_{DR}$, and sometimes associated with reduced $\rho_{HV}$ and convergence evident in $V_R$. Considering the method by which $K_{DP}$ is calculated (i.e., linear regression of filtered $\phi_{DP}$ over a 1.5-km range), the resolution of the $K_{DP}$ data tends to be too coarse to properly sample the narrow feature.

On the evening of 10 June 2010 (Fig. 5), a post-tornado supercell in eastern Colorado exhibited a similar structure—a ribbon of reduced $Z_H$ that extends from the hook echo and leftward (relative to storm motion) into the FFD. In this case, reductions in $Z_H$ are approximately

### Table 2

<table>
<thead>
<tr>
<th>Feature</th>
<th>Date</th>
<th>Description</th>
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<tbody>
<tr>
<td>LRR</td>
<td>23 May 2008</td>
<td>Tornadic supercell (NW OK)</td>
</tr>
<tr>
<td></td>
<td>5 Jun 2009</td>
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<td></td>
<td>7 Jun 2009</td>
<td>Tornadic supercell (NW MO)</td>
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<tr>
<td></td>
<td>9 Jun 2009</td>
<td>Nontornadic supercell (SW KS)</td>
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<tr>
<td></td>
<td>18 May 2010</td>
<td>Tornadic supercell (NW TX)</td>
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<tr>
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<td></td>
<td>10 Jun 2010</td>
<td>Tornadic supercell (E CO)</td>
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<tr>
<td>LoRB</td>
<td>31 May 2007</td>
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<td></td>
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<td>Nontornadic supercell (NW OK)</td>
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10–15 dB (Fig. 5a) and are most evident below ~3 km ARL. As is observed in the previous case, \( Z_{DR} \) near this band is also locally reduced by as much as 4 dB, spatially dislocated very slightly to the rear side of the observed \( Z_H \) reduction. In addition, a reduction in \( r_{HV} \) is also apparent (Fig. 5d). There are no readily apparent organized patterns in the \( V_R \) field (Fig. 5c) near the observed region of locally reduced \( Z_H \) and \( Z_{DR} \). The feature is visible for approximately 10 min, and it decays as the primary mesocyclone occludes and moves rearward.

A tornadic supercell that was scanned intensively by participants of VORTEX 2 on 18 May 2010 in the northern Texas Panhandle exhibited similar local reductions in \( Z_H \) and \( Z_{DR} \) (Fig. 6). The ribbon of low \( Z_H \) and \( Z_{DR} \) varies between 650 and 1000 m in width, with magnitudes of reduction of 15–20 dBZ and 2–4 dB in \( Z_H \) and \( Z_{DR} \), respectively. Tornadoes were reported approximately 30 min before and after this scan. The ribbon initially is most evident at the highest elevation angles (which, considering the short range of the storm from the radar, results in a beam height of only ~2.5 km ARL), and it is visible for at least 5 min before the radar stopped scanning to reposition. The feature moves rearward with time relative to the position of the hook echo.
Radial profiles of $Z_H$ and $Z_{DR}$ (filtered to remove high-frequency variability in the observations) through the LRR clearly show the local minima in $Z_H$ and $Z_{DR}$ centered near the 17.7- (Fig. 7a) and 10.4-km range (Fig. 7b) on scans from the evenings of 10 June 2010 (Fig. 5) and 18 May 2010 (Fig. 6). In neither case is there substantial spatial dislocation between the $Z_H$ and $Z_{DR}$ minima, though the maxima in $Z_H$ along either side of the LRR in the latter case are shifted slightly farther in range compared to the maxima in $Z_{DR}$ surrounding the LRR. Note that the decrease in both $Z_H$ and $Z_{DR}$ several kilometers beyond the LRR is the result of attenuation. In the 11 June 2010 case, there is a reduction in $\rho_{HV}$ associated with the LRR, though the minimum is slightly up-radial relative to the LRR. In the 19 May 2010 case, there is little reflection of the LRR in $\rho_{HV}$, but there is also an anomalous local peak in $\Phi_{DP}$ within the LRR. It appears more likely that this peak is the result of enhanced $\delta$ from the scatterers with appreciable resonance effects within the LRR and less likely that the
peak is caused by scatterers that have large $K_{DP}$ along the leading edge of the LRR and $K_{DP} < 0^\circ$ s$^{-1}$ along the rear edge of the LRR.

In data from a supercell collected at 0120 UTC 7 June 2009, a ribbon of low $Z_{HH}$ and $Z_{DR}$ is evident in a similar storm-relative location (Figs. 8a,b), but the ribbon is aligned in a more north–south or northwest–southeast orientation. In this case, separate tornadoes were reported at 0113 and 0127 UTC. In a tornadic supercell that occurred along the Kansas–Colorado border on 25 May 2010 (Figs. 8c,d), similar reductions in $Z_{HH}$ and, to a considerably less-clear extent, in $Z_{DR}$, are observed in a very similar storm-relative location. A tornado was developing at the time of these data as well.

A supercell observed on 23 May 2008 in extreme northwestern Oklahoma (Fig. 9) provides a unique opportunity to examine the LRR, owing to the close proximity of the storm to the radar. In fact, the hook echo and extremely strong rear-flank downdraft (RFD), which blew over a semitruck very near the radar deployment location, overtook the radar during data collection. Similar to most aforementioned LRR examples, the feature is very evident in $Z_{DR}$ data (Fig. 9d), with relatively little spatial association with anomalies in the $\rho_{HV}$ (Fig. 9f) and $K_{DP}$ (Fig. 9b) fields. Because the radar was so close to the developing hook echo—in fact, the hook echo moved over the radar during the deployment—the radar was able to sample the development of the hook

![Fig. 6](image-url). The (a) $Z_{HH}$, (b) $Z_{DR}$, and (c) $V_R$ from 0016:07 UTC 18 May 2010. Black arrows in (a) and (b) mark the location of the LRR, and the solid black line in (a) marks the radial from which the data in Fig. 7b are shown. (d) A wide-angle photograph of the supercell as it appeared from the deployment location at approximately 0009 UTC looking to the west-northwest (courtesy of J. Snyder).
echo and tornado with particularly high spatial resolution. Data collected very close to the surface (e.g., data in Fig. 10 were collected at an elevation angle of 4.2° with a beam height of <500 m for the observed hook echo and LRR) show the LRR best in $Z_{DR}$ (middle column of Fig. 10), though it is evident in $Z_{H}$ as well (left column of Fig. 10). Between 2339:51 and 2342:47 UTC, the hook echo takes on significant cyclonic curvature. Nearly collocated with the LRR is observed strong radial convergence (right column in Fig. 10), with 30–35 m s$^{-1}$ inbound $V_R$; this radial convergence weakens as near-surface cyclonic rotation intensifies through this time period. By 2344:29 UTC (bottom row of Fig. 10), there is a broad cyclonic vortex near the surface, with peak $V_R$ of 45 m s$^{-1}$ within 1 km of the radar. During the time spanned in Fig. 10, $Z_{DR}$ within the hook echo is significantly lower than that observed to the north and northwest of the hook echo, indicating the possibility that the mean DSD within this part of the hook echo has a relatively small mean diameter [similar to the
FIG. 9. (a) A photograph, taken near 2331 UTC, of a wall-cloud produced by a supercell on 23 May 2008 in extreme northwestern Oklahoma (courtesy of H. Bluestein). UMass X-Pol deployed ahead of the hook echo and strong RFD: (b) $K_{DP}$, (c) $Z_{H'}$, (d) $Z_{DR'}$, (e) $V_R$, and (f) $\rho_{HV}$ valid at 2341:42 UTC. The arrows mark the location of the LRR, which is more evident in $Z_{DR'}$ than $Z_{H'}$. 
FIG. 10. The (left) $Z_{H'}$, (middle) $Z_{DR'}$, and (right) $V_R$ valid (from top to bottom) at 2239:51, 2341:20, 2342:47, and 2344:29 UTC at $-4.2^\circ$ elevation angle as a hook echo wraps up over UMass X-Pol on 23 May 2008. The LRR is clearer in $Z_{DR'}$ than in $Z_{H'}$. At this elevation angle, strong radial convergence is associated with the LRR. Peak $V_R$ in the hook echo reaches 45 m s$^{-1}$ by the latest time $-1.3$ km west of the radar. Range rings are in 2-km increments.
observations of Kumjian (2011)]. Throughout the deployment, enhanced spectrum width (not shown) was observed within the LRR.

While strong radial convergence is observed, at least initially, near the surface (<700 m ARL), at higher elevation angles there are indications of small, tightly spaced vortex signatures along the inside portion of the hook echo. These vortices are apparent in $Z_H$ and $V_R$ fields with a quasi-regular spacing of 400–600 m, and they stream rapidly southeastward through the inside portion of the hook echo as it wraps up through 2344 UTC. Evidence of these vortices is contained in $Z_H$, $Z_{DR}$, and $V_R$ data from a relatively short sequence of scans collected at elevation angles of 6.1°, 8.0°, and 10.0° (Fig. 11). The vortices appear to be located within the LRR seen in both the $Z_H$ and $Z_{DR}$ fields; the LRR that is seen extending into the rear of the FFD (top center of each image in Fig. 11) appears to show several vortices in an arc, evident in the $Z_H$, $Z_{DR}$, and $V_R$ fields. These vortices move rapidly southward, wrapping cyclonically along the inside part of the hook echo. At times, stronger vortices with a spacing of ~1 km can be seen in the $V_R$ data. The 6.1° elevation angle data subsequent to the times presented in Fig. 11 indicate that peak $V_R$ is approximately 50 m s$^{-1}$ within 1 km of the radar. The predominance of cyclonic vortices without apparent anticyclonic vortices suggests that shear instability, and not tilting, is a potential causative mechanism. The observation that the vortices become stronger with height may be an indication that vortex stretching is occurring as well.

In total, LRRs are evident in at least seven supercell datasets collected by UMass X-Pol between 2007 and 2010. In most of the observed cases, the depression in $Z_H$ is 5–15 dBZ, though a local reduction of greater than 20 dBZ is observed in at least one case. The width of this feature ranges from ~300 m to ~1 km, and it is often most evident below approximately 2.5–3.0 km ARL, though it is sometimes observed at greater heights. Associated with the ribbon of reduced $Z_H$ is almost always an equally narrow zone of reduced $Z_{DR}$ located either coincident with the $Z_H$ minimum or within approximately one-half the width of the $Z_H$ depression. In only one of the observed cases of the LRR is there almost no discernible variation in $Z_{DR}$, and in only one case is the $Z_{DR}$ lowest along the leading (often east) edge of the LRR. In the remainder of the observed cases of the LRR, the lowest $Z_{DR}$ is found either centered with the LRR or along the rear edge of the LRR. In general, the measured $Z_{DR}$ minima are in the 0–2 dB range, yielding local depressions of 2–5 dB relative to the surrounding areas. In most cases, there is little reflection of this signature in $K_{DP}$ or $\rho_{HV}$, and there is little consistency within anomalies in the $V_R$ field (e.g., some cases suggest radial convergence along the LRR, one case shows tightly spaced cyclonic vortices, and some cases show no distinct heterogeneity near the LRR). The majority of cases in which an LRR was observed were associated with tornadic supercells, though the sample size is too small to infer any possible relationship between the LRR (and processes responsible for the LRR) and tornado occurrence.

b. Reduced midlevel $\rho_{HV}$ to the left of the BWER

The BWER (Chisholm 1973) typically encloses the updraft of strong convective storms, as very strong vertical velocities quickly loft precipitation upward. Away from the strongest part of the updraft, weaker vertical velocities more slowly evacuate precipitation from the area, allowing larger particles to fall earthward (e.g., hydrometeors for which the terminal velocity exceeds the updraft’s vertical velocity). In at least nine supercells on which UMass X-Pol collected data (Table 2), anomalously low $\rho_{HV}$ was found along the left side of the BWER (where left is relative to the storm’s motion vector). Oftentimes, this area of reduced $\rho_{HV}$ was located adjacent to and rearward from the top of the $Z_{DR}$ column or rearward from the northwest extent of the $Z_{DR}$ ring. For simplicity, this feature will be referred to as the LoRB (low $\rho_{HV}$ on the left and rear edge of the BWER).

One example of this feature is observed in a supercell that occurred in eastern New Mexico during the afternoon of 17 May 2010 (Fig. 12). Rearward and to left of the BWER evident in $Z_H$ (Fig. 12a) is an expansive region of $\rho_{HV} < 0.55$ collocated with the wall of the BWER (characterized by $Z_H$ of 30–45 dBZ; enclosed by the black ellipse in Fig. 12). Much of the area that has low $\rho_{HV}$ has $Z_{DR}$ near 2 dB. It is possible that there are mixed-phase hydrometeors with complex shapes residing in the northwest wall of the BWER, which would account for the low $\rho_{HV}$, and the positive $Z_{DR}$ suggests the possibility of oblate, possibly water-coated hydrometeors, though resonance effects associated with non-Rayleigh scattering may also yield positive $Z_{DR}$ even without appreciable oblateness. Tumbling, wet graupel or hail may also help explain the combination of $Z_{DR}$, $Z_H$ of 30–45 dBZ, and $\rho_{HV}$ of 0.40–0.55.

Similar areas of reduced $\rho_{HV}$ are evident leftward and rearward of two BWERs associated with two primary updrafts sampled on the evening of 18 May 2010 (Fig. 13). In this case, a $\rho_{HV}$ of 0.45–0.60 occurs within the left and rear sections of the BWERs, where $Z_H$ as high as 50 dBZ is measured. In contrast to the 17 May 2010 case (Fig. 12), however, the LoRB is located beyond the area of $Z_{DR}$ > 1 dB. Yet the $Z_{DR}$ is quite variable—seemingly
FIG. 11. The (left) $Z_{HH}$, (middle) $Z_{DR}$, and (right) $V_R$ valid at (top) 2343:09, (middle) 2343:31, and (bottom) 2343:53 UTC at 6.1°, 8.0°, and 10.4° elevation angle. Small-scale vortices (several of which are marked by black circles) stream rapidly southward into the inside part of the wrapping hook echo. Low-level rotation continues to intensify beyond that shown in (bottom right); by 2344:51 (not shown), $V_R$ increases to 50 m s$^{-1}$ inbound and 45 m s$^{-1}$ outbound, with the extrema separated by 1.0 km in the azimuthal direction.
“noisy” almost—in the LoRB, which is unsurprising given the relatively low $\rho_{HV}$. The effects of particularly strong attenuation in $Z_{\ell r}$ are apparent in the northwestern part of the eastern BWER (seen as “shadowing” in the $Z_{\ell r}$), where an enhanced increase in $\Phi_{DP}$ with range is observed. Significant heterogeneities in particle composition and size distributions can result in large gradients in $\Phi_{DP}$ (implying large gradients in attenuation rates), signaling potential complications from nonuniform beam filling (often seen as significantly reduced $\rho_{HV}$ downrange of the initial $\Phi_{DP}$ gradients).

Another example of the LoRB is shown in Figs. 14a,b; the observed supercell that occurred on 31 May 2007 is characterized by $\rho_{HV} < 0.7$ (with local minima to $-0.50$) in an area $Z_{\ell r}$ of 30–45 dBZ. Areas of $\rho_{HV} < 0.7$ extend to the top of the scanned domain in this dataset, so the zone of low $\rho_{HV}$ extends upward to a height of at least 5.5 km ARL. A final and less extreme example of reduced $\rho_{HV}$ along the rear edge of the BWER comes from data collected in northern Oklahoma on 24 May 2008 (Fig. 15). Rearward of the BWER is an area of reduced $\rho_{HV}$, though the magnitude of the reduction is significantly less than that seen in Fig. 12.

It is important to mention that nonuniform beam filling (NBF) can bias polarimetric measurements and detrimentally affect the quality of the measured quantities. Ryzhkov (2007, cf. Figs. 1–3) noted that NBF typically results in radially oriented “streaks” of

![Figure 12](image_url)
reduced $\rho_{HV}$ beyond the area of significant NBF, since NBF is, essentially, a range-cumulative effect. Although NBF scales with radar frequency (i.e., stronger NBF at X band than at S band), the convective phenomena often scanned by UMass X-Pol occur within 30 km of the radar and, in some cases presented in this paper, within 15 km. At a range of 20 km, for example, the radar resolution volume size is 150 m in range with a cross-sectional diameter of approximately 436 m. Undoubtedly, the measurements at and radially beyond areas in which NBF is present are being biased by the NBF. However, this effect does not appear to be the primary reason for the appearance of the LoRB.

The LoRB described above may be similar to the linear depolarization ratio (LDR) “cap” discussed by Hubbert et al. (1998), wherein increased LDR and reduced $\rho_{HV}$ were observed at the top of the $Z_{DR}$ column in a Colorado supercell. The so-called LDR cap was also discussed in Kennedy et al. (2001), in which it was postulated that areas of relatively large LDR located atop the $Z_{DR}$ column in the 0° and −20°C layer of non-supercell storms were likely associated with regions of hail growth. Jameson et al. (1996) observed a similar structure in Florida thunderstorms and attributed it to the freezing of supercooled raindrops. In UMass X-Pol cases, the reductions in $\rho_{HV}$ are much greater than those observed in Hubbert et al. (1998). Typically, radar volumes containing meteorological scatterers tend to be characterized by relatively high $\rho_{HV}$, and the values of $\rho_{HV}$ measured in the observed LoRB cases (e.g., $\rho_{HV} < 0.60$) are typically thought to be in the realm of non-meteorological scatterers (e.g., biological scatterers, ground clutter, etc.). The presence of such low $\rho_{HV}$ collocated with relatively large $Z_{H}$ likely is the result of very significant resonance effects associated with non-Rayleigh scattering that can occur at X band in the presence of large, likely mixed-phase hydrometeors with potentially varying shapes.

Others have observed reduced $\rho_{HV}$ aloft in reference to the $\rho_{HV}$ ring, but note that the LoRB is different than the $\rho_{HV}$ ring highlighted in KR08, Payne et al. (2010), and Palmer et al. (2011). Picca and Ryzhkov (2012) observed low $\rho_{HV}$ above the ambient freezing level in a supercell sampled by polarimetric S- and C-band radars attributed to areas of large hail growth, but that discussion did not address the relationship between the BWER and particularly low $\rho_{HV}$, KR08 and Kumjian et al. (2010) discussed low $\rho_{HV}$ aloft as a proxy for
updraft location. If the BWER is nearly centered on
the updraft, however, then the observations of the
LoRB presented in this paper mean that the very low
\( \rho_{HV} \) within the LoRB is offset, perhaps substantially
(at least 5 km in several storms), from the center of
the updraft.

c. Other polarimetric signatures associated with
supercells

Since 2008, the collection of volumetric data (i.e., data
from near the surface to 8+ km AGL) has been priori-
tized, allowing for the examination of structures within
the polarimetric fields near and above the freezing level
of many of the storms on which data were collected. For
the most part, many of the previously seen polarimetric
signatures are evident in various datasets collected by
the UMass X-Pol. For example, midlevel \( Z_{DR} \) columns,
rings, or half-rings are apparent in data from 18 May
2010 (Fig. 13), 31 May 2007 (Fig. 14), 24 May 2008
(Figs. 15, 16), and 22 May 2008 (Fig. 17).

On 18 May 2010, two BWERS associated with the
updrafts of two severe thunderstorms were associated
with rings of enhanced \( Z_{DR} \) (Fig. 13b), with values from 3
to nearly 6 dB. Located with the eastern ring is a similarly
shaped ring of enhanced \( \Phi_{DP} \) (Fig. 13c), likely resulting
from significant \( \delta \) from non-Rayleigh scattering. Note
that the accumulated increase in \( \Phi_{DP} \) with range down-
radial of the northwestern section of the eastern BWER
is collocated with the shadowing in \( Z_{H} \) that is indicative
of substantial attenuation in the same area. The radially
oriented reduction in \( \rho_{HV} \) in the same area may be the
result of both reduced signal-to-noise ratio (SNR) and
NBF. Differential attenuation is seen as radially oriented
reductions in \( Z_{DR} \) through and beyond the left rear
section of both BWERS.

A supercell in the Oklahoma Panhandle on 31 May
2007 exhibited many of the above-mentioned polarimetric
signatures. On the 11.7° elevation angle scan, a \( Z_{DR} \) half-ring is apparent (Fig. 14d), located on the
inflow side of the supercell beyond which differential
attenuation is present [an observation similar to that
seen in Palmer et al. (2011)], consistent with the obser-
vations of KR08. Above the rearmost extent of the \( Z_{DR} \)
half-ring is a large area of very low \( \rho_{HV} \) (Fig. 14b). At
higher elevations, such as on the 18.0° scan (Fig. 14f),
a complete \( \rho_{HV} \) ring is apparent. Some reduced \( \rho_{HV} \) is

![Fig. 14. A small sampling of midlevel polarimetric signatures associated with a supercell that occurred on 31 May 2007: (a) \( Z_{H} \) and (b) \( \rho_{HV} \) valid at 2336:00 UTC (12.2° elevation), (c) \( Z_{H} \) and (d) \( Z_{DR} \) valid at 2348:55 UTC (13.0° elevation), and (e) \( Z_{H} \) and (f) \( \rho_{HV} \) valid at 2349:24 UTC (18.0° elevation). A LoRB, \( Z_{DR} \) half-ring, and \( \rho_{HV} \) ring are evident in (b),(d), and (f), respectively.](http://example.com/fig14.jpg)
located to the north of this ring. Again, it is likely that mixed-phase hydrometeors reside within the HV ring. The top extents of the ZDR and KDP columns [Figs. 15b,c; the latter of which is located rearward of the former, consistent with observations by KR08 and Hubbert et al. (1998), among others] are evident in data from a tornadic supercell that occurred on 24 May 2008 (Fig. 15). The radar beam height at the center of the BWER in Fig. 15 is ~6.3 km ARL, or more than 2 km above the ambient freezing level (~4.1 km AGL determined from nearby radiosonde data). An attenuation-corrected, reconstructed range–height indicator (RHI) plot through the BWER clearly displays the weak-echo hole associated with the updraft (Fig. 16a). A significant upward extension of ZDR > 1 dB is evident along the edges of the BWER (Fig. 16b), with the highest ZDR associated with the echo overhang at a range of approximately 7–10 km from the radar; KDP in the echo overhang is quite small (Fig. 16c). The presence of a KDP column is evident in Fig. 15c as KDP > 5° km⁻¹ nearly collocated with the small BWER and the area of positive ZDR.

Data collected on a northwestern Oklahoma supercell that occurred on 22 May 2008 contain well-defined midlevel ZDR and ρHV half-rings (Fig. 17). The ZDR half-ring has a diameter of approximately 4.5 km and is
The largest of the BWER (black line) displayed in Fig. 15. The reconstructed echo overhang at 8–10-km range and 2–6-km ARL height, with a diameter of at least 7 km and minimum tilt from the lowest elevation angle (2°) to the highest (16°) in the radar volume from which Fig. 18 is produced. At the given range from the radar (~30 km), the radar beam height is approximately 7.5 km ARL, yet a \( Z_{\text{DR}} \) of 3 dB is observed along the inside rear portion of the BWER (Fig. 18b).

The \( Z_{\text{DR}} \) arc described in KR08 has also been observed within supercells observed by UMass X-Pol [e.g., Fig. 5b; cf. Fig. 10 in Snyder et al. (2010b)]. In datasets from UMass X-Pol, however, there is sometimes a local maximum in \( \Phi_{\text{DP}} \) along or very near the location of the \( Z_{\text{DR}} \) arc, beyond which \( \Phi_{\text{DP}} \) decreases with range. There seems to be two primary reasons why this occurs. First, according to (1), a gradient in \( \delta \) such that \( \delta \) decreases with range more quickly than \( 2 \times K_{\text{DP}} \) results in \( \Phi_{\text{DP}} \) decreasing with range. In some cases, an apparent “\( \delta \) arc” associated with the \( Z_{\text{DR}} \) arc is seen. For example, on the middle right side of Fig. 5f, immediately south of the 30-dBZ isoecho, \( \Phi_{\text{DP}} \) is locally maximized in the region of very high \( Z_{\text{DR}} \) (>5 dB) with \( \rho_{\text{HV}} \) between 0.85 (along the far edge of the echo) and ~0.98. Similarly, in the right column of Fig. 19, the area marked along the \( Z_{\text{DR}} \) gradient is characterized by \( Z_{\text{DR}} > 5 \) dB with \( \rho_{\text{HV}} > 0.96 \). This is not completely unexpected considering the likely microphysical composition of hydrometeors within the \( Z_{\text{DR}} \) arc, namely, DSDs that have significantly large mean drop diameters with a dearth of small drops yielding high \( Z_{\text{DR}} \).

A second reason why \( \Phi_{\text{DP}} \) may decrease slightly with range along the far right side of the forward-flank downdraft is that \( K_{\text{DP}} \) may legitimately be less than 0° km\(^{-1}\), which could occur in hail (Fig. 1). Outside of the \( Z_{\text{DR}} \) arc, gradients in \( \delta \) may be located along the edge of the forward-flank downdraft echo nearest the storm inflow region in areas of implied hail fall (typically characterized by relatively low \( \rho_{\text{HV}} \)); hailstones may also have a particular shape and size such that resonance effects create intrinsic \( K_{\text{DP}} < 0° \) km\(^{-1}\). Examples of the locally maximized \( \Phi_{\text{DP}} \) in areas that likely contain appreciable amounts of hail are seen in the two rearward enclosed areas in both the left and middle columns of Fig. 19; the eastern enclosed areas in both columns appear to be associated with the \( Z_{\text{DR}} \) arc and are likely primarily rain (because \( \rho_{\text{HV}} > 0.95 \)). Regardless of whether the cause for the \( \Phi_{\text{DP}} \) peak is attributable to resonance effects from large drops in the \( Z_{\text{DR}} \) arc or hailstones along the edge of the primary echo, it is difficult to remove the effect of gradients in \( \delta \) along the edge of the primary echo when calculating \( \Phi_{\text{DP}} \) and \( K_{\text{DP}} \). As a result, it is not uncommon to have \( K_{\text{DP}} < 0° \) km\(^{-1}\) on the immediate inside edge of the \( Z_{\text{DR}} \) arc and along the right edge of the precipitation echo, which detrimentally affects attenuation estimates and hydrometeor classification. This is usually not a problem at S band.

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**Fig. 16.** Reconstructed RHIs (based upon a series of plan position indicators) of (a) \( Z_{\text{H}} \), (b) \( Z_{\text{DR}} \), and (c) \( K_{\text{DP}} \) through the center of the BWER (black line) displayed in Fig. 15. The reconstructed RHIs are oriented nearly east (lhs) to west (rhs) across the plots. The largest \( Z_{\text{DR}} \) observed above ~2 km ARL is along the bottom of the echo overhang at 8–10-km range and 2–6-km ARL height.

characterized by \( Z_{\text{DR}} \) of 3–4 dB. Slightly beyond the \( Z_{\text{DR}} \) half-ring is a \( \rho_{\text{HV}} \) half-ring (Fig. 17c), having a diameter of at least 7 km and minimum \( \rho_{\text{HV}} \) in the 0.45–0.50 range. The \( Z_{\text{DR}} \) associated with the \( \rho_{\text{HV}} \) half-ring is actually 0.5–1 dB lower than farther away from the \( Z_{\text{DR}} \) half-ring. Little indication of the presence of these polarimetric signatures is found in \( Z_{\text{H}} \), evidence of the significant benefit of the additional data provided by polarimetric radars. *Without such data, it would be significantly more difficult to make any assessments regarding the microphysical characteristics of the radar echoes.* Additionally, the use of polarimetric data can allow one to locate more quickly and easily the location of the updraft and other storm-scale features, an ability that can aid radar interpretation.

To provide one final example of a midtropospheric \( Z_{\text{DR}} \) feature, data collected on the evening of 10 June 2010 are shown in Fig. 18, selected because of the storm’s spectacular BWER and visual structure (Fig. 18d). The local maximum in \( Z_{\text{H}} \) that is nearly incircled by the crescent-shaped BWER shows very little vertical tilt from the lowest elevation angle (2°) to the highest

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because the change in $d$ with changing drop diameter is significantly smaller than that which occurs at C and X bands.

4. Conclusions

Although previous papers have examined several polarimetric signatures (e.g., Ryzhkov et al. 2005b,c; KR08; R08), one previously undocumented signature (the LRR) and one signature that has seen little documentation at X band (the LoRB) have been observed in UMass X-Pol data. The LRR is a narrow zone of reduced $Z_H$ and $Z_{DR}$ that is located near the location where the hook echo or appendage along the upshear side of a supercell interacts with the rear part of the FFD (Fig. 20a). The $Z_H$ and $Z_{DR}$ depressions are typically 5–20 dBZ and 3–5 dB, respectively, lower than the surroundings, and the LRR tends to be 300–800 m in width. Although exactly what the signature represents is not known, it is hypothesized, based upon the polarimetric characteristics of the signature, that this area may be characterized by either DSDs with an appreciably smaller median drop diameter compared to the surrounding or by hail of unknown size and number distribution. The former explains the observed reduction in $Z_H$ and $Z_{DR}$ (both of which are sensitive to drop size) and the sometimes-observed unaffected $\rho_{HV}$ field. In those cases in which the $Z_H$ and $Z_{DR}$ depressions are offset, it is possible that size-sorting mechanisms act along at least a part of the LRR. However, there are cases for which $\rho_{HV}$ is depressed (0.8–0.9) in the LRR, which is lower than would be expected if only rain were present (Balakrishnan and Zrnić 1990), suggesting the presence of hail. Unfortunately, extremely limited disdrometer data are available near these features (Dawson and Romine 2010), and “ground truth” data of sufficient resolution are unavailable for nearly all of the observed radar datasets.

As to why this feature has thus far gone undocumented in the formal literature, there may be a couple of reasons. Considering the relatively narrow nature of the observed LRRs (often only 300–800 m in width), the observing radar system must be able to collect data at sufficiently high resolution to sample these narrow features. Oftentimes, this requires that the storm be located very near the radar, which is a benefit of a mobile...
platform. It is also possible that, as a result of the sometimes significantly different scattering properties of S versus X bands (Fig. 1) caused by resonance effects, the LRR may just be more apparent at X band than at lower radar frequencies.

The larger issue of what this feature reveals, if anything, about the dynamics and organization of these particular supercells remains unknown. It seems reasonable to suggest that the distinct heterogeneity in the observed radar quantities is associated with heterogeneities in low-level thermodynamic or buoyancy fields, as hydrometeor type and concentration can affect rates of evaporational cooling and precipitation drag. It is also possible that the LRR is the result of other storm-scale processes and is the by-product of microphysical processes occurring with undiagnosed dynamical processes.

The second polarimetric feature specifically examined in this project is an observed region of very low $\rho_{HV}$ located along the left side of the BWER (LoRB; Fig. 20b). In the cases in which the LoRB is evident, $\rho_{HV} < 0.6$ is juxtaposed with $Z_{H'}$ of 25–50 dBZ. Typically, $\rho_{HV}$ this low is observed with nonmeteorological scatterers (e.g., biological scatterers, tornado debris, etc.). Given the location of the observations, however, it seems likely

![Figure 18](image-url)
that the radar is detecting the presence of significant mixed-phase hydrometeors with the reduction in $\rho_{HV}$ exacerbated by resonance effects at X band; the LoRB, which may be analogous to the “LDR cap” or updraft signature observed by others at C and S bands, may also represent areas of very large hail aloft. Considering the mixture of hydrometeor types that is likely to compose the LoRB, it is possible that the LoRB marks an area of wet hail growth, and there may be diagnostic, if not prognostic, value in detecting the presence of this feature and examining its evolution over time (Picca and Ryzhkov 2012). In addition, the characteristics of the LoRB (e.g., the height at which it is observed relative to the ambient freezing level, the area-averaged $\rho_{HV}$ collocated with relatively high $Z_H$, etc.) may be related to hail number density and size. Although one can infer hydrometeor type based upon the polarimetric quantities, it would be extremely beneficial to have in situ

![Image of radar data with annotations and figures related to mixed-phase hydrometeors and LoRB features.](image-url)

**FIG. 19.** The $Z_H$, $Z_{DR}$, $\rho_{HV}$, and $\Phi_{DP}$, respectively, are shown in first, second, third, and fourth rows from (left) 0118 UTC 9 Jun 2010, (middle) 0459 UTC 9 Jun 2010, and (right) 0148 UTC 10 Jun 2010. The black outlines mark areas of local maxima in $\Phi_{DP}$ (before and after which $\Phi_{DP}$ decreases). These maxima are either the result of local maxima in $\delta$ or enhanced resonance effects (and perhaps hydrometeor shapes and orientations) that yield $K_{DP} < 0$ km$^{-1}$. 
observations—such as those from a penetrating aircraft—to provide the ground truth for what is actually responsible for this signature.

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Fig. 20. Generalized configurations for the (a) LRR and (b) LoRB; (a) is valid within 1 km AGL, and (b) is valid near and within 1 km of the ambient freezing level. As a result of the deployment locations typical of data collection efforts, there often is very high attenuation (sometimes to extinction) along the rear portion (often north and northwest for typical UMass X-Pol deployments) of observed supercells. As such, confidence is low in this region; the double black line at the top of (a) indicates this uncertainty.


