Polarimetric radar data from NCAR’s S-Pol are presented for a severe, hail-producing convective storm and for widespread migrating insects.

Research radars have led the way for many years by demonstrating new polarimetric measurement capabilities that are not possible with Doppler-only radars. Indeed, dual-polarization variables have improved rainfall estimates, made it possible to discriminate ice and rain, provided identification of hail cores and updraft regions, and in general increased data quality (Chandrasekar et al. 2013; Kumjian 2013a,b,c). Today, modern weather radar manufacturers employ dual-polarization technology because of this new proven capability. Many countries have procured dual-polarization technology, and some have upgraded or plan to upgrade their national fleet of radars to dual polarization. Such operational government radars have standard scanning strategies that emphasize fast updates for storm tracking and evolution. The fast updates are obtained with fast scan rates (~15°–30° s⁻¹), which translate to fewer samples that are integrated per resolution volume as compared to slower scan rates. Since S-band dual-polarization Doppler radar (S-Pol) is a research radar, it typically scans at significantly slower rates for better signal statistics: plan position indicators (PPIs), 8°–10° s⁻¹, and range–height indicators (RHIs), 3°–6° s⁻¹, although these rates are user selectable. The Weather Surveillance Radar-1988 Doppler polarimetric (WSR-88DP)¹ is not able to scan along vertical planes (RHIs), and while this has not been a significant disadvantage for operational purposes, it does limit research objectives. This will be illustrated in the following RHI examples from S-Pol. Also, increased range resolution is obtained by S-Pol, which normally uses a 1-μs transmit pulse length that corresponds to 150-m-range samples as compared to WSR-88DP’s 250-m resolution. The result is that S-Pol is able to obtain high-resolution, high-data-quality measurements that reveal intricate

¹ NEXRAD refers to the network of NWS radars, while WSR-88DP is the type of radar in the NEXRAD network, though they are used interchangeably.
storm structure and microphysics that would be difficult to see with operational scanning strategies.

The purpose of this paper is to provide, via example, the high-resolution precipitation microphysics phenomena and insect behavior that can be revealed with data from a state-of-the-art polarimetric S-band radar like National Center for Atmospheric Research (NCAR)’s S-Pol. While the examples are from S-Pol, other research S-band radars have similar capabilities. The WSR-88DPs have potentially the same basic capabilities, but their operational mode requires faster scanning procedures. For comparable data quality measurements with a WSR-88DP that used slower scanning rates, see Melnikov et al. (2011).

Using the fact that raindrops become more oblate as they get larger and that they are well oriented as they fall, Seliga and Bringi (1976) first reported on the potential of dual-polarization measurements, that is, differential reflectivity Z_{DR} to describe the oblateness of raindrops and thereby improve rain-rate estimation. The first Z_{DR} measurements were made soon after by the University of Chicago–Illinois State Water Survey (CHILL) radar facility in 1977 (Seliga et al. 1979). Several research radars soon followed and made polarization measurements mostly by transmitting alternate pulses of horizontal (H) and vertical (V) polarized waves (Seliga et al. 1990). Doviak et al. (2000) proposed using simultaneous transmission of the H and V polarized waves (SHV) to achieve dual-polarization measurements, the result of which is that today almost all polarimetric weather radars transmit both H and V polarized waves simultaneously, such as the WSR-88DP, while a few, primarily research radars, transmit fast alternating pulses of H and V (FHV) polarized waves. SHV mode works well but has been shown to produce biases under certain weather scenarios. For example, in regions of ice crystals that have been aligned and canted by an electric field, cross coupling of the H and V waves occurs, which causes radial Z_{DR} streaks (Ryzhkov and Zrnić 2007). Also, antenna-polarization errors cause cross coupling that biases Z_{DR}, as a function of copolar differential phase ρ_{HV} when using SHV mode (Wang and Chandrasekar 2006; Hubert et al. 2010a,b).

These errors do not occur with S-Pol since it achieves dual polarization by transmitting fast alternating pulses of H and V polarized waves. An advantage of SHV radars is that twice as many samples in each polarization are gathered in SHV mode as compared to FHV mode for the same sampling period (dwell time) and transmit pulse repetition time (PRT). More samples typically mean better signal statistics. This is a distinct advantage for SHV mode for fast scan rates with fewer samples per resolution volume. However, for slower scan rates and shorter PRTs, which S-Pol employs, this advantage of additional samples does not necessarily translate to significantly better signal statistics, which depend more on the number of independent samples [see Bringi and Chandrasekar (2001), their Figs. 6.29c and 6.30c, for a comparison of SHV and FHV statistics]. A disadvantage of SHV operations is the elimination of the capability to

**POLARIMETRIC VARIABLE INTERPRETATION**

The reflectivity factor Z indicates the quantity of precipitation and has units of mm² m⁻³ (dBZ). For particles with diameters much less than the transmitted wavelength (i.e., Rayleigh scattering), the received power is proportional to the sum of the sixth power of the particles’ equivolumetric spherical diameters per unit volume. Typical values are 50 dBZ and greater in the core of a thunderstorm and 20 dBZ in light rain.

The differential reflectivity Z_{DR} is a measure of the reflectivity-weighted mean axis ratio of the precipitation particle distribution and is a hail versus rain discriminator. Typical values in rain are slightly positive to about 3 dB; however, for hail, Z_{DR} is typically near 0 dB.

The differential phase ϕ_{DP} and its derivative with respect to radar range, specific differential phase K_{dp}, in degrees per kilometer is used for rainfall estimation, with 1° km⁻¹ yielding about 45 mm h⁻¹.

The copolar correlation coefficient ρ_{hv} is an indicator of mixed phase, large hail, and the bright band (melting snow). Taking the correlation product of the copolar H and V received signals for a resolution volume yields ρ_{hv}. In rain ρ_{hv} is usually >0.97 while in hail and in the bright band ρ_{hv} < 0.95.

LDR is an indicator of the presence of asymmetric particles such as wet snow and ice. For rain, LDR is typically less than −28 dB, while asymmetric particles in the bright band and wet hail typically yield LDR greater than −27 dB. LDR is not measured by SHV radars such as NEXRAD.

The co- to cross-correlation coefficient ρ_{co-x} is an indicator of ice crystals that are canted away from the horizontal because of the presence of an electric field. In rain and in many ice crystal regions, ρ_{co-x} is less than 0.3, while areas containing sufficient aligned ice crystals with a nonzero mean canting angle have ρ_{co-x} greater than 0.4.

The backscatter copolar differential phase shift δ is an indicator of resonant scatterers with particle diameters greater than 8 mm (for S band) such as larger water-covered ice and hail.

See the online supplementary material for more details on polarimetric variables (https://doi.org/10.1175/BAMS-D-17-0317.2).
measure the cross-polar signals (e.g., transmit H and receive V polarization). The ratio of the cross-polar to copolar powers is termed the linear depolarization ratio (LDR), which is valuable for identifying regions of wet ice. Additionally, FHV radars can measure the correlation of the copolar to cross-polar signals $\rho_{\text{co-x}}$ that can indicate regions of cloud electrification (Ryzhkov et al. 2002; Hubbert et al. 2015).

There are two other advantages that S-Pol enjoys: 1) S-Pol operates without a radome, which can distort signals, especially when it is wet (Salazar-Cerreno et al. 2014), and 2) S-Pol uses copolar and cross-polar receivers instead of H and V receivers. Since the copolar H and V signals use the same receiver, signal statistics are immune to any time-fluctuating receiver gain, thereby improving both bias and standard deviation of $Z_{\text{DR}}$, copolar differential phase $\phi_{\text{DP}}$, and copolar correlation coefficient $\rho_{\text{hv}}$. For a detailed discussion on weather radar, there are books such as Doviak and Zrnić (1993), Bringi and Chandrasekar (2001), Fabry (2015), and Zhang (2017). A good introductory text is Rinehart (2004). A few articles discussing polarimetric radar are Herzegh and Jameson (1992), Zrnić and Ryzhkov (1999), Ryzhkov et al. (2005), Chandrasekar et al. (2013), and Kumjian (2013a,b,c).

**STORM STRUCTURE REVEALED BY AN RHI THROUGH A CONVECTIVE CELL DURING PECAN.** From 1 June to 15 July 2015, S-Pol collected data for the field campaign Plains Elevated Convection at Night (PECAN; Geerts et al. 2016; Earth Observing Laboratory 2015; Lutz et al. 1995), which was centered at Hays, Kansas. S-Pol was located 42 km southwest of Hays close to McCracken, Kansas. The standard scan strategy for S-Pol was to alternate PPI volume scans with a series of RHI scans placed at 30° increments in azimuth. The PPI surveillance scan rate was 12° s$^{-1}$ with 0.75° azimuth resolution, and the RHI scan rate was 3.6° s$^{-1}$ with 0.25° elevation resolution. The NCAR-developed algorithm, clutter mitigation decision (CMD; Hubbert et al. 2009b,a), is used to identify clutter-contaminated data, and a Gaussian model adaptive processing (GMAP)-like clutter filter is applied (Siggia and Passarelli 2004). Both CMD and GMAP are used by Next Generation Weather Radar (NEXRAD). S-Pol’s $Z_{\text{DR}}$ is very well calibrated for the PECAN dataset using a new technique based on the cross-polar power method (Hubbert et al. 2003; Hubbert 2017), which takes into account diurnal temperature-driven variation of the $Z_{\text{DR}}$ bias. The uncertainty of the $Z_{\text{DR}}$ calibration is estimated to be less than 0.1 dB at the 98% confidence level (Hubbert 2017).

On the afternoon of 25 June 2015, there was convection along a cold-frontal boundary near S-Pol. Frontal overrunning of the southerly low-level jet led to ongoing convection initiation along and north of the cold front throughout the evening and overnight. The convection grew upscale into mesoscale convective systems that led to the generation of multiple outflow boundaries, bores, and other waves and further convection initiation throughout the night. We next show data from one of the strong convective cells. Shown in Fig. 1 is a reflectivity PPI scan at 0.5° elevation angle gathered at 0004:07 UTC 26 Jun 2015. The yellow line marks the location of the subsequent RHI data.

![Fig. 1. Reflectivity PPI scan at 0.5° elevation angle gathered at 0004:07 UTC 26 Jun 2015. The yellow line marks the location of the subsequent RHI data.](image-url)
Website: www.spc.noaa.gov/. At 0027:00 UTC at 38°20′24″N, 99°6′36″W near Ash valley and relative to S-Pol at 121° azimuth (from north) and 44-km range, the NOAA site reports, “There were several episodes of damaging hail at this location. The corn crop was shredded and the wheat was at least 50 percent destroyed.” This is the location of the RHI data reported here. There is a remarkable amount of information contained in the individual polarimetric variables, described below, and especially evident in the $Z_{DR}$ plot. We next discuss some of the scattering signatures seen in the RHI plots.

Description of echo regions.

Regions 1, 2, and 4: Insects. Regions 1, 2, and 4, to the northwest of the storm core, are characterized by mostly low reflectivities (−10 to 6 dBZ; Fig. 2), very high $Z_{DR}$ (4 to 14 dB; Fig. 3), and low $\rho_{hv}$ ($\lesssim$0.9; Fig. 4), which is the signature of insects (Wilson et al. 1994; Zrnić and Ryzhkov 1998; Melnikov et al. 2015). Insects are also distinguishable from weather by the increased spatial texture (variability) of the $Z_{DR}$ and $\phi_{dp}$ which is consistent with the characteristic low $\rho_{hv}$ (Chandrasekar et al. 2013). These regions consist primarily of horizontally oriented insects, which yield the observed high $Z_{DR}$, with the likely presence of a few birds, but they are hard to distinguish in the insect-dominated returns. Birds can have distinct polarimetric signatures from insects (Zrnić and Ryzhkov 1998) and are particularly obvious when colonies emerge from roost or a cave (e.g., bats; Russell et al. 1998). Since insects are characterized by lower $\rho_{hv}$ as compared to most precipitation, precipitation regions are typically easily distinguishable from areas of insects as seen in Fig. 4.

Where different air masses collide, updrafts are generated. Insects resist being carried aloft, and thus, the number density increases, resulting in lines

![Fig. 2. A reflectivity RHI of a large convective cell gathered at 0005:23 UTC 26 Jun 2015 from along the yellow line in Fig. 1. Eight regions are marked with white contour lines and are labeled. The dashed line marks the 55-dBZ contour; 60 dBZ is seen up to 13 km MSL, indicating the likely presence of large hail.](image1)

![Fig. 3. Differential reflectivity $Z_{DR}$ corresponding to Fig. 2. It is particularly effective for delineating various storm regions as indicated by the white contour lines in the plot.](image2)
of increased reflectivity (Wilson et al. 1994) as seen in Fig. 1 (lines marked as convergence lines) and as seen in region 2 of Fig. 2. Region 4 likely contains insects, indicated by the high $Z_{DR}$ values. It appears that a layer of insects resides above the layer marked Bragg scatter (discussed below), perhaps carried aloft in the updrafts caused by boundary layer horizontal convective rolls, and are up against the 0°C isotherm (Weckwerth et al. 1997; LeMone 1973). Insects avoid turbulent regions and freezing temperatures (Drake and Reynolds 2012).

In region 1, especially close to the ground, some residual clutter remains that the clutter filter was unable to eliminate, and this is likely the source of the higher reflectivity values (>9 dBZ). Many times, ground clutter will be characterized by negative $Z_{DR}$ since many ground clutter targets have longer vertical than horizontal dimensions. This likely causes most of the negative $Z_{DR}$ close to ground in Fig. 3. There are many $Z_{DR}$ values in excess of 8 dB in the insect regions. WSR-88DP’s maximum measurable $Z_{DR}$ is 7.9 dB by design (Melnikov et al. 2015) since NEXRAD’s focus is weather; therefore, such high $Z_{DR}$ values will not be observable with WSR-88DPs.

**Region 3: Bragg Scatter.** Region 3 is characterized by low reflectivity ($\leq 5$ dBZ), high $\rho_{hv}$ ($\geq 0.99$), and near-0 dB $Z_{DR}$. This is the signature of Bragg scatter (Gossard 1977, 1990; Doviak and Zrnić 1993; Wilson et al. 1994; Melnikov et al. 2011). Bragg scatter occurs in the atmosphere when turbulence mixes air masses of different refractive indices on the scale of half the radar wavelength, and it frequently occurs at the top of the boundary layer (Gossard 1990; Melnikov et al. 2013). Some of the $\rho_{hv}$ values in the Bragg layer are lower than its expected value of >0.99, but this is due to low signal-to-noise ratio (SNR), insect contamination, or sidelobe ground clutter. Bragg scatter is difficult to distinguish from clouds composed of very small droplets since the radar signatures are the same, and for this reason, NCAR’s particle identification (PID) algorithm combines cloud and Bragg scatter into one category.

One way to distinguish between Bragg and cloud scatter is the use of visual observations. S-Pol is equipped with four wide-angle cameras, facing north, east, south, and west, that capture images about every 30 s. For PECAN at the time of the RHI discussed here, the images show fairly clear skies out to the lower part of the convective cell and gust front that support the classification of Bragg scatter (see supplemental photographs online; https://doi.org/10.1175/BAMS-D-17-0317.3). However, the region above the gust front (labeled in the RHI) is difficult to discern from the photographs, so clouds could be present there. Thus, it is very possible that there are small cloud droplets that have increased the reflectivity. Additionally, the velocity fields from the available RHIs (sampled at every 30° in azimuth) show wind shear (e.g., Fig. 5) that would produce turbulence, which corresponds to the Bragg scatter layer. Bragg scatter at the top of the boundary layer was seen frequently during PECAN. It is also well known that Bragg scatter occurs as “mantle echoes” on the outside edges of early convective cells (Knight and Miller 1993).

**Region 5: Ice Crystals.** Region 5 is characterized by low reflectivity (<5 dBZ), high $Z_{DR}$ (>3 dB), and high $\rho_{hv}$ (>0.98) (where there is sufficient SNR), and below-0°C temperatures. It is inferred to be an ice cloud with horizontally oriented ice crystals with axis ratios significantly departing from unity such as ice plates. Since insects avoid freezing temperatures and they typically have reduced $\rho_{hv}$, they are very unlikely to be there. Note the variation in $Z_{DR}$ values as a function
of elevation angle in this layer. At 22-km range (about 13° elevation angle), $Z_{DR}$ is 6–8 dB, and at 6-km range (about 40° elevation angle), $Z_{DR}$ is 2–3 dB. This is likely due to the ice crystal’s reduced H-to-V aspect ratio apparent to the radar at higher elevation angles. This agrees very well with ice crystal scattering studies for plate crystals with a mean canting angle of 0° and a standard deviation of 10° (Aydin and Tang 1997; Battaglia et al. 2001) and further supports the ice crystal classification of this region.

**Region 6: Positive $Z_{DR}$ column.** Region 6 contains a very large positive $Z_{DR}$ column, indicating large oblate raindrops or oriented, wet ice particles, extending to 7.5 km MSL or about 3 km higher than the 0°C level as seen in Fig. 3. The highest $Z_{DR}$ is about 4 dB which corresponds to scattering from a 6mm rain drop as a point of reference (see Fig.ES2 in supplementary material). The $Z_{DR}$ columns are typically located in or on the fringe of the storm’s updraft region (Illingworth et al. 1987; Conway and Zrnić 1993; Kumjian et al. 2014). 2 Positive $Z_{DR}$ columns are caused by large oblate supercooled raindrops or water-covered ice, which has been verified by aircraft penetration studies.

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2 For a detailed study of $Z_{DR}$ columns and more references, see Kumjian et al. (2014).
A small reflectivity notch is seen in Fig. 2 at 40-km range at the 0°C level that corresponds to the storm inflow region supported by the radial velocity RHI of Fig. 5, which shows positive velocities into the $Z_{DR}$ column with a convergence signature on the back side of the $Z_{DR}$ column. At the top of the $Z_{DR}$ column, LDR is high (–17 to –20 dB; Fig. 6), while $\rho_{hv}$ is low (0.92–0.96). This is the well-known “LDR cap” that marks a mixed-phase transition where raindrops freeze and there may be wet growth (Br ingi et al. 1996; Hubbert et al. 1998; Jameson et al. 1996; Kennedy et al. 2001; Kumjian 2012). The size and strength of the $Z_{DR}$ column has been linked to hail growth and hail extent at the ground (Picca et al. 2010; Kumjian et al. 2014).

**Regions 7 and 8: negative $Z_{DR}$ column.** Regions 7 and 8 are likely wet graupel or hail. These regions have predominately negative $Z_{DR}$ with very high LDR <–22 dB, which indicates asymmetric particles with high dielectric constants (i.e., wet ice; Bringi and Chandrasekar 2001). The negative $Z_{DR}$ above the positive $Z_{DR}$ column have been observed before (Zrnić et al. 1993; Kumjian et al. 2014); however, the negative $Z_{DR}$ region in Fig. 3 extends to 12 km MSL, which is quite unusual. Reflectivities exceeding 60 dBZ around and above the negative $Z_{DR}$ column and the radial velocities indicating convergence in the storm core region and in back of the negative $Z_{DR}$ column suggest that continued hail growth is taking place and there is either large vertically oriented hail (Zrnić et al. 1993) or very large oblate hail with resonant scattering (Balakrishnan and Zrnić 1990; Aydin and Zhao 1990; Ryzhkov et al. 2013). Interestingly, another negative $Z_{DR}$ signature, region 7, extends to the front edge of the positive $Z_{DR}$ column from about 2 to 6 km MSL, coincident with very low reflectivities (~5 to 18 dBZ) and very high LDR (~25 to ~15 dB), and this suggests that a very low concentration of vertically oriented wet graupel/hail or large oblate hail could be falling out of the storm. Conical or cone-shaped ice particles are known to orient themselves vertically so that negative $Z_{DR}$ values result (Aydin et al. 1984). The negative $Z_{DR}$ signatures are not unique to this RHI and are even more dramatic in other neighboring RHIs (see the supplemental Z and $Z_{DR}$ figures; https://doi.org/10.1175/BAMS-D-17-0317.4).

**Positive $K_{DP}$ column.** Figures 7 and 8 show RHIs of copolar differential phase $\phi_{DP}$ and its range derivative (slope), specific differential phase $K_{DP}$, respectively, that correspond to Fig. 2. Note the $\phi_{DP}$ color-scale increments of just 1° up to 10° and 2° steps thereafter. These small increments and the spatial smoothness of the plot are indicative of S-Pol’s low $\phi_{DP}$ measurement error.

There is a vertical column of positive $K_{DP}$ extending above the 0°C level at about 41-km range that is coincident with the positive $Z_{DR}$ column. The $K_{DP}$ columns (i.e., positive $K_{DP}$ values that are above the 0°C level) have been well studied and documented (Hubbert et al. 1998; Loney et al. 2002; Ryzhkov et al. 2005; Kumjian et al. 2010; van Lier-Walqui et al. 2016). Many times, there is a spatial offset between the positive $Z_{DR}$ and $K_{DP}$ columns (Kumjian and Ryzhkov 2008), but here, they are coincident with the $K_{DP}$ column extending to nearly the top of the $Z_{DR}$ column. At about 6.6 km MSL, the maximum $K_{DP}$ is 1.7° km⁻¹ where the temperature is ~20°C, $Z_{DR}$ is up to 3.4 dB, the reflectivities exceed 55 dBZ, LDR is greater than ~22 dB, and $\rho_{hv}$ is between 0.94 and 0.97. This indicates there are supercooled raindrops and/
or oblate-oriented water-coated ice (hail) particles that cause the high $Z_{\text{DR}}$, and their concentration is high enough to cause the positive $K_{\text{DP}}$. This is likely a strong updraft region where hail is experiencing wet growth, which would cause the high LDR and low $\rho_{hv}$ (Balakrishnan and Zrnić 1990; Kumjian et al. 2010; Picca and Ryzhkov 2012). When hail experiences wet growth, the hailstones can shed raindrops, and these drops could be in part the source of the high $K_{\text{DP}}$ (Rasmussen and Heymsfield 1987).

**Automated Classification.** Much of the above classification can and has been automated with fuzzy logic. The first fuzzy logic precipitation particle identification inference we know of was done by Straka and Zrnić (1993) and then by Vivekanandan et al. (1999). The fuzzy logic algorithm in Vivekanandan et al. (1999) essentially became NCAR’s PID algorithm, the results of which are shown next. Figure 9 shows the results of the PID corresponding to Fig. 2 with human-expert classification overlaid. The PID algorithm inputs are the radar variables ($Z$, $Z_{\text{DR}}$, $\rho_{hv}$, $K_{\text{DP}}$, and LDR), the local spatial standard deviation of both $Z_{\text{DR}}$ and $\phi_{\text{DP}}$, and a vertical temperature profile. The temperature profile can come from data sources such as soundings or models. PID includes several nonhydrometeor types such as insects and ground clutter. The PID is designed to identify the most likely dominant scatterer in the radar volume. For example, large Z and near-zero or negative $Z_{\text{DR}}$ is a strong indicator of hail; however, if the hail is mixed with small ice or cloud drops, only the reflectivity-dominant hail will be detected. In the example RHI shown in Fig. 9, the PID yields a tenable classification and identifies features of the storm such as the large-hail region (yellow). Below the hail signal near the ground, melting hail (light green) is identified. Melting hail (light green) and melting graupel (dark green) can also be seen in the $Z_{\text{DR}}$-column region. The insect clear-air and ground-clutter returns are identified near the radar, close to the ground and separated from the ice and cloud/Bragg layers. The PID erroneously identifies the sidelobe contamination at the top of the storm echo as ice crystals. The PID may be in error if unusual or contaminated radar echoes occur, but it is quite useful for identifying the general structure of convection.

**Storm Electrification Revealed by Polarimetric Variables.** The topic of charge separation and storm electrification is a continued area of research interest (Korolev et al. 2017; Stough et al. 2017). It is known that when larger ice crystals (>30 µm) fall in stagnant air that is not electrified, they fall with their major axis horizontal (Zikmunda and Vali 1972; Foster and Hallett 2002). This has been reported to be true even in turbulent cumulus clouds (Cho et al. 1981). This means that nonelectrified regions in the ice phase of clouds will be characterized by $K_{\text{DP}} \geq 0$. It is also known that electric fields in clouds can orient ice crystals along the lines of the electric field (Weinheimer and Few 1987; Foster and Hallett 2002; Saunders and Rimmer 1999). This has been verified by radar studies that have shown regions where $K_{\text{DP}}$ is negative, indicating vertically oriented ice crystals (Hendry and McCormick 1976; Krebbiel et al. 1996; Galloway et al. 1997; Ryzhkov and Zrnić 2007; Hubbert et al. 2014b). Caylor and Chandrasekar (1996) and Metcalf (1997) reported that after observed lightning discharges, the associated negative $K_{\text{DP}}$ disappeared, indicating the ice crystals returned to their natural horizontal orientation state.

**Fig. 8.** Specific differential phase $K_{\text{DP}}$ corresponding to Fig. 2; $K_{\text{DP}}$ is the range slope of $\phi_{\text{DP}}$. Here, an interesting positive $K_{\text{DP}}$ column is seen extending above the 0° isotherm, indicating the presence of liquid drops and/or aligned water-covered wet ice. Higher in the figure, negative $K_{\text{DP}}$ is seen, indicating ice crystals aligned vertically by an electric field.
Indication of vertically oriented ice crystals are seen both in $\phi_{DP}$ of Fig. 7 and in $K_{DP}$ in Fig. 8 at about 45-km range and 10 km MSL. The $\phi_{DP}$ clearly shows a decreasing trend along the radar radial beginning at about 45-km range and 8-km height with the color scale changing from gray to light green to light blue to dark blue and then to magenta. The accompanying negative $K_{DP}$ is labeled in Fig. 8. This again is very likely caused by ice crystals aligned toward the vertical by a strong electric field. We note that the observed differential phase shifts would be larger in magnitude for shorter-wavelength radars (e.g., C band and X band).

The $\rho_{co-x}$: An indicator of storm electrification. A quite sensitive indicator of ice crystals that are canted away from the horizontal by an electric field is the co- to cross-channel correlation coefficient $\rho_{co-x}$, which is measured by FHV radars and not by SHV radars. This is a radar variable that has received little attention in the literature with a few notable exceptions (Ryzhkov et al. 2002; Hubbert et al. 2015; Reimann and Hagen 2014; Hubbert et al. 2014c). It is well known via modeling that for an ensemble of precipitation particles that possess symmetry about the vertical axis, the theoretical co- to cross covariances are zero (Bringi and Chandrasekar 2001; i.e., $\rho_{co-x} = 0$). Experimentally, $\rho_{co-x}$ is small but does not go to zero for several reasons: 1) estimates are based on finite-length data, 2) cross coupling of H and V signals caused by antenna imperfections, and 3) orientation distributions are not symmetric about the vertical. From experience with S-Pol data, in regions outside of canted ice crystals, $\rho_{co-x}$ is less than about 0.30 and has a high spatial variance. In regions of ice crystals aligned by electric fields, $\rho_{co-x}$ is greater than 0.30.

**Fig. 9.** An RHI of the NCAR PID algorithm corresponding to Fig. 2. The labeled regions within the contours are human-expert classifications. By and large, the PID and human-expert classifications agree well. The PID did not recognize region 4 as insects.

**Fig. 10.** An RHI of $\rho_{co-x}$ corresponding to Fig. 2. Under only the influences of aerodynamics will ice crystals align with their major axis in the horizontal, and in such cases, $\rho_{co-x}$ is theoretically zero. Practically, $\rho_{co-x} \leq 0.25$ is indicative of this. When $\rho_{co-x} > 0.4$ over a region, this indicates a particle population with nonzero mean canting angle. Above about 7 km, there are three discernible radial steaks of elevated $\rho_{co-x}$ that indicate ice crystals aligned because of an inferred electric field.
by a strong electric field, $\rho_{co-x}$ is consistently above 0.3. For example, Fig. 10 shows $\rho_{co-x}$ corresponding to Figs. 2–8, with visible radial streaks of elevated $\rho_{co-x}$ (>0.32) located between 8 and 15 km MSL and between 42- and 70-km range. These radar radial streaks are similar to the radial streaks shown in Ryzhkov and Zrnić (2007) for SHV $Z_{DP}$ caused by canted ice crystals.

Cross coupling occurs both at backscatter and for forward scatter. When the cross coupling is caused by forward scattering, the cross-coupled signals remain in the cross channel, thus creating radial streaks in $\rho_{co-x}$, LDR, and SHV $Z_{DR}$ if sufficient signal is cross coupled. However, among the three, $\rho_{co-x}$ is the most sensitive to scattering from canted ice crystals since it is a cross-channel correlation product rather than a power (the co- and cross-channel signals have uncorrelated noise). For example, in Fig. 10, the 0-dB SNR cross-polar power contour is shown by the larger dashed white line. Note the ability of $\rho_{co-x}$ to detect cross coupling even when the cross-polar power is lower than 0-dB SNR (e.g., 65-km range and 11-km height). Also, it is where $\rho_{co-x}$ is increasing along a radar radial that it is most indicative of the presence of oriented and canted ice crystals. The elevated $\rho_{co-x}$ values below the melting level at closer ranges are a manifestation of cross coupling caused by the insects and residual ground clutter. The high values at the very top of the storm are caused by sidelobes.

Figure 11 shows a further example of S-Pol’s ability to detect ice crystals canted by an electric field. The data are from PECAN at 0135:30 UTC 26 June in a four-panel PPI plot: $Z$, $Z_{DR}$, $\phi_{DP}$, and $\rho_{co-x}$ at 10° elevation angle. The melting level is about 4.5 km MSL, which translates to about 26-km range (range rings are labeled in the Z plot). Thus, nearly all the observed echoes are above the 0°C level. We infer that charged particles are likely being generated in the convective core regions and then are advected out into the anvil region. We see that there is evidence of this in the $\rho_{co-x}$ as manifest by the red radial streaks, which are indicated by white contour lines that are also superimposed on the $\phi_{DP}$ plot. The $\rho_{co-x}$ is maximized for ice crystals canted at 45° where $K_{DP}$ would be at a minimum (Hubbert et al. 2015). The $\phi_{DP}$ plot also shows evidence of ice crystals that are more horizontally oriented (in yellow and red colors) and more vertically oriented (in blue and magenta colors). Again, it is where $\phi_{DP}$ is increasing or decreasing in range that the anisotropic, aligned ice crystals are located.

The $Z_{DR}$ plot shows values from about 0 dB (gray color) to slightly positive (0.2 to 0.4 dB (green color)) in the regions where $\phi_{DP}$ and $\rho_{co-x}$ streaks exist. Modeling studies have shown that these regions can consist of two coexisting classes of particle types: 1) small anisotropic ice crystals that can be aligned by the electric field and give rise to the observed $\phi_{DP}$ and $\rho_{co-x}$ signatures and 2) larger polarimetrically isotropic particles that produce $Z_{DR}$ values close to 0 dB (Hubbert et al. 2014a,b; Ryzhkov and Zrnić 2007). Maximum increase (decrease) of $\phi_{DP}$ in range occurs when the

![Fig. 11. A PPI at 10° elevation angle of Z, Z_{DR}, \phi_{DP}, and \rho_{co-x} from PECAN data gathered at 0135:30 UTC 26 Jun 2015. The radial red streaks in \rho_{co-x} are evidence of electric fields that cant the ice crystals.](image-url)
particles are aligned horizontally (vertically). Thus, where there are adjacent radials of increasing $\phi_{DP}$ and decreasing $\phi_{DP}$ with range, we can conclude that an electric field caused ice crystals to change orientation from more horizontal to more vertical across those radials. Also, in Hubbert et al. (2015), it is shown that $\rho_{co-x}$ detected the presence of an electric field via canted ice particles before the first electrical discharge was detected by a Lightning Mapping Array (LMA; Rison et al. 1999). Thus, $\rho_{co-x}$ may be a useful measurement for studying the early electrification of convective cells.

**INSECTS.** During the warmer months (temperatures $>10^\circ$C), insects typically fill the skies over almost all land areas of the world. The literature contains numerous articles of such observations (Mueller and Larken 1985; Wilson et al. 1994; Melnikov et al. 2015; Zrnić and Ryzhkov 1998; Chilson et al. 2012; Vivekanandan et al. 2013; Lang et al. 2004; Drake and Reynolds 2012). In a recent study in the United Kingdom, researchers estimate that over the southern United Kingdom for high-flying ($>150$ m) insects, "that about 3.5 trillion insects (3200 tons of biomass) migrate above the region annually" (Hu et al. 2016, p. 1582). This explains why the field of radar entomology is becoming an area of increased interest.

When migrating, the insects align themselves in a common direction; thus, in a 360° PPI scan, the reflectivity will maximize in the direction where the insects are oriented perpendicular to the radar beam and minimize in the direction where they are aligned parallel to the radar beam. This gives rise to the so-called dumbbell pattern (Mueller and Larken 1985; Drake and Reynolds 2012) as observed in Fig. 12. Likewise, $Z_{DR}$ will maximize and minimize similarly. When insects are not migrating, they will have no preferred orientation, and thus, the dumbbell pattern is absent. Figure 12 shows PPI plots of $Z$, $Z_{DR}$, radial velocity, and $\phi_{DP}$ of S-Pol data from PECAN gathered at 1111:01 UTC 20 June 2015 at 1° elevation angle. Clear skies throughout the PECAN domain dominated on 20 June 2015, which provides an opportunity to examine the details of S-Pol’s clear-air return. Winds from a low-level jet are 25 m s$^{-1}$ from the southwest. The $Z$ and $Z_{DR}$ values range from about 0 to 20 dBZ and 0 to 15 dB, respectively. The southwest-to-northeast black line in Fig. 12 is drawn through the highest $Z$ and $Z_{DR}$ values. The other orthogonal black line then is an estimate of the insect flight orientation, which is southeast to northwest. A white dashed line is located through the highest-magnitude Doppler velocity. As shown, the insect flight orientation is about 60° from the maximum wind velocity direction. The insect $\phi_{DP}$ signature shows significant differential phase shift at backscatter $\delta$. 

![Fig. 12. A PPI of insect echo at 1° elevation angle of $Z$, $Z_{DR}$, velocity, and $\phi_{DP}$ from PECAN data gathered at 1111:01 UTC 20 Jun. The black arrow in the $Z$ plot shows the estimated direction of insect flight based on the maximum $Z$ and $Z_{DR}$ regions. The flight direction angle is about 60° from the wind direction (white dashed line). The white dashed ovals in the $\phi_{DP}$ plot indicate regions with interesting phase shift at backscatter $\delta$.](image-url)
by dashed contours in the plot. The intrinsic \( \phi_{\text{DP}} \) (i.e., starting value) of the radar is about \(-60^\circ\) (light blue color scale). The large values of \( \delta \) suggest backscatter from insects is well into the resonant scattering regime, and thus, the insects are likely 1 cm or larger in length. Also, the large positive and negative \( \delta \) do not align with the maximum and \( Z \) and \( Z_{\text{DR}} \) as might be expected. We believe this indicates that the insects likely fly with a pitch angle from the horizontal and the insects are not symmetric physically. These factors can cause the asymmetric \( \delta \) signature; however, we offer no supporting modeling such as was done in Melnikov et al. (2015). Figure 13 shows a four-panel RHI located along the yellow line in Fig. 12. Two distinct layers of insects are shown centered at about 1 and 3 km MSL. The plot of \( \phi_{\text{DP}} \) of the lower insect level shows a phase shift at a backscatter \( \delta \) of about \( 20^\circ-40^\circ \).

**Fig. 13.** An RHI of insect echo at 240° azimuth angle (yellow line in Fig. 12) of \( Z \), \( Z_{\text{DR}} \), velocity, and \( \phi_{\text{DP}} \) from PECAN data gathered at 1111:01 UTC 20 Jun. Two distinct layers can be seen at about 1 and 3 km MSL. The plot of \( \phi_{\text{DP}} \) of the lower insect level shows a phase shift at a backscatter \( \delta \) of about \( 20^\circ-40^\circ \).

**SUMMARY.** We have shown two examples of S-Pol polarimetric data 1) from a very strong convective storm and 2) from insects in clear air with both datasets from the PECAN field campaign centered in Kansas. S-Pol’s availability to scan slowly, execute RHIs, and transmit fast alternating H and V polarizations contribute to the data quality and the detail of storm structure and help to demonstrate the power of polarimetric data. S-Pol is operated by NCAR for the National Science Foundation (NSF) and is available to the NSF scientific community as part of the NSF-supported Lower Atmosphere Observing Facilities (LOAF; please visit [www.eol.ucar.edu/laof-guidebook](http://www.eol.ucar.edu/laof-guidebook)).

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