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# THE ARMOR C-BAND RADAR POLARIMETRIC RADAR SIGNATURES OF LARGE HAIL: APRIL10, 2009 SEVERE WEATHER OUTBREAK OVER NORTHERN ALABAMA

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## 1. INTRODUCTION

Dual-Polarization radar variables have greatly improved the knowledge of the radar meteorologist in correctly identifying the hydrometeor type being observed. Studies for the classification of hydrometeors based on their polarimetric variables have been conducted at both S-Band (e.g. Aydin et al. 1986, Bringi et al. 1986, Herzegh and Jameson 1992, Hubbert et al. 1998, Staka et. al. 2000, Kennedy et al. 2001) and C-Band (e.g. Meischner et al. 1991, Höller et al. 1994, Keenan et al. 2003, Baldini et al. 2004, Deierling et al. 2005). The emphasis of this study will examine polarimetric signatures from well sampled large hail producing supercells using the ARMOR C-Band dual-polarimetric radar.

In the literature, there are numerous examples of how to identify hail with S-Band polarimetric radar. Differential Reflectivity ($Z_{dr}$) is the measure of the difference between horizontal and vertical polarization. Therefore, $Z_{dr}$ is helpful in identifying the oblateness of a particle (e.g. rain drop). The larger the $Z_{dr}$ the more oblate the particle would be expected. The effect of oblateness for hail can be different because of the tumbling motions and near random orientations. Hail can appear to the radar as an effective sphere. In this case, the value of $Z_{dr}$ for hail would be expected to be near 0 dB associated with large reflectivity ($Z_h$). There are several examples of in the literature at S-Band (e.g. Aydin et al. 1986, Bringi et al. 1986, Herzegh and Jameson 1992, Hubbert et al. 1998, Kennedy et al. 2001). Based on this concept, Aydin et al. (1986) developed a quantitative hail signal $H_{dr}$, where $H_{dr} = Z - f(Z_{dr})$ that has been useful for identifying hail at S-Band (Depue et al. 2007).

However, studies at C-Band have not necessarily been as conclusive. It has been shown that near 0 dB is not what can be expected in areas of hail at C-Band (Meischner et al. 1991, Ryzhkov et. al. 2007). Meischner et al. (1991) attributes the anomalously high $Z_{dr}$ to smaller melting hail and resonance effects due to the smaller wavelength. Smaller melting hail stones can appear to the radar as large wet raindrops and exhibit high $Z_{dr}$. Resonance begins to take place at C-Band for particles larger than 5 mm (Zrnic et al. 2000). Therefore, when large particles are present $Z_h$ and $Z_{dr}$ can be significantly higher at C-Band compared to S-Band (Zrnic et al. 2000). $Z_{dr}$ is the measure of the reflectivity weighted axis ratio and is sensitive to dielectric and size. Therefore, the hydrometeors that contribute most to the reflectivity would be expected to be dominant in $Z_{dr}$. Melting hail is usually most dominant when present because of its size and dielectric. Ryzhkov et al. (2007) suggest that the anomalously high $Z_{dr}$ can be explained by large raindrops and small melting hail outweighing the effect of larger near 0 dB hailstones. Both studies indicate that the traditional S-Band approach for $Z_h$ and $Z_{dr}$ can not be used when trying to identify hail at C-Band. The polarimetric signatures of hail for C-Band must be better understood in order for hail to be properly classified.

Examining the literature above, it is easy to see that there are some obvious differences between hail signatures at C- and S-Band. This study will show clear examples of polarimetric signatures of hail from the ARMOR C-Band dual polarimetric radar. The April 10, 2009 hail event provided an excellent high quality case in close proximity to the radar (< 25 km) for observing C-Band polarimetric signatures of hail. The study will make some general comparisons to other studies performed at C-Band and show obvious differences from S-Band studies for identifying regions of hail. A version of the NCAR fuzzy logic based particle identification (PID) (Vivekanandan et al. 1999) algorithm, which was modified for C-Band (Deierling et al. 2005) will be examined for its overall utility for identifying hail at C-Band, and some general conclusions will be made from the results on how to better identify hail at C-Band.

## 2. EVENT OVERVIEW

On the morning of April 10, 2009 SPC had outlined the Tennessee Valley in an area of moderate risk with the forecast calling for the development of supercells associated with significant wind shear and instability ahead of an approaching cold front. As the day progressed and conditions worsened SPC issued a high risk. The event produced an EF-4 tornado in Murfreesboro,

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TN and an EF-3 tornado in Marshall and Jackson counties in Alabama. Strong tornadoes are not all that rare in the spring across the southeast.

The NWS in Huntsville, Alabama received over 85 reports of severe hail (> 1.9 cm) in a 14 county CWA in 4 hours. The large number of hail reports is a rare occurrence across the southeast. Hail sizes ranged from 1.9-7 cm. Figure 1 indicates CAPE of 2920 J/kg a LI of -10.8 °C, 0-1 km SRH of 233 $m^2s^{-2}$ and a freezing level of 2999 m. The large instability coupled with the below normal freezing height aided in the lofting of large particles well above the freezing level and the subsequent growth of large hail.

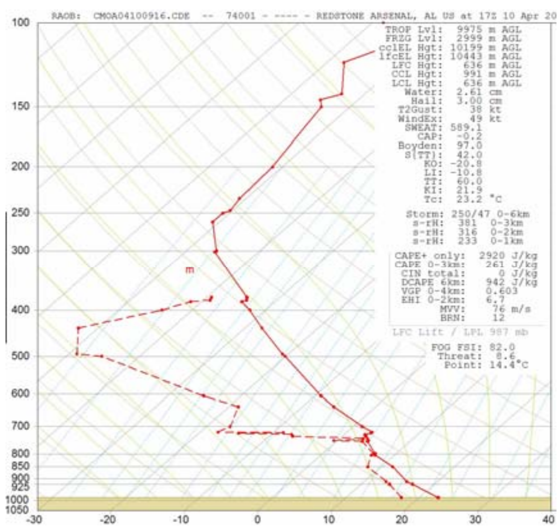


***Figure 1*** *Sounding from Redstone Arsenal at 17z on 10 April 2009. Courtesy of HUN SOO Chris Darden.*

## 3. DATA AND METHODOLOGY

As part of a larger investigation of this severe weather event, an internet survey was conducted to add to the National Weather Service reports. The survey was sent out to addresses from the NASA Marshall Space Flight Center and the National Science Space and Technology Center email lists. Questions in the survey asked about the size, shape, hail characteristics, location, time, confidence of report, and how the measurement was made. The number of responses came to 65 but because of some inaccuracy in the surveyors answers only 57 reports were used in this study. All of the respondents in the survey were received from only two storms in the early afternoon due to the storms close proximity to population centers. The participants in the survey reported hail sizes from 0.5 – 5.7 cm. Surveyors mentioned that the hail contained lumps, lobes, and noticeable growth rings. The shapes ranged from spherical, disc, and oblate with the smaller hail being mostly spherical and the larger hail mostly oblate. The survey helped to provide a dense network of reports, shown in Figure 2, in close proximity to the radar that was helpful in analyzing the polarimetric data.

The information from the reports was then used to make a detailed comparison with the polarimetric data corresponding to that data point and time. The data was taken from the ARMOR Dual-Polarimetric C-Band radar located at the Huntsville International Airport. ARMOR is a simultaneous transmit and receive dual polarimetric radar (Petersen et. al. 2005).

The $Z_h$ and $Z_{dr}$ utilized in this study were corrected for the effects of attenuation and differential attenuation, following Testud et al. (2001), Smyth and Illingworth (2001), and Bringi et al. (2001). ARMOR routinely does absolute calibration based on the polarimetric self-consistency methodology outlined in Ryzhkov et al. (2005) and relative $Z_{dr}$ calibration using “bird bath scanning techniques” on natural and known targets such as light rain and drizzle (Bringi and Chandrasekar 2001, p. 336-338). Light rain and drizzle would be expected to have $Z_{dr}$ values near 0 dB because of there axis ratio are near one. The bias of the radar is then assessed and a correction is implemented to the data. The event was a high quality event with supercells and large hail reports in close proximity to the radar (Fig. 2). Therefore, polarimetric data quality issues such as beam broadening (Ryzhkov 2007) are mitigated by the fact that the data was taken primarily at close range. The data format utilized most in this study is Universal Format (UF). UF read and write routines were used to produce ASCII files for each report. The ASCII file contains data points within 1km of each report. The data was then analyzed using Interactive Data Language (IDL) to make numerous plots and comparisons.

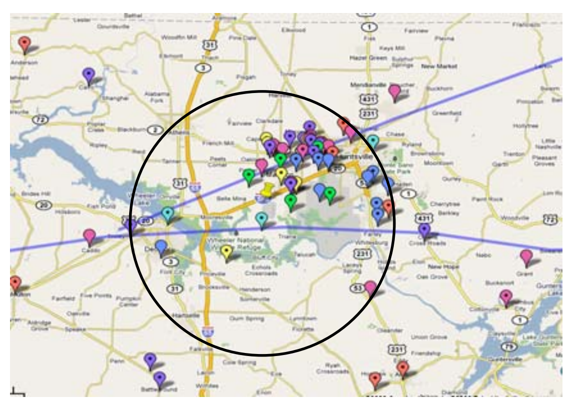


***Figure 2*** *Google Map of reports received from participants in internet survey. Marks indicate locations of hail reports with the purples and pinks representing hail > 4.5 cm. Blue lines indicate storms tracks. Yellow thumbnail location of the ARMOR Radar. Black line range ring is 25km away from radar.*

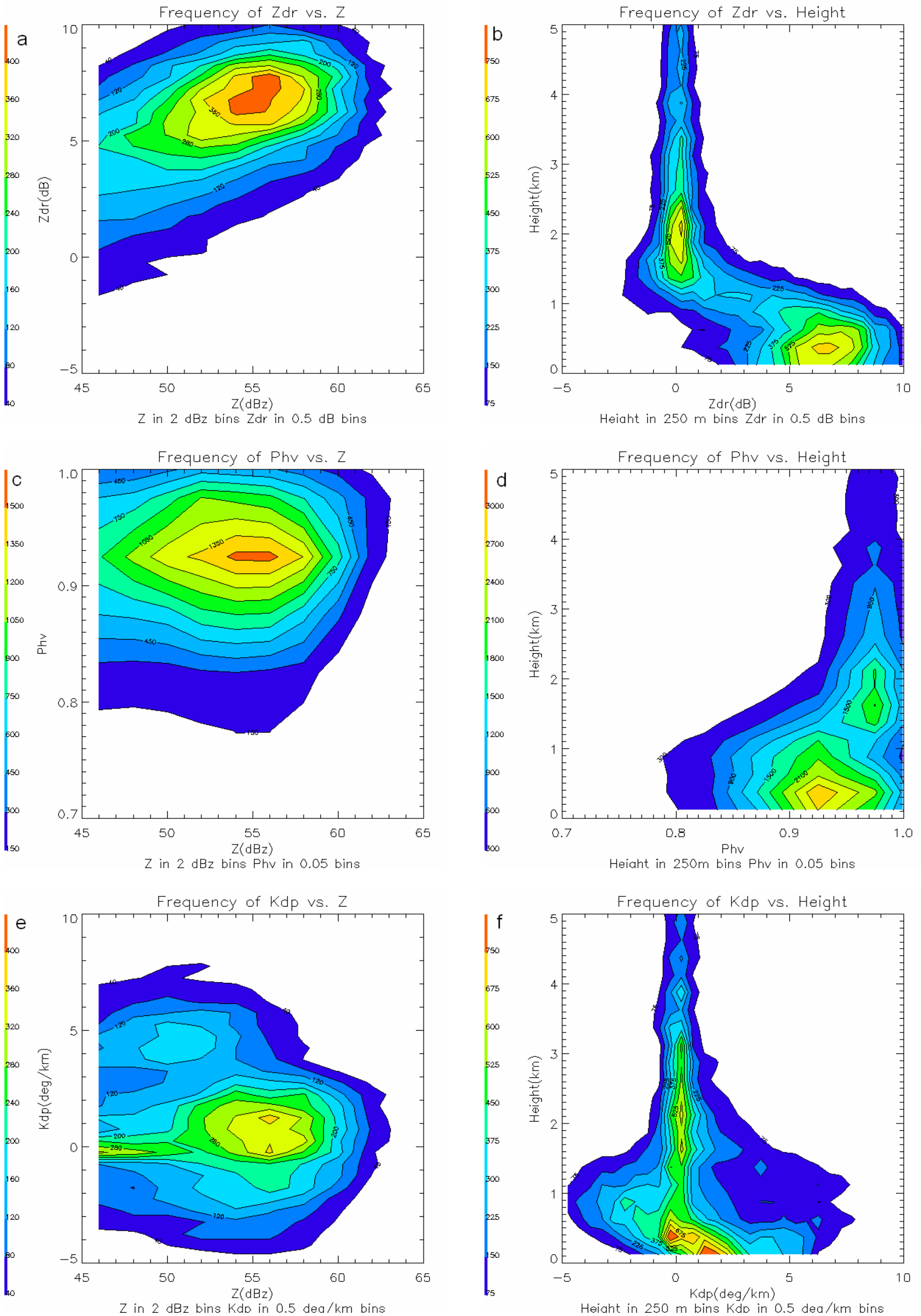



***Figure 3*** *Frequency of polarimetric variables vs. $Z_h$ (left) and height (right). All data points taken within 1 km of hail reports where $Z_h$ is > 45 dBz. (a) Frequency of $Z_{dr}$ vs. $Z_h$ (b) Frequency of $Z_{dr}$ vs. height (c) Frequency of $\rho_{hv}$ vs. $Z_h$ (d) Frequency of $\rho_{hv}$ vs. height (e) Frequency of $K_{dp}$ vs. $Z_h$ (f) Frequency of $K_{dp}$ vs. height.*

The NCAR PID (Vivekanandan et al. 1999) modified for C-Band (Deierling et al. 2005) was also investigated in this study. The program was utilized to provide a rough evaluation of how well the NCAR PID identifies the presence of hail at C-Band. The NCAR PID produces Sweep files that can be viewed in NCAR SOLOII. NCAR SOLOII is software developed by NCAR that is helpful for visualizing and editing radar data.

## 4. RESULTS

### 4.1 $Z_{dr}$ vs. $Z_h$ and Height Comparisons

The $Z_{dr}$ vs. $Z_h$ radar range gates located around all the hail reports are characterized by anomalously high $Z_{dr}$ for areas of high $Z_h$ (Fig. 3a). There is a $Z_{dr}$ mode of 7 dB that occurs at 56 dBz with over 400 points falling into this location. These results are similar to what was found in Meischner et al. (1991). As noted earlier the anomalously high $Z_{dr}$, is theorized to be due to smaller melting hailstones that appear as large raindrops to the radar. When melting occurs, the water torus on the outside of the drop can become sufficient enough to stabilizing the drop (Aydin and Zhao 1990). In this case, one would expect high $Z_{dr}$. Resonance also plays an important role for particles over 5 mm at C-Band, which is what was observed for this event. Maximum $Z_{dr}$ values are observed as high as 10 dB. These results indicate that conventional S-Band knowledge does not seem to apply at C-Band for this event.

A striking result that goes against traditional S-Band knowledge can be found in $Z_{dr}$ vs. height (Fig. 3b). The freezing level indicated on the 17 UTC sounding from Redstone Arsenal was shown to be near 3 km. $Z_{dr}$ in this example is around 0 dB above the freezing level, which is what has also been observed at S-Band. As the hail continues below the melting level, $Z_{dr}$ begins to increase toward high positive values with a mode near the surface of 6.5 dB and a maximum of near 10 dB, which is unlike past S-Band studies. The increase takes place below 2 km where the hailstones have had enough time to begin to melt and develop a sufficient water torus.

### 4.2 $\rho_{hv}$ vs. $Z_h$ and Height Comparisons

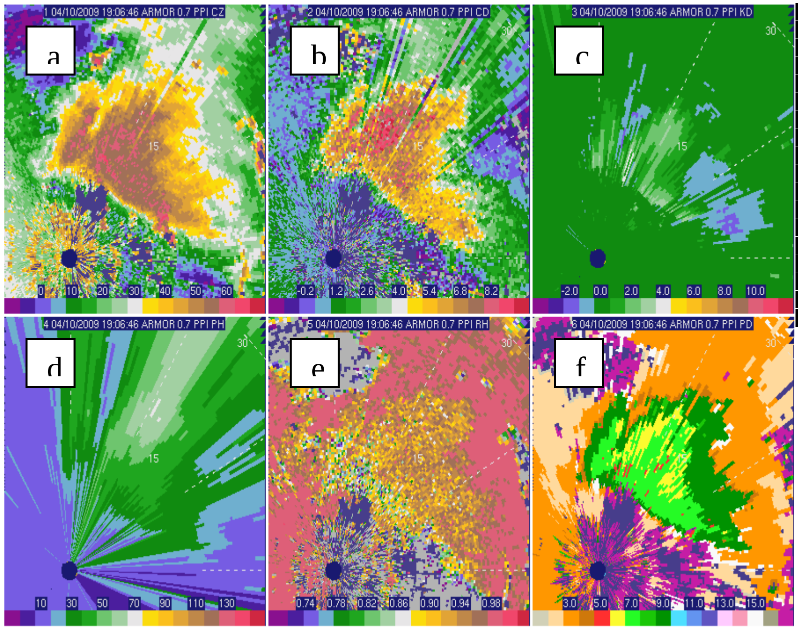
When comparing $\rho_{hv}$ vs. $Z_h$, the signatures are similar to what has been observed at S-Band for situations involving hail (Balakrishnan and Zrnic 1990a). There is a $\rho_{hv}$ mode of 0.925 with $Z_h$ of 56 dBZ, which is what would be expected in area of mixed hydrometeors (Fig. 3c). Previous studies have observed that $\rho_{hv}$ in pure rain can drop as low as 0.94-0.95 at C-Band because of resonant effects at shorter wavelengths (Zrnic et al. 2000, Keenan et al. 2000, Carey et al. 2000). Therefore, the mode and minimum near 0.8 suggests that the radar volumes in this study likely contained a mixture of rain and hail (Tabary et al. 2009). Balakrishnan and Zrnic (1990a) explained possible reasons for drops in $\rho_{hv}$, such as Mie scattering, irregular shaped hydrometeors, a mixture of hydrometeors, and a variety of hydrometeor shapes. Therefore, it is possible that there was a mixture of hydrometeors including rain and hail. It also suggests that the lobes and lumps from the hail observed by the participants in the study could have contributed to the lowering in $\rho_{hv}$.

Clear distinctions can be made for $\rho_{hv}$ above and below the melting level (Fig. 3d). Above the melting level, $\rho_{hv}$ is near unity indicating a uniform hydrometeor type such as hail. Below the melting level, a decrease in $\rho_{hv}$ occurs with a mode near 0.925, which is indicative of hailstones with irregular shapes and that there is likely a variety of hydrometeors below the melting level (Fig. 3d). Therefore, the lowering of $\rho_{hv}$ can be attributed to a variety of possibilities such as resonance (large rain drops and/or wet hail), irregular shaped hydrometeors (hail with lumps and lobes), and a mixture of hydrometeors (rain and hail). All of these interpretations are generally consistent with the hail reports.

### 4.3 $K_{dp}$ vs. $Z_h$ and Height Comparisons

The distribution of $K_{dp}$ vs. $Z_h$ is consistent with prior S-Band studies. The mode for the figure occurs at 1 $^{o}km^{-1}$ for $K_{dp}$ and 56 dBz for $Z_h$ (Fig 3e). Specific differential phase ($K_{dp}$) depends only on the hydrometeor size, shape, and orientation. When $K_{dp}$ is near zero this indicates that the targets are isotropic (Balakrishnan and Zrnic 1990b). Therefore, it has been observed that near 0 $^{o}km^{-1}$ $K_{dp}$ is associated with hail in the case of high $Z_h$ (Balakrishnan and Zrnic 1990b). There is a secondary maximum that occurs near 4.5 $^{o}km^{-1}$ and 50 dBz. It is theorized that this maximum may occur in an area where heavier rain is present. The rain rate is calculated at 58 mm/hr in this area using $K_{dp}$-based calculations at C-Band (Aydin and Giridhar 1992). The secondary maximum was caused specifically within one cell that might have produced more of a mixture of hydrometeors. The values of $K_{dp}$ near 4.5 $^{o}km^{-1}$ in this secondary maximum are more associated with values found in rain from C-Band at the specified $Z_h$ values (Bringi et al. 1991).

$K_{dp}$ is consistently near 0 $^{o}km^{-1}$ above the melting level but becomes rather noisy below (Fig 3f). The near 0 $^{o}km^{-1}$ above the melting level suggest isotropic hydrometeors as stated earlier, but below the melting level $K_{dp}$ values range from -5 $^{o}km^{-1}$ to 7 $^{o}km^{-1}$. The mode, however, stays near 0 $^{o}km^{-1}$. Ryzhkov et al. (2007) suggested that $K_{dp}$ maybe useful in identify regions of hail at C-Band. However, the overall noisiness of the $K_{dp}$ observations suggests that it may have limitations in reliably distinguishing between areas of rain, hail, and their mixtures. Since it is one-half the range




| Category | Color | NCAR PID |
|---|---|---|
| 1 | | Cloud |
| 2 | | Drizzle |
| 3 | | Light Rain |
| 4 | | Moderate Rain |
| 5 | | Heavy Rain |
| 6 | | Hail |
| 7 | | Rain and Hail |
| 8 | | Graupel and Small Hail |
| 9 | | Graupel and Rain |
| 10 | | Dry Snow |
| 11 | | Wet Snow |
| 12 | | Ice Crystals |
| 13 | | Irregular Ice Crystals |
| 14 | | Supercooled Liquid Drops |
| 15 | | Flying Insects |
| 16 | | 2nd Trip |
| 17 | | Ground Clutter |

***Figure 4** Above is the chart for the NCAR PID. To the left PPI image from ARMOR at 1906UTC at 0.5 elevation. (a) Corrected $Z_h$ (b) Corrected $Z_{dr}$ (c) $K_{dp}$ (d) $\Phi_{dp}$ (e) $\rho_{hv}$ (f) NCAR PID.*

derivative of the already noisy differential propagation phase, $K_{dp}$ can be a particularly noisy field (e.g. Bringi and Chandrasekar 2001, p. 548-550). The combination of random and systematic errors in $K_{dp}$ and intrinsic variability of $K_{dp}$ in a rain and hail mixture could make it difficult to use reliably to locate hail at C-Band. Smyth et al. (1999) suggest that oblate hail can cause non-zero values of $K_{dp}$ in hail due to both intrinsic positive propagation phase and improperly removed backscatter phase during resonance, further complicating the matter at C-Band.

**4.4 NCAR PID**

In this study, the NCAR PID was utilized to identify areas of hail. The NCAR PID uses fuzzy logic to identify the most likely hydrometeor type based on polarimetric variables and was first developed by Vivekanandan et al. (1999). The version of the code used in this study was modified by Deierling et al. (2005) for use at C-Band. Since ARMOR is a simultaneous transmit and receive radar it does not have the capability to measure LDR. The weighting scheme for the variables is similar to that suggest by Zrnic et al. (2001) except that $\rho_{hv}$ is weighted higher because of the absence of LDR.

After running the modified version of the NCAR PID, it is easy to see that most of the storm composed of hail or rain hail mixtures. The nature of the event and the number of reports in this area suggest that the output from the NCAR PID would be a reasonable assumption. However, the NCAR PID arrives at these results using traditional low $Z_{dr}$ high $Z_h$ method for identifying areas of hail. The NCAR PID could have identified the areas of hail because of the weighting effects of $\rho_{hv}$ and $Z_h$. A better understanding of resonance and melting hail could lead to better weighting functions in the NCAR PID for variables such as $Z_{dr}$.

**5. SUMMARY**

A severe weather system moved across the Tennessee Valley producing copious amounts of severe hail. The event is a excellent opportunity to evaluate the polarimetric parameters at C-Band, to understand better hail signature at C-band and improve upon identifying large hail using the NCAR PID at C-Band. ARMOR observed the same anomalously high $Z_{dr}$ at C-Band as was observed by Meischner et al. (1991). In the Meischner et al. (1991) study it was concluded that the high $Z_{dr}$ was due to melting hail appearing as large raindrops to the radar because of resonance. In this event, there was also large hail present (> 5 cm). Ryzhkov et al. (2007) suggest that large raindrops and small melting hail dominate $Z_{dr}$ in these situations. It is not apparent in this event if smaller hail was present at the time of the largest hail. Hopefully, future work using the T-matrix and Mueller matrix scattering (Bringi and Chandrasekar 2001, p. 591-594, and p.129-131, respectively) model can lead to more conclusive results.

Overall, improvements can be made to the NCAR PID for identification of large hail at C-Band. Improvements must first be made in understanding the polarimetric signatures at C-Band for hail before being able to adequately adjust the NCAR PID membership functions (Vivekanandan et. al. 1999). However, preliminary results from this event show that there maybe some separation between $Z_{dr}$ for heavy rain and hail to begin to adjust the weight of

$Z_{dr}$ for hail. The $Z_{dr}$ mean of 7dB found in this study shows that at C-band $Z_{dr}$ is the opposite of what has been observed at S-band. Studies have modeled large rain drops at C-Band and found $Z_{dr}$ to be near 3-4 dB (Bringi et al 1991), suggesting there maybe enough separation between $Z_{dr}$ for large hail and heavy rain to begin to adjust the NCAR PID. The results of high $Z_{dr}$ and high $Z_h$ maybe contrary to what has been found at S-Band but our study suggests that weighting very large $Z_{dr}$ toward melting hail could be a possible solution for C-Band. The results in this study show a $\rho_{hv}$ mode of 0.925 with a minimum as low as 0.8 demonstrating that there is some separation between the $\rho_{hv}$ for rain and hail at high $Z_h$. As a result, $\rho_{hv}$ should play an important role distinguishing between rain and hail. As noted earlier, $\rho_{hv}$ is already weighted more due to the absence of LDR. The overall noisiness of $K_{dp}$ suggests that it should perhaps be weighted less than the other variables for identifying regions of hail near the surface, although further research is needed. This overall approach will have to be further investigated with modeling and more case studies.

Future studies to improve upon evaluating C-Band polarimetric signatures in hail will be aided by a the use of the Rasmussen and Heymsfield (1987a,b) hail melting model and more case studies. The model will aid in a better understanding of the microphysics associated with melting hail such as the axis ratio, ice core diameter, and particle diameter. More events will help in answering the question if high $Z_{dr}$ (> 5 dB) occurs in all events associated with C-Band radars or if there are some cases that are different. Overall, this study has shown that there are some clear differences between what has been observed at S-Band and C-Band for identifying regions of large hail using polarimetric variables in southeastern United States and these differences must be properly implemented in PID algorithms.

**6. ACKNOLODGEMENTS**

*The authors gratefully acknowledge research support from the NOAA Hazardous Weather Test Bed.*

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