Dual-Polarimetric Analysis of Raindrop Size Distribution Parameters for the Boulder Flooding Event of 11-12 September 2013

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December 3, 2015
1. **Introduction**

The estimation of rainfall rate and quantitative precipitation estimates (QPE) from Doppler weather radars has long been used as a means to develop a “high resolution" spatial distribution of accumulated precipitation in extreme weather events (Battan, 1973; Brander, 1975; Smith et al., 1996; Krajewski and Smith, 2002; Ryzkov et al., 2005a). With the introduction of dual-polarization radars, more information is available that can be leveraged to understand the drop size distribution (DSD) parameters and provide better radar reflectivity factor/ rainfall rate (Z-R) relationships. However, the current Z-R relationship most commonly used in research is a power-law relationship using only radar reflectivity and is given by $Z = 200R^{1.6}$ (Rinehart, 2010). While this rainfall rate has proven useful through the years, it does not account for the DSD parameters as is possible through dual-pol measurements. QPE estimates from Z-R relationships are meant to provide the forecaster with the knowledge of the total accumulated precipitation; however, if the proper rain rate algorithms are not used or if the radar is not calibrated properly, the QPE can provide potentially misleading estimates (Rinehart, 2010).

The original Z-R power-law relationship was derived by assessing DSDs in different precipitation modes and geographic locations and a Z-R computing rainfall rate from radar reflectivity factor using single polarization (horizontal) weather radars. The power-law relationship takes the form $Z = aR^b$ where $a$ and $b$ are constants that are specific to precipitation type and geographic location making for over 60 different useful Z-R relationships (Battan, 1973; Austin, 1987; Rinehart, 2010). Currently, the National Oceanic Atmospheric Administration (NOAA) uses $Z = 300R^{1.4}$ operationally for the Next-Generation Radar (NEXRAD) Level III product (Cunha et al., 2015). The performance of the power-law relationship is highly dependent upon the DSD as $Z = f(D^6)$. Because of the dependence of Z-R relationships on the DSD and the variability of the DSD with geographic location, dual-pol variables have been used to develop a more consistent rainfall rate algorithm for QPE analysis (Bringi et al., 2003).
Dual-Polarization radars transmit and receive in both the horizontal and vertical polarizations providing measurements of reflectivity and phase shift for both polarizations which can be used to obtain properties of the scanned particles in a radar range gate. Dual-pol variables can be used collectively to obtain information on drop shape, size, orientation, phase, etc. as well as the droplet concentration (Krajewski et al., 2002). Dual-polarimetric radar retrieves horizontal radar reflectivity factor ($Z_h$), differential reflectivity ($Z_{dr}$), differential phase shift ($\Phi_{dp}$), and cross-polar correlation coefficient ($\rho_{hv}$) among others. More recent rain-rate algorithms take advantage of the dual-pol variables to improve the QPE estimates from the operational Z-R relationship. Several common dual-pol rain-rate algorithms used are $R(Z_h, Z_{dr})$, $R(K_{dp})$, and $R(K_{dp}, Z_{dr})$ (Bringi and Chandrasekar, 2001; Cifelli et al., 2011). $K_{dp}$ is the specific differential phase shift and is a derived dual-pol variable and is dependent upon the measurements of differential propagation phase ($\phi_{dp}$), but is beneficial because it is immune to beam blocking and radar calibration issues (Cifelli et al., 2011). The difference between single-pol and dual-pol rain-rate algorithms tends to increase as rain-rate increases with dual-pol providing better results at middle to higher rain rates. This can be explained because of the increased likelihood of ice contamination at higher rain rates, which can be better identified by dual-pol variables (Chandrasekar et al., 2008; Cifelli et al., 2011).

Cifelli et al. (2011) analyzed the performance of seven different rain-rate algorithms for three different intense precipitation events in the greater Denver, Colorado area. Similar analysis was performed for a heavy rainfall event on 11-12 September 2013 near Boulder, Colorado. Radar derived QPE from the various rain-rate algorithms was compared to accumulated precipitation from a rain gauge located at the University of Colorado- Boulder (CU-Boulder) for the duration of the event in Figure 1. The results showed the $R(K_{dp}, Z_{dr})$ algorithm performed the best for this particular case, while the other algorithms underestimated rainfall by anywhere from 20 - 70 %. The difference between the rain-rate algorithms seemed to be magnified as rain-rate increased, suggesting the possibility of ice contamination as stated in Chandrasekar et al. (2008) and Cifelli (2011). This study utilizes dual-
polarimetric radar techniques to estimate the parameters of the gamma DSD from dual-pol radar data. Analysis of the DSD will focus on differences between convective and stratiform precipitation and the evolution of the gamma parameters at the CU-Boulder site. Dual-pol variables will be used to identify potential ice contamination using reconstructed range height indicators (RHIs) during convective events and a time-height cross-section over CU-boulder.

2. Methods

Dual-polarimetric data was retrieved for a ~10 hour period of a heavy precipitation event which led to significant flooding in the greater Boulder, Colorado area during the overnight hours of 11-12 September 2013. During this event, Boulder received between 100-125 mm of rainfall (University of Colorado, N.D.) from a quasi-stationary linear feature with embedded convection. This heavy precipitation event was only one of a series of events that brought rainfall totals exceeding 250 mm for the week of 9-15 September 2013. The 11-12 September event was selected because of the large variability in the rain rate algorithms, almost all of which underestimated accumulated rainfall when compared to the tipping bucket rain gauge at CU-Boulder.

(a) Radar Data

Level II and Level III radar data was provided by the KFTG WSR-88D located near Denver, Colorado and obtained from the National Climate Data Center (NCDC) dataset. The KFTG WSR-88D is an S-Band radar operating at ~3 GHz with a wavelength of 10.7 cm, a 3-dB beamwidth of 1°. The radar is located at 39.79 °N and 104.55 °W at an elevation of 1.7-km. During this event, the radar was scanning with the volume coverage pattern (VCP) 212 which consists of 14 elevation angles and 17 azimuthal scans and takes about 4 minutes and 40 seconds for a full volume scan. The VCP212 scanning strategy tends to perform better in regions with complex topography and is typically used in scenarios where convection is present within the scanning domain (OFCM, 2006).

Level II data was gridded using the Radx software with horizontal (x,y) and vertical
(z) grid spacing of 1 kilometer and 250 meters respectively. Values of $K_{dp}$ at the $1.5^\circ$ elevation angle were obtained from NEXRAD Level III NCDC data. The $1.5^\circ$ elevation level was chosen to mitigate the effects of ground clutter on the $K_{dp}$ field. $K_{dp}$ was gridded using the NOAA Weather and Climate Toolkit and interpolated to the Radx grid using a four-point nearest-neighbor interpolation scheme. In addition to $K_{dp}$, the other dual-polarization variables selected to understand the microphysical properties for this event are $Z_h$, $Z_{dr}$, $\Phi_{dp}$, and $\rho_{hv}$. Radar retrieval algorithms for these variables are provided in Bringi and Chandresekar (2001).

(b) Derivation of Gamma DSD Parameters

Understanding the performance of the different rain rate algorithms requires analysis of the drop size distribution (DSD). The suite of dual-pol variables listed above are leveraged to obtain the microphysical parameters of the drop size distribution using the $\beta$-method (Gorgucci et al., 2000, 2001) and the DSD retrieval algorithms developed from Gorgucci et al. (2001, 2002), Bringi et al. (2002), and Brandes et al. (2004). The $\beta$ parameter is the slope of the linear relationship between drop size and axis for a given DSD and can be directly compared to the Pruppacher and Beard (1970) linear axis-ratio relationship for which $\beta = 0.062$. To calculate $\beta$, a non-linear regression using $Z_h$, $Z_{dr}$, and $K_{dp}$ is used:

$$
\beta = 2.08Z_h^{-0.365}K_{dp}^{0.380}\zeta_{dr}^{-0.965}
$$

(1)

where $Z_h$ is in units of $mm^6\ m^{-3}$, $K_{dp}$ is in units of $degrees\ km^{-1}$ and $\zeta_{dr}$ is in linear units. When $\beta > 0.062$, drops are estimated to be more oblate than the PB70 algorithm and when $\beta < 0.062$, drops are estimated to be less oblate. DSD parameters are then calculated based on thresholds on the three dual-pol variables developed by Bringi et al. (2002) and Brandes et al. (2004). Thresholds for $Z_h$, $Z_{dr}$, and $K_{dp}$ are meant to categorize the precipitation into convective ($RR > 15\ mm\ h^{-1}$) and stratiform ($RR \leq 15\ mm\ h^{-1}$) precipitation modes. The rainfall rate demarcation is estimated from the $K_{dp}$ threshold used in the algorithm.
Here, we follow the approach by Brandes et al. (2004) and set the $K_{dp}$ demarcation to be $0.20 \degree km^{-1}$. Thus, the dual-pol variables suggest convective precipitation when $Z_h \geq 35 \text{ dBZ}$, $Z_{dr} \geq 0.20 \text{ dB}$, and $K_{dp} > 0.20 \degree km^{-1}$ and the following equations are used for the DSD parameters:

$$D_0 = 0.56 Z_h^{0.064} \zeta_{dr}^{0.024\beta^{-1.42}} \tag{2}$$

$$\log_{10} N_w = 3.29 Z_h^{0.058} \zeta_{dr}^{-0.023\beta^{-1.389}} \tag{3}$$

$$\mu = \frac{200\beta^{1.89} D_0^{2.23 \beta^{0.039}}}{\zeta_{dr} - 1} - 3.16\beta^{-0.046} \zeta_{cr}^{-0.374\beta^{-0.355}} \tag{4}$$

where $D_0$ is the drop median volume diameter, $N_w$ is the normalized drop concentration, and $\mu$ is the shape parameter of the distribution. Bringi et al. (2002) suggest the precipitation is in stratiform mode if $Z_h < 35 \text{ dBZ}$ and $Z_{dr} \geq 0.2 \text{ dB}$ and use the following equations to compute the DSD parameters:

$$D_0 = 1.81 \zeta_{dr}^{0.486} \tag{5}$$

$$N_w = \frac{21 Z_H}{D_0^{1.353}} \tag{6}$$

The precipitation is also in stratiform mode when $Z_h < 35 \text{ dBZ}$ and $Z_{dr} < 0.2 \text{ dB}$, but the following equations for the DSD parameters are used:

$$D_0 = 1.81 \left( \frac{\zeta_{dr}}{Z_h^{0.37}} \right)^{0.486} Z_h^{0.136} \tag{7}$$

$$N_w = \left( \frac{1.513}{(\zeta_{dr}/Z_h^{0.37})^{0.486}} \right)^{7.35} \tag{8}$$

For both stratiform cases, it is assumed $\mu = 3$ as in Brandes et al. (2004).

Raindrop DSD parameters are derived as a function of time at the surface observation
platform at the CU-Boulder for a Constant Altitude Plan Position Indicator (CAPPI) at 2-km above ground level (AGL). The CU-Boulder station is located at ∼ 66 kilometers range from the KFTG radar; thus, a 2-km or higher CAPPI is required. The CU-Boulder station is located at 40.01 °N and 105.27 °W and is a component of the Integrated Sensor Suite (ISS). Raindrop DSD parameters were also analyzed for the entire radar range for statistical analysis between the two precipitation modes. The statistical analysis separates the precipitation into stratiform and convective modes, and distributions of $D_0$ and $N_w$ are compared between the modes, to highlight differences and verify algorithm results match theoretical understanding.

3. Results

(a) Gamma DSD Parameters

Gamma DSD parameters were analyzed for both the CU-Boulder site and over the entire gridded radar domain. The gamma DSD parameters for the CAPPI of the entire gridded radar domain yielded 815,000 and 76,000 pixels for stratiform and convective modes respectively. From the frequency histograms of $D_0$ and $\log_{10} N_w$ provided in Figure 2, the differences in $D_0$ and $N_w$ between the two precipitation modes matches the current understanding. The distribution of the gamma parameters for convective precipitation supports the notion that convective precipitation is characterized by higher concentrations of smaller drops. The mean drop size is approximately 1.2 $mm$, with a mean weighted concentration of $10^5 \text{mm}^{-1} \text{m}^{-3}$ which in theory is supportive of heavier rain-rates.

The distribution of the gamma parameters for stratiform precipitation shows a bi-modal distribution for drop size, but a consistently lower number concentration. The bi-modal distribution is a result of the two different algorithms for computing $D_0$ for stratiform precipitation based on $Z_{dr}$ values. The peak near 2.0 $mm$ is the stratiform rain with $Z_{dr} \geq 0.2 \text{dB}$, while the peak near 1.3 $mm$ has $Z_{dr} < 0.2 \text{dB}$. While the lower $Z_{dr}$ stratiform rain shows a similar distribution to the convective precip with respect to $D_0$, the $D_0$ for stratiform
with higher $Z_{dr}$ is almost entirely outside of the distribution of the convective precipitation. The number concentration peaks near $10^2 \text{ mm}^{-1}\text{m}^{-3}$ for both stratiform cases suggesting a decrease in the number of droplets relative to the convective mode. The distributions of the gamma parameters for each precipitation mode suggest the heaviest rain-rates can be expected in the convective precipitation followed by the higher $Z_{dr}$ stratiform and the lowest rain-rates would be expected with the lower $Z_{dr}$ stratiform. These results are consistent with prior studies (Bringi et al., 2002) which provides confidence in the ability of the algorithm to appropriately distinguish between the precipitation modes and retrieve reasonably accurate estimates of the gamma DSD parameters.

The evolution of the gamma DSD with time over the CU-Boulder site is provided in Figure 3. The evolution of $D_0$ shows the variability in the drop size between the two stratiform modes which are given by the blue-colored portion of the line. The times where the algorithm deemed the precipitation to be convective are located in red and are associated with decreases in $D_0$ with respect to the blue-colored stratiform. The same color scheme is used in the $N_w$ and $\mu$ time-series. For each convective event, increases in the number concentration are observed. Number concentrations observed in the stratiform precipitation are consistently lower than the convective events, which is consistent with the results of the statistical analysis for the entire domain. Values for $\mu$ were set to 3 for both stratiform cases as in Brandes et al. (2004); however, the $\mu$ values for convective events are sporadic and inconclusive. There are instances where $\mu$ is positive suggesting a decrease in smaller drops and larger drops and other cases where $\mu$ is negative suggesting an increase in smaller drops and larger drops. The inconclusive results from the time-series of $\mu$ could be representative of complex microphysical processes (coalescence, breakup, evaporation, etc.) within the radar range gate that are causing large, unrealistic values for the estimated shape of the DSD using the dual-pol variables. The blue segments of the time series where $\mu \neq 3$ occur in transition regions between convective and stratiform modes and the uncertainty in the color scheme during precipitation mode transitions is representative of the other two time
In addition to the gamma parameters, the drop shape was compared to the PB70 drop shape algorithm shown in the lower right panel of Figure 3. The $\beta$ values are evenly scattered around the PB70 line suggesting that for this case the drop shapes are typical and $\beta$ correction is not necessary. This was verified by using the rain-rate algorithm from Bringi et al. (2002) given by:

$$R = 0.105\beta^{0.865}Z_h^{0.93}z_{dr}^{-0.585\beta-0.703}$$

and calculating total accumulated rainfall for the duration of the event at the CU-Boulder site. The accumulated rainfall between the standard $R(Z_h, Z_{dr})$ relationship from Bringi and Chandrasekar (2001) where $\beta$ is assumed constant and Equation 9 was within 10% (71 and 78 mm respectively). The slight difference in total accumulated precipitation between these two algorithms further reinforces that the drop shape versus axis ratio is consistent with typical DSDs and therefore the standard $R(Z_h, Z_{dr})$ relationship is sufficient for this case.

(b) Dual-Polarimetric Analysis

Analysis of the gamma DSD parameters over the CU-Boulder site indicated the passage of several distinct convective cells over the duration of the precipitation event. A time-height cross-section of $Z_h, Z_{dr}, \Phi_{dp}, \rho_{hv}$ is provided in Figure 4 and was used to verify the convective events and identify potential dual-pol signatures within them. From the figure, there are approximately five convective events that pass over CU-Boulder, three of which last longer than 10 minutes. These three convective events are considered to be unique events since they are spaced more than an hour apart; therefore, they will be analyzed separately. A reconstructed RHI was created to identify any possible dual-pol signatures within each case.

The first convective event passed over the CU-Boulder site at approximately 01:45 UTC on 12 September. The reconstructed RHI of $Z_h, Z_{dr}, \Phi_{dp},$ and $\rho_{hv}$ for this case is provided in Figure 5 (Note: the radar is located off to the right of each of the plots). The RHI is along the
constant latitude line of the CU-Boulder site and is centered there (105.27°W). The dominant convective feature consists of two regions of reflectivity > 40 dBZ separated by ~ 5-km with higher reflectivity aloft in both regions. In both regions, $Z_{dr}$ values greater than 0.5 dB are observed in the lower 1.5-km of the RHI (up to 5-km above mean sea level [MSL]) indicating the presence of a $Z_{dr}$ column. The KDNR 00Z sounding for 12 September indicated a melting level around 4.75-km mean sea level (MSL) above which both $Z_{dr}$ columns extend. A $Z_{dr}$ column above the melting level could be indicative of melting graupel or small hail within the convective core storm (Hubbert et al., 1998); therefore suggesting ice contamination in the dual-pol retrievals. A peak in $\Phi_{dp}$ is observed just offset down range from the peak in the $Z_{dr}$ column near $-105.2^\circ$ indicating heavy rainfall potentially mixed with melting graupel at the bottom of the RHI (2-km AGL). The values of the dual-pol variables for these two cells is consistent with the rain mixed with wet graupel signatures outlined in Hubbert et al. (1998). During this time, rain-rates at the CU-Boulder rain gauge were in excess of 70 mm h$^{-1}$ while the standard NEXRAD rain-rate algorithm estimated values slightly under 30 mm h$^{-1}$. The poor performance of the NEXRAD rain-rate algorithm and the dual-pol signatures support the claim that these cells contained melting graupel leading to significant underestimation of QPE for this particular convective event.

The second convective event passed over the CU-Boulder site at approximately 04:20 UTC on 12 September (Figure 6). This convective event featured a single convective cell with over a 10-km swath of reflectivity values > 35 dBZ. The maximum reflectivity within the storm is ~ 45 dBZ and is located almost 6-km MSL. Similar to the previous case, a $Z_{dr}$ column of $Z_{dr} > 0.75 \text{ dB}$ is observed; however, it extends nearly 7-km MSL (nearly 2-km above the melting level). The strong peak in $\Phi_{dp}$ observed in the first case is not observed with this one as there is only a slight $\Phi_{dp}$ response beyond the main core of enhanced reflectivity. Values of $\rho$ within the storm remain above 0.95 through the reflectivity core. Like the previous case, the dual-pol signatures observed are consistent with the findings of Hubbert et al. (1998) when wet graupel is mixing with precipitation; however, the limited
Φ_{dp} response suggests complete melting is occurring prior to the precipitation reaching the surface. Observed rainfall rates during this storm peak at roughly 60 \text{ mm hr}^{-1} while the NEXRAD algorithm elicits a peak value of 25 \text{ mm h}^{-1}. From the time-height cross section in Figure 4, this event lasted nearly 30 minutes, which means radar derived QPE were underestimated by over 50% during this time period.

The third convective event passed over the CU-Boulder site at approximately 05:45 UTC on 12 September (Figure 7). This convective event featured a single convective cell nearly 20-km across, but only 5-6 km in depth. The maximum reflectivity within the storm is \sim 50 \text{ dBZ}, but is significantly lower than the previous storm (2-km AGL). Similar to the previous cases, a \textit{Z}_{dr} column is collocated with the main reflectivity core and it extends to roughly 5-km MSL and increases with height. A local maximum in \textit{Φ}_{dp} is observed just down range of the main reflectivity core consistent with heavy rain potentially mixing with wet graupel. Further down range from the radar, there is a maximum in the \textit{Z}_{dr} and \textit{Φ}_{dp} beneath a local maximum of enhanced reflectivity aloft. Interestingly, reflectivity values in beneath the local maximum at 5-km MSL are < 35 \text{ dBZ}, which would most likely be categorized as stratiform rain using the thresholds of Bringi et al. (2002) and Brandes et al. (2004) indicating lighter rainfall rates. The local maximum in \textit{Φ}_{dp} down range of the \textit{Z}_{dr} maximum suggests the presence of large raindrops exceeding 2.5-3.0 \text{ mm} in diameter possibly caused by size sorting by differential terminal fall velocities along the leading edge of the convection. The time-series of \textit{D}_0 in Figure 3 shows evidence of size sorting with this storm as a maximum in \textit{D}_0 near 3 \text{ mm} was observed followed by a sharp decrease in drop diameter in the next radar scan. Rainfall rates exceeding 75 \text{ mm hr}^{-1} were observed during this event; however, the NEXRAD algorithm estimates a peak rain-rate of about 40 \text{ mm hr}^{-1}. The elevated maximum of the \textit{Z}_{dr} column above the melting level, 50 > \textit{Z}_h > 45 \text{ dBZ}, and \textit{Z}_h > 1.0 \rho > 0.95 near the maximum reflectivity core are consistent with the signatures for heavy rain and wet graupel at the surface given in Hibbert et al. (1998).
4. Summary & Conclusions

The microphysical properties of a significant flooding event near Boulder, CO where operational weather radar QPE was significantly underestimated was studied. The dual-pol derived microphysical parameters were found to be consistent with observations in typical DSDs. Distinct differences in the gamma DSD parameters between convective and stratiform precipitation modes was observed, particularly for drop size and number concentration. Rain identified as stratiform mode from the Bringi et al. (2002) and Brandes et al. (2004) algorithm was found to have consistently larger drops with lower concentrations than rain identified as convective. Analysis of the gamma DSD parameters at the CU-Boulder site was consistent with these findings providing confidence in the performance of the algorithm to obtain accurate estimates of drop size and number concentration from the dual-pol data allowing for meaningful analysis. Convective precipitation events embedded within the precipitation event were further evaluated using available dual-pol variables.

A time-height cross-section for the event over the CU-Boulder site along with the derived gamma DSD parameters was used to identify convective events longer than 10 minutes in duration. Three cases were identified and dual-pol variables were used to identify potential ice contamination within the radar sample that could negatively impact QPE and explain the poor performance of the NEXRAD rain-rate algorithm for this event. Each of the cases was found to have dual-pol signatures consistent with wet graupel and small hail signatures observed in Hibbert et al. (1998). Additionally, the NEXRAD algorithm underestimated the peak rain-rates by more than 40 % when compared to the surface rainfall data at CU-Boulder for each of the cases. Possible evidence of size sorting caused by differential terminal fall velocities on the leading edge of the convection was observed in the third case from enhanced $Z_{dr}$ and $\Phi_{dp}$ in a region where $Z_{dr} < 35 \text{ dBz}$ 10-km away from the convective core of the storm.

The improved performance of the $R(Z_{dr}, K_{dp})$ algorithm with respect to the other algorithms in Figure 1 could possibly be explained by ice contamination in the form of graupel
located near the updraft of the convection. For this event, significant underestimation of accumulated rainfall was observed with the operational NEXRAD Z-R relationship particularly when convective precipitation was observed. More surprisingly, the significant underestimation occurred in an event where the drop size and shape were typical for standard algorithm application. This suggests the ability of $K_{dp}$ in conjunction with $Z_{dr}$ to properly identify ice contamination in convective events of this nature makes it the preferred rain-rate algorithm for events that are microphysically similar to the ones studied.
References


Figure 1: Accumulated rainfall for the entire data collection period for each of the rain rate algorithms. Single- and dual-pol parameter algorithms are denoted by a solid line with each represented by a different color. Optimization algorithms are denoted by a dashed line (JPOLE in red, CSU-ICE in blue) and the rain gauge data is denoted by a bold dashed-dot line.
Figure 2: Frequency histograms of median drop diameter, $D_0$ (mm) and the normalized drop concentration, $N_w$ (mm$^{-1}$ m$^{-3}$) for convective and stratiform precipitation modes for the entire KFTG radar domain for the duration of the 11-12 September rainfall event.
Figure 3: Evolution of the gamma DSD parameters $D_0$, $N_w$, and $\mu$ with time over the CU-Boulder Station. The red lines indicate times when precipitation is convective in mode and blue lines indicate stratiform precipitation. The $\beta$-parameter as a function of $Z_{dr}$ is provided in the lower right panel with the PB70 $\beta$-value given by the dotted line. The colors transition from cooler (dark blue) to warmer colors (dark red) with time.
Figure 4: Time-height cross-section of $Z_h$, $Z_{dr}$, $\Phi_{dp}$, and $\rho_{hv}$ over the CU-Boulder site for the duration of the 11-12 September rainfall event.
Figure 5: Reconstructed RHI of $Z_h$, $Z_{dr}$, $\Phi_{dp}$, and $\rho_{hv}$ centered over CU-Boulder site at constant latitude ($40.01^\circ$) for 01:44:25 UTC on 12 September 2013.
Figure 6: Reconstructed RHI of $Z_h$, $Z_{dr}$, $\Phi_{dp}$, and $\rho_{hv}$ centered over CU-Boulder site at constant latitude ($40.01^\circ$) for 04:25:28 UTC on 12 September 2013.
Figure 7: Reconstructed RHI of $Z_h$, $Z_{dr}$, $\Phi_{dp}$, and $\rho_{hv}$ centered over CU-Boulder site at constant latitude ($40.01^\circ$) for 05:44:49 UTC on 12 September 2013.