8A.5 DROP SHAPES VERSUS FALL VELOCITIES IN RAIN: 2 CONTRASTING EXAMPLES

M. Thurai[1], V.N. Bringi[1], W.A. Petersen[2], L.D. Carey[3], P.N. Gatlin[3], and A. Tokay[4]

[1]Dept. of Electrical & Computer Eng., Colorado State Univ., Fort Collins, CO
[2]NASA Wallops Flight Facility, Wallops Island, VA
[3]University of Alabama in Huntsville, NSSTC, Huntsville, AL
[4]JCET/Univ. of Maryland, Baltimore

1. INTRODUCTION

The estimation of rainfall rates from polarimetric radar measurements is implicitly based on certain assumptions regarding drop shapes, orientations and drop fall velocities within the radar pulse volume. Typically it is assumed that: (i) the drop axis ratio versus drop equivalent diameter (D_{eq}) follows a single, monotonic variation (eg. Brandes et al., 2002), (ii) the drop canting angles have a Gaussian distribution with a mean of zero degrees and a standard deviation of around 7-8 degrees, and (iii) the fall velocity has a unique variation with D_{eq}, for example, the formula given in Atlas et al. (1973) at sea level. Polarimetric radar measurements are then used to retrieve the drop size distribution (DSD) within the pulse volume assuming such 'bulk' assumptions, which is then followed by rainrate estimates.

While the above approach results in reasonably accurate estimates of rainrate (see, for example, Ryzhkov et al. 2005, Bringi et al. 2011), there have also been a few studies which show that such bulk assumptions may not apply universally. For example, Gorgucci et al. (2000) use Z_h, Z_{dr}, and K_{dp} to estimate the 'effective' drop shapes and subsequently modify the rainrate retrieval algorithms using the so-called 'effective beta-method'. Another study (Thurai et al. 2009) demonstrated that scattering calculations based on shape (and size), and orientation of individual drops determined from a well-calibrated 2D-video disdrometer (2DVD) gave closer agreement with polarimetric radar measurements (Z_h, Z_{dr}, K_{dp} as well as ρ_{hv}) than those based on the measured DSDs and using bulk assumptions. Indeed the study high-lighted the possibility of 'significant deviation' from the mean shape assumptions in one event study.

It is well established that the 2DVD (Shönhuber et al., 2008) if calibrated accurately can measure shape, orientation and fall velocity of individual drops transiting its sensor area. Such measurements have been reported previously in Thurai and Bringi, (2008), and Huang et al. (2008). In this paper, we report 2 case-events which occurred within 7 days of each-other, one conforming to the 'bulk-assumptions' regarding drop axis ratios and fall velocities and the other showing significant deviations within one part of the storm. Measurements were made using two collocated (i.e. a few meters apart), and accurately calibrated 2DVDs as well as a C-band polarimatric radar (ARMOR, see Petersen et al. 2007) located 15 km from the 2DVD site. The measurements were part of an on-going long-term campaign in Huntsville, Alabama.

2. THE TWO EVENTS

The two events which occurred on 18 December 2009 and 25 December 2009 were of long duration lasting several hours. Fig. 1(a) and 1(b) show composite radar images of the two events around the Huntsville area. The white cross in both panels marks the 2DVD location. In both cases, the event had high reflectivities, but for case 2, a well-defined embedded thin line of convection can be seen crossing the Huntsville area. Both events had relatively high rainfall accumulations. Table 1 compares the daily totals from the two 2DVD data and from a Geonor rain-gage, also collocated.

Table 1: Total rainfall (mm) from the two 2DVDs and from the collocated Geonor

Date	SN16	SN25	Geonor
Event 1: 18 Dec 2009:	35.5	>33.2†	34.5
Event 2: 25 Dec 2009:	26.2	24.4	25.4

(† some loss of data for several minutes)

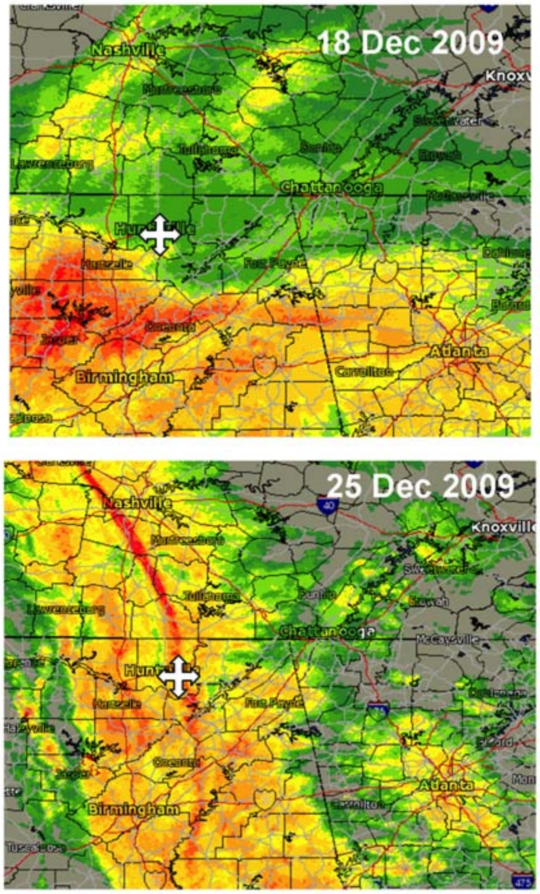

Fig 1: Composite radar images of the two events considered in this study. The white cross shows the location of the two 2DVDs. The ARMOR radar is situated 15 km away in the south-west direction. Note event 2 has a line convection crossing the 2DVD location.

3. 2DVD MEASUREMENTS

As mentioned above, the 2DVD measures the drop fall speed (i.e. the vertical velocity) for each drop falling within the sensor area, as well as the shape, size and orientation. Fig. 2(a) and 2(b) shows the distribution of the measured vertical velocity for all the 3 mm drops (to be precise 3 ± 0.1 mm) for both events. In both panels, the blue curve represents the distribution determined from one of the instruments (the low-profile 2DVD, also labeled SN-16) and the red curve represents the distribution determined from the other instrument (the compact 2DVD, labeled SN-25). In both cases the red and the blue curves show good agreement (thus providing confidence in the 2DVD measurements) but the two events show different characteristics in terms of their probability distributions. Whereas for event 1, the distributions are narrow, symmetric and have a mode close to the expected fall velocity for D_{eq} = 3 mm (7.9 m/s), the second event shows a wider distribution with a noticeable negative skewness. While both events likely had different wind conditions with different up-down drafts, and turbulence etc., the skewness in Fig. 2(b) cannot be explained easily. Moreover, as will be shown later, the second event also shows significant deviation from our standard 'mean-shape' during a certain period of the event.

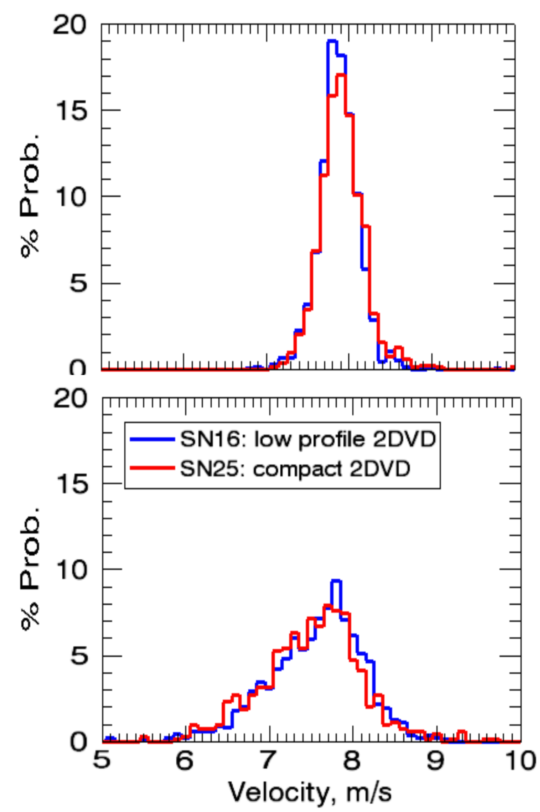

Fig. 2: Distribution of measured velocities of all the 3 mm drops, from the two 2DVD measurements for event 1 (top) and event 2 (bottom).

We now investigate the fall velocity of each of the individual 3 mm drops captured by the two 2DVDs for event 2. The upper panels in Fig. 3 show these velocities plotted as time series as the event passed over the 2DVD site. In both sets of measurements, the same observations can be made, that is, larger velocity fluctuations between 03:30 and 03:50 UTC, with a significant proportion of the drops having lower than the expected velocities. Outside this time range, the 3 mm drop velocities show much less variation and are centered around the 7.95 m/s expected value. Clearly, the negative skewness in Fig. 2 arises primarily due to the 'slower' 3 mm drops captured between 03:30 and 03:50 UTC. This is significant, and cannot be dismissed as being due to any instrument 'calibration problems'. Note the velocities represent the actual fall speed, with no contribution from the wind-induced horizontal component.

Using the unique image processing capability of the 2DVD, i.e. the contoured images of each drop, both datasets were used to determine the maximum horizontal and vertical dimensions of each drop, after removing the effects due to drop orientations as well as the drop horizontal velocity components (Fig. 3, lower panels). Again, both sets of measurements show similar features/characteristics, i.e. between 03:30 and 03:50 UTC, there appear large variations in the drop dimensions as compared with other times. The larger variation is particularly noticeable for the horizontal dimension, with a significant number of drops showing larger than expected values (the mean horizontal dimension is around 3.2 to 3.3 mm). These larger horizontal dimensions will result in lower axis ratios, i.e. an <u>increase in oblateness</u>, a somewhat surprising and unusual finding. In the next section, we examine the C-band polarimetric radar observations.

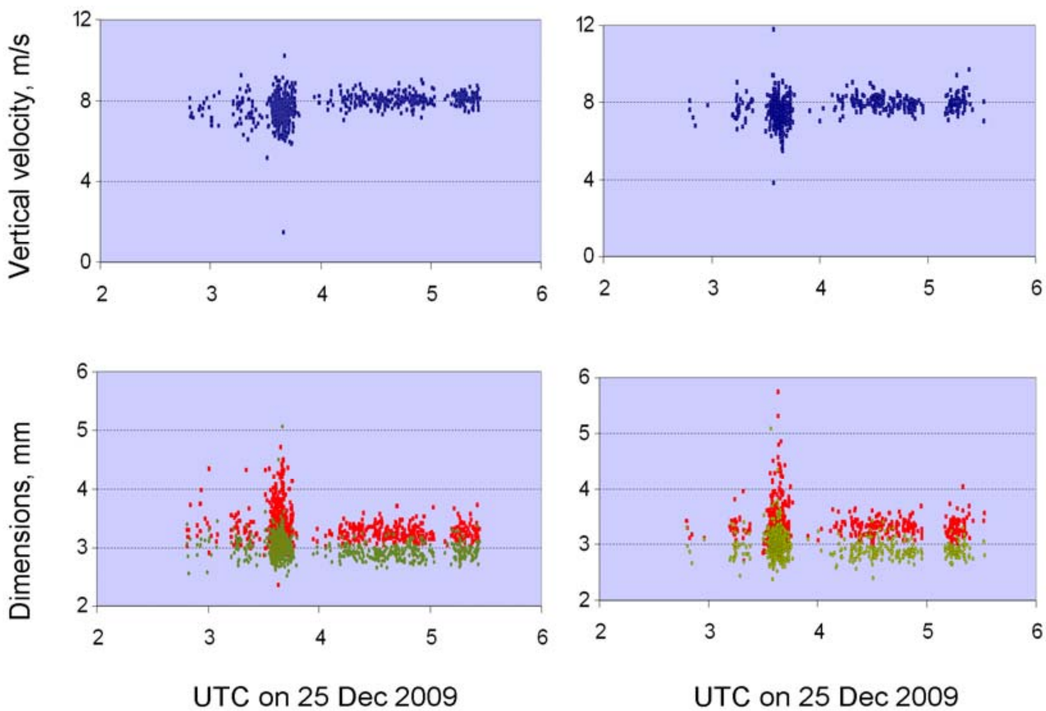

Fig. 3: The measured fall velocity of each individual 3 mm drops, as time series (top panels) and their corresponding horizontal and vertical dimensions (red and green respectively) measured by the SN16 (left panels) and SN-25 (right panels) for event 2. Fluctuations are noticeable between 03:30 and 03:45 UTC. See main text.

4. RADAR OBSERVATIONS (EVENT 2)

The composite image in Fig. 1b for event 2 shows that the convective line crossed the 2DVD site, and the time sequence of Fig. 3 demonstrates that it crossed the Huntsville area between 03:00 and 04:00 UTC. The ARMOR radar made routine observations during the day, and in Fig. 4 we show a set of panels of 1.3 deg elevation PPI scans taken at 03:05, 03:40 and 03:55 UTC. The upper panels show the reflectivity Z_h, the middle panels show Z_{dr} and the lower panels show K_{dp}. The organized convective line can be seen to move from south-west to north-east, and at 03:40, the line can be seen to lie directly above the 2DVD site. It is around this time that the 2DVD measurements (Fig. 3) show the larger velocity fluctuations and the large axis ratio variations, resulting in 'slower drops' with higher oblateness. At 03:55 UTC, the line is to the north-east of the 2DVD site and is seen to be fragmenting and/or decaying. In the 03:05 case, i.e. when the line was well-defined and well-organized, the Z_{dr} correction procedure failed to correct for the total differential attenuation beyond the convective line. Since the correction procedures are based on our mean drop shapes (and big drop regime assumptions), the difficulty in correcting for differential attenuation indicates an increase in drop oblateness in the region of the line convection. The implications for proper attenuation correction such instances are interesting to consider from the perspective of operational mapping of rainfall characteristics using C-band polarimetric radar.

5. INTERPRETATION OF OBSERVATIONS

Ancillary meteorological data for Huntsville indicates that this event was associated with a decrease in wind velocity near the time of convective line passage, dropping from ~8 m/s at 03:00 to ~4 m/s at 04:00. Nevertheless, there is a possibility that surface layer (i.e. close to ground level) turbulence could have facilitated unusual drop oscillation modes, such as mixed and/or horizontal oscillation modes (Beard et al. 2010) which result in increased drop axis ratios, and a possible corresponding reduction in fall velocity. In the literature, the effect of drop axis ratio variations on the fall velocity has not been addressed in a quantitative manner due to the complexity, but some interesting discussion can be found in section 5(a) of Beard (1976) regarding the interpretation of some previously published results, for example by Jones (1959), which implies that turbulence may cause drop shape distortion. Interestingly, Jones' data showed the axis ratios of the 4 mm drops ranging from 0.5 to 1.3 determined from 2000 photographs taken at ground level during turbulent events, compared with our results for the 3 mm drops ranging from 0.6 to 1.2 during the line convection period.

The question remains whether the mixed mode oscillations (including the horizontal mode) associated with the line convection in event 2 occurs only within the surface layer near the 2DVD or at higher heights too. To address this, we analyze the radar data in Fig. 4. The higher than normal axis ratios within the line convection should be reflected in higher Z_{dr} for a given DSD. On the other hand, the retrieval of the DSD, and in particular, the mean volume diameter, D_0, from Z_{dr} is based on an assumed axis ratio dependence on D_{eq}. To overcome this 'circular ambiguity', we have tried to apply the so-called 'effective-beta method' to the PPI scans. This method involves the calculation of the β-effective parameter (β_{eff}) which represents the approximate slope of the curve representing the axis-ratio versus D_{eq} variation. The parameter β_{eff} is calculated using Z_h, Z_{dr} and K_{dp}, and is mostly independent of the DSD within the pulse volume. The calculated values can enable one to assess whether the radar observations conform to the 'bulk assumptions' regarding drop axis ratios. However, for the method to be applicable, both Z_h and Z_{dr} need to be accurately calibrated and properly corrected for attenuation, and, moreover, the expected values of (β_{eff}) depend on the exact equation used to derive it.

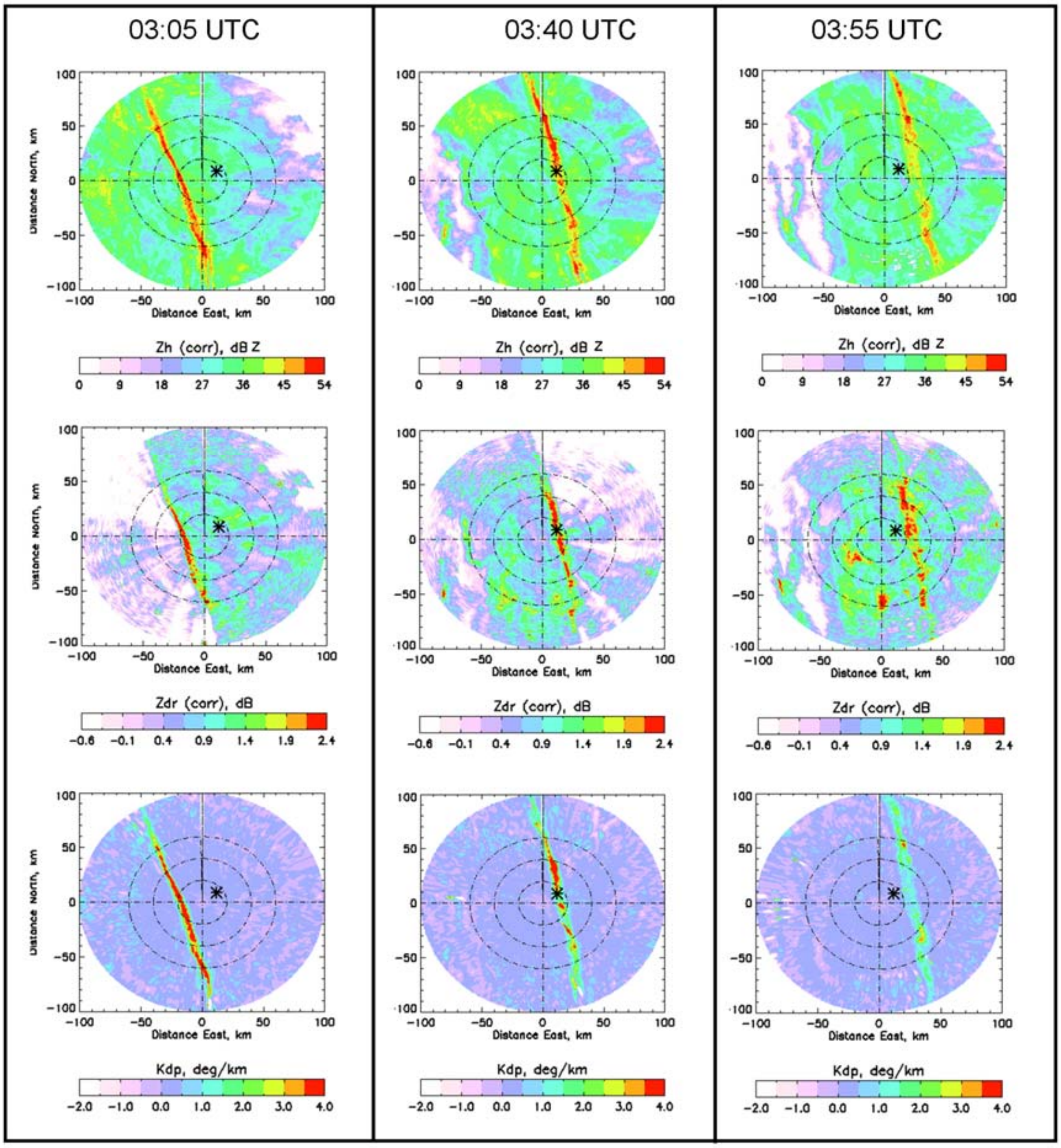

Fig. 4: PPI scans of Zh (1st row), Zdr (2nd row) and Kdp (3rd row), taken at 03:05, 03:40 and 03:50 UTC. The 2DVD site is marked with a star (azimuth 52º, range 15 km). Note Z_{dr} suffers severe differential attenuation beyond the convection line, particularly for the 03:05 case, even after applying attenuation correction procedures based on our mean drop shapes, implying the presence of more oblate drops than normal.

The calibration of Z_h and Z_{dr} were established by comparing the radar data extracted over the disdrometer site with corresponding 2DVD measurements collected well after the line of convection passed the 2DVD site between 04:00 and 05:00 UTC. The calibration factors were found to be relatively steady throughout the hour for both Z_h and Z_{dr}. The PPI scans given in Fig. 4 represent radar data after applying the calibrations.

The range profiles extracted from the 03:40 PPI scan along azimuths between 50 to 55 degrees are shown in Figure 5. At the 2DVD site, which is located at 15 km from the radar, reflectivity values of 50-55 dBZ can be observed, together with Z_{dr} of around 4 dB and K_{dp} of 4 to 5 deg/km. In this region, the calculated values of β_{eff} (using an equation based on DSD model based simulations) are also significantly higher, as compared with say those at 17-25 km range. The higher values of β_{eff} seen at the 2DVD site indicate a steeper slope of the axis ratio versus D_{eq} variation, which is consistent with the presence of more oblate drops in the 2DVD measurements (Fig. 3). However, some caution with respect to the calculated β_{eff} values is warranted for regions beyond the line of convection, because of the lowered $Z_{dr,}$ even after correcting for differential attenuation, as was mentioned earlier.

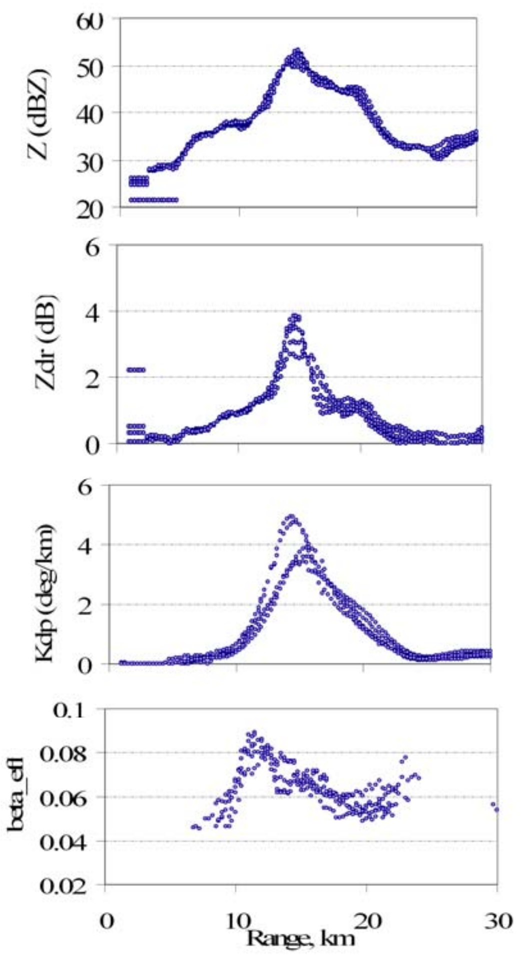

Fig. 5: Range profiles taken along 50-55 deg azimuth of Z_h (top), Z_{dr} (2^{nd}), K_{dp} (3^{rd}) and the calculated β_{eff} (lowest), after attenuation correction and calibration. The 2DVDs are located at 15 km range.

The β_{eff} values calculated for the PPI scan at 03:40 are shown in Fig. 6. Some smoothing has been applied in order to better identify regions of 'abnormal' β_{eff} values. Additionally, the β_{eff} values were only calculated in regions with Z_h> 35 dBZ, Z_{dr} > 0.3 dB and K_{dp} > 0.3 deg/km. Most regions within the line of convection met these criteria, as did a number of other isolated areas. Within the convective line, small areas of relatively high β_{eff} values (> 0.7) can be observed very close to the 2DVD site (marked with a black star). Further to the south, a larger area of higher β_{eff} values can also be seen whereas in other regions within the line convection, more moderate β_{eff} values or 0.05 to 0.06 are obtained.

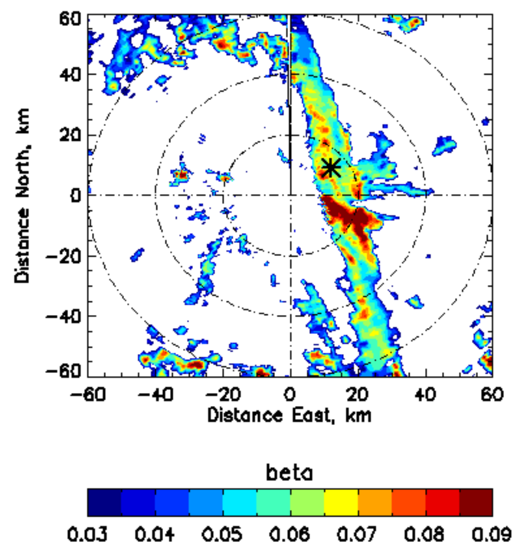

Fig. 6: The calculated β_{eff} for the scan at 03:40 UTC. Red regions are a qualitative indication of higher slope for axis ratio versus D_{eq} variation.

6. FURTHER COMMENTS

As mentioned above, the β_{eff} values in Fig. 5(d) and 6 depend on the specific equation used, but in relative terms, the higher values (i.e. the regions in red color) do indicate that the slope of the axis ratios versus D_{eq} is larger than the 'mean' variation. The presence of more oblate drops (perhaps with mixed-mode oscillations) is likely in these regions, and the 2DVD measurements in Fig. 3 support this, albeit at ground level.

It should be stressed here that this particular event (i.e. event 2 on 25 Dec 2009) is a somewhat unusual case, which was investigated because of the negative skewness in the fall velocity distributions (Fig. 2) from the 2DVD measurements. In several other cases which have been examined to date, no evidence was found to indicate mixed-mode drop oscillations resulting in higher axis ratios and lower velocities. In the literature, evidence of unusual drop oscillations (especially relating to horizontal mode) is relatively scarce, but not non-existent. One example is Goodall (1976) who had conducted a microwave scattering study (both H and V) of drop oscillations in a wind-tunnel. The results, reported in Feng and Beard (1991) and later included in Beard et al. (2010), had shown the inferred oscillation modes (from frequency analysis) included the mode which showed large variations in the horizontal dimension and hardly any in the vertical dimension, i.e. the horizontal oscillation mode. The results- in terms of oscillation frequency versus drop diameter - were mainly quoted for drop diameters larger than 4 mm.

In another study (Jameson and Durden, 1996), some inferences regarding horizontal oscillations for large drops were made in natural rain from nadir-pointing radar measurements in a convective tropical storm. Relatively high LDR measurements were seen in certain sections of the convective storm which were attributed to the possibility of 'horizontal distortions' particularly for large drops. Further, the authors state that 'collisions between large and small drops are adequate to produce and sustain the horizontal oscillations…'. It is conceivable that such a scenario also applies to our case, i.e. to some regions within the line of convection in Fig. 5, 6, part of which was fortuitously captured by the two 2DVDs. Another case (08 April 2010, not reported here) has also indicated similar characteristics during our preliminary analysis. The fact that there are two collocated 2DVDs greatly enhances our confidence in these measurements (provided there is agreement between the two). Such data, together with simultaneous ARMOR observations will form part of an on-going study to identify cases where significant deviations from our mean shapes and the expected fall velocities seem to occur.

7. SUMMARY

Two events which occurred 7 days apart in Huntsville, Alabama, have been investigated using two collocated 2DVDs, both at ground level, as well as simultaneous observations from the ARMOR C-band polarimetric radar. For each event drop fall velocities and shapes were examined from the 2DVD measurements, with specific focus placed on 3 mm diameter drops. The first event – on 18 Dec 2009 - showed the expected fall velocities; for example, the 3 mm drops had velocities which were symmetrically distributed, with a mode at around 7.9 to 8 m/s. The distribution was narrow. The second event – on 25 Dec 2009 – showed a skewed distribution, with a negative skewness with significant number of drops having lower fall velocities. The event had a highly organized, narrow, embedded line of convection which had fortuitously traversed the 2DVD site. Time series of the 3 mm drop fall velocity measurements showed that these 'slow' drops were detected only during passage of this line. The drop maximum dimensions were also examined (after removing drop canting effects as well as drop horizontal velocities). Large fluctuations in the horizontal and vertical dimensions were observed during the same time period; though fluctuations in the horizontal dimensions were larger, and were observed to trend towards higher values, indicating the presence of horizontal mode oscillations, or at least mixed mode oscillations, which include horizontal mode oscillations.

Simultaneous radar observations from the ARMOR radar were also analyzed for altitudes above the surface. Here the so-called β-effective method was applied, which enables one to qualitatively identify areas which do not conform to the standard bulk assumptions often used in polarimetric radar algorithms designed to diagnose rain characteristics. The results indicated higher than normal β_{eff} in some regions within the convective line, including a small region directly above the 2DVD site. The implication is that horizontal mode drop oscillations (or at least mixed-mode oscillations) were occurring in some regions within the convective line, not only at ground level but also aloft. The difficulty in correcting for differential attenuation, especially when the convection line was highly organized (at

03:05), also corroborates the notion of drop horizontal oscillations occurring within this region. Studies are on-going to identify other cases which show significant deviations from our mean shapes and the expected fall velocities, observed from both 2DVDs, accompanied by the C-band polarimetric radar observations.

ACKNOWLEDGEMENTS

The work is primarily supported by the National Science Foundation via grant AGS-0924622. Support from NASA Grant Award NNX10AJ12G, Dr. Ramesh Kakar of NASA Precipitation Science Program, and the NASA GPM Project are also gratefully acknowledged.

REFERENCES

Atlas D., Srivastava, R. C., Sekkon, R. S.: Doppler radar characteristics of precipitation at vertical incidence. Rev Geophys Space GE 2:1-35, 1973.

Beard, K. V., 1976: Terminal velocity and shape of cloud and precipitation drops aloft, J. Atmos. Sci., vol. 33, 851-864.

Beard, K. V., Bringi, V. N. and Thurai, M.: A new understanding of raindrop shape, Atmos. Res., Atmos Res., vol. 97, 396-415, 2010.

Brandes, E. A., Zhang, G., and Vivekanandan, J. 2002: Experiments in rainfall estimation with a polarimetric radar in a sub-tropical environment. J Appl Meteorol 41:674-684

Bringi, V. N., Rico-Ramirez, M. A. and Thurai, M. 2011: Rainfall estimation with an operational polarimetric C-band radar in the UK: Comparison with a Gage Network and Error Analysis. J. Hydrometeorology, early on-line release, doi: 10.1175/JHM-D-10-05013.1.

Feng, J.Q., K. V. Beard, 1991: A perturbation model of raindrop oscillation characteristics with aerodynamic effects. J. Atmos. Sci. 48, 1856–1868.

Goodall, F., 1976: Propagation through distorted water drops at 11 GHz. Ph.D. dissertation, University of Bradford, Bradford, UK, 205pp.

Gorgucci, E., G. Scarchilli, V. Chandrasekar, and V. Bringi: Measurement of mean raindrop shape from polarimetric radar observations. J. Atmos. Sci., 57, 3406-3413, 2000.

Jameson, A. R., and Durden, S. L., 1996, A possible origin of linear depolarization observed at vertical incidence in rain, J. Appl. Meteorol., vol. 35, 271-277.

Jones, D. M.,1959: The shape of raindrops, J. Meteorol., vol. 16, 504-510.

Petersen, W. A., Knupp, K. R., Cecil, D. J., and Mecikalski, J. R.: The University of Alabama Huntsville THOR Center instrumentation: Research and operational collaboration, 33rd Int. Conf. on Radar Meteorology, AMS, Cairns, Australia, 2007.

Ryzhkov, A., S. E. Giangrande and T. J. Schuur, 2005b: Rainfall estimation with a polarimetric prototype of WSR-88D, J Appl. Meteor, vol. 44, 502–515.

Schönhuber, M., Lammer, G. and Randeu, W. L.: The 2D-video-vistrometer, Chapter 1 in “Precipitation: Advances in Measurement, Estimation and Prediction”, Michaelides, Silas. (Ed.), Springer, ISBN: 978-3-540-77654-3, 2008.

Thurai, M., and Bringi, V. N.: Rain microstructure from polarimetric radar and advanced disdrometers, Chapter 10 in “Precipitation: Advances in Measurement, Estimation and Prediction”, Michaelides, Silas. (Ed.), Springer, ISBN: 978-3-540-77654-3, 2008.

Thurai, M., V. N. Bringi and W. A. Petersen, 2009: Rain microstructure retrievals using 2-D video disdrometer and C-band polarimetric radar, Adv. Geosci., vol. 20, 13-18.