

## Drop Axis Ratio Distributions in Stratiform and Convective Rain

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### ABSTRACT

A fully calibrated low profile 2D video disdrometer (2DVD) has been recording many different rainfall events in Northern Alabama (USA) since June 2007. An earlier publication reported drop shapes and axis ratio distributions determined for some of the events. For one of the cases examined, a noticeable shift in the 3.5 – 3.75 mm drop axis ratio distribution was noted.

In this paper, we extend the earlier work by separating the 2DVD measurements into stratiform and convective rain. The separation is made possible by using the minute-by-minute drop size distribution (DSD) measured by the 2DVD. The 1-minute DSDs are fitted to a gamma distribution, and using a simple indexing technique which involves two of the fitted parameters, periods of convective and stratiform rain are separated for a given event. The output of the DSD indexing technique is qualitatively confirmed by comparing with simultaneous time series observations from a co-located UHF profiler which continuously records height profiles of reflectivity, Doppler mean and spectral width, all of which enable the identification of bright-band periods and, furthermore, periods of moderate and deep convection. Excellent consistency is found between the output of the DSD-based separation method and the profiler observations.

Next, we utilize the output of DSD index-based separation method to ‘flag’ the periods of severe convection for a given event. Drop axis ratios during the flagged periods are derived and compared with those during stratiform rain periods. Five cases have been considered. Axis ratio distributions do not show appreciable differences between stratiform and convective periods for four of the cases. The fifth case (the same case as reported earlier) shows a shift in the 3.5 -3.75 mm drop axis ratios during a prolonged period of convection. The contoured shapes for these drops determined from the 2DVD camera data indicate the possibility of non-axisymmetric oscillations, compared with the contoured images for other events which fit well to our ‘reference’ drop shapes.

For all of above cases, observations from a C-band polarimetric radar - situated 15 km away – are examined. The variations between the co-polar radar reflectivity and the differential reflectivity as well as the specific differential phase are compared with the 2DVD data based scattering calculations for the 5 events. The implications will be discussed.

# Drop axis ratio distributions in stratiform and convective rain

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## 1. Introduction

Drop shapes and axis ratio distributions play a central role in the algorithm development for estimating rainfall rates from polarimetric radar measurements (Bringi and Chandrasekhar, 2001). Previous work on drop shapes has ranged from laboratory and wind-tunnel measurements (see Beard et al. 2010 for a recent review) to inferences from polarimetric data (Goddard et al. 1982) as well as theoretical modeling studies (Beard and Chuang, 1987). Additionally, the 2D-video disdrometer (Schönhuber et al., 2008) has been utilized to determine drop shapes from an artificial rain experiment (Thurai and Bringi, 2005, Thurai et al. 2007) as well as in natural rain (Thurai et al. 2008). Here, we examine 2DVD measurements of drop shapes in stratiform and convective rain separately in order to investigate whether there are significant and consistent differences. The events reported here had simultaneous measurements from a C-band polarimetric radar as well as observations from a UHF profiler co-located with the 2DVD in Northern Alabama.

## 2. Separating stratiform and convective events

### 2.1 Using 1-minute drop size distribution from 2DVD

The 2DVD gives full information on each individual drop falling through its 10 cm by 10 cm sensor area. From the 2 fast line scan cameras which are set up orthogonal to each other, it is possible to correct for drop horizontal velocity by de-skewing the individual images and then by assuming bodies of revolution, determine the shape, size and orientation of each drop (see, for example, Huang et al. 2008). To separate stratiform and convective rain, we make use of the 1-minute drop size distribution (DSD) from the 2DVD measurements of the drop sizes. These 1-minute DSD, denoted by  $N(D)$ , are fitted to a normalized gamma function given by the equation:

$$N(D) = N_w f(\mu) \left(\frac{D}{D_0}\right)^\mu \exp\left[-(3.67 + \mu)\left(\frac{D}{D_0}\right)\right] \quad \text{where} \quad f(\mu) = \frac{6}{3.67^4} \frac{(\mu + 3.67)^{\mu+4}}{\Gamma(\mu+4)} \quad (1)$$

Definition of the parameters  $N_w$ ,  $D_0$  and  $\mu$  can be seen in Bringi et al. (2003), together with details of the fitting procedure.

Recently, Bringi et al., (2009) - using dual-frequency profiler and dual-polarization radar in Darwin, Australia - found that stratiform and convective rain can be separated in the  $N_w - D_0$  domain. Fig. 1 shows the average value of  $\log_{10}(N_w)$  with  $\pm 1\sigma$  (standard deviation) bars versus the mass weighted mean diameter  $D_m$  from disdrometer measurements (open circles) and as retrieved from dual-polarization radar (open squares) for various locations given in Bringi et al. (2003), for stratiform rain (in blue) and convective rain (red). The data are from many different rain climatologies. The units for  $N_w$  are in  $\text{mm}^{-1} \text{m}^{-3}$ . The green lines represent a 'separator line' equation determined independently from the Darwin observations, for a range of typical  $\mu$  values of -2, 0, 3 and 5.

By defining a 'separator index',  $i$ , which is dependent on the fitted  $N_w$  and  $D_0$  values for each 1-minute DSD, it becomes possible to flag the time periods of convective and stratiform rain (as well as mixed/uncertain/transition rain).

Fig. 2 shows (in the lower panel) an example of the time variation of  $i$  determined from the 2DVD measurements in Huntsville, Alabama, USA. The upper panel shows the mean vertical velocity determined from the co-located UHF profiler, as a height-time variation. The transition at around 4.5 km height seen prior to 10:00 UTC (for example) is due to the melting process of snow/ice hydrometeors in the zero degree isotherm region. The profiler observations indicate stratiform rain during this period, and is also indicated by the negative  $i$  values determined from the 1 minute DSD from the 2DVD. On the other hand, the period at around 11:00 UTC shows positive  $i$  values and correspond to the 'white' regions (representing fall speeds corresponding to raindrops) extending to heights well above 5 km. The 'red arrows' shown in the figure connect the positive  $i$  values with periods of convection from the profiler data.

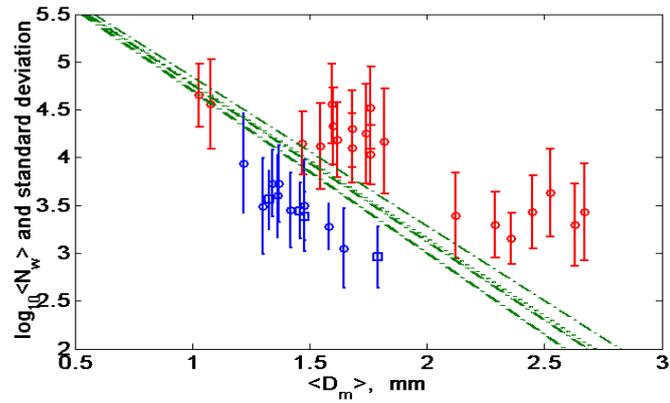


Fig. 1: The average value of  $\log_{10}(N_w)$  with  $\pm 1\sigma$  (standard deviation) bars versus  $D_m$  (mm) from discrometer (open circles) and as retrieved from dual-polarization radar (open squares) for various rain climatologies. The green lines represent the separation equation determined independently from the Darwin observations, for  $\mu$  values of 2, 0, 3 and 5, where  $\mu$  is used to convert from  $D_0$  to  $D_m$ .

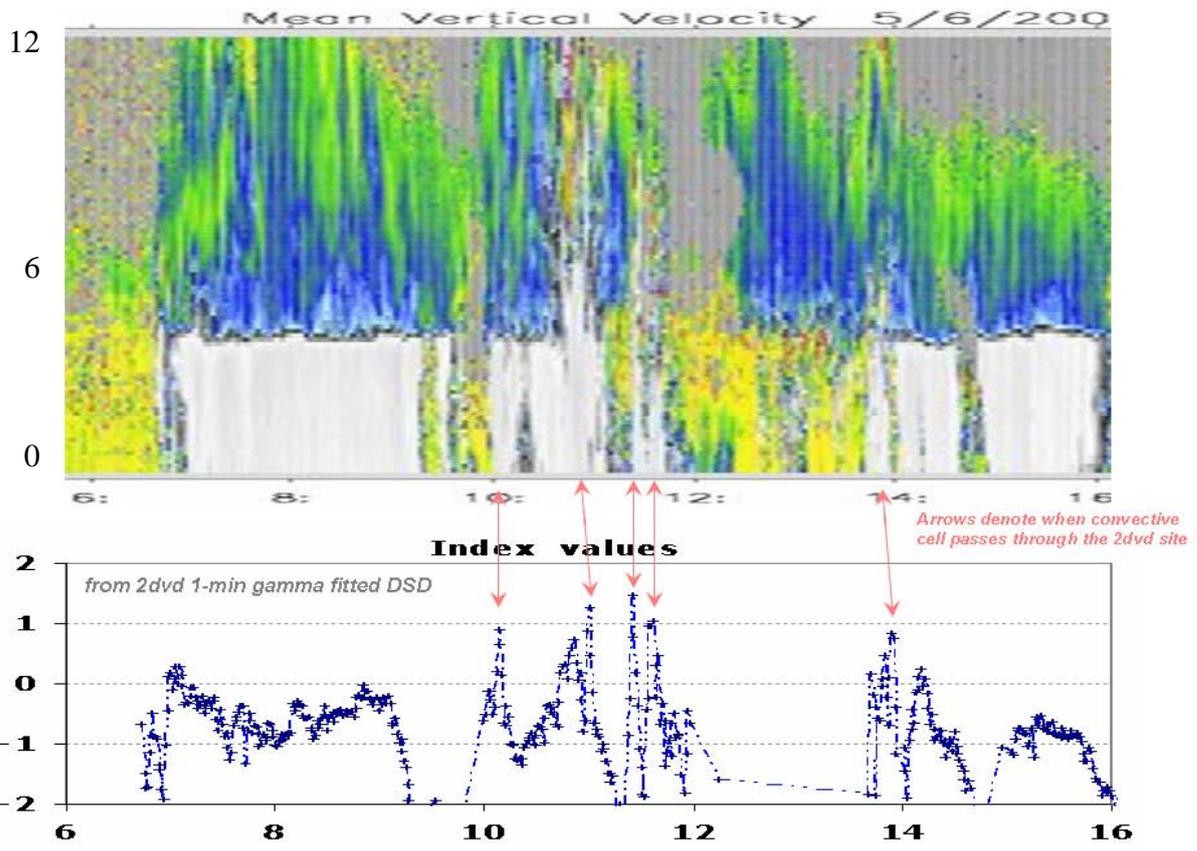


Fig. 2: A stratiform event with embedded convection shown as time series: (a) mean Doppler velocity from a UHF profiler (vertical scale represents the height in km) and (b) the index values determined from the 2DVD 1-minute DSD. The red arrows connect the positive values to convective regions seen by the profiler.

2.2 Drop axis ratio distributions

The above findings enable the drop axis ratios from the 2DVD measurements to be compared between stratiform and convective periods, i.e. for periods with mostly positive  $i$  and mostly negative  $i$  values. Fig. 3 shows the measured axis ratio distributions for the 2.9 – 3.1 mm drops, for two time periods, (i) in between 11:00 and 14:00 representing predominantly convective rain and (ii) outside this time period, representing predominantly stratiform rain. Though the axis ratio distributions have not been deconvolved by the instrument spread function, only a small shift in the mode of the measured distribution – slightly towards more sphericity – can be observed for the convective period. However, several other cases with embedded convection within stratiform rain were also examined and these did not show any noticeable differences in the axis ratio distributions.

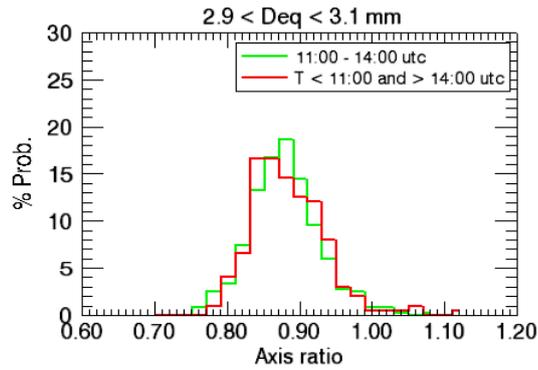


Fig. 3: Axis ratio distributions for the event shown in Fig. 3 for drop diameters in the range 2.9 mm to 3.1 mm

### 2.3 Prolonged convection

Another example of a convective event, this time a prolonged one, is shown in Fig. 4. Though part of a more widespread system (as seen from PPI scans from a C-band radar – not shown here), the 2DVD captured much of the convective elements of the event at the beginning of the storm.

The top two panels of Fig. 4 show the profiler observations, with signal-to-noise (SNR) in the top panel and the Doppler mean (vertical velocity) in the 2<sup>nd</sup> panel. The lower 3 panels show the 2DVD data, in terms of the DSD (3<sup>rd</sup> panel), the rainfall rate (4<sup>th</sup> panel) and the index determined from the 1-minute DSD fitted parameters (last panel). Prior to 07:30 UTC, no bright-band (due to melting layer) can be seen from the SNR from the profiler data and the Doppler data does not show any sudden transition. After 07:30, the SNR data does show a bright-band at around 4.5 km, together with a clear transition in the Doppler mean velocity data. Correspondingly, the index values in the last panel of Fig. 4 determined from the 1 minute DSD from the 2DVD also gives mostly positive values prior to 07:30 and negative values thereafter.

In Thurai et al. (2008), the axis ratio distributions for this event had been examined and the results were related to a set of observations from a C-band polarimetric radar. Fig. 5 shows the axis ratio distributions for the 3.5 – 3.75 mm drops. The histogram after 06:30 UTC is similar to the axis ratio distributions determined from the 80 m fall (artificial) rain experiment conducted under calm conditions (Thurai and Bringi, 2005), whereas the histogram before 06:30 shows significantly higher axis ratios (i.e. relatively more spherical shapes) and a wider distribution. It is likely that the ‘more spherical shapes’ seen during the convective period represent mixed-mode oscillations (see for example Beard et al., 2008). This possibility does not apply to the second half of the event, and particularly for  $T > 07:00$  UTC, i.e. during the stratiform period of the event where the axis ratios show distributions similar to the expected distributions.

### 3. Drop shapes

As mentioned earlier, the fast line scan cameras of the 2DVD can be used to determine drop shapes and their orientation angles assuming rotational symmetry. Description of the techniques can be found in Schönhuber et al. (2008), Thurai et al. (2007) and Huang et al. (2008). In the latter two references, analysis of over 115,000 drops had shown that the mean drop shapes could be fitted to a smoothed conical equation depending on the equi-volume diameter,  $D_{eq}$ . Fig. 6a shows the drop shapes derived from several rain events (other than 25 Aug 2007) in Alabama for  $D_{eq}$  in the range 3.5 - 3.75 mm and compares them with the fitted conical equation from the artificial rain experiment for the corresponding diameter interval. The color scale in Fig. 6a represents the probability values of the drop shape contours and the finite ‘thickness’ of the contours is indicative of the shape variations (due to say drop oscillations). However, the most probable shape lies close to the fitted equation. On the other hand, Fig. 6b which corresponds to the shape data for the 25 Aug 2007 event shows noticeable deviation from our ‘reference’ mean shape, and is in fact more spherical than our fitted equation. The axis ratio distribution during the prolonged convection period - shown earlier in Fig. 5 - results from such shape ‘deformation’, arising perhaps due to mixed-mode, non-axi-symmetric, oscillations, as was noted earlier. Such mixed mode oscillations can be either caused by collisional forcing of drop oscillations and/or some component of spontaneous transverse oscillations.

Another possible explanation for the shape deviation is the presence of melting/melted or wet hail. However, using the drop-by-drop calculations of scattering parameters assuming fully melted hydrometeors had given good agreement with simultaneous C-band polarimetric radar measurements (ARMOR, Petersen et al. 2007) of co-polar reflectivity ( $Z_h$ ), differential reflectivity ( $Z_{dr}$ ), specific differential phase ( $K_{dp}$ ) and co-polar correlation coefficient ( $\rho_{hv}$ ), as was reported in Thurai et al. (2008). Moreover, the vertical velocities determined from the 2DVD measurements showed the expected fall velocities for fully melted drops, and so the possible presence of wet hail for this event can be excluded.

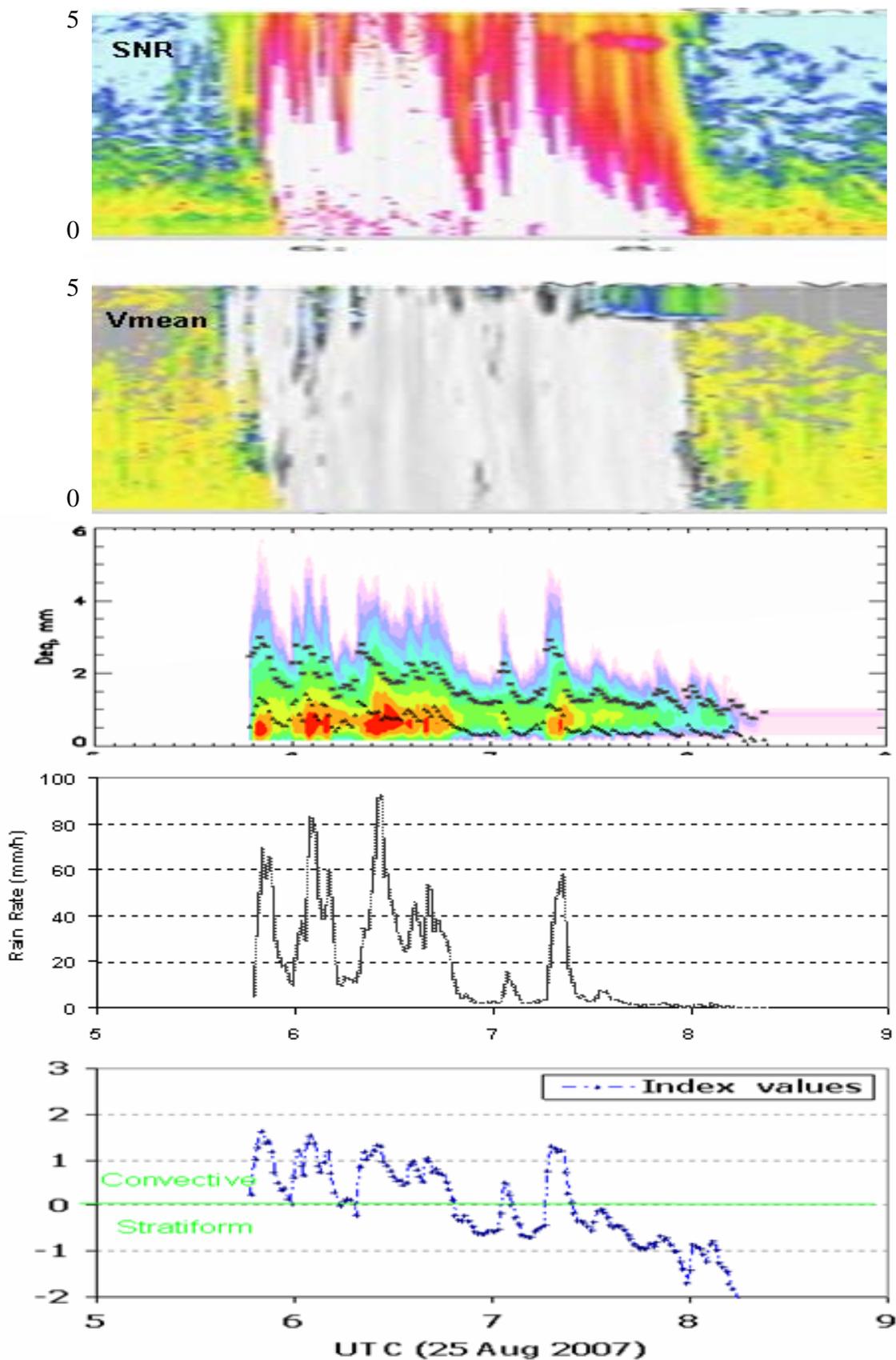


Fig. 4: An example of a prolonged convective event. The top panel shows the signal-to-noise ratio from the UHF profiler, the second panel shows the mean Doppler velocity. The height scale ranges from 0 km to 5 km. The third panel shows the corresponding -minute DSD from the 2DVD; the fourth panel shows the resulting rainfall rate and the fifth panel shows the index value from the 2DVD data.

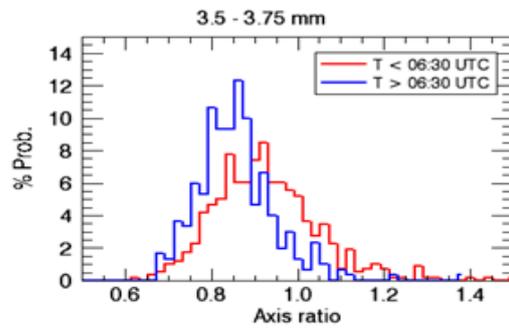


Fig. 5: Axis ratio distributions for the event in Fig.4 for 3.5 mm to 3.75 mm drops, before and after 06:30 UTC.

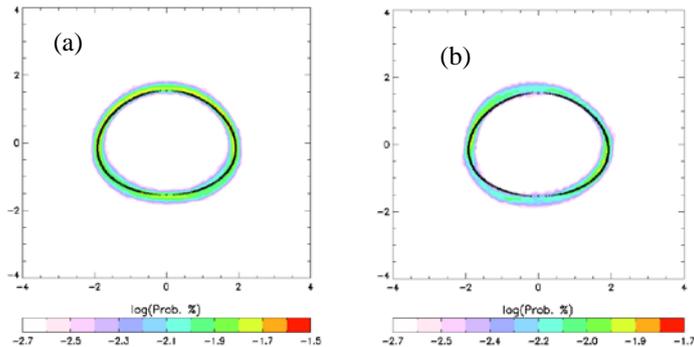


Fig. 6: Drop shapes in terms of ‘probability contours’ for 3.5 – 3.75 mm drops for (a) several events and (b) the 25 Aug 2007 event. Superimposed in black are the curves derived using the fitted equation given in Thurai et al. (2007).

Out of six events considered, the prolonged convection event was the one which showed the most significant drop shape deviation. Other events did not produce significantly different axis ratio distributions during convection, with the exception of the case considered earlier in section 2.1 which showed marginally higher axis ratios during deep convection. The variation of  $Z_h$  with  $Z_{dr}$  from the C-band polarimetric radar measurements had been examined for all six events and in several of these cases, the expected trend was obtained. An example is shown in Fig. 7, where the color represents the joint frequency of occurrence (between  $Z_h$  and  $Z_{dr}$ ) determined from several PPI scans taken during a long duration event. Over-plotted as grey circles are scattering calculations using the 1-minute drop size distributions from 2DVD for the same event and assuming our reference drop shapes. The close agreement with the radar data implies that no significant deviation from the reference shapes is occurring for this event. This inference is independently confirmed by the 2DVD measurements of drop shapes and axis ratio distributions.

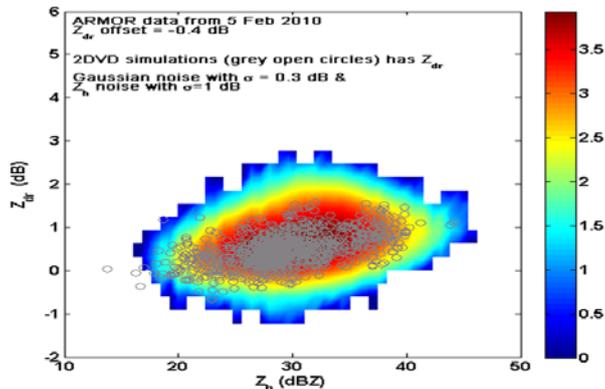


Fig. 7: Variation of  $Z_{dr}$  versus  $Z_h$  from several PPI sweeps taken during a long duration event, given in terms of the joint frequency of occurrence. The color scale indicates the number of occurrences on a log scale. The grey circles are simulations using 1-minute DSD from 2DVD measurements for the same event and assuming the reference drop shapes.

#### 4. Conclusions and further analysis

Drop axis ratio distributions in stratiform and convective rain have been separately examined. The separation was made possible using their drop size distribution characteristics, specifically, in the  $N_W - D_0$  domain. The separation method was validated using observations from a co-located UHF vertical profiler.

Six events were considered. One event (a prolonged convection event) showed significant differences from the expected distributions. The shapes of the drops determined from the 2DVD fast line scan cameras for this event also show significant deviation from our reference shapes, indicating the possibility of non-axisymmetric oscillations. Further corroboration comes from C-band polarimetric measurements which showed lower than expected  $Z_{dr}$  and  $K_{dp}$  for this case. Other five cases considered did not show any appreciable differences in axis ratio distributions between stratiform and convective periods (with the exception of perhaps one case with deep convection). Simultaneous observations from the C-band radar show the expected trend between  $Z_h$  and  $Z_{dr}$  for most of these cases.

There are many other recorded events in Huntsville, Alabama, which will be analyzed in due course. The C-band radar has also been used to dwell over the 2DVD site over a long period in order to ‘capture’ the  $Z_h$ ,  $Z_{dr}$  and  $K_{dp}$  time variation and. The dwelling enables time series of polarimetric data to be recorded, which can be subsequently filtered in time using various techniques, which in turn can be used to correlate with the 2DVD measurements of size, shape and orientation angles of drops. Any deviation from the reference shapes can then be easily and conclusively identified. Measurements from accurately calibrated 2DVD from other locations such as Brisbane, Australia, and Lausanne, Switzerland, are also being examined.

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