Comparison of Dual-Polarization Radar-Derived and
Disdrometer Drop-Size Distributions With S- and X- Band Radars

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Disdrometer Drop-Size Distributions With S- and X- Band Radars

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Abstract

There have been many studies on the evaluations of drop-size distributions and the parameters that affect these distributions, however, few, if any, have directly compared the relationship between the radar-derived parameters and those parameters that are disdrometer-derived. This study focuses on many different features of thunderstorms that changes the structure of the drop-size distribution (DSD) including: Horizontal reflectivity (Z_H), differential reflectivity (Z_{DR}), median drop diameter (D_0), the shape parameter of the gamma-distributed DSD (μ), and the slope parameter of the gamma-distributed DSD (Λ). This work compares data collected by two disdrometers (OTT PARSEL and the Campbell Scientific Present Weather Sensor 100) against DSD parameters derived from dual-polarization radar observations. Using the Warning Decision Support System-Integrated Information (WDSS-II), radar data was merged at 1-km resolution to account for the movement of the precipitation systems before comparing to the 10-minute disdrometer data intervals. It was found that to accurately estimate DSDs from the perspective of using a weather radar, a larger precipitation event is needed. At the beginning and end of a precipitation event the difference between the radar retrieved values of D_0 , μ , and Λ and those sampled by the disdrometer were much greater than during the middle of the event. Throughout the majority of the cases, the radar-derived reflectivity values were consistently lower than those collected by the disdrometers.

Chapter 1: Introduction

No two thunderstorms are the same, therefore, no two thunderstorms have the same DSDs as another. This is true for all precipitation events even if they have the same radar reflectivities or same appearance physically and on radar imagery. This idea is responsible for the dozens of rain-rate algorithms already in publication, see Villarini and Krajewski (2009). The United States National Weather Service (NWS) uses three rain rates as default based on the characteristics of the storm: Tropical, Convective, and Stratiform precipitation. These three rain-rate algorithms were created based on the differing physical properties of the rain drops within the storm. Each storm has a highly varying drop-size distribution (DSD) and this is just as true for different segments of the same system (stratiform vs. convective). These differences in DSDs provide significant differences in their respective reflectivity to rain-rate equations (Z-R relationships) (Tokay et al. 2001).

This study analyzes data from two different disdrometers as well as two different weather radar types (S-band and X-band). The United States is covered by a vast network (Figure 1.1) of Next Generation Radars (NEXRAD) that provides an economical way to estimate precipitation amounts and to visualize each storm's physical appearance and classification (convective, stratiform, etc.). As previously mentioned, each climate, and within that, each storm has a different DSD. Being able to accurately measure the relationship of the drops to the reflectivity and rainfall rates is pertinent to forecasting rainfall amounts and to help forecast flash floods.

Figure 1.1: A graphical view of the radar coverage in the CONUS. All grey, orange, and yellow filled areas have radar coverage from 10,000 feet above ground level or lower. Credit: NOAA

1.1 Statement of Thesis

This study was aimed to investigate the comparison of dual-polarization radar-derived and disdrometer-derived drop-size distributions. More specifically, considering how well certain variables derived by the radar compare to the disdrometer data. Since the addition of the MZZU radar a few miles from the University of Missouri- Columbia campus, radar data were available from two sampling levels of the thunderstorm (KLSX and MZZU). This is in addition to the ground truth received from the HOBO tipping bucket rain gauges and the raw-drop counts from the disdrometer.

DSDs play a vital role in the quantitative values of rain as well as the qualitative. One metric of a DSD is the μ -value. Consider the DSD as represented by the Marshall-Palmer (MP) equation in terms of a gamma distribution function (Illingworth and Blackman, 2002):

$$N(D) = N_0 D^\mu \exp(-\Lambda D) \quad (1.1)$$

where,

$$\Lambda = (3.67 + \mu)/D_0 \quad (1.2)$$

and,

N_0 = Measure of raindrop concentration

D_0 = Median drop size

μ = Shape parameter of the gamma spectrum

Λ = Slope parameter of the gamma spectrum

Equation 1.1 is similar to the Marshall and Palmer (1948) equation in that setting $\mu=0$, we retrieve the original MP equation. When looking at the gamma fit distribution curve, as μ and Λ increase, the curve of the distribution shrinks and moves to the right, respectively. In simple terms, the range of the drop sizes shrinks and the median drop size increases. The μ value also correlates with the median drop size as a function of Z_{DR} (Brandes et al. 2004).

With μ values, thunderstorms can be better evaluated for their respective DSDs. A thunderstorm with a larger μ -value would theoretically have less range in drop diameter concentrations but greater amounts of a particular drop size. A larger Λ represents a lower median drop-size diameter. This study calculated μ and Λ based on the DSDs

retrieved from the disdrometers and then compared those values to the calculated values based on the radar observations from the MZZU and KLSX radar. It should be noted that the KLSX beam height is approximately 9000 feet AGL whereas the MZZU radar beam is approximately 1100 feet AGL at the location at the surface where the disdrometers are located. The positions of the radars will allow for the thunderstorm to be sampled at 9000 feet with KLSX, 1100 feet with MZZU, and on the surface using the disdrometers. Using these three data sets, a better sense of thunderstorm structure was determined and the values calculated based on the separate radars were used to get a sense of where the values are closer to the true value. The specific objectives of this study were to:

1. Validate the new Present Weather Sensor disdrometer (PWS)
2. Determine if μ and Λ values can be better sampled by a S-band radar at 9000 feet AGL or by a X-band radar at 1100 feet AGL
3. Determine the accuracy, for events where the data is available, of the rain accumulations between the tipping buckets and the PWS100 disdrometers

Chapter Two: Literature Review

To accomplish the objectives that this research study set forth, a series of previous studies with similar objectives were studied and analyzed. The first section, 2.1, includes an overview of radar principles as well the products that are produced from weather radars. The second section gives further details on how different hydrometeor sizes and shapes affect the results of radar's output, which is important to understand when comparing DSDs and radar imagery together. The third section encompasses all the uncertainties to consider when evaluating DSDs through disdrometers and radar.

2.1 Weather Radars and Their Products

Next-Generation Radars (NEXRAD or WSR-88D) were developed to replace and upgrade the existing national radar network that consisted of WSR-57 and WSR-74 radars. Being an S-band radar, they were designed and placed strategically throughout the United States to provide as full and continuous coverage as possible. This also was designed to backup other radars that may go down during severe weather or maintenance. In total, over 160 WSR-88Ds were deployed throughout the CONUS, non-CONUS territories and states, as well as some United States military bases (Fulton et al. 1998). It took from the years of 1991 until 1997 to fully place these radars and began supplying new Doppler imagery that the WSR-57 and 74 could not produce.

In the early 2010's the WSR-88D fleet received an upgrade adding in three new products that were provided by the addition of vertical polarization (Z_V). The new products come from a relationship between the horizontal reflectivities and the vertical: Differential Reflectivity (Z_{DR}), Correlation Coefficient, and Specific Differential Phase

(NWS Louisville, 2011). Measuring hydrometeors in both the horizontal and vertical (dual-polarization) creates a two-dimensional image of the precipitation field. Couple the vertical and horizontal scans with each radar's many elevation scans and it creates a robust three-dimensional view of the atmosphere with respect to hydrometeor scatterers. The WSR-88D is able to complete an entire volume scan from 0.5° to 20° for the vertical beam direction, and every 1° in horizontal azimuth with one-kilometer bin widths on the order of five minutes (Fulton et al. 1998). The dual-polarization (Z_{DR}) and standard horizontal reflectivity (Z or Z_H) will be the primary focus of this study.

Reflectivity (hereafter Z_H) is a quantity determined by the drop-size distribution of precipitation. Equation 2.1 explains that Z_H is equal to the number of drops of a given size ($N(D)$), multiplied by the size of the drop diameter (D) to the sixth power given in $\text{mm}^6 \text{m}^{-3}$:

$$Z_H = \sum_{i=1}^{\infty} N(D) D^6 \quad (2.1)$$

Turning Z_H from $\text{mm}^6 \text{m}^{-3}$ to the more common unit of dBz can be done by taking the log of Z_H and multiplying by 10, as seen in equation 2.2:

$$\xi_H = 10 \log_{10}(Z) \quad (2.2)$$

Reflectivity is a measure of power of the scatterers. This power is an exponential function which heavily weights the biggest drop in the sample volume, for example: 1,000,000 drops of 0.1 mm in diameter have the same reflectivity value as 1 drop of 1.0 mm in diameter (Donaldson, 1961). With this, it can be inferred that with increasing reflectivities comes increasing drop size diameters. A typical range of values of Z_H , in dBz, is about 10 to 75. Féral and Soula (2003) stated that a convective storm with rain and no hail can only reach an approximate Z_H value of 57 dBz, with $Z_{DR} > 0.5 \text{ dB}$

(explained in further detail later in the paper). With this threshold, it is inferred that any value over this criterion is assumed to be because the presence of hail.

As explained in Seliga and Bringi (1976), adding the vertical component of reflectivity (Z_V) to the WSR-88D allows for greater hydrometeor microphysical information when obtaining differential reflectivity which aids in the identification of hydrometeors size and type. Ryzkhov and Zrnić (1995) developed their own Z-R rain-rate relationship that includes Z_{DR} in its algorithm that shows improvement in accuracy over the standard Z-R relationships without Z_{DR} . It was known prior to dual-polarization that drops become oblate as they fall through the air due to air drag, but now with Z_{DR} the exact comparison of horizontal to vertical is known. Before this upgrade to dual-pol radar, the radar assumed that an oblate drop was the actual size of the raindrop, when in reality, frictional drag adds to the horizontal diameter at the expense of the vertical (Illingworth and Blackman, 2001). Positive values of Z_{DR} represent a drop that is more wide than it is tall, whereas a negative value or values of zero represents a drop that is more tall than it is wide and a drop that is equal in width and height, respectively. Equation 2.3 represents the equation used to calculate Z_{DR} and its units are in dB (decibels) with a typical range of -2 to 8 dB.

$$Z_{DR} = 10 \log \frac{Z_H}{Z_V} \quad (2.3)$$

2.2 How Do Drop Sizes Affect Radar Values- Drop Size Distribution

Knowing how radar values change with changing hydrometeors and sizes is imperative to understanding and accurately estimating precipitation values. Testud et al. (2001) showed that drop sizes of a rain event change over time, with different storm types or areas within the storm, seasons, temperatures, and even latitude. Ulbrich (1983) also explained the importance (equation 1.1) of treating convective events as a gamma distribution of the drop sizes in a thunderstorm.

When precipitation events occur, it is important to know how much rain occurs throughout the precipitation area. When keeping in mind Z_H alone, it is known that Z_H is heavily weighted to the largest drop in the sample volume. This does not represent the majority of the drops, or any amount of concentration of the drops of lower diameters. After all, 1 million drops of 0.1mm will have the same reflectivity as one 1.0 mm drop, but not the same amount of water content.

Using Z_{DR} as a secondary look at precipitation events can be quite advantageous. Knowing how a drop behaves when forming and falling from the sky gives more information about the overall shape of the drop. Friction drags on drops as they fall in the air pulling the horizontal axis outward at the expense of the vertical axis diameter. An explanation of this concept can be seen below in Figure 2.1. Many studies have been done to facilitate in the comparison of Z_{DR} values to the hydrometeor type. Figure 2.2 gives the NWS operational table of hydrometeor versus Z_{DR} .

Spherical (drizzle, small hail, etc.)	Horizontally Oriented (rain, melting hail, etc.)

$Z_H \sim Z_V$	$Z_H > Z_V$
$Z_H - Z_V \sim 0$	$Z_H - Z_V > 0$
$ZDR \sim 0 \text{ dB}$	$ZDR > 0 \text{ dB}$

Figure 2.1. A graphical description of Z_{DR} .
Credit: NWS Louisville

Figure 2.2. NWS Operational hydrometeor versus Z_{DR} table.
Credit: NWS Louisville

Z_{DR} is one of the more used new products from the dual-polarization upgrade to the WSR-88D radar network. Its advantages were shown in Figure 2.2. This new parameter establishes a better ability to differentiate between hydrometeors within a storm cell (or system) than with just Z_H alone. As mentioned previously, and shown in Figure 2.1, this is due to Z_{DR} physically measuring the difference between horizontal and vertical axes diameters. This method produces results near zero for tumbling hail or small rain drops. Coupling high Z_H with a low Z_{DR} it can be inferred that hail is present in this location (Kumjian, 2013). In cases of larger rain drops, or larger raindrops with hail embedded, Z_{DR} is found to be much greater. Therefore, greater values of Z_H collocated with higher values of Z_{DR} would be assumed a heavier rainfall event with an increase of larger drops into the sample volume.

The μ values become important at this point in assuming a storm's DSD. Since μ is directly related to the median drop diameter, D_0 , from equations 1.1 and 1.2 (also described in equation 2.4 below). D_0 is directly related to Z_{DR} as seen in equation 2.5 below (Brandes et. al, 2004):

$$D_0 = 0.171Z_{DR}^3 - 0.725Z_{DR}^2 + 1.479Z_{DR} + 0.717 \quad (2.4)$$

where Z_{DR} is used in its dB unit, and μ below is unitless. Brandes et. al (2004) shows these to be most accurate with Z_{DR} values were between 0.3 and 3.0:

$$\mu = 6.084D_0^2 - 29.85D_0 + 34.64 \quad (2.5)$$

where these equations are empirical based on observations. A comparison for Z_{DR} and D_0 , μ and D_0 , and μ and Z_{DR} can be seen in Figures 2.3, 2.4, and 2.5 respectively.

Figure 2.3: Graph displaying the theoretical behavior between Z_{DR} and D_0 (mm), as found in Brandes et al. (2004).

Figure 2.4: Graph displaying the theoretical behavior between μ and D_0 (mm), as found in Brandes et al. (2004).

Figure 2.5: Graph displaying the theoretical behavior between μ and Z_{DR} , as found in Brandes et al. (2004).

Bringi et. al (2003) also analyzed an equation (from Gorgucci et al. (2002)) to calculate the above variables using both Z_H and Z_{DR} ; however, this work is a more in-depth and has more strict guidelines on when it can be used. They used a minimum Z_H value of 35 dBz or greater and Z_{DR} being greater than 0.2 dB. The equations below are all empirical based on observations from Bringi et. al (2003):

$$\xi_{DR} = 10^{(Z_{DR}/10)}, \quad (2.6)$$

where ξ_{DR} is the differential reflectivity expressed as a ratio,

$$\beta = 0.0049\xi_{DR}^2 - 0.0043\xi_{DR} + 0.0433, \quad (2.7)$$

and $\xi_{DR} > 1$. The median drop diameter, D_0 , is then derived as:

$$D_0 = aZ_H^b(\xi_{DR})^c \text{ mm}^{-1} \quad (2.8)$$

where,

$$a=0.56 \quad (2.8a)$$

$$b=0.064, \text{ and} \quad (2.8b)$$

$$c=0.024\beta^{-1.42}. \quad (2.8c)$$

From this, Bringi et. al (2003) expresses μ as:

$$\mu = \frac{aD_0^b}{\xi_{DR}-1} - c(\xi_{DR})^d \quad (2.9)$$

where,

$$a=200\beta^{1.89} \quad (2.9a)$$

$$b=2.23\beta^{0.039} \quad (2.9b)$$

$$c=3.16\beta^{-0.046}, \text{ and} \quad (2.9c)$$

$$d=0.374\beta^{-0.355} \text{ mm h}^{-1}. \quad (2.9d)$$

This equation was not chosen due to the complexity of the equation, as same values of Z_H can yield drastically different DSDs and Z_{DR} can arise from a variety of Z_H values or DSDs, which leads to the inability to be used quickly throughout operational radar nowcasting. The equation from Brandes et al. (2004) determined μ only from Z_{DR} , allowing it to be used more quickly from an operational standpoint.

2.3 Sources of Error and Uncertainty

As previously mentioned, it is largely accepted that DSDs from storm-to-storm and the same storm over time are very sensitive to the many microphysical properties of the storm and atmosphere. Bringi and Chandrasekar (2001) have also found that as Z_H values increase, the accuracy of Z_{DR} should also increase. In applying this to the variable, μ , it should be found that the accuracy of μ will increase as rainfall intensity increases, as the estimation of μ is dependent on Z_{DR} . Bringi et al. (2011) also found that rainfall intensities have a larger error for lower rainfall rates than for greater rainfall rates. In other words, as rainfall intensity increases, the error of the radar data should also decrease. Sources of error that will be discussed in this section will include: instrumentation error, sampling error, and atmospheric processes error.

2.3.1 Radar Calibration Errors

Firstly, in any study it is crucial to begin with an instrument that has been proven to some degree of accuracy. The weather radars used in this study were assumed to be in good calibration as direct calibration techniques of these radars (especially the NEXRAD) were unattainable. Radar components can begin to have their calibrations drift as a simple function of time. Each radars transmitter, receiver, and antenna are vulnerable to this process. It has been found that an estimate accuracy of 1 dB is required to support good precipitation estimation performance (Ice et al., 2015). To detect miscalibration of radars, their values and results must be compared against another radar that samples the same area, rain gauges, or another instrument that can estimate rainfall amounts and intensity, like a disdrometer using its DSD. Ulbrich (1983) mentions that the

calibration of weather radars is essential for the use of weather radars in terms of research and operational use. It is also crucial to ensure the instruments that are used to calibrate your radar, are calibrated themselves, which is true for every instrument used in any study.

2.3.2 Radar Attenuation and Radome Wetness

Radar attenuation, as adapted from the AMS glossary definition of attenuation, is a decrease in radar signal strength lost in transmission from the radar to some point. As the electromagnetic wave travels through the atmosphere, it is absorbed and scattered by hydrometeors, buildings or some other obstruction. Essentially any medium that prevents the radar's electromagnetic pulse from reaching its maximum range is attenuation. With weather radars, this correlates to a less than actual radar return values. This is common with X-band radars as mentioned by Frasier et al. (2013) who found that X-band radar attenuation was significantly greater than wavelength frequencies of C-band and lower. As the radar beam travels through an area of heavy precipitation, or high Z_H , not all of the electromagnetic radiation makes it through the heaviest precipitation values. This "blockage" is then considered to be attenuation and generally leaves an area of low, or zero, values of reflectivities behind the "wall" of heavy precipitation.

As precipitation falls and travels in space over time, it becomes increasing more likely that this rain will move overhead of the weather radar. As rain falls and hits the protective dome of the radar, or "radome", it will begin to collect and roll off of the radar. When rainfall intensities increase, it can cause a consistent film of water on the radome which the radars electromagnetic radiation is then required to travel through. Normally

the radome is designed, while in clear weather, to be transparent for the radar's beam while still providing protection from the elements. Frasier et al. (2013) found that presence of water on the surface of the Radome can significantly impact the performance of the radar. They mention that normally radars are coated with a hydrophobic coating that is designed to reduce the amount of water that can stay on the radome and to facilitate and increase the rate at which the water will slide off of the dome. Over time, he mentions that this coat can degrade due to elemental exposure.

Frech (2009) also experimented with the attenuation of Z_{DR} due to radome wetness and found that the hydrophobic coating can actually create differential attenuation. Referencing a uniform coating of water on a radome would produce attenuation of the same degree for the horizontal and vertical waves. However, if the hydrophobic coating produces water "beading" on the surface of the radome, the coating will no longer be uniform and can produce a lower loss of transmission than a uniform film. This beading of the rain on the surface of the Radome was then found to attenuate the vertical polarization more than the horizontal (assuming the beads are vertically orientated as they slid along the Radome) which would tend to produce an overestimation of Z_{DR} .

2.3.3 Radar Anomalous Propagation and Radar Clutter

In this study, radar value averaging occurs on a kilometer scale. Due to this methodology, all radar properties should be accounted for. During times of calm weather and surface inversion present can create two layers of air with two different densities which can cause a refraction of the radar beam towards the surface- this is known as anomalous propagation. This anomalous propagation then returns a reflectivity echo that is not a true value (Bean and Dutton, 1968). Ground clutter on the radar is caused by the radar beam coming into contact or being obstructed by fixed objects, for example, trees, buildings, technological infrastructure, biological targets, and many other features as well (Rinehart, 2004). These features can be identified when comparing the echoes from Z_H to values of Doppler velocity (looking for values close to zero), as well as going up in vertical scans to see if the feature is continuous.

2.3.4 Radar Beam Spreading and Partial Beam Filling

As the radar beam travels through space, the beam width and height expands and begins sampling a larger volume. It has been found in many studies, including Chumchean et al. (2003, 2004), that as the spreading of the radar beam increases, rainfall intensity is increasingly underestimated. It is inferred by this then that many radar properties, including a storm's DSD, is often misrepresented. Areal coverage of precipitation was also found to be overestimated as the beam spreading increases while heavier precipitation becomes increasingly more averaged over a greater area with space and time. This increase of beam height with distance from the radar can cause the radar to shoot its beam higher than where the actual precipitation is occurring. Partial beam filling

becomes an issue at farther ranges from the radar. Partial beam filling occurs as a function of the radar beam spreading with time. It occurs as the radar beam only samples a portion of the hydrometeors. This can become an issue because the reflectivity value from the radar is received as an average over the entire beam width, which can cause the underestimate of Z_H as well as the misrepresentation of DSDs (Tees and Austin, 1991, Fabry et al. 1992).

2.3.5 Vertical Structure of Storms

As the radar beam travels through the air, the Earth below it curves away from the beam; the beam itself is released at a certain degree of elevation to begin its journey as well (0.5° for the National Weather Service WSR-88D network). This curvature of the earth below the beam, and the beam's elevation angle results in the atmosphere being sampled at greater height above the ground with an increasing horizontal distance. With the addition of partial beam filling, the widening of the beam, and increase in height with time can begin to sample non-homogenous precipitation systems, which will be averaged over the beam width, and can cause a misrepresentation of both Z_H and the DSD (Villarini and Krajewski, 2009).

2.3.6 Changing DSDs Shapes and Quantities

Variability of DSDs within storms is widely known already to be qualitatively and quantitatively significant. When including even more dynamics and microphysical properties the variability can become even more complex. Drops can grow bigger through collision and coalescence; split one bigger drop into two or three smaller drops due to frictional drag of the air resistance; and become smaller or even disappear altogether due to entrainment and evaporation.

Phase change of the hydrometeors will produce an increased retrieved radar reflectivity value throughout the melting layer of the storm. This is produced as a small layer of water is produced on the frozen hydrometeor, effectively increasing the drop diameter, so reflectivity values will be lower on each side of the melting layer.

2.3.7 Hydrometeor Drift

Vertical air motion is a consistent feature in Earth's atmosphere that is independent of time and location. The magnitude of this effect is the only change in this feature. DSDs are already affected by almost every aspect of dynamics, physics, and location, and air motion is no exception. The methodology of this study has an inherently large spatial resolution by both choice and characteristics and physics of the radar electromagnetic radiation waves as mentioned in section 2.3.4, "Radar Beam Spreading and Partial Beam Filling". Due to this, it was shown in Lack and Fox (2005; 2007), that the impact of hydrometeor drift is especially significant at higher spatial resolutions. This drift can be caused by vertical motions, i.e. updrafts and downdrafts and horizontal motions determined by wind velocity (which can also, and often does, vary with height).

DSDs will lose the presence of their small drops within the area of an updraft because smaller drops will be unable to fall through the rising air (faster updraft speeds will increase the drop size that is unable to fall through the updraft) as shown in Smith et al. (1996).

Chapter Three: Instrumentation and Methodology

This study encompassed the usage of the OTT PARSIVEL disdrometer, the Campbell Scientific Present Weather Sensor 100 (hereafter PWS), and the computing language MatLab. The data sets are in two separate groups; OTT data were collected in May of 2013 at the Atmospheric and Climatic Experiment Station at South Farm of the University of Missouri in Columbia, and the PWS data were collected at the Foremost Dairy Center of the College of Agriculture, Forestry, and Natural Resources in Columbia, Missouri. OTT event data were collected sporadically from 2010 to 2013 and analyzed previously by Cooley (2011) for its kinetic energy and soil erosion properties. This study found that only data from May of 2013 was usable due to the lack of convective events with the data from 2012, and the lack of dual-polarization data in 2010 as Z_{DR} is necessary for this study. The PWS data were collected from October of 2015 and is still currently collecting data as of May 2017. An unfortunate hard drive error eliminated data collected up until November of 2016.

Once the disdrometer data were collected, a MatLab script analyzed the data and acquired a gamma-fit distribution of the dataset. This gamma fit was responsible for acquiring the μ and Λ values from the disdrometer's DSD. The last two sections in this chapter will discuss in detail the process of acquiring, processing, and analyzing the radar data.

3.1 OTT PARSIVEL: PARticle Size and VELocity Disdrometer

The PARticle Size and VELocity, or PARSIVEL, disdrometer is a laser-based weather instrument that is designed to count each hydrometeors size and its fall velocity. This instrument was used to collect the data used in this study from 2013. It is manufactured by OTT Hydromet. The size of the particle is estimated based upon the magnitude of the disruption in the laser-beam signal and the duration of the disruption that occurs is proportional to the velocity at which the particle is falling. The laser analyzes and records particles on a laser beam that is 54 cm² (or 18cm long by 3cm wide) with a wavelength of 650nm, output power of 0.2mW and with the capabilities to measure rain fall intensities up to 1200 mm per hour or 100 dBZ with an accuracy of +/- 5% for solid precipitation on which this study will be focused. The PARSIVEL disdrometer can measure solid particles from 0.2 to 25 mm and liquid-based particles from 0.2 to 8.0 mm. The velocities of any particle can be analyzed from 0.2 to 20 m s⁻¹. The measurements in size and velocity of the particles are sorted into bins, the PARSIVEL has 32 bins. These bins create a 32 by 32 matrix with 32 size bins and 32 velocity bins where the particles are then sorted and placed by their respective size and velocities with an accuracy of +/- one bin class (OTT, 2017). Since each size bin has 32 respective velocity bins, the velocity data can be used as a means of quality control. If a particle falls through the edge of the beam, its particle size is recorded as smaller than its actual size as. As drops grow larger, their velocities tend to increase; the larger raindrop that fell through the partial beam will be recorded as a smaller raindrop with an apparent high velocity compared to the other drops in that bin size- this is known as the marginal effect. The PARSIVEL software will automatically reject this raindrop as erroneous data.

In this study and studies prior to this including, Tokay et al. (2013), the lowest 3 bins are ignored and not used at all because of their low signal-to-noise ratio.

Many studies have been completed analyzing the accuracy of the PARSIVEL disdrometer. Tokay et al. (2013) found in their study an underestimation of small drops with a slight overestimation of the larger drops, with a significantly larger D_0 . Jaffrain Berne (2011) found, however, the opposite of Tokay et al. (2013) which led to an overestimation of rainfall which was attributed to the overestimation of the smaller drops. It should be noted that many studies have shown a potential source of misrepresentation of the smaller drops in stronger winds due to some splashing effect (Friedrich et al. 2013). Splashing is caused as drops that fall through the air and hit the instrument. On contact, the drops break up into smaller drops and fall through the laser. It is also possible for the drops to splash back up and into the laser from underneath. A possible way to identify this was identified earlier in this section, matching up a drop size to its velocity and identifying and removing any drops that appear as an outlier. For example, the splash back drops would have a velocity near zero. Friedrich et al. (2013) also found that during stronger wind precipitation events, PARSIVEL misrepresents the drops as the horizontal velocity of the drops, changes the time the drop spends in the beam, and analyzes the drops as having unrealistically slow velocities. As previously mentioned, the PARSIVEL outputs its data into a 32 x 32 bin array. Due to this methodology, there is risk for potential error since the instrument outputs the data into a bin rather than having its output being the actual drop size. Each bin has its own range of values; the middle point of this range is the drop diameter that is used to classify all the drops in that bin as that size-i.e. all drops in a bin range from 0mm to 1mm will be assumed to have a drop

diameter of 0.5mm. Table A.1, in the appendix, shows the range of bins used in the PARSIVEL output methodology. As shown in table A.1, the ranges of the bins varies over the entire bin size array. This variance provides another opportunity for an instrumental, methodology-induced error. For data with this disdrometer, drops greater than 6mm were excluded due to the commonly accepted idea that drops of that size are not likely to exist naturally and would heavily alter calculated values that are a function of the DSD in this study (Van Dijk et al. 2002).

3.1.1 OTT Disdrometer Calibration

As previously mentioned previous work with and the calibration of this disdrometer was demonstrated by Cooley (2011). When working with any instrument that provides an output to be used for research and operations, it is important to start with good calibration of the instrument to reduce error as best as possible. It is commonly accepted, especially with numerical weather prediction, that inputting poor data cannot equate to a quality output. To ensure this, Cooley (2011) conducted 3 separate runs of tests. One with no mitigation of splashing drops, one with an extra splash protection on the optical housing unit, and the last with the mesh guard to prevent splashing on the power supply as well as the optical housing unit. This was necessary because as drops fell and hit the instrument, the larger drops hit the instrument and broke up causing some smaller drops to travel back through the optical laser that counts the drops size and velocity.

To calibrate the OTT disdrometer, Cooley (2011) used a large rainfall simulator in the Agriculture Engineering building, on the University of Missouri-Columbia campus, that was able to have a uniform DSD (Regmi and Thompson, 2000). The uniform DSD was tested by conducting several separate tests of to obtain a volume of the drops water content; using the volume's mass as a proxy to obtain the approximate drop size. The tested uniform DSD was approximately 4.5mm. The first test, with no added splash protection, had a large error that was attributed to splashing. As the tested DSD had hundreds of drops outside this value of 4.5mm. After adding a splash protection measure on the optical unit, the test was ran again. After the optics mesh was placed, a decrease in drops from 2mm to 3 mm was seen, but still included some drops that were larger than 4.5mm as well. These larger drops were attributed to splashing drops hitting and staying on the optical window. With the second mesh being placed on the power supply, Cooley (2011), found the majority of the drops being analyzed as less than 0.5 mm and right around 4.5 mm with a few drops outside of these ranges. With this calibration, it was decided to exclude drops from the first 3 bins as they provided little in terms of soil erosion and could not be completely accounted for. The calibration results of Cooley (2011) encouraged the work in this study to ignore the first three bins as well as many of the larger bins as they are not found naturally in the atmosphere, which can limit erroneous drops from being counted in the study. The results of the calibration efforts in Cooley (2011) can be found in Figure 3.1.

Figure 3.1: Calibration results from Cooley (2011). Note the significant increase of drops approximately 4.5 mm wide-the tested drop size.

3.2 Campbell Scientific: Present Weather Sensor 100 Disdrometer

The Campbell Scientific PWS100 is the second laser-based instrument used in this study that measures precipitation and visibility by determining the size and velocity of drop particles in the air. It senses drops much differently than the OTT; its beam is not a stand-alone horizontal plane, but rather, three beams deviated through 20° in the horizontal plane, one 20° in the vertical plane, and the third is on the horizontal plane (Campbell Scientific, 2015). As a particle falls through the overlapping planes, a well-defined signal peaks and the time of this peak is used to calculate the fall speed. The size of the drop is attributed to the strength of the peak. The PWS100 can also analyze drops with a series of fuzzy logic routines, differentiate and output the hydrometeor type into one of nine classes from size and velocity measurements, and the structure of the received signal: drizzle, freezing drizzle, rain, freezing rain, snow grains, snowflakes, ice pellets,

hail, and graupel are their classes analyzed. Similar to the functionality of the OTT, described in section 3.1, the PWS100 has the same limitations such as: bin assignment induced error, marginal effect, and was assumed to have some splashing error attributed with the data. This study had originally planned to calibrate the disdrometer in a similar fashion used in Cooley (2011); however, the lab that was used in this study was under construction. The data were assumed to be calibrated for this study which is considered a possible source of error.

One of the primary goals of this study was to deploy and validate the PWS100 data collected in the field. At first, the algorithms used counted an average of drops over a one-minute interval rather than counting the raw total number of drops. This was changed to count the raw total number of drops on 26 February 2017 and that data can be seen in sections 4.2.6 and 4.2.7. Currently, the PWS100 disdrometer analyzes a median drop size close to double of the analyzed drops with the OTT data with similar precipitation events. This was assumed to be partially attributed to splashing drops as well as multiple drops falling through the beam at once (being analyzed as one larger drop rather than two smaller drops). It was not assumed that drops were attaching to the lens of the instrument as a protective housing unit contains the lens inside of the head of the sensor. It was also found that less drops were being counted compared to data of similar reflectivity values counted with the OTT. With the smaller sampling area, it was assumed that some of the disparity in counted drops was due to this. The PWS100 also scans the air less frequently than the OTT disdrometer does, which was ruled as a definitive reason for counting less drops per 10-minute intervals.

3.2.1 Comparison Table Between the OTT and the PWS100

Table 3.1: Comparisons between the OTT and PWS100 for several measuring parameters.

<u>Measuring Parameter</u>	<u>OTT</u>	<u>PWS100</u>
Measuring Area (<i>mm; cm²</i>)	180 x 30; 54	200 x 20; 40
Wavelength (<i>nm</i>)	650	830
Particle Size (<i>mm</i>)	0.2 to 25	0.1 to 30
Min Rain Rate Intensity (<i>mm hr⁻¹</i>)	0	0
Max Rain Rate Intensity (<i>mm hr⁻¹</i>)	1200	400
Particle Velocity (<i>ms⁻¹</i>)	0.2 to 20	0.16 to 30
Bin Sizes	32	20, 32, 34

3.3 Radar Data Collection and Processing

Radar data for KLSX (Saint Louis, Missouri) was collected and provided by the National Oceanic and Atmospheric Administration's (NOAA) National Center for Environmental Information (NCEI), Hierarchical Data Storage System (HDSS). Only data from precipitation days were collected; data were collected from one hour prior to the first drop being analyzed by the disdrometer to one hour after the last drop was analyzed. This system for collecting data allowed for the processing system to save time and computational power. Prior to being processed through the Warning Decision Support System-Integrated Information, or WDSS-II, it was required to unzip the compressed folders of data with the programming language of MatLab, and then untar each individual data file with the Linux OS terminal. The only parameters analyzed from the processed radar data were Reflectivity and Z_{DR} , both at the lowest altitude.

3.3.1 Warning Decision Support System-Integrated Information (WDSS-II)

WDSS-II is a software developed in cooperation between the National Severe Storms Laboratory and the Cooperative Institute for Mesoscale Meteorological Studies, which is at the University of Oklahoma. As mentioned in section 3.3, WDSS-II (hereafter, WDSS) is able to merge data from many elevation scans to create Z_H and Z_{DR} at lowest altitudes. An advantage of using the lowest altitude is that radar data are merged together along the lowest heights possible above the ground level (AGL). This becomes advantageous in that it is no longer necessary to process and analyze each radar's individual elevation scans as the lowest possible data are all placed into merged matrices of data. This study analyzed radar data processed through WDSS every 300 seconds at 1 km resolution which created a 256 km x 256 km Cartesian grid. A more detailed description of WDSS and its operational and research capabilities can be found in Lakshmanan et al. (2006, 2007). As mentioned earlier, the merged CAPPI data analyzed in this study is along the lowest altitude possible.

WDSS has approximately 200 schemes that can be used to process radar data in equally as many ways. More specifically, WDSS in this study was used to process radar data with the *w2merger* scheme. *W2merger* is the tool used for fusing data from multiple radars and multiple scans onto a common Cartesian grid. An algorithm in the merger scheme uses radar geometry, gaps between radars, the different scan times between multiple radars, storm movement, variations between radar wavelengths, and many other aspects of radar to create an accurate three-dimensional radar grid. In most cases, *w2merger* can take in more than one input; however, in this study only a single radar site was used as an input. Multiple outputs were still received in the form of netCDF files

from the single radar data input. The ability to have netCDF files allows for many other programs to use and visualize the processed data, such as MatLab, in this study. The WDSS *w2merger* data were then used as the input to equations 1.2, 2.4, and 2.5 calculated via MatLab.

3.4 MatLab Analysis

WDSS enabled the ability to use the MatLab software as an analysis tool for this study by creating a 256 km x 256 km Cartesian grid. For the events to be discussed in Chapter 4, MatLab used the WDSS-processed radar data to analyze horizontal reflectivity and differential reflectivity to be compared against the MatLab-analyzed disdrometer data. At any period that the disdrometer analyzed a drop particle, radar data were analyzed through MatLab for that period. The exact code used to extract data from the disdrometers and placed into an excel spreadsheet through MatLab can be found in the appendix. To acquire the radar values that were used to calculate the variables that were compared, a MatLab code was run. This code loaded the radar data onto a 256 km x 256 km grid. Using the GPS coordinates of the disdrometer, MatLab overlaid the lat/lon space on the Cartesian grid. Establishing a new variable that was equal to the latitude and longitude of the disdrometer, the data in the matrix at the disdrometer location was able to be extracted and exported to an excel spreadsheet with its respected radar scan time. This scan time was then used to compare against the 10-minute intervals of the disdrometer data; each 10-minute disdrometer interval corresponded to two radar scans during that period. Holding on to the Z_{DR} that was exported to the excel spreadsheet, D_0 , μ , and Λ , from equations 2.4, 2.5, and 1.2 respectively, were calculated at that location

and for their respected time before being exported to the excel spreadsheet for comparison. The μ and Λ were calculated using MatLab's *gamfit* function which provided the gamma distribution fit for all of the drops counted as well as removing some of the lower disdrometer bins in an attempt to more accurately resemble the DSD. The data in this study was solely based on the all of the disdrometers's bins, or the full fit. This code can also be found in the appendix.

In this study, disdrometer data were accumulated to 10-minute samples. In order to account for this in the movement of thunderstorms and thunderstorms DSD characteristics over time, the radar data were processed and averaged over a 1-km square from the chosen GPS coordinates. Then, taking two radar scan times and comparing those results to the results of the disdrometer data, the analysis of the comparisons between the two could be performed.

Chapter 4: Data and Results

Chapter 4 will go into detail on the specific cases for each disdrometer and the respective radar sites. In section 4.1, data from the OTT disdrometer was compared against results processed at 1 km and retrieved from the S-band Saint Louis radar (KLSX). In section 4.2, data from the PWS disdrometer was compared against results processed at 1 km and retrieved from the S-band Saint Louis radar (KLSX) and the X-band radar in Columbia, Missouri (MZZU). All times used in this study are in UTC (GMT). The convective mode in these cases was based upon visual inspection of the national radar mosaic from NCEI. The disdrometer data time encompasses the previous 10 minutes, i.e. if the disdrometer time displays as 0340 UTC, the collected data sample was from 0330 UTC to 0340 UTC. The tables that contain the compared data will use the format in Table 4.1.

Table 4.1: Depiction of how data will be compared between radar retrieved values and those values analyzed by the disdrometer data for the selected events

Radar Time #1	$Z_H\#1$	$D_0\#1$	$\mu\#1$	$\Lambda\#1$
Radar Time #2	$Z_H\#2$	$D_0\#2$	$\mu\#2$	$\Lambda\#2$
Disdrometer Time for the duration of Radar Time #1 and #2	Z_H	D_0	μ	Λ
Repeating the previous 3 cells for duration of event	...	...	...	...

4.1 May 2013: OTT PARSIVEL Cases

In 4.1, there are four cases that were analyzed. Within each case, were separate times for analysis due to multiple periods of convection throughout the day. These cases will be broken up into additional sub-sections of their respective day. Table 4.2, below, describes the cases in terms of convective mode, time of day, and its date. An asterisk denotes the time period ending on the following day.

Table 4.2: Cases from the OTT disdrometer broken up by time period and their convective mode.

Date	Time (UTC)	Convective Mode
20 May 2013	0250-0420	First QLCS Line
20 May 2013	0540-1120	Second QLCS Line
20 May 2013	2330-0210*	Multicell / QLCS
25 May 2013	1330-1700	Remnant MCS / Multicell
27 May 2013	0620-0800	Remnant Bow Echo
27 May 2013	1700-2300	MCS
30 May 2013	1050-1120	Single Cell
30 May 2013	1940-2240	Trailing QLCS

4.1.1 20 May 2013

On 20 May 2013, the location of the disdrometer received 35.3 millimeters of rain over the course of the three separate rain events denoted in Table 4.2. Of this precipitation, 2.8 millimeters fell in from the time period of 0250 UTC and 0420 UTC, 10.7 millimeters of rain fell between 0540 UTC and 1120 UTC, and 21.8 millimeters fell in the last time period from 2330 UTC on the 20th, and 0210 UTC on the 21st. The convective modes of these events are shown in Figures 4.1 and 4.3 respectively (the first two events share the same figure).

Figure 4.1: KLSX reflectivity image at 0346 UTC, on 20 May 2013, showing the first line of storms moving through Columbia, Missouri with a secondary line coming into view of the radar.

Table 4.3: Data comparison for 20 May 2013 between OTT and KLSX between 0330 and 0350 UTC.

Time (UTC)	Z _H (dBZ)	D ₀ (mm)	μ	Λ
0334	30.0	1.86	0.1	2.0
0339	20.7	1.74	1.1	2.7
0340	46.6	1.06	1.8	3.5
0344	20.1	1.85	0.2	2.1
0349	29.9	2.19	-1.4	1.0
0350	39.7	0.94	11.0	4.3

Figure 4.2: Gamma distribution at 0340 UTC on 20 May 2013. A μ value of 1.8, and a Λ value of 3.5.

At this range from the radar, reflectivity values do not match up well to those collected by the OTT. As seen in Figure 4.1, precipitation was not well spread, the partial beam filling and WDSS averaging scheme limited the ability to calculate Λ and μ well. The first time set matches fairly well to the observed, while the second set does not. Figure 4.2 shows the gamma distribution from the OTT disdrometer at 0340 UTC on 20 May 2013. The blue line denotes the gamma fit for when all bin sizes are included; the green line is when roughly every third bin is included to illustrate the difference; however, all values in the tables are directly from the blue line. The red x's are the raw drop counts at each respective size. This will be the format throughout the rest of this study.

Figure 4.3: KLSX reflectivity image at 2349 UTC, on 20 May 2013, showing multicellular line of storms moving through Columbia, Missouri.

Table 4.4: Data comparison for 20 May 2013 between OTT and KLSX between 2340 and 0000 UTC.

Time (UTC)	Z _H (dBZ)	D ₀ (mm)	μ	Λ
2341	11.6	0.67	17.3	31.0
2346	24.6	1.44	4.3	5.5
2350	24.6	0.53	4.4	11.1
2351	31.3	1.74	1.1	2.7
2356	14.2	1.38	5.1	6.3
0000	20.5	0.76	2.6	5.6

The second event on 20 May 2013 provides a similar result to the first event in that reflectivity values from the radar vary drastically between the radar scans, however, between the two scans of the radar, the data matches up well when compared to the disdrometer. The line of precipitation moved parallel to the disdrometer for this event with the main line of convective precipitation being slightly north of the disdrometer. Figure 4.4 shows the gamma fit on 21 May 2013 at 0000 UTC. Reflectivity values were lower at this time which is illustrated by the low drop concentrations.

Figure 4.4: Gamma distribution at 0000 UTC on 21 May 2013. A μ value of 2.6, and a Λ value of 5.6.

4.1.2 25 May 2013

On 25 May 2013, the location of the disdrometer received 16.5 millimeters of rain over the course rain event denoted in Table 4.2. The convective mode of this event is shown in Figure 4.5.

Figure 4.5: KLSX reflectivity image at 1409 UTC, on 25 May 2013, showing QLCS line of storms moving through Columbia, Missouri.

Table 4.5: Data comparison for 25 May 2013 between OTT and KLSX between 1400 and 1430 UTC.

Time (UTC)	Z _H (dBZ)	D ₀ (mm)	μ	Λ
1403	32.0	0.88	7.5	9.3
1408	29.3	1.01	11.3	15.4
1410	32.2	0.89	3.2	5.3
1413	39.4	0.81	3.3	4.6
1418	39.0	0.98	2.6	4.0
1420	42.3	1.04	2.3	4.3
1424	42.6	1.22	1.5	3.1
1429	44.2	1.70	1.0	2.7
1430	48.4	0.99	2.3	4.8
1434	42.4	1.41	4.7	5.9
1439	43.4	1.40	4.8	6.1
1440	40.5	1.08	2.1	4.1
1444	45.3	1.84	0.3	2.2
1449	32.8	1.90	-0.1	1.9
1450	38.9	1.01	1.9	4.0

Figure 4.6: Gamma distribution at 1430 UTC on 25 May 2013. A μ value of 2.3, and a Λ value of 4.3.

The event on 25 May 2013 produced comparisons between radar reflectivity and disdrometer reflectivity to match quite well. The good comparisons in reflectivity for this event were credited to a more wide-spread precipitation shield. WDSS merger can often under-estimate radar values due to the averaging on a 1-km resolution, however, for more widespread results like 25 May 2013, this is less severe. Values of μ and Λ were comparable for this event which was also credited to the wide-spread, deeper convection. Figure 4.6 illustrates the reflectivity value of 48.3 dBZ well. The lower value of μ is a result of the larger spread in drop sizes with the larger Λ shows the gradual decline in drop concentrations as the drop sizes increases.

4.1.3 27 May 2013

On 27 May 2013, the location of the disdrometer received 36.6 millimeters of rain over the course of the two separate rain events denoted in Table 4.2 above. Of this precipitation, 7.1 millimeters fell in from the time period of 0620 UTC and 0800 UTC and 29.5 millimeters of rain fell between 1700 and 2300. The convective modes of these events are shown in Figures 4.7 and 4.9 respectively.

Figure 4.7: KLSX reflectivity image at 0622 UTC, on 27 May 2013, showing a remnant line of storms moving through Columbia, Missouri.

Table 4.6: Data comparison for 27 May 2013 between OTT and KLSX between 0600 and 0630 UTC.

Time (UTC)	Z _H (dBZ)	D ₀ (mm)	μ	Λ
0601	28.5	0.90	12.6	17.9
0606	35.0	1.02	6.4	14.0
0610	37.4	0.86	2.4	4.7
0611	25.0	1.65	1.9	3.4
0616	23.5	1.18	1.0	2.6
0620	40.3	0.96	2.5	4.5
0621	22.0	1.25	6.8	8.35
0627	31.9	1.86	0.2	2.0
0630	30.0	0.82	3.1	5.5

Figure 4.8: Gamma distribution at 0620 UTC on 27 May 2013. A μ value of 2.5, and a Λ value of 4.5.

The first event on 27 May 2013 was another example of under-estimated reflectivity values. Figure 4.7 shows a smaller precipitation event; the small precipitation event was believed to lead WDSS to average in more smaller reflectivity values, drowning out the peaks. Values of μ and Λ did not match up well at the beginning of the event, however, were within the range of the disdrometer-based values. Figure 4.8 shows a similar result to the previous event, Figure 4.6, in that a higher reflectivity with a low μ and a moderate Λ results in the slow decline of drop concentrations with increasing drop size.

Figure 4.9: KLSX reflectivity image at 1702 UTC, on 27 May 2013, showing the southerly line of storms associated with a MCS moving through Columbia, Missouri.

Table 4.7: Data comparison for May 27th, 2013 between OTT and KLSX between 1650 and 1720 UTC.

Time (UTC)	Z _H (dBZ)	D ₀ (mm)	μ	Λ
1651	33.7	1.46	4.0	5.2
1656	35.7	1.66	1.8	3.3
1700	42.5	1.09	1.8	4.2
1701	35.3	1.69	1.6	3.1
1707	41.9	1.80	4.6	5.9
1710	46.1	0.85	2.6	5.5
1712	31.4	1.20	3.4	4.6
1717	33.3	1.38	3.4	4.6
1720	37.6	0.79	2.9	5.9

The second event of 27 May 2013 was consistent in the under-estimation of reflectivity values. This can be a result of the WDSS averaging methodology used or the height level of the precipitation. As has been the case in the previous events, μ and Λ values from the radar encompass the ground-truth values from the OTT.

4.1.4 30 May 2013

On 30 May 2013, the location of the disdrometer received 66.6 millimeters of rain over the course of the three separate rain events denoted in Table 4.2. Of this precipitation, 8.4 millimeters fell in from the period of 1050 UTC and 1120 UTC and 58.2 millimeters of rain fell between 1940 UTC and 2240 UTC. The convective modes of these events are shown in Figures 4.10 and 4.11 respectively.

Figure 4.10: KLSX reflectivity image at 1056 UTC, on 30 May 2013, showing a single-cellular line moving through Columbia, Missouri.

Table 4.8: Data comparison for May 30th, 2013 between OTT and KLSX between 1050 and 1120 UTC.

Time (UTC)	Z_H (dBZ)	D₀ (mm)	μ	Λ
-	-	-	-	-
-	-	-	-	-
1050	44.6	1.00	2.1	4.2
-	-	-	-	-
-	-	-	-	-
1100	21.7	0.66	4.3	8.3
-	-	-	-	-
-	-	-	-	-
1110	43.2	0.99	2.3	4.3
-	-	-	-	-
-	-	-	-	-
1120	32.2	0.81	2.5	5.3

The first event on 30 May 2013 was included in the results (Table 4.8) to illustrate the importance of having a larger area of precipitation for this methodology. As WDSS merged together the data, there was not enough coverage for the 1-km averaging to produce any output (no recorded values at all), despite disdrometer values of reflectivity to be quite high compared to the other events.

Figure 4.11: KLSX reflectivity image at 2057 UTC, on 30 May 2013, showing a convective line of storms with trailing stratiform precipitation moving through Columbia, Missouri.

Table 4.9: Data comparison for 30 May 2013 between OTT and KLSX between 2030 and 2100 UTC.

Time (UTC)	Z_H (dBZ)	D_0 (mm)	μ	Λ
2032	29.8	1.55	3.0	4.3
2037	41.6	1.64	-0.5	3.4
2040	33.6	1.14	1.5	2.9
2042	29.3	1.64	2.1	2.1
2047	40.1	1.86	0.1	2.1
2050	49.6	1.21	1.6	3.4
2052	43.6	2.22	-1.4	0.8
2058	35.1	1.79	0.6	2.4
2100	47.6	0.91	2.5	5

Figure 4.12: Gamma distribution at 2100 UTC on 30 May 2013. A μ value of 2.5, and a Λ value of 5.0.

The second event on 30 May 2013 was initially hypothesized as a great case when this study began. The results in table 4.9 show comparable values of Z_H , μ , and Λ . Figure 4.12 shows the gamma distribution on 30 May 2013 at 2100 UTC. Similar results to previous events, Figures 4.6 and 4.8, shows a large values for reflectivity (47.6 dBZ) with a moderate decline of drop concentrations with an increasing drop size. As has been a trend for all events in section 4.1, D_0 has not been accurate in its comparisons between the radar and the disdrometer which may be a result of the methodology, or equation 2.4 which will be later discussed in Chapter 5.

4.2 Campbell Scientific PWS100 Cases

In this section, there are five cases that were analyzed. Within each case, are separate times for analysis due to multiple periods of convection throughout the day- these cases will be broken up into additional sub-sections of their respective day. Table 4.10, below, describes the cases in terms of convective mode, time of day, and its date. This disdrometer is in a different location than where the OTT disdrometer was located, because of this difference, these events were sampled 1300 feet higher AGL than the OTT cases. The radar also is 10.4 nautical miles further from KLSX at this location than the OTT which may be responsible for producing an increased amount of errors as described in section 2.3. All cases used the 34 x 34 bin size matrix unless noted otherwise. Some days, the automated algorithm of the instrument managed to change and instead of writing out the 34 x 34 matrix, it began to write out the 20 x 20 and 32 x 32. It can be said, however, that when analyzing those arrays, the 20 x 20 underestimates reflectivity and median drop sizes compared to the 32 x 32. The 32 x 32 matrix underestimated reflectivity, but not median drop size when compared to the 34 x 34. This study determined that the 34 x 34 matrix provides the best quality data. This was attributed to the evenly spaced bins with smaller bin spacing, which limited the artificially-created measurement-methodology error.

Table 4.10: Cases from the PWS100 disdrometer broken up by time period and their convective mode.

Date	Time (UTC)	Convective Mode
02 November 2016	2300-2320	Single Cellular from Front
26 December 2016	0500-0800	Trailing QLCS
17 January 2017	0120-0220	Remnant Stratiform, Jan 16 th low
01 March 2017	0400-0740	Cold Front QLCS
07 March 2017	0400-0600	Cold Front QLCS with Trailing

4.2.1 2 November 2016

On 02 November 2016, the location of the disdrometer received 7.1 millimeters of rain over the course of thirty minutes from 2240-2310 UTC. Table 4.11 has the comparisons between the X-band radar and the disdrometer, while Table 4.12 has the comparisons between the S-band radar and the disdrometer. Figure 4.13 shows the radar-based convective mode for this event.

Figure 4.13: MZZU reflectivity image at 2246 UTC, on 02 Nov 2016, showing a single-cellular line moving through Columbia, Missouri.

Table 4.11: Data comparison for 02 November 2016 between PWS100 and MZZU between 2230 and 2300 UTC.

Time (UTC)	Z _H (dBZ)	D ₀ (mm)	μ	Λ
2233	13.8	0.30	25.1	83.1
2239	27.5	0.20	29.1	167.9
2240	29.2	2.22	2.6	1.5
2244	33.7	0.19	31.0	279.5
2249	35.5	-	-	-
2250	47.4	2.29	1.1	1.2
2254	37.8	1.25	6.8	8.4
2259	42.8	0.97	11.3	15.4
2300	34.9	2.41	2.0	1.4

Results (Table 4.11) from the comparison between MZZU and the PWS100 had comparable reflectivity values, however, did not produce any μ or Λ values of any quality. Empty cells are uncalculatable data due to attenuation; radar attenuation led to erroneous values of Z_{DR} that are not able to produce a μ or Λ value. Data sets with similar results to table 4.11 will be discussed in chapter 5.

Table 4.12: Data comparison for 02 November 2016 between PWS100 and KLSX between 2230 and 2300 UTC.

Time (UTC)	Z_H (dBZ)	D_0 (mm)	μ	Λ
2231	24.1	1.42	4.5	5.8
2236	25.6	1.56	2.9	4.2
2240	29.2	2.22	2.6	1.5
2242	31.5	1.86	0.2	2.1
2247	34.2	1.94	-0.4	1.7
2250	47.4	2.29	1.1	1.2
2252	35.1	1.91	-0.2	1.8
2258	38.6	1.83	0.4	2.2
2300	34.9	2.41	2.0	1.4

When comparing KLSX data to the PWS100 (Table 4.12), values matched up better than what was originally hypothesized. Reflectivity values were under-estimated but like events in 4.1, this was expected at this range from the radar. Values of μ and Λ quite close to those analyzed by the PWS100. This event was encouraging to continue moving forward with the remaining events with a similar methodology. The gamma distribution in Figure 4.14 shows the results from the PWS100 disdrometer. For the first three events from Table 4.10, the disdrometer was averaging the drops counted per minute, this results in the smaller number of drop concentrations. It should be reminded that the PWS100 has still not been calibrated. The gamma distribution of this event, seen in Figure 14, has a very low μ and Λ value shows very little concentration of any drop size which is similar to the uncalibrated results of Cooley (2011) seen in Figure 3.1.

Figure 4.14: Gamma distribution at 2250 UTC on 02 Nov 2016. A μ value of 1.1, and a Λ value of 1.2.

4.2.2 26 December 2016

On 26 December 2016, the location of the disdrometer received 14.0 millimeters of rain over the time period from 0400-0800 UTC. Figure 4.15 shows the Z_H (left) and Z_{DR} (right) moving over Columbia, MO with values of Z_{DR} at or below 0 in grey.

Figure 4.15: MZZU radar at 0507 UTC. The red dot denotes location of disdrometer.

Table 4.13: Data comparison for 26 December 2016 between PWS100 and MZZU between 0500 and 0530 UTC.

Time (UTC)	Z _H (dBZ)	D ₀ (mm)	μ	Λ
0501	25.5	-	-	-
0507	17.97	-	-	-
0510	43.3	1.33	4.4	4.9
0511	29.6	-	-	-
0515	40.6	0.61	18.6	36.5
0520	39.9	1.25	5.2	5.4
0521	40.1	1.18	7.9	9.8
0526	38.5	0.92	12.4	17.6
0530	29.2	0.91	10.3	12.5

Table 4.13 encompasses the comparison results between MZZU and the PWS100. Attenuation of the radar beam produced erroneous values of Z_{DR} (Figure 4.15) which led to the inability to calculate the other variables. The attenuation in Figure 4.15 was seen in other events as well but this is the only image that includes the Z_{DR} portion. Other than Z_H the results between the two did not compare well.

Table 4.14: Data comparison for 26 December 2016 between PWS100 and KLSX between 0500 and 0530 UTC.

Time (UTC)	Z_H (dBZ)	D₀ (mm)	μ	Λ
0502	32.9	1.36	5.3	6.6
0507	16.4	0.54	20.2	43.9
0510	43.3	1.33	4.4	4.9
0512	17.3	0.31	25.9	94.1
0517	5.8	0.78	14.9	23.7
0520	39.9	1.25	5.2	5.4
0522	5.2	1.88	0.1	2.0
0527	8	1.57	2.8	4.1
0530	29.2	0.91	10.3	12.5

Partial beam filling and range degradation was believed to attribute to the high error in the values in Table 4.14, comparing KLSX and the PWS100. Only one time step compared well (0502 UTC) in this event had comparable results. Figure 4.16 shows the gamma distribution at 0520 UTC on 26 Dec 2016, the higher values for D₀ can be seen as a result of the lack of any smaller drops being analyzed or counted. This was attributed to the disdrometer not being calibrated at this time. The μ and Λ values are more in line for what was seen in other events; however, these values need to be analyzed with caution due to the PWS100 not being calibrated. At this range, if the convection is not deep, the results will be highly differing. This will be further discussed in Chapter 5.

Figure 4.16: Gamma distribution at 0520 UTC on 26 Dec 2016. A μ value of 5.2, and a Λ value of 5.4.

4.2.3 17 January 2017

On 17 January 2017, the location of the disdrometer received 5.1 millimeters of rain over the time period from 0020-0120 UTC. Figures 4.17 and 4.18 show the radar imagery from MZZU on 17 January 2017 at 0133 UTC and 0140 UTC respectively. At 0133 UTC, a line of thunderstorms was moving towards the MZZU radar, at 0140 UTC the thunderstorm is directly overhead of the MZZU radar. The MZZU radar had begun to have radome wetness attenuation at a time between these two figures which resulted in the higher reflectivities in Figure 4.17 to disappear in Figure 4.18. The attenuation seen in Figures 4.17 and 4.18 occurred after the precipitation had moved away from the disdrometers location near Rocheport (Figure 4.17).

Figure 4.17: MZZU radar at 0133 UTC. Red and yellow colors show thunderstorms.

Figure 4.18: MZZU radar at 0140 UTC. At this time, attenuation causes the radar to not analyze the thunderstorms properly.

Table 4.15: Data comparison for 17 January 2017 between PWS100 and MZZU between 0020 and 0100 UTC.

Time (UTC)	Z_H (dBZ)	D₀ (mm)	μ	Λ
0024	26.6	0.56	19.7	41.5
0029	29.7	0.98	11.2	15.1
0030	28.1	1.08	6.7	7.7
0034	30.3	0.63	18.0	33.9
0039	31.1	0.70	16.5	28.4
0040	31.1	1.11	5.6	6.25
0044	33.5	1.38	27.7	128.9
0049	35.9	1.58	4.5	5.8
0050	35.8	1.26	5.5	5.6
0054	38.0	1.74	1.1	2.7
0059	34.9	1.13	8.6	10.9
0100	41.2	1.24	5.3	5.9

Table 4.15 shows a good comparison in reflectivity between MZZU and KLSX.

At this time, Z_{DR} had begun to attenuate, leading to erroneous values of μ and Λ, matches reflectivity well.

Table 4.16: Data comparison for 17 January 2017 between PWS100 and KLSX between 0020 and 0100 UTC.

Time (UTC)	Z_H (dBZ)	D₀ (mm)	μ	Λ
0023	22.8	1.41	4.6	5.8
0028	19.0	1.53	3.2	4.5
0030	28.1	1.08	6.7	7.7
0033	18.7	1.31	6.0	7.4
0038	21.4	1.68	1.6	3.1
0040	31.1	1.11	5.6	6.5
0044	21.4	1.41	4.6	5.8
0049	20.3	0.64	18.0	33.7
0050	35.8	1.26	5.5	5.6
0054	24.1	1.72	1.3	2.8
0059	30.8	0.20	28.9	158.3
0100	41.2	1.24	5.3	5.9

The trend of under-estimating reflectivity values compared to the ground-truth values of the disdrometer continued in Table 4.16 comparing KLSX to the PWS100 data. A change of comparing well to not well can be seen before and after 0040 UTC above respectively. Partial beam filling and range degradation were attributed to the high error for this case as storm heights were quite low. Figure 4.19 shows the gamma-fit distribution at 0050 UTC on 17 January 2017. The higher μ and Λ values illustrate larger concentrations around D_0 with a gradual decline of drop concentrations with an increasing drop size.

Figure 4.19: Gamma distribution at 0050 UTC on 17 Jan 2017. A μ value of 5.5, and a Λ value of 5.6.

4.2.4 01 March 2017

On 1 March 2017, the location of the disdrometer received 11.9 millimeters of rain over the time period from 0400-0800 UTC. Figure 4.20 shows the MZZU radar imagery at 0511 UTC on 01 March 2017. The precipitation is just reaching the disdrometer at this point with maximum Z_H values near 54 dBZ. The storm tracked directly over the radar which resulted in attenuation.

Figure 4.20: MZZU radar at 0511 UTC.

Table 4.17: Data comparison for 01 March 2017 between PWS100 and MZZU between 0500 and 0540 UTC.

Time (UTC)	Z_H (dBZ)	D₀ (mm)	μ	Λ
0504	31.8	0.38	24.3	74.3
0509	24.7	0.87	13.3	19.5
0510	42.9	1.96	1.7	1.7
0514	32.6	1.22	7.2	8.9
0519	37.9	1.59	7.1	8.8
0520	47.4	1.97	2.3	2.4
0524	10.4	-	-	-
0529	17.1	-	-	-
0530	45.7	1.88	1.9	2.2
0534	24.7	-	-	-
0539	32.0	1.13	8.7	10.9
0540	32.7	1.26	4.5	4.8

Z_{DR} attenuation continues to hinder the ability to calculate μ and Λ values when comparing MZZU to the PWS100. Z_{DR} and Z_H attenuation hindered a μ or Λ estimation and was the reasoning for the sudden drop in reflectivity values respectively.

Table 4.18: Data comparison for 01 March 2017 between PWS100 and KLSX between 0500 and 0540 UTC.

Time	Z_H (dBZ)	D₀ (mm)	μ	Λ
0501	33.8	0.99	11.1	14.9
0505	26.6	0.62	18.5	35.7
0510	42.9	1.96	1.7	1.7
0511	27.5	0.95	11.8	16.2
0516	30.8	1.15	8.4	10.5
0520	47.4	1.97	2.3	2.4
0521	30.8	0.92	12.4	17.4
0526	32.0	1.12	8.8	11.0
0530	45.7	1.88	1.9	2.2
0532	31.7	1.10	9.2	11.6
0537	30.5	1.21	7.5	9.2
0540	32.7	1.26	4.5	4.8

The results of this event when comparing KLSX to the PWS100 (Table 4.18) produced similar Z_H values, but was unable to accurately compare values of μ and Λ . Partial beam filling and range degradation were attributed to the high error for this case as storm heights were quite low. Figure 4.21 shows the gamma distribution at 0510 UTC on 01 March 2017. A large D_0 and very low μ and Λ was the result of the PWS100 analyzing a greater number of larger drops than what was expected. This event was the first event that used the raw total amount of drops counted by the disdrometer rather than the average number of drops in a minute. This event was helped provide evidence for the hypothesis that the OTT PARSIVEL disdrometer would count more drops than the PWS100 for similar events.

Figure 4.21: Gamma distribution at 0510 UTC on 01 March 2017. A μ value of 1.7, and a Λ value of 1.7.

4.2.5 07 March 2017

On 07 March 2017, the location of the disdrometer received 11.2 millimeters of rain over the time period from 0400-0600 UTC. Figure 4.22 shows the precipitation event at the rain began to move overhead of the disdrometer. After the heaviest precipitation moves past the disdrometer, there was a trailing stratiform precipitation event that was also collected drops; however, Figures 4.23 and 4.24 show the precipitation had begun to attenuate as it moved over head of the radome. This event's attenuation was more classic attenuation than the radome wetness attenuation as the stratiform precipitation behind the line of thunderstorms can be seen, in some capacity, in Figure 4.22 as the shades of blue beyond the line of thunderstorms is what was left after radar attenuation.

Figure 4.22: MZZU radar at 0403 UTC as the precipitation was directly overhead of the PWS100.

Figure 4.23: MZZU radar at 0419 UTC as the precipitation was just reaching the MZZU radar site. Attenuation had begun to become evident.

Figure 4.24: MZZU radar at 0423 UTC as the precipitation was overhead the MZZU radar site. Attenuation resulted in the loss radar values beyond a kilometer or two from the radar.

Table 4.19: Data comparison for 07 March 2017 between PWS100 and MZZU between 0400 and 0430 UTC.

Time (UTC)	Z_H (dBZ)	D₀ (mm)	μ	Λ
0401	34.3	1.12	6.9	10.4
0406	37.6	1.41	5.7	7.1
0410	42.1	1.35	4.1	4.5
0411	35.5	1.16	8.3	10.3
0416	11.1	-	-	-
0420	45.9	1.55	3.7	3.8
0421	11.0	-	-	-
0426	10.3	-	-	-
0430	33.2	1.16	6.4	6.5

Z_{DR} attenuation hindered a μ or Λ estimation or was the reasoning for the sudden drop in reflectivity values. Prior to the attenuation, values of reflectivity were comparable.

Table 4.20: Data comparison for 07 March 2017 between PWS100 and KLSX between 0400 and 0430 UTC.

Time	Z_H (dBZ)	D₀ (mm)	μ	Λ
0404	-	-	-	-
0409	-	-	-	-
0410	42.1	1.35	4.1	4.5
0414	31.6	0.89	7.3	11.4
0419	29.1	1.4	4.1	5.1
0420	45.9	1.55	3.7	3.8
0421	28.1	1.1	6.1	9.6
0426	33.9	1.4	0.2	3.1
0430	33.2	1.16	6.4	6.5

Partial beam filling and range degradation were attributed to the high error for this case as seen with no data analyzed by the radar when the disdrometer analyzed heavy precipitation. This was due to WDSS averaging not analyzing any precipitation until after a few more scans moved into the averaging area. Figure 4.25 shows the gamma

distributions at 0420 UTC. With high values of Z_H and moderate values of μ and Λ , a larger concentration of drops near 1 mm were counted. This provided a steady decline in drop concentrations as the drop size increased.

Figure 4.25: Gamma distribution at 0420 UTC on 07 March 2017. A μ value of 3.7, and a Λ value of 3.8.

4.3 Rain-Rate Comparisons Between Disdrometer and HOBO Tipping Buckets

A comparison between HOBO tipping bucket rain accumulation amounts and the disdrometer-derived rain accumulation amounts was done as a secondary objective in this study, the results of four cases can be seen below in Tables 4.21, 4.22, 4.23, and 4.24. Further reflection on the results are seen in the conclusion; however, the disdrometer-derived rain rates were approximately double the amount of the HOBO gauges which further emphasized the need to calibrate the PWS100 disdrometers.

Table 4.21: Rain accumulation comparisons, in mm, between PWS100 raw drop counts and the collocated HOBO tipping Bucket on 26 December 2016

Time (UTC)	Rain Total from Disdrometer	Rain Total from Tipping Bucket
0500-0510	13.05	6.86
0510-0520	11.78	5.59
0520-0530	2.67	1.50

Table 4.22: Rain accumulation comparisons, in mm, between PWS100 raw drop counts and the collocated HOBO tipping Bucket on 17 January 2017

Time (UTC)	Rain Total from Disdrometer	Rain Total from Tipping Bucket
0020-0030	1.53	0.51
0030-0040	2.34	0.76
0040-0050	3.88	1.78
0050-0100	6.61	2.80

Table 4.23: Rain accumulation comparisons, in mm, between PWS100 raw drop counts and the collocated HOBO tipping Bucket on 01 March 2017

Time (UTC)	Rain Total from Disdrometer	Rain Total from Tipping Bucket
0500-0510	2.20	1.27
0510-0520	8.86	5.08
0520-0530	7.13	3.05
0530-0540	2.04	1.27

Table 4.24: Rain accumulation comparisons, in mm, between PWS100 raw drop counts and the collocated HOBO tipping Bucket on 07 March 2017

Time (UTC)	Rain Total from Disdrometer	Rain Total from Tipping Bucket
0400-0410	6.16	6.10
0410-0420	16.51	6.35
0420-0430	3.98	1.78

Chapter 5: Conclusions

This study had originally set out to see if μ and Λ values can be better sampled by a S-band radar at 9000 feet AGL or by a X-band radar at 1100 feet AGL. Results from 2013 were included with the radar scanning at approximately 7800 feet AGL to establish a base line for what to expect when moving forward to comparing the new data from the MZZU X-band radar. As the study progressed, many sources of error were found to hinder or alter either the ability to sample the atmosphere accurately or to accurately estimate the values of μ and Λ .

It was found that the WDSS merging routine used with the methodology of this study required a larger area of precipitation to be present for the routine to accurately display values of Z_H and Z_{DR} . Without proper precipitation coverage, the WDSS routine drastically lowered Z_H values because of averaging in more lower values surrounding the higher values of reflectivity. In some instances, there was not enough precipitation in the 1-km averaging radius to output a value at all. For values of differential reflectivity, this averaging was more noticeable. Z_{DR} changes quickly in a short distance in thunderstorms as the DSD within each precipitation event changes depending on where in the storm it is being sampled. This was known going into this study as a source of significant error; however, it did not affect the S-band radar results as much as the results from the X-band radar. Range degradation of the S-band radar beam continually produced lower than actual reflectivity values that were seen at the surface, which was attributed to two things: sampling the atmosphere roughly 8000 feet AGL as well the averaging of the partial beam filling combined with the WDSS merger routine.

Most of the estimations of D_0 in this study did not compare well to those seen at the ground with the disdrometer. This study used D_0 as a function of Z_{DR} and as seen in Figure 2.3, is very sensitive outside of Z_{DR} values of 1 to 3. A slight miscalculation of Z_{DR} can yield results that are not comparable. Another thing that can affect this is that DSDs are drastically different inside of the storm before they fall through the cloud. As drops fall, they break up into smaller drops because of friction which is believed to have been the contributing factor in this study, rather than the equations used to calculate the median drop diameter.

Overall, results from the OTT and KLSX comparison proved to be quite encouraging. For the majority of the cases, values of μ and Λ were comparable to those sampled by the disdrometer. When analyzing the PWS100 disdrometer, accounting for the lack of calibrating the instrument before collecting data had to be done. The PWS100 continually observed larger median drop sizes than the OTT disdrometer. One possible cause of this can be that the PWS100 has a smaller sampling frequency as well a smaller measuring area. The sampling rate and measuring surface area led to a significant decrease in the amount of drops that were counted and analyzed by the PWS100 than were by the OTT.

With the exception of D_0 , this study found that it is possible to sample the atmosphere 8000 feet AGL to produce useful μ and Λ . More research is needed to choose the right rain-rate equation to produce better rainfall estimations. Knowing the concentrations of what size of drops are present in the precipitation event can change the desired equation used to calculate rainfall.

Rain rate comparisons (Tables 4.21, 4.22, 4.23, 4.24) in section 4.3 proved even further the need to calibrate the PWS100 disdrometer. The results of these comparisons show that the disdrometer-based rain-rate estimations were close to double than the true rain accumulations provided by the HOBO tipping buckets. These results were assumed to be the result from many more large drops being counted than was expected and seen in the results of Cooley (2011).

This study shows many of the factors that go into accurately analyzing DSDs in precipitation events. The conclusions drawn from this study can be further studied and examined in many ways. Moving a disdrometer closer to a WSR-88D would, in theory, decrease many of the radar sampling-induced errors such as partial beam filling and range degradation. Applying a Z_{DR} attenuation scheme should also prove to be useful. Whenever precipitation hit the radome of the X-band radar, the results captured by the radar become unusable for estimations of μ and Λ due to the attenuation of both Z_H and Z_{DR} . Testing and calibrating the PWS100 would also help to better understand why the disdrometer counts and analyzes more larger drops than the OTT disdrometer. Similar to the results found in Cooley (2011), splashing and drops attaching to the lens of the instrument could be a significant reason for this as well as the possibility that if more than one drop is being sampled at a time, the disdrometer counts this drop as one big drop rather than many smaller drops. Watching the disdrometer during a precipitation event could provide some insight on if these sources of error are present with the PWS100 disdrometer.

Appendix

*Recall with the diameters below, the disdrometer actually records the middle point of the bin, for example, Drop size recorded= Diameter + (0.5*Width).

Table A.1: OTT 32 x 32 Bin Size and Widths

Bin	Diameter (mm)	Width (mm)	Speed (ms⁻¹)	Width (ms⁻¹)
1	0.0	0.125	0.0	0.1
2	0.125	0.125	0.1	0.1
3	0.25	0.125	0.2	0.1
4	0.375	0.125	0.3	0.1
5	0.5	0.125	0.4	0.1
6	0.625	0.125	0.5	0.1
7	0.75	0.125	0.6	0.1
8	0.875	0.125	0.7	0.1
9	1.0	0.125	0.8	0.1
10	1.125	0.125	0.9	0.1
11	1.250	0.25	1.0	0.2
12	1.5	0.25	1.2	0.2
13	1.75	0.25	1.4	0.2
14	2.0	0.25	1.6	0.2
15	2.25	0.25	1.8	0.2
16	2.5	0.5	2.0	0.4
17	3.0	0.5	2.4	0.4
18	3.5	0.5	2.8	0.4
19	4.0	0.5	3.2	0.4
20	4.5	0.5	3.6	0.4
21	5.0	1.0	4.0	0.8
22	6.0	1.0	4.8	0.8
23	7.0	1.0	5.6	0.8
24	8.0	1.0	6.4	0.8
25	9.0	1.0	7.2	0.8
26	10.0	2.0	8.0	1.6
27	12.0	2.0	9.6	1.6
28	14.0	2.0	11.2	1.6
29	16.0	2.0	12.8	1.6
30	18.0	2.0	14.4	1.6
31	20.0	3.0	16.0	3.2
32	23.0	3.0	19.2	3.2

Table A.2: PWS 20 x 20 Bin Size and Widths

Bin	Diameter (mm)	Width (mm)	Speed (ms⁻¹)	Width (ms⁻¹)
1	0.0	0.24	0.0	0.2
2	0.24	0.12	0.2	0.2
3	0.36	0.14	0.4	0.2
4	0.50	0.25	0.6	0.2
5	0.75	0.25	0.8	0.2
6	1.00	0.25	1.0	0.4
7	1.25	0.25	1.4	0.4
8	1.5	0.25	1.8	0.4
9	1.75	0.25	2.2	0.4
10	2.00	0.50	2.6	0.4
11	2.50	0.50	3.0	0.4
12	3.00	0.50	3.4	0.8
13	3.50	0.50	4.2	0.8
14	4.00	0.50	5.0	0.8
15	4.50	0.50	5.8	0.8
16	5.00	0.50	6.6	0.8
17	5.50	0.50	7.4	0.8
18	6.00	0.50	8.2	0.8
19	6.50	0.50	9.0	1.0
20	7.00	93.00	10.0	90.0

Table A.3: PWS 32 x 32 Bin Size and Widths

Bin	Diameter (mm)	Width (mm)	Speed (ms⁻¹)	Width (ms⁻¹)
1	0.60	0.12	0.05	0.1
2	0.180	0.12	0.15	0.1
3	0.30	0.12	0.25	0.1
4	0.42	0.12	0.35	0.1
5	0.54	0.12	0.45	0.1
6	0.665	0.13	0.55	0.1
7	0.795	0.13	0.65	0.1
8	0.925	0.13	0.75	0.1
9	1.055	0.13	0.85	0.15
10	1.185	0.13	0.95	0.1
11	1.375	0.25	1.10	0.2
12	1.625	0.25	1.30	0.2
13	1.875	0.25	1.50	0.2
14	2.125	0.25	1.70	0.2
15	2.375	0.25	1.90	0.2
16	2.75	0.50	2.20	0.4
17	3.25	0.50	2.60	0.4
18	3.75	0.50	3.00	0.4
19	4.25	0.50	3.40	0.4
20	4.75	0.50	3.80	0.4
21	5.5	1.00	4.40	0.8
22	6.5	1.00	5.20	0.8
23	7.5	1.00	6.00	0.8
24	8.5	1.00	6.80	0.8
25	9.5	1.50	7.60	0.8
26	11.0	2.00	8.80	1.6
27	13.0	2.00	10.40	1.6
28	15.0	2.00	12.00	1.6
29	17.0	2.00	1.60	1.6
30	19.0	2.50	15.20	1.6
31	21.5	1.50	17.60	3.2
32	23.0	77.00	19.20	80.8

Table A.4: PWS 34 x 34 Bin Size and Widths

Bin	Diameter (mm)	Width (mm)	Speed (ms⁻¹)	Width (ms⁻¹)
1	0.0	0.1	0.0	0.1
2	0.1	0.1	0.1	0.1
3	0.2	0.1	0.2	0.1
4	0.3	0.1	0.3	0.1
5	0.4	0.1	0.4	0.1
6	0.5	0.1	0.5	0.1
7	0.6	0.1	0.6	0.1
8	0.7	0.1	0.7	0.1
9	0.8	0.1	0.8	0.1
10	0.9	0.1	0.9	0.1
11	1.0	0.2	1.0	0.2
12	1.20	0.2	1.2	0.2
13	1.40	0.2	1.4	0.2
14	1.60	0.2	1.6	0.2
15	1.80	0.2	1.8	0.2
16	2.0	0.4	2.0	0.4
17	2.40	0.4	2.40	0.4
18	2.80	0.4	2.80	0.4
19	3.20	0.4	3.20	0.4
20	3.60	0.4	3.60	0.4
21	4.0	0.8	4.0	0.8
22	4.80	0.8	4.80	0.8
23	5.60	0.8	5.60	0.8
24	6.40	0.8	6.40	0.8
25	7.20	0.8	7.20	0.8
26	8.0	1.6	8.0	1.6
27	9.60	1.6	9.60	1.6
28	11.20	1.6	11.20	1.6
29	12.80	1.6	12.80	1.6
30	14.40	1.6	14.40	1.6
31	16.00	3.2	16.00	3.2
32	19.20	3.2	19.20	3.2
33	22.40	3.2	22.40	3.2
34	25.60	74.4	25.60	74.4

Automated Code Used for the OTT

```
%version 6 Feb 2016
%This program is designed to use data from an OTT Parsival disdrometer
%raw drop counts are taken and:
    %concentration calculated
    %individual bin contributions found for rainrate, reflectivity,
    %kinetic energy (tried to add a robust zdr)
    %total bin contributions summed for r, z, ke
    %fits gamma distribution to drop concentrartions
    %calculates r, z, ke from fitted distribution
    %Writes out selected data to an excel data file
%version using prepared dsds
%DSDs are prepared by importing raw data into matlab
%then simply sum the columns to get total drop counts for each bin(this
removes
%observed terminal velocity data)
%this code is designed to work for a entire data directory time period
%first two columns and lasr few removed to give 24 columns of drop
counts starting with 0.31mm up to 11mm

%Read in .mis files and reformat to 32x32 array
% sum columns to get total drop counts in each size bin

% CONVERT TO CONCENTRATIONS IN m-3 USING OTT SAMPLE VOLUME

% If previously prepared dsds.mat file
%load dsds

datadir = 'E:\Thesis OTT Days\2013\may27\1650-2030';
datadir2 = dir(datadir);

%Loop designed to run program for entire directory selected above
for j = 3:length(datadir2);

dsd1=dlmread(datadir2(j).name, ';');
dsdv1=reshape(dsd1,32,32);
dsds=sum(dsdv1');

%Removes last 3 bins
dsds=dsds([1:29]);
%time interval in seconds
t=600;
%Names excel data output as last file in directory
fname=regexprep(datadir2(j).name, '.txt', '');
fname1=regexprep(fname, fname(1:9), '');

% bin mean diameter
d=[0.3125 0.4375 0.5625 0.6875 0.8125 0.9375 1.0625 1.1875 1.375 1.625
1.875 2.125 2.375 2.750 3.250 3.750 4.250 4.750 5.5 6.5 7.5 8.5 9.5 11
13 15];
binwidth=[0.125 0.125 0.125 0.125 0.125 0.125 0.125 0.125 0.25 0.25
0.25 0.25 0.25 0.5 0.5 0.5 0.5 0.5 1 1 1 1 1 2 2 2];
```

```

%Gunn and Kinzer
gsv=9.4*(1-exp(-1.57*d.^1.15));

%sample volume varies by bin: multiply disdrometer beam area by fall
speed
%and observation time interval
svol=gsv*0.0054*t;

%using prepared dsds
% set up arrays to fill with calculated parameter values

[m n]=size(dsds);
c=[4:n];
rawtot=zeros(m,n-3); % raw bin counts
tot=zeros(m,n-3); % raw bin concentration in m^-3
ntot=zeros(m,n-3); %bin concentration normalized for bin width in m^-3
mm^-1
z=zeros(m,n-3); % bin contributions to reflectivity
ztot=zeros(1,m); % reflectivity sum
dbz=zeros(1,m); % reflectivity in dBZ
zrain=zeros(1,m); %rainrate calculated from summed reflectivity
r=zeros(m,n-3); %bin contributions to rainrate
k=zeros(m,n-3); %bin contributions to ke
ke=zeros(1,m); %total ke
k3=zeros(m,n-3); % bin contributions to ke flux
ke3=zeros(1,m); %ke flux total
rain=zeros(1,m); % rainrate total
x=zeros(1,n-3);

ng=zeros(m,n-3); %integer bin conc. (rounding up)
nt=zeros(m,n-3); %integer bin conc. (rounding down)
a=zeros(m,2); %gamma fit parameter set
mu=zeros(1,m); %gamma fit mu values
mu1=zeros(1,m); %gamma fit mu-1 values
lamda=zeros(1,m); %gamma fit lamda values
lam1=zeros(1,m); %gamma fit 1/lamda
nd=zeros(m,n-3); %calculated drop conc.
n0=zeros(1,m); % n0 for gamma fit
r0=zeros(1,m); %rainrate from gamma fit
ke0=zeros(1,m); %ke from gamma fit
z0=zeros(1,m); %reflectivity from gamma fit

mu2=zeros(1,m); % sparse gamma fit mu-1 values
mu11=zeros(1,m);
lamda2=zeros(1,m);
lam2=zeros(1,m); % sparse gamma fit 1/lamda
nd2=zeros(m,n-3); %drop conc. from sparse gamma fit
n2=zeros(1,m); %n0 for sparse gamma fit
r2=zeros(1,m); %rainrate from sparse gamma fit
ke2=zeros(1,m); %KE from sparse gamma fit
z2=zeros(1,m); %reflectivity from sparse gamma fit

zdr=zeros(m,n-3); % bin contributions to zdr

```

```

zdrtot=zeros(1,m); % zdr sum
zdrdb=zeros(1,m); % zdr in dB
zv=zeros(1,m);% vertical reflectivity from gamma fit
zdr0=zeros(1,m);%zdr from gamma fit
zdrdb0=zeros(1,m);%zdr in dB from gamma fit

d50=zeros(1,m); %median drop diameter by summation

%Effort to calculate Zdr%
vd=[0.3125 0.4375 0.5625 0.6875 0.8125 0.9375 1.0257 1.1376 1.3021
1.516 1.722 1.922 2.116 2.395 2.746 2.762 3.379 3.664 4.055 4.512 0 0 0
0 0 0];
zdr1db=zeros(1,m);
zdr1=zeros(1,m);
zh1tot=zeros(1,m);
zv1tot=zeros(1,m);

%Now does the calculations for entire directory
for i=1:m

rawtot(i,:)=dsds(i,c);

tot(i,:)=rawtot(i,:) ./svol;
ntot(i,:)=tot(i,:) ./(binwidth);

z(i,:)=tot(i,:) .*d .^6;
ztot(i)=sum(z(i,:));
dbz(i)=10*log10(ztot(i));
zrain(i)=(ztot(i)/300)^(1/1.4);

zh1(i,:)=(tot(i,:) .*d .^6);
zv1(i,:)=(tot(i,:) .*vd.^6);
zh1tot(i)= sum(zh1(i,:));
zv1tot(i)= sum(zv1(i,:));
zdr1(i)=zh1tot(i)/zv1tot(i);
zdr1db(i)=10*log10(zdr1(i));

%calculate rainfall rate mm/hr
%convert drop size in mm to radius in m (/2000)
%convert back to mm (*1000)
%convert per s rate to per hr (*3600)
d50(i)=((sum(tot(i,:) .* (d .^3)))/(2*sum(tot(i,:))))^(1/3);
r(i,:)=3600*1000*(4/3)*pi*tot(i,:) .* (d/2000) .^3 .*gsv;

rain(i)=sum(r(i,:));

k(i,:)=0.5*1000*(4/3)*pi*tot(i,:) .* ((d/2000) .^3) .* (gsv .^2);
ke(i)=sum(k(i,:));
k3(i,:)=0.5*1000*(4/3)*pi*tot(i,:) .* ((d/2000) .^3) .* (gsv .^3);
ke3(i)=sum(k3(i,:));
ng(i,:)=ceil(ntot(i,:)); %fitting function only works with integers
%nt(i,:)=floor(tot(i,:));

```

```

%find the gamma distribution parameters
%gamma in dsd equations of the form  $n(d)=n_0*d^{\mu}*e^{(-\lambda*d)}$ 
%but the fit gives  $\mu-1$  and  $1/\lambda$ 
a(i,:)=gamfit(d,0.01,x,ng(i,:));
mu1(i)=a(i,1);
lam(i)=a(i,2);
mu(i)=a(i,1)-1;
lamda(i)=1/a(i,2);

% fit does not provide value of  $n_0$ 
%find the drop concentration per mm for the fit
n0(i)=sum(tot(i,:))*lamda(i)^(mu(i)+1)/gamma(mu(i)+1);
nd(i,:)=n0(i)*d.^mu(i).*exp(-1*lamda(i).*d);

%find the rainfall rate and kinetic energy using the Ulbrich drop
velocity
%formula
r0(i)=n0(i)*(pi*3.778/6)*gamma(4.67+mu(i))/(lamda(i)^(4.67+mu(i)))*3600
/1000000; %volume is in mm^3, need m3 = 10^-9mm3
ke0(i)=n0(i)*(pi*(3.778^3)/12)*gamma(6+mu(i))/(lamda(i)^(6+mu(i)))*10000
00; %volume is in mm^3, need density = 10^-6 kg/mm^3
z0(i)=10*log10((n0(i)*gamma(7+mu(i)))/(lamda(i)^(7+mu(i))));

% gamfit weights all points equally
%as there are more bins at small diameters the fit works better for
%concentrations of small drops, but z and ke depend on getting large
drops
%right. so select evenly spaced bins to make the fit
p=[2 5 9 11 13 14 15 16 17 18 19];
a2(i,:)=gamfit(d(p),0.01,x(p),ng(i,p));

mu2(i)=a2(i,1)-1;
lamda2(i)=1/a2(i,2);

n2(i)=sum(tot(i,:))*lamda2(i)^(mu2(i)+1)/gamma(mu2(i)+1);
nd2(i,:)=n2(i)*d.^mu2(i).*exp(-1*lamda2(i).*d);
r2(i)=n2(i)*(pi*3.778/6)*gamma(4.67+mu2(i))/(lamda2(i)^(4.67+mu2(i)))*3
600/1000000; %volume is in mm^3, need m3 = 10^-9mm3
ke2(i)=n2(i)*(pi*(3.778^3)/12)*gamma(6+mu2(i))/(lamda2(i)^(6+mu2(i)))*10
00000; %volume is in mm^3, need density = 10^-6 kg/mm^3
z2(i)=10*log10((n2(i)*gamma(7+mu2(i)))/(lamda2(i)^(7+mu2(i))));

%Creates a figure for the graph of drop concentrations and
%automatically saves the figure as the file name from which
%the data came from
figure
plot(d,nd(i,:))
axis([0 6 0 max(nd(i,:))*1.1])
hold;
plot(d,nd2(i,:), 'g')
plot(d,ntot(i,:), 'xr')
xlabel('Drop diameter (mm)'),ylabel('Drop concentration (m^-3 mm^-1)')
legend('Full Fit','Part Fit','Raw',0)
saveas(gcf,fname,'png')

```

```

end

%grabs time from each file name to be an output to the excel file
time=str2num(fname1);
time=double(time);
results(j-2,:)= [time' n0' dbz' zdr1db' mu' lam' rain' zrain' r0' ke2'
ke0' ke3' z0' r2' d50'];
end
%prepares the excel file with headers
xlsfilename = regexprep(datadir2(j).name, '.txt', '');
xlsfilename = [xlsfilename, '.xls'];
xlswrite(xlsfilename, cellstr('time'), 'sheet1', 'b1');
xlswrite(xlsfilename, cellstr('n0'), 'sheet1', 'c1');
xlswrite(xlsfilename, cellstr('dbz'), 'sheet1', 'd1');
xlswrite(xlsfilename, cellstr('zdr1db'), 'sheet1', 'e1');
xlswrite(xlsfilename, cellstr('mu'), 'sheet1', 'f1');
xlswrite(xlsfilename, cellstr('lam'), 'sheet1', 'g1');
xlswrite(xlsfilename, cellstr('rain'), 'sheet1', 'h1');
xlswrite(xlsfilename, cellstr('zrain'), 'sheet1', 'i1');
xlswrite(xlsfilename, cellstr('r0'), 'sheet1', 'j1');
xlswrite(xlsfilename, cellstr('ke2'), 'sheet1', 'k1');
xlswrite(xlsfilename, cellstr('ke0'), 'sheet1', 'l1');
xlswrite(xlsfilename, cellstr('ke3'), 'sheet1', 'm1');
xlswrite(xlsfilename, cellstr('z0'), 'sheet1', 'n1');
xlswrite(xlsfilename, cellstr('r2'), 'sheet1', 'o1');
xlswrite(xlsfilename, cellstr('d50'), 'sheet1', 'p1');
%Writes the chosen data from the results variable to the excel file
xlswrite(xlsfilename, results, 'sheet1', 'b2');

```


Automated Code Used for the PWS100

This code is the same as the code used for the OTT, except the portion that is listed below (and the bin sizes). This is due to the way that the data is ingested into MatLab from the data files. OTT data comes from .MIS files, whereas PWS100 data comes from an excel spreadsheet. Below is the beginning portion of the code where the excel data file was loaded in, and oriented to match the OTT disdrometer data layout. Adding together ten one-minute data rows on MatLab from excel retrieves the 10-minute data samples. Adding together all individual bin columns to retrieve the 32 x 32 (or 34 x 34) matrix array to then be analyzed in the same format as the OTT disdrometer.

```
dsdall=xlsread('Midway_2017.csv','E5:ARP1444');

%Names new output excel file for calculations to be appended to
xlsfilename='test_34x34';

countyrow=1:10:1441;
countycol=1:34:1157;

%Sums up columns and rows to create a 32 x 32 x 10 matrix for 32 sizes
and velocities at 10-minute intervals

for row = 1:length(countyrow)-1

    countyrow2(row,:) = countyrow(row):countyrow(row+1)-1;

end

for col = 1:length(countycol)-1

    countycol2(col,:) = countycol(col):countycol(col+1)-1;

end

for col2 = 1:length(countycol2)

    for col3 = 1:1440

        sumcol(col3,col2) =
sum(dsdall(col3,countycol2(col2,1):countycol2(col2,34)));

    end

end

for rowf = 1:length(countyrow2)-1

    for colf =11:25
```

```
        sum_final(rowf,colf) =  
sum(sumcol(countyrow2(rowf,1):countyrow2(rowf+1)-1,colf));  
  
    end  
  
end  
  
dsd1 = sum_final;  
dsds=dsd1;
```

Code for Radar Data Retrieval and Analysis in MatLab

```
%Load in ZDR%
%For multiple times%

%Zdr
path='D:\Wendt_Data\20170301\ZdrAtLowestAltitude\00.00';
%Z
path2='D:\Wendt_Data\20170301\ReflectivityAtLowestAltitude\00.00';

filenames = dir([path, '/*.netcdf']);
filenames2=dir([path2, '/*.netcdf']);

for c=3:length(filenames); %looping through all time steps in the
directory

    disp(['Reading file Zdr ', filenames(c,1).name])
    %Loading and naming variable zdr
    filepathandname = [path, '/', filenames(c,1).name];
    ncid = netcdf.open(filepathandname, 'NC_NOWRITE');
    [varname, xtype, varDimIDs, varAtts] = netcdf.inqVar(ncid,0);
    varid = netcdf.inqVarID(ncid,varname);
    zdr=netcdf.getVar(ncid,varid);

    disp(['Reading file Z ', filenames2(c,1).name])
    %Loading and naming variable z
    filepathandname2 = [path2, '/', filenames2(c,1).name];
    ncid2 = netcdf.open(filepathandname2, 'NC_NOWRITE');
    [varname2, xtype, varDimIDs, varAtts] = netcdf.inqVar(ncid2,0);
    varid2 = netcdf.inqVarID(ncid2,varname2);
    z=netcdf.getVar(ncid2,varid2);
    %Gather data from files for lat and long
    global_att_name =
    netcdf.inqAttName(ncid,netcdf.getConstant('NC_GLOBAL'),2);
    global_att_value =
    netcdf.getAtt(ncid,netcdf.getConstant('NC_GLOBAL'),global_att_name);
    latitude=global_att_value;
    global_att_name =
    netcdf.inqAttName(ncid,netcdf.getConstant('NC_GLOBAL'),3);
    global_att_value =
    netcdf.getAtt(ncid,netcdf.getConstant('NC_GLOBAL'),global_att_name);
    longitude=abs(global_att_value);
    global_att_name =
    netcdf.inqAttName(ncid,netcdf.getConstant('NC_GLOBAL'),12);
    global_att_value =
    netcdf.getAtt(ncid,netcdf.getConstant('NC_GLOBAL'),global_att_name);
    latspace=global_att_value;
    global_att_name =
    netcdf.inqAttName(ncid,netcdf.getConstant('NC_GLOBAL'),13);
    global_att_value =
    netcdf.getAtt(ncid,netcdf.getConstant('NC_GLOBAL'),global_att_name);
    longspace=global_att_value;

    [m n]=size(zdr);
```

```

%Choose the latitude
i=floor((latitude-38.993437)/latspace);
%Choose longitude
j=floor((longitude-92.482305)/longspace);

%%Do Expresses median drop diameter%%

%%Units in dB for Zdr. mu-values%%

%Now set i and j to the lat and long respectively of the Disdrometer at
Midway

Do(c)=0.171*((zdr(i,j))^3)-0.725*((zdr(i,j))^2)+1.479*zdr(i,j)+0.717;
    if Do(c)<0;
        Do(c)=nan;
    end
    mu(c)=6.084*((Do(c))^2)-29.85*Do(c)+34.64;
    lamda(c)=(3.67+mu(c))/Do(c);

z(c) = z(i,j);
zdr(c) = zdr(i,j);

%Extracts the time from the file to be placed on Excel with Results
time=regexprep(filenamees(c).name, '.netcdf', '');
timefinal=regexprep(time,time(1:9), '');

resultstime(c,:) = [str2num(timefinal)'];

results(c,:)=[Do(c)' z(c)' zdr(c)' mu(c)' lamda(c)'];
end

xlsfilename='20170301_MZZU1KM.xls';
xlswrite(xlsfilename,cellstr('time(UTC,hr,min,s)'), 'sheet1', 'a1');
xlswrite(xlsfilename,cellstr('Do'), 'sheet1', 'b1');
xlswrite(xlsfilename,cellstr('z'), 'sheet1', 'c1');
xlswrite(xlsfilename,cellstr('zdr'), 'sheet1', 'd1');
xlswrite(xlsfilename,cellstr('mu'), 'sheet1', 'e1');
xlswrite(xlsfilename,cellstr('lamda'), 'sheet1', 'f1');
xlswrite(xlsfilename,resultstime, 'sheet1', 'a2');
xlswrite(xlsfilename,results, 'sheet1', 'b2');

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References

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