On the Retrieval of Drop Size Distribution
by Vertically Pointing Radar

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Abstract

Three different algorithms of drop size distribution (DSD) retrieval by vertically pointing radar (i.e. profiler) have been simulated utilizing Joss-Waldvogel disdrometer (JWD) measurements. The disdrometer data used in this study was collected during NASA Tropical Rainfall Measuring Mission (TRMM) field campaign in Amazon basin of Brazil. The retrieval algorithm that utilizes three-parameter gamma distribution had the best outcome, however, a numerical solution was not granted for the 10% of observations. The gamma distribution requires the knowledge of all three measurements of the profiler. Algorithms that utilize two-parameter exponential distribution employ spectral width and reflectivity or Doppler velocity and reflectivity measurements. The former pair resulted in the least accurate, while a bias in derived rain parameters was evident at high rain rates when the latter pair is used. Since the profiler parameters are calculated from disdrometer DSD measurements, the broadening of the Doppler spectra by turbulence and vertical air motions have not been taken into account. In addition, the sample volume of the JWD is smaller than that of profiler. These issues have been discussed by comparing difference in disdrometer and collocated dual wavelength profiler measurements of reflectivity, Doppler velocity, and spectral width. Despite time-height ambiguity and other physical differences, a good agreement is found between profiler and disdrometer measurements even at high rain rates. Moreover, a comparison of time series of reflectivity from disdrometer and profiler observations reveals that 2835 MHz profiler observations had a better agreement with the disdrometer observations than the 915 MHz profiler observations. This is because 2835 MHz profiler is more sensitive to the precipitating hydrometeors. In addition, the lowest two gates of the 2835 MHz profiler has been corrupted, therefore, the study suggests to employ 2835 MHz profiler's third lowest gate and above to retrieve DSD and related integral rain parameters.

1. Introduction

Knowledge of drop size distribution (DSD) is important in meteorology, hydrology, and other related sciences. Most important to this paper is the application of DSD to the physics of rain process. Integral rain parameters that are associated with clouds and rainfall are based upon DSD and its moments (Sauvageot and Lacaux 1995). Radar rainfall estimation, for instance, seeks a relationship between the measured reflectivity (Z) and the estimated rainfall (R). The characteristics of DSD, which are important for cloud physics studies, are subject to variation depending upon the precipitation type for a climatological region and can be derived from long term observations of DSD by a disdrometer.

The applications of DSD mentioned above are essential for NASA Tropical Rainfall Measuring Mission (TRMM) program. The primary objective of the TRMM program is to increase the extent and accuracy of tropical rainfall measurement, where two thirds of the global precipitation falls. The TRMM satellite has five sensors, three of which are directly related to rainfall measurements. It has an inclination of 35° and covers the tropical belt at which the oceans have 70% coverage. Among its sensor, TRMM precipitation radar swaps about 220 km wide array with horizontal resolution of 4.3 x 4.3 km, and vertical resolution of 250 m. The precipitation radar operates at 2.17 cm wavelength where attenuation (K) is severe. Attenuation is a function of DSD and precipitation radar seeks relationship between attenuation and radar reflectivity for the attenuation correction. To accomplish this task, long term observations of DSD measurements are required at various sites around the tropics where the rainfall has different characteristics. Figure 1 shows the monthly precipitation climatology of six locations around the world, four of which lie within ten degrees latitude of the equator. Obvious are the seasonal variations and large amounts of rainfall associated with most of these sites located in the tropics

The TRMM Ground Validation Program (TRMM-GV) focuses on developing validation methods and obtaining the necessary state-of-the-art surface-based observations of rainfall. The TRMM-GV established ten sites all across the world, each corresponding to a different climatic region in addition to five field campaigns were conducted in a year and a half starting March 1998. This study uses the DSD observations collected during the field campaign in the Amazon basin of Brazil during the months of January and February, 1999. The DSD measurements were collected primary by the Joss-Waldvogel disdrometer (JWD) and also by two-dimensional video disdrometer (2DVD). In addition, measurements of f tipping bucket rain gauges and of dual wavelength (915 MHz and 2835 MHz) vertically pointed radar (i.e. profiler) were also used. All these instrument were collocated.

The JWD operated continuously for 45 days starting on January 17, 1999. The 2DVD was under non-continuous operation for 17 days starting January 22 and ending February 23, and the profiler operated continuously during the same period as the JWD. The JWD collected 292 mm of rainfall in 79 rainy hours. During the 45 days in which the JWD operated, Brazil experienced both easterly and westerly regimes of rain. The westerly regime can be characterized as monsoon-like rain, while the easterly represents break periods with short but intense rain. Rainfall associated with dual wind regimes has been previously observed in Darwin, Australia, which experiences much of the same characteristics as Brazil. For example, in 1994 a shift in wind direction occurred between February 12 and 15 producing a switch from the break season to the monsoon season. Regarding DSD, more large drops are observed in break periods than monsoon periods.

The primary goal of this study is to broaden our knowledge on the retrieval of DSD measurements from vertically pointing radar. Section 2 will describe the general characteristics of DSD. Section 3 discusses the six integral rainfall parameters and expresses them mathematically. Section 4 describes in detail two particular case studies that were extracted from the 45 days of the field campaign. Section 5 is the main part of the paper. This section includes histograms of six integral rainfall parameters from section 4, graphs of three scenarios used for DSD retrieval, and one-to-one relationship scatter diagrams of the observed versus retrieved values from the disdrometer for the rain rate, liquid water content, and mass weighted drop diameter. Section 6 describes some assumptions that were made in the study and factors that must be taken into account. Section 7 is the summary and conclusions, which highlights the most important points from the paper. Finally, Section 8 briefly describes where this study is headed in the future.

2. Drop Size Distribution

DSD can be parameterized using three different distributions, the exponential, gamma, log normal. The exponential distribution has two parameters (N_0 and Λ) and can be given by

$$N(D) = N_o\, e^{-\Lambda D} \qquad (D_{min} \leq D \leq D_{max}) \tag{1}$$

where N(D)dD is the number concentration of drops between diameters D and D+dD, N_o is the intercept parameter in $m^{-3}mm^{-1}$, D is the drop diameter in mm, and Λ is the slope parameter in mm^{-1}. The Marshall Palmer (1948) distribution is a special form of the exponential distribution with a fixed N_0 and Λ is a function of the rain rate. More specifically,

$$N_o = 8000\ m^{-3}mm^{-1}$$

and $\Lambda = 4.1R^{-0.21}\ mm^{-1}$

where R is the rainfall rate in mmh^{-1}. The gamma distribution takes the form of

$$N(D) = N_o\, D^m\, e^{-\Lambda D} \qquad (D_{min} \leq D \leq D_{max}) \tag{2}$$

where m is the shape parameter. In the gamma distribution, when m is equal to zero, the function becomes exponential. The final distribution that can be applied is the log normal distribution which is a three parameter alternative to the gamma distribution, however, this distribution tends to give the same results as the gamma distribution.

In this study the exponential and gamma distributions have been employed. Figures 2 and 3 demonstrate varieties in the characteristics of two-parameter exponential distribution. Figure 2a has Λ constant at 2 mm^{-1} and Figure 2b has N_0 kept constant at 1000 $m^{-3}mm^{-1}$. The percentage values given correspond to the contribution of the small (D≤1mm), medium (1mm≤D≤3mm), and large drops (D≥3mm) to the particular integral parameter at the given condition. The integral rain parameters presented here are liquid water content, rain rate, and radar reflectivity. The dependence of the integral rain parameters to DSD is shown in the following section.

Figure 2a shows that as N_0 increases, the number of drops, in all sizes, increases while the contribution of small, medium, and large drops to the integral parameters remains the same. As the slope increases, the number of drops decreases which results in a decrease in the integral rain parameters (Figure 2b). The decrease in the integral rain parameters is largely due to the decrease in large drops. For example, as Λ is increased from 1 to 2 mm^{-1} the contribution of large drops decreases for reflectivity from 96% to 59%, for rain rate from 65% to 20%, and for liquid water content from 58% to 15%. This corresponds to a sharp decrease in reflectivity (17 dBZ), rain rate (71 mm hr^{-1}), and the liquid water content (2.5 gm^{-3}).

Figure 3a-c shows the same sort of scenarios at which reflectivity, rain rate, and liquid water content were held constant. In Figure 3a, the reflectivity was 30dBZ. From this graph it can be concluded that a DSD with more small drops and less large drops gives a higher liquid water content and rain rate than a DSD with less small drops and more large drops. Figure 3b shows that when fixing the rain rate to 10 $mmhr^{-1}$ a DSD with more small drops and less large drops gives a higher liquid water cotent but lower reflectivity than a DSD with less small drops and more large drops. Figure 3c shows that a DSD with more small drops and less large drops gives a lower rain rate and reflectivity than a DSD with less small drops and more large drops. Also, in all three graphs a DSD with less small drops and more large drops gives smaller N_0 and Λ values than a DSD with more small drops and less large drops. A similar exercise would be repeated for gamma DSD, however, it is relatively more complicated with the involvement of shape parameter.

3. Integral Rainfall Parameters

The purpose of this study is to examine the retrieval of DSD of profiler observations and derive rainfall parameters. Of particular interest, the rainfall parameters are liquid water content, rainfall rate, and mass weighted drop diameter. The profiler observables, on the other hand, are Doppler velocity, spectral width, and reflectivity. The DSD is approximated by the gamma distribution with the assumption that the minimum drop diameter is zero and the maximum drop diameter is infinity. Out of these six parameters, rain rate, mean Doppler fall speed and spectral width require the knowledge of drop fall velocity. The fall speed of raindrops is given as (Atlas et al. 1973)

$$V_t = 9.65 - 10.3\exp(-0.6D)$$

Mean Doppler velocity (ms^{-1}) is a function of Λ and m and can be expressed by

$$V_d = V_z + w = \frac{\int_{D\min}^{D\max} V_t D^6 N(D)dD}{\int_{D\min}^{D\max} D^6 N(D)dD} + w$$

$$\frac{\int_0^\infty (9.65 - 10.30e^{-0.6D})D^6 N_0 D^m e^{-\Lambda D} dD}{\int_0^\infty D^6 N_0 D^m e^{-\Lambda D} dD} + w = 9.65 - 10.30\left(\frac{\Lambda}{\Lambda + 0.6}\right)^{m+7} + w$$

(3)

Spectral width (m s^{-1}) is also a function of Λ and m and it can be given by

$$\sigma_w = \left(\langle V_d^2 \rangle - \langle V_d \rangle^2 \right)^{\frac{1}{2}}$$

$$= \left[\left(\frac{\int_{D\min}^{D\max} V_t^2 D^6 N(D)dD}{\int_{D\min}^{D\max} D^6 N(D)dD} \right) - \left(\frac{\int_{D\min}^{D\max} V_t D^6 N(D)dD}{\int_{D\min}^{D\max} D^6 N(D)dD} \right)^2 \right]^{\frac{1}{2}}$$

$$= \left[\left(\frac{\int_0^\infty V_t^2 D^6 N_0 D^m e^{-\Lambda D} dD}{\int_0^\infty D^6 N_0 D^m e^{-\Lambda D} dD} \right) - \left(\frac{\int_0^\infty V_t D^6 N_0 D^m e^{-\Lambda D} dD}{\int_0^\infty D^6 N_0 D^m e^{-\Lambda D} dD} \right)^2 \right]^{\frac{1}{2}}$$

$$= 10.3 \left[\left(\frac{\Lambda}{\Lambda + 1.2} \right)^{7+m} - \left(\frac{\Lambda}{\Lambda + 0.6} \right)^{2m+14} \right]^{\frac{1}{2}}$$

(4)

Reflectivity (dBZ) is a function of three parameters (Λ, m, and N_o) and is given by

$$Z = \int_{D\min}^{D\max} D^6 N(D)dD \quad \int_0^\infty N_0 D^6 D^m e^{-\Lambda D} dD = N_0 \frac{\Gamma(m+7)}{\Lambda^{m+7}}$$

(5)

The liquid water content (gm^{-3}) is a function of Λ, m, and N_0 and is defined as

$$M = \rho_w \frac{\pi}{6} 10^{-3} \int_{D\min}^{D\max} D^3 N(D) dD \quad \rho_w \frac{\pi}{6} 10^{-3} \int_0^{\infty} D^3 N_0 D^m e^{-\Lambda D} dD = \rho_w \frac{\pi}{6} 10^{-3} N_0 \frac{\Gamma(m+4)}{\Lambda^{m+4}} \tag{6}$$

The rain rate (mmh^{-1}) is also function of of Λ, m, and N_0 and is defined as

$$R = 6\pi 10^{-4} \int_{D\min}^{D\max} V_t D^3 N(D) dD \quad 6\pi 10^{-4} \int_0^{\infty} \left(9.65 - 10.3 e^{-0.6D}\right) D^3 N_0 D^m e^{-\Lambda D} dD$$

$$= 6\pi 10^{-4} N_0 \left[9.65 \left(\frac{\Gamma(4+m)}{\Lambda^{4+m}} \right) - 10.3 \left(\frac{\Gamma(4+m)}{(\Lambda + .6)^{4+m}} \right) \right] \tag{7}$$

The mass weighted drop diameter (mm) is a function of Λ and m and is defined as

$$D_m = \frac{\int_{D\min}^{D\max} D^4 N(D) dD}{\int_{D\min}^{D\max} D^3 N(D) dD} \quad \frac{\int_0^{\infty} D^4 N_0 D_m e^{-\Lambda D} dD}{\int_0^{\infty} D^3 N_0 e^{-\Lambda D} dD} = \frac{4+m}{\Lambda} \tag{8}$$

These six parameters can also be calculated directly from the disdrometer. In this study the parameters of exponential and gamma distributions are derived from disdrometer based mean Doppler fall speed, spectral width, and reflectivity. The liquid water content, rain rate, and mass weighted drop diameter are calculated and compared with their direct measurements by the disdrometer.

4. Case Studies

Six case studies were extracted from the 45 days of this field campaign. For each case, time series for rain rate, spectral width, mean Doppler velocity, and reflectivity were constructed, utilizing both the 2835 MHz and 915 MHz profiler, and the 2DVD and JWD. The measurements of DSD from each disdrometers are averaged to a minute. The profilers operated at two different modes with dwell time of 30 seconds. During the first dwell period the profilers observed with 105 meter pulse length up to 10 km. The lowest gate was centered at 402 m height. During the second dwell period, the 915 MHz profilers observed with 250 meter pulse length up to 18 km while the 2835 MHz profiler observed with 60 meter pulse length up to 6 km. The lowest gate was centered at 218 m for 2835 MHz profiler. In this study, the 2835 MHz profiler was primarily used. The levels of 402 and 507 meters were selected during the first thirty seconds and the levels of 258 and 318 meters for the second thirty seconds. Several scenarios for each integral parameter each day were created. However, only the scenarios from the days of February 3 and February 4 will be described in detail.

February 3 exhibited three hours of stratiform rainfall with the presence of a bright band and westerly regime characteristics. The rainfall rate reached a peak of 7.0 $mmhr^{-1}$ with the 2DVD and 6.5 $mmhr^{-1}$ with the JWD (Fig. 4a). The 2DVD measured 2.95 mm of and the JWD measured a total of 2.31 mm of rain. The collocated rain gauges had rain totals of 2.54 and 2.80 mm. From the data collected on this day, it can be deduced that the 2835 MHz profiler at 402 meters agrees the best with the two disdrometers. Figure 5 is a reflectivity time series plotting the observations from the 915 MHz profiler at 402 meters, the 2835 MHz profiler at 402 meters, the 2DVD, and the JWD. When comparing the two profilers at the same height (402 meters), the 915 MHz profiler noticeably underestimates the reflectivity. The 2835 MHz profiler is a much better representation of the observations by the two disdrometers. Figure 6 is another reflectivity time series with three profilers at different heights (258, 318, 402 meters), the 2DVD, and JWD. The 2835 MHz profiler at 258 meters does not correspond to the observations of the disdrometers. As the profilers increase in height they become better representations of the observations by the disdrometers, the 2835 MHz profiler at 402 meters being the best. Figures 4b-d show the comparison of reflectivity, Doppler velocity, and spectral width of the 2835 MHz profiler at 402 meters and 2835 MHz profiler at 507 meters. There is no evident difference between the 2835 MHz profiler at 507 meters and the two disdrometers, in fact these graphs conclude that the 2835 MHz profiler at 402 and 507 meters are in good agreement with the disdrometers for all three parameters.

February 4 was a very short convective rain event with again westerly regime characteristics. The rain rate reaches a maximum of 62.9 mm hr^{-1} for the 2DVD and 60.7 mm hr^{-1} for the JWD (Fig. 7a). During this period of heavy rain, the 2DVD measured a total rainfall of 4.78 mm and the JWD measured a total rainfall of 4.32 mm. The collocated rain gauges had rain totals of 4.83 and 5.59 mm. Much like the February 3 case, the comparison of reflectivity, Doppler velocity, and spectral width of the 2835 MHz profiler at 402 meters and 2835 MHz profiler at 507 meters shows agreement with the disdrometers (Figures 7b-d). However, the agreement is not as good as the February 3 case, this can be attributed to the convective nature of this rain event.

5. Drop Size Distribution Retrievals

This section has been divide into three subsections. The first subsection consists of histograms of integral rainfall parameters. The second describes the retrieval algorithms used in this study. Finally, the last subsection shows the test of the performance of the retrievals.

a) *Histograms*

Histograms of all six integral parameters to show the expected limits of the observed and retrieved of those parameters are shown in Figures 8 and 9. These histograms show the probability of occurrence for the parameters based on 4750 1-minute of observations collected by the disdrometer. In the presence of turbulence broadening and up and down drafts, the spectral width and mean Doppler velocity may deviate outside the boundaries specified by the histograms. The spectral width histogram range was setup to be from 0 to 2 m s^{-1} in increments of .1 m s^{-1} (Fig. 8a). The mean spectral width was 0.8 m s^{-1} and the mode was 0.9 m s^{-1}. The majority of the observations lie (> 4%) between the values of .5 and 1.2 m s^{-1}. The mean Doppler velocity histogram was setup with a range of 0 to 10 ms^{-1} in increments of .25 m s^{-1} (Fig. 8b). The mean Doppler velocity was 5.1 m s^{-1} and the mode was 4.25 m s^{-1}. Most of the observations lie (> 2%) between the values of 3 and 7.75 ms^{-1}. The reflectivity histogram was constructed with a range from 0 to 60 dBZ in increments of 2 dBZ (Fig. 8c). The mean reflectivity was 22.9 dBZ and the mode was approximately 19 dBZ. The majority of the observations lie (> 2%) between the values of 10 and 38 dBZ.

The rainfall rate histogram was constructed with a range between -9 and 21 dBR (Fig. 9a). The average rainfall rate was 6 dBR and the mode was -3 dBR. Most of the observations lie (> 2.5%) between the values of -9 and 7 dBR. The liquid water content histogram was given a range of -22 to 8 dBM with increments of 2 dBM (Fig. 9b). The average liquid water content was -7.6 dBM with a mode of -16 dBM. Most of the observations lie (> 2.5%) between the values of -20 and -2 dBM. Finally, the mass weighted drop diameter histogram was given a range of 0 to 5 mm with increments of .1 mm (Fig. 9c). The average mass weighted drop diameter was 1.19 mm with a mode of 1 mm. Most of the observations lie (> 5%) between the values of .7 and 1.4 mm.

b) *Retrieval Algorithms*

The mass weighted drop diameter is a function of m and Λ for the gamma distribution (see equation 8). By fixing m and varying Λ according to the mass weighted drop diameter observations (from .5 to 4.5 ms^{-1}), the spectral width (Fig. 10a) and the mean Doppler velocity (Fig. 10b) distributions can be calculated following equations 4 and 7. Reflectivity is a function of m, Λ, and N_0 for the gamma distribution. By fixing N_0 equal to 8000 and varying m, Λ was calculated based on the mass weighted drop diameter observations. Finally, using the reflectivity equation (5) and the value of Λ, the reflectivity distribution was calculated (Fig. 10c). Also plotted on Figures 10a-c are the 4750 1-minute of observations by the disdrometer.

Three different scenarios were used for the retrieval of DSD. The parameters of profiler observables, namely mean Doppler velocity, spectra with, and reflectivity are considered as given, while rain rate, liquid water content, and mass weighted drop diameter were derived utilizing exponential or gamma function. A flow chart of the retrieval algorithms is shown in Figure 11, while Figure 10 helps to interpret the performance of each algorithm.

First, the exponential distribution using the spectral width and reflectivity was employed (Fig. 11a). The slope parameter, Λ, was obtained from the spectral width measurements (see equation 4) and then used with reflectivity measurements to determine the intercept parameter, N_0 (see equation 5). Regarding its performance, the yellow line in Figure 10a represents the exponential distribution (where m=0) and most of the observations are far from the line (most are m≥4). This large difference gives dramatic errors. Also, the spectral width values for D_m<2 mm are highly spaced for given values of m. The relationship between the spectral width and Λ is not linear, giving 89% of the data two solutions.

The second scenario again used the exponential distribution but instead used the mean Doppler velocity and the reflectivity (Fig. 11a). Most of the points are far from the exponential line (where m=0), but for a given m, the Doppler velocity values are fairly closely spaced (Fig. 10b). Also, unlike the other exponential distribution scenario, this gives a single solution for all the data points. In general, the exponential distribution is more advantageous for retrieval because there is a solution for every distribution and it is less calculation intensive.

The final scenario took the gamma distribution with all three parameters (spectral width, Doppler velocity, and reflectivity) and was concluded to be the best scenario (Fig. 11b). The equations for spectral width (4) and mean Doppler velocity (3), each of which has two unknowns, are used to force it into a single solution. The advantage to the gamma distribution is that because of the three parameters, a better retrieval is found. However, it should be noted that for m>30 the fitting technique becomes unstable for the reflectivity equation and a retrieval cannot be made.

c) *Derived versus Observed Integral Parameters*

One to one relationships of the rain rate testing the retrieved values with those observed by the disdrometer are shown in Figures 12a-c. Figure 12a is the exponential distribution scenario with the spectral width and reflectivity. The mean absolute error and bias were calculated using the following equations

$$MAE = \left\langle \frac{\left| R_{obs} - R_{ret} \right|}{R_{obs}} \right\rangle \tag{9}$$

$$Bias = \langle R_{obs} \rangle - \langle R_{ret} \rangle \tag{10}$$

For this scenario the retrieved rain rates largely underestimated the observed rain rates. Therefore, the mean absolute error was 87% and the bias was 2.6 mmh^{-1}, both of which are too high. The case where the exponential distribution was used with the Doppler velocity and reflectivity showed that the retrieved values over estimated the observed values by the disdrometer (Fig. 12b). The reason for this over estimation is because m was forced to be equal to zero (exponential distribution). The mean absolute error and bias were more reasonable at 25% and -.88 mmh^{-1}, respectively. The bias in the scenario was rain rate dependent. For less than 1 mmh^{-1} the bias was -0.097 mmh^{-1}, from 1 to 10 mmh^{-1} the bias was -0.702 mmh^{-1}, and greater than 10 mm/hr the bias was -7.5 mmh^{-1}. The final case, where the gamma distribution was employed using all three measurements, showed a remarkable agreement between derived and observed rain rate (Fig. 12c). The mean absolute error was only 4.5% and the bias was 0.06 mm/hr. For the gamma distribution approximately 10% data points were eliminated due to m being greater than 30 where no numerical solution is available.

Similarly, one to one relationships of the liquid water content testing the retrieved values with those observed by the disdrometer were created (Figures 13a-c). Again, the exponential distribution using the spectral width and reflectivity (Figure 10a) found the retrieved values to largely underestimate the observed values by the disdrometer. The mean absolute error was 90% and the bias was 0.128 g $m-^{3}$. Using the exponential distribution with the mean Doppler velocity and reflectivity found the retrieved values to again overestimate the observed values by the disdrometer (Fig. 13b). The mean absolute error was 71% and the bias was -0.1 g $m-^{3}$. Like rain rate the bias different water content. At liquid water content less than .01 g $m-^{3}$, the bias was -0.006 g $m-^{3-}$, while the bias was -0.025 g $m-^{3}$ at a range of from .01 to 1 g $m-^{3}$. At liquid water content larger than 1 g $m-^{3}$, the bias was -0.935 g m^{-3}. The gamma, with 10% of the data points missing, showed the best outcome for liquid water content retrieval (Fig. 13c). For low values of liquid water content, observations were spread out on both sides of the 1:1 line, but for larger values of liquid water content, they seemed to have become more uniform with the 1:1 line. The mean absolute error was 8.7% and the bias was 0.005 g m^{-3}.

The final set of one to one relationships involves testing the retrieved values with those observed by the disdrometer for the mass weighted drop diameter (Figs. 14a-c). Again the exponential distribution using the spectral width and reflectivity did not show a good one to one relationship, but this time the retrieved values largely overestimated the observed values by the disdrometer (Figure 14a). The mean absolute error was 202% and the bias was -1.83 mm. The exponential distribution using mean Doppler velocity and reflectivity showed a better one to one relationship than its exponential counterpart (Fig. 11b). The retrieved values underestimated the observed values by the disdrometer. The mean absolute error was 25.6% and the bias was 0.281 mm. In this case, the bias was broken up into sections: a) $D_m < 2$ mm, b) $D_m \geq 2$ mm. The corresponding biases were 0.267 mm and 0.457 mm, respectively. The gamma distribution showed a fairly good one to one relationship, though in some cases the retrieved values were larger than the observed values (Fig. 14c). The mean absolute error was 4.9% and the bias was -0.048 mm.

6. Discussion

The retrieval algorithm that was described and tested above has its shortcomings. The profiler's mean Doppler velocity takes into account both the hydrometeor fall speed and air velocity (see equation 3). In addition, profiler's Doppler spectrum is subject to turbulence broadening. In this study, the air velocity was assumed to be zero and turbulent broadening does not taken into account. However, it should be noted that more sophisticated DSD retrieval algorithms examines the Doppler spectra itself and try to quantify the air motion component (Dr. Christopher Williams, personal communications). As a recent study, Cifelli et al. (2000) utilized 50 MHz and 915 MHz profiler observations for the retrieval process. The 50 MHz profiler is sensitive to the air motions only and therefore, the difference in two profiler's Doppler velocity was attributed to the air motion. Given these limitations of the current method, it is expected that this retrieval algorithm adequately represent the DSD in stratiform rain, while it has large error bars in convective rain.

Once the DSD is retrieved, it is important to compare the derived rain parameters at profiler's lowest reliable gate with the direct observations at the surface. In that regard, a time-space ambiguity between disdrometer and profiler measurements is present. Drops of different sizes fall at different speeds, so the sample of drops at one height may not be the same sample of drops at another height and at the surface. Also, rain falling at a height of profiler gate may change direction and not be picked up by the disdrometer at the surface, especially in a case of convective rain. Finally, profilers are vertically pointing radar in the shape of a cone, therefore, the volume sampled at one height will not be the same volume of a sample at another height. The disdrometer has much small sample volume than the profiler.

To look a little more in depth at the time-space ambiguity, the differences in mean Doppler velocity, spectral width, and reflectivity between profiler's two adjacent heights and between profiler and disdrometer measurements was constructed as a function of rain rate. The 2835 MHz profiler was used in these comparisons. Figures 15 demonstrate the mean Doppler velocity difference between profiler and disdrometer measurements, between profiler measurements at two adjacent heights. Suprisingly, the mean Doppler velocity difference is confined within ± 1 m s^{-1} regardless of rain rate. Among three comparisons, the best agreement (i.e. least difference) was obtained when profiler's mean Doppler velocity at 218 m was compared with that at 318 m resulting in an absolute mean of 0.308 m s^{-1}. Figure 16 is similar to Figure 15, but for spectral width. Again, the agreement was the best for the same pair of difference with an absolute mean of 0.120 m s^{-1}. Finally, Figure 17 presents the reflectivity difference between profiler's two heights (402 m and 507 m) and JWD for a given rain rate. It should be noted that the first two gates of profiler reflectivity were cropped due to instrument problems. As expected, the profiler reflectivity at 402 meters (Figure 17b) showed the best agreement with the JWD reflectivity with an absolute mean of 1.09 dB.

7. Summary and Conclusions

The retrieval of DSD by profiler observations has been tested utilizing the exponential and gamma distributions. To accomplish this task, the Joss-Waldvogel disdrometer data during a field campaign in the Amazon basin of Brazil was employed. The profiler observations calculated from the JWD were compared with the direct observations of 915 MHz and 2835 MHz profiler observations at their low level gates as well as with the observations calculated by the 2DVD on a case by case basis.

The conclusions of this study are as follows:

a) A comparison between the 915 MHz and 2835 MHz profilers with the JWD observations reveals that the 2835 MHz profiler agrees better with the JWD than the 915 MHz profiler. This may be due to the fact that the 915 MHz profiler is more sensitive to air motion. Therefore, 2835 MHz profiler should be employed to the retrieval algorithms.
b) A comparison of 2835 MHz profilers with the JWD at the first four layers reveals that the first two gates of the profiler reflectivity are cropped. Therefore, the third gate (402 meters) and above should be employed for retrieving algorithms.
c) A good agreement was obtained among 2835 MHz profilers observations at 402 and 507 meters, with 2DVD and JWD DSD measurements for the two cases presented in this study.
d) Using the exponential distribution through the spectral width and reflectivity. However, it was concluded that this could not be used because most of the observations were giving dramatic errors due to the distance from the line m=0, and the fact that 89% of the data had two solutions.
e) Using the exponential distribution through the Doppler velocity and reflectivity. This was a better fit than the other exponential distribution scenario because it gives only one solution and the mean Doppler velocity values are closely spaced.
f) Using the gamma distribution through all three parameters (Λ, m, N_0). This ended up being the best fit. However, some of the data points had to be eliminated because values the fitting technique becomes unstable and a retrieval cannot be made where m is greater than 30.

8. Future Research

This study is not complete due to time constraints, but plans for future research are in progress. Profiler observations will be looked at in more detail by using histograms of those observations at different heights and comparing them to the disdrometer values. Since this particular method is limited to stratiform rain, stratiform rain will be looked at in more detail by examining bright band structure. Finally, the integral rain parameters (liquid water content, rain rate, and reflectivity) will be derived from the profiler measurements and compared with the disdrometer observations, on a case by case basis and all rain events, on scatter diagrams. The relationships between integral rain parameters such as Z-R relationships for ground based radars and Ze-R and K-R relationships for TRMM precipitation radar will then be derived at the heights of profiler observations.

References:

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