P3A.2 ON THE MEASUREMENT ERRORS OF THE JOSS-WALDVOGEL DISDROMETER

Ali Tokay*[1,2], K. R. Wolff[2,3], Paul Bashor[4,5], and O. K. Dursun[6]

[1] JCET/UMBC, Baltimore, MD [3]SSAI, Lanham, MD [5]CSC, Wallops Island, VA
[2] NASA/GSFC, Greenbelt MD [4]NASA/WFF, Wallops Island, VA [6]Dept. of Meteorological Eng., ITU, Istanbul, Turkey

1. INRODUCTION

The Joss-Waldvogel disdrometer (JWD) is considered to be a reference instrument for drop size distribution (DSD) measurements. It has been commercially available for over 30 years (Joss and Waldvogel 1967) and has been widely used in many field campaigns to complement validation efforts of radar rainfall estimation. It has also been incorporated in radar rain gauge networks at several ground validation sites for NASA's Tropical Rainfall Measuring Mission (TRMM). It is anticipated that the Joss-Waldvogel disdrometer will be one of the key instruments for ground validation of the upcoming Global Precipitation Measurement (GPM) mission. The JWD is an impact type disdrometer and has several shortcomings. One such shortcoming is that it underestimates the number of small drops in heavy rain due to the disdrometer "dead time." The detection of smaller drops is also suppressed in the presence of background noise. Further, drops larger than 5.0 to 5.5 mm diameter cannot be distinguished by the disdrometer. The JWD assumes that all raindrops fall at their terminal fall speed. Ignoring the influence of vertical air motion on raindrop fall speed results in errors in determining the raindrop size. Also, the bulk descriptors of rainfall that is calculated employing the fall speed of the drops will be overestimated or underestimated due to errors in measured size and assumed fall velocity.

In support of the Microwave Link facility, a unique multi-sensor surface rain observational network has been operating at the NASA Wallops Flight Facility (WFF) since May 2000. The master site of the network is also used to test the performance of rain gauges and disdrometers. In that regard, a two-dimensional video disdrometer (2DVD), multiple Joss-Waldvogel disdrometers, two laser-optical disdrometers (Parsivel), an x-band disdrometer (Pludix), and several tipping bucket rain gauges have been tested during the past three years. The 2DVD measures size, fall velocity, and shape of individual hydrometeors (Kruger and Krajewski 2001), while the measured size and fall velocity of the hydrometeors are given in a matrix form of 32 size and velocity intervals in the Parsivel (Löeffler-Mang and Joss 2000). The Pludix infers the DSD from measured Doppler spectra (Prodi et al. 2000). The performances of the above mentioned sensors were reported to their respective manufacturers. Close collaboration with the manufacturers resulted in upgrades in both hardware and software of the sensors. For example, an upgrade on several optical components of the 2DVD overcame existing malfunctioning of the instrument due to daily temperature gradients. An addition of glass screens to the Parsivel eliminated wind-induced spurious drops. Calibration of the gauges improved their performance substantially.

**Corresponding author address*: Ali Tokay, NASA Goddard Space Flight Center, Code 912.1, Greenbelt, MD 20771; e-mail: tokay@radar.gsfc.nasa.gov

Figure 1 shows a picture of the main site at NASA/WFF in February 2002. In this study, we utilized disdrometer and rain gauge observations during the first half of 2002. At that time, the upgrade of the 2DVD was complete, but not for the Parsivel. However, we selected the rain events for which spurious drops were not an issue in Parsivel observations. The gauges were also not calibrated until May 2002, therefore, they were not included in this study except for specific cases. The calibration test showed that two TRMM office gauges underestimated rain total. This study aims to evaluate the performance of the JWD. Considering 2DVD measurements as a reference, the rainfall and DSD measurements of the JWD and 2DVD are compared in sections 2 and 3, respectively. The differences between the measured and theoretical fall velocities are shown through Parsivel and 2DVD measurements in section 4. The optical disdrometers are used to simulate the JWD DSD and derived relations between the bulk descriptors of rainfall in section 5. The last section shows the specific aspects of DSD sampling variability in derived relations between the integral rain parameters.

Fig. 1. A picture of the NASA/WFF rain gauge and disdrometer farm.

2. RAINFALL MEASUREMENTS

During the first half of 2002, the 2DVD recorded 96 rain events, accumulating 286 mm of rainfall, while the JWD had a rain total of 420 mm in 117 rain events. Here, the criterion for establishing a new rain event was a minimum of 30-minute rain-free period after the preceding event. The major discrepancy between the two disdrometers' records was due to the power outages that occurred after working hours. The JWD computer was able to reboot itself when the power was restored, while the 2DVD computers remained down until restarted through human interference. To compare the performance of the disdrometers, the rain events for which the 2DVD recorded at least 5 mm rainfall in 2DVD were considered. This corresponded to 15 rain events that had a rain total of 220 mm in 73.1 rainy hours. The JWD accumulated 216 mm in 74.1 rainy hours in these 15 rain events. The one hour difference in rainy periods was mainly due to the two winter rain events where the JWD had a greater sensitivity to very light rainfall (R < 1 mm h^{-1}). Regarding event rain totals, the difference was less than 10% in all except two episodes. Interestingly, the JWD had a higher accumulation in both episodes. The collocated gauge accumulations favored the JWD indicating an underestimation of rainfall in the 2DVD in these two rain events. Overall, the JWD had higher rain totals in 3 rain events only (Figure 2a). The mean event rain total difference was 7.6%±7.0%. The cumulative rain rate distributions of the 2DVD and JWD showed that the contribution to the total rain was identical at rain rates less than 4 mm h^{-1} (Figure 2b). The JWD contributed slightly more to the total rainfall than the 2DVD for the rain rate intervals between 4 and 7 mm h^{-1} and between 15 and 50 mm h^{-1}, while the reverse was true for the rain rate intervals of 7 to 15 mm h^{-1} and rates larger than 50 mm h^{-1}. The overall agreement between the two disdrometers was well within the accepted range of previous studies (Tokay et al. 2001, 2002, Hagen and Yuter 2003).

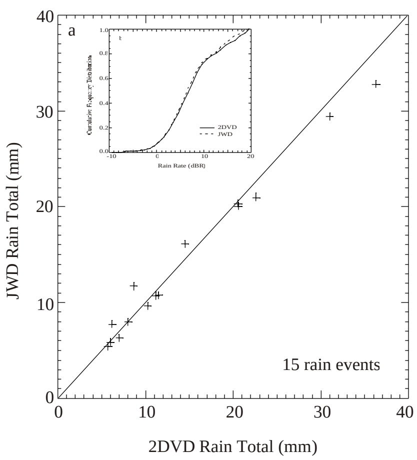

Fig. 2. (a) 1:1 event rain totals of the 2DVD and JWD. (b) Cumulative density function of rain amount in the 2DVD and JWD.

3. RAINDROP SIZE DISTRIBUTION

The composite drop size distributions of the 2DVD and JWD agreed well with one another at medium drop size range (1 < D ≤ 3 mm). The JWD recorded more drops at sizes smaller than 0.7 mm diameter, while the 2DVD had more drops at sizes larger than 3 mm diameter (Figure 3a). The difference in small-size drop concentrations is attributed to the differences of the instruments sensitivity to these drops, while the sampling fluctuations are the main cause for the differences in large-size drop concentrations. Although the 2DVD has nearly twice the sampling cross-section of the JWD, it recorded only 49% more drops in a minute. This is mainly due to the difference in the number of small drops detected by the two disdrometers. The collocated laser-optical disdrometer favored the JWD, showing even more small drops. This may lead to the conclusion that the 2DVD undercounted the small drops. In a sample population of raindrops, the large drops are rare, as indicated by the exponential nature of the size distribution. The 2DVD showed only 5% of the drops that were larger than 3 mm diameter in a population of 1,858,116 drops. The number of drops that were larger than 4 and 5 mm diameter was only 0.05% and 0.005%, respectively, of the total drop count for the 2DVD. Very large drops (D > 5 mm) comprised only 0.006% and 0.002% of the 1-minute spectra for the 2DVD and JWD, respectively. The comparison of the frequency distribution of the drop counts showed that the 2DVD had more weight toward large drops than the JWD (Figure 3b).

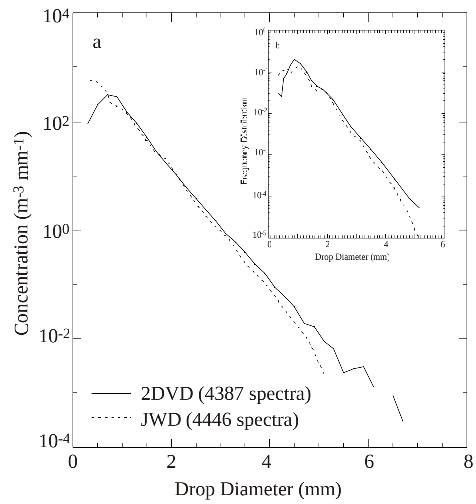

Fig. 3. (a) Composite DSD of the JWD and 2DVD. (b) Frequency distribution of composite drop counts of the JWD and 2DVD.

4. RAINDROP FALL VELOCITY

A recent study by Salles and Creutin (2003, SC03 hereafter) showed that the Z-R relationships were sensitive to the fall velocity of the drops when they were derived from disdrometer measurements. SC03 examined five moderate rain events that were measured by a collocated JWD and French optical spectropluviometer. The latter sensor was able to measure the residence time of the drops in the sampling area. Thus, the bulk properties of the rainfall were calculated without any assumption on the fall velocity of the drops. The measured fall velocities were higher than the terminal fall speed of the raindrops at sizes less than 1.5 mm on average, while the reverse was true for drops larger than 2.0 mm (Figure 6 of SC03).

Figure 4 shows the measured drop fall velocities of the 2DVD and Parsivel based on 11 rain events, where the 2DVD and Parsivel counted 1,095,930 and 859,430 drops, respectively. The measured drop fall velocities of the 2DVD and Parsivel were less than the terminal fall speed at sizes larger than 0.4 mm and 0.8 mm on average, respectively. The Parsivel drop fall velocities were substantially lower (> 0. 5 m s^{-1} difference in the mean) than the 2DVD drop velocities at drop sizes larger than 1.5 mm diameter. The standard deviations of the Parsivel drop fall velocities were also larger than 1 m s^{-1} at drop sizes larger than 3.5 mm diameter.

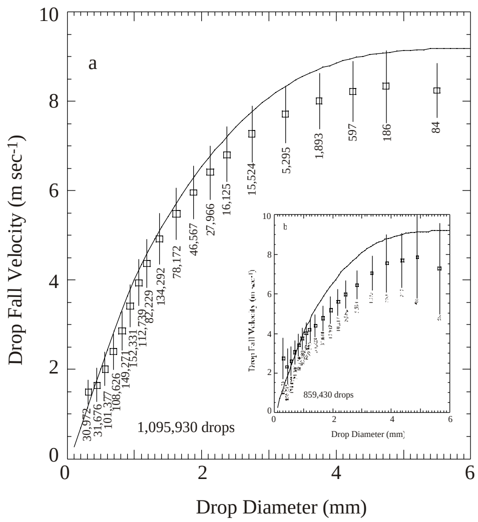

Fig. 4. (a) Measured (mean and standard deviation) and theoretical (curve) drop fall velocities of the 2DVD. The number of drops in each drop size interval is also given. (b) Same as (a) but for the Parsivel.

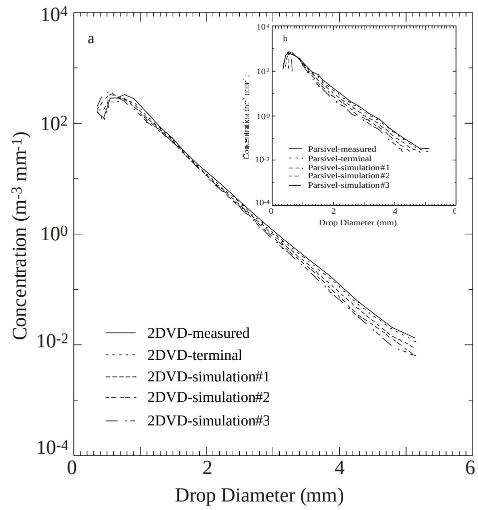

Fig. 5. (a) Composite observed and simulated DSDs representing JWD utilizing 2DVD measurements. (b) Same as (a) but for the Parsivel.

5. SIMULATED DSD AND Z-R RELATIONS

As concluded by SC03, the Z-R relationships that are derived from the disdrometer measurements could be significantly different if Z and R were calculated under the assumption of theoretical terminal fall speed rather than directly from measured drop fall velocities. The difference in Z-R relationships was due to the incorrect determination of drop size and deviations of measured fall speeds from their theoretical values. The drop size distribution and all integral rain parameters are affected by both factors except rain rate that does not require fall speed measurement when it is calculated from disdrometric measurements (Tokay et al. 2001). Here, we implemented the SC03 study by simulating the JWD measurements through the 2DVD and the Parsivel observations.

The simulated drop size (D) is expressed as $D = D_m \, (v(D_m) / v_t(D_m))^{\alpha/\beta}$, where D_m represents the measured drop size, $v(D_m)$ and $v_t(D_m)$ are the measured and theoretical fall speed of the drop, respectively. The coefficients α and β had three values for three different simulations representing momentum (α=1, β=3), kinetic energy (α=2, β=3), and peak value of the impact (α=2, β=2) of the drop (SC03). In all three simulations, the drop diameter is underestimated when the measured fall speeds are less than the theoretical values, while the reverse is also true when the measured fall speeds are higher than the corresponding theoretical values. Since the former dictates our observations in Figure 4, the drop concentrations were lower than the observed spectra in both simulations (Figure 5). This partially explains the presence of relatively fewer large drops for the JWD in Figure 2. The dispersion in DSD in the Parsivel simulations was more noticeable than that in the 2DVD simulations. This was due to the larger deviations of the measured fall speeds from theoretical values in the Parsivel than in the 2DVD. This had a major impact on the derived Z-R relationships.

The difference in absolute rain rate for a given reflectivity was significantly less between the observed and simulated Z-R relationships in the 2DVD than in the Parsivel (Figure 6). Interestingly, the Z-R difference between observed 2DVD and JWD resulted in relatively insignificant differences in absolute rain rate. The Z-R difference between observed Parsivel and JWD coincided with the difference between the observed and first simulation of the Parsivel. Although both 2DVD and Parsivel measurements of drop fall velocity are subject to error, we believe the latter instrument is more prone to error. Therefore, 2DVD measurements were considered as the reference. Since SC03 used an older technology of Parsivel, we believe their results are also subject to error such that simulated Z-R relationships should not differ from the observations substantially.

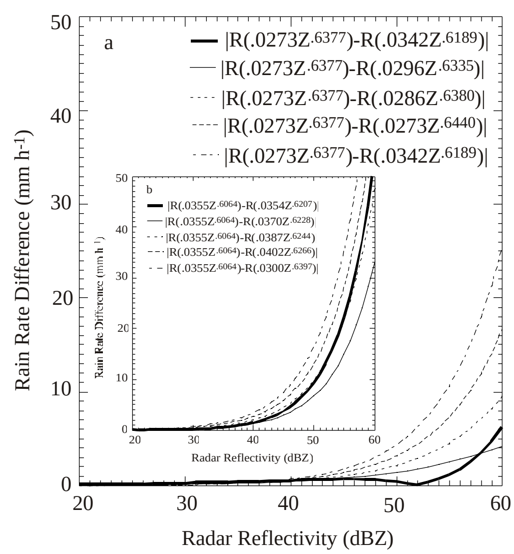

Fig. 6. (a) Absolute difference in rain rate between the observed and simulated Z-R relationships of the 2DVD, and between observed 2DVD and JWD (thick solid curve). (b) Same as (a) but for Parsivel.

6. SAMPLING VARIABILITY

A recent study by Jameson and Kostinski (2002, JK02 hereafter) examined the required minimum number of drops in each sample of observations for a derived integral rain parameter through Monte Carlo simulations. They claimed that nearly all reported Z-R relationships were likely to be spurious due to the inadequate number of drops in each sample. Although increasing the number of drops in a sample reduces the uncertainty in Z-R relationships down to 5% to 10%, this requires time averaging in disdrometer observations at scales well beyond the changes in the microphysical characteristics of the DSD within a storm. Therefore, an optimum time averaging should be considered in disdrometer observations prior to the derivation of bulk descriptors of rainfall. Hagen and Yuter (2003) applied 10-minute averaging to the 1-minute disdrometer observations where the minimum drop count (N) was 20 and the rain rate threshold was 2 mm h^{-1}.

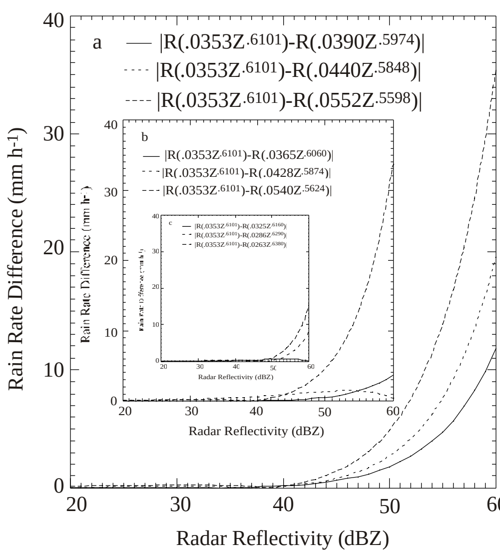

Fig. 7. (a) Absolute difference in rain rate between the Z-R relationships that were derived at different rain rate thresholds. (b-c) Same as (a) but Z-R relationships were derived at different minimum number of drops and time averaging, respectively.

Here, we derived 64 Z-R relationships utilizing JWD observations that were collected during the first half of 2002. The Z-R relationships were derived in combinations of 1, 5, 10, and 15-minute time averaging, minimum number of drops of 10, 20, 50, and 100, and rain rate thresholds of 0.1, 0.2, 0.5, and 1 mm h^{-1}. The relationships were derived through a linear least squares fit where Z was the dependent variable. The sample size decreased from 10721 to 413 1-minute spectra from the most tolerant (1-minute samples with $N \geq 10$ drops and $R \geq 0.1$ mm h-1) to the most stringent (15-minute samples with $N \geq 100$ drops and $R \geq 1$ mm h^{-1}) criteria. The Z-R relationships are the most sensitive to the rain rate thresholds, while time averaging had the least influence. In most of the cases, absolute rain rate differences were significant (≥ 2 mm h^{-1}) at $Z \geq 45$ to 50 dBZ (Figure 7). Since a significant part of the rainfall falls in the high reflectivity regime, it is important to determine the variability of Z-R relationships in instantaneous and monthly radar rainfall maps. The sampling variability can also be investigated through a network of disdrometers that can adequately represent a radar volume. The direct comparison of disdrometer-derived and radar-measured quantities such as reflectivity also provides useful information on the disdrometer sampling errors (Gage et al. 2000, Brandes et al. 2003).

Acknowledgements, This study was supported by the NASA Tropical Rainfall Measuring Mission (TRMM) Ground Validation (GV) program under Dr. R. Kakar. We would like to thank Mr. Rich Lawrence of NASA/GFSC and Dr. Raymond Hoff of UMBC for the financial support of the visiting student, O. K. Dursun.

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