Comparison of Simultaneous Rain Drop Size Distributions Estimated from Two Surface Disdrometers and a UHF Profiler

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Abstract. In support of the NASA Tropical Rainfall Measuring Mission (TRMM) Ground Validation Program, a suite of surface instruments and vertical pointing Doppler radar profilers were deployed in central Florida to quantify the number and size of the rain drops reaching the surface. Analyzing 276 minutes of simultaneous observations from two surface disdrometers and one profiler revealed good agreement among the instruments for drop sizes > 1.5 mm diameter but poor agreement for smaller drop sizes. The magnitude of the difference in small drop estimation was proportional to the reflectivity (and rainrate). At reflectivities greater than 40 dBZ, the differences in the estimation of the number of small drops yielded differences in estimates of mass-weighted diameter of > 13% and of rainrate > 25%. The combined effect of these uncertainties impact the interpretation of the precipitation processes and the development and validation of space-based precipitation retrieval algorithms.

Introduction

The Tropical Rainfall Measuring Mission (TRMM) satellite combines passive and active remote sensors to estimate monthly rainfall over 5 degree latitude by 5 degree longitude boxes with an accuracy greater than 1 mm/day or 10% in heavy precipitation (Chang et al. 1999). To achieve this accuracy, the algorithms that convert the observed quantities into rainfall estimates must account for the variations in the precipitation processes over the different geographic regions of the tropics. An important quantity thought to vary over the different life cycles of the precipitation processes is the rain drop size distribution (DSD).

During the second phase of the TRMM Ground Validation Program TEXas - FLorida UNderflight Experiment (TEFLUN-B), a Joss-Waldvogel disdrometer (JWD), a two-dimensional video disdrometer (2DVD), and a vertically pointing profiler operating at 915 MHz were deployed on Triple-N-Ranch approximately 40 km west of Melbourne, Florida. All instruments were within 20 meters of each other and were operational for the months of August and September 1998.

These instruments were deployed in the TRMM Ground Validation Field Campaigns to quantify the rain drop size distribution near the surface.

Equipment Description

Joss-Waldvogel Disdrometer

The Joss-Waldvogel disdrometer (JWD) (Joss and Waldvogel 1967) is manufactured by Distromet Inc. The JWD's durability and accuracy in measuring integral DSD parameters like rainrate and reflectivity has made it the standard instrument for surface precipitation measurements for the last 30 years. The JWD estimates the diameter of the drops by sensing the voltage induced from the downward displacement of a 50 cm² styrofoam cone. The output voltage relates to the diameter of the raindrop falling at terminal velocity (Joss and Waldvogel 1977).

This disdrometer has a dead-time associated with the recovery time of the transducer immediately following the impact of a rain drop. No rain drops are detected during this dead-time. An analytic correction has been proposed by the manufacturer to account for the drops missed during the dead-time and has also been reported by Sheppard and Joe (1994) and Sauvageot and Lacaux (1995):

\[
N'_D = N_D \exp \left[ \frac{0.035}{T} \sum_{D_j=0.5}^{D_{max}} \frac{N_j \ln(1 - \frac{D_k}{0.85(D_j - 0.25)})}{0.85(D_j - 0.25)} \right]
\]

where \(N_D\) is the number of drops with diameter \(D\), without correction, \(N'_D\) is the number of drops with diameter \(D\), with correction, and \(T\) is the sampling time in seconds (see Sauvageot and Lacaux (1995) for more details). The JWD observations used in this study were corrected for the instrument dead time using (1). The JWD was calibrated by the factory on 6 April 1998.

Two-Dimensional Video Disdrometer

With the advance of optical electronics and video signal processing, Joanneum Research, Graz, Austria, developed a new device called a two-Dimensional Video Disdrometer (2DVD). As a raindrop passes through a 10 cm wide sheet of light, a fast line-scanning camera detects the projected shadow and records the two-dimensional shape of the raindrop. At approximately 6 mm below the first sheet of light lies a second sheet of light projecting in the orthogonal plane. Video processing of the two images removes beam blockage effects from multiple drops not resolved from a single view angle. For this study, the nominal diameter resolution was a constant 0.2 mm with a minimum diameter centered on 0.5 mm. The largest observed drop was 6.3 mm.

Vertical Pointing Doppler Profiler

The vertically pointing profiler observes the Doppler velocity of the air motion or hydrometeors directly overhead
(Gage et al. 1994; Carter et al. 1995). Operating at 915 MHz, the profiler detects backscattered energy from gradients in the refractive index in clear-air (Bragg scattering) and from hydrometeors (Rayleigh scattering) (Gage et al. 1999). The profiler estimates the rain drop size distribution from the spectrum of raindrop terminal fallspeeds. Therefore, the observed Doppler velocity spectra of the hydrometeor motions must be shifted by the mean air motion to obtain the terminal fallspeed spectra. A multiple peak picking routine separates the air motion and hydrometeor motion portions of the Doppler spectra. After shifting the hydrometeor portion of the spectra by the mean air motion, the discrete rain drop size distribution is estimated using the formulation (Atlas et al. 1973):

\[ N(D) = \frac{S(v)dv}{D^6dD} \]  

where \( S(v) \) is the reflectivity at each Doppler velocity spectral point \( v \), \( dv \) is the Doppler velocity resolution, \( D \) is the diameter in \( \text{mm} \), and \( dD \) is the diameter resolution associated with each \( D \). The observed Doppler velocities are converted into diameters using the relation (Atlas et al. 1973):

\[ V_t(D) = 9.65 - 10.3 \exp[-0.6D] \]  

where \( V_t(D) \) is the terminal fallspeed in \( \text{ms}^{-1} \) of the drop of diameter \( D \) expressed in \( \text{mm} \). For this study, the profiler observations at the range gate centered at 307 meters above the surface were compared with the surface observations.

**Observed Rain Drop Size Distributions**

On 17 September 1998, a precipitation event passed over the instrument site generating 276 minutes of simultaneous observations. This event produced the total rainfall accumulation of 76 mm mainly due to heavy convective precipitation, with corresponding reflectivities greater than 50 dBZ.

**DSD Number Concentration for each Minute**

Figure 1 shows the time evolution of the surface precipitation. Panels 1a and 1b show the total reflectivity and rainrate for all three instruments. Panels 1c, 1d, and 1e show the rain drop size distributions obtained from all three instruments. The number concentration, \( N(D) \), in units of number of drops per cubic meter per diameter interval, accounts for the different sampling volumes of the three instruments. Superimposed on the number concentration panels (1c, 1d, and 1e) are the calculated mass weighted mean diameters, \( D_m \):

\[ D_m = \frac{\int N(D)D^3dD}{\int N(D)D^4dD} \]  

Comparing number concentrations from the two surface disdrometers, both similarly resolve the maximum diameter for each minute observation. The JWD maximum resolved diameter of 5.25 mm (based on hardware constraints) is reached during the convective rain near 19:15 UTC. The consistency in the envelope of maximum diameter between the two instruments suggests their similar sensitivity to the large diameter region of the drop size spectra. As opposed to the consistency of the maximum resolved diameter between the two disdrometers, discrepancies exist in the small diameter regime. The JWD appears to be underestimating the number of small drops relative to the 2DVD. The underestimation occurs throughout the event.

The bottom panel of Figure 1 shows the 915 MHz profiler derived rain drop number concentration. The largest diameter detected in the profiler DSD parallels the largest diameters detected by the JWD and 2DVD, indicating that these instruments observe the same general features of this precipitation event. The profiler derived DSD does not have a decrease in number concentration at diameters less than 1 mm as observed by the JWD. Instead, the number concentration increases with decreasing diameters, consistent with the 2DVD observations. The ability of the multiple peak picking algorithm to separate the air motion and hydrometeor motion in the Doppler velocity spectra determines the smallest resolved diameter in the profiler observations. Overlapping Bragg and Rayleigh portions of the spectra increases the minimum resolved diameter.

**Figure 1.** Reflectivity (a) and rainrate (b) calculated from the surface Joss-Waldvogel disdrometer (blue), the surface two-dimensional video disdrometer (red), and the 915 MHz profiler (green) at 327 meters above the ground. Drop size distribution number concentration, \( N(D) \), estimated from the Joss-Waldvogel disdrometer (c), the two-dimensional video disdrometer (d), and the 915 MHz profiler (e). The solid line in (c), (d), and (e) indicates the mass weighted mean diameter, \( D_m \).
In order to more clearly illustrate the effect of underestimating the small drop region in the retrieved size distribution, the mean drop size distributions, the mass weighted mean diameters, and rain rate are calculated for each instrument. Figure 2 shows these mean quantities for the reflectivity intervals 30-35, 40-45, and 50-55 dBZ.

The mean number concentrations shown in Panel 2a can be analyzed over three different diameter ranges: small drops (less than 1.5 mm), medium drops (between 1.5 and 3 mm), and large drops (greater than 3 mm). Of these three diameter regions, the best agreement between the three instruments occurs in the medium drop regime. For the small diameter region, the JWD underestimates the number concentration for all quartiles relative to the 2DVD and profiler. The amount of disagreement between the JWD and the other two instruments increases with reflectivity.

Panels 2b and 2c show the mass weighted mean diameter, $D_m$, and mean rain rate for each 5 dBZ reflectivity interval for the surface disdrometers. These panels illustrate the diversion of the calculated values for these two instruments at and above the 30-35 dBZ reflectivity interval. The diversion is caused by the underestimation of the small drops in the DSD. Fifty percent of the observations in this precipitation event had 2DVD reflectivities greater than 34 dBZ. Thus, the diversion in the calculated values effects approximately 50% of the observations in this case study.

**Discussion**

The Joss-Waldvogel impact disdrometer, designed to measure the total integrated rain rate and radar reflectivity factor of the surface rain in order to improve scanning radar estimates of rainfall (Joss and Waldvogel 1977), has gained favor as the reference surface disdrometer due to its durability and accuracy. Although not designed for detailed studies of the rain drop size distribution, many researchers have successfully used the JWD to investigate the DSD to improve understanding of the cloud processes associated with precipitation (see for example, Waldvogel 1974; Ulbrich 1983; Feingold and Levin 1986; McFarquhar and List 1993). Two limitations of the JWD for detailed rain drop size distribution analysis have been documented in previous studies. First, the minimum resolved diameter is variable and greater than 0.3 mm depending on the ambient noise and the rain intensity (Joss and Gori 1976; Sauvageot and Lacaux 1995; McFarquhar et al. 1996). Second, the total calibration is accurate for integrated reflectivity estimates but the diameter-to-diameter calibration is not adequate for identifying multiple peak distributions (Sheppard 1990).

The analysis presented in this work is consistent with the first documented limitation. Namely, the minimum resolved diameter is variable and sensitive to noise in the environment. In this study, the insensitivity of the JWD may extend to 1.5 mm diameter during heavy rain rates (greater than 40 dBZ) when the effects of noise in the environment and noise produced by the rain itself are combined.

**Conclusion**

During TEFUN-B, a precipitation event on 17 September 1998 yielded 276 minutes of simultaneous measurements from collocated JWD, 2DVD, and profiler instruments. Analysis of
the resulting drop spectra showed that while there was general agreement among the instruments for larger drop sizes (greater than 1.5 mm diameter), there was poor agreement among the instruments for smaller drop sizes. The JWD measured significantly fewer drops at sizes < 1.5 mm diameter in comparison to the other instruments. At reflectivities greater than 40 dBZ, the differences in the estimation of the number of small drops by the JWD compared to the 2DVD yield differences in estimates of mass-weighted diameter of more than 13% and of rainrate of more than 25%.

From this work, one should not conclude that rain drop size distributions are best analytically described with exponential functions. At low intensity rainrates, the one-minute DSDs obtained from the 2DVD and profiler had curvature substantially different from exponential (not shown in this work). The analysis presented in this work does not refute the curvature of the DSDs, but it demonstrates that the JWD observations may overemphasize the convexity of the drop size distribution. This increased curvature in the DSD increases the calculated mass weighted mean diameter, $D_m$, and decreases the calculated rainrate.

It is very difficult to estimate the small drop regime of the DSD particularly at high rainrates using any one of the three retrieval technologies presented. Using computational fluid mechanic methods, the 2DVD underestimated the number of small drops during windy conditions (Nešpor et al. 2000). Not including the turbulent air motions in the profiler retrieval overestimates the number of smaller drops. The agreement among the three instruments at diameters greater than 1.5 mm indicates that the three retrieval technologies are complementary in this size range and should be deployed together to exploit their inherent strengths. Further analyzes of the profiler, JWD, and 2DVD derived-DSD and comparisons to tipping bucket rain gauges and in situ aircraft data must be performed to understand the causes and to quantify the uncertainties between the different DSD measurement technologies.

The main ramification for TRMM physical validation studies incorporating DSD measurements is that the uncertainties associated with DSDs have, in addition to sample size dependence, a functional dependence on drop size that is likely different among the profiler, 2DVD, and JWD instruments. The combined effect of these uncertainties impact the interpretation of the precipitation processes and the development and validation of space-based precipitation retrieval algorithms.

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References


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