Comparison of Raindrop Size Distribution between NASA’s S-Band Polarimetric Radar and Two-Dimensional Video Disdrometers

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ABSTRACT

The ground-based-radar-derived raindrop size distribution (DSD) parameters—mass-weighted drop diameter $D_{\text{mass}}$ and normalized intercept parameter $N_W$—are the sole resource for direct validation of the National Aeronautics and Space Administration (NASA) Global Precipitation Measurement (GPM) mission Core Observatory satellite-based retrieved DSD. Both $D_{\text{mass}}$ and $N_W$ are obtained from radar-measured reflectivity $Z_H$ and differential reflectivity $Z_{\text{DR}}$ through empirical relationships. This study uses existing relationships that were determined for the GPM ground validation (GV) program and directly compares the NASA S-band polarimetric radar (NPOL) observables of $Z_H$ and $Z_{\text{DR}}$ and derived $D_{\text{mass}}$ and $N_W$ with those calculated by two-dimensional video disdrometer (2DVD). The joint NPOL and 2DVD datasets were acquired during three GPM GV field campaigns conducted in eastern Iowa, southern Appalachia, and western Washington State. The comparative study quantifies the level of agreement for $Z_H$, $Z_{\text{DR}}$, $D_{\text{mass}}$, and $\log(N_W)$ at an optimum distance (15–40 km) from the radar as well as at distances greater than 60 km from radar and over mountainous terrain. Interestingly, roughly 10%–15% of the NPOL $Z_H-Z_{\text{DR}}$ pairs were well outside the envelope of 2DVD-estimated $Z_H-Z_{\text{DR}}$ pairs. The exclusion of these pairs improved the comparisons noticeably.

1. Introduction

Estimation of the mass-weighted mean drop diameter $D_{\text{mass}}$ to within $\pm0.5$-mm accuracy from the Dual-Frequency Precipitation Radar (DPR) on board National Aeronautics and Space Administration (NASA) Global Precipitation Measurement (GPM) Core Observatory is one of the level 1 science requirements of the GPM mission (Skofronick-Jackson et al. 2017). The GPM DPR algorithm adopted a normalized gamma raindrop size distribution (DSD) defined by $D_{\text{mass}}$, the normalized intercept parameter $N_W$, and the shape parameter $\mu$ (Seto et al. 2013). The shape parameter is assumed to be constant with $\mu = 2$ for the combined radar–radiometer algorithm (Grecu et al. 2016) and $\mu = 3$ for the DPR algorithm (Iguchi et al. 2017). The accuracy of the DPR-derived $D_{\text{mass}}$ and $N_W$ is evaluated through direct comparison of ground-based radar products following volumetric footprint matching.

The GPM ground validation team routinely processes a select subset of 70+ National Weather Service (NWS) dual-polarization radars as well as several research radars over the United States with an addition of several tropical and high-latitude oceanic sites for all GPM core satellite overpasses (Pippitt et al. 2015). This labor-intensive, quality-controlled dataset includes $D_{\text{mass}}$ and $N_W$ and is produced using the Validation Network architecture (Schwaller and Morris 2011). The $D_{\text{mass}}$ and $N_W$ are derived from dual-polarized radar measurements of horizontal reflectivity $Z_H$ and differential reflectivity $Z_{\text{DR}}$ through empirical $D_{\text{mass}}(Z_{\text{DR}})$ and $N_W(Z_H, D_{\text{mass}})$ relationships. In turn, the empirical relationships are based on combined analysis of two-dimensional video disdrometer (2DVD) data obtained...
during six different GPM field campaigns (Tokay et al. 2020).

From the perspective of ground validation traceability, it is important to evaluate the accuracy of the ground-based-radar-derived DSD. Historically, the radar-derived products are often evaluated through comparative studies with surface measurements, which are considered as a reference. For the radar rainfall estimate, there are numerous studies in the literature on quantitative analysis of radar-estimated and gauge-measured rainfall (Cifelli et al. 2011; Giangrande et al. 2014a). For radar-derived DSD, however, there are a limited number of studies where radar-estimated and disdrometer-measured DSD parameters have been compared (Brandes et al. 2004, hereinafter B04; Thurai et al. 2012, hereinafter T12). This is mainly due to the unavailability of such datasets; however, they have recently become more plentiful through NASA GPM and the U.S. Department of Energy Atmospheric Radiation Measurement Program’s (Giangrande et al. 2014b) field studies.

Both B04 and T12 were event-based studies in which a single 2DVD was 38 and 15 km from S- and C-band polarimetric radars, respectively. Both studies derived empirical relationships between radar observables of Z_H and Z_{DR} and constrained gamma DSD parameters of median volume diameter D_0 and N_W using simulated and disdrometer-based size distributions and prescribed drop shapes. Comparative studies are subject to measurement errors from both radars and disdrometers, as well as the time–height ambiguity and significant sampling volume differences. Measurement errors can be mitigated by calibrating radar and disdrometer while the time–height ambiguity depends on the characteristics of precipitation and the experimental setup. Both B04 and T12 selected relatively uniform stratiform events where the radar pixel was approximately 350 and 250 m above ground, respectively. B04 and T12 showed good agreement between radar-derived and disdrometer-calculated D_0 and log(N_W). A key to their success in estimating D_0 and log(N_W) was the good agreement between radar-measured and disdrometer-calculated Z_H and Z_{DR}.

One of the main causes of the discrepancy between disdrometer- and radar-measured or disdrometer- and radar-derived parameters is the vertical variability of precipitation. As the distance between the disdrometer and radar measurement increases, the radar pulse volumes and the vertical variability of hydrometeors increases and becomes more complicated in the presence of mixed or frozen particles at the radar pixel height. The radar measurements are also vulnerable to surface clutter. Despite the error sources listed above, there is merit in quantifying the differences between disdrometer and radar measurements at various disdrometer–radar distances, different climate regimes, and various weather systems. Comparative studies provide a realistic range of differences between the two platforms for measured and derived parameters.

This study is dedicated exclusively to the quantification of observed differences in DSD parameters between radar and disdrometer platforms. The dataset used in this study had several diverse features. The precipitation systems were originated both over the land and over the ocean. Both frontal and orographic lifting initiated the precipitation formation. Airmass thunderstorms and mesoscale convective systems provided abundant precipitation. The rest of the paper is organized as follows: Section 2 summarizes the database used in this study. Section 3 describes the mathematical form of the relationships between the DSD parameters of D_{mass} and N_W and dual-polarization radar observables of Z_H and Z_{DR} with the derivation methods using disdrometer datasets. Section 4 presents a comparative study of the disdrometer-calculated and radar-measured radar parameters of Z_H and Z_{DR} as well as disdrometer-calculated and radar-estimated D_{mass} and N_W. A dedicated section 4c describes the fraction of the radar-based Z_H and Z_{DR} pairs that were outside the envelope of the disdrometer observations. Conclusions are presented in section 5.

2. Database

The database was constructed from coincident NASA’s S-band polarimetric radar (NPOL) and 2DVD observations during three GPM ground validation (GV) field campaigns: the Iowa Flood Studies (IFloodS), the Integrated Precipitation and Hydrology Experiment (IPHEX), and the Olympic Mountain Experiment (OLYMPEX).

Figure 1 depicts the position of the 2DVDs with respect to the NPOL during these field campaigns, and Table 1 lists the location and duration of the field campaigns as well as the number of 2DVDs and their sampling size.

Considering the NPOL database, Z_{DR} was calibrated by vertical profiles of natural precipitation targets (Gorgucci et al. 1999). Absolute Z_H calibration was then determined via self-consistency of the polarimetric variables (Ryzhkov et al. 2005) and the stability of the calibration was monitored using the relative calibration adjustment (Silberstein et al. 2008; Wolff et al. 2015). After labor-intensive quality control of NPOL data for ground clutter and nonmeteorological echo removal and subsequent calibration (Pippitt et al. 2015), the radar data were ready for analyses. Nine radar pixels, one directly above the 2DVDs and eight neighboring pixels, were identified and extracted for this study. It should be noted that it is not feasible to totally avoid ground clutter, especially when it is embedded.
with meteorological echo. In these cases, clutter cannot be completely removed because high quality control thresholds would remove too much real echo. In addition, higher radar elevation beams can intersect the bright band, especially at far distances. For this study, the comparison of radar observables of $Z_H$ and $Z_{DR}$ and derived DSD parameters of $D_{mass}$ and $\log(N_W)$ are shown for NPOL gates directly above the 2DVs. A comparative study using the neighboring eight radar pixels did not significantly alter the findings of this study.

Considering the 2DVD database, a “rain” threshold was considered as the occurrence of a minimum of 10 drops and minimum rain rate of 0.01 mm h$^{-1}$ in 1-min observations. For this study, the average DSD is calculated for three consecutive rainy minutes centered at the radar scan time. A study using 5-, 7-, and 9-min DSD average did not significantly alter the findings of this study. Very light rain was eliminated from the coincident dataset by setting a $Z_H$ threshold of 5 dB to both the NPOL and 2DVD datasets. The $Z_{DR}$ was also bounded by a maximum of 4 dB to be consistent with the conditions of the derived $D_{mass}(Z_{DR})$ relationship. The initial sample sizes that were given in Table 1 reflect the coincident database after the $Z_H$ and $Z_{DR}$ thresholds were applied. The $D_{mass}(Z_{DR})$ relationship has an additional bound on $D_{mass}$ as being greater than 0.5 mm and less than 4.0 mm. The resultant samples after these additional thresholds on $D_{mass}$ were applied to the comparison of DSD parameters and the resultant sample sizes are shown in Table 1 in parenthesis.

In the presence of abundant rainfall and six 2DVD units, IFloodS provided a richer sample of coincident datasets with respect to the other two experiments. During OLYMPEx, rain was also abundant (Zagrodnik et al. 2018) but the coincident sample size was substantially lower with the availability of only three 2DVD units. Despite the fact that five 2DVD units were available during IPHEx, sample sizes were limited as a result of the fewer rain events than during IFloodS and OLYMPEx.

Cumulative distributions of rain rate (RR), $D_{mass}$, and $\log(N_W)$ showed the diverse nature of rainfall between the three field campaigns (Fig. 2). Light rain (RR < 1 mm h$^{-1}$) occurred the most during IFloodS, while heavy rain (RR ≳ 10 mm h$^{-1}$) was most frequently observed during IPHEx (Fig. 2a). The mean RR was substantially higher during IPHEx, while median and maximum RR were distinctly lower during IFloodS and OLYMPEx, respectively (Table 2). These statistics were based on the 3-min-average 2DVD RR that coincides with the radar scan time. The datasets were diverse in terms of population of small ($D < 1$ mm),
midsize \((1 \leq D < 3\text{ mm})\), and large \((D \geq 3\text{ mm})\) drops. The OLYMPEx dataset consists of mostly small–midsize raindrops resulting in the highest occurrence of \(D_{\text{mass}} < 1.2\text{ mm}\) and \(\log(N_W) \equiv 3.5\) (Figs. 2b,c). For the purpose of this study, we considered \(D_{\text{mass}}\) of 1.2 mm as a characteristic size such that the DSD samples dominated by small drops have \(D_{\text{mass}} < 1.2\text{ mm}\). Similarly, \(\log(N_W)\) of 3.5 is the characteristic value above which represents the samples with abundant number of raindrops. Both \(D_{\text{mass}}\) and \(\log(N_W)\) characteristic values are subjective and are determined through examining the cumulative distributions of these parameters from six different field studies (Tokay et al. 2020). IPHEx had substantially more samples at \(D_{\text{mass}} < 1.2\text{ mm}\) range and IFloodS had the highest number of samples at \(\log(N_W) < 3.5\) among the three field campaigns. The lowest mean and median \(D_{\text{mass}}\) and the highest mean and median \(\log(N_W)\) were also observed during OLYMPEx. The similarities in the distribution of rain rate and diversities in the distribution of DSD parameters between the IFloodS and OLYMPEx demonstrate the common observation that the similar rain rates can result from completely different contributions of small, medium, and large drops. This was emphasized when rainfall from convective and stratiform clouds was examined in tropical systems (Tokay and Short 1996; Thompson et al. 2015).

3. Method

Bias and absolute bias between NPOL and 2DVD parameters are considered as the two statistics to quantify the results for the comparative study. Bias is the difference between estimated variable \(X\) and reference variable \(Y\) and therefore is also referred to as relative error. In this study, the 2DVD was considered as the reference instrument and the parameters of interest are \(Z_H, Z_{DR}, D_{\text{mass}},\) and \(\log(N_W)\). Bias is defined as

\[
\text{bias} = \frac{1}{N} \sum_{i=1}^{N} (X_i - Y_i). \tag{1}
\]

Absolute bias (often referred to as mean absolute error) is the absolute value of the difference between the estimated and reference variables:

\[
\text{absolute bias} = \frac{1}{N} \sum_{i=1}^{N} |X_i - Y_i|. \tag{2}
\]
Between the two statistics, absolute bias is more reliable for evaluating the level of agreement between the two variables. Considering paired samples on both sides of the 1:1 line, bias could be near zero but absolute bias would be significant if the samples are not near the 1:1 line.

Reflectivities $Z_H$ and $Z_{DR}$ were measured by NPOL and were calculated from size and fall velocity measurements of the 2DVD. Although 2DVD was also capable of measuring drop axis ratios, this study used the laboratory-based observed axis ratios following Andsager et al. (1999) for drops up to 6 mm and equilibrium drop shapes (Beard and Chuang 1987) for drops larger than 6 mm; $Z_H$ and $Z_{DR}$ were derived for S-band wavelength (NPOL’s operational frequency) following Rayleigh–Gans theory (Tokay et al. 2002). The $Z_{DR}$ is the ratio of reflectivity at horizontal polarization $Z_H$ to reflectivity at vertical polarization $Z_V$. The reflectivity at horizontal and vertical polarization is expressed as a function of wavelength $\lambda$, dielectric constant of water $|K_{water}|^2$, and shape factors $S_{H,V}$ as follows:

$$Z_{H,V} = \frac{\lambda^4}{\pi^2 |K_{water}|^2} \int_{D_{min}}^{D_{max}} S_{H,V}(D, r) D^5 N(D) dD,$$  

(3)

where the shape factors are a function of drop axis ratio $r$. Drop diameter $D_{mass}$ is the ratio of the fourth moment to the third moment of size distribution and is expressed in millimeters. It is calculated from 2DVD size and fall velocity measurements as

$$D_{mass} = \frac{\int_{D_{min}}^{D_{max}} D^4 N(D) dD}{\int_{D_{min}}^{D_{max}} D^3 N(D) dD}.$$

(4)

The $D_{mass}$ is also calculated from NPOL $Z_{DR}$ measurements through a third-order polynomial as

$$D_{mass} = aZ_{DR}^3 + bZ_{DR}^2 + cZ_{DR} + d,$$

(5)

where $Z_{DR}$ is in decibels and the $a$, $b$, $c$, and $d$ coefficients are derived from 2DVD datasets for each field campaign (Table 3). Since the 2DVD datasets in each field campaign may not have sufficient sample size at high $Z_{DR}$ intervals, a generic $D_{mass}(Z_{DR})$ relationship was derived combining all available 2DVD datasets from six different field campaigns to determine $D_{mass}$ at these ranges. The three additional 2DVD datasets that are not used in this study were collected during the Midlatitude Continental Convective Clouds Experiment in northern Oklahoma, and long-term (more than a year) field studies at the NASA Goddard Space Flight Center Wallops Flight Facility in Wallops Island, Virginia, and the NASA Marshall Space Flight Center in Huntsville, Alabama (Tokay et al. 2020).

Parameter $N_w$ is the normalized intercept parameter and is expressed as a function of $D_{mass}$ in millimeters and liquid water content $W$ in grams per meter cubed, both of which are calculated from 2DVD size and fall velocity measurements. The formulation includes density of water $\rho_w$ in grams per centimeter cubed and several constants that are related to the complete gamma function solution of $D_{mass}$ and $W$ (Testud et al. 2001):

$$N_w = \frac{4^410^3\pi^\frac{4}{3}W^\frac{4}{3}}{\pi^\frac{2}{3}\rho_w D_{mass}^4};$$

(6)

$N_w$ is analogous to the intercept parameter of the gamma size distribution (Ulbrich 1983) and is therefore sensitive to the number of drops. It has a wide numerical range covering over four orders of magnitude and is therefore expressed in logarithmic units $\log(N_w)$ rather than its linear dimension $(m^{-3} \text{ mm}^{-1})$.

Parameter $N_w$ is also retrieved from measured NPOL $Z_H$ and $Z_{DR}$ after $D_{mass}$ is calculated from Eq. (5). The empirical equation is derived combining 2DVD

<table>
<thead>
<tr>
<th>Field campaign</th>
<th>$a$</th>
<th>$b$</th>
<th>$c$</th>
<th>$d$</th>
<th>$\text{max } Z_{DR}$ (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>IFoodS</td>
<td>0.1988</td>
<td>-1.0747</td>
<td>2.3786</td>
<td>0.3623</td>
<td>3.05</td>
</tr>
<tr>
<td>IPHEEx</td>
<td>0.1887</td>
<td>-1.0024</td>
<td>2.3153</td>
<td>0.3834</td>
<td>2.85</td>
</tr>
<tr>
<td>OLYMPEx</td>
<td>0.2209</td>
<td>-1.1577</td>
<td>2.3162</td>
<td>0.3486</td>
<td>2.65</td>
</tr>
<tr>
<td>ALL</td>
<td>0.0138</td>
<td>-0.1696</td>
<td>1.1592</td>
<td>0.7215</td>
<td>3.95</td>
</tr>
</tbody>
</table>

Table 3. The coefficients of the $D_{mass}$-$Z_{DR}$ relationship and the maximum $Z_{DR}$ range for the three different 2DVD datasets and the combined dataset, which includes three additional field campaigns.
database from six different field campaigns (Tokay et al. 2020) and is given as

\[ N_W = aZ_H D_{mass}^b, \]  

(7)

where \( D_{mass} \) is in millimeters, \( Z_H \) is in linear units (\( mm^6 m^{-3} \)), and \( a \) and \( b \) are 35.3 and \(-7.2\), respectively. The coefficient \( a \) and exponent \( b \) were indistinguishable among the six different field campaigns. Reflectivity \( Z_{DR} \) is sensitive to the drop shape, which is spherical for the drops of less than 1 mm (Tokay and Beard 1996). The radar measurements of \( Z_{DR} \) are noisy in the presence of abundant small drops and absence of large drops. Using the formulation in Eqs. (5) and (7), when \( Z_{DR} \) is 0.1 dB, \( D_{mass} \) can still be 0.5 mm or higher but \( \log(N_W) \) is greater than 6 at 30 dBZ. The 2DVD observations show that this is an unrealistic DSD (Table 2). The uncertainty in estimating \( \log(N_W) \) was mitigated by setting realistic \( \log(N_W) \) thresholds between 0.5 and 6.

4. NPOL–2DVD comparisons

The level of agreement between NPOL-measured and 2DVD-calculated \( Z_H \) and \( Z_{DR} \) is related to the agreement between NPOL-derived and 2DVD-calculated \( D_{mass} \) and \( N_W \). Midsize to large drops are the main contributors to the \( Z_H \) (Adirosi et al. 2015) and because of its power-weighted nature, \( Z_{DR} \) is very sensitive to the presence of a few large drops that have the lowest axis ratios (Tokay et al. 2020). The presence or absence of a few large drops could therefore result in noticeably different 2DVD-calculated \( Z_H \) and \( Z_{DR} \) values. Both parameters are therefore heavily affected by the differences in sampling volumes of NPOL and 2DVD.

The sampling volume of NWS operational radars can exceed that of the 2DVD by a factor of \( 10^7 \) or more at a distance of 30 km (Cao et al. 2008). The disdrometer sampling volume is a multiplicative function of sampling cross section, fall velocity that corresponds to the characteristic size, and sampling interval (Campos and Zawadzki 2000). The cross section of the 2DVD is nominally 0.01 m\(^2\), and the integration period was 180 s in this study. If mean or median drop size is the characteristic size, the sampling size is less than 15 m\(^3\) among the three field campaigns. If maximum drop size is the characteristic size, the sampling volume is less than 18 m\(^3\). The sampling volume of the radar depends on the beamwidth, range gate size, and the distance from radar. The beamwidth of NPOL was 0.98° in all three field campaigns, and the range gate was 150 m during IFloodS and 125 m during IPHEx and OLYMPEx. Table 4 lists the 2DVD-NPOL distances as well as NPOL elevation angles and beam heights. For IFloodS, the NPOL sampling volume is 3,378,908 m\(^3\).
at its closest distance of 5 km and 1.550794368 m³ at its farthest distance of 106 km. The NPOL sampling volumes were within this range for the other two field campaigns. The differences in sampling volume ranged from 10⁵ to 10⁷ orders of magnitude at distances from 5 to 106 km from the radar. The beam heights were calculated on the basis of a 4/3 Earth radius model under standard atmospheric conditions. The possible pitfalls of this model were presented by Zeng et al. (2014) and are beyond the scope of this study. For the sites that are located at higher elevations than the NPOL, the distance of the beam height to the ground is less than what was reported in Table 4. During IPHEX, the farthest three sites (SN36, SN37, and SN38) were 380, 732, and 1072 m higher elevation than the NPOL.

The time–height ambiguity is another source of disagreement between disdrometer and radar measurements. The vertical variability of the DSD results in a non-uniform profile of $Z_H$ and $Z_{DR}$ between the altitude of the radar scan and the ground. For fast moving storms, there is a time lag between the radar scan time and disdrometer observations especially at far distances. These factors are best investigated through collocated vertically pointing radars and disdrometers (Tokay et al. 2009).

Because NPOL is a transportable facility and not situated on a tower (the antenna feed horn is ~8 m above ground level at an elevation angle of 0°), the first elevation angle is often subject to ground clutter. The second elevation is therefore selected to compare 2DVD and NPOL variables except at the farthest distances during IFloodS and OLYMPEX. It should also be added that no corrections for height-dependent drop fall-speed time lags or vertical wind shear/direction impacts on drop trajectories were applied. Based on the environmental conditions, the bright band was not a factor for this study.

### a. $Z_H$ and $Z_{DR}$

Good agreement was evident between 2DVD-calculated and NPOL-measured $Z_H$. During IFloodS, the NPOL bias relative to the 2DVD observations ranged from as high as $-1.48$ dB to $+0.50$ dB (Table 5). Note that the negative bias shows the underestimation of the NPOL variable while the overestimation of the NPOL variable is depicted with a positive bias. The absolute bias increased with range, spanning values from 3.28 dB at 15 km to 4.66 dB at 69 km range, but was lower at the farthest distance where the vertical distance between the NPOL pixel and 2DVD was less than the closer sites because of the use of first elevation angle (Table 4). While there was large scatter around the 1:1 line (Fig. 3a), the majority of the observations were aligned along the

### TABLE 5. Comparison of 2DVD-calculated and NPOL-measured $Z_H$ (dBZ) during IFloodS, IPHEX, and OLYMPEX. Considering $Z_H$ of 2DVD as a reference, bias and absolute bias are presented at each 2DVD site for each field campaign. The sample sizes are also given.

<table>
<thead>
<tr>
<th></th>
<th>IFloodS</th>
<th></th>
<th></th>
<th>IPHEX</th>
<th></th>
<th></th>
<th>OLYMPEX</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Bias</td>
<td>Absolute bias</td>
<td>Sample size</td>
<td>Bias</td>
<td>Absolute bias</td>
<td>Sample size</td>
<td>Bias</td>
<td>Absolute bias</td>
<td>Sample size</td>
</tr>
<tr>
<td>0.50</td>
<td>3.32</td>
<td>1378</td>
<td></td>
<td>1.24</td>
<td>3.60</td>
<td>244</td>
<td>1.30</td>
<td>3.70</td>
<td>528</td>
</tr>
<tr>
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<td>1901</td>
<td></td>
<td>-0.83</td>
<td>5.45</td>
<td>126</td>
<td>1.10</td>
<td>4.39</td>
<td>489</td>
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<tr>
<td>-1.12</td>
<td>3.95</td>
<td>1206</td>
<td></td>
<td>-1.41</td>
<td>4.60</td>
<td>347</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
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<td>4.55</td>
<td>1444</td>
<td></td>
<td>-2.73</td>
<td>6.80</td>
<td>388</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>-0.61</td>
<td>4.66</td>
<td>855</td>
<td></td>
<td>-2.33</td>
<td>7.10</td>
<td>240</td>
<td>0.52</td>
<td>3.96</td>
<td>617</td>
</tr>
<tr>
<td>-0.10</td>
<td>4.57</td>
<td>952</td>
<td></td>
<td>-</td>
<td>-</td>
<td></td>
<td>-</td>
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<td></td>
</tr>
</tbody>
</table>

![Fig. 3](https://via.placeholder.com/150.png?text=Fig.+3.+Scatter+diagram+of+2DVD-calculated+and+NPOL-measured+$Z^H$+during+(a)+IFloodS,+ (b)+IPHEX,+and+(c)+OLYMPEX.+The+colors+represent+the+specific+2DVD+site+during+each+field+campaign.)

Fig. 3. Scatter diagram of 2DVD-calculated and NPOL-measured $Z_H$ during (a) IFloodS, (b) IPHEX, and (c) OLYMPEX. The colors represent the specific 2DVD site during each field campaign.
1:1 line (Fig. 4a). Several outliers are visible in the figures. Among those, a couple of outliers at the SN37 site had $Z_H$ of 2DVD that was higher than 50 dB and $Z_H$ of NPOL that was less than 20 dB (Fig. 3a).

During IPHEx, the NPOL underestimated $Z_H$ with noticeably high biases of $-2.73$ and $-2.33$ dB at the two farthest sites (SN37 and SN38) at ranges greater than 100 km and in higher terrain. The corresponding absolute biases in these two sites, 6.80 and 7.10 dB, were the highest among three field campaigns. A relatively small sample of high $Z_H$ in the 2DVD resulted in this high bias and they were not event specific (Fig. 3b). Among those, one sample at SN37 had $Z_H$ of 2DVD that was higher than 50 dB and $Z_H$ of NPOL that was less than 20 dB. These samples were not visible in the frequency diagram where most of the observations lay on the 1:1 line (Fig. 4b). This demonstrates the importance of both scatter and 2D density diagrams.

During OLYMPEx, the NPOL overestimated $Z_H$ for all three sites but the bias at the farthest site (SN38) was at least one-half of its value of the closest two sites (SN35 and SN36) (Table 5). The absolute bias increased from 3.70 to 4.39 dB between the closest two distances but was 3.96 dB at the farthest distance. The NPOL beam height was 145 m lower at the SN38 site than at the SN35 site because of the differences in elevation angles (Table 4). The SN38 site was also only 8.4 km farther from NPOL than the SN36 site. Important was that the majority of the observations were aligned with the 1:1 line (Fig. 4c) and the scatter about the 1:1 line was considerably less pronounced, with relatively fewer outliers than the other two field campaigns. Two of the outliers at the SN35 site had $Z_H$ of 2DVD that was less than 10 dB and $Z_H$ of NPOL that was around 35 dB (Fig. 3c).

There were considerable differences between 2DVD-calculated and NPOL-measured $Z_{DR}$. The $Z_{DR}$ biases were positive, indicating an overestimation by NPOL relative to the 2DVD, at all sites during all three field campaigns, but were drastically different in magnitude between the sites (Table 6). The $Z_{DR}$ bias at its closest 2DVD-NPOL distance was the highest, 0.6 dB, among all sites during IFloods. The rest of the five sites had low $Z_{DR}$ bias ($\leq 0.1$ dB). The high bias at the closest site was attributed to surface clutter, which also played a role at the closest 2DVD-NPOL distance during IPHEx. Both sites were less than 10 km of distance from NPOL in respective field campaigns. High $Z_{DR}$ biases were also present at the two farthest sites, which were located at higher elevation, during IPHEx. High biases were mainly driven by the samples of NPOL $Z_{DR}$ that were greater than 2 dB and 2DVD $Z_{DR}$ that were less than 0.5 dB (Fig. 5). The wide scatter on both side of the 1:1 line, on the other hand, reflected the combination of low

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**Table 6.** Comparison of 2DVD-calculated and NPOL-measured $Z_{DR}$ (dB) during IFloods, IPHEx, and OLYMPEx. Considering $Z_{DR}$ of 2DVD as a reference, bias and absolute bias are presented at each 2DVD site for each field campaign.

<table>
<thead>
<tr>
<th>2DVD serial no.</th>
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<th>OLYMPEx</th>
</tr>
</thead>
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<td>Bias</td>
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<tr>
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<td>0.31</td>
<td>0.02</td>
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<tr>
<td>SN 70</td>
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<td>0.35</td>
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</table>
bias (<0.1 dB) and considerably higher absolute bias (0.27–0.35 dB) in $Z_{DR}$ at total of eight sites in three field campaigns (Figs. 5 and 6). This highlights that the low bias itself can mislead for the evaluation of the level of agreement.

b. $D_{mass}$ and $N_w$

NPOL-based $D_{mass}$ is derived from $Z_{DR}$ and the comparison of $D_{mass}$ between 2DVD and NPOL had similar statistics as for $Z_{DR}$. The $D_{mass}$ bias was very high—0.32 mm—at the closest NPOL–2DVD distance and was low ($\leq 0.05$ mm) for the other five sites during IFloodS (Table 7). The $D_{mass}$ biases were also low at all sites except for the two farthest sites (SN37, SN38) where time–height ambiguity was significant during IPHEX. The $D_{mass}$ bias was very low at SN35 site but the absolute biases in $D_{mass}$ were about the same at SN35 and SN38 sites. Although SN38 site was farthest away from NPOL, the radar beam height was the closest to the ground since the first rather than the second beam was used at SN38 site in this study (Table 4). The absolute bias in $D_{mass}$ remained less than 0.4 mm at the sites where biases were equal to or less than 0.1 mm during the three field campaigns. The absolute bias in $D_{mass}$ was as high as 0.62 mm at the SN37 site during IPHEX where bias was also the highest—0.34 mm—among the field campaigns. The positive bias in $D_{mass}$ indicates that the mass-weighted size spectrum is shifted toward smaller sizes in 2DVD. This means that the normalized size spectrum will have more small drops and/or a lack of large drops, resulting in lower $D_{mass}$.

On closer examination, the scatter and 2D density diagrams of 2DVD-calculated and NPOL-estimated $D_{mass}$ revealed wide scatter from 1:1 line especially during IFloodS (Fig. 7). At the same time, a majority of the observations aligned on the 1:1 line during IFloodS, while they diverge from the 1:1 line biased toward NPOL and 2DVD $D_{mass}$ during IPHEX, and OLYMPEX, respectively (Fig. 8). There were no site-specific outliers in each field campaign except a small cluster of outliers were visible at NPOL-estimated $D_{mass}$ that are greater than 3 mm during OLYMPEX (Fig. 7c). The scatter diagram also showed five samples of 2DVD-calculated $D_{mass}$ that were larger than 3.6 mm during
IFloodS (Fig. 7a). These samples were underestimated by NPOL with no range dependency.

$N_W$ is a function of both $Z_H$ and $D_{mass}$ and the log($N_W$) statistics followed somewhat similar trends as $D_{mass}$. Absolute biases of log($N_W$) were less than 1 except the nearest 2DVD site (SN25) during IFloodS, the farthest two sites (SN37 and SN38) during IPHEx and the middle site (SN36) during OLYMPEx (Table 8). The log($N_W$) bias was near 0.6 and negative at the nearest site where ground clutter was the factor during IFloodS. The negative and high biases were also present at two farthest sites during IPHEx. The biases were relatively low during OLYMPEx where the highest bias—0.27—was at the closest site (SN35). $N_W$ is related to the peak of the number of drops per given volume per size interval and the drop counts per volume typically decreases with size. The negative bias therefore indicates fewer drops per volume in NPOL and the vice versa is true for positive bias.

The order of magnitude of log($N_W$) was substantially higher and was at the limits of the GPM GV DSD retrieval algorithm for NPOL-derived log($N_W$). The vast majority of the 2DVD observations, on the other hand, were within values log($N_W$) of 2–4.5 (Figs. 9 and 10).

Following Eq. (7), high $Z_H$ and low $D_{mass}$ results in high log($N_W$). The unlikely combination of $Z_H$ of 45 dB and $D_{mass}$ of 1.4 mm, for instance, corresponds to log($N_W$) of 5. The combination of $Z_H$ of 30 dB and $D_{mass}$ of 3.1 mm, on the other hand, results in log($N_W$) of 1. Although these pairs do not exist in the 2DVD database, they exist in the NPOL database since $D_{mass}$ is the derived quantity. It is therefore expected that the estimation of log($N_W$) is poorer than the estimation of $D_{mass}$.

c. Outliers

The diagram of $Z_H/Z_{DR}$ fields, which have been previously used for determining hail by radar (Aydin et al. 1986), precipitation segments (e.g., stratiform rain vs thunderstorm core), and precipitation type (e.g., continental vs tropical) by disdrometer (Zhang et al. 2006; Kumjian 2013), shows the major differences in radar and disdrometer observations. Cao et al. (2008) who overlaid 2DVD and dual-polarization-radar-based $Z_H/Z_{DR}$ fields, marked the high $Z_{DR}$ region observed by radar only. This region is attributed to the leading edge of convection with large drops and relatively low drop concentrations. As noted by Kumjian (2013), $Z_{DR}$ varies with drop size and shape and a few large drops can result in

<table>
<thead>
<tr>
<th>2DVD serial no.</th>
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<th>IPHEx</th>
<th>OLYMPEx</th>
</tr>
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<tr>
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</tr>
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<tr>
<td>SN 37</td>
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<td>0.33</td>
<td>1324</td>
</tr>
<tr>
<td>SN 38</td>
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<td>0.37</td>
<td>803</td>
</tr>
<tr>
<td>SN 70</td>
<td>0.04</td>
<td>0.37</td>
<td>877</td>
</tr>
</tbody>
</table>

Fig. 7. Scatter diagram of 2DVD-calculated and NPOL-estimated $D_{mass}$ (mm) during (a) IFloodS, (b) IPHEx, and (c) OLYMPEx. The colors represent the specific 2DVD site during each field campaign.
very high $Z_{DR}$ values (>2.5 dB). $Z_H$, on the other hand, is directly proportional to the particle concentration and may have moderate values (25–30 dB). Given the fact that the sample volume of the disdrometers is much smaller than the radar, the relatively infrequent big drops may not be caught by the disdrometer.

The 2DVD observations from three field sites were merged to determine the boundaries of the envelope of the $Z_H/Z_{DR}$ field (Fig. 11a). The envelope was wide in both $Z_H$ and $Z_{DR}$ space. At $Z_H$ of 40 dB, $Z_{DR}$ ranged from 0.3 to 3.8 dB. Similarly, at $Z_{DR}$ of 1 dB, $Z_H$ ranged from 15 to 50 dB. The majority of the observations fell in much narrower range centering at $Z_H$ of 20 dB and $Z_{DR}$ of 0.2 dB (Fig. 11b). The NPOL $Z_H/Z_{DR}$ observations outside the 2DVD $Z_H/Z_{DR}$ envelope mostly occurred at moderate-to-high $Z_{DR}$ and low-to-moderate $Z_H$ regime (Regime I) (Fig. 11c). The IPHEx radar data had the highest percentage, 15%, of observations with respect to IFloodS and OLYMPEx in this regime (Table 9). The low $Z_{DR}$ and high $Z_H$ regime (Regime II), on the other hand, had 2% or less of the observations in a given field campaign. None of the two regimes corresponded to a particular segment of the storms. There was no correlation between the leading edge of the convective events and Regime I as previously reported by Cao et al. (2008).

The combined Regimes I and II consist of 15% of the observations during IPHEx, 5% and 5.5% higher than the OLYMPEx and IFloodS, respectively. The recalculated bias and absolute bias after eliminating observations in these two regimes was noticeably less for $Z_{DR}$ and $\log(N_W)$ and marginally less for $Z_H$ and $D_{mass}$ (Table 9). The reduction in absolute bias was 0.35 and 0.12 dB for $Z_H$ and $Z_{DR}$ and 0.05 mm and 0.14 for $D_{mass}$, and $\log(N_W)$, respectively, during IPHEx.

The majority of the Regime-I samples occurred with $Z_H$ of less than 30 dB, with a slight bias toward the 2DVD observations (Fig. 12a). The Regime-II samples occurred with $Z_H$ of higher than 30 dB, with no significant bias. The observations for Regimes I and II were very distinct in $Z_{DR}$ (Fig. 12b). Almost all of the Regime-I observations occurred in a narrow zone where $Z_{DR}$-2DVD was less than 0.6 dB and $Z_{DR}$-NPOL was above 0.2 dB. The Regime-II observations, on the other hand, were mainly observed at $Z_{DR}$-NPOL less than 0.4 dB and $Z_{DR}$-2DVD less than 1 dB. Regime I corresponded to the overestimation of $D_{mass}$ and underestimation of $\log(N_W)$ by NPOL, and the vice versa is true for Regime II (Figs. 12c,d). Observations for both Regime I and Regime II fell into the envelope of the rest of the observations in $D_{mass}$ but were at the edge of the observations in $\log(N_W)$. The reduction of dynamic range

![Fig. 8. A 2D density plot of 2DVD-calculated and NPOL-estimated $D_{mass}$ during (a) IFloodS, (b) IPHEx, and (c) OLYMPEx.](https://example.com/fig8.png)
of NPOL-estimated $\log(N_W)$ resulting from the absence of Regime I was significant.

A key question relates to the origin of Regimes I and II in NPOL observations. The 2DVD is widely used as a reference instrument for DSD measurements (Tokay et al. 2013). The underestimation of small drops has been recognized and recently investigated through field studies where 2DVD was collocated with a Meteorological Particle Spectrometer (Thurai and Bringi 2018). In this study, we tested three DSDs that had abundant small drops and maximum drop diameter of 2.9 mm or less. These DSDs had $Z_{DR}$ of 0.43–0.55 dB, very similar to Regime-II $Z_{DR}$ values. The corresponding $Z_H$ ranged between 29.1 and 35.7 dB. Considering that 0.9 mm is the smallest drop size where 2DVD has the correct drop number counts, we reassigned drop concentration for the first size bins, 0.1–0.7 mm, extending the slope of the distribution such that the modified DSDs had essentially an exponential distribution. While total concentration drastically increased before and after the modified DSD, the increase in $Z_H$ was less than 0.1 dB. This exercise showed that Regime II was not related to underestimation of small drops by 2DVD. Given the fact that the radar samples much greater volume than the disdrometer, it is feasible that the disdrometer may not sample less-frequent large drops. We artificially added a single drop at 1-, 2-, and 3-mm diameter larger than the observed $D_{\text{max}}$ of the three samples mentioned above. The presence of the additional drop enhanced $Z_H$ and $Z_{DR}$ as much as 6 and 2.3 dB, respectively, but it did not cross over to Regime I or II. It was also evident that NPOL observations in Regimes I and II were present regardless of 2DVD site distance to radar throughout field campaigns. Since this study was based on NPOL measurements, we questioned whether Regimes I and II exist in operational radars. Indeed, Regime I and Regime II do exist in NWS dual-polarization radars. To differentiate these unrealistic DSDs in radar observations, a matrix of $Z_H/Z_{DR}$ was created following Fig. 11c and is shown in Fig. 11d.

5. Conclusions

This study was motivated by the fact that the dual-polarization radar-based $N_W$ and $D_{\text{mass}}$ are required products for the validation of GPM DPR $N_W$ and $D_{\text{mass}}$ estimates. More specifically, the evaluation of the

FIG. 9. As in Fig. 7, but for log($N_W$).

FIG. 10. As in Fig. 8, but for log($N_W$).
ground-radar-based $D_{\text{mass}}$ is a requirement for the GPM GV program because it is a NASA level 1 science requirement for the GPM mission. Algorithm developers seek information on possible shortcomings of both ground- and spaceborne radar DSD estimates. A comparative study of radar-measured and disdrometer-calculated $Z_H$ and $Z_{DR}$ is the basis but is also a difficult task for evaluating radar-derived DSD parameters. Previous studies carefully selected and examined the agreement between disdrometer/radar $Z_H$ and $Z_{DR}$ pairs at optimum radar-disdrometer distance (15–40 km at S-band) (B04; T12), which is shorter for higher-frequency radars. This study included one or two optimum sites in each field campaign, but the ground clutter was a factor at the lowest elevation angle due to the site of NPOL antenna at the top of the container rather than on a tower. Using the second-lowest elevation, the NPOL beam height was 369 m above the ground at a distance of 15.2 km. This is comparable to the previous studies as being the best-case scenario. For most of the field studies including radar-estimated and gauge-measured rainfall comparative studies (Giangrande and Ryzhkov 2008; Cunha et al. 2013), the logistics did not allow deployment of the in situ devices near the radar site. Having the 2DVDs at various ranges from the NPOL radar (Fig. 1) enabled this study to quantify the level of agreement with distance.

As the best-case scenario, the absolute biases of $Z_H$ and $Z_{DR}$ were relatively low, ranging from 3.3 to 3.7 and from 0.27 to 0.32 dB, respectively at the shortest distance (15–20 km from the radar) in the absence of surface clutter for the three field campaigns. The corresponding absolute biases of $D_{\text{mass}}$ and $\log(N_W)$ were 0.31–0.36 mm and 0.34–0.98, respectively. The absolute bias in $Z_H$ increased with distance but was relatively low at the farthest distance during IFloodS and OLYMPEEx where the first elevation rather than the second elevation was used for the comparative study. Specifically, the absolute biases...
biases of $Z_H$ were about the same at 47.4 and 106.1 km distances from radar but the difference in the NPOL beam height was only 129 m because of the choice of first versus second elevation angles during IFloodS. This highlights the importance of time–height ambiguity.

During IPHEx, the absolute biases of $Z_H$ were higher at a given distance than during the other two field campaigns. This could be result of higher occurrence of heavy rain where size sorting is significant. Two of the 2DVDs (SN37 and SN38) were deployed in mountainous terrain to determine the role of orography in DSD characteristics. These two 2DVDs were over 100 km from NPOL with radar beam height 3.2 and 2.5 km above the ground after accounting the height difference between NPOL and the two sites. Considering the greater time–height ambiguity and greater difference in sampling volumes between 2DVD and NPOL observations, the agreement in $Z_H$ was poor at these two sites and they do not serve as a validation site for evaluating dual-polarization radar DSD retrieval algorithm.

A closer look at the NPOL-measured and 2DVD-calculated $Z_H$ and $Z_{DR}$ fields revealed two regimes. These regimes coincided with either under or overestimated NPOL-derived $\log(N_W)$. The combined Regimes I and II covered a considerable amount of the total observation, 9%–15%, of the coincident NPOL/2DVD database. When these regimes were removed from the database, the absolute biases were noticeably reduced for $Z_H$, $Z_{DR}$, $D_{mass}$, and $\log(N_W)$.

The 2DVD, a reference instrument, underestimates the concentration of small drops (Thurai and Bringi 2018) but the addition of small drops does not correspond to either Regime I or Regime II. The implication of these unrealistic DSD in NPOL observations could be significant for radar rainfall estimation. Hydrologists rely on radar rainfall estimates for flood forecasting and the majority of the comparative studies use rain gauges as a reference (Cunha et al. 2013). The accuracy of $Z_H/Z_{DR}$ couples should therefore independently be evaluated prior to radar rainfall estimation. The envelope of $Z_H/Z_{DR}$ presented here could be used as a reference in these studies.

Reflectivities $Z_H$ and $Z_{DR}$ are vital radar measurements for radar rainfall mapping. The study presented here showed the presence of surface clutter at radar distances of less than 15 km even after labor-intensive radar quality control. The quality control had to be relaxed; otherwise true precipitation would be removed along with the clutter. The best agreement between point 2DVD and areal NPOL $Z_H$ and $Z_{DR}$ was mostly at the second elevation of the radar except for the farthest sites during IFloodS and OLYMPEx. These factors play an important role in radar rainfall and DSD parameter mapping, both of which are used to direct comparison with the GPM satellite estimates.

There are parallel efforts in comparing ground-based and DPR-based rainfall (Petracca et al. 2018) and DSD parameters over Italy and the United States (D’Adderio et al. 2018; Petersen et al. 2020). One significant aspect of the comparison process is the careful DPR to ground-based geometric volume matching that has been implemented in the Validation Network software. The similar measurement

### Table 9. Comparison of 2DVD-calculated and NPOL-measured/estimated $Z_H$, $Z_{DR}$, $D_{mass}$, and $\log(N_W)$ before and after removal of the $Z_H/Z_{DR}$ pairs outside the 2DVD $Z_H/Z_{DR}$ envelope during IFloodS, IPHEx, and OLYMPEx. The bias and absolute bias statistics are given before (italics) and after (boldface) the removal of Regime I and II clusters. The reduction in sample size and its partitioning after removal of Regime I and II are also given.

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<th>Bias</th>
<th>Absolute bias</th>
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<td>$0.88$</td>
<td>$8.4$</td>
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type (radar) and closer spatial and temporal scales matched (Schwaller and Morris 2011) combined with an intrinsically large number of coincident samples should help to firmly establish (in a statistical sense) the degree to which the space-based estimates of the DSD converge with ground-based estimates toward demonstrating attainment of GPM level 1 science requirements that pertain to the DSD.

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