Comparative Evaluation of the OTT PARSIVEL2 Using a Collocated Two-Dimensional Video Disdrometer

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ABSTRACT

The performance of the OTT second-generation Particle Size Velocity (PARSIVEL2) laser weather sensor is evaluated by comparing it with a collocated two-dimensional video disdrometer (2DVD) and rain gauges using data collected over a total of 36 rain events. A comparison of raindrop size distributions (DSDs) between the 2DVD and two PARSIVEL2 reveals good agreement for weak rainfall rates below approximately 10 mm h\(^{-1}\) and for midsize drops with diameters between 0.6 and 4.0 mm irrespective of rainfall rates, whereas the PARSIVEL2 produces overestimations of large drops with diameters above 4 mm during heavy rainfall above approximately 20 mm h\(^{-1}\). The resultant DSD parameters of the PARSIVEL2 present overestimations of the mean diameter \(D_m\) in the normalized gamma function and the maximum drop diameter \(D_{\text{max}}\), and underestimations of the intercept parameter \(N_w\) and total number of drops \(N_T\). Furthermore, how the characteristics of DSDs from the PARSIVEL2 affect the polarimetric radar variables, such as differential reflectivity \(Z_{\text{DR}}\) and specific differential phase \(K_{\text{DP}}\), is examined, as well as how these characteristics affect empirical relations required in radar hydrometeorological applications such as quantitative rainfall estimations. Based on these examinations, it can be concluded that the OTT PARSIVEL2 still produces overestimations of large drops and underestimations of small drops during heavy rainfall, similar to older models of PARSIVEL, despite significant improvements to the PARSIVEL2 system, and furthermore that the uses of PARSIVEL2 measurements can act as a source of error in radar hydrometeorological applications such as radar rainfall estimations.

1. Introduction

Various types of disdrometers have been developed to measure raindrop size distribution (DSD) at the surface level, and information such as drop shape and fall velocity, based on a variety of different physical principles: 1) the impact-type electromechanical disdrometer developed by Joss and Waldvogel (1967), called JWD, which is based on the relationship between the sizes of falling raindrops and their colliding momentum on the sensor surface; 2) small Doppler radar–type disdrometers that retrieve DSD data from Doppler spectra, such as the Precipitation Occurrence Sensor System (POSS; Sheppard 1990) and Pludix (Caracciolo et al. 2006); and 3) optical disdrometers that analyze the amount a light source is interrupted by hydrometeors or that photograph silhouettes of hydrometeors, such as the Particle Size Velocity (PARSIVEL; Löffler-Mang and Joss 2000), the Thies Laser Precipitation Monitor (LPM; Frasson et al. 2011), the optical disdrometer ODM 470 (Bumke and Seltmann 2012), the two-dimensional video disdrometer (2DVD; Kruger and Krajewski 2002; Schönhuber et al. 2008), the Hydrometeor Velocity and Shape Detector (HVSD; Barthazy et al. 2004), and the high-speed optical disdrometer (HOD; Testik and Rahman 2016). Recently, among these types of disdrometers, PARSIVEL devices, as well as the LPM, which operates under a similar physical principle to PARSIVEL, have been widely employed to study the characteristics of precipitation (e.g., Yuter et al. 2006; Friedrich et al. 2013a, 2016). The PARSIVEL has advantages over other types of disdrometers, such as a relatively low cost, ease of installation and...
maintenance, and durability of hardware (Löffler-Mang and Joss 2000; Tokay et al. 2014). These advantages are useful points, particularly for experiments where multiple disdrometers are required, such as in studies of the spatial variability of precipitation within a small area (e.g., Tapiador et al. 2010; Jaffrain et al. 2011; Jameson et al. 2015; Raupach and Berne 2016).

The performance of the PARSIVEL disdrometer has been examined through several field experiments. Based on rain experiments, Krajewski et al. (2006) showed that the DSD data from PARSIVEL agreed well with those from a collocated 2DVD within the diameter range from 1.0 to 3.0 mm, whereas the PARSIVEL tended to measure higher numbers of small drops with diameter under 1.0 mm and to overestimate the mean drop diameter. Furthermore, they reported that the rainfall rates recorded by PARSIVEL were higher than those from the collocated 2DVD and rain gauges, particularly for high rainfall. Lanzinger et al. (2006) and Lanza and Vuerich (2009) also reported that the PARSIVEL and LPM overestimated rainfall rates compared with collocated rain gauges, and that this overestimation increased with increasing rainfall rate. From a comparison between collocated PARSIVEL and 2DVD, Thurai et al. (2011) found that the PARSIVEL measurements agreed well with the 2DVD measurements at low rainfall rates (<20 mm h\(^{-1}\)), but that at higher rainfall rates the PARSIVEL overestimated rainfall rates by 20% – 30% and that it also overestimated the mass-weighted mean diameters and standard deviations of the mass spectra. These results indicate that the PARSIVEL tends to overestimate large-sized raindrops. Tokay et al. (2013) also reported similar PARSIVEL performance results based on a comparative analysis with collocated 2DVD and JWD; when hourly rainfall rates exceeded 2.5 mm h\(^{-1}\), the drop concentration was overestimated for diameters above 2.4 mm and underestimated for diameters less than 0.76 mm. They further showed that this difference in DSDs had a pronounced effect on the DSD parameters fitted to normalized gamma distributions.

Regarding these PARSIVEL measurements, Krajewski et al. (2006) suggested that the overestimation of small drops may be affected by raindrop splashing associated with the structure of the instrument and condensation of water vapor on the glasses protecting the laser device. Battaglia et al. (2010) showed that the PARSIVEL system tended to overestimate sizes of particles by measuring the widest horizontal dimension as the representative equivolumetric diameter. Thurai et al. (2011) pointed out a coincidence (or double time) effect as a cause of the significant differences in PARSIVEL measurements. Because PARSIVEL detects hydrometeors passing through one sheet of the laser beam, two or more coinciding drops on the beam sheet may be detected as a single larger drop. In addition, small drops behind a larger drop cannot be counted. In general, this coincidence effect occurs more frequently in heavier rainfall. The coincidence effect of PARSIVEL was also mentioned by Yuter et al. (2006) and Battaglia et al. (2010). To resolve this problem, the PARSIVEL system employs a separation algorithm proposed by Raasch and Umhauer (1984); the coincidence effect persists however, although the probability of its occurrence is below 10%, as described in Löffler-Mang and Joss (2000). In contrast, through communication with the PARSIVEL manufacturer, Tokay et al. (2013) ascribed the over- and underestimations of the PARSIVEL device to the inhomogeneity of the laser beam. Adachi et al. (2013) resolved the issue of PARSIVEL’s rainfall overestimations by changing the predefined channels of drop diameter to new diameter values for which a concept of equivolumetric diameters was considered, based on the findings of Battaglia et al. (2010). Raupach and Berne (2015) proposed a method for correcting the PARSIVEL measurements, using a collocated 2DVD as a reference instrument, where the fall velocities of drops measured by PARSIVEL were adjusted to the theoretical terminal fall velocities in the literature and the drop concentrations measured by PARSIVEL were corrected so as to match those from 2DVD in a statistical way.

Many of the aforementioned studies of PARSIVEL used older models of the instrument, that is, the PM Tech model (Krajewski et al. 2006; Battaglia et al. 2010) or the first-generation model by OTT (Yuter et al. 2006; Tapiador et al. 2010; Jaffrain et al. 2011; Thurai et al. 2011; Tokay et al. 2013; Friedrich et al. 2013a,b, 2016; Adachi et al. 2013; Raupach and Berne 2015). The PARSIVEL system has been upgraded since the manufacture of the original version by PM Tech. In 2005, the PARSIVEL system was redesigned by OTT Hydromet with improvements such as protection from splashing and improvement of the sampling rate from 10 to 25 kHz (Battaglia et al. 2010). After further improvements, OTT recently (2011) developed the second-generation model of PARSIVEL (PARSIVEL\(^2\)); its main improvement is the more homogenous beams generated by the better laser device (Tokay et al. 2014). This upgraded model of OTT PARSIVEL\(^2\) was evaluated by Tokay et al. (2014) through a comparison with a collocated JWD, the first model of OTT PARSIVEL, and rain gauges. They confirmed from comparisons of hourly mean DSDs relative to the older PARSIVEL model that data from the PARSIVEL\(^2\) agreed better with those from the JWD not only for midsized drops between 0.5 and 4 mm but also for smaller and larger drops. In addition, they showed that the rainfall amounts recorded by PARSIVEL\(^2\) were in better agreement.
with those from rain gauges. Further, Tokay et al. (2016) showed good agreements between 2DVD and PARSIVEL\textsuperscript{2} using drop spectra collected from persistent light rainfall rates below approximately 10 mm h\textsuperscript{-1}, through comparisons of the probability density functions of the DSD and rain parameters. On the other hand, Raupach and Berne (2015) reported that the PARSIVEL\textsuperscript{2} still overestimated large drops compared to the 2DVD measurements, although the degree of overestimation was much smaller than that of the older OTT PARSIVEL model.

The findings of Tokay et al. (2014, 2016) demonstrate the reliability of the PARSIVEL\textsuperscript{2} system for use in studies of the microphysical processes of precipitation systems. However, because the JWD used by Tokay et al. (2014) as a reference instrument measures drops up to 5.3 mm in diameter, the performance of PARSIVEL\textsuperscript{2} for measuring larger drops is still unclear. The findings of Tokay et al. (2016) should also be extended to heavier rainfall, for a more robust evaluation of the PARSIVEL\textsuperscript{2}. In addition, in their examination, the impacts of differences in DSDs on dual-polarimetric radar variables (such as the radar reflectivity factor at horizontal polarization $Z_H$, the differential reflectivity $Z_{DR}$, and the specific differential phase $K_{DP}$) were not analyzed in detail. Therefore, for a more robust investigation of the reliability of the PARSIVEL\textsuperscript{2}, the performance of the PARSIVEL\textsuperscript{2} must be investigated further regarding measurements of small and large drops, and regarding the use of PARSIVEL\textsuperscript{2}'s DSDs in radar hydrometeorological applications such as in derivations of radar rainfall estimators and the various empirical relationships required in algorithms for validating and correcting radar measurements from real precipitations (e.g., Ryzhkov et al. 2005a,b; Park et al. 2005; Bellon and Fabry 2014; Frech et al. 2017).

In 2014, the Weather Radar Center (WRC) of the Korea Meteorological Administration (KMA) installed a test bed dual-polarimetric radar operating at an S-band frequency of 2.883 GHz (model: DWSR-8501S/K/SDP by the Enterprise Electronics Corporation). At the same time, a surface validation site (36.9824\textdegree N, 127.4445\textdegree E) was set up 29 km from the test bed radar for use in radar hydrometeorological applications. One 2DVD, two OTT PARSIVEL\textsuperscript{2}, and rain gauges (a total of eight) were set up 29 km from the test bed radar for use in validation site. The fall velocity of particles is also determined from the difference in time between when a particle is detected by particles in pixels. Using this pixel information from two different views, the characteristics of particles such as size and oblateness (or axis ratio) are calculated (Kruger and Krajewski 2002; Schönhuber et al. 2008). The full velocity of particles is also determined from the difference in time between when a particle is detected at each light sheet by two camera–lamp pairs, which are vertically separated by a height of approximately 6 mm. Because the 2DVD provides geometrical shape, size, and fall velocity data for individual hydrometeors, it has attracted attention for use in radar hydrometeorological studies (e.g., Bringi et al. 2001; Ryzhkov et al. 2005a,b; Thurai et al. 2007, 2014) and has further been used as a reference instrument in comparative evaluations of other types of disdrometers (Krajewski et al. 2006; Battaglia et al. 2010; Thurai et al. 2011; Tokay et al. 2013, 2016; Raupach and Berne 2015).

The 2DVD installed at the validation site is a compact type (serial number 79), and the line-scan camera has a frequency of 55 kHz (0.018 ms). The measurement area that is horizontally crossed by the two orthogonal light sheets is approximately 10 cm $\times$ 10 cm, which corresponds to 630 $\times$ 630 pixels with a resolution of approximately 0.165 mm, which slightly varies with...
distance from the camera because the measurement area is not an exact rectangle. To ensure high-quality measurements, the 2DVD system was calibrated via the embedded techniques using spherical iron balls with known diameters (Schönhuber et al. 2008). “Low-level calibration,” which involves dropping iron balls with diameters of 0.5–10.0 mm in order to fine-tune the 2DVD software to measure accurate particle sizes, was conducted in August 2014 and May 2015. “Plane distance calibration,” which is performed to obtain accurate fall velocity data through determination of the vertical height between the two light sheets, was conducted every 3–4 weeks.

The PARSIVEL system measures the size and fall velocity of particles that pass through a laser beam sheet. Size is determined from the decrease in voltage of the laser beam caused by a falling particle, whereas fall velocity is determined from the length of time that the laser beam is blocked (Löffler-Mang and Joss 2000; Battaglia et al. 2010). The two PARSIVELs installed at the validation site are the upgraded model of OTT PARSIVEL$^2$ (serial numbers 341497 and 341498). The transmitter and receiver of a laser beam are opposite to each other, in alignment with the east–west direction, and the laser beam has a wavelength of 780 nm. A sampling area of a laser beam sheet is 54 cm$^2$ (length: 180 mm, width: 30 mm, and depth: 1 mm) and a sampling frequency is 50 kHz. The PARSIVEL system records the number of particles detected every minute at the predefined 32 $\times$ 32 channels of diameter and fall velocity. The channels of diameter vary from 0.062 to 24.5 mm, with bin sizes increasing from 0.125 to 3.0 mm with diameter. The channels of fall velocity vary from 0.05 to 20.8 m s$^{-1}$, with bin sizes increasing from 0.1 to 3.2 m s$^{-1}$. One notable consideration is that the number of particles in the first (0.062 mm) and second (0.187 mm) diameter channels are always forced to be zero, because of the uncertainty associated with the low signal-to-noise ratio of the laser beam as noted in Tokay et al. (2014); consequently, in practice, particles are counted from the third channel (0.312 mm) with a bin size of 0.125 mm. Other assumptions and underlying limits employed in the PARSIVEL system, including the preassumed oblate shape for hydrometeors, the exaggeration of the equivolumetric diameter, the uncertainty in the fall velocity measurements, and the coincidence effect, are found in Battaglia et al. (2010).

3. Data and analysis

a. Data

To examine the performance of PARSIVEL$^2$, drop spectra collected from the 2DVD and PARSIVELs at the validation site during May–November 2014 and April–July 2015 were analyzed and compared. Data were collected from a total of 36 rain events, which included various types of precipitation, such as a single storm cell on 24 June 2015 that produced a total of 18 mm of rainfall over 40 min with a maximum 1-min rainfall rate of 102 mm h$^{-1}$; deep convective cells that passed consecutively on 18 July 2014 and produced 133 mm of rainfall over 9 h; and stratiform rainfall on 20–22 October 2014 with a total of 85 mm of rainfall over 28 h. Using the measurements collected during these 36 rain events, the OTT PARSIVEL$^2$ system was
evaluated through a comparison with measurements from the 2DVD and rain gauges, after data processing with the quality control procedures described below.

b. Processing the 2DVD measurements

The 2DVD measurements were first aggregated in intervals of 1 min. To remove mismatched drops (or outliers) and to extract pure raindrops, the velocity-based filter suggested by Kruger and Krajewski (2002) was then applied individually to these 1-min data. In this filtering scheme, drops outside the range of \( \pm 40\% \) from the expected velocity based on the velocity–diameter relation in Atlas et al. (1973) were removed. After the filtered 1-min data were categorized into 32 diameter channels (from 0.125 to 7.875 mm with a bin size of 0.25 mm), 1-min DSD \( [N(D) \text{ in } \text{mm}^{-1}\text{m}^{-3}] \) data were determined according to the formula of Kruger and Krajewski (2002):

\[
N(D_i) = \frac{10^6}{\Delta D \Delta t} \sum_j \frac{1}{A_j v_j},
\]

where \( \Delta D \) and \( \Delta t \) denote the bin size (0.25 mm) and sampling time (60 s), respectively; \( D_i \) and \( v_j \) denote the diameter (mm) at the \( i \)th channel and the fall velocity (ms\(^{-1}\)) of the \( j \)th drop, respectively; \( A_j \) is the effective measuring area (mm\(^2\)) for drop \( j \). In this study, in (1) the terminal fall velocities expected by the diameter–fall velocity relation of Atlas et al. (1973) were simply used, instead of the measured velocities from the 2DVD, because it is known that the fall velocities measured by 2DVD are very consistent with terminal velocities expected from diameter–fall velocity relations in the literature (e.g., as shown in Raupach and Berne 2015). Individual 1-min DSDs calculated by (1) were further processed: DSDs were removed if the total number of drops was less than 30 m\(^{-3}\) or if the number of channels where drops were detected was smaller than 4. DSDs with rainfall rates below 0.01 mm h\(^{-1}\) were also removed.

In the 2DVD system, lockup of data acquisition occurs sometimes, as noted in Kruger and Krajewski (2002). At midnight each day, the system is locked up and rebooted over approximately 2 min to create a file set for the new day, and at every hour on the hour for a few tens of seconds to normalize the background video signal. In addition to these systematic lockups, the system is randomly locked up by an embedded watchdog program when unexpectedly large objects such as insects are detected. The system would also be locked up occasionally under strong wind conditions because raindrops aggregate on the slit through which the light passes, and the large resulting water drop obscures the light’s path. Although the durations of these lockups may be short, from a few seconds to several minutes, the resulting losses of valuable data are not negligible, especially under intense rainfall (see the appendix for an example). In this study, to compare DSDs from 2DVD and PARSIVEL quantitatively, these losses of 2DVD measurements were checked using the “log files” that contain size and time information (at 3-s intervals) for data transferred from the data acquisition unit to the analysis unit (see Table 1 of Kruger and Krajewski 2002). During the collection of a given 1-min DSD, when data missing from the data transfer were found in the log file, the 1-min DSD was removed. However, in comparison of rainfall amounts with rain gauges, this loss of 2DVD measurements was not considered, and all of the DSD data were accumulated.

c. Processing the PARSIVEL measurements

The PARSIVEL measurements for 1-min intervals were processed using a filtering scheme proposed by Friedrich et al. (2013b) to remove margin fallers, splashes, and nonraindrops. As shown in Fig. B1 of Friedrich et al. (2013b), the rain regime is limited to up to 8 mm in diameter (i.e., the 23rd channel), and for small and midsized drops (\( D < 4 \) mm) the upper and lower boundaries of the rain regime correspond to a velocity range from approximately 60% to \( \pm 40\% \) from the expected velocity based on the velocity–diameter relation of Atlas et al. (1973), while for large drops (\( D > 4 \) mm) the lower boundary denotes higher velocities than those of the \( \pm 40\% \) boundary applied to the 2DVD data. Using these filtered data, the 1-min DSDs \( [N(D) \text{ in } \text{mm}^{-1}\text{m}^{-3}] \) were determined as

\[
N(D_i) = \sum_j \frac{10^6 n(D_i, v_j)}{A_j \Delta D_i \Delta t},
\]

where \( n(D_i, v_j) \) denotes the number of drops measured at the \( i \)th diameter (mm) channel and the \( j \)th velocity (ms\(^{-1}\)) channel; \( \Delta D_i \) is the bin size of the \( i \)th diameter channel (Friedrich et al. 2013b; Tokay et al. 2014); and \( A \) and \( \Delta t \) denote the sampling area (mm\(^2\)) and the sampling interval (s), defined as 180 mm \( \times (30 \text{ mm} - 0.5D_i) \) and 60 s, respectively, for our PARSIVEL system. In (2), the fall velocities measured directly by the PARSIVEL systems were used, because the purpose of this study is to evaluate the performance of the PARSIVEL\(^2\). The 1-min DSDs calculated using (2) were further processed with the same thresholds defined in the 2DVD processing procedure, that is, a total number of drops of at least 30 m\(^{-3}\), a total number of channels of detected drops of at least 4, and a rainfall rate of at least 0.01 mm h\(^{-1}\).

In recording PARSIVEL measurements, a problematic phenomenon occasionally occurs in which measurements taken over consecutive time steps are not
recorded at each accurate time step but are recorded together at the next time step, as if unreasonably numerous drops were detected during that 1 min (see the appendix for an example). Based on our observations, this delay occurs randomly and is not related to rainfall intensity. In this study, for a quantitative comparison of DSDs between PARSIVEL and 2DVD, DSDs recorded when this delay occurred were removed. However, in calculations of rainfall amounts, all 1-min DSDs were accumulated, including these delayed DSDs.

d. Calculation of rain parameters and scattering simulation

The 1-min DSDs from 2DVD and PARSIVEL processed by the procedures described above were then used to derive rainfall amounts, DSD parameters fitted to the normalized gamma function, and theoretical radar variables. For integration of DSDs to calculate rainfall rates, the diameter–fall velocity relation of Atlas et al. (1973) was applied to both the 2DVD and PARSIVEL data, instead of directly using the measured values from each instrument, to eliminate instrumental differences in the fall velocity measurements. The DSD parameters of the normalized gamma function (Testud et al. 2000), defined by three parameters of the intercept parameter $N_w$ (mm$^{-1}$m$^{-3}$), the mass-weighted mean diameter $D_m$ (mm), and the shape parameter $\mu$, were derived through the scheme presented by Bringi et al. (2001). The water content $W$ (g m$^{-3}$) from the integration of the collected drops and $D_m$ from the third- and fourth-order moments of the drop spectra are first calculated, from which the $N_w$ is calculated. Using the calculated $N_w$ and $D_m$ values, an optimum $\mu$ is found so as to most closely fit to a measured DSD. In addition to these three parameters, the total number of drops $N_T$ (m$^{-3}$) and the maximum drop diameter $D_{max}$ (mm) were also calculated and compared between the 2DVD and PARSIVELs.

The polarimetric radar variables of $Z_A$, $Z_{DR}$, and $K_{DP}$ were calculated via a T-matrix scattering simulation algorithm (courtesy of Professor V. N. Bringi of Colorado State University) at the frequency (2.883 GHz) of the test bed radar of KMA’s WRC, with conditions of a temperature of 10°C, an elevation angle of the radar antenna of 0°, and a Gaussian canting angle distribution with a mean of 0° and a standard deviation of 7°. For raindrop oblateness, the formulas recommended by Thurai et al. (2007) were used; that is, for $D > 1.5$ mm the formula obtained by Thurai et al. (2007) from the 80-m fall bridge experiments was used, whereas that by Beard and Kubesh (1991) was used for $0.7 \leq D \leq 1.5$ mm, and a spherical shape was used for $D < 0.7$ mm. These conditions were applied equally to both the 2DVD and PARSIVEL DSDs.

4. Results

a. Drop size distributions

For the 36 rain events, the procedures described above resulted in a total of 13,353 coincident 1-min DSDs from the 2DVD and two PARSIVELs. Using these datasets, DSDs averaged in categories divided based on rainfall rate were first compared as shown in Fig. 2. The DSDs from the 2DVD and PARSIVELs show good agreement for midsize drops of about 0.6–4.0 mm in diameter irrespective of rainfall rates. In addition, the concentrations of small drops below 0.6 mm show good agreement at weak and moderate rainfall ($R < 10$ mm h$^{-1}$). These results are very consistent with the findings of Tokay et al. (2014, 2016). At higher rainfall however, the DSDs of PARSIVELs differ slightly from those of the 2DVD for small drops below 0.6 mm and large drops above 4.0 mm in diameter. The PARSIVELs present lower concentrations than the 2DVD for small drops, whereas the opposite is the case for large drops. The overestimation of PARSIVEL for large drops is clearer at higher rainfall rates (cf. Fig. 2e vs Fig. 2f), in which the maximum drop diameters are also larger from PARSIVEL than from the 2DVD.

Figure 3 shows comparisons of the DSD parameters for the drop spectra obtained from the 2DVD and the two PARSIVELs. In this comparison, the differences between the PARSIVEL data and the 2DVD data were quantified in terms of normalized relative error (NRE) and normalized relative bias (NRB), defined as

$$\text{NRE} = \left(\frac{\{P(\text{PARSIVEL}) - P(\text{2DVD})\}}{P(\text{2DVD})}\right) \times 100\%,$$  

and

$$\text{NRB} = \left(\frac{\{P(\text{PARSIVEL}) - P(\text{2DVD})\}}{P(\text{2DVD})}\right) \times 100\%,$$  

where $P$ denotes one of the DSD parameters and the angle brackets $<>$ denote a mean value. To evaluate the performance of the PARSIVEL system, as in (3), the 2DVD data were considered reference values because they have relatively high reliability through objective calibrations using spherical iron balls with known diameters, as described in section 2. Table 1, which lists the resulting NRE and NRB values, shows that the discrepancies of the DSD parameters are slightly larger in the comparisons between the 2DVD and PARSIVELs than in the comparisons between the PA1 and PA2. In the case of $N_w$, for example, the NRE of 23.6% in the comparison between the PA1 and PA2 slightly increases to 31.5% and 24.2% in the comparisons between the 2DVD and PA1 and between the 2DVD and PA2, respectively. The other DSD parameters also
present somewhat larger NRE values in comparisons between the 2DVD and PARSIVELs than in comparisons of the two PARSIVELs. The discrepancies of the DSD parameters between the two PARSIVELs can be mainly attributed to sampling differences associated with the finescale spatial variability of precipitation. Regarding the increases in discrepancies between the 2DVD and PARSIVELs, however, a difference in

Fig. 2. Mean DSDs in the individual categories of $R$ (mm h$^{-1}$). Symbols $\bullet$, $+$, and $\Delta$ denote the mean drop spectra from 2DVD, PA1, and PA2, respectively. DSDs fitted to the normalized gamma function (lines).
performance between the two different instruments should be considered as a major cause, considering the 14-m distance between the two PARSIVELs with the 2DVD located at the center between them, as shown in Fig. 1.

Compared to the other DSD parameters, $\mu$ presents relatively large increases of NRE values in the comparisons between the 2DVD and PARSIVELs, and significant discrepancies between the 2DVD and PARSIVEL data are apparent in Fig. 3c. Most (the central 90th percentile) of the $\mu$ values obtained from the 2DVD shown in Fig. 3c occurred within 0.2–8.0, with a mode of 3.0. This range is consistent with previously reported results, such as those of Maki et al. (2005) from drop spectra collected via JWD in Darwin, Australia, where the central 90th percentile of $\mu$ values

**Fig. 3.** Comparisons of the DSD parameters obtained from the 2DVD and the two PARSIVELs: (a) $D_m$, (b) $N_w$, (c) $\mu$, (d) $D_{max}$, and (e) $N_T$. Color scales and contours denote the number concentrations of the data pairs (logarithmic scale) for PA1 and PA2, respectively.
occurred within a range of 1.5–7.0, with a mode of 2.2. In contrast, the range of \( m \) values from the PARSIVELs was too wide; on average, the 90th percentile ranged from 20.7 to 18.4, with a mode of 4.5. One notable thing in Fig. 3 is that the DSD parameters of the two PARSIVELs tend to deviate greatly from those of the 2DVD as their values increase, although good agreement is shown for smaller values. The \( \mu \) values of the PARSIVELs are larger than those of the 2DVD at values above approximately 2 mm, whereas the \( N_w \) and \( N_T \) values of the PARSIVELs are underestimated at values above approximately \( 10^2 \text{mm}^{-1} \text{m}^{-3} \) and \( 10^3 \text{m}^{-3} \), respectively, compared to those of the 2DVD.

Because the larger values of the DSD parameters usually correspond to higher rainfall rates, differences in the DSD parameters between the 2DVD and PARSIVELs were analyzed with respect to rainfall rates (\( \mu \) was not analyzed because it is not directly related to rainfall rate). As shown in Fig. 4, where the DSD parameters were averaged for the rainfall rates from each respective instrument, the DSD parameters from the two PARSIVELs are similar to each other, and the subtle differences between them do not vary with rainfall rate, whereas the differences in these parameters between the 2DVD and the two PARSIVELs increase with increasing rainfall rates. The \( D_m \) values from the 2DVD and the two PARSIVELs agree well up to a rainfall rate of about 20 mm h\(^{-1}\), whereas at 50 mm h\(^{-1}\) the values from the 2DVD and the two PARSIVELs are 1.92 and 2.14 mm, respectively, which correspond to an overestimation of 11% for the PARSIVELs. At the higher rainfall rate of 120 mm h\(^{-1}\), the overestimation of the PARSIVELs increases to 34%, with \( D_m \) values from the 2DVD and PARSIVELs of 1.86 and 2.5 mm, respectively. In the case of \( N_w \), the PARSIVELs present underestimates at rainfall rates above 20 mm h\(^{-1}\), of −6% and −13% at 50 and 120 mm h\(^{-1}\), respectively. The \( D_{max} \) values from the PARSIVELs present overestimations of 1.4% and 29% at rainfall rates of 50 and 120 mm h\(^{-1}\), respectively. In the case of \( N_T \), the

| TABLE 1. NRE and NRB (%) of the DSD parameters between the 2DVD and two PARSIVELs. In the comparison of PA1 vs PA2, the NRE and NRB values denote those of PA2 with respect to PA1, whereas the other columns show comparisons of the PARSIVELs with respect to the 2DVD. |
|---------------------------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
|                                | PA1 vs PA2       | 2DVD vs PA1     | 2DVD vs PA2     |                  |                  |                  |
|                                | NRE  | NRB  | NRE  | NRB  | NRE  | NRB  |
| \( D_m \)                      | 5.5  | −0.4 | 6.2  | 0.2  | 5.9  | −0.2 |
| \( N_w \)                      | 23.6 | 18.4 | 31.5 | −20.4 | 24.2 | −6.3 |
| \( \mu \)                      | 32.0 | −17.6 | 96.4 | 79.9 | 73.1 | 47.8 |
| \( D_{max} \)                  | 12.0 | 1.1  | 12.1 | −4.0 | 12.0 | −2.9 |
| \( N_T \)                      | 20.6 | 19.0 | 44.5 | −43.1 | 38.3 | −33.4 |

FIG. 4. Variations of the DSD parameters with rainfall rates: (a) \( D_m \), (b) \( N_w \), (c) \( D_{max} \) and (d) \( N_T \). 2DVD 1-min data (gray dots). Mean values over rainfall-rate intervals of 10 mm h\(^{-1}\) (lines).
Fig. 5. Comparisons of the DSD parameters from the 2DVD and two PARSIVELs during the period 0500–1200 LST 24 Jul 2015: (a),(b) $D_m$; (c),(d) $\log_{10}(N_w)$; (e),(f) $\mu$; (g),(h) $D_{\text{max}}$; (i),(j) $\log_{10}(N_T)$; and (k),(l) rainfall rates and cumulative amounts. (left) Time series and (right) scatterplots. Indicated rainfall rates and amounts from gauges represent the mean values of the three RGT01 gauges.
PARSIVELS underestimate in the entire range of rainfall rates, up to -21% at 120 mm h⁻¹. These increases in the discrepancies of the DSD parameters with rainfall rates are also clearly presented in Fig. 5, which shows variations of the DSD parameters with time for an event on 24 July 2015. For times near 0810 and 0910 LST, when rainfall rates above 40 mm h⁻¹ were recorded by the rain gauges (Fig. 5f), the PARSIVELS present larger $D_m$ and $D_{\text{max}}$ values than does the 2DVD, whereas the PARSIVEL $N_w$ and $N_T$ values are smaller than those from the 2DVD. In contrast, at weak rainfall rates below 20 mm h⁻¹—for example, at 1000 LST—good agreement between the 2DVD and the two PARSIVELS is shown.

Regarding these characteristics of DSDs from the PARSIVEL² system—that is, underestimation of small drops and overestimation of large drops, and consequent overestimations of $D_m$ and $D_{\text{max}}$ and underestimations of $N_w$ and $N_T$ during heavy rainfall above approximately 20 mm h⁻¹—it should be considered that the PARSIVEL² system forces the measurements at the lowest two diameter channels to be zero, and that the diameter channels and bin sizes used to construct 1-min DSDs differ from those of the 2DVD. To examine these effects, the abovementioned analyses were conducted again after the DSDs from the 2DVD were reconstructed using the same diameter channels and bin sizes used by the PARSIVEL system with no drops in the first and second channels. Although this reexamination varied the DSDs from the 2DVD, the impact was too small to discern any apparent differences from the results described above. In the case of $\mu$, for example, the large differences between the 2DVD and PARSIVELS described above were slightly reduced; the reconstructed drop spectra of the 2DVD presented the central 90th percentile range of $\mu$ from -2.0 to 13.1. In the case of $D_{\text{max}}$, the reconstructed data of the 2DVD produced NRE (NRB) values of 11.8% (-4.2%) and 11.6% (-3.1%) for the PA1 and PA2, respectively, which are very similar to the values in Table 1. This low variation of $D_{\text{max}}$ indicates that a quantization error caused by the bin broadening of the PARSIVEL (i.e., the bin widths of the PARSIVEL increase with diameter and reach 1.0 mm at a diameter channel of 5.5 mm, whereas in the 2DVD they are fixed to 0.25 mm for all diameter channels) is not an important factor in the quantitative comparison of $D_{\text{max}}$ shown in the previous analyses. Note that the negative NRB values are due to the slightly larger $D_{\text{max}}$ from the 2DVD compared with the PARSIVELS at $R < 10 \text{ mm h}^{-1}$, where numerous data exist, as shown to a degree in Fig. 4c. However, at higher rainfall ($R > 20 \text{ mm h}^{-1}$), the PARSIVELS still produced larger $D_{\text{max}}$ values than did the 2DVD, despite bin synchronization. In the case of $N_T$, the NREs
(NRBs) of PA1 and PA2 with respect to the 2DVD decreased to slightly 39.8% (−37.7%) and 34.3% (−26.7%), respectively, compared with those in Table 1, which indicates that the \( N_T \) values from 2DVD became slightly closer to those from the PARSIVELs. However, the underestimation of \( N_T \) in the PARSIVEL measurements nevertheless occurred, with similar differences to those shown in Fig. 4. This minor variation of \( N_T \) occurs because the bin synchronization with the PARSIVEL results in removal of drops only in the first diameter channel (\( D < 0.25 \text{ mm} \)) in the 2DVD drop spectra. The other DSD parameters (\( D_m \) and \( N_w \)) also did not present any apparent differences from those in Fig. 4 (the results are not shown). Therefore, it can be concluded that the binning effect is negligible in the quantitative comparisons of the 2DVD and PARSIVELs conducted in this study.

Another cause of the characteristics of the PARSIVEL\(^2\) DSDs may be a strong wind effect. Friedrich et al. (2013b) reported that the stationary PARSIVEL system, with a fixed laser beam orientation like that of the PARSIVELs in this study, consistently produced artifacts characterized by a high concentration of raindrops with large diameters (above 5 mm) and unrealistically low fall velocities (below 1 m s\(^{-1}\)) under strong winds with speeds above 10 m s\(^{-1}\). They therefore suggested the deployment of an articulating PARSIVEL system that rotates in azimuthal and elevational directions such that the long axis of the laser beam sheet can be perpendicular to the wind direction. An analysis of the wind measurements from the collocated ultrasonic anemometer installed 1 m to the east of the 2DVD (Fig. 1) revealed that the winds during the rain events analyzed in this study were weak. Based on the 1-min mean wind data, most measured wind speeds (98.1%) were below 3.4 m s\(^{-1}\) and strong wind speeds above 8.0 m s\(^{-1}\) were not observed. The prevailing winds were easterly and east-northeasterly, with frequencies of occurrence of 10.4% and 11.9%, respectively, and the other wind directions occurred with frequencies below 6% each. For maximum instantaneous winds over an interval of 1 min, 83.4% of the measurements showed speeds below 3.4 m s\(^{-1}\), and strong wind speeds above 8.0 m s\(^{-1}\) accounted for only 0.1% of the total. Therefore, under these weak wind conditions, it is likely that the impact of winds on the PARSIVEL measurements was not large enough to alter the characteristics of the PARSIVEL\(^2\) DSDs obtained in this study. In practice, the PARSIVEL measurements used in this study did not present artifacts and large scattering of drop spectra in the diameter–fall velocity histograms such as those presented by Friedrich et al. (2013b). Furthermore, the PARSIVEL measurements in this study were already processed using the filtering scheme suggested by Friedrich et al. (2013b), and an overestimation of large drops as a result of strong winds is therefore unlikely to be significant. However, to mitigate the wind effect, the present orientation of the laser beam sheet of the PARSIVELs installed at the validation site should be changed to alignment with the north–south direction, such that the long axis of the laser sheet can be perpendicular to the prevailing wind. In addition, it may be helpful to deploy and compare with an articulating PARSIVEL system for more robust quantification of the strong wind effect.

Because the purpose of this study was to evaluate the performance of the PARSIVEL\(^2\), the 1-min DSDs from the PARSIVELs in (2) were made using the measured fall velocities. However, the fall velocities measured by the PARSIVELs are somewhat erroneous as reported by Tokay et al. (2014, 2016). To examine the effect of fall velocity on DSDs, 1-min DSDs of the PARSIVELs were recalculated using terminal fall velocities from the relation of Atlas et al. (1973). In comparing 1-h rainfall accumulations with the rain gauge measurements, the DSDs of the PARSIVELs using the terminal fall velocities produced underestimations, with NRE (NRB) values of 7.7% (−5.0%) and 7.7% (−4.7%) for PA1 and PA2, respectively. These underestimations are opposite of the results in Fig. 6, which will be shown in section 4b, where the rainfall accumulations from the PARSIVELs are derived from DSDs calculated using the measured fall velocities by each instrument and they present overestimations with respect to the rain gauge measurements. These underestimations from using the terminal velocities indicate that the concentrations of drops decreased slightly, because of relatively small measured velocities compared to the terminal velocities. In practice, it was revealed that the fall velocities measured by the PARSIVELs during the 36 rain events were smaller by approximately 1 m s\(^{-1}\) than the terminal velocities for drops with diameters above 1 mm, similar to the results shown in Tokay et al. (2014). However, despite these decreases in drop concentrations, the DSDs from the PARSIVEL\(^2\) still presented overestimations of large drops during heavy rainfall, although the magnitude of the differences from those of the 2DVD was slightly reduced. Furthermore, the DSD parameters from the PARSIVEL\(^2\) still presented overestimations of \( D_m \) and \( D_{\text{max}} \) and underestimations of \( N_w \) and \( N_T \), with magnitudes of differences from the 2DVD similar to those shown in Fig. 4.

Based on the abovementioned results, it is concluded that the OTT PARSIVEL\(^2\) system still produces overestimations of large drops at high rainfall above approximately 20 mm h\(^{-1}\), as reported in previous studies.
of older models of PARSIVEL (Thurai et al. 2011; Tokay et al. 2013), although the PARSIVEL2 system produces significantly better DSD measurements than do older models, as described by Tokay et al. (2014).

b. Rainfall amounts

Figure 6 shows comparisons of 1-h rainfall amounts between the 2DVD and rain gauges (Fig. 6a) and between the PARSIVELs and rain gauges (Fig. 6b). In this comparison, the rainfall amounts from the three RGT01 gauges were averaged to mitigate the finescale spatial variability of precipitation. As shown in this figure, the rainfall amounts recorded by the 2DVD and PARSIVELs present good agreement with those from the gauges, with NREs of approximately 7%. The 2DVD slightly underestimated rainfall amounts with a bias of −3.9%, whereas the two PARSIVELs overestimated amounts with a mean bias of 4.4%. These biases of approximately ±4% obtained from the 2DVD and PARSIVELs are small enough to be acceptable for radar hydrometeorological applications.

c. Radar variables

The effects of the characteristics of DSDs from the PARSIVEL2 system—that is, the overestimation of large drops and the underestimation of small drops at high rainfall—on the radar variables of $Z_H$, $Z_{DR}$, and $K_{DP}$ were investigated. Figure 7 shows comparisons of the radar variables simulated from 13 353 coincident 1-min drop spectra of the 2DVD and the PARSIVELs, and Table 2 contains the NRE and NRB values of the radar variables from the PARSIVELs with respect to those from the 2DVD. Similar to the comparisons of the DSD parameters described earlier, Table 2 shows that the radar variables have relatively large differences between the 2DVD and PARSIVELs in contrast to comparisons between the two PARSIVELs. In particular, the biases increase significantly in comparisons between the 2DVD and the PARSIVELs. The NRB value of $Z_{DR}$ is only 2.4% between the two PARSIVELs, whereas it increases to −18.5% and −16.2% in the comparisons of PA1 and PA2, respectively, with the 2DVD. The $K_{DP}$ values from the PARSIVELs also present significant underestimations, with biases of −12.2% and −11.7% for PA1 and PA2, respectively. In the case of $Z_H$, the two PARSIVELs present relatively small underestimations compared to the other variables, −5.7% and −5.1%, respectively.

These underestimations of the radar variables from the PARSIVELs are confirmed in Fig. 7. The $Z_H$ values (Fig. 7a) from the PARSIVELs agree well with those from the 2DVD, without an apparent underestimation, as expected from the small underestimations listed in Table 2. However, the $Z_{DR}$ values from the PARSIVELs (Fig. 7b) are smaller than those from the 2DVD, in the range below approximately 0.8 dB, which includes most data (90%), whereas at larger values above 0.8 dB $Z_{DR}$ values from the PARSIVELs are larger than those from the 2DVD. The $K_{DP}$ values from the PARSIVELs (Fig. 7c) are also smaller than those from the 2DVD over the entire range. These phenomena of the radar variables are shown more clearly in Fig. 8, which presents variations of these radar variables with time and scatterplots for the rain event during the period 0500–1200 LST 24 July 2015. Unlike the $Z_H$ values, which show good agreement, the $Z_{DR}$ and $K_{DP}$ values reveal significant differences between the 2DVD and PARSIVEL results, with similar patterns to those shown in Fig. 7. In particular, the $Z_{DR}$ values from the
PARSIVELs present spikes above 0.8 dB, with significantly larger values than those from the 2DVD, at 0615, 0705, and 0735 LST, and near 0810 and 0910 LST (Fig. 8b), when rainfall rates higher than 20 mm h\(^{-1}\) were recorded (Fig. 5f) and when the \(D_{\text{max}}\) values from the PARSIVELs were larger than those from the 2DVD (Fig. 5d). These spikes in \(Z_{\text{DR}}\) at high rainfall rates are found in the regime of overestimation above 0.8 dB shown in Fig. 8e, in which a value of 1 dB from the 2DVD corresponds to a value of about 1.7 dB from the PARSIVELs. In contrast, the \(Z_{\text{DR}}\) values at weak rainfall are found in the regime of underestimation in Fig. 8e. In the case of \(K_{\text{DP}}\) (Fig. 8f), the underestimations of the PARSIVELs are shown to become more severe gradually as its value increases, that is, as the rainfall rate increases.

For weak rainfall, the underestimations of \(Z_{\text{H}}, Z_{\text{DR}},\) and \(K_{\text{DP}}\) by the PARSIVELs are natural because \(N_T\) is smaller in PARSIVEL data than in the 2DVD data, as described above. For the \(Z_{\text{H}}\) values from the PARSIVELs at high rainfall, with similar or slightly lower values than those from the 2DVD, it is inferred that in integration for calculating \(Z_{\text{H}}\), the increase from overestimation of large drops by the PARSIVELs counterbalances the decrease from the underestimated small drops, because the number concentrations of small drops are much higher than those of large drops. In contrast, for the underestimation of \(K_{\text{DP}}\) by the PARSIVELs at high rainfall rates, it is inferred that \(K_{\text{DP}}\) is affected more strongly by the decrease associated with underestimation of small drops than by the increase from overestimation of large drops because \(K_{\text{DP}}\) is less sensitive to natural variations in DSD (i.e., proportional to the 4.24th moment of the drop diameter at S-band frequency) than is \(Z_{\text{H}}\) (i.e., proportional to the 6th moment) (Ryzhkov and Zrnić 1996). In practice, Maki et al. (2005, see their Fig. 8) showed that the \(K_{\text{DP}}\) for a DSD is affected more strongly by relatively small drops compared to \(Z_{\text{H}}\) which is more strongly affected by relatively large drops. Regarding the overestimations of \(Z_{\text{DR}}\) by the PARSIVELs at high rainfall rates, it should be noted that \(Z_{\text{DR}}\) is related to the \(D_m\) of a DSD by a power law (e.g., Thurai et al. (2008)). Consequently, at high rainfall rates, the \(Z_{\text{DR}}\) values of the PARSIVELs

<table>
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<th>Table 2. As in Table 1, but for the radar variables.</th>
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<td>(Z_{\text{H}})</td>
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FIG. 7. Comparisons of (a) \(Z_{\text{H}},\) (b) \(Z_{\text{DR}},\) and (c) \(K_{\text{DP}}\) between the 2DVD and PARSIVELs for a total of 36 rain events. Color scales and contours denote the number concentrations of the data pairs (logarithmic scale) for PA1 and PA2, respectively.
become much larger than those of the 2DVD because of the overestimation of large drops, as represented by larger $D_m$ and $D_{max}$ values in Fig. 5.

d. Relations among the radar variables and rainfall estimators

It was examined how much the differences in the radar variables between the 2DVD and PARSIVELs results affect the relations required in hydrometeorological applications. Table 3 lists the $Z_{DR}$-$Z_H$, $K_{DP}$-$Z_H$, and $K_{DP}$-$Z_{DR}$ relations derived via nonlinear regression analysis from the radar variables calculated using 13 353 coincident 1-min DSDs of the 2DVD and PARSIVELs. These types of relations have been widely used to evaluate radar measurements of real precipitation and to calibrate the $Z_H$ and $Z_{DR}$ measurements for system gain biases (e.g., Park et al. 2005; Ryzhkov et al. 2005b; Bellon and Fabry 2014) based on self-consistency among the radar variables (Gorgucci et al. 1999). As shown in Table 3, the relations between two PARSIVELs are very close, whereas relatively large differences are found in comparisons between the 2DVD and PARSIVELs. For example, the coefficients and exponents of the $Z_{DR}$-$Z_H$ relations of the PARSIVELs are almost same, 0.04 and 0.34, respectively, whereas those of the 2DVD relation are 0.07
and 0.28, respectively. In contrast to the $Z_{DR}-Z_H$ and $K_{DP}-Z_H$ relations, the $K_{DP}-(Z_H,Z_{DR})$ relation of the 2DVD is almost the same as those of the two PARSIVELs. Figure 9 shows comparisons of these relations between the 2DVD and PARSIVELs, including the relative estimation errors of the PARSIVEL relations (Figs. 10b, 10d, and 10f), with respect to the 2DVD relations. In calculations of these relative errors, the $Z_{DR}$ and $K_{DP}$ values were first selected arbitrarily. From these reference values, the $Z_H$ values were calculated reciprocally from the 2DVD relations and were then substituted into the PARSIVEL relations. Therefore, the retrieved values from the 2DVD relations based on the inputted reference values correspond correctly to the reference values without any errors, as indicated by the 1:1 lines and the dashed black lines in the right panels of the figure. In contrast, the retrieved values from the relations of the PARSIVELs deviate from the 1:1 lines, and these differences are defined as the relative estimation errors of the PARSIVEL relations. As shown in the figure, the $Z_{DR}-Z_H$ (Fig. 9a) and $K_{DP}-Z_H$ relations (Fig. 9c) of the 2DVD describe its 1-min data well, which demonstrates the reliability of the relations derived in this study. The $K_{DP}$ values retrieved from the $K_{DP}-(Z_H,Z_{DR})$ of the 2DVD data (Fig. 9e) are also in good agreement with the corresponding inputted 1-min data.

Based on a comparison of the $Z_{DR}-Z_H$ relations between the 2DVD and the PARSIVELs (Fig. 9a), the PARSIVEL relations overestimate $Z_{DR}$ compared with the 2DVD relation when $Z_H > 40$ dBZ, whereas the opposite is the case for $Z_H$ values below 40 dBZ, because of the overestimations of $Z_{DR}$ by the PARSIVELs at high rainfall rates and underestimations at weaker rainfall, as discussed above. These differences result in relative estimation errors from $-20\%$ to $30\%$ with increasing $Z_{DR_{reference}}$ from 0.3 to 3 dB (Fig. 9b). The $K_{DP}-Z_H$ relations of the PARSIVELs underestimate $K_{DP}$ in the overall range of $Z_H$ (Fig. 9c) compared with the 2DVD relation and, consequently, their estimation errors reach approximately $-15\%$ within the $K_{DP_{reference}}$, range of 1$^\circ\sim$4$^\circ$ km$^{-1}$ (Fig. 9d). In contrast, the $K_{DP}-(Z_H,Z_{DR})$ relations from the PARSIVELs are in good agreement with those from the 2DVD without apparent error (Figs. 9e-f), as expected based on Table 3.

Table 3 contains the polarimetric radar rainfall estimators of $R-Z_H$, $R-K_{DP}$, $R-(Z_H,Z_{DR})$, and $R-(K_{DP}$, $Z_{DR})$ derived from the 1-min DSDs of the 2DVD and PARSIVELs via nonlinear regression analysis. The $R-Z_H$ relations were derived separately for weak and high rainfall with a threshold of 35 dBZ. The estimators based on the $K_{DP}$ and/or $Z_{DR}$ data were derived from the data for $K_{DP} > 0.3$ dB and $Z_{DR} > 0.3$ dB to consider their typical measurement errors in real radar observations (e.g., Park et al. 2005). It should be noted that the rainfall estimators derived in this study are the ones suitable for rainfall in the validation site in South Korea; therefore, these estimators differ somewhat from those used in previous studies derived in different climatological regimes. For example, compared with the default Z–R relation ($Z = 300R^{1.4}$) of the National Weather Service (NWS; Ryzhkov et al. 2005a), the $R-Z_H$ relation of the 2DVD for high rainfall ($Z = 162R^{1.6}$) produces a similar rainfall rate of 46 mm h$^{-1}$ at a $Z_H$ value of 48 dBZ but a higher rainfall rate with a $Z_H$ value of 55 dBZ; the $R-Z_H$ relations of the 2DVD and NWS produce 129 and 144 mm h$^{-1}$, respectively. In the case of the $R-K_{DP}$ relation, the relation of the 2DVD found in this study ($R = 43.1 K_{DP}^{0.801}$) is very close to that of the NWS, $R = 44.0 K_{DP}^{0.822}$ (Ryzhkov et al. 2005a), but it slightly underestimates rainfall rates at high rainfall ($R > 40$ mm h$^{-1}$ or $K_{DP} > 1$ km$^{-1}$) because of the smaller exponent in the relation.

| TABLE 3. Coefficients and exponents of the $Z_{DR} = aZ_H^\alpha$, $K_{DP} = aZ_H^\beta$, and $K_{DP} = aZ_H^\beta 10^{\frac{\gamma}{Z_{DR}}}$ relations for the 1-min DSDs collected by the PARSIVELs and 2DVD at S-band frequency. Values of $Z_H$, $Z_{DR}$, and $K_{DP}$ are in mm$^3$ m$^{-3}$, dB, and $^\circ$ km$^{-1}$, respectively. NRE and NRB in percent of the retrieved values from each relation are also presented, with respect to the original values obtained from each respective instrument. |
|---------------------------------|----------------|----------------|----------------|
|                                | $Z_{DR}$-$Z_H$ | $K_{DP}$-$Z_H$ | $K_{DP}$-($Z_H,Z_{DR}$) |
|                                | $\alpha$     | $\beta$       | $K_{DP}$       |
| PA1                             | 0.039         | 0.339         | 39.0 (4.5)     |
| NRE (NRB)                       | 0.040         | 0.339         | 39.2 (4.7)     |
| PA2                             | 0.040         | 0.337         | 34.1 (2.5)     |
| 2DVD                            | 0.069         | 0.277         | 15.7 (6.6)     |
|                                | $\beta$     | $\gamma$     | $\gamma$     |
| PA1                             | 1.47 x $10^{-4}$ | 0.795     | 3.41 x $10^{-5}$ |
| NRE (NRB)                       | 1.20 x $10^{-4}$ | 18.1 (9.1) | 3.50 x $10^{-3}$ |
| PA2                             | 9.73 x $10^{-5}$ | 15.7 (6.6) | 3.71 x $10^{-3}$ |
| 2DVD                            | 8.44         | 15.7 (6.6) | 8.993         |
|                                | $\gamma$     | $\gamma$     | $\gamma$     |
| PA1                             | -2.076       | -2.167       | -2.213        |
| NRE (NRB)                       | 3.1 (1.0)    | 2.9 (1.6)    | 1.3 (0.0)     |
Fig. 9. Comparisons of the following relations derived from the 2DVD and PARSIVELs: (a), (b) $Z_{DR} - Z_H$, (c), (d) $K_{DP} - Z_H$, and (e), (f) $K_{DP} - (Z_H, Z_{DR})$. In (a) and (c), the 1-min data from the 2DVD (plus sign) and the fitted data by the relations of the 2DVD and PARSIVELs (lines). In (e), the retrieved $K_{DP}$ values from the $K_{DP} - (Z_H, Z_{DR})$ relations of the 2DVD (gray +), PA1 (red +), and PA2 (green +), for the 1-min dataset. (right) Retrieved values from the relations of 2DVD (solid black), PA1 (solid red), and PA2 (solid green) using the reference values, and relative estimation errors of the PARSIVEL relations (dotted lines), with respect to the 2DVD relation.
Comparing individual estimators among the 2DVD and two PARSIVELs, the estimators between the two PARSIVELs are very close to each other, whereas the estimators of the 2DVD differ somewhat from those of the PARSIVELs (Table 4). In the case of the $R - (K_{DP}, Z_{DR})$ relation, for example, the two PARSIVELs present nearly the same relation, with $\alpha$, $\beta$, and $\gamma$ values of 92.5, 0.97, and $-2.0$, respectively, whereas the corresponding coefficient and exponents of the 2DVD relation are 69.2, 0.90, and $-1.7$. To examine the impact of these differences in these rainfall estimators, the relative estimation errors of the rainfall estimators of the PARSIVELs with respect to those of the 2DVD were calculated (Fig. 10). As in Fig. 9, the estimation errors are defined as the differences in rainfall rates estimated from the relations of the 2DVD and PARSIVELs using the same inputted values of the polarimetric variables derived reciprocally from the 2DVD relations based on prefixed reference rainfall rates. As shown in Fig. 10a, the $R - Z_{H}$ relations of the PARSIVELs for high rainfall ($Z_{H} > 35 \text{ dBZ}$) present estimation errors within approximately $\pm10\%$ with respect to the 2DVD relation and underestimate at rainfall rates above $40 \text{ mm h}^{-1}$.

The $R - K_{DP}$ relations of the PARSIVELs (Fig. 10b) present overestimations at the overall reference rainfall rates. These overestimations decrease with increasing rainfall rates, to below 10% for $R_{\text{reference}} > 40 \text{ mm h}^{-1}$ and below 5% for $R_{\text{reference}} > 100 \text{ mm h}^{-1}$. In contrast to the $R - Z_{H}$ and $R - K_{DP}$ estimators, the $R - (Z_{H}, Z_{DR})$ and $R - (K_{DP}, Z_{DR})$ relations of the PARSIVELs present significant overestimations of over 10% at the overall reference rainfall rates. These overestimations increase gradually with the rainfall rate and reach 30% at 150 mm h$^{-1}$. These results imply that in the procedure to quantitatively estimate rainfall amounts from real radar observations, the use of the rainfall estimators derived from the PARSIVEL as empirical climatological relations can produce significant errors compared to the use of the relations derived from 2DVD, because of the fundamental characteristics of the DSDs from the PARSIVEL measurements.

5. Summary and conclusions

The performance of the OTT PARSIVEL$^2$ was evaluated through a comparison with a collocated
TABLE 4. Coefficients and exponents of the rainfall estimators of \( R = a Z_H^\alpha, R = aK_{DP}^\beta, R = aZ_m^\delta(10^{0.1Z_{DR}}), \) and \( R = aK_{DP}^\beta10^{0.1Z_{DR}} \) for the 1-min DSDs collected by the PARSIVELs and 2DVD at S-band frequency. Values of \( R, Z_H, Z_{DR}, \) and \( K_{DP} \) are in mm h\(^{-1}\), mm\(^3\) m\(^{-3}\), dB, and \(^{\circ}\) km\(^{-1}\), respectively. NRE and NRB in percent of the retrieved values from each relation are also presented, with respect to the original values obtained from each respective instrument.

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<th>( R-Z_H )</th>
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<th>( Z_H &gt; 35 \text{ dBZ} )</th>
<th>( R-K_{DP} )</th>
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<td>NRE (NRB)</td>
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<td>( \alpha )</td>
<td>47.36</td>
<td>12.9 (0.1)</td>
<td>12.1 (-0.3)</td>
<td>0.738</td>
<td>0.931</td>
<td>0.876</td>
<td>-3.825</td>
<td>69.20</td>
</tr>
<tr>
<td>( \beta )</td>
<td>47.43</td>
<td>0.764</td>
<td>0.801</td>
<td>0.970</td>
<td>0.966</td>
<td>0.903</td>
<td>0.970</td>
<td></td>
</tr>
<tr>
<td>( \gamma )</td>
<td>28.4 (0.8)</td>
<td>28.4 (0.5)</td>
<td>29.0 (0.3)</td>
<td>28.4 (0.8)</td>
<td>28.4 (0.5)</td>
<td>29.0 (0.3)</td>
<td>0.738</td>
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</tr>
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</table>

2DVD and rain gauges using data collected for a total of 36 rain events during May–November 2014 and April–July 2015 at the radar validation site of the KMA’s WRC in South Korea. The results from the comparisons of DSDs between the 2DVD and two PARSIVEL\(^2\) are as follows: The DSDs from the two PARSIVEL\(^2\) were in good agreement with those from the 2DVD at weak and moderate rainfall \((R < 10 \text{ mm h}^{-1})\). In addition, the concentrations of midsize drops \((0.6–4.0\text{ mm in diameter})\) from the PARSIVELs agreed well with those from the 2DVD, irrespective of rainfall intensity. These results are very consistent with the findings of Tokay et al. (2014, 2016). In contrast, at higher rainfall rates than approximately 20 mm h\(^{-1}\), it was found that the OTT PARSIVEL\(^2\) system tended to overestimate large drops \((D > 4 \text{ mm})\), compared to the collocated 2DVD. Furthermore, this phenomenon became more apparent at higher rainfall rates. The characteristics of DSDs from the PARSIVELs had a significant influence on the DSD parameters—that is, overestimations of \( D_m \) and \( D_{\text{max}} \) and underestimations of \( N_w \) and \( N_T \) compared to those from the 2DVD. At the high rainfall rate of 120 mm h\(^{-1}\), the differences in \( D_m, N_w, D_{\text{max}}, \) and \( N_T \) of the PARSIVELs compared with those of the 2DVD reached 34%, -13%, 29%, and -21%, respectively, whereas at weak rainfall below 20 mm h\(^{-1}\), an apparent difference was not detected, except for \( N_T \), which was underestimated apparently irrespective of rainfall intensity.

The effects of the characteristics of DSDs from the PARSIVEL\(^2\) system on the polarimetric radar variables are as follows: the \( Z_H \) values from the PARSIVELs were similar to those from the 2DVD, with only small biases of about -5.4%, whereas the \( K_{DP} \) values from the PARSIVELs were smaller by approximately -12% compared to those from the 2DVD, with a pattern of underestimations increasing gradually with increasing rainfall rates. The PARSIVELs underestimated \( Z_{DR} \) by approximately -17% overall, but the PARSIVEL \( Z_{DR} \) values became much larger than those from the 2DVD data at high rainfall with \( Z_{DR} > 0.8 \text{ dB} \).

Comparisons of the empirical relations based on self-consistency among the radar variables revealed that the \( K_{DP}-Z_H \) relations of the PARSIVELs presented a mean underestimation of approximately -15% with respect to the 2DVD data. In the case of the \( K_{DP}-(Z_H,Z_{DR}) \) relations, no apparent difference was found in the comparison between the 2DVD and PARSIVELs. The \( Z_{DR}-Z_H \) relations from PARSIVELs resulted in differences from -20% to 30% with increasing rainfall rates. From comparisons of the polarimetric radar rainfall estimators between the 2DVD and PARSIVELs, the following results were obtained. The \( R-Z_H \) relations of the PARSIVELs presented differences within ±10% with respect to the 2DVD relation, with underestimations at rainfall rates above 40 mm h\(^{-1}\). The \( R-K_{DP} \) relations of the PARSIVELs present overestimations of less than 10% for \( R_{\text{reference}} > 40 \text{ mm h}^{-1}\). In contrast, the \( R-(Z_H,Z_{DR}) \) and \( R-(K_{DP},Z_{DR}) \) relations of the PARSIVELs present significant overestimations—between 10% and 30%—with respect to those of 2DVD.
Based on these results, it can be concluded that the OTT PARSIVEL$^2$ system still produces overestimations of large drops during heavy rainfall above approximately 20 mm h$^{-1}$, similar to findings in the previous studies using older models of the PARSIVEL system (Thurai et al. 2011; Tokay et al. 2013), despite the significant improvements to the PARSIVEL$^2$ system and the resultant better DSD measurements relative to older models as described by Tokay et al. (2014). Consequently, it should be considered that the uses of DSDs from the PARSIVEL$^2$ and further empirical relations among the radar variables and rainfall estimators derived therefrom can act as an extra error source in the radar hydrometeorological applications, such as quantitative rainfall estimations.

Regarding causes of the characteristics of DSD from the PARSIVEL$^2$, the authors cannot provide a definite origin, as this question is beyond the scope of this study. The underestimation of small drops during heavier rainfall may be ameliorated by mitigating the filtering width for small-sized drops, defined by the upper and lower boundaries from the diameter–fall velocity relation employed for removing suspect particles. In practice, it is known that the 2DVD, employed as a reference instrument in this study, has relatively large uncertainty in measurements of small drops (below approximately 0.8 mm) compared to larger drops because of the difficulty in matching each small drop by the two cameras (Thurai et al. 2013). To evaluate more accurately the PARSIVEL measurements for small drops, it is beneficial to compare them with drop spectra collected from an instrument that has a finer temporal–spatial resolution, such as the Meteorological Particle Spectrometer (MPS; Baumgardner et al. 2002) in an experiment conducted by Thurai et al. (2017). In contrast, for large drops the 2DVD provides high reliability because of much larger sizes than the resolution of the cameras (approximately 0.165 mm). Further, the filtering widths applied to the 2DVD and PARSIVEL measurements for removing suspect particles, described in sections 3b and 3c, are slightly shallower in the PARSIVELs than in the 2DVD for large drops above 4 mm. Therefore, for the overestimation of large drops during heavy rainfall, the implicit assumptions of the PARSIVEL system should be considered as the main causes, such as the assumed oblate shape for hydrometeors, the exaggeration of the equivolumetric diameter, the uncertainty of the fall velocity measurements, and the coincidence effect, as noted by Battaglia et al. (2010), Thurai et al. (2011), and Raupach and Berne (2015). Despite these limitations, the PARSIVEL system has certain advantages over other types of disdrometers and therefore has attracted the attention of potential users interested in the applications of high-quality DSDs. Therefore, it would be beneficial to improve the measurements of PARSIVEL$^2$ in this respect, using correction methods such as those proposed by Adachi et al. (2013) and Raupach and Berne (2015). Such experiments for correcting the data used in this study are left to future work.

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APPENDIX

Examples of Loss of 2DVD Measurements and Delay in the Recording of PARSIVEL Measurements

Examples of the loss of the 2DVD measurements and the delay in the recording of the PARSIVEL measurements described in section 3 are presented here, and simple methods for detecting these losses and delays are described. Figure A1 shows comparisons of the rainfall rates and accumulations obtained from the 2DVD and rain gauge during 1700–1800 LST 24 June 2015. The rainfall rates from the 2DVD present relatively large differences from the gauge measurements during the period 1737–1739 LST, compared with the remaining time. Correspondingly, the rainfall accumulation from the 2DVD presents an underestimation from 1737 LST. Figure A2 corresponds to a part of the 2DVD log file, from 1737:00 to 1738:00 LST. In principle, the 2DVD system records the size and time information of the data transferred from the outdoor measurement unit every 3 s, even when no precipitation occurs with a base data amount of 828 bytes. However, as shown in the figure, a total of seven 3-s records are missing, from 1737:27 to 1737:45 LST. This phenomenon indicates the loss of 2DVD measurements, which results in the underestimation of the rainfall amount. In addition to the loss at 1737 LST, data losses occurred at 1738 and 1739 LST, with two 3-s records lost at each time step. During these 3 min when losses occurred, the differences of the rainfall rates between the 2DVD and rain gauges corresponded to a decrease of 3.0 mm in the recorded rainfall amount.
The magnitude of this underestimation is comparable with that of the total rainfall amount at 1800 LST (2.2 mm). Therefore, in this study, if the number of 3-s records in a log file was not 20 during a given 1-min interval, then the corresponding 1-min DSD was not used in comparisons with the PARSIVEL measurements, except for rainfall accumulations.

Figure A3 shows the DSDs obtained from the 2DVD and two PARSIVELs during 0405–0409 LST 18 July 2014, with an interval of 1 min. The DSDs from the 2DVD and PA2 are in good agreement at all time steps. In contrast, no DSDs from PA1 are found before 0409 LST, and the DSD at 0409 LST presents more numerous drops than do the 2DVD and PA2 data. This unreasonable DSD recorded by PA1 at 0409 LST agrees well with that of the PA2 summed from 0405 to 0409 LST. This phenomenon indicates that the PA1 DSDs from 0405 to 0408 LST were not recorded at each time step but recorded altogether at 0409 LST. Therefore, in the quantitative comparisons with 2DVD measurements, all DSD data from 0405 to 0409 LST were not used, except for rainfall accumulations. The PARSIVEL system used in this study is configured for each 1-min DSD to be recorded in a file named with the corresponding time, even when no precipitation occurs. When the delay phenomenon occurs however, a file is not generated. Therefore, the DSDs affected by this delay can be easily detected by checking whether the corresponding 1-min DSD file exists.

The 36 rain events selected in this study resulted in a total of 17 196 time steps of 1-min duration and the total amount of rainfall recorded by the rain gauge was 801.5 mm. Of this dataset from the 2DVD, a total of 643 (3.7% of the total) 1-min DSD data were affected by the loss of 3-s records because of the systematic lockups embedded in the 2DVD system. The corresponding amount of rainfall loss was 26.8 mm (3.3%), based on a comparison with rain gauge measurements. In addition, the 1-min DSDs from the 2DVD were affected by an unexpected data loss, with a total of 276 (1.6%) data affected and a rainfall amount of 12.9 mm (1.6%). In the case of the PARSIVEL systems, the total number of 1-min DSDs affected by the delay phenomenon were 57 (0.3%) and 291 (1.7%) for PA1 and PA2, respectively, and the corresponding rainfall amounts were 18.8 mm (2.3%) and 8.5 mm (1.1%), respectively. Although these occurrence frequencies can be considered small and negligible, in this study the 1-min DSDs affected by the
loss of 3-s records in the 2DVD and by the delay phenomenon in the PARSIVEL measurements were not used in the quantitative comparisons of DSDs between the 2DVD and PARSIVELs. However, all 1-min DSDs were included in comparisons of rainfall amounts with the rain gauge measurements. Finally, it should be noted that the occurrences of these phenomena in the 2DVD and PARSIVEL measurements are limited to only our
instruments and cannot be generalized to other 2DVD and PARSLVEIL units employing different instrumental configurations and under different meteorological environments.

REFERENCES


