Advantage of Volume Scanning Video Disdrometer in Solid-Precipitation Observation

Yuta Katsuyama$^1$ and Masaru Inatsu$^2$

$^1$Tohkamachi Experimental Station, Forestry and Forest Products Research Institute, Tohkamachi, Niigata, Japan
$^2$Faculty of Science, and Center for Natural Hazards Research, Hokkaido University, Sapporo, Japan

Abstract

This study developed a volume scan-type disdrometer and investigated the size distribution of solid-precipitation particles observed by flux- and volume-scan type disdrometers, installed in 2016−2017 winter in Sapporo, Japan. The former disdrometer detected particles, by line sensors, of which frequency is proportional to the particle number per area. On the other hand, the latter directly observed the particle number per volume using an image sensor. The flux-scan data are known to have the bias of more frequency in higher-speed (or larger-size) particles, but this bias was hardly corrected due to the error of estimated particles’ velocity. It was first validated that the volume scan-type disdrometer could observe particle size between 0.5 mm and 13 mm, consistently with the flux scan-type one. Then, we examined how many events observed particle size between 0.5 mm and 13 mm, consistently with the flux scan type. The result showed that 84% of the total events examined fell into the class where they were significantly different, partially due to fast-falling graupels.

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1. Introduction

Disdrometers have been widely used to measure the distribution, size and velocity of precipitation particles because they provide an aspect of upper-air cloud microphysical processes (Lohmann et al. 2016), the observed statistics to convert radar reflectivity to precipitation intensity (Huang et al. 2010), and initial snow-cover density related to avalanche (Ishizaka et al. 2016). Among them, Two-Dimensional Video Disdrometer (2DVD; Kruger and Krajewski 2002), Particle Size Velocity (PARSIVEL; Löffler-Mang and Joss 2000; Battaglia et al. 2010; Angulo-Martínez et al. 2018), and Laser Precipitation Monitor (LPM; Angulo-Martínez et al. 2018) are disseminated for their capability to observe both liquid and solid precipitation particles, but they faced many technical problems such as inhomogeneous precipitation particle shape (Battaglia et al. 2010), the effect of riming (Locatelli and Hobbs 1974; Yuter et al. 2006; Bernauer et al. 2016). One may resolve this bias problem by dividing the number of particles by a sampling volume swept by a particle, $V/ΔA Δt$, where $A$ (m$^2$) is an area of detection region of disdrometer and $Δt$ (s) is an observation time interval (Ignaccolo and De Michele 2014). However, this trial of bias correction would be failed by the erroneous data with abnormally large velocity in the small-size side often observed in flux-scan type disdrometers as shown in Section 4. Despite that this bias-correction problem took place in the observation, it has not been considered deeply yet.

This study aims to develop a volume scan-type disdrometer motivated from the work by Muramoto and Shina (1989) and to test the size distribution difference from that based on a flux scan-type disdrometer, 2DVD, installed at Sapporo, Japan. Two sets of size-velocity data were obtained by the continuous observation through 2016/17 winter. The analysis began with the validation of the developed disdrometer. Next, we classified the snowfall events into cases where the size distributions were different between the two disdrometers. Then, we demonstrated the strength of VSVD called volume-scan type. Katsuyama and Inatsu (2020) have recently put a caveat on the use of the flux scan-type disdrometer data. They argued that the joint PDF of size-velocity originally observed by the flux-scan type disdrometer must be biased, because the disdrometer measured the particle number in area. Given that the joint PDF was constructed by the diameter $D$ (mm) following the Gamma distribution,

$$G(D) = \frac{λ^{μ+1}D^μ}{Γ(μ+1)} \exp(-λD),$$

where $μ$ is a shape parameter, $λ$ is a slope parameter, and $Γ$ is the Gamma function, and the velocity $V$ (m s$^{-1}$) following the normal distribution under a constraint of the velocity-diameter (V-D) relationship, $V = aD^β$, the extent of bias was a factor of $Γ(μD^β)|Eq. (8)|$ of Katsuyama and Inatsu (2020). The flux-scan type disdrometer data contained another bias that the shape parameter for the size distribution increased by $b$. These biases were hardly corrected, because $b$ is highly sensitive to the particle type, phase, and degree of riming (Locatelli and Hobbs 1974; Yuter et al. 2006; Bernauer et al. 2016). One may resolve this bias problem by dividing the number of particles by a sampling volume swept by a particle, $V/ΔA Δt$, where $A$ (m$^2$) is an area of detection region of disdrometer and $Δt$ (s) is an observation time interval (Ignaccolo and De Michele 2014). However, this trial of bias correction would be failed by the erroneous data with abnormally large velocity in the small-size side often observed in flux-scan type disdrometers as shown in Section 4. Despite that this bias-correction problem took place in the observation, it has not been considered deeply yet.

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We installed the VSVD at Institute of Low Temperature Science, Hokkaido University, Sapporo, Japan, located at 43.083°N, 141.339°E, from 1 December 2016 to 31 March 2017. The instrument was fixed at 1 m above the ground, not to be buried in snow-cover. It is enclosed by double windbreaking nets to prevent an effect of turbulence. The diameter-velocity data were collected every five-minute interval. We only used the data larger than 0.5 mm because of the effective detectable range of the instrument (Section 4.1) and faster than 0.5 m s\(^{-1}\) in order to align the observational velocity range with 2DVD. The measurable velocity ranged between \(V_{\text{min}} = D \times 10^{-3}/\Delta t\) and \(V_{\text{max}} = (H_c - 0.5w) \times 10^{-3}/\Delta t\): \(V_{\text{min}}\) was determined by considering the possible maximum difference of afterimages between spherical and ellipsoid particles and \(V_{\text{max}}\) was determined by the height of captured region.

A 2DVD installed just 2 m beside the VSVD (Fig. 1c) measured precipitation particle diameter and velocity by matching two images captured by line sensors installed at an upper and a lower position with a sampling area of \(\sim 0.01\) m\(^2\) (Kruger and Krajewski 2002). We only used data larger than 0.5 mm in order to align the observational size range with VSVD and faster than 0.5 m s\(^{-1}\) because slow particles were undetectable by 2DVD. The diameter and velocity data were corrected to eliminate the effect of detection fraction reduction in a finite detection volume as well as VSVD (Supplement 1). They were moreover corrected to eliminate the effect of the detection fraction reduction in a finite detection volume (Supplement 1).

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3. Methods

We here used the particle number density per unit volume (PND/V; m\(^{-3}\) mm\(^{-1}\) m\(^{2}\) s) and the particle number density per unit horizontal area (PND/A; m\(^{-2}\) mm\(^{-1}\) m\(^{-1}\) s) in the validation of VSVD data. The former is a quantity directly observed by VSVD, generally called particle number concentration rate, while the latter is a quantity directly observed by 2DVD. First, regardless of instruments, an observation of the single particle labelled \(i\) provided three attributions of the diameter \(D_{i}\), the fall velocity \(V_{i}\), and the effective number \(Z_{i}\). Hereafter VSVD and 2DVD observations are respectively denoted by the subscripts V and F. Collecting the VSVD data with their diameter in \([D_{F}, D_{F} + \Delta D]\) and velocity in \([V_{F}, V_{F} + \Delta V]\), then the PND/V observed by VSVD was simply

\[
\sigma_{T}(D_{V}, V_{V}) = \frac{1}{\Delta D \Delta V} \sum_{D_{F}, V_{F} \in [D_{F}, D_{F} + \Delta D] \cup [V_{F}, V_{F} + \Delta V]} Z_{F,i} \langle n_{F}(D_{F}, V_{F}) \rangle
\]

By using the fall velocity data, PND/V and PND/A are interchangeable. The PND/V estimated from the 2DVD observation in a time interval of \(\Delta t\) was

\[
\sigma_{T}(D_{V}, V_{V}) = \frac{1}{\Delta D \Delta V} \sum_{D_{F}, V_{F} \in [D_{F}, D_{F} + \Delta D] \cup [V_{F}, V_{F} + \Delta V]} Z_{F,i} \langle n_{F}(D_{F}, V_{F}) \rangle
\]

and the PND/A estimated from the VSVD observation was

\[
\sigma_{T}(D_{V}, V_{V}) = \frac{1}{\Delta D \Delta V} \sum_{D_{F}, V_{F} \in [D_{F}, D_{F} + \Delta D] \cup [V_{F}, V_{F} + \Delta V]} Z_{F,i} \langle n_{F}(D_{F}, V_{F}) \rangle
\]

The size distribution was then made by integrating Eq. (2), (3), (4), or (5) over velocity. With the above consideration, \(n_{V}\) and \(n_{F}\) must match when \(D_{V}, D_{F}\), and \(V_{V}\) were consistently observed; \(\sigma_{T}\) and \(\sigma_{T}\) must match when \(D_{V}, D_{F}\), and \(V_{V}\) were consistently observed. Hence, the matching of either PND/V or PND/A means the data consistency between VSVD and 2DVD. It is here emphasized that the PDFs, used in the analysis of this paper, were made from the PND/Vs without the two-sample Kolmogorov-Smirnov (KS) explained next.

The KS test was used to classify the events into cases when the size distributions of PND/A by 2DVD were different with that of PND/V by VSVD. The KS statistics is defined as

\[
U(A, B) = \max_{b, d} \left| L_{b} \sum_{i} Z_{F,i} H(D - D_{i}) - L_{d} \sum_{i} Z_{F,i} H(D - D_{i}) \right|
\]

where \(H\) is the Heaviside step function and \(L\) is the total particle number. A null hypothesis was rejected with a statistical significance level at 1% if \(U \sqrt{L_{b} L_{d}} / (L_{b} + L_{d}) > 1.62\) (Cugene and De Michele 2015). In the events classified into the significantly different cases, VSVD has an advantage to observe PND/V since PND/V estimated from 2DVD strongly depends on the error of velocity estimation (Eq. (4)).

4. Results

4.1 Validation of VSVD

Figure 2 shows size distributions of PND/V and PND/A averaged for all of 378 cases examined in this study. The PND/A of VSVD and 2DVD matched in the diameter range from 0.5 mm to 4 mm. The PND/Vs of them matched in the diameter range from 4 mm to 13 mm. Therefore, the diameter of VSVD and 2DVD were consistently observed for particle size from 0.5 mm to 13 mm. On the other hand, for the diameter larger than 13 mm, the PND/V and PND/A by 2DVD were much less than those by VSVD. It is worthwhile noting that the plummet and bumpy signals in 2DVD data toward the larger particle side suggested that the problem was originated in 2DVD. Therefore, we limited the size range between 0.5 mm and 13 mm in the following analysis.

The PND/A matching in the small particle range between 0.5 mm and 4 mm (Fig. 2a) and the PND/V matching in the intermediate particle range between 4 mm and 13 mm (Fig. 2b) assured the data consistency of the particle size between VSVD and 2DVD. These matching also suggested the data consistency in the velocity data of VSVD in the small particle range and in the velocity data of 2DVD in the intermediate particle range. It is then uncertain that the velocity data of VSVD were consistent in the intermediate range. A slight underestimation of PND/A meant that the fall velocity is slower in the VSVD (Eq. (5)). This difference was probably caused by the underestimation related to the assumption of ellipsoid as particle shape (Section 5). Similarly, a slight underestimation of the PND/V of 2DVD indicates that 2DVD overestimates the particle velocity in the size range (Eq. (4)) due to the matching error as shown later.

4.2 Comparison of PDF

Figure 3 shows a case in 15:25−15:30 on 24 January 2017, when the size distribution made from PND/A by 2DVD was significantly different with that made from PND/V by VSVD based on the KS test at a 1% level. The difference moderately decreased by converting PND/A by 2DVD to the PND/V using Eq. (4) (Fig. 3a). The PDF of velocity-diameter of VSVD was bimodal: one branch distributed along with a V-D relationship of densely rimed aggregates, \(V = 1.1 D^{3/5}\) (Ishizaka 1995), and another branch dis-
other hand, about 23% of the total fell into the class where the size 

\[ V = V_{s} = 0.0225D \theta, \]

where \( D \) is the diameter of particle itself between 0.5 mm and 13 mm in average (Ishizaka et al. 2013), whereas the matching often fails due to the afterimage and the matching may resolve the problem.

Like the above case, the PND/A by 2DVD were statistically different from PND/Vs by VSVD (Fig. 3b). This indicated that two different particle types were detected by the VSVD. Similarly, the 2DVD also detected particles along with V-D relationships of the graupel and aggregates models, but the matching error caused an additional branch distributed with much large variance of velocity (Fig. 3c). Because this additional branch broadened the joint PDF larger, the other branches were distributed to larger particle size side (Figs. 3b and 3c).

Like the above case, the PND/A by 2DVD were statistically different from PND/Vs by VSVD for 307 cases among the total based on the KS test. The size distribution of 2DVD was shifted to the large particle side in the average of significantly different cases (Fig. 4a), because the sampling volume swept by particles was underestimated due to the erroneously large velocity (Fig. 4e). In these cases, the velocity-diameter distribution was sometimes bimodal, and one of the branches indicated the fast-falling (Fig. 4c). This suggested that the PND/A by 2DVD and the PND/V by VSVD differed the fast particles such as graupel. On the other hand, about 23% of the total fell into the class where the size distributions made from PND/A by 2DVD and PND/V by VSVD were not significantly different. In contrast to the significantly different cases, the velocity-diameter distribution was monomodal in VSVD data in the other cases (Fig. 4d). The branch with large velocity only found in 2DVD indicated erroneous data due to the matching failure (Fig. 4f). This erroneous data again caused to underestimate probability for small particles (Fig. 4b). It should be again emphasized that, in all case examined here, VSVD directly observed unbiased size distributions of PND/Vs while 2DVD did not (Section 3).

5. Discussion

This paper has demonstrated the strength of VSVD that provided the unbiased size distribution in the comparison with the flux scan-type that suffered from the bias in the size distribution. However, the VSVD contained another problem in the assumption that a precipitation particle was shaped as ellipsoid (Section 2), which caused an error in the fall-velocity estimation (Section 4.1; Battaglia et al. 2010). The magnitude of error due to the assumption was \[ |\Delta V| = 0.0225D_{\theta, 90^\circ}, \] so that the error was small for small size particles such as graupels (Fig. 2a). In contrast, the relative error attained 20–30% for large size particles; for example, it was 0.225 m s\(^{-1}\) at \( D = 10\) mm, which was almost consistent with the results (Fig. 4). This problem can be relieved by estimating velocity by matching particles in two images taken at slightly different timings (Ishizaka et al. 2013), whereas the matching often fails for small particles. Hence, a combined velocity estimation by the afterimage and the matching may resolve the problem.

6. Conclusions

We developed a VSVD to measure precipitation particle’s diameter and velocity without the bias that was inevitable in the flux scan type disdrometer. The VSVD and 2DVD were nearby installed at Hokkaido University, Sapporo, Japan (Fig. 1), and 378 events were selected with a threshold of \( > 500 \) particles in five minutes from the observation during 2016/17 winter. The comparison between VSVD and 2DVD with the PND/V and PND/A validated that both disdrometers consistently observed the diameter of particle itself between 0.5 mm and 13 mm in average (Fig. 2). The nonparametric statistical test showed that the original size distribution of 2DVD, PND/A, were significantly biased in 81% of the total cases, partially due to a mixture of graupel and aggregates (Figs. 3 and 4). The bias of size distribution would not be enough corrected by dividing the particle number with velocity due to the matching error of 2DVD (Figs. 4a and 4e). Hence, the VSVD would have a strength to observe PND/V in cases of the mixture of graupel and aggregates.

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Supplements

Supplement 1: Correction for volume scanning video disdrometer data
Supplement 2: Preprocess for two-dimensional video disdrometer

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