An introduction of Three-Dimensional Precipitation Particles Imager (3D-PPI)

Response to the reviewers

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Original Referee comments are in italic

manuscript text is indented, with added text underlined and ~~removed text crossed out.~~

We would like to thank the reviewers for their very helpful comments. We revised the manuscript thoroughly and responded to all of the reviewers' comments.

General Comments:

1.How robust are the camera alignment and 3D measurements to thermal expansion shifting the cameras (since the cameras are enclosed in a housing, I assume the effects of wind on camera alignment will be negligible)? Adding a brief discussion of how these might affect the measurements would be helpful. Some tests of how much measurement error is produced from slight changes in camera alignment after the calibration could also be illuminating.

Thanks for your comments. To mitigate the effects of wind on camera alignment, we have designed a protective housing of 3D-PPI that effectively shields the cameras from wind disturbances. Additionally, to further address potential temperature-related impacts, we have added a semiconductor air conditioner in the housing of 3D-PPI. This will help maintain a stable temperature around the cameras and minimize any thermal expansion effects. We have added a brief discussion in the revised manuscript.

Line 182:

> Even small movements of the high-resolution camera can alter the projection matrix. This requires the instrument to be more robust. To mitigate the effects of wind on camera alignment, the instrument housing has been specifically designed for stability. Additionally, a semiconductor air conditioner has been installed in the housing, which will prevent minor camera expansion caused by temperature fluctuations.

Line 460:

> However, even minor displacements of the high-resolution cameras can alter the projection matrix, which may adversely affect the subsequent reconstruction results.

Therefore, it is essential to perform periodic calibration to ensure the accuracy and reliability of the projection matrix.

2.Given that the sampling volume is so close to the instrument housing, how will wind flow affect the representativeness of the measurements (e.g., increasing or decreasing the collection efficiency of the sampling volume)? While I understand that a full engineering analysis of the wind effects (similar to what was presented in Fig 3 of Newman et al. 2009, https://doi.org/10.1175/2008JTECHA1148.1) may be outside the scope of this paper, some analysis that compares the 3D-PPI to the PARSEVAL with the wind coming from certain directions relative to the camera pointing direction might help give some insight into how well the instrument handles these conditions.

Thanks for your comments. We have added the wind field simulation in the Appendix C.

Appendix C: Wind field simulation

To determine the optimal orientation of the 3D-PPI installation (mainly considering the relationship with the prevailing wind direction), we conducted wind field simulations using Solid flow simulation software. The simulation results are shown in Fig. B.1.

When the 3D-PPI is facing the wind (Fig.B.1a), the observation volume experiences an average wind speed of approximately 6.0 m/s. Besides, turbulence may occur within the observation volume. When the 3D-PPI is back facing the wind (Fig. C.1b), the average wind speed in the observation volume is only about 3.5 m/s, which is obviously due to the shielding of the wind by the instrument. When the 3D-PPI is side facing the wind (Fig. B.1c), the observation volume shows an average wind speed of about 8.5 m/s, exhibiting the smallest difference from 10m/s, compared to the other two situations. However, part of the observation volume close to the instrument is still shielded by the housing, which to some extent also affects the representativeness of the wind field, and subsequent consideration will need to be given to improving the instrument design to solve this problem.

In addition to 10m/s, we also simulated 5m/s, 20m/s, and 40m/s wind speed fields, and all of them got the consistent conclusion that the wind speed in the observation volume is closest to the simulated wind speed when the instrument is side facing the prevailing wind direction. Therefore, the instrument should be installed sideways to the dominant wind direction in the area, to minimize the disturbance of the instrument to the natural wind field. The prevailing wind direction in the area is west, so the 3D-PPI is installed facing towards the south.

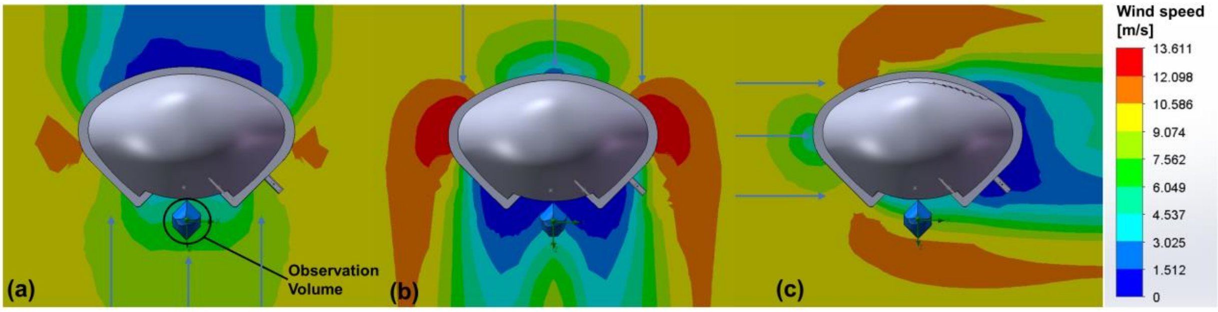


Figure C.1. Top view of wind speed distribution in the simulated wind field. 3D-PPI facing 10 m/s wind (a); back facing 10 m/s wind (b); side facing 10 m/s wind (c). The color gradient represents wind speed, with the observation volume indicated in (a).

3.Since LEDs rapidly flash to produce light, it would be worth clarifying how the LED interacts with the cameras. Is the 20-microsecond effective exposure time due to the duration of the LED flash being 20 microseconds? Is there some mechanism to ensure that the LED is synchronized with the camera exposures in some way to ensure each frame has consistent illumination (or is the system sufficiently robust that inconsistencies in LED illumination are not a problem)?

Thank you for your comments. To clarify, our LEDs remain continuously illuminated once triggered, eliminating the concern about a specific exposure time related to the LED flash. Therefore, there is no defined exposure duration for the LEDs. Furthermore, we have proposed an adaptive thresholding method in our image processing algorithms, it help us to mitigate variations in illumination and ensures robust data analysis. We appreciate your attention to detail, and we have added this clarification in the revised manuscript Line 135:

Once triggered, the LEDs will continue to illuminate, providing consistent lighting throughout the exposure period.

4.How are particles at the edge of the field of view handled? I seem to recall reading somewhere in the manuscript that particles touching the edge are ignored (but I can't seem to find where that was now, sorry if I'm mistaken). If the edge particles are discarded, I think the effective sampling volume would need to be a function of particle size (with the sampling volume being smaller for larger particles).

Thank you for your comments. We indeed discard the particles at the edge of the field of view, we have added the following paragraph in the revised manuscript Line 227:

If the connected region of a particle contains points located at the edges of the image, the particle is considered not to be fully captured, and it should be discarded.

We recognize that discarding particles at the edges of the field of view does influence the effective sampling volume, so we modified Eq. (7) and Eq. (8) for the calculation of the average PSD as follows:

Where PSD (D_i) ($mm^{-1} \cdot m^{-3}$) is the number concentration of particles per unit volume per unit size interval ΔD_i for snowflake size D_i (mm); n_{ij} is the number of snowflakes within size bin i and velocity bin j; T (s) is the sampling time (60 s in this study), and V_j (m/s) is the falling speed for velocity bin j; S (m^2) is the effective sampling area (0.18 m×0.03 m).

The time-averaged PSD calculated from 3D-PPI counting over a specified period is as follows:

$$PSD(D_i) = \frac{N_i}{\triangle D_i \cdot \sum_{j=1}^{N_{ima}} V_j} \tag{7}$$

Where N_i is the number of particles in the i^{th} size bin; N_{ima} is the number of acquired images over a period of time; The size descriptor D for 3D-PPI is D_{max} or D_{eq} in this paper; V_j (m^3) is the valid OV of the Cam0 at the j^{th} moment. Since the we discard particles at the edges of the image in Sec. 4.1, V_j is a function of the average particle size $\overline{D_j}$ at the j^{th} moment, shown in Eq. (8). The a, b, and d represent the length (0.17m), width (0.125m), and depth (0.1043m) of field of view respectively.

$$V_j = \begin{cases} \left(a - \overline{D_j}\right) \times b \times d & \text{,when the particles at left or right edges discarded;} \\ a \times \left(b - \overline{D_j}\right) \times d & \text{,when the particles at top or bottom edges discarded;} \\ \left(a - \overline{D_j}\right) \times \left(b - \overline{D_j}\right) \times d & \text{,both conditions exists at the same time;} \\ a \times b \times d & \text{, no edge particles are discarded.} \end{cases} \tag{8}$$

5. Is the tracking software intended to work for rain drops as well as frozen precipitation? It is clear from the manuscript that the instrument is designed for measuring snowflakes, it might be worth noting in section 5.3 whether or not the tracking software is designed to handle any faster falling precipitation.

Yes, the tracking software is primarily designed to measure precipitation particles including raindrops as well as frozen precipitation. The sampling area of high-speed camera is 72mm (width) × 54mm (height), and the sampling rate is 200 fps. For a raindrop with diameter 5 mm, the maximum speed that can be measured according to two consecutive images between 5ms is 8.8m/s.

$$\frac{(54 - 5 - 5)\,\text{mm}}{5\,\text{ms}} = 8.8\,\text{m/s}$$

6.I have some concerns with the tracking algorithm, although it is possible these concerns are due to misunderstanding on my part and/or a need for further clarification in the manuscript. When first reading over the tracking method, I was somewhat concerned that particle motion wasn't being considered as, in my personal experience, that is the best way to match an existing particle to its new location (although this isn't possible in the first two frames of the particle and some other criteria must be applied). After having studied the description more closely, it sounds like there might be some shape matching going on. I base this on Line 393, where the pixel coordinates of a particle are mentioned. Are these pixel coordinates being used to match the shape of the particle (e.g., the spatial distribution of these pixels relative to some particle centroid is compared between frames via some method)? If so, this warrants more discussion in the manuscript. If not, how are these pixel positions being used (or am I misunderstanding what is meant by pixel coordinates)? Given that the position *difference allows for up to 8 m/s of particle motion, I would expect that the other criteria need to be very robust to avoid mismatches.*

Thank you for your comments. To clarify, our tracking algorithm relies on matching the same particle across consecutive frames based on their size (D_{max} and D_{eq}), and pixel coordinates of the centroid of particle contours in the image (including horizontal and vertical coordinates). Our approach focuses on extracting the centroid pixel coordinates of the particles, as well as D_{max} and D_{eq}. Considering that the differences in centroid pixel coordinates of the same particle between consecutive frames, as well as D_{max} and D_{eq}, do not vary significantly, the possible mismatch particles can be filtered out, as stated in the revised manuscript Line 411.

We sincerely apologize for the mistakes in our manuscript. We only extracted the centroid pixel coordinates of the particle contours to perform matching and calculations based on centroid pixel coordinates changes, rather than using the pixel locations. Additionally, we found that the upper limit of 8 m/s was too high, therefore, we have revised it to 4 m/s to reduce the likelihood of matching errors. We have modified the corresponding sentence in the revised manuscript Line 408:

> (ii) the pixel coordinates of the centroid of the contours of the same particle in consecutive frames are similar (the vertical velocity of the snowflake is generally not more than 4~~8~~m/s, so the ~~interval~~ distance between the vertical pixel coordinates of the same particle centroid in two adjacent image frames ~~neighboring snowflakes~~ is not more than 100~~200~~ pixels);

Specific Comments:

1.Title: suggest adding "the" before "Three-Dimensional"

Changed as suggested.

2.Line 16: change "OTT a good agreement" to "OTT have good agreement"

Changed as suggested.

3.Table 1: Thank you for including this table! Having these technical specifications in one place is very useful.

Thanks for your positive feedback!

4.Lines 107 – 111: These numbers don't seem to agree with those in Table 1. Specifically, the telecentric lens pixel size is listed as 3.45 microns in the table and 42 microns in the paragraph. Similarly, the table lists the non-telecentric lens as having a pixel size of 6.9 microns while the text lists 265 microns. It's very possible that these are referring to two different measurements and if that is the case, I encourage the authors to make that clear either in the text or in the table caption.

We apologize for the unclear explanation in the manuscript, which may have led to some misunderstandings. The pixel size of the telecentric lens (non-telecentric lens*)* is 3.45 (6.9) microns, the magnification rate is 0.083 (0.026), the corresponding field of view size is 41.5 (265) microns. We have rephrased in the revised manuscript Line 116:

> For the high-resolution camera, the single pixel size is 3.45 μm, and the magnification of the lens is 0.083, meaning that the pixel resolution is 41.2 $\mu m \cdot px^{-1}$. Telecentric lens distortion is 0.044% and allowed to be ignored. For the high-speed camera, the single pixel size is 3.45 μm, and the magnification is 0.026 at a working distance of 450mm, meaning that the pixel resolution is 265.4 $\mu m \cdot px^{-1}$.

5.Lines 177 – 179: the parenthetical "(Dmax is the distance between the two largest points of the particle profile…" could use rewording. Perhaps replacing "largest" with "farthest" would improve the readability?

Thank you for your advice, "largest" is indeed inappropriate and caused misunderstandings. Changed as suggested.

6.Line 180: add "the" before "spheres"

Thank you for your advice, changed as suggested.

7.Figure 6: Move the first line of the caption to below panel b.

Thank you for your advice, changed as suggested.

8.Lines 208 – 210: These sentences could use some clarification. Are these particle centers as seen from a single camera or are these the particle centers from multiple cameras? If these are from the same camera, it might help clarify things to mention that sometimes a single particle will appear as two particles due to being on the edge of the image processing threshold (or whatever reason is appropriate). Just based on the flow of the manuscript, I assume these are for a single camera, but it might help make things clearer to specify that.

Thank you for your advice. These particle centers are indeed seen from a single camera. The image processing algorithms in section 4.1 were all about images from a single camera. We have modified the sentences in the revised manuscript, Line 222:

> Secondly, combine regions into a single particle when the centroids of connected regions in a single image are detected to be less than 4 mm apart. This step is necessary because a single particle may sometimes be perceived as two separate particles due to its position near the edge of the image processing threshold.

9.Line 224: Are the ceramic spheres the same as the ones used in section 3.2? If yes, perhaps changing the text from "different diameters in section 3.2 were dropped" to "different diameters, as described in section 3.2, were dropped" would make that clear.

Thank you for your advice, we did use the same ceramic spheres as in section 3.2. Changed as suggested.

10.Line 227 – 234: The text mentions that the measurements of the smaller spheres tend *to be larger than the true size, but the average error of Deq for the small spheres is negative. I may be missing something, but wouldn't a negative error mean the measurements of the small spheres are smaller than their true value? Also, the authors state that this is the average absolute error, which to me implies that it is the mean of the absolute value of the difference between the measured and true Deq and, therefore, should not be negative. I assume the authors are using "absolute" error in contrast with "relative" error. I'm not sure how best to fix this misunderstanding though.*

Thank you for your comments and sorry for our mistakes. The "absolute error" actually refers to the "error". The error is defined as: the measured value - the true value, where a positive value indicates that the size of the particle tends to be overestimated, and a negative value indicates that it tends to be underestimated. Similarly, the relative error is calculated as: (measured value - true value) / true value.

We have modified the sentences in the revised manuscript Line 245-249.

> Regarding the Dmax measurement results (Fig. 8a), smaller spheres (8 mm and below) tend to show measurements that are slightly greater than the true values, while larger particles exhibit measurements that are slightly lower than the true values. The average error for all spheres across different diameters is -0.048 mm, and the average relative error is +2.2%. As for Deq measurement results (Fig. 8b), all diameter measurements underestimate the true values. The average error for all spheres is -0.33 mm, and the average relative error is -2.7%.

11.Figure 8: Are these plots for the high-resolution camera or the high-speed camera? It might be helpful to mention which in the caption.

Thank you for your advice, these plots are for the high-resolution cameras. Changes are as follows:

> **Figure 8** ~~Measured values~~ The average values of measurements of D_{max} **(a)** and D_{eq} **(b)** for ceramic spheres of different diameters from three high-resolution cameras.

12.Lines 389 and 401: Line 389 mentions that the frames need to be adjacent to one another (which I interpret to mean that a missing frame is not allowed), but Line 401 mentions that a missing frame is allowed. This seems like a contradiction, but I suspect I'm just misinterpreting the authors' meaning. Some additional clarification in the text might be needed.

Thank you for your advice. We would like to clarify our previous statements from the perspective of the processing algorithm flow. The process begins with high-speed image processing, where all particles in the images are detected. A particle can only be considered the same if it appears in adjacent frames; it is not possible for a particle to be captured in one frame, not seen in the next few, and then reappear later. This is an obvious point that I failed to state clearly, which may have led to some misunderstandings. Perhaps I should consider removing the first principle stated in Line 403 to avoid any confusion. Thank you for your understanding.

13.Lines 390 – 391: Is the 200 pixels interval purely in the vertical or is that include the horizontal component of the distance as well. If that includes the horizontal distance, it might be worth noting that this means the instrument will have difficulty producing accurate particle fall speeds at high cross-camera-view wind speeds (which isn't a problem, but is good to know for anyone performing an analysis of the data).

Thank you for your comments. The 200 pixels interval represents a purely vertical speed measurement. The horizontal velocity of snowflakes is heavily influenced by wind speed, which can exceed 10 m/s, while the vertical velocity typically does not exceed 4 m/s. We appreciate your reminder regarding the 8 m/s speed; indeed, it is somewhat higher. We have reformulated that statement to reflect that the maximum vertical speed is 4 m/s:

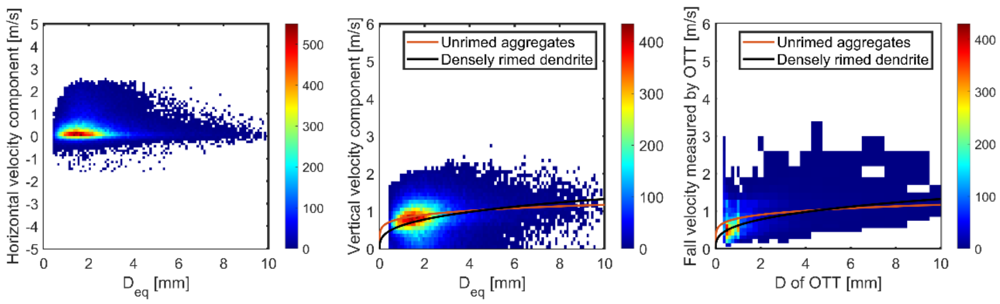
> (ii) the pixel coordinates in the particle images are similar (the falling velocity of the snowflake is generally not more than 4~~8~~m/s, so the interval between neighboring snowflakes is not more than 100~~200~~ pixels);

14.Lines 416 – 417: If westward motion is positive, I assume the 3D-PPI was facing towards the south? It might be useful to mention the direction the instrument is facing in the paragraph starting on Line 324 (preferably as a bearing, but a general direction would do if you don't know the exact bearing)

Yes, your assumption is correct; the instrument was indeed facing towards the south. We appreciate your attention to detail and have added the description about the instrument orientation in the revised manuscript Line 340.

15.Lines 426 – 428: Are these outliers real or are they a result of mismatches by the tracking algorithm. If they're a result of mismatches, it might be helpful to provide some statistics regarding how prevalent these outlier are (e.g., what percentage of the total sample population or the a reasonable range of percentages of their size bin populations) so the reader can determine if they are sufficiently infrequent to be considered negligible.

Thank you for your advice. We apologize for the error in the velocity calculations, which led to the mistakes in Figure 16. It has been corrected, the modified Figure 16 are shown as follows:



The modified Figure 16 shows a significant reduction in outliers, only less than 3% of the total samples are identified as anomalous particles caused by incorrect matching, we believe that less than 3% is negligible.

16.Lines 434: Ensure the 41.5 microns per pixel matches what is said in the text (Lines 107 – 111) and in Table 1.

Thank you for your advice. The 3.45 microns in Table 1 refers to the size of a single pixel, while the resolution of high-resolution camera in Lines 434 is the actual object size that occupies only one pixel in the image, that is the smallest particle size can theoretically be measured is 3.45/0.083=41.5 microns.

To avoid the misunderstanding, we have modified the corresponding content in Lines 116- 119 and Table 1 in the revised manuscript.

Table 1: Technical specifications of the cameras.

		High-resolution camera	High-speed camera
Image sensor	Type	CMOS, Global shutter	CMOS, Global shutter
	Model	Sony IMX304	Sony IMX287
	Single pixel size [μm]	3.45 × 3.45	6.9 × 6.9
	Resolution [px]	4096×3000	720×540
	Pixel resolution [$\mu m \cdot px^{-1}$]	41.6	265.4 (450mm distance)
	Size of the field of view (a × b) [mm]	170 × 125	191 × 143 (450mm distance)
	Frame rate [fps]	5	200
	Effective exposure time [μs]	20	20
Lens	Type	Telecentric lenes	25mm non-telecentric lenes
	Aperture	F6.5	F2.4 to F16
	Magnification of lens	0.083 (constant)	0.026 (450mm distance)
	Distortion	0.044%	0.16%