Manuscript amt-2024-106

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

The manuscript describes a new instrument, the 3D-PPI, to image snowflakes from three different directions. Conceptually the 3D-PPI is similar to previous instruments, in particular the MASC and the VISSS, however it differs in the number of simultaneous images or the FOV. The authors attempted a detailed description of the instrument. In addition to this description of the 3D-PPI and its calibration, the manuscript presents details of a first measurement campaign including the comparison to a disdrometer (OTT).

Development of instruments to measure snow is important, and I therefore welcome this publication. However, a thorough revision is required to address some shortcomings and missing details or discussions. In addition, a particular issue that needs fixing consists in problems with language and clarity which are present throughout the whole manuscript.

Below are my comments. Firstly, I am addressing important issues that are not only caused by unclear or wrong language. Secondly, I am listing minor issues.
There are many issues with wrong English or otherwise unclear text and statements in the manuscript. This made it difficult to focus the review on other issues and in many places it was difficult to follow and understand the authors' explanations. I am reporting these issues together with the minor issues.

In my comments I will refer to line numbers using simply numbers (e.g. "143" refers to line number 143 in the manuscript). I will also use "um" to indicate micrometer without using special fonts.

Important points in the order they appear in the manuscript

1)
Previous instruments are presented such as the VISSS and the MASC. When describing the MASC the following statement is done (73-75): "Nevertheless, only 10^2–10^4 particles were observed during a typical snowfall event (Gergely and Garrett, 2016), which is insufficient to permit the reliable estimation of the particle size distribution (PSD) (Gergely and Garrett, 2016)." I don't see why this sample size would be insufficient and I don't see Gergely and Garrett, 2016 saying that. It is a bit misleading to look at sampled number of particles during specific storms rather than snowfall rates or snow number concentrations. The authors should instead look at the observation

volume or something similar if they want to put the MASC in relation to 3D-PPI. The MASC has three cameras, as the 3D-PPI, but they are all located in one plane. However, the MASC was extended to five cameras with the additional two not being in the same horizontal plane as the original three cameras (Notaros et al. 2016, Kleinkort et al. 2017).

2)
a) What is the actual resolution (combination of optical resolution and illumination that allows details of a certain size to be resolved)? What are the smallest details that can be resolved? This is not discussed but an important detail of a new instrument. I can only guess from the images (mostly Fig. 1c). The images look similar to MASC images of snow, likely due to a similar illumination scheme. The smallest details are very faintly grey and seem to disappear in the black background. Due to this and due to the missing description of the detection algorithm and thresholds (see further comment on image processing (comment 8) below), it is not possible to do a fair judgment of the actual resolution for detection of small details (e.g. thin branches).
b) Judging from Fig 6b, the sizes of the smallest ceramic spheres are underestimated. For each camera, the linear fit has a negative offset (see comment below) with the observed size being on or below that fit. So, there seems to be a systematic bias for sizing of the smallest details. Please comment on this.
c) Related to this is in 207 “Snowflakes that are too small in diameter are ignored”. What is this diameter, how did you decide on its value? Also, in the next sentence you state that you connect apparently separate detected regions if they are up to 4mm apart. This indicates that you expect that smaller details that may be connecting these regions are not being detected.

3)
Inconsistent and wrong or confusing use of ”resolution”, ”pixel resolution”, ”pixel size”, and ”magnification”. Revise and use better and consistent terminology throughout the paper.
Examples:
a) In Sect 2: 92, I would not call this "resolution" as that can be confused with pixel resolution or optical resolution. Say something that is less ambiguous like: “The sensor has 4096 x 3000 pixels.”
b) Tab 1: The “pixel resolution” is given as 3.45 um. In the text instead a single pixel size is stated as 0.042mm. This seems wrong or confusing to me. What you mean likely is that the sensor has a pixel size of 3.45 um and the pixel resolution (given by the magnification and pixel size) of 41.5 um/px.
c) Add magnification and pixel resolution to the table.
d) 402, 230um/px is pixel resolution, not “magnification”.
e)The magnification 0.026 and pixel size of 6.9um gives a pixel resolution of 265um/px. Why do you state 230um/px here?
f) In Conclusion "resolution of 41.5um/px" is used.

4)
102, “observation volume size of 1505.327cm3”: Part of the observation volume is out of focus (as depth of focus with 104mm is smaller than the FOV dimensions). Three digits after the decimal point are not needed.

5)
156 “super-determined”: Does this refer to an overdetermined system with more equations than unknowns? What are the unknowns here in that case?
Do "super-determined" and "super-deterministic" refer to the same thing?

6)
163-169, explanations why the planar two-dimensional checkerboard grid cannot be used for calibration:
a) 164-165, “but then the values of all three dimensional world coordinate points are the same”: this sounds very general; explain better what you mean, which points/coordinates are the same?
b) The sentence continues that with that A equals a matrix, which is the same matrix as the matrix KMi is multiplied with in Eq (2).
c) The matrix A has not been defined before. Please do that.
d) 165-167, “The third and fourth-row values are the same …” This sentence is not correct. Please revise. The fourth-row values are all 1, did you want to say that all values in the third row are 1, or are the same but not necessarily 1 but any other value?
e) 167, “determinant of A is 0”: as far as I know, the determinant is defined for square matrices, but A is not (unless j=4).
f) 168, “impossible to inverse” should be “impossible to invert”

7)
171-172, in this sentence at the end of Sect 3.1, you present an “average reprojection error”. Nowhere in Sect 3.1 you present any calibration results related to the theoretical treatment presented. The theory presented seems needed to determine KMi, which are needed for the matching algorithm. Define what the average reprojection error is and how you have determined it. Here you say 0.32 pixels, in the Conclusion 0.4 pixels.

8)
Determination of pixel resolution (41.5um/px) in Sect 3.2 (Calibration of image binarization) and image processing in Sect. 4.1:
a) 181, “is optimally binarized manually”: How has this manual binarization be performed. Is each image treated differently. Is this using the image processing algorithm described in Sect. 4 (where the details of the detection are missing, see comment about “adaptive thresholding below”)?

b) You determine the pixel resolution from the reciprocals of the slopes in Fig 6b (Dmax/px vs Dmax/mm). You are not discussing the role of the offset of between 0.5px to 4px in Equations (3)-(5).
c) The pixel resolution should also result from the calibrations using chessboards. Has this been attempted and the values compared to the pixel resolution reported in Sect 3.2?
d) The pixel resolution using chessboards would be similar to using micrometer or millimeter scales. The advantage over ceramic spheres would be that it would not depend on image processing (selection of specific grey level threshold to detect the contours of the ceramic spheres), which may result in under- or over-sizing of the spheres. The details of this image processing are, however, not disclosed. You only state (Sect. 4.1, 204) that the images are "binarized through adaptive thresholding" without giving any reference or explaining what adaptive thresholding is in your specific case. Please explain this method.
e) In Sect. 4.1 describing the image processing you show results from imaging the ceramic spheres (Fig. 8a and 8b) in terms of measured size vs real size (both in mm). You must have used the pixel resolution resulting from imaging the ceramic spheres (Sect. 3.2, Fig 6b). For the "calibration of image binarization" you must have used the image processing algorithms described in Sect. 4.1. That means that Fig 8 does not show anything new or independent from previously reported Fig 6b. You are presenting the same ceramic sphere measurements in two related ways. Consequently, the error analysis related to Fig 8 is only a re-interpretation of the error analysis of Fig 6b.
f) In any case, the presented error analyses are unclear and confusing:
L196-197, "The estimated random errors from the normalized root square errors, derived from the observed and true size difference ..."
Unclear what "observed and true size difference" is.
Unclear what "random" refers to?
Does it refer to variations in 20 observations of the size of the same ceramic sphere?
g) Due to the offset in your linear least squares fits, the reciprocals of the coefficient px/mm (24px/mm here) are not equal to the coefficients that would result from fitting true size vs observed size (mm/px). Redo that fit or comment.
h) 227, "average absolute error of Dmax measurements for all diameters of small spheres is -0.048mm,"
An absolute error is positive, but you state that it is -0.048mm. Same for Deq with -0.33mm.
Then it is unclear what the "average relative error" (229, 230) is.

9)
206-207, "Detecting connected regions ... enables the removal of small noise ..."
Missing/wrong logic:
What is enabling the removal of noise from image? What is small noise on the image?

10)
207, "Snowflakes that are too small in diameter are ignored"
What is this diameter, how did you decide on its value?

This is related to the comment about actual resolution. Here you seem to have defined a smallest particle that is accepted.

11)
243-252, explanation of matching algorithm:
This is a clever way to use the matrices KMi (i=1,2,3) from camera calibration for matching. The following issues/unclarities result from wrong language or unclear formulation.
a) I would not re-use the index i, that previously was used to refer to the three cameras, to refer now to a particle number. Use another index or no index.
b) 245, “i underdetermined linear equations”: Is there one underdetermined linear equation for each particle? Refer to an equation number in the paper or explain better what these equations are (and why/how underdetermined).
c) Would be good to add equation (if appropriate in Appendix), the solution of which is Li. Then also another equation showing the multiplication of KM1 and KM2 to produce the projection of Li onto Cam1 and Cam2 image planes.
d) 246, “ith straight lines” should be “i straight lines”?
e) 247, “the lines Li is the back-projection” should be “the lines Li are the back-projections”.
f) 248, “multiplying the projection matrices KM1 and KM2,” should be “multiplying the projection matrices KM2 and KM3, respectively, with Li,”
g) 249, “resulting in ith line segments” should be “resulting in i line segments on each of the image planes of Cam1 and Cam2”
h) 251-252: from the text it is unclear if each particle has to be on all three lines, or each particle on its respective line in each of the images. Describe for one particle (to avoid confusion between THREE cameras, and THREE particles/lines).

12)
259-294, 3D reconstruction:
The description of how particle is located to enable/simplify 3D reconstruction is unclear. Here a few things that make it difficult to follow:
a) Add new sub-section (now it is part of 4.2 Particle matching and localization).
b) 259, Not sure what voxels are and why/how they are used traditionally. Provide a reference.
c) 260-261, Explain or discuss how are “traditional methods” “computationally inefficient”.
e) 264, “particles' localizations” should be “particles' locations”?
f) 266-271, Unclear why irregular particles pose a problem. You probably need to be more specific in explaining the issue
g) 277-278, confusing use of indices:
“Lines L1”, I thought L1 is one line, the back-projected line from P1 on image of Cam0.
“L2” according to earlier explanations (247), this is the back-projected line from P2 (particle 2) on image of Cam0, but here is redefined.
h) How can L2, a line, be “represented as a 2-row by 1-column matrix”?
279-280, “P2” and “P2’”, what is P2 (it is not the P2 on image of Cam0, 243)?

It becomes more and more tedious to follow the remaining explanations. This whole section should be revised for consistency and clarity.

13)
Sect 4.3: It is not immediately clear if and how this connects to explanations in 259-294.
296-297: “silhouettes that have been serially calibrated using multiple viewpoints around the target” The section starts with unclear formulations like this one (are silhouettes contours, multiple viewpoints refer to Cam0,1,2, what does “serially calibrated mean”?).
I did not review the remaining of this section. After revising the previous section, this section should be revised too.

14)
a) Explain better Eq (7).
b) “Nima is the number of particles” should be “Nima is the number of acquired images”?
c) You state that (339) “the probability of capturing the same snowflake in two consecutive frames is very low.” How often can the same snowflake be captured twice? Discuss if anything is done to account for this or, if not, how big of an error this may cause.
d) You are getting the PSDs only from Cam0 here. That means Vobservation is different from the observation volume reported in 102 (1505cm3). Vobservation is calculated using the depth of focus (104mm). How well-defined is the depth of focus? Are particles outside depth of focus detected but then rejected reliably?

15)
From Fig16b I would guess that the PSD peaks at Deq between 1 and 2 mm, whereas in Fig 13 the PSD peaks at Deq of about 0.4mm. Is everything consistent here and I am only being confused and misled by something?

16)
Negative velocities:
a) L416-417 “The average value of the horizontal velocity component measured by 3D-PPI is +0.05m/s (positive and negative values indicate westward and eastward velocities, respectively), and the standard deviation is 2.56m/s (Fig. 16a).”
Unclear if your average is an absolute average (or do you consider positive and negative values when averaging)? Consequently, the meaning of the standard deviation is unclear.
b) I would expect horizontal speed to be characterized by speed (absolute value) and direction (0 – 360degrees). Instead, you use positive and negative values to indicate westward and eastward. Why choosing to give info on west-east, and not north-south or the actual direction in degrees?

c) If you choose to include directional information, why are you not analyzing the direction.
I would expect the horizontal speed direction to correlate with local wind direction. Was the local wind measured and compared to horizontal speed? This could be part of a discussion how wind affects measurements.

Minor issues

1)
The three cameras are numbered 0,1,2 (Cam0, ...), whereas you use the indices i=1,2,3 to indicate the three cameras (e.g. KM1, KM2, KM3).
Can you use the same indices to reduce confusion?

2)
“and” in wrong place in a list (85, 185).

3)
86-87, “capacitive rain sensor is adopted as a trigger, the cameras only work when the precipitation occurs.”
Rain sensors detect rain. When you say the cameras only work when precipitation occurs, do you mean when it rains? I would expect you want to measure with snow but perhaps not with rain? Please clarify.

4)
Fig 1a: It would be useful to label the different parts. Without labels it is, for example, not clear which/where is the fourth non-telecentric camera. Labels are a complement to more clarity in the text.

5)
98-99, “45° angle relative to the optical axis of the high-speed camera” Be more specific: two cameras are positioned, at 45 degrees, on either side of the high-speed camera in the same horizontal plane, the third .... at 45 degrees vertically above

6)
100-101, "overlapping region of the LED lighting beams" and intersection of the "three rectangular light columns"???
I don't think you are talking about the LED lightning?! Do you mean the intersection of the FOVs of the three cameras (which may be approximated by rectangular light columns)? But I assume the LED lightning beams are larger than the FOVs (and not exactly rectangular and change in cross section).

7)
Be consistent with units.

102 you state the FOV as 17cm and 12.5cm, later you write 170mm and 125mm.

8)
101-103, the text referring to Fig 2 describes light reflected and scattered by snow particles, which is not shown in Fig 2.

9)
Fig 2: You have talked about rectangular columns earlier; you should now show these (rather than the circular columns you do show).
“Optical structure” doesn’t seem to be the appropriate expression. Some more info in the caption would be useful.

10)
114-115, “which leads to a difference in the method of performing 3D reconstruction later in Sec. 4”. Are you referring to a difference of the method”. How is the method different from what?

11)
127 “The LED light sources are arranged in a parallel configuration, leading to a unidirectional power supply interface.”
Are you talking about electrical set-up or spatial placement of LEDs?
Are you talking about LEDs or LED arrays?
What do you mean with “unidirectional power supply interface”?

12)
128: specify (or re-word) “consistent light output” as it is unclear.

13)
Fig 4a is not needed, you have the same information as Fig 4b.

14)
139-140: “projection matrix KMi of the transformation relationship between the 3D spatial points and each pixel plane pixel point in the world coordinate system”
a) Re-formulate this for clarity.
What is a “pixel plane pixel point” if it is not a mistake?
A pixel point is not “in the world coordinate system”.
b) Also, define the World Coordinate System when you first use it.

15)
142-144: Something is missing or wrong in this sentence (in particular “ and the apparent 3D …”).

16)
a) 153-154: Define/describe the 3D checkerboard.
b) I would be consistently using only “checkerboard” or only “chessboard”.
c) Reconsider sentence: “from the same localization using three cameras” is wrong. The three cameras image from three different views/locations.

17)
157 “such as Eq. (2)”: should that be “shown in Eq. (2)”? (Eq (2) is not an example but shows exactly the equations you want)

18)
170-171, “The two … define a common …WCS”
Two planes do not define a WCS. Should it be “The three…”?

19)
Eq.s (3)-(5): “Dmax [um]” should be “Dmax [mm]”

20)
Fig 6a and 6b: You show 13 spheres in Fig 6a and 15 points on the plot Fig 6b. How many spheres did you use?

21)
209, “is necessary is an essential step” Check and correct.

22)
239, “which poses a challenge for particle identification from the images captured by three cameras”
Did you mean a “challenge for particle matching”?

23)
Comparison between 3D-PPI and OTT measurements
Fig 16, What are the numbers on the colour scale?
Would be interesting to see speed distribution for a few particle sizes (you mentioned such a distribution in 402 “snowflake velocity distribution with diameter was calculated”).

24)
343-344, “PSDs are described …”
a) What is the meaning of this sentence?
b) “across a larger range of sizes”?

25)
344, “The peaks of Deq…”
Deq does not peak. Be more precise and correct with your formulations.

26)
a) 348-352, “Comparison of temporal plots…”
Long sentence with several statements that are unclear.
b) Same next sentence (meaning of “which means the aggregation of snowflakes was weakened”). Please revise.

27)
Eq. (8): What is surface area S? Surface area of the 3D reconstructed hull?

28)
381, “so blurring that particle motion is insignificant” Check sentence for correct English.

29)
383, “and the same particle is merged into a single image in Fig. 15a”
Describe better what was merged into a single image (and that it is done only to better visualize something in the paper/Fig).

30)
In Sect. 6 Conclusion:
446, “pre-calibration” is used only once so that it is unclear what it refers to (add reference to section in paper and use consistent names).
Revise the whole Section after revising the manuscript.

31)
Comparisons without clear reference:
342, “across a larger range of sizes”
345, “more and more concentrated small particles”
345-346, “average particle size was consistently smaller” smaller than? (also unclear what “consistently” means)
391, “generally not more than 20%.” What is 20%?
435-436, “estimate PSD more accurately”
436, “calculation of velocity more accurately”