Introducing the Video In Situ Snowfall Sensor (VISSS) 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.~~

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We thank the reviewers and the editor for their—again—very helpful comments. We responded to all comments and changed the manuscript accordingly.

1 Review by Thomas Kuhn

I thank the authors for carefully considering all the feedback. I appreciate that they improved many descriptions and some algorithms resulting in a clearer manuscript. Thank you for demonstrating the optical resolution. I can see almost all lines of the microscope slide you are showing. So, it is fair to say the resolution is on the order of 50µm given that these lines have a similar thickness. Regarding small particles, I agree with your concern that you are likely "loosing" (not detecting) some of the smallest particles during image processing. I am still curious, however, to see examples of 2-px particles alongside their contour and Dmax, A, p values. As you have published data, I will have a look and do not suggest adding anything to the paper. In the following I am only asking for a few clarifications, which mostly refer to changed sections. I am referring to line numbers of manuscript-version 2.

We thank Thomas Kuhn for taking the time to review the paper again and his helpful comments.

Sect 3.1 Particle Detection
L153: "... particles in the moving foreground mask are systematically too large." You talk about a moving ROI, then moving mask, and eventually about moving foreground mask. I am not sure what is the "particle" at this stage? Or do you mean the ROI is larger than the particle?
L156-159: What is a "gap in the contour"? For me a contour is a continuous line. It is hard to follow exactly what is done here. Perhaps and illustrated example of what could happen and how it is prevented would help a lot (could be in Appendix B).

Both comments are addressed together: We reworded the paragraph to use the word contour more precisely and to name the moving mask more consistently

> Instead, the moving ~~region of interest (ROI)~~ mask of pixels is identified by openCV's BackgroundSubtractorKNN class (Zivkovic and van der Heijden, 2006) in the image coordinate system (horizontal dimension X, vertical dimension Y pointing to the ground). ~~The~~ In the moving mask identified by the background subtraction ~~methods cannot be used directly for particle detection because the particles in the moving foreground mask~~ method, the individual particles are systematically too large so that the moving mask cannot be used directly for particle sizing. For each particle, i.e. connected group of moving pixels, we select a 10 ~~pixel~~ px padded box around the region of interest (ROI) which is the smallest non-rotated rectangular box around the particle's moving mask (Fig. 3). ~~Then, we use~~ This extended ROI is the input for openCV's Canny edge detection (after applying a Gaussian blur with a standard deviation of 1.5 ~~pixels~~px) to identify the edges of the particle~~and the corresponding particle masks. To fill in small gaps in the particle contour~~. To estimate the particle mask by filling in the retrieved particle edges, gaps (typically 1 px in size) between the particle edges must be closed. For this, we dilate the ~~contour~~ retrieved edges by 1 ~~pixel, fill the contour, erode~~ px to form a closed contour, fill in the created contour, and erode the filled shape by 1 ~~pixel, and identify the new contour. This method closes potential holes in the particle mask that~~ px to obtain the particle mask. To detect potential particle holes, which should be retained to avoid ~~overestimation of particle area. Therefore, the final particle mask contains only values confirmed by the Canny filter and~~ overestimating the particle area, the ~~background detection mask~~ Canny filter particle mask and the moving mask are combined for the final particle mask.

L154: "non-rotated". Is there a better way to define this type of smallest rectangular box? (major axis along x or y?)

Yes, this is actually estimated by the minAreaRect algorithm which is one of the algorithms used for determining the aspectRatio. But the ROI is more a technical step required for determining the region where other algorithms like blur estimation, Canny edge detection etc. are applied to.

L154: Replace "region of interest (ROI)" with "ROI".

Not changed, because the previous mention of ROI was removed.

Sect 3.2 Particle Matching, L 191-192: The sentence "Since pixel measurements are discrete with 1 px steps, the PDF is integrated for an interval of ±0.5 px" for me omits why the PDF is integrated. This may be obvious for some, but for clarity I would anyhow include it (correct me if I am wrong): "To determine the probability (of, for example, a certain vertical extent), the PDF is integrated over an interval of ±0.5 px (representing the discrete 1-px steps)."

Changed to

> ~~Since pixel measurements are discrete with 1 px steps,~~ To determine the probability (of e.g., measuring a certain vertical extent), the PDF is integrated ~~for~~ over an interval of ~~±~~ ±0.5 px representing the discrete 1 px steps.

Sect 3.4 Particle Tracking, L358-359 "shape difference": Shape refers to area here? Better say "area difference" then.

Changed as suggested.

Sect 3.4, Fig 4c,d. It took me some time to understand what exactly is shown. Perhaps small changes in the caption can improve it: "... shows a frame of the leader (c) and the matched frame of the follower (d). ... For each particle (surrounded by boxes) the particle track is shown. The tracks indicate past ..."

Changed as suggested.

Sect 3.5, L270-273: This sentence suggests that the PSD is a property averaged in size bins. Isn't it instead the number concentration in size bins (normalized with the bin width)? So, I would suggest being correct and clearer by saying something like (guessing how you determine concentration and account for size dependent observation volume, see comment on L335-336 below): "To estimate the particle size distribution (PSD), i.e., the particle number concentration as a function of size, the individual particle data are binned by particle size (1 px spacing, i.e. 43.125 or 58.75 .m) and the number of particles in the bins are divided by the observation volume. These binned number concentrations are then averaged over all frames during one-minute periods. Then also binned particle properties such as area and perimeter are averaged to one minute resolution for." Correct me if I am wrong and try to improve sentence accordingly.

We agree that this was formulated in a confusing way. To improve readability, we renamed the section from Particle size distributions to Time-resolved properties and moved it behind the calibration section. Also, we moved the estimation of the observation volume to the description of the PSD so that both are discussed together:

> Particle size distributions Time-resolved particle properties
>
> While Level 1 products contain per-particle properties, Level 2 products provide time-resolved properties. This includes the particle size distribution (PSD), which is the concentration of particles as a function of size normalized to the bin width. To estimate the PSD, the individual particle data are binned by particle size (1 px spacing, i.e. 43.125 or 58.75 µm), averaged over all frames during one-minute periods, and divided by the observation volume. For perfectly aligned cameras, this the observation volume would simply be the volume of a rectangular cuboid with a base of 1280 px x 1280 px and a height of 1024 px. However, due to misalignment of the cameras, the actual joint observation volume is slightly smaller than a rectangular cuboid and can have an irregular shape. Therefore, the observation volumes are first calculated separately for leader and follower. To calculate the intersection of the two individual observation volumes, the eight vertices of the follower observation volume are rotated to the leader coordinate system, and the OpenSCAD library is used to calculate the intersection of the two separate observation volumes in pixel units. To account for the removal of partially observed particles detected at the edge of the image, the effective observation volume is reduced by D_{max} $D_{\mathrm{max}}/2$ px on all sides. Consequently, each size bin of the PSD is calibrated independently with a different, D_{max}-dependent effective observation volume. Finally, the volume is converted from pixel units to m^3 using the calibration factor estimated above.

The rest if the paragraph has been mostly flagged as new by latexdiff because it was moved from section 3.5

> The Level 2 products are available based on the level1match and level1track products. For level2match, binned particle properties are available either from one of the cameras or using the minimum, average or maximum from both cameras for each observed particle property. This means that the multiple observations of the same particle all contribute to the PSD. This does not bias the PSD because the number of observed particles is divided by the number of frames, and the PSD describes how many particles are *on average* in the observation volume. For level2track, the distributions are based on the observed tracks instead of individual particles, and are calculated using the minimum, maximum, mean, or standard deviation along the observed track using both cameras. The use of the maximum (minimum) value along a track is motivated by the assumption that the estimated

> properties of a particle such as D_{max} (AR) of a particle will be closer to the true value than when ignoring the different perspectives of a particle along the track obtained by the two cameras.
>
> For both level2 variants, the binned PSD and A, perimeter p, and particle complexity c are available binned with D_{max} and D_{eq} to allow comparison with instruments using either size definition. In addition to the distributions, PSD-weighted mean values with one minute resolution are available for A, AR, and c in addition to the first to fourth and sixth moments of the PSD that can be used to describe normalized size distributions (Delanoë et al., 2005; Maahn et al., 2015).

Sect 3.6 Calibration, L330,331: From the Response Comments you seemed to agree that it was sufficient to say "cuboid". But I see twice the term "rectangular cuboid".

We must have overlooked that, changed as suggested.

Sect 3.6 Calibration, L 336-336: " To account for the removal of partially observed particles detected at the edge of the image, the effective observation volume is reduced by Dmax/2 px on all sides." This means that the observation volume is size dependent. What if two or more particles are in the observation volume, how is concentration calculated (as I guessed above, see comment on L270-273)? It may be good to mention the size dependence and how you take care about it (for example referring to Sect 3.5) or how it affects results, if it does). With that, you also make it clear that and how you use the observation volume, for which you just described how to determine it.

We moved that paragraph to section 3.6 and added the following sentence:

> Consequently, each size bin of the PSD is calibrated independently with a different, D_{max}-dependent effective observation volume.

Sect 4.1 I would extend the sentence ending in L384 for clarity (of what 50% advantage means): "... reduced to 50% more particles than observed by Parsivel and PIP."

Changed as suggested.

Sect 4.3, L439 "orientating": Would "orientation" be better? Technical: I would, according to standards, use roman font (not italics) for indices that are descriptive (i.e. do not refer to other variables): Dmax, Deq, XL, ... Check for inconsistent use of font (variables that appear in both italics and roman): N0, Dmax and Deq (Fig8 caption), D32 (is D23 in Fig6 caption).*

Changed as suggested.

2 Review by Charles Helms

The authors have satisfactorily addressed all of the comments I raised in my previous review and I feel like this manuscript is ready for publication. That said, there are a few very minor suggested corrections (almost exclusively typos) that I have included at the end of this review.

Following up to the authors' response to my comment on the PSD and slower falling particles: Thank you for the explanation regarding the interpretation of the PSD not as the number of particles that fall through the volume in a given time but as the average number of particles in a volume at any given time. My work with the PIP and other instruments has mostly focused on the measurements themselves rather than the resulting PSD. Not sure about the PIP subsampling, but it's not particularly relevant to the manuscript anyway. That said, it does seem odd that the PIP data would be subsample given the goal is the average number of particles in the volume at any given time; perhaps there was some other reason I'm not aware of (or perhaps the person who told me that the PIP PSD used the subsampled data was mistaken).

We thank Charles Helms for taking the time to review the paper again and his helpful comments.

Line 198: "This allow to identify..." should be something like "This allows us to identify. . . " or "This allows the algorithm to identify. . . "
Line 199: "We found that this method gives already stable results. . . "; suggest removing "already"
Line 205: "campaign" should be plural
Line 218: ". . . but this would not allow to generally. . . "; add "us" (or similar word) after "allow"

All changed as suggested.

Line 262-263: The authors might also want to mention how the tracking is initialized when there are no previously tracked particles (e.g., at start up). I assume this is taken care of either alongside the camera alignment steps or via some default value, but it might be a good idea to state things explicitly.

We added

> Without a past trajectory, the Kalman filter uses a first guess which we derive from the velocities of 200 previously tracked particles. If no previous particles are available, the tracking algorithm is applied twice to the first 400 particles to avoid a potential bias caused by using a not case-specific fixed value as a first guess.

Line 308: "...but the offset is this time negative..."; suggest removing "this time"
Line 423: "...probably related to problems of the PIP image processing."; the wording is a bit awkward, suggest something like "probably as a result of the PIP image processing implementation" or "probably as a result of limitations in the PIP image processing implementation"
Line 449: "When exploiting also the varying orientations during tracking" sounds awkward. Suggest something like "When the varying orientations are taken into account

All changed as suggested.