======= REVIEWER #1 =======

amt-2021-427: Helms et al. A Comparative Evaluation of Snowflake Particle Size and Shape Estimation Techniques used by the Precipitation Imaging Package (PIP), Multi-Angle Snowflake Camera (MASC), and Two-Dimensional Video Disdrometer (2DVD)

In short: This study compares the different algorithms behind the measurement techniques of three digital video disdrometers: the Precipitation Imaging Package (PIP), the Multi-Angle Snowflake Camera (MASC), and the Two-Dimensional Video Disdrometer (2DVD) in observing snowflakes. The focus is on defining the uncertainties in the defined area influencing the equivalent diameter, and the aspect ratio. The authors quantify the motion blurring, in the case of PIP also the image compression, the shape-fitting measurements, and in the case of 2DVD, the estimate of the bounding box measurement when particle horizontal motion needs to be adjusted with an unskewing algorithm.

The topic is interesting and relevant for surface observations and the development of retrieval methods in global monitoring of snowfall. The study has novelty in the way it examines the measurement algorithms internal to the instruments, which typically are not transparent to the end-user of the data. The theory is clearly outlined with illustrative examples, and the conclusions are well-supported and valid. The manuscript is well written and provides a clear storyline, however, at least in my opinion, it leaves the reader questioning what is the magnitude/importance of these studied uncertainties in respect to the other uncertainties e.g. particles out of focus or only a fraction of particles observed, wind effects to particle fall velocity, miss-matching of particles, partially illuminated measurement space or limited observations of particles from only one plane projection, these are referred in several publications prior to this one. I would like to see more discussion on this topic and references to other related studies. My recommendation is to publish the paper after addressing this concern and some small remarks mentioned below.

I've added a discussion section that takes a look at how the findings of this study compare to other studies (Section 6, Lines 550 – 587).

Minor comments:

Line 11: "… PIP or 2DVD which provide similar precision once the effects of the PIP image compression algorithm are taken into account." This sentence is somehow unclearly connected to the previous statement in lines 10-11 and is not clear for a reader who just reads the abstract. Please rephase.

I rewrote that bit of the abstract and this sentence was removed.

Line 41: "There are numerous examples of studies which rely heavily on either of these measures of particle size." The statement "numerous examples" follows only by two references, leaving for example relevant fields such as the snow model or satellite retrieval development unmentioned. I would like to see a broader scan of the research field, just mentioning applications and example references would be enough.

The previous paragraph gives a list of five studies which use one of the two measures of particle size. As such, I've reworded the start of the paragraph that started on Line 41 (and now starts on Line 39) with the intent of making the paragraph serve as a deeper dive into one of the studies. The paragraph now starts off with:

"In the case of Han and Braun (2021), the authors characterize the global three-dimensional distribution of precipitation mean particle sizes using satellite radar data; they used a form of the equivalent diameter as their metric of particle size, specifically the mass-weighted mean liquid-water-equivalent diameter." Lines 39 – 41

Subsequent paragraphs delve into some of the other studies listed (Pettersen et al 2020,2021; Locatelli and Hobbs 1974; Heymsfield and Westbrook 2010).

Line 64: "separate from the snowflake size," This is unclear. I don't understand how these mentioned studies are concerning only aspect ratio separate from size. Please rephrase.

My intent was to make sure the reader wasn't thinking of snowflake shape as referring to the combination of relative dimensions and overall size. In hindsight, I don't think the clarification is strictly necessary, especially if it has the potential to cause confusion. As such, I've simply opted to delete the clause. Line 61

Line 87: Altitude of the site?

Added altitude (789 m) after the latitude and longitude coordinates. Line 94

Line 89-91: I would like to see more data of this event to support the assumptions of aggregation and lump graupels, e.g., time series of temperature, PSD, and mean fall velocity.

I've added a figure showing the PSD, mean fall speed, and the air temperature (Fig. 1). I've also added the following text to the end of the paragraph:

"Although the general presence of these habits were primarily identified through visual inspection of the PIP data, further support of their presence can be found by examining the time series of the particle size distribution, particle fall speed, and air temperature, as depicted in Fig. 1. Periods when aggregates are present can be identified by the larger equivalent diameters and slower fall speeds and periods with lump graupel can be identified by the smaller equivalent diameters and faster fall speeds; the lump graupel can be discerned from liquid precipitation based on the below freezing temperatures, which extend over a deep layer according to a nearby thermodynamic sounding (not shown)." Lines 98 – 103

Line 336-8: “Even with a very fast fall speed of 4 m/s, the overestimation of the equivalent diameter for very large circular particles (diameter ~ 10 mm) is approximately two orders of magnitude or smaller than the actual equivalent diameter.” Two orders of magnitude? This is not clear to me.

A fractional bias of 0.01 would mean that the bias is two orders of magnitude smaller than the measurement. In this case, a fraction bias of 0.01 for a circular particle with a diameter of 10 mm would mean the bias is 0.1 mm. I’ve clarified this point in the text by changing the sentence to read

“For a very fast fall speed of 4 m s^{-1}, the overestimation of the equivalent diameter for very large circular particles (diameter $\gtrsim$ 10 mm) is approximately two orders of magnitude smaller than the actual equivalent diameter (i.e., a fractional bias of 0.01).” Lines 389 – 391

Line 339: “perfectly circular”. Why assumed the particle to be circular, though written in lines 68-69 “aspect ratio is frequently prescribed, often with a mean value of 0.6 assumed (e.g., Matrosov et al., 2005)” and then without quantification stated that for the oblate particles “the relative (and absolute) effects of motion blurring on the area and equivalent diameter measurements will also grow”. Please justify and elaborate.

The choice of using a circular particle comes down to simplicity: a circle is easy to mentally picture, there’s no need to worry about assuming an orientation, and the equivalent diameter is equal to the diameter so the “ground truth” is easy to convey in the plots. As for oblate particles, if you make the particle more oblate without changing the area, the number of top-edge pixels will grow, which will increase the area and equivalent diameter biases (i.e., the “absolute effects”) as they are more or less proportional to the number of top-edge pixels (as well as the particle speed of course). As we are keeping the area and equivalent diameter constant, the fractional bias (i.e., the “relative effects”) will increase as well. I don’t feel like this needs quantification to back it up, but it certainly could do with more of an explanation. The text now reads:

“As the particles under consideration become more oblate, with their horizontal dimension growing relative to their vertical dimension, both the absolute and relative effects of motion blurring on the measured area and equivalent diameter will increase relative to circular particles of the same area. An oblate particle of equal area to a circular particle will have more top-edge pixels than the circular particle. Increasing the number of top-edge pixels increases the number of pixels that the motion blur is applied to, thereby increasing the absolute effects of the motion blurring. Furthermore, because the particle area remains constant, the relative effects of the motion blurring are also increasing. For similar reasons, increasing the complexity of the particle outline such that the number of top-edge pixels increases will also result in larger biases due to motion blur.” Lines 393 - 400

Figure 4: Could you add the number of analyzed particles and a density plot would add information instead of a scatter plot.

Switched to a 2D histogram and added particle count to color bar title of Fig. 5.

Figure 6. Just to add more information about the particle habit, could the approx. fall velocity be added to the corner of the image? The colored fitted shapes, could the line be slightly thinner or the image larger, it is now hard to see the lines in respect to the shaded image, they are all on top of each other.

I've gone through and added fall speeds for each particle and played around with the line thicknesses of Fig. 7. Annoyingly, it seems that particles (c) and (d) are not listed in the PIP velocity tables, so I had to go through and manually calculate the fall speeds for these. I've also made the annotated circles for the MASC and tensor methods thinner to make the PIP annotated circles easier to see.

Lines 404-406. As PIP is only seeing a plane projection of the particle, but here the particle is referred to as an ellipsoid, it is confusing whether in this perimeter stretching factor analysis, the computations are performed in 3D with ellipsoids and is it then assumed the same axes ratio in both directions or is it performed in the 2D projection. Could you please clarify this?

It seems that this is a bit of sloppy word choice on my part. I've changed ellipsoid to ellipse. Line 464

Paragraphs 408 – 445: I understood that this section provides explanations why the ellipse-fit in PIP has an arbitrary upper threshold close to 0.6, and why with the rectangular fit in PIP, there is a gap in aspect ratio between 0.9 and 1.0. However, it was not always clear, which "gap" the authors were pointing at. I would suggest that you would refer in the text (when addressing for the first time) to the image, where the "gap" is shown. E.g. in lines 436-438, I assume here the authors are referring to Figure 5b?

I've gone through this section of the text and tried to clarify the wording and point the reader to relevant figures more frequently. Lines 464 – 507

Figure 9. Same as Figure 4. It would be nice to see the number of analyzed particles and then rather a density plot than a scatter plot.

Swapped to 2D histograms and added the number of analyzed particles to the colorbar title for Fig. 10. I've also removed the height plot based on reviewer 3's comments.

Lines 526-527: "and, as a result, the maximum dimension and aspect ratio measurements are unreliable; however, the PIP variables other than the ellipse and rectangle dimensions appear to be reliable" I assume here it is referred that the PIP-fitted maximum dimension of an ellipse is unreliable and not that the observed maximum dimension is unreliable. Please clarify.

Clarified. The text now reads:

“Unfortunately, the PIP shape-fitting routines do not perform well on precipitation particles and, as a result, the PIP-fitted ellipse and rectangle dimension (and, therefore, aspect ratio) measurements are unreliable; however, the PIP variables other than the ellipse and rectangle dimensions appear to be reliable.” Lines 525 – 528

Lines 528-530: “As the present study has demonstrated, the PIP imagery can be reprocessed and reliable measurements of maximum dimension (the previous comment) and aspect ratio can be made via the application of an alternative ellipse-fitting algorithm, such as the MASC or tensor-based algorithms.” In the manuscript, it was described that the AVI file contains only the first 2000 frames from the 10 - minute section, and with 380 frames per second, this translates to 5.3 seconds of data. It is unclear that can an end-user reprocess the whole data volume or just the sample frames in the AVI-files? Could this be elaborated?

The good news is that yes, the entire data volume can be reprocessed from the raw files. The bad news is that this is a massive amount of data. My own efforts ended up taking an excessive amount of time to reprocess even a day of the raw data files. I’ve been told that the actual PIP processing code is written such that it can be used to reprocess data. From what I’ve seen, it should be possible to implement the tensor-based ellipse-fitting method using the IMAQ software so perhaps the data set can be reprocessed that way at some point in the future.

All that aside, I added the following paragraph to the Method section (just after introducing the AVI files for the first time) to make it more clear that the complete data set could (theoretically) be reprocessed:

“Ideally, we would include all PIP images from the 7--8 March 2018 period in our study rather than just those images that are included in the AVI files. Since the raw PIP image files are archived and contain every frame with precipitation, this is theoretically possible. That said, due to the very high data rates involved with the PIP data, the processing code would need to be highly optimized or use specialized software packages in order to process even a couple days of the raw data in a reasonable time frame. Thankfully, the AVI files contain a sufficiently large collection of precipitation particles to enable us to perform our study.” Lines 202 – 207