RC1: Review of "Development and Characterization of an Advanced Holographic Instrument for Atmospheric Research"

General Comments **The manuscript introduces HOLODROPS and HOLODROPS TRACK, two configurations of a holographic instrument designed for atmospheric research. HOLODROPS provides long term measurements of cloud droplet size distributions, while HOLODROPS TRACK performs short interval 3D particle tracking. The authors also introduce a novel eventbased Particle Image Velocimetry (ePIV) system. This ePIV system assesses fluid flow in real time and helps identify optimal measurement windows for the data intensive holographic hardware. The systems were characterized in the laboratory and successfully tested outdoors during a drizzle event.**

The development of these new instruments fits very well within the scope of AMT. However, the manuscript requires major revisions in both content and structure before it can be accepted for publication. Jan Henneberger

Response: We genuinely thank the reviewer for their valuable feedback and have responded to the comments in detail below.

Major Revisions

First, the use of event-based cameras is a novel method and needs much more explanation and validation. Please clarify exactly how the event camera translates particle movement into positive and negative events.

Response: Thank you very much for the suggestions. We have improved the manuscript and added additional information about event cameras' functional operation and ePIV in Section 2.2, the ePIV prototype and in Section 3.5, Evaluation of the Tracking Capability of ePIV.

Second, a robust discussion of uncertainties is missing. Please define the uncertainty of the size calculations. I strongly recommend repeating the glass bead measurements at larger sizes because the current large discrepancy is unexpected. Furthermore, please discuss the expected errors in particle velocities. This does not need to be a complicated calculation, but a clear estimate of the expected error is necessary.

Response: To quantify the uncertainty in the particle tracking, a polynomial was fitted to the particle trajectories. This provides an estimate for the random error in the particle tracks from the residual fits. Paragraphs were added to describe this in detail. Subsequently, to assess PIV uncertainty, synthetic images were created and processed using the same PIV method. This gives a correspondence between the sig2noise ratio and actually particle displacement error. Particles were simulated using synthpix. More details were provided in section 3.5, Evaluation of the Tracking Capability of ePIV.

Third, the comparison of measured particle velocities between HOLODROPS TRACK and the ePIV system is the core of the manuscript and must be expanded. Please compare different averaging intervals to show their influence on the particle speed distribution and any shifts in the mean velocity caused by turbulence. You should also investigate if there is a variation of the mean velocity over time.

Response: A parameter study was performed across different ePIV measurement intervals. This information was added and discussed. A plot of instantaneous mean velocity and global convergence of the mean was also added to this supplementary section. To better quantify the turbulence, Reynolds decomposition was applied to the flow fields, and the covariance vector was calculated. This is not meant to be a rigorous analysis but should add more context and information to the paper. More details were provided in the supplemental section.

Finally, please improve the overall structure and presentation. Be specific with your statements and remove unnecessary repetitions. Ensure consistent naming of the instruments throughout the text. The quality of the plots must also be improved. Please include proper units, axis labels, descriptions of variables, and larger font sizes.

Response: We have revised the manuscript and improved the figures' readability.

Specific Comments

Introduction: Be more specific with your statements and support them with references. For example, explain why knowing the droplet size distribution helps us understand why some clouds rain. Clarify what you mean by the internal structure of clouds and cite examples where cloud properties varied on a meter scale.

Response: An explanation and example with a reference were added to the introduction to explain why droplet size distribution is important for cloud rain (line 38).

Line 41: Change to "phase of hydrometeors".

Response: Changed.

Line 45: Consider changing to "scattering or imaging" because a holographic camera does not simply capture the shadow of a particle.

Response: Thank you. Details were added to discuss holographic imaging, as it is distinct from scattering or a particle's shadow.

Line 46: Start the paragraph by distinguishing between bulk measurement and single particle instruments. Baumgardner et al. (2011) provides a great overview.

Response: Information on bulk measurements and single particle instruments was added and expanded in the introduction.

Line 50: Either remove the remote sensing discussion or expand it. Mention Lidar and multi frequency Radar observations and clarify the RADAR acronym.

Response: A paragraph was added covering remote sensing applications.

Line 66: Change to "between ice crystals and droplets".

Response: The following has been changed

Line 67: Move this sentence to the previous paragraph.

Response: The following has been changed.

Line 72: Make the benefits of single droplet versus bulk measurements clearer and describe how holographic cameras combine both.

Response: Information has been added to describe the properties of single-particle and bulk measurements that holography can provide.

Line 78: Move this discussion to the next section after introducing holography. Please define "large volume". The main advantage is obtaining a complete droplet size distribution from a single

hologram. Also clarify that airflow is necessary for non-holographic methods to avoid resampling a stagnant volume, and they require a precise aspiration speed to calculate concentrations. Holography does not have this limitation.

Response: The following line has been moved to the next section. The large volume has been quantified in cm^3, and a discussion has been added about the large depth of field that holography can provide over a focal point. The advantage of holography capturing complete size distribution has been added.

Line 83: Change "Outlet" to "Inlet".

Response: This has been changed in the text.

Line 93: Define "very small scale" and "large number of droplets".

Response: Very small scale has been changed to few holograms, and large number of droplets has been changed to thousands.

Line 97: Explain why a non-mobile deployment would increase the sample volume.

Response: This system has a variable placement between the laser source and camera. This allows for a larger distance between the sensor and laser, which will provide a larger depth of field compared to mobile systems where the distance is fixed. This has been added to the manuscript.

Table 1: Include columns for resolution, sample volume, and frame rate. Compare the actual instruments rather than the platforms. HoloGondel and HoloBalloon are deployment platforms. The latest version of the holographic imager is described in Ramelli et al. (2020), and a holographic imager optimized for small droplets (smHOLIMO) was developed recently (Fuchs et al., 2025).

Response: Columns were added to show resolution, sample volume, and framerate.

Section 1.2.2: Many statements here need precision. The components must be well chosen for all holographic systems regardless of their deployment setting. For wavelength, note that a smaller wavelength increases the detection volume rather than limiting resolution. For energy, emphasize illuminating the entire camera surface without dark edges. For pixel size, note that the detection volume depends strongly on pixel size, so making it too small is not beneficial. Line 137: This section repeats statements made earlier.

Chapter 2: Add an overview table detailing key parameters like optical resolution, pixel size, number of pixels, detection volume, frame rate, weight, and power consumption for all three instruments. Please also include the specifications of the lens systems used.

Response: This section was rewritten to be more precise and objective. A table was added at the end displaying each system's parameters.

Line 180: Based on the two-pixel limit described in Section 1.2.2, the optical resolution limit is approximately 6.9 micrometers.

Response: This was changed from >6 micrometers to >6.9 micrometers.

Line 181: Explain why fine resolution limits the possible frame rate of the instrument.

Response: A sentence was added elaborating on the readout bandwidth, digitization and data transfer capacity.

Line 186: State the resolution for a sample volume several meters away from the camera.

Response: The sample volume for HOLODROPS at 1 meter was added.

Line 216: Provide the weight and power consumption for both the event camera and the high speed camera.

Response: This information was added at the end of the text.

Figure 3: Target 6.5 is resolved but the three bars of target 6.6 at a distance of 125.5 mm cannot be identified.

Response: Do you mean the images at a distance of 125.5 cm? If so, we apologize that the purple-highlighted rectangular overlay was placed on one of the three bars. We will improve the image once we have access to it. One of the leading authors, Susanne, is on family leave, and the rest of us don't have access to her images.

Line 245: Define the HR and high resolution camera. Make the connection to the HOLODROPS and HOLODROPS-TRACK instruments clear.

Response: HOLODROPS uses a 31.4 megapixel camera with 3.5 micrometer pixels while the HOLODROPS-TRACK uses a 8.3 megapixel camera with 4.5 micrometers. HOLODROPS is considered the high resolution system in this text. A few sentences were added to clarify this distinction.

Section 3.2: State the uncertainty of the glass bead diameters and the diameters measured by the holographic systems. Adding a table with these results would help. Explain why air turbulence leads to oversizing and why different bead sizes were used for different cameras. Clarify why the 50 micrometer beads had a higher noise level in the high speed camera but not in the high resolution camera.

Response: We have revised section 3.2 as suggested and added additional Table 2 to the manuscript. We clarified the discrepancy of 50 micrometer beads in different systems as, "we attribute it to the injection conditions: the heavier 50 µm beads required a stronger carrier flow to be entrained into the sample volume, thereby increasing both the interference aerosol loading and the inhomogeneity along the beam path. The same trend, though weaker, is present in the high-resolution data. The effect is amplified in the high-speed system because its shorter exposure time and larger pixels yield a lower signal-to-noise ratio per frame, so a given level of background fluctuation degrades fringe contrast, and hence more severely edge localization."

Figure 4: The histogram labels are too small and the y axis is missing.

Response: We have updated Figure 4 as best as we can. Our first author, Susanne, is on family leave and we don't have access to her original plots.

Figure 5: The histogram labels are too small.

Response: We have updated Figure 5.

Line 302: Correct the typo to "location".

Response: Corrected.

Line 309: The camera records holograms and HoloSuite reconstructs the particles. Are "frame" and "hologram" used interchangeably here? Please clarify.

Response: The term "hootsuite is used to create holograms" was changed "holosuite is used to reconstruct particles." Frame and hologram are used interchangeable in the text. Typically, frame refers to the data read by the camera, while hologram refers to the data contained in the frame.

Figure 6: The plot labels are too small. Provide statistics on the accuracy of the measured distance moved.

Response: One of the leading authors, Susanne, is on family leave, and the rest of us don't have access to her images. We will improve the plot as soon as she can respond.

Line 320: Move these lines to the beginning of the chapter. Clarify if high speed HOLODROPS is the same as HOLODROPS TRACK.

Response: The distinction between HOLODROPS and HOLODROPS-TRACK is specified in section 2.1. This line has been changed to refer to HOLODROPS-TRACK

Line 349: This repeats the previous paragraph.

Response: The ePIV uses a light sheet to perform 2-component PIV to measure the x- and y-flow fields. To compare these measurements to the PTV measurements, which have 3 components, two measurements were taken. One with the nebulizer facing towards the light sheet propagation direction, and a second with the nebulizer rotated 90 degrees with the sprout facing perpendicular to the light sheet. This description was added to clarify this approach.

Figure 8: The legend and scaled axes are missing. Explain in the main text how positive and negative events are generated and interpreted.

Response: A description in the text has been added.

Line 364: Is it possible to calculate the mean using only frames that contain particles?

Response: This modification was added for the ePIV results and changes the magnitude of the average flow fields. In addition, the velocity magnitude measured at the center is now lower, and the velocity magnitude outside is higher. This difference is due to overcounting the number of measured vectors, which increases the denominator.

Figure 10: Define the unit of velocity. Explain vx, vy, and vz. Ensure consistent instrument naming. Explain the difference between the first and second rows of figures.

Response: Correct units were added to the plots, as well as subsequent details to describe the measurements. Descriptions were also added to the text.

Line 385: I expect ePIV to be less sensitive to turbulence since it covers a longer time interval. Please compare a shorter ePIV time interval to the holographic tracking. Showing the evolution of the ePIV velocity distribution over time would be a great way to observe turbulent motion. Finally, explain if the negative mean vx and vy velocities in the holographic tracking are a consequence of turbulent motion or if there is another cause.

Response: This comparison between ePIV and holographic tracking is a bit tricky to make. The ePIV data can be processed much more easily, so we are able to analyze data for up to 15 seconds of data and observe many velocity components over this period. For the particle tracking, we only analyze 50 frames of data and only analyze 192 tracked particles.

In addition, the opposite seems to be true. After applying a polynomial fit to quantify particle tracks, we obtain much more consistent results for the particle tracks' position and velocity components. Compared to ePIV, when operated at a much shorter time interval (0.1 ms), turbulence is more pronounced in the results and affects the final mean results. This is captured in the supplemental material section. When the ePIV system results are analyzed for a longer time interval (10 ms), turbulence is less prevalent in the results.

Supplement: Add missing reference (Line 13), remove double brackets (Line 32), and update the reference format (Line 35).

Response: References were added with proper citations and updated.

Figure S1: The right plots appear to show (1 minus Attenuation). Please verify. Make the connection between Figure S1, Figure S2, and the main manuscript clearer.

Response: The plots on the right show exponential decay in mean particle size and particle concentration. This is normalized so the initial light intensity is 1. The intend of Figures S1 and S2 is to show the limit for what particle size, density, and optical depth would allow the systems to effectively collect droplets. A paragraph was added to connect these plots to the main manuscript.

References

Baumgardner, D., et al. (2011). Airborne instruments to measure atmospheric aerosol particles, clouds and radiation. Atmospheric Research, 102.

Fuchs, C., et al. (2025). Putting the spotlight on small cloud droplets with SmHOLIMO a new holographic imager for in situ measurements of clouds. Atmos. Meas. Tech., 18, 2969.

Ramelli, F., et al. (2020). Using a holographic imager on a tethered balloon system for microphysical observations of boundary layer clouds. Atmos. Meas. Tech., 13, 925.