Editor comments:

1. Please add the section "Author contribution".

Response: **Added to the revision. Thank you.**

2. Please include the mandatory section called "Data availability", "Code availability", or "Code and data availability" according to the guidelines at: https://publications.copernicus.org/for_authors/manuscript_preparation.html#assets => data sets

Response: **Added to the revision. Thank you.**

3. Please ensure that the colour schemes used in your maps and charts allow readers with colour vision deficiencies to correctly interpret your findings. Please check your figures using the Coblis – Color Blindness Simulator (https://www.color-blindness.com/coblis-color-blindness-simulator/) and revise the colour schemes accordingly. => Figure 7

Response: **Figure 7 has color scheme has been revised accordingly.**

Referee #3

The manuscript has been substantially improved, and most of the previous concerns have been addressed. I only have four remaining comments.

We thank the reviewer for the constructive comments and for helping us improve this manuscript.

1. The new glass bead analysis is useful, but please distinguish more clearly between systematic sizing bias and measurement uncertainty. A practical sizing uncertainty or accuracy range should be stated explicitly.

Response: **Thank you. These two uncertainties are separate concerns, and we added text (lines 343-349) to clarify them more. "In practice, the measurement uncertainty is somewhat dependent on the conditions, as indicated by the high uncertainty encountered when a strong carrier flow is present. Therefore, we conclude that the**

uncertainty of size measurements by HOLODROPS is at least 1 pixel and at most the maximum bias we measured with beads, between 3.45-6.6 µm for the high-resolution camera and 4.5-13.3 µm for the high-speed camera. For most conditions with clean holograms, the bias is expected to be closer to the 1-pixel size, while with strong turbulence and noisy holograms it can be closer to the upper bounds. ”

We also added an accuracy range in Table 2, with the understanding that this is considered an upper limit. The glass beads experiment introduced significant turbulent carrier flow, especially for the large-sized glass beads suspension; without the carrier flow, the holograms should be cleaner and have less uncertainty, as shown in the outdoor experiments with drizzle. Therefore, uncertainty should depend on the measurement conditions. Since we do not expect such strong carrier flows in real outdoor measurement settings, the laboratory results, including the carrier flow, are an upper bound.

2. The explanation that the large bias is caused by stronger carrier flow and reduced fringe contrast is plausible, but not directly demonstrated. Please present this as a likely explanation rather than a confirmed cause.

Response: Thank you, this is a good point. We have rephrased the relevant section to indicate it is the most likely cause. Line 333: “Instead, the most likely explanation are the injection conditions”

3. Both ePIV and HOLODROPS-TRACK use 532 nm CW illumination. Please briefly clarify whether simultaneous operation can introduce optical cross-talk, stray light, or speckle in the holographic measurements.

Response: We thank the reviewer for this question. In the present study, the two instruments were deployed separately and never operated simultaneously, so the reported results are unaffected. The intended mode of operation is sequential, with ePIV acting as a scouting instrument before HOLODROPS-TRACK is deployed. Simultaneous operation, along with more autonomous deployments, remains a primary goal for future development We have added a brief discussion of the expected interactions to Section 3.5.4.

For simultaneous operation, each system would use its own laser. A shared, split source would make the two beams mutually coherent and allow stationary interference. In contrast, independent lasers are mutually incoherent: their optical frequency difference far exceeds the inverse of the holographic exposure time, so any

interference term averages to zero and the intensities simply add. The ePIV system light therefore cannot interfere with the holographic reference wave or produce spurious fringes or reconstructed particles.

The remaining effect is an additive background, consisting of diffuse stray light and the self-speckle of ePIV light scattered by surfaces and particles. Static components can be removed by background subtraction. However, the associated reduction in fringe visibility, the increase in shot noise, and time-varying speckle from moving particles cannot be removed in processing and would mainly affect the weak fringes of the smallest droplets. Cross-talk can also occur in the reverse direction: particles crossing the holographic beam may scatter light toward the event camera and generate out-of-plane events in the ePIV data.

Isolation can be achieved spectrally and geometrically. Because holographic resolution depends on wavelength, HOLODROPS-TRACK would remain at 532 nm, while ePIV would operate at 632 nm, with a 532 nm bandpass filter on the holographic camera and a 632 nm bandpass filter on the event camera. For droplets much larger than the wavelength, scattering efficiency is nearly independent of wavelength, so the main penalty would be the lower quantum efficiency of the event sensor, which we expect to be acceptable. Geometrically, the ePIV sheet can be oriented orthogonal to the holographic optical axis and positioned just upstream of the holographic volume, outside the sensor's field of view.

We also note that the event camera could, in principle, image particles directly within the holographic illumination volume. However, this yields particle motion at different depths, and out of focus projections. We therefore used light-sheet illumination, which defines the measurement plane and provides in-focus particle images suitable for PIV.

4. Section 3.5.2 states that pseudo-frames were constructed at 1 ms intervals, whereas the uncertainty calculation later uses 0.01 ms. Please check and correct this inconsistency, as it directly affects the calculated velocity uncertainty.

Response: The 0.01 ms is a typo and was meant to be seconds. Since this paragraph discusses uncertainty in instantaneous velocity, and to be more consistent, this has been changed to 1 ms. Thank you for catching this issue.

Referee #4

General comments

This manuscript presents a useful effort to develop holographic instruments for atmospheric droplet characterization and three-dimensional tracking, complemented by an event-camera-based PIV system. I appreciate the authors' attention to both sustained measurements of droplet size distributions and measurements of individual particle motion. The laboratory characterization and preliminary outdoor deployment provide a helpful foundation for further development. Combining these capabilities could contribute to studies of cloud microphysics and droplet dynamics. To strengthen the manuscript, I encourage the authors to clarify the holographic processing and optical geometry and provide a more quantitative justification and uncertainty assessment for ePIV.

We thank the reviewer for the constructive comments and for helping us improve this manuscript.

1. The manuscript states that Holosuite is used to reconstruct holograms and determine 3D particle positions, but the processing description is insufficient to understand how these positions are obtained. Please describe the principal steps, including background correction, numerical propagation, particle detection and segmentation, and axial localization. In particular, what focus criterion identifies the longitudinal position of each particle? Is it based on reconstructed amplitude, phase, image gradients, or another quantity? Are positions assigned to discrete reconstruction planes, or refined through interpolation? The recent review by Kumar and Hong, "A review of 3D particle tracking and flow diagnostics using digital holography," Measurement Science and Technology, 36, 032005 (2025), provides relevant context for reconstruction and particlelocalization methods, including different focus metrics and their limitations. Connecting the implemented Holosuite procedure to this methodological framework would help readers understand the choices made and the factors controlling performance.

   The axial uncertainty assessment also needs clarification. The approximately 100 μm reconstruction step describes numerical sampling, but does not by itself establish axial resolution or localization accuracy. These quantities also depend on the optical configuration, particle properties, hologram quality, and focus-selection method. Please distinguish reconstruction spacing, the ability to resolve neighboring particles in depth, and uncertainty in locating an individual particle.

   The reported mean axial residual of approximately 115 μm is useful as a measure of scatter around fitted trajectories, but it does not independently establish absolute

position accuracy. Systematic depth errors can remain undetected by this approach, while genuine particle motion that departs from the assumed quadratic trajectory can contribute to the residuals. A controlled axial translation experiment, covering representative particle sizes and positions within the sample volume, would provide stronger validation. Representative focus-metric curves and a reconstruction-step sensitivity test would also be informative. The synthetic example involving a 3 mm axial displacement demonstrates functionality but does not sufficiently test localization at the reported uncertainty scale.

Finally, please explain how position uncertainty is propagated into velocity uncertainty, including the track durations, fitting windows, time units, and coefficient covariance. The effect of trajectory fitting on the temporal resolution of the measurements should be considered when discussing applications to turbulence and collision–coalescence.

Response:

We appreciate the reviewer's help and have read and added the review articles by Kumar and Hong to the introduction section. The details of how Holosuite determines particles and their location are described in Schledewitz, 2016; Fugal, 2009; and Fugal, 2004, and we made sure to add the references in relevant sections of the manuscript. We use Holosuite in its standard configuration with 7 background images for the background removal. Holosuite then reconstructs the image slice by slice (i.e., reconstructing the image at a variety of distances along the optical axis) and finds dark patches, which are later linked in space to create 3D voxel groups. The particle location is determined by the center of the pixel group in x/y, and along z (the optical axis) by the phase change. The outline of the image is determined by high contrast (dark and bright pixels). Each particle has over 50 associated properties, which are used to separate artifacts from real particles. We do not interpolate each particle's z-location because the step width (100 um) is small enough, and interpolation would introduce pseudo-accuracy. Therefore, in z-axis, the uncertainty of the location is +-100 um. This step width was chosen because smaller steps would not improve this number due to physical uncertainties.

We added text on how systematic errors such as depth can go undetected, and how particle motion can affect residuals.

We calculate velocity by taking the derivative of the polynomial fit of the particle position. The residual variance is estimated from using $\sigma_p^2 = \frac{\Sigma j \ (p_j - \hat{p}_j)^2}{n-3}$. A second order polynomial is then fitted to each track. Then the coefficient covariance

matrix from a linear regression is found with $C_\beta = \frac{\sigma_p^2}{X^T X}$ with $X_i = [1\ t_i\ t_i^2]$, and σ_p^2 as the residual variance. The velocity is found by taking the derivative of the fit to give $g(t) = [0\ 1\ 2t]^T$. Then the uncertainty in velocity is then propagated from the residuals with $\sigma_v = \sqrt{g(t)^T\ C_\beta g(t)}$. The center time between data points is used during propagation. A short description of this method has been added to the text. This approach is similar to the method applied in Janke and Michaelis paper *Uncertainty quantification for PTV/LPT data and adaptive track filtering*.

2. Please clarify the location of the initial hologram recording plane relative to the sample volume. Figure 1 appears to show direct recording without an imaging lens, but the photograph does not establish the complete optical geometry. A schematic identifying the sensor, any imaging or relay optics, and the reconstruction boundaries would be helpful.
   If the system records holograms directly on the sensor, with all particles located on one side, the known sample geometry can exclude the conjugate focus on the opposite side. However, the defocused twin-image contribution can still affect reconstruction quality. If an imaging lens instead places the plane conjugate to the sensor within the sample volume, particles may occupy both sides, creating an ambiguity in the sign of their axial distance. Please explain how the initial plane is selected to avoid this ambiguity, or how particles on opposite sides are distinguished.
   The manuscript should state whether any twin-image suppression or artifact-rejection procedure is applied and discuss its implications for particle detection, sizing, and axial localization.

Response: Thank you. The system records the images directly on the sensor, without any relay optics. If the hologram plane was not located at the camera sensor, particles could indeed be on both sides and interfere with our results. However, with the co-located camera sensor and hologram plane, HOLODROPS eliminates this concern. Other instruments may have either real particles or even dirt on the relay optics that show up as particles in the sample volume; HOLODROPS does not. However, the defocused twin image contribution is indeed in our data. Because it is defocused, the HOLOSuite software does not detect it as another particle. While the twin image can contribute to noise and additional artifacts, these are all filtered out in post-processing.

We have added this information to Figure 3 and in the text (line 220). "In both cases the hologram plane is collocated with the camera sensor. If they are separate, particles

could be located between the camera and hologram plane, which would show up as particles in the sample volume due to the processing. This concern is removed in HOLODROPS."

3. The use of ePIV for continuous monitoring and selection of suitable holographic measurement intervals is potentially useful. However, the manuscript should more clearly establish what advantages require an event camera.
   For example, how would ePIV compare with using the existing holographic camera together with a lightweight particle-presence detector that selectively streams or saves frames containing particles? Such a detector could potentially operate on raw hologram changes or fringe features without performing full 3D reconstruction. This would be a relevant baseline for assessing the proposed reduction in data volume.
   The comparison should distinguish sensor readout, data transfer, storage, and processing costs. Selective saving after transfer to a computer would reduce storage but would not necessarily reduce camera readout or transfer bandwidth. Conversely, an event camera can reduce data generation at the sensor, although its advantage will depend on particle concentration and scene activity. Please identify the actual bottleneck in HOLODROPS-TRACK and quantify the improvement provided by ePIV under representative conditions.
   Particle-presence detection would also provide different information from a velocity field. If the purpose of ePIV is to recognize particular flow conditions rather than simply detect droplets, please specify the relevant flow quantities and selection criteria. An example showing how ePIV identifies a scientifically valuable acquisition interval would strengthen this rationale. Because the event stream is accumulated into pseudo-frames for conventional cross-correlation, sensor latency should also be distinguished from the latency and temporal resolution of the resulting velocity measurements.
   The ePIV uncertainty analysis needs stronger support. Synthetic particle images matched by size, density, and correlation signal-to-noise ratio do not necessarily reproduce the characteristics of event-derived pseudo-frames. Please explain how event polarity, contrast thresholds, and accumulation duration are represented. The omission of synthetic sensor noise and the different filtering applied to synthetic and experimental data also require justification. Without experimental validation or evidence of conservatism, describing the synthetic estimate as an "upper bound" appears premature.
   The velocity-error conversion requires particular attention. The manuscript generally specifies a 1 ms interval, whereas line 471 states 0.01 ms and gives a factor of 3.3. At 0.033 mm/pixel and 1 ms, the conversion factor is 33 mm/s per pixel. If the reported

displacement errors of 1.7–4.7 pixels are used as displacement uncertainties, they correspond to approximately 56–155 mm/s. Please reconcile these values, define the error statistic used, and assess its implications for instantaneous and time-averaged measurements separately.

Response: **A description of key constraints—including data rate, camera buffering, and data offloading—has been added to the manuscript. A brief comparison with particle-presence detection methods is now also included. Because HOLODROPS-TRACK is designed to capture particle trajectories, image individual particles, and obtain size distributions, while ePIV is intended to measure relevant flow conditions and particle concentrations, this distinction has been further clarified in the main text.**

The uncertainty analysis is meant to estimate displacement error relative to the peak-to-peak signal-to-noise ratio obtained during cross-correlation. This approach does not explicitly account for event-camera characteristics such as contrast threshold, polarity, or accumulation time. Since the median filter effectively removes sensor noise, we expect sensor noise to have minimal impact on the error. Likewise, because only "on" events are analyzed and "off" events are discarded, we anticipate that the contrast threshold has little influence. The event-camera latency is on the order of 100 microseconds, while the smallest time interval used is 1 ms—an order of magnitude larger—so timing uncertainty is also expected to contribute minimally. Accumulation time, however, has a significant impact: longer accumulation intervals suppress fast transient motion. A more rigorous analysis that studies the effect of accumulation time, and sensor properties is left as future work. Our assumption is that pixel displacement is the dominant contributor to uncertainty in this analysis. Rather than providing an upper bound, our approach yields an estimate for the error, as additional factors may further contribute to uncertainty. These points have been incorporated into the revised text. The use of upper bound has been removed.

Lastly the velocity error conversion is a valid point, and we appreciate the thoughtful comment. The velocity error conversion in the original manuscript contained a typographical error, which has now been corrected. The conversion applies to instantaneous velocity, meaning it is based on single displacement measurements. For ePIV measurements the time intervals used was 1 ms and results over longer durations are averaged. Therefore applying a displacement uncertainty over a full second is not appropriate. This clarification has been added to the text along with a separate equation that specifies how the average uncertainty should be calculated

Editorial mistakes

1. Lines 389–390 exclude tracks shorter than 20 frames, whereas lines 401–403 and the Figure 8 caption use a four-point minimum. Please clarify which criterion was applied to each result.

Response: Initial track linkage used an 800-micrometer search radius and excluded 20 frames for track analysis. The revised manuscript used a polynomial fit for improved tracking and error analysis, and now uses a 600-micrometer search radius and excludes 4 frames. This has been edited in the text for consistency.

2. The equation near line 395 is dimensionally inconsistent as printed. For the stated quadratic fit, the conventional expression is

$$s_p = \sqrt{\frac{\sum_j (p_j - \hat{p}_j)^2}{n-3}}.$$

Response: Thank you for catching this issue. The equation in the text is a typo and is missing the square root as indicated. The following has been corrected in the text.

3. The 3D panel uses μm, while the corresponding projections use mm. Please correct the labels and check consistency with Table 3 and Figure 7.

Response: This labeling error has been corrected, and the units were checked in the analysis. The units used throughout are micrometers, but for the trajectory plots, this was converted to mm since the trajectories cover a long range.

4. Near line 379, three pixels are equated to 10.5 μm. Please specify the pixel scale used for this simulation, since the high-speed camera is described elsewhere as having 4.5 μm pixels.

Response: Thank you. The simulation was done at 3.5 μm per pixel, which corresponds to 10.5 μm for 3 pixels, while the real camera has a resolution of 4.5 μm per pixel. We have added this information to the text.

5. Line 447 reports “1–3 particles per pixel.” Please verify whether this should refer to particles per interrogation window or another area measure.

Response: **Synthpix takes particles per pixel as a parameter for simulating different PIV scenarios. Since the nebulizer produces locally dense plumes estimating the number of particles per frame can underestimate the particle per pixel. To better estimate the local density of particles we only look at interrogation windows that have a certain number of particles. This information has been added to the text to clarification.**

6. Use HOLODROPS-TRACK consistently throughout, replacing variants such as HOLODROPS-TRACKs, HOLODROPS-TRACKS, and HOLODROPS-HS.

Response: **Thank you. Corrected.**

7. Replace “Table X” near line 198 and the unresolved citation “{Gallego, 2020 #37}” near line 250.

Response: **Thank you. Corrected to Table S1.**

8. Several passages require language correction, particularly lines 369–375 and 460–463. Examples include “particlesand,” “dispalcment,” “fround,” and “transvered.” “HVec” near line 502 presumably means “HVAC.”

Response: **Thank you. We have revised the manuscript and corrected all the typos.**

9. Figure 4: 15 mm should be “15 um”

Response: **Thank you. We have revised Figure 4.**