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Development and Characterization of an Advanced Holographic Instrument for Atmospheric Research

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Abstract.

In this study, we develop and characterize an advanced holographic instrument — HOLODROPS (HOLOgraphic DROPlet Sensor) — along with a complementary event-based Particle Image Velocimetry (ePIV) system. HOLODROPS operates in two configurations: (1) HOLODROPS, designed for long-term, high-precision measurements of cloud droplet size distributions, and (2) HOLODROPS-TRACK, designed for short-interval particle tracking to study turbulence and collision-coalescence processes. Unlike traditional optical scattering or imaging probes, both configurations can simultaneously capture the size, shape, and three-dimensional position of multiple droplets and ice crystals larger than 8.8 µm within a sample volume, eliminating the need for multiple instruments and yielding more accurate and cohesive data. However, the detailed three-dimensional particle tracking provided by HOLODROPS-TRACK requires significant computational resources for hologram reconstruction and data processing, limiting its use over extended measurement periods. To address this challenge, we developed the ePIV system, which leverages an event-based camera to assess key cloud motion features in real time with substantially lower data volume and processing. By rapidly characterizing the flow conditions, ePIV identifies optimal measurement windows and informs targeted deployment of HOLODROPS-TRACK, paving the road for efficient, high-resolution particle tracking when conditions are most scientifically valuable. All three systems have been successfully characterized and validated in the laboratory. Additionally, we tested HOLODROPS successfully in an outdoor setting with a drizzle event.

Short Summary

Knowing accurate cloud droplet size distributions and droplet movement is important to understand cloud formation and lifetime. To better measure these, we developed and tested the HOLOgraphic DROPlet Sensor (HOLODROPS) with two operational configurations, which can be used for both long-term cloud measurements and for short-term droplet tracking, in conjunction with an event-camera-based Particle Imaging Velocimetry (ePIV) system for fast analysis of droplet movements.

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1 Introduction

The study of atmospheric processes is intricately linked with the advancement of instrumentation, as cutting-edge tools are essential for unravelling the complexities of the atmosphere. Especially clouds still contain many secrets that we need to uncover to fully understand the underlying processes, and to improve both weather and climate predictions. To understand, for example, why some clouds rain, and others do not, we need to be able to know the internal structure of the clouds and the droplet size distributions accurately, which can only be done with measurements by deploying the high precision instruments in a cloud chamber or a real cloudy environment.

Generally, advanced techniques can be divided into in-situ and remote sensing methods. For in-situ measurements, either airborne or on mountaintops, the instrument is exposed to the cloud and measures directly the size, number of concentration and sometimes phase of the droplets. Typically, individual droplets are measured, and a size distribution is determined after averaging over time. Counting statistics are typically high enough to get meaningful size distributions within one second. This means for an airborne instrument flying at 100 m/s, averaging over 100 m, and even for a ground-based instrument, the cloud can change significantly within that time.

For in-situ instruments, there are two main techniques used, scattering or shadow imaging. Shadow imaging, as the name suggests, uses shadow images to determine the size and shape of each individual hydrometeor, and counts them to obtain a size distribution. For scattering, Mie theory is used (Lance et al., 2010): A droplet scatters light at a predetermined angle at a known intensity and thus can be sized when that intensity is measured. Again, individual droplets are measured to obtain the size distribution. Furthermore, there are techniques that determine the bulk properties of clouds, such as liquid water content.

Remote sensing instruments are typically ground- or space-borne instruments measuring a bulk of the cloud simultaneously. However, often for RADAR or satellite observations a droplet size distribution shape is already assumed, and individual droplet properties are not determined. Also, the measurement is over a large area and thus averages in space.

1.1 Currently available cloud droplet measurement instruments

Due to the importance of accurate measurement of cloud droplet size distributions, several instruments and techniques have been developed for a variety of applications and size ranges. A popular method for measuring droplet sizes up to 50 um in-situ is using the amount of light scattered to determine the droplet sizes following Mie theory. Examples of these type of instruments are the Cloud Droplet Probe (CDP, (Lance et al., 2010)), the Fast Cloud Droplet Probe (FCDP) and the Forward Scattering Spectrometer Probe (FSSP/FFSSP, (Pinsky and Khain, 2001)), as well as the Polar Nephelometer. The Phase Doppler Particle Analyzer (PDPA) uses the Doppler shift of scattered laser light to measure the velocity and size of cloud droplets. A relatively new technique that uses interferometry to measure the size and velocity of cloud droplets is the Interferometric Mie Imaging Probe (IMIP), providing high-resolution, high-speed measurements and can measure droplets as small as 1 um in diameter. Shadow imaging and direct particle imaging is another common technique; instruments either get triggered by a passing particle (e.g. Cloud Particle Imager (CPI)) or scan a passing particle as it passes through the sample volume (e.g. Two-Dimensional Stereo Probe (2DS), High Volume Precipitation Spectrometer (HVPS), Cloud Imaging Probe (CIP)). These instruments measure larger particles, with the smallest reliable size ranges from 20 um, and can potentially differentiate between ice and liquid.

The aforementioned instruments all measure one particle at a time, and therefore results need to be averaged over time or space to give statistically relevant results. For bulk in-situ measurements there are instruments such as the Hot-wire Liquid Water Content (LWC) Sensor (Strapp et al., 2003), measuring the LWC by heating a wire and measuring the cooling effect of evaporating droplets. Similarly, the Particle Volume Monitor (PVM) measures bulk LWC by analyzing the light scattered from an ensemble of droplets. None of these instruments can give information about individual droplets.

Holographic Measurement (e.g. (Fugal and Shaw, 2009)) combines the individual droplet measurements with the benefit of bulk measurements. It is a relatively rarely used technique for cloud droplet measurement, and involves using a laser to create a hologram of a volume of cloud, which can then be reconstructed to give three-dimensional information about the location of droplets in space, and two-dimensional images of the cloud droplets. This allows for the measurement of droplet size, shape, and concentration, as well as the spatial distribution of droplets within the cloud. Holography has the advantage of being able to capture a large volume of cloud at once, and it can measure droplets ranging from a few micrometers to several millimeters in size. However, it's a technique that generates a large amount of data, requiring large computational power for data analysis.

The largest drawback for a vast majority of methods is the need for airflow and the accurate knowledge of it. In airborne applications, the aircraft speed is much higher than the negligible amount of natural air flow, which is why these methods work so well. In a laboratory setting, such as within a cloud chamber, or in stationary measurements such as on a mountaintop however, airflow is very small and not well known. Only if there is airflow induced (such as an outlet for droplet sampling), these methods can be used. However, an induced airflow will impact the turbulence and other physical processes and is therefore not desired. Holography does not require air flow and is therefore the ideal candidate for our application.

1.2 Review of holographic techniques

Conventional cloud instrumentation, described above, measures single droplets at a time. In contrast to that, holography can measure a large sample volume at a single time with many droplets inside. Thus, there is no need for airflow, making this technique perfect for a chamber setting. Therefore, the need to average over time is not given, and the cloud structure can be examined on a very small scale. Holography can detect the size, number concentration, phase and spatial distribution of a large number of droplets at one time. These instruments provide valuable information about cloud droplets and can be used in conjunction with other methods to get a more complete picture of cloud properties. However, holography is a complex technique that requires sophisticated equipment and data analysis.

1.2.1 Existing holographic instruments

Most of the existing holographic instruments are designed for a mobile deployment either on aircraft, balloon or gondola, and are therefore somewhat restricted in the sample volume; a summary with key properties can be found in Table 1. The Holographic Droplet Sensor (HOLODROPS) presented here is designed for ground-based measurements of clouds and hydrometeors, allowing for a larger sample volume and more versatile deployments, such as in a laboratory setting (e.g. in a cloud chamber) or on mountaintop observatories. The current design has a variable sample volume that can be adapted to the desired circumstances. Furthermore, we also developed HOLODROPS-TRACK, a system specifically designed for tracking particles in the same versatile environment, as well as ePIV (Event Particle Image Velocimetry) to complement the holographic measurements with instant flow determination. This suite of capabilities fills a niche the existing instruments are unable to cover, with high versatility, large sample volume and fast flow processing.

Instrument	**Developer**	**Platform**	**Pros**	**Cons / Development Challenges**
HOLODEC	Michigan Tech / NCAR (Fugal and Shaw, 2009; Fugal et al., 2004; Spuler and Fugal, 2011))	Airborne (aircraft)	Measures size, shape, and concentration; wide range (few µm to mm); well-established heritage with multiple publications	Requires aircraft deployment (costly); limited sample volume; averaging still needed for statistics
HALOHolo	University of Mainz (Schlenczek, 2017)	Airborne (aircraft)	Larger sample volume than HOLODEC; higher frame rate	Still aircraft-dependent; similar complexity to HOLODEC; limited to airborne campaigns
HCP (Holographic Cloud Probe)	SPEC Inc.	Airborne (aircraft)	High-resolution 3D imaging of cloud droplets	Not commercially available; limited accessibility for the research community
HoloGondel / HOLIMO	ETH Zürich (Beck et al., 2017; Henneberger et al., 2013)	Ground-based (cable car, mountaintop)	Samples large cloud volume via cable car traverse; ground-based accessibility	Limited to locations with cable car infrastructure; not freely deployable; site-specific
HoloBalloon	ETH Zürich	Balloon-borne	Unique in-cloud sampling perspective; can reach altitudes without aircraft	Limited payload capacity; tethered operation constraints; weather-dependent deployment
ICEMET	Finnish Meteorological	Ground-based (mountaintop)	Specializes in icing detection; expanding	**Variable particle sizing accuracy** across sample volume due to expanding beam

Instrument	Developer	Platform	Pros	Cons / Development Challenges
	Institute (Tiitta et al., 2022)		beam design	geometry; site-specific
HoloTrack	MPI-DS (Thiede et al., 2025a, b; Thiede et al., 2025c)	Airborne (kite)	Captures sizes, 3D positions **and** velocities; low-cost platform compared to aircraft	**Very small sample volume (~17 cm³);** limited by kite payload and stability

Table 1: Summary of existing holographic instruments.

1.2.2 Holographic techniques development/challenges

For a holographic system in a stationary setting such as a cloud chamber the components should be well chosen. However, a few trade-offs also have to be made between Lasers and camera options.

1. Laser
   - Wavelength: A good laser should have a small wavelength, since the wavelength is proportional to the smallest detectable particle. This is why a UV laser is desirable. A visible (e.g. green) laser might also work, but if the same size particles should be detected, the optical magnification should be much larger.
   - Mode: A pulsed laser is essential to the measurement method. A single short laser pulse illuminates the sample volume and all particles within, creating a hologram. Continuous lasers could be too long and streaklines would be measured, because camera exposure times are not short enough to compensate for the movement of the droplets. This is true for fast-moving droplets.
   - Energy: The laser should have enough energy to illuminate the entire length of the chamber. If a dual system is built for particle tracking, the volume has to be illuminated simultaneously, which would require one laser and a beam splitter. This would reduce the power of the laser for each system.
2. Camera options with pros/cons
   - Speed: The camera speed is not very important, because the exposure time is mainly dependent on the laser pulse width, which is much shorter. However, for fast-moving droplets the camera and laser have to be matched such that only one pulse per image is recorded. If the camera and laser are not matched and the droplets move fast, there is a potential for multiple imaging of the same droplet in the same frame. Alternatively, a continuous laser can be used if the exposure time is small enough to not capture particle motion blur.
   - Pixel size: The ideal pixel size is as small as possible, so small particles can be detected. The minimum size particle to be detected is two pixels in diameter; below that it is too uncertain and could be noise(Henneberger et al., 2013; Kaikkonen et al., 2020).

- Detector size: Detector size should be as large as possible to capture a large sample volume.
- Frame rate: Frame rate is a trade-off: For particle tracking a high-speed camera is necessary to capture the same particle many times in the same frame. However, these cannot run for hours, and even if they could, too much data that cannot be processed currently, would be recorded. So, we aim for two sets, one low frame rate camera that can record for many hours and gives us an idea what the conditions in the chamber are, and a system with two high-speed cameras for particle tracking.

A holographic instrument is crucial for atmospheric research because it provides comprehensive and high-resolution measurements of cloud droplets, enabling a deeper understanding of cloud microphysics and dynamics.

As outlined above, holographic instruments such as HOLODEC, HALOHolo, HoloGondel, and others have demonstrated remarkable capability in simultaneously capturing the size, shape, three-dimensional position, and concentration of cloud droplets within a sample volume — a feat that conventional single-particle probes cannot achieve. Beyond these static microphysical properties, holography also offers the unique potential to track the movements of individual droplets across successive hologram frames, enabling direct observation of particle velocities, turbulence-driven relative motion, and even collision-coalescence events as they occur. However, this tracking capability comes at a significant cost: holographic reconstruction is a complex technique that requires sophisticated data analysis, and extracting full three-dimensional trajectories from dense hologram sequences demands substantial computational resources and processing time. This creates a fundamental tension — while holographic tracking can provide unparalleled microphysical detail, it is impractical to apply continuously over extended measurement periods or across large datasets.

1.3 Particle Image Velocimetry (PIV) and Particle Tracking Velocimetry (PTV) Methods

Particle Image Velocimetry (PIV) offers a complementary path forward. It is a widely-used technique for measuring fluid flows (Willert and Gharib, 1991). Unlike Particle Tracking Velocimetry (PTV), PIV adopts a Eulerian approach, providing a macroscopic description of velocity at multiple points in space. This generates vector fields offering a detailed representation of the fluid flow over an area of interest. PIV is particularly robust in delivering dense, instantaneous velocity fields for a defined interrogation region and is well-suited for applications involving high particle concentrations.

On the other hand, PTV provides insights into individual particle movements, making it ideal for capturing complex dynamics, such as transient phenomena and rapid changes in flow behavior (Lu et al., 2008). In essence, PIV and PTV are complementary techniques for studying fluid flow dynamics: PIV offers an overarching view of particle flows, while PTV emphasizes individual particle trajectories.

Both Particle Tracking Velocimetry (PTV) and Particle Image Velocimetry (PIV) are highly suitable techniques for characterizing clouds, with cloud droplets serving as effective tracer particles. PTV specializes in tracking individual particles, measuring their velocities, and capturing droplet dynamics such as growth, ice crystal formation, aggregation, coalescence, and collision processes. On the other hand, PIV excels in providing flow characterization, assessing turbulence, spatial averaging, and identifying fluid currents, including phenomena such as evaporation and condensation.

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In this study, to evaluate the PIV setup, a spray nozzle was employed for measurement and characterization. The spray nozzle generates inherently turbulent and chaotic fluid flows, and was aligned to direct particle motion primarily along the x-axis. This configuration facilitated testing of instantaneous velocity fields and enabled the determination of average velocity fields.

In Section 2, we describe the development of a new holographic system, including an additional particle-tracking configuration and an ePIV setup. In Section 3, we present the calibration, characterization and validation of all three systems, outlining the calibration and initial testing in a lab setting and deployment in an outdoor drizzle case. We conclude Section 4 with an outlook on future developments and improvements.

2 Prototype Development and Instrument Description

2.1 HOLODROPS prototype

We developed two separate holographic configurations, HOLODROPS and HOLODROPS-TRACK. HOLODROPS is designed for long-term, high precision measurements of ongoing cloud conditions, while HOLODROPS-TRACK is meant to be operated in limited time frames to measure turbulence by tracking the individual particles in the sample volume. Due to these two different purposes, the systems contain different components to maximize the benefits of each. The layout of both HOLODROPS and HOLODROPS-TRACK are the same, and the setup for HOLODROPS-TRACK is shown in Figure 1.

HOLODROPS contains a UV-laser (355 nm) and a high-resolution camera (3.45 um resolution), such that very small particles (>6 um) can be imaged accurately. However, such a fine resolution limits the possible output of the instrument, which is 6 Hz maximum. The current design of HOLODROPS uses an enclosure for all components that allows for safe laboratory operations. It is designed modular such that the system can be adapted to a variety of laboratory situations, including varying the sample volume desired. While the enclosure itself is made out of laser-safe materials, the optical path passes through windows made of uncoated calcium fluoride. With this design the benefits of HOLODROPS become obvious; the variable sample volume that allows distances of several meters allows the use of HOLODROPS with many different laboratory settings, including cloud chambers, as well as a flexible setup on ground-based observatories.

HOLODROPS-TRACK contains a high-speed camera with 4.5 um resolution, in combination with a green laser (532 nm). It is intended to be operated in bursts when particle tracking is desired due to the limits of the camera operation. The highest data acquisition rate for this system is 1397 FPS at 8-bit.

Currently, the instrument can be deployed for brief periods of time outside, since it can be easily made water-proof. For extended outside operations we plan to add heaters and cooling fans to keep the components at room temperature. We also plan to add a detector for times HOLODROPS should be recording, i.e. only when there is a cloud or precipitation, in order to limit the amount of data collected that has no droplets. For an outdoor deployment on e.g. a mountaintop, HOLODROPS also needs to be easily aligned between the camera and laser, which we plan on having a mount between them, designed to minimize influence on the airflow. Lastly, the instrument should always be pointed into the wind to reduce effects of shading of droplets as well as shattering/breaking of hydrometeors, and as such a wind vane would have to be added to the current design.

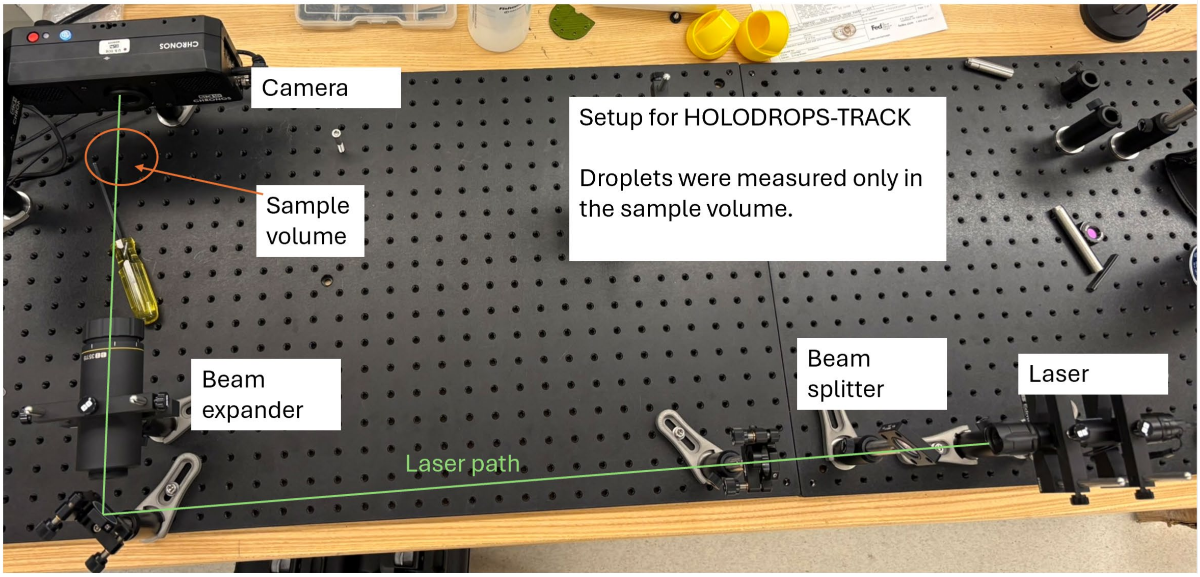

Figure 1: A prototype HOLODROPS, configuration for High-Speed Camera sampling, same setup used for High-Resolution sampling.

2.2 ePIV prototype

Experimental Setup for PIV Using an Event Camera

The event camera-based PIV system (ePIV) employs a continuous green laser (wavelength: 532 nm) to illuminate water droplets. A cylindrical lens is used to focus the laser light into a thin line along the z-axis, forming a thin laser sheet to illuminate the particles. A camera is carefully positioned and focused on the laser sheet at a distance of approximately 50 mm. Water droplets for testing are introduced into the setup using a nebulizer (Figure 2).

In this experiment, an event camera serves as the imaging sensor. Event cameras, also known as neuromorphic cameras, are inspired by the functioning of the human eye. Instead of capturing traditional intensity-based images, they operate asynchronously, measuring changes in pixel intensity. This distinctive readout results in low latency and sparse data representation, with latency as low as 100 microseconds. Though event cameras do not record frames in the conventional sense, an equivalent frame rate would be comparable to 10,000 FPS (Gallego et al., 2020). In contrast, traditional high-speed cameras face bandwidth limitations as they capture full frames at high framerates. Event cameras overcome this limitation by only measuring changes, dramatically reducing the amount of data captured per frame. Additional advantages of event cameras include their lightweight design and lower power consumption compared to high-speed cameras.

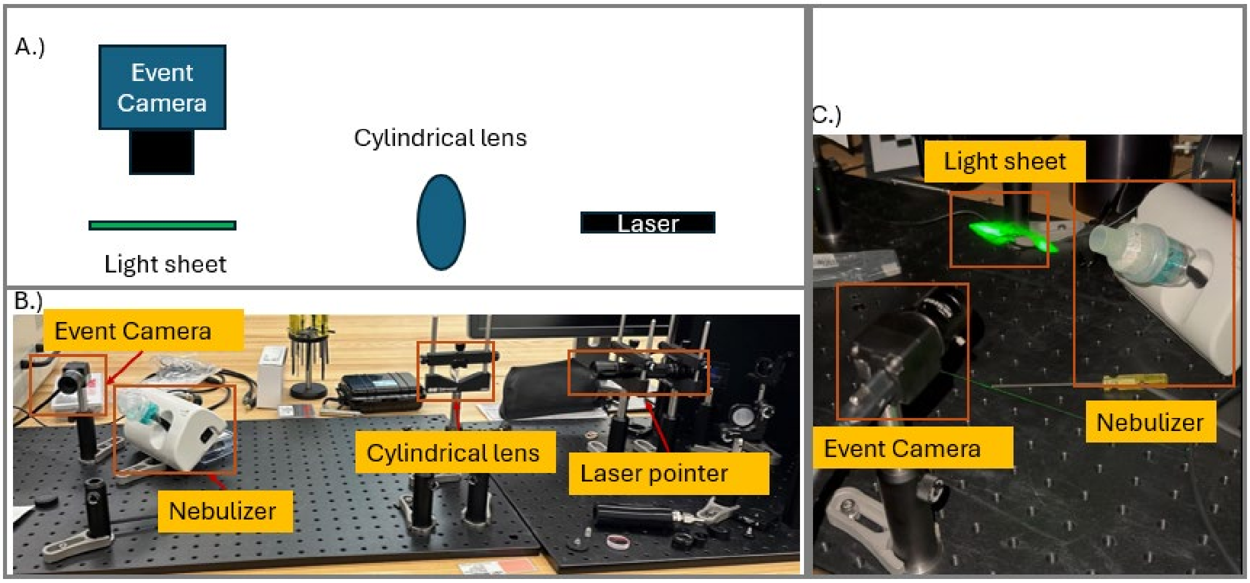

Figure 2 A.) Typical PIV set up. B.) Side view of the experimental setup. C.) image of the water droplets illuminated by the laser.

Event Cameras for Fluid Flow Imaging

Event cameras are highly effective at imaging fluid flows due to their ability to inherently measure changes in pixel intensity (Willert and Klinner, 2022). This characteristic allows for the automatic detection of particles within a frame, eliminating the need for manual thresholding and significantly streamlining the analysis process. Furthermore, the low latency of these cameras enables the detection of particles at high speeds, making them ideal for dynamic imaging applications.

Unlike standard cameras that capture entire frames, event cameras record only changes in pixel intensity, focusing solely on alterations within the scene. This approach minimizes redundant information and significantly reduces data bandwidth requirements. For instance, fluid flows captured from the nebulizer are efficiently visualized using this technique.

To facilitate analysis, the event data is transformed into pseudo-frames over fixed time intervals. This conversion ensures compatibility with open-source Particle Image Velocimetry (PIV) software (Shirinzad et al., 2023). In this study, the openPIV package was utilized, which applies cross-correlation methods within defined interrogation windows to calculate fluid velocity fields across different spatial regions (Willert and Gharib, 1991).

3. Calibration, Characterization and Validation

The calibration and characterization is very important to ensure accurate measurements in the future. Therefore, we measure the effective size of individual pixels of the system, its efficacy and accuracy in processing in a few different ways. These are done under controlled conditions in the laboratory, to determine the possibilities of the instrument in ideal conditions. First, we use a USAF1951 resolution target to determine the effective pixel size at various distances and to determine the best distances between camera and laser. Then, we use calibration glass beads of known sizes to confirm with more realistic shapes. Synthetic holograms were used to determine the accuracy of the particle detection and tracking methods. Lastly, we used a nebulizer to confirm how water droplets are seen and detected by the system.

3.1 Resolution target

We used a USAF1951 resolution target in the sample volume of both systems to verify the effective pixel sizes. This target has patterns of three horizontal and vertical lines of various sizes, and the smallest completely resolvable pattern shows the resolution of the system (Figure 3). The resolution of the HR camera system is as expected, with a 4.4 µm resolution at a distance of 125.5 cm. This means that features of 4.4 µm can be resolved at this large distance, and even more conservative approaches of twice the resolution will yield detectable droplets of 8.8 µm diameter, and therefore below 10 µm, which we were aiming to achieve. The HS camera system was tested at a shorter distance since in real conditions it will also be closer to the objects to detect. It also performed really well, with a resolution of 5.5 µm; again, if twice this resolution is used, we can detect droplets at 11 µm, the size range we were aiming for.

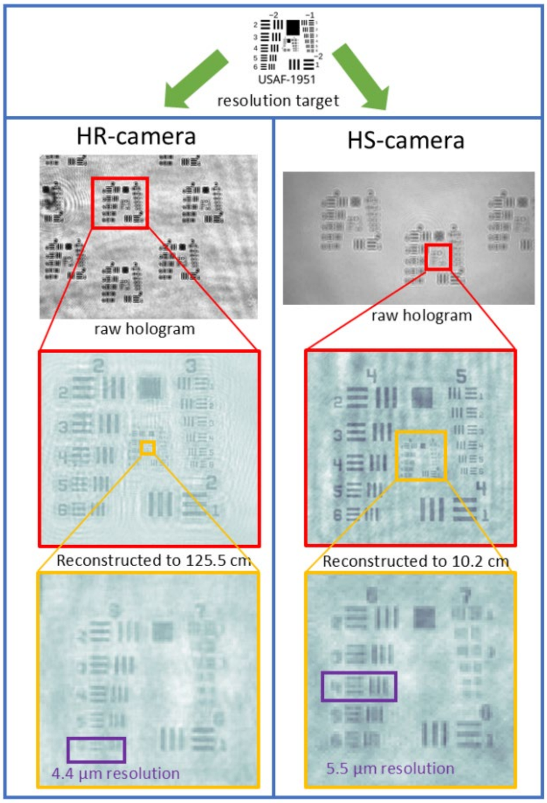

Figure 3: Resolution target results with both the high resolution (left column) and high speed (right column) camera

3.2 **Glass beads**

To determine how accurate the sizing is for round objects in the size range of droplets, we use glass beads in the sample volume. The glass beads are of a known size, and the chosen sizes cover a range of size detections. In holography, glass beads will show the same as droplets in the data, and therefore can be used to simulate droplets of an exactly known size.

For the high resolution camera three sizes were chosen, 15 um, 30 um and 50 um. It detects all three sizes well (Figure 4). Both the 15 um and 30 um beads were measured within one pixel accuracy – at 18.5 um and 32.9 um respectively. The 50 um beads were still rather close at 55.9 um.

The dataset is unfortunately not very clean and a lot of air turbulence can be seen, as shown in the example holograms in Figure 4. The glass beads have to be transported into the sample volume, and the air turbulence from the carrier air flow was rather strong and can be seen in the holograms. This leads to a slight oversizing of the beads due to more intensity fluctuations of the background image, as particles are harder to find in these circumstances.

For the high speed camera, beads with diameters of 40 um and 50 um were chosen (Figure 4, right column). While the 40 um were detected very close to the actual size (40.8 um from HOLODROPS), the 50 um beads were measured larger (62.6 um). This discrepancy can be explained by the fact that the 50 um beads had much higher noise levels due to the air flow than the 40 um beads, similar to the oversizing of the HR system.

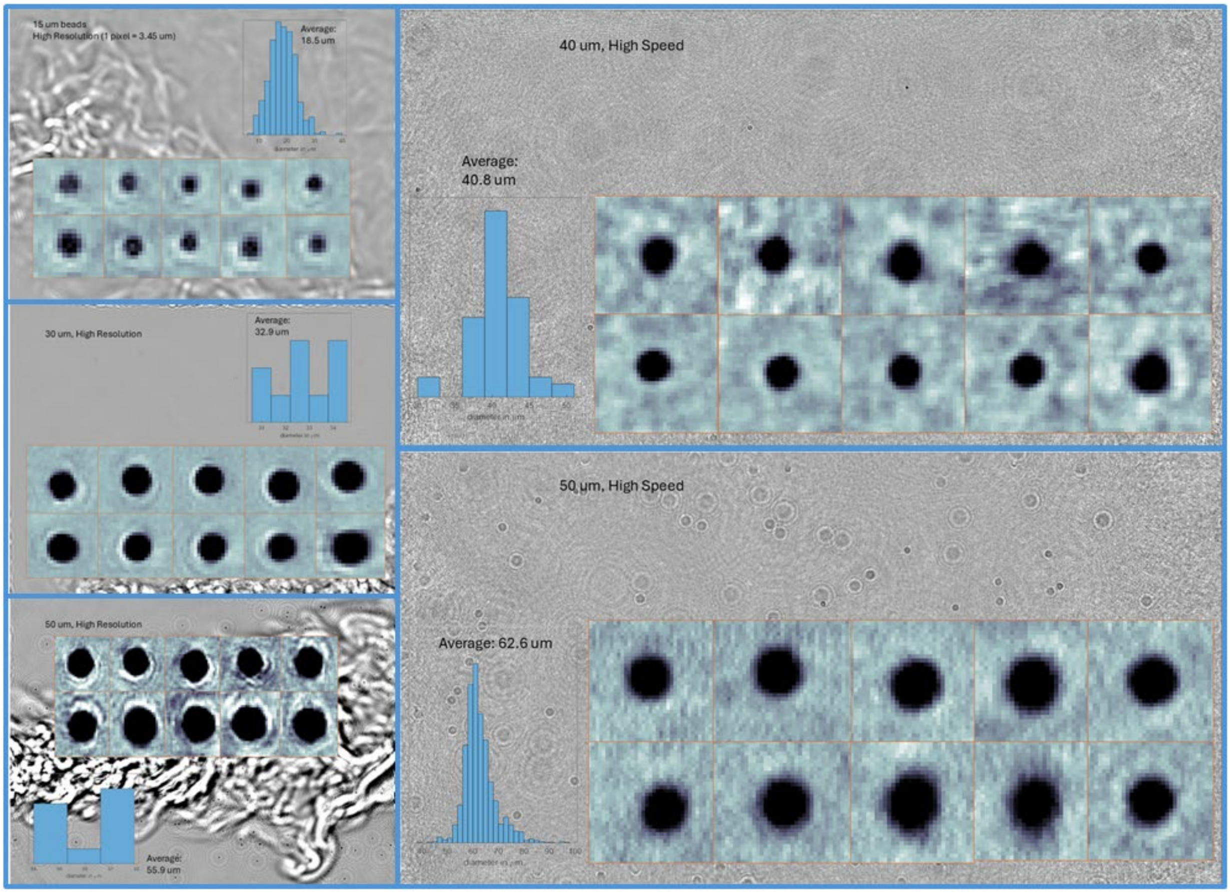

Figure 4: Results of glass bead tests with both systems: High resolution (left) and high speed (right) camera. Each panel shows a reconstructed plane of one of the holograms taken for this size (background), 10 examples of what beads looked like and the determined size distribution.

3.3 Outdoor drizzle measurements

To test the instrument at realistic conditions, we deployed HOLODROPS at an instrument platform outside during a drizzle event on 13 March 2026 in Richland, WA, USA. The setup and results are shown in Figure 5; shown are the laser system, the camera system, and the sample volume. The sample distance between camera and laser system was 32.3 cm, leading to an effective sample volume of 106 cm^3. Unfortunately, the system was not able to be properly aligned, leading to the shading of parts of the hologram (large semi-circle in the righthand part of the hologram in Figure 5), which will necessitate some improvements of the setup. It reduced the sample volume by 12%, still giving a very large sample volume for this experiment. The black covers shown in the setup were a necessary safety feature eliminating laser scattering, and while it will impact airflow and thus results, there are plans to improve laser safety and deployments to a location where these safeguards are not needed.

During the duration of the measurement was constant drizzle with varying intensity, shown in the time series in Figure 5. The average size of drizzle drops was 377 um, with a large spread. The holograms are great quality and the drops are well detected, with clear images obtained from reconstruction.

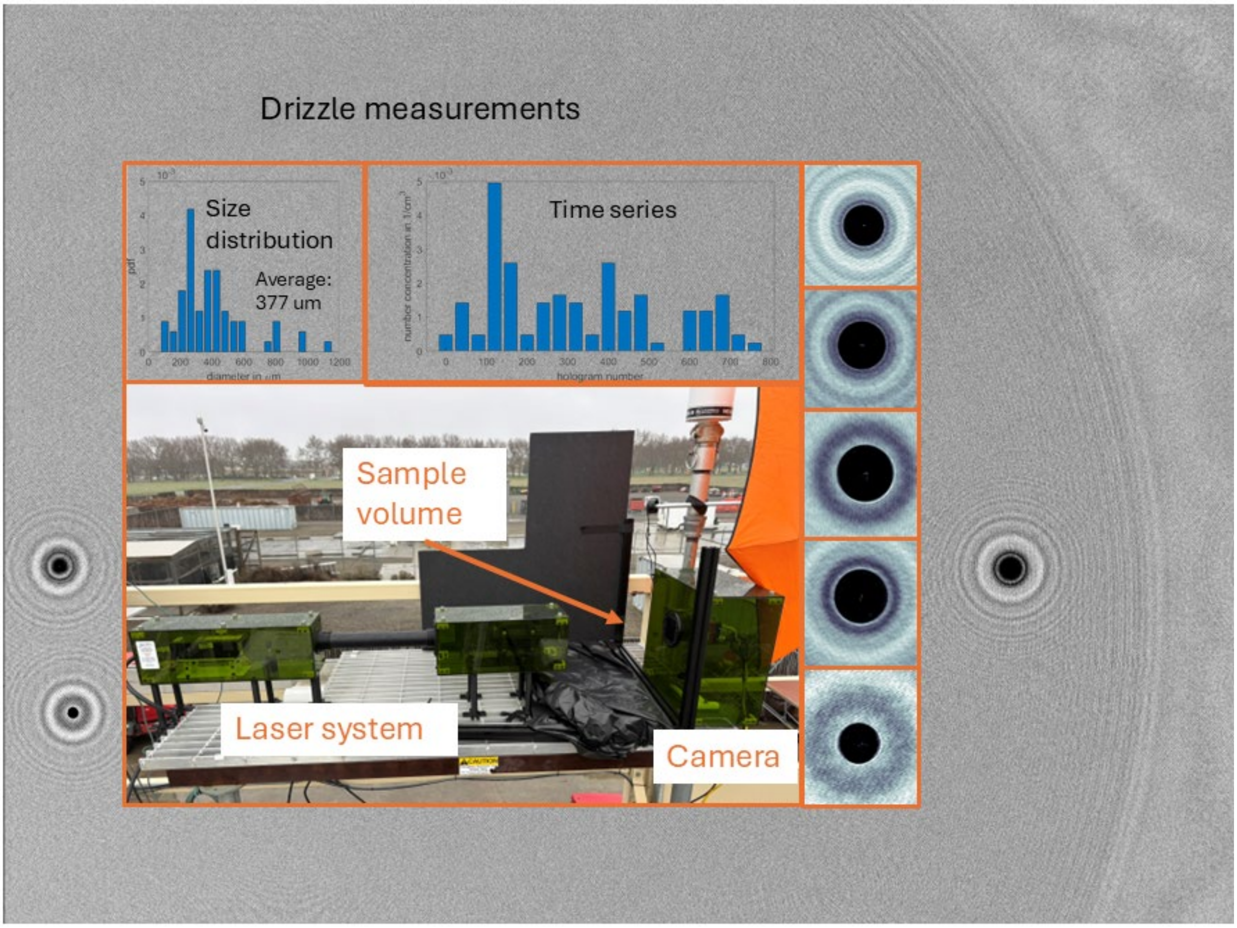

Figure 5: Results from outdoor drizzle measurements: Background shows an example of a hologram with three drizzle drops within the same frame; insert shows the size distribution and time series measured as well as the experimental setup and five examples of drizzle drops.

Overall, the outdoor deployment was a successful proof of concept, and HOLODROPS will be able to be used in both indoor and outdoor situations. For long-term outdoor operation, a few improvements will be made, such as temperature control of the electronics, waterproofing of the housing, better splash-resistance of the windows, and improved laser safety with less impact on the sample volume air-flow. We also saw some movement of the components in wind, and therefore a sturdier, smaller enclosure of the laser setup will be designed. However, even without these future improvements the system works remarkably well with clean data.

3.4 Evaluation of Particle Tracking Capability of HOLODROPS-TRACK

With the use of the high-speed cameras for image and hologram captures we can capture droplets lactation and sizes in in rapid succession. This creates the possibility of employing particle tracking software to infer additional information from the droplets such as individuals a combined particle velocities in a 3D. This will require software that can link particles together between holograms and determining the vector velocities for further analysis. Now there is no particle tracking software specifically designed for droplet holograms, but there are many general articles tracking software's that could be valid candidates.

For this project, Holosuite is used to create holograms and determine the 3-dimensional positions of particles between frames and Trackpy was used to link the particles together to represent the same particle between frames. Along with information on the pixel sizes, and framerate of the camera, it allows to determine the velocity and direction of each individual particle. We used synthetic holograms for testing of the tracking calculations, and the results are shown in Figure 6. Each simulated particle is set to move 3 mm in z, and 3 pixels, which translates to 10.5 um in both x and y dimension, and the results reflect that. Each particle was found and moved by the prescribed distance.

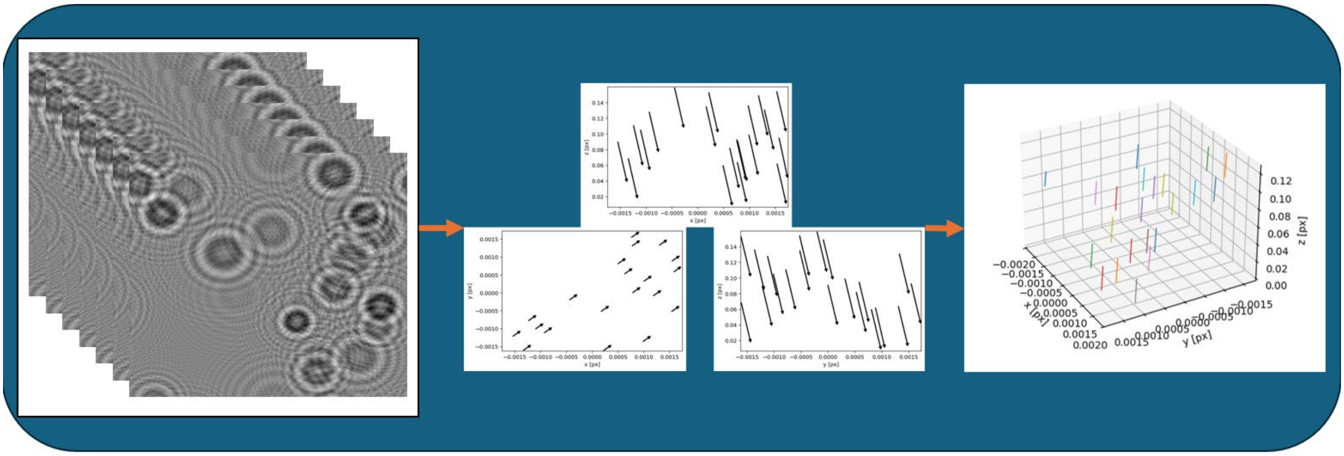

Figure 6: Results from particle tracking with synthetic holograms. Left: raw synthetic holograms. Center: Reconstructed particle movements in all three planes. Right: Particle tracks and movements in space.

The nebulizer flow was imaged using the high-speed HOLODROPS holographic system. Frames were recorded at 1397 frames per second with an exposure time of 15.99 µs. Raw holograms were reconstructed using the Holosuite software (Schlenczek, 2017) to obtain three-dimensional particle positions.

After reconstruction, particle trajectories were identified using the trackpy Python package(Allan et al., 2018; Crocker and Grier, 1996) Particle linking was performed with a search radius of 800 µm, and trajectories shorter than 20 frames were excluded from further analysis. Particle velocities were then calculated by taking finite differences of the particle positions along each trajectory between consecutive frames.

Figure 7 shows representative particle trajectories obtained from the holographic reconstruction. Each color corresponds to an individual particle track. The three-dimensional trajectories are shown together with their two-dimensional projections onto the x–y and y–z planes. The left panel of Figure 7 shows the y–z projection of the trajectories, while the right panel shows the x–y projection.

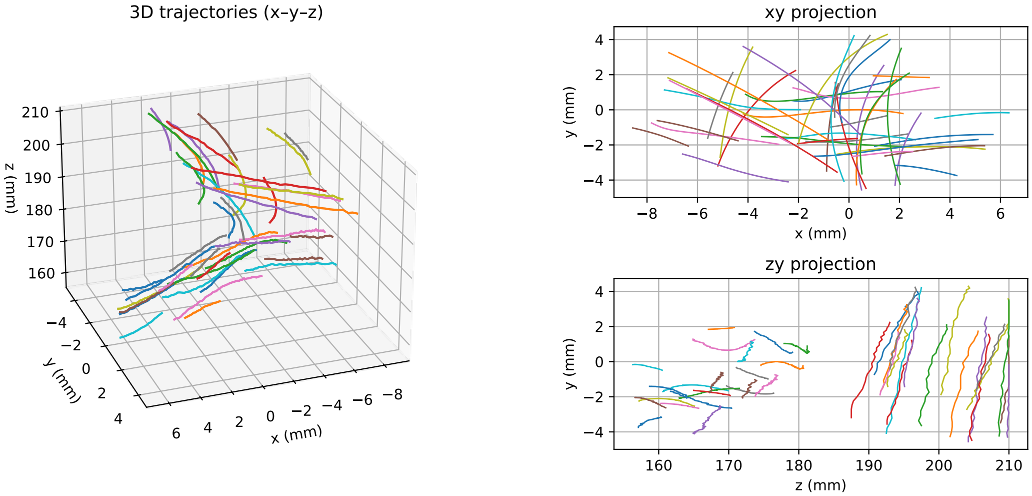

Figure 7: Left: Three-dimensional particle trajectories obtained from holographic reconstruction, along with their 2D projections. Right Top: x–y projection of the particle tracks. Each color represents a different particle. Left Bottom: z-y projection of the particle tracks.

3.5 Evaluation of the Tracking Capability of ePIV

After constructing pseudo-frames at 10-millisecond intervals, openPIV (Shirinzad et al., 2023) was employed to analyze the frames and calculate the velocity field. Before processing, a median filter was applied to the pseudo-frames to eliminate pixel noise generated by the event camera. The extended search method was utilized to calculate cross-correlation between frames, with an interrogation window size set to 16 pixels and a search area of 19 pixels.

Velocity fields were determined for each pair of consecutive frames. The average velocity field was obtained by summing the vector field components across all frames and dividing by the total number of frames.

For the ePIV (Event Particle Image Velocimetry) measurements, a laser light sheet was positioned 50 mm from the front of the camera lens. Measurements were performed with the nebulizer located (i) directly to the side of the light sheet and (ii) directly in front of it. The flow field was recorded for a duration of 10 s, and velocity fields were computed between successive image pairs with a time separation of 10 ms. The resulting instantaneous velocity fields were then averaged over the full 10 s acquisition period. Given the efficient read out, and sparse data representation, several minutes of data was recorded, but 10 seconds was sufficient to capture the flow field dynamics. Examples of captured particle flows are shown in Figure 8.

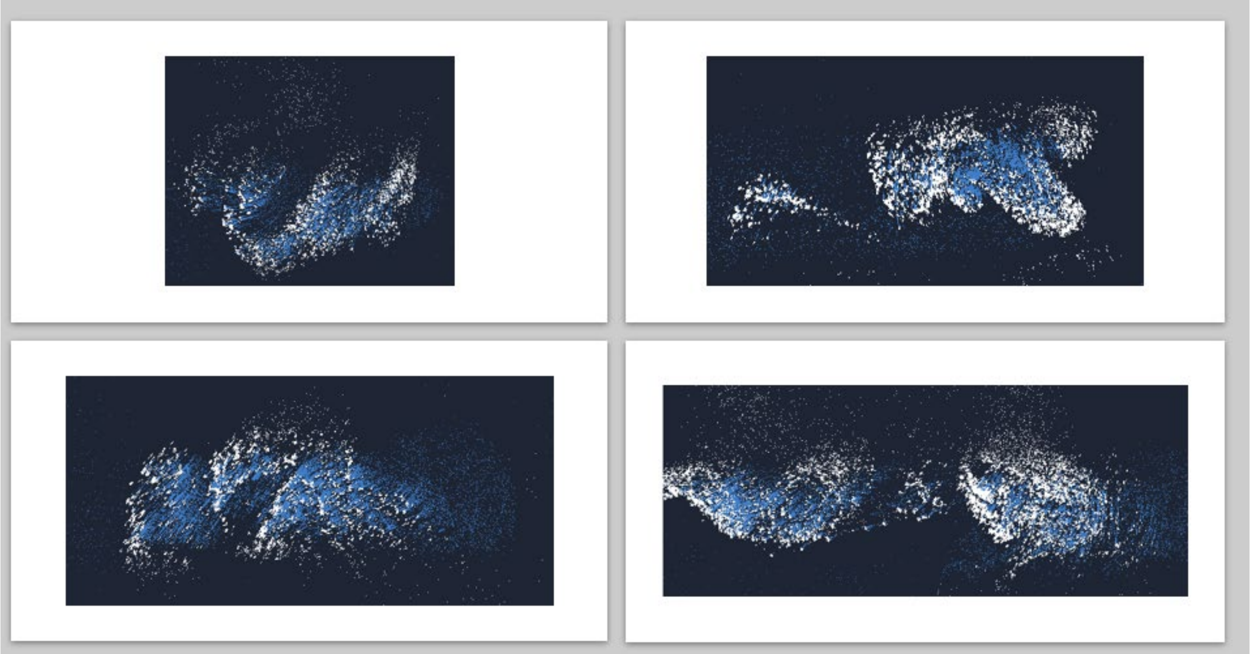

Figure 8: Captured fluid flows using an event camera: The event data was collected over a 2-millisecond time interval. Positive events, represented by white markings, signify areas where light intensity increases, while negative events, marked in blue, denote regions where light intensity decreases. These visualizations can be interpreted as follows: the white markings highlight the current locations of water droplets, whereas the blue markings indicate past positions of the droplets as they moved.

To determine the spatial calibration, a checkerboard calibration target was placed 50 mm in front of the optical system. The known square size was used to compute the pixel-to-distance conversion factor. At this distance, the scaling factor was found to be 31.6 pixels/mm. This calibration was used to convert the measured velocities from pixels/s to mm/s.

The time-averaged velocity fields are shown in Figure 9. Both the side-view and front-view configurations reveal a persistent background flow in the room, with a dominant velocity component in the x-direction. During the 10 s acquisition period, many frames can be empty, or only show a few particles present within the light sheet. For this reason, the average velocity field appears quite small even though instantaneous velocities can be quite high. On average the particle velocities are closer to 20 mm/s, but in a few cases can be as large as 300 mm/s. The overall distribution of recorded speeds is shown in Figure 10.

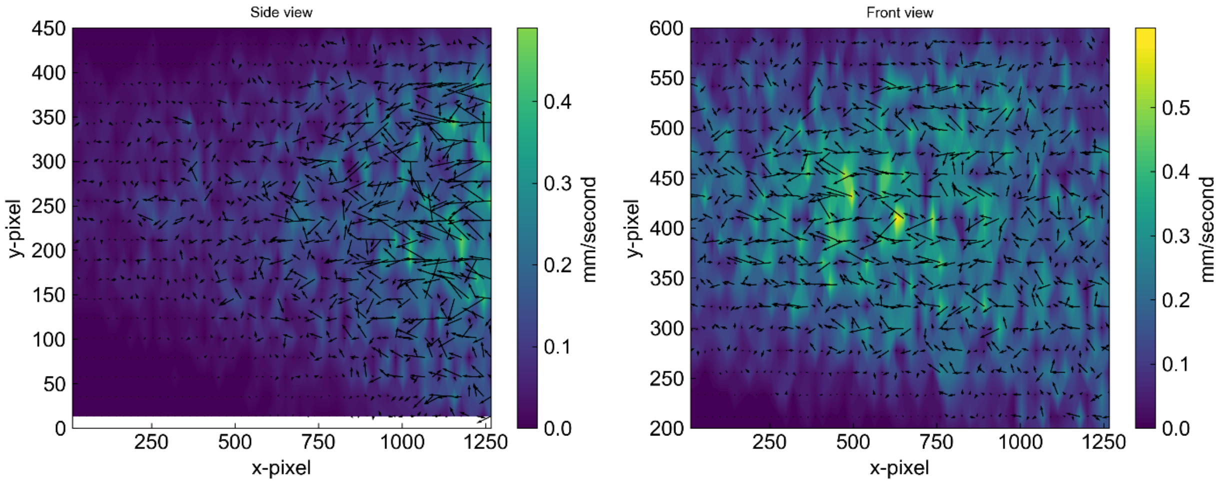

Figure 9: Time-averaged velocity fields measured using the ePIV system. Left: side-view measurement of the nebulizer relative to the light sheet. Right: front-view measurement. Arrows indicate the direction and magnitude of the measured velocity.

3.6 HOLODROPS-TRACK and ePIV Performance Comparison

The distributions of particle velocities are shown in Figure 10. Both the ePIV measurements and the particle tracking results exhibit a pronounced mean flow in the negative x-direction. The distributions of the y-velocity components are approximately centered around zero for both methods, indicating no significant net motion in the y-direction.

In the ePIV configuration, only a thin slice of the flow intersecting the light sheet is captured, so the measured velocities represent a cross-section of the full three-dimensional motion. In contrast, the HOLODROPS-HS holographic system resolves the full 3D position of individual particles over time, enabling direct estimation of all three velocity components, including the z-component. From the reconstructed z-positions, a net flow in the negative z-direction is observed. However, because the axial (z) position is inferred from holographic reconstruction, its spatial resolution is lower than that of the x and y coordinates, leading to comparatively higher uncertainty in the z-velocity component.

385 Additionally, the ePIV measurements cover a longer time interval and a larger number of particles passing through the light sheet compared to the holographic particle tracking, which is limited to a shorter acquisition duration. As a result, the ePIV system is more sensitive to intermittent and turbulent fluctuations over extended timescales, whereas the holographic tracking provides detailed, fully three-dimensional trajectories over shorter periods.

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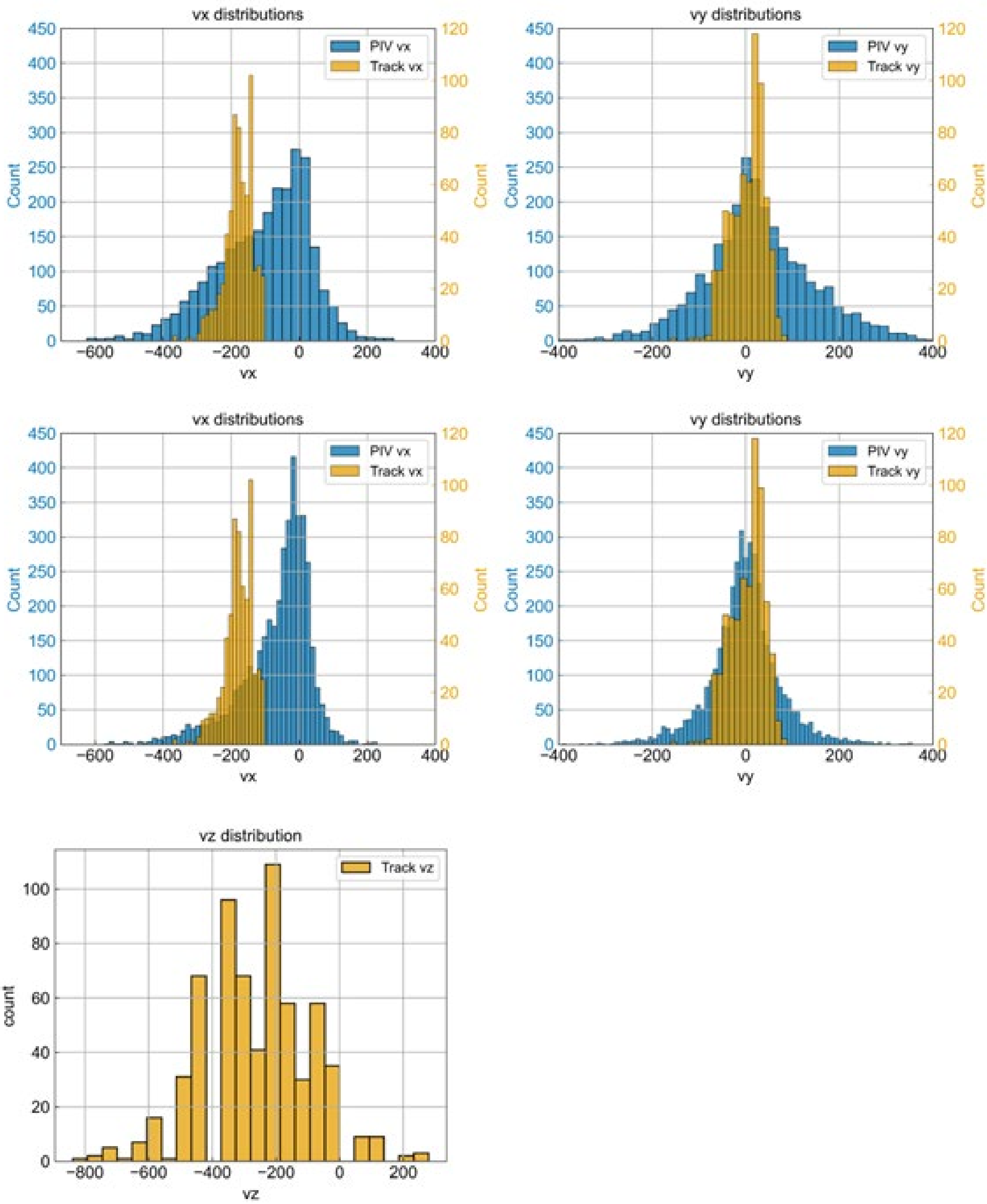

Figure 10: Comparison of velocity distributions measured by holographic particle tracking and the ePIV system. Top: front-view

configuration, showing x-velocity (left) and y-velocity (right) distributions for both methods. Bottom: side-view ePIV measurements of the nebulizer flow field.

In summary, this study highlights the effectiveness of event cameras and inline holographic imaging for analyzing fluid flows and particle scattering dynamics. The event camera's low latency and inherent ability to detect pixel intensity changes enabled the real-time visualization of velocity fields and particle distribution.

4. Conclusions and Future Work

Three new cloud measurement systems were developed, HOLODROPS, HOLODROPS-TRACK and ePIV, and all were successfully characterized. The holographic systems are for long-term measurements of cloud droplet size distributions (HOLODROPS) and for particle tracking at short intervals (HOLODROPS-TRACK). We showed successful measuring of droplets larger than 8.8 um in diameter, both in a laboratory setting and in a drizzle case outside. HOLODROPS-TRACK identified 3-dimensional tracks of the particles moving through the sample volume, which will enable direct studies of atmospheric turbulence as well as the detection of collision-coalescence as it happens. HOLODROPS is designed to capture the entire size distribution range of cloud droplets up to drizzle and ice crystals, without the need of several instruments with narrow size ranges. HOLODROPS can run outside in drizzle conditions, however, for longer deployments the system still needs to be thoroughly weatherproofed. This is the next step for HOLODROPS, with the addition of waterproof housing. Furthermore, in the future HOLODROPS will be run in extreme hot and cold conditions, such as mountain-tops in winter as well as the heat of summer, so heating and cooling elements for the critical electronic components (laser, camera and data acquisition) will be necessary.

Initial data processing for HOLODROPS and HOLODROPS-TRACK is currently done with Holosuite software, and very time consuming and computationally expensive. Future work would therefore focus on speeding up the processing time, which would enable faster data accessibility, and improving the particle detection, leading to better data quality.

The ePIV is an event-camera based particle imaging velocimetry system, which perfectly complements the holographic measurements. It measures the flow directly and can be viewed in real time to inform ongoing measurements. Due to the dynamic readout the ePIV system produces lower data volume and processing time, which is a limitation to HOLODROPS-TRACK system. ePIV can operate continuous for long periods of time; ePIV can inform users about cloud conditions much faster than holography, and can inform when the conditions would be ideal to collect data with HOLODROPS-TRACK for finer detail. Both HOLODROPS-TRACK and ePIV are able to capture comparable fluid flows. Though the HOLODROPS-TRACK provides more detailed information for the individual particles tracked. In comparison, ePIV is not limited to individual particles and can gather information on a larger sample size. Future work will extend ePIV to measure 3 dimensional fluid flows.

Author contribution

SG, KLB, and FM conceptualized HOLODROPS and ePIV verification. JS secured financial support for the project that led to this publication. SG and KLB developed the HOLODROP prototype instrument and carried out the characterization experiments. SG and KLB performed the analysis. SG, KLB, and FM interpreted the results. SG, KLB, and FM wrote the initial draft of the paper. SG, KLB, JS and FM proofread and edited the paper.

Data and Code Availability

The datasets in this article are available upon request. Contact Bertschinger, Kevin L (kevin.bertschinger@pnnl.gov) for access. The study utilized three main software tools for data analysis and processing: **Holosuite** (https://git.iac.ethz.ch/janhe/holosuite) was used for the initial processing of holographic data from both HOLODROPS and HOLODROPS-TRACK systems. This software reconstructs particle positions and sizes from holographic images, enabling the study of droplet distributions and three-dimensional particle trajectories. **trackpy** (https://soft-matter.github.io/trackpy/v0.7/) is an open-source Python package designed for tracking individual particles in video and image sequences. **PIV** (https://openpiv.readthedocs.io/en/latest/) refers to particle image velocimetry software, which processes event-camera data from the ePIV system. PIV analyzes the movement of particles within a flow field, delivering real-time velocity measurements and enabling rapid assessment of fluid dynamics.

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