Response to the Referees

Dear Editor and Referees,

We sincerely thank the Editor and the Referees for their careful reading of our manuscript and for their constructive comments and suggestions. We have revised the manuscript accordingly and believe that these changes have improved its clarity and quality.

For clarity, the referees' comments are reproduced in **blue**, and our responses are given in **black**.

Below, we address all comments point by point.

Sincerely,
The authors

Response to Anonymous Referee #1

Referee comment This is a well-written, well-structured manuscript presenting an instrumented tethered aerostat, the airborne Max Planck CloudKite (MPCK+), for atmospheric and cloud research. It also presents the devoted measurement system, the MPCK+, which combines inline holography and particle image velocimetry (PIV). The CloudKite is designed to make high-resolution observations of cloud microphysics and turbulence at heights of up to 2 km above ground level. The authors describe the design of the platform and instrument in detail. They also discuss laboratory characterisations and performance under wind tunnel and field conditions in detail. The MPCK platform and the MPCK+ are not exclusively introduced here. They have already been partially described in previous works, which are cited in the manuscript. However, the authors provide a comprehensive description of the system here, including detailed specifications, analysis and calibration methods, and improved data quality, such as particle shape detection.
The holography and PIV sampling volumes intersect, providing a region in which the links between cloud microphysics and local turbulence in natural clouds can be investigated directly. The holographic system has a minimum detection limit of 6 µm and can reliably detect and size droplets larger than 8 µm. The sizing and detection efficiencies depend on the size and position of particles within the detection volume. The detection limits of the PIV system depend on droplet size, scattering angle and ambient illumination. Simulations indicated that, for water droplets with a scattering angle of nearly 90°, minimum detectable diameters of approximately 4 µm during the day and approximately 2 µm at night are achievable. The natural variability in cloud droplet number concentration was also considered in the system design to ensure sufficient seeding to adapt to airborne conditions. Both systems show very good agreement on absolute concentrations for droplets larger than 8 µm in individual cloud events.
The influence of the mounting method on velocity measurements was discussed in detail. The authors found that the tether-mount produced the smallest deviations, the keel-mount produced intermediate deviations, and the spar-mount produced the largest deviations. The aerodynamic disturbances caused by the system were investigated by placing the MPCK+ instrument in a wind tunnel in order to derive consistent corrections from calibration measurements. No correlation was found between the correction values and far-field wind speed, enabling these corrections to be applied straightforwardly to field measurements. All velocity measurements required correction due to disturbances caused by the external geometry of the MPCK+. These corrections were

validated through wind-tunnel calibrations and have been shown to be reliably applicable. The manuscript included other onboard instruments (Fast Cloud Droplet Probe (FCDP), 1D Pitot (airspeed, static pressure and temperature), 3D Pitot (five-hole probe) and humidity (RHT)) and discussed their function, how they work, their role and how they compare with the MPCK+ system. A direct comparison of the droplet measurements from holography, PIV and the FCDP was performed to assess their consistency. In cloud-free conditions, relative humidity and temperature readings closely matched those of radiosondes, whereas in-cloud performance was less reliable and requires further improvement. Velocity measurements from pitot tubes generally agreed with each other and with PIV; however, there were caveats relating to in-cloud conditions, as well as sensitivity to the mounting method when it came to characterising turbulence features. Supporting systems (e.g. for navigation, video recording and data transfer) were mentioned briefly. Minor corrections are required to this paper before it can be accepted for final publication. In order to prepare the manuscript for publication, the authors should consider the following points:

Response: We thank the reviewer for the careful reading of our manuscript and for the positive assessment of the MPCK platform and the MPCK+ instrument. We have addressed each of these points in the revised manuscript and provide our detailed responses below.

General comment

Referee comment 1. I advise the authors to revise the conclusion section and improve the sequence of the findings.

Response: We thank the referee for this suggestion. We have substantially reorganised and shortened the Conclusions section to improve the sequence of the findings and reduce repetition. The revised section now progresses from the platform and mounting configurations to the performance of the environmental and airflow measurements, followed by the PIV turbulence measurements, holographic characterisation, and intercomparisons of cloud microphysical measurements. We have also consolidated related findings and revised the final paragraph to provide a clearer synthesis of the instrument's demonstrated capabilities and remaining limitations.

Specific comments

Referee comment 2. L6-8: "The MPCK+ instrument combines advanced airborne imaging techniques: inline holography, which characterises particle size, concentration, and shape in three dimensions, and particle image velocimetry (PIV), implemented here for the first time in an in-situ airborne setting." As the authors stated, the function of holography is to 'characterise particle size', please also state the function of PIV here.

Response: We thank the referee for this suggestion. We have revised the sentence in the abstract to explicitly describe the function of the PIV system in characterising turbulence at high spatial and temporal resolution.

Referee comment 3. L89-92: "Prior to the development of the MPCK project, which began in early 2016, imaging technologies developed had advanced beyond traditional optical array probes to include holographic systems such as HOLODEC (Fugal and Shaw, 2009a), PHIPS-HALO (Abdelmonem et al., 2016), and HALOHolo (Schlenczek, 2018), as well as the video ice particle

sampler (VIPS) (Heymsfield and McFarquhar, 1996), among others." PHIPS-HALO should be mentioned as a non-holographic but "stereo" imaging probe with simultaneous polar scattering measurement.

Response: We have improved the wording to more clearly distinguish between the different cloud-particle imaging techniques and to describe PHIPS-HALO more accurately as a stereo imaging probe with simultaneous single-particle light-scattering measurements.

Referee comment 4. L124-126: "Helikites combine helium buoyancy with aerodynamic 125 lift generated its kite, composed of a keel and sail, enabling stable flight even in strong winds of up to 25 m/s (depending on the model)." What is the highest wind speed you encountered so far?

Response: The highest wind speed at which we have successfully operated the Helikite is approximately 25 m/s. We have revised the wording to clarify that this value is based on our operational experience with the platform.

Referee comment 5. L133-135: "For example, for the primary 250 m3 MPCK aerostat operating in tandem with a 34 m3 Helikite, we have measured tether line tensions exceeding 1000 kg at wind speeds of about 25 m/s. " Does this mean that you tested the system at the modelled speed of 25 m/s?

Response: Yes, this is what we intended to convey. The platform was successfully operated at wind speeds of approximately 25 m/s, during which we measured tether tensions exceeding 12 kN. We have revised the manuscript to clarify that these values were obtained during actual field operations rather than being based solely on model predictions.

Referee comment 6. L137-138: "The Helikite is tethered to the ground by a 2–4 km made of ultra-high-molecularweight polyethylene (e.g. Dyneema or equivalent) tether and controlled using a petrol or a diesel powered winch." Hard to read. I suggest rewording. Example: "The Helikite is tethered to the ground by a 2-4 km ultra-high-molecular-weight polyethylene tether, typically made from Dyneema or an equivalent material, and is controlled using a petrol- or diesel-powered winch."

Response: We thank the reviewer for the suggestion. We have reworded the sentence to improve its clarity and readability.

Referee comment 7 L172-180: "Many established instruments commonly used in cloud research. . . ".
I suggest that the authors add a table comparing the detection volume, particle size ranges and sampling rate with those of other instruments, either here or in the SI.
Please note that, in addition to the scattering phase function, PHIPS-HALO provides stereo imaging that allows the individual particles to be viewed from two angles for better sizing and observation of morphology, and for symmetrical particles, reconstruction of a 3D particle image.

Response: We considered including such a comparison table during the initial preparation of the manuscript, as we agree that placing the capabilities of different cloud-particle instruments in perspective would be valuable. However, we found that a fair quantitative comparison is not straightforward, as the instruments differ substantially in their measurement principles, scientific

objectives, and operating conditions. In particular, sampling volumes and effective sampling rates can depend strongly on instrument configuration and platform speed. Furthermore, nominal specifications reported by manufacturers or in instrument descriptions do not always correspond to the performance demonstrated under actual field conditions. Other characteristics, such as spatial resolution, image quality, and the type of information retrieved, are also important and cannot be adequately represented by the three proposed parameters alone. A comprehensive and balanced comparison would therefore require a dedicated analysis beyond the scope of the present study. Including such an analysis would also considerably lengthen an already extensive manuscript and divert attention from its primary objective: the description and performance evaluation of the MPCK platform and MPCK+ instrument. As a result, we decided not to include a comparison table, as we believe it could lead to misleading interpretations without a more comprehensive assessment of the individual instruments. Instead, we have revised the relevant discussion to focus on the measurement capabilities and fundamental differences between the techniques, removing ambiguous qualitative descriptions such as "small" or "large" sampling volumes that could be misleading without a consistent basis for comparison. We also thank the referee for the clarification regarding PHIPS-HALO. We have expanded its description to acknowledge its combined stereo imaging and single-particle light-scattering measurements.

Referee comment 8 Page 11, Figure 3b: Why don't you show here the photo of the newer version (after 2022)?

Response: We thank the referee for this helpful suggestion. We have updated Fig. 2 to include a photograph of the modified instrument design after 2022. We have retained the photograph of the original holography arm cover in Fig. 3b to illustrate its construction and the attachment points of the PIV laser-beam block. We have also revised the caption of Fig. 3 to refer to the updated design shown in Fig. 2b.

Referee comment 9 L312-316: "In Figure 5, holograms were recorded using the full system, with the outer covers of the arms removed to compensate for the brightness reduction caused by the calibration-mask-substrate, and reconstructed with Holo Suite. At small z (0.94 cm), all shapes were distinguishable, except for the 20 µm circle and hexagon. At large z (23.51 cm), diffraction reduced contrast, making 20 µm targets barely visible and 40 µm targets only marginally distinguishable. All larger shapes remained clearly identifiable"
I assume here that the particles were recorded at the center of the hologram plane(s), correct? Did you also compare the images at different distances from the z-axis? How does the image quality change with distance from the z-axis?

Response: In Fig. 5 of the present manuscript, we show the shape-detection performance at two distances representing the near and far ends of the measurement volume, from close to the camera plane to the opposite end near the laser window. These measurements therefore illustrate the range of shape-detection quality across the full z-extent of the measurement volume, with intermediate distances expected to exhibit performance between the two cases shown. However, we have extensively characterised the performance of the holographic system at different distances from the camera plane (z), as well as at different positions within the transverse (x–y) plane. These investigations are presented in detail in our previous work (see, e.g., Figs.6–10 in Thiede et al., 2025). We found that, apart from a region approximately 1 mm wide near the image boundaries, the particle detection efficiency is largely uniform across the x–y plane. The detection efficiency depends primarily on the distance from the camera plane (z), as discussed in the manuscript and in Thiede et al. (2025).

Referee comment 10 L331-332: "A Nikon 28 mm f/2.8 lens sets the required magnification and depth of field" What was the magnification and depth of field under the typical operation conditions?

Response: Under typical operating conditions, the PIV imaging system has a magnification of approximately 0.094 and an estimated depth of field exceeding 1 cm, which is larger than the laser-sheet thickness of approximately 4 mm. We have added these values to the revised manuscript.

Referee comment 11 L342-343: "This cycle is repeated during in-cloud events until the available storage is filled, corresponding to a total acquisition time of approximately several hours."
You mentioned previously (L276-277) that "the storage capacity has recently been upgraded to 16 TB, enabling up to 140 min of continuous acquisition per flight". Mentioning "several hours" here is a bit exaggeration. You may use the term "couple of hours".

Response: We thank the referee for pointing out this ambiguity. The acquisition times refer to two different imaging systems: the 140 min limit applies to the holographic system, whereas the acquisition time of several hours refers to the PIV module alone. We have revised both passages to clarify these distinctions.

Referee comment 12 Page 16, Figure 6: "(a) Diagram of the 2-frame PIV system. . . "Why (a)? Where is (b)?

Response: We thank the referee for noticing this error. Figure 6 contains only a single panel, so the label "(a)" was unnecessary and has been removed from the caption.

Referee comment 13 L502: "folloiwng". Correct to "following"

Response: We thank the referee for noticing this typo, which we have fixed now.

Referee comment 14 L554-555: "ppp (range 0.006–0.015 ppp)." PPP not defined

Response: We thank the referee for pointing this out. We have defined ppp as "particles per pixel" in the revised manuscript.

Referee comment 15 L633-635: "A likely explanation is sampling: the day time dataset is about an order of magnitude smaller, and the clouds encountered during these flights were dominated by small droplets, limiting robust correlations with larger diameter thresholds. "
Did the authors try to do such a comparison under well controlled laboratory conditions (e.g. at cloud simulation chambers)? If not, it can be considered in future work.

Response: We have not yet performed a systematic comparison under controlled laboratory conditions. We agree that experiments in cloud simulation chambers would be valuable for investigating these differences independently of the variability encountered during field measurements. We have revised the discussion to clarify the limitations of the daytime dataset and added a sentence highlighting controlled laboratory experiments as a potential direction for future investigation.

References

B. Thiede, O. Schlenczek, K. Stieger, A. Ecker, E. Bodenschatz, and G. Bagheri. In-line holographic droplet imaging: accelerated classification with convolutional neural networks and quantitative experimental validation. *Atmospheric Measurement Techniques*, 18(21):6291–6314, 2025. doi: 10.5194/amt-18-6291-2025. URL `https://amt.copernicus.org/articles/18/6291/2025/`.