The Max Planck CloudKite (MPCK): High-Resolution Airborne Measurements of Turbulence and Cloud Microphysics

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:

General comment:

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

Specific comments:

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.

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.

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?

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?

6. L137-138: "*The Helikite is tethered to the ground by a 2–4 km made of ultra-high-molecular-weight 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."

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.

8. Page 11, Figure 3b:

   Why don't you show here the photo of the newer version (after 2022)?

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?

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?

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".

12. Page 16, Figure 6: "(a) Diagram of the 2-frame PIV system…"

    Why (a)? Where is (b)?

13. L502: "*folloiwng*".

    Correct to "following"

14. L554-555: "*ppp (range 0.006–0.015 ppp).*"

    PPP not defined

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.