Response to Referees

Putting the spotlight on small cloud droplets with SmHOLIMO –
A new holographic imager for in situ measurements of clouds

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Dear editor and referees,

We appreciate the editor's efforts in handling our manuscript and thank the referees for their thorough and thoughtful evaluation of the manuscript. Below, we provide detailed responses to all comments. The referee comments appear in purple boxes, our responses are in plain text, and quotations from the revised manuscript are presented in italic font. Additionally, we have uploaded a version of the manuscript with highlighted track changes, which also shows smaller typesetting changes.

Best regards,
Christopher Fuchs et al.

Response to referee #1

Comments to the Author

From my point of view, the paper is well written and the data, methodology and results are scientifically sound. Even if there is not so much technological novelty involved in the step from HOLIMO to SmHOLIMO, the technical improvements are very helpful for the cloud and aerosol physics community. One could argue that an inline holographic imager stays an inline holographic imager if just the optical properties are modified. The key point from my perspective is that the smaller pixel size enables the operator to probe a more substantial part of the left tail of the cloud droplet size distribution, which was one of the major weaknesses of holographic imagers in the past. This is extremely important for obtaining bulk cloud microphysical properties and performing intercomparison studies between passive and active remote sensing instruments and in-situ measurements.

Thank you for your thoughtful and positive feedback. We appreciate your recognition of the scientific relevance of our work and the impact of SmHOLIMO's technical improvements. We fully agree that the ability to better capture the left tail of the cloud droplet size distribution is a crucial advancement, addressing a key limitation of previous holographic imagers.

Major comments

However, I would like to have a bit more discussion about the sizing accuracy in the context of Figure 5, in particular for the panels q and u. For me it looks like the HOLIMO captured some of the small particles, but the sizing is incorrect (due to resolution limit effects).

Thanks for this remark. Yes that could also be one issue that in this region with very small cloud droplets some of the droplets might be incorrectly sized by HOLIMO, thereby increasing the first one or two bins. However, our hypothesis is the other way round. We think that SmHOLIMO undercounts cloud droplets, since the sample volume (top side) was blocked from below by the electronics housing due to a non-ideal mounting. Furthermore, on this specific day the horizontal wind speed was rather low ($\approx 2\,\mathrm{m\,s^{-1}}$) and thereby comparable to the descent velocity of the balloon ($\approx 1.5\,\mathrm{m\,s^{-1}}$), resulting in an air flow direction from 30° below, resulting in non-isokinetic sampling. Additionally, this overcounting/incorrect sizing by HOLIMO does not appear to be a systematic error, as it only occurs in some CDSDs in the cloud base region rather than across all CDSDs presented in Fig. 5.

Further, it is important to mention that SmHOLIMO and HOLIMO were separated by approximately 1.5 m. While this separation is relatively small and unlikely to fully explain the observed significant deviations, it could still contribute to slight mismatches, particularly in transient cloud regions such as cloud bases.
Nonetheless, your hypothesis is valid, and we have include it into our discussion. Additionally, we conducted an intercomparison campaign involving SmHOLIMO, HOLIMO, and a fog monitor (FM-120) at the Sonnblick Observatory, Austria. The data from this campaign is currently being analyzed and should provide further insights into the origin of the observed discrepancies to better clarify whether they arise from airflow effects, incorrect droplet sizing, or a combination of both factors.

We changed the sentence in line 257-259: *"For the descending profiles, i.e. P4 and P18, we observe a deviation between the CDSDs measured by SmHOLIMO and HOLIMO, with SmHOLIMO measuring lower concentrations of larger cloud droplets and HOLIMO measures higher concentrations of small droplets especially in the cloud center and cloud base regions (e.g., Fig. 5k, m, o, q, u)."*

We added sentence in lines 266-274: *"Another hypothesis is that, in the lower cloud and cloud base regions, some of the smaller cloud droplets may have been incorrectly sized by HOLIMO due to resolution limit effects, causing them to be assigned to a larger size bin, e.g., Fig. 5q and u. This feature persists across all cloud base region CDSDs (Figs. 5s to v), where HOLIMO generally measures higher concentrations in the smallest size bin compared to SmHOLIMO. However, as noted earlier, measurements in the smallest size bin should be interpreted with caution. Since the descending profiles are not trustworthy, we will discard them from the following analysis and focus on the data from ascending profiles only. To better assess the source of this discrepancy we conducted an intercomparison campaign at Mt. Sonnblick Observatory, Austria, between SmHOLIMO, HOLIMO and a fog monitor (FM-120, Droplet Measurement Techniques, USA). The data is currently being analyzed."*

Minor comments

> Line 37: There is more literature available about the application of in-situ holography via tethered balloon systems, for example the setup by MPI-DS Goettingen on research vessel Maria S. Merian. Please add reference (Stevens et al., 2021).

Thank you very much for this information. We have now included Stevens et al. (2021) as a reference.

> Section 3.2.: I have some questions regarding the calibration. Could you please add information about temperature and relative humidity and also discuss the particle travel time between the outlet of the VOAG and the sample volume of both SmHOLIMO and APS? This is important to understand if evaporation could have changed the droplet size and might have introduced a bias in the calibration process.

Thank you for your comment. We found a minor error in our manuscript. Specifically, we did not use a **water**-polyethylene glycol emulsion, but rather an **isopropanol**-polyethylene glycol emulsion, and changed it respectively. The emulsion jet was first injected into a 12 cm × 1 m (≈ 11 L, drying column). This cylinder was ventilated turbulently with dried air (dilution air) at room temperature (≈ 20 °C) at a flow rate of 50 to 70 $\mathrm{L\,min^{-1}}$. The combination of the dilution air and drying tube ensures the evaporation of isopropanol, leaving behind nearly pure, monodispersed polyethylene glycol droplets, which have a negligible vapor pressure at room temperature.
SmHOLIMO was placed immediately at the opening of the drying tube, resulting in a travel time of approximately ≈ 11 s. The APS was positioned beneath SmHOLIMO, and a ≈ 35 cm long, 5 mm diameter black tube was used to sample the plume directly next to the SmHOLIMO volume. The APS was operated with a flow rate of 1.2 $\mathrm{L\,min^{-1}}$, adding an additional 0.4 s of travel time, which represents a marginal difference between SmHOLIMO and the APS. Furthermore, the black tube was aligned vertically, with minimal bends, to maintain high transport efficiency of larger droplets.

We adapted and restructured the sentences in lines 159-164: *"The validation of the sizing algorithm is performed using a vibrating orifice aerosol generator (VOAG, model 3450, TSI, USA) that produces a jet of droplets from a isopropanol-polyethylene glycol emulsion. After the VOAG, the droplet jet was dispersed into a homogeneous plume by passing it through a ventilated cylinder (12* cm × *1* m, *flow rate of 50 to 70* $\mathrm{L\,min^{-1}}$*). The residence time within the cylinder was* ≈ 11 s *to ensure full evaporation of the isopropanol yielding nearly mono-disperse droplets of polyethylene glycol. A total of six different droplet sizes were generated, with diameters ranging from ≈4* µm *to ≈19* µm *(see Table 1)."*

Response to referee #2

Comments to the Author

This is not a novel instrument design. The authors describe a simplified digital, in-line, holographic instrument that operates in the design space where the "typical resolution" is improved from 6µm to 4µm by reducing the sample volume by roughly a factor of 30. The sample volume of SmHOLIMO is 0.5 cm3; whereas, the two other operational digital inline holographic instruments for cloud study, HOLODEC-II and HOLIMO3B, have sample volumes of 15 cm3. The SmHOLIMO instrument's ability to resolve "seemingly marginally smaller" particle diameters comes at the cost of limiting the instrument's ability to address other important cloud studies. So the key question becomes, do the authors demonstrate that design trade was worth it?

To help answer this, it would be helpful to have further discussion about the instrument design trades. Something akin to Spuler and Fugal 2011, describing the HOLODEC instrument that was used in Beals et al., 2015; Larsen et al., 2018; Glienke et al., 2020. In that case, it was clear that design choices were made to enable study of fine scale cloud droplet clustering and non-uniformity down to cm scales. In this manuscript, it seems that this key advantage of holography was given up to gain a slight advantage in resolution. Does it enable some new novel science? For the limited case shown, it appears advantageous, but somewhat unclear why this instrument would be used versus others.

Thank you for your comment. We believe that addressing these questions has significantly improved the quality of the manuscript, allowing us to better demonstrate the capabilities of SmHOLIMO, highlight the advantages of using a holographic instrument, and pointing out specific use cases.

First, we acknowledge that SmHOLIMO is indeed a niche instrument, particularly within the category of holographic instruments. Its design is specifically optimized for measuring cloud droplets in liquid and mixed-phase clouds, which means that some of the broader advantages (large sample volume) of holography are reduced compared to instruments like HOLODEC and HOLIMO3B. While other instruments may provide similar insights, we believe that SmHOLIMO's key strengths still lie in its open-path configuration and well-defined sample volume characteristic for holographic imagers. This setup enables operation under varying wind speed conditions, on non-moving measurement platforms and not requiring an inlet. Additionally, the well-defined sample volume allows for highly localized cloud characterization, both within a single hologram ($0.5\,\mathrm{cm}^3$) and spatially down to $\approx 1\,\mathrm{m}$ (assuming a wind speed of 10 m/s), whereas most aircraft-based measurements have a higher spatial resolutions. Further, we have shown (see Fig. R1) that SmHOLIMO, despite its small sample volume can be used to infer cloud droplet structuring and therefore still giving potential for spatial analysis.

The primary scientific applications of SmHOLIMO are in the study of continental clouds, which generally have smaller cloud droplets than maritime clouds. SmHOLIMO enables detailed examination of transient regions, such as cloud edges, where entrainment can cause droplets to shrink or fully evaporate, leading to voids and filament structures (see Fig. R1, and Beals et al., 2015). Another key application is studying cloud base regions, where droplet sizes are inherently small. Additionally, SmHOLIMO can be used to characterize the liquid phase in mixed-phase clouds, particularly transitions from liquid to mixed-phase and fully glaciated regions that occur over small spatial scales (see Korolev and Milbrandt, 2022). Here we think a co-located setup with another holographic imager observing the ice phase (e.g., HOLIMO) can be highly advantageous.

A specific example where SmHOLIMO in combination with HOLIMO would have been particularly useful is the CLOUDLAB project (Henneberger et al., 2013; Ramelli et al., 2024), to better understand how the Wegener-Bergeron-Findeisen process affects cloud droplet size. Within CLOUDLAB, HOLIMO frequently observed transitions from liquid to apparently fully glaciated cloud regions, but it could only monitor droplet size reductions down to $6\,\mu$m due to its resolution limit. This raised the important question of whether these clouds were truly fully glaciated or if smaller cloud droplets were present but unresolved. SmHOLIMO, with its enhanced resolution for small droplets, could provide valuable answers in such cases.

Finally, we strongly believe that instrument diversity, particularly using different measurement techniques, is highly beneficial and needed for intercomparison studies. These are crucial for identifying undetected flaws and errors in instruments, whether they originate from technical, software, or data analysis aspects. Such intercomparisons help refine our methodologies and improve the reliability of cloud microphysical in situ measurements.

We changed the sentence in lines 62-66: *"In this study, we present the Small Holographic Imager for Microscopic Objects (SmHOLIMO), a newly developed instrument specifically designed to measure cloud droplets down to small scales (3.7*$\,\mu$m*) in conditions of low and variable wind speeds (*$<10\,\mathrm{m\,s^{-1}}$*), such as seen for ground-based or balloon-borne applications. SmHOLIMO thereby retains the advantages of holography (open path configuration, well-defined* *sample volume, and potential for spatial analysis) while nearing the resolution of forward scattering probes."*

We added a new paragraph in lines 348-368: *"SmHOLIMO is a specialized in situ instrument within the field of holographic imagers. Unlike other holographic imagers (e.g., HOLIMO or HOLODEC) designed to capture both cloud droplets and ice crystals, SmHOLIMO is specifically optimized for detecting small cloud droplets, thereby trading sample volume for resolution. Scientific applications of SmHOLIMO include the precise measurements of liquid-phase cloud microphysical properties from highly localized cloud volumes ($0.5\,\mathrm{cm}^3$) using single holograms. This enables the study of small-scale features that would otherwise be lost when averaging over larger cloud sections (Beals et al., 2015). In liquid-phase clouds, this capability is particularly valuable for characterizing transient regions such as cloud edges, where entrainment can cause droplets to shrink or to completely evaporate. This entrainment can result in homogeneous or inhomogeneous mixing (Korolev et al., 2016) and thereby lead to the formation of cloud droplet voids and filament structures. Similarly, at cloud base regions, SmHOLIMO can provide insights into the initial stages of cloud droplet formation.*
In mixed-phase clouds, SmHOLIMO can complement a "standard" holographic imager (e.g., HOLIMO) in a co-located setup to investigate transitions between fully liquid and fully glaciated regions. This setup is particularly useful for studying how the ice phase influences the liquid phase, improving the discrimination between genuinely (cloud droplets and ice appear homogeneously mixed) and conditionally (cloud droplets and ice crystals appear in separated pockets) mixed-phase clouds (see Korolev et al., 2017). A specific example, where such a setup would have been beneficial is the CLOUDLAB project (Henneberger et al., 2023), which investigated the Wegener-Bergeron-Findeisen (WBF) process (Wegener, 1911; Bergeron, 1935; Findeisen, 1938) through glaciogenic cloud seeding experiments. In situ observations from HOLIMO showed that transitions between fully liquid and (apparently) fully glaciated cloud sections occur on scales of $< 10\,\mathrm{m}$. However, since HOLIMO can only resolve droplets down to $6\,\mu\mathrm{m}$, it remains uncertain whether these cloud regions were truly free of cloud droplets or whether the WBF process had reduced droplet sizes below the detection threshold of HOLIMO ($6\,\mu\mathrm{m}$). SmHOLIMO, with its enhanced resolution, could have helped to better constrain this ambiguity."

Specific questions

> Line 11: SmHOLIMO has the “potential for spatial analyses”? With such a small volume what are the scientific problems that could be addressed?

Yes, the small sample volume does reduce the ability to conduct spatial analysis compared to the scales observed with HOLODEC or HOLIMO. While the hologram's x and y dimensions (6.6 mm and 4.4 mm, respectively) may be relatively small, the z-dimension (18 mm) is sufficient for detecting relevant features.
For example, cloud droplet clustering and filament structures at cloud edges, which are key to studying entrainment, can still be investigated (see Beals et al., 2015). Figure R1 presents four exemplary holograms recorded in the cloud-top region of profile P13 (see Table B1 in the manuscript). These holograms clearly show cloud droplet clustering and filament structures at the cloud edges, demonstrating the potential for spatial distribution analysis. Approaches such as Voronoi tessellation could be applied to further quantify the sizes of clusters and voids. We further want to refer to Fig. R2 showing how single holograms can be used to infer cloud droplet size distributions.

The well-defined sample volume also enables the retrieval of key cloud properties, including CDNC, LWC, mean cloud droplet diameter, and optical depth, at very local scales. Assuming a CDNC of $200\,\mathrm{cm}^{-3}$, the counting statistics remain robust, with approximately 100 cloud droplets per hologram. The ability to retrieve local CDSD provides valuable insights into cloud microphysics, as significant variations can occur at small scales, as demonstrated by Allwayin et al. (2024).

> Line 18: “We unequivocally show the importance of capturing the lower tail of the CDSD, which significantly affects the derived quantities” In section 4.3, the authors show that the 2.3 µm improvement in resolution provides a more complete picture of the Cloud Droplet Size Distribution. But for the derived projects, what happens when including the camera pixel uncertainty of 1.4μm (a large uncertainty when talking about an improvement in resolution of 2.3μm) In other words how much certainty do you have in these derived products: Cloud Droplet Number Concentration (CDNC), Liquid water content (LWC), and Cloud Optical Depth? Especially since in Line 5 they state: “precise and accurate in situ measurements of cloud doppler size distribution, especially of cloud droplets smaller than 6 μm, are still lacking. This can lead to uncertainties in the microphysics and thus in weather and climate models, which are based on parameterizations often derived from these measurements"

Thank you for highlighting this concern. We carefully reviewed our statement and sources regarding pixel uncer-

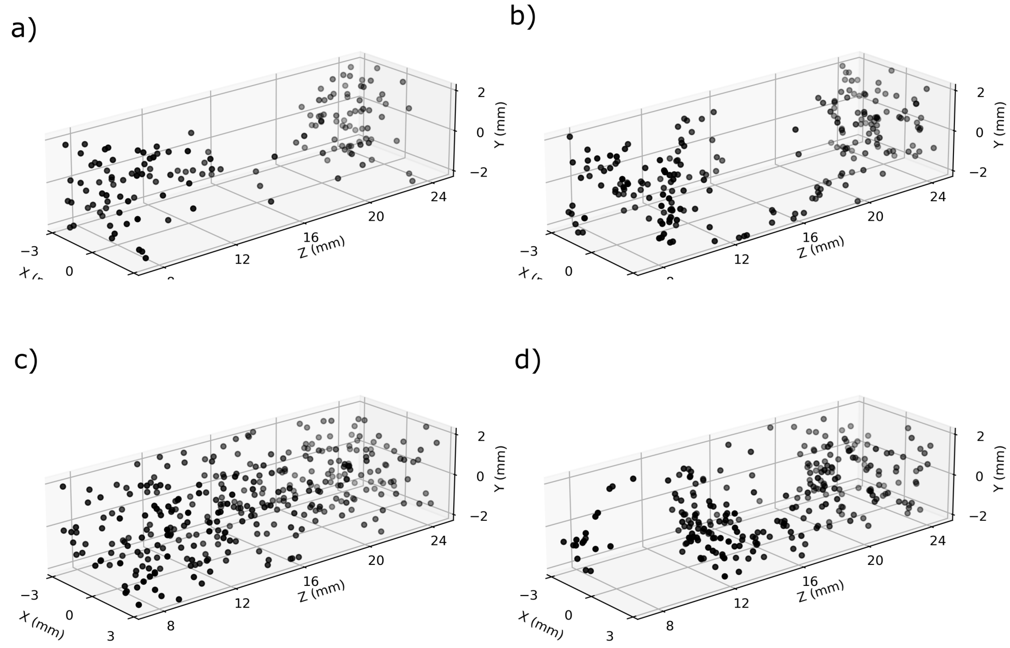

Figure R1: Cloud droplet spatial distributions of four holograms recorded in the cloud top region during profile P13 (see Table B1, in manuscript). In **a)** (09:13:16.212075 UTC), **b** (9:13:16.849852 UTC), and **d** (9:13:35.409767 UTC) show cloud droplet clustering and cloud droplet voids. In **c** (9:13:19.058766 UTC) shows a comparably uniform distribution of cloud droplets.

tainty and concluded that the previously used approach was incorrect, resulting in an error that propagated through previous manuscripts. Specifically, the square-root approach is unit-dependent, demonstrated by the inconsistent results for a relative uncertainty: e.g., $\sqrt{1.85\,\mu\mathrm{m}}/1.85\,\mu\mathrm{m} = 0.73$ vs. $\sqrt{1850\,\mathrm{nm}}/1850\,\mathrm{nm} = 0.02$. Moreover, this method implies that measurements become less accurate with decreasing pixel sizes, which is physically incorrect.
Upon further literature review, we refer to Fugal et al. (2004), who stated: "Note that the reconstructed diameter is accurate to within 1 pixel (4.65,μm) of the known diameter." Similarly, Adrian and Westerweel (2011) concluded that the uncertainty for each detected edge is ± 0.5 pixels, resulting in a combined uncertainty of ± 1 pixel (two droplet edges) in diameter for a single droplet measurement ($\Delta d_1 = \pm 1\,\mathrm{pix}$).
When measuring N independent droplets, the total uncertainty decreases according to the Central Limit Theorem due to random error reduction, yielding: $\Delta d_N = {}^{\Delta d}/\sqrt{N}$. For instance, considering a low concentration scenario with 10 cloud droplets in the smallest size bin (diameter of $3.7\,\mu$m), the absolute uncertainty becomes $\Delta d_N = \pm 0.6\,\mu\mathrm{m}$, corresponding to a relative error of approximately 15 %. Measuring a single larger droplet (e.g., $20\,\mu$m diameter) results in an absolute uncertainty of $\pm 1.85\,\mu$m, corresponding to a relative error of about 10 %. Going to larger number of droplets, other sources of error will dominate. For example uncertainties in magnification/pixel size, z-position, optical distortion encompassed in systematic uncertainties (Δd_{sys}). The final uncertainty for droplet diameter measurements thus combines both statistical and systematic contributions: $\Delta d = \sqrt{\left({}^{d_s}/\sqrt{N}\right)^2 + \Delta d_{sys}^2}$, although systematic uncertainties are challenging to precisely quantify. We would estimate that the error gets never below 10 % since it is also the standard deviation of the measured diameters during the validation experiments shown in Tab. 1 and Fig. 3 (only for the $4.34\,\mu$m experiment a bit higher).
When deriving quantities such as CDNC and LWC, we usually average over a larger number of particles (≈ 100 cloud droplets for CDNC$= 200\,\mathrm{cm}^{-3}$), thereby reducing the overall uncertainty. In Sect. 3.2 of our manuscript, we demonstrate that SmHOLIMO can reliably detect small droplets, with a standard deviation of only $\pm 0.61\,\mu$m for the experiment involving the smallest droplets (see Table 1, Fig. 3, and Fig. A.1 in the manuscript). Additionally, Fig. 6b shows that the mean cloud droplet diameter at cloud base can be reliably resolved.

In general, pixel uncertainty does not significantly impact CDNC. While LWC is affected to some extent, its dependence on larger droplets minimizes this effect. The cloud optical depth, however, is more sensitive to this uncertainty.
It is also important to note that for most in situ instruments, the smallest resolvable sizes are associated with the largest uncertainties in single-particle measurements. Accurately translating pixel uncertainty into measurement uncertainty remains challenging for many in situ instrument, and in many cases, only estimates or no uncertainty values are provided (e.g., Baumgardner et al., 2001; Lawson et al., 2001, 2006).

We have now removed the respective lines 170-171 (non-revised manuscript) stating *"[...] camera pixel uncertainty defined by the square root of the pixel size* ($\sqrt{1.85}\,\mu$m $= \pm 1.36\,\mu$m)*."*, since we think it was incorrect.

We added the sentence, lines 178-179: *"Overall, the droplet diameters measured by SmHOLIMO and APS are in good agreement without any significant deviations and all measurements fully overlap within their respective uncertainties (see Table 1 and Fig. 3)."*

We added sentences in lines 218-223: *"The uncertainty in retrieving the diameter of a single droplet with SmHOLIMO is defined by the pixel pitch, yielding* $\Delta d_s = 1.85\,\mu$m *(Fugal et al., 2004; Adrian and Westerweel, 2011). When measuring N independent droplets, the total uncertainty decreases according to the Central Limit Theorem due to random error reduction, resulting in:* $\Delta d_N = \Delta d_s \cdot \sqrt{N}^{-1}$*. The uncertainty associated with CDNC follows counting statistics and is thus described by* $\sqrt{N}$*, where N represents the total number of detected droplets. Exemplary CDSDs, including their corresponding uncertainties, are presented in Fig. C1."*

We included a new section on page 21 *Appendix C: Uncertainties in cloud droplet size distributions* including a new Figure, Fig. C1 (see Fig. R2 below) showing four exemplary cloud droplet size distributions with associated diameter and counting uncertainties.

> Line 33-34: After introducing in-line holography, the authors list references using photographic plate holography (e.g., Kozikowska et al. 1984, Borrmann and Jaenicke 1993) They appear to be claiming that photographic plates are "a promising in situ approach" with a "robust setup"? It would be helpful to make a distinction between those early precursors and operational digital holographic methods.

Thanks for this comment. We thereby mainly wanted to highlight the historic aspects of holography. We now made a more clear distinction between analog and digital holographic measurements.

We made changes in line 33-37: *"A promising in situ measurement approach is in-line holography, which has been applied for cloud measurements since more than 40 years (e.g., Conway et al., 1982; Kozikowska et al., 1984; Borrmann and Jaenicke, 1993). Since the introduction of digital in-line holography in the mid 90s (Lawson and Cormack, 1995), the setup of holographic instruments became relatively simple and robust yielding to widespread use in stationary ground-based field measurements (e.g., Raupach et al., 2006; Henneberger et al., 2013; Kaikkonen et al., 2020), and on [...]"*

> Line 53: The authors state "The main reason that the resolution of holographic imagers is limited to around 6 to 10 μm is that they are designed to reliably observe both liquid and ice phase particles. Since under natural conditions ice crystal concentrations are usually several orders of magnitudes lower than cloud droplet concentrations (a few per liter vs. a few hundred per cm3)." HOLODEC and HOLIMO instruments have a 6μm resolution imposed by a pixel resolution limit (Spuler and Fugal 2011, Ramelli et al 2020). These instruments could resolve smaller particles by simply switching to higher resolution sensors (i.e., cameras with smaller pixels within the same frame size). So it appears to be a design trade choice. The reason for NOT pushing to higher resolution while maintaining large volumes exposes the much more serious limitation with digital holography – the extremely large computational expense to process the data.

Thank you for your insights on this aspect and yes your statement is valid - reconstructing large holograms can be computationally expensive. However, with the rapid advancements in computational power, especially the transition to GPU computing in the last couple of years, this concern has become increasingly less significant. While holography is definitely not yet an online in situ technique providing real-time data, the computational burden of reconstruction does not impose such a huge challenge anymore. As an example, the reconstruction of all the holographic data presented in this manuscript took around 2 weeks ($\approx$30.100 and holograms for SmHOLIMO and $\approx$ 7.900 holograms for HOLIMO). Further, most of the reconstruction processes runs in the background with the software taking care of proper parallelization etc. having minimal need for manual interventions.
Regarding the design choices and simply switching the camera, we hold a different standpoint. Both HOLODEC

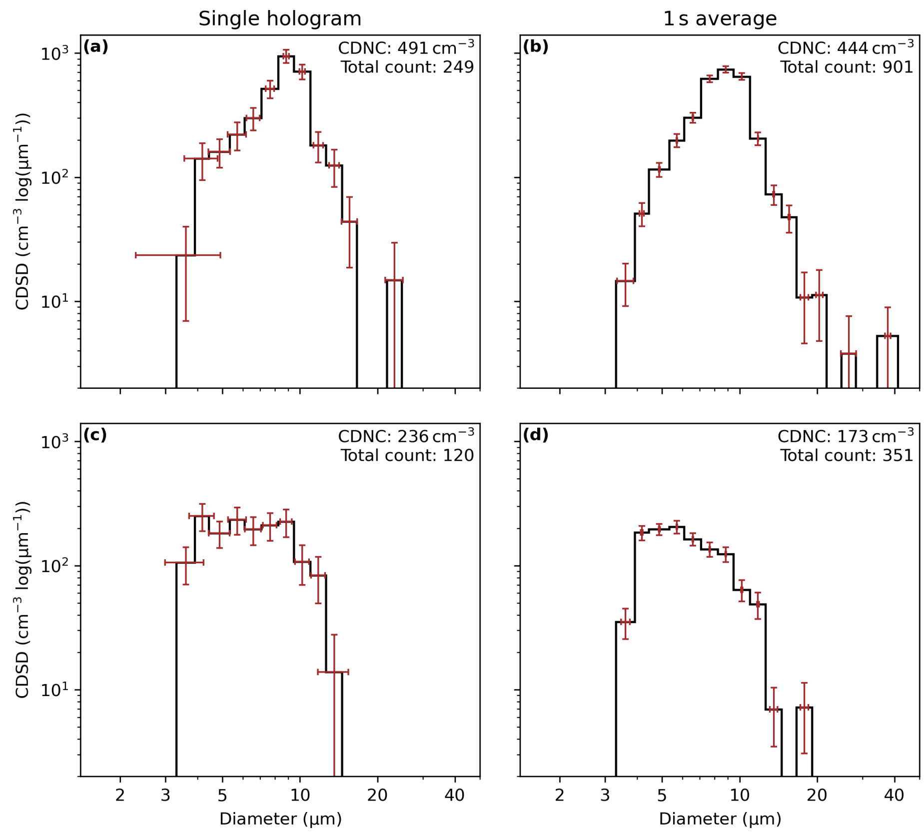

Figure R2: Exemplary cloud droplet size distributions (CDSDs) measured with SmHOLIMO in black with associated diameter and counting uncertainties (red error bars). **(a)** and **(c)** show CDSDs retrieved from single holograms recorded at 08:09:59.736 UTC and 08:39:59.955 UTC, respectively. **(b)** and **(d)** show CDSDs averaged over 1-second intervals, recorded between 08:09:59 - 08:10:00 UTC and 08:39:59 - 08:40:00 UTC, respectively. Diameter uncertainties are calculated as $\Delta d = d_s \cdot \sqrt{N}^{-1}$ with $d_s = 1.85\,\mu$m the error of a single droplet measurement of pixel pitch and N being the number of droplets in each size bin. Counting uncertainties are derived from counting statistics as $\sqrt{N}$. The CDNC and respective total number of droplets are indicated in the upper right corner of each panel.

and HOLIMO were specifically designed to achieve their intended resolutions of $\approx 5\,\mu$m and $\approx 6\,\mu$m, respectively. The decision not to push for even smaller resolutions was deliberate. We assume for HOLODEC and know for HOLIMO that during the development of the instruments, the best available cameras on the market were carefully selected to meet these requirements.

For example, Spuler and Fugal (2011) states: *"To unambiguously resolve the smallest particle size we are interested in ($\approx 5\,\mu$m) with a 7.4 μm pixel camera required a optical magnification of approximately 3×."* and a similar statement is valid for HOLIMO. Had a camera been available at the time with a 2.96 μm pixel size and an appropriately scaled sensor (9.6× 14.4 mm after magnification for HOLODEC), magnification would not have been necessary, simplifying the system and also lowering the costs. From both perspectives, if a better-fitting camera had existed, magnification wouldn't have been required, and if a smaller resolution had been the goal, higher magnification could have been chosen.

Another critical factor is the technical limitations of cameras. In holography, nanosecond laser pulses are typically used to acquire holograms, necessitating a global shutter that exposes and reads all pixels simultaneously. As pixel count increases, finding a suitable global shutter camera becomes increasingly difficult, as most high-pixel count cameras rely on rolling shutters or are extremely expensive.

Selecting an appropriate camera for SmHOLIMO hence was particularly challenging, as it required to be monochrome, smallest possible pixels but a large sensor (high pixel count), and a global shutter. Had there been a better monochrome camera option on the market with the same pixel size but a larger sensor and global shutter, we would have undoubtedly chosen it.

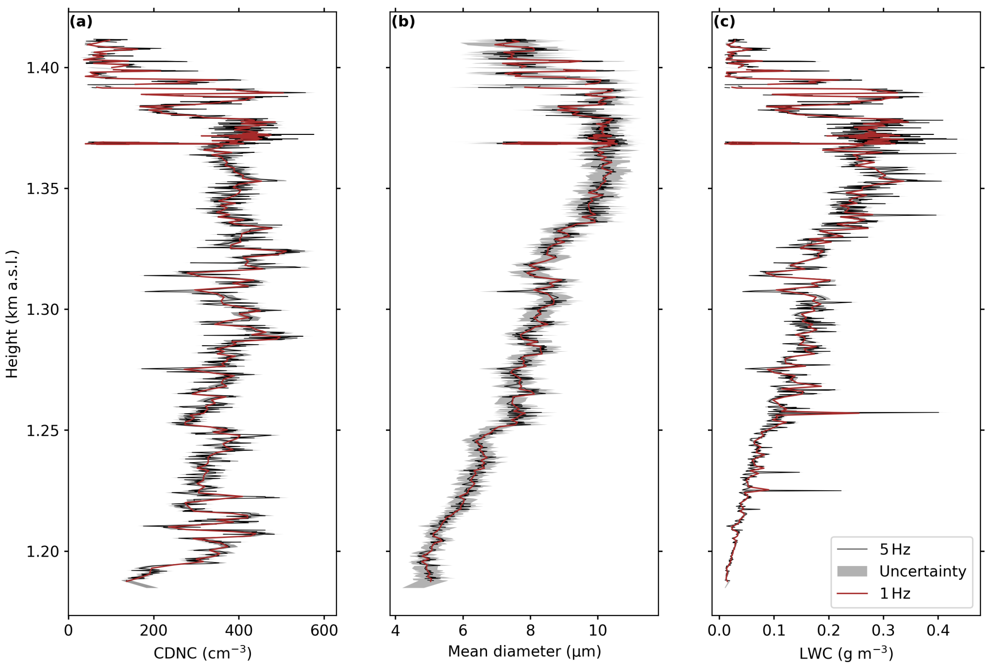

Figure R3: CDNC in **(a)**, mean diameter in **(b)**, and LWC in **(c)** of profile P5 measured with SmHOLIMO. The hologram based quantities in 5 Hz are shown in black with gray shading representing the uncertainty due to counting statistics and in red the 1 s averages are shown.

> Line 67: The authors state that the instrument was designed to maintain "‥, a large enough sample volume for sufficient counting statistic [sic] for large droplets." Yet, for the work here, it required averaging 5 volumes (1 second integration at 5Hz) as discussed on Line 194 "To achieve a more accurate counting statistics the data was averaged to 1 s". So what volume is needed to have sufficient counting statistics? In the quest for higher resolution, this instrument appears to have given up the ability to enable measurements within a single volume (for example, understanding the interaction of droplets on relevant length scales).

Thanks for pointing this out. Yes indeed we average the SmHOLIMO data over 1 s which corresponds to 4 to 5 holograms. The main reason for this was that on the measurement day we were mainly interested in the large scale evolution of the cloud and not in small scale features. For that reason we only evaluated HOLIMO down to a frequency of 1 Hz. SmHOLIMO was analyzed down to a frequency of 5 Hz since we wanted to test the capabilities. To homogenize the time resolution of HOLIMO and SmHOLIMO we decided to use an 1 second average on the SmHOLIMO data. The more accurate counting statistics hence was mainly a side effect and not the actual incentive to do the averaging.
In Fig. R3, we present the non-averaged derived quantities of CDNC, mean diameter, and LWC for profile P5 measured with SmHOLIMO. The observed small-scale fluctuations in CDNC (Fig. R3a black line) are significantly larger than the uncertainty range (gray shading) estimated from counting statistics. This demonstrates that the fluctuations represent real cloud features rather than measurement artifacts and demonstrating that SmHOLIMO facilitates a hologram based analysis.

We made changes and additions in lines 204-206: *"The primary objective of the measurements is to observe the large-scale temporal evolution of the cloud. Therefore, a recording frequency of 5* Hz *was chosen instead of the maximum 10* Hz *to enable continuous measurements for 4.6* h*, constrained by the 1* TB *storage capacity."*

We once more refer to the new section on page 21 *"Appendix C: Uncertainties in cloud droplet size distributions"* that shows how also single holograms are sufficient to retrieve cloud droplet size distributions.

> Line 111: "‥the data transfer speed of the single-board computer limits the frame rate in field operations to 10 fps" , yet on Line 192 it says "The SmHOLIMO data was analyzed with a frequency of 5 Hz (5 holograms per second)" Why the change?

Yes, we did not only analyze with 5 Hz but also recorded with 5 Hz. Our reasoning aligns with the previous answer. On this particular day, our primary goal was not to capture small-scale cloud structures, which would have required recording at higher frequencies. Instead, we aimed to characterize the evolution and dissipation of the observed low stratus cloud - we think a frequency of 1 Hz like HOLIMO would have also been sufficient.
Furthermore, since the duration of this process, the dissipation of the cloud, is unpredictable, we deliberately chose a 5 Hz recording frequency to enable continuous measurements over a minimum 4.6 hours, constrained by the 1 TB SSD storage capacity. This decision traded temporal/spatial resolution for uninterrupted data collection process, as landing the balloon and replacing the hard drive would have required approximately 30 min.

We adapted lines 202: *"The SmHOLIMO data was recorded and analyzed with a frequency of 5* Hz*[...]"*.
We made changes and additions in lines 206-209: *"Additionally, we average the SmHOLIMO data over 1* s*, as our focus (in this specific measurement) is not on capturing small-scale fluctuations in cloud microphysical properties. This also ensures consistency in time resolution with HOLIMO while further improving accuracy through enhanced counting statistics."*

> Line 128: "A uniform optical resolution across the whole sample volume is important to avoid a sampling bias linked to the size of cloud droplets". Please explain this further. One can divide up the sample volume however desired with holography. Seems you could correct for this since you have measured the resolution limit of the instrument.

Yes, this would indeed be possible with holography. The achievable resolution in holography is constrained by three factors: the numerical aperture of the lens (which is not used in SmHOLIMO), the pixel resolution limit, and the reconstruction depth-dependent (z-axis) resolution limit imposed by diffraction effects. For SmHOLIMO, we observe that beyond z > 25 mm the diffraction-related resolution limit becomes dominant, surpassing the pixel resolution limit.
For our analysis, we focus on using only the "best part" of the sample volume—where resolution is highest and unifrom. This ensures that we consistently capture the full range of cloud droplet sizes with maximum accuracy. While it would be possible to account for the depth-dependent resolution in size retrieval, doing so would make the sample volume itself dependent on cloud droplet size. This dependency would need to be carefully integrated into the derivation of all cloud microphysical variables. Since the resolution transitions smoothly along the z-axis, a variable sample volume would introduce additional uncertainties. Given that we have already demonstrated that the SmHOLIMO sample volume is sufficient for characterizing liquid-phase clouds based on single holograms, we aim to avoid such additional complexity in the analysis.

We adapted lines 150-154: *"Although the increase in resolution limit beyond $z_{rec} = 25$ mm, is known and could be corrected for, we restrict the SmHOLIMO reconstruction depth to this value. This ensures the highest and a uniform optical resolution across the entire sample volume while maintaining a sample volume that is independent of cloud droplet size."*

> Line 146: "To obtain accurate cloud droplet diameters a calibration of the particle sizing algorithm is required." Holography does not require calibration. In fact, this exact "calibration" process was done in Ramelli et al. 2020 and they state " no correction to the sizing algorithm was made, because all size measurements agree within the square root of the pixel size ($\sqrt{3.01}\,\mu$m = 1.73 μm)." Nearly the same statement is repeated in this manuscript on line 167. So this is not a calibration – albeit perhaps useful as "sanity check" and a way to fine tune a brightness threshold.

Thanks for this remark, which is indeed true. Holography does not require a calibration. This process was done to ensure that the sizing algorithm is well tuned via the brightness threshold. Since the brightness threshold of SmHOLIMO (0.5) and HOLIMO (0.47) are nearly identical we are now even more confident in its accuracy.

We have changed the respective sentences and will call it further on validation of the sizing algorithm. Changes to the manuscript were made in:

- line 131: *"Instrument characterization and validation of the sizing algorithm"*
- line 154: *"Validation of the particle sizing algorithm"*
- line 155: *"To ensure that SmHOLIMO accurately measures cloud droplet diameters we want to validate the particle sizing algorithm."*

- Caption Table 1: *"Measured diameters of the size algorithm validation of SmHOLIMO for [...]"*
- Caption Fig 3: *"[...] for six size algorithm validation experiments [...]"*
- Line 159: *"The validation of the sizing algorithm is performed [...]"*
- Line 164: *"The six different validation experiments [...]"*
- Line 167: *"To validate the sizing algorithm of SmHOLIMO, [...]"*

Line 237: "There are two interrelated reasons for this underestimation" The authors are suggesting a possible explanation for the discrepancy. This was not experimentally verified to be the actual cause.

Yes, indeed, we have not yet experimentally verified this, and it remains a hypothesis based on observing the same behavior in multiple descending profiles beyond the two shown in Fig. 5. Since SmHOLIMO was mounted with the sample volume on top and the electronics housing below we assume that the flow was blocked from below. On this specific day the wind speed and balloon ascent/descent speed were comparable with $\approx 2\,\mathrm{m\,s^{-1}}$ and $\approx 1.5\,\mathrm{m\,s^{-1}}$, respectively, yielding an aspiration direction of $\approx 30°$. However, we believe that a full experimental verification goes beyond the scope of this publication.
To address this, we have already conducted a ground-based campaign at Mt. Sonnblick Observatory, Austria, using SmHOLIMO, HOLIMO, and a Fog Monitor (FM-120). This campaign specifically investigates this issue, and the collected data is currently being analyzed.

We changed the sentence in line 272-274: *"Our main hypothesis is that, there are two interrelated [...]"* We added a sentence in lines *"To better assess the source of this discrepancy we conducted an intercomparison campaign at Mt. Sonnblick Observatory, Austria, between SmHOLIMO, HOLIMO and a fog monitor (FM-120, Droplet Measurement Techniques, USA). The data is currently being analyzed."*

Response to referee #3

General comments

The paper "Putting the spotlight on small cloud droplets with SmHOLIMO – A new holographic imager for in situ measurements of clouds" by Christopher Fuchs and colleagues demonstrates the capabilities of the smHOLIMO instrument. While the instrument design itself is not novel—it follows the same layout as other in-line holographic probes—a better camera and smart sample volume selection enable it to measure droplets as small as 3.7 microns, compared to the previous 6-micron limit. This improvement makes SmHOLIMO comparable to existing forward scattering probes, an important step toward making holographic instruments more mainstream, and is beneficial for cloud research. However, this comes at the cost of reduced capabilities to the previous design, especially a significant reduction in sample volume.

Thank you for this comment. Indeed, the sample volume of SmHOLIMO ($\approx 0.5\,\mathrm{cm}^3$) is significantly smaller compared to other holographic imagers, such as HOLODEC ($\approx 15\,\mathrm{cm}^3$) and HOLIMO ($\approx 20\,\mathrm{cm}^3$) (Spuler and Fugal, 2011; Ramelli et al., 2020).

For improved clarity, we have added the following sentence in lines 81-83: *"Since the sample volume scales with the spatial resolution as $V_{hol} \propto D_{res}^4$, the sample volume of SmHOLIMO is $\approx 0.5\,\mathrm{cm}^3$, and thus significantly smaller than the volumes of other holographic imagers, typically ranging from 15 to 20 cm^3 (e.g., Spuler and Fugal, 2011; Ramelli et al., 2020)."*

For the tethered balloon system, which moves slowly (say 1-1.5 m/s) this is acceptable, as it allows for a hologram every 20–30 cm (at 5Hz). However, for an aircraft moving at much higher speeds(100-150 m/s), such a system would not be comparable to a scattering probe, nor to the existing holographic probes.

Yes, indeed, with a sampling frequency of 5 Hz, SmHOLIMO would only capture one hologram every 20 m at a flight speed of $100\,\mathrm{m\,s^{-1}}$. However, this frequency was used during the field measurements mainly to enable an uninterrupted measurement duration of 4.6 h, constrained by the available storage capacity of 1 TB. The maximum sampling frequency of SmHOLIMO is actually 10 Hz (see Sect. 2.2, Hardware design), yielding a spatial resolution of 10 m. Consequently, SmHOLIMO would provide approximately three times higher spatial coverage than HOLODEC (Spuler and Fugal, 2011; Beals et al., 2015; Allwayin et al., 2024), operating at a sampling frequency of 3.3 Hz and 1.6 times higher spatial coverage than HaloHOLO (Schlenczek, 2018), with 6.2 Hz.

When comparing SmHOLIMO to HOLIMO, the mode of the cloud size distribution is below 10 microns—where HOLIMO tends to miss most of the droplets. This is a well-known limitation of previous holographic instruments and is more pronounced near the cloud base where the smallest droplets are. This effect should reduce as we go higher up and the mode shifts to larger sizes, say above 15 microns, where the differences might not be as drastic.

Yes, this is correct, and we indeed observe this behavior in Fig.6b, where the mean droplet diameters from SmHOLIMO and HOLIMO converge in the upper cloud region. Thus, SmHOLIMO's improved spatial resolution is particularly advantageous when examining transient regions such as cloud boundaries (see Fig.R1), cloud bases, or when deployed in a co-located setup with HOLIMO for detailed studies in mixed-phase clouds, specifically focusing on evaporating droplets.

To clearly highlight the measurement conditions under which SmHOLIMO provides improved scientific value, we have added the following paragraph in the conclusions (lines 348-368): *"SmHOLIMO is a specialized in situ instrument [...]"*, as outlined in our response to the first comment from referee #2.

Given these considerations, I think the changes to the instrument design merit publication, but its scope is primarily limited to cloud droplet size distribution measurements on slow-moving or stationary platforms. While the authors mention that the instrument is specifically designed for a tethered balloon system, this point should be made more visible.

Yes we will try to better emphasize that SmHOLIMOs intended measurement location are either ground-based or balloon-born measurements. During the design we did not focus in developing an instrument suitable for aircraft measurements.

We adapted the sentences in lines 62-66: *"In this study, we present the Small Holographic Imager for Microscopic Objects (SmHOLIMO), a newly developed instrument specifically designed to measure cloud droplets down to small scales in conditions of low and variable wind speeds (<10* $\mathrm{m\,s^{-1}}$*), such as seen for ground based or balloon borne applications. SmHOLIMO thereby retains the advantages of holography (open path configuration, well-defined sample volume, and potential for spatial analysis) while nearing the resolution of forward scattering probes."*
We adapted the sentence in lines 104-166: *"SmHOLIMO's primary deployment sites are either ground-based locations (e.g., mountain tops) or balloon-borne platforms (e.g., TBS; see Sect. 4), which typically experience highly variable wind conditions. Therefore, SmHOLIMO was specifically designed to be lightweight (*$\approx 5.3\,\mathrm{kg}$*) and compact, measuring* $45\,\mathrm{cm}\times 40\,\mathrm{cm}\times 13\,\mathrm{cm}$ *(height × width × depth)."*

Specific comments

The paper is well written and easy to follow, but since this is an instrument design paper, the limitations of the instrument should be presented more clearly. Below are more specific comments:

1. Sizing uncertainty – With a pixel size of 1.85 microns, the sizing uncertainty is 1.36 microns (line 169), which introduces significant errors for smaller droplets near the resolution limit. For 3.7-micron droplets, this corresponds to a ≈35% error, and for 5.55-micron droplets, it's around ≈25%. This should be accounted for, especially when analyzing the left-hand tail of the droplet size distribution. Additionally, considering a horizontal wind speed of 2 m/s (Figure 4d) and a pulse width of 220 ns, the particle displacement in a hologram would be ≈0.4 microns—small but potentially contributing to the sizing uncertainty for the smallest droplets.

We have carefully reviewed our previous statement regarding sizing uncertainty, which was based on the square root of the pixel size, and found it to be incorrect. This square-root approach is inherently dependent on the unit (e.g., $\sqrt{1.85\,\mu\mathrm{m}}/1.85\,\mu\mathrm{m} = 0.73$ vs. $\sqrt{1850\,\mathrm{nm}}/1850\,\mathrm{nm} = 0.02$), which is obviously wrong. Moreover, it falsely suggests that reducing pixel size would lead to less accurate results, which contradicts fundamental principles of measurement accuracy.
Based on a new literature review (Fugal et al., 2004; Adrian and Westerweel, 2011) we conclude that the uncertainty for a single droplet measurement is $\Delta d_1 = \pm 1,\mathrm{pix}$. For N independent droplet measurements, the uncertainty reduces due to random error reduction $\Delta d_N = \Delta d_1/\sqrt{N}$, following the Central Limit Theorem. Apart from statistical uncertainty, additional systematic errors must be considered, yielding a final uncertainty of $\Delta d = \sqrt{\left(d_s/\sqrt{N}\right)^2 + \Delta d_{sys}^2}$.
For large sample sizes, systematic uncertainties (such as magnification errors, pixel size calibration, z-position variations, and optical distortions) become dominant. Based on our estimations, the total uncertainty will not fall below 10 %. Since this concern was previously raised by Referee #2, we also would like to refer to our earlier responses, where we provided a more detailed explanation.

We have now removed the respective lines 170-171 (non-revised manuscript) stating *"[...] camera pixel uncertainty defined by the square root of the pixel size (*$\sqrt{1.85}\,\mu\mathrm{m} = \pm 1.36\,\mu\mathrm{m}$*)."*, since we think it is misleading as we use averages over large amount of measured droplets.

We added the sentence, lines 178-179: *"Overall, the droplet diameters measured by SmHOLIMO and APS are in good agreement without any significant deviations and all measurements fully overlap within their respective uncertainties (see Table 1 and Fig. 3)."*

We added sentences in lines 118-223: *The uncertainty in retrieving the diameter of a single droplet with SmHOLIMO is defined by the pixel pitch, yielding* $\Delta d_s = 1.85\,\mu\mathrm{m}$ *(Fugal et al., 2004; Adrian and Westerweel, 2011). When measuring N independent droplets, the total uncertainty decreases according to the Central Limit Theorem due to random error reduction, resulting in:* $\Delta d_N = \Delta d_s \cdot \sqrt{N}^{-1}$*. The uncertainty associated with CDNC follows counting statistics and is thus described by* $\sqrt{N}$*, where N represents the total number of detected droplets. Exemplary CDSDs, including their corresponding uncertainties, are presented in Fig. C1.*

We included a new section on page 21 *"Appendix C: Uncertainties in cloud droplet size distributions"* including a new Figure C1 (see Fig. R2 above) showing four exemplary CDSDs with associated diameter and counting uncertainties.

2. Hologram image quality – The hologram quality is known to degrade due to speckle noise, particularly at

higher droplet concentrations (Hui Meng et al., J. Opt. Soc. Am. A, 1993). This could become an issue when measuring clouds with high number concentrations, such as congestus or deep cumulus. It would be useful to add a sentence acknowledging this limitation and providing a rough estimate on limits for number concentrations.

Thank you very much for this helpful hint, which is useful to estimating the maximum number of cloud droplets per volume. Meng et al. (1993) introduced the speckle parameter G defined as:

$$G = \frac{\pi^3}{16} \cdot d^2 \cdot n_s \cdot L, \tag{1}$$

where d is the particle diameter, n_s is the particle concentration, and L represents the sample volume depth. They further state that *"an upper limit for in-line holography to be usable is approximately $G = 1$."* By applying this condition ($G \leq 1$) to the equation above, we obtain the following constraint:

$$n_s \leq \frac{16}{\pi^3 \cdot d^2 \cdot L}. \tag{2}$$

Inserting practical parameters relevant for the SmHOLIMO system ($d = 20\,\mu$m and $L = 5\,$cm, the open-path size), this yields $n_s \leq 25800\,\mathrm{cm}^{-3}$, which strongly exceeds typical droplet concentrations observed in natural clouds.

Considering a very conservative cloud scenario with $n_s = 1000\,\mathrm{cm}^{-3}$ and $d_s = 25\,\mu$m (typical for cumulus humilis and cumulus mediocris, Lohmann et al., 2016), corresponding to a liquid water content of approximately $8\,\mathrm{g\,m}^{-3}$, we obtain a speckle parameter $G \approx 0.06 \ll 1$ for SmHOLIMO. For HOLIMO, with a larger sample depth ($L = 20\,$cm), the calculated value is $G \approx 0.24$, which is still well below the usability limit, given by Meng et al. (1993).

We added sentences in lines 223-226: *Additionally, reconstruction quality in in-line holography decreases at higher hydrometeor concentrations due to speckle formation on the hologram. Following the approach of Meng et al. (1993) and assuming a mean particle diameter of* $20\,\mu$m*, SmHOLIMO and HOLIMO can reliably detect number concentrations up to* $25.800\,\mathrm{cm}^{-3}$ *and* $6.450\,\mathrm{cm}^{-3}$*, respectively.*

3. Regarding Figure 5- Comparing SmHOLIMO to HOLIMO: It is unlikely that both instruments will measure all the droplets in their smallest size ranges. Therefore, in the 6–10 micron range, SmHOLIMO is expected to detect more droplets than HOLIMO. But It is surprising to see that concentration in this range for HOLIMO matches or in some cases is larger than that of SmHOLIMO. It looks like the bins are not the same for both instruments. Is this an artifact of the bin sizes? Showing both plots with identical bins would provide a clearer one-to-one comparison. Similarly, the particles in the smallest bins for SmHOLIMO are likely to be undercounted. A comparison with a forward scattering probe can be useful for the future, although forward scattering probes have their limitations in terms of sizing and particle counts as well.

Yes, this observation is correct. In the smallest size bin, droplets are likely undercounted, and therefore, we interpret results from this bin with caution.

We believe that the main discrepancies in the CDSD between SmHOLIMO and HOLIMO on that day primarily result from an unfortunate mounting of SmHOLIMO. Specifically, SmHOLIMO was installed with the sampling volume on top and the electronics housing below. Since the horizontal wind speed on that day ($\approx 2\,\mathrm{m\,s}^{-1}$) was comparable to the vertical descent speed of the balloon ($\approx 1.5\,\mathrm{m\,s}^{-1}$) the aspiration direction was roughly from 30 ° below. This led to non-isokinetic sampling of hydrometeors—an issue that could have been avoided by rotating SmHOLIMO by 90 °.

To address this, we introduced two hypotheses into our discussion: (1) SmHOLIMO potentially undercounts droplets due to airflow blockage from below, and (2) HOLIMO might incorrectly size some smaller droplets. The second hypothesis was suggested by referee #1, and we have incorporated the second hypothesis into our discussion and also refer to our previous response to Referee #1 in Section: Major Comments.

Additionally, your point regarding bin sizes is valid. This arises from the fact that we measure discrete droplet sizes due to the finite pixel resolution, and the bin sizes account for this effect. Since SmHOLIMO has smaller pixels, its resulting size bins are more narrowly spaced, making a direct comparison with similar-sized bins challenging.

We changed the sentence in line 257-259: *"For the descending profiles, i.e. P4 and P18, we observe a deviation between the CDSDs measured by SmHOLIMO and HOLIMO, with SmHOLIMO measuring lower concentrations of larger cloud droplets and HOLIMO measures higher concentrations of small droplets especially between the cloud center and cloud base region (e.g., Fig. 5k, m, o, q, u)."*

We added sentence in lines 266-274: *"Another hypothesis is that, in the lower cloud and cloud base regions, some of the smaller cloud droplets may have been incorrectly sized by HOLIMO due to resolution limit effects, causing them to be assigned to a larger size bin, e.g., Fig. 5q and u. This feature persists across all cloud base region CDSDs (Figs. 5s to v), where HOLIMO generally measures higher concentrations in the smallest size bin compared to SmHOLIMO. However, as noted earlier, measurements in the smallest size bin should be interpreted with caution. Since the descending profiles are not trustworthy, we will discard them from the following analysis and focus on the data from ascending profiles only. To better assess the source of this discrepancy we conducted an intercomparison campaign at Mt. Sonnblick Observatory, Austria, between SmHOLIMO, HOLIMO and a fog monitor (FM-120, Droplet Measurement Techniques, USA). The data is currently being analyzed."*

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