Interactive comment on "HoloGondel: in-situ cloud observations on a cable car in the Swiss Alps using a holographic imager" by Alexander Beck et al.

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We thank Darrel Baumgardner for his valuable comments and suggestions. This reply is structured in the following way. First, we repeat the question or the comment of the reviewer. In case of a comment in the annotated manuscript we also mention the page and line. The response is in bold and possible changes in the manuscript are in blue with the page and line where the changes are made.

1) It is mentioned that there is a link between background noise and number concentration. What is the maximum concentration that is practical to measure?

The noise of the hologram increases with the number of particles in the sample volume due to particle-particle scattering and reference wave distortion. Following the argumentation of Beals et al. (2015) the noise begins to noticeable increase if the projected area of all the particles in the sample volume exceeds 1% of the hologram area. Therefore, the particle number concentration for which a noticeable increase in noise is expected is given by $n = 4f/\pi d^2 l$, where f is the fraction of the hologram area covered by particles, d is the mean particle diameter and l the length of the sample volume. For a mean droplet diameter of 10 µm, this increase is expected for a number concentration larger than 500 cm^{-3}. We also included this explanation in the discussion section of the revised manuscript.

p. 12 line 29: With an increasing number of particles in the sample volume the noise level is expected to increase due to particle-particle scattering and reference wave distortion. Following the argumentation of Beals et al. (2015), the noise begins to noticeable increase if the projected area of all the particles in the sample volume exceeds 1% of the hologram area. Therefore, the particle number concentration for which a noticeable increase in noise is expected is given by

$$n = 4f/\pi d2l \qquad (9)$$

where f is the fraction of the hologram covered by particles, d is the mean particle diameter and l the length of the sample volume. For a mean droplet diameter of 10 µm this increase is expected for a number concentration larger than 500 cm^{-3}. Manual inspection by eye of cloud particles classified as cloud droplets by the HOLOSuite software has shown that HOLIMO 3G is capable of reliably observing cloud droplets starting at a size of 6.2 µm for the run at 13:51 on 23 February 2016, when the CDNC is close to 400 cm^{-3}. This is in agreement with these theoretical considerations.

2) Droplets and ice crystals melting on the heated windows may leave residue, particularly if there is ambient pollution from wood fire burning or BC from diesel generators producing the electricity.

This is correct. Residues from droplets and ice crystals melting on the heated windows increase the background over time. The residues on the window and other optical components of HOLIMO 3G are stationary background. Although this stationary background is removed with a background division by the median intensity of sequential holograms (Fugal et al., 2009) , the residues decrease the local intensity of the illumination, which results in a decreased signal-to-noise ratio. Therefore the windows were regularly cleaned.

3) What limits the spatial resolution that can be measured between drops/xtals?

In general, the spatial resolution in x and y direction (see Fig. 3 in the manuscript) is only limited by the size of the pixels and is similar to the resolution limit of the instrument (6.2 µm). For the z direction the limitation is the reconstruction distance, i.e. the distance between two reconstructed images. For the data analysis in the presented manuscript this value was set to 100 µm. Because the entire volume taken up by the cloud droplets and ice crystals is much smaller than the sample volume (on the order of 0.002% for a CDNC of 100 cm^{-3} and 15 µm of diameter) and the mean distance between the particles is large compared to their size (on the order of 1 mm for a CDNC of 100 cm^{-3}), the spatial resolution is high enough to separate the cloud particles. However, large cloud droplets and ice crystals strongly increase the background noise in surrounding pixels and reconstruction planes. Therefore, small particles may be missed in the neighborhood of large droplets and ice crystals.

4) How long does it take to process a single hologram?

The reconstruction of a single hologram requires approximately 4h on a single CPU. Using multiple CPU on a computer cluster we can process up to 5000 holograms a day.

5) Long term measurements are mentioned but where do the thousands if not millions of terabytes get stored?

HOLOGondel records data only during runs of the cable car. The duration of one run of the Eggishorn cable car is approximately 200 s with up to 20 runs a day. With a maximum acquisition speed of 180 MB/s this results in 36 GB of data for a single run. To reduce the amount of data recorded with HoloGondel data is only recorder during cloudy conditions. From the campaign 2015 at the Eggishorn, which lasted for 60 days, 20 TB of data were collected, which is still a feasible amount to be stored on a Network Attached Storage (NAS) system.

6) p.1 line 15: "*The role of clouds remains a large source of uncertainty in climate and weather models (Flato et al., 2013), because our level of understanding of clouds is still limited*." This is overstated. Our understanding is very good for some types of clouds. I would be more specific and say that probably mixed phased clouds the least well known.

The sentence is slightly changed in the revised manuscript.

p. 1 line 15: The role of clouds remains a large source of uncertainty in climate and weather models (Flato et al., 2013), because our level of understanding in particular of mixed-phase clouds is still low.

7) p. 1 line 23: I would strongly recommend rewriting this section. I don't think that the cable car approach needs to be justified with respect to aircraft or tethersonde measurements. It should only

be compared to mountaintop laboratories like Stormpeak, Elk Mountain, Jungfraujoch and Zugspitze since they are the ones comparable to the cable car approach but they are fixed whereas the cable car isn't.

It was not the intention of the authors to justify the approach of the HoloGondel platform in this section. This section summarizes the advantages and disadvantages of different measurement strategies (aircraft, tethered balloon, ground-based). The HoloGondel platform is integrated in this set of strategies with its own advantages and disadvantages. In fact, the HoloGondel platform has to be seen as an additional strategy with the opportunity to measure at locations where other strategies can't sample. We rewrote parts of the introduction to support this intention.

p. 3 line 4: Mounting the HoloGondel platform on a cable car enables acquisition of vertical profiles in complex alpine terrain. This is a major step forward compared to single point measurements conducted at mountain top research stations and HoloGondel can easily be mounted on cable cars at other locations. (…) The combined observations of vertical profiles of the phase-resolved particle size distribution and the spatial distribution of cloud particles with the meteorological parameters on the HoloGondel platform can enrich the already existing and comprehensive observations of cloud parameters with aircrafts, tethered balloons and at mountain top research stations and help to improve our understanding of clouds.

8) p. 2 line 4: "*In addition, the high traveling speed of an aircraft causes ice shattering on the tips of the instruments (Baumgardner et al., 2012).*" - There are better references, more direct like the Korolev papers.

The reference has been replaced with the following references:

Korolev and Coauthors, 2011: Small ice particle observations in tropospheric clouds: Fact or artifact? Airborne Icing Instrumentation Evaluation Experiment. B. Am. Meteo. Soc., 92, 967–973.

A. V. Korolev, E. F. Emery, J. W. Strapp, S. G. Cober, and G. A. Isaac, 2013: Quantification of the Effects of Shattering on Airborne Ice Particle Measurements. J. Atmos. Ocean. Tech., 30, 2527–2553.

9) p.3 line 5: "*The portable design of the HoloGondel platform, unlike a tethered balloon system, enables easy shifts between different cable cars at different locations.*" - I don't understand. Tethersondes can be launched anywhere. Best not to even make this comparison. Again I emphasize that it is not necessary to continue justifying the technique. Good measurements with interesting results are enough to speak for themselves.

This sentence was changed in the revised manuscript (See also answer to comment 7)).

10) p.3 line 13: *"These observations suggest that a surface-based ice multiplication process is active to produce the large ICNCs (Rogers and Vali, 1987; Geerts et al., 2015; Lloyd et al., 2015; Farrington et al., 2015)."* - I don't understand what this means. The only "surface-based" ice multiplication would be blowing snow. Is this what the author means?

Possible surface-based ice multiplication processes include blowing snow and hoar frost, which was recently suggested by Farrington et al. (2015). The sentence was changed to emphasize the authors intention.

p. 3 line 13: These observations suggest that a surface-based ice multiplication process like blowing snow (Rogers and Vali, 1987; Geerts et al., 2015) or hoar frost (Lloyd et al., 2015; Farrington et al., 2015) is active to produce the large ICNCs.

11) p.5 line 27: *"Following the considerations in Henneberger (2013a) the threshold to differentiate between cloud droplets and ice crystals was set to 25 µm, which corresponds to 8 times the pixel size."* – Below it says resolution is 6.2 µm. Hence 25 µm would be only 4 times.

The pixel size of the sensor is 5.5 µm. With a 1.8 times magnifying lens system the effective pixel size on the image side is 3.1 µm. To ensure a reliable detection the smallest object size is set to 6.2 µm, which is two times the effective pixel size and corresponds to the resolution limit of the instrument of 6.2 µm. The minimal size to distinguish between a cloud droplet and an ice crystal was set to 25 µm, which is about 8 times the effective pixel size. We have made the following changes in the manuscript to make this statement clearer:

p.5 line 25: Cloud droplets larger than 6.2 µm can be observed with HOLIMO 3G, which is approximately two times the effective pixel size of 3.1 µm. To separate cloud droplets from ice crystals based on the shape of the particle, a picture of at least eight pixels is needed. Following the considerations in Henneberger (2013) the threshold to differentiate between cloud droplets and ice crystals was set to 25 µm, which corresponds to 8 times the effective pixel size of the camera sensor.

p.7 line 2: One limitation is imposed by the pixel size of the camera (Dpixel) and the magnification of the lens system (M)

$$D_{res,pixel} = 2D_{pixel} / M = 2 * D_{pixel,eff} , \quad (1)$$

where $D_{pixel,eff}$ is the effective pixel size on the image side of the system.

12) p.6 line 13: *"The windows are made of sapphire because of its high heat conductivity compared to the standard N-BK7 glass and are heated to prevent freezing and to evaporate cloud particles stuck to the window."* - Evaporating water droplets and ice crystals leave a residue. How does this residue affect laser transmission and image reception? What is the impact of the emissions from the diesel generators that are used to provide the electricity for the cable car?

See answer to comment number 2).

13) p.6 line 28: "*For the smaller sample volume of 17 cm^3 and a droplet concentration on the order of 100 cm^{-3}), the Poisson counting error is less than 3%."* - I calculate 0.3%. sqrt(1700)/1700.

The authors have recalculated the value and sqrt(1700)/1700 = 0.024 which corresponds to 2.4%. Therefore, this value was not changed in the manuscript. However, the calculated values for the fewer ice crystals were wrong and have been corrected in the revised manuscript.

p. 6 line 27: For the smaller sample volume of 17 cm^3 and a droplet concentration on the order of 100 cm^3, the Poisson counting error is less than 3%. However, for the smaller ice crystals concentration on the order of 100 L^{-1} the Poisson counting error yields 73% for the small sample volume of a single hologram. Therefore, at least 50 holograms were grouped together to decrease

the Poisson counting error for the ice crystals to a value below 11% and below 1% for the cloud droplets.

14) p.10 line 5: "*Although the background in a hologram increases at such high number concentrations manual inspection of the classified particles has shown that the algorithm is still capable to reliably distinguish between artifacts and cloud droplets.*" - Does this mean that there is an upper threshold of concentration that limits the measurements?

See answer to comment number 1).

15) p.11 line 6: "*It is important to mention that the cable car is above the ski slope during its ride and the production of artificial snow with snow canons can be a possible explanation for the high variability in the ICNC.*" - Are there records that will show where and when these were in operation?

Yes, the operator of the cable car keeps records of the operation of the snow canons. The information is accessible and will be used in future studies.

16) p.12 line 1: This should be shown quantitatively, i.e. a frequency distribution of the inter-arrival times compared with the one that would be predicted from the measured concentration.

An inter-arrival time analysis is not possible with a holographic instrument, because an entire sample volume is recorded simultaneously and not single particles. However, a nearest neighbor analysis has been performed and the calculated average distance has been compared to the theoretical value for a random distribution. The following sentences have been added to the revised manuscript.

p. 11 line 34: **A unique feature of holography is the information about the spatial distribution of the cloud particles within the sample volume (Fig. 11). The randomness of the spatial distribution of the cloud particles has been tested using nearest neighbour analysis. The measured mean inter-particle distance is compared to the theoretical mean inter-particle distance for a random distribution (citation Hertz 1909)**

$$< r_{random} > = 0.554\ \frac{1}{\sqrt[3]{n}} \qquad (6)$$

where n is the particle concentration in the volume. If the ratio

$$R = \frac{<r>}{<r_{random}>} \qquad (7)$$

is equal to one, the particles are randomly distributed in the volume. The larger the deviation of the ratio R from 1 to smaller values, the stronger are the particles clustered within in the observed volume.

The presented examples are from the run at 9:31. The spatial distribution on top of Fig. 11 represents a cloud at an altitude of 2600m with a ICNC of 605 L^{-1} and a CDNC of 118 cm^{-3}. For the cloud droplets the ratio R is equal to 1.033, whereas it is much smaller for the ice crystals and was calculated as R = 0.65. This suggests, that the cloud droplets are distributed randomly within the sample volume, whereas the ice crystals are clustered. This reflects the high variability of the ICNC compared to the CDNC discussed above. The spatial distribution on the bottom of Fig. 11 was

taken at an altitude of 2300m with smaller ice crystal (< 50 cm^{-3}) and cloud droplet (< 50 cm^{-3}) number concentrations. This is in the region of the cloud base and the cloud volume is strongly diluted and filamented possibly due to turbulent mixing with clear air as it was also observed in Beals et al. (2015). This observation is reflected in a small value of R of 0.51. Because only a single ice crystal was observed in this hologram the nearest neighbour analysis was not possible for the ice crystals.

17) p.12 line 9: *"As described in section 2 the wind measurements of the 3D Sonic Anemometer have to be corrected for movement of the cable car."* - This is a 3D anemometer. Are vertical velocities not shown because of interference from the gondola?

Vertical wind speeds are not shown, because of the larger uncertainty of the altitude measurement with the GPS sensor.

18) p12. Line 25: *"Given that the measured temperature difference is less than the saturated adiabatic lapse rate suggests that the air was absolutely stable somewhere along the ride."* - This sentence is not complete, or needs rewriting.

This sentence was rewritten and will be in the revised manuscript as follows:

p. 12 line 25: This is less than the saturated adiabatic lapse rate, suggesting that the air was absolutely stable stratified over this layer.

19) p.12 line 28: *"Laboratory measurements with the HOLIMO 3G instrument have shown its capability to resolve spherical particles larger than 6.2 μm (Fig. 4)."* - This conflicts with an earlier statement that sphericity can't be resolved below 25 μm.

This is correct. For particles smaller 25 μm the shape cannot be resolved. Therefore, the word "spherical" **was deleted in the revised manuscript. All particles smaller than 25 μm are assumed to be liquid droplets. See also answer to comment 11).**

20) p.13 line 12: *"As described in the work of Beals et al. (2015), the investigation of local inhomogeneities in the spatial distribution of cloud droplets and ice crystals on a centimeter scale as well as the droplet size distribution of single holograms is possible with this unique feature of holography."* - I don't understand why it isn't possible to resolve at smaller scales. Also p.15 line 5: Why not shorter scales?

It is possible to resolve the spatial distribution of the particles at smaller scales (see answer to comment 3). Because the expected mean distance between the particles is on the order of millimeters, the scale has been changed in the entire manuscript to millimeters.

21) p.13 line 29: *"Because the height above the surface of the cable car is not constant during a run of the cable car…"* Height of what? This isn't clear.

For more clarity this sentence was rewritten:

p. 13 line 29: As the height above the surface is not constant during a run of the cable car, the dependency of the microphysical parameters on the distance above the surface is an additional point of interest for further studies.

22) p.14 line 4: *"To be able to recharge the battery the cable car cabin with the HoloGondel platform on top has to be in the lower station and it is desirable that the operator of the cable car recharges the batteries because this way the user of the HoloGondel platform does not have to be present during the entire field campaign."* Re-write for clarity in more than one sentence.

For more clarity this sentence was rewritten:

p. 14 line 4: To recharge the battery overnight, the cable car cabin with HoloGondel has to be in the lower station. This is not automatically the case and has to be taken care of by the operators of the cable car.

23) General comments of the reviewer on the spelling and grammar.

The authors thank for the comments on the spelling and grammar and have corrected them accordingly.

References used in the reply to the reviewers comments:

Beals, M. J., Fugal, J. P., Shaw, R. a., Lu, J., Spuler, S. M., and Stith, J. L.: Holographic measurements of inhomogeneous cloud mixing at the centimeter scale, Science, 350, 87–90, doi:10.1126/science.aab0751, 2015.

Fugal, J. P., Schulz, T. J., and Shaw, R. A.: Practical methods for automated reconstruction and characterization of particles in digital in-line holograms, Measurement Science and Technology, 20, 075 501, 2009

Farrington, R. J., Connolly, P. J., Lloyd, G., Bower, K. N., Flynn, M. J., Gallagher, M. W., Field, P. R., Dearden, C., and Choularton, T. W.: Comparing model and measured ice crystal concentrations in orographic clouds during the INUPIAQ campaign, Atmospheric Chemistry and Physics Discussions, 15, 25 647–25 694, doi:10.5194/acpd-15-25647-2015, 2015.