Authors' Response to the Anonymous Referee #2

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We are grateful to the Referee #2 for the insightful comments and suggestions on our manuscript. We respond to them in detail below. The original review is given in black, our anwers in blue. The responses mention also specific corrections which were applied to the manuscript.

General comments

Would it be possible to use the shadowgraph system to obtain some 3D information about the position of the cloud droplets?

Unfortunately, the diameter-dependent sample volume is generally too small to obtain the information about the 3D arrangement of the droplets in a typical atmospheric cloud. For instance, in Fig. 5. one can see the DOF for the droplet of a diameter 20 μm is about 200 μm (twice the z_{max}). Multiplied by the FOV (see Table 1) it results in the SV of about 5.90, 1.50 and 0.35 mm^3, for magnifications x1, x2 and x4, respectively. Even if the concentration was 1000 cm^{-3} and all the droplets had 20 μm, we would expect on average around 5.9, 1.5 or 0.35 counts per frame, respectively. For smaller diameters, the DOF and hence the SV as well as the expected counts per frame are accordingly much smaller. For the field measurement described in sec. 5, the concentrations were estimated to about 928 cm^{-3} and 798 cm^{-3}. During the first round with magnification x2, there were on average only 0.7 counts per frame. During the second round with magnification x4, there were on average only 0.08 counts per frame.

Another issue might be the shape of the SV resembling more a slice than a cube as the z-dimension is much smaller than x and y. On top of that, only the absolute value of z coordinate of a droplet is estimated. It is unknown, on which side of the focal plane the object is.

Could you give any estimate for the largest detectable number concentration? In case of large number concentrations, for example, it might be possible that droplets "hide" one after the other.

Due to the small slice-shaped SV, the problem of the largest detectable concentration is not relevant for typical atmospheric clouds. Similarly to the previous question, we may consider mono-dispersed droplets of a diameter 20 μm and concentration 1000 cm^{-3}. Then, the expected number in the single cylinder of a diameter 40 μm and the height equal to the DOF (around 200 μm) is only $2.5 \cdot 10^{-4}$. For smaller droplets, it would be accordingly smaller. Therefore, the coincidence of two droplets at similar (x, y) position seems highly improbable.

In the field measurements, there was on average even below 1 count per frame. The concentration in the plume used during the laboratory experiment was about two orders of magnitude larger which gave 18-54 counts per frame (depending on magnification). In the limited number of the inspected test images we did not spot coincidences. However, in the course of the longer measurement the images are not stored but processed in real time (see sec. 2.1) which makes the problem of coincidences hardly possible to verify afterwards.

On the other hand, what we observed during the laboratory experiment is that the dense plume filling the considerable space between the camera and the laser but outside the SV can influence the average brightness of the image. The thresholds implemented in the software adapt to the average brightness but still such shadow diminishes signal-to-noise ratio of individual particles as discussed for the magnification x1 in sec. 3.5. In our opinion, the effect is not significant in atmospheric clouds due to smaller concentration, hence limited scattering.

Concerning the application of the shadowgraph system in the atmospheric cloud (Section 5): Has there been any other cloud probe which measured the size distribution at the same time as the shadowgraph system? If so, could you present a comparison of the obtained droplet size distributions and its moments, respectively? If not, I would suggest, for a future study, to have a comparison to another cloud probe.

During two observational periods in July and August 2019, the size distribution was measured also by the Phase Doppler Interferometer (PDI). The two instruments, intentionally located side-by-side were not simultaneously operational in all the runs but we have data from overlapping periods. This data is still subject to processing and detailed analysis. In case of the PDI, the sample volume depends non-trivially not only on droplet size but also on the wind velocity, highly variable in the turbulent experimental conditions. Therefore, we are working on proper systematic comparison which considers those issues and shows some limitations of ground-base measurements with the instruments developed for high true air speeds. We intend to describe the details and submit it to the AMT as soon as the analysis and interpretation is finished.

Specific comments

1. Page 7, line 145-146: Looking on Fig. 1, I would think that the direction of the droplet flow was vertically aligned.

   Fig. 1. illustrates the components of the setup. The photograph was taken during another short test performed with the same instruments but different mounting of the pipe. It is neither analyzed nor discussed in the paper. During the measurements described in the paper, the outflow from the pipe was horizontally aligned. Unfortunately, no picture of this particular configuration is available.

   Appropriate explanation was added to the text in sec. 3.1:

   > The flow velocity was estimated to be of the order of $10\,\mathrm{cm\,s^{-1}}$ and the direction of the flow was aligned horizontally from left to right (i.e. the direction of the pipe exit was perpendicular to what is shown in Fig. 1).

2. Fig. 5c: For diameters larger than 30 µm, z_{max} deviates significantly from the analytical approximation z_{95}. Do you have any explanation for that?

   The discrepancy relates to the poor statistics of large droplets. Each point in the plot represents one diameter bin and shows the distance from the focal plane corresponding to the furthest detected droplet from that bin. Diameters larger than 30 µm are very scarce in the plume (see the size distribution in Fig. 7), so the number of detections is also small and they do not fill equally the entire sample volume. Therefore, it can happen that all of them randomly appear at the positions closer to the focal plane than the maximum possible distance z_{95}. For instance, in the case of the measurement with the magnification x4 presented in Fig. 5c, there were only 3 counts in the last bin and only 15 in the one before last. The sample volume decreases strongly with magnification implying the limited chance of detecting infrequent large droplets which explains why the effect is most pronounced for x4.

   We added a short comment to the text:

   > The discrepancy observed for largest sizes is related to the poor statistics, i.e. small number of counts of large droplets which are infrequent in the measured plume.

3. Fig. 7 and Fig. 15 and the corresponding text: In Fig. 7 only DSDs applying methods“def” and “ind” are shown, for given reasons. However, later in Fig. 15, DSDs for “def”,“cor” and “ind” are shown. Wouldn’t it make more sense, to show DSDs for methods“def”, “cor” and “ind” in Fig. 7 and explain that there are only small differences between methods “cor” and “ind” and then only show DSDs for “def” and “ind” in Fig. 15?

   We added the missing method to Fig. 7 and decided to keep all of them in Fig. 15 for consistency. The caption of Fig. 7 was modified accordingly.

4. Page 14, line 280: This gradual decrease from the center to the sides is obvious for x1, but not really for x2 and x4. Could you please comment on that?

   Our interpretation of the logarithmic plot given in the text was too simplistic. We changed the quantity presented in panels (a), (b) of Fig. 8 by normalizing $N_V(x)$ or $N_V(y)$ by the mean concentration to show the relative changes. After this correction it is clear the maximum is located left from the center.

   The corrected description reads:

   > Figure 8 in panels (a) and (b) shows normalized droplet concentration $N_V(x)/N_V$ and $N_V(y)/N_V$ suitably integrated over size and over other dimensions, divided by the total concentration in order to highlight the relative dependence on position inside the sample volume. The values mostly decrease gradually from the maximum (located left from the center) to the sides in case of horizontal direction and from the bottom to the top in case of vertical. The relative differences, except from very close to the edges, are of the order of 10 %. They are small enough to be possibly caused by the non-uniformities of the plume.

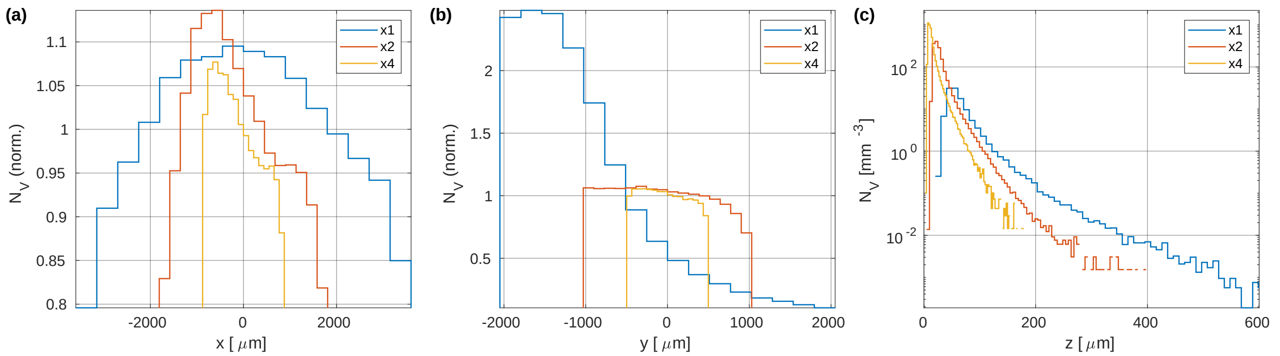

Figure 8 corrected. Dependence of droplet concentration on (a) horizontal, (b) vertical and (c) axial position.

5. Page 14, line 284-291: I think the speculation given here is reasonable. However, could this also be true for x2 and x4? But here more (smaller) droplets are detected, both in a smaller FOV compared to x1 which compensates this feature?

   As far as we understand, the reviewer suggests the suspected y-dependent concentration concerns large droplets regardless of the magnification setting used. This effect is then supposedly not clearly visible for x2 and x4 because of the dominant number of small droplets detected in a more uniform manner.

   We verified this claim to be true. The concentration $N_V(y)$ of the droplets larger than 12 μm only is indeed more y-dependent than the same quantity for the droplets smaller than 12 μm, in case of both magnifications x2 and x4. We cannot exclude the contribution of gravity sorting to that effect. However, the relative decrease of the $N_V(y)$ of large droplets from the bottom to the top is significantly smaller than over the same distance in case of the magnification x1.

   The exact influence of the non-uniform illumination on the results of DSD and DNC is hardly possible to be estimated with the available data. We emphasize the importance of precise alignment of the laser and camera lens positions. This is done manually, so the positioning can differ slightly between the experiments. As stated in the paper, achieving close to uniform illumination is much easier for magnifications x2 and x4 than x1 because of the smaller FOV to be fitted into the same laser beam.

   We modified the text:

   > The y-dependence of the concentration is more pronounced for large droplets above 12 μm (not shown) which might be the influence of gravity sorting. However, in case of the series recorded with lens setting x1, the concentration falls with height y by a factor of more than 10 from the bottom to the top of the FOV. We speculate this effect is of instrumental origin, as the difference is rather too large (almost exponential) and the timescale too short to allow for the explanation only by gravity sorting of the droplets in the plume.

6. Page 15, Line 318: Could you please provide a size range where you would not use x1. As later said, x1 makes sense for larger droplets in the drizzle and rain size range. Please make clearer under which circumstances you would avoid using x1, and vice versa.

   We estimated the minimum diameter for uniform detection to 12 μm so the magnification x1 is not recommended to measure any droplets smaller than that. Another limit, related to the issue of illumination, is not so precise because the image quality depends to some extent on the accuracy of manual alignment. In order to avoid poor signal-to-noise ratio we would suggest, as a rule of thumb, a diameter an order of magnitude larger than the effective pixel size which results in around 40 μm. On the other hand, the objects need to fit into the FOV, so the largest measured size should be a few times smaller than the shorter dimension (4.1 mm). Eventually, we expect the setting x1 to perform well in the range of roughly 40-400 μm. So far, we have not collected much data on drizzle to confirm this expectation experimentally. Nevertheless, in the sizing experiment (sec. 4) we had indeed no issues for 39.35 μm droplets but still some inaccuracies for 20.13 μm.

   We included this information in the text:

   > As a consequence, the authors discourage using lens setting x1 in further studies of cloud droplets. The large minimum particle size for uniform detection reported earlier ($\sim$12 μm) makes this option of limited utility anyway. Instead, x1 can possibly serve well for the measurements of drizzle drops. In order to avoid the illumination and signal-to-noise issue described above, we would suggest, as a rule of thumb, the lower limit an order of magnitude larger than the effective pixel size (3.69 μm). On the other hand, the objects need to fit into the FOV, so the largest measured size should be a few times smaller than the shorter dimension (4.1 mm) which eventually results in the conservative range of roughly 40-400 μm. Notwithstanding, so far insufficient data on drizzle has been collected to confirm this expectation experimentally.

7. Fig. 9 and respective text: Does the discrepancy in the first and second z-bin has any consequences on the calculation of the DSD and DNC?

   We consider the question relevant however cannot estimate the effect quantitatively based on the available data. In order to investigate this issue we increased the number of z-bins from 20 to 80 which implied the changes in Fig. 8c and Fig. 9. This operation allowed to identify a lower limit on the distance z and the probable reason for the discrepancy observed earlier - diffraction around the objects close to the focal plane. In the paragraphs added to the text we discuss the mechanism and speculate the influence on the DSD and the DNC within the valid size range is rather minor. In our opinion, one solution to systematically eliminate the problem would be to add the term representing diffraction to Eq. (1). This requires repeating the calibration procedure to obtain the correct new values of a_1 and a_2. At best, also implementing the corrected equation in the software processing routine.

   We corrected the interpretation of Fig. 8c:

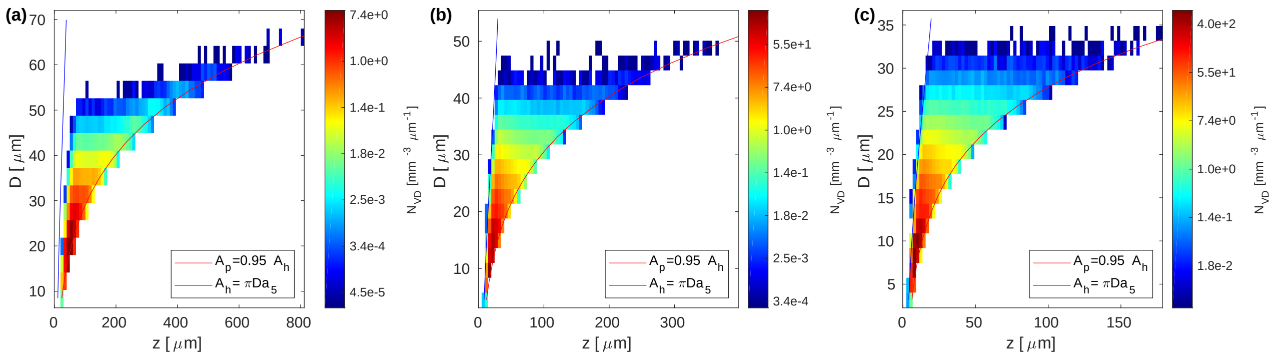

Figure 9 corrected. Variability of droplet detection properties in size-space domain for lens setting (a) x1, (b) x2, (c) x4.

Interestingly, the first z ranges contain a much smaller number of droplets than the maximum located further from the focal plane, regardless of the lens setting.

We added the paragraphs discussing the issue:

On the other side, the minimum distance z_{min} for a given diameter is well approximated by assuming the halo area in the focal plane equal to the diffraction term ($A_h = \pi D a_5$), analogously to Fig. 4, and solving Eq. (1) for z (blue line).

(...)

In experimental runs with higher magnifications, i.e. lens setting x2 and x4, the (z, D) map features the decrease of concentration with z from the maximum located a bit above z_{min}. The same effect was noticed in Fig. 8 panel (c). Most probably, it relates to the diffraction which is not included in the modeled dependence of the halo area A_h on the diameter D and distance z in Eq. (1). Namely, the equation is not correct in the limit of small z because it implies the object in the focal plane ($z = 0$) should be ideally sharp ($A_h = 0$). Consequently, in this limit the calculated z position is overestimated with respect to the true one. The counts representing droplets standing very close to the focal plane are shifted to the further z-bins in Fig. 9. The extent of this shift is probably not constant but decreases with the true z. Hence, the counts cumulate at some point above z_{min} creating a maximum in $N_V(z)$. We expect the shift to decrease because the calibration constants a_1 and a_2 were fitted by the manufacturer in the procedure resembling Kashdan et al. (2003) so that the Eq. (1) performs satisfactorily in the range of defocus distances and particle diameters typical for industrious applications, i.e. a bit larger than analysed here. Therefore, the estimated z should approach the true one with increasing defocus and droplet diameter.

The shift of the estimated z positions with respect to the true ones is most pronounced in case of the small distances from the focal plane. Importantly, it should have no effect on the accuracy of the sample volume calculation, hence the DNC and the DSD, as long as the z_{95} is not overestimated but represents the true distance at which the droplets are no longer counted. We expect this condition to be met if the largest possible defocus z_{95} is significantly higher than the smallest z_{min}. For instance, they differ by a factor of two for diameters larger than 8.0, 6.3, 4.8 μm in case of lens settings x1, x2 and x4, respectively. Those values are close to the minimum diameter for uniform detection estimated in sec. 3.4. It implies the influence on the DSD and the DNC within the valid size range is probably minor. However, we cannot quantify it with high confidence based on the available data.

Minor comments

1. Page 2, Line 50: I would suggest to write either "shadowgraphy" or "the shadowgraph technique".
2. Page 3, line 70: Please add "the" at the beginning of the sentence: "The two main parts[...]".
3. Page 6, line 120: Since "z" is a parameter it should be given in italic type font.
4. Page 7, line 137: Please write "[...] inverting Eqs. (1) and (2)".
5. Page 7, line 142: It should read "[...] in the range of 2-20 μm [...]".
6. Page 7, line 143-144: I would suggest to write: "Care was taken to fill [...]".
7. Page 8, line 169: Please add "DOF" in the brackets behind "(depth of field)".
8. Fig. 14: I would suggest increasing the size of the symbols in the figures here.

We agree with the minor comments and applied the specific corrections according to the reviewer's suggestions.

References

Kashdan, J. T., Shrimpton, J. S., and Whybrew, A.: Two-Phase Flow Characterization by Automated Digital Image Analysis. Part 1: Fundamental Principles and Calibration of the Technique, Particle & Particle Systems Characterization, 20, 387–397, https://doi.org/10.1002/ppsc.200300897, 2003.