Point-by-point response to the reviews

We thank D. Baumgardner and the anonymous referee for their detailed review and valuable comments. The manuscript has been modified according to the suggestions proposed by the reviewers and corresponding answers of the authors. The remainder is devoted to the specific response item-by-item of the reviewer's comments.

D. Baumgardner (Referee #1)

This study is a relatively detailed evaluation of the impact of diffraction on non-spherical particles passing through the laser beam of OAPs at varying distances from the center of focus (COF). The results do not differ from those published many years ago by Korolev. The primary difference is that the authors extend the Korolev results from spheres to columns and capped columns.

- **Response:** We agree that effects of diffraction on spherical particles were addressed in the literature for decades and size correction algorithms were proposed. Such corrections are possible, which is mostly due to the rotation symmetry of disks used to model diffraction patterns of spherical particles.

  Only few studies exist that are addressing diffraction on non-spherical particles, although such particles are of upmost importance in ice and mixed-phase clouds. As can be seen from experimental cloud data and numerical results presented in this study, diffraction patterns of non-spherical particles can be much more complex (Fig. 5, 6, 7) than diffraction patterns of disks (Fig. B1). This is a very important point, and indeed we do observe in real cloud data very frequently OAP images resembling those in Figs. 5–7. In our opinion, those images do need comprehensive investigations. A thorough study with the 50 % intensity threshold is a necessary step of such investigations especially since a large number of contemporary OAP instruments are using that threshold. This work is not dedicated to work out differences between binary and grayscale OAP devices, which is beyond the scope of this study but certainly worth a separate study to confirm or disprove, if grayscale option is a valuable means to remediate diffraction pattern failures of binary OAP probes.

In addition, the uncertainties in sizing that they derive are only marginally larger than have been published in many previous studies. This takes nothing away from the current study that provides more validation using comparisons with the most current state-of-the-art OAP.

- **Response:** To our knowledge, there exist no publications addressing in more detail OAP probe uncertainties in sizing caused by diffraction on non-spherical particles. Even if one may consider the uncertainties "marginally larger" than what is known from uncertainty calculations for spherical particles, this conclusion is new and based on the results of this work. Thus, our results can be used as a reference for the scientific community citing uncertainties of OAP probes for non-spherical small particles selected for this study.

I think that the paper could be significantly shortened by removing a lot of the detailed description of how the images become distorted but that is not a major distraction.

- **Response:** Spinning glass discs with opaque shapes imprinted on the surfaces became useful tools of laboratory tests addressing the performance of the 2D imaging probes. Our detailed comparison of simulations and measurement results for different non-spherical opaque planar objects confirmed good accuracy of that technique. Thus, we prefer not removing the paragraphs devoted to the distorted images.

On the other hand, the paper could be lengthened and strengthened by adding what I consider to be an obvious extension, i.e. adding the grayscale information. I realize that the OAP they were evaluating the model with does not have grayscale, nor do I expect them to extend the study by comparing with a grayscale. On the other hand, a number of the features that they show that are caused by a single threshold could be totally or partially mitigated by processing with more than a single threshold, such as can be currently done with the Cloud Imaging Probe

(CiP) with the grayscale option. As the authors are probably aware, there is another study in peer review in AMT that shows with laboratory studies that using the grayscale thresholds, the DOF can be much better defined. I think the current study would be especially powerful and complementary to the sister study in review on the grayscale.

- **Response:** We agree with the reviewer that a study based on the grayscale information is of considerable importance. Full grayscale diffraction patterns can be found in the videos accompanying this work. Using for example three levels of grayscale shadows with improved definition of the DOF and then studying uncertainties in sizing of non-spherical particles is a subject for future work, but not within the scope of this study.

I have attached an annotated pdf with some grammatical corrections.

- **Response:** We are grateful to D. Baumgardner for the series of suggested grammatical corrections. All of them are considered. The corresponding sentences are revised in the manuscript.

In Introduction (p. 2, l. 6): "[…] careful OAP image processing (e.g., Field et al., 2006; Korolev and Field, 2015) which aims to remove small particle fragments produced by shattering of larger ice crystals impacting on aircraft or probe surfaces (e.g., Gardiner and Hallett, 1985; Korolev and Isaac, 2005; Korolev et al., 2011; Field et al., 2017)." I don't think we have a way to remove aircraft shattered crystals. Would remove this.

- **Response:** We agree with the reviewer.
- **Manuscript modification:**
  - In Introduction (p. 2, l. 6): "[…] impacting on ~~aircraft or~~ probe surfaces [...]".

In Sect. 2.1 (p. 3, l. 16): "Despite the apparent differences, "the angular spectrum approach and the first Rayleigh–Sommerfeld solution yield identical predictions of diffracted fields" (Goodman, 1996, p. 61).". Identical or almost identical?

- **Response:** This sentence is from p. 61 of the book *Introduction to Fourier optics* by Goodman (1996). In our opinion, predictions are identical from point of view of the mathematics. Numerical implementations should give almost identical predictions. We prefer to keep the sentence exactly as it is written in the book.

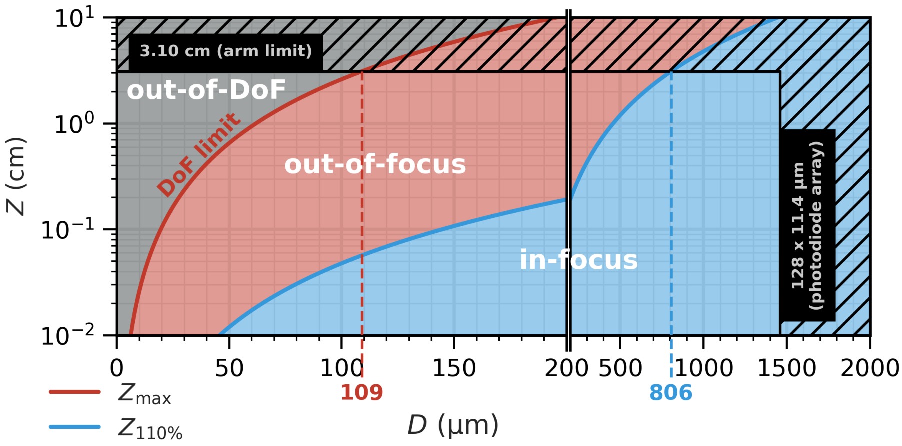
In Sect. 2.2 (p. 5, l. 7): "Thus, we can assume that a particle is illuminated by a monochromatic plane wave." How well collimated?

- **Response:** For information, the 2D-S has been completely checked by the probe manufacturer one month before performing the lab experiments with the spinning discs. In order to answer the reviewer's question on collimation quality, the following text has been added in the Conclusions.
- **Manuscript modification:**
  - In Conclusions (p. 17, l. 3–8): "The good agreement between the simulated and measured diffraction patterns (see Figs. 5, 6, 7, and B1) suggests that the laser beam of the used 2D-S probe is well collimated and the use of the plane-wave approximation is well founded. Future investigations, especially concerning grayscale thresholds, could take into account properties of the laser beam and the optical system. For example, the Angular Spectrum Theory was used in the work by Hayman et al. (2016) to simulate diffraction pattern of an opaque disc illuminated by an elliptical Gaussian beam, where an optical receiver point spread function was considered.".

Figure 4: Perhaps make the Y axis logarithmic?

- **Response:** We don't think that a logarithmic scale of *Z* in Fig. 4 improves readability. The main message is that particles up to 200 µm are in-focus only very close to the focal plane. Particles between 200 µm and 806 µm are increasingly observed in-focus with increasing distance *Z*. Particles between 109 and

200 µm are mainly out-of focus without reaching out-of-DoF at arm limits. For particles smaller 109 µm DoF is falling below arm limits. These messages do not suffer from a linear representation of Fig. 4.



Anonymous Referee #2

This manuscripts presents a series of diffraction simulations and laboratory calibrations designed to test the ability of optical array probes to accurately measure the size and shape of non-spherical ice particles. This topic is of interest to the community of OAP users and the work here is relevant and important to extending our understanding of probe response characteristics in ice. In my view, the most important findings are how differently the same particle can appear at different Z positions, which has implications for habit identification using OAPs (particularly in cirrus), and how particle size changes as a function of Z, which will affect the accuracy of size distributions due to uncertainties in both size and DoF. The writing, logic, and data presentation are all very good, and I do not have any serious reservations about this manuscript being published in AMT. A few minor considerations and comments are listed below.

P3, line 9: Spherical particles act as a lens which makes them largely opaque. Ice particles, however, often have flat surfaces that will allow significant light transmission through the particle. I think the assumption of opaqueness is OK for this manuscript, but it should be stated here that it will not always apply to real ice particles, and thus the simulations/calibrations and resulting measurements (such as D_eq) will have additional sources of error that are not captured in this experiment.

- **Response:** We agree with the reviewer that ice particles often allow light transmission and that additional errors could appear with real ice particles.
- **Manuscript modification:**
  - In Sect. 2.1 (p. 3, l. 4–7): "As a first approximation, it is convenient to neglect the refraction and transmission of light by the particle, i.e. considering the cloud particle as an opaque particle. It should be noted that ice particles which allow significant light transmission will have additional sources of error that are not captured in this experiment.".

P5, line 7: Was the divergence of the beam tested? OAP lasers are not perfectly collimated, which will affect the diffraction pattern and how it changes through the depth of field. Some other simulation-based experiments have considered this, e.g. Hayman et al. (JTECH 2016).

- **Response:** For information, the 2D-S has been completely checked by the probe manufacturer one month before performing the lab experiments with the spinning discs. In order to answer the reviewer's question on collimation quality, the following text has been added in the Conclusions.
- **Manuscript modification:**
  - In Conclusions (p. 17, l. 3–8): "The good agreement between the simulated and measured diffraction patterns (see Figs. 5, 6, 7, and B1) suggests that the laser beam of the used 2D-S probe is well collimated and the use of the plane-wave approximation is well founded. Future investigations, especially concerning grayscale thresholds, could take into account properties of the laser beam and the optical system. For example, the Angular Spectrum Theory was used in the work by Hayman et al. (2016) to simulate diffraction pattern of an opaque disc illuminated by an elliptical Gaussian beam, where an optical receiver point spread function was considered.".

P6, line 8: "perfectly seen" should be rephrased, smaller features will still be distorted in real-life situations.

- **Manuscript modification:**
  - In Sect. 2.2 (p. 6, l. 8–9): "Particles larger than 806 μm should be ~~perfectly seen~~imaged by the 2D-S~~,~~ without important distortion, since $Z_{110\%}$ > 3.1 cm for ~~that~~ sizes larger than 806 μm.".

P12, line 24: Defining the DoF limit in terms of D_eq or D_max here seems tricky. In practice, the measured diameter will be used to define DoF, rather than the actual diameter of the underlying particle, as is implied here.

Even though D_eq may give a better DoF estimate in this case, I suspect that the DoF limit is highly shape-dependent. Did the authors attempt to test non-spherical DoF for a wider variety shapes?

- **Response:** We are aware of the fact that current approaches for DoF estimations in the ice microphysics community are questionable. It is also true that the developed fast simulation method of diffraction patterns would allow an extended study of ice particle DoF topic for multiple non-spherical crystal shapes in order to decrease uncertainties in the current simplistic approach of DoF calculations. Actually, DoF calculations are imperfect since measured (used for DoF calculation) and real diameters deviate (Fig. 8). Also the community is applying DoF calculations, thereby using one and the same equation (per OAP instrument), independently of chosen diameter definition. Improving the actual knowledge of DoF calculation is beyond the scope of this study, but should be performed urgently in a proper study. We added an explicit sentence in section 3.2 in order to support the choice of D_{eq} for classical DoF calculation, without further correction/discussion.
- **Manuscript modification:**
  - In Sect. 3.2 (p. 12, l. 29–32): "For this particle, using the DoF limit estimations with D_{eq} would be closer to the DoF limit (Z = 1.8 cm) found from diffraction simulation. Moreover, as the uncertainty on D_{eq} for out-of-focus particle is relatively small (Table 2) compared to D_{max} (Fig. 8), it should be a relatively good option to estimate the DoF limit.".

P12, line 29: I'm not sure I understand what this sentence is referring to. The original diameter definition used to compute DoF can be found in Knollenberg 1970 (JAM).

- **Response:** We agree with the reviewer that this sentence is confusing. It has been rewritten as follows.
- **Manuscript modification:**
  - In Sect. 3.2 (p. 12, l. 32–33): "However, ~~the~~our arbitrary diameter definition used in the classical DoF limit calculation remains questionable, since ice particles are primarily non-spherical.".

P13, line 9: What was the equivalent air speed of the spinning disk? Was there any attempt to try the experiment at different speeds in order to test the effects of electronic response time?

- **Response:** The equivalent speed particles on the spinning disc is 9.5 m s^{-1}. In order to test the effects of electronic response time, higher equivalent air speeds are necessary. However, due to the smallness of the disc (limited by second pair of 2D-S arms) and associated mechanical limitations for the rotation speed, it was not possible to increase the rotation and corresponding particle speed of the test bench.
- **Manuscript modification:**
  - In Sect. 3.3 (p. 13, l. 12–15): "We simulate and measure 10 s of disc spinning at 108.6 ±0.2 rps (≈ 9.5 m s^{-1} in equivalent particle speed), which should result for each of the four short columns in about 19,500 images. 9.5 m s^{-1} already represents the maximum equivalent speed of particles on the rotating disc, which is small compared to aircraft speeds and therefore does not allow to study possible effects of electronic response time related to disc speed.".

P14, line 35: I think this is already done in some software packages, e.g. 'reacceptance' in McFarquhar et al 2017.

- **Response:** We agree with the reviewer. The corresponding paragraph was revised as follows.
- **Manuscript modification:**
  - In Sect. 3.3 (p. 15, l. 5–10): "This effect is particularly striking at Z = 3 cm~~. Thus, future algorithm developments should focus on reprocessing of particles separated into two images by the probe.~~ and is consistent with findings published in the literature. For example, fragmented diffraction patterns of spherical droplets traversing the sample area near the edges of the DoF were shown in the work by Korolev (2007); diffraction fringes around out-of-focus images measured by CIP were underscored by Korolev and Field (2015). 'Reacceptance' algorithms (see, e.g, Korolev and Field, 2015; McFarquhar et al., 2017a) should address rigorously the problem of intact, i.e not shattered, but fragmented particles."

Appendix A, line 20: What type of filter was applied to the image?

- **Response:** A low-pass filter is applied to the image in order to remove high-frequency aliasing noise. The cut-off frequency of the low-pass filter (f_c = 0.06 µm^{-1}) was chosen in order to minimize the root mean square deviation between the artifact-free image from MRM-based calculations and the image from AST-FFT. More details are provided in Vaillant de Guélis et al. (2019).

  – Vaillant de Guélis, T., Shcherbakov, V., and Schwarzenböck, A.: Diffraction patterns from opaque planar objects simulated with Maggi-Rubinowicz method and angular spectrum theory. Opt. Express, 27, 9372–9381, https://doi.org/10.1364/OE.27.009372, 2019.

- **Manuscript modification:**
  - In Sect. 2.1 (p. 3, l. 15–16): "In this study, we employed ~~another method~~the method proposed in Vaillant de Guélis et al. (2019), which is based on the Angular Spectrum Theory (AST; see Appendix A).".

Appendix C: I think this appendix is unnecessary. The minimum circle problem is well known and there are much more modern approaches to the problem (Welzl, etc.). It is also discussed in the context of OAP images in Wu and McFarquhar (JTECH, 2016).

- **Response:** We agree to withdraw Appendix C.
- **Manuscript modification:**
  - In Sect. 3.2 (p. 11, l. 19–20): "D_{max} is defined as the diameter of the smallest circle encompassing the particle image (e.g., Chrystal, 1885; Welzl, 1991; Heymsfield et al., 2013; Wu and McFarquhar, 2016~~see also Appendix C~~).".
  - Appendix C: Removed.