

1 **Characterising optical array particle imaging probes: implications**  
2 **for small ice crystal observations**

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20

21 **Abstract**

22 The cloud particle concentration, size and shape data from optical array probes (OAPs) are  
23 routinely used to parameterise cloud properties and constrain remote sensing retrievals. This  
24 paper characterises the optical response of OAPs using a combination of modelling, laboratory  
25 and field experiments. Significant uncertainties are found to exist with such probes for ice  
26 crystal measurements. We describe and test two independent methods to constrain a probe’s

1 sample volume that removes the most severely mis-sized particles: (1) greyscale image analysis  
2 and (2) co-location using stereoscopic imaging. These methods are tested using field  
3 measurements from three research flights in cirrus. For these cases, the new methodologies  
4 significantly improve agreement with a holographic imaging probe compared to conventional  
5 data processing protocols, either removing or significantly reducing the concentration of small  
6 ice crystals ( $<200\ \mu\text{m}$ ) in certain conditions. This work suggests that the observational evidence  
7 for a ubiquitous mode of small ice particles in ice clouds is likely due to a systematic instrument  
8 bias. Size distribution parameterisations based on OAP measurements need to be revisited using  
9 these improved methodologies.

10

## 11 **1 Introduction**

12 A significant amount of our current understanding of cloud microphysics is based on in-situ  
13 measurements made using Optical Array Probes (OAPs). This includes how cloud properties  
14 are parameterised in numerical climate/weather models and how they are retrieved from remote  
15 sensing datasets, including global cloud and precipitation monitoring satellites such as NASA's  
16 GPM (Global Precipitation Mission), CloudSat and CALIPSO (Cloud-Aerosol Lidar and  
17 Infrared Pathfinder Satellite Observation) (Mitchell et al., 2018; Sourdeval et al., 2018; Ekelund  
18 et al., 2020; Eriksson et al., 2020; Fontaine et al., 2020).

19 Optical array probes are a family of instruments that have been widely used by the cloud physics  
20 community for the last 40+ years. Primarily OAPs have been operated on research aircraft  
21 (Wendisch and Brenguier, 2013). They collect images of cloud particles and are used to derive  
22 cloud particle concentration, size and crystal habit (shape). Optical array probes operate by  
23 recording a shadow image as a particle crosses a laser beam that is illuminating a 1-D linear  
24 array of photodiode detectors. If the light intensity at any of the detectors drops below a  
25 threshold value, the probe records an image of the particle and the corresponding timestamp.  
26 A two-dimensional image of the particle is constructed by appending consecutive one  
27 dimensional "slices" from the array of detectors as the particle moves perpendicular to the laser  
28 beam due to the motion of air through the probe.

29 The rate at which data needs to be acquired from the detectors depends on the air speed through  
30 the probe and the required image resolution. For example, when operated on research aircraft  
31 at a typical airspeed of  $100\ \text{m s}^{-1}$  image slices from the detectors are acquired every  $0.1\ \mu\text{s}$  to  
32 achieve an image resolution of  $10\ \mu\text{m}$ . Modern OAPs have 64 to 128 element detector arrays

1 with pixel resolutions ranging from 10 to 200  $\mu\text{m}$ . Monoscale probes use a 50% drop in intensity  
2 as a threshold for detection which results in 1-bit binary images (Knollenberg, 1970; Lawson  
3 et al., 2006), while most greyscale OAPs have three intensity thresholds, which result in 2-bit  
4 grayscale images (Baumgardner et al., 2001).

5 When particles pass through the object plane of a probe they are in focus and accurate digitized  
6 images are recorded. When particles are offset from this plane the diffraction of light by the  
7 particle alters the size and shape of the recorded image from its original form. When the distance  
8 from the object plane ( $Z$ ) is sufficiently large the reduction in light intensity at the detector will  
9 no longer exceed the detection threshold. This distance is known as the probe's depth of field  
10 (DoF). For large particle sizes the DoF is constrained by the physical separation between the  
11 laser transmit and receive optics, which are in protruding structures referred to as "arms". The  
12 following equation is generally used to define the DoF of monoscale probes using a 50%  
13 intensity threshold for detection (Knollenberg, 1970)

$$14 \quad DoF = \pm \frac{cD_0^2}{4\lambda}$$

15 Equation 1

16 where  $D_0$  is the particle diameter and  $\lambda$  is the laser wavelength.  $c$  is a dimensionless constant,  
17 typically between 3 and 8 (Lawson et al., 2006; Gurganus & Lawson, 2018). The DoF is used  
18 to determine particle concentration, and as a result uncertainty in  $c$  propagates into uncertainty  
19 in the derived concentration. Particle concentration can be calculated by dividing the number  
20 of counts by the sample volume (SVol), which is given by,

$$21 \quad SVol = TAS \int_{-DoF}^{+DoF} (R(E - 1) - D_{||}D(Z)) dZ,$$

22 Equation 2

23 Where TAS is the true air speed,  $E$  is the number of detector array elements,  $R$  is the pixel size  
24 of the probe and  $D_{||}$  is the image diameter in the axes parallel to the optical array. The integration  
25 of the effective array width ( $\overline{ER(E-1)} - D_{||}(Z)$ ) is performed over whichever is smaller out of the  
26 DoF and the armwidth of the probe.

27 For spherical particles, corrections exist ~~which correct~~ for the diffraction effects of sampling  
28 offset from the object plane, which allows the calculation of the true particle size from the  
29 measured image size. Korolev et al. (1991) show that the diffraction from spherical liquid drops

1 can be approximated by the Fresnel diffraction from an opaque disk. The ratio of the measured  
2 image diameter to the true particle diameter is a function of the dimensionless distance from  
3 the object plane  $Z_d$ :

$$4 \quad Z_d = \frac{4\lambda Z}{D_0^2}$$

5 Equation 3

6 Korolev et al. (2007, hereafter K07) describes how the size of the bright spot at the centre of a  
7 diffraction image can be used to determine a sphere's distance from the object plane and  
8 therefore true size. O'Shea et al. (2019, hereafter O19) show that this correction is effective for  
9 modern OAPs up to approximately  $Z_d = 6$ , after which the images are too fragmented to reliably  
10 correct. O19 show that greyscale information can be used to remove these fragments by  
11 identifying the distance from the object plane of spherical particles in the range  $Z_d = 3.5$  to  $8.5$ .  
12 This allows a new DoF to be defined that excludes the fragmented images.

13 There has been significant discussion in the literature about the presence of high concentrations  
14 of small ice particles ( $< 200 \mu\text{m}$ ) observed by OAPs in cirrus and other types of ice clouds  
15 (Jensen et al., 2009; Korolev et al., 2011). O19 shows that fragmented images near the edge of  
16 the DoF have the potential to significantly bias OAP particle size distributions (PSDs) and result  
17 in an artificially high concentration of small particles.

18 This paper quantifies the uncertainties in OAP size and shape measurements of non-spherical  
19 ice crystals and presents corrections that removes large biases from OAP datasets. In Sect. 3.1,  
20 3-D ice crystal analogs are repetitively passed through the sample volume of an OAP at  
21 different distances from the object plane. These results are used to examine the ability of a  
22 diffraction model based on angular spectrum theory to characterise the response of OAPs. In  
23 Sections 3.2 to 3.5 a variety of ice crystals from commonly occurring habits are tested with the  
24 diffraction model to quantify how OAP image quality degrades throughout a probe's sample  
25 volume. Section 4 suggests and tests methods to improve OAP data quality. The impact these  
26 results have on ice crystal PSDs is examined using field measurements collected during three  
27 research flights in frontal cirrus. The impacts OAP measurement bias has on our understanding  
28 of ice cloud microphysics are discussed in Sect. 5.

29

## 1    2    **Methods**

### 2    2.1    **Optical array probes**

3    This paper uses data from two types of commercially available OAP: a CIP-15 (Cloud imaging  
4    probe, DMT Inc., USA; Baumgardner et al., 2001) and a 2D-S (2D stereo, SPEC Inc., USA;  
5    Lawson et al., 2006). The CIP-15 has a 64 element photodiode array and effective pixel size of  
6    15  $\mu\text{m}$ . The laboratory experiments were conducted with a CIP-15 with an arm separation of  
7    70 mm (Sect. 3.1) and the field measurements with a second CIP-15 with an arm separation of  
8    40 mm (Sect. 4.1). Images are recorded at three greyscale intensity thresholds. For this work  
9    they were set to the manufacturer default settings of 25%, 50% and 75%. The 2D-S consists of  
10   two optical arrays and lasers orientated at right angles to each other and the direction of motion  
11   of the particles/aircraft. The laser beams overlap at the centre of the probe's arms, and each pair  
12   of transmit/receive arms are separated by 63 mm. Each optical array has 128 elements and 10  
13    $\mu\text{m}$  pixel resolution. The 2D-S is a monoscale probe with a single 50% intensity detection  
14   threshold. Both probes are fitted with anti-shatter tips to minimise ice shattering on the leading  
15   edge of the probe during field measurements. This was further minimised by removing particles  
16   with inter-arrival times less than  $1 \times 10^{-5}$  s when calculating PSDs from field measurements  
17   (Field et al., 2006).

18   Baumgardner & Korolev (1997) show that the electronic time response of older probes can  
19   significantly reduce the DoF of small particles. This affect has been minimised in more modern  
20   probes such as the 2D-S and CIP-15, which have an order of magnitude faster time response.

21   A range of definitions have been used to define the diameter of ice crystals from OAP images.  
22   Here we test three metrics that have been widely used by the community. First, the mean of the  
23   particle extent along the axes parallel and perpendicular to the optical array (mean X-Y  
24   diameter). Second, the diameter calculated using  $D = (4A/\pi)^{1/2}$  where A is the particle area  
25   calculated as the sum of the pixels (circle equivalent diameter). Third the major axis length of  
26   the ellipse that has the same normalized second central moments as the region (maximum  
27   diameter).

28   An image frame from an OAP may contain more than one object, where individual objects are  
29   defined as collections of pixels with 8-neighbor connectivity. This can be due to diffraction,  
30   with a single particle appearing as more than one object as the structure and intensity of the  
31   transmitted light degrades due to poor focus. However, it may also be due to shattering causing

1 multiple particles to have sufficiently small separations that they are captured in the same image  
2 frame or occasionally when there are very high concentrations of ambient particles. A particle  
3 sizing metric can either relate to the largest object in an image frame or use the bounding box  
4 encompassing all objects. Some previous studies have filled any internal voids within objects  
5 in an image frame. For this work, unless otherwise stated both the mean X-Y, maximum and  
6 circle equivalent diameters are calculated using the bounding box encompassing all objects in  
7 an image frame and any internal voids are not filled.

8

## 9 **2.2 Ice crystal analogs**

10 Three-dimensional ice crystal analogs were grown from a sodium fluorosilicate solution  
11 (Ulanowski et al., 2003). These analogs have similar crystal habits to ice and a refractive index  
12 of 1.31, virtually identical to that for ice at visible wavelengths. Three rosette shapes were used  
13 in these experiments with approximate diameters 118  $\mu\text{m}$  (ROS118), 250  $\mu\text{m}$  (ROS250) and  
14 300  $\mu\text{m}$  (ROS300) (Fig. 1). The CIP-15 was mounted as shown in Fig. 2 so that the laser beam  
15 was vertically aligned. Each analog was in turn placed on an anti-reflective optical window that  
16 was attached to a 3-axis translation system that allowed the analog's 3D position to be  
17 controlled. The stages that moved along the axes parallel (X axis) to the diode array and laser  
18 beam (Z axis) each had a unidirectional position accuracy of 15  $\mu\text{m}$  and travel ranges of 100  
19 mm and 150 mm, respectively (X-LRM050A and Z-LRM150A, Zaber Technologies Inc,  
20 Canada). Movements along the axis that air flows through the probe under normal operation (Y  
21 axis) were made using a belt-driven stage with a maximum speed of 1.1  $\text{m s}^{-1}$ , positional  
22 accuracy of 200  $\mu\text{m}$  and maximum travel range of 70 mm (X-BLQ0070-EO1, Zaber  
23 Technologies Inc, Canada).

24 CIP-15 images of the ice crystal analogs were collected by moving them through the laser beam  
25 along the axis of airflow. For each analog this was repeated 5 times before its position was  
26 stepped in 0.5 mm increments between the probe's vertical arms (along the Z axis). This allows  
27 images of the analogs to be compared at different distances from the object plane.

28 Images were post-processed to take account of any difference in velocity between the stage and  
29 the CIP-15 data acquisition rate by resampling the images along the axis perpendicular to the  
30 optical array. This was performed to match the aspect ratio at  $Z=0$  of the CIP-15 image and a

1 microscope image of each analog. This typically corresponded to a particle stage velocity of ~  
2  $0.1 \text{ m s}^{-1}$ .

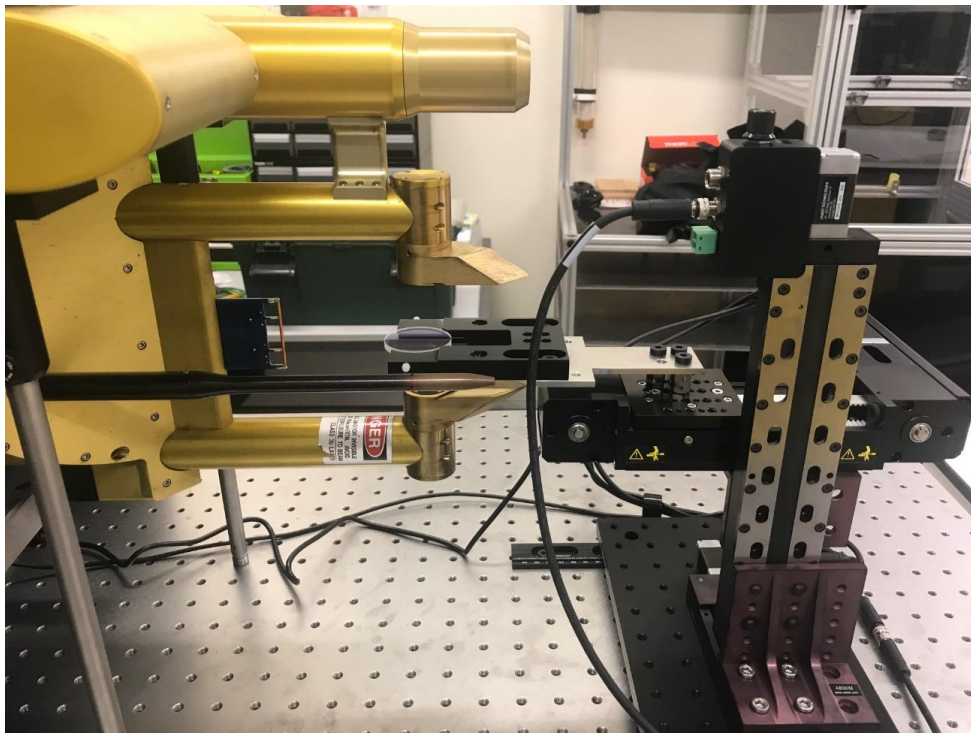
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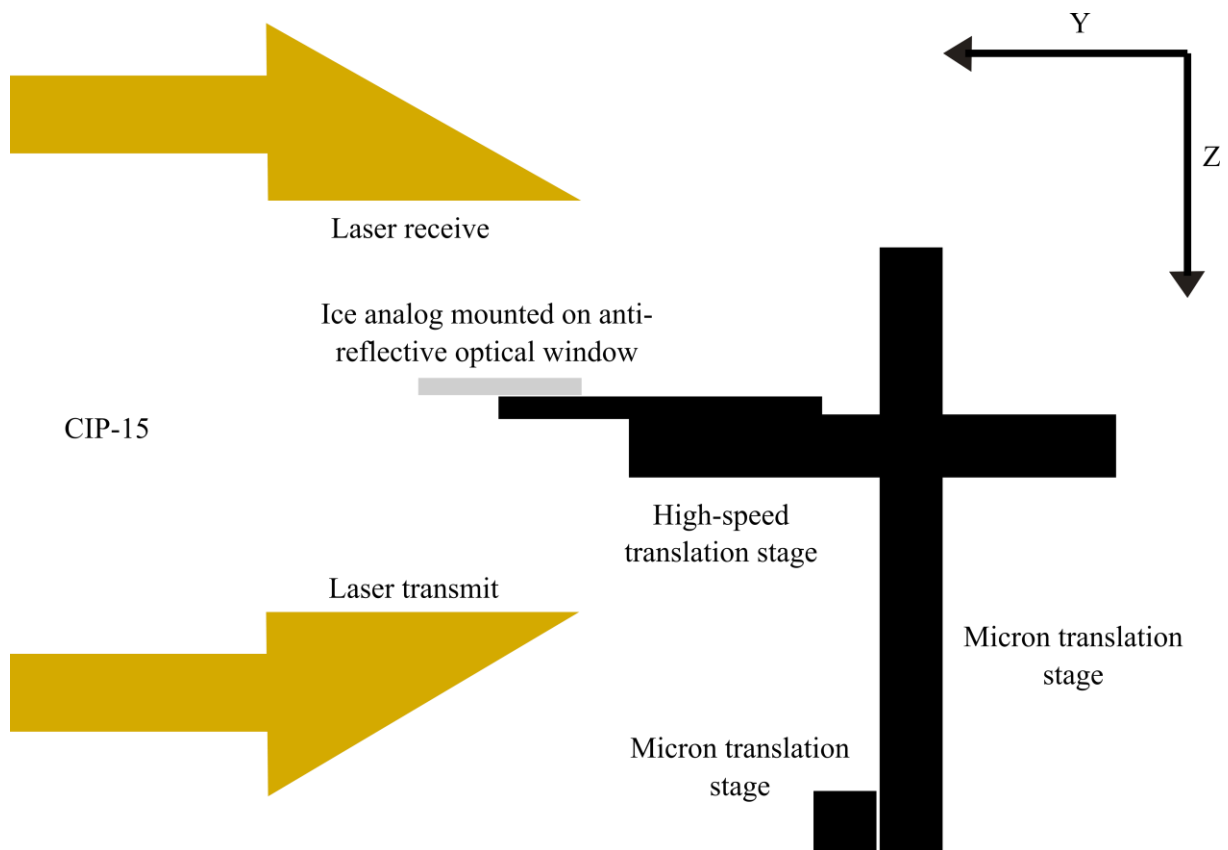
5 *Figure 1. Microscope images of sodium fluorosilicate crystals that were used as analogs for*  
6 *ice crystals. These are referred to as ROS118 (left), ROS250 (middle) and ROS300 (right).*

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1

2 *Figure 2. Top panel. Image of the experimental setup for the ice crystal analog tests of the CIP-*  
 3 *15. The bottom panel shows a schematic of the experimental set-up. The CIP-15 is horizontally*  
 4 *mounted on the left of the image. The translation stages used to move ice crystal analogs*  
 5 *through CIP-15 sample volume is shown on the right of the image. The X axes is perpendicular*  
 6 *to the plane of drawing.*

7

### 8 **2.3 Synthetic data (Angular spectrum theory)**

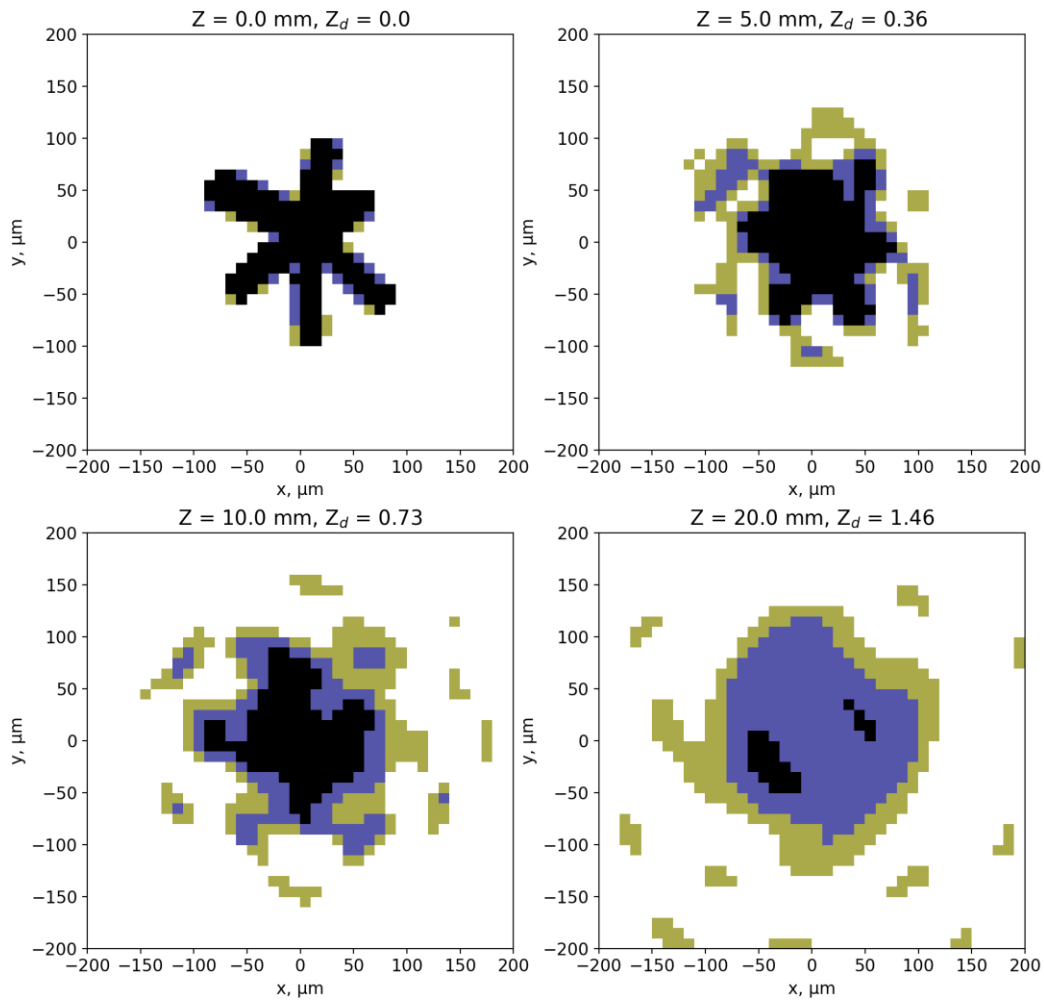
9 Theoretical shadow images of 2D non-spherical shapes were calculated using a diffraction  
 10 model based on Angular Spectrum Theory (referred to as the AST model). Several previous  
 11 studies describe this model in detail (Vaillant de Guélis et al., 2019a, 2019b). We initialised the  
 12 model using a 2-D binary image of an opaque shape at the object plane ( $Z = 0$ ) and calculate  
 13 the wave field for different positions between the probe arms in the Z axis. This model has been  
 14 shown to give good agreement with OAP images of several types of 2D rectangular columns  
 15 using images printed on a rotating disk (Vaillant de Guélis et al., 2019a).



1 In this study, we use a variety of different shapes to initialise the model. In Sect. 3.1, the  
2 diffraction model is compared to CIP15 images of 3D ice crystal analogs. To initialise the model  
3 for the comparisons with ROS250 and ROS300 the CIP-15 image of them at  $Z=0$  is used. Due  
4 to the smaller size of ROS118 and coarse pixel size of the CIP-15, a microscope image of the  
5 analog is used to initialize the model. This image converted to a binary image.

6 In Sect. 3.2 the quality of OAP images of commonly occurring ice crystal habits is explored.  
7 This is done by initialising the model with a variety of different ice crystal images. The ice  
8 crystal dataset contains 1060 images that were collected using a Cloud Particle Imager (CPI,  
9 SPEC Inc., USA) and has previously been used to train habit recognition algorithms  
10 (Lindqvist et al., 2012; O'Shea et al., 2016). It includes images of ice crystals from arctic,  
11 mid-latitude and tropical clouds. These images have been manually classified into 7 habits  
12 (rosette, column/bullet, plate, quasi-spherical, column-aggregate, rosette-aggregate and  
13 plate-aggregate). To initialise the model each CPI image was converted to a binary image.  
14 Shadow images were calculated every 2 mm for the range  $Z = 0$  to 100 mm. These images were  
15 averaged to 10  $\mu\text{m}$  pixel resolution, which is typical of modern OAPs. All simulations were  
16 performed using a light wavelength of 0.658  $\mu\text{m}$ .

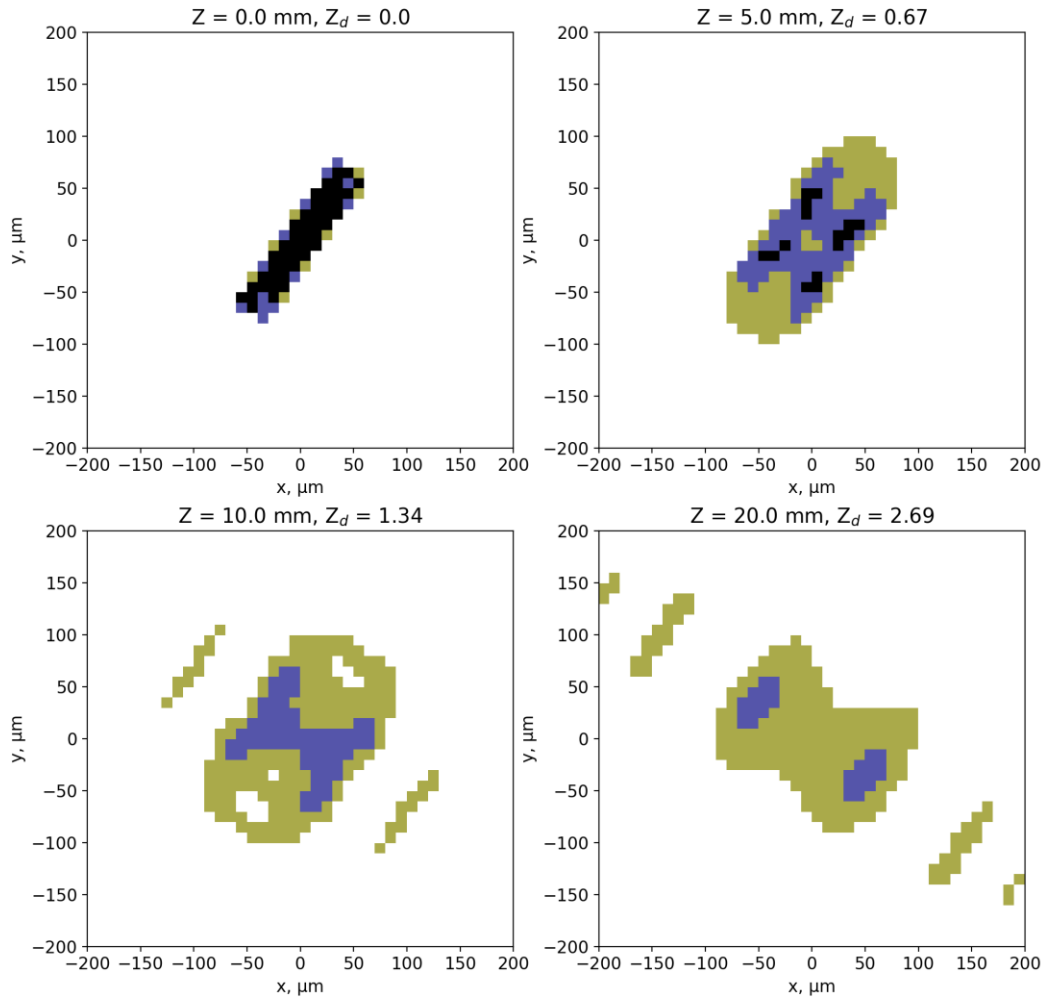
17 An example simulation for a rosette crystal is shown in Fig. 3 and a column in Fig. 4, the top  
18 left panels show the images at  $Z=0$  that are used to initialise the model. The other panels show  
19 images of the crystals at different distances from the object plane. Green, blue and black pixels  
20 correspond to decreases in detector intensity of 25 to 50%, 50 to 75% and  $> 75\%$ , respectively.  
21 Figures 3 and 4 show the rapid deterioration in image quality within a few mm of the object  
22 plane, which will impact derived properties such as particle size, number and habit. This  
23 compares to many 10s of mm for the typical arm separation of modern OAPs.



1

2 *Figure 3. Diffraction simulations from an image of a rosette crystal collected in cirrus cloud*  
 3 *using a CPI (see text for details). Top left panel show the image at  $Z=0$  that is used to initialise*  
 4 *the model. The other panels show images at different distances from the object plane ( $Z= 5, 10$*   
 5 *and  $20 \text{ mm}$ ). Green, blue and black pixels correspond to decreases in detector intensity of 25*  
 6 *to 50%, 50 to 75% and greater than 75%, respectively.*

7



1

2 *Figure 4. Same as Figure 3 but for a column.*

### 3 **2.4 Aircraft measurements**

4 This paper uses measurements from three flights by the FAAM Bae-146 research aircraft  
 5 sampling frontal cirrus in the UK on the 11 March 2015 (nominal flight number B895), 7  
 6 February 2018 (C078) and 23 April 2018 (C097). The first two flights have previously been  
 7 described in detail in by O’Shea et al. (2016) and O19. For all 3 flights the aircraft performed  
 8 straight and level runs of approximately 10 minutes at different temperatures within the cloud.  
 9 Ice crystals were dominated by rosettes, columns and aggregates. Data from a 2D-S is available  
 10 for the 11 March 2015 and CIP-15 for 7 February 2018 and 23 April 2018. On all flights the

1 FAAM BAe-146 was fitted with a holographic imaging probe (HALOHolo). HALOHolo has a  
2  $6576 \times 4384$  pixel CCD detector with an effective pixel size of  $2.95 \mu\text{m}$  and arm separation of  
3  $155 \text{ mm}$ . The probe acquires 6 frames per second, which equates to a volume sample rate of  
4  $\sim 230 \text{ cm}^3 \text{ s}^{-1}$ . The detection of small particles is limited by noise in the background image.  
5 Therefore, a minimum size threshold of  $35 \mu\text{m}$  is applied, above which it is estimated that the  
6 probe's detection rate is greater than 90% (Schlenczek, 2017). Shattered particles were  
7 minimised by removing all particles with inter particle distances less than  $10 \text{ mm}$  (Fugal &  
8 Shaw, 2009; O'Shea et al., 2016).

9 Section 4.2 shows a comparison between the 2D-S and a Cloud droplet probe (CDP, DMT Inc.)  
10 during a flight in liquid stratus on 17 August 2018 (C031). The CDP sizes particles ( $3$  to  $50$   
11  $\mu\text{m}$ ) using the scattered light intensity assuming Mie-scattering theory and spherical particles  
12 (Lance et al., 2010). The probe was calibrated during the campaign using glass spheres.

13

### 14 **3 Results & discussion**

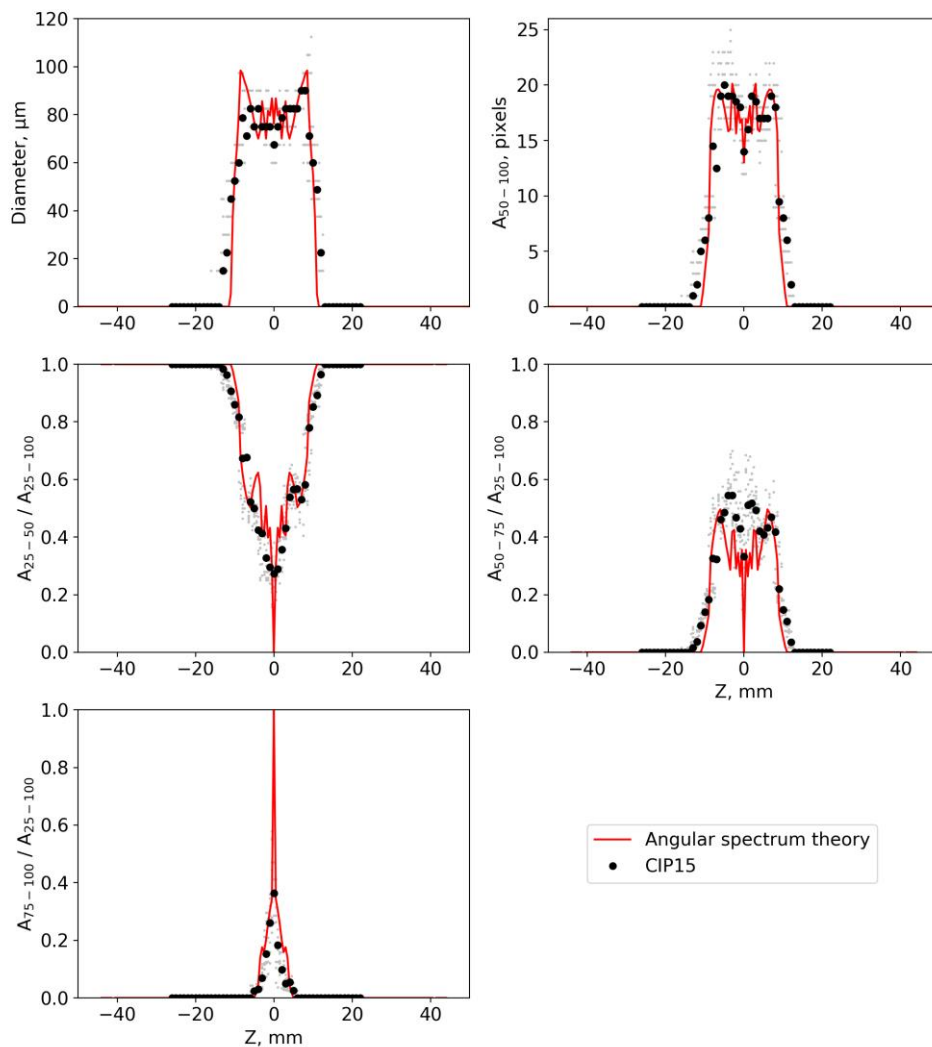
#### 15 **3.1 OAP and AST model comparison using ice crystal analogs**

16 This section compares CIP-15 images of ice crystal analogs with diffraction simulations using  
17 the AST model. Figures 5-7 show the image size of the ice crystal analogs ROS118, ROS250  
18 and ROS300 at different distances ( $Z$ ) from the object plane measured by the CIP-15 (black  
19 markers) and modelled using angular spectrum theory (red lines). Top left panels show the  
20 image diameter (mean X-Y), while the particle area is shown in the top right, both use a 50%  
21 drop in light intensity for the detection threshold. The other panels show different combinations  
22 of simple greyscale ratios. The abbreviations  $A_{25-50}$ ,  $A_{50-75}$  and  $A_{75-100}$  are used to denote the  
23 number of pixels associated with a decrease in detector signal of 25 – 50%, 50 – 75% and 75 –  
24 100%, respectively. Example CIP-15 images of the ice crystal analog ROS300 at 3 distance  
25 from the object plane are shown in Fig. 8.

26 All three analogs have a general trend of diameter initially increasing with  $Z$ . The full DoF was  
27 sampled for ROS118 and shows the images fragmenting and diameter decreasing near the edge  
28 of the DoF. In addition to these general trends there is a significant amount of fine scale  
29 structure that is specific to each sample. There is a general trend of the greyscale ratio  $A_{75-100}$   
30 decreasing with  $Z$ , while both  $A_{25-50}$  and  $A_{50-75}$  initially increase for all 3 analogs. Like the

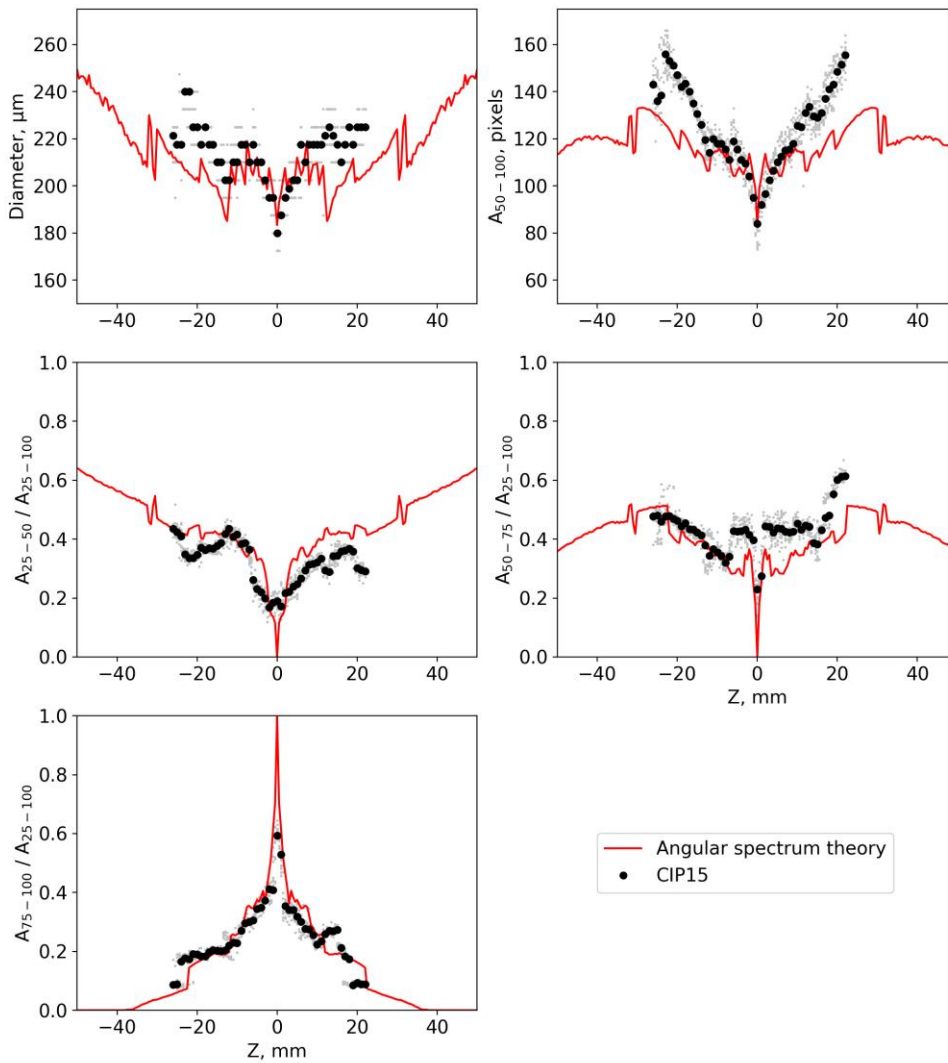
1 diameter vs Z plots there is a significant amount of fine scale structure overlaying these general  
2 trends.

3 In general, the AST model can capture the large-scale structure in these measured parameters,  
4 although some discrepancies are present in the finer detail. For ROS118 the DoF from the  
5 experiments and the model agree to within  $\pm 1$  mm (Fig. 5). The size and greyscale parameters  
6 calculated from CIP-15 images are not completely symmetrical about Z=0. The reason for this  
7 is unclear, potential causes are if the CIP-15 laser beam is not perfectly collimated, additional  
8 refraction caused by the optical window used to mount the sample, or changes to the CIP-15  
9 background/dark current calculation due to attenuation by the optical window.



1 *Figure 5 A comparison between CIP-15 images and diffraction simulations (red lines) of the*  
 2 *ice crystal analog ROS118. Grey dots show data from individual CIP-15 images and black dots*  
 3 *show the median for each 1 mm Z bin. Top left panel shows the mean X-Y image diameter. Top*  
 4 *right shows the number of pixels using 50% detection thresholds. Other panels show the ratio*  
 5 *of number of pixels (area) at different greyscale thresholds.*

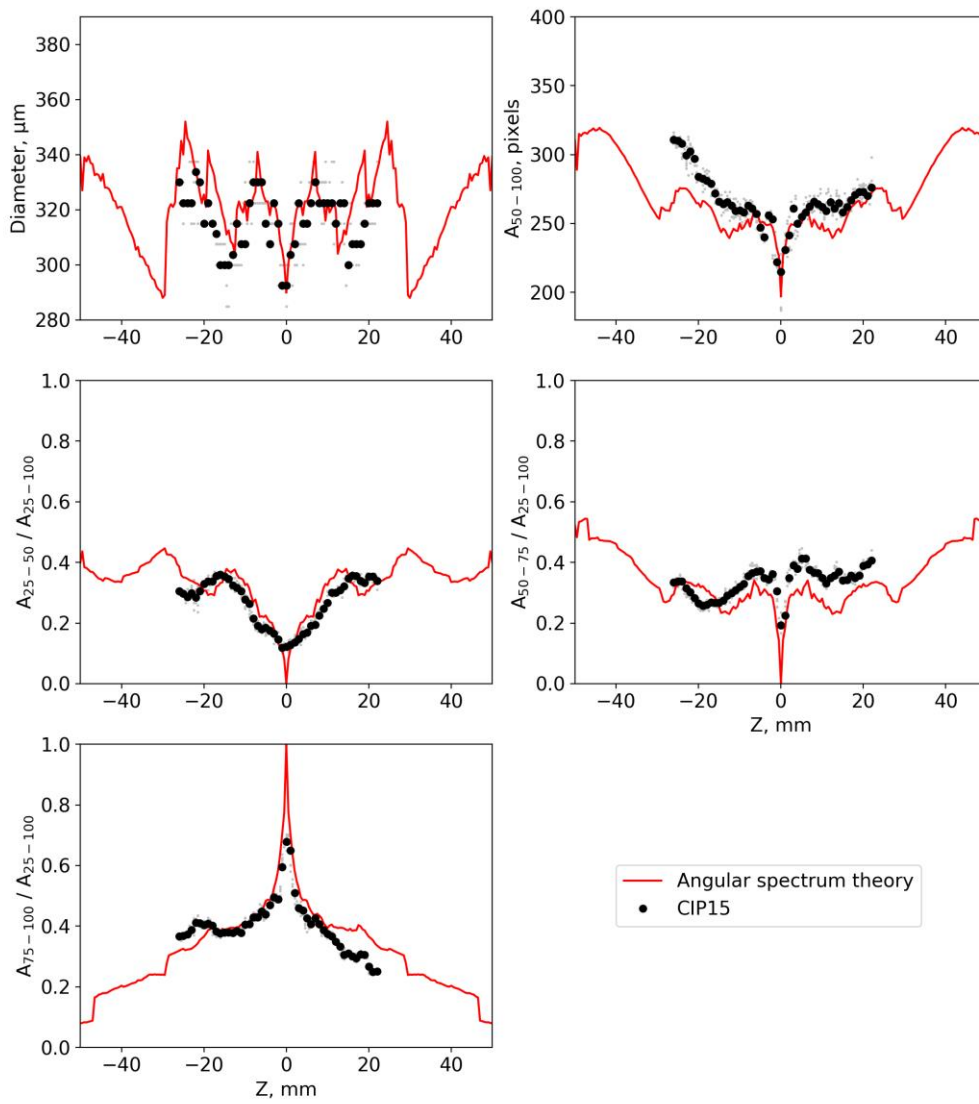
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7

8 *Figure 6. Same as Fig. 5 but for the ice crystal analog ROS250.*

1

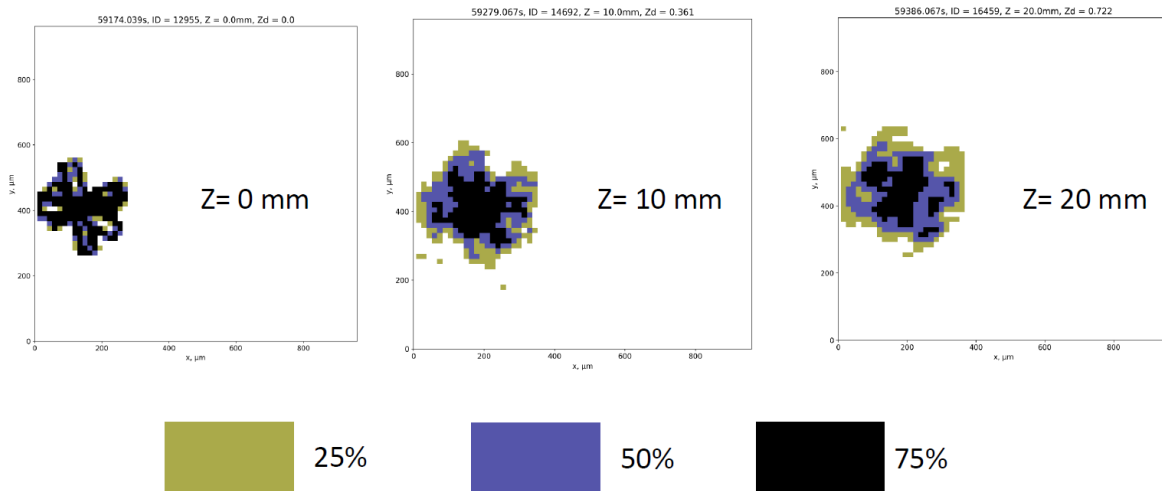


2

3 *Figure 7. Same as Fig. 5 but for the ice crystal analog ROS300.*

4

5



1  
2 *Figure 8. CIP-15 images of the ice crystal analog ROS300 at 3 distances from the object plane.*

### 3 **3.2 OAP ice crystal sizing**

4 Having investigated the performance of the AST model using 3-D analogs of complex ice, we  
5 will now use the AST model to examine the ability of OAPs to correctly determine the size of  
6 commonly occurring ice crystals. Figure 9 left panels show the ratio of the measured diameter  
7 ( $D$ ) to the true diameter ( $D_0$ ) vs  $Z_d$  for diffraction simulations of 1060 ice crystals. The data for  
8 each individual ice crystal is shown as grey lines, while the coloured lines are the median for  
9 each habit. Top panels show plots using the circle equivalent diameter, while the middle panels  
10 use the mean X-Y diameter and maximum diameter. Right panels show histograms of  $D/D_0$  for  
11 each habit calculated for the  $Z_d$  range from 0 to 10.

12 Figure 9 shows large differences in these relationships depending on whether the mean X-Y,  
13 maximum or circle equivalent diameter is used to define the particle size. For the 1060 ice  
14 crystal images used in this study the median  $D/D_0$  over the  $Z_d$  range from 0 to 8 is 1.1 using  
15 circle equivalent diameter, 1.0 using the mean X-Y diameter and 1.0 using the maximum  
16 diameter. However, there is significantly less variability between crystals using circle  
17 equivalent diameter, which has an inter-quartile range  $D/D_0$  of 0.2 compared to 1.1 and 1.3  
18 using the mean X-Y and maximum diameters, respectively. This is also shown in Table S1-S3,  
19 which gives the median and inter-quartile range  $D/D_0$  at selected  $Z_d$  for each habit using the  
20 three different size metrics.

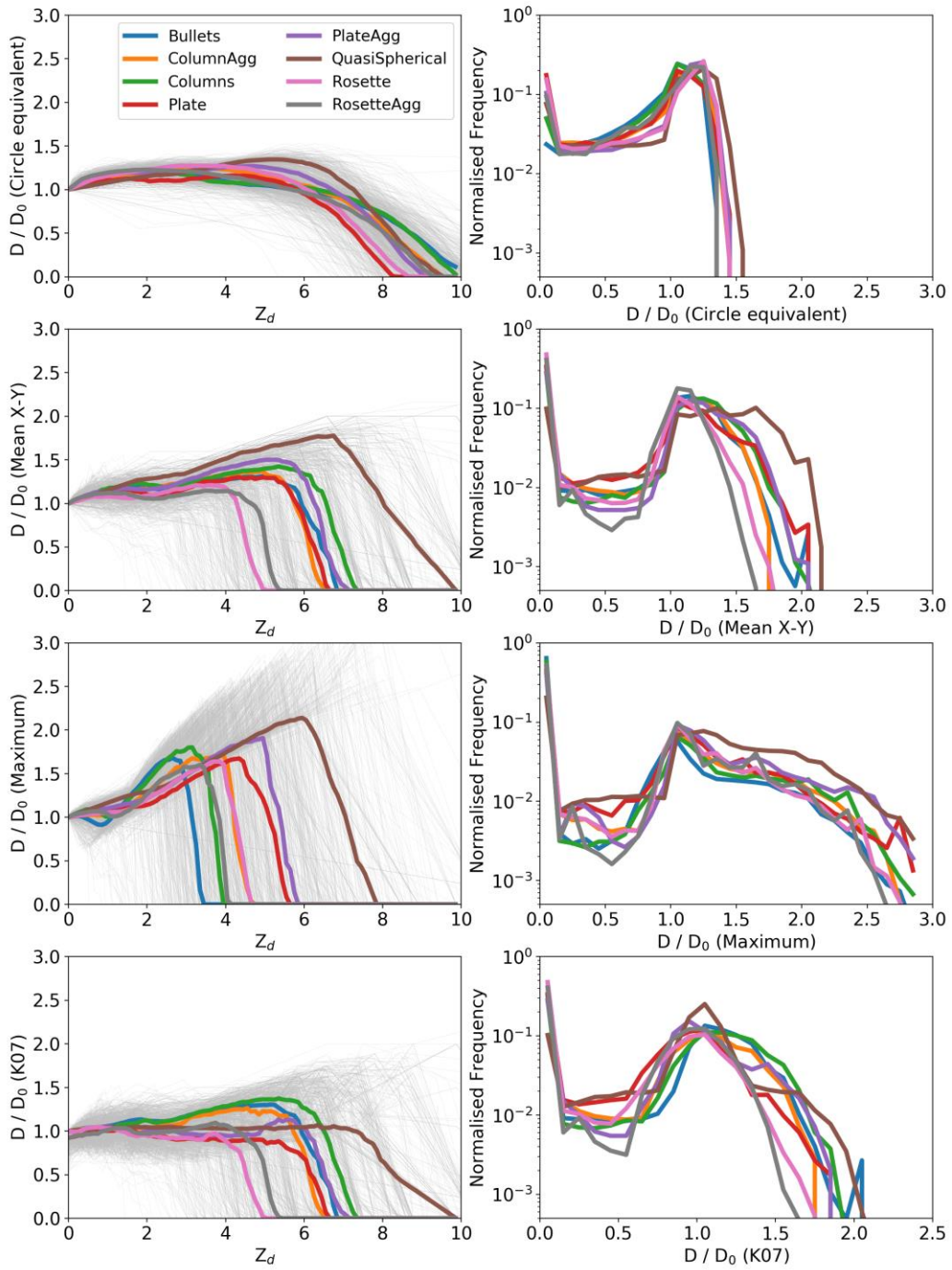


1 There is a general trend of increasing size with distance from the object plane. Over-sizing is  
2 up to approximately 100%, 200% and 50% using mean X-Y, maximum and circle equivalent  
3 diameters, respectively. However, the degree of oversizing is dependent on habit, with quasi-  
4 spherical and plate aggregates most significantly over-sized using all D definitions. In  
5 agreement with O19, once D reaches a maximum, further increases in Z cause the images to  
6 fragment and their size to decrease until they are no longer visible.

7 K07 uses the size of the internal voids within images of droplets to determine their  $Z_d$  and  
8 correct their size. O19 shows that this algorithm is effective using modern OAPs for droplets  
9 with  $Z_d < \sim 6$ . For  $Z_d > 6$  the images are too fragmented for their size to be corrected. The K07  
10 approach was derived by considering Fresnel diffraction from opaque discs, and has only been  
11 tested for images of spherical droplets. However, in the absence of an alternative previous  
12 studies have applied K07 to images of ice crystals (e.g. Davis et al., 2010). To examine the  
13 efficacy of this approach, Fig. 9 bottom panels shows the mean X-Y diameter of the simulated  
14 images of ice crystals once K07 has been applied. The ratio of their K07 corrected diameter to  
15 their true particle diameter is shown as a function of  $Z_d$  (left panel), while probability density  
16 functions of  $D/D_0$  for each habit are shown in the right panel. The median  $D/D_0$  for the  $Z_d$  range  
17 0 to 8 is 0.9 and the inter-quartile range is 1.1. For a number of habits (rosette, plate, quasi-  
18 spherical, rosette-aggregate and plate-aggregate) K07 reduces the number of over-sized  
19 particles across most of the DoF. For bullets, columns and column aggregates K07 has minimal  
20 impact on the probe sizing. Like for droplets For all habits, K07 is not able to remove the small  
21 image fragments that occur when a particle is near the edge of the DoF.

22

23



1 *Figure 9. Left panels show the ratio of the measured diameter ( $D$ ) to the true diameter ( $D_0$ ) vs*  
2  *$Z_d$  for diffraction simulations of 1060 ice crystals. The data for each individual ice crystal is*  
3 *shown as grey lines, while the coloured lines are the median for each habit. Right panels show*  
4 *histograms of  $D/D_0$  for each habit calculated for the  $Z_d$  range 0 to 10. Top panels show plots*  
5 *using the circle equivalent diameter, while the middle panels use the mean X-Y and maximum*  
6 *diameters. Bottom panels show the diameter corrected using K07.*

7

### 8 **3.3 Depth of field dependence on particle habit**

9 Uncertainty of derived physical quantities (e.g. number concentration) from OAPs is dependent  
10 on the sample volume and therefore uncertainty in the DoF (see Eq. 2). The DoF of an OAP is  
11 commonly calculated using Eq. 1 with a single  $c$  value. The variable  $c$  in this equation is the  $Z_d$   
12 where a particle is no longer detected by the OAP. If a single  $c$  value is used this would need  
13 to be independent of particle shape. Table 1 shows the median and inter-quartile range  $Z_d$  where  
14 particles are no longer visible for each habit using the maximum, mean X-Y and circle  
15 equivalent diameters. Using mean X-Y the habit median DoF varies between  $Z_d = 5.0$  and  $9.9$   
16 for rosettes and quasi-spherical particles, respectively. Using the maximum as the particle  
17 sizing metric the median DoF varies by a similar amount ranging between  $Z_d = 3.4$  to  $7.8$  for  
18 bullets and quasi-spherical crystals. In addition, particles have significant intra-habit variability  
19 using both maximum and mean X-Y, with most habits DoF inter-quartile ranges greater than  $2$   
20  $Z_d$ . The variability is lower using circle equivalent diameter, with median DoFs ranging  
21 between  $8.2$  and  $10.2$  for plates and bullets, respectively with habit inter-quartile ranges near  $1$   
22  $Z_d$ . As a result, derived physical quantities such as number concentration will have lower  
23 uncertainty if circle equivalent diameter is used to define the particle size compared to  
24 maximum and mean X-Y diameter.

25

		Bullets	Column- aggregates	Columns	Plates	Plate- aggregates	Quasi- spherical	Rosettes	Rosette- aggregates
Maximum	Median	3.4	4.6	3.9	5.6	5.8	7.8	4.6	4.1
	IQR	1.3	1.5	2.0	2.8	1.9	2.0	1.9	1.9
	Median	6.8	6.6	7.2	7.0	7.0	9.9	5.0	5.4

Mean X-Y	IQR	2.0	1.7	2.1	3.0	2.4	2.0	2.0	2.0
Circle equivalent diameter	Median	10.2	9.4	9.9	8.2	9.0	9.4	8.6	9.2
	IQR	1.0	1.0	0.9	1.2	1.1	1.4	1.3	1.1

1 *Table 1. Median and inter-quartile range (IQR) normalised dimensionless distance from the*  
2 *object plane ( $Z_d$ ) where particles are no longer visible for different habits, this is equivalent to*  
3  *$c$  in Eq. 1*

4

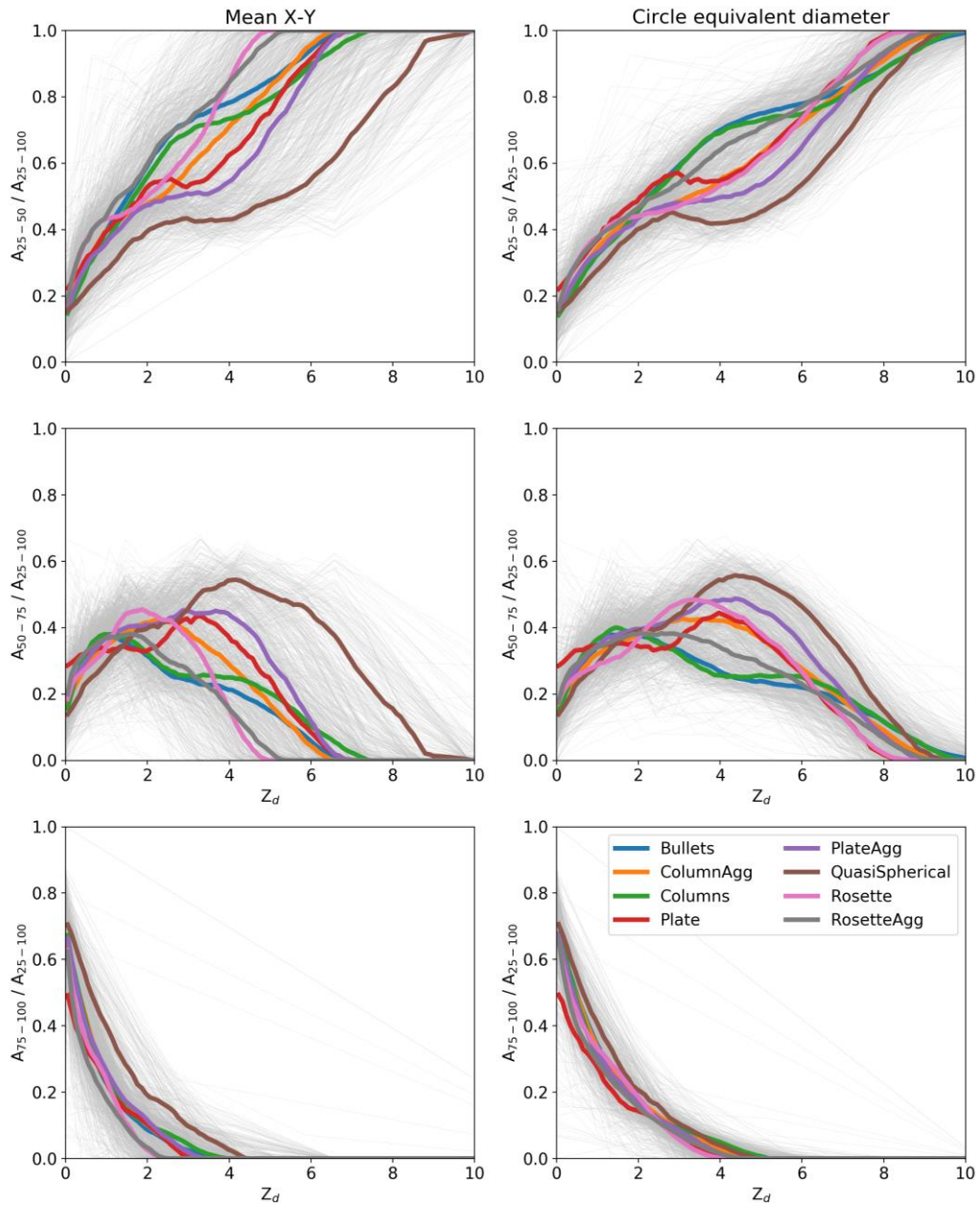
### 5 **3.4 Greyscale information**

6 Greyscale information in OAP imagery has previously been used to filter severely mis-sized  
7 images and enforce a DoF threshold that improves data quality (O19). Figure 10 shows  
8 combinations of simple greyscale ratios as a function of  $Z_d$  for the simulation of 1060 ice crystal  
9 images described in the previous section. Left panels use the size metric mean X-Y diameter in  
10 the  $Z_d$  calculation, whereas the right panels use circle equivalent diameter in the  $Z_d$  calculation.  
11 Like the ratio  $D/D_0$  (Fig. 9), the greyscale ratios also show significant variability between habits  
12 as a function of  $Z_d$ . Figure 10 shows this variability is greater if mean X-Y diameter is used to  
13 calculate  $Z_d$ , though it is still significant using circle equivalent diameter. The variability is  
14 larger still using maximum diameter (not shown).

15 O19 uses simple greyscale ratios to determine  $Z_d$  for spherical liquid droplets near the edge of  
16 the DoF ( $3.5 < Z_d < 8.5$ ). This allows a new DoF to be defined that excludes fragmented images,  
17 removing significant biases in the PSD. This is possible since all spherical droplets independent  
18 of size have the same greyscale ratios at a given  $Z_d$ . Figure 10 shows that this is not true for ice  
19 crystals where the initial shape of the ice crystal has an impact on the greyscale ratios at a given  
20  $Z_d$ . As a result, O19 cannot be used to determine  $Z_d$  in the same way.

21

22



1

2 *Figure 10. Combinations of number of pixels at different greyscale ratios as a function of  $Z_d$*   
 3 *for the simulated ice crystal images. Left panels show plots where mean X-Y is used as the*  
 4 *sizing metric, while the right panels use circle equivalent diameter.*

### 1 3.5 Habit recognition

2 The shape of ice crystals is a key microphysical parameter impacting cloud radiative properties  
3 in ~~a number of several~~ ways. A variety of automatic image recognition algorithms have been  
4 applied to OAP datasets to classify particles into different habits (Korolev & Sussman, 2000;  
5 Crosier et al., 2011; Praz et al., 2018). These algorithms typically rely on geometrical features  
6 extracted from OAP images that have characteristic values for specific habits. These  
7 characteristic values are usually determined by manually classifying images into habits. These  
8 images are then used to set thresholds or train machine learning algorithms to automatically  
9 classify new images. For example, Crosier et al. (2011) used the following ratio to discriminate  
10 between ice crystals and liquid droplets:

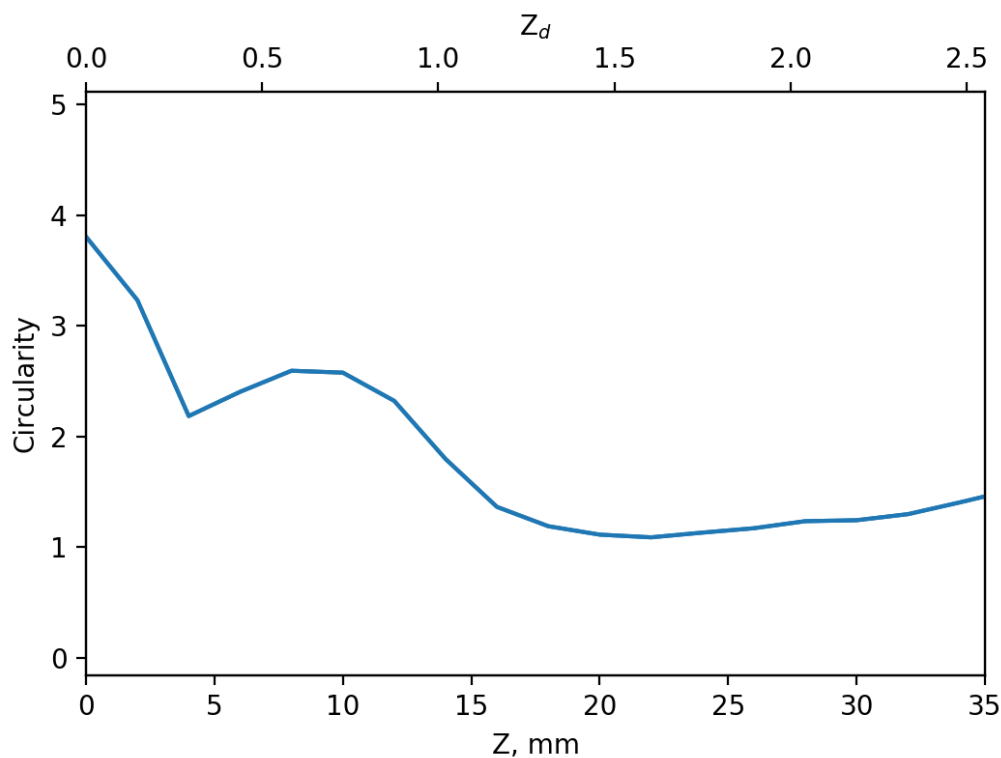
$$11 \quad \text{Circularity} = \frac{P^2}{4\pi A}$$

12 Equation 4

13 where P is the particle perimeter, and A is the particle area including any internal void. Crosier  
14 et al. (2011) used a threshold of 1.25 to discriminate between these two categories. When  
15 images are manually selected to train habit recognition algorithms only images that can be  
16 identified ‘by-eye’ as a specific habit will be included. For OAPs this is likely to be images that  
17 are ‘in-focus’. However, the shape of an OAP image and therefore the geometrical features that  
18 are used in habit recognition algorithms depend on where in the probe’s sample volume a  
19 particle is detected. For example, Figure 3 shows a simulated 190 μm rosette at different  
20 distances from the object plane. It is only in the top left panel (Z=0) that it can be identified as  
21 a rosette from its image alone. Figure 11 shows how this particle’s circularity changes with Z  
22 and Z<sub>d</sub>. At Z=0 its circularity is near 4, while at Z=20 mm it is near 1 and may be confused with  
23 a spherical droplet. Figure 11 demonstrates that the measured particle shape is highly dependent  
24 on the position in the sample volume Z<sub>d</sub> (and Z) with the circularity decreasing by a factor 2 by  
25 Z<sub>d</sub>=1; in comparison the particle size has only changed by 15%.

26 The variance in geometrical features for each habit will not only be due to natural variability in  
27 the shape of ice crystals, but also due to their position in the sample volume when measured.  
28 To date, this second effect has not been accounted for by habit recognition algorithms.  
29 Therefore, currently the results of habit classification algorithms on OAP datasets cannot be  
30 considered quantitative.

31



1

2 *Figure 11. The circularity (Eq. 4) of the rosette shown in Fig. 3 as function of distance from the*  
 3 *object plane Z and  $Z_d$ .*

4

#### 5 **4 Methods to improve OAP size distributions**

6 Depending on where in the sample volume a particle is observed the OAP image size can range  
 7 between being as small as a single pixel or up to twice the true particle diameter (see Fig. 9).

8 Algorithms such as K07 and O19 have been derived using spherical shapes and are therefore  
 9 not directly applicable to OAP PSDs of non-spherical shapes. However, there are several  
 10 possible approaches that could be used to correct OAP ice crystal size distributions.

11

#### 12 **4.1 Greyscale filtering**

13 Unlike for liquid droplets, O19 does not accurately determine  $Z_d$  for non-spherical ice crystals.

14 We now describe a new technique to use greyscale information to remove the most severely  
 15 mis-sized ice crystals and constrain the sample volume with a reasonable uncertainty using  
 16 circle equivalent diameter as the particle sizing metric. For example, if the diffraction  
 17 simulations are filtered to only include images that have at least one pixel with a greater than a

1 75% drop in light intensity (Fig. 7) then the median position where particles are no longer  
 2 visible (using a 50% intensity threshold) is  $Z_d = 4.6$  (interquartile range 1.1 in  $Z_d$ ). This removes  
 3 the fragmented images that begin to occur at approximately  $|Z_d| > 6$ . The median ratio  $D/D_0$  for  
 4  $Z_d < 4.6$  is 1.2 (interquartile range = 0.1), however, particles may still be oversized by  
 5 approximately 40% even with this filter applied (Fig. 7). Other greyscale thresholds may be  
 6 used to provide a more or less restrictive DoF constraint. Table 2 shows the median  
 7 (interquartile range)  $c$  values for various greyscale thresholds between 65 and 85%. Using a  
 8 65% threshold the median  $c$  value is 6.2 (interquartile range = 1.3), while for 85% it is 3.2  
 9 (interquartile range = 0.9). It should be noted that the lower the greyscale threshold the higher  
 10 the probability of a fragmented image being observed, and the small particle concentration  
 11 being biased.

12 When determining the effective array width (Eq. 2), the image size along the direction of the  
 13 photodiode array should be used. However, this size is a function of the particle's Z position,  
 14 which is the reason why the effective array width needs to be integrated over the depth of field  
 15 to determine the sample volume (Eq. 2). This can be calculated using the AST model if the true  
 16 particle shape can be assumed (e.g. spherical particles in liquid cloud). However, if the true  
 17 particle shape is not known, as is often the case for ice clouds, then it remains a source of  
 18 uncertainty in the calculated sample volume.

19  
20

Greyscale intensity threshold, %	65	70	75	80	85
$c$	6.2 (1.3)	5.4 (1.1)	4.6 (1.1)	4.0 (1.2)	3.2 (0.9)
$D/D_0$	1.2 (0.1)	1.2 (0.1)	1.2 (0.1)	1.2 (0.1)	1.2 (0.1)

21 *Table 2. Median (interquartile range) depth of field  $c$  value (Eq. 1) for 1060 ice crystal images*  
 22 *using various greyscale intensity thresholds and circle equivalent diameter. The median*  
 23 *(interquartile range) ratio  $D/D_0$  for  $Z_d < c$  is also given.*

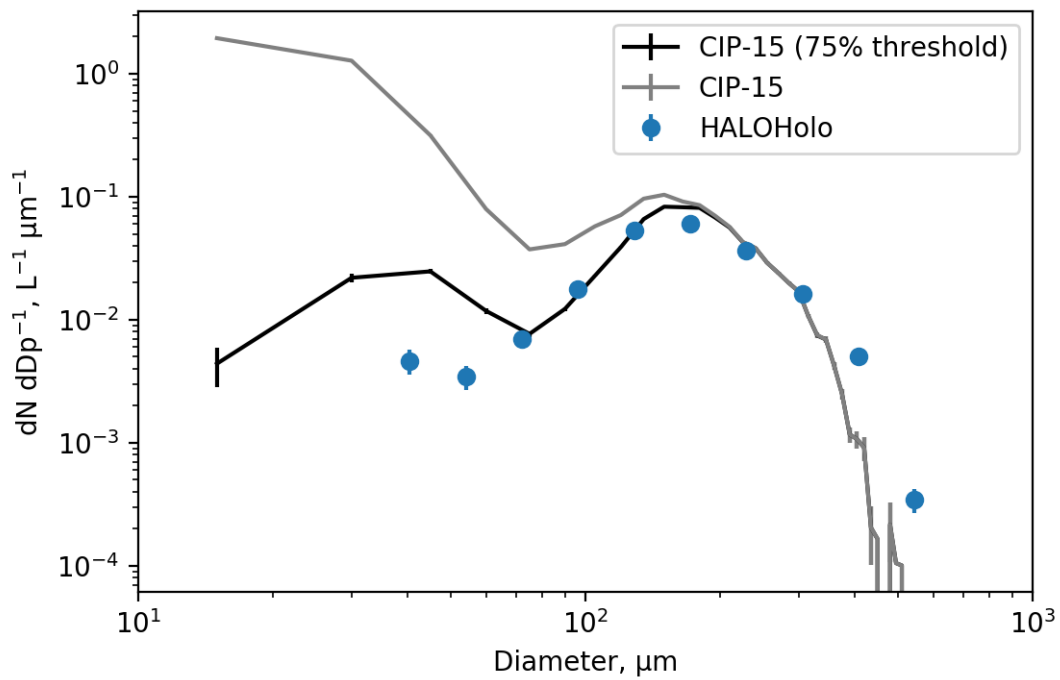
24



1 Figures 12 and 13 apply this new methodology to ambient measurements collected during  
2 research flights in cirrus on 7 February 2018 and 23 April 2018. Figure 12 shows PSDs from  
3 the CIP-15 and HALOHolo for a run at  $-42^{\circ}\text{C}$  on 7 February 2018 (16:02:00 to 16:10:00 GMT).  
4 This flight has previously been discussed by O19. Figure 13 shows equivalent PSDs for  
5 temperatures between  $-47$  and  $-40^{\circ}\text{C}$  collected on 23 April 2018. For both probes the particle  
6 diameter given is the circle equivalent diameter and particles in contact with the edge of the  
7 CIP-15 optical array have not been included in the PSD calculation. The black lines show the  
8 CIP-15 size distribution when images are filtered to only include those with at least one pixel  
9 at the 75% intensity threshold. This threshold significantly reduces the concentration of small  
10 particles ( $<200\ \mu\text{m}$ ) compared to when this filtering is not applied (grey lines) and generally is  
11 in much better agreement with HALOHolo a holographic imaging probe (blue markers). This  
12 suggests that for these cases using current data processing techniques, a significant fraction of  
13 the ice crystal number concentration at sizes  $< 200\ \mu\text{m}$  is an artefact due to optical effects.

14 HALOHolo's sample volume is not as strongly dependent on particle size as it is for OAPs.  
15 However as described earlier, measurements of small particles from HALOHolo are limited by  
16 noise in the background image. For a complete description of the HALOHolo data processing  
17 and quality control procedures see Schlenczek (2017). HALOHolo uses supervised machine  
18 learning to discriminate real particles from artefacts due to noise in the background image.  
19 However, it is possible that small particles could be misclassified as artefacts or vice versa, and  
20 as a result HALOHolo could either underestimate or overestimate the small ice concentration.  
21 For particles  $> 35\ \mu\text{m}$  it is estimated that the probe's detection rate is  $>90\%$  and previous work  
22 has shown excellent agreement with a CDP in liquid clouds (Schlenczek, 2017). However,  
23 HALOHolo PSDs should not be considered the true PSD, but rather another piece of evidence  
24 that suggests for these cases OAPs overestimate small ice concentrations using current data  
25 processing techniques.

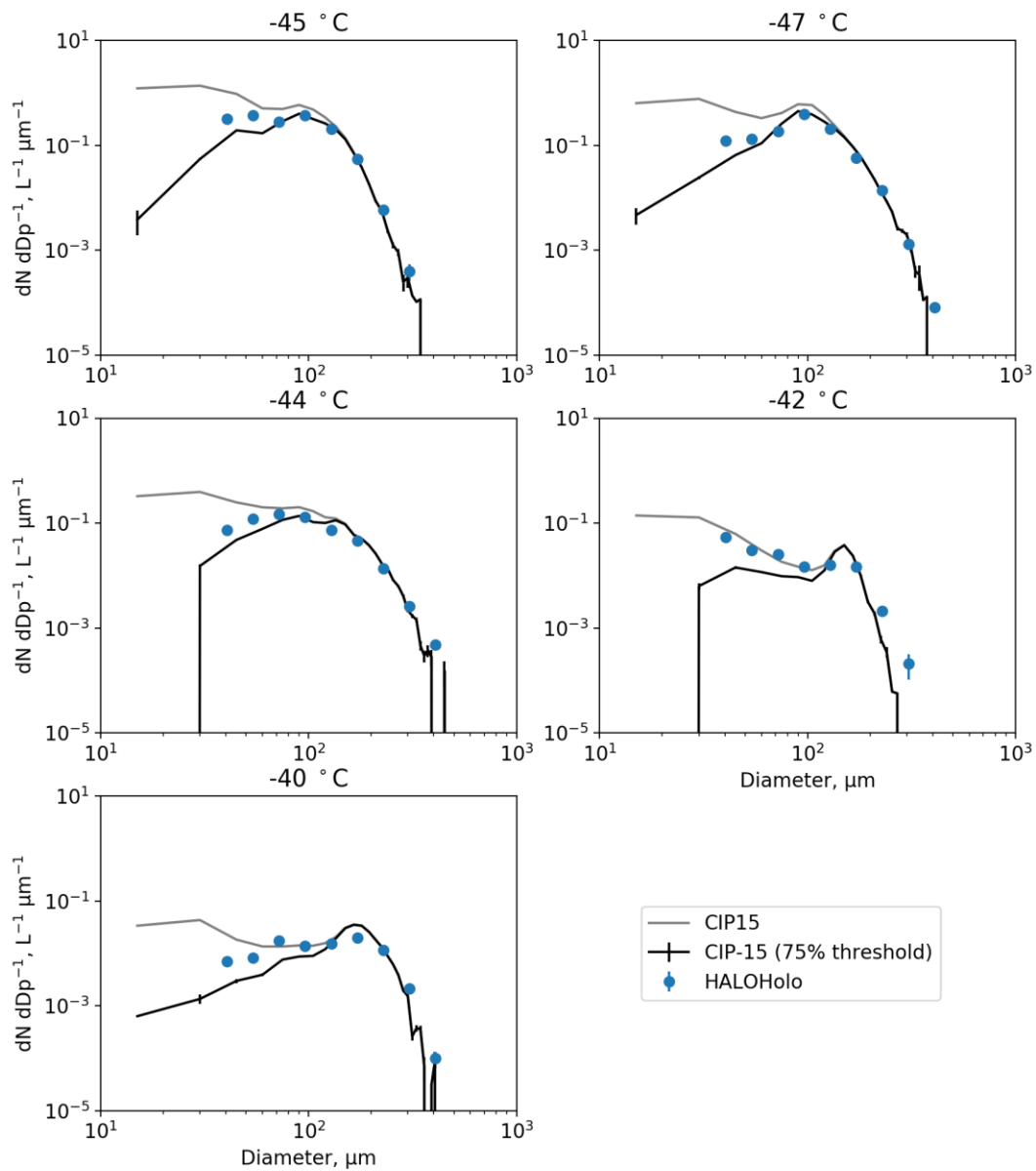
26



1

2 *Figure 12. Size distributions from the CIP-15 and HALOHolo for a run at -42°C on 7 February*  
 3 *2018. The black line shows the CIP-15 size distribution when images are filtered to only include*  
 4 *those with at least one pixel at the 75% intensity threshold.*

5



1

2 *Figure 13. Size distributions from the CIP-15 and HALOHolo for  $\alpha$  runs between -47 and -*  
 3 *40°C on 23 April 2018. The black line shows the CIP-15 size distribution when images are*  
 4 *filtered to only include those with at least one pixel at the 75% intensity threshold.*

5

## 1 4.2 Stereoscopic imaging

2 A second method that could be used to constrain the DoF of an OAP is to use the stereoscopic  
3 imaging that is possible with the 2D-S. The 2D-S in effect consists of two OAPs (known as  
4 channels) orientated perpendicular to each other and the direction of motion of the  
5 particle/instrument. Under normal operation the probe is oriented so that one laser beam is  
6 horizontal and the other is vertical. The two lasers overlap at the centre of each channel's arms.  
7 As well as increasing sampling statistics by having two channels which can be  
8 merged/averaged, this design also allows some ice crystals to be viewed from two orientations  
9 to study their aspect ratios. In this study we use this feature to constrain the probe's DoF, which  
10 greatly limits the magnitude of diffraction artefacts, and represents the first implementation of  
11 stereoscopic analysis on an ambient OAP dataset. The 2D-S was designed so that  $Z=0$  on both  
12 channels is in the region where the two lasers overlap. We refer to particles observed by both  
13 channels as co-located particles. Co-located particles have tightly constrained  $Z$  position and  
14 should not be subject to significant mis-sizing due to diffraction. For the 2D-S this is likely to  
15 be true for  $D_0 > 20 \mu\text{m}$ . For a hypothetical stereoscopic probe with larger optical arrays ~~(NR)~~ it  
16 may be necessary to restrict the distance a particle can be from the centre of the optical array.

17 For the case where channel 0 is used for particle sizing and channel 1 is used to constrain the  
18 particle  $Z$  position, the sample volume of co-located particles is given by,

$$19 \quad SVol = TAS \left( \text{minimum} \left( cD^2 / 2\lambda, ER \right) \right) (R(E - 1)R - D_{CH0})$$

20 Equation 5

21 Where  $TAS$  is the true air speed,  $E$  is the number of array elements,  $R$  is the resolution of the  
22 probe,  $D$  is the measured particle diameter and  $D_{CH0}$  is the particle diameter measured along the  
23 axes of the channel 0 optical array. This requires that particles in contact with the edge of the  
24 channel 0 optical array have been removed. If channel 1 is used for particle sizing instead of  
25 channel 0 then particles in contact with the edge of the channel 1 optical array are removed  
26 instead of channel 0, and  $D_{CH0}$  is replaced by  $D_{CH1}$  in Eq. 5.

27 For this method to be applicable it is important to validate that  $Z=0$  on both channels is in the  
28 laser overlap region. If it is significantly offset this would prevent small co-located particles  
29 from being observed, since the DoF from one channel would not overlap with the optical array  
30 of the other channel. Increasingly large offsets between the channels prevent increasingly large  
31 co-located particles from being observed. It is therefore important to check that this offset is

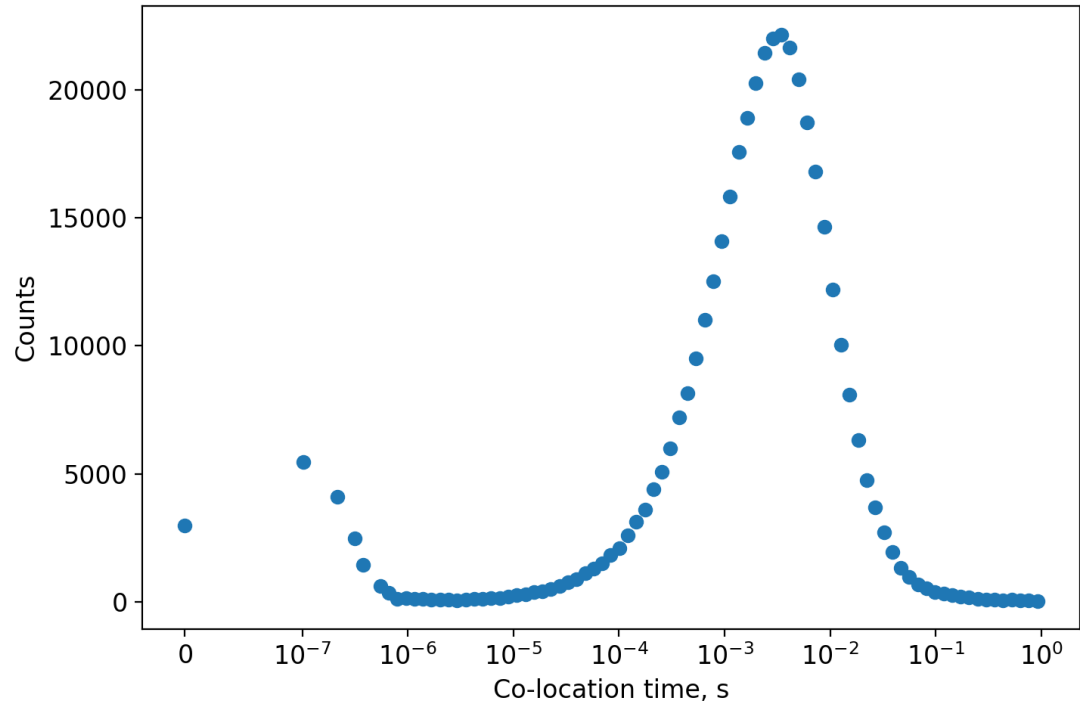
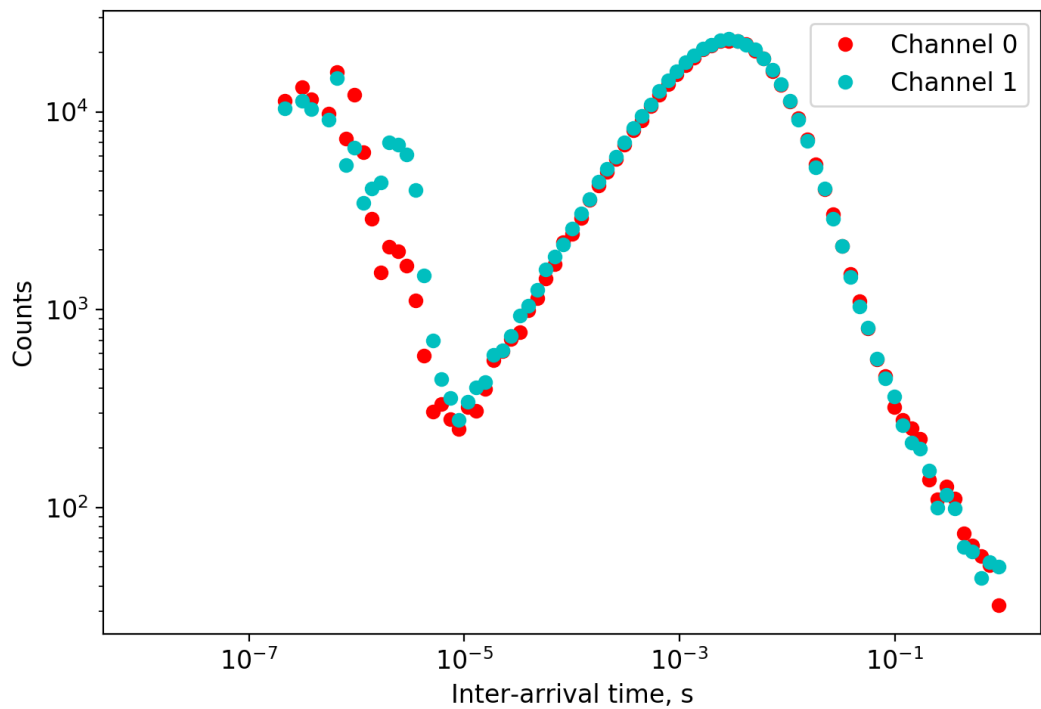
1 not significant by regularly sampling in environments where small particles are present (i.e. in  
2 liquid cloud or using a droplet generator in a laboratory as in O19).

3 Co-located particles could be confused with shattered particles since they are also associated  
4 with short inter-arrival times. Figure 14 (top panel) shows a histogram of inter-arrival time for  
5 particles on the same channel for measurements in cirrus on 7 February 2018. To minimise  
6 shattering events, each channel was independently filtered for particles using an inter-arrival  
7 threshold of  $1 \times 10^{-5}$  s. It may still be possible to mistakenly detect shattered particles as co-  
8 located particles if one shattering fragment splits into two particles, triggering each channel  
9 simultaneously but in spatially independent parts of the sample volume. However, examination  
10 of co-located images suggest that this is rare.

11 To identify co-located particles, we use the difference in arrival time between a particle on one  
12 channel and their closest neighbour on the other channel. Figure 14 shows a histogram of co-  
13 location times for measurements in cirrus on 7 February 2018. This distribution is bi-modal  
14 with a larger mode centred at approximately  $1 \times 10^{-3}$  s. and a smaller mode at  $1 \times 10^{-7}$  s. The larger  
15 mode is associated with the typical spatial separation between ambient particles, with its  
16 position dependent on the particle concentration. Examining pairs of images from the smaller  
17 mode suggests these images are the same ice crystal viewed from different orientations. Figure  
18 15 shows example pairs of co-located images, with channel 0 images shown in yellow and  
19 channel 1 images shown in blue. In addition to overall consistency in the geometrical shapes  
20 between channel 0 and channel 1 images, there is also excellent consistency in the particle size  
21 along the airspeed direction (x-axis in Figure 15) between these two channels.

22 Figure 14 shows that most co-located particles don't trigger both channels simultaneously  
23 within the time resolution of the data acquisition system but are offset by a few hundred  
24 nanoseconds. At  $100 \text{ m s}^{-1}$  data slices from the detectors are acquired every  $1 \times 10^{-7}$  s, which  
25 corresponds to a spatial separation of  $10 \text{ }\mu\text{m}$ . Using the laboratory droplet generator system  
26 described in O19, we were able to generate a continuous stream of droplets of known size,  
27 velocity, rate, and with precise control over the position within the sample volume. These  
28 experiments with particle velocities of  $1 \text{ m s}^{-1}$  resulted in a  $1 \times 10^{-5}$  s mode time delay in detection  
29 events between the two channels of the 2D-S. This also corresponds to an offset of  $10 \text{ }\mu\text{m}$  in  
30 the sample volume in the axis of airflow through the probe (Y axis). These two sets of analysis  
31 provide a robust independent verification of the spatial offset between the two channels of the

- 1 2D-S. Therefore, when considering ambient data, we classify co-located particles as those with
- 2 time separations less than  $5 \times 10^{-7}$  s.



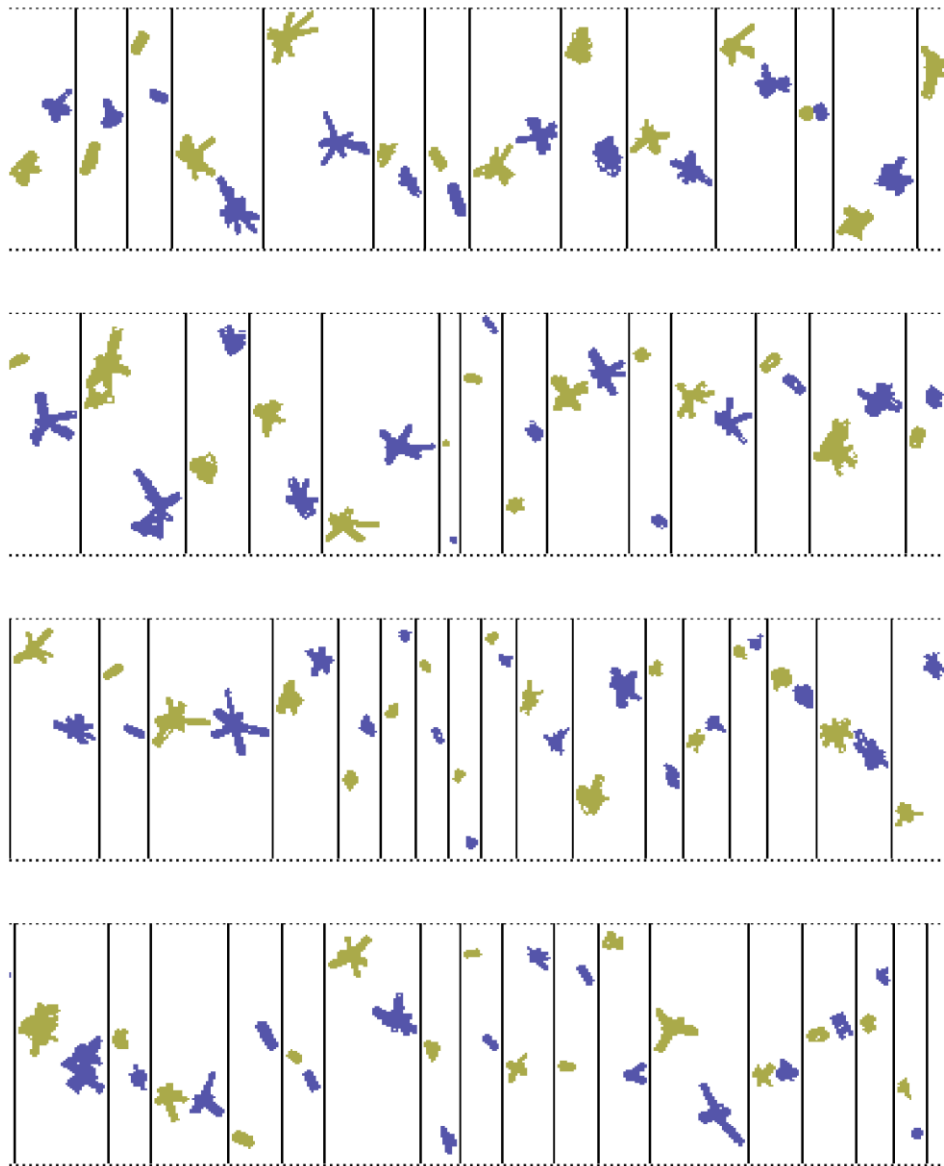
1 *Figure 14. Top panel. Histograms of inter-arrival times for particles on the same 2D-S channel*  
2 *for measurements in cirrus on 7 February 2018. Bottom panel. A histogram of the difference in*  
3 *arrival time between a particle on one channel and their closest neighbour on the other channel.*

4

5

6





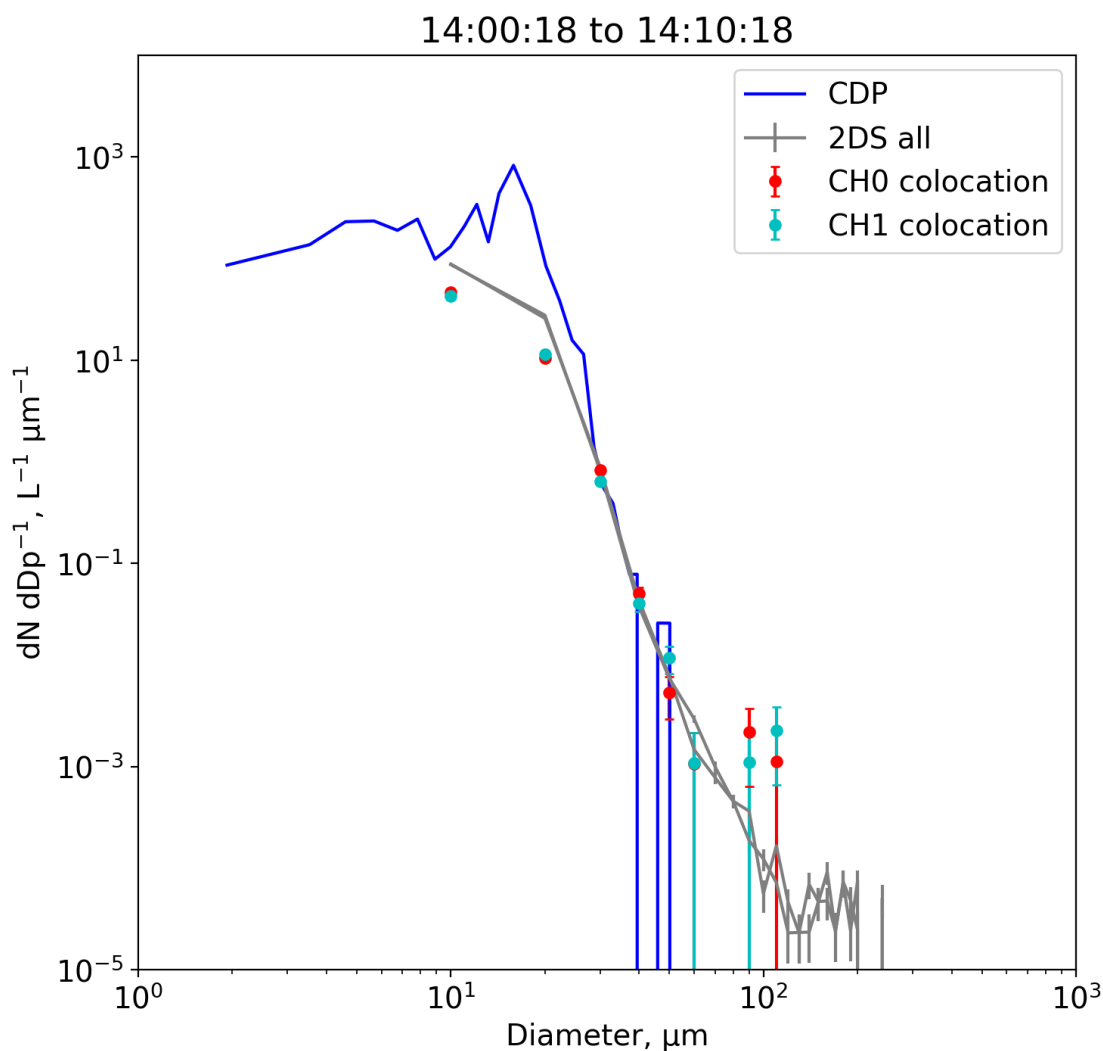
1

2 *Figure 15. Example ice crystals observed by both channels of the 2D-S. Images from channel*  
3 *0 are shown in yellow and images from channel 1 are shown in blue.*

4

1 ~~When determining the particle size from co-located images it is advantageous to use the largest~~  
2 ~~object in the image frame. Occasions where a single particle have been imaged as two objects~~  
3 ~~in the same image frame due to diffraction are removed by restricting the sample volume to a~~  
4 ~~narrow Z range. When sampling in environments with very high concentrations of small~~  
5 ~~partieles (e.g. in liquid cloud) it is possible that two ambient particles could occur in the same~~  
6 ~~image frame. Under these circumstances using the largest particle in the image frame prevents~~  
7 ~~significant particle mis-sizing.~~

8 Figure 16 shows a comparison between PSDs collected in liquid stratus cloud at 13 °C on 17  
9 August 2018. The grey lines show the 2D-S data for each channel using conventional data  
10 processing protocols without constraining the DoF, while the green and red lines show PSDs  
11 for just the co-located particles. The CDP is shown in blue. For this case no particles larger than  
12 approximately 200 µm are present. ~~and~~ All data processing methods are in good agreement up  
13 to 100 µm. For larger sizes the measurements using the co-located particles are limited by  
14 counting statistics due to the low concentration of these particles~~all data processing methods~~  
15 ~~are in good agreement.~~ This illustrates the ability of the 2D-S to detect small co-located  
16 particles.



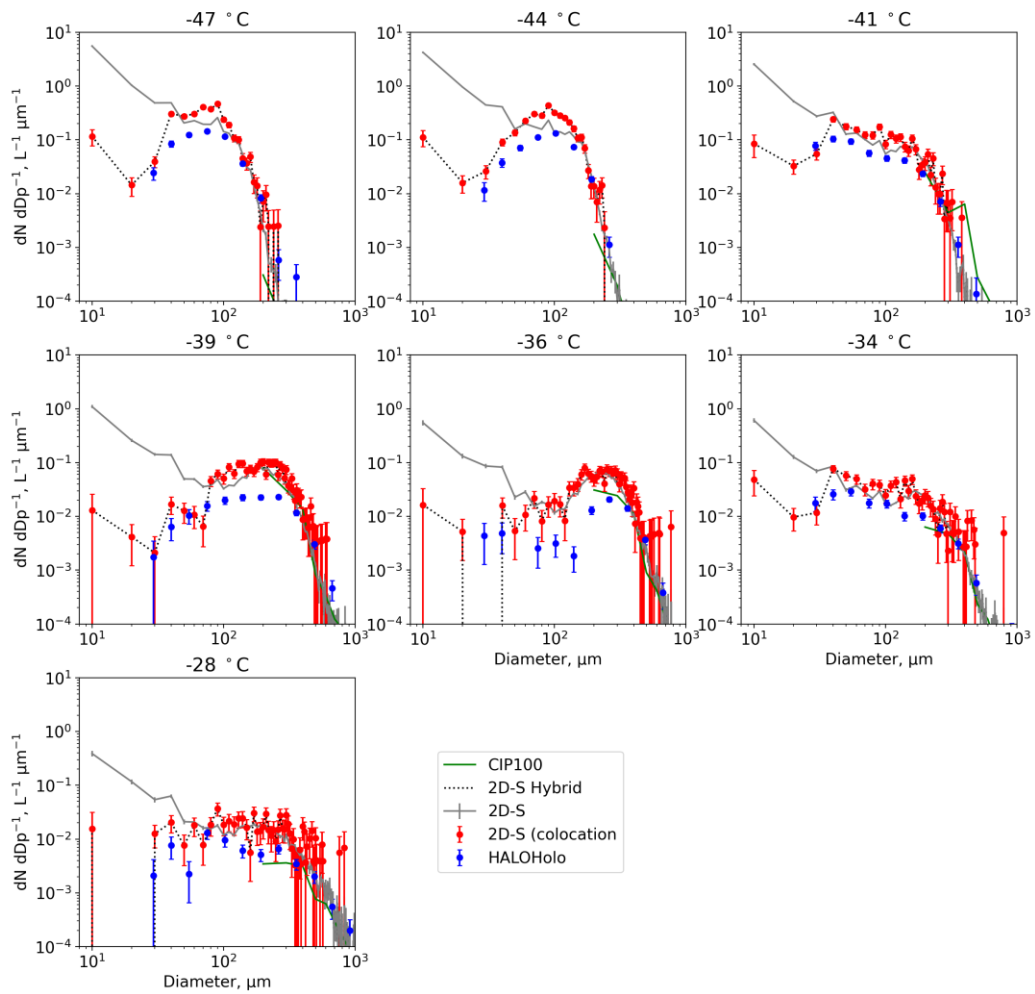
1  
 2 *Figure 16. Size distributions from the 2D-S and CDP for different temperatures during a*  
 3 *research flight in liquid stratus 17 August 2018 at 13 °C. The grey lines show the 2D-S data*  
 4 *using conventional data processing protocols without constraining the DoF, while the green*  
 5 *and red lines show size distributions for just the co-located particles. CDP size distributions*  
 6 *are shown in blue.*

7  
 8 Figure 17 shows size distributions from the 2D-S and HALOHolo for different temperatures  
 9 (averaged over ~10 minutes) during a research flight in cirrus on 11 March 2015 (see O'Shea  
 10 et al., 2016). The grey lines show the 2D-S data for each channel using conventional data  
 11 processing protocols without constraining the DoF, while the red lines show size distributions

1 for just the co-located particles. HALOHolo size distributions are shown in blue. For all  
2 temperatures the conventional 2D-S data processing shows an ice crystal mode at small sizes  
3 ( $< 200 \mu\text{m}$ ). At warmer temperatures ( $> -39 \text{ }^\circ\text{C}$ ) there is also a clear second mode at larger sizes.  
4 However, these high concentrations of small ice particles are not present in the co-located and  
5 the HALOHolo size distributions. This suggests using only co-located particles on the dual  
6 channel 2D-S probe is effective at removing significant biases at small particle sizes. At larger  
7 sizes ( $> 300 \mu\text{m}$ ) the 2D-S data processing using conventional and stereoscopic methods are in  
8 good agreement, however the latter method is limited by sampling statistics.

9 Stereoscopic data processing has the advantage of removing out-of-focus artefacts that bias the  
10 PSD at small sizes, while at larger sizes traditional processing methods offers significantly  
11 improved sampling statistics. Therefore, a hybrid approach using stereoscopic processing for  
12 small sizes and traditional processing methods for larger sizes is advantageous. The choice of  
13 size threshold to switch between the two methods is dependent on the arm width of the probe  
14 and the level of mis-sizing that is deemed acceptable. To give an idea of a suitable threshold,  
15 we will choose a size limit that prevents all particles with  $Z_d > 2$  from being included in the  
16 PSD. The maximum Z that the 2D-S can observe a particle is  $Z=31.5 \text{ mm}$  ( $2\text{D-S armwidth}/2$ )  
17 This corresponds to a  $222 \mu\text{m}$  particle at  $Z_d = 2$ . However, since particles can be mis-sized by  
18 a factor 1.4 then a size threshold of  $300 \mu\text{m}$  is needed to ensure that no particle with  $Z_d > 2$  is  
19 included. Figure 17 dashed lines shows 2D-S PSDs processed using this hybrid approach.

20



1

2 *Figure 17. Size distributions from the 2D-S and HALOHolo for different temperatures during*  
 3 *a research flight in cirrus on 11 March 2015. The grey lines show the 2D-S data using*  
 4 *conventional data processing protocols without constraining the DoF, while the green and red*  
 5 *lines show size distributions for just the co-located particles. The dashed black line shows a*  
 6 *2D-S processed using a hybrid of conventional and co-location data processing (see text for*  
 7 *details). HALOHolo size distributions are shown in blue.*

8

### 1 **4.3 Other potential methods**

2 There are several other potential methods that could be used to improve OAP PSD  
3 measurements. First reducing a probe's arm width to physically limit a distance a particle can  
4 be from the object plane would reduce out-of-focus particles. The amount the arm width would  
5 need to be decreased depends on the level of mis-sizing that is deemed acceptable for a given  
6 particle size, with more accurate sizing and smaller particles requiring smaller arm widths.  
7 However, as well as decreasing the sample volume, reducing the probe's arm width is likely to  
8 increase the proportion of shattered artefacts particles compared to ambient particles that the  
9 probe measures, since shattered artefacts are thought to cluster near the probe's arms.

10 Second, statistical retrievals have been applied to particle size distribution measurements where  
11 the instrument response is a distorted version of the true ambient distribution. These methods  
12 are reliant on knowing or empirically approximating the instrument function that distorts the  
13 ambient distribution. These methods have been applied to OAP measurements of spherical  
14 droplets (Korolev et al., 1998; Jensen & Granek, 2002). For non-spherical particles the  
15 distortion function is dependent on the ice crystal habits present and therefore the derived size  
16 distributions would have greater uncertainty, unless the particle shape is known a priori.  
17 However, this methodology may still result in an acceptable level of uncertainty if circle  
18 equivalent diameter is used, since its intra- and inter-habit  $D/D_0(Z_d)$  variance is smaller than for  
19 the mean X-Y and maximum diameter.

20

### 21 **5 Implications for small ice crystal observations**

22 In-situ measurements of ice clouds have consistently observed a mode in particle size  
23 distributions at small sizes ( $< 200 \mu\text{m}$ ). This would imply that ice nucleation occurs at all cloud  
24 levels, since small ice particles would rapidly grow in regions of ice super-saturation or sublime  
25 in sub-saturated regions. Particle shattering on the leading edge of a probe has previously been  
26 identified as a possible explanation (Korolev et al., 2005; Korolev et al., 2011). However, the  
27 impacts of shattering are thought to have been minimised by modifying the leading edges of  
28 probes (Korolev et al., 2013) and using particle inter-arrival time algorithms (Field et al., 2006).  
29 Yet even with these improved measurements a small ice mode has been found to be ubiquitous  
30 in ice cloud observations (McFarquhar et al., 2007; Jensen et al., 2009; Cotton et al., 2013;  
31 Jackson et al., 2015; O'Shea et al. 2016).

1 This work has shown that depending on where in the OAP sample volume a particle is observed  
 2 its image size can be as small as a single pixel or up to a 200% overestimate of the true particle  
 3 diameter (see Fig. 9). Only a relatively small proportion of undersized larger particles are  
 4 required to generate a significant bias in number concentration at small sizes ( $< 200 \mu\text{m}$ ) due  
 5 to the size dependence of the DoF (Eq. 1) (O19). We have tested two methods that could be  
 6 used to remove out-of-focus artefacts: greyscale filtering (Sect. 4.1) and stereoscopic imaging  
 7 (Sect. 4.2). Both methods either remove or significantly reduce the concentration of small ice  
 8 crystals observed in specific cirrus cloud cases (Figures 12, 13 and 17).

9 To further explore the impact OAP mis-sizing has on the measured PSD shape we use the results  
 10 from the AST model. Consider the ambient ice crystal PSD  $N(D_0)$  with units  $\text{L}^{-1} \mu\text{m}^{-1}$ . If this  
 11 distribution is observed by an OAP with size dependent sample volume  $SVol(D_0)$  (units:  $\text{L}^{-1} \text{s}^{-1}$ ,  
 12 Eq. 2) then the number of ice crystals observed by the probe as a function of true particle  
 13 diameter  $C(D_0)$  (units:  $\mu\text{m}^{-1} \text{s}^{-1}$ ) is given by,

$$C(D_0) = N(D_0)SVol(D_0)$$

Equation 6

16 The number of ice crystals observed as a function of the measured diameter  $C(D)$  is given by,

$$C(D) = M(D, D_0) \cdot C(D_0)$$

Equation 7

19  $M(D, D_0)$  is an  $E \times E$  matrix, where  $E$  is the number of detector elements. Each row of  $M(D,$   
 20  $D_0)$  is the probability distribution that a particle of measured size  $D$  has true size  $D_0$ . These  
 21 probabilities are dependent on the particle shape, the particle sizing metric, probe characteristics  
 22 (e.g. armwidth, laser wavelength) and the data processing protocols used (e.g. greyscale  
 23 filtering, co-location). The PSD observed by the probe  $N(D)$  can then be calculated by,

$$N(D) = \frac{C(D)}{SVol(D)}$$

Equation 8

26 The probe armwidth limits the maximum  $Z_d$  that a particle of given  $D_0$  can be observed. By  
 27 choosing an armwidth it is possible to calculate a probability distribution function of possible  
 28  $D$  for each  $D_0$  from one of the  $D/D_0(Z_d)$  relationships shown in Fig. 9. For our example, we use  
 29 an armwidth of 70 mm and the median  $D/D_0(Z_d)$  relationship for rosettes. We calculate  $M(D,$

1  $D_0$ ) for two cases: when mean X-Y and circle equivalent diameter are used as the particle sizing  
2 metric. To represent the true ambient distribution, we use three different gamma distributions  
3 that all have the form,

$$N(D) = N_0 D^\mu e^{-\lambda D}$$

5 Equation 9

6 Figure 18 shows three combinations of the coefficients  $\mu$ ,  $\lambda$  ( $\text{cm}^{-1}$ ) and  $N_0$  ( $\text{L}^{-1} \text{cm}^{-1}$ ). Left panel  
7 shows plots using mean X-Y diameter and the right panels shows circle equivalent diameter.  
8 The ambient PSDs (blue lines) are compared to simulated OAP observations using different  
9 data processing methodologies. The grey lines represent an OAP with armwidth of 70 mm using  
10 conventional data processing methods. The red markers represent a 2D-S using only co-located  
11 particles, which has the effect of limiting the maximum Z a particle can be observed to 0.64  
12 mm. The blue markers show simulated OAP measurements from a greyscale probe with 70 mm  
13 arm width when the data has been filtered to only include particles that have at least one pixel  
14 with a greater than 75% decrease in light intensity.

15 It should be noted that these simulated distributions only include mis-sizing due to diffraction  
16 and do not include other sources of OAP measurement uncertainty (e.g. counting statistics).  
17 Counting statistics will be responsible for a larger uncertainty for the co-located PSDs  
18 compared to conventional data processing methods.

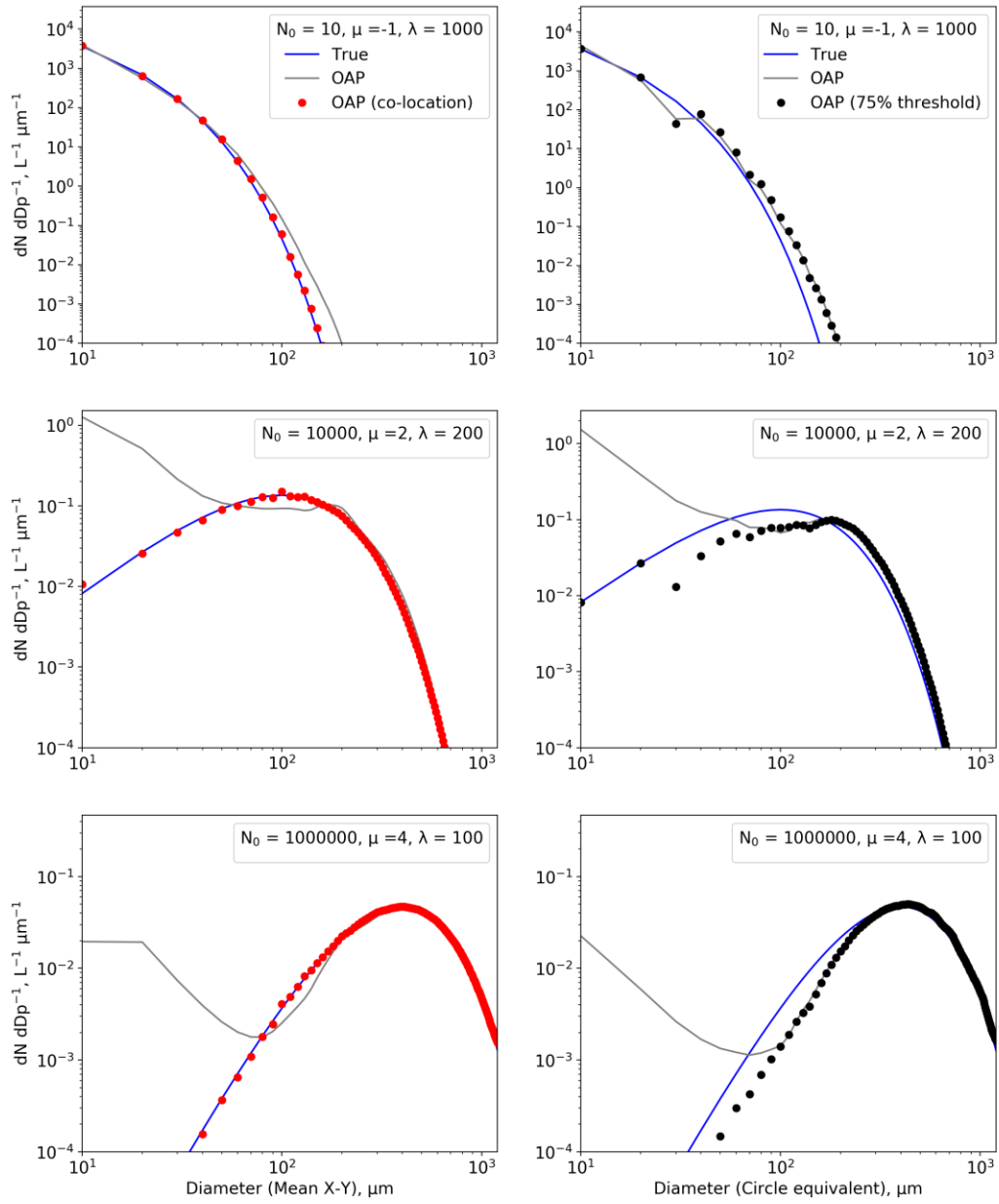
19 Figure 18 top panels show an ambient distribution (blue lines) dominated by small particles ( $\mu =$   
20  $-1$ ,  $\lambda = 1000 \text{ cm}^{-1}$  and  $N_0 = 10 \text{ L}^{-1} \text{ cm}^{-1}$ ), with concentrations increasing with decreasing size  
21 over the displayed size range 10 to 1280  $\mu\text{m}$ , which is representative of modern OAPs. The  
22 grey lines show the simulated OAP observations of this PSD, which have a similar  
23 characteristic shape. The total particle concentration observed by the simulated OAP over the  
24 size range 10 to 1280  $\mu\text{m}$  is 3% and 13% higher than the true PSD using mean X-Y and circle  
25 equivalent diameter, respectively. Figure 18 top left panel show the PSD that a 2D-S would  
26 observe when only co-located particles are included (red markers). The total particle  
27 concentration from the co-located PSD differs from the ambient distribution by less the one  
28 percent. The total particle concentration when greyscale filtering is applied is 2% lower than the  
29 true distribution.

30 Figure 18 middle panels show an ambient distribution with mode near 100  $\mu\text{m}$  particles ( $\mu = 2$ ,  
31  $\lambda = 200 \text{ cm}^{-1}$  and  $N_0 = 1 \times 10^4 \text{ L}^{-1} \text{ cm}^{-1}$ ). The simulated OAP PSDs have significantly different



1 shape with much higher concentrations of particles  $<100 \mu\text{m}$ . Here the OAP overestimates the  
2 total particle concentration over the size range 10 to  $1280 \mu\text{m}$  by 74% and 80% using mean X-  
3 Y and circle equivalent diameter, respectively. When stereoscopic imaging is used to constrain  
4 the OAP sample volume (red lines) the small particle mode is removed. The true and simulated  
5 OAP total particle concentration differ by  $< 1\%$ . Greyscale filtering again removes the small  
6 particle mode, though underestimates the total particle concentration by 11%.

7 Figure 18 bottom panels show an ambient PSD with mode near  $400 \mu\text{m}$  particles ( $\mu = 4, \lambda = 100$   
8  $\text{cm}^{-1}$  and  $N_0 = 1 \times 10^6 \text{ L}^{-1} \text{ cm}^{-1}$ ), like the previous case the simulated OAP PSD significantly  
9 overestimates the small particle concentration. The simulated OAP PSD is bi-modal, while the  
10 true PSD is mono-modal. However, in this case the artificial small particles contribute a  
11 relatively small proportion to the total number concentration in the 10 to  $1280 \mu\text{m}$  size range,  
12 as a result the simulated OAP only overestimates this by 4% using both particle size metrics.



1

2 *Figure 18. Simulations of OAP measurements of different gamma PSDs (blue lines). The*  
 3 *coefficients  $\mu$ ,  $\lambda$  ( $cm^{-1}$ ) and  $N_0$  ( $L^{-1} cm^{-1}$ ) for each gamma PSD are shown in text boxes. Left*  
 4 *panel shows plots using mean X-Y diameter and the right panels shows circle equivalent*  
 5 *diameter. The grey lines show simulated OAP PSDs with armwidth of 70 mm if all the particles*

1 *are rosettes. The red markers show simulated 2D-S measurements using only co-located*  
2 *particles, which has the effect of limiting the maximum Z a particle can be observed to 0.64*  
3 *mm. The blue markers show simulated OAP measurements from a greyscale probe with 70 mm*  
4 *arm width when the data has been filtered to only include particles that have at least one pixel*  
5 *with a greater than 75% decrease in light intensity.*

6

7 A significant amount of our understanding of clouds microphysics is based on OAP  
8 measurements, with the small particle artefact being present and manifesting in some manner.  
9 This includes how PSDs are parameterised in numerical models and remote sensing retrievals.  
10 Generally in the literature some formulation of exponential or gamma function has been used to  
11 represent ice crystal PSDs for observation or modelling studies (e.g. Cazenave et al., 2019;  
12 Delanoë et al., 2005; 2014; Field et al., 2007; Heymsfield et al., 2013; McFarquhar, &  
13 Heymsfield, 1997). These functions and the coefficients that are used in the literature all result  
14 in the highest ice crystal concentrations at the smallest sizes. For example, Field et al. (2007)  
15 describes a parameterisation based on OAP measurements that is widely used by the passive  
16 and radar remote sensing communities (e.g. Mitchell et al., 2018; Sourdeval et al., 2018;  
17 Ekelund et al., 2020; Eriksson et al., 2020; Fontaine et al., 2020). It describes a characteristic  
18 ice crystal PSD that can be used to calculate moments of a PSD when the ice water content is  
19 known. The functional form of the parameterisation consists of the summation of a gamma and  
20 exponential distribution.

21 Figure 19 shows a comparison between the 2D-S PSD for 11 March 2015 and the Field et al.  
22 (2007) parameterisations for tropical (Eq. 10) and mid-latitude (Eq. 11) ice clouds.

$$23 \quad N(D) \frac{M_3^3}{M_4^2} = 152 e^{-12.4x} + 3.28 x^{-0.78} e^{-1.94x}$$

24 Equation 10

$$25 \quad N(D) \frac{M_3^3}{M_4^2} = 141 e^{-16.8x} + 102x^{2.07} e^{-4.82x}$$

26 Equation 11

27

28

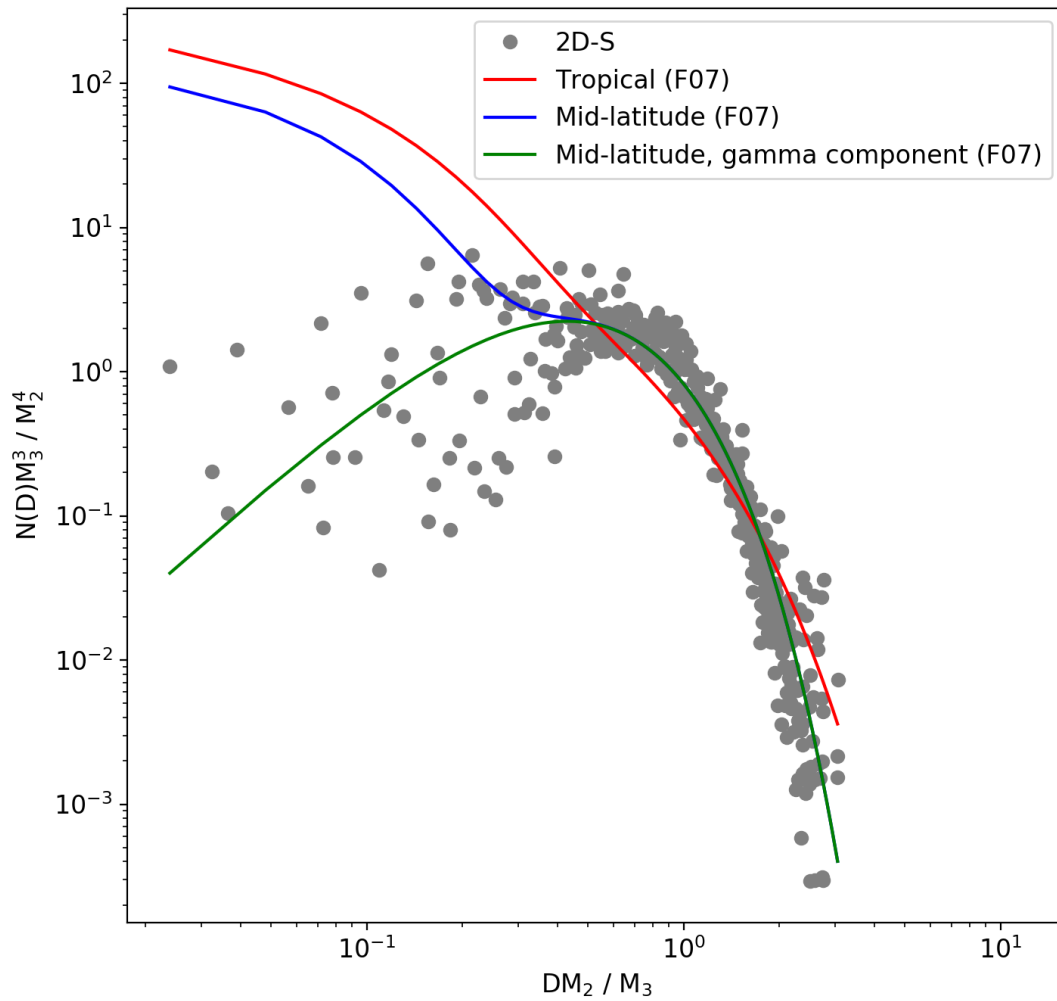
1

2 where the number concentration ( $N(D)$ ) and diameter are normalised using the second (M2)  
3 and third (M3) moments of the PSD and  $x$  is equal to  $DM_2/M_3$ . The 2D-S PSD in Fig. 19 has  
4 been calculated using only co-located particles for  $D < 300 \mu\text{m}$  and all particles for  $D > 300 \mu\text{m}$ .  
5 Both the tropical and mid-latitude parameterisations show rapidly increasing concentrations  
6 with decreasing size. At larger sizes the 2D-S and these parameterisations are in good  
7 agreement, while they diverge at smaller sizes. The green line in Fig. 19 shows the gamma  
8 component of the mid-latitude F07 parameterisation (Eq. 12), which is in much better  
9 agreement with the observations at small sizes.

10 
$$N(D) \frac{M_3^3}{M_4^2} = 102x^{2.07} e^{-4.82x}$$

11 Equation 12

12 This work suggests that the data used for derived PSDs parameterisations is subject to  
13 significant artefacts. As a result, the parameterisations are likely to have incorrect fundamental  
14 shape for ice cloud PSDs. The impacts of these artefacts can be expected to propagate to  
15 inaccuracies in remote sensing retrievals, which will be assimilated into weather forecast  
16 models, and to incorrect radiative properties due to a bias towards small particle sizes. Future  
17 work is needed to quantify the impact on retrievals and our understanding of ice microphysics  
18 and cloud radiative properties using the improved measurement methodologies presented in  
19 this paper.



1

2 *Figure 19. Comparison between 2D-S size distributions of co-located particles from a research*  
 3 *flight in cirrus on 11 March 2015 and Field et al. (2007) parameterisations for tropical and*  
 4 *mid-latitude ice clouds.*

5

## 6 **6 Conclusions**

7 This paper quantifies the optical response of OAPs to non-spherical particles for understanding  
 8 ice crystal observations, expanding the work of O19. We make the following comments and  
 9 recommendations on the use of OAP data:

- 1       • The shape and size of an OAP image depends significantly on where in the OAP sample  
2       volume a particle is observed. Particles < 200  $\mu\text{m}$  are the most significantly mis-sized.  
3       The measured size of a particle can range between being as small as a single pixel up to  
4       being as large as a 200% overestimate of the true particle.  
5
- 6       • Particle mis-sizing and the size dependence of the OAP sample volume causes an  
7       artefact which results in systematic overestimate of small ice (< 200  $\mu\text{m}$ ) concentrations.  
8       The persistent mode of small sizes observed in many previously studied cases is likely  
9       artificial. However, the importance of this artefact is strongly influenced by the true  
10      shape of the ambient PSD.  
11
- 12      • Algorithms to correct OAP size distributions such as K07 and O19 that have derived  
13      using spherical particles are not applicable to non-spherical ice crystal images without  
14      significant uncertainty.  
15
- 16      • New methods that may be used to filter OAP ice crystal size distributions were tested,  
17      including filtering using grayscale, and the use of stereoscopic imaging.  
18
- 19      • For greyscale instruments (such as the CIP-15), filtering images so that they must  
20      include one pixel with at least a 75% decrease in detector intensity removes the most  
21      severely fragmented particles near the edge of the DoF. This approach constrains the  
22      DoF to  $c = 4.6$  (interquartile range 1.1) using circle equivalent diameter.  
23
- 24      • Using the stereoscopic imaging that is possible with the 2D-S can constrain the sample  
25      volume to only ‘in-focus’ images. A hybrid approach using stereoscopic processing for  
26      small sizes and traditional processing methods for larger sizes is advantageous, as it  
27      limits any negative impacts on sample volume and therefore counting statistics. The  
28      choice of size threshold to switch between the two methods is dependent on the arm  
29      width of the probe and the level of mis-sizing that is deemed acceptable. For the 2D-S  
30      we suggest that 300  $\mu\text{m}$  is a suitable threshold for particle sizing using the mean X-Y  
31      diameter.  
32

- 1       • These new methodologies were tested using data from three research flights sampling  
2       cirrus. In these cases, they significantly improved agreement with a holographic  
3       imaging probe compared to conventional data processing protocols and either removed  
4       or significantly reduced the concentration mode at small particle sizes ( $<200\ \mu\text{m}$ ). This  
5       raises the question over the interpretation of many existing datasets such as those used  
6       to parameterise PSDs (e.g. Delanoë et al., 2005; 2014; Field et al, 2007), and the  
7       persistent observation of small particles throughout the entire vertical extent of ice  
8       clouds which has been difficult to reconcile with concepts of ice nucleation.
- 9
- 10       • Past datasets from OAPs need to be revisited, where possible the filtering and sample  
11       volume adjustments described in this paper should be applied. The impact these  
12       corrections have on how PSDs are parameterised in numerical models; remote sensing  
13       retrievals and radiative calculations of ice clouds need to be examined.

#### 14

#### 15 **Data availability**

16 The data presented here can be provided on request to the contact author.  
17  
18

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29

## 1 **References**

- 2 Baumgardner, D., Jonsson, H., Dawson, W., O'Connor, D., and Newton, R.: The cloud, aerosol  
3 and precipitation spectrometer: a new instrument for cloud investigations, *Atmos. Res.*, 59–60,  
4 251–264, [https://doi.org/10.1016/S0169-8095\(01\)00119-3](https://doi.org/10.1016/S0169-8095(01)00119-3), 2001.
- 5 Baumgardner, D. and Korolev, A.: Airspeed Corrections for Optical Array Probe Sample  
6 Volumes, *J. Atmos. Ocean. Tech.*, 14, 1224–1229, [https://doi.org/10.1175/1520-](https://doi.org/10.1175/1520-0426(1997)014<1224:ACFOAP>2.0.CO;2)  
7 [0426\(1997\)014<1224:ACFOAP>2.0.CO;2](https://doi.org/10.1175/1520-0426(1997)014<1224:ACFOAP>2.0.CO;2), 1997.
- 8 Cazenave, Q., Ceccaldi, M., Delanoë, J., Pelon, J., Groß, S., and Heymsfield, A.: Evolution of  
9 DARDAR-CLOUD ice cloud retrievals: new parameters and impacts on the retrieved  
10 microphysical properties, *Atmos. Meas. Tech.*, 12, 2819–2835, [https://doi.org/10.5194/amt-12-](https://doi.org/10.5194/amt-12-2819-2019)  
11 [2819-2019](https://doi.org/10.5194/amt-12-2819-2019), 2019.
- 12 Cotton, R. J., Field, P. R., Ulanowski, Z., Kaye, P. H., Hirst, E., Greenaway, R. S., Crawford,  
13 I., Crosier, J., and Dorsey, J.: The effective density of small ice particles obtained from in situ  
14 aircraft observations of mid-latitude cirrus, *Q. J. Royal Meteor. Soc.*, 139, 1923–1934, 2013.
- 15 Crosier, J., Bower, K. N., Choulaton, T. W., Westbrook, C. D., Connolly, P. J., Cui, Z.  
16 Q., Crawford, I. P., Capes, G. L., Coe, H., Dorsey, J. R., Williams, P. I., Illingworth, A. J.,  
17 Gallagher, M. W., and Blyth, A. M.: Observations of ice multiplication in a weakly  
18 convective cell embedded in supercooled mid-level stratus, *Atmos. Chem. Phys.*, 11, 257-  
19 273, <https://doi.org/10.5194/acp-11-257-2011>, 2011.
- 20 Davis, S., Hlavka, D., Jensen, E., Rosenlof, K., Yang, Q., Schmidt, S., Borrmann, S., Frey, W.,  
21 Lawson, P., Voemel, H., and Voemel, T. P.: In situ and lidar observations of tropopause  
22 subvisible cirrus clouds during TC4, *J. Geophys. Res.-Atmos.*, 115, D00J17,  
23 [doi:10.1029/2009JD013093](https://doi.org/10.1029/2009JD013093), 2010.
- 24 Delanoë, J., A. Protat, J. Testud, D. Bouniol, A. J. Heymsfield, A. Bansemer, P. R. A. Brown,  
25 and R. M. Forbes: Statistical properties of the normalized ice particle size distribution, *J.*  
26 *Geophys. Res.*, 110, D10201, [doi:10.1029/2004JD005405](https://doi.org/10.1029/2004JD005405), 2005.
- 27 Delanoë, J. M. E., Heymsfield, A. J., Protat, A., Bansemer, A., and Hogan, R. J.: Normalized  
28 particle size distribution for remote sensing application, *J. Geophys. Res.-Atmos.*, 119, 4204–  
29 4227, <https://doi.org/10.1002/2013JD020700>, 2014.
- 30 Ekelund, R., Eriksson, P., and Pfreundschuh, S.: Using passive and active observations at



1 microwave and sub-millimetre wavelengths to constrain ice particle models, *Atmos. Meas.*  
2 *Tech.*, 13, 501–520, <https://doi.org/10.5194/amt-13-501-2020>, 2020.

3 Eriksson, P., Rydberg, B., Mattioli, V., Thoss, A., Accadia, C., Klein, U., and Buehler, S. A.:  
4 Towards an operational Ice Cloud Imager (ICI) retrieval product, *Atmos. Meas. Tech.*, 13, 53–  
5 71, <https://doi.org/10.5194/amt-13-53-2020>, 2020.

6 Field, P. R., Heymsfield, A. J., and Bansemer, A.: Shattering and Particle Interarrival Times  
7 Measured by Optical Array Probes in Ice Clouds, *J. Atmos. Oceanic Technol.*, 23, 1357–1371,  
8 2006.

9 Field, P. R., Heymsfield, A. J., and Bansemer, A.: Snow Size Distribution Parameterization for  
10 Midlatitude and Tropical Ice Clouds, *J. Atmos. Sci.*, 64, 4346–4365,  
11 <https://doi.org/10.1175/2007JAS2344.1>, 2007.

12 Fontaine, E., Schwarzenboeck, A., Leroy, D., Delanoë, J., Protat, A., Dezitter, F., Strapp, J. W.,  
13 and Lilie, L. E.: Statistical analysis of ice microphysical properties in tropical mesoscale  
14 convective systems derived from cloud radar and in situ microphysical observations, *Atmos.*  
15 *Chem. Phys.*, 20, 3503–3553, <https://doi.org/10.5194/acp-20-3503-2020>, 2020.

16 Fugal, J. P. and Shaw, R. A.: Cloud particle size distributions measured with an airborne digital  
17 in-line holographic instrument, *Atmos. Meas. Tech.*, 2, 259–271, <https://doi.org/10.5194/amt->  
18 [2-259-2009](https://doi.org/10.5194/amt-2-259-2009), 2009.

19 Gurganus, C., and Lawson, P.: Laboratory and flight tests of 2D imaging probes: Toward a  
20 better understanding of instrument performance and the impact on archived data, *J. Atmos.*  
21 *Oceanic Technol.* 35, 7, 1533–1553, doi: 10.1175/JTECH-D-17-0202.1, 2018.

22 Heymsfield, A. J., Schmitt, C., and Bansemer, A.: Ice cloud particle size distributions and  
23 pressure dependent terminal velocities from in situ observations at temperatures from 0 to -  
24 86C, *J. Atmos. Sci.*, 70, 4123–4154, 2013.

25 Jackson, R. C., McFarquhar, G. M., Fridlind, A. M., and Atlas, R.: The dependence of cirrus  
26 gamma size distributions expressed as volumes in  $N_0$ - $\lambda$ - $\mu$  phase space and bulk cloud properties  
27 on environmental conditions: Results from the Small Ice Particles in Cirrus Experiment  
28 (SPARTICUS), *J. Geophys. Res.-Atmos.*, 120, 10351–10377, doi:10.1002/2015JD023492,  
29 2015.

30 Jensen, J.B., and Granek, H.: Optoelectronic Simulation of the PMS 260X Optical Array Probe

1 and Application to Drizzle in a Marine Stratocumulus, *J. Atmos. Oceanic Technol.*, 19, 568–  
2 585, [https://doi.org/10.1175/1520-0426\(2002\)019<0568:OSOTPO>2.0.CO;2](https://doi.org/10.1175/1520-0426(2002)019<0568:OSOTPO>2.0.CO;2), 2002.

3 Jensen, E. J., Lawson, P., Baker, B., Pilon, B., Mo, Q., Heymsfield, A. J., Bansemer, A., Bui,  
4 T. P., McGill, M., Hlavka, D., Heymsfield, G., Platnick, S., Arnold, G. T., and Tanelli, S.: On  
5 the importance of small ice crystals in tropical anvil cirrus, *Atmos. Chem. Phys.*, 9, 5519–5537,  
6 <https://doi.org/10.5194/acp-9-5519-2009>, 2009.

7 Lance, S., Brock, C. A., Rogers, D., and Gordon, J. A.: Wa- ter droplet calibration of the Cloud  
8 Droplet Probe (CDP) and in-flight performance in liquid, ice and mixed-phase clouds during  
9 ARCPAC, *Atmos. Meas. Tech.*, 3, 1683–1706, <https://doi.org/10.5194/amt-3-1683-2010>,  
10 2010.

11 Lawson, R. P., O’Connor, D., Zmarzly, P., Weaver, K., Baker, B., Mo, Q., and Jonsson, H.:  
12 The 2D-S (stereo) probe: design and preliminary tests of a new airborne, high-speed, high-  
13 resolution particle imaging probe, *J. Atmos. Ocean. Tech.*, 23, 1462–1477,  
14 <https://doi.org/10.1175/JTECH1927.1>, 2006.

15 Lindqvist, H., Muinonen, K., Nousiainen, T., Um, J., McFarquhar, G. M., Haapanala, P.,  
16 Makkonen, R., and Hakkarainen, H.: Ice cloud particle habit classification using principal  
17 components, *J. Geophys. Res.*, 117, D16206, doi:10.1029/2012JD017573, 2012.

18 McFarquhar, G. M. and Heymsfield, A. J.: Parameterization of tropical cirrus ice crystal size  
19 distributions and im- plications for radiative transfer: Results from CEPEX, *J. Atmos. Sci.*, 54,  
20 2187–2200, [https://doi.org/10.1175/1520-0469\(1997\)054<2187:POTCIC>2.0.CO;2](https://doi.org/10.1175/1520-0469(1997)054<2187:POTCIC>2.0.CO;2), 1997.

21 McFarquhar, G. M., Um, J., Freer, M., Baumgardner, D., Kok, G. L., and Mace, G.: The  
22 importance of small ice crystals to cirrus properties: Observations from the Tropical Warm Pool  
23 International cloud Experiment (TWP-ICE), *Geophys. Res. Lett.*, 57, L13803,  
24 doi:10.1029/2007GL029865, 2007.

25 Praz, C., Ding, S., McFarquhar, G. M., & Berne, A.: A versatile method for ice particle  
26 habit classification using airborne imaging probe data, *J. Geophys. Res.*, 123, 13,472–  
27 13,495. <https://doi.org/10.1029/2018JD029163>, 2018.

28 Knollenberg, R. G.: The optical array: An alternative to scattering or extinction for airborne  
29 particle size determination, *J. Appl. Meteorol.*, 9, 86–103, doi:10.1175/1520-  
30 0450(1970)009<0086:TOAAAT>2.0.CO;2, 1970.

1 Korolev, A. and Isaac, G. A.: Shattering during sampling by OAPs and HVPS. Part 1: Snow  
2 particles, *J. Atmos. Ocean. Tech.*, 22, 528–542, <https://doi.org/10.1175/JTECH1720.1>, 2005.

3 Korolev, A.: Reconstruction of the sizes of spherical particles from their shadow images. Part  
4 I: Theoretical considerations, *J. Atmos. Ocean. Tech.*, 24, 376–389, 2007.

5 Korolev, A. V., Emery, E. F., Strapp, J. W., Cober, S. G., Isaac, G. A., Wasey, M. and Marcotte,  
6 D.: Small ice particles in tropospheric clouds: Fact or artifact? Airborne icing instrumentation  
7 evaluation experiment, *Bull. Am. Meteorol. Soc.*, 92(8), 967–973,  
8 doi:10.1175/2010BAMS3141.1, 2011.

9 Korolev, A. V., Kuznetsov, S. V., Makarov, Yu. E., and Novikov, V. S.: Evaluation of  
10 measurements of particle size and sample area from optical array probes. *J. Atmos. Oceanic  
11 Technol.*, 8, 514–522, 1991.

12 Korolev, A. and Field, P. R.: Assessment of the performance of the inter-arrival time  
13 algorithm to identify ice shattering artifacts in cloud particle probe measurements, *Atmos.  
14 Meas. Tech.*, 8, 761–777, <https://doi.org/10.5194/amt-8-761-2015>, 2015.

15 Korolev, A. V., Strapp, J. W., and Isaac, G. A.: Evaluation of the accuracy of PMS optical array  
16 probes, *J. Atmos. Ocean. Tech.*, 15, 708–720, [https://doi.org/10.1175/1520-  
17 0426\(1998\)0152.0.CO;2](https://doi.org/10.1175/1520-0426(1998)0152.0.CO;2), 1998.

18 Korolev, A. and Sussman, B.: A technique for habit classification of cloud particles, *J.  
19 Atmos. Ocean. Tech.*, 17, 1048–1057, 2000.

20 Korolev, A., Emery, E., and Creelman, K.: Modification and Tests of Particle Probe Tips  
21 to Mitigate Effects of Ice Shattering, *J. Atmos. Ocean. Tech.*, 30, 690–708,  
22 <https://doi.org/10.1175/JTECH-D-12-00142.1>, 2013.

23 Korolev, A. V., Emery, E. F., Strapp, J. W., Cober, S. G., Isaac, G. A., Wasey, M., and  
24 Marcotte, D.: Small Ice Particles in Tropospheric Clouds: Fact or Artifact? Airborne Icing  
25 Instrumentation Evaluation Experiment, *B. Am. Meteorol. Soc.*, 92, 967–973,  
26 <https://doi.org/10.1175/2010BAMS3141.1>, 2011.

27 Lawson, R. P., O’Connor, D., Zmarzly, P., Weaver, K., Baker, B., Mo, Q. and Jonsson, H.: The  
28 2D-S (stereo) probe: Design and preliminary tests of a new airborne, high-speed, high-  
29 resolution particle imaging probe, *J. Atmos. Ocean. Technol.*, 23(11), 1462–1477,  
30 doi:10.1175/JTECH1927.1, 2006.

1 Mitchell, D. L., Garnier, A., Pelon, J., and Erfani, E.: CALIPSO (IIR–CALIOP) retrievals of  
2 cirrus cloud ice-particle concentrations, *Atmos. Chem. Phys.*, 18, 17325–17354,  
3 <https://doi.org/10.5194/acp-18-17325-2018>, 2018.

4 O'Shea, S. J., Choulaton, T. W., Lloyd, G., Crosier, J., Bower, K. N., Gallagher, M., Abel, S.  
5 J., Cotton, R. J., Brown, P. R. A., Fugal, J. P., Schlenczek, O., Borrmann, S., and Pickering, J.  
6 C.: Airborne observations of the microphysical structure of two contrasting cirrus clouds, *J.*  
7 *Geophys. Res.*, 121, 13510–13536, <https://doi.org/10.1002/2016JD025278>, 2016.

8 O'Shea, S. J., Crosier, J., Dorsey, J., Schledewitz, W., Crawford, I., Borrmann, S., Cotton, R.,  
9 and Bansemer, A.: Revisiting particle sizing using greyscale optical array probes: evaluation  
10 using laboratory experiments and synthetic data, *Atmos. Meas. Tech.*, 12, 3067–3079,  
11 <https://doi.org/10.5194/amt-12-3067-2019>, 2019.

12 Schlenczek, O.: Airborne and ground-based holographic measurement of hydrometeors in  
13 liquid-phase, mixed-phase and ice clouds, PhD Thesis, University of Mainz, 2017.

14 Sourdeval, O., Gryspeerdt, E., Krämer, M., Goren, T., Delanoë, J., Afchine, A., Hemmer, F.,  
15 and Quaas, J.: Ice crystal number concentration estimates from lidar–radar satellite remote  
16 sensing – Part 1: Method and evaluation, *Atmos. Chem. Phys.*, 18, 14327–14350,  
17 <https://doi.org/10.5194/acp-18-14327-2018>, 2018.

18 Ulanowski, Z., Hesse, E., Kaye, P. H., Baran, A. J., and Chandrasekhar, R.: Scattering of light  
19 from atmospheric ice analogues, *J. Quant. Spectrosc. Ra.*, 79, 1091–1102, 2003.

20 Vaillant de Guélis, T., Schwarzenböck, A., Shcherbakov, V., Gourbeyre, C., Laurent, B.,  
21 Dupuy, R., Coutris, P., and Duroure, C.: Study of the diffraction pattern of cloud particles and  
22 the respective responses of optical array probes, *Atmos. Meas. Tech.*, 12, 2513–2529,  
23 <https://doi.org/10.5194/amt-12-2513-2019>, 2019a.

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

27 Wendisch, M. and Brenguier, J.-L. (Eds.): Airborne Measurements for Environmental  
28 Research: Methods and Instruments, vol. ISBN: 978-3-527-40996-9, Wiley-VCH Verlag  
29 GmbH and Co. KGaA, Weinheim, Germany, 2013.

We would like to thank both reviewers for their constructive comments about our manuscript. We now address their comments individually. For clarity referee comments are shown in red and our responses in black.

For context, the comments from referee 2 were received in pre-review and have been at least partially addressed before publication in AMTD. The referee may not have seen the changes in the version published in AMTD.

#### Referee 1

As pointed out in the manuscript, in situ measurements of ice particle size distributions (PSDs) have been made to a large extent by optical array probes (OAPs) and they are still in frequent use. These probes have indicated high number concentrations of particles at sizes below 100  $\mu\text{m}$ . It has been shown that this is partly an artefact of shattering of larger particles. Measures to remove the impact of shattering have been developed. The question is if PSDs derived from these optical probes now are roughly correct, or if there still exist basic issues?

It seems that this study is motivated by remaining discrepancies between PSDs derived by OAPs and another type of sensor, HALOHolo, observed for some flights by the FAAM Bae-146 research. By developing and applying measures to remove the impact of particles out of focus, that then are mis-sized, the discrepancies are largely removed.

The analysis behind the measures to avoid mis-sizing is ambitious and appears to have been performed in a solid manner. The change in PSDs for particles below 30  $\mu\text{m}$  varies but can reach orders of magnitude. Such changes in PSDs have broad implications for the radiative transfer involving ice particles, both inside atmospheric models and inversions of observations.

The overall analysis has intrinsic value and is sufficient to make the article highly relevant. However, it would of course be nice to know if we now can trust PSDs derived from OAPs (if measures to avoid mis-sizing are applied)? The authors do not claim this, but the much-improved agreement with HALOHolo still hints in this direction. Anyhow, the agreement with HALOHolo works as a proof of concept and that makes the quality of the HALOHolo PSDs important. In summary, I find the manuscript very interesting and having an overall high quality.

General comments:

The manuscript is relatively long. There is already a supplement and I suggest moving some figures to the supplement. For example, despite it is nice to see the hardware, Figure 2 did not help me to understand the measurement setup. It is sufficiently well described in the text. It could suffice to just show one of Fig, 5, 6, and 7 in the manuscript. Maybe the same for Fig 12 and 13.

We are aware that the paper is relatively long, however we would prefer to include these plots in the main paper. The level of agreement between the laboratory experiments and model is very important when considering the strength of the conclusions that are drawn from the model simulations later in the paper. Including these plots in the main paper makes them more easily accessible to the reader and we expect more widely referred to.

On the other hand, I would like to see an extension around HALOHolo. As discussed above, the accuracy of HALOHolo PSDs is quite crucial for the final interpretation of the results. Could HALOHolo in any way miss particles of 10-30  $\mu\text{m}$  size? Maybe a naive question, but I don't know anything about HALOHolo and the manuscript does not give any hints. Adding some reference(s) is a basic demand, but I would prefer to also see a critical discussion.

The following sentences have been added to Sect 4.1 discussing HALOHolo:

“HALOHolo’s sample volume is not as strongly dependent on particle size as it is for OAPs. However as described earlier, measurements of small particles from HALOHolo are limited by noise in the background image. For a complete description of the HALOHolo data processing and quality control procedures see Schlenczek (2017). HALOHolo uses supervised machine learning to discriminate real particles from artefacts due to noise in the background image. However, it is possible that small particles could be misclassified as artefacts or vice versa, and as a result HALOHolo could either underestimate or overestimate the small ice concentration. For particles  $> 35 \mu\text{m}$  it is estimated that the probe’s detection rate is  $>90\%$  and previous work has shown excellent agreement with a CDP in liquid clouds (Schlenczek, 2017). However, HALOHolo PSDs should not be considered the true PSD, but rather another piece of evidence that suggests for these cases OAPs overestimate small ice concentrations using current data processing techniques.”

I can not find any clear rule on how to name variables in the AMT guideline, but I would still suggest using letters for variables instead of acronyms. A basic problem with using acronyms is found in e.g. Eq 2. Is ER here a variable, or the product between E and R? Maybe OK in an equation but can cause severe confusion on the text (e.g. page 27, line 15). In any case, variables shall be typeset in a consistent manner, and not be different between text and equations.

The abbreviations DoF (depth of field), SVol (sample volume), and TAS (true airspeed) are widely used in the literature when presenting the OAP sample volume equations (for example the review paper McFarguhar et al., 2017). To maintain consistency with previous work we would prefer to continue using these abbreviations. ER is the product of E and R, both E and R are defined immediately after the equation.

Note there was a mistake in the effective array width in equation 2 and 5. The effective array width should be given by  $R(E-1)-D$ , this is corrected in the revised manuscript.

Section 3 should be renamed to "Results and discussion".

Done

Smaller issues: The text is in general very clear. The only part I could not follow is the first paragraph on page 33. The problem is likely the start sentence.

This sentence concerns a side point and has been removed in the revised manuscript.

More or less the same for figures. I don’t understand the right panel of Figure 16 (also on page 33!). Why is it needed? And are the two panels really consistent?

The left panel shows the particle size distribution and the right panel shows instrument counts versus size for the same period. The right panel is not needed and has been removed in the revised manuscript. Note that Fig 16 and 17 have updated after removing a small bug in the stereo sample volume calculation, there are no change in the results/conclusions from these plots.

Further, CDP seems to disagree above  $50 \mu\text{m}$ , in contrast to what is written at line 12.

This has been corrected in the revised manuscript to read:

“All data processing methods are in good agreement up to  $100 \mu\text{m}$ . For larger sizes the measurements using the co-located particles are limited by counting statistics due to the low concentration of these particles.”

Some even smaller issues I leave for the copy editing.

Referee 2

Recommendation: Requires major revision after which its suitability for publication can be reassessed

The subject matter of this manuscript is timely and within the scope of AMT. It has been long recognized that there are significant uncertainties in the concentrations of small ice crystals that are measured by optical array probes due not only to the possibility of ice crystal shattering, but also because there is a small, poorly defined and dimensional-dependent depth of field. This paper attempts to improve upon the determination of a probe's sample volume by using grayscale image analysis and co-location using stereoscopic imaging. Although the former has already been treated in the literature, the later is especially a novel contribution that deserves publication. Further, the manuscript is well written and the figures are of high quality. As such, it appears that the paper should eventually appear in AMT. However, as the conclusions of this study can be far-reaching, it is important that the technical details of the study have the highest quality. There are some overarching concerns about some of the analysis and some misinterpretations of previous studies that should be corrected before this paper is accepted.

First, the Korolev (2007) technique was never designed to work on non-spherical particles so the application of this technique to non-spherical particles is not appropriate here, even if prior studies have applied the technique to non-spherical particles.

In the manuscript we state that Korolev (2007) was designed for spherical particles. However, in the absence of an alternative it has also been applied to non-spherical particles (e.g. Davis et al., 2010). This work tests and discusses the efficacy of this approach. The following text is from Sect 3.2 of the manuscript:

"The K07 approach was derived by considering Fresnel diffraction from opaque discs and has only been tested for images of spherical droplets. However, in the absence of an alternative previous studies have applied K07 to images of ice crystals (e.g. Davis et al., 2010)."

We conclude in Sect. 3.2 that:

"For a number of habits (rosette, plate, quasi-spherical, rosette-aggregate and plate-aggregate) K07 reduces the number of over-sized particles across most of the DoF. For bullets, columns and column aggregates K07 has minimal impact on the probe sizing. For all habits, K07 is not able to remove the small image fragments that occur when a particle is near the edge of the DoF."

Second, for the determination of the probe sample volume, there are optical reasons why the diameter in the direction of the photodiode array should be used in the consideration of the depth of field of the instrument. If this definition is not used, a proper depth of field dependence on particle habit/placement in the array cannot be derived.

We are only aware of a few publications that have determined the OAP depth of field for non-spherical particles (e.g. Vaillant de Guélis et al., 2019; Gurganus, & Lawson, 2018), these studies only focused on a limited number of particle shapes and specific sizes. They do not present general rules for a range of particle shapes and sizes. This information is needed to calculate accurate particle concentrations from field measurements in ice clouds. Wu et al. (2016) show that ice cloud PSDs have high sensitivity to the choice of ice crystal size metric. However, we are not aware of any previous study that examines the suitability of different definitions of particle size to determine the depth of field. Our paper determines the depth of field for a wide range of crystal habits and examines the variability between them depending on the particle size metric used. We find that if circle equivalent diameter is used to calculate the depth of field then there is less variability between habits compared to using the mean X-Y or maximum dimension.

We have added the following paragraph to section 4.1 on the calculation of the effective array width, which should use the image size parallel to the optical array

“When determining the effective array width (Eq. 2), the image size along the direction of the photodiode array should be used. However, this size is a function of the particle’s Z position, which is the reason why the effective array width needs to be integrated over the depth of field to determine the sample volume (Eq. 2). This can be calculated using the AST model if the true particle shape can be assumed (e.g. spherical particles in liquid cloud). However, if the true particle shape is not known, as is often the case for ice clouds, then it remains a source of uncertainty in the calculated sample volume.”

Third, the paper exaggerates the implications of the study for the parameterizations or representations of small ice crystals. Most previous studies have specifically noted that there are large uncertainties in quantifying the contributions of particles with dimensions smaller than 150 micrometers due to small and poorly defined depths of field for small particles (going back to a study of Baumgardner and Korolev 1997 that has been cited many times). This study is not even referenced here! This study seems to be using a threshold size of 200 um rather than 150 um, so there is a bit of a difference here. But, the findings of the manuscript should be better placed in the context of other studies that have already been conducted as otherwise the implications of this study are overexaggerated.

There are several uncertainties associated with measuring small particles using OAPs: electronic time response; poorly defined depth of field; poor counting statistics due to a small depth of field; and miss-sizing due to diffraction. These have been addressed to varying degrees in the literature.

Baumgardner and Korolev (1997) discusses the uncertainty due to the electronic time response of the probe. This is already referenced in Sect 2.1 of the paper:

“Baumgardner & Korolev (1997) show that the electronic time response of older probes can significantly reduce the DoF of small particles. This affect has been minimised in more modern probes such as the 2D-S and CIP-15, which have an order of magnitude faster time response.”

Counting uncertainty can be relatively simply quantified and can be mitigated by using longer averaging times. Generally, previous studies address this source of uncertainty (see for example the recent cirrus climatology paper Kramer et al., 2020).

However, studies examining the sizing uncertainty due to the diffraction from non-spherical shapes are rare (we are only aware of Vaillant de Guélis et al., 2019). No corrections for OAP PSDs of non-spherical particles exist as they do for spherical particles (e.g. Korolev et al., 2007; O’Shea et al., 2019). Despite this uncertainty, OAP measurements of ice crystal PSDs for particles smaller than 150 um are still widely used in parameterisations (e.g. Delanoe et al., 2014) and process studies (e.g. Cotton et al., 2013; Jackson et al., 2015).

I’m not sure that the data availability statement meets the threshold required by the journal. In general, the data should be available at a publicly accessible web site rather than only on request to the contact author. If this study is going to have far-reaching implications, these data should be more openly available for others to test their algorithms with. I’ll leave it for the Chief Editor to decide if this statement is adequate.

We will follow the editor’s advice regarding this.

#### References

Baumgardner, D. and Korolev, A.: Airspeed Corrections for Optical Array Probe Sample Volumes, J.



Atmos. Ocean. Tech., 14, 1224–1229, [https://doi.org/10.1175/1520-0426\(1997\)014<1224:ACFOAP>2.0.CO;2](https://doi.org/10.1175/1520-0426(1997)014<1224:ACFOAP>2.0.CO;2), 1997.

Cotton, R. J., Field, P. R., Ulanowski, Z., Kaye, P. H., Hirst, E., Greenaway, R. S., Crawford, I., Crosier, J., and Dorsey, J.: The effective density of small ice particles obtained from in situ aircraft observations of mid-latitude cirrus, *Q. J. Royal Meteor. Soc.*, 139, 1923–1934, 2013.

Davis, S., Hlavka, D., Jensen, E., Rosenlof, K., Yang, Q., Schmidt, S., Borrmann, S., Frey, W., Lawson, P., Voemel, H., and Voemel, T. P.: In situ and lidar observations of tropopause subvisible cirrus clouds during TC4, *J. Geophys. Res.-Atmos.*, 115, D00J17, [doi:10.1029/2009JD013093](https://doi.org/10.1029/2009JD013093), 2010.

Delanoë, J. M. E., Heymsfield, A. J., Protat, A., Bansemer, A., and Hogan, R. J.: Normalized particle size distribution for remote sensing application, *J. Geophys. Res.-Atmos.*, 119, 4204–4227, <https://doi.org/10.1002/2013JD020700>, 2014.

Gurganus, C. and Lawson, P.: Laboratory and flight tests of 2D imaging probes: Toward a better understanding of instrument performance and the impact on archived data, *J. Atmos. Ocean. Tech.*, 35, 7, 1533–1553, <https://doi.org/10.1175/JTECH-D-17-0202.1>, 2018.

Jackson, R. C., McFarquhar, G. M., Fridlind, A. M., and Atlas, R.: The dependence of cirrus gamma size distributions expressed as volumes in  $\text{NO}-\lambda-\mu$  phase space and bulk cloud properties on environmental conditions: Results from the Small Ice Particles in Cirrus Experiment (SPARTICUS), *J. Geophys. Res.-Atmos.*, 120, 10351–10377, [doi:10.1002/2015JD023492](https://doi.org/10.1002/2015JD023492), 2015.

Korolev, A.: Reconstruction of the sizes of spherical particles from their shadow images. Part I: Theoretical considerations, *J. Atmos. Ocean. Tech.*, 24, 376–389, 2007.

Krämer, M., Rolf, C., Spelten, N., Afchine, A., Fahey, D., Jensen, E., Khaykin, S., Kuhn, T., Lawson, P., Lykov, A., Pan, L. L., Riese, M., Rollins, A., Stroh, F., Thornberry, T., Wolf, V., Woods, S., Spichtinger, P., Quaas, J., and Sourdeval, O.: A Microphysics Guide to Cirrus – Part II: Climatologies of Clouds and Humidity from Observations, *Atmos. Chem. Phys. Discuss.*, <https://doi.org/10.5194/acp-2020-40>, in review, 2020.

McFarquhar, G. M., Baumgardner, D., Bansemer, A., Abel, S. J., Crosier, J., French, J., Rosenberg, P., Korolev, A., Schwarzenböck, A., Leroy, D., Um, J., Wu, W., Heymsfield, A. J., Twohy, C., Detwiler, A., Field, P., Neumann, A., Cotton, R., Axisa, D., and Dong, J.: 11 – Processing of Ice Cloud In Situ Data Collected by Bulk Water, Scattering, and Imaging Probes: Fundamentals, Uncertainties, and Efforts toward Consistency, *Meteor. Mon.*, 58, 11.1–11.33, <https://doi.org/10.1175/AMSMONOGRAPHS-D-16-0007.1>, 2017

O'Shea, S. J., Crosier, J., Dorsey, J., Schledewitz, W., Crawford, I., Borrmann, S., Cotton, R., and Bansemer, A.: Revisiting particle sizing using greyscale optical array probes: evaluation using laboratory experiments and synthetic data, *Atmos. Meas. Tech.*, 12, 3067–3079, <https://doi.org/10.5194/amt-12-3067-2019>, 2019.

Vaillant de Guélis, T., Schwarzenböck, A., Shcherbakov, V., Goubeyre, C., Laurent, B., Dupuy, R., Coutris, P., and Durore, C.: Study of the diffraction pattern of cloud particles and the respective responses of optical array probes, *Atmos. Meas. Tech.*, 12, 2513–2529, <https://doi.org/10.5194/amt-12-2513-2019>, 2019.

Wu, W. and McFarquhar, G. M.: On the Impacts of Different Definitions of Maximum Dimension for Nonspherical Particles Recorded by 2D Imaging Probes, *J. Atmos. Ocean. Tech.*, 33, 1057–1072, <https://doi.org/10.1175/JTECH-D-15-0177.1>, 2016.

