



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 $0.1\ \mu\text{s}$
32 to 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 μm . 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 λ 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 by dividing the number of counts by the sample volume
19 (SVol), which is given by,

$$20 \quad SVol = TAS \int_{-DoF}^{+DoF} (ER - D(Z)) dZ,$$

21 Equation 2

22 Where TAS is the true air speed, E is the number of detector array elements, R is pixel size of
23 the probe and D is the image diameter. The integration of the effective array width ($ER - D(Z)$)
24 is performed over whichever is smaller out of the DoF and the armwidth of the probe.

25 For spherical particles, corrections exist which correct for the diffraction effects of sampling
26 offset from the object plane, which allows the calculation of the true particle size from the
27 measured image size. Korolev et al. (1991) show that the diffraction from spherical liquid drops
28 can be approximated by the Fresnel diffraction from an opaque disk. The ratio of the measured
29 image diameter to the true particle diameter is a function of the dimensionless distance from
30 the object plane Z_d :



1

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

2

Equation 3

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

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

15 This paper quantifies the uncertainties in OAP size and shape measurements of non-spherical
16 ice crystals and presents corrections that removes large biases from OAP datasets. In Sect. 3.1,
17 3-D ice crystal analogs are repetitively passed through the sample volume of an OAP at
18 different distances from the object plane. These results are used to examine the ability of a
19 diffraction model based on angular spectrum theory to characterise the response of OAPs. In
20 Sections 3.2 to 3.5 a variety of ice crystals from commonly occurring habits are tested with the
21 diffraction model to quantify how OAP image quality degrades throughout a probe's sample
22 volume. Section 4 suggests and tests methods to improve OAP data quality. The impact these
23 results have on ice crystal PSDs is examined using field measurements collected during three
24 research flights in frontal cirrus. The impacts OAP measurement bias has on our understanding
25 of ice cloud microphysics are discussed in Sect. 5.

26



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 μm . 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 μm 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 1×10^{-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 and 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 μm (ROS118), 250 μm (ROS250) and
14 300 μm (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 μm 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 m s^{-1} , positional
22 accuracy of 200 μm 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.

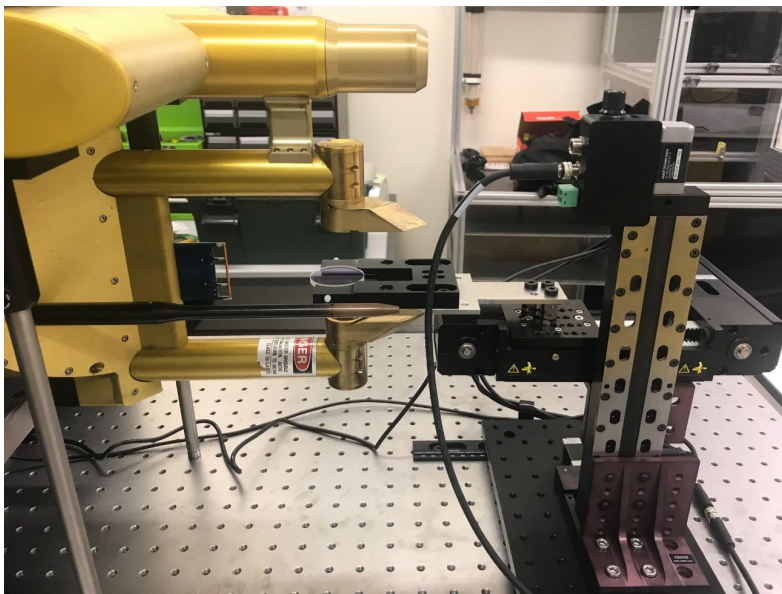
28 Images were post-processed to take account of any difference in velocity between the stage and
29 the CIP-15 data acquisition rate by resampling the images along the axis perpendicular to the
30 optical array. This was performed to match the aspect ratio at Z=0 of the CIP-15 image and a



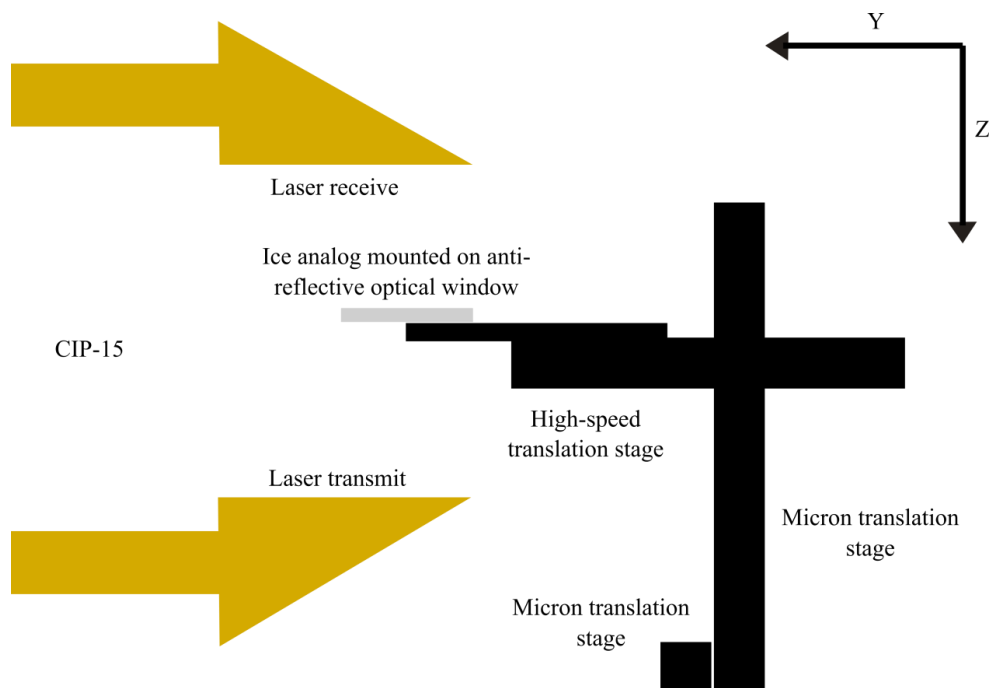
1 microscope image of each analog. This typically corresponded to a particle stage velocity of ~
2 0.1 m s^{-1} .
3



4
5 *Figure 1. Microscope images of sodium fluosilicate 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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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)**

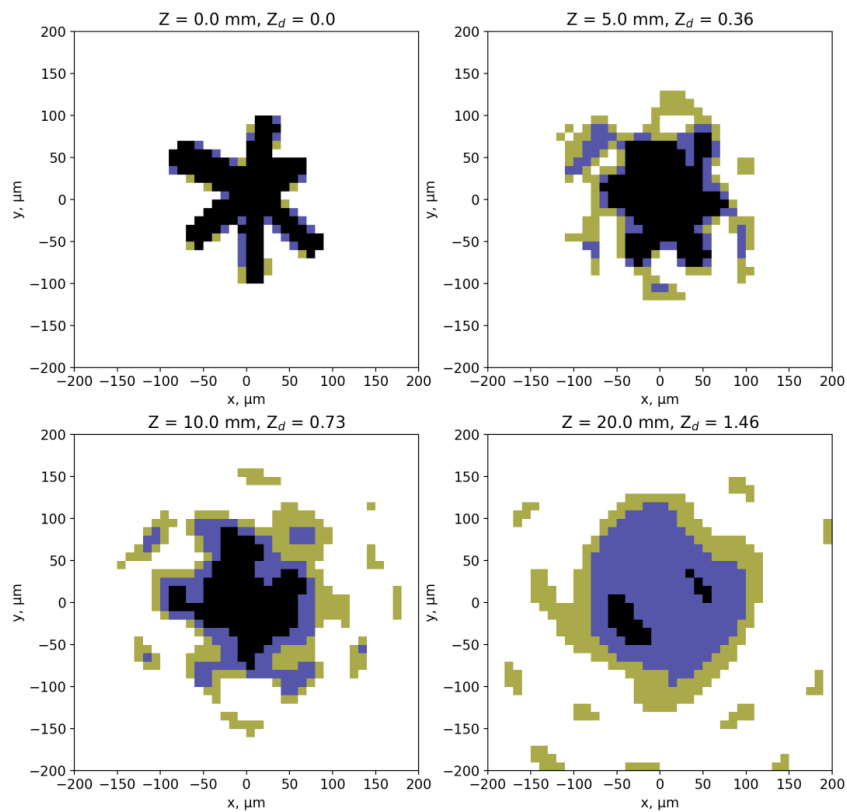
9 Theoretical shadow images of 2D non-spherical shapes were calculated using a diffraction
10 model based on Angular Spectrum Theory (referred to as the AST model). Several previous
11 studies describe this model in detail (Vaillant de Guélis et al., 2019a, 2019b). We initialised the
12 model using a 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 μm pixel resolution, which is typical of modern OAPs. All simulations were
16 performed using a light wavelength of 0.658 μm .

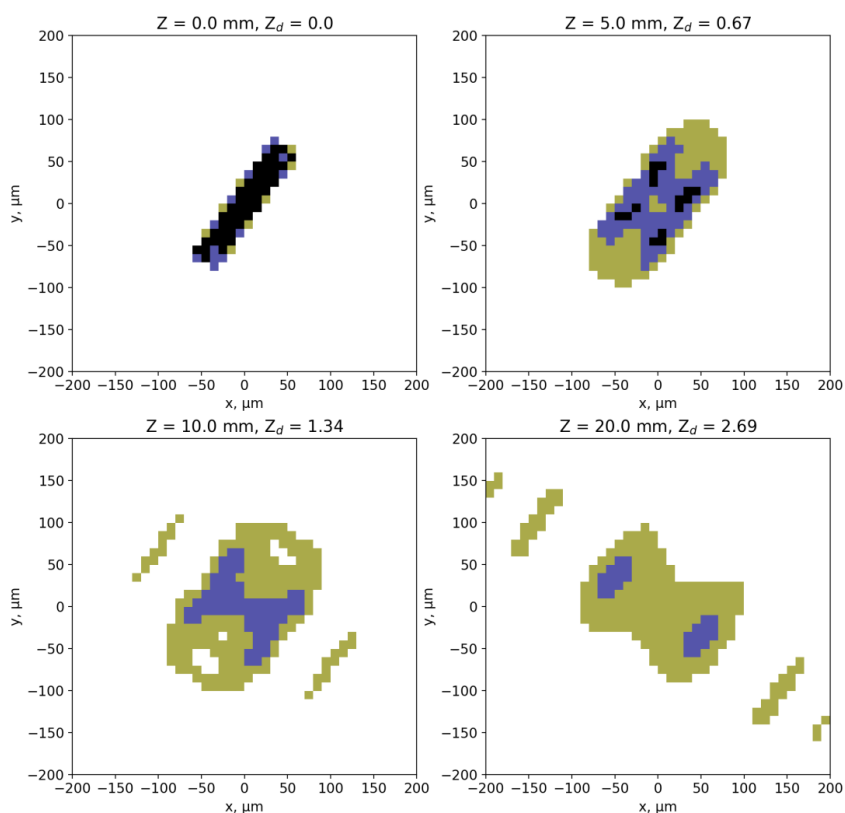
17 An example simulation for a rosette crystal is shown in Fig. 3 and a column in Fig. 4, the top
18 left panels show the images at $Z=0$ that are used to initialise the model. The other panels show
19 images of the crystals at different distances from the object plane. Green, blue and black pixels
20 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 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 6576×4384 pixel CCD detector with an effective pixel size of $2.95 \mu\text{m}$ and arm separation of
3 155 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 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 μm) 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**

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

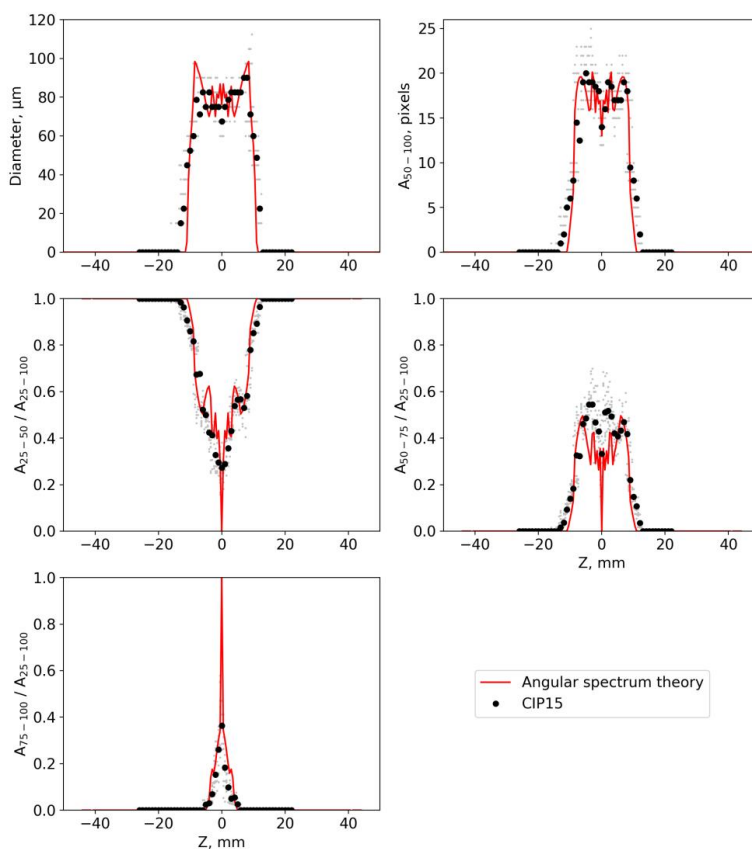
16 This section compares CIP-15 images of ice crystal analogs with diffraction simulations using
17 the AST model. Figures 5-7 show the image size of the ice crystal analogs ROS118, ROS250
18 and ROS300 at different distances (Z) from the object plane measured by the CIP-15 (black
19 markers) and modelled 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.

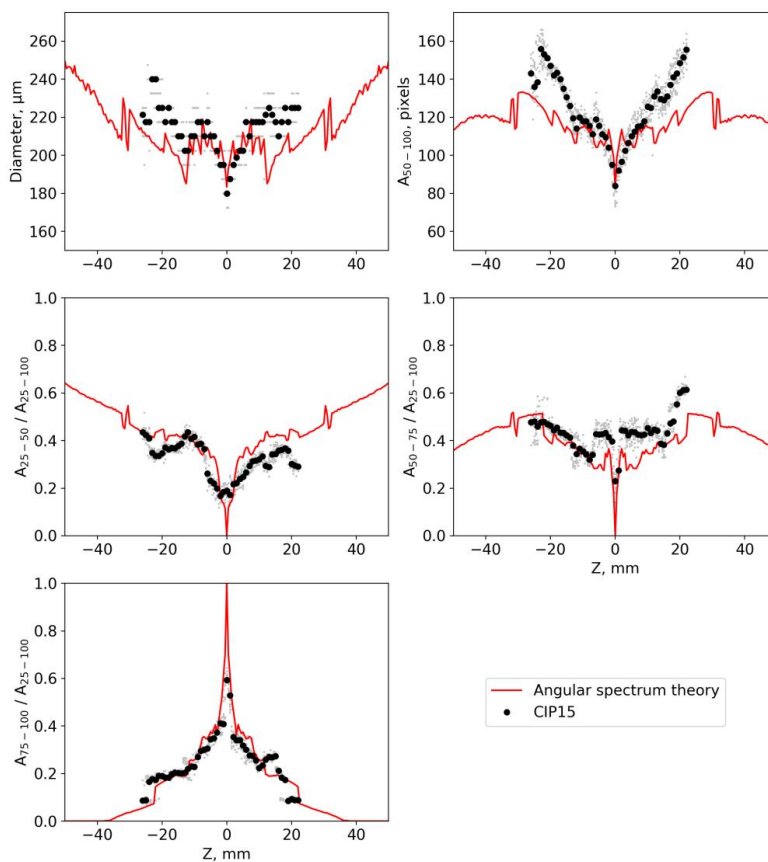
3 In general, the AST model can capture the large-scale structure in these measured parameters,
4 although some discrepancies are present in the finer detail. For ROS118 the DoF from the
5 experiments and the model agree to within ± 1 mm (Fig. 5). The size and greyscale parameters
6 calculated from CIP-15 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.*

6

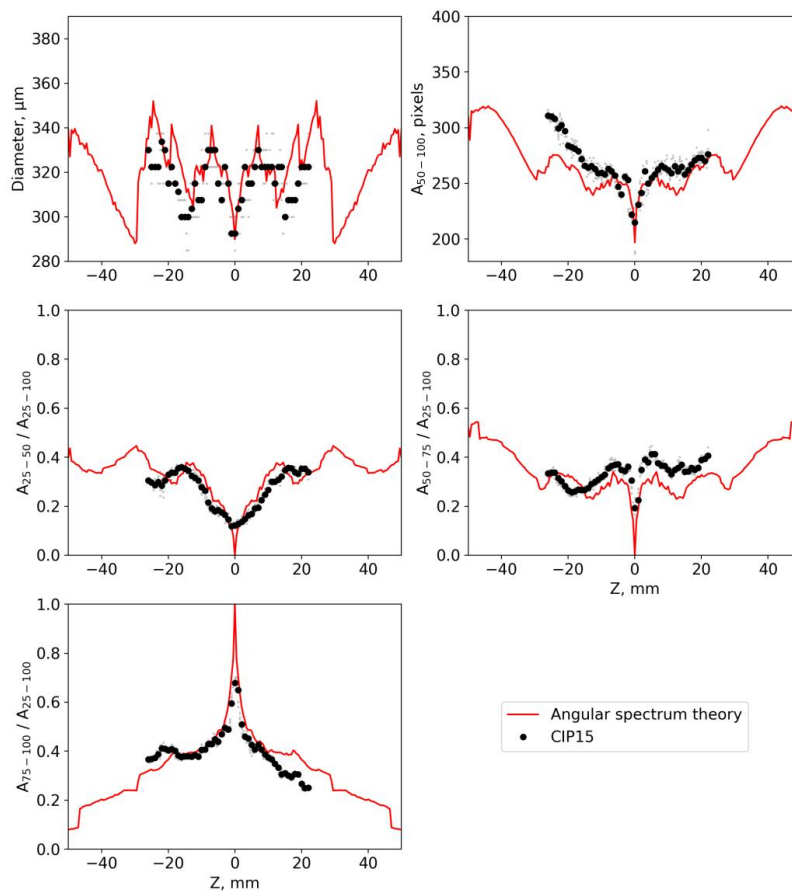


7

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



1

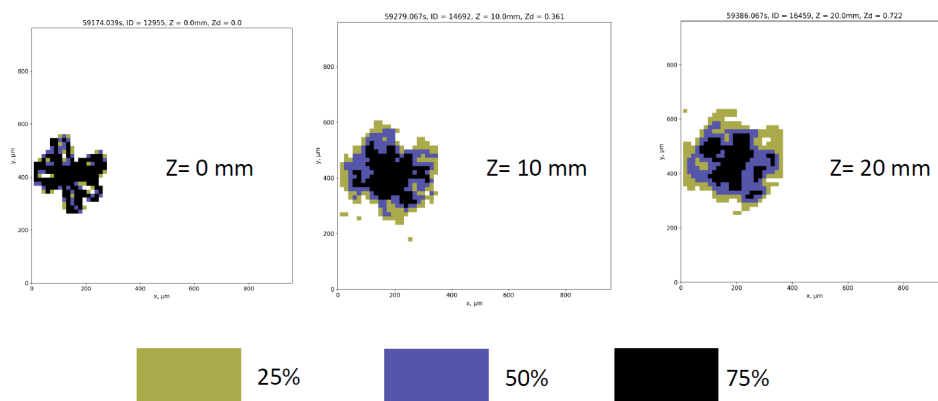


2

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

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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
11 for 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.

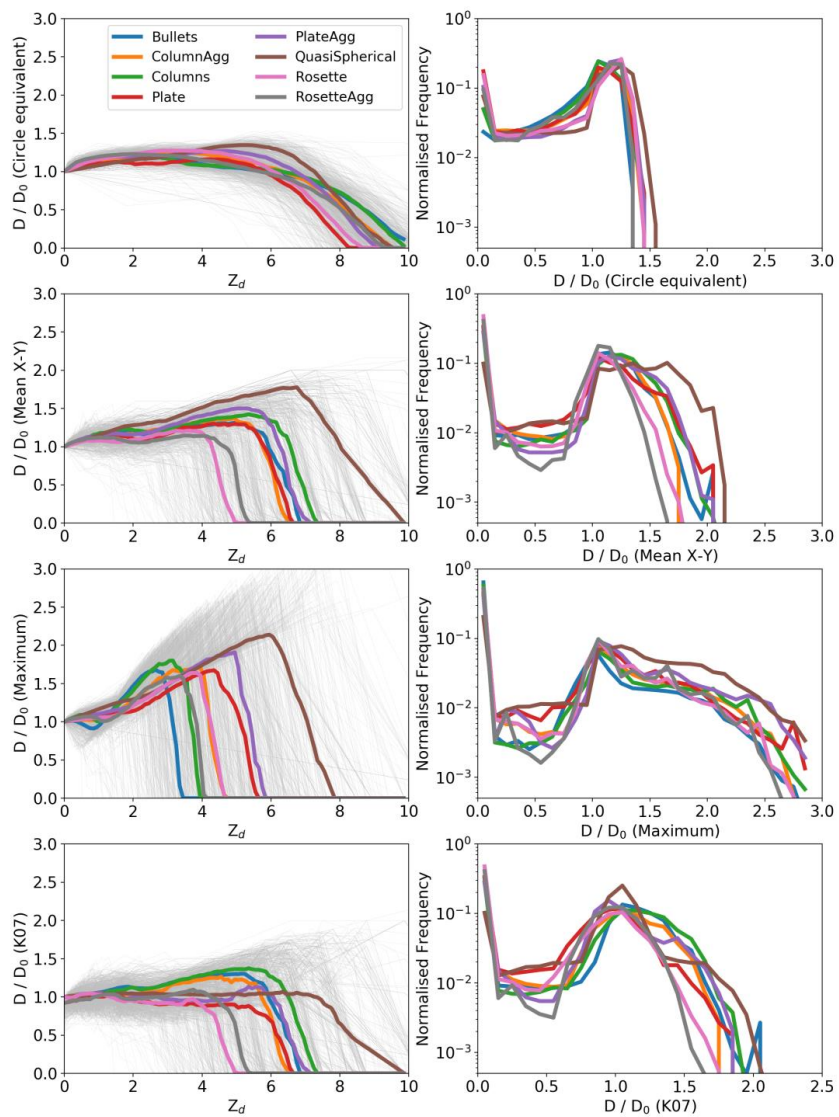


1 There is a general trend of increasing size with distance from the object plane. Over-sizing is
2 up to approximately 100%, 200% and 50% using mean X-Y, maximum and circle equivalent
3 diameters, respectively. However, the degree of oversizing is dependent on habit, with quasi-
4 spherical and plate 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, previous studies have applied K07 to images
12 of ice crystals (e.g. Davis et al., 2010). To examine the efficacy of this approach, Fig. 9 bottom
13 panels shows the mean X-Y diameter of the simulated images of ice crystals once K07 has been
14 applied. The ratio of their K07 corrected diameter to their true particle diameter is shown as a
15 function of Z_d (left panel), while probability density functions of D/D_0 for each habit are shown
16 in the right panel. The median D/D_0 for the Z_d range 0 to 8 is 0.9 and the inter-quartile range is
17 1.1. For a number of habits (rosette, plate, quasi-spherical, rosette-aggregate and plate-
18 aggregate) K07 reduces the number of over-sized particles across most of the DoF. For bullets,
19 columns and column aggregates K07 has minimal impact on the probe sizing. Like for droplets,
20 K07 is not able to remove the small image fragments that occur when a particle is near the edge
21 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

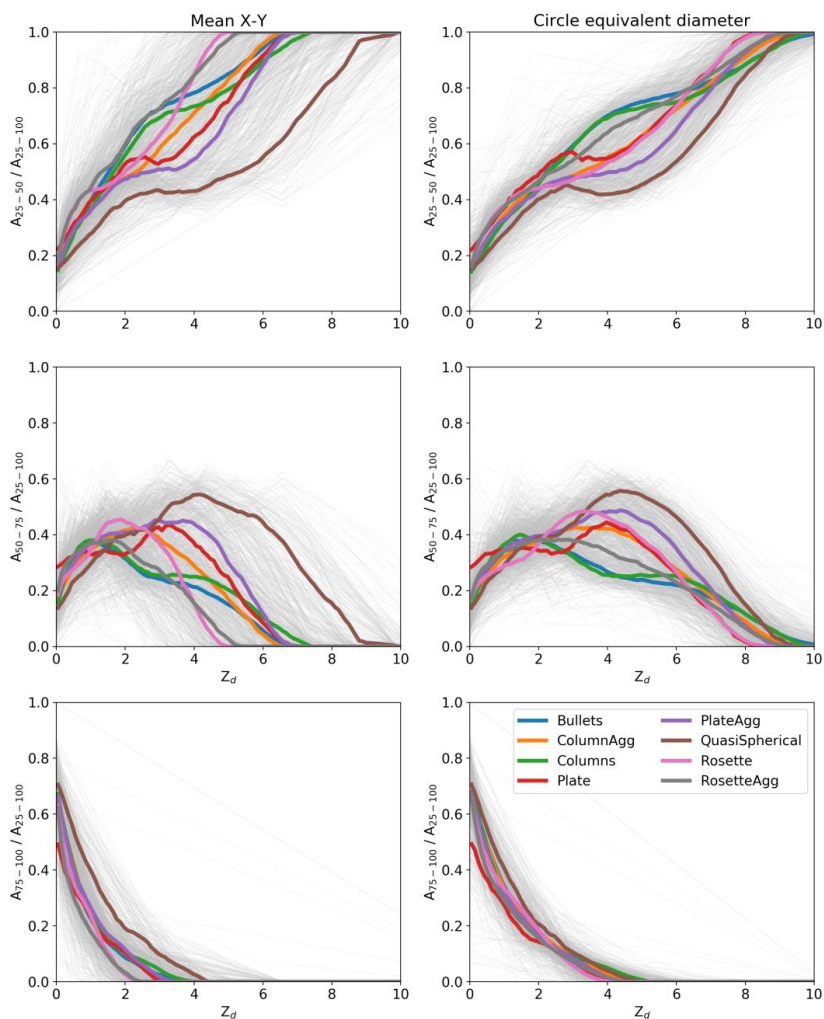
5 **3.4 Greyscale information**

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

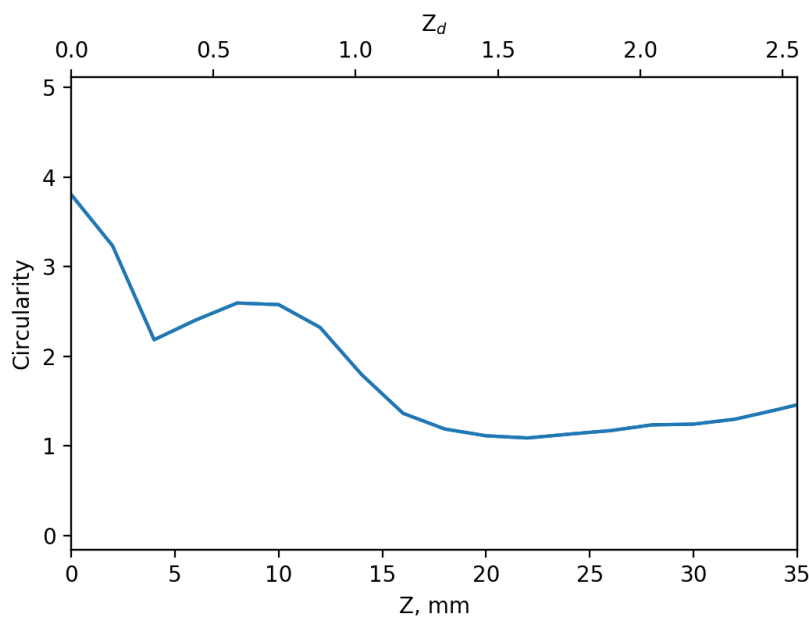
$$11 \quad \textit{Circularity} = \frac{P^2}{4\pi A}$$

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_d. 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_d (and Z) with the circularity decreasing by a factor 2 by
25 Z_d=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

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)

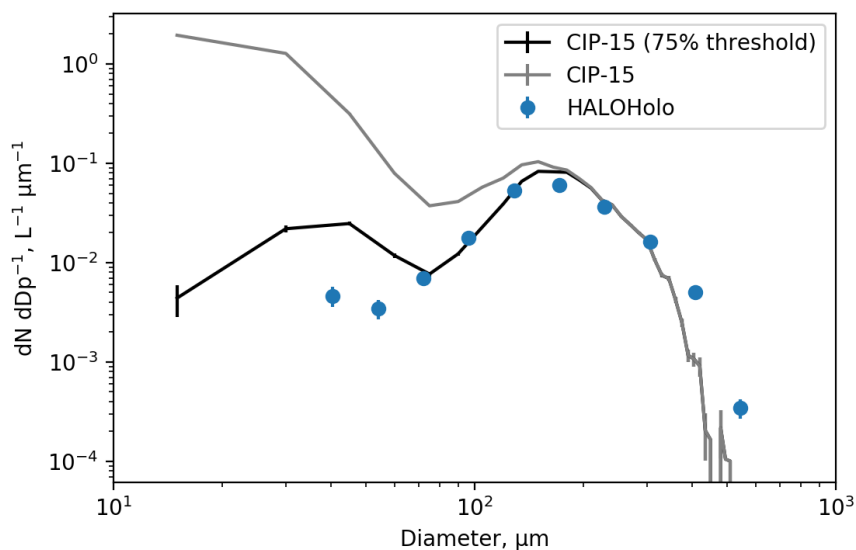
13 *Table 2. Median (interquartile range) depth of field c value (Eq. 1) for 1060 ice crystal images*
14 *using various greyscale intensity thresholds and circle equivalent diameter. The median*
15 *(interquartile range) ratio D/D_0 for $Z_d < c$ is also given.*

16

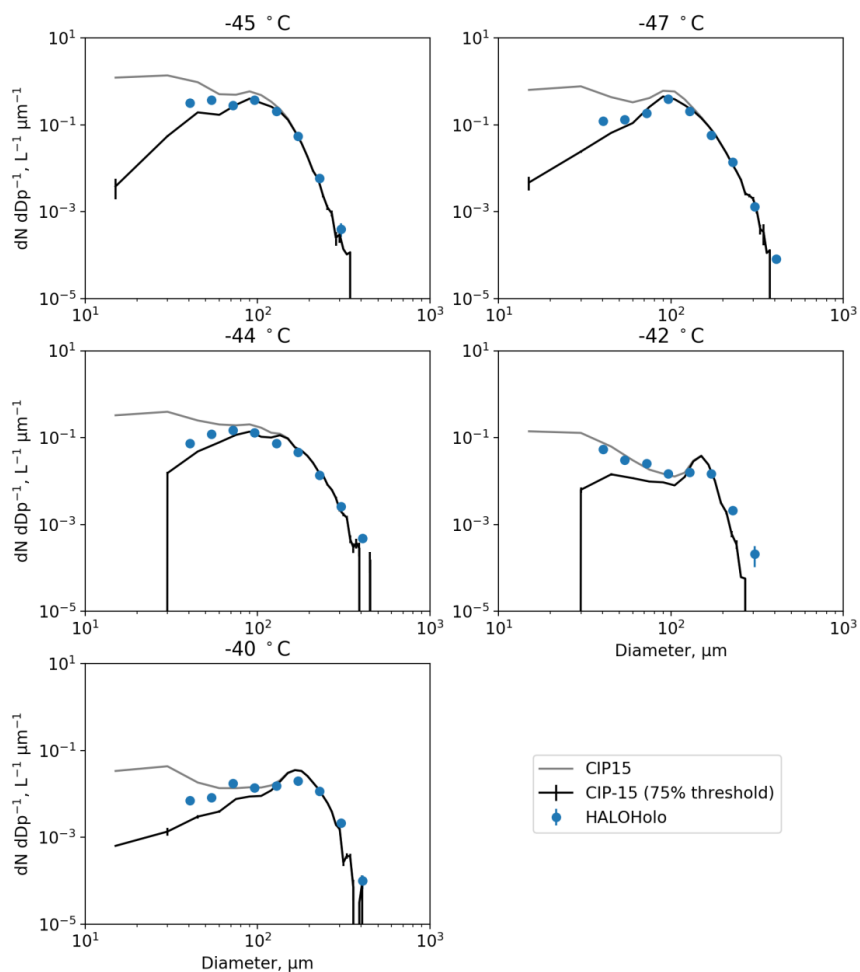
17 Figures 12 and 13 apply this new methodology to ambient measurements collected during
18 research flights in cirrus on 7 February 2018 and 23 April 2018. Figure 12 shows PSDs from
19 the CIP-15 and HALOHolo for a run at -42°C on 7 February 2018 (16:02:00 to 16:10:00 GMT).
20 This flight has previously been discussed by O19. Figure 13 shows equivalent PSDs for
21 temperatures between -47 and -40°C collected on 23 April 2018. For both probes the particle
22 diameter given is the circle equivalent diameter and particles in contact with the edge of the
23 CIP-15 optical array have not been included in the PSD calculation. The black lines show the
24 CIP-15 size distribution when images are filtered to only include those with at least one pixel
25 at the 75% intensity threshold. This threshold significantly reduces the concentration of small
26 particles ($<200\ \mu\text{m}$) compared to when this filtering is not applied (grey lines) and generally is



1 in much better agreement with HALOHolo a holographic imaging probe (blue markers). This
2 suggests that for these cases using current data processing techniques, a significant fraction of
3 the ice crystal number concentration at sizes $< 200 \mu\text{m}$ is an artefact due to optical effects.
4



5
6 *Figure 12. Size distributions from the CIP-15 and HALOHolo for a run at -42°C on 7 February*
7 *2018. The black line shows the CIP-15 size distribution when images are filtered to only include*
8 *those with at least one pixel at the 75% intensity threshold.*
9



1

2 *Figure 13. Size distributions from the CIP-15 and HALOHolo for a 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,

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

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).

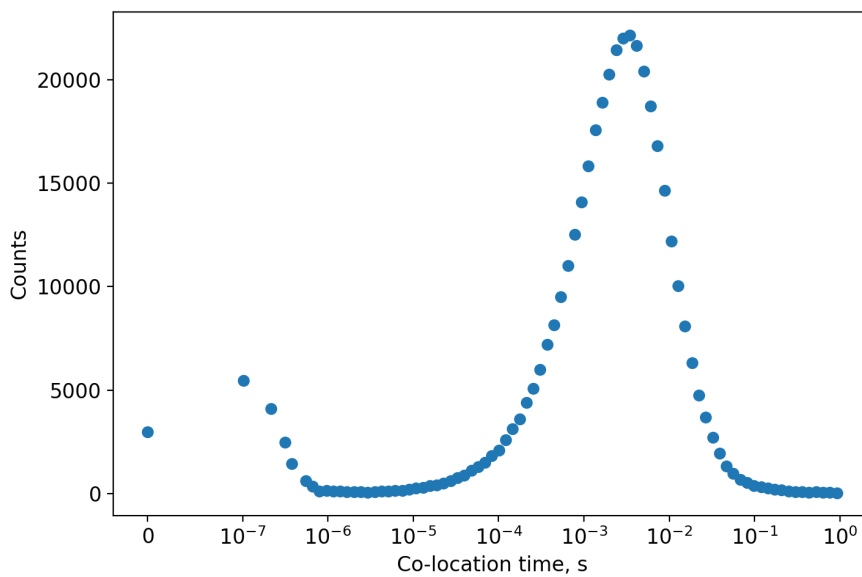
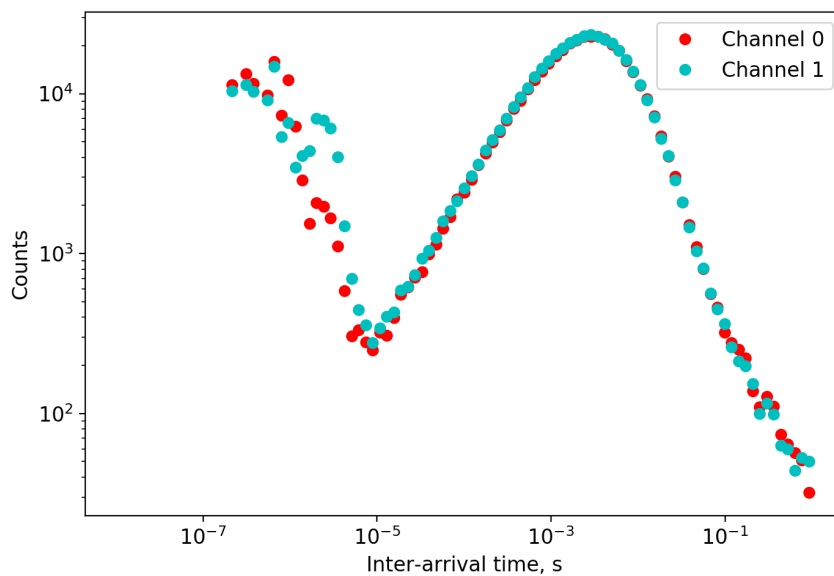
3 Co-located particles could be confused with shattered particles since they are also associated
4 with short inter-arrival times. Figure 14 (top panel) shows a histogram of inter-arrival time for
5 particles on the same channel for measurements in cirrus on 7 February 2018. To minimise
6 shattering events, each channel was independently filtered for particles using an inter-arrival
7 threshold of 1×10^{-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 1×10^{-3} s. and a smaller mode at 1×10^{-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 m s^{-1} data slices from the detectors are acquired every 1×10^{-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 m s^{-1} resulted in a 1×10^{-5} s mode time delay in detection
29 events between the two channels of the 2D-S. This also corresponds to an offset of $10 \text{ }\mu\text{m}$
30 in 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 5×10^{-7} s.

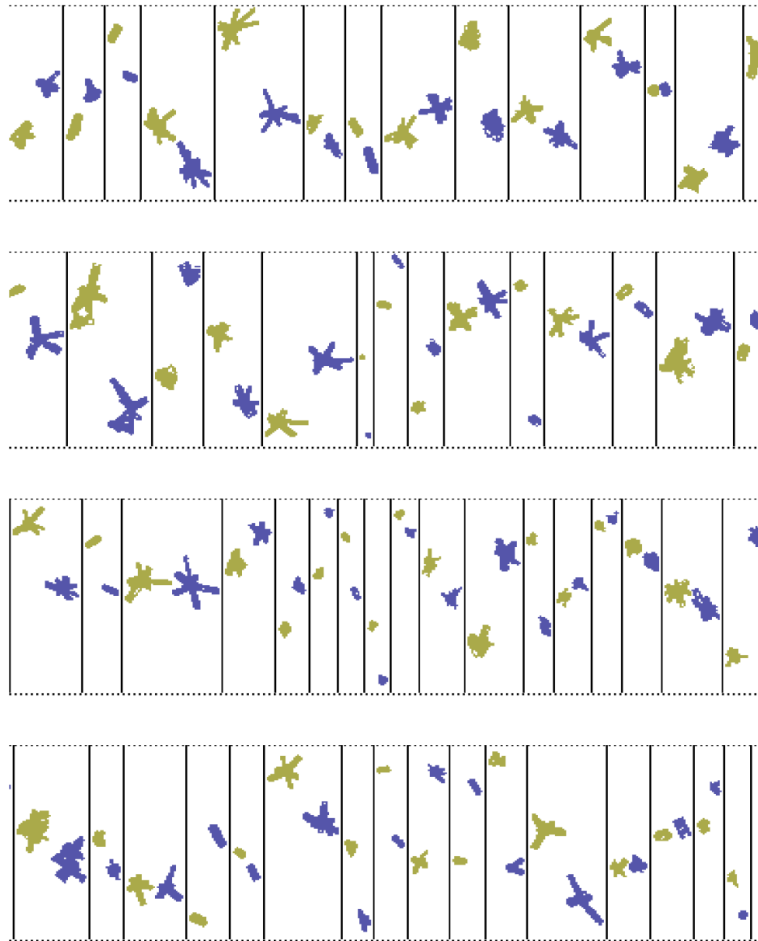




- 1 *Figure 14. Top panel. Histograms of inter-arrival times for particles on the same 2D-S channel*
- 2 *for measurements in cirrus on 7 February 2018. Bottom panel. A histogram of the difference in*
- 3 *arrival time between a particle on one channel and their closest neighbour on the other channel.*
- 4
- 5
- 6



10:53:06.883000 to 10:53:25.383000

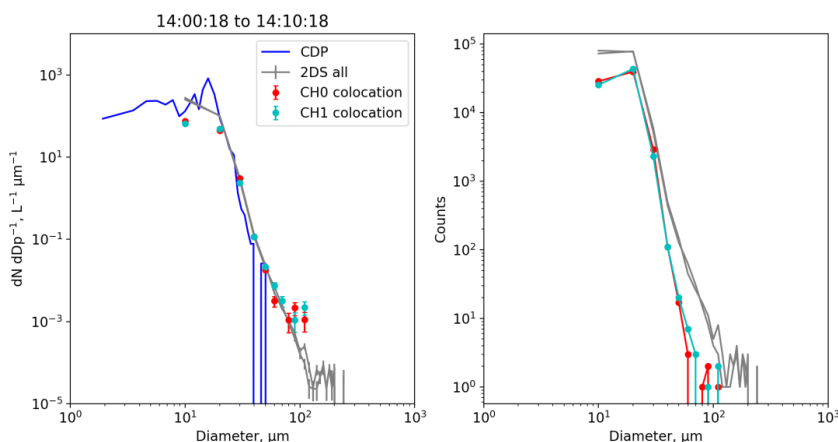


1
2 *Figure 15. Example ice crystals observed by both channels of the 2D-S. Images from channel*
3 *0 are shown in yellow and images from channel 1 are shown in blue.*
4



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 particles (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. This
13 illustrates the ability of the 2D-S to detect small co-located particles.



14

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

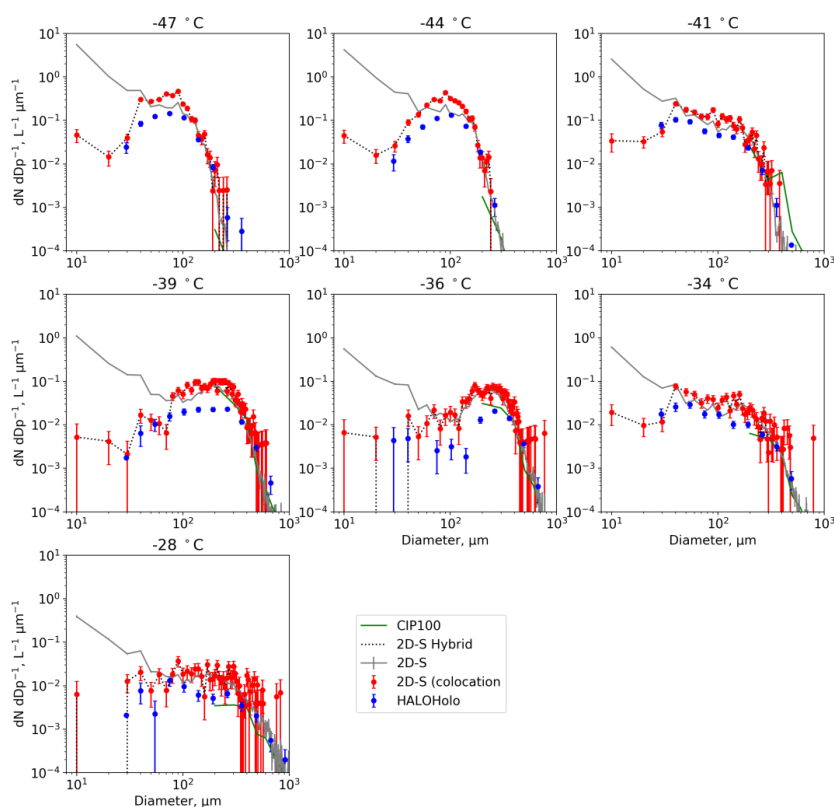
20



1 Figure 17 shows size distributions from the 2D-S and HALOHolo for different temperatures
2 (averaged over ~10 minutes) during a research flight in cirrus on 11 March 2015 (see O’Shea
3 et al., 2016). The grey lines show the 2D-S data for each channel using conventional data
4 processing protocols without constraining the DoF, while the red lines show size distributions
5 for just the co-located particles. HALOHolo size distributions are shown in blue. For all
6 temperatures the conventional 2D-S data processing shows an ice crystal mode at small sizes
7 ($< 200 \mu\text{m}$). At warmer temperatures ($> -39 \text{ }^\circ\text{C}$) there is also a clear second mode at larger sizes.
8 However, these high concentrations of small ice particles are not present in the co-located and
9 the HALOHolo size distributions. This suggests using only co-located particles on the dual
10 channel 2D-S probe is effective at removing significant biases at small particle sizes. At larger
11 sizes ($> 300 \mu\text{m}$) the 2D-S data processing using conventional and stereoscopic methods are in
12 good agreement, however the latter method is limited by sampling statistics.

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

24



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,

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

4
5 Equation 9

6 Figure 18 shows three combinations of the coefficients μ , λ (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.

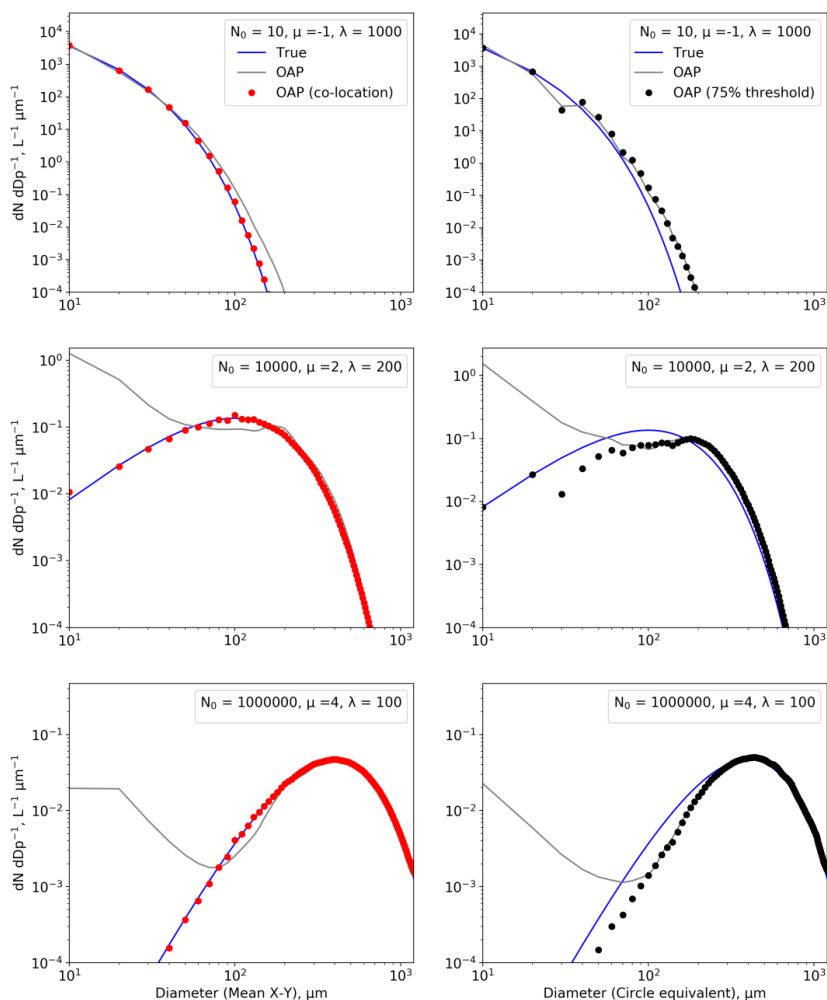
19 Figure 18 top panels show an ambient distribution (blue lines) dominated by small particles ($\mu =$
20 -1 , $\lambda = 1000 \text{ cm}^{-1}$ and $N_0 = 10 \text{ L}^{-1} \text{ cm}^{-1}$), with concentrations increasing with decreasing size
21 over the displayed size range 10 to 1280 μm , which is 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 μm 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 μm 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 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 μ , λ (cm^{-1}) and N_0 ($\text{L}^{-1} \text{cm}^{-1}$) 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

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

24

Equation 10

25

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

26

Equation 11

27

28



1

2 where the number concentration ($N(D)$) and diameter are normalised using the second (M_2)
3 and third (M_3) 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.

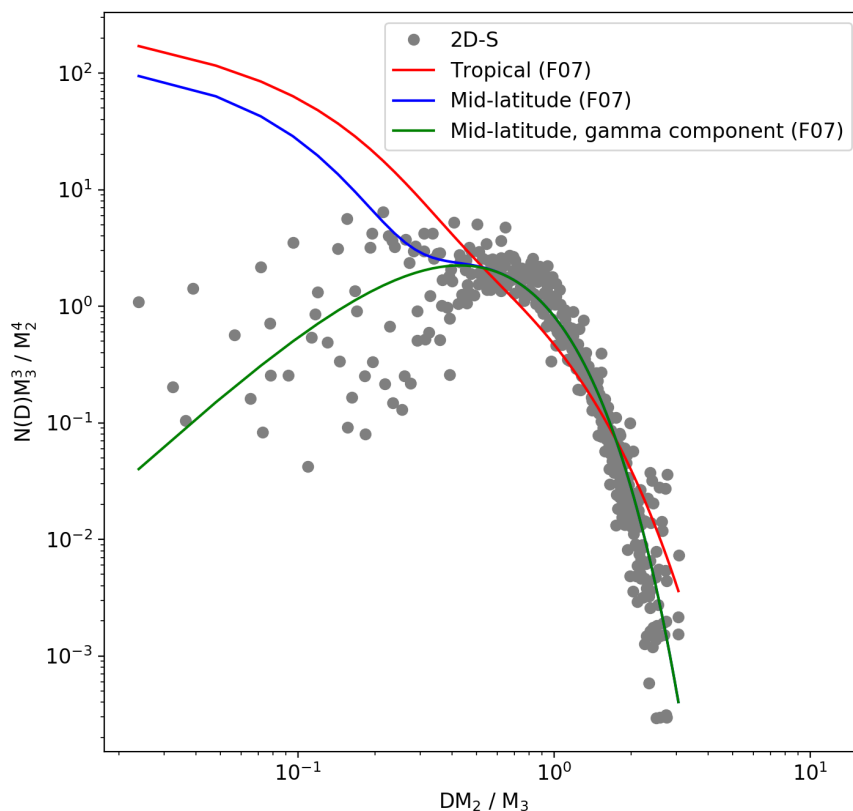
10

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

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

19 **Acknowledgements**

20 We would like to thank Thibault Vaillant de Guélis for his help with the AST model. We are
21 grateful to Jacob Fugal for assistance with HALOHolo. The authors wish to thank Hannakaisa
22 Lindqvist (CSU) for making available her CPI training data set. Airborne data were obtained
23 using the BAe-146-301 Atmospheric Research Aircraft (ARA) flown by Directflight Ltd and
24 managed by the Facility for Airborne Atmospheric Measurements (FAAM), which is a joint
25 entity of the Natural Environment Research Council (NERC) and the Met Office. The CIP-15s
26 were provided by the National Centre for Atmospheric Science and FAAM. The National
27 Centre for Atmospheric Science provided support for the ice crystal analog experiments. This
28 work was supported by the NERC grants NE/P012426/1 and NE/L013584/1.

29



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