

Wind Tunnel PSD and MVD Characterization Using New 1D2D Optical Array Probes

B. M. Esposito¹,

Italian Aerospace Research Centre, Capua 81043, Italy

L. E. Lilie²,

Science Engineering Associates, Tolland, CT

E. N. Timko³ and L. E. Hux⁴,

Jacobs Technology, Inc., Cleveland, OH

J. W. Strapp⁵, and

Met Analytics, Inc., Aurora, ON, L4G 4Y1, Canada

A. Bansemer⁶,

NSF National Center for Atmospheric Research, Boulder, Colorado

This work explores characterization of the liquid clouds using a combination of a forward scattering probe and two Optical Array Probes. Current OAP probes provide particle shape, size, and number concentration from two-dimensional shadow images. However, past studies have shown that such images are subject to distortion when outside of the focal plane. This affects the retrieval of particle size distributions, particularly in the Supercooled Large Droplet size range. In this article, the use of a Droplet Measurement Technologies Cloud Droplet Probe and two new OAPs produced by Science Engineering Associates, is examined using wind tunnel data, to assess suitability for use in a wind tunnel calibration in SLD conditions. The new OAP probes exploit a flexible and simple grey scale imaging method to eliminate some present shortcomings of commonly used OAPs, and to reduce correction factors. Spinning disk measurements were used to specify probe depth of field, and average size errors. Composite spectra covering the nominal 2-3200 μm size range were formed by crossing over from the CDP to 1D2D-X at 48 μm , and then to the 1D2D-Y at about 400 μm . A good overlap was found at the crossover points without any artificial scaling. Composite spectra adequately closed the liquid water content distribution, and provided integrated LWCs within about 35% of the hot-wire LWCs used for tunnel calibration. This discrepancy was at least partially attributed to LWC underestimation by the hot-wire at high MVD. A model of probe performance was used to show an example of expected accuracy of ideal probes subject to the same OAP distortions and using the same mitigating procedures and corrections, predicting PSD Median Volume Diameter and integrated LWC errors of less than 10%.

¹ Senior advisor, Cloud measurement and generation techniques, Large Ground Testing Facilities

² President

³ Icing Cloud Calibration Engineer, Test Engineering Service, Member AIAA

⁴ Icing Cloud Calibration Engineer, Test Engineering Service, Member AIAA

⁵ Physical Scientist

⁶ Cloud Physicist

I. Nomenclature

<i>AIWT</i>	=	Altitude Icing Wind Tunnel (NRC)
<i>CDP</i>	=	Cloud Droplet Probe (DMT)
<i>CIRA</i>	=	Centro Italiano Ricerche Aerospaziali
<i>DMT</i>	=	Droplet Measurement Technologies
<i>DOF</i>	=	Depth of Field
<i>EASA</i>	=	European Union Aviation Safety Agency
<i>FAA</i>	=	Federal Aviation Administration
<i>FPGA</i>	=	Field Programmable Gate Array
<i>IKP2</i>	=	Isokinetic Probe, second generation
<i>IRT</i>	=	Icing Research Tunnel (NASA)
<i>IRTLWC</i>	=	NASA IRT Calibration LWC
<i>IRTMVD</i>	=	NASA IRT Calibration MVD
<i>IWT</i>	=	Icing Wind Tunnel (CIRA)
<i>LWC</i>	=	Liquid Water Content
<i>Mode 1</i>	=	Mode of operation of 1D2D probes, no 75% shadow requirement
<i>Mode 2</i>	=	Mode of operation of 1D2D probes, n pixels required at 75% shadow level ($n \geq 1$ for this study)
<i>Mode 3</i>	=	Mode of operation of 1D2D probes, x% of pixels required at 75% shadow ($x \geq 50\%$ for this study)
<i>MVD</i>	=	Median Volume Diameter
<i>MW</i>	=	Multi Wire (SEA Multi-Element Probe)
<i>NASA</i>	=	National Aeronautics and Space Administration
<i>NCAR</i>	=	National Center for Atmospheric Research
<i>NRC</i>	=	National Research Council (of Canada)
<i>NFS</i>	=	National Science Foundation
<i>OAP</i>	=	Optical Array Probe
<i>PMS</i>	=	Particle Measuring Systems
<i>PSD</i>	=	particle size distribution
<i>SEA</i>	=	Science Engineering Associates
<i>SLD</i>	=	Supercooled Large Droplets
<i>SODA-2</i>	=	System for Optical Array Probe Data Analysis (version 2)
<i>SPEC</i>	=	Stratton Park Engineering Co.
<i>TWC</i>	=	Total Water Content
<i>1D2D-X</i>	=	1 dimensional and 2 dimensional OAP, 15-960 μm (SEA)
<i>1D2D-Y</i>	=	1 dimensional and 2 dimensional OAP, 50-3200 μm (SEA)
<i>2D-S</i>	=	2D Stereo (OAP)

II. Introduction

With the advent of the new FAA 14 CFR Part 25 and EASA CS-25 Appendix O icing envelope, icing wind tunnels are developing Supercooled Large Droplet (SLD) simulation capabilities to assist in future means of compliance activities. This has presented challenges in establishing accurate calibrations of Liquid Water Content (LWC) and Median Volume Diameter (MVD) in SLD conditions, due to known shortcomings of current and commonly used instruments. The Italian Aerospace Research Centre (Centro Italiano Ricerche Aerospaziali – CIRA) will in the near future be calibrating its Icing Wind Tunnel (IWT) SLD simulations for LWC and Particle Size Distribution (PSD) properties, including MVD. In this study, a method for calibrating PSD properties is examined, to determine the quality of measurements made by a combination of probes including a forward scattering probe and two Optical Array Probes (OAPs). The method is essentially the same as that used by the NASA Icing Research Tunnel (IRT), but with new OAPs upgraded to improve SLD measurement accuracy.

Various OAP probes have been commercially available since the 1970s, and there is a long history of performance testing and cloud measurements from them in the atmospheric science literature. The earliest probes manufactured by Particle Measuring Systems (PMS) Inc. [1], measured the size of the shadow of a particle above a certain shadow threshold (e.g. 50%), that was detected on an array of photodiodes, providing size distributions in discrete size bins. These were commonly called one-dimensional, or 1D OAPs, and these probes are still used to this day. In the late 1970s, PMS updated these probes to rapidly scan and record the photodiode response [2], providing 2D pictographs of the particles, eventually at up to four grey scale levels. These probes were commonly called 2D OAPs. Modernized

versions of these OAPs with enhancements are still commercially produced, covering different size ranges at different pixel resolutions. The highest performance OAP recently in common use has arguably been the Stratton Park Engineering Co. (SPEC) 2D-Stereo (2D-S) probe [3], which provides monochromatic 2D probe imagery at 10 μm resolution, covering the 10-1280 μm size range. SPEC and Droplet Measurement Technologies (DMT) now also provide versions of their probes that provide images in four grey scale shadow levels. Recent OAPs have overcome time response problems that created sizing and sample volume uncertainties in the earliest probes. One of the most important limitations has been sizing error of particles that pass outside the focal plane of the laser sample area (the location of best focus near the centre between the two probe arms) [4]. Coupled with a size-sensitive DOF in the critical sub-100 μm size range, accuracy of OAP PSDs in SLD conditions has continued to be a topical issue.

The study follows an article describing the new Science Engineering Associates (SEA) OAP 1D2D-X probe [5], which covers PSD measurements up to 960 μm . That study used a model of OAP performance developed by the National Center for Atmospheric Research (NCAR), that used Fresnel diffraction calculations to predict particle two-dimensional (2D) imagery produced by the probe. Three modes of 1D2D probe operation were studied (Table 1), with Mode 1 being a standard used for OAP operation in the atmospheric science community, and Modes 2 and 3 being more restrictive in constraining the Depth of Field (DOF) and oversizing of out-of-focus images. The model provided estimates of probe DOF, and predictions of sizing errors. DOF is an important parameter in the calculation of sample volume and no DOF estimates for Mode 3 were available prior to the model study. Several tests were conducted at the CIRA IWT in 2022, providing spectra for preliminary assessment. The model also provided absolute error estimates of LWC distributions and MVD for a sample true spectrum, predicting MVD and LWC errors of less than 10% for operation of the 1D2D under Mode 3.

Table 1. Modes of operation of the 1D2D probe compared in this article. Implementation of a particular mode affects 1D2D image recording. N_{50} and N_{75} are the number of pixels shadowed at the 50% and 75% shadow depth respectively. See text for cited instruments. Adapted from [5].

Mode	Sizing shadow level	75% shadow requirement	Comments
1	50%	none	Commonly used in the research community for monochromatic OAP probes (e.g. PMS 2D-C, SPEC 2D-S)
2	50%	$N_{75} \geq a2$	Real-time option available in some grey-scale OAPs (e.g. DMT CIP-gray), and similar to that used in early 1D OAPs. Can also be implemented in grey-scale probes (e.g. DMT CIP-gray, SPEC Fast 2D-Gray) in post processing. Value of $a2$ is user selectable value > 0 ; $a2=1$ for this study mode 2.
3	50%	$N_{75}/N_{50} \geq a3$	New option with the strictest real-time image constraining of out-of-focus particles. The value of $a3$ is user selectable, and for this study was chosen to the 0.5 for mode 3. Can also be implemented in grey-scale probes in post processing.

The current study picks up where Ref. [5] left off. A new SEA 1D2D-Y probe was developed covering the nominal size range up to 3200 μm , which enabled assessment of the importance of measurements beyond the 960 μm limit of the 1D2D-X. It was decided to focus on measurements from Modes 1 and 3 for comparison, the latter being that currently favoured by this study. A series of wind tunnel tests at the NASA IRT were used to assess the performance of a combination of the DMT Cloud Droplet Probe (CDP), and the new SEA 1D2D-X and 1D2D-Y OAP probes in SLD conditions over a wide range of MVDs. The assessment included comparison to the independently measured bulk LWC of the NASA IRT calibration, which was not available for the CIRA testing of [5]. In addition, new spinning disk measurements from the manufacturer provided measured DOFs of both 1D2D probes, and average size errors across the DOF. The NCAR System for Optical Array Probe Data Analysis (SODA-2) software package was again used for OAP analysis, which incorporated artifact rejection and size correction commonly used in the community. But a final correction to PSDs based on the average remaining size error predicted by spinning disk testing was applied, as recommended but not performed by [5]. While an absolute reference of MVD is not available, this

study will use comparisons of PSD integrated LWC to bulk hot-wire LWC, overlap between the forward scatter probe and the 1D2D-X in size range where OAPs are typically least accurate, and further predictions of the NCAR OAP performance model as indicators of the quality of the final spectra.

The recent rapid evolution of technology has led to other new developments in PSD measuring probes. A multi-agency investigation of some of these more promising instruments is currently underway with CIRA participation [6]. While the important emphasis of that investigation is to define the accuracy of the instruments, and ultimately identify those most accurate for SLD measurement, the conclusions of its investigation may still be several years away. The CIRA IWT SLD calibration must take place within the next year to explore and characterize conditions achievable after a spray bar nozzle update to encompass the full Appendix O envelope, funded within the ICE-GENESIS European program. Furthermore, it is not assured that the most accurate instruments under investigation by [6] will be practical for calibration at the CIRA IWT. CIRA has a long history of the use of phase doppler probes, and a well-developed understanding of the technology. The CIRA phase doppler probes are currently being upgraded, and final testing has not been completed. It should be noted that substitution of one or more phase doppler probes for PSD measurement in the CIRA IWT calibration will also be considered depending on the success and schedule of the upgrade.

Each of the instruments used in the current study are described in the subsections below.

III. Instrumentation

A. The Droplet Measuring Technologies CDP probe.

The DMT CDP is a forward scattering spectrometer that measures the droplet spectrum in the 2-50 μm size range, typically in 30 size bins of about 2 μm resolution, although the channel set-up is user selectable [7]. High resolution size bins of this sort are required for the 14 CFR Part 25 Appendix C portion of the size distribution, and are not accurately determined by OAP probes due to pixel resolution and a rapidly changing DOF with size.

B. The Science Engineering Associates 1D2D-X probe

In 2020, CIRA requested an upgrade to their 64-photodiode-array PMS 1D260-X OAP probe to add recording of particle imagery. The upgrade evolved into a wholesale change and the development of a new OAP probe optimized for wind tunnel calibration, with some enhancements that are exploited to reduce the out-of-focus sizing errors noted above. SEA named this probe the 1D2D probe, due to additional efforts to provide an accurate real-time 1D size distribution for wind tunnel calibration activities.

The 1D2D-X probe images particles in a nominal 15-960 μm size range with 15 μm pixel resolution, and uses fibre optics linked to avalanche photodiodes to achieve a very fast response time of 12 ns or better, eliminating any electronic performance degradation for the velocities of normal wind tunnel operations [5]. Field Programmable Gate Array (FPGA) electronics provide fast real-time processing and data handling. The probe is housed in a standard airborne canister, as commonly used for other OAPs, and enhanced de-icing has been provided to enable extended operation in the icing environment of a tunnel calibration. Particle imagery can be provided at either the 50% or 75% shadow level, although the 50% level is normally used. The image record however contains the number of pixels shadowed at the second level, and there is a user selectable feature that allows hardware rejection of recording of particles that do not shadow adequate numbers of pixels at the second level. This can either be a set number of pixels (Mode 2, Table 1, e.g. a single pixel, like used in the original PMS 1D OAPs), or a selectable ratio of second level to primary level pixels (Mode 3, Table 1, e.g. half of the pixels must be at the higher shadow level). The use of such second level pixel requirements reduces the DOF for a given particle size, while overall reducing the degree of out-of-focus oversizing. It also decreases the amount of probe dead time in high concentration probe-overload situations. This feature addresses the recommendation of [8] to avoid the use of purely monochromatic OAPs (e.g. Mode 1, Table 1) that produced highly out-of-focus and potentially uncorrectable artifacts at the edge of the DOF. While the same end result could be achieved with a full four-level 2D-grey probe data in post processing with the use of its other grey scale levels, it is contended here that the simpler monochromatic imagery of the 1D2D probe, with additional second shadow level information for each particle, provides the desired results while creating a smaller and more manageable dataset than a full 2D grey equivalent. Furthermore, it is anticipated that with hardware rejection of out-of-focus particles, the real-time PSDs provided by the 1D2D probe will be close in accuracy to post-processed PSDs, a very important feature in operation of wind tunnels. The evaluation of real-time PSDs will be a major focus of future research efforts. The 1D2D-X has been successfully tested at the National Research Council (NRC) Altitude Icing Wind Tunnel (AIWT), the CIRA IWT, and the NASA IRT.

C. The Science Engineering Associates 1D2D-Y probe

A second 1D2D probe was produced for the NASA IRT as a backup and potential replacement to their existing PMS OAP-230Y probe. The 1D2D-Y provides measurements with the same 50 μm pixel resolution, but covers the nominal 50-3200 μm size range rather than the OAP-230Y's 50-1500 μm . It is also housed in a standard airborne canister, and has a forward arm "Y" configuration like the original PMS precipitation probes. The 1D2D-Y uses the same electronics as the 1D2D-X and the same monochromatic imagery with second-level pixel number recording. It provides the same capability of DOF manipulation for constraining out-of-focus oversizing. The 1D2D-Y has been successfully tested at the NASA IRT.

Both 1D2D probes also have the ability to sample only particles larger than a user-selected size, which may be useful in sampling tails of distributions, but this feature has not been extensively explored to date.

IV. PSD Calibration Strategy Based on NASA IRT Testing

A series of test points at the NASA IRT were used to evaluate the use of the DMT CDP and the SEA 1D2D-X and 1D2D-Y probes to form a composite spectrum over a range of MVDs. Spectra were merged for each SLD spray condition from consecutive measurements of the three probes at the same tunnel-centre location. Simultaneous measurements were not considered due to gradients of the cloud properties between probe locations, and potential aerodynamic influence of one probe on the other [9,10]. Consecutive measurements require a high level of tunnel PSD repeatability, which will be demonstrated in section VI (B).

CDP data processing was straightforward. The counts in discrete size channels were converted to concentrations and LWC spectra knowing the probe sample area and the tunnel velocity. OAP image processing was more complex, and can be subject to significant agency bias. The strategy was to use the NCAR SODA-2 software package [11]. The software has been developed over decades of use in cloud physics research, and is regularly tested on benchmark datasets and compared against other software packages. The source and executable code are publicly available, an important consideration for transparency and any future inter-facility standardization.

A brief description of the SODA-2 processing follows. Only particles that did not touch end elements were accepted, allowing for a less ambiguous estimate of size without reconstruction of partial images. The SODA X-Size option was used to estimate the particle diameters. This is the across-array difference between positions of the edge shadowed pixels of an image, and is not sensitive to possible errors created by differences in the drop velocity and that which was used to strobe the probe imagery (i.e. usually the tunnel air velocity). A SODA-2 option to detect infrequent coincidences and accept only the larger of the two particles was enabled. A "water option", designed to detect images that did not resemble water drops, was also enabled. This did not have much effect on spinning disk spectra, but had a major effect on wind tunnel spectra by rejecting splashes and other artifacts. A discussion on the importance of the water option was provided in [5]. SODA-2 identified short-interval-time artifacts and corrected spectra if required. The SODA-2 software provided individual size distributions of the 1D2D-X and 1D2D-Y probes for Modes 1 and 3. Mode 3 restricted the DOF and constrained but did not eliminate out-of-focus oversizing. Drops were corrected for out-of-focus oversizing using the method described in [12]. These corrections are effective for out-of-focus particles that have developed a Poisson spot, a central 'hole' in the image that does not reach the first shadow threshold, but do not correct sizes for particles close to the focal plane that have not developed a Poisson spot. The PSDs thus still retained a net oversizing after the correction of [12]. As a final treatment after SODA-2 processing, the OAP spectra were corrected using a technique suggested by [13]. In that study, the channel bin thresholds were redefined based the average sizes calculated for a true size, as predicted from a diffraction model of the probe performance. In this article, the average sizes were alternatively estimated from number-weighted average sizes, from arm to arm, obtained from spinning disk calibrations of known dot sizes. The average oversizing, and the DOFs applicable to 1D2D-X and Y operational Mode 3 from this laboratory testing, is summarized in section V. More details on the probe data processing and merging are contained in the following sections.

V. Spinning Disk Calibrations of DOF and Size

Calibrations of the 1D2D-X and 1D2D-Y were performed by SEA, using spinning glass disks with dots of known diameters (e.g. see [14]). For safety reasons, a velocity of 50 ms^{-1} was used for most testing, lower than most wind tunnel calibrations, but the fast time response time of the 1D2D probes would indicate that the results should be transferrable to speeds of at least 175 ms^{-1} [5]. The dot sizes were 51.7, 101.8, 151.4, 201.3, 250.3, 301.2, 399.9, 498.7, 603.5, 703.1, 803.6, 1003.4, and 2100 μm , where the largest three were not tested for the 1D2D-X due to either exceeding or being too close to the its maximum size. The disk was moved across the sample volume at a constant rate of about 0.22 and 1.0 mm/sec for the 1D2D-X and 1D2D-Y respectively, and 2D images were recorded from one

OAP arm to the other. The 20 dots per revolution and constant rotation rate produced a constant and measured dot rate. SODA-2 was then used to calculate the measured image rate and average size as a function of distance along the DOF. Since the final DOF and number-weighted average size from arm to arm were dependent on the particular software processing (e.g. whether out-of-focus size corrections of [12] were applied), SODA-2 was run with the same settings to be used in the wind tunnel calibration data processing¹.

A. 1D2D-X spinning disk results

Figures 1 and 2 show counting and sizing results for the 101.8 μm dot size, and will be used to illustrate some advantages of Mode 3, and some of the nuances of the probe response. Figure 1 shows the measured counts from one end of the exposed laser to the other, with the end points of the axis being the mechanical limits defined by the standard tips at the openings to the arms. The thick grey line shows the measured dot rate of about 4200 per second. The olive line shows the counts measured in Mode 1, approximately the same as the dot rate from one end to the other. The Mode 1 DOF for this particle size was thus the full exposed laser width, or about 58.3 mm. The red line shows the counting for Mode 3. At increasing distance from the focal plane, located at about 0.3 mm on the plot's X axis, the number of pixels shadowed at the 75% level decreased, eventually not reaching the minimum required fraction of 0.5, and counting stopped. Due to the non-monotonic nature of diffraction away from the focal plane, two distinct side lobes were observed centered at about -8 and +9 mm from the center, as particles temporarily came back into focus. This required a somewhat different procedure for determining DOF than for other modes of operation. The total number of accepted particles was divided by the total number of dots exposed to the probe across the entire width, and then multiplied by the full exposed laser distance. Using this method, the DOF for Figure 1 was estimated at 7.05 mm, compared to the 58.3 mm for Mode 1.

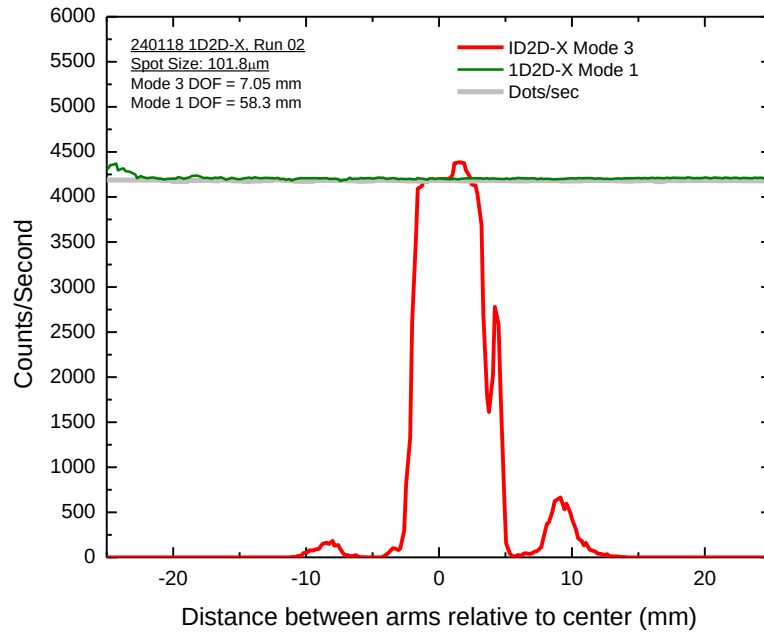


Figure 1. Mode 1 and Mode 3 spinning disk measurements of the 1D2D-X for a 101.8 μm dot size. The edges of the laser sample length are the edges of the X axis. Mode 3 requires 50% or more of the pixels to reach the 75% shadow level.

¹ The interarrival time option for spinning disk analysis was not used due to the non-random spacing of dots on the disk.

Figure 2 shows three different plots of average sizing measured along the same path. The olive line shows the average sizing of the probe operated in Mode 1, with no corrections for out-of-focus oversizing. The average size of particles across the entire DOF was 116.2 μm . Particle size generally increased either side of the focal plane, and sizes up to about 180 μm were measured nearing the edge of the DOF. The blue line shows the Mode 1 average sizing after application of the out-of-focus size correction of [12], where the corresponding end-to-end average size was 102.6 μm . Approximately the same pre-correction size-versus-position would be observed in Mode 3 within its smaller DOF described below. The red line shows the Mode 3 average size after applying the same correction. The overall average across the Mode 3 DOF was 104.7 μm . The dotted line with the inset Y-axis shows the fraction of particles that received the out-of-focus correction across the DOF, shown for Mode 1, but it was approximately the same for Mode 3 within its DOF. This illustrates an important point. The out-of-focus correction required the particle to have developed the Poisson spot. Nearest to the focal plane, none of the particles were size-corrected due to the lack of the Poisson spot, reflected in the zero fraction. This central region still experienced oversizing, but it was not correctable by the method of [12]. The correction fraction, dashed line, rapidly climbed to near unity by ± 5 mm away from the focal plane, and remained high until approaching the edges of the Mode 1 DOF. Note also that the size adjustment tended to over-correct away from the central region, particularly on the transmitter side (plot left side) of the laser path. The overall average was therefore somewhat of a cancellation of the oversizing in the central area, and net under sizing after correction in the outer regions. The asymmetry will be returned to later in this section.

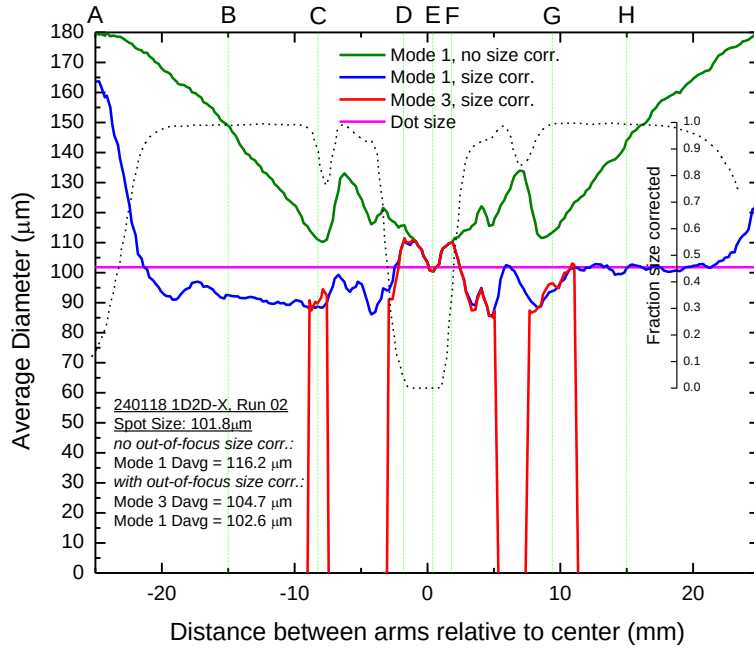


Figure 2. Average sizing versus length along the laser path for the same 101.8 μm dot in Fig. 1. Results are shown for Mode 1 with and without out-of-focus size corrections of [12], and for Mode 3 with the same corrections. The fraction of particles receiving the correction is shown by the dotted line with the inset Y-axis. The A-I labels across the top axis identify locations referred to in the text and in Fig. 3.

Figure 2 includes reference locations labeled from A-I above the top axis. In Figure 3, sample Mode 1 images for these locations are shown, along with the fraction of particles that were size corrected, and the average magnitude of the correction when it was applied. At the edges of the Mode 1 DOF (A and I), the particles exhibited large Poisson spots and overall diameters of almost a factor 1.8 larger than actual. Due to breakup of the particle perimeters, only a

small fraction of 11% were identified as having Poisson spots, and the other 89% received no size correction. This explains why the average size of Mode 1 started to increase at the edges of the DOF.

The size of the Poisson spot decreased approaching the focal plane (E). Approaching from the probe arms, point C was the first location at which Mode 3 accepted particles. There, 97% of the particles were size corrected, and the average size reduction was a factor of 1.28. In the central region (D-F), only 11% of particles had Poisson spots at D, and no Poisson spots were observed at E and F. Overall, by using the second shadow level, Mode 3 avoided the need for large corrections of out-of-focus particles at the outer regions of the DOF, and avoided the complications of particle image breakups at the edges of the DOF as recommended by [8]. It constrained the DOF to the central region between points C and G, where the side lobes centered on C and G received an out-of-focus size correction, but only a partial fraction were size-corrected in the more central region.

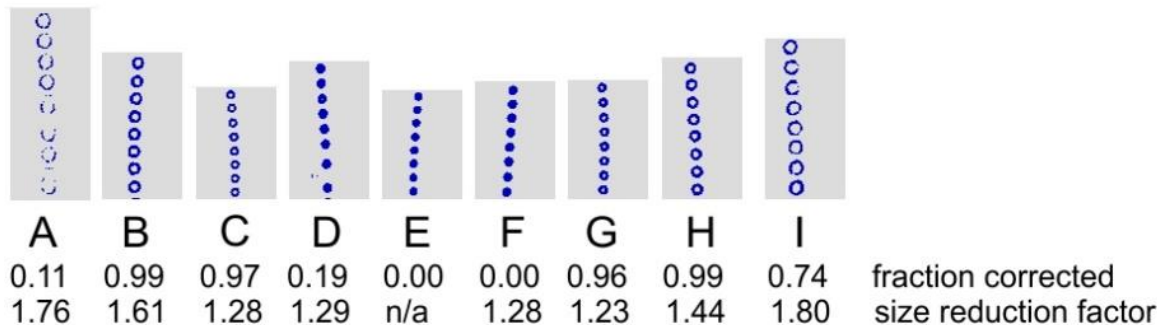


Figure 3. Mode 1 Images of particles at locations A-I of Fig. 2, along with the fraction corrected for out-of-focus sizing, and the size reduction factor when corrected.

The description of the design and optical characteristics of the first OAP [1] established the expectation for symmetrical sizing and DOF around the focal plane, and stated that “diffracted light is all that needs to be considered for shadow reconstruction” (i.e. that the effect of reflection and refraction was negligible) and that laser divergence insignificantly affected DOF. Refs. [15] and [4] subsequently used Fresnel diffraction calculations to predict OAP sizing and DOF characteristics. Their probe calibration measurements versus distance from the focal plane compared well to their calculations. They also concluded that an additional effect of the probe aperture, not considered in their calculations, was negligible. The Fresnel calculations of particle size versus distance along the DOF produced by [4] are similar to the uncorrected Mode 1 plot (olive curve) of Figure 2. Simulated particle images of [4] are also similar to those of Figure 3. That study also described how the symmetrical pattern of observed size versus distance from the focal plane was scalable according to particle size. For the fixed exposed laser length of an OAP, the pattern simply stretched outward with increasing particle size. These general characteristics have been observed by others in laboratory testing (e.g. [16, 14, 17]) and was observed during the current study’s spinning disk tests. The central region of particles with no Poisson spot expanded with dot size, and the DOF increased to eventually encompass the entire exposed laser length, even for Mode 3. Therefore, the Mode 1 and Mode 3 solutions became increasingly similar for large particle sizes, with both modes having oversizing uncorrectable by the method of [12] near the centre of the DOF. Nevertheless, for this set of 1D2D-X spinning disk tests, even for the largest particle size of 703 μm , there were still particles with Poisson spots, and some improvement of particle size after applying that correction.

Figure 2 revealed a somewhat asymmetrical response of the 1D2D-X relative to the focal plane, mostly observable in the size-corrected values. On the transmitter side, the out-of-focus correction mostly over-adjusted, whereas on the receiver side it more closely corrected to the true size. This behaviour is consistent with the Poisson spot being relatively larger on the transmitting side for the same distance from the focal plane. Figure 1 also showed that the Mode 3 DOF was skewed to the receiver side, consistent with a deeper level of shadow on that side. The asymmetry was also observed on the 1D2D-Y probe, and similarly in spinning disk tests by the authors with a PMS OAP-230X probe. It can also be observed in the spinning disk tests of an unspecified NASA PMS 1D OAP [14] and a PMS 2D-C [17], and possibly in the glass bead calibrations of a PMS 2D-grey probe [16]. It is not so clear in other references in the literature, but this was not a focus of their investigations, and consequently the material presented was insufficient to convincingly identify asymmetry. As far as we could determine, there has been no previous discussion of asymmetry of OAP response in the literature. The reason for the asymmetry in the current study is currently not

known, and will be the topic of further investigation, including an analysis of the optical path components of the 1D2D probes. However, practically speaking, if it is not an artifact of the spinning disk method, the asymmetry presents only minor inaccuracies that are taken into account using the analysis method described in this study. In fact, the over-correction of size on the transmitter side somewhat compensated for the lack of correction near the focal plane.

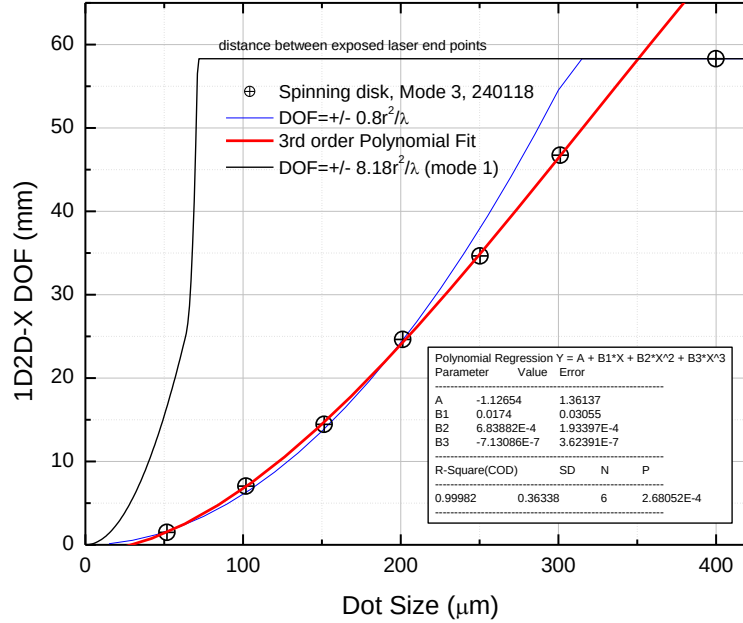


Figure 4. Depth of Field estimates from spinning disk calibrations of the 1D2D-X probe using Mode 3 operation.

Figure 4 contains the final DOF versus size results from the 1D2D-X spinning disk testing. The results are from testing on 18-Jan-2024 at 50 ms^{-1} . Further analysis from 21-Jul-2023 and 25-Jan-2024 (not shown) provided nearly identical results but contained some foreign particles on the disk that resulted in more scatter. The DOF was limited at the larger sizes by the maximum exposed laser distance of 58.3 mm between the two probe arms. In the earliest investigations of OAPs, Ref. [1] expressed DOF values in the form $\pm cr^2/\lambda$, where r was the radius of the particle, λ the laser wavelength, and c was a constant. Ref. [4] calculated that an ideal monochromatic 50% shadow threshold probe, such as the monochromatic DMT CIP, the SPEC 2D-S probe, or the 1D2D used in Mode 1, would have a c value of 8.18. The $\pm 8.18 r^2/\lambda$ relationship is shown as the black line in Figure 4 for reference, and will be returned to later in this article. The primary results are for Mode 3, where the individual spot size DOF estimates are shown as black open symbols. Data points for sizes larger than 399.9 μm were at the maximum DOF defined by the full exposed laser length, and were not plotted in order to focus on the variable DOF region. The data nearly followed the $\pm 0.8r^2/\lambda$ blue line, but were better represented by the third order polynomial fit to the points (red line). Rather than fitting the polynomial to the spinning disk data point at 399.9 μm , it was decided to fit only the smaller dot sizes, and extrapolate the polynomial to the intersection of the constant 58.3 mm DOF line, as it better represented the expected $\pm cr^2/\lambda$ shape. The maximum DOF of 1D2D-X Mode 3 was thus reached at about 350 μm . The use of the polynomial allowed for the estimation of the DOF at specific 1D2D-X channel thresholds.

The Mode 3 average sizes for each spinning disk run (e.g. 104.7 μm in Figure 2) represent the expected average size of all particles measured across the entire DOF. These averages are plotted for all dot sizes in Figure 5. Note that even after applying the out-of-focus size correction, there was a small net oversizing averaging about 2% (see inset of Figure 5), largely due to the region closest to the focal plane where particles with no Poisson spot cannot be corrected. As a final step in the correction of the Mode 3 spectra, the technique suggested by [13] was applied. Ref. [13] used predictions of a model of OAP performance to adjust nominal OAP channel bin diameters to model predicted average values. Although not as rigorous as particle-by-particle corrections, their study suggested this as a practical approximate correction for an OAP probe that did not provide particle imagery that would enable the particle-by-particle correction of [12]. In the present study, the technique was used after the particle-by-particle size correction to address the residual oversizing displayed in Figure 5. The third order polynomial fit to the spinning disk data in

Figure 5 was used to redefine the thresholds of the 64 1D2D-X channel bins, and the DOFs applicable to the central diameter of the new bins were calculated from the third order polynomial of Figure 4. For sizes smaller than 50 μm , DOFs provided by an NCAR model of OAP performance [5] were alternatively used, because the extrapolation of the polynomial from the smallest dot size of Figure 4 to smaller sizes did not appear to provide reasonable results. As will be shown in section VI (C), these lower channels of the 1D2D-X were not used in the composite spectrum in any event. The final 1D2D-X channel file is provided in Appendix A.

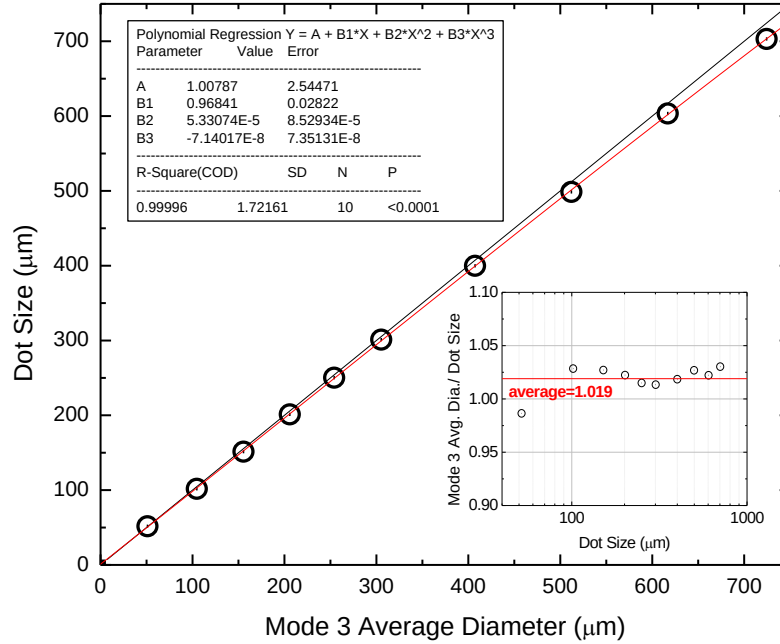


Figure 5. Average sizes measured by the 1D2D-X for spinning disk dot sizes of 51.7 - 703.1 μm . The inset diagram shows the ratio of measured to actual sizes.

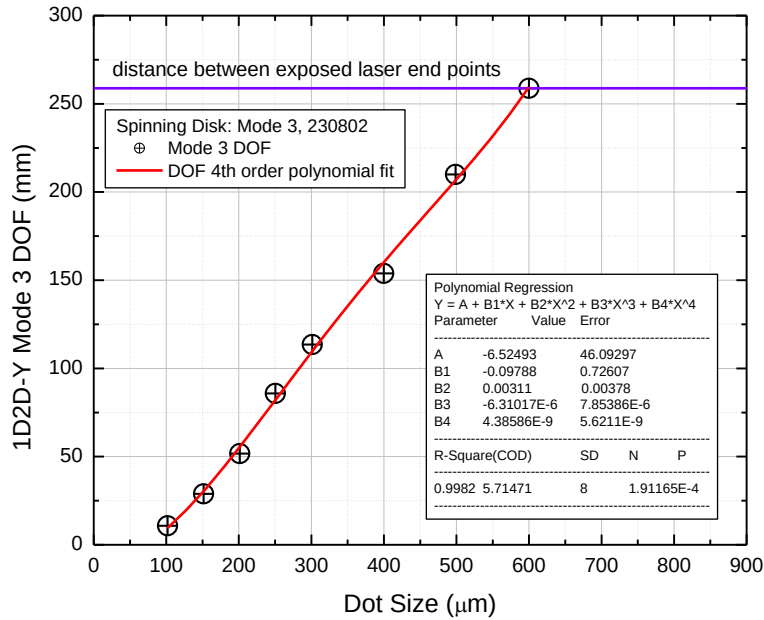


Figure 6. As in Fig. 4, but for the 1D2D-Y in Mode 3 operation.

B. 1D2D-Y spinning disk results

The same procedures described in section V (A) were followed for 1D2D-Y spinning disk calibration, with the same intention of deriving DOFs and new threshold diameters for the probe size bins. Due to the angle of the Y-shaped probe arms, the disk could only sample to within ± 29 mm of the full 258.8 mm exposed laser length. Figure 6 shows the measured Mode 3 DOF versus size for the variable DOF region. The 1D2D-Y exhibited the same type of side lobes observed for the 1D2D-X. Although the DOFs for the larger dot sizes clearly had reached the maximum exposed length of the laser, uncertainty arose for intermediate dot sizes when side lobes entered the unsampled edge regions. Some assumptions had to be made as to how to adjust the DOFs and average sizes for the 301.2-498.7 μm dot sizes. This edge effect was an unanticipated result, and likely led to some of the scatter in Figure 6. Future exploration of Mode 2 operation (Table 1), which does not produce DOF side lobes, may produce preferred results. But for the current study, the polynomial fit of Figure 6 was used to define the 1D2D-Y Mode 3 DOFs, in the same manner as the 1D2D-X.

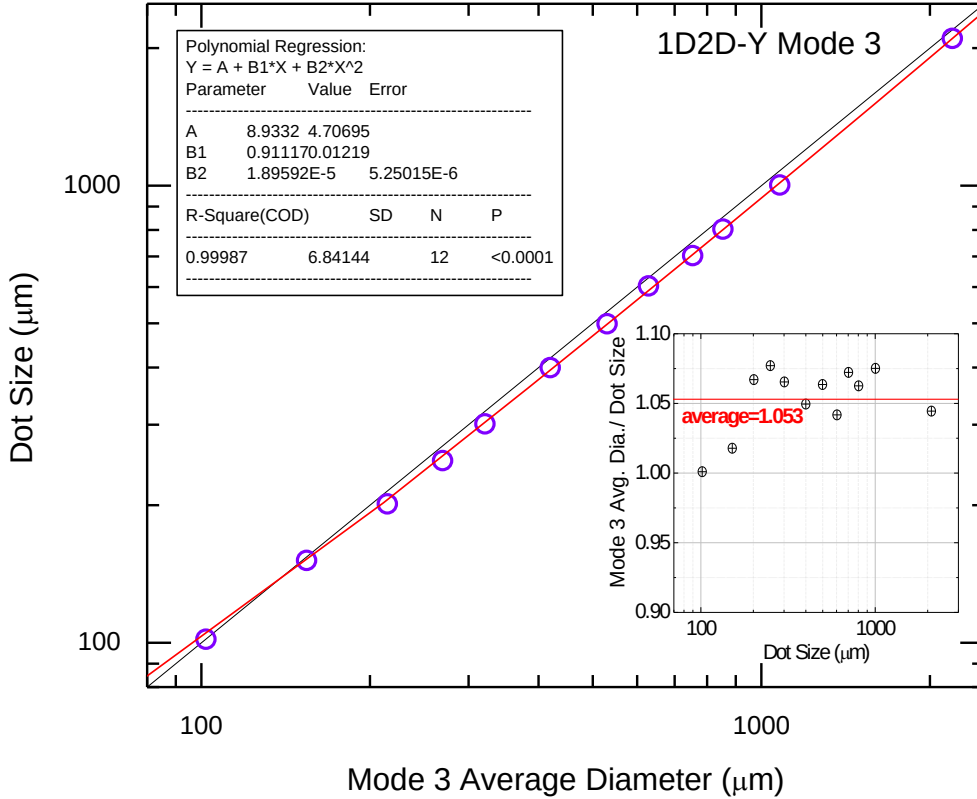


Figure 7. As in Fig. 5, but for the 1D2D-Y in Mode 3 operation.

Figure 7 shows the number weighted Mode 3 average size across the entire 1D2D-Y DOF. As in the case of the 1D2D-X, there was a net oversizing after correction for out-of-focus particles due to the lack of a Poisson spot near the focal plane, averaging about 5.3% over the range of dot sizes. The polynomial of Figure 7 was then used to down-adjust bin sizes accordingly to spinning disk average values estimated by the fit, as per the technique of [13]. The final channel file, including adjusted bin sizes and DOFs, is also included in Appendix A.

VI. Composite Spectra from the Oct./Nov. 2023 IRT Testing

A. Test points, data collection, and processing

The dataset was collected at the NASA IRT in October and November 2023, in SLD conditions over a wide range of MVDs. Testing was performed at both 66 and 77 ms^{-1} , but only the latter will be presented here, because it more closely matched one of the future CIRA calibration velocities of 80 ms^{-1} , and because a wider range of MVDs

was sampled. For all following discussions, the IRT calibration and some exploratory MVD and LWC values will be identified as “IRTMVD” and “IRTLWC”, to differentiate them from the current study’s composite PSD values. IRTMVDs ranged from 30.9 μm to 471.9 μm , and IRTLWCs ranged from 0.66 to 2.47 gm^{-3} , with LWC selection sometimes limited by nozzle performance. The IRT calibration values were from the last full IRT calibration in 2019 [18], which were intermittently checked in the interim, and were being updated during the period of the current study. Testing was performed in the three operational modes of the 1D2D probes listed in Table 1. Imagery was collected at the 50% shadow level, with second level pixel counts stored with the particle image. Table 2 shows the final number of data collections for each operational mode at each test matrix point. For this study, most results will be presented for Mode 3, with some limited comparisons to Mode 1. Mode 3 data collections were usually 150 seconds, and typically decreased to 105 seconds to exclude spray transitions.

IRTMVD μm	IRTLWC gm^{-3}	1D2D-X / 1D2D-Y		
		Mode 1	Mode 2	Mode 3
30.9	2.47	1 / 0	1 / 0	1 / 0
58.2	0.69	2 / 1	2 / 1	2 / 1
98.2	0.66	2 / 2	2 / 1	2 / 2
129.2	0.79	2 / 2	2 / 2	2 / 2
160.8	0.72	3 / 2	3 / 1	3 / 2
277.0	1.08	1 / 2	1 / 2	1 / 2
471.9	1.63	2 / 2	2 / 1	2 / 2

Table 2. Test matrix points for Oct.-Nov. 2023 IRT testing, and number of data collections for the 1D2D-X and 1D2D-Y in each mode of operation. The numbers under each mode represent the number of times the test matrix point was tested for each 1D2D probe.

Data were also collected with the DMT CDP, and processed into a single average PSD for each test matrix point. 1D2D-X and 1D2D-Y spectra were separately averaged over the chosen interval, and repeats were kept separate for evaluation of tunnel repeatability. The NCAR SODA-2 software was used to create PSDs that were modified in post processing to apply the channel files produced from the spinning disk measurements, and contained in Appendix A. To provide a final spectrum, the CDP, 1D2D-X, and 1D2D-Y spectra were merged into a composite spectrum, as describe in section VI (D).

B. Tunnel PSD repeatability

In order to form tunnel composite spectra from probe data taken at different times, it is necessary that the tunnel PSD is consistently repeatability. Table 2 showed that test points were usually repeated at least once in Mode 3 for both the 1D2D-X and 1D2D-Y. A typical 1D2D-X repeat comparison is shown in Figure 8 for the 160.7 μm IRTMVD test point. Plots of this type were produced and inspected for all repeats, and it was concluded that repeatability was more than adequate for 105 second data collections. For the 1D2D-X, the PSD integrated LWC usually repeated to within 4%, with one test point reaching 7%. For MVD, repeatability was usually within 2% and reached a maximum of 4%. For the 1D2D-Y, LWC and MVD repeatability for dual collections was better than 5% and 2% respectively. Since these percentage differences were provided mainly from single repeats, they do not represent statistically significant repeatability estimates, but serve as rough indicators.

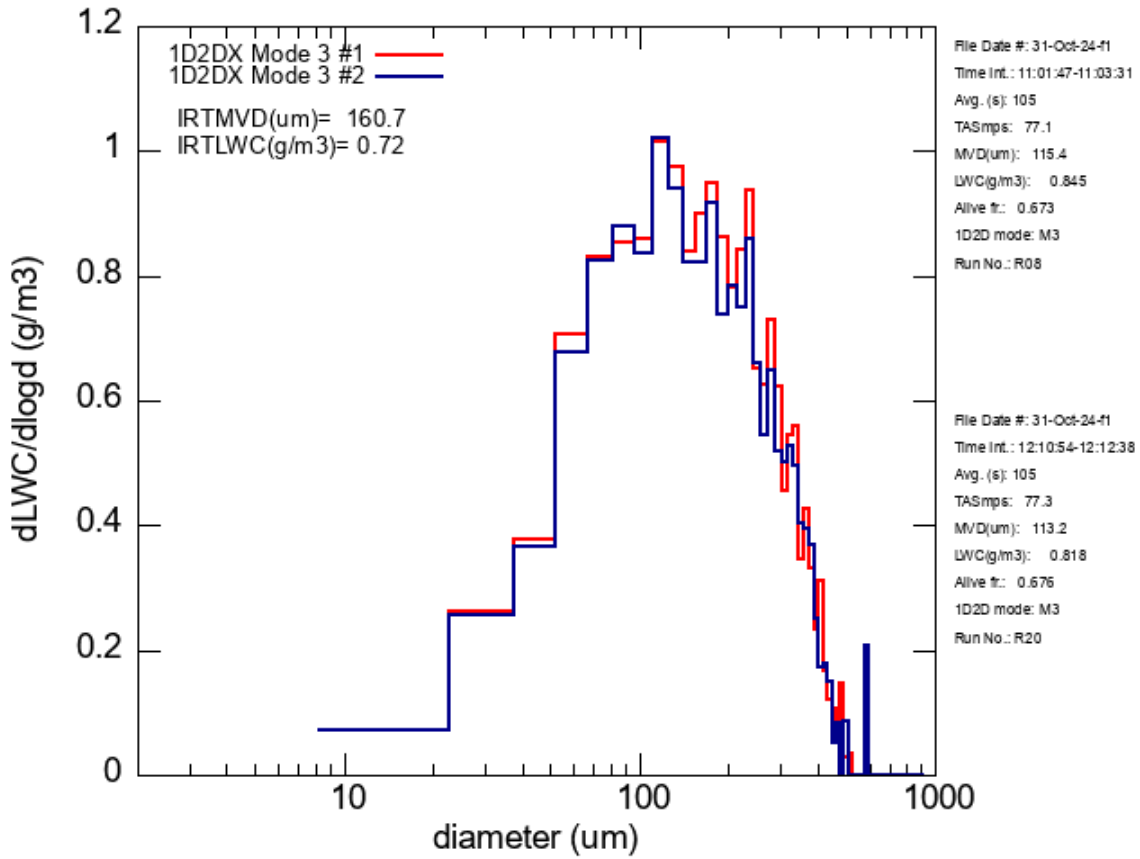


Figure 8. Example 1D2D-X Mode 3 repeats of the 160.7 μm IRTMVD test point, displaying the $d\text{LWC}/d\log D$ spectra for two periods averaged over 105 seconds. Details on the two sampling periods, including PSD LWC and MVD derived solely from the 1D2D-X probes, are provided to the right edge of the plot.

C. Probe merging for composite spectra, and probe overlap.

The strategy for producing composite spectra was to use the high-resolution measurements of the CDP for the nominal sub-50 μm part of the spectrum, which was required to obtain adequate size resolution for test points dominated by Appendix C conditions. The 1D2D-X, with a size resolution of 15 μm , was not well suited for this size range. Next, the 1D2D-X was used for larger droplets, the upper limit to be determined by overlap with the 1D2D-Y, and the eventual loss of 105-second sample statistics exacerbated by the decreasing sample volume with increasing diameter. The 1D2D-Y provided a much larger sample volume to represent the tail of the spectrum.

Figure 9 illustrates the merging of spectra and the probe overlap behaviour for the test matrix point of 129.2 μm IRTMVD. The nature of the overlap of probes is common to all test points, which can be evaluated collectively in section VI (E). First, the overlap from the top of the CDP spectrum (red) to the 1D2D-X (dark blue) was very good, as was previously observed in [5]. The poor resolution of the 1D2D-X at smaller diameters was apparent. It was therefore sensible to use the CDP to its top channel (46-48 μm)², and switch to the 1D2D-X in its fourth channel (52.0-66.6 μm). This required establishing an artificial bridging channel (48-52 μm), where its LWC per μm was calculated by simple interpolation of the neighbouring channels. The overlap between the 1D2D-Y (magenta) and the 1D2D-X was not as good as hoped for the lower 1D2D-Y channels, but was very good for sizes above about 400 μm in Figure 9, and sometimes lower for other MVDs. While some of this overlap discrepancy may be due to the

² There is one higher channel on the CDP which always contained abnormally high concentration, which is believed to contain concentrations of all particles larger than the top threshold. This top channel was excluded from the analysis.

larger uncertainty in DOF for the 1D2D-Y, or the small number of pixels defining the 1D2D-Y particle size in this lower size range, this remains an open issue that will be the subject future investigation. Given the favourable overlap for sizes larger than 400 μm , and the diminishing sample volume of the 1D2D-X, it was then sensible to define a crossover point to the 1D2D-Y at around this size. Accordingly, the last 1D2D-X channel used in the composite spectrum was 375.2-389.9 μm , and the first 1D2D-Y channels was 399.6-446.0 μm , requiring the creation of a small artificial bridging channel from 389.9-399.6 μm by normalized mass interpolation. In this particular case, the 1D2D-X appeared to be measuring the tail of the spectrum similarly to the 1D2D-Y, as was the case for most other test points. However, as will be shown in VI (F), for the two test points with the highest MVDs, the 1D2D-Y exhibited a more extended tail than the 1D2D-X.

Using the merge strategy described above, the final composite spectrum is shown in Figure 9 by the thick cyan line. In this dLWC/dlogD representation of the LWC spectrum, the area of a diameter interval under the curve is proportional to the its LWC contribution, and a log-normal LWC distribution would appear as a “bell-shaped” curve. At this MVD, the distribution did appear to be close to log-normal. The combination of the CDP and 1D2D-X alone appeared to close the LWC distribution for all practical purposes. Note that the merging of the probe spectra, particularly the CDP to 1D2D-X, did not apply any artificial scaling to improve probe overlap, as is sometimes used to improve probe blending.

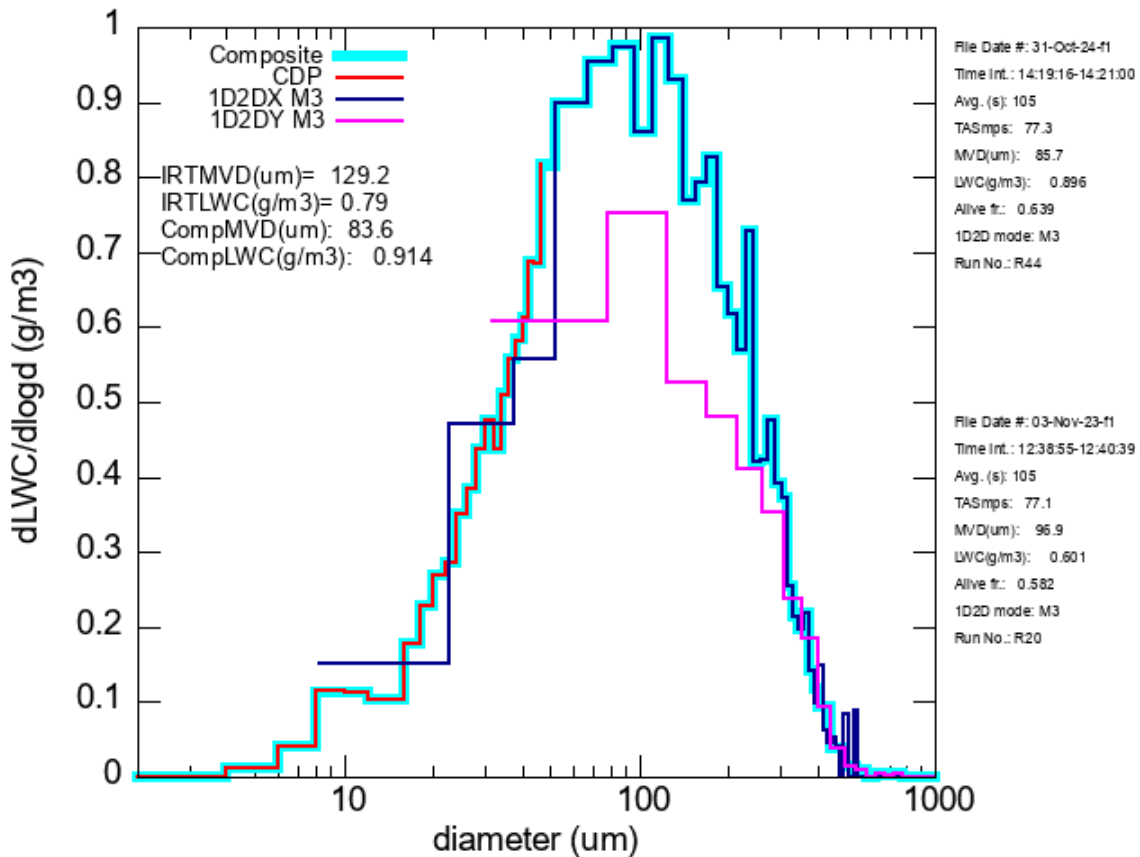


Figure 9. Illustration of probe overlap between the CDP and 1D2D-X, and the 1D2D-X and 1D2D-Y probes in Mode 3 operation. The final composite spectrum is shown in the thick cyan line. See text for merge strategy. Text summaries at the right of plots are for the 1D2D-X (top) and 1D2D-Y (bottom).

A comparison of the final merged spectrum MVD and integrated LWC to the IRTMVD and IRTLWC is provided in the top left legend of Figure 9. Comparisons to IRTLWC and IRTMVD will be discussed in sections VI (F) and (G).

D. Comparison of 1D2D-X Mode 3 and to Mode 1 interarrival time characteristics and LWC distributions

Figure 10 shows sample plots of interarrival time distributions for the 129.2 μm IRTMVD test point. The Mode 1 distributions (Fig. 10a, olive plot) showed a distinct secondary maximum between 10^{-7} and 10^{-6} seconds, which was not observed in the Mode 3 distribution (Fig. 10b). The secondary lower interarrival time mode has been commonly identified by the atmospheric science community as an artifact due to particles impacting on probe upwind surfaces, leading to closely spaced breakups detected shortly thereafter within the probe sample area. The phenomenon has primarily been associated with shattering of ice crystals in ice clouds (e.g. [19]). This difference between Modes 1 and 3 was consistently observed for all test points, and on both the 1D2D-X and 1D2D-Y probes³. The question arose as to whether this was somehow specific to the 1D2D probe, for example due to probe arm tip design. But analysis of 2D-S measurements collected at the IRT in April 2023 at a similar test condition (Fig. 10a, red line) also exhibited the secondary short interarrival time mode. While the cause of the secondary mode is not obvious in liquid conditions, another possibility other than breakup may be probe interpretation of highly fractured images at the extreme edges of the DOF as closely spaced separate particles. A correction for the secondary low-interarrival time mode has been provided by [20], and is implemented in SODA-2 and shown in Figure 10a (green line). The algorithm rejects the short interarrival time particles below a threshold interarrival time value, and makes a small correction for predicted real particles rejected by the algorithm. This correction was used below for Mode 1 but was concluded to be unnecessary for Mode 3, a distinct advantage of Mode 3 in reducing corrections.

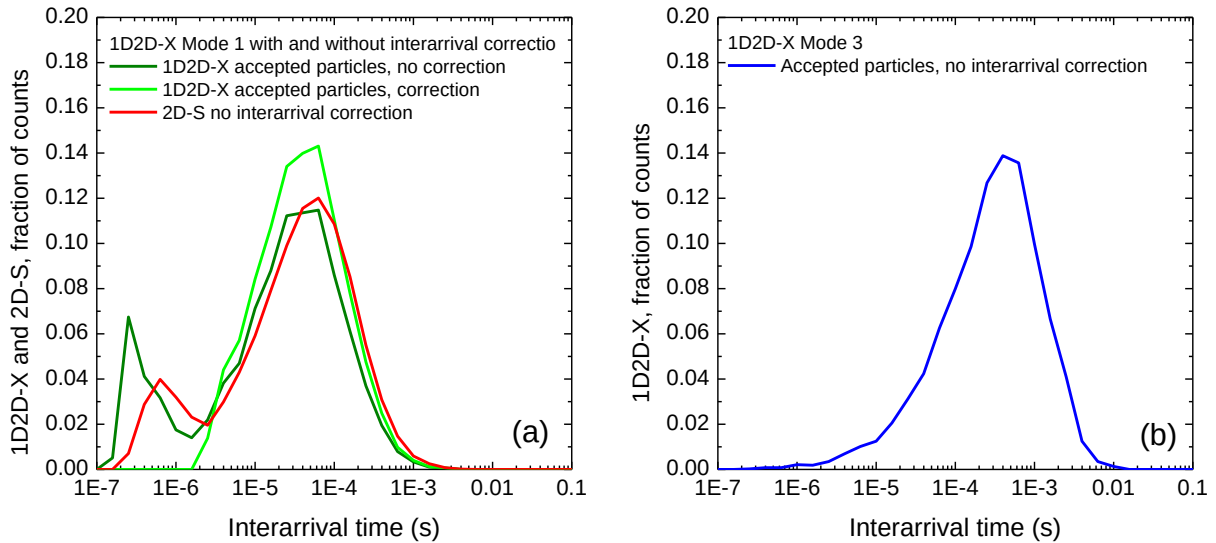


Figure 10. (a) Interarrival time distributions for the 31-Oct-2023 129.2 μm IRTMVD test point for IRT1D2D-X Mode 1 (green and olive), and 2D-S interarrival times for the 1-Apr-2023 120 μm IRTMVD test point, and (b) the 1D2D-X Mode 3 interarrival time for 31-Oct-2023 129.2 μm IRTMVD. The uncorrected 1D2D-X Mode 1 and 2D-S distributions show a distinct short interarrival time secondary maximum.

³ Mode 2 also did not exhibit a short interarrival time maximum for either the 1D2D-X or 1D2D-Y.

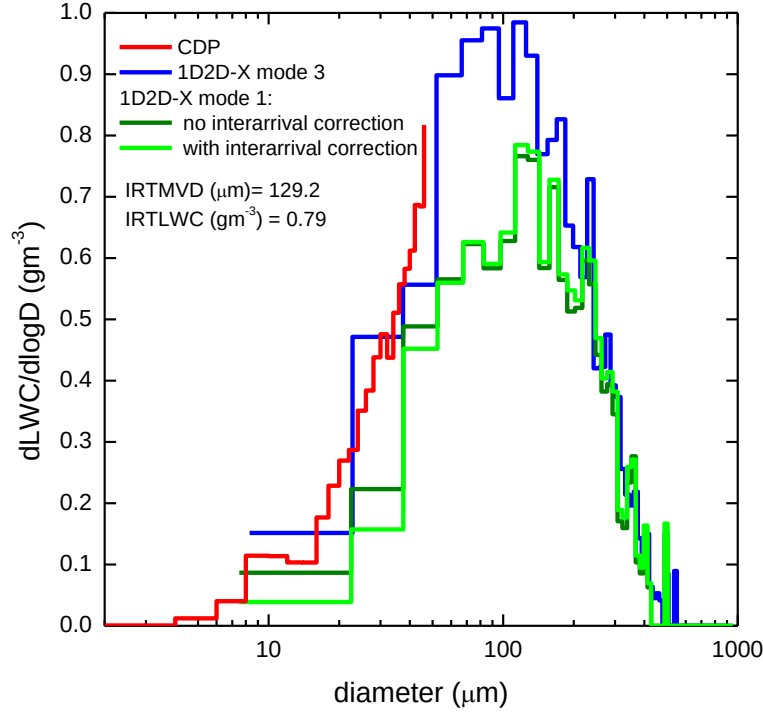


Figure 11. Comparison of 1D2D-X solutions for Mode 3, as in Fig. 9, and in Mode 1, a conventional method of PSD calculation for 50% shadow threshold monochromatic probes. Both 1D2D-X spectra have been size corrected for out-of-focus particles using the method of [12].

Comparisons were also made of the 1D2D-X Mode 3 and Mode 1 LWC distributions. The Mode 1 treatment is commonly used in the research community for monochromatic and even 2D-grey OAP processing. In both cases, the out-of-focus size corrections of [12] were applied. For Mode 1, the standard 15 μm per bin channel sizes and a DOF of $\pm 8.18r^2/\lambda$ were used. Figure 11 shows the comparison using the same test point as Figure 9. Mode 1 solutions with and without correction for the short-interarrival-time particle mode are shown in olive and green respectively. The correction had only minor effect on the LWC distribution. The Mode 1 solutions provided consistently lower concentrations than Mode 3 (blue) for sub-200 μm sizes, and a poor overlap to the CDP. Its use would typically require some artificial scaling to harmonize the crossover point between the CDP and 1D2D-X. Above 200 μm , the Mode 1 and 3 solutions were approximately the same. These behaviours were observed for all test matrix points (not shown), although at high MVDs the Mode 1 solutions in the distribution tails were typically noisier. The reasons for disagreement between Modes 1 and 3 are possibly complex, particularly for the smallest sizes. The DOFs for Modes 1 and 3 were shown in Figure 4. The Mode 1 DOF is the theoretical prediction of $\pm 8.18 r^2/\lambda$ from [4], which has been closely corroborated by [21] using a droplet generator. DOF measurements from spinning disk measurements for such low diameters can be difficult to determine due to the size resolution of the probe, and the difficulty in separating background dust and scratches from the actual dots. Only one dot size of the spinning disk testing of section VI (A) was in the Mode 1 variable DOF region size range. The Figure 4 Mode 1 DOF rises steeply to its mechanical limit in the sub-100 μm size range. The measured Mode 3 increase in DOF was more gradual. Although its variable DOF region was broader, reaching its mechanical limit by a diameter of about 350 μm , the spinning disk DOF measurements for dot sizes 100 μm and above were straightforward and repeatable, and there is a high level of confidence in them. For both modes, sizing errors in the variable DOF regions due to spectral broadening, caused in large part by limitations of the out-of-focus size correction, likely deposited particles in neighbouring bins with different DOFs, potentially causing significant PSD errors. In the case of Mode 3, these sizing errors may be smaller due to elimination of the more out-of-focus particles, especially at the edge of the Mode 1 DOF.

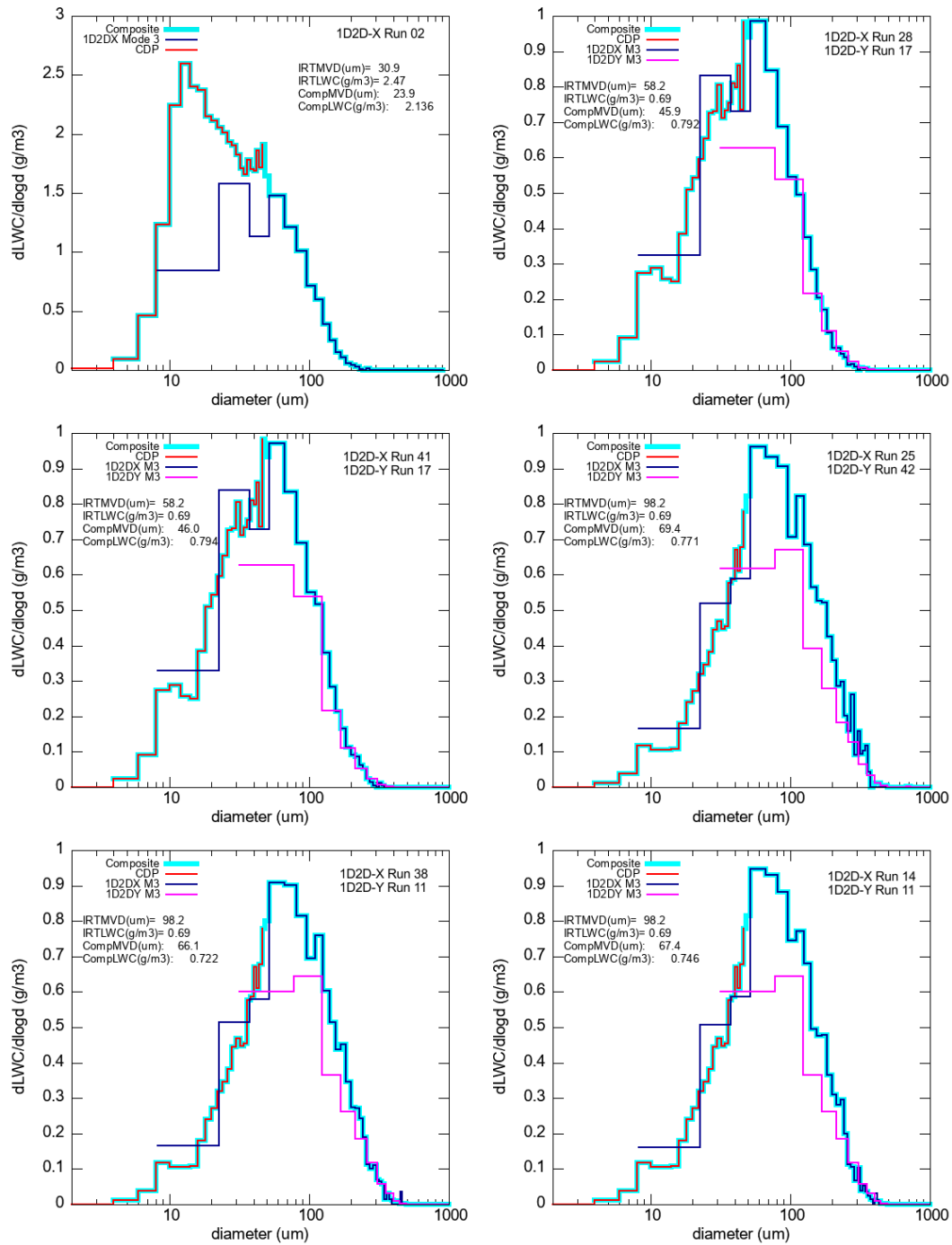


Figure 12. LWC spectra for the Oct./Nov. 2023 IRT testing at 77 ms⁻¹. Individual probes shown as red (CDP), 1D2D-X Mode 3 (dark blue), and 1D2D-Y Mode 3 (magenta). Final merged composite spectra are shown as the thick cyan lines, and composite MVD and integrated LWC are included in the legends. Shown are test matrix points from 31.9 to 98.2 μm IRTMVD

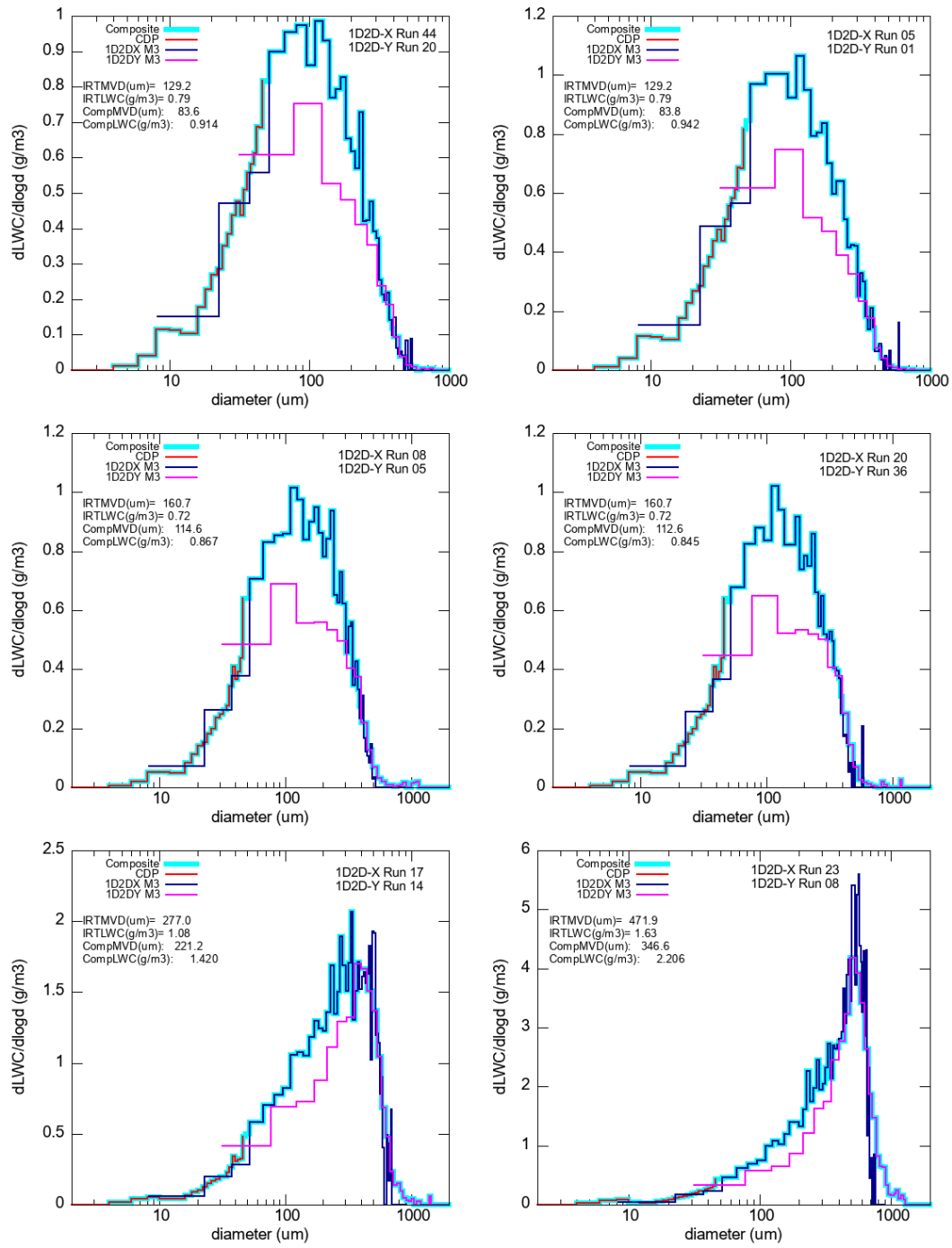


Figure 13. As in Fig. 12, but continuing with test matrix points from 129.2 to 471.9 μm IRTMVD.

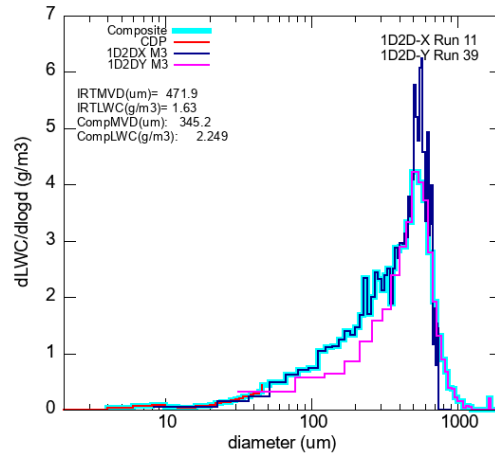


Figure 14. As in Fig. 12, but for the final combination of CDP, 1D2D-X and 1D2D-Y runs for the test matrix point of 471.9 μm IRTMVD.

In summary, the main justifications for favouring Mode 3 solutions over Mode 1 were as follows: (1) Mode 3 exhibited closer agreement in the overlap region of the CDP, and did not require artificial scaling to smooth the probe crossover point; (2) Mode 3 did not require a correction for short-interarrival-time particles, eliminating one possible source of uncertainty; (3) Mode 3 eliminated highly out-of-focus problematic particles at the edge of the Mode 1 DOF that had larger size corrections, some of which may have been uncorrectable due to image fracturing, as pointed out by [8], and may have been interpreted by the probe as more than one particle, and (5) the Mode 1 DOF may have been more affected by the use of the important “water” option in SODA-2 than Mode 3. This effect on Mode 1 DOF was difficult to evaluate due to the lack of calibration points in its rapidly changing DOF with size. As a side benefit, due to the lower DOF at smaller sizes, Mode 3 collected fewer small particles, reducing the probe dead time in high probe overload conditions, thereby improving the statistics for the tail of the 1D2D-X distribution.

E. Final merged spectra

Figures 12-14 contain plots of the final merged spectra from the Oct./Nov 2023 IRT testing at 77 ms^{-1} . All spectra computations used the merging strategy described in section VI (C). The final spectra are represented by the wide cyan-coloured lines, and individual CDP, 1D2D-X and 1D2D-Y components are shown to allow the reader further examination of the probe overlap behaviour described in section VI (C). In order to show repeats where only one of the probes had additional runs, the results for the other unrepeatable probe may be shown twice. Refer to the 1D2D-X and 1D2D-Y run numbers in the top right of each figure to determine such cases. Note that the 1D2D-X and 1D2D-Y were operated on different days, and the run numbers were assigned by the analyst in sequence for that day, so common run numbers between the two probes do not denote the same spray conditions. Due to time constraints, only one version of the CDP data was available for each test matrix condition for this article.

The merged spectra for test points that did not reach the 400 μm crossover point to the 1D2D-Y are of course comprised only of CDP and 1D2D-X probe data. The 30.9 μm IRTMVD test point (Figure 12, top left) was unusual, in that its main purpose was to humidify the tunnel at the outset of testing using a high LWC, low MVD spray. The CDP spectrum for this case displayed an unusual rise in the tail which we believed to be spurious, and which degrades the overlap to the 1D2D-X. In spite of its more operational objective, this test point was the only one well within the Appendix C envelope, and was thus considered important to include in this study. The overlap for the higher MVDs always appeared to be quite good, without any artificial scaling applied.

The LWC spectrum appeared to have been reasonably well closed by the CDP and 1D2D-X alone for IRTMVDs up to 160.8 μm . For the two highest MVD test points, there is some indication that the 1D2D-Y was measuring a tail beyond the 1D2D-X (see the 277.0 μm IRTMVD plot of Figure 13, bottom left, and the 471.9 μm IRTMVD plots of Figure 13, bottom right, and Figure 14). However, the additional LWC provided in this extended tail appeared to be small, and would likely not have altered the MVD by a substantial amount. For these high-MVD cases, it was also

evident that the 1D2D-X spectra were becoming noisy relative to the 1D2D-Y at the higher diameters, likely due to the former's diminishing sample volume with diameter, and its narrower bin widths.

F. PSD LWC closure

In the absence of any generally accepted absolute reference to the final LWC distributions summarized in Figures 12-14, the integrated LWCs from the distributions were used to provide an indirect indication of their accuracy. The IRT test point LWC was determined by hot wire measurements of the SEA Multi-Element Probe (MW⁴) TWC sensor [22], as part of the standard IRTLWC calibration. IRT staff have estimated this method to fall within 10% of a generated curve fit for Appendix C conditions and 20% for large drop (> 50 μm) conditions [18], and to have an expected superior LWC response to the icing blade in high LWC and SLD conditions [23]. These authors acknowledged that the MW response to SLD could be limited due to splashing and pooling in the TWC element.

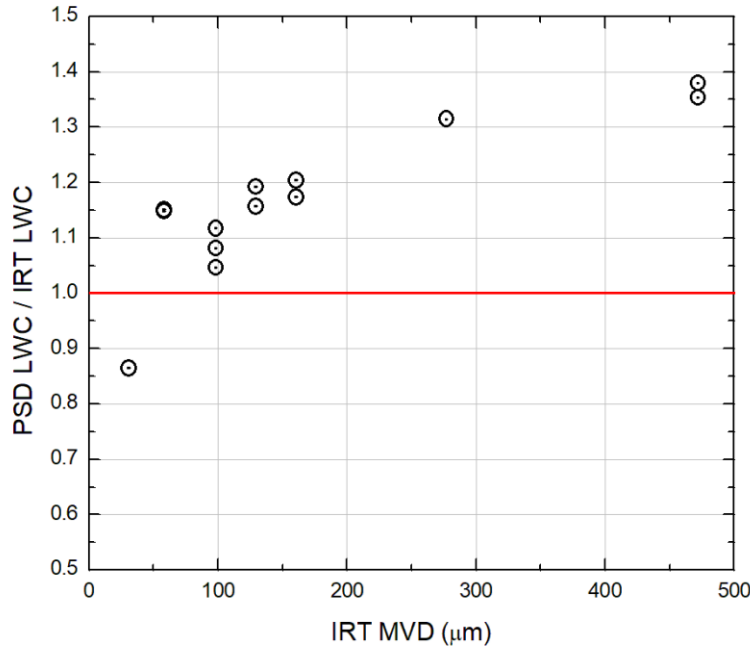


Figure 15. Ratios of PSD integrated LWC from the plots of Figs. 12-14, to IRTLWCs, the latter derived from hot-wire measurements.

Figure 15 displays the ratio of the final merged spectrum integrated LWCs to the IRTLWCs, as a function of IRTMVD. There was a clear increase in PSD LWC relative to hot-wire with increasing MVD, rising from about a factor of 0.86 at 30.9 μm IRTMVD, to about 1.35 at 471.9 μm IRTMVD. As noted previously, the 30.9 μm IRTMVD was unusual in that it was used operationally to humidify the tunnel, and its LWC may therefore not follow the IRTLWC calibration equations. Furthermore, its LWC is dominated by the CDP size range, and the low ratio here may also reflect uncertainty of the CDP in this unusually high LWC test point. In general, it should be noted that the accuracy of PSD integrated LWC estimates might intuitively be expected to be less accurate than bulk hot-wire estimates, due to the cumulative errors of integrating the cube of the diameter in the PSD estimate. However, there is evidence that hot-wire estimates at high MVD have their own uncertainties. Ref. [24] showed that different hot wire TWC sensor geometries provided differing responses in SLD conditions in wind tunnel testing, including both scale factor differences across all MVDs, and different relative responses with increasing MVD. The latter behaviour was speculated to be due to the differing depths of the TWC sensors, and thus differing sensitivities

⁴ Also known as the multi-wire (MW)

to splashing. The MW probe, the shallowest of all TWC sensors, showed a decreasing response with increasing MVD relative to other TWC sensors. For example, Ref. [24] showed that the MW's response relative to the deeper SEA Robust probe [25], decreased a factor of 1.34 from estimated MVDs of approximately 100 to 300 μm , similar to changes in the magnitude to the differences observed in Figure 15. Furthermore, Ref. [26] analysed isokinetic evaporator IKP2 [27, 28] response at the IRT under similar test points to this study. The IKP2 should in theory have superior large droplet response due to its isokinetic sampling and flow-through sample volume (i.e. no splash-out). In that study, the IKP2 LWC was found to rise relative to the IRTLWC by about a factor of 1.22 from about 100 to 460 μm IRTMVD. So, there is a case to be made that a good fraction of the increase with MVD in the ratio of PSD to MW LWC in Figure 15 could be due to decreased response of the IRT hot-wire LWC estimate. In any event, it is contended that the LWC comparisons of Figure 15 are generally good and provide support for PSD distribution accuracy, even before considering the possibility of hot-wire underestimates at high MVD. If the TWC discrepancy of about 1.35 at 471.9 μm IRTMVD were attributed solely to spectrum oversizing, the rough estimate of MVD overestimation would be the cube root of 1.35, or about 10%. If the LWC ratio were reduced to a factor of 1.15 due to possible IRTLWC underestimation, the corresponding MVD overestimate under the same assumptions would be about 5%.

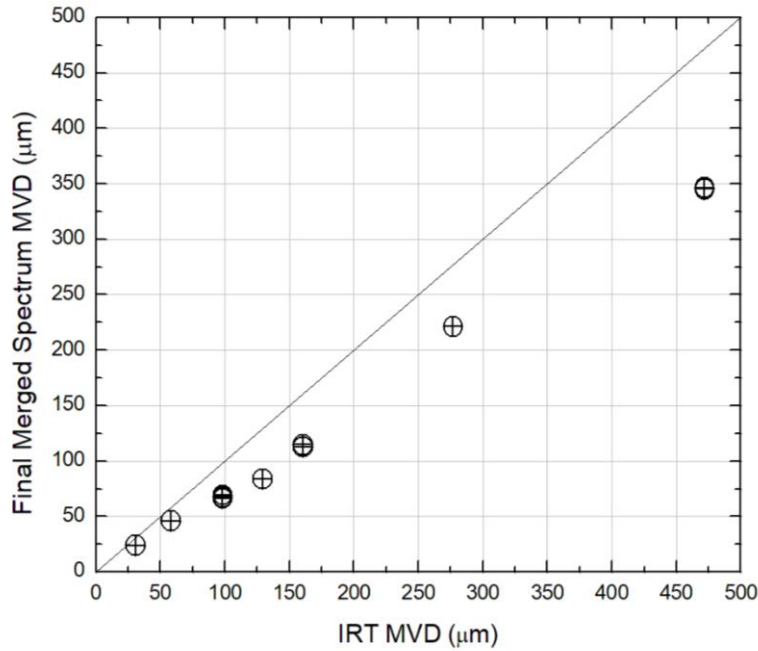


Figure 16. Comparison of MVDs calculated from the merged spectra of this study, to IRTMVDs.

G. Comparison to IRTMVDs

As discussed earlier, the IRTMVDs and IRTLWCs used in this study were those determined by the previous 2019 tunnel calibration. The IRTMVDs result from merging of spectra from different probes in a manner similar to the present study. The probes used by the IRT are the DMT CDP, the PMS OAP-230X (15-450 μm), and the OAP-230Y (50-1500 μm). The latter two probes are one-dimensional probes that produce spectra automatically in real-time, but do not produce particle imagery.

The MVDs of the final merged spectra of Figures 12-14 are compared to the IRTMVD in Figure 16. The merged spectrum MVDs from this study were consistently lower (65-80%) than the IRTMVDs, with the lowest percentage observed at 129.2 μm IRTMVD. The overall average percentage was 72%. The differences were substantial, and are believed to be due primarily to the fact that the standard size distributions produced by the IRT OAP probes are not correctable for out-of-focus oversizing using the method of [12], and the bin adjustment method of [13] has not yet been evaluated. Furthermore, the response to artifacts such as splashing is unknown due to the

lack of particle imagery. Even though the second-level DOF requirements of the IRT OAPs, i.e. one pixel at the 67% shadow level [29], tempers the full effect of oversizing somewhat by restricting the DOF, no oversizing correction is applied. In the case of the 1D2D probe analysis of this study, restricting the DOF, applying the out-of-focus size correction, and applying the final adjustment of bin sizes to compensate for remaining oversizing have all been used to minimize sizing error. Also, the water option of SODA-2 minimized the effect of artifacts on the PSDs. The discrepancy between the current study MVDs and the IRTMVDs is being reviewed by NASA and will be the subject of capability improvement studies for the IRT SLD cloud calibration.

VII. An Example of a Model Estimate of Absolute Accuracy

The NCAR model of OAP performance produces simulated 2D imagery, which when analyzed with the same SODA-2 software and options used in tunnel PSD analysis, provides an idealized estimate of the expected OAP measurement accuracy.

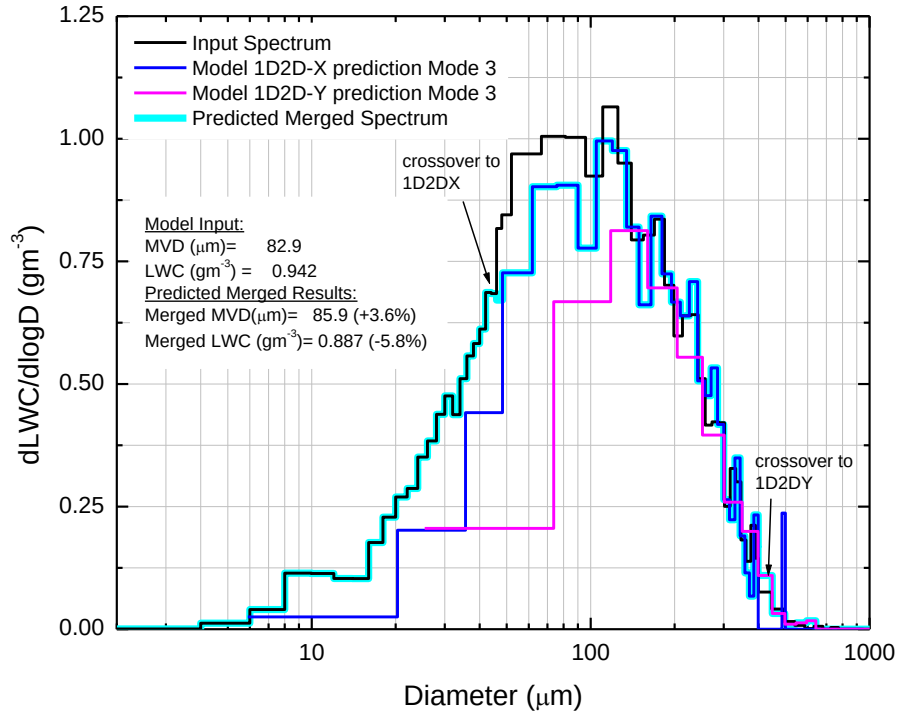


Figure 17. Results of NCAR model simulations of 1D2D-X and 1D2D-Y performance in Mode 3 for an input spectrum (black line) of 82.9 μm MVD, and 0.942 gm^{-3} LWC. Final merged model prediction is the wide cyan line.

Ref. [5] provided an example of the use of the model to estimate what the 1D2D-X probe would produce within its size range for a given true input distribution of 166.9 μm MVD and 0.56 gm^{-3} . The model was used to predict MVD differences resulting from application of different drop diameter definitions from 2D images. Using the X-size diameter definition of the current study, and applying the out-of-focus size correction, the measured MVD and LWC were 179.4 μm and 0.53 gm^{-3} respectively. For the current study, the same process was followed with an IRT distribution, except that the simulations were run for both the 1D2D-X and 1D2D-Y probes, and the final spectrum was merged in the same way as described in section VI (F). SODA-2 Mode 3 operation, the water option, the out-of-focus size correction of [12], and the final adjustment of [13] to bin diameters to account for residual error were all applied. Average size errors used to create the adjusted bin thresholds and DOFs were all provided by model runs with

discrete drop sizes. A spectrum very close⁵ to the merged spectrum of Figure 13, top right, with 82.9 μm MVD and 0.942 gm^{-3} LWC, was used as input to the NCAR model as a hypothetical true distribution, and comparison of SODA-2 merged output provided the model prediction of absolute error. This input spectrum was chosen because it was expected to experience the worst out-of-focus oversizing overall for the IRT test points. The model prediction is shown in Figure 17. The black line represents the input spectrum. As in the case of the IRT data analysis, the data were considered fixed in the CDP size range to 48 μm , and the merged spectrum crossed over to the 1D2D-X in its fourth channel and to the 1D2D-Y in its ninth channel, in both cases with a small artificial bridging bin. The crossover to the 1D2D-X was quite smooth without any artificial scaling. There was a tendency for the 1D2D-X to underestimate the input spectrum for sizes less than about 100 μm , which caused the merged spectrum LWC mode to be lower than the input, but the larger sizes were well predicted. The 1D2D-Y prediction underestimated the input and 1D2D-X spectra for its first three channels. A similar behaviour was observed in the comparisons of the 1D2D-X and 1D2D-Y IRT data in Figure 12-14, although there the IRT 1D2D-Y data tended to read lower for up to the first six channels. Little mass was contributed by the 1D2D-Y for this test point, so its impact on the final merged spectrum was minimal. The final spectrum is shown in the wide cyan line. Comparing to the input spectrum, this provided the model prediction of absolute accuracy for Mode 3 MVD and LWC using this process, an MVD and LWC of 85.9 μm and 0.887 gm^{-3} , about 3.6% higher and 5.8 % lower than the input spectrum.

A few further model results will be noted briefly below. First, accuracy estimates for Modes 1 and 2 were as good as Mode 3, but of course the number of particles requiring correction, and the magnitude of their corrections was overall larger than Mode 3. Such corrections were idealized and consistent with calculations that produced the simulated imagery. Second, the final bin size adjustment of [13], when used after the particle-by-particle out-of-focus size correction of [12], improved accuracy only slightly or insignificantly. For example, in Mode 3 where the largest effect was observed, the final MVD and LWC predictions without the final correction were 9.7% and 3.9% higher, versus the 3.6% higher and 5.8% lower with the final correction. Third, when the final bin size adjustment was used without the particle-by-particle out-of-focus size correction, the predicted Mode 3 accuracy was almost identical to that when it was included. This was probably due to the relatively small fraction of Poisson spots in its constrained dataset. Mode 2 also performed well with only the final bin size adjustment. With neither size correction, Mode 2 MVD and LWC predictions were both about 33.4% high, and after adding only the bin size adjustment, they were 3.6% high and 0.7% low. These results would suggest that producing real-time spectra in Modes 2 or 3 with the bin adjustment and without the particle-by-particle size correction shows promise. However, for Mode 1, the final bin adjustment was a poor substitute for the particle-by-particle correction, overpredicting MVD and LWC by 40% and 18.7% respectively. Finally, it should be noted that the accuracy estimates above apply to an idealized model of probe performance, DOF, and size corrections, and should represent only a first estimate of actual expected accuracy in real conditions.

VIII. Summary and Conclusions

Results from a series of wind tunnel tests at the NASA IRT in SLD conditions have provided a dataset for evaluating a method for future calibration of MVD and LWC distributions in SLD conditions at the CIRA IWT. Test points included a range of MVDs estimated by IRT calibration to be between 30.9 and 471.9 μm . The current study used a DMT CDP probe, and two new optical array 1D2D probes manufactured by Science Engineering Associates designed specifically to improve accuracy and performance for wind tunnel calibrations, and currently including increased 1D2D-X de-icing for extended calibration sampling. The new probes covered the intermediate and large particle size ranges to a nominal 3200 μm , and added features to constrain one of the primary sources of OAP uncertainty in SLD measurement, sizing and imaging errors due to out-of-focus particles, by using information from two image shadow levels. The new probes provided both particle imagery and binned channel concentrations for real-time use, although only post-processed PSDs were evaluated here. Post processing of OAP data was performed using the NCAR SODA-2 software, a publicly available and well documented utility. Full details on the 1D2D probes features have been provided in [5].

PSD evaluations were performed for the new probes operating in a conventional Mode 1, with no requirements for particle shadowing at the 75% level, and a Mode 3 in which at least 50% of the pixels were required to shadow at the 75% level. Mode 1 operation would mimic what could be expected using a monochromatic OAP, such as a PMS 2D-C probe or SPEC 2D-S probe. Spinning disk measurements of known dot sizes were used to characterize the DOF

⁵ An earlier version of the merged spectrum of Fig. 13, top right, was used as the input spectrum, with a slightly lower MVD (82.9 versus 83.8 μm), but the same LWC. Since the input spectrum was arbitrary, this does not affect conclusions.

versus size for Mode 3, which was the primary mode of 1D2D operation for this study. The Mode 3 DOF, before reaching the mechanical limit of the exposed laser length, was reduced by about a factor of 10 relative to Mode 1, and was constricted to the region nearest the focal plane, reducing the overall magnitude of the out-of-focus oversizing correction. The Mode 3 DOF reached its limit at particle sizes of about 350 μm , compared to about 95 μm for Mode 1. Measurement of the 1D2D-Y DOF was more complicated due to the Y shape of the arms, resulting in limitations in reaching the edges of the exposed laser. Some assumptions were made for the un-sampled edges in order to complete the DOF estimation. DOF was estimated to reach the maximum exposed laser length at particle sizes of about 600 μm . For both probes, polynomials were fit to measurements to enable estimation of DOFs at arbitrary sizes.

Examination of spinning disk results of Mode 1 away from the focal plane revealed that sizes reached about a factor of 1.8 of true values at the extreme edges of the DOF, where images became fractured and uncorrectable using the SODA-2 particle-by-particle size correction algorithm of [12]. The use of Mode 3 eliminated the recording of the worst imagery at the edge of the Mode 1 DOF, and constrained the overall oversizing to the lesser levels experienced near the focal plane. Neither mode allowed for full size correction approaching the focal plane, due to diminishing occurrence of a Poisson spot required to make this correction. Therefore, even after particle-by-particle size correction, which could overcorrect when active, there was a net PSD oversizing. For Mode 3, this net oversizing was corrected in a final step by adjusting 1D2D bin diameters and DOFs, using a method suggested by [13]. These final corrections were of minor importance to final merged spectrum LWC and MVD. Mode 3 also had the advantage of eliminating a short-interarrival-time distribution mode that is commonly associated with artifacts, one that was present in all Mode 1 testing, and also in a 2D-S probe independently tested at the IRT prior to the current study. Though of secondary importance and correctable, the absence of this artifact in Mode 3 spectra was considered an additional advantage.

Final Mode 3 merged spectra were created by crossing over from the CDP to 1D2D-X at 48 μm , and to the 1D2D-Y at approximately 400 μm , in each case with a small bridging channel added by mass interpolation. Final spectra from seven different test points yielded MVDs from about 24 to 346 μm . The overlap between the CDP and 1D2D-X at the crossover was very good without any artificial scaling applied, and was superior to that of Mode 1, which is commonly used in monochromatic probes. The 1D2D-Y LWC spectrum under-read that of the 1D2D-X below 300 μm , but overlap was very good for the larger sizes that were used for the merged spectrum. The CDP and 1D2D-X by themselves adequately closed the LWC spectrum up to a measured MVD of about 114 μm . The two highest MVD test points exhibited an extended tail on the 1D2D-Y that was absent on the 1D2D-X. This was at least partially due to the latter's greatly decreasing sample area approaching its 960 μm maximum size, a consequence of deliberately rejecting partial OAP images to avoid sizing uncertainty. Still, at the highest test point measuring 346.6 μm MVD, the extended 1D2D-Y tail was of minor importance to LWC and MVD.

The comparison of PSD LWC to the hot-wire bulk estimates that are used for IRT calibration were generally positive. PSD LWCs were usually higher, with ratios rising from 0.86 to about 1.36 with increasing MVD. The rise with MVD may actually be linked to underestimation of the hot-wire LWC with increasing MVD, as reported by [24] for the same type of device used for IRT LWC calibration. In rough terms, a factor of 1.36 would suggest an outside MVD error estimated by its cube root, or approximately a 10% overestimate. When considering a certain degree of hot-wire LWC underestimation, if the factor were speculated to reduce to 1.15, sub-5% MVD errors might be suggested. A comparison of MVDs from this study to those calibrated for the IRT revealed that Mode 3 MVDs were 65-80% of IRT values, a substantial difference. The results of this study would suggest that these differences were due to its use of the out-of-focus size correction, other advanced features of the 1D2D probes, and possible artifacts in the IRT 1D OAP probe data that cannot be corrected due to the lack of particle imagery. However, this was not the focus of this study, and more detailed investigation of these MVD differences will be explored by NASA and others in future work.

Finally, an NCAR model of simulated OAP performance was used to estimate the absolute accuracy of a true particle spectrum of 82.9 μm MVD, 0.942 gm^{-3} provided from Figure 13 of this study, and representing the test point most affected by oversizing due to out-of-focus particles. All OAP corrections summarized in section VI, and used in the analysis of the IRT data of this study, were applied in the simulation, and the same method of merging individual probe spectra was followed. The model-predicted Mode 3 spectrum had MVD and LWC values 3.6% higher and 5.8 % lower than the input (true) spectrum. The model also predicted that Modes 2 and 3 could produce similar errors in these bulk parameters using only a final bin adjustment, and without the particle-by-particle size correction for out-of-focus particles. This is important for the generation of real-time PSDs and MVD during tunnel calibration and testing exercises, and will be the topic of future research. It is important to note that the accuracy estimates above apply to an idealized model of probe performance, DOF, and size corrections, and should represent only a first estimate

of actual expected accuracy in real conditions. Still, it seems realistic that MVD and LWC errors of the order of 10% may be possible using the PSD measurement process of this study.

It is therefore concluded that the CDP, and the two new 1D2D OAPs provided a combination that minimized the occurrence of common OAP errors and the magnitude of correction of remaining errors, and addressed issues with edge-of-DOF sampling reported by [8]. Spinning disk testing provided actual DOF measurements and residual oversizing estimates. Overlap at probe crossover points was very good without any artificial scaling. Comparison of integrated PSD to hot-wire bulk LWC estimates was generally very good with largest discrepancies possibly explainable by hot-wire underestimation at high MVD. In very rough terms, LWC comparisons could be interpreted to suggest MVD errors of less than about 10%. An NCAR model of idealized OAP performance also predicted LWC and MVD accuracy to within 10%.

The method described herein presents one option for the costly and time-consuming CIRA IWT PSD calibration, which is expected to be performed within the next year. The method of this study will be compared to other options, including the use of phase dopplers, in terms of practicality, current level of testing, overall risk, and defense of accuracy, and a final decision will be made as the calibration approaches.

Acknowledgments

The authors wish to acknowledge the following facilities and agencies for their contributions to this paper and the IRT data collection: the NASA Aerosciences Evaluation and Test Capabilities Office (AETC), and the NASA Glenn Research Center IRT. We further acknowledge the contributions of Chris Sivo and Dan Bouley in the development of the probe and in collection of the spinning disk data. We are grateful for the valuable comments of Tom Ratvasky of NASA Glenn Research Center on this article.

References

- [1] Knollenberg, R. G., "The Optical Array: An Alternative to Scattering or Extinction for Airborne Particle Size Determination," *J. Appl. Meteor.*, 9 86-103, 1970.
- [2] Knollenberg, R. G., "Three New Instruments for Cloud Physics Measurements: The 2-D Spectrometer Probe, the Forward Scattering Spectrometer Probe and the Active Scattering Aerosol Spectrometer," Reprints of *American Met. Society, Int'l Conf. on Cloud Physics*, 554-561. 1976.
- [3] Lawson, R. P., O'Connor, D., Zmarzly, P., Weaver, K., Baker, B.A., Mo, Q., and Jonsson, H., "The 2D-S (Stereo) Probe: Design and Preliminary Tests of a New Airborne, High Speed, High-Resolution Particle Imaging Probe," *J. of Atmos. Oceanic Technol.*, 23, 1462-1477, 2006.
- [4] Korolev A. V., Strapp, J.W., and Isaac, G.A., "Evaluation of Accuracy of PMS Optical Array Probes," *J. Atmos. Oceanic Technol.*, 15, 708-720, 1998.
- [5] Lilie, L., Bouley, D., Sivo, C., Esposito, B. and Bansemer, A., "A New 1D2D Optical Array Particle Imaging Probe for Airborne and Ground Simulation Cloud Measurements," SAE Technical Paper 2023-01-1415, 2023, doi:10.4271/2023-01-1415.
- [6] Van Zante, J.F., Riley, J.T., Strapp, J.W., Esposito, B., Orchard, D., and Korolev, A., "SLD Instrumentation in Icing Wind Tunnels – Investigation Overview". *AIAA Aviation Forum*, Reno, NV 15-19 June, 2020.
- [7] Lance, S., Brock, C. A., Rogers, D., and Gordon, J. A., "Water Droplet Calibration of the Cloud Droplet Probe (CDP) and In-Flight Performance in Liquid, Ice and Mixed-Phase Clouds During ARCPAC," *Atmos. Meas. Tech.*, 3, 1683-1706, doi:10.5194/amt-3-1683-2010, 2010.
- [8] 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.
- [9] King-Steen, L.E., Lilie, L., Bouley, D., "An Examination of Causes of Multi-Wire Bias During SLD Instrumentation Testing in the IRT," AIAA Paper 2021-2653, August 2021. <https://doi.org/10.2514/6.2021-2653>
- [10] Clark, C. and Orchard, D., "Liquid Water Content Instrumentation Study at the NRC AIWT," SAE Technical Paper 2023-01-1424, 2023, <https://doi.org/10.4271/2023-01-1424>.
- [11] Bansemer, A., abansemer/soda2: v2.24.0 (v2.24.0). Zenodo, 2024, <https://doi.org/10.5281/zenodo.10914403>

- [12] Korolev, A.V., "Reconstruction of the Sizes of Spherical Particles from Their Shadow Images. Part I: Theoretical Considerations." *Journal of Atmospheric and Oceanic Technology*, 24(3), 376–389, 2007, <https://doi.org/10.1175/JTECH1980.1>
- [13] Jensen, J.B., and Granek, H., "Optoelectronics Simulation of the PMS 260X Optical Array Probe and Application to Drizzle in a Marine Stratocumulus," *J. Atmos. Oceanic Technol.*, 19, 568–585, 2002, [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).
- [14] Hovenac, E. A., and Hirleman, E.D., "Use of Rotating Pinholes and Reticles for Calibration of Cloud Droplet Instrumentation," *J. Atmos. Oceanic Technol.*, 8, 166–171, 1991, [https://doi.org/10.1175/1520-0426\(1991\)008<0166:UORPAR>2.0.CO;2](https://doi.org/10.1175/1520-0426(1991)008<0166:UORPAR>2.0.CO;2).
- [15] Korolev, A. V., Kuznetsov, S.V., Makarov, Y.E., and Novikov, V.S., "Evaluation of Measurements of Particle Size and Sample Area from Optical Array Probes," *J. Atmos. Oceanic Technol.*, 8, 514–522, 1991, [https://doi.org/10.1175/1520-0426\(1991\)008<0514:EOMOPS>2.0.CO;2](https://doi.org/10.1175/1520-0426(1991)008<0514:EOMOPS>2.0.CO;2).
- [16] Joe, P., and List, R., "Testing and Performance of Two-Dimensional Optical Array Spectrometer with Greyscale," *J. Atmos. Ocean. Technol.*, 4, 139–150, 1987.
- [17] Strapp, J. W., Albers, F., Reuter, A., Korolev, A.V., Maixner, U., Rashke, E., and Vukovic, Z., "Laboratory Measurements of the Response of a PMS OAP-2DC," *J. Atmos. Oceanic Technol.*, 18, 1150–1170, 2001, [https://doi.org/10.1175/1520-0426\(2001\)018,1150:LMOTRO.2.0.CO;2](https://doi.org/10.1175/1520-0426(2001)018,1150:LMOTRO.2.0.CO;2).
- [18] Timko, E.N., King-Steen, L. E., Van Zante, J. F., and Acosta, W. J., "NASA Glenn Icing Research Tunnel: 2019 Cloud Calibration Procedure and Results," *NASA Technical Memorandum*, 2021
- [19] Korolev, A., Emery, E., Strapp, J. W., Cober, S., Isaac, G., Wasey, M., and Marcotte, D., "Small Ice Particles in Tropospheric Clouds: Fact or Artifact? Airborne Icing Instrumentation Evaluation Experiment," *Bulletin of the Amer. Meteor. Soc.*, 92, 2011.
- [20] Field, P. R., Heymsfield, A. J., and Bansemer, A., "Shattering and Particle Interarrival Times Measured by Optical Array Probes in Ice Clouds," *J. Atmos. Oceanic Technol.*, 23, 1357–1371, 2006.
- [21] 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 Technol.*, 2018, doi: 10.1175/JTECH-D-17-0202.1
- [22] Lilie, L.E., Emery, E., Strapp, J.W., and Emery, J., "A Multiwire Hot-Wire Device for Measurement of Icing Severity, Total Water Content, Liquid Water Content, and Droplet Diameter," *43rd AIAA Aerospace Sciences Meeting and Exhibit*, 10 - 13 January 2005, Reno, Nevada, AIAA 2005-859, 2005.
- [23] Steen, L.E., Ide, R.F., and Van Zante, J.F., "An Assessment of the Icing Blade and the SEA Multi-Element Sensor for Liquid Water Content Calibration of the NASA GRC Icing Research Tunnel," *8th AIAA Atmospheric and Space Environments Conference*, 13-17 June 2016, Washington, D.C., AIAA 2016-4051, 2016.
- [24] Esposito, B.M., Orchard, D., Lucke, J., Nichman, L., Bliankinshtein, N., Lilie, L.E., and Strapp, J.W., "Comparability of Hot-Wire Estimates of Liquid Water Content in SLD Conditions," *SAE Technical Paper* 2023-01-1423, 2023, doi:10.4271/2023-01-1423.
- [25] Strapp, J.W., MacLeod, J., and Lilie, L.E., "Calibration of Ice Water Content in a Wind Tunnel/Engine Test Cell Facility," *15th International Conference on Clouds and Precipitation*, Cancun, Mexico, 2008.
- [26] Ratvasky, T.P., Strapp, J.W., and Lilie, L.E., "Isokinetic Probe Total Water Content Measurements in the NASA Icing Research Tunnel with Supercooled Large Drop Conditions," *AIAA 2021-2649. AIAA AVIATION 2021 FORUM*. August 2021.
- [27] Davison, C., Strapp, J.W., Lilie, L.E., Ratvasky, T.P., Dumont, C., "Isokinetic TWC Evaporator Probe: Calculations and Systematic Uncertainty Analysis," *AIAA Paper* 2016-4060, June 2016. doi: 10.2514/6.2016-4060
- [28] Strapp, J.W., Lilie, L.E., Ratvasky, T.P., Davison, C.R., and C. Dumont, "Isokinetic TWC Evaporator Probe: Development of the IKP2 and Performance Testing for the HAIC-HIWC Darwin 2014 and Cayenne Field Campaigns," *8th AIAA Atmospheric and Space Environments Conference*, AIAA 2016-4059, 2016, <http://dx.doi.org/10.2514/6.2016-4059>
- [29] Baumgardner, D., and Korolev, A., "Airspeed Corrections for Optical Array Probe Sample Volumes," *J. Atmos. Oceanic Technol.*, 14, 1224–1229, 1997, [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).

Appendix A. Channels Files for the 1D2D-X and 1D2D-Y in Mode 3 Operation Used in this Study.

Table A.1. Mode 3 channel file derived for the 1D2D-X probe: greater than or equal to 50% pixels shadowed at 75%, image edge-rejects, SODA-2 water option, spinning disk derived DOFs and residual average size errors.

Bin	Dia.min (μm)	Dia.mid (μm)	Dia.max (μm)	ΔD (μm)	DOF (mm)
1	8.27	15.55	22.82	14.55	0.068
2	22.82	30.11	37.39	14.57	0.57
3	37.39	44.69	51.99	14.59	0.95
4	51.99	59.29	66.60	14.61	2.16
5	66.60	73.91	81.22	14.63	3.61
6	81.22	88.54	95.87	14.64	5.28
7	95.87	103.20	110.53	14.66	7.17
8	110.53	117.86	125.20	14.67	9.26
9	125.20	132.54	139.88	14.68	11.53
10	139.88	147.23	154.58	14.69	13.98
11	154.58	161.93	169.28	14.70	16.59
12	169.28	176.63	183.99	14.71	19.35
13	183.99	191.35	198.70	14.72	22.25
14	198.70	206.06	213.42	14.72	25.26
15	213.42	220.79	228.15	14.72	28.38
16	228.15	235.51	242.87	14.72	31.59
17	242.87	250.23	257.60	14.72	34.88
18	257.60	264.96	272.32	14.72	38.23
19	272.32	279.68	287.04	14.72	41.63
20	287.04	294.40	301.76	14.72	45.07
21	301.76	309.11	316.47	14.71	48.54
22	316.47	323.82	331.17	14.70	52.01
23	331.17	338.52	345.87	14.70	55.47
24	345.87	353.21	360.55	14.69	58.30
25	360.55	367.89	375.23	14.67	58.30
26	375.23	382.56	389.89	14.66	58.30
27	389.89	397.21	404.54	14.65	58.30
28	404.54	411.85	419.17	14.63	58.30
29	419.17	426.48	433.78	14.61	58.30
30	433.78	441.08	448.38	14.60	58.30
31	448.38	455.67	462.95	14.57	58.30
32	462.95	470.23	477.50	14.55	58.30

Bin	Dia.min (μm)	Dia.mid (μm)	Dia.max (μm)	ΔD (μm)	DOF (mm)
33	477.50	484.77	492.03	14.53	58.30
34	492.03	499.29	506.54	14.51	58.30
35	506.54	513.78	521.02	14.48	58.30
36	521.02	528.25	535.47	14.45	58.30
37	535.47	542.69	549.90	14.42	58.30
38	549.90	557.10	564.29	14.39	58.30
39	564.29	571.48	578.65	14.36	58.30
40	578.65	585.82	592.98	14.33	58.30
41	592.98	600.13	607.28	14.29	58.30
42	607.28	614.41	621.53	14.26	58.30
43	621.53	628.65	635.76	14.22	58.30
44	635.76	642.85	649.94	14.18	58.30
45	649.94	657.01	664.08	14.14	58.30
46	664.08	671.13	678.18	14.10	58.30
47	678.18	685.21	692.24	14.06	58.30
48	692.24	699.25	706.25	14.01	58.30
49	706.25	713.24	720.21	13.97	58.30
50	720.21	727.18	734.13	13.92	58.30
51	734.13	741.07	748.00	13.87	58.30
52	748.00	754.92	761.82	13.82	58.30
53	761.82	768.71	775.59	13.77	58.30
54	775.59	782.45	789.30	13.71	58.30
55	789.30	796.14	802.96	13.66	58.30
56	802.96	809.77	816.56	13.60	58.30
57	816.56	823.34	830.10	13.54	58.30
58	830.10	836.85	843.59	13.49	58.30
59	843.59	850.31	857.01	13.42	58.30
60	857.01	863.70	870.38	13.36	58.30
61	870.38	877.04	883.68	13.30	58.30
62	883.68	890.30	896.91	13.23	58.30
63	896.91	903.50	910.08	13.17	58.30
64	910.08	916.64	923.18	13.10	58.30

Table A.1. Mode 3 channel file derived for the 1D2D-Y probe: greater than or equal to 50% pixels shadowed at 75%, image edge-rejects, SODA-2 water option, spinning disk derived DOFs and residual average size errors.

Bin	Dia.min (μm)	Dia.mid (μm)	Dia.max (μm)	ΔD (μm)	DOF (mm)
1	31.72	54.54	77.38	45.653	1.06
2	77.38	100.24	123.13	45.748	8.55
3	123.13	146.04	168.97	45.843	25.85
4	168.97	191.93	214.91	45.938	50.59
5	214.91	237.91	260.94	46.032	75.30
6	260.94	283.99	307.07	46.127	100.50
7	307.07	330.17	353.29	46.222	125.18
8	353.29	376.43	399.60	46.317	148.80
9	399.60	422.80	446.02	46.412	171.26
10	446.02	469.26	492.52	46.506	193.00
11	492.52	515.81	539.12	46.601	214.92
12	539.12	562.46	585.82	46.696	238.43
13	585.82	609.20	632.61	46.791	258.80
14	632.61	656.04	679.50	46.886	258.80
15	679.50	702.98	726.48	46.980	258.80
16	726.48	750.00	773.55	47.075	258.80
17	773.55	797.13	820.72	47.170	258.80
18	820.72	844.34	867.99	47.265	258.80
19	867.99	891.66	915.35	47.360	258.80
20	915.35	939.06	962.80	47.454	258.80
21	962.80	986.56	1010.35	47.549	258.80
22	1010.35	1034.16	1057.99	47.644	258.80
23	1057.99	1081.85	1105.73	47.739	258.80
24	1105.73	1129.64	1153.57	47.834	258.80
25	1153.57	1177.52	1201.50	47.928	258.80
26	1201.50	1225.50	1249.52	48.023	258.80
27	1249.52	1273.57	1297.64	48.118	258.80
28	1297.64	1321.73	1345.85	48.213	258.80
29	1345.85	1369.99	1394.16	48.308	258.80
30	1394.16	1418.35	1442.56	48.402	258.80
31	1442.56	1466.80	1491.06	48.497	258.80
32	1491.06	1515.34	1539.65	48.592	258.80

Bin	Dia.min (μm)	Dia.mid (μm)	Dia.max (μm)	ΔD (μm)	DOF (mm)
33	1539.65	1563.98	1588.34	48.687	258.80
34	1588.34	1612.71	1637.12	48.782	258.80
35	1637.12	1661.54	1685.99	48.876	258.80
36	1685.99	1710.47	1734.96	48.971	258.80
37	1734.96	1759.49	1784.03	49.066	258.80
38	1784.03	1808.60	1833.19	49.161	258.80
39	1833.19	1857.81	1882.45	49.256	258.80
40	1882.45	1907.11	1931.80	49.350	258.80
41	1931.80	1956.51	1981.24	49.445	258.80
42	1981.24	2006.00	2030.78	49.540	258.80
43	2030.78	2055.59	2080.42	49.635	258.80
44	2080.42	2105.27	2130.15	49.730	258.80
45	2130.15	2155.05	2179.97	49.824	258.80
46	2179.97	2204.92	2229.89	49.919	258.80
47	2229.89	2254.88	2279.90	50.014	258.80
48	2279.90	2304.95	2330.01	50.109	258.80
49	2330.01	2355.10	2380.22	50.204	258.80
50	2380.22	2405.35	2430.51	50.298	258.80
51	2430.51	2455.70	2480.91	50.393	258.80
52	2480.91	2506.14	2531.40	50.488	258.80
53	2531.40	2556.67	2581.98	50.583	258.80
54	2581.98	2607.30	2632.66	50.677	258.80
55	2632.66	2658.03	2683.43	50.772	258.80
56	2683.43	2708.85	2734.29	50.867	258.80
57	2734.29	2759.76	2785.26	50.962	258.80
58	2785.26	2810.77	2836.31	51.057	258.80
59	2836.31	2861.88	2887.46	51.151	258.80
60	2887.46	2913.08	2938.71	51.246	258.80
61	2938.71	2964.37	2990.05	51.341	258.80
62	2990.05	3015.76	3041.49	51.436	258.80
63	3041.49	3067.24	3093.02	51.531	258.80
64	3093.02	3118.82	3144.64	51.625	258.80