SLD Instrumentation in Icing Wind Tunnels – Investigation Overview

Judith F. Van Zante[1]
NASA Glenn Research Center, Cleveland, OH, 44135, USA

J. Walter Strapp[2]
Met Analytics, Inc., Aurora, ON, L4G 4Y1, CANADA

Biagio Esposito[3]
CIRA, 81043 Capua (CE), ITALY

David Orchard[4]
NRCC, Ottawa, Ontario, K1A 0R6, CANADA

Alexei Korolev[5]
ECCC, Toronto, Ontario, M3H 5T4, CANADA

Thomas P. Ratvasky[6]
NASA Glenn Research Center, Cleveland, OH, 44135, USA

James T. Riley [7]
FAA Tech Center, Atlantic City, NJ, 08405, USA

A collaborative effort to better understand cloud characterization probes in Supercooled Large Drop (SLD) conditions, as well the ability to simulate these conditions in several icing wind tunnels, was undertaken by NASA, NRCC, CIRA, ECCC, FAA and Met Analytics, Inc. Both drop sizing and liquid water content, LWC, were measured with various probes using current to emerging technologies. To ensure the best possible data quality from the newest probes, the probe manufacturers, SEA, Inc. and Artium, Inc. were invited to support testing and data analysis efforts. A common set of probes was identified to test in each of the three participating facilities: NRCC's Altitude Icing Wind Tunnel, NASA's Icing Research Tunnel and CIRA's Icing Wind Tunnel. From the common set of probes, a subset were identified to use for comparison across the three facilities. These were the CDP-2 and 2D-S for drop sizing, and the Multi-wire for LWC. The LWC value was also checked by measuring the ice accretion

[1] Technical Lead: Icing Engineering, Facilities and Test Division, AIAA Senior Member.
[2] Physical Scientist.
[3] Technical Lead: Cloud measurement and generation techniques, Large Ground Testing Facilities.
[4] Senior Research Officer, Aerodynamics Lab.
[5] Senior Scientist, Atmospheric Science and Technology Branch, AIAA Member.
[6] Aerospace Engineer, Icing Branch, AIAA Member.
[7] Manager, Aircraft Icing Research Program.

thickness under hard rime conditions on a NACA-0012 airfoil. A common test matrix with sweeps in both LWC and median volume diameter, MVD, was developed. Each facility achieved these conditions as determined by their own calibration. The MVD ranged from 20 to at least 200 um, and LWC ranged from 0.5 to 3 g/m^3. The comparison probes tested at common conditions in each facility were intended to allow for a direct comparison, and check of potential facility bias.

I. Nomenclature

National Agencies

CIRA = Centro Italiano Ricerche Aerospaziali SCpA (IT)
ECCC = Environment and Climate Change Canada (CA)
FAA = Federal Aviation Administration (US)
NASA = National Aeronautics and Space Administration (US)
NRCC = National Research Council Canada (CA)

Facilities and Flight Campaigns

AIWT = Altitude Icing Wind Tunnel (NRCC)
ICICLE = In-Cloud ICing and Large-drop Experiment (flight campaign)
IRT = Icing Research Tunnel (NASA)
IWT = Icing Wind Tunnel (CIRA)

Probes – Water Content

IKP-2 = Iso-Kinetic Probe (SEA/NRCC)
MW = Multi-Wire, or Multi-Element (SEA)
ICD = Ice Crystal Detector (SEA)

Probes – Sizing

2D-S = Two Dimensional Stereo (SPEC)
ADA = Airborne Droplet Analyser (Aerometrics)
CDP = Cloud Droplet Probe (DMT)
HSI = High Speed Imaging (Artium)
OAP = Optical Array Probe (PMS)
PDI = Phase Doppler Interferometer (Artium)
Probe Extensions
-2 = Second Generation
-4D = Four Detectors
-FPDR = Flight Probe, Dual Range

Probe Manufacturers

Artium = Artium Technologies, Inc.
DMT = Droplet Measurement Technologies, Inc.
PMS = Particle Measuring Systems, Inc.
SEA = Science Engineering Associates, Inc.
SPEC = Stratton Park Engineering Company, Inc.

General

DvNN = Cumulative Volume Diameter, at NN percentile, e.g., Dv50 = MVD
LWC = Liquid Water Content, a measure of the mass of liquid water per unit volume (g/m^3)
MVD = Median Volume Diameter, a metric of the PSD (microns)
PSD = Particle Size Distribution
SLD = Supercooled Large Drop
VTAS = Velocity, true air speed (m/s or kts)
um = micron, micrometer

II. Background

The crash of an ATR-72 in Roselawn, Indiana on 31 Oct 1994 due to supercooled large drop (SLD) icing focused attention on the need to better understand this condition. In 2015, the regulatory authorities US Federal Aviation Administration (FAA) and European Aviation Safety Agency (EASA) released new rules requiring certification in large drop conditions. This new Appendix O [1, 2] is shown in Fig. 2. For comparison, the Appendix C for 'typical' stratus and cumulus cloud droplets is shown in Fig. 1. In the intervening time, significant research efforts have been invested to 1) understand and characterize the atmospheric conditions that produce these large drops, 2) investigate, modify or develop new icing cloud characterization instrumentation to measure in SLD, and 3) modify or adapt ground-based icing facilities to produce SLD conditions.

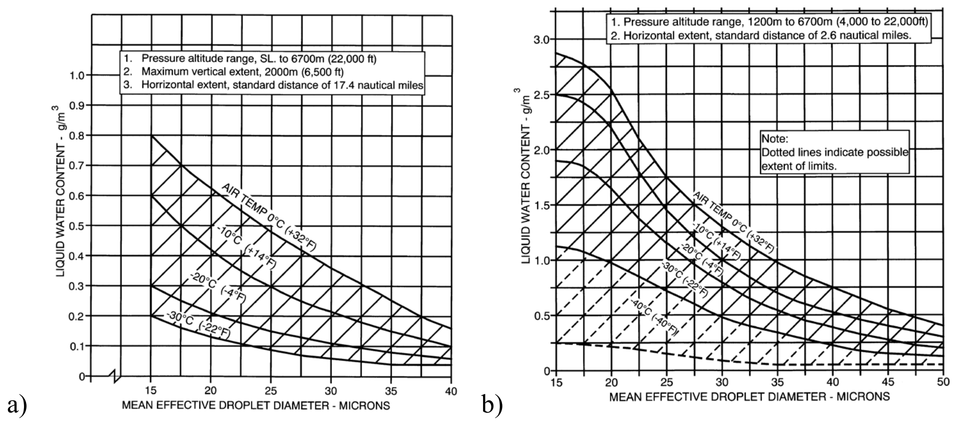


Fig. 1. Appendix C Atmospheric Icing Conditions, Liquid Water Content vs Mean Effective Drop Diameter. a) Continuous Maximum, CM (stratiform), b) Intermittent Maximum, IM (cumuliform). [Ref. 2]

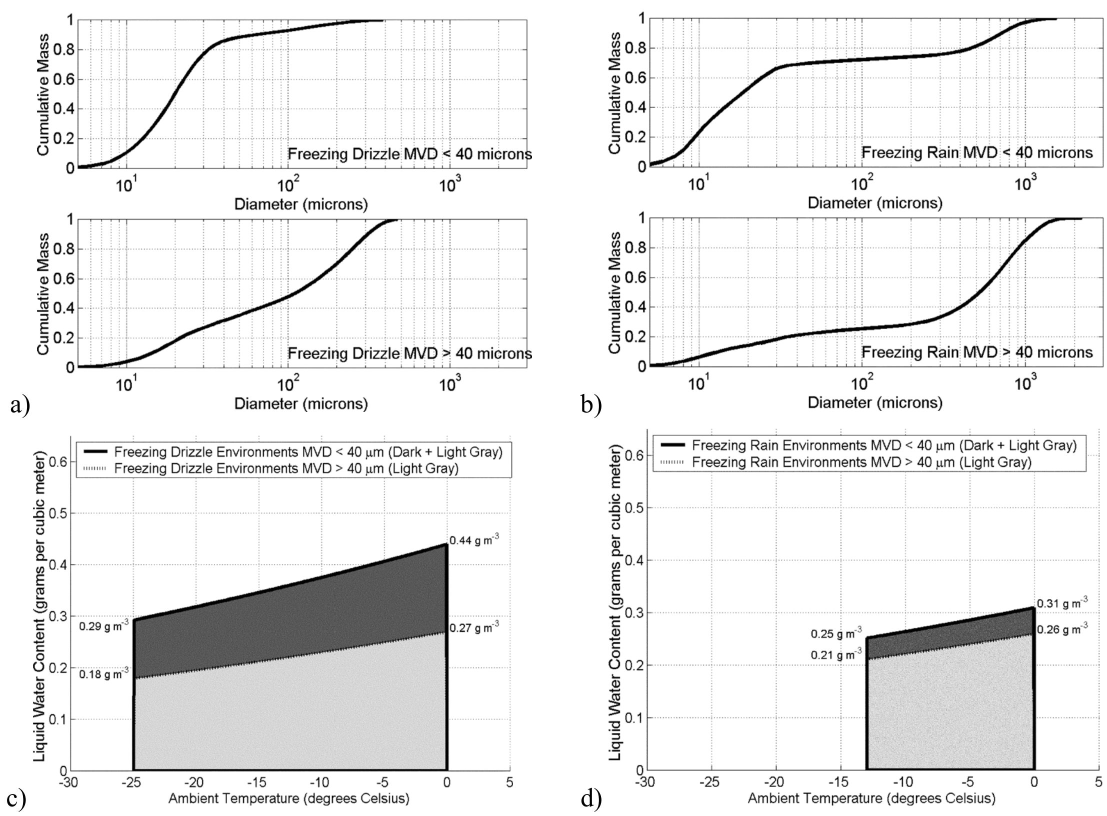


Fig. 2. Appendix O SLD Icing Conditions: Drop distribution requirements for a) Freezing Drizzle and b) Freezing Rain; LWC requirements for c) Freezing Drizzle and d) Freezing Rain. [Ref. 1]

Large drops present additional challenges for cloud characterization instrumentation. While the smallest accretable droplets remain around 2 um, the largest drops can be an order of magnitude larger than typical Appendix C drops. Thus, drop sizing instrumentation needs to measure, in a statistically significant manner, from 2 to about 2000 um. Number densities of the largest drops can be five or six orders of magnitude lower than the smallest droplets. These ranges require the results from several different probes be merged together to provide the overall particle size distribution, PSD. Furthermore, these ranges in size and number density highlight probe sample area and acquisition time issues with the goal to improve sampling statistics, particularly at the larger sizes. This inspired some creative ways to effectively increase sample area with the existing probe hardware of optical array probes in common use at the time, [3, 4].

As the volume of a drop scales with the cube of its diameter, drop splashing becomes a significant issue with larger drops, especially for liquid water content, LWC, measurements. Some of the impinging mass can splash off or out of surfaces, leading to an under measurement. Any impact-based sensors (e.g., rotating cylinders, ice blades), including heated-element sensors (e.g., King, Johnson-Williams) likely undermeasure LWC in large drop conditions. [5, 6]

A number of icing wind tunnels began the work to expand into and characterize larger drop regimes. Challenges include generating larger drops that remain intact to the test section, overcoming gravity and shear forces through the contraction, and ensuring the larger drops have supercooled sufficiently. Finally, as can be seen from Fig. 2, the published Appendix O drop distributions are bimodal. A single spray nozzle produces a mono-modal distribution; therefore, the facility operators need to be creative in producing two distinct plumes, one with smaller droplets and the other with larger drops, that result in a spatially uniform LWC profile.

Several significant instrumentation tests and collaborative efforts have occurred prior to the effort reported here. In 1998, then-current state-of-the-art probes measuring LWC and drop size spectra were tested in the IRT under large drop conditions [5]. NASA included instrumentation in its SLD Engineering Tools roadmap [7], and hosted an SLD Instrumentation Workshop in 2004; the purpose of which was “to evaluate the cloud water content and drop size measurement capability in SLD conditions, and to determine what remaining technical issues need to be resolved before this instrumentation can be used to support SLD certification activities beginning in 2006.” [8] These early efforts and workshops helped to improve instrumentation for large drop conditions, as well as help spawn new technologies.

In 2015, CIRA proposed to the international community an effort to characterize current cloud instrumentation technologies in SLD conditions. From this came this SLD Instrumentation Collaboration comprised of representatives from CIRA, ECCC, FAA, NASA, NRCC and Met Analytics, Inc. This team determined the scope of the effort would be to characterize drop sizing and liquid water content probes from current to emerging technologies. In addition to testing in the CIRA IWT, both NRCC and NASA offered the use of their icing wind tunnels.

III. Motivation and Goals

The goals of the SLD Instrumentation Collaboration effort are to better understand cloud characterization probes in SLD conditions, as well the ability to simulate these conditions in several facilities. Specific goals are to:

1) Better understand state-of-the-art technologies for drop sizing and liquid water content characterization probes in SLD conditions, including data processing algorithms.
2) Better understand the ability to simulate SLD conditions in several facilities: NRCC’s Altitude Icing Wind Tunnel (AIWT), NASA Glenn’s Icing Research Tunnel (IRT), and CIRA’s Icing Wind Tunnel (IWT).
3) Establish links with current instrumentation employed in icing wind tunnels and assess inter-facility differences in SLD simulations.

There are several items to consider. Regarding the probes themselves, several probe manufacturers have and are attempting to overcome the limitations identified in Section II with newer measurement methods. Therefore, this SLD Instrumentation effort reports on a combination of ‘current’ through ‘emerging’ probe technologies as of 2016, when planning began. To ensure the best quality data and data analysis from the newer technologies, the Team enlisted the support of the probe manufactures Artium Technologies, Inc. (Artium) and Science Engineering Associates, Inc. (SEA). Recognize also that the facilities have different characteristics that can be expected to produce different PSDs at the same median volume diameter (MVD). Different spray nozzle technologies produce different initial PSDs and plume angles. These drops travel different distances through different contraction sections to reach the test section. Weber number, gravitational settling of the largest drops, and residence time to supercool the drops also vary. An example can be seen in Fig. 3, where the three facilities have produced roughly the same MVD, as measured by their native instrumentation, but have different PSD profiles. For comparison, the PSDs from the Common Reference probes CDP-2 and 2D-S are plotted for similar, but not the same, spray conditions for the NRCC and NASA facilities.

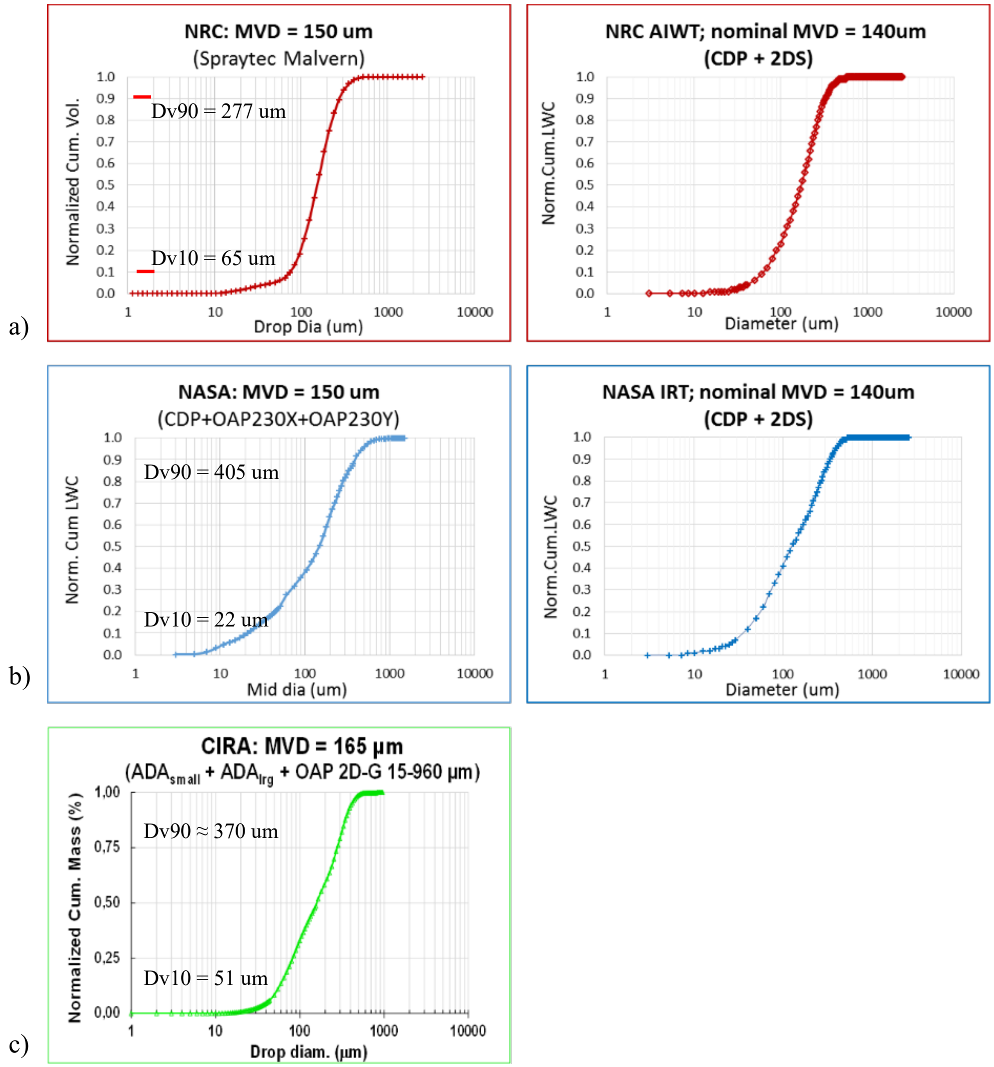


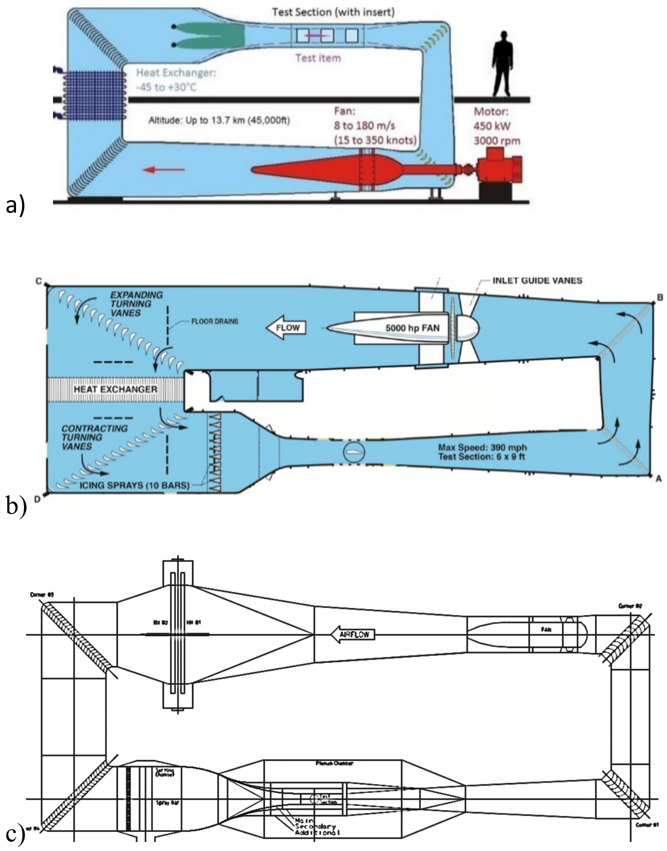
Fig. 3. Particle Size Distributions (PSDs) at nominally the same MVD. Left column: measured with native calibration instruments as indicated, right column: measured with Common Reference CDP-2 and 2D-S, but not necessarily the same spray condition. a) NRCC AIWT MVD = 150 um, b) NASA IRT MVD = 150 um, and c) CIRA IWT MVD = 165 um. Percent volume diameters, Dv10 and Dv90, are also noted.

IV. Facilities

A. NRCC AIWT Description

The NRCC AIWT is a refrigerated closed-loop low-speed wind tunnel oriented in a vertical plane as indicated in Fig. 4a. The wind tunnel has two test sections available: 1) a 57 cm wide by 57 cm high test section, contraction ratio 5.8:1, with a demonstrated top simulated wind speed of over 100 m/s (195 kt), and 2) a profiled insert, 52 cm wide by 33 cm high, that increases the contraction ratio to 10.9:1 and the top wind speed to 180 m/s (350 kts). The distance from the spray bars to the center of the test section is 13 ft (3.96 m). The air temperature in the AIWT is controlled by varying the amount of chilled cooling fluid passing through a heat exchanger located in the tunnel circuit, resulting in achievable static air temperatures at Mach 0.3 ranging from -40°C to +20°C or warmer. A vacuum pump can be used to evacuate a portion of the air in the tunnel. By controlling the amount of evacuated airflow, the pressure in the tunnel can be controlled between about 101 to 19 kPa. This permits simulations of flight at altitudes between ground level and 40,000 ft. The tunnel airspeed is calculated through the use of total temperature and total pressure sensors located just upstream of the spray bars in the settling chamber as well as static pressure ports located at the entry of the AIWT test section.

The cloud is generated with an array of spraying systems externally mixed air atomizing nozzles that use a range of different water and atomizing air pressures to provide different cloud MVD's and LWC's. To provide a full range of drop sizes that encompass both Appendix C and Appendix O icing conditions, two types of air atomizing nozzle caps are used: small caps for smaller drop sizes up to and including MVD's of 60 µm, and large caps for drop sizes greater than 60 µm. An icing grid measures cloud LWC uniformity, and a single 2.42-mm diameter rotating icing cylinder is used to measure LWC at the center of the test section. A Malvern Panalytical Spraytec laser diffraction system, range 0.1 – 2000 um, unobtrusively measures the PSDs. Calibrations curves are generated as a function of water flow rate, air pressure and airspeed for LWC and delta pressure, water flow rate and air pressure for MVD. [9]



NRC
Altitude Icing Wind Tunnel
0.57 x 0.57 m^2
6:1

NASA
Icing Research Tunnel
1.83 x 2.74 m^2
14:1

CIRA
Icing Wind Tunnel
2.35 x 2.25 m^2
10:1

Fig. 4. Facility Schematics and characteristics including test section size and contraction ratio: a) NRCC AIWT, b) NASA IRT, and c) CIRA IWT.

B. NASA IRT Description

The NASA IRT, shown in Fig. 4b, is a closed-loop, refrigerated wind tunnel. A 5000-hp motor drives a 24-ft fan that pushes air through a heat exchanger and past the 10 spraybars at the end of the settling chamber. There is a 14:1 contraction ratio to the test section, and distance of 44-ft (13.4-m) from the spraybars to the center of test section. The test section itself is 20-ft (6.10-m) long, 6-ft (1.83-m) tall and 9-ft (2.74-m) wide. The calibrated speed range is 50 to 300 kts (25 to 155 m/s), and temperature range from +10C total to -35C static. Airspeed is calculated from aircraft-grade heated pitot-static ports at the test section inlet, and total temperature is calculated from 24 RTDs mounted on the turning vanes between the heat exchanger and the spraybars.

The cloud is generated with two different sets of internally mixed nozzles; the Mod1 nozzles have a smaller hypodermic water tube than the Standard nozzles. These nozzles are placed to generate as uniform a cloud in the test section as possible. Cloud LWC uniformity is measured with an icing grid, while the SEA Multi-wire is used to measure LWC at the center point. Data from up to three probes are combined to provide PSD data: DMT's Cloud Droplet Probe (2 – 50 um), and two Optical Array Probes: OAP-230X (15 – 450 um) and OAP-230Y (50 – 1500 um). The drop sizing calibration occurs at 130 kts. Drop size is sensitive to atomizing air pressure and delta (water – air) pressure. The LWC calibration curves are a function of these as well as airspeed (VTAS) and MVD. The calibration reports applicable for this test effort are the 2014/15 Calibration Report [10] and 2018 MVD correction [11].

Larger drops were first characterized in 1996 [12] by reducing the atomizing air pressure to the Mod1 spray nozzles below the previous minimum of 10 psig. It was found that values between 2 – 8 psig produced stable and repeatable clouds with much larger droplets. Bimodal clouds can be reproduced in limited sense by simultaneously spraying the Mod1 and Standard nozzles at lower Pair values. These PSDs match the Appendix O Freezing Drizzle, MVD < 40 um targets reasonably well and are quite uniform: spatial LWC values are within 10%. However, overall LWC values are three to five times greater than Appendix O LWC targets. Further details are provided in Ref [13]. Since then, several large drop studies have been conducted, including the 2006 SLD ice accretion database on a range of airfoil models [14]. It should be noted the calibration for these studies relied upon the icing blade for LWC. With today's knowledge, we know the blade undermeasured the true LWC for most of these SLD cases [27].

C. CIRA IWT Description

The CIRA-IWT [15] is a closed loop circuit, refrigerated wind tunnel, shown in Fig. 4c, with three interchangeable test sections and an open jet configuration. The facility is driven at the desired airspeed by a 24 blade, variable speed, variable blade pitch, fan with an external diameter of 3.9 m, located in the return circuit. A 4 MW motor achieves a maximum fan rotation speed of 750 rpm that makes it possible to achieve from 0.25 to 0.7 Mach, based upon the test section configuration in use. The Main Test Section (MTS - 7.00-m long, 2.35-m height, and 2.25-m width) is the configuration considered in this study, with a contraction ratio (10.1:1) that allows calibration speeds in the range of 40 to 120 m/s, and air temperature from – 30 to +20°C or warmer. Two heat exchangers installed in the return circuit maintain the air in the test section at the desired temperature thanks to a 6.4 MW refrigeration plant. The evacuation air system allows the static pressure to be controlled from 101 to 39 kPa (abs), to simulate the flight altitude up to about 7000 m.

The features of the spray bar system offer the flexibility to mitigate the effect of different tunnel test section configuration. Due to the 50 spraying nozzles positions available for each of 20 bars, similar cloud droplet spectra could be achievable with a spray grid optimization process that consists in the activation of up to 25 spray nozzles per bar which position can be remotely selected between the available locations via solenoid valve mounted at the upstream of each spray nozzle water supply line. The spray bar system is located in the settling chamber 18-m from the center of the test section and is equipped with commercial SS 1/8JJ air atomizing spray nozzle type with SUJ12 set-up that are able to generate a wide range of droplet size and concentration included in the FAR 25 Appendix C envelope. In addition to the standard spray nozzle, from 2010 the spray bar system can be equipped with a second spray nozzle set up that contributes in the reduction of the LWC introducing the possibility to improve the PSDs to better generate Appendix O cloud requirements [16].

An icing grid can characterize cloud homogeneity and coverage area in the test section, and standard icing blade (300 mm long, 600 mm deep, and 3 mm thick) at the center of the test section is used to measure the LWC for Appendix C in rime ice conditions over a range of airspeed and water droplet sizes below Ludlam limit. For MVD/PSDs cloud measurements two optical probes based on phase Doppler technique (ADA-Airborne Droplet Analyzer) are used to characterize small (0.5 – 165 um) and large (2 – 870 um) portion of particle size distribution [17, 18]. Besides these instruments, the SEA Robust probe and OAP-2D-GA2 (gray probe) with 15 um of size resolution and 930 um of maximum measurable diameter, have been used respectively for LWC and MVD/PSDs characterization in the larger test section configuration (8.00-m long, 2.35-m height, and 3.6-m width) for SLD calibration check during the EXTICE European research project [19].

V. Instrumentation

The Team identified the sizing and water content instruments to be inter-compared at the facilities. Different technologies, from current to those emerging to meet the new SLD rule [1, 2] were of interest. The sizing or PSD/MVD probes and the water content or LWC probes are listed in Table 1. The Team further identified a subset of these to be used to estimate inter-facility PSD, MVD and LWC differences; these were labeled "Common Reference" probes. These select probes were chosen for technical and practical reasons. These probes are currently in common use, fairly well understood and vetted, and generally highly regarded. More practically, within the Team is the expertise and ability to transport, install and operate these probes at each facility, then analyze their data in a consistent manner. The Team does not pre-emptively believe these Common Reference probes will provide the most accurate data.

Common Reference PSDs were obtained from ECCC-owned probes, the CDP-2, made by DMT, and 2D-S, made by SPEC, shown in Fig. 5. These probes are in common use and generally considered among the most advanced in the airborne atmospheric science community. These particular probes also flew on the recently completed ICICLE flight campaign. ECCC also conducted the data collection and analysis. They have a long history of evaluation, testing and operation of these probes in both tunnel and airborne environments. For the CDP-2, ECCC has mapped their probe's depth of field, used their own definition of size bins (smoothed Mie scattering curve) and corrected for particle coincidence according to a method similar to that provided by Ref. [20] for the Forward Scattering Spectrometer Probe. ECCC's 2D-S has 128 10-um diodes, so the nominal range is 10 – 1280 um. ECCC has developed and improved their image analysis software over the years to reconstruct fragmented images, correct for oversizing of out-of-focus images [21], adjust sample volume for probe dead time, and extend the maximum detectable size to 2560 µm using an algorithm for partial image (center-out) reconstruction [22]. These algorithms, frozen in Aug 2018, are described in Ref. [23], and will be used to process the CIRA data in the same way. Ref. [23] also compares these Common Reference PSDs to the AIWT facility native PSDs.

Table 1. PSD and LWC Instrumentation tested at each facility. Common Reference probes are identified with bold text. Parentheses in the Owner column denote the sponsoring organization.

PSD Probes	Full Name	Range (um)	Manufacturer	Owner
CDP-2	Cloud Droplet Probe	2 – 50	DMT	ECCC
2D-S	2Dimensional Stereo	10 – 2560	SPEC	ECCC
PDI-FPDR-2	Phase Doppler	Small: 1 – 130	Artium	Artium (ECCC)
PDI-4D	Interferometer	Large: 7 – 1000	Artium	CIRA
HSI-FPDR	High Speed	5 – 1500	Artium	ECCC
HSI w/ trigger	Imaging	5 – 1800	Artium	CIRA

LWC Probes	Full Name	Manufacturer	Owner
MW	Multi-wire	SEA	NASA
IKP-2	Iso-Kinetic Probe	SEA, NRCC	NASA
ICD	Ice Crystal Detector	SEA	SEA (NASA)
NACA-0012	Airfoil		Facility

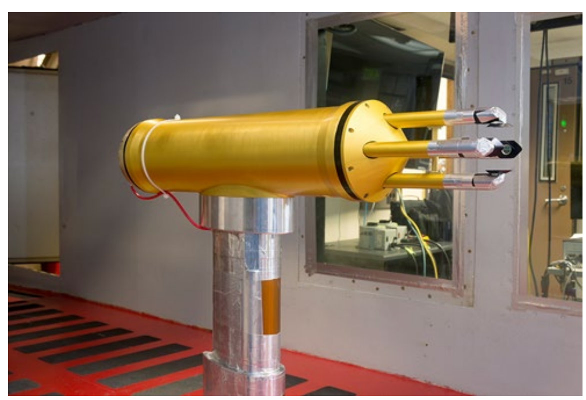
a)  b) 

Fig. 5. Common Reference PSD probes as installed in the IRT a) CDP-2, and b) 2D-S

Additional sizing probes include the Phase Doppler Interferometer, PDI and High Speed Imaging, HSI, probes both made by Artium and shown in Fig. 6. The PDI uses far-field fringe patterns scattered by individual particles in intersecting laser beams to deduce particle size and velocity [24, 25] The PDI-FPDR-2, supplied by Artium and sponsored by ECCC is a second generation flight probe with two (dual) ranges. The PDI-4D provided by CIRA features a fourth detector (compared to the usual three) for a third independent measure of phase shift to reduce reflection/refraction errors. This allows it to discriminate and size liquid droplets (only) in mixed-phase conditions and better differentiate liquid droplets or other spherical particles from irregularly-shaped solids. The HSI is a high-resolution imaging probe that employs multiple illumination sources focused at plane. The multi-angle illumination reduces measurement errors due to depth-of-field variation. It provides photographic quality images, which enables accurate sizing of any particle, liquid or solid, passing through the sample volume.

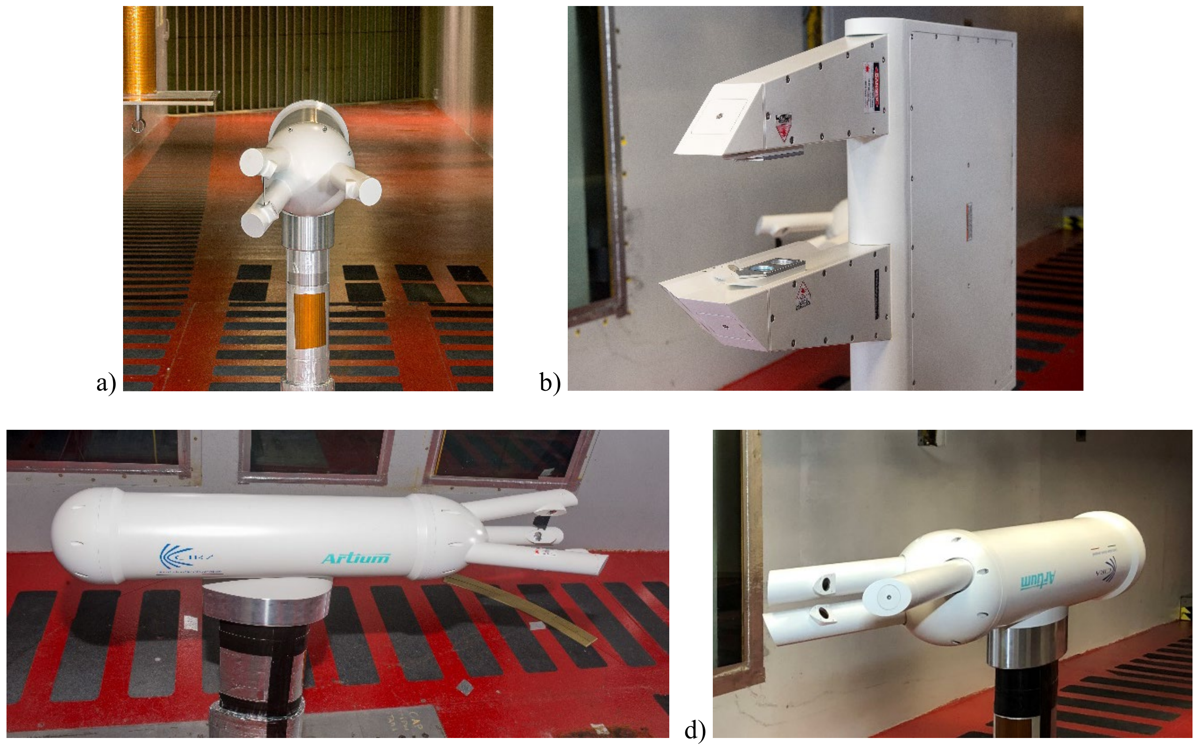
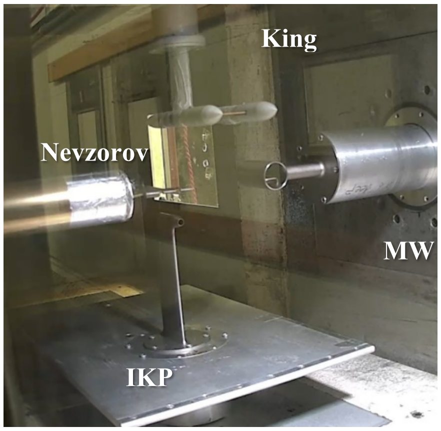


Fig. 6. Other PSD probes as installed in the IRT; a) ECCC sponsored Artium's PDI-FPDR, b) ECCC's HSI-FPDR, c) CIRA's PDI-4D and d) CIRA's HSI with trigger.

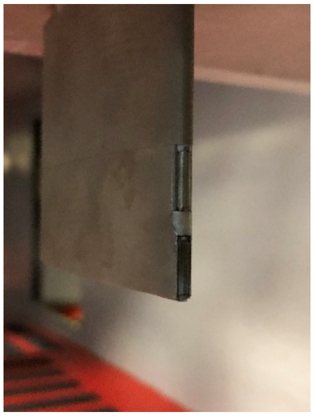
Common Reference LWCs were obtained using NASA's Multi-wire, MW, SN# 2022, made by SEA and shown in Fig. 7. This probe has three heated elements that ideally evaporate the impinging water on impact. The power required to hold the element temperatures is used to calculate the LWC. It has the standard design of the 2-mm concave half-pipe in the center, and on either side a convex 2-mm half-pipe and 0.5-mm wire. Measurements from the central TWC or concave element, corrected for collection efficiency [26], compare well to that of the MW SN# 2023 used for IRT Tunnel LWC calibration, which also compare well to measurements from the Icing Blade at low impingement rates and MVD values below approximately 30 µm. A more complete description of the MW–Blade comparison and Ludlam limit restrictions can be found in Ref. [27]. NASA IRT Engineers operated and processed the MW data in a manner similar to that as for their LWC calibration. The process is described in Ref [10]; briefly, the values are averaged, tared and corrected for collection efficiency. For this study, the mono-dispersed MVD was used to calculate the collection efficiency, not the full PSD spectrum. As a separate evaluation of the LWC measurement, both AIWT and IRT measured hard rime ice thicknesses on their own NACA-0012, 21-in chord, full-span airfoil at zero angle-of-attack for a range of MVD values. The MW values compared to facility LWC are presented in Ref. [28] for both the AIWT and IRT. Additional issues uncovered during the course of this SLD study with the MW are presented in Ref. [29]. These are sensitivity to downstream blockage and proper maintenance of the probe.

Fig. 7. Common Reference LWC probe, the SEA MW, installed in the IRT.

a)



b)



c)

Fig. 8. Additional LWC probes a) IKP-2 in IRT with the MW to the left and forward plus two ceiling-mounted background water vapor intakes to the right, b) AIWT with four LWC probes during probe check-out phase; clockwise from top: King probe, MW, compact IKP and Nevzorov. c) ICD in IRT

Additional LWC instruments tested include two different versions of an iso-kinetic probe, IKP. The IKP ingests all phases of water, which are then fully evaporated. A separate background humidity or water vapor measurement is required to subtract off that component, leaving a measurement of only the total (solid and liquid) water content. An accurate cloud-on water vapor measurement in a typically saturated icing wind tunnel test section can be challenging. NASA's IKP-2 is shown as installed in the IRT in Fig. 8a, along with two of the three background water vapor sensors (the third is located on the probe). A MW, located in its upstream position, is 16-in downstream of the IKP tip. Results from this study are provided in Ref [30]. NRCC's compact IKP is shown installed in the AIWT in Fig. 8b. Note that this image is from the probe check-out phase, and not when the probe was solo at centerline. The solo centerline position provided the final data set. This probe has been designed for smaller tunnels; only the iso-kinetic tip is in the facility, the remainder of the probe is external. Both of these probes have been comparison tested in the IRT [31]. In addition, SEA's Ice Crystal Detector, ICD, SN #4008 was tested in both the IRT (Fig. 8c) and AIWT. Results from this study are reported in Ref. [32]. While the authors are not aware of a collection efficiency study on the ICD geometry, one has been conducted on another SEA probe of similar design, the Robust Probe [33]. It is speculated that the collection efficiency of the ICD is bounded by this value and one. Also seen in Fig. 8b, are the additional LWC probes tested at the AIWT: the Nevzorov and King probes. As part of this SLD Instrumentation study, NRCC Engineers have published a study comparing the LWC from their rotating cylinders of various diameters to the airfoil [34].

VI. Test Matrix

A common test matrix was developed from the overlap region of each facility. The primary airspeed chosen was well within each tunnel's normal operating window. All tests were conducted at ambient pressure, that is, without active control of test section pressure. As able, facilities also tested at a faster airspeed and/or intentionally produced bimodal distributions. For the target test matrix, primary test points included a sweep in MVD at constant LWC and a sweep in LWC at constant MVD, as shown in Table 2. Each facility produced the target LWC and MVD according to their native calibration curves generated from their native calibration instrumentation and process.

The NRCC approach was to hit the target test matrix points per their calibration curve fits. Some of these test points also matched calibrated conditions. The NASA approach, on the other hand, was to exclusively pick calibration test points as close to the targets as possible to allow direct comparison between the IRT and Common Reference probes. For example, each point in the MVD sweep had a PSD measured with native instruments. The downside of this approach is that the secondary parameter, LWC in this example, could not necessarily be maintained. Table 3 shows the actual primary test points run or to be run for each of the three facilities. Please note this list is not exhaustive. It should be noted that both NRCC and NASA adjusted their MVD values following the Oct. 2019 Workshop. Staff at the NRCC caught an error where the incorrect MVD calibration curve fit was applied to the data acquired with the large cap nozzles. The NASA staff gained an improved understanding of their CDP probe sample volume in 2018 [11]; this correction was applied retroactively to the native IRT PSDs.

Table 2. Target Test Matrix primary points: LWC and MVD sweeps at an airspeed of roughly 80 m/s.

LWC Sweep			***MVD Sweep***	
LWC (g/m3)	**MVD (um)**		**LWC (g/m3)**	**MVD (um)**
0.5	20		0.5	20
1.0	20		0.5	50
1.5	20		0.5	100
2.0	20		0.5	150
2.5	20		0.5	200
3.0	20		0.5	250

Table 3. Actual test matrix run by NRCC and NASA, and planned for CIRA.

NRC				NASA				CIRA			
Test point	VTAS (m/s)	LWC (g/m3)	MVD (µm)	Test point	VTAS (m/s)	LWC (g/m3)	MVD (µm)	Test point	VTAS (m/s)	LWC (g/m3)	MVD (µm)
AIWT LWC Sweep				**IRT LWC sweep**				**IWT LWC sweep**			
AIWT-2	80	0.35	20	IRT-1	77.2	0.42	14.5	IWT-1	80	0.35	20
AIWT-3	80	0.5	20	IRT-1a	77.2	0.47	19.8				
AIWT-4	80	0.9	20					IWT-2	80	0.89	23
AIWT-5	80	1.0	20	IRT-2a	77.2	0.97	22.2				
AIWT-6	80	1.4	20					IWT-3	80	1.4	20
AIWT-7	80	1.5	20	IRT-3	77.2	1.57	20.0				
AIWT-8	80	2.0	20	IRT-4a	77.2	1.98	19.7	IWT-4	80	2.0	20
AIWT-9	80	2.5	20	IRT-5	77.2	2.64	22.8	IWT-5	80	2.5	20
AIWT-10	80	3.0	20	IRT-6b	77.2	3.02	20.3	IWT-6	80	3.0	20
AIWT MVD Sweep				**IRT MVD Sweep**				**IWT MVD sweep**			
AIWT-21	80	0.5	15	IRT-21c	77.2	0.42	14.9	IWT-21	80	0.40	15
AIWT-23	80	0.5	28	IRT-22	77.2	0.57	30	IWT-22	80	0.65	25
AIWT-24	80	0.5	40					IWT-23	80	0.65	40
AIWT-25	80	0.5	45	IRT-23	77.2	0.50	46				
AIWT-26	80	0.5	60	IRT-24	77.2	0.54	60	IWT-24	80	0.68	60
AIWT-27	80	0.5	76	IRT-25	77.2	0.51	108	IWT-25	80	0.89	90
AIWT-28	80	0.5	116	IRT-26a	77.2	0.45	142	IWT-26	80	0.83	145
AIWT-29	80	0.5	178	IRT-26	77.2	0.60	169	IWT-27	80	0.89	160
AIWT-30	80	0.5	199	IRT-27	77.2	0.71	208				
AIWT-31	80	0.5	227	IRT-28	77.2	0.91	275				
AIWT-32	80	0.5	262	IRT-29	77.2	1.36	460	IWT-28	80	higher	300
AIWT BiModal				**IRT BiModal**							
AIWT-51	80	0.5	< 40	IRT-51	77.2	2.00	< 40				
AIWT-52	80	0.5	> 40								
				LWC sweep, 129 m/s				**IWT LWC sweep, 140 m/s**			
				IRT-11	128.6	0.61	20.0	IWT-11	140	0.44	25
				IRT-12	128.6	1.17	19.7	IWT-12	140	1.38	20
				IRT-13	128.6	2.00	25.6	IWT-13	140	2.00	20
				LWC sweep, MVD = 140 um							
				IRT-81	77.2	0.45	142				
				IRT-82	77.2	0.56	140				
				IRT-83	77.2	0.62	138				
				IRT-84	77.2	0.75	138				
				IRT-85	77.2	0.87	139				

VII. Accomplishments to Date

A. Completed Tests

Tables 4 and 5 list the tests completed thus far at NRCC and NASA, including the time frame, number of test days, the probe(s) and number of sprays for that probe. The identity of each MW is also listed, as it turned out to be important [29].[8] The tests in 2018 were added to investigate open issues after the planned round of tests.

One of these issues was the effect of a downstream canister on the flow-through MW. As listed in Table 5, the initial phase of the IRT test campaign had two probes mounted in the tunnel at the same time. The probe designated ‘primary’ for that night was installed at the tunnel center, per typical cloud calibration procedure. A ‘secondary’ probe was installed with the intent to identify any operational issues prior to its turn in the primary position. As shown in Fig. 9, the secondary floor-mount was 69-in downstream and 30-in to the side of the primary probe. The stand height was typically set to put a canister-style probe at 24-in from the floor. When the Multi-wire was in the secondary position, it was ceiling-mounted in either a forward or aft position and at center height. During the latter phases of testing, typically only one probe was installed at the primary position.

[8] This table uses the same mnemonic as [29] to distinguish the different MW probes. HGR refers to the NASA Hangar, and GTL the NRCC Gas Turbine Lab.

Table 4. Completed NRCC AIWT test campaigns

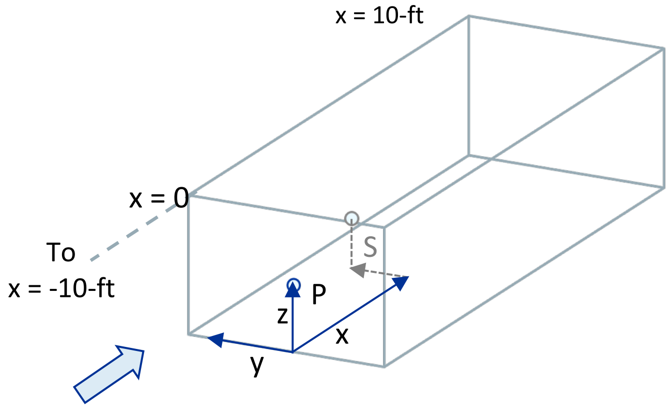
No. Days	Entry	Probe @ Center	# Sprays
9	**May 2017**	**Total Sprays**	**308**
	Phase 1	Rotating Cylinder	89
		4 simultaneous LWC probes	116
		Tunnel IKP @ CL	16
		Nevzorov @ CL	35
		MW #2036 (GTL) @ CL	15
		King @ CL	16
		NACA-0012, 21-in (NRCC)	18
5	**Aug 2017**	**Total Sprays**	**141**
	Phase 2	MW #2045 (HGR-2)	27
		Malvern & CDP-2	33
		Malvern & 2D-S	24
		PDI	28
		Malvern & HSI	29
1	**Feb 2018**	**Total Sprays**	**80**
	Phase 3	MW #2022 (IRT-2)	40
		MW #2032 (HGR-1)	20
		ICD #4008	20

Table 5. Completed NASA IRT test campaigns

Test Day	2017	Primary Probe	Secondary Probe	# Sprays
1	5-Oct	NACA-0012, 21-in (NASA)	TAT, Raman Scattering (NASA)	9
2	10-Oct	CDP-2 (ECCC)	2D-S (ECCC)	37
3	11-Oct	2D-S (ECCC)	HSI-FPDR (ECCC)	20
4	12-Oct	HSI-FPDR (ECCC)	PDI-FPDR-2 (ECCC, Artium)	17
5	13-Oct	PDI-FPDR-2 (Artium, ECCC)	MW #2032 (HGR-1) - aft	23
6	16-Oct	MW #2032, MW #2045 (HGR-1,2)	CCP (SEA, NASA), removed	24, 17
7	17-Oct	CCP (NASA, SEA)	MW #2023 (IRT-1) - aft	25
8	18-Oct	IKP-2 (NASA), Water vapor	MW #2023 (IRT-1) - fwd	35
9	20-Oct	MW #2022 (IRT-2)	with dummy canister, removed	11, 35
10	7-Nov	PDI-4D (CIRA)	-	17
11	8-Nov	PDI-4D (CIRA)	-	13
12	9-Nov	PDI-4D (CIRA)	-	23
	2018			
13	11-Apr	HSI w/ trigger (CIRA)	-	14
14	12-Apr	HSI w/ trigger (CIRA)	-	21
15	13-Apr	ICD #4008 (NASA, SEA)	-	38

B. Data analyzed; Initial Results discussed in Workshop #1.

The Team gathered together 23–25 October 2019 in Colorado Springs, CO, USA for the first of two planned workshops. After a discussion of the planned vs actual goals achieved thus far, the FAA offered their perspective on this Collaboration effort. Specifically, the FAA is hoping to establish a preferred suite of instruments for SLD measurements and a uniform methodology for data reduction procedures. In the future, they hope performance and reliability standards can be established for SLD instrumentation. Each facility highlighted their native calibration



a)

b)

c)

Fig. 9 IRT primary (P) location and secondary (S) locations. Primary is at tunnel center (0, 0, 36): a) sketch of IRT test section showing the Secondary (S) floor mount placement at (69, 30, 0); probes in the secondary position (S) were typically 24-in from the floor; b) image with 2D-S at Primary location, and HSI-FPDR at Secondary location; c) Image showing PSI-FPDR-2 in Primary location and ceiling-mounted MW in aft secondary location at approximately (48, 24, 36).

procedures and provided an overview of the as-run SLD Instrumentation test campaigns. The LWC results were tackled next with discussions of the various instrumentation technologies, and comparison of instrument results to each other and to the facility calibrations. The PSD discussion began with technical overviews of the various probes including their principle of operation, strengths and weaknesses and data analysis techniques. Results were then compared to the native facility calibration PSDs. While the Common Reference PSD probes are compared to the AIWT Malvern in Ref. [23], their data from the IRT requires further analysis, described in the Future Plans section.

The Team also notes the complexity of SLD PSDs is not adequately captured in the sole value of MVD (= Dv50). In facilities, the width or range of the PSD can vary. This nuance can be captured by identifying the edges of the spectrum, for example the 10% and 90% volume diameters, Dv10 and Dv90, as indicated in Fig. 3. The Team has agreed the range Dv90 – Dv10 is a good measure of the width of the PSD spectrum for its use.

C. Publications and Presentations

Team members have and will report aspects of the data and analyses from the AIWT and IRT tests to date. These are summarized in Table 6.

Table 6. List of publications and presentation to date from this SLD Instrumentation Test Collaboration

Ref.	Topic	Lead Author
[35]	SLD Instrumentation in Icing Wind Tunnels – Investigation Overview	J. Van Zante
[34]	Measurement of LWC for SLD Conditions in the NRC's AIWT	D. Orchard
[28]	Inter-Facility LWC Differences in Appendix C and SLD Conditions	L. King-Steen
[29]	Causes of Multi-Wire Bias During SLD Instrumentation Testing in the IRT	L. King-Steen
[30]	Isokinetic Probe TWC Measurements in the NASA IRT with SLD Conditions	T. Ratvasky
[32]	SEA Ice Crystal Detector (ICD) under SLD Conditions at the NASA IRT Tunnel	L. Lilie
[23]	PSD and MVD measured by various instruments in SLD at NRC AIWT	A. Korolev

VIII. Conclusions and Future Plans

This effort has further advanced the group's understanding of SLD Instrumentation and facility performance, but more work remains. Without a true PSD reference, there are no means of validating drop-size probe measurements, and sizing comparisons require an in-depth understanding of the instrument and its theory of operation. There is still limited confidence in PSD measurements in the 50 – 150 um range due to out-of-focus and depth of field uncertainties in optical array probes. Application of correction algorithms for broken or out-of-focus images is still under investigation. LWC measurements in SLD conditions also warrant further investigation, although it is encouraging that the Multi-wire concave TWC element and Iso-Kinetic Probe compared favorably (within 10%) up to 200 um in this study. Moreover, facility differences in spray nozzle characteristics, contraction ratio, distance from spray bars to test section center and airspeed imply additional difficulties to analyze to reduce the uncertainty in the SLD calibration.

To begin to address some of these issues, additional tests are planned at both the IRT and AIWT. The IRT tests were to have occurred the week of Mar 16, 2020, the week NASA Glenn locked down due to COVID-19. The plan is to retest the PDI and HSI, as well as the CDP-2 and 2D-S since the IRT underwent a full calibration in 2019. The IRT also plans to send its drop sizing probes to the AIWT for a direct comparison of the PSD instrumentation. Furthermore, ECCC plans to characterize the depth of field response of the IRT 1D OAPs. The NRCC tests, which were to have occurred in Jun 2020, are still planned but delayed. More clarity regarding the airfoil studies is also warranted.

CIRA has recently installed new nozzles to better simulate the SLD environment and in June 2021 is conducting a full calibration. The 1-month SLD Instrumentation test at CIRA is scheduled for Spring 2022.

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The SLD Instrumentation Test Team has included:

NASA: Judith Van Zante, Thomas Ratvasky, Laura King-Steen, Emily Timko, Mark Potapczuk, Mary Wadel, Jack Oldenburg
NRCC: David Orchard, Catherine Clark, Gislain Chevrette
CIRA: Biagio Esposito
ECCC: Alexei Korolev, Ivan Heckman, Jason Iwachow, Mike Harwood
FAA: Tom Bond, Jim Riley, John Fisher, Chris Dumont
Met Analytics: Walter Strapp

With support from probe manufacturers:

Artium: William Bachalo
SEA: Lyle Lilie

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