CIRA – Icing Wind Tunnel

WP6 improvement and calibration

Prepared by

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Presented by

Biagio Esposito,

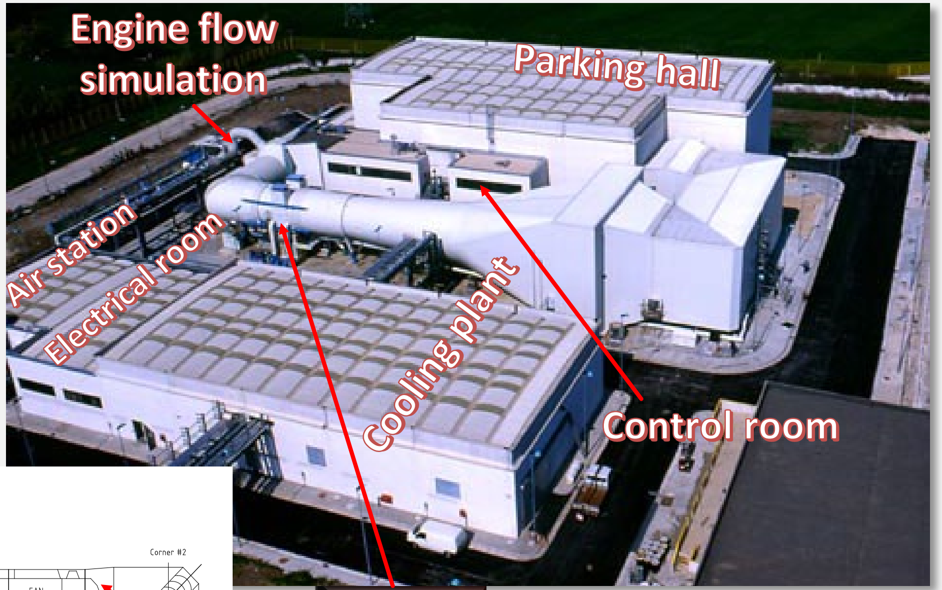
CIRA

Outline

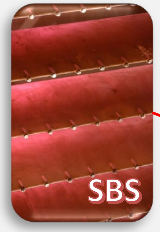
- CIRA Icing Wind Tunnel features
- Objective to cover within the program
- Preparatory activities
- Calibration methodology
- Preliminary results of CIRA-IWT vs. Appendix O
- Conclusions

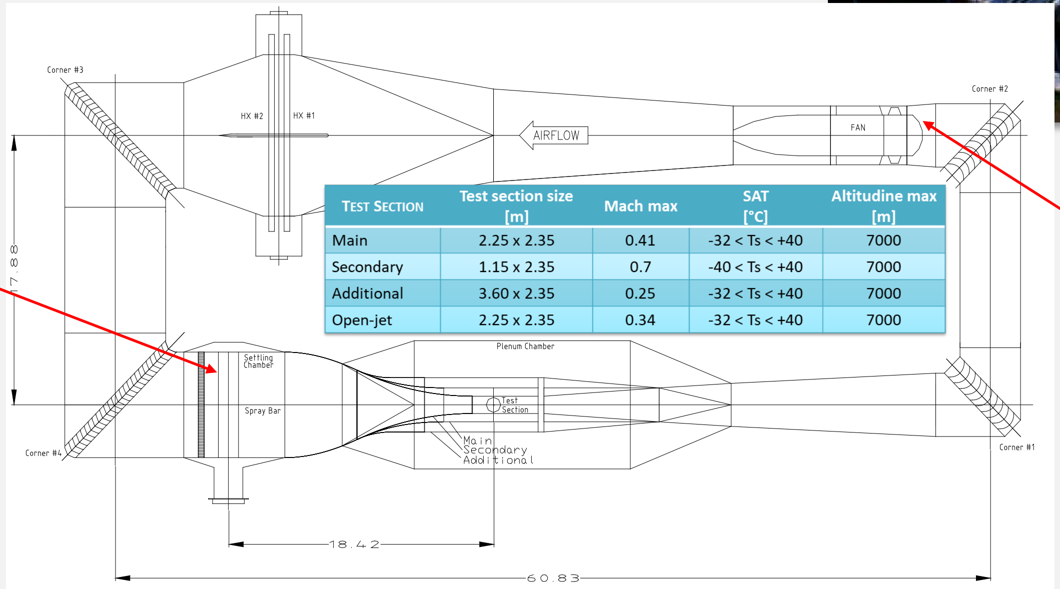
CIRA – Icing Wind Tunnel

- Operational since 2003
- Goal: To simulate the flight conditions requested for ice certification
- Use: To test ice protection systems and ice accretion effects on flight safety

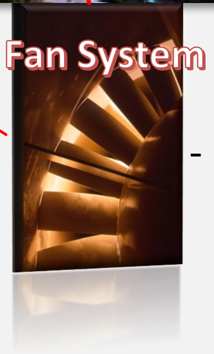


- 20 stainless steel bars, 50 nozzles locations for each bar, max 500 active nozzles
- On/off valve at each spraying location
- Air and water pressure control in each bar





Test Section	Test section size [m]	Mach max	SAT [°C]	Altitudine max [m]
Main	2.25 x 2.35	0.41	-32 < Ts < +40	7000
Secondary	1.15 x 2.35	0.7	-40 < Ts < +40	7000
Additional	3.60 x 2.35	0.25	-32 < Ts < +40	7000
Open-jet	2.25 x 2.35	0.34	-32 < Ts < +40	7000

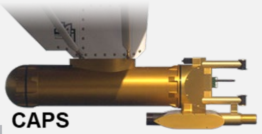


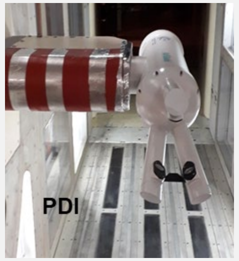
- 24 blades, variable pitch, 750 rpm fan unit

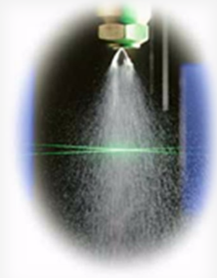
Objective

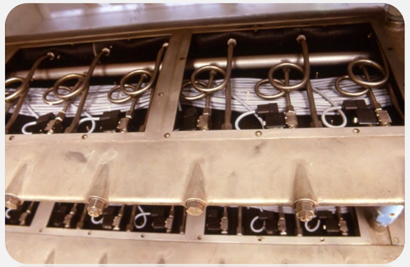

Icing Blade

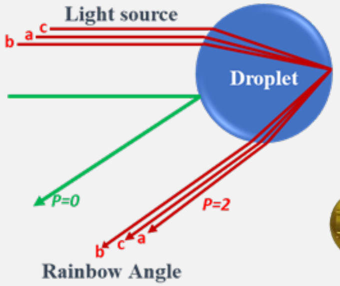

Nevzorov 2 cup

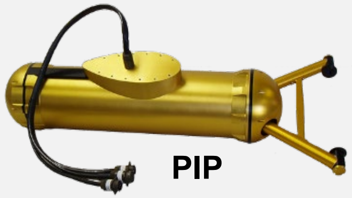

CAPS

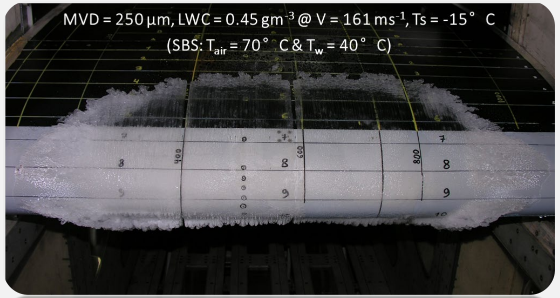

PDI

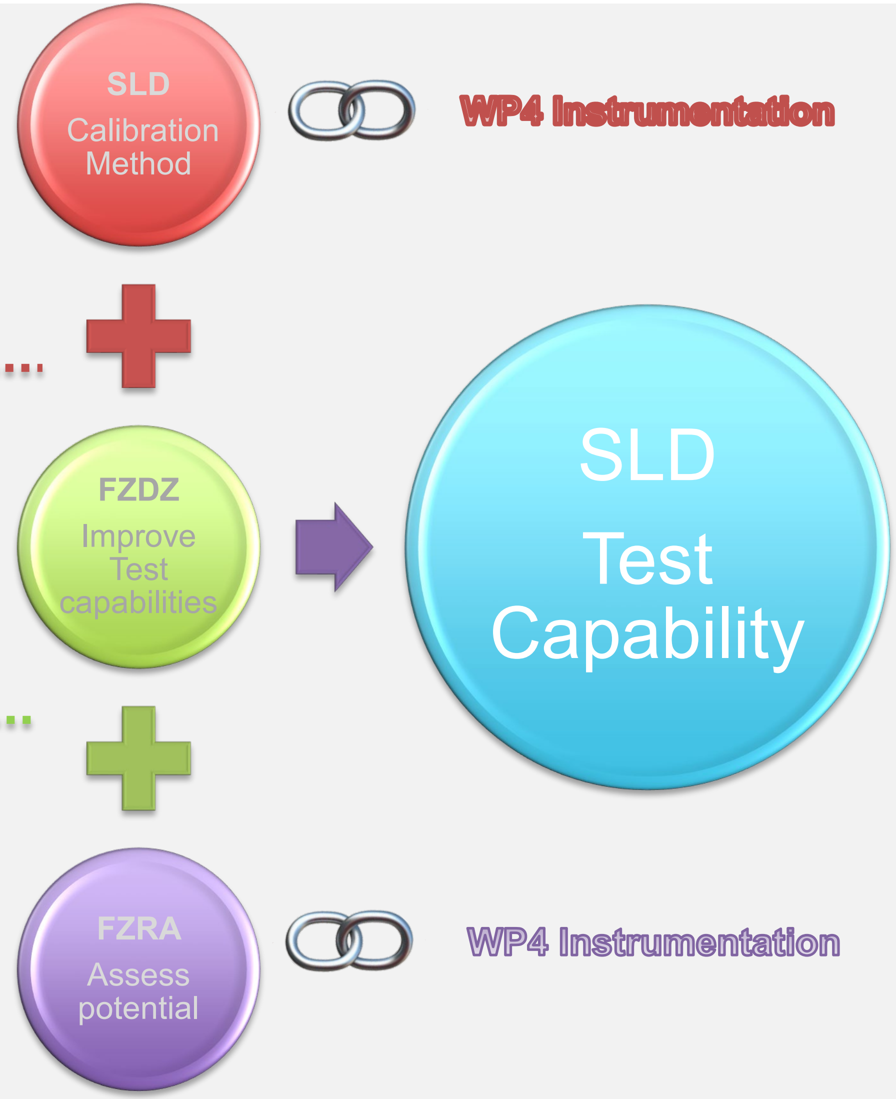





Light source
b
a
c
Droplet
P=0
P=2
b
c
a
Rainbow Angle


PIP


MVD = 250 μm, LWC = 0.45 gm-3 @ V = 161 ms-1, Ts = -15° C
(SBS: Tair = 70° C & Tw = 40° C)


SLD
Calibration Method
WP4 Instrumentation
FZDZ
Improve Test capabilities
SLD
Test Capability
FZRA
Assess potential
WP4 Instrumentation

Objective

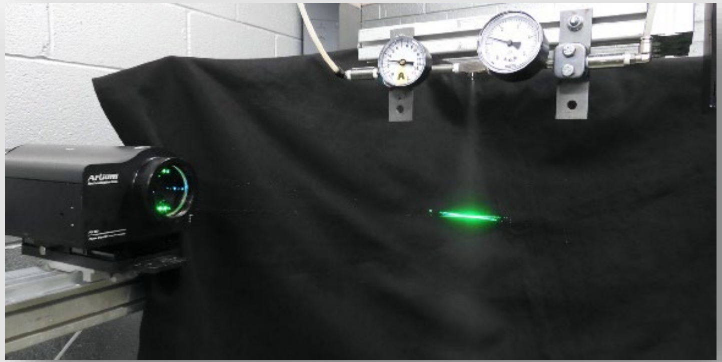
Improve the spray bar system capability to reduce the performance gap with SLD-FZDZ requirements.

- Define a complementary set of spray nozzles to the current ones in use to achieve better cloud coverage and homogeneity area in the test section at low values of LWC.
- Characterizing the measurement methodologies through wind tunnel investigation as a goal for reliable information from:
  - Hot-wire LWC measurement devices, accounting for their response as varies with wire-geometry and droplet size (MVD) to reduce the effect of mass-losses of large droplets upon their impact on heating elements.
  - Optical methods for PSDs/MVDs measurements by comparison of new technologies with some legacy instruments to assess uncertainty and provide information on the potential differences.
  - Cloud homogeneity check includes both LWC and PSD/MVDs instruments.
  - Cloud temperature measurements to assess thermal equilibrium between water droplets and airstream temperature.
- Perform the CIRA-IWT cloud calibration using a baseline combination of two series of spray nozzles with different spray plume characteristics and compare the achievable FZDZ conditions with the requirements to define the improvements versus the current gap.

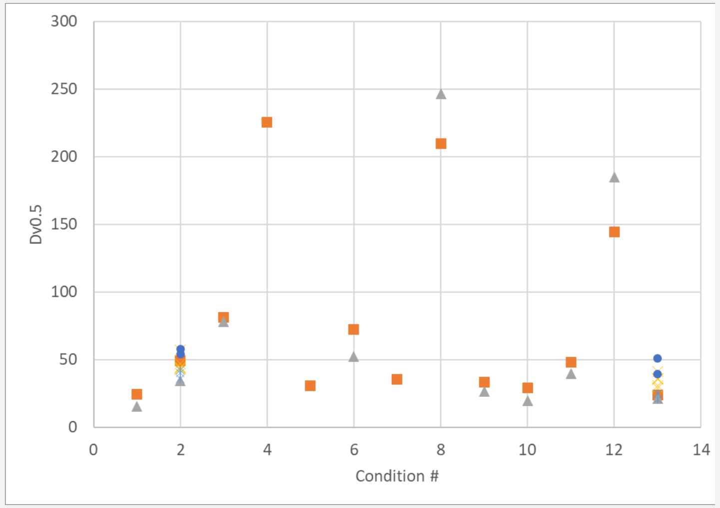
Preparatory activities: improve the SLD cloud conditions

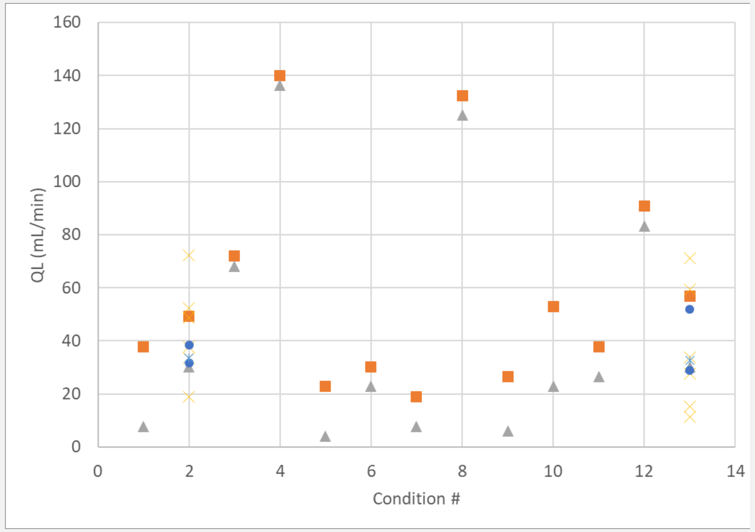
Spray nozzle R&D with Spraying Systems Co. (SS)

- Down-selection from 5 spray nozzle setups to improve the achievement of Appendix O, mandatory for FZDZ and exploratory for FZRA.
- Review existing drop size data from the available SS database and collect a new data set for candidate spray nozzle selection in ambient conditions (spray chamber).



- 2D-PDI-200MD
- 500 mm or 1000 mm TRM f.l.
- size range of approximately 2µm – 380µm (or 760µm)
- 11 measurement points in the spray plume at 150 mm from the nozzle exit

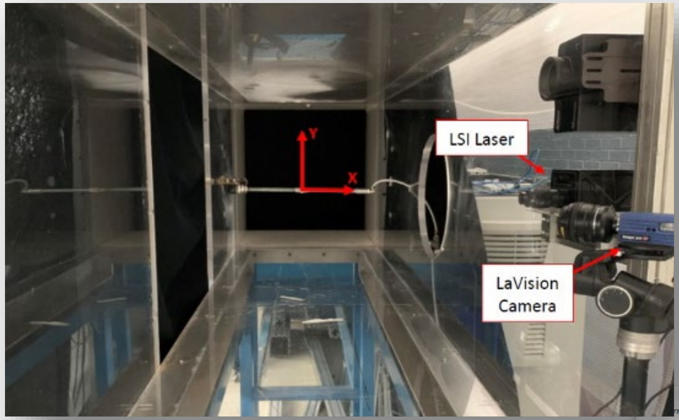


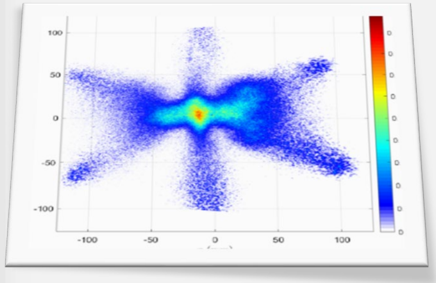


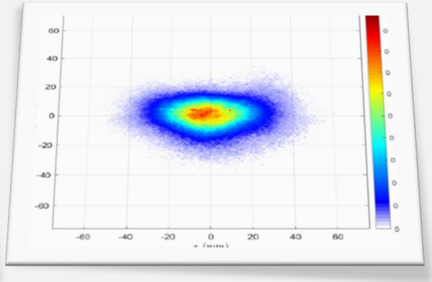
Preparatory activities: improve the SLD cloud conditions

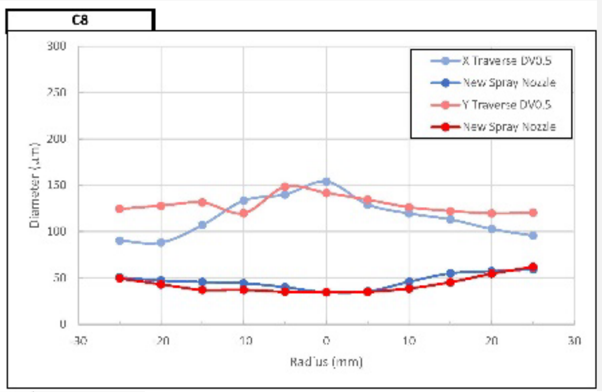
Spray nozzle (cont'd)

- Wind tunnel tests to assessing and compare the performance of different spray nozzle setups in ambient wind tunnel conditions, reproducing airflow conditions (average airspeed) and spray nozzles combinations as in CIRA-IWT stetting chamber.

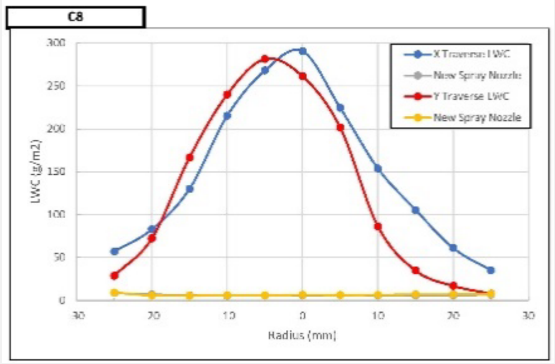








(mm)	X (mm)	Volume Flux (cm/s)	LWC (g/m³)	V_Z (m/s)	V_Y (m/s)	D_{Min} (µm)	$D_{V0.1}$ (µm)	$D_{V0.5}$ (µm)	$D_{V0.9}$ (µm)	$D_{V0.99}$ (µm)	D_{Max} (µm)	D_{10} (µm)	D_{20} (µm)	D_{30} (µm)	D_{32} (µm
-25	0	0,01660	13,833	9,418	0,022	8,6	25,8	50	127,1	193,8	193,8	30,2	32,8	36,6	45,6
-20	0	0,01690	14,386	9,431	0,035	8,6	21,7	41,3	89,6	125,8	134,2	24,9	27,1	30,1	37,2
-15	0	0,01890	16,539	9,537	0,076	8,1	18,5	42,3	102	125,6	146,2	20,3	22,7	26,2	35,2
-10	0	0,02330	21,066	9,558	0,153	6,8	18,3	56	106,4	172,9	172,9	18,3	21,4	26,2	39,3
-5	0	0,02270	19,678	9,672	0,339	5,5	18,1	56,7	98,2	151,7	151,7	17	20,4	25,3	39
0	0	0,01300	10,776	9,926	0,572	5,4	15,1	42,8	90,6	132,5	132,5	15,9	18,2	21,8	31,2
5	0	0,00969	8,034	9,892	0,63	5,8	14,9	34,4	96	168,3	168,3	16,2	18	20,9	28,4
10	0	0,00682	6,054	9,614	0,637	7,9	15,3	23,4	61,4	92,3	109,1	17,3	18,5	20,1	24
15	0	0,00710	6,372	9,427	0,598	7	18,6	27,7	66,7	104,8	117,4	21,6	22,8	24,5	28,3
20	0	0,00702	11,236	9,417	0,554	6,4	22,1	34,3	77,6	112,8	116,1	26,2	27,6	29,8	34,5
25	0	0,00670	5,902	9,454	0,457	8,1	25,3	40,2	85,3	135,6	142,8	30,1	31,8	34,2	39,5
0	-25	0,01333	12	9,252	-	6,1	17,8	44,5	93,4	153,4	153,4	17,2	19,9	23,9	34,4
0	-20	0,01444	13	9,338	-	6,3	18	48,5	98,4	176,2	176,2	17,3	20,2	24,4	35,8
0	-15	0,01111	10	9,39	0,198	5,9	18	49,5	101,1	169,9	169,9	16,8	19,8	24,2	36
0	-10	0,01360	12,231	9,523	0,236	5,2	17,3	46,8	99,4	152,3	152,5	16,4	19,3	23,5	35
0	-5	0,00889	8	9,946	0,212	5,2	16,2	46,3	94,1	133,6	133,6	15,7	18,5	22,5	33,6
0	0	0,01320	10,744	10,297	0,244	5,2	14,7	45,2	100,7	183,9	183,9	14,6	17	20,9	31,7
0	5	0,00789	6,319	10,089	0,186	5	15,5	45,6	84,5	110,8	119	15,5	18,1	22	32,3
0	10	0,01210	10,2	9,672	0,204	5,2	18,4	50,6	96,3	145,1	145,1	16,8	20,1	24,7	37,1
0	15	0,00827	7,262	9,396	0,181	5,8	18,7	53,1	104,8	157,9	157,9	17,2	20,5	25,3	38,5
0	20	0,00898	9,127	9,352	-	6,4	17,6	49,9	103,7	165,7	165,7	17,3	20,2	24,5	36,1
0	25	0,01040	9,334	9,278	-	7	17,6	44,8	90,1	119,3	123,4	17,6	20,3	24,1	34



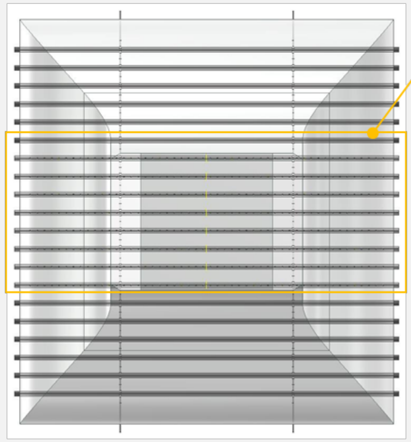
- LaVision SprayMaster system
- Size, shape and relative distribution of the spray plume.
- 2D spray concentration results

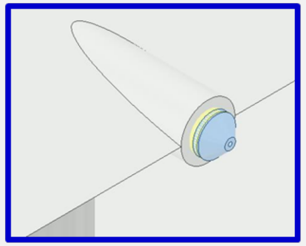
Preparatory activities: improve the SLD cloud conditions

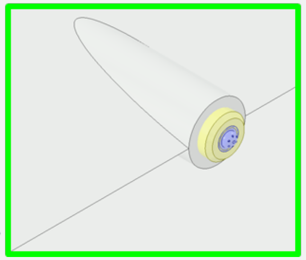
Spray nozzle (cont'd)

Case C Spray Header

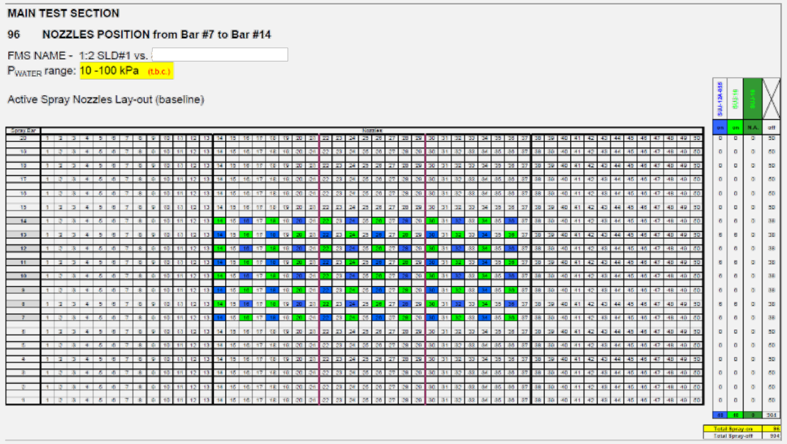
Spray bars with active nozzles

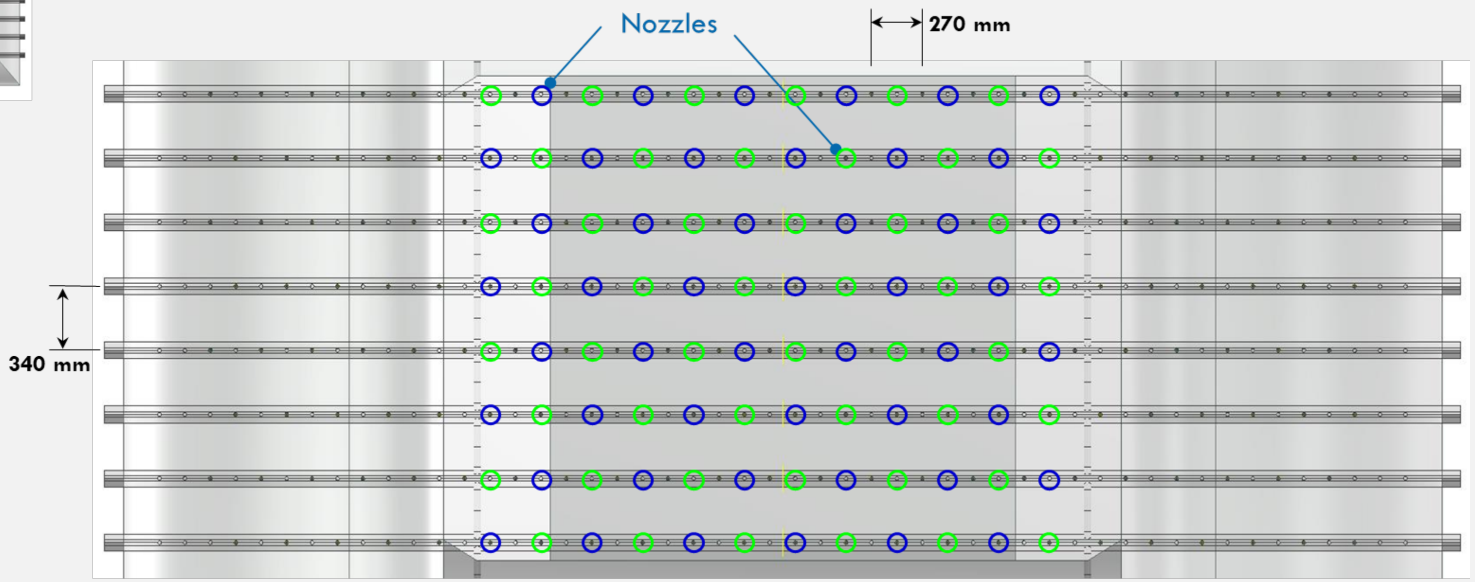






Spray bar view from test section

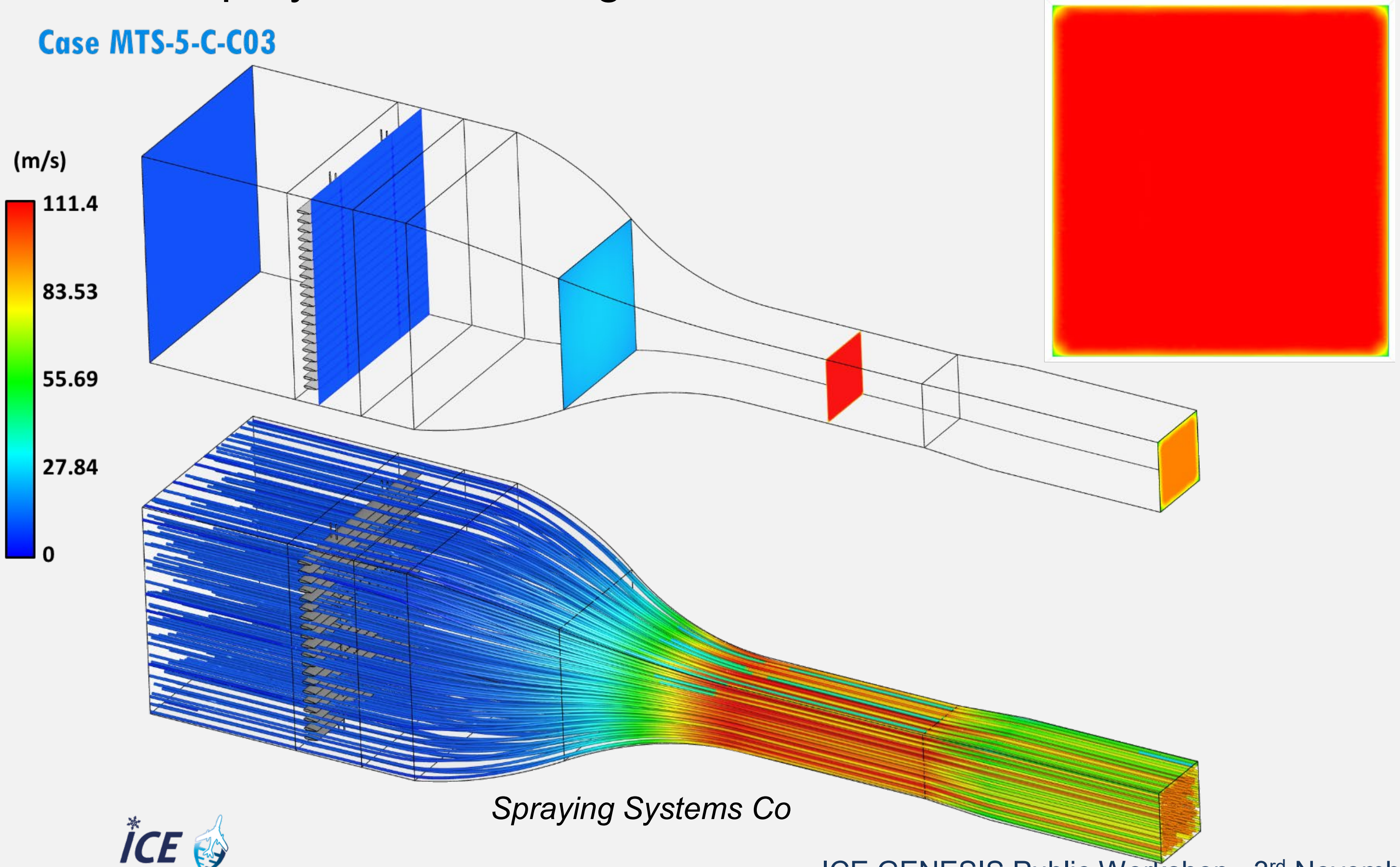




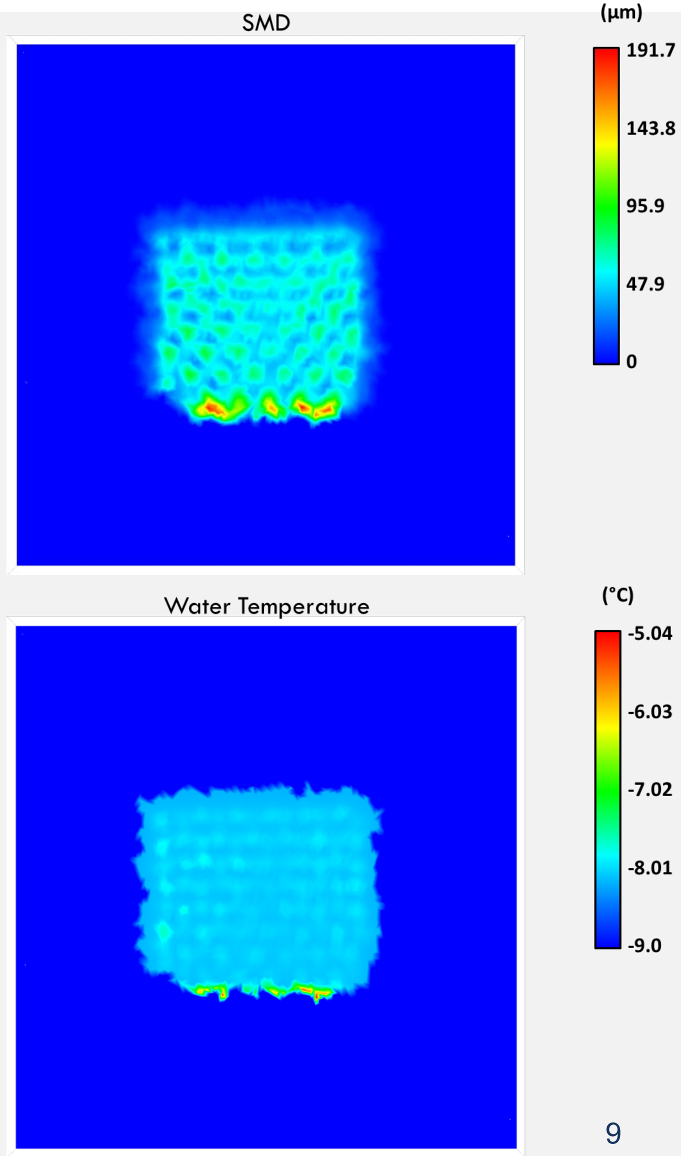
Preparatory activities: improve the SLD cloud conditions

Spray nozzle (cont'd)

- Modeling tools (SS-Fluent + CIRA-Imp3D) for preliminary assessment of new spray nozzles configuration on CIRA-IWT spray bar module.



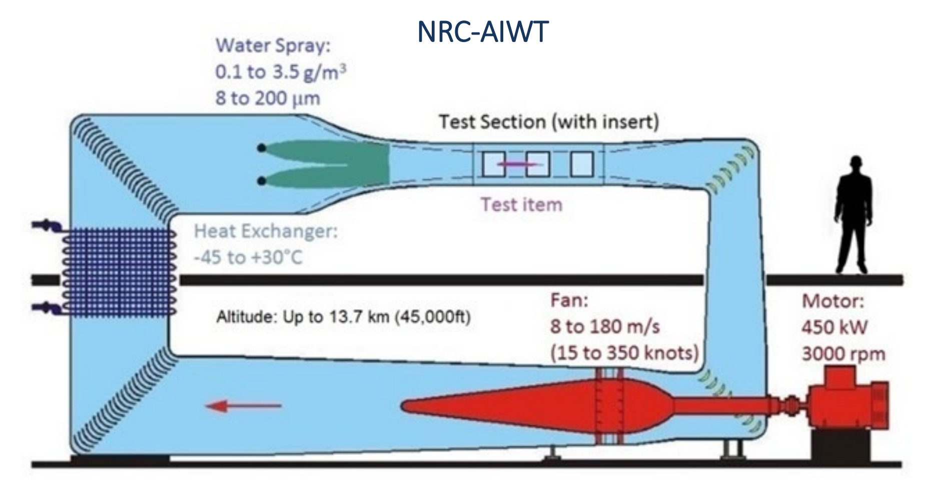
Spraying Systems Co

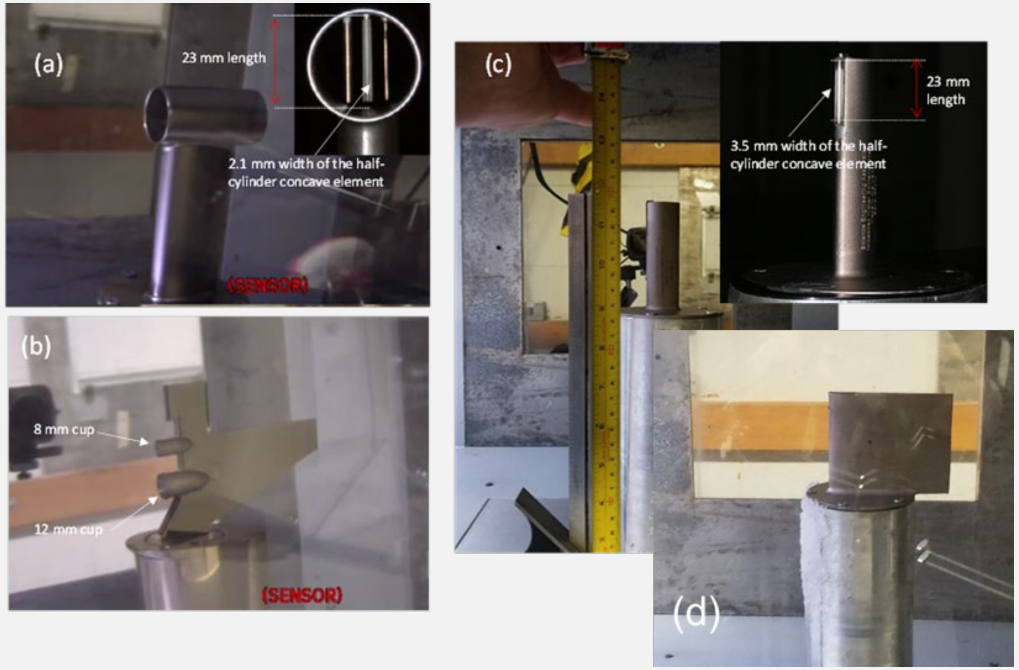


Calibration methodology: improvement of measurement capabilities

Icing wind tunnel calibration methods – hot-wire LWC sensor selection vs. SLD

CIRA Italian Aerospace Research Center · Met Analytics · NRC-CNRC Canada · DLR · SEA





Test section	Size H (m) x W (m) x L (m)	Airspeed (m/s)	SAT (°C)	Altitude (m)
Full size	0.57 x 0.57 x 1.8	10 - 100	to -40	s.l. - 12000

1. Ext. Multi-Wire **(a)**
2. Nevzorov 2-cup **(b)**
3. Standard Nevzorov
4. Robust probe **(c)**
5. Ice Crystal Detector **(d)**

- 30 spray conditions at -5 °C and three speed (40, 80, and 100 ms^{-1})
- LWC sweep @ 20 µm, 100 µm and 250 µm
- MVDs sweep @ 0,5 g m^{-3} and 0,2 g m^{-3}

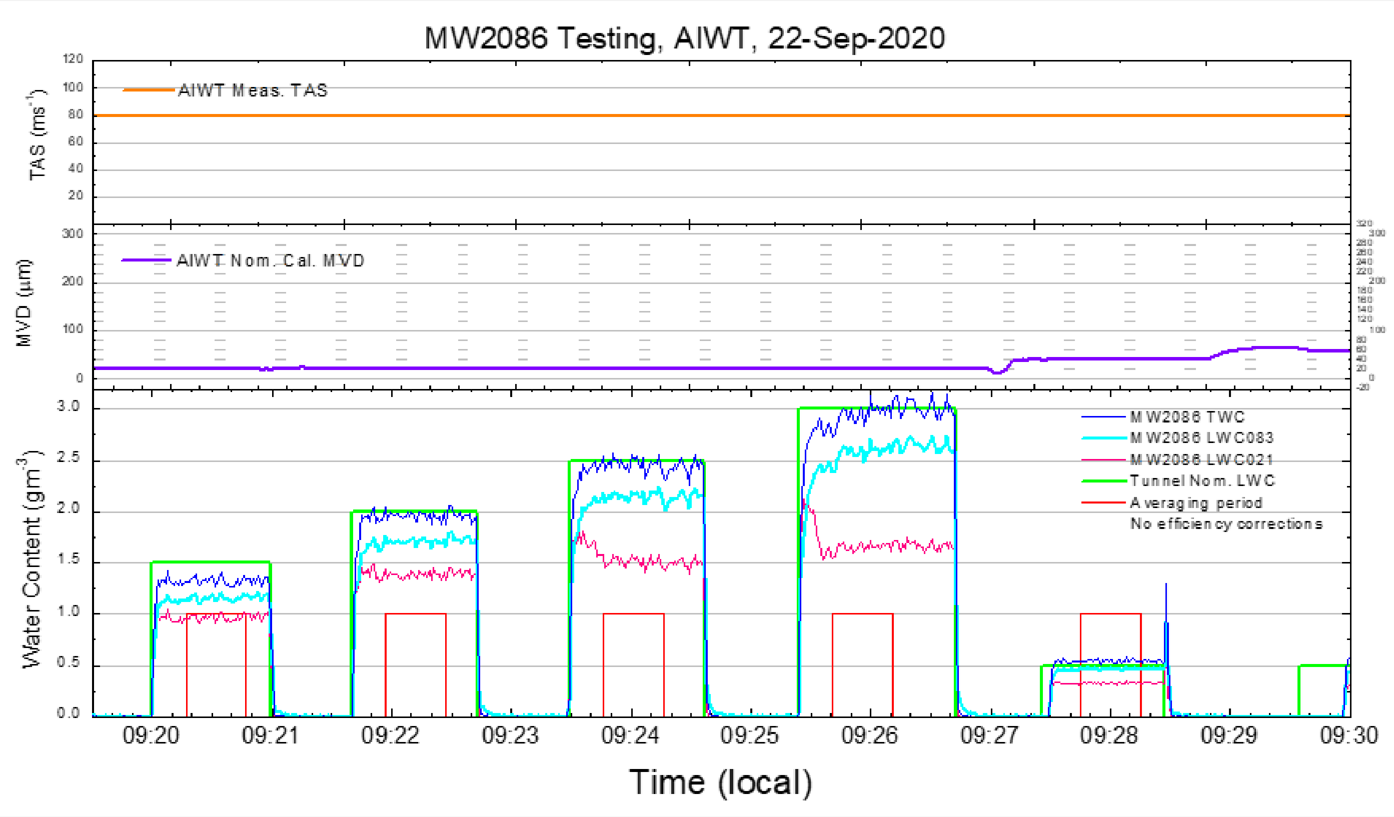
CIRA would like to acknowledge:

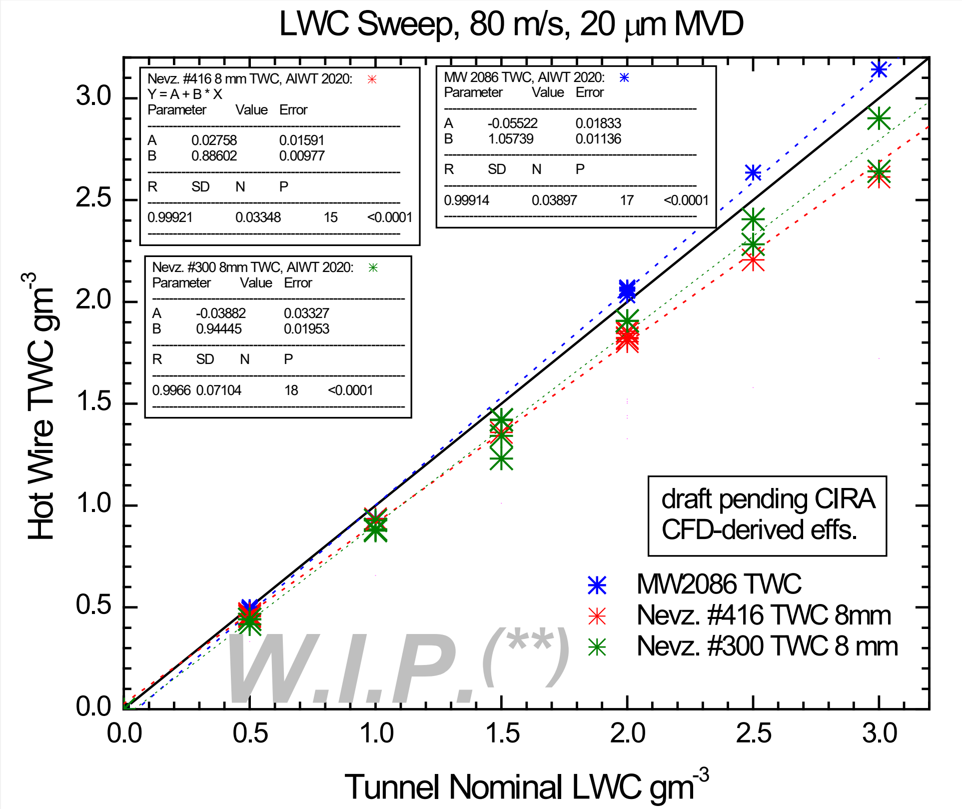
- *David Orchard and Gislain Chevrette (NRC-AIWT) for providing facility time-slot*
- *Mengistu Wolde, Natalia Bliankinshtein and Leonid Nichman, collected and organized data from all 5 sensors used in this analysis, shared the NRC's ICD and Nevzorov data and their initial analysis as part of the GLAZEICE project funded by the NRC APDC program*
- *Christiane Voigt and Johannes Lucke (DLR) for providing Nevzorov 2-cup and processing its data*

Calibration methodology: improvement of measurement capabilities

Icing wind tunnel calibration methods – hot-wire LWC sensor selection vs. SLD

SEA MW2086 and Nevzorov TWC sensors (*)





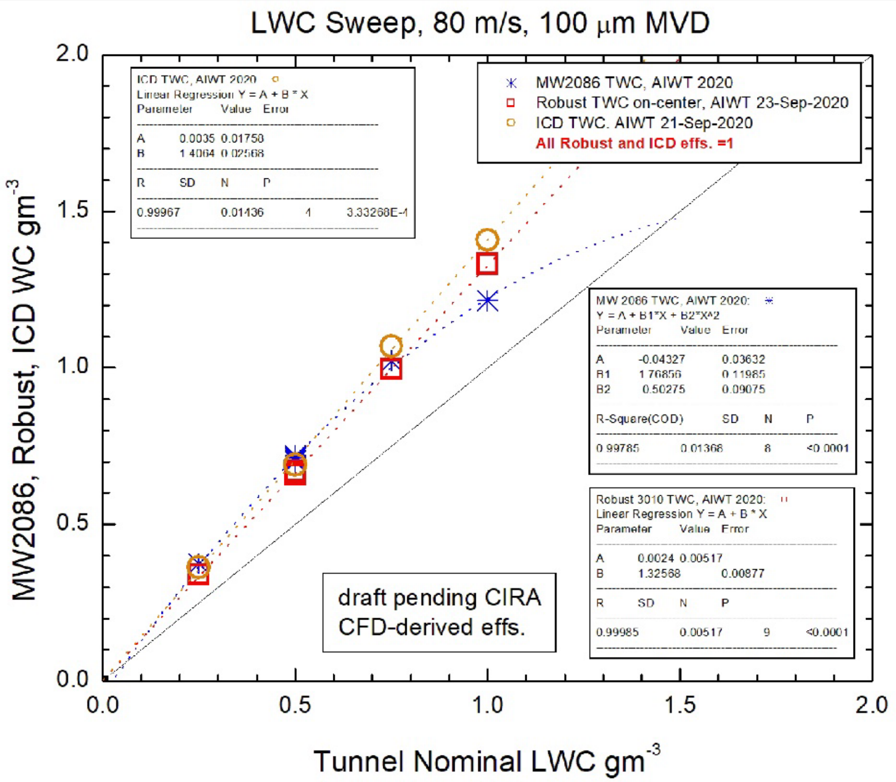
(*) *Data processing and analyzing by Met Analytics, Inc.*

(**) "Lucke, J., Jurkat-Witschas, T., Heller, R., Hahn, V., Hamman, M., Breitfuss, W., Bora, V. R., Moser, M., and Voigt, C.: Icing Wind Tunnel Measurements of Supercooled Large Droplets Using the 12 mm Total Water Content Cone of the Nevzorov Probe, Atmos. Meas. Tech. Discuss., https://doi.org/10.5194/egusphere-2022-647, 2022."

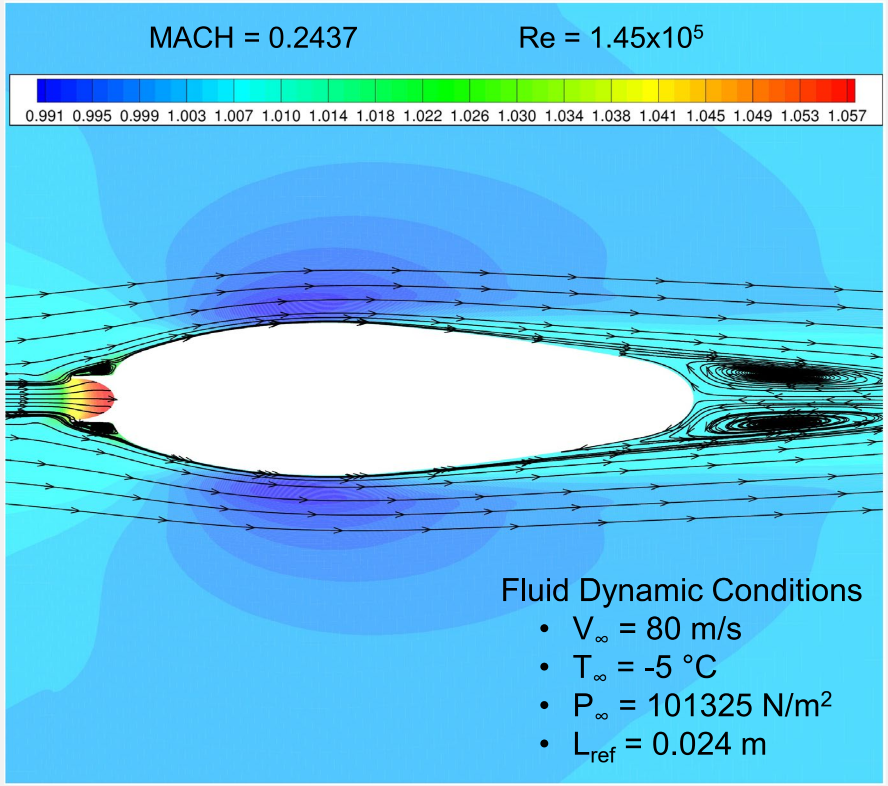
Calibration methodology: improvement of measurement capabilities

Icing wind tunnel calibration methods – hot-wire LWC sensor selection vs. SLD

SEA MW2086, ICD, and Robust TWC sensors (*)



W.I.P.



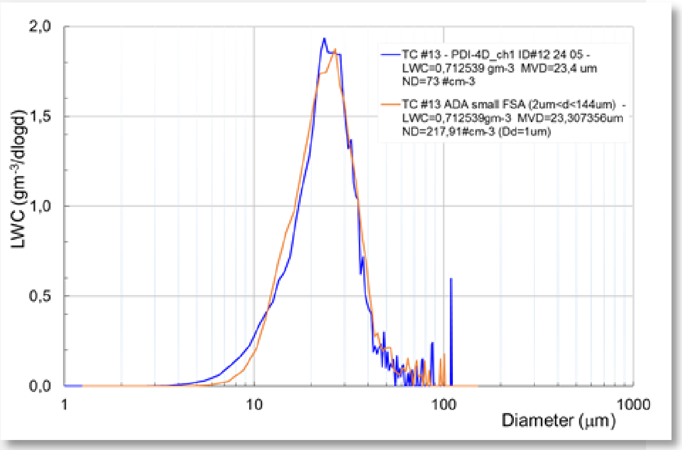
CIRA CFD to assess Robust probe and ICD collection efficiency vs. MVD at different flow conditions

(*) paper in preparation to submit at the SAE International Conference on Icing of Aircraft, Engines, and Structures (June 2023 in Vienna, Austria)

Calibration methodology: improvement of measurement capabilities

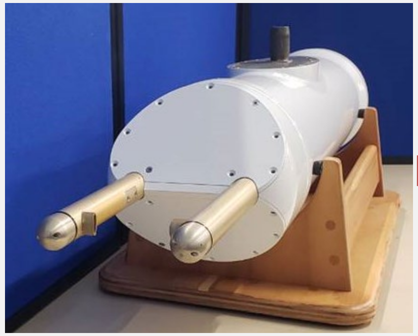
Icing wind tunnel calibration methods – PSD/MVD instrumentation selection

- **To better cover critical 50 µm – 150 µm size range**
  - New phase Doppler PDI-4D probe with four detectors configuration (primary probe)
  - ADA probes based on standard phase Doppler with new processors for signal analysis (backup probes)

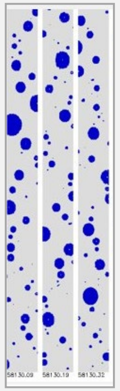


- **SEA-1D2DX probe – 2D implementation significantly enhanced from classic PMS 2D**
  - The 1D and 2D sections in the FPGA (Field Programmable Gate Array) share access to all 64 detectors
    - 64 bits of shadow at the 50% level
    - 64 bits of shadow at the 75% level (DOF)
  - While the 1D and 2D sections start with the same information, the processing of each is different.

OAP260-X



SEA 1D2D-X



Droplet Images
SEA Tunnel

Calibration methodology: improvement of measurement capabilities

Icing wind tunnel calibration methods – PSD/MVD instrumentation selection

- **SEA 1D2D optical array particle imaging probe was developed specifically for CIRA to provide the large-droplet part of spectrum for a composite PDI / 1D2D SLD spectrum (crossover to 1D2D at ~ 100 μm)(*)**

  - **Features:**
    - ✓ 15 μm diode resolution, 64 diodes, for nominal 15-960 μm imaging and sizing
    - ✓ Standard 50% shadow image
    - ✓ No of pixels at 75% shadow level also stored with each image (can be used to help reduce more extreme out of focus particles, and reduce out-of-focus sizing correction)
    - ✓ Optional real-time image rejection (using various algorithms with 75% level, end element rejection, minimum particle size); for possible future optimization of large particle sampling, reduction of dead-time
    - ✓ Detailed particle timing, for precise and unambiguous dead time correction
    - ✓ 1D data stream, intended for future accurate simple real-time spectra, LWC, and MVD once optimized
    - ✓ Superior de-icing relative to conventional optical array probes

(*) paper in preparation to submit at the SAE International Conference on Icing of Aircraft, Engines, and Structures (June 2023 in Vienna, Austria)

Calibration methodology: improvement of measurement capabilities

Icing wind tunnel calibration methods – PSD/MVD instrumentation selection

Mode #	Imaging Shadow Level	Image recording:			
		Image touches end element	< 1 pixel at 75%	#50% pixels / #75% pixels ≤ 2	Record if minimum Y size in pixels ≥ value below
1	50%	**Reject**	**Reject**	Accept	1
2	50%	Accept	**Reject**	Accept	1
3	50%	Accept	Accept	**Reject**	1
4	50%	Accept	Accept	Accept	1
5	50%	Accept	Accept	Accept	2
7	50%	Accept	Accept	Accept	5

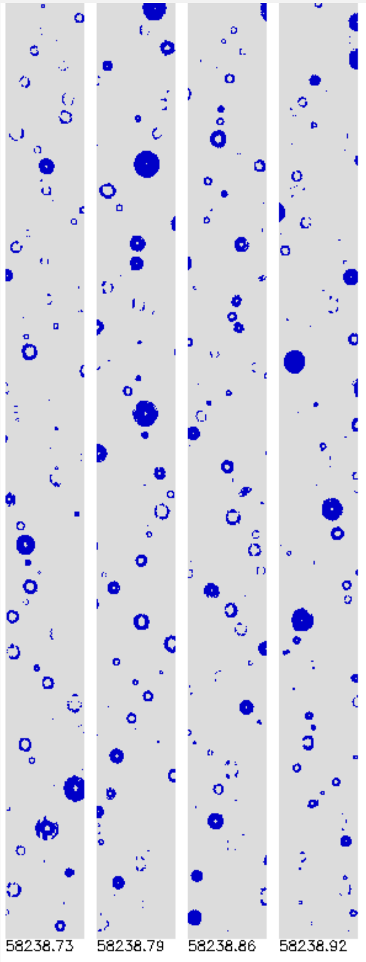
Note

- mode 4 is essentially the SPEC 2D-S mode
- Mode 2 is similar to how many CIPgrey probes are analyzed

Calibration methodology: improvement of measurement capabilities

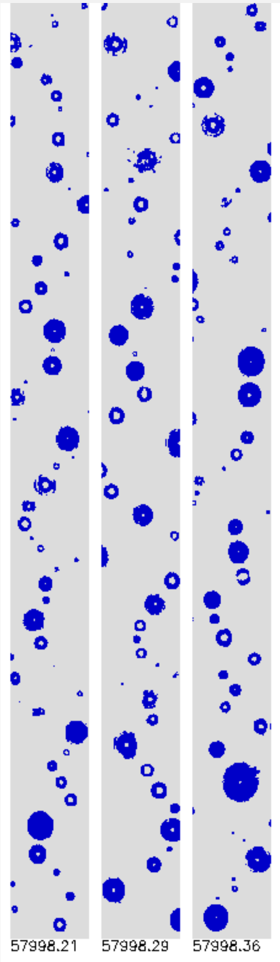
Icing wind tunnel calibration methods – 1D1DX sample imagery of modes 2, 3, and 4

Mode 4 DOF = $8r^2/\lambda$



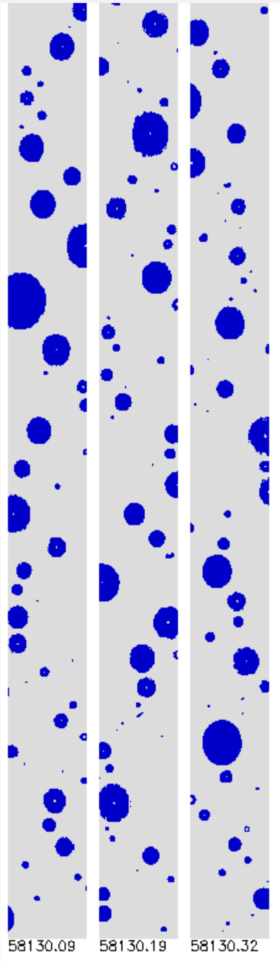
- "2D-S mode"
- Note highly out-of-focus and fragmented particles
- Out-of-focus size correction is large
- DOF estimate available

Mode 2 DOF = $3{,}5\ r^2/\lambda$



- "CIPgrey mode"
- 1 pixel at 75% required
- Note particles more in focus
- Most fragmented images eliminated
- Out-of-focus size correction is reduced relative to mode 4
- DOF estimate available

Mode 3 DOF = ???



- 50% of pixels at 75% required
- Note best mode of in focus sampling
- Fragmented images eliminated
- Out-of-focus sizing correction minimized
- But DOF-versus-size not yet available
- May be future best choice

Calibration methodology: improvement of measurement capabilities

2D Probe Traverse Mechanism designed by Science Engineering Associates, Inc.

- Allow traversing of two hot-wires sensors to cover up to 60% of the reference area in the test section to assess LWC distribution.
- Allow the traversing of the µ-physics instruments to assess the gravitational effect on PSDs/MVDs for SLD clouds.
- Accomplish the PSD/MVD and LWC/TWC measurements over 60% of width and 60% of the height of T/S up to max speed (100 m/s).

Preliminary results of CIRA-IWT vs. Appendix O

- Systems commissioning and FZDZ calibration were conducted over the period <u>January - June 2022</u>.
- Matrix of spray conditions foresees up to four lay-outs of nebulizers on the spray bar system:
  - Two SBM baselines to investigate the behavior of each different spray nozzle type at environment cond.
  - Two spray bar configurations to generate low LWCs and bi-modal PSDs.

Spray Bar	Nozzles																																																	
20	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50
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Spray Bar	Nozzles																																																	
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- 13 bars of SBM were activated for the cloud generation suitable for the requested coverage area in the tests section (vertical TM).
- From 10 (1A3_SLD#6) to 15 (1A2_SLD#5) spray nozzles per bar were activated for water nebulization.

Preliminary results of CIRA-IWT vs. Appendix O

Cloud conditions:

- Up to 128 spray conditions
- Both Appendix C and Appendix O
- Ranges:
  - For LWC => 0,1 gm^{-3} – ~1,2 gm^{-3} (t.b.c.)
  - For MVDs => 12 µm – >134 µm (t.b.c.)
  - PSDs => mono-modals and bi-modals

µ-physics instruments

Primary

- CIRA-PDI4D
- DLR-CCP (comb. CDP + CIP-GS)

Backup

- NASA CIP-GS / SEA-1D2DX

LWC/TWC instruments

Primary

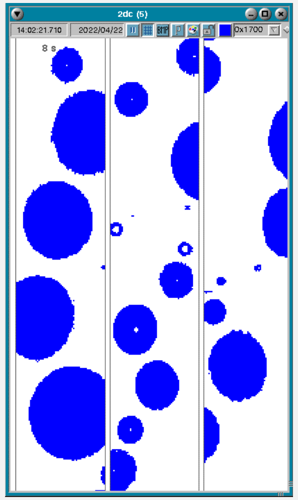
- SEA-MW (#2)

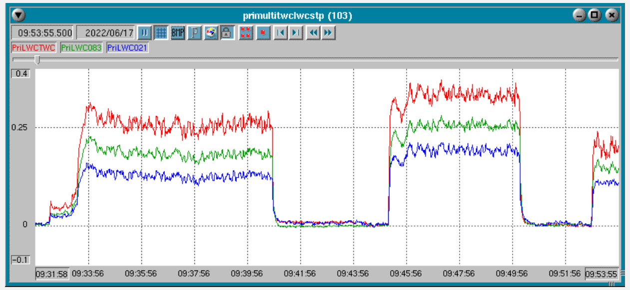
Backup

- SEA-RP / SEA-ICD

Flow conditions:

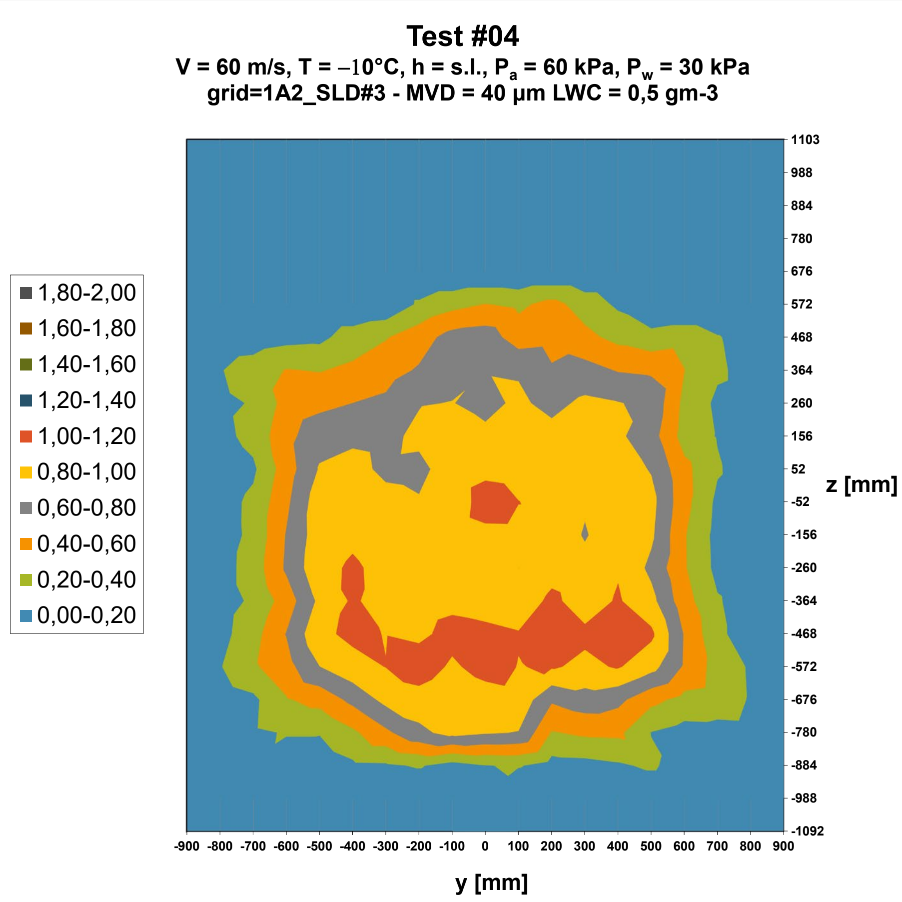
- Two airspeeds: 60 m s-1 and 110 m s-1
- Three pressure altitudes: s.l., 20,000 ft and 5,000 ft
- Static air temperature:
  - For LWC => -25°C, -18°C, -8°C,
  - For MVDs/PSDs => -8°C, -6 °C
  - For RV GRT-Mini (cloud temperature) => -18°C, -12°C, -6°C





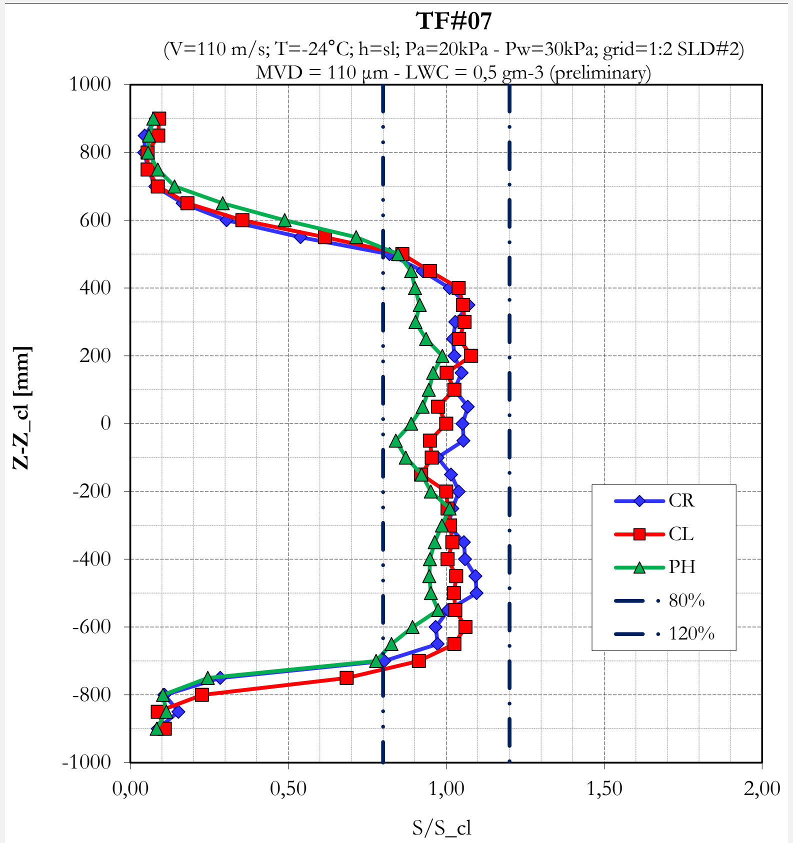
Preliminary results of CIRA-IWT vs. Appendix O

- Use of the Icing Grid to assess the functionality of different combinations of the spray nozzles for specific benchmark conditions at 60 and 110 m/s and optimize the nebulizer location on the SBM.



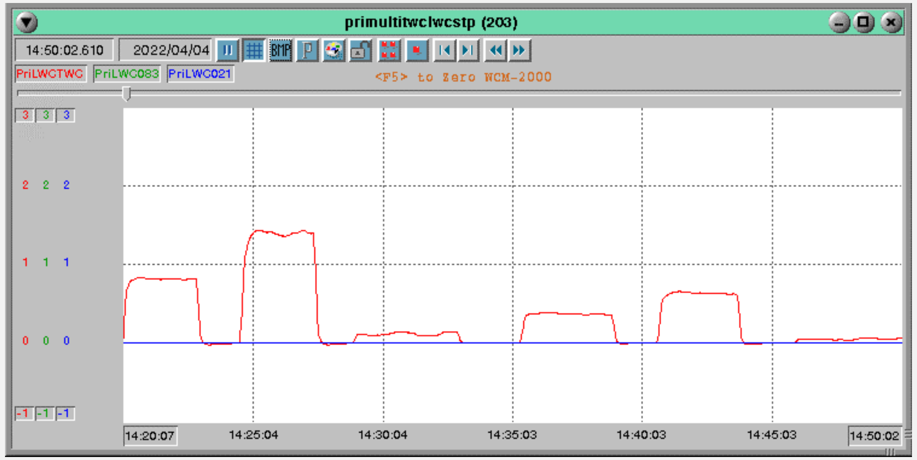
Preliminary results of CIRA-IWT vs. Appendix O

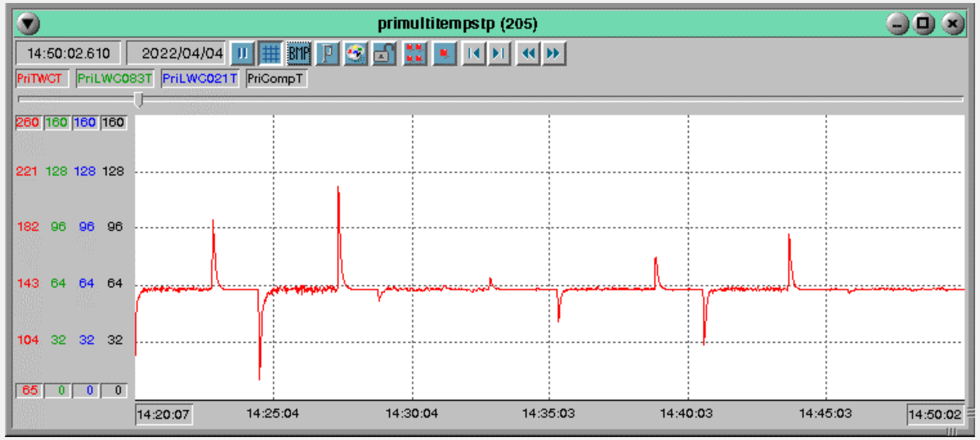
- Three icing cylinders were installed in the reference area of the test section to optimize the cloud homogeneity at low and high airspeed.These cloud assessment measurements anticipate those with microphysics instruments with their sampling volume placed on the centerline of the test section.



Preliminary results of CIRA-IWT vs. Appendix O

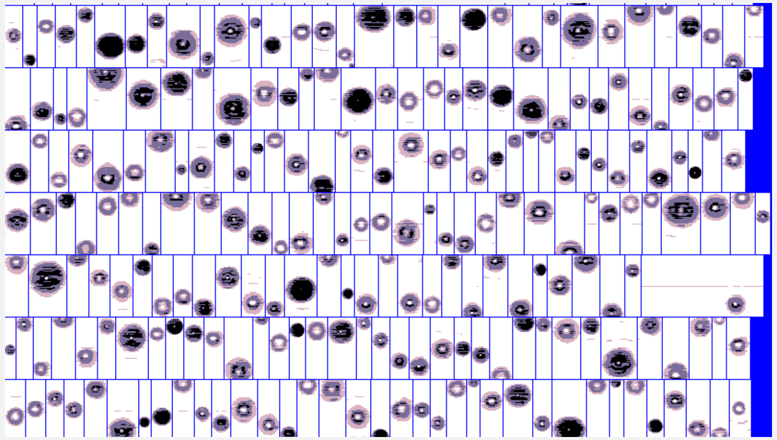
- Due to the LWC underestimate for MW at higher MVD (>100 μm), to explore a wide range of air/water pressures of the SBM, the RP measurements at the centerline were performed at the beginning of the program.



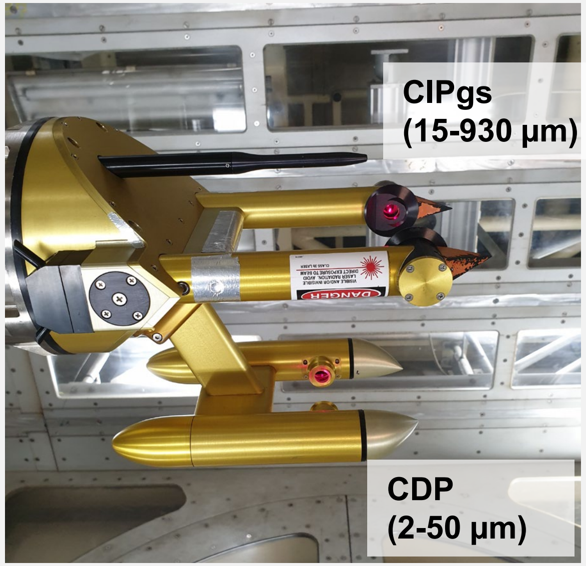


Preliminary results of CIRA-IWT vs. Appendix O

- **DLR-CCP measurements conducted from 2nd to 5th May 2022**
  - App C & O (FZDZ) conditions:
    - -6°C static air temperature
    - 60 ms-1, 110 ms-1
    - Sea level, 1524 m, 6096



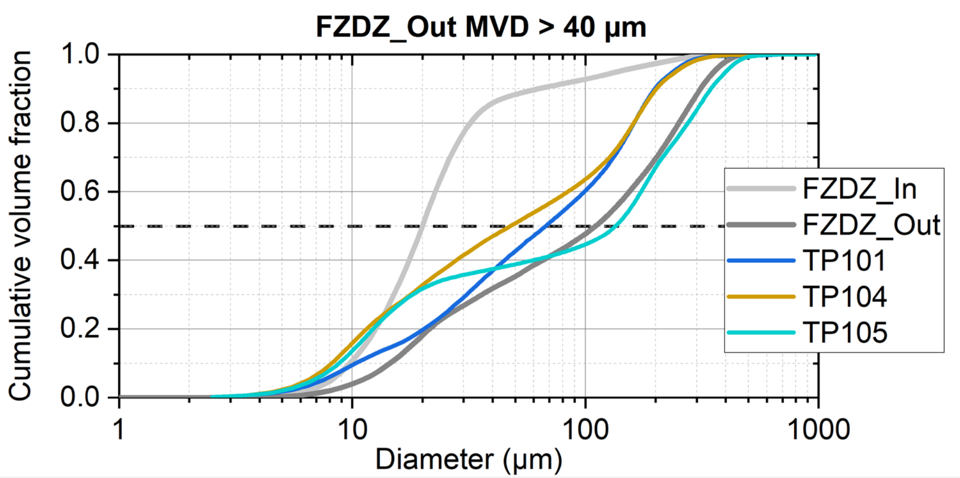
FZDZ: droplets larger 100 µm



DLR CCP (Cloud Combination Probe) installed @ CIRA IWT

Preliminary results of CIRA-IWT vs. Appendix O

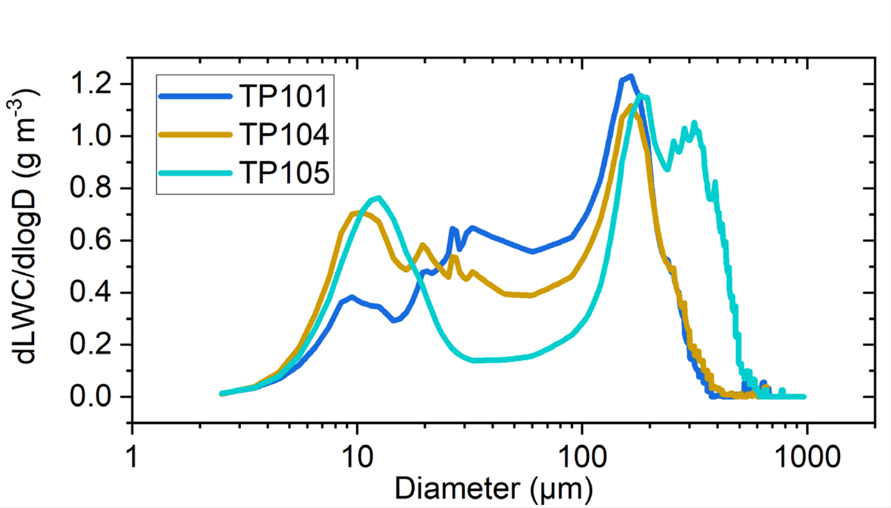
- **DLR-CCP measurements conducted from 2nd to 5th May 2022**
  - CIRA – DLR: Preliminary results
    - Spray bar configuration 1A2_SLD#5
    - 110 ms-1 Airspeed
    - 1524 m Altitude
    - -6°C Static Temperature



- TP101/104:
  - MVD 68/48 µm, LWC ~0.4 gm^{-3}

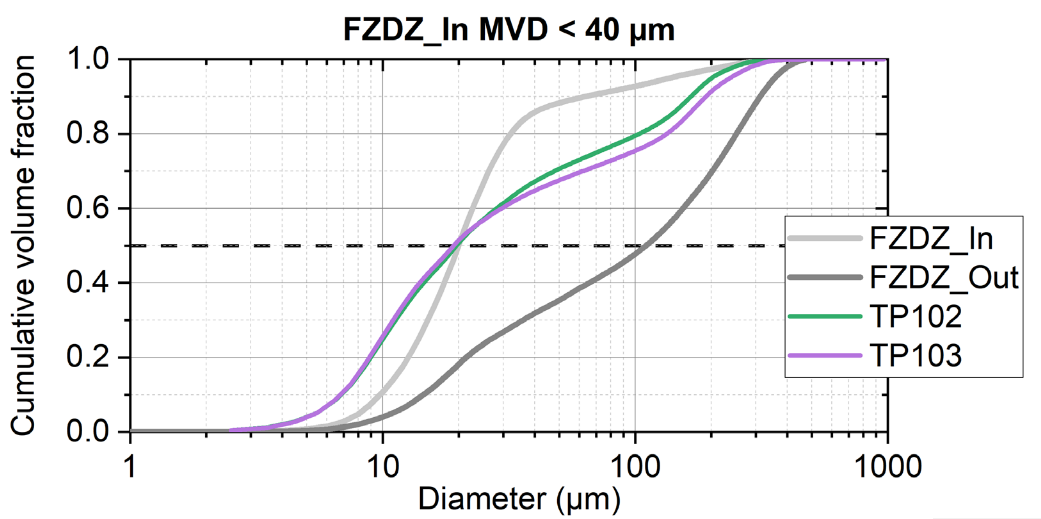
- TP105:
  - MVD 134 µm, LWC 1.17 gm^{-3}

W.I.P.



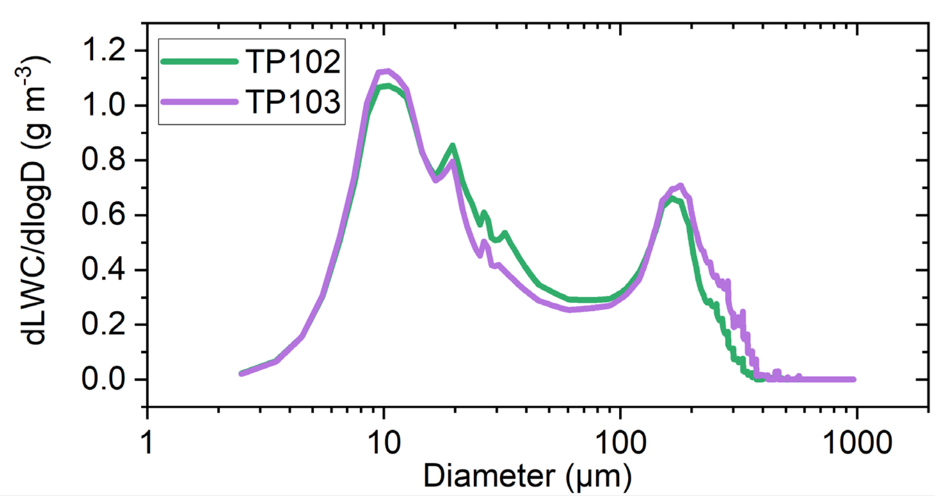
Preliminary results of CIRA-IWT vs. Appendix O

- **DLR-CCP measurements conducted from 2nd to 5th May 2022**
  - CIRA – DLR: Preliminary results
    - Spray bar configuration 1A2_SLD#5
    - 110 ms-1 Airspeed
    - 1524 m Altitude
    - -6°C Static Temperature



- TP102/103
  - MVD 20 µm, LWC ~0.3 gm^{-3}

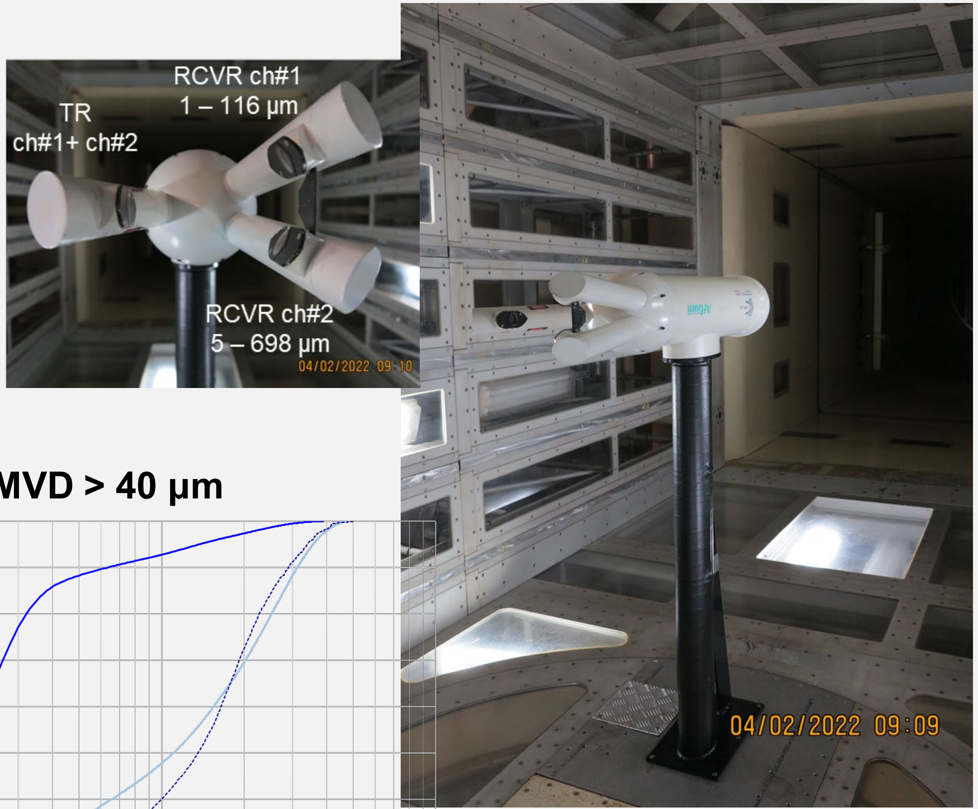
W.I.P.



Preliminary results of CIRA-IWT vs. Appendix O

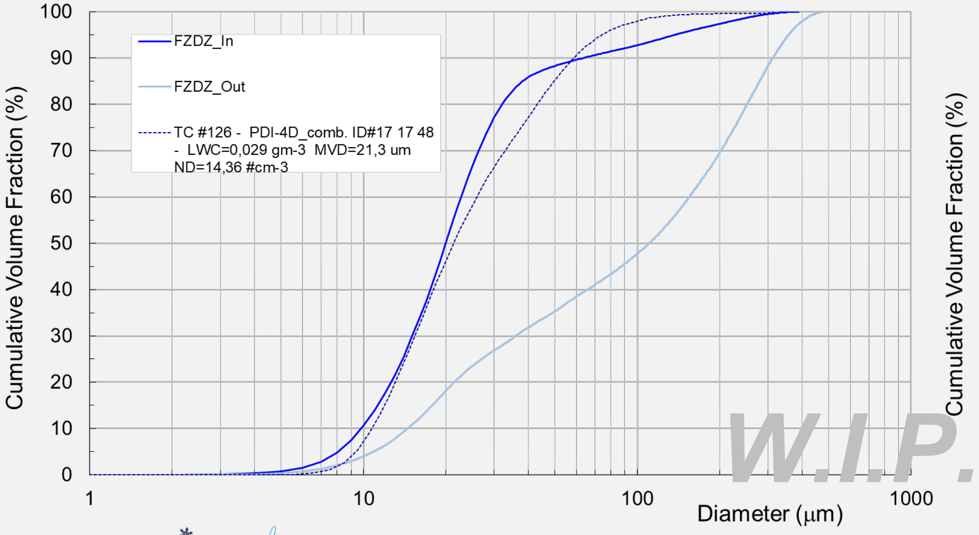
CIRA-PDI4D

- App C & O (FZDZ) conditions:
  - 4 Spray bar configurations
  - 110 ms-1 Airspeed
  - 0 m, 1524 m, and 5000 m of pressure altitude
  - -6°C Static Temperature

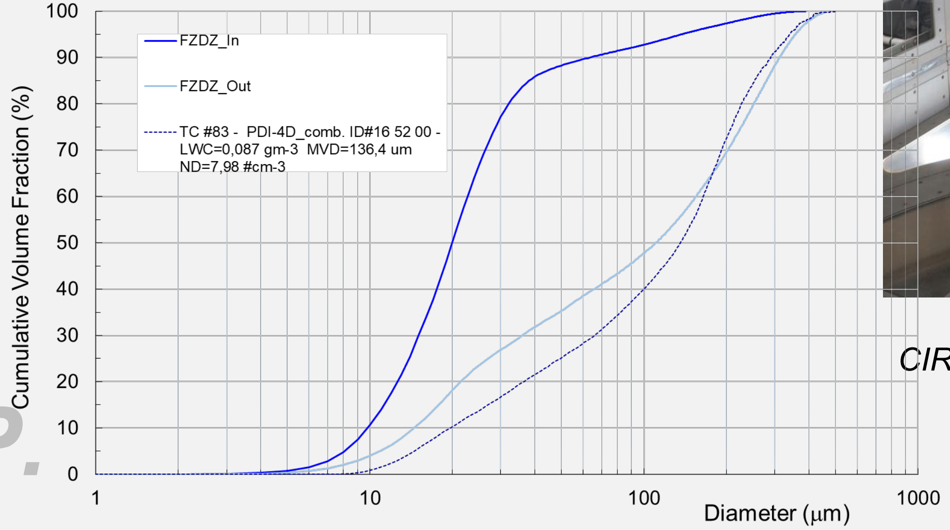


CIRA PDI4D installed in CIRA-IWT during the phase 2

FZDZ_In MVD < 40 µm

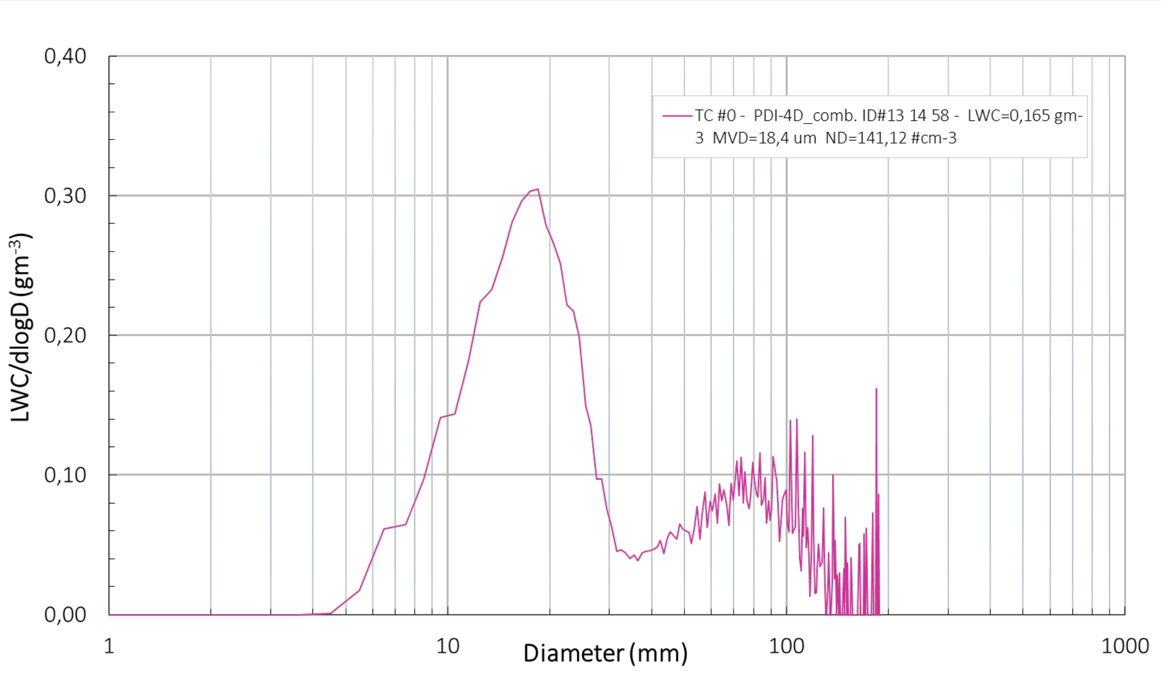


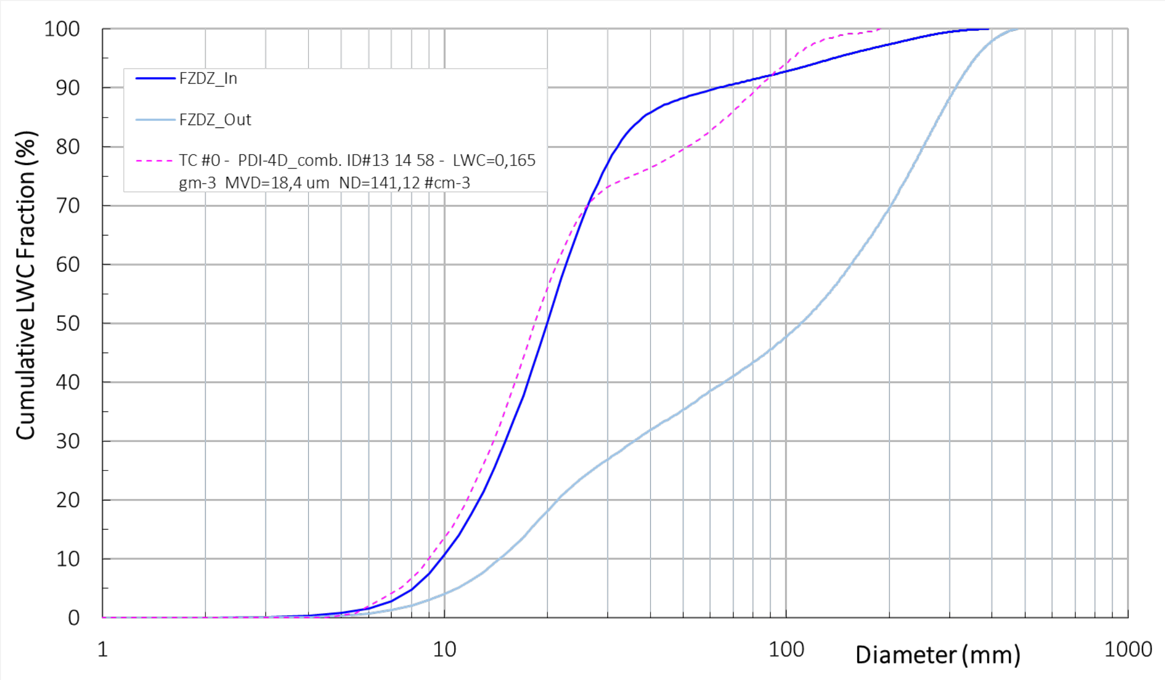
FZDZ_Out MVD > 40 µm



Preliminary results of CIRA-IWT vs. Appendix O

Selected mono-modal and bi-modal PSDs for Dassault test campaign





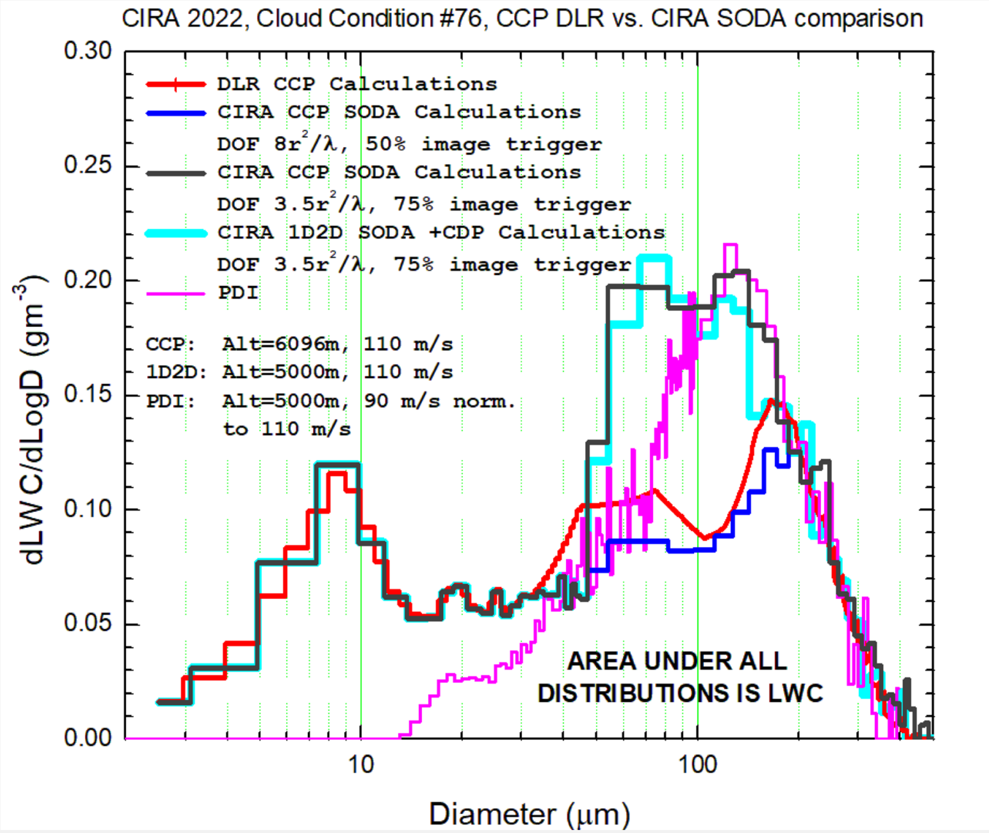
Flow/cloud conditions: for **FZDZ#1** w/ B-modal PSD

MVD = 18,4 µm - LWC = 0,41 g m-3

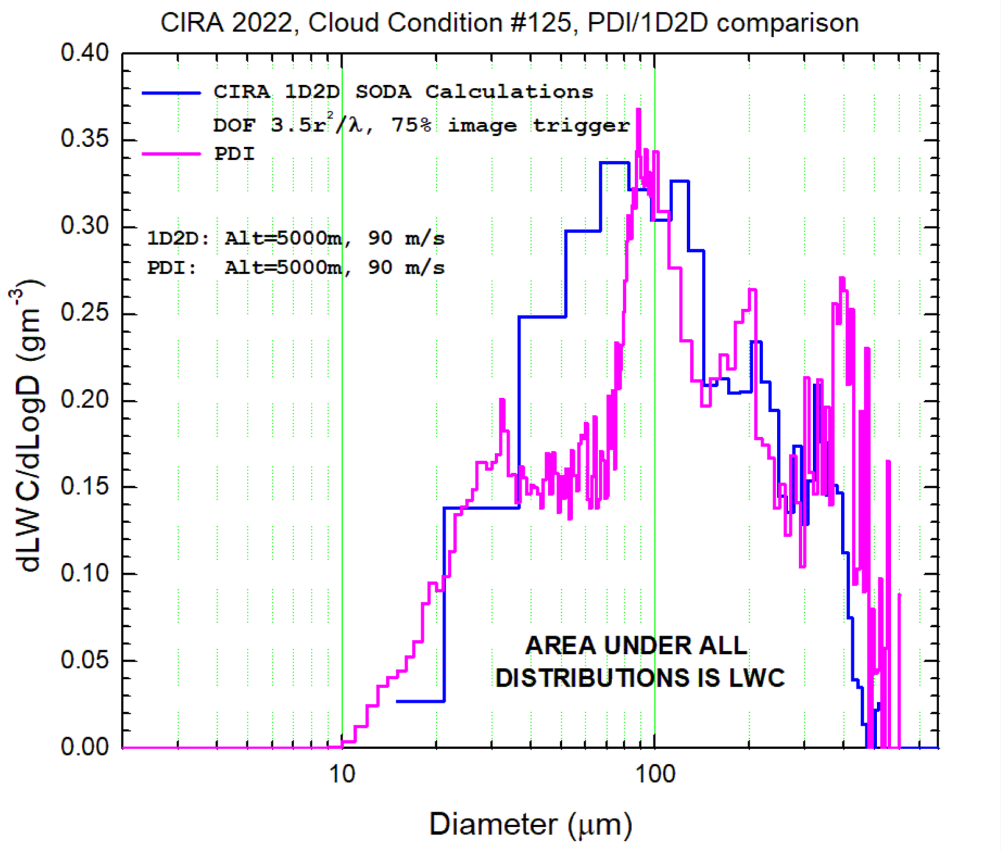
PDI4D TP_-CC126: speed 90 ms-1 Altitude 20,000-ft w/ SBS: Pa 120 kPa – Pw 80 kPa – 1A2_SLD2

Preliminary results of CIRA-IWT vs. Appendix O

Selected mono-modal and bi-modal PSDs for Dassault test campaign



W.I.P.



Flow/cloud conditions: for **FZDZ#2** w/ B-modal PSD

MVD = 65 μm - LWC = 0,21 gm^{-3}

CCP TP11-CC76: TAS 110 ms^{-1} Alt. 20,000-ft w/ SBS: Pa 140 kPa – Pw 80 kPa – 1A2_SLD3
1D2DX TP18-CC76: TAS 110 ms^{-1} Alt. 16,404-ft w/ SBS: Pa 140 kPa – Pw 80 kPa – 1A2_SLD3
PDI4D TP_-CC75: TAS 90 ms^{-1} Alt. 16,404-ft w/ SBS: Pa 140 kPa – Pw 80 kPa – 1A2_SLD3

Flow/cloud conditions: for **FZDZ#3** w/ B-modal PSD

MVD = 98 μm - LWC = 0,27 gm^{-3}

1D2DX TP61-CC125: TAS 90 ms^{-1} Alt. 16,404-ft w/ SBS: Pa 60 kPa – Pw 40 kPa – 1A3_SLD6
PDI4D TP_-CC125: TAS 90 ms^{-1} Alt. 16,404-ft w/ SBS: Pa 60 kPa – Pw 40 kPa – 1A3_SLD6

Preliminary results of CIRA-IWT vs. Appendix O

Using 75% level for sharpening images, and Depth of Field (DOF) Implications

From O'Shea et al. , AMT, 2019

- Recommends sizing at 50% level, but using pixels at 75% level to filter out fragmented particles, that are not properly size corrected for out-of-focus oversizing by current algorithms.
  - This feature can be implemented on grey scale probes (e.g. DLR CCP)
  - This feature cannot be implements on the SPEC 2D-S probe, a current state-of-the-art probe.
  - This feature can be implemented on the new 1D2D probe

- Using 75% pixels to filter the worst out-of-focus images also shrinks the depth of field (DOF) when not limited by aperture
  - O'Shea provides a DOF versus size for particles requiring one pixel at 75% of $\mathbf{\pm 3.5\ r^2/\lambda}$
  - This will be used for 1D2D mode 2 calculations of particle concentrations.

From Lawson et al. , J. Atmos. And Oceanic Technol., 2006.

- An estimate of $\pm 8\ r^2/\lambda$ for the DOF versus size is appropriate for a simple 50% shadow level monochromatic probe, which would be used for 1D2D modes 4, 5, and 7.

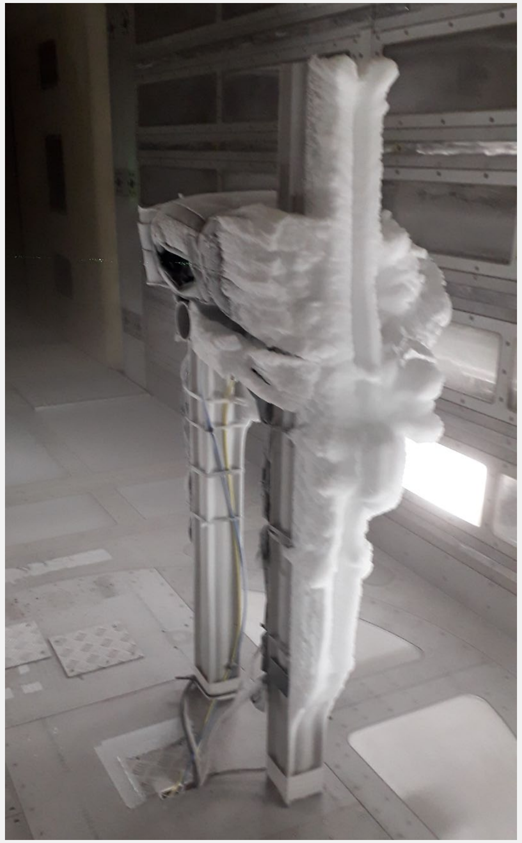
Preliminary results of CIRA-IWT vs. Appendix O

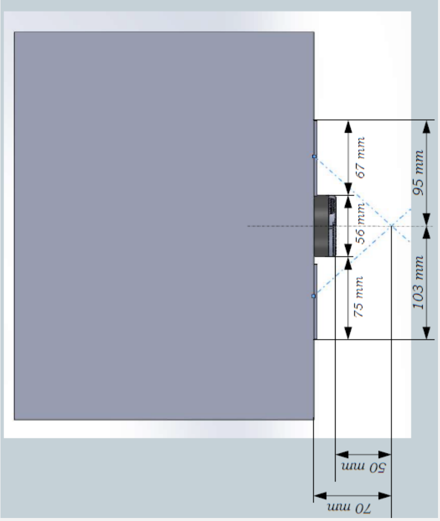
LWC vs Appendix O

comparison of LWCs vs requirements → *W.I.P.*

Preliminary results of CIRA-IWT vs. Appendix O

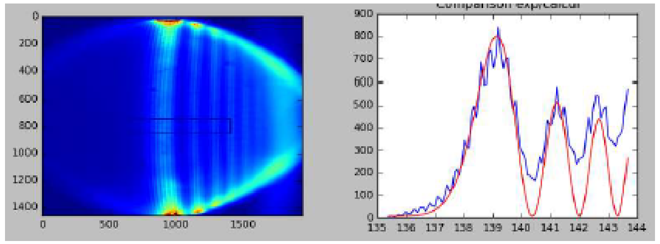
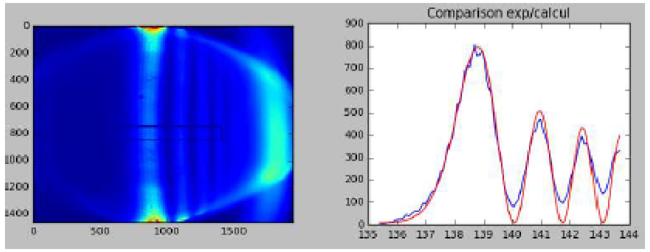
Cloud droplet temperature assessment (TBC)





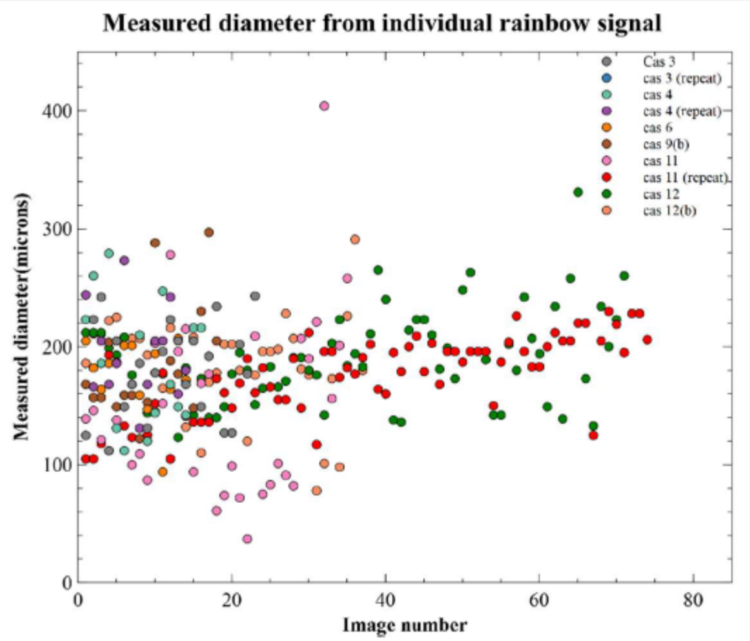
W.I.P.

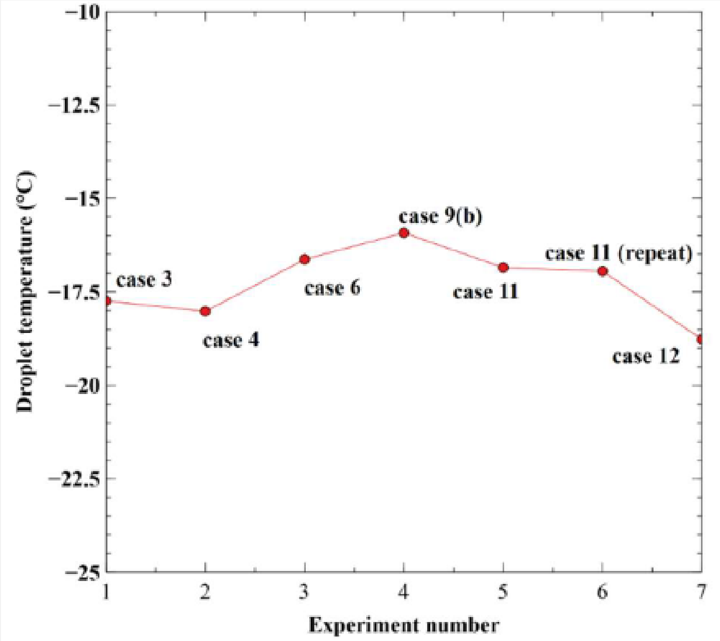
- A very low liquid water content (0.1 – 0.58 gm^{-3}) at large droplet size reduced the probability to achieve enough statistics of large droplet inside the probe volume during the camera exposure time;
- The real-time processing of the global rainbow signal to measure droplet temperature has been replaced with a multi-step strategy;
- The icing contamination on the struct upstream of the probe volume affects the particle trajectories upstream of the sampling volume;

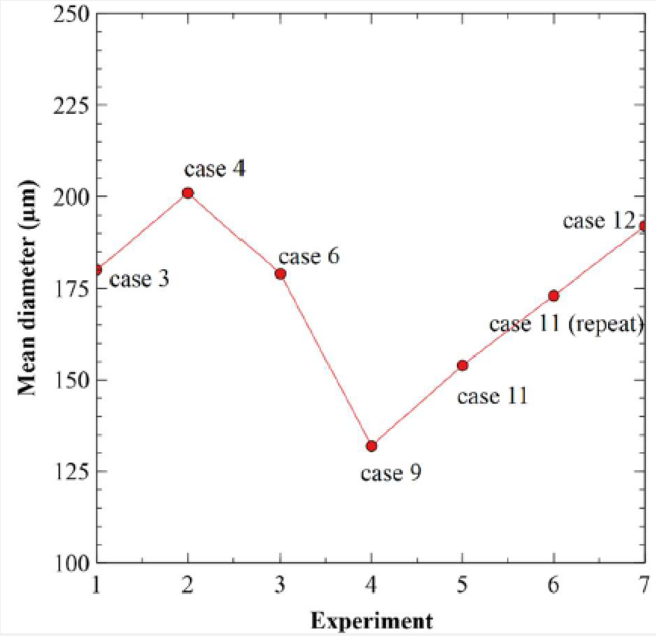
Rainbow image and associated rainbow signal	Extracted droplet size
	214 µm
	207 µm

Preliminary results of CIRA-IWT vs. Appendix O

Cloud droplet temperature assessment (TBC)







- Droplet size and temperature measured with GRT-Mini for different clud conditions at 45 ms^{-1} and -18 °C of SAT;
- Results shows droplet temperature slightly higher than SAT
- Needs same magnitude of validated individual images for each cloud condition
- To confirm the data quality, experiments at different SAT must be performed

W.I.P.

Conclusions / Perspectives

- The improvements on the CIRA-IWT spray bar with new spray nozzles provide extended flexibility to generate bi-modal PSDs at low and medium LWC (IG, TRL3 passed successfully)
- Measurements for SLD-FZDZ calibration have only been partially completed
  - Additional measurements of cloud droplet temperature to assess the thermal equilibrium between the large droplets and static air temperature are pending
  - PSDs uncertainty
    - PSDs are significantly affected by choice of optical array probe (OAP) settings, and likely also by image processing software. The assumed depth of field versus size (DOF), and the software size-correction for out-of-focus particles are particularly important to intermediate MVD test conditions (e.g. 50-150 µm).
    - For commonly used probe settings, the OAP 50% image trigger threshold (ITT) setting has the largest potential dead time, the largest out-of-focus size correction, and the highest likelihood or sizing errors at the edge of the DOF (O'Shea et al. 2019). The SPEC 2D-S uses this ITT, and this mode is available for the CCP and 1D2D. DOF commonly used is $\pm 8r^2/\lambda$,
    - The OAP 75% ITT reduces dead time, out of focus sizing corrections, and greatly reduces sizing errors at the edge of the DOF (O'Shea et al. 2019). This ITT is available to both the CCP and the 1D2D. DOF is approximately $\pm 3.5r^2/\lambda$ (O'Shea et al. 2019).
    - The 1D2D has further ITT modes that can nearly eliminate out-of-focus sizing corrections, but DOF with these new modes can be greatly altered, and is currently unknown.

Conclusions / Perspectives

- Measurements for SLD-FZDZ calibration have only been partially completed
  - PSDs uncertainty (cont'd)
    - Current discrepancies between PSDs calculated using the different methods above reveal the sensitivity of the MVD accuracy.
      - The largest improvement in accuracy and comparability could arguably be achieved by performing empirical DOF measurements (spinning disk, droplet generator) for the particular probe settings and image software used by the different agencies.
      - CCP and 1D2DX data comparability could also be improved by harmonization of software, either by intercomparisons to identify and rectify discrepancies, or by common use of the same mutually agreeable community image processing package (e.g. SODA)
      - Many more PSD measurements are required to complete the calibration for MTS configuration (e.g., at the different airspeeds and pressure altitudes)
  - LWC
    - Preparatory wind tunnel hot-wire comparisons were successfully collected by CIRA at the NRC AIWT, to be used to select the best device for CIRA-IWT FZDZ and FZRA calibrations
      - Preliminary LWC agreement of ± 20% through direct comparison of **CIRA Multiwire TWC** to **DLR Nevzorov 12mm TWC** has been confirmed, and should support use of either probe for calibration (t.b.c.).
    - A large number of LWC measurements were made at CIRA in April-June 2022 with the Multiwire and the Robust probe, under many test conditions. More are required to complete the calibration.
    - Data analysis is on progress

THANK YOU

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