ICE GENESIS Final Public Workshop

6-7 December 2023
Toulouse, France

The project leading to this application has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 824310.

Liquid Conditions Part 1: Test capabilities

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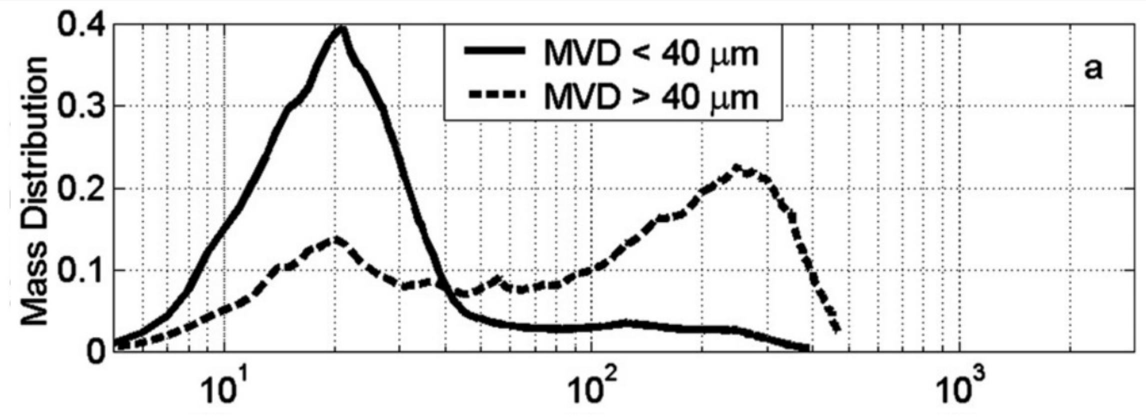
The project leading to this application has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 824310.

Outline

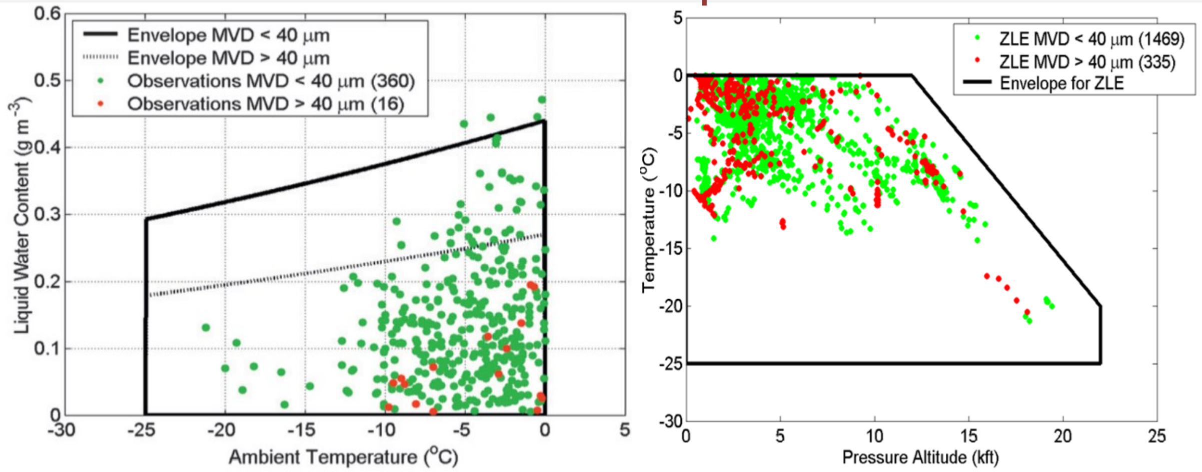
- Appendix O target requirements for facilities qualification in SLD environment
- Icing Instrumentation: Overview and Conclusion
- SLD cloud generation capabilities and main calibration results IG icing facilities
- Conclusions on gaps and prospective

Appendix O target requirements

- FAA 14 CFR Part 25 and EASA CS-25 Appendix O conditions to reproduce in W/Ts



FZDZ envelope(*)



"Provide requirements for test capability needed for SLD"

IWTT performance target

Parameters	Instrumentation Accuracy/Uncertainty	W/T C_L Temporal stability	Spatial Uniformity	Limit
Cloud Uniformity				
Liquid Water Content	± 10%	± 20%	± 20%	N/A
Median Volumetric Diameter	± 10%	± 20%	± 20%	
Drop trajectory relative to the flow +/- %	± 10%	± 20%	± 20%	
Droplet's temp. deviation from free-stream SAT	± 3 °C	+10 °C	N/A	
Drop distribution Deviation from reference PSD: RSF	± 5%	±10%	±10%	
Drop sphericity	± 10%	± 20%	± 20%	
Relative Humidity	± 3%	± 10%		

(*) Federal Aviation Administration FAA, "Data and Analysis for the Development of an Engineering Standard for Supercooled Large Drop Conditions," DOT/FAA/AR-09/10, National Technical Information Services (NTIS), Spriengfield, Virginia 22161, 2009

Icing Instrumentation (WP4)

<u>WP4 supported by</u>:
DLR
CIRA
Cranfield University
RTA
Rainbow Vision
AIIS
TUBS
UCF

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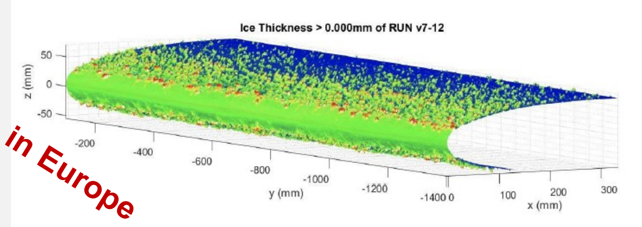
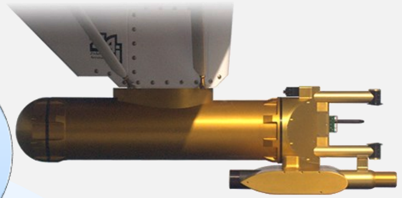
Icing Instrumentation - Objectives

Innovative in Europe



3D-Scanning System



CAPS-DPOL: Cloud, Aerosol, and Precipitation Spectrometer with Deploarization

Develop and select the most appropriate instrumentation for experiments in App. C/O icing conditions.

1 - Particle Size Distribution ✓

Determine MVD for droplet size spectra: 40 – 2500 µm

2 - Liquid Water Content ✓

Cover LWC range:

0.1 – 3 gm^{-3}

3 - Droplet Temperature ✓

Validation of supercooled droplets in the W/T test section

4 - Cloud Homogeneity ✓

Ensure cloud uniformity in the W/T test section

5 - Ice Shape ✓

Characterize surface roughness and ice density

Instrumentation to be calibrated and tested in SLD conditions @ CIRA, RTA, TUBS IWT

CU-IKP: Isokinetic Probe

GSI: Generalized Scattering Imaging

Innovative in Europe

GRT: Global Rainbow technique

Icing Instrumentation – Objectives & Challenges

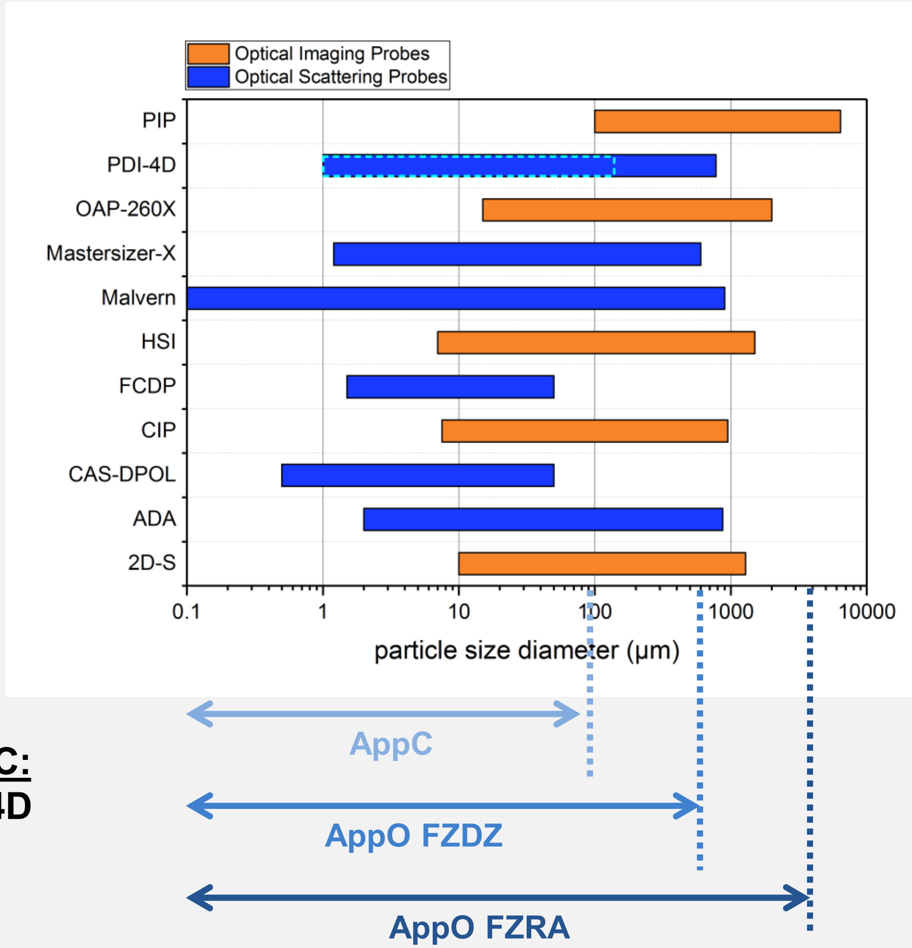
- **Select most appropriate instrumentation for W/T calibration in Appendix O icing conditions**
- **Instrument calibration / characterization in lab**
- **Wind tunnel testing by using reference instruments**

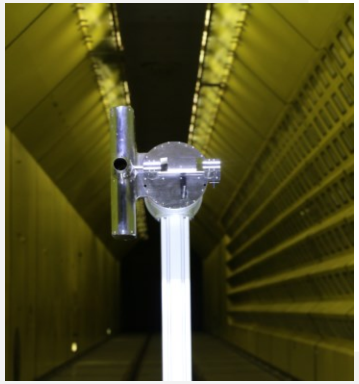
- **Main challenges**
  - Droplet size range to cover (1 µm up to ~3 mm)
  - Representation of bimodal particle size distribution
  - Resolution of «critical size range» 50 µm – 150 µm
  - Retention efficiency of the hot-wire elements (e.g. TWC) suffer for large droplets that may splash on impact
  - Improve understanding of correction methods for bulk LWC measurements (e.g. collision efficiencies)
  - Droplets' temperature reaching the supercool regime in the W/T test section
  - Optimization of 3D-scanning system to be used inside IWT

Instrumentation assessment and selection for PSD measurement (1)

- **<u>Combination of instruments</u> necessary to:**
  - Cover large droplet size range
  - Representation of bimodal size distribution
  - Improve covering critical size range 50 µm – 100 µm

- Instrument uncertainty for sizing and concentration of particles: about ±15% to ±20%

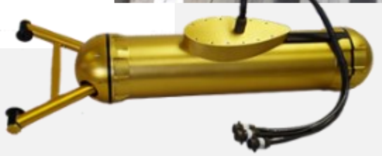




<u>FZDZ:</u> CAPS-DPOL

<u>FZDZ:</u> Malvern Spraytec

<u>App C:</u> PDI-4D



<u>FZRA:</u> PIP

PIP: *Precipitation Imaging Probe*
HSI: *High-Speed Imaging Probe*
2D-S: *2D-Stereo Probe*
CIP: *Cloud Imaging Probe*
CAS-DPOL: *Cloud and Aerosol Spectrometer with Deploarization*
PDI-4D: *Phase Doppler Interferometer with 4 Detectors*
ADA: *Airborne Droplet Analyser*
FCDP: *Fast Cloud Droplet Probe*

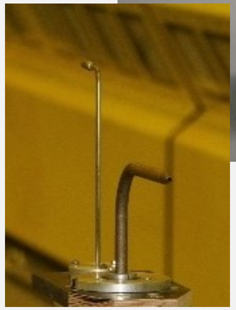
[1] *Lilie, L., et al.: A New 1D2D Optical Array Particle Imaging Probe for Airborne and Ground Simulation Cloud Measurements, SAE Tecnical Paper, https://doi.org/10.4271/2023-01-1415, 2023.*

Instrumentation assessment and selection for LWC measurement (2)

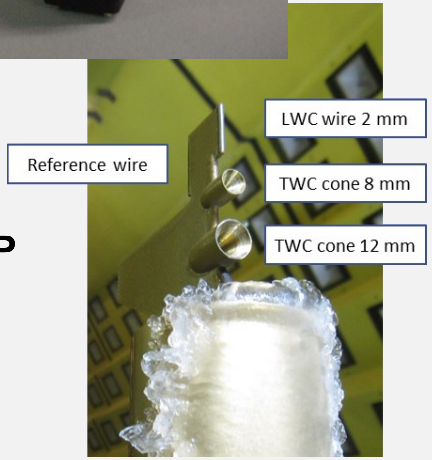
- **Selection of instruments – Recommendations**
  - **CIRA:** Multi-wire MW, Robust Probe
  - **RTA:** WCM-2000, Nevzorov Probe, Icing Blade (low wind speed), CU-IKP (App C)
- **Appendix C conditions:**
  - Agreement between instruments better than ±10% for Isokinetic Probe CU-IKP and multi-wire instruments WCM-2000, Nevzorov Probe and Robust Probe (tests at RTA, CIRA, NRC-AIWT)
- **Appendix O FZDZ conditions:**
  - Deviation of individual instruments from a multi-instrument mean less than 25%
- Instrument uncertainty: about ±10% to ±15%

App C: **Robust Probe**

App C, App O: **WCM-2000**



App C: **CU-IKP**



App C, App O:
Nevzorov 2 cup

[1] *Lucke, J., et al.: Icing wind tunnel measurements of supercooled large droplets using the 12 mm total water content cone of the Nevzorov probe, Atmos. Meas. Tech., 15, 7375–7394, https://doi.org/10.5194/amt-15-7375-2022, 2022.*
[2] *Esposito, B., et al.: Comparability of Hot-Wire Estimates of Liquid Water Content in SLD Conditions, SAE Technical Paper, 2023, https://doi.org/10.4271/2023-01-1423, 2023.*

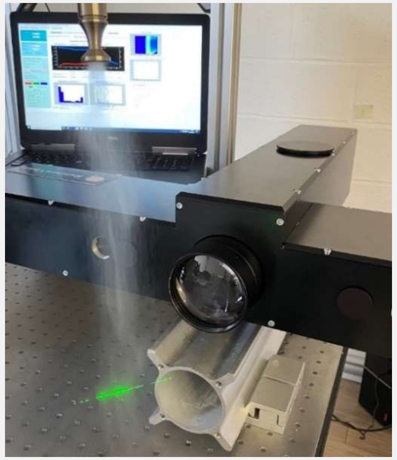
CU-IKP: *Cranfield University – Isokinetic Probe*
WCM-2000: *Multi-Element Water Content System*

Instrumentation for droplet temperature measurement (3)

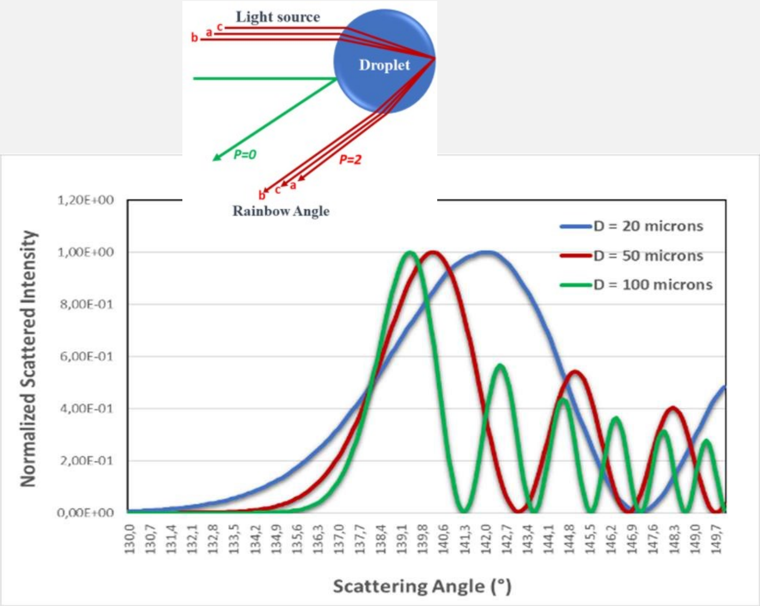
Innovative in Europe

- **Global Rainbow technique (GRT) for measurement of droplet temperature**

- **Challenge:**
  - Development of GRT technique for small and large droplets (bimodal distribution)
  - Different model types for use in several wind tunnel dimensions
  - Validation of supercooled status of the droplets in wind tunnel test sections, definition of uncertainties



GRT-XL (used outside small IWT) in the lab



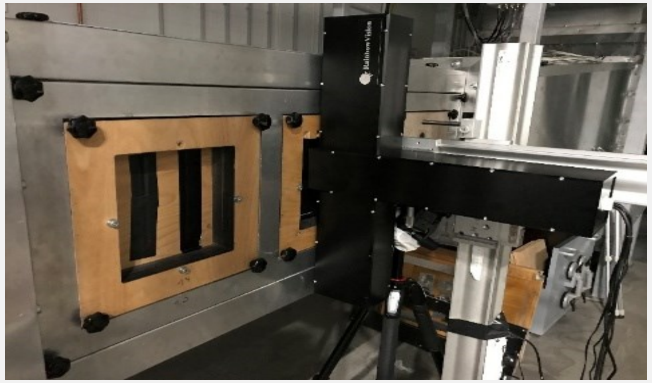
- Rainbow angular location of a certain wavelength: function of the refractive index → function of the **droplet temperature**
- Evaluation of light scattered around the rainbow angle (~138°, for water) enables a measurement of the droplet temperature
- Shape of the light scattered around the rainbow angle depends on the **droplet size**

[1] *Droplet Temperature Measurements for Efficient Combustors and Icing Safety, Sawitree Saengkaew & Gerard Grehan (rainbowVision), SAE International Conference (AeroTech Europe), September 2020, Bordeaux.*
[2] *Supercooled Large Droplets Temperature Measurements by Global Rainbow Technique, Sawitree Saengkaew & Gerard Grehan (rainbowVision), 20th Annual Conference on Liquid Atomization and Spray Systems, December 2020, Ubé, Japan.*

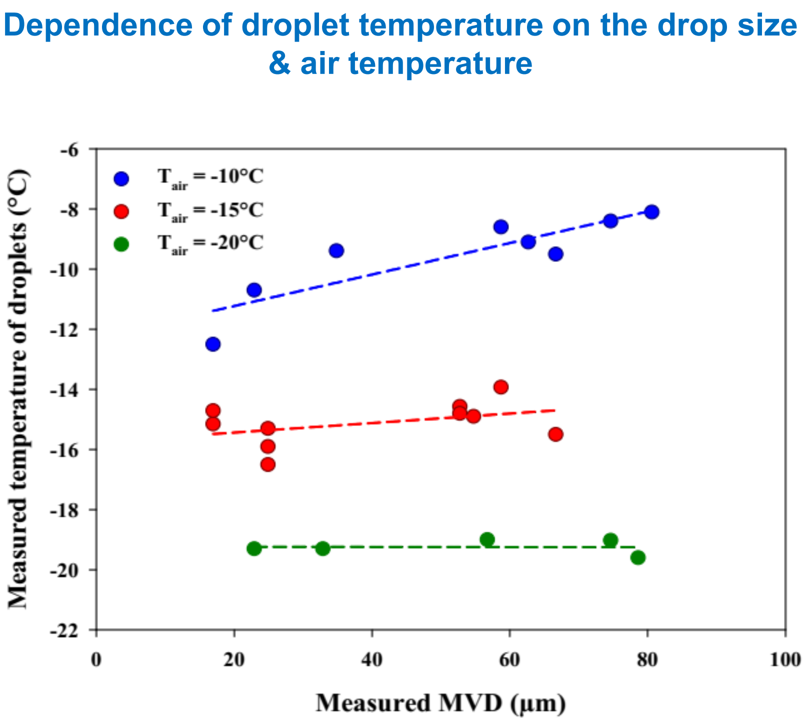
Instrumentation for droplet temperature measurement (3)

- **GRT in small wind tunnel (TUBS)**

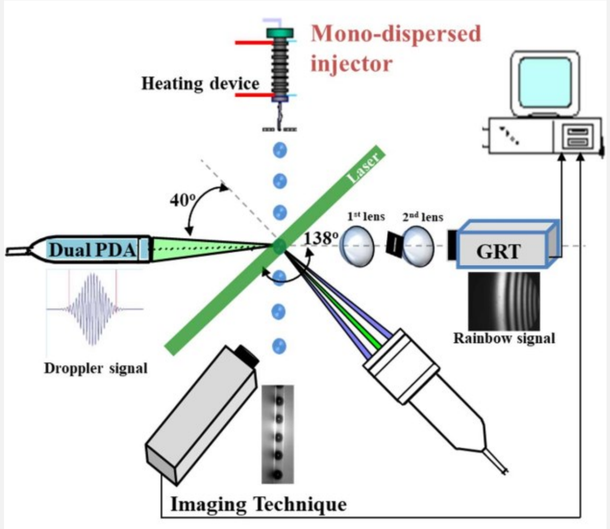
- Accuracy of temperature measurement:
  - About 1°C in the lab
  - About 2-3°C in challenging IWT conditions



GRT measurement in TUBS's IWT



Accuracy determination of GRT (development of RainbowVision)



Instrumentation for droplet temperature measurement (3)

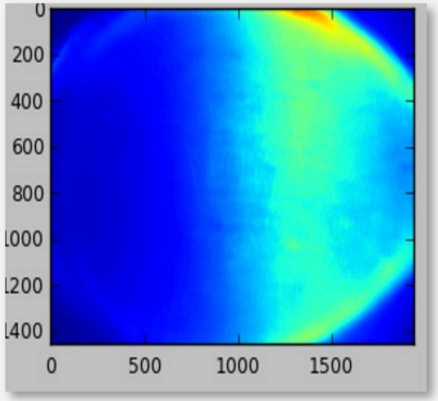
GRT in large wind tunnel (RTA) for SLD conditions

- Measurement of droplet sizes by GRT has been proven up to 500 µm

Before

After

Example of validated signal

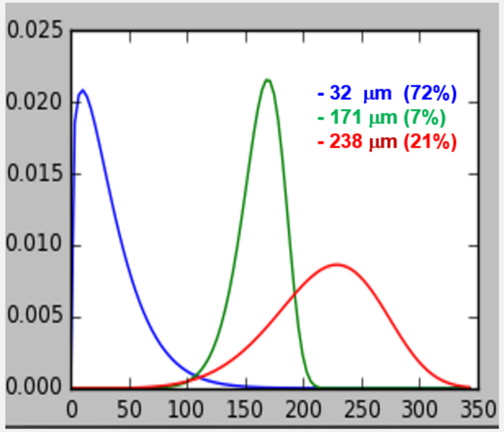


Signal Processing

Measurement results

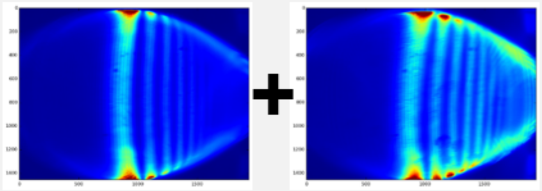
Droplets temperature = - 4,1°C

Droplets size distribution

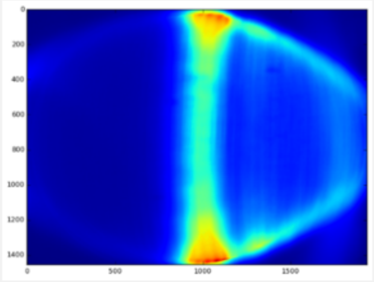


GRT in large wind tunnel (CIRA) for SLD conditions

- SLD size obtained directly from individual GRT images

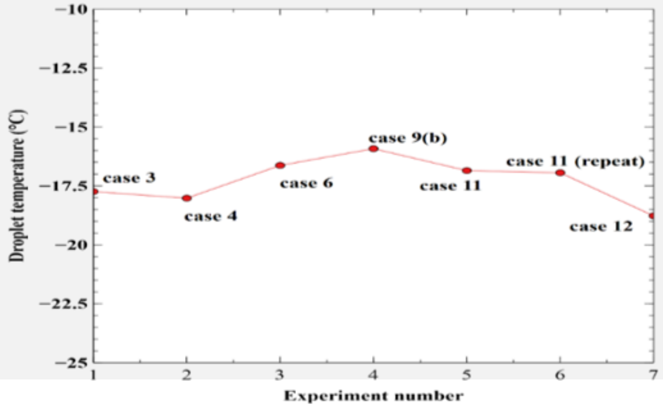


Summation of indiviual rainbow



Signal Processing

Droplet temperature measurement by global rainbow

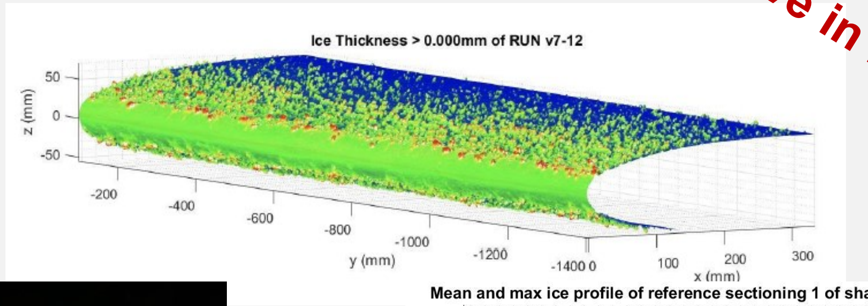


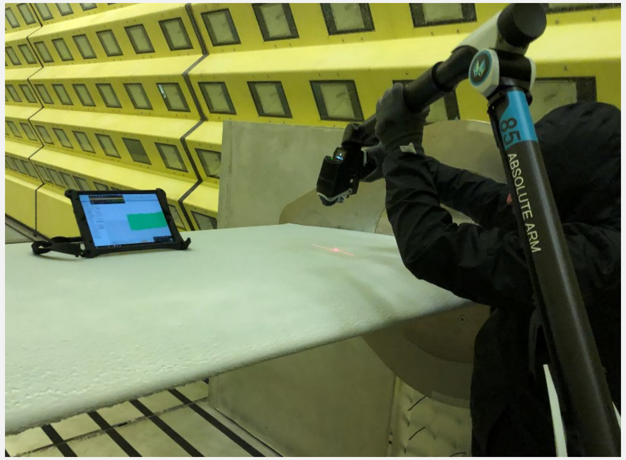
Instrumentation for 3D-scanning of ice shapes (5)

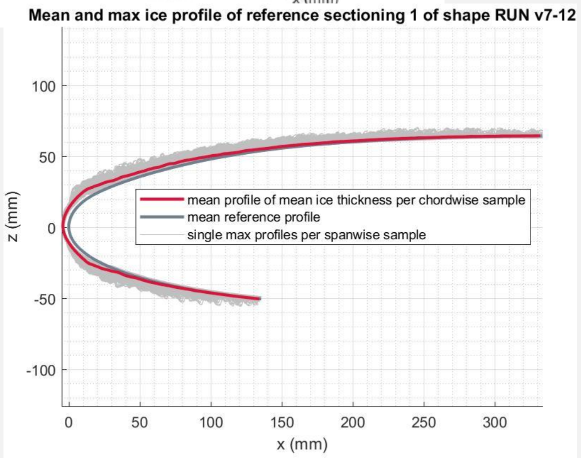
Innovative in Europe

- **Development of mobile 3D-scanning system**
- **Development of evaluation tool**

- **Challenge:**
  - Optimization of 3D-scanning system to be used inside IWT
  - Post-processing tool for 2D and 3D scans





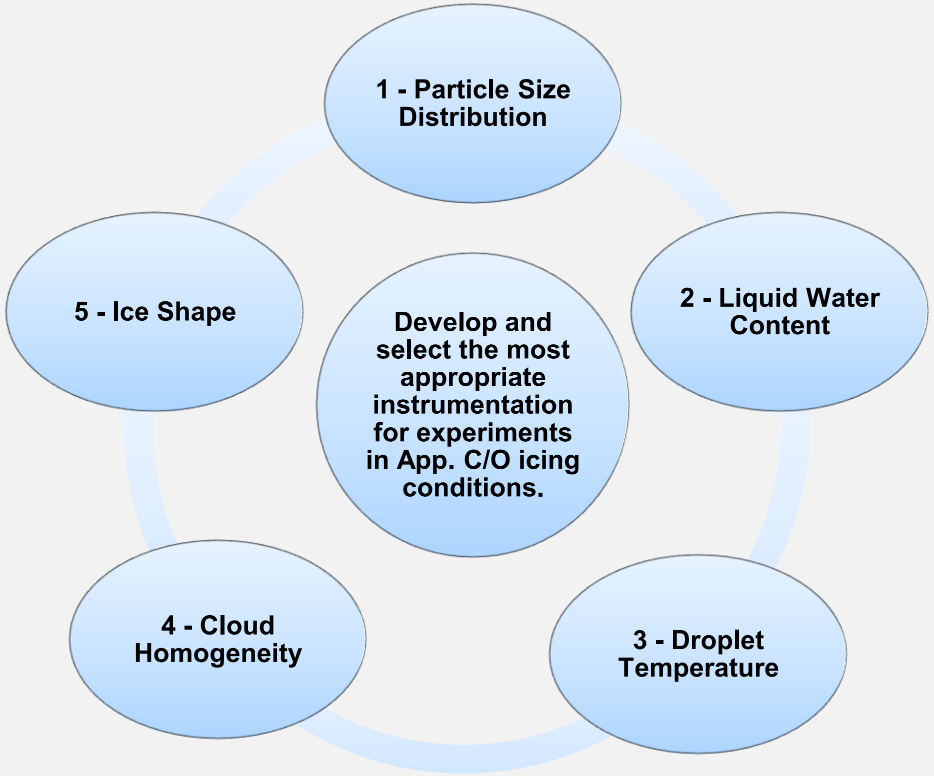


[1]Neubauer, T., Kozomara, D., Puffing, R.F.A., Hassler, W., *"Validation of Ice Roughness Analysis Based on 3D-Scanning and Self-Organizing Maps," SAE Technical Paper, presented at the SAE International Conference, 2019.*
[2]Neubauer, T., Hassler, W., and Puffing, R., *"Ice Shape Roughness Assessment Based on a Three-Dimensional Self-Organizing Map Approach," presented at the AIAA AVIATION Forum, 5-19 June, 2020.*
[3]Neubauer, T., and Puffing, R., *"Assessment of Ice Shape Roughness via Automatic Spacing of Codebook Vectors in a Two-Dimensional Self-Organizing Map," presented at the AIAA AVIATION Forum, 5-19 June, 2020.*
[4]Kozomara, D., Neubauer, T., Puffing, R., Bednar, I., and Breitfuss, W., *„Experimental Investigation on the Effects of Icing on Multicopter UAS Operation ", AIAA AVIATION FORUM 2021, DOI: https://doi.org/10.2514/6.2021-2676.*

Icing Instrumentation - Open Questions

- **Very good progress to select appropriate instrumentation for experiments in SLD conditions was made within ICE GENESIS**
- **Further effort to provide additional measurements and involve more W/T**

- <u>FZDZ / FZRA: </u>Enhance data statistics for various different conditions to improve the envelope for icing instrumentation
- <u>FZRA:</u> Enhance W/T cloud drop range in various conditions: low LWC, low droplet number concentration, large droplet sizes
- <u>PSD:</u> Further improve data processing for PSD probes → out-of-focus correction
- <u>LWC:</u> Improve understanding of uncertainty for bi-modal PSD with very large droplets (hot wire probes)
- <u>Droplet Temperature:</u> Further validation of GRT (e.g. Accuracy of temperature, measurement from large droplets at different IWT temperatures and under high windspeeds)
- Update of requirements for instrument uncertainty (MVD, LWC)



SLD calibration methodology in use in icing wind tunnels (WP6)

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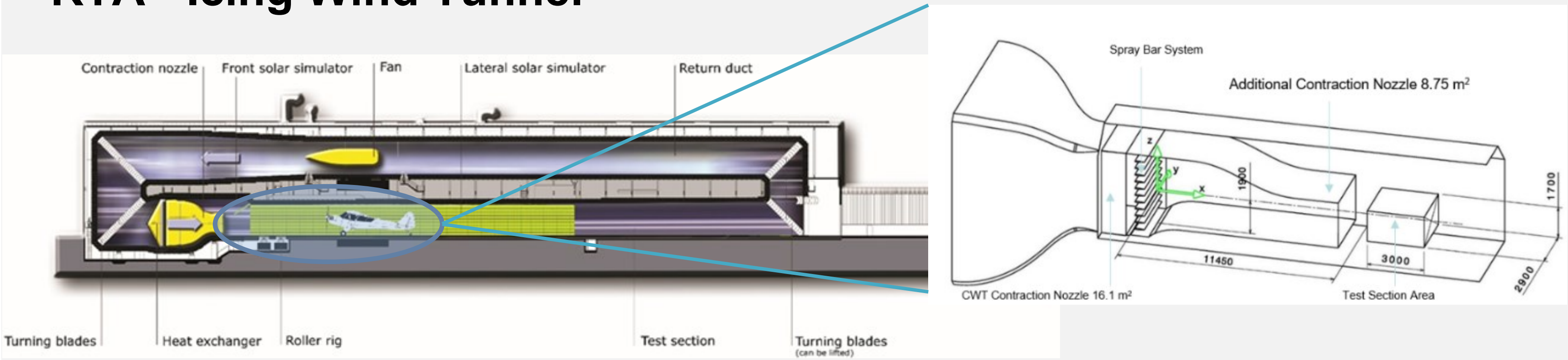
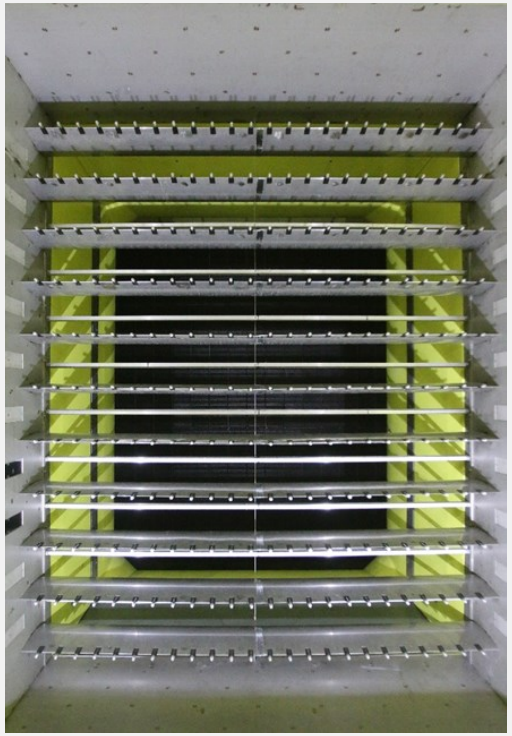
Cloud generation methods and implications on the SLD calibration…

RTA - Icing Wind Tunnel

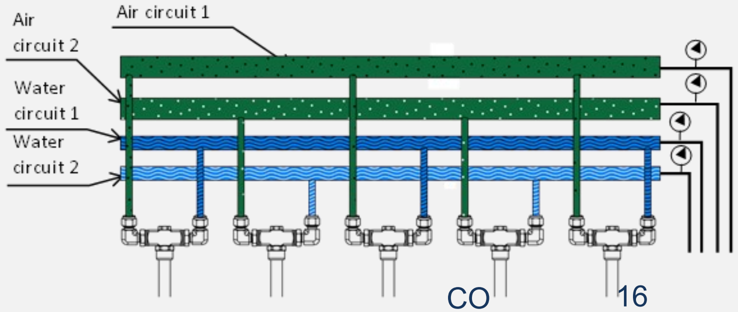




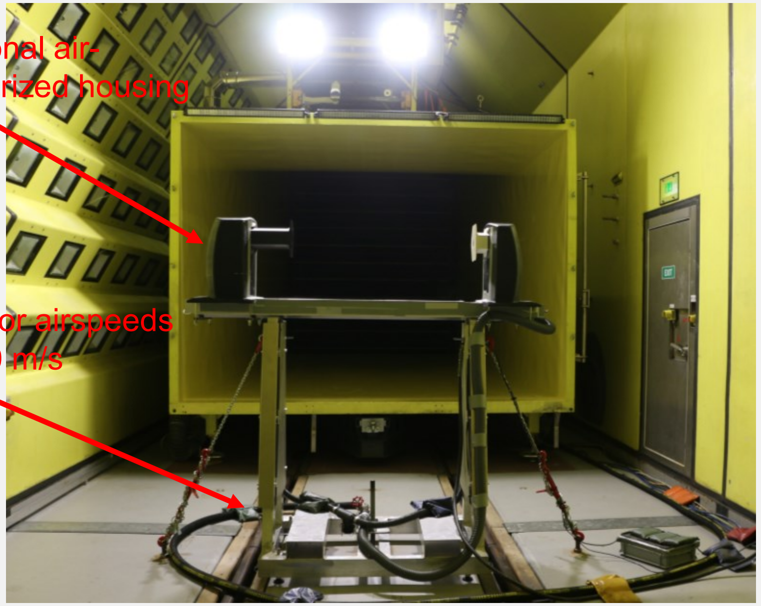
Test section	Size H (m) x W (m) x L (m)	Airspeed (m/s)	SAT (°C)	Altitude (m)
Reduced cross section	3.5 x 2.5 x 90.0 (1.7 x 2.9 x 3.0)	20 to 80	-2°C to -30°C.	sea level

Spray bar process to generate SLD:

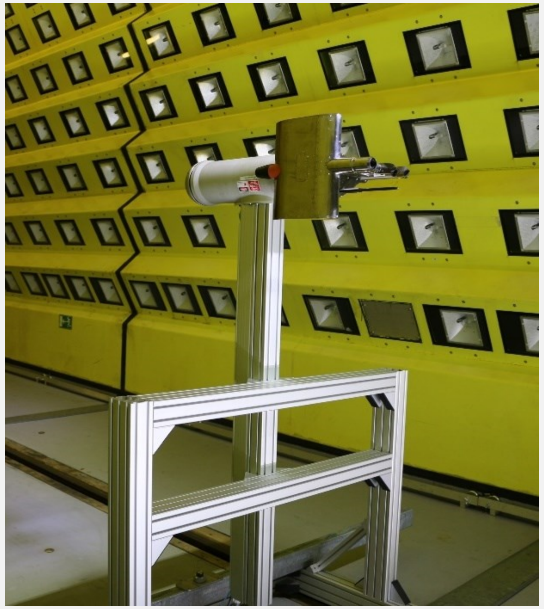
- 264 Nozzles on 11 Spray bars
- Eleven spray bars with 24 spray nozzles, each one alternatively connected into two separate water/air controllable circuits.
- Each circuit has independent control of air/water pressure and temperature to generate bimodal PSD with droplets at a suitable water temperature and closer to the air temperature (SAT).
- up to 30 rotating for FZRA to improve uniformity (4 spray bars)



RTA - PSD centreline measurements for EASA CS-25/29 Appendix C and Appendix O



Malvern Spraytec installed in the RTA IWT

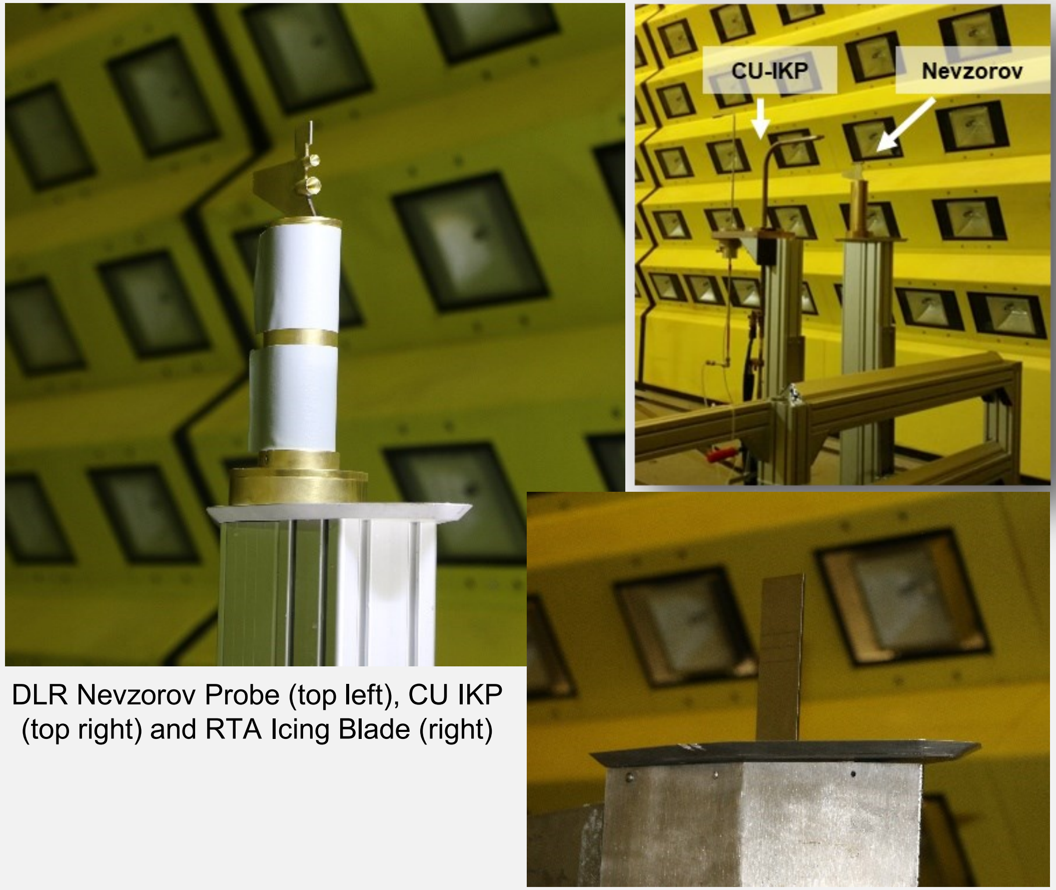

DLR CAPS probe in the RTA IWT

- **FZDZ MVD < 40 µm**
  - **Malvern Spraytec** measurements outside of ICE-GENESIS
  - **CAPS** supported by DLR
- **FZDZ MVD > 40 µm**
  - **Malvern Spraytec** measurements outside of ICE-GENESIS (2016)
  - **FCDP/2D-S** measurements supported by DLR
  - **CAPS** measurements supported by DLR
- **FZRA MVD > 40 µm**
  - **Malvern Spraytec**
  - **FCDP/2D-S**
  - **PIP**
- **FZRA MVD < 40 µm not assessed**

Cloud generation methods and implications on the SLD calibration…

RTA - LWC centreline measurements for EASA CS-25/29 Appendix C and Appendix O

- **FZDZ MVD < 40 µm**
  - **Icing Blade** and **waterflow per spray bar circuit**
  - LWC derived from **CAPS** measurements (DLR)
- **FZDZ MVD > 40 µm**
  - 4 spray nozzle settings have been analysed in detail
  - Measurement data from **Icing Blade, WCM-2000, CU IKP** and **waterflow investigations**
  - **Nevzorov Probe** measurements were supported by DLR
  - LWC derived from **CAPS** measurements (DLR)
- **FZRA MVD > 40 µm**
  - LWC calibration (**IKP, Nevzorov Probe**)
  - LWC uniformity (**Ice Accretion Grid / NACA0012**)
- **FZRA MVD < 40 µm not assessed**



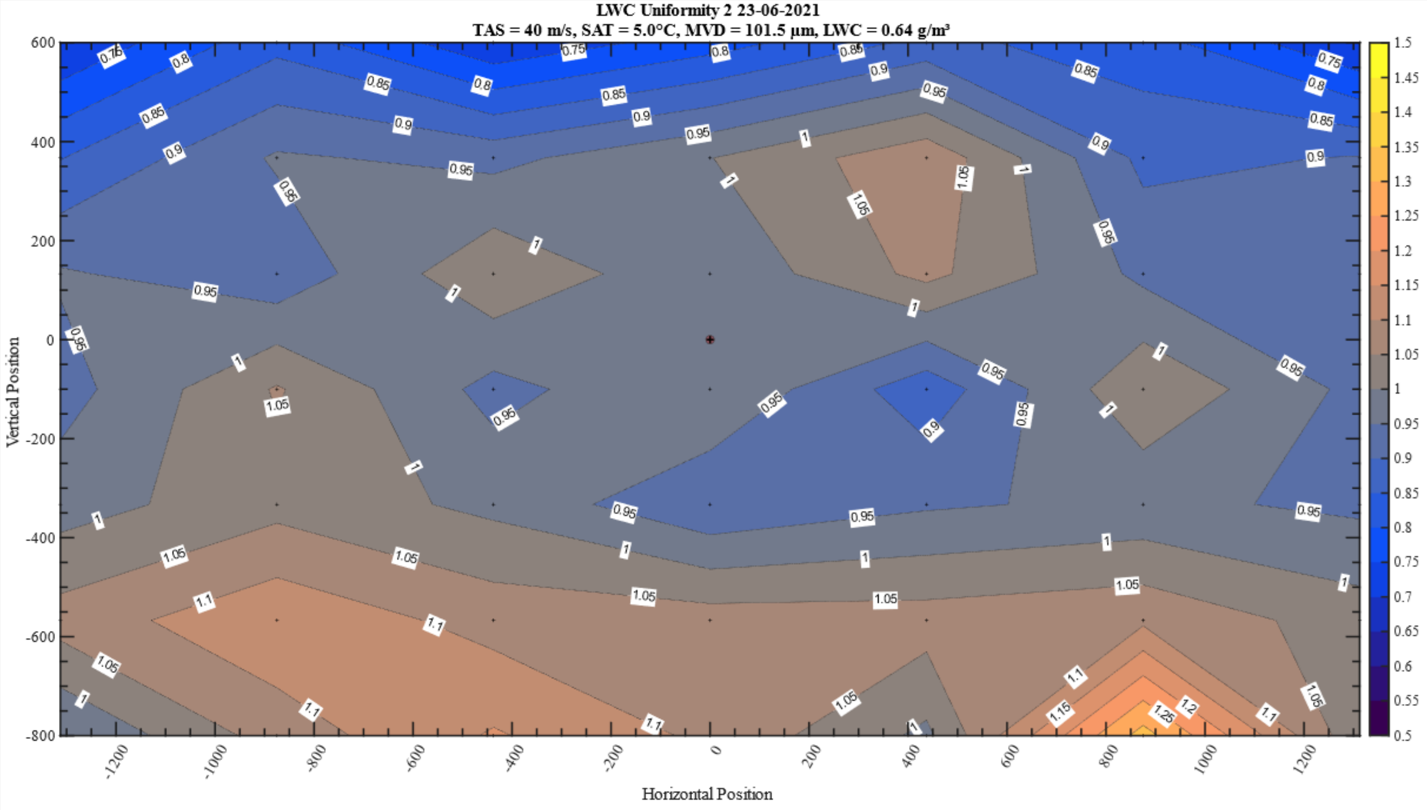
DLR Nevzorov Probe (top left), CU IKP (top right) and RTA Icing Blade (right)

Cloud generation methods and implications on the SLD calibration…

RTA – Cloud uniformity for EASA CS-25/29 Appendix C and Appendix O

- **LWC uniformity comparison measurements for FZDZ MVD < 40 µm and MVD > 40 µm**
  - **Nevzorov Probe** supported by DLR (as WCM-2000 was not available)
  - **Ice Accretion Grid** measurements (available from previous research work)
- **PSD uniformity measurements for FZDZ MVD > 40 µm**
  - **CAPS** probe supported by DLR

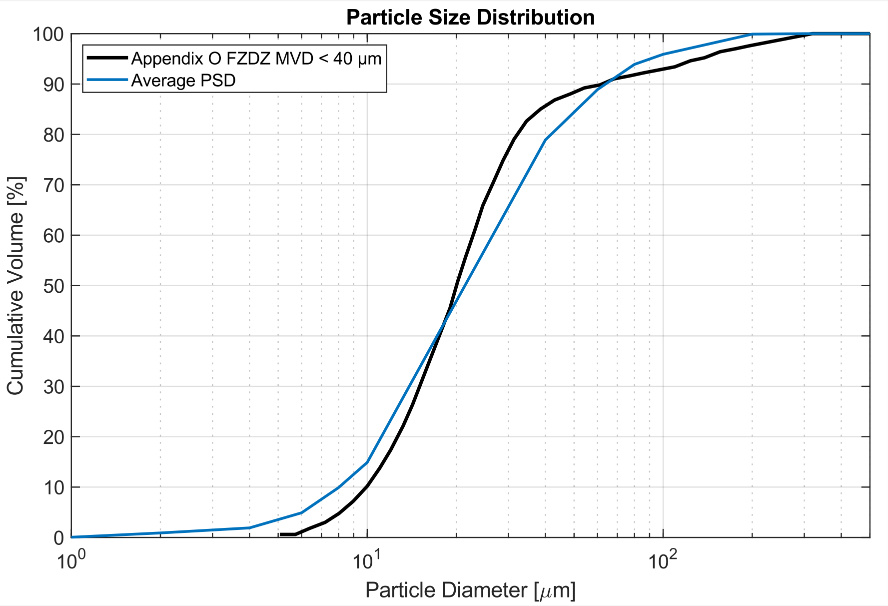
DLR CAPS probe (left) and DLR Nevzorov Probe (right) mounted on traversing system in the RTA IWT

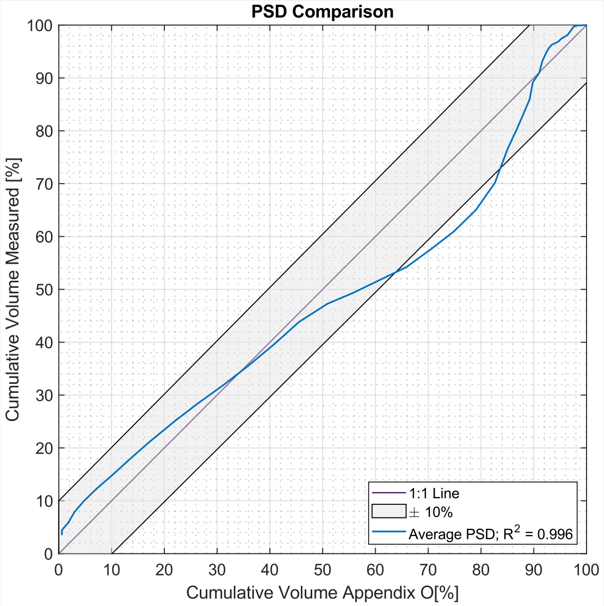


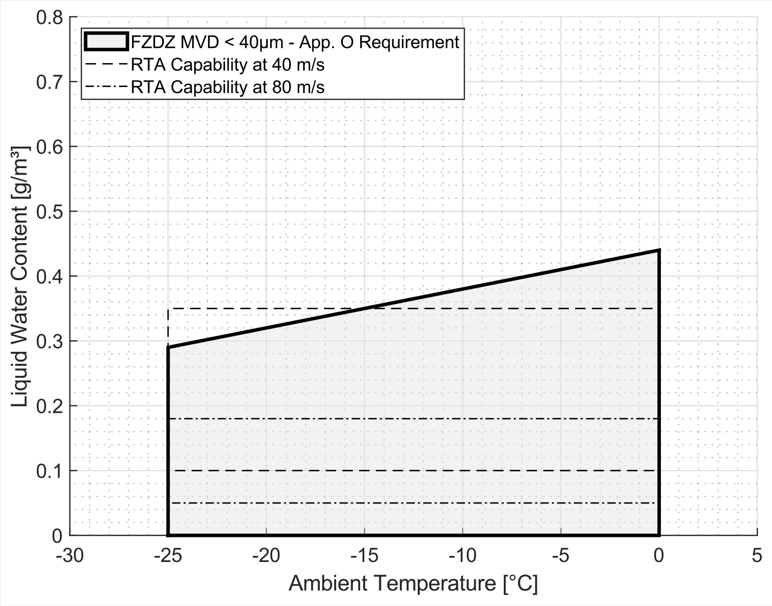
Cloud generation methods and implications on the SLD calibration…

RTA - Icing Wind Tunnel - MVD/PSD calibration

- **<u>FZDZ MVD ≤ 40 µm (MVD: 18 – 26 µm @ LWC: 0,05 – 0,35 g m^{-3})</u>**
  - <u>MVD calibration</u>: the standard calibration curve provide good approximation of the measured MVD.
  - <u>PSD calibration</u>: a separate calibration curve was generated to estimate the PSD. The curve describes the average PSDs from all measurements and can be scaled with the calibrated MVD.
  - The calibration curve can predict the cumulative volume with an accuracy of ±10%





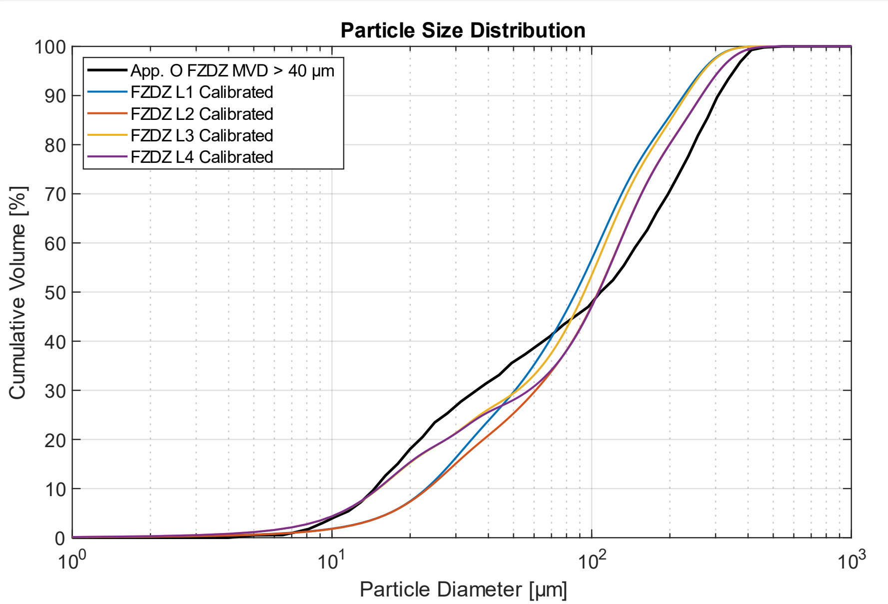


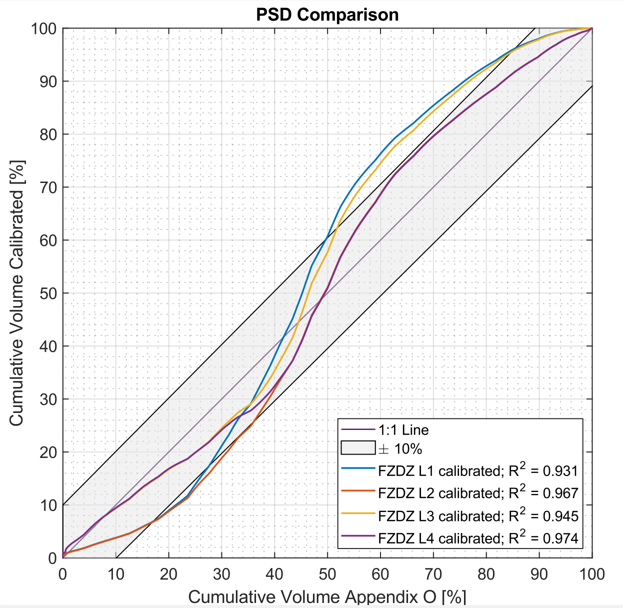
18 µm < MVD < 26 µm - 0,05 g m-3 < LWC < 0,35 (depending on airspeed and MVD)

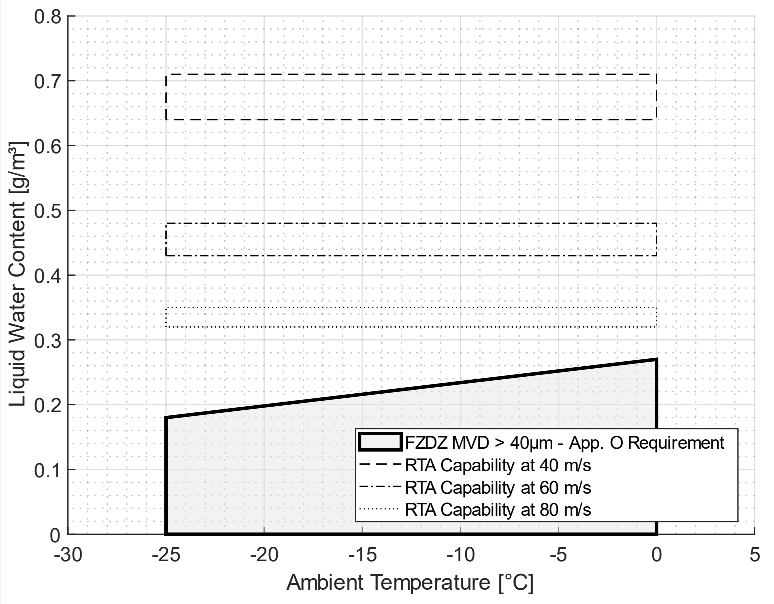
Cloud generation methods and implications on the SLD calibration…

RTA - Icing Wind Tunnel - MVD/PSD calibration

- **FZDZ MVD > 40 µm (MVD: 85 – 105 µm @ LWC: 0,32 – 0,71 g m^{-3} depending on airspeed)**
  - MVD calibration: for the small Mode the standard Appendix C calibration curve is used; for the large Mode, separate calibration curve was created by fitting measurement data from different instruments (Malvern, FCDP/2D-S and CAPS). For combined MVD, the LWC ratio calculated by the LWC calibration curves is used.
  - PSD calibration: “is based on Langmuir distributions (“E” for small mode and “F” for large mode), which are generated with the MVDs of the corresponding MVD calibrations for the small and the large mode and corrected with a scaling factor in order to better match the combined calibrated MVDs.”







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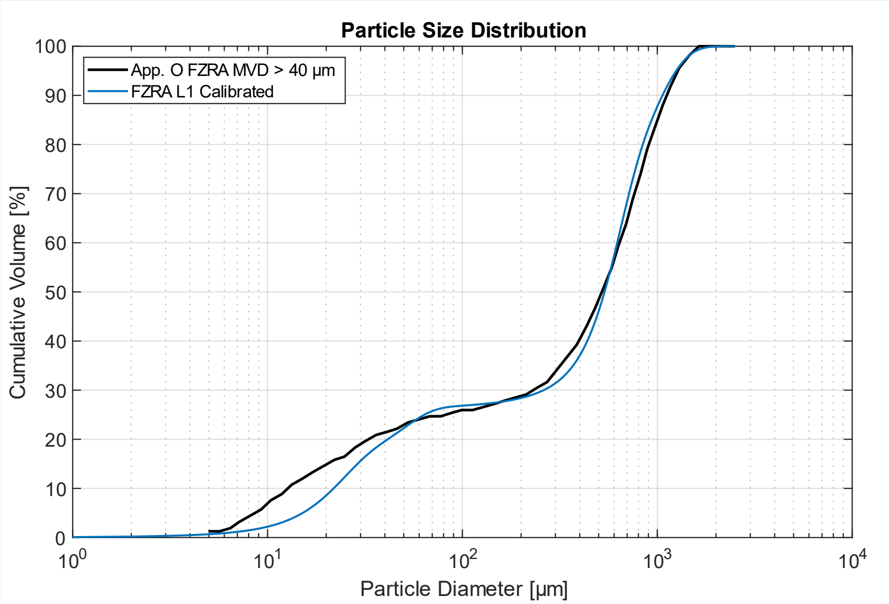
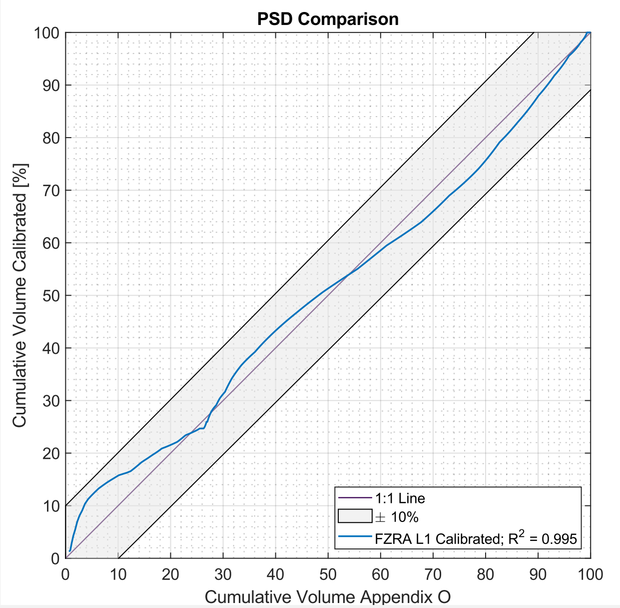
85 µm < MVD < 105 µm - 0,32 g m-3 < LWC < 0,71 (depending on airspeed and MVD)

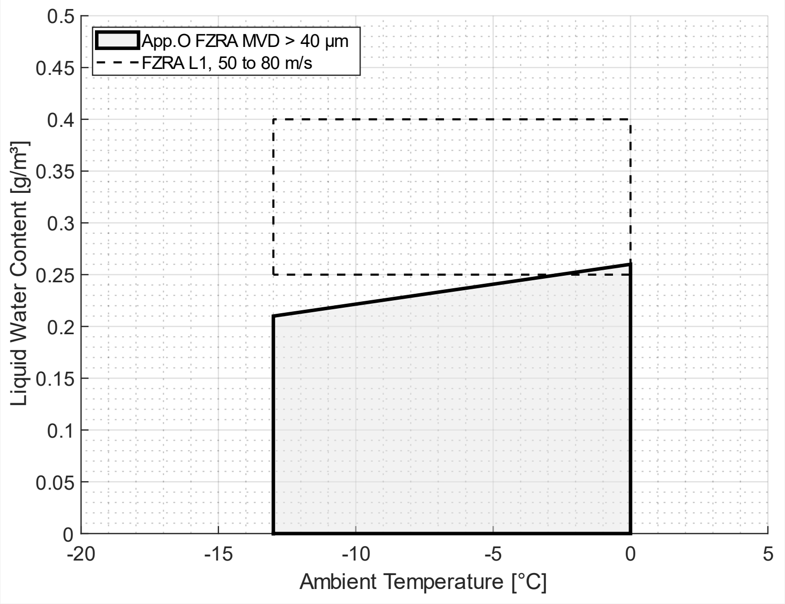
Cloud generation methods and implications on the SLD calibration…

RTA - Icing Wind Tunnel - MVD/PSD calibration

- **FZRA MVD > 40 µm (MVD: 535 µm @ LWC: 0,25 – 0,4 g m^{-3} depending on airspeed)**
  - MVD calibration: for the small Mode the standard Appendix C calibration curve is used; for the large Mode, separate calibration curve was created by fitting measurement data from different instruments (Malvern Spraytec and Malvern Insitec). For combined MVD, the LWC ratio calculated by the LWC calibration curves is used.
  - PSD calibration: “is based on Langmuir distributions (“F” for small mode and “D” for large mode), which are generated with the MVDs of the corresponding MVD calibrations for the small and the large mode and corrected with a scaling factor in order to better match the combined calibrated MVDs.”



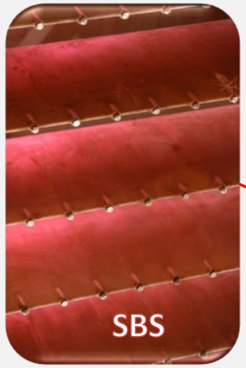


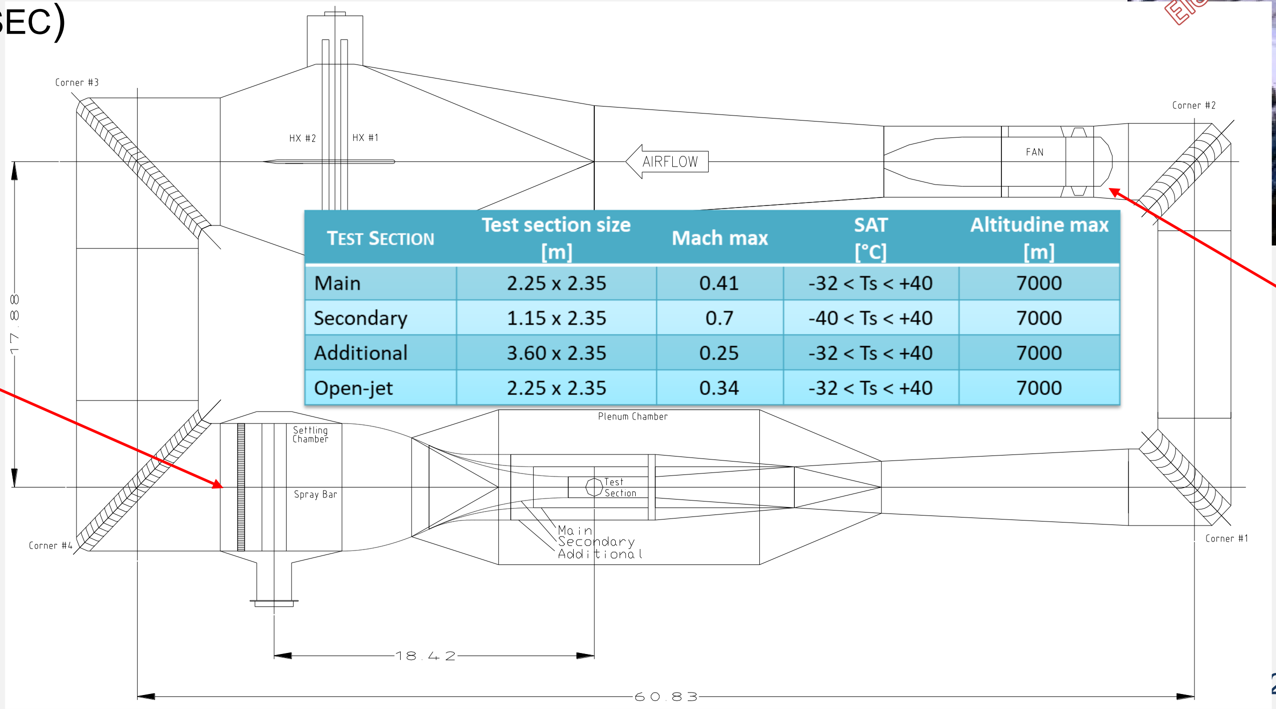


MVD = 535 µm - 0,25 g m-3 < LWC < 0,4 (depending on airspeed)

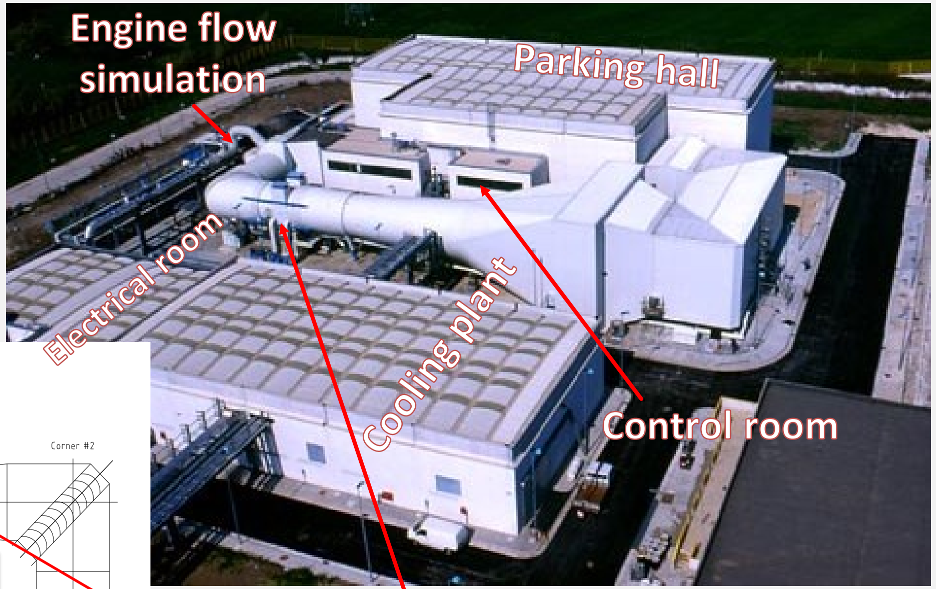
CIRA - Icing Wind Tunnel

- 20 STAINLESS STEEL BARS WITH 50 NOZZLES LOCATIONS FOR EACH BAR, MAX 500 ACTIVE NOZZLES
- ON/OFF SOLENOID VALVE AT EACH SPRAYING LOCATION
- AIR AND WATER PRESSURE CONTROL IN EACH BAR
- FAST SWITCHING BETWEEN MCI AND IMI CONDITION (NO LONGER THAN 10 SEC)



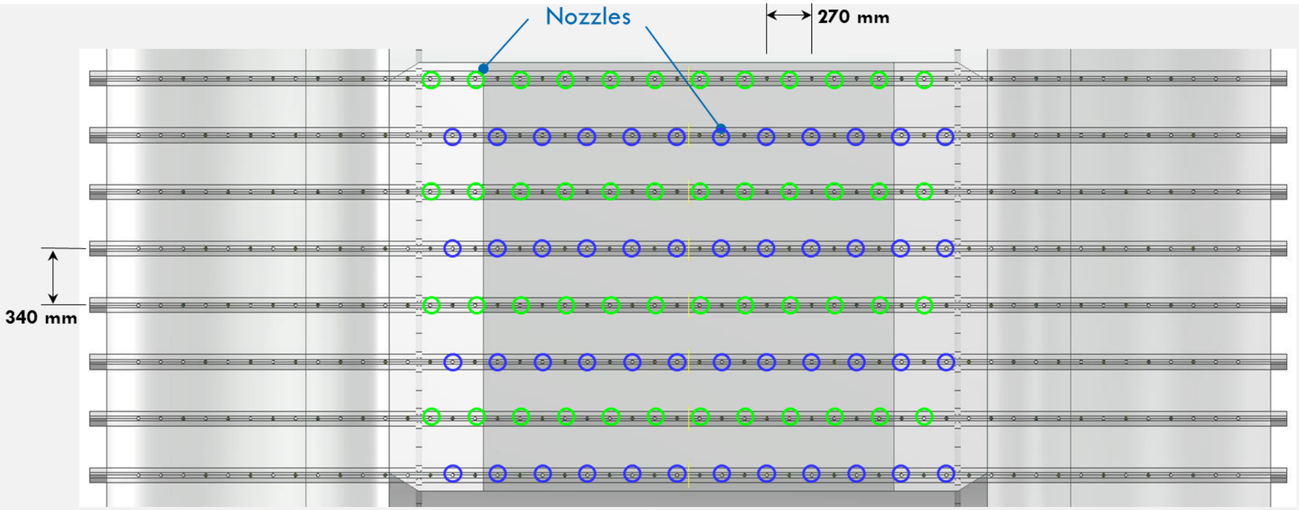


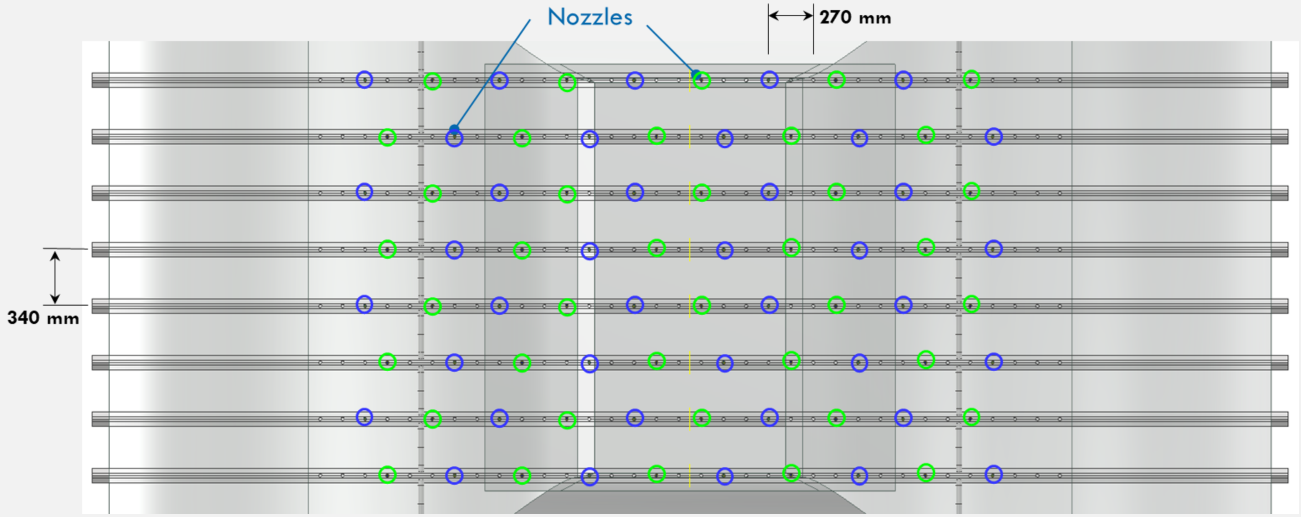
TEST SECTION	Test section size [m]	Mach max	SAT [°C]	Altitudine max [m]
Main	2.25 x 2.35	0.41	-32 < Ts < +40	7000
Secondary	1.15 x 2.35	0.7	-40 < Ts < +40	7000
Additional	3.60 x 2.35	0.25	-32 < Ts < +40	7000
Open-jet	2.25 x 2.35	0.34	-32 < Ts < +40	7000



24 blades, variable pitch, 750 rpm fan unit

Cloud generation methods and implications on the SLD calibration…





<u>Three</u> sets of spray nozzle set-ups are availably to cover wide range of Appendix C and Appendix O requirements

- **1A2_SLD#5 SB grid configuration**
  - For upper part of LWC envelope with medium high MVD
    - 13 active spray
    - up to 195 active nozzles (15 per bar, alternating each spray nozzle setup in odd and even bar)
    - bi-modal PSD, with the mass distribution ctrl. option

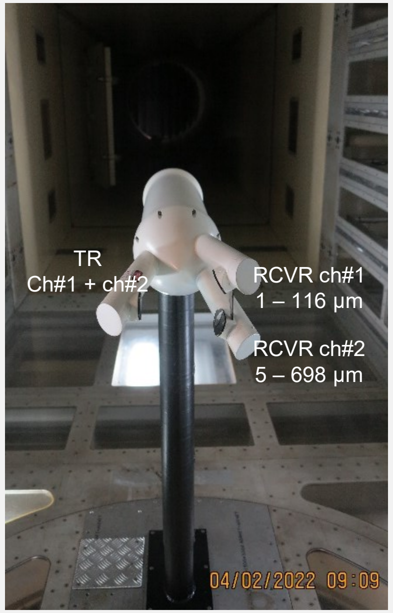
- **1A3_SLD#6 SB grid configuration**
  - For lower part of LWC envelop with high MVD
    - 13 active spray bars
    - up to 130 active nozzles, with two types of spray nozzles alternating in each bar.
    - bi-modal PSD without the mass distribution ctrl. option

CO

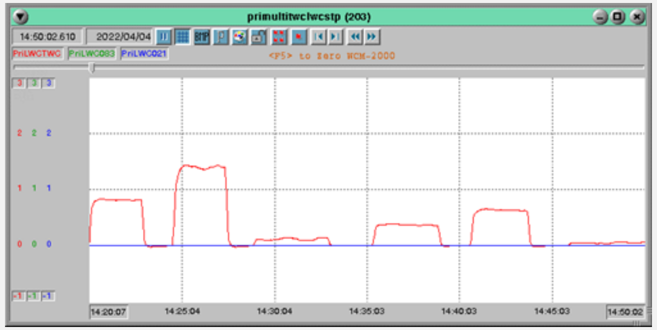
Instrumentation and data processing

PSD/MVD and LWC centerline measurements

- Up to 109 test points were collected by CCP supported by DLR and 126 by PDI-4D for conditions generated by four SB configurations.
- Two airspeeds (60 and 110 m/s), four pressure altitude (0m, 1524m, and 6096m) , and three SAT (-8C, -6C, -2C).



DLR CCP (left) and CIRA PDI-4D (right) were installed in the main test section configuration of the CIRA-IWT.



Hot-wire centerline LWC measurements

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Robust probe (RP):

- 97 test points were collected for conditions generated by four SB conf.
- Two airspeeds (60 and 110 m/s), four pressure altitudes (0m, 1524m, and 6096m) , and three SAT (-8C, -18C, -25C)

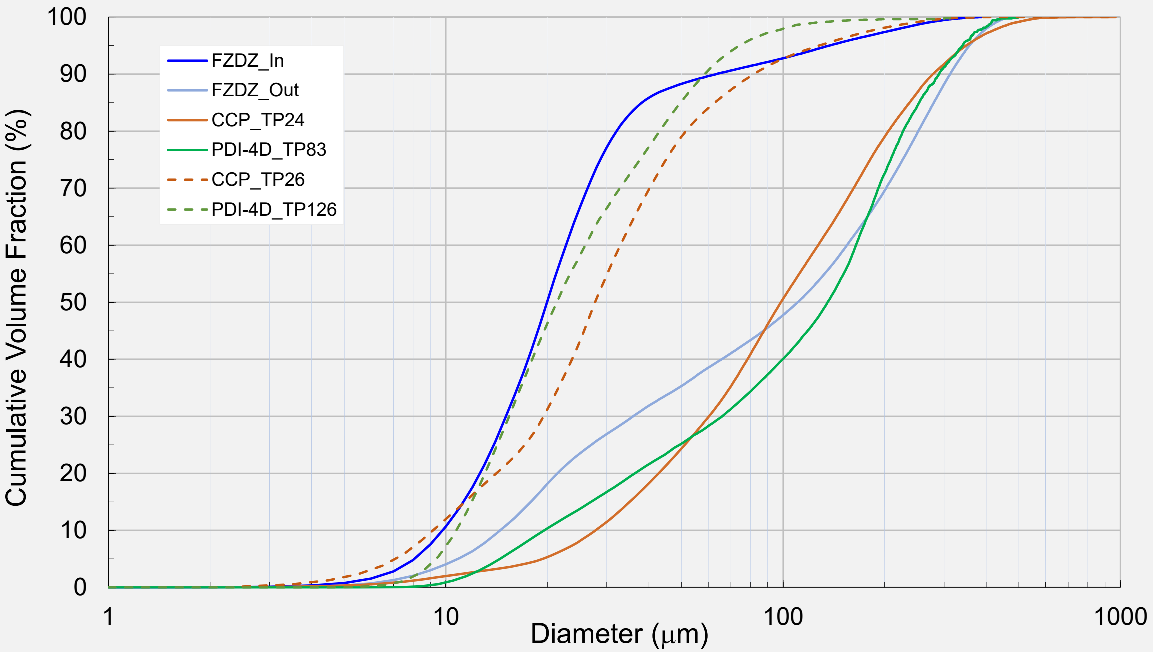
Multi-Wire (MW):

- 70 test points were collected for conditions generated by two SB conf.
- Two airspeeds (60 and 110 m/s), four pressure altitudes (0m, 1524m, and 5000m) , and two SAT (-8C, -12C)

Cloud generation methods and implications on the SLD calibration…

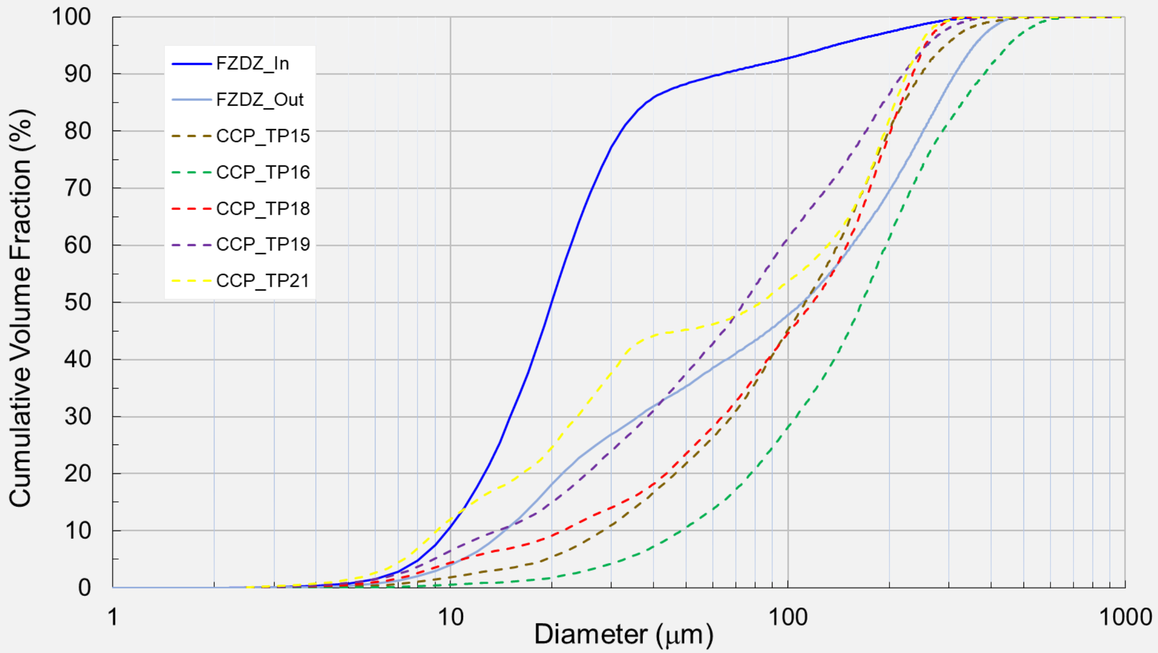
CIRA - Icing Wind Tunnel – FZDZ calibration for MTS configuration

- Spray bar grid configuration 1A2_SLD#2
- Pressure altitude at sea-level
- Airspeed at 110 m/s



Probe_TP_Id	MVD (um)	LWC (g m-3)
PDI-4D #83	136,4	0,1
PDI-4D #126	21,3	0,05
CCP #26	28	0,54
CCP #21	99,3	0,6

- Spray bar grid configuration 1A2_SLD#3
- Pressure altitude at sea-level
- Airspeed at 110 m/s



Probe_TP_Id	MVD (um)	LWC (g m-3)
CCP #15	113	0,53
CCP #16	163	0,36
CCP #48	119	0,05
CCP #19	74,8	0,44
CCP #21	82	0,05

Cloud generation methods and implications on the SLD calibration…

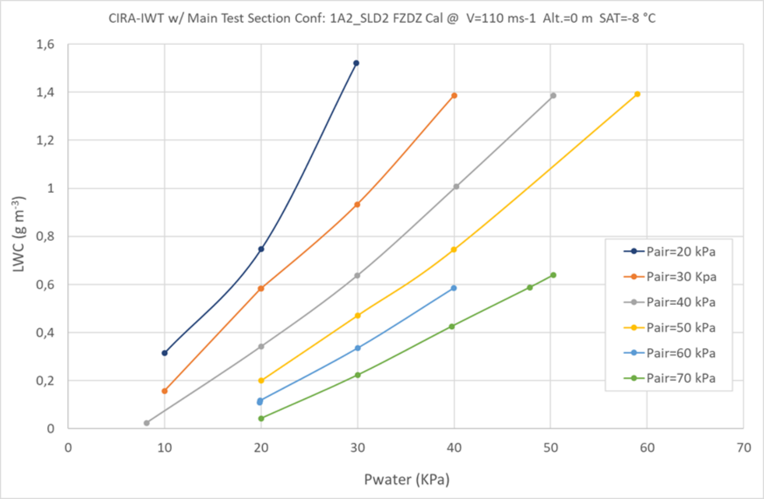
CIRA - Icing Wind Tunnel – FZDZ calibration for MTS configuration

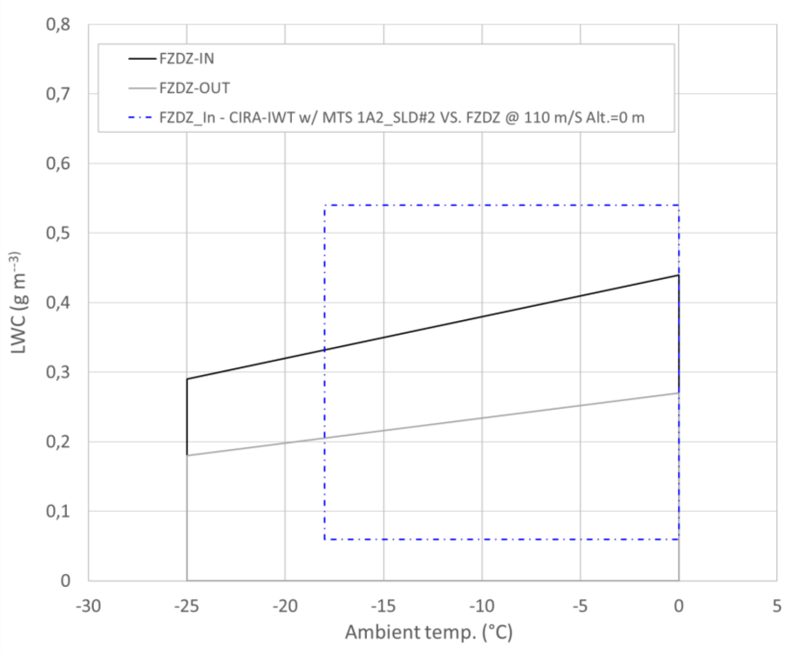
FZDZ_In MVD>40 µm / FZDZ_Out (1A2_SLD#2)

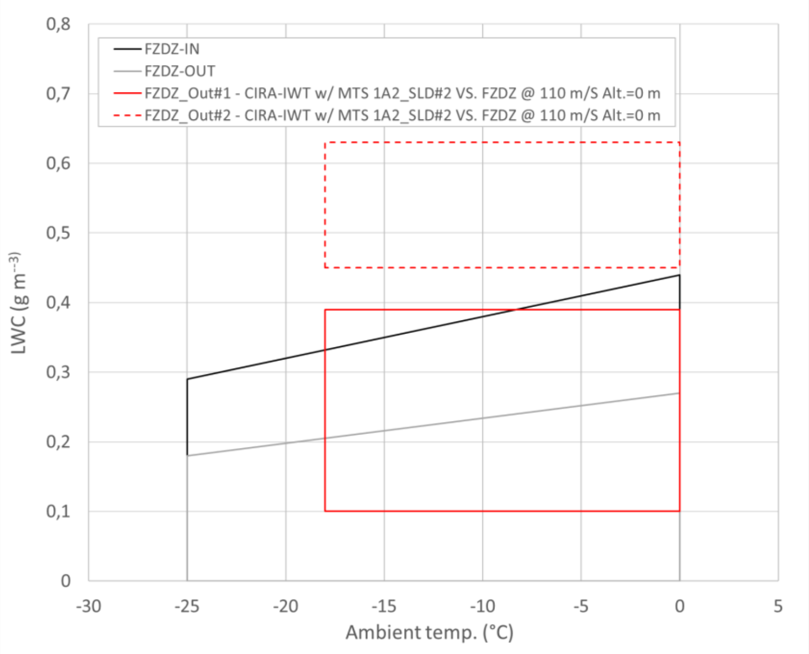
- 17 µm < MVD < 32 µm - 0,06 g m-3 < LWC < 0,54 gm-3 - 200 µm < Dmax < 500 µm

FZDZ_In / FZDZ_Out (1A2_SLD#2)

- 57 µm < MVD < 147 µm - 0,1 g m-3 < LWC < 0,63 gm-3 - 400 µm < Dmax < 800 µm



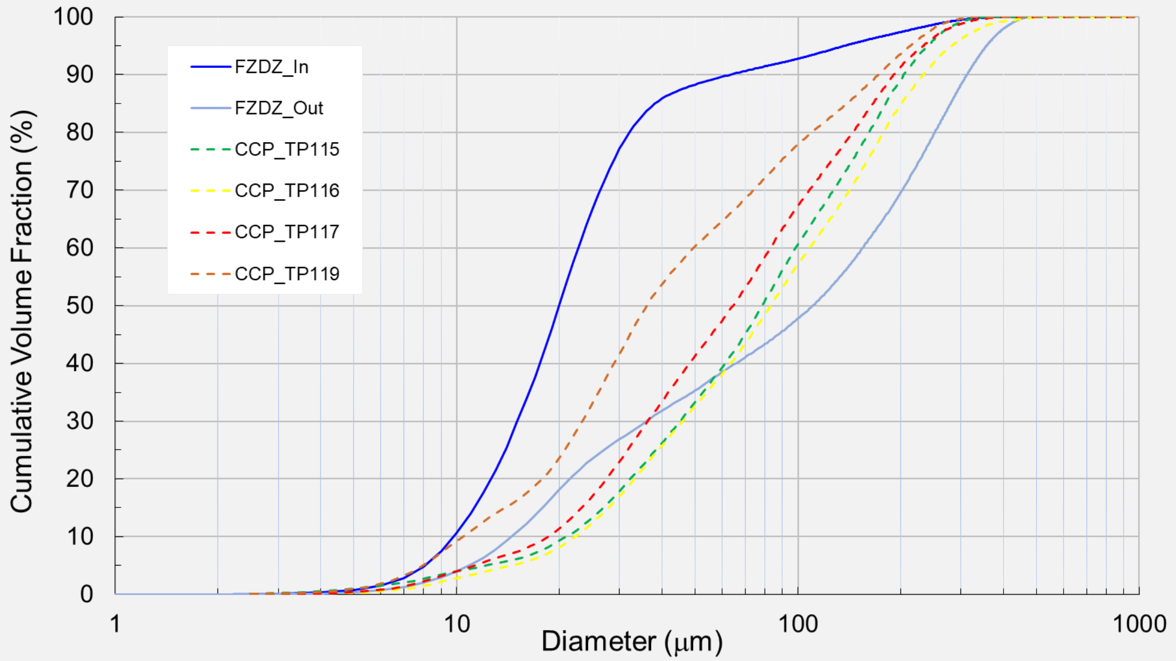




Cloud generation methods and implications on the SLD calibration…

CIRA - Icing Wind Tunnel – FZDZ calibration for MTS configuration

- Spray bar grid configuration 1A3_SLD#6
- Pressure altitude at sea-level
- Airspeed at 110 m/s



Probe_TP_Id	MVD (um)	LWC (g m-3)
CCP #115	79	0,63
CCP #116	83	0,3
CCP #117	65	0,4
CCP #119	36,6	0,23

- The first step of SLD calibration in the CIRA-IWT was based on the assessment performance of different layouts of the SB system, which can be equipped with two types of nozzles.
- Although not equipped with two separate air and water lines on each bar, the ability to set each bar at different pressures allows for some control in generating bimodal PSDs.
- Considering the variability of cloud conditions as a function of speed and required altitude pressure and SB configurations, a full calibration of such a system requires more effort.

Conclusions on gaps and prospective

The airframers need to investigate:

- the SLD ice accretion effects on unprotected lifting surfaces (ice morphology, surface roughness, lobster tail shapes,..)
- The effects of accreted ice on protected surfaces (e.g., drops runback on ice shapes, self accretion on runback ice shapes, ice shedding)
- Fully calibrated facilities and procedure for their high productivity before take part to the certification programs
- How the W/Ts assessing the capabilities in the FZDZ icing domain even for limited conditions

The status of W/Ts is not yet fully useable for a standalone certification purpose, but...

- Complementary applications with numerical tools and analysis in current certification process maybe possible.
- Future testing to address technology readiness, CFD validations, and scaling laws study for Freezing Rain can sustain.

Conclusions on gaps and prospective

- **Facility limitations**
  - Despite the significant progress made during the project, some initial limitations and gaps still present difficulties that will require additional effort to address to meet most target requirements defined at the beginning of the project:
  - The W/Ts airspeed limits for larger droplet diameter PSD tail (e.g., for FZDZ > 40 µm or for FZRA with drop's deformation or breakup due to Reynolds slip) imply the development of the SLD scaling laws to be validate.
  - Instrumentation uncertainties and limits for some key parameters:
    - Droplets' temperature in actual flow condition (high airspeed)
    - Particle size distribution
    - LWC
  - The technologies level achieved are suitable for FZDZ envelope but limited for the FZRA one (TRL5 achieved by RTA).
- Review "facilities target requirements" through sensibility study using numerical investigations and SLD icing scaling laws (as part of AeroTex - RTA on-going activity) it is necessary.