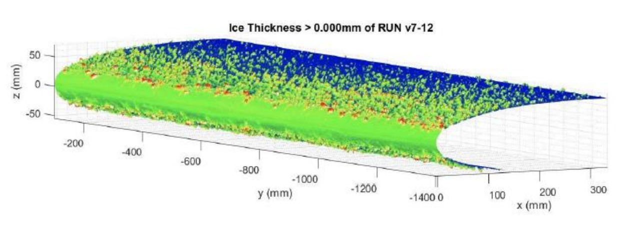
Liquid conditions: Instrumentation

R. Heller (DLR)

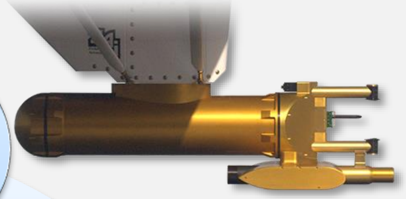
WP4 supported by:
C.Voigt (DLR), B.Esposito (CIRA), H.Pervier (U-Cranf),
H.Ferschitz (RTA), S.Sawitree (RV),
A.Schwarzenboeck (UCF), S.Bansmer (TUBS), T. Neubauer (AIIS)

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.

Icing Instrumentation - Objectives



3D-Scanning System



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

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

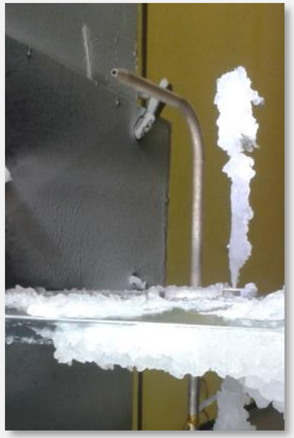
4 - Cloud Homogeneity

Ensure cloud uniformity in the W/T test section

5 - Ice Shape

Characterize surface roughness and ice density

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



CU-IKP: Isokinetic Probe

GSI: Generalized Scattering Imaging

GRT: Global Rainbow technique

Icing Instrumentation – Target Requirements

Target Requirements to assess the most appropriate instrumentation in Appendix C & O icing conditions

- Definition of SLD icing conditions documented in the FAR/CS-25 Appendix C & O:

Definition	MVD range	D_{max} range	MVD (50% VD)	D_{max} (99.9% VD)	Max LWC (99.9% LWC)
App. C_stratiform	15 – 40 µm	< 100 µm			0.05-0.8 g m^{-3}
App. C_convective	15 – 50 µm	< 100 µm			0.25-2.8 g m^{-3}
FZDZ_In	**< 40 µm**	**100 – 500 µm**	**20 µm**	**389 µm**	**0.44 g m^{-3}**
FZDZ_Out	**> 40 µm**	**100 – 500 µm**	**110 µm**	**474 µm**	**0.27 g m^{-3}**
FZRA_In	< 40 µm	> 500 µm	19 µm	1553 µm	0.31 g m^{-3}
FZRA_Out	> 40 µm	> 500 µm	526 µm	2229 µm	0.26 g m^{-3}

Main focus

Parameter	Instrument Uncertainty/ Accuracy
Liquid Water Content	± 10%
Median Volumetric Diameter	± 10%
Drop trajectory relative to the flow +/- %	± 10%
Droplet's temp. deviation from free-stream SAT	± 3 °C
Drop distribution Deviation from reference PSD: RSF	± 5%
Drop sphericity	± 10%
Relative Humidity	± 3%

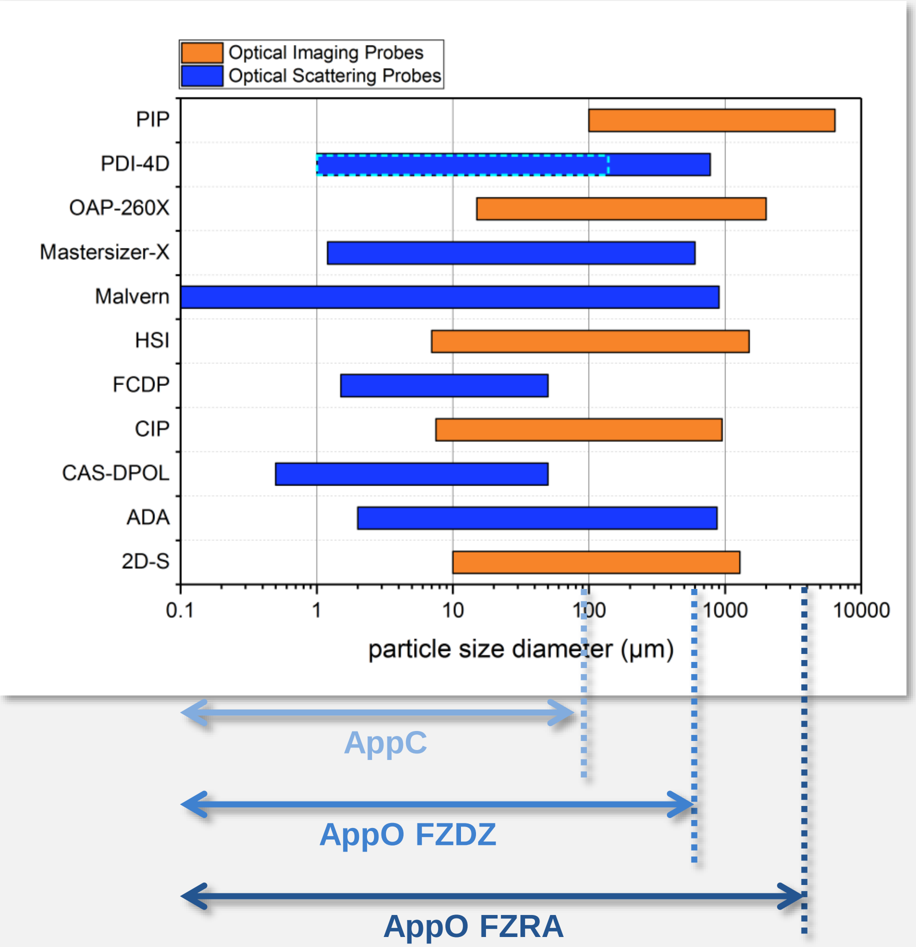
- Definition of W/T performance target:

Instrument uncertainty: Table 2 in D3.1 "Definition of the target requirements for Test facilities operating envelopes for Appendix O"

Instrumentation assessment and selection for PSD measurement (1)

- **Selection of instruments**
- **Calibration in the lab**
- **Testing in wind tunnels**

- **Challenge:**
  - Cover large droplet size range
  - Representation of bimodal size distribution
  - Improve covering critical size range 50 µm – 100 µm



CAPS-DPOL

Malvern Spraytec

PDI-4D

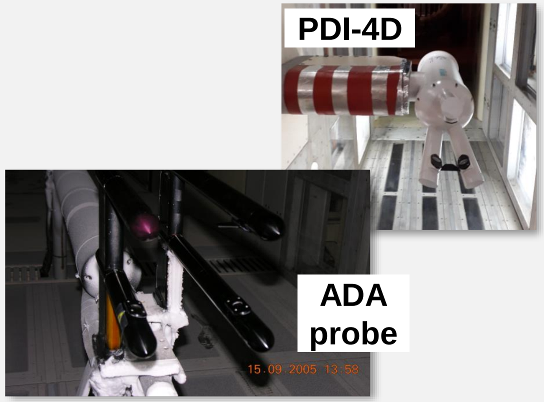
__CAPS-DPOL:__ Cloud, Aerosol, and Precipitation Spectrometer with Deploarization, (combination __CAS-DPOL__ & __CIP__)
__PDI-4D:__ Phase Doppler Interferometer with 4 Detectors

[1]Knop, I., Bansmer, S. E., Hahn, V., and Voigt, C.: Comparison of different droplet measurement techniques in the Braunschweig Icing Wind Tunnel, Atmos. Meas. Tech., 14, 1761–1781, https://doi.org/10.5194/amt-14-1761-2021, 2021.
[2]Jurkat-Witschas, T., C. Voigt, et al., "Aerosol influence on the altitude of glaciation in convective clouds," SAE Technical Paper, presented at the SAE International Conference on Icing of Aircraft, Engines, and Structures, 2019.

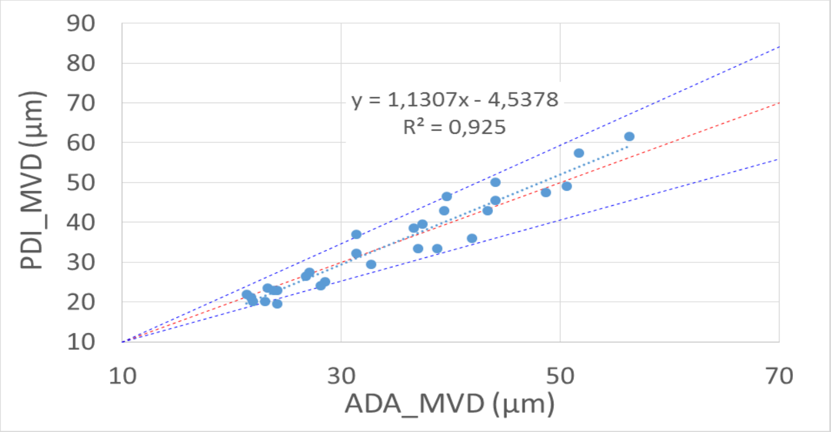
Instrumentation assessment and selection for PSD measurement (1)

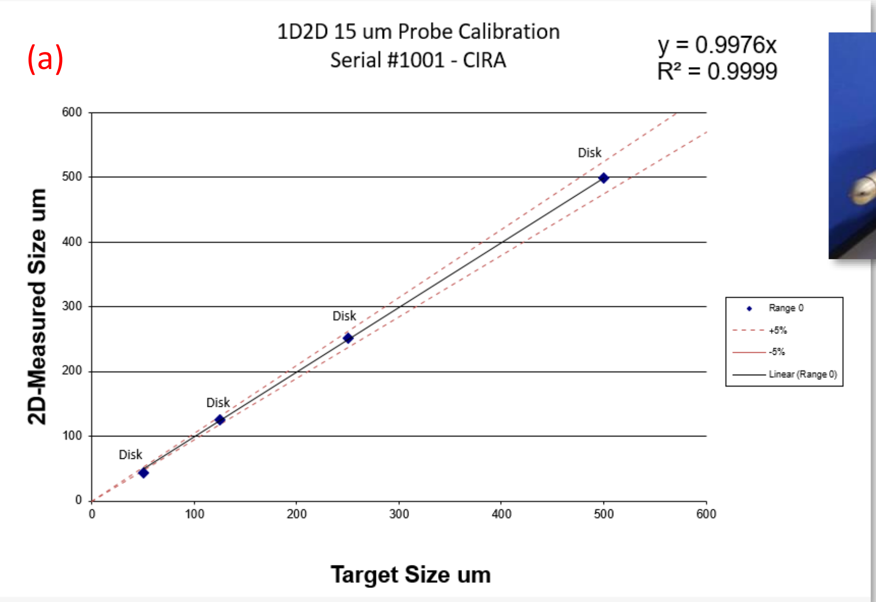
- **CIRA IWT**

- Comparison of instruments in App C + App O FZDZ range
- Calibration of instruments



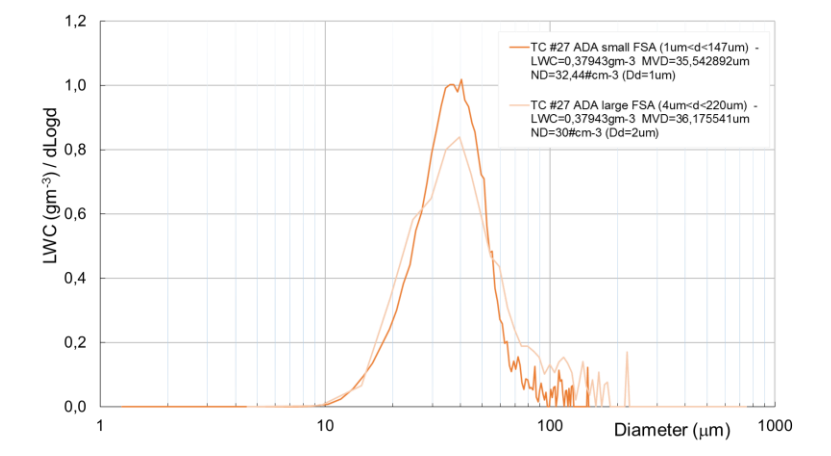
App C





Rebuild of OAP-260X to 1D2D-X probe

Calibration with Spinning Disk



App O FZDZ < 40 µm, ADA small + large size range

See presentation "CIRA – Icing Wind Tunnel: WP6 improvement and calibration"

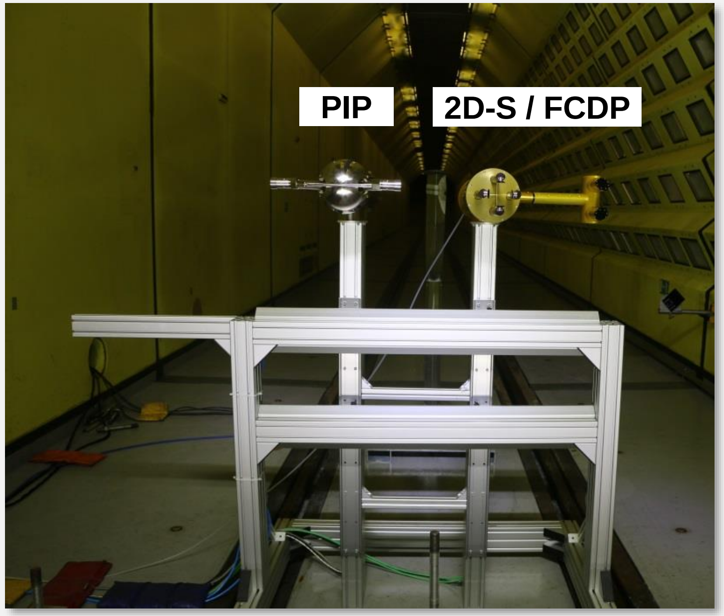
ADA: *Airborne Droplet Analyzer*
OAP-260X: *Optical Array Probe*
PDI-4D: *Phase Doppler Interferometer with 4 Detectors*

Instrumentation assessment and selection for PSD measurement (1)

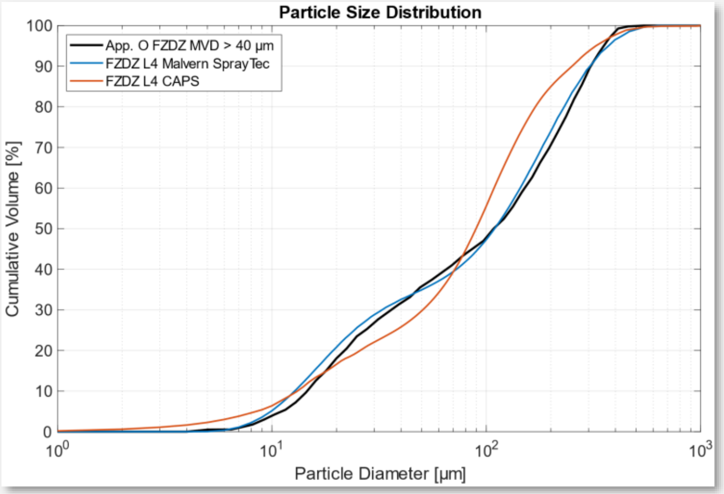
- **RTA IWT**

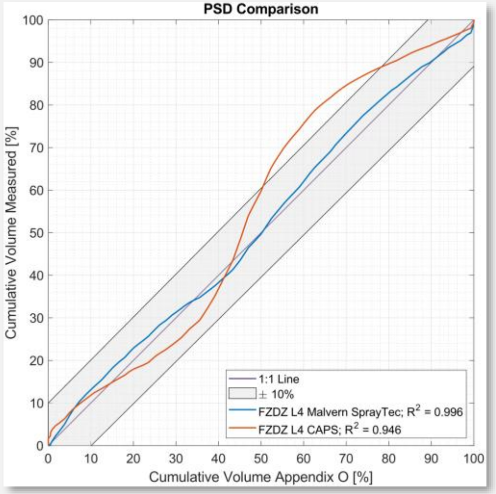
- Several tests in FZDZ/FZRA conditions
- Comparison of Malvern Spraytec (RTA) and FCDP/2D-S, CAPS-DPOL, PIP (DLR)

Malvern Spraytec

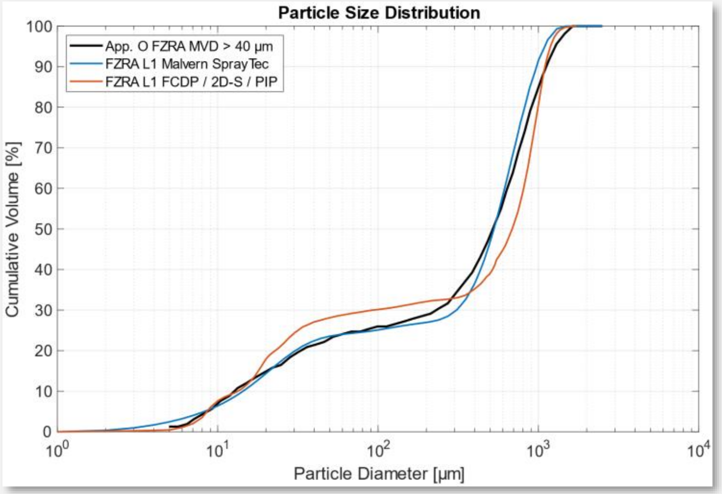


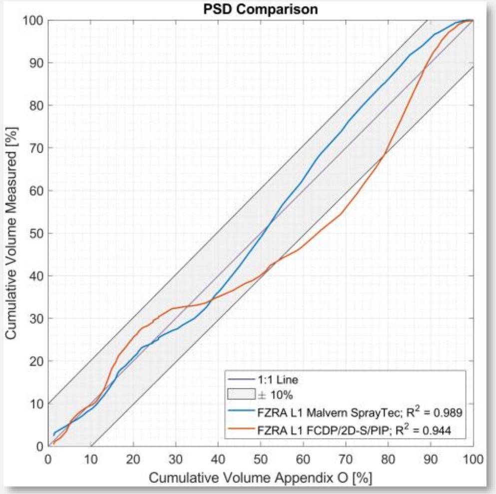
FZDZ MVD > 40 µm





FZRA MVD > 40 µm





CAPS-DPOL: *Cloud, Aerosol, and Precipitation Spectrometer with Deploarization*
FCDP: *Fast Cloud Droplet Probe*
2D-S: *2D Stereo Probe*
PIP: *Precipitation Imaging Probe*

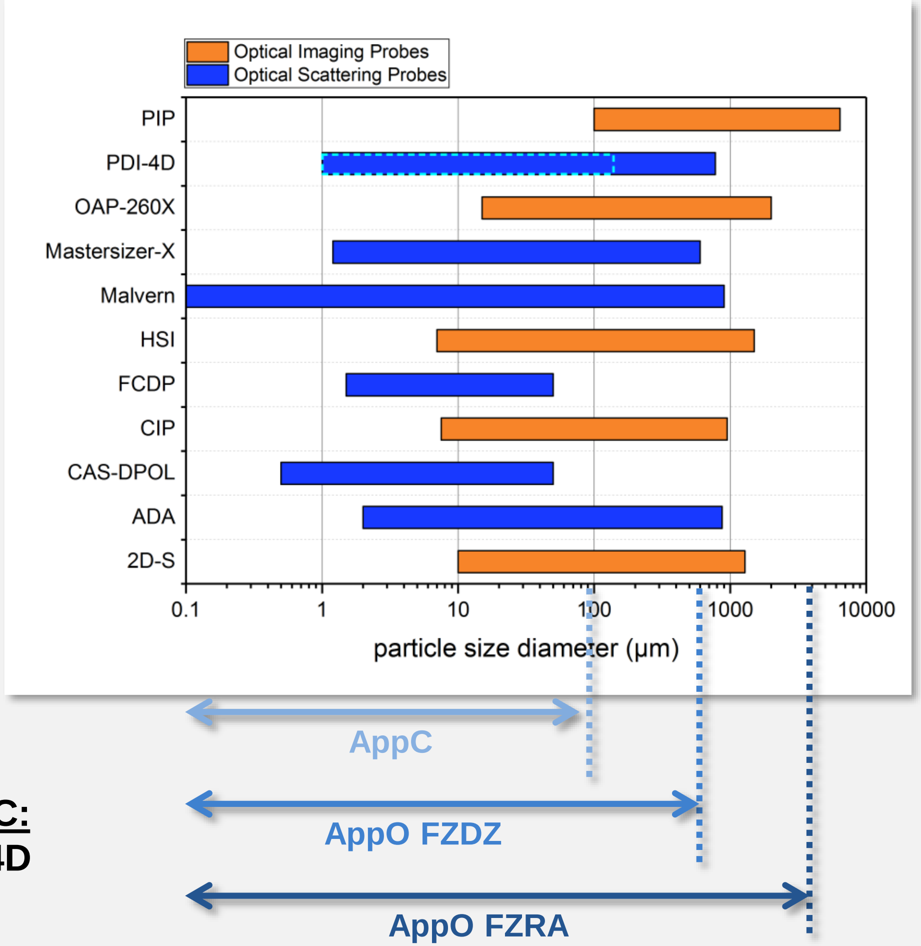
Instrumentation assessment and selection for PSD measurement (1)

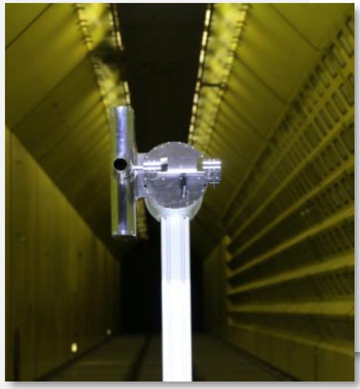
Selection of instruments - Recommendations

<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

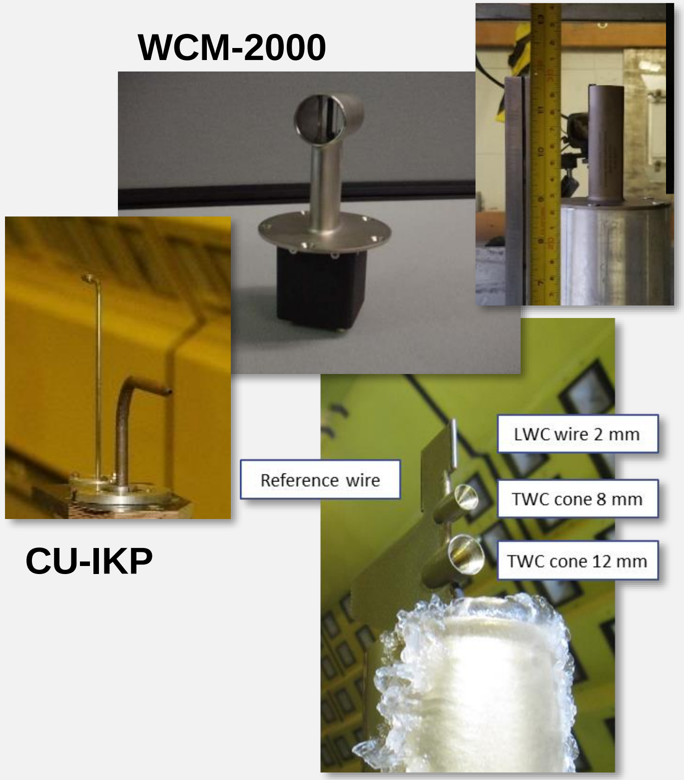
<u>FZRA:</u> PIP

***CAPS-DPOL:** Cloud, Aerosol, and Precipitation Spectrometer with Deploarization*
***PDI-4D:** Phase Doppler Interferometer with 4 Detectors*
***PIP:** Precipitation Imaging Probe*

Instrumentation assessment and selection for LWC measurement (2)

- **Selection of instruments**
- **Calibration in the lab**
- **Testing in wind tunnels**

- **Challenge:**
  - Cover wide LWC range: 0.1 – 3.0 gm^{-3}
  - Representation of large droplet size spectra and bimodal distributions
  - Improve understanding of correction methods for bulk measurements (e.g. collision efficiencies)



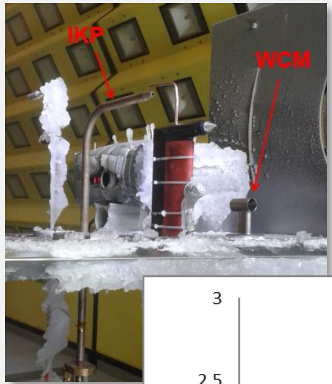
[1]Lucke, J., Jurkat-Witschas, T., Heller, R., Hahn, V., Hamman, M., Breitfuss, W., Bora, V. R., Moser, M., and Voigt, C.: Icing Wind Tunnel Measurements of Supercooled Large Droplets Using the 12 mm Total Water Content Cone of the Nevzorov Probe, Atmos. Meas. Tech. Discuss., https://doi.org/10.5194/egusphere-2022-647,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

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

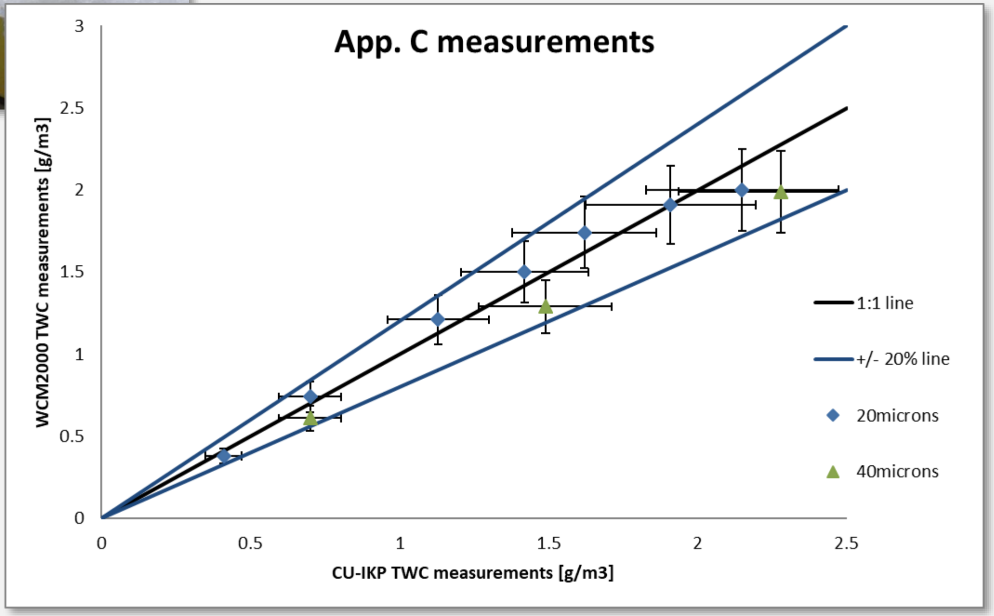
Instrumentation assessment and selection for LWC measurement (2)

Tests @ RTA: Appendix C & Appendix O FZDZ MVD > 40 µm

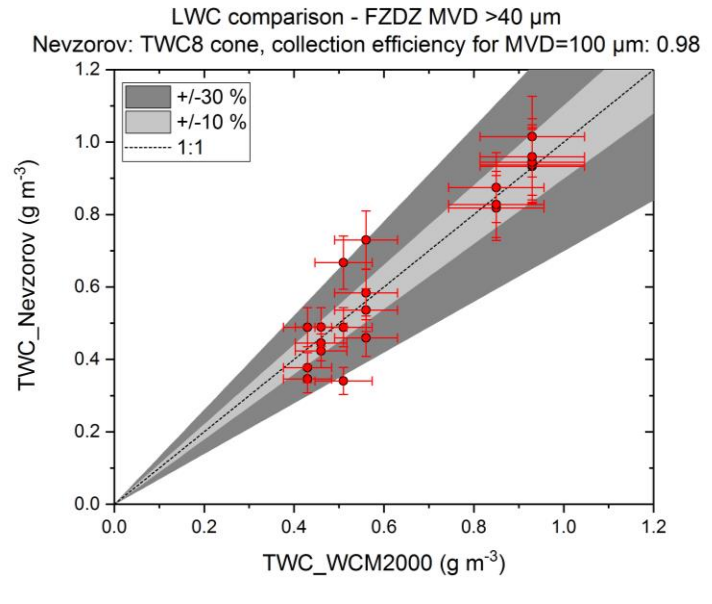
- Total Water Content (TWC) measurements in App C and App O - FZDZ conditions



App C:
WCM-2000 vs. CU-IKP
Agreement within ± 10 %



App O, FZDZ:
WCM-2000 vs. DLR Nevzorov Probe TWC cone 8mm
Agreement within less than ± 30 %

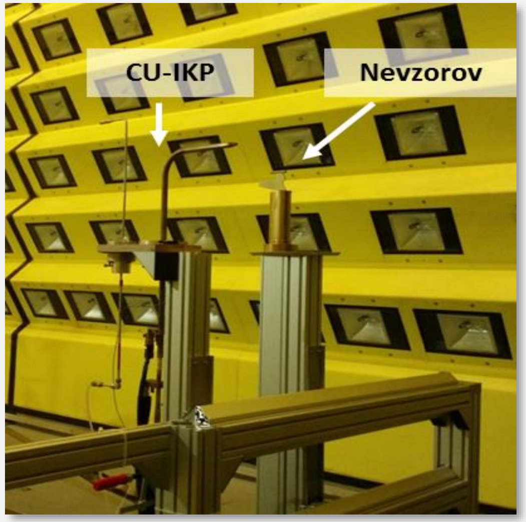


***CU-IKP:** Cranfield University – Isokinetic Probe*
***WCM-2000:** Multi-Element Water Content System*

Instrumentation assessment and selection for LWC measurement (2)

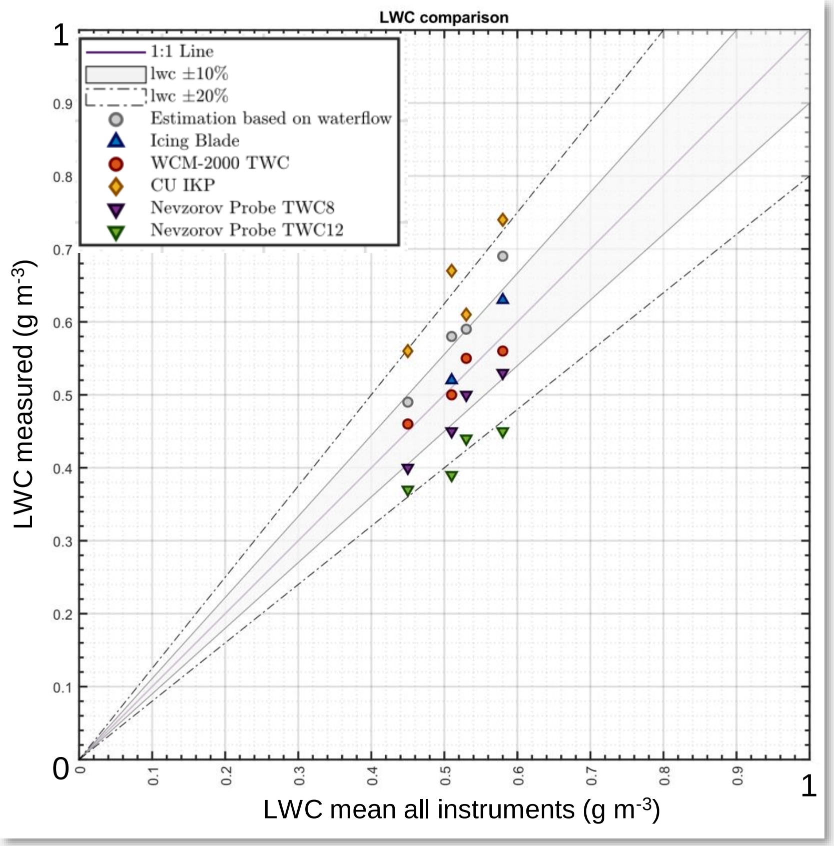
- **Tests @ RTA: Appendix O FZDZ MVD > 40 µm**

- Result of several test measurement performed at RTA within ICE GENESIS and before: calculation of a LWC multi instrument mean



CU-IKP and DLR Nevzorov Probe installed inside RTA IWT

Measurement device	deviation from the mean LWC (%)
Icing Blade	+5.50
WCM2000 TWC half pipe element	+0.60
Nevzorov TWC8 cone	-4.70
Nevzorov TWC12 cone	-19.80
CU-IKP	+25.50

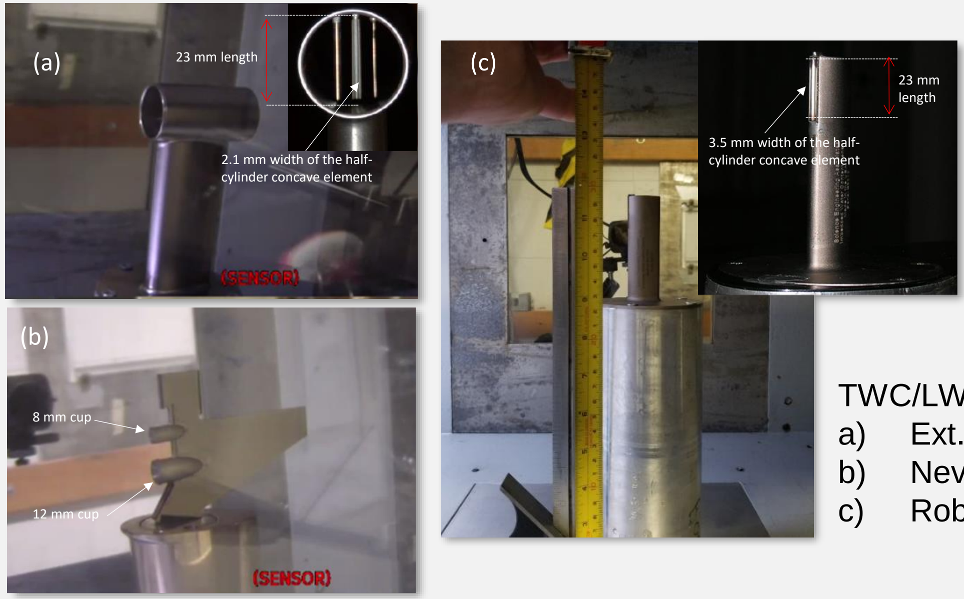


CU-IKP: *Cranfield University – Isokinetic Probe*
WCM-2000: *Multi-Element Water Content System*

Instrumentation assessment and selection for LWC measurement (2)

Test @ NRC-AIWT; cooperation with CIRA, DLR

- Comparison of LWC/TWC hot-wire instrumentation in App C and App O FZDZ conditions
- See presentation “CIRA – Icing Wind Tunnel: WP6 improvement and calibration”



TWC/LWC hotwire instrumentation at NRC-AIWT 2020:
a) Ext. Multi-Wire
b) Nevzorov 2-cup
c) Robust Probe

Instrumentation assessment and selection for LWC measurement (2)

Selection of instruments – Recommendations

- **CIRA:** Multi-wire MW, Robust Probe
- **RTA:** WCM-2000, Nevzorov Probe (, CU-IKP)

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)

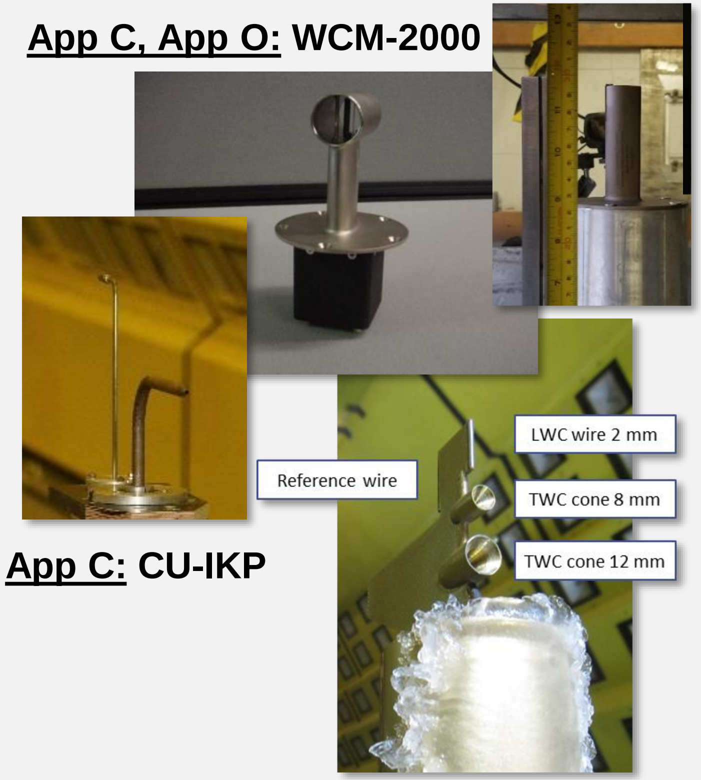
Appendix O FZDZ conditions:

- Deviation of individual instruments from a multi-instrument mean less than 25%

Instrument uncertainty: about ±10% to ±15%

<u>App C:</u> **Robust Probe**

<u>App C, App O:</u> **WCM-2000**



<u>App C:</u> **CU-IKP**

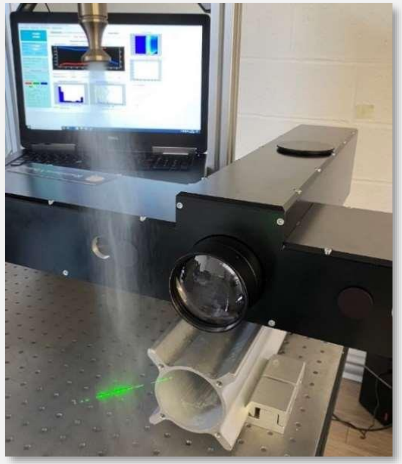
<u>App C, App O:</u>
Nevzorov 2 cup

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

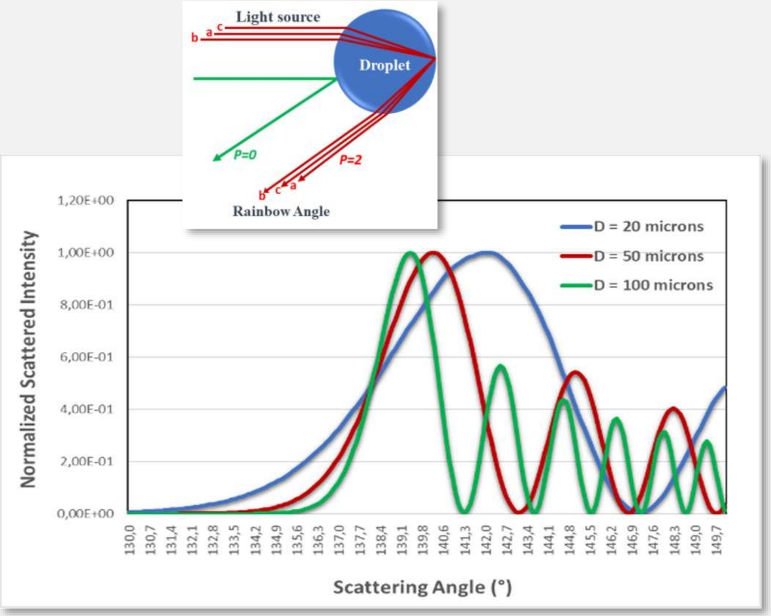
Instrumentation for droplet temperature measurement (3)

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**

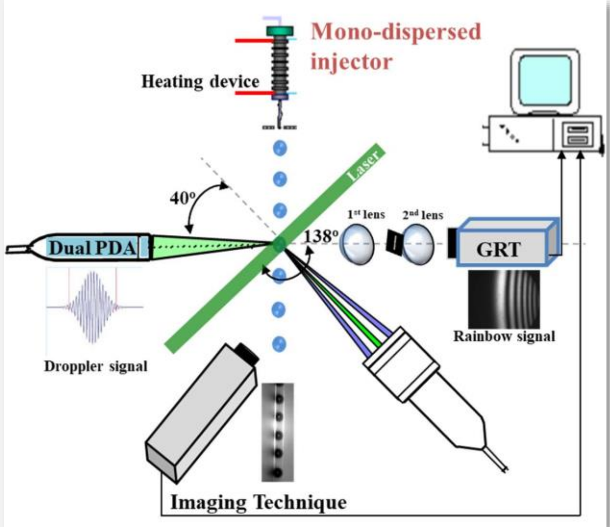
[1] Droplet Temperature Measurements for Efficient Combustors and Icing Safety, Sawitree Saengkaew & Gerard Grehan (rainbowVision), SAE International Conference (AeroTech Europe), September 2020, Bordeaux.
[2] Supercooled Large Droplets Temperature Measurements by Global Rainbow Technique, Sawitree Saengkaew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

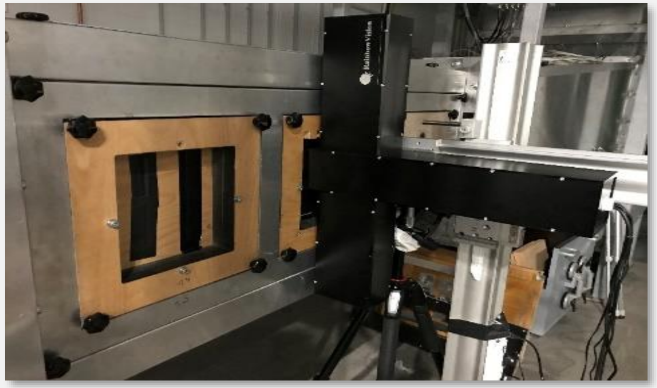
Instrumentation for droplet temperature measurement (3)

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

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

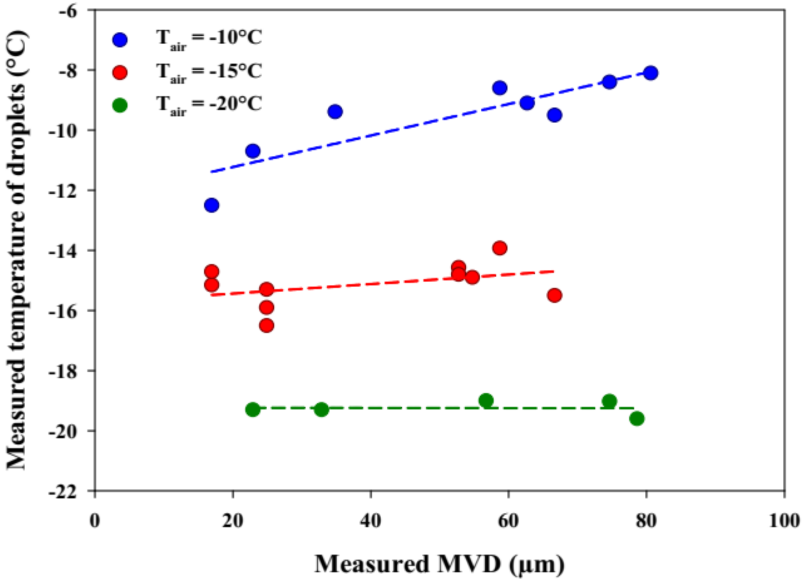
Accuracy determination of GRT (development of RainbowVision)





GRT measurement in TUBS's IWT

Dependence of droplet temperature on the drop size & air temperature



Instrumentation for droplet temperature measurement (3)

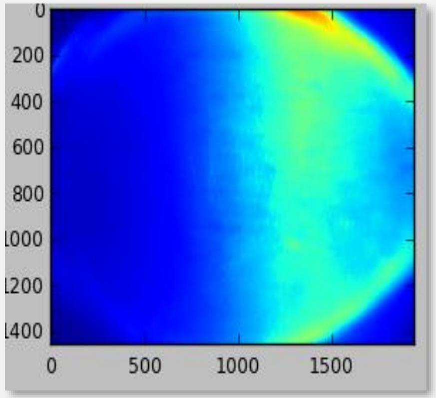
- **GRT in large wind tunnel (RTA) for SLD conditions**

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

Before

After

Example of validated signal

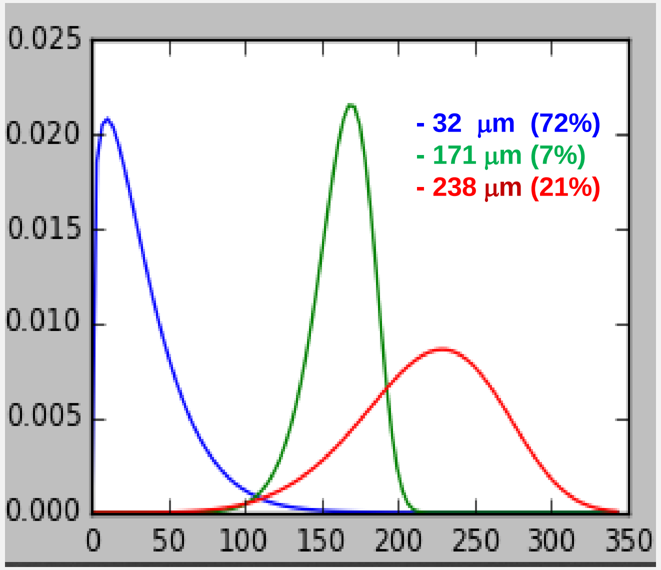


Signal Processing

Measurement results

Droplets temperature = - 4,1°C

Droplets size distribution



Instrumentation for droplet temperature measurement (3)

- **GRT in large wind tunnel (CIRA) for SLD conditions**

- Measurements at -18°C with expected MVD up to 450 µm for bimodal PSD at different simulated altitudes
- GRT-Mini: successful upgraded version to eliminate deposition of fog on optical windows and lens

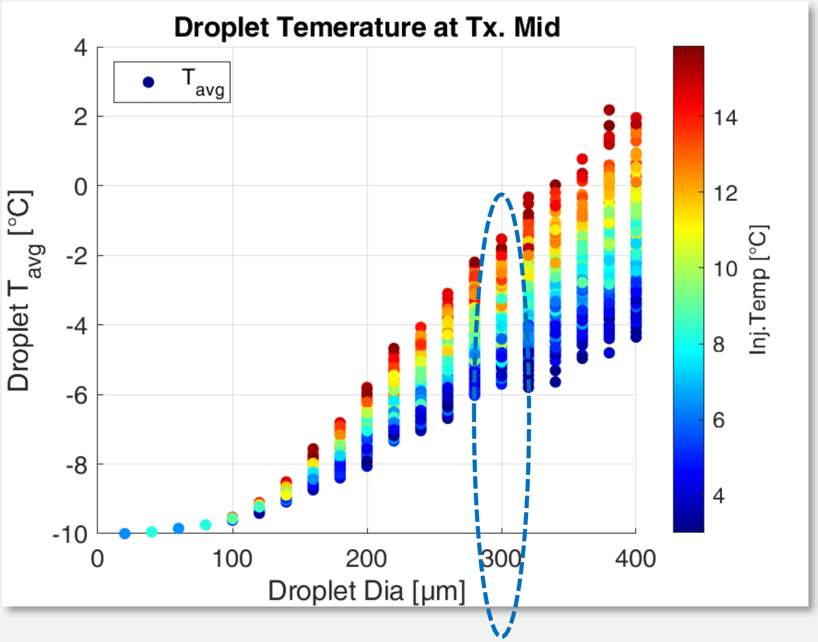
GRT-Mini installed inside CIRA IWT

  - See presentation “CIRA – Icing Wind Tunnel: WP6 improvement and calibration”

Instrumentation for droplet temperature measurement (3)

- **Validation by numerical simulations @ TUBS**

- Validation of simplifications made in GRT measurements
- Droplet final temperature more sensitive to the injection temperature than the injection velocity and the relative humidity
- The larger the droplets are, the larger the range of possible temperature: 300 µm diameter droplet, the possible temperature range: about -5°C to 0°C



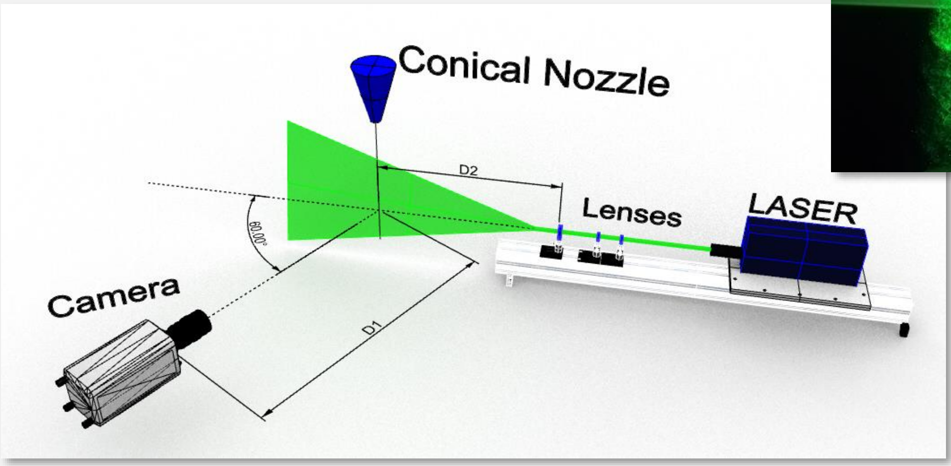
Instrumentation for cloud homogeneity characterisation (4)

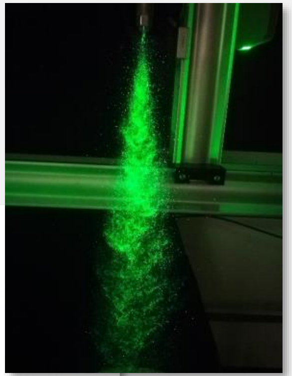
- **Review of existing techniques for cloud homogeneity measurements in wind tunnels**
- **Development of new technique @ CIRA: Generalized Scattering Imaging (GSI)**

- **Challenge:**
  - Enhance measurement capabilities to assess cloud uniformity distribution across the test section
  - Development of new, non-intrusive technique for CIRA-IWT

Ice accretion: Icing Grid, Icing Blade @ RTA IWT

Non-intrusive optical method @ CIRA IWT: GSI





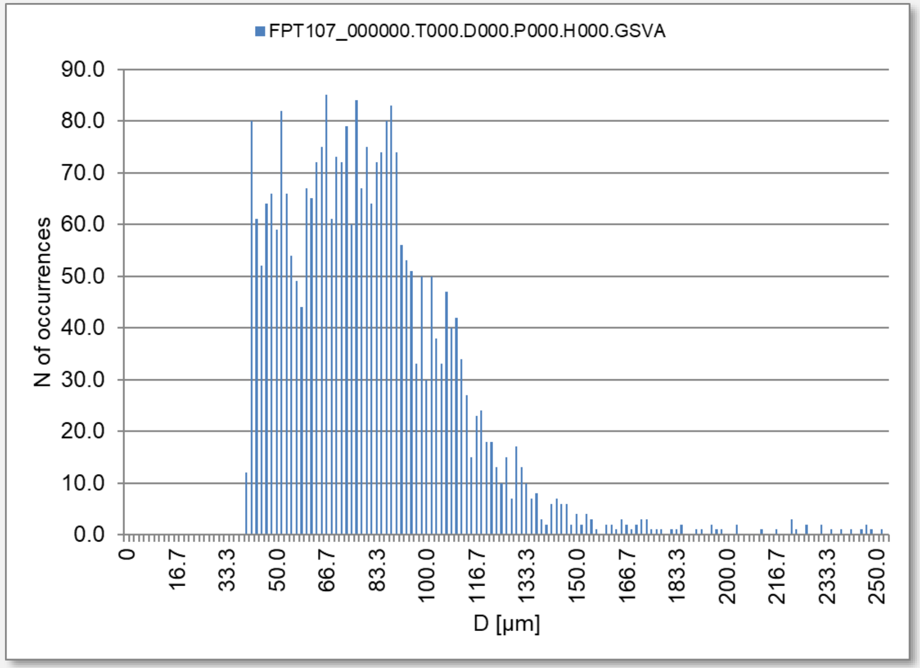
Instrumentation for cloud homogeneity characterisation (4)

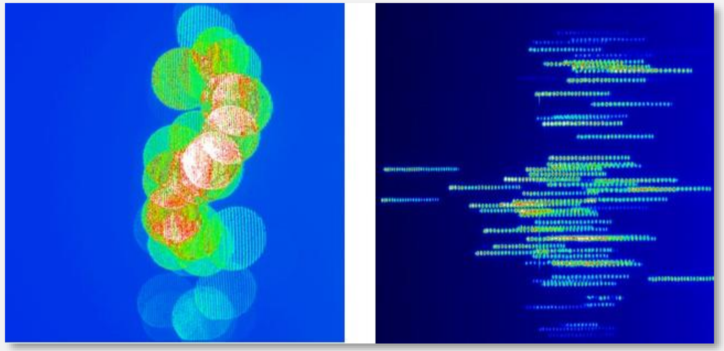
- **GSI technique characterised and optimised in laboratory tests (CIRA)**

- Same conical nozzle as in the CIRA-IWT was used

- GSI technique was shown to measure:
  - size distribution of multi-disperse droplets
  - droplet diameters up to 500 µm
  - a spatial area of 20 cm^2 x 20 cm^2

Multi-disperse droplets: distribution of the number of occurrences of the droplet diameter



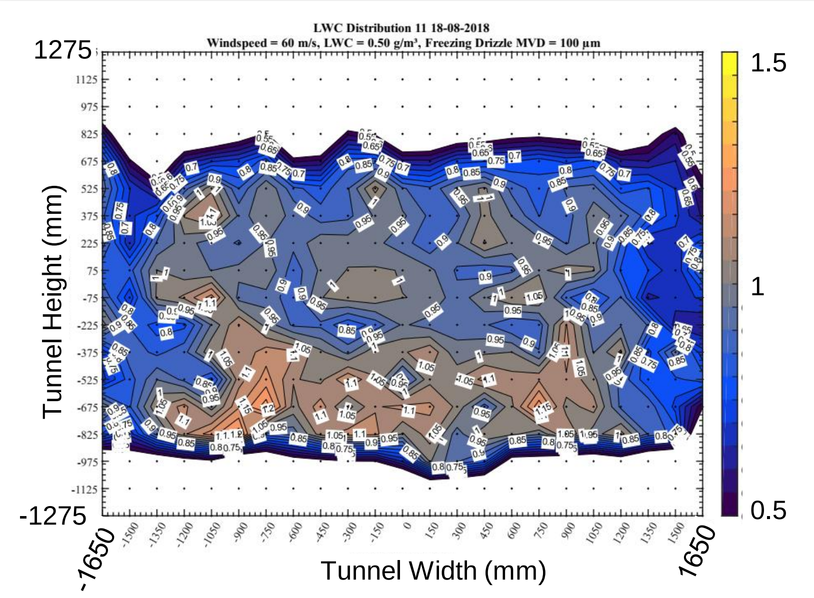


“Full” and “string” out of focus images of grouped water droplets of 70 µm. Each string in the right picture corresponds to a droplet, i.e., to a circular image on the left.

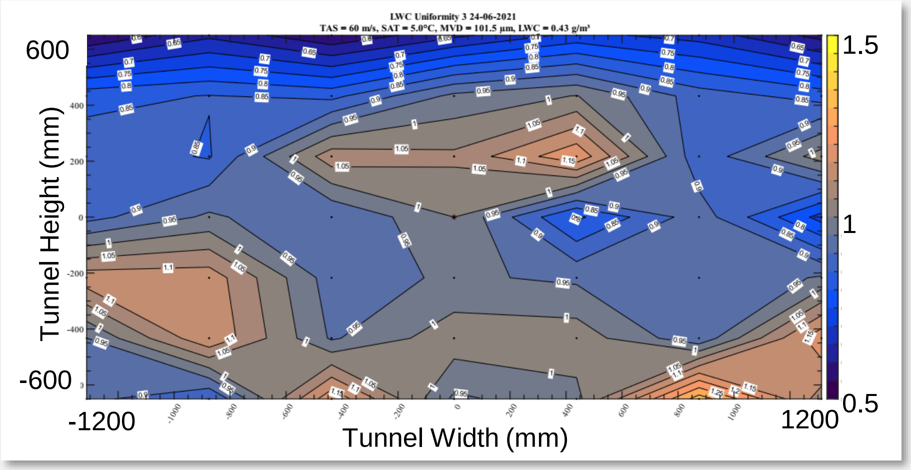
Instrumentation for cloud homogeneity characterisation (4)

Methods @ RTA IWT

Ice Accretion Grid



Examples LWC Distribution:
FZDZ MVD > 40 µm,
Windspeed 40, 60 m/s,
LWC 0.50 g/m^3, 0.64 g/m^3,
MVD ~ 100 µm



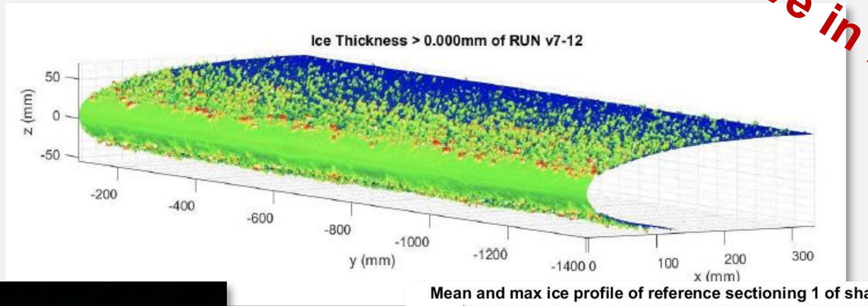
Traversing system: Nevzorov Probe

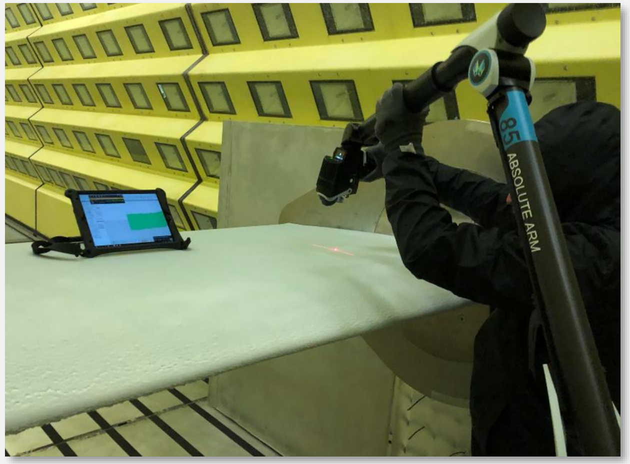
Instrumentation for 3D-scanning of ice shapes (5)

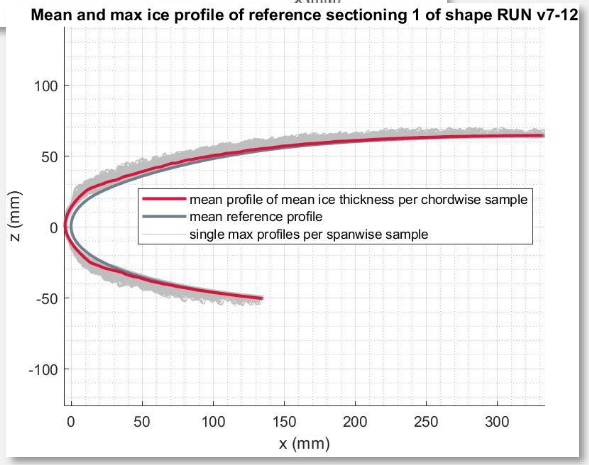
Innovative in Europe

- **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





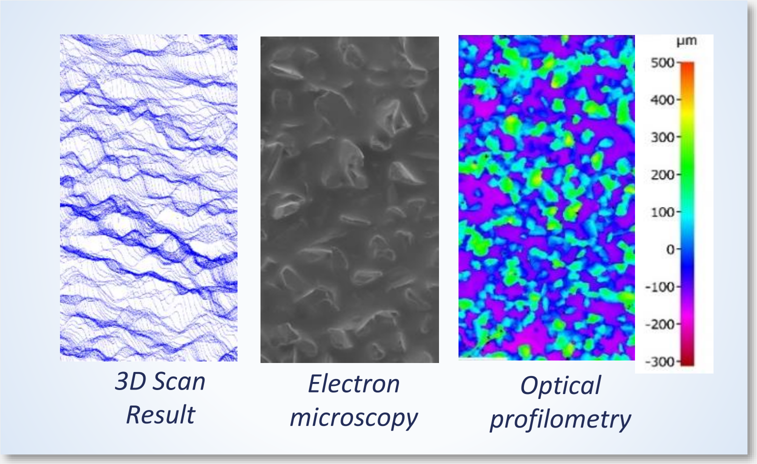


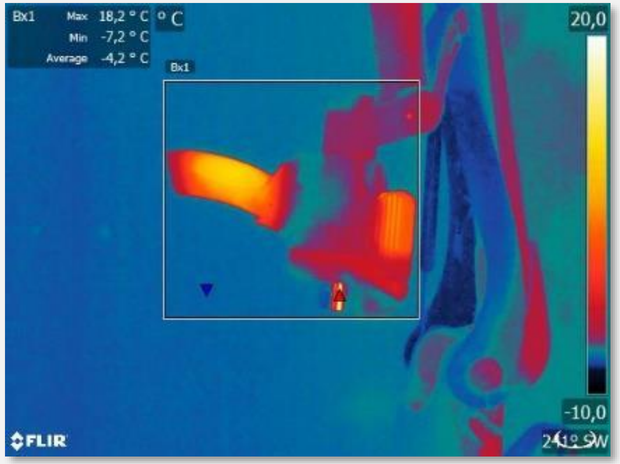
[1]Neubauer, T., Kozomara, D., Puffing, R.F.A., Hassler, W., "Validation of Ice Roughness Analysis Based on 3D-Scanning and Self-Organizing Maps," SAE Technical Paper, presented at the SAE International Conference, 2019.
[2]Neubauer, T., Hassler, W., and Puffing, R., "Ice Shape Roughness Assessment Based 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.

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

- **3D-scanning system**

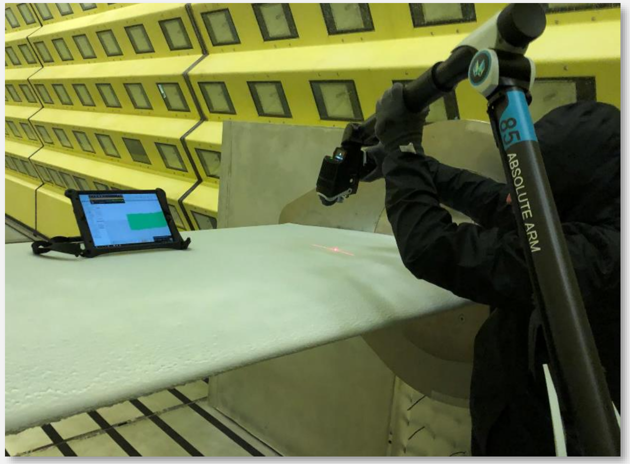
- Evaluation of mobile 3D scanning systems Hexagon RS5 and Hexagon RS6
- Development of heating system for scanning head to allow appropriate usage in harsh IWT environments
- Thermal stability of 3D scanning results validated to -10°C in a climatic chamber
- 3D scanning system global accuracy validated to 40 µm





Thermal imaging of RS5 laser scanner during tests in climatic chamber

Arm-based 3D laser scanning system @ RTA IWT



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

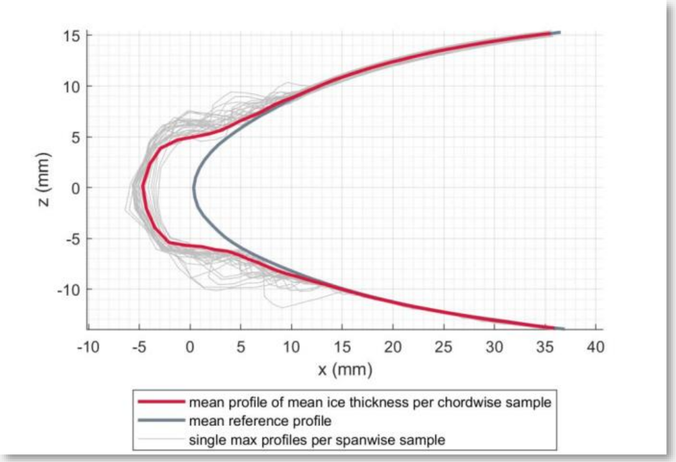
- **Evaluation tool**

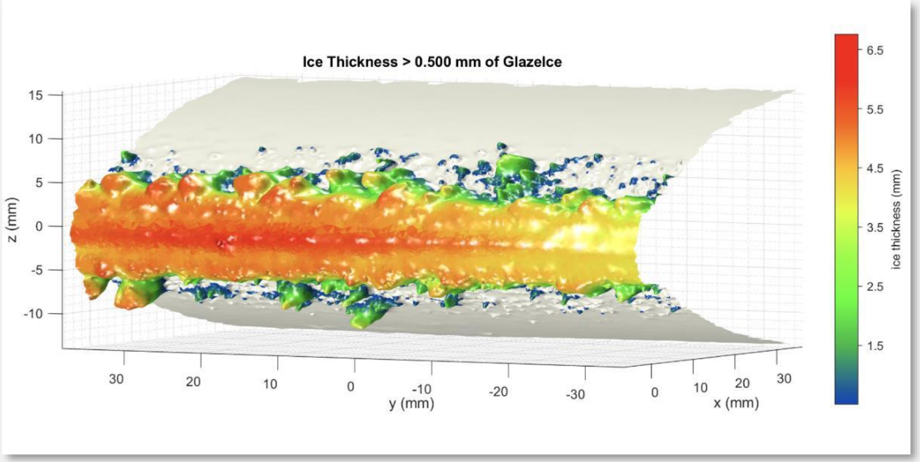
- Automatic reporting for ice thickness, mean ice shape, cumulated ice thickness, roughness and ice volume successfully applied
- 2D and 3D ice surface roughness evaluation based on Self-Organizing maps

Software capabilities developed and improved by AIIS as part of ICE GENESIS

IceLab

Icing test comparison	2D/3D analysis	2D surface roughness analysis
Ice thickness	Ice volume	3D surface roughness analysis
Cross-sectional views	Reporting	Ice density combined with weighing device

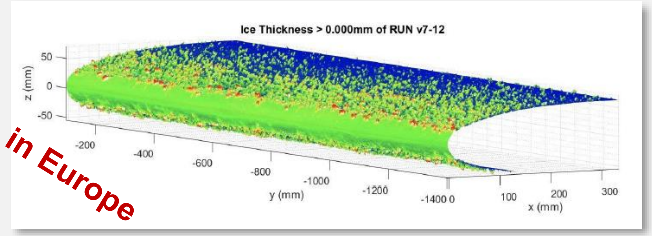




Mean shape of the ice, ice thickness (examples evaluation tool)

Icing Instrumentation - Objectives

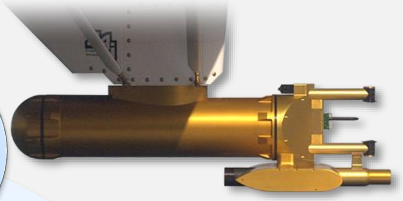
Innovative in Europe



3D-Scanning System

1 - Particle Size Distribution

Determine MVD for droplet size spectra: 40 – 2500 µm

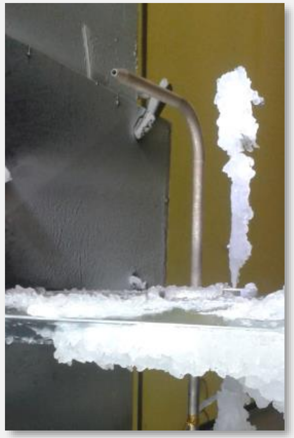


CAPS-DPOL: Cloud, Aerosol, and Precipitation Spectrometer with Deploarization

2 - Liquid Water Content

Cover LWC range:

0.1 – 3 gm^{-3}



CU-IKP: Isokinetic Probe

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

5 - Ice Shape

Characterize surface roughness and ice density

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

GSI: Generalized Scattering Imaging

4 - Cloud Homogeneity

Ensure cloud uniformity in the W/T test section

3 - Droplet Temperature

Validation of supercooled droplets in the W/T test section

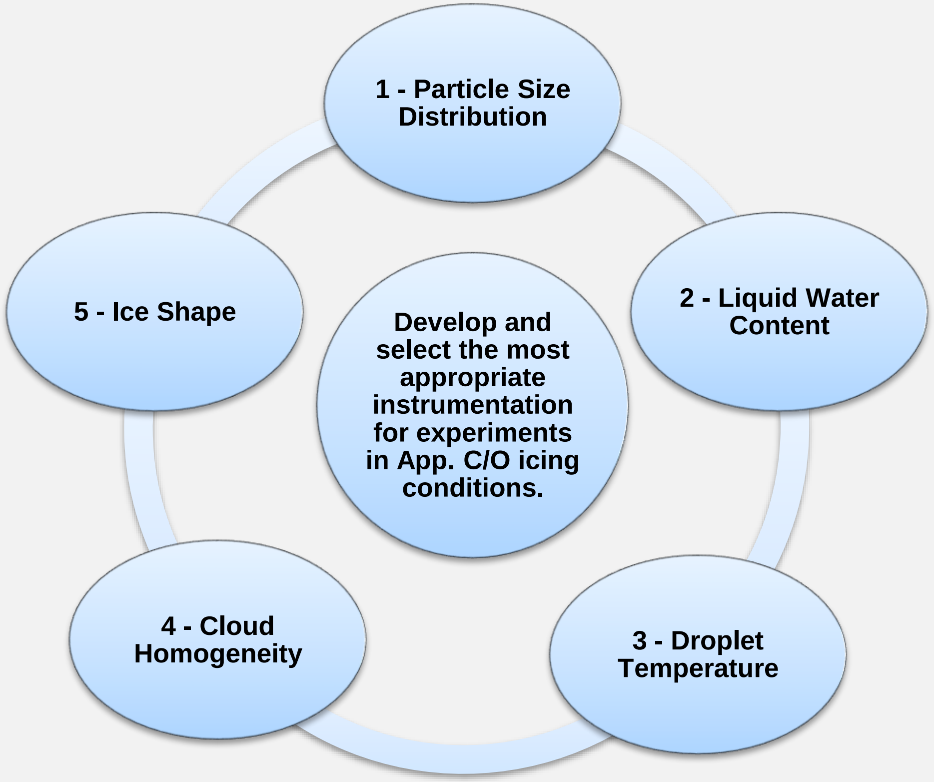
Innovative in Europe

GRT: Global Rainbow technique

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**

- FZDZ: Enhance data statistics for various different conditions to improve the envelope for icing instrumentation
- FZRA: Provide more measurements and data points to improve statistics and comparisons between different W/T facilities
- FZRA: Enhance W/T cloud drop range in various conditions: low LWC, low droplet number concentration, large droplet sizes
- Further improvements and validation of Global Rainbow technique: Accuracy of temperature measurement from large droplets at different IWT temperatures
- Consider an update of requirements for instrument uncertainty (MVD, LWC)



THANK YOU

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