ICE GENESIS PUBLIC WORKSHOP

WP6 SLD TEST CAPABILITY
RTA CALIBRATION RESULTS

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Vienna, Austria

RTA

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OVERVIEW

- Introduction on **ICE GENESIS** WP6
- Target Requirements – **Appendix O** Icing Conditions
- Facility **Performance Targets**
- **RTA** Icing Wind Tunnel
- **Calibration activities**
- **FZDZ Envelopes**
- **FZRA** Capability Assessment

Figure 1: FZRA MVD > 40µm ice accretion on NACA0012 wing section, at RTA IWT

INTRODUCTION

- Ambition of **ICE GENESIS WP6:**
  - Improve **experimental test capabilities** of icing facilities to generate or reproduce representative **Supercooled Large Droplet** (SLD) conditions
  - Define a common **calibration methodology**
  - **Calibration** of IWTs for **FZDZ** conditions
  - Assessment of **FZRA capabilities**

TARGET REQUIREMENTS

- Defined in **FAA** CFR Title 14 Part 25 **Appendix O** [2] or **EASA** Certification Specification CS-25 **Appendix O** [3]
- SLD conditions can be divided into 4 subsets
  - Envelopes of max. LWC as a function of horizontal extent and temperature
  - The particle size distributions (PSDs) and LWC envelopes are based on in-situ measurements performed between 1995 and 2000
    - PMS FSSP
    - PMS 2D-C, 2D-G and 2D-P
    - PMS King LWC probes
    - Nevzorov LWC-TWC

Table 1: MVD, D_{max} and LWC values for each SLD subset [4]

Definition	MVD Range	D_{max} Range	MVD	D_{max}	LWC_{max}
FZDZ In	< 40 µm	100 – 500 µm	20 µm	389 µm	0.44 g/m³
FZDZ Out	> 40 µm	100 – 500 µm	110 µm	474 µm	0.27 g/m³
FZRA In	< 40 µm	> 500 µm	19 µm	1553 µm	0.31 g/m³
FZRA Out	> 40 µm	> 500 µm	526 µm	2229 µm	0.26 g/m³

TARGET REQUIREMENTS

- **Freezing Drizzle** (FZDZ) conditions:

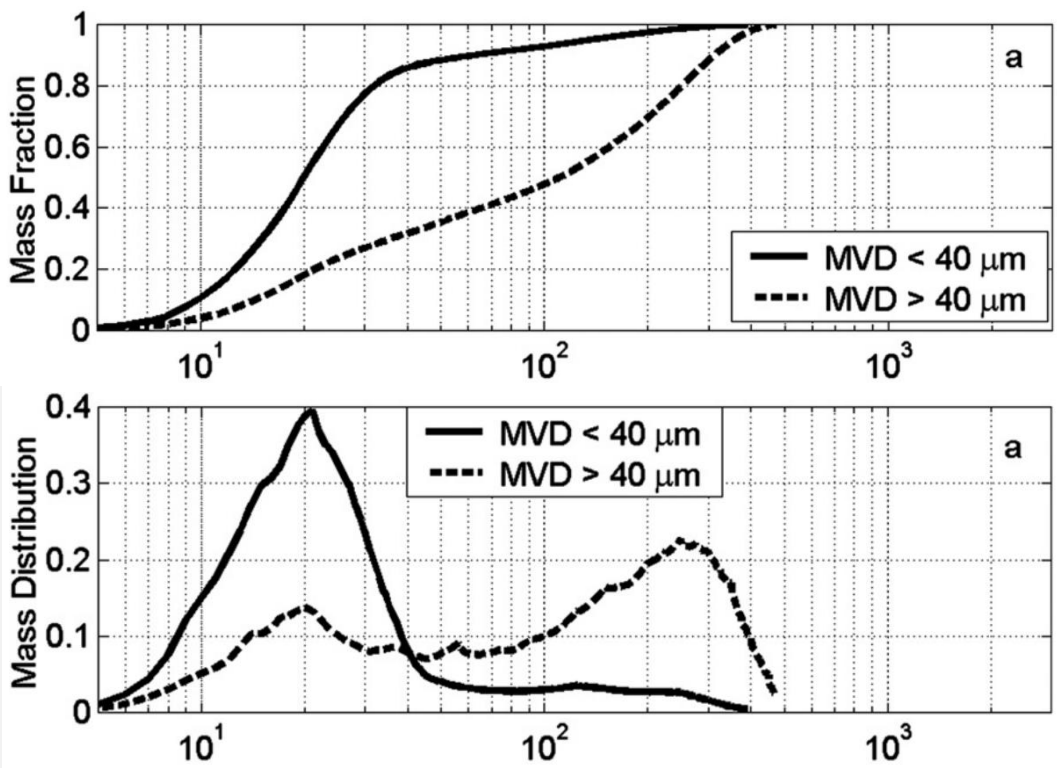


Figure 2: Cumulative mass fraction distributions (top) and normalised mass distributions (bottom) for FZDZ environments [4]

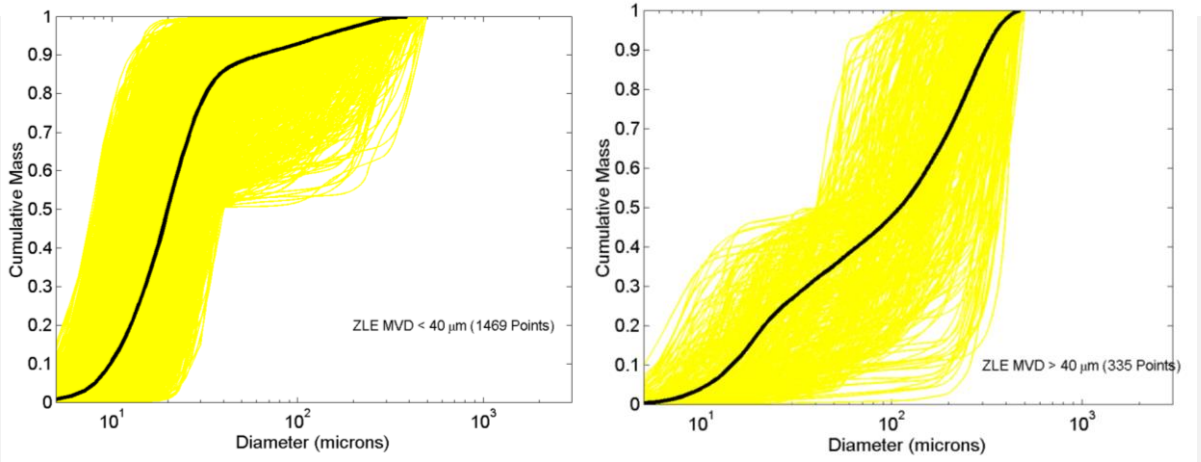


Figure 3: Average PSD compared to each individual PSD for FZDZ [5]

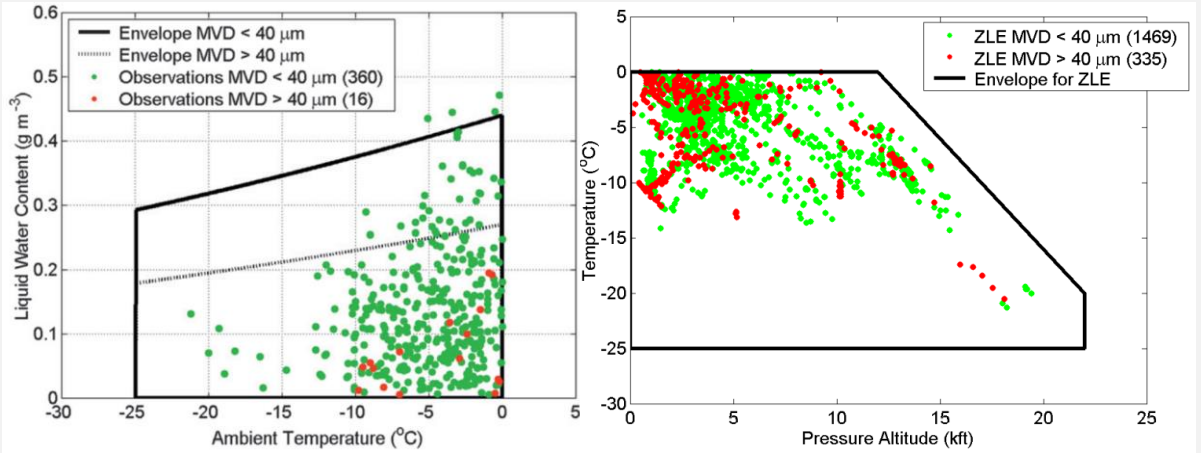


Figure 4: LWC envelopes vs temperature for FZDZ, altitude vs temperature envelopes for FZDZ [5]

TARGET REQUIREMENTS

- **Freezing Rain** (FZRA) conditions:

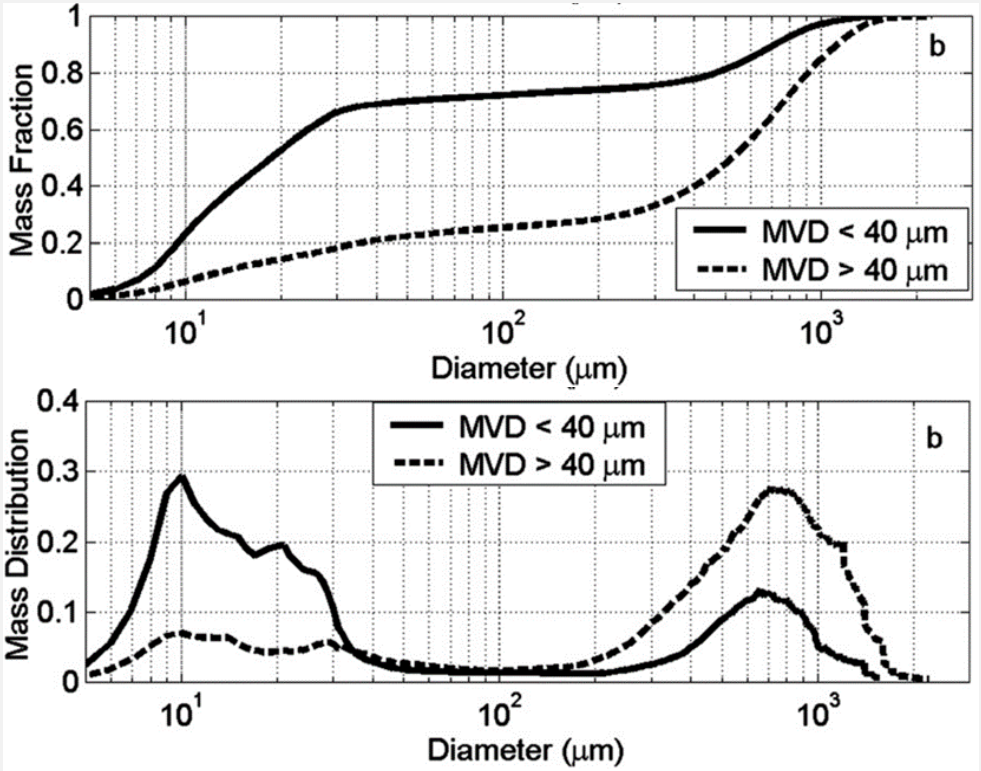


Figure 5: Cumulative mass fraction distributions (top) and normalised mass distributions (bottom) for FZRA environments [4]

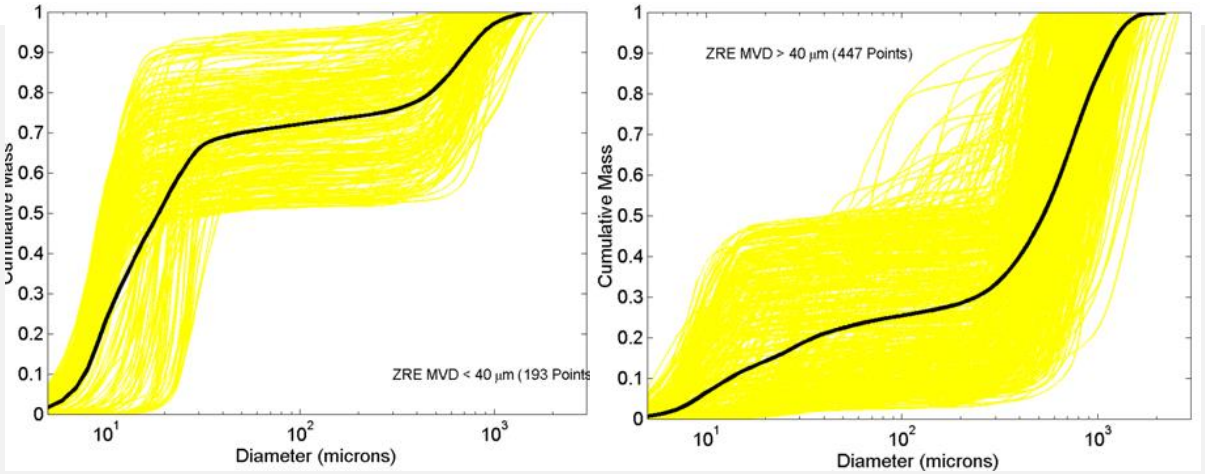


Figure 6: Average PSD compared to each individual PSD for FZRA [5]

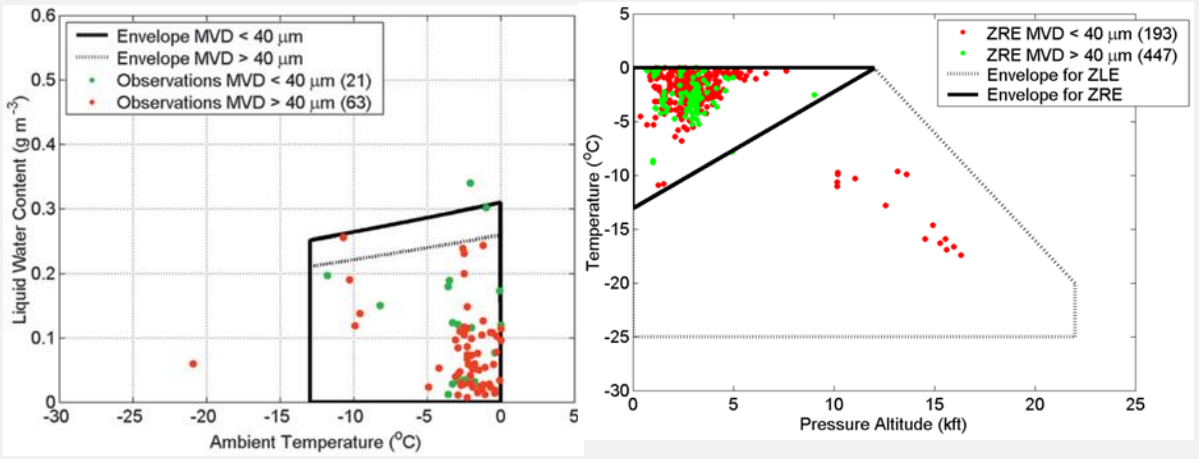


Figure 7: LWC envelopes vs temperature for FZRA, altitude vs temperature envelopes for FZRA [5]

FACILITY PERFORMANCE TARGETS

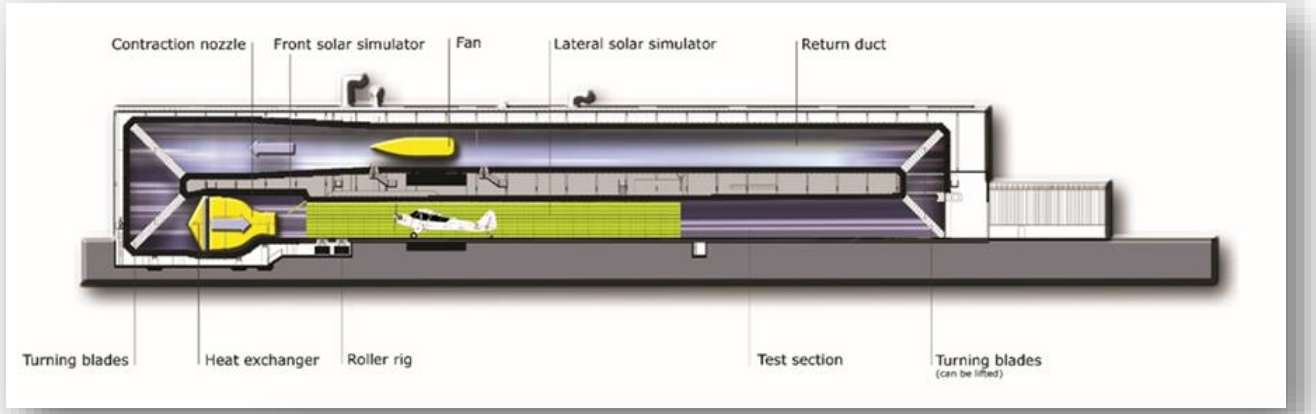
- Similar approach as for Appendix C conditions
  - Instrumentation uncertainty, temporal stability, spatial uniformity, test section calibration
- Higher measurement uncertainty for **MVD** and **LWC** for Appendix O
  - ± 15-20%
- **Additional parameters:**
  - Particle Size distribution
  - Droplet trajectory relative to airflow
  - Droplet temperature deviation to free stream SAT
  - Droplet sphericity

Table 2: Icing cloud test section performance targets

Parameters	Instrumentation Uncertainty	Tunnel Centreline Temporal Stability	Spatial Uniformity	Limit value	Test Section Calibrations
Cloud & Cloud Uniformity Parameters					
Liquid Water Content	± 15 %	± 20 %	± 20 %	N/A	± 15 %
Median Volumetric Diameter	± 15 %	± 20 %	± 20 %	N/A	± 15 %
Drop trajectory relative to airflow	± 10 %	± 20 %	± 20 %	N/A	N/A
Droplet temperature deviation from free stream SAT	± 3°C	+ 10°C	N/A	N/A	N/A
Droplet sphericity	± 10 %	± 20 %	± 20 %	N/A	N/A
Relative humidity	± 3 %	± 10 %	N/A	N/A	N/A

RTA ICING WIND TUNNEL

- **Test Section**
  - Additional Contraction nozzle outlet: 8.75 m²
- **Calibrated test section**
  - 1.7 m x 2.9 m x 3.0 m
- **Airspeed**
  - 20 – 80 m/s
- **Temperature**
  - -2°C to -30°C
- **Altitude**
  - Sea level
- **Spray Bar System**
  - 264 Nozzles on 11 Spray bars
  - 2 separately controllable curcuits on each spray bar



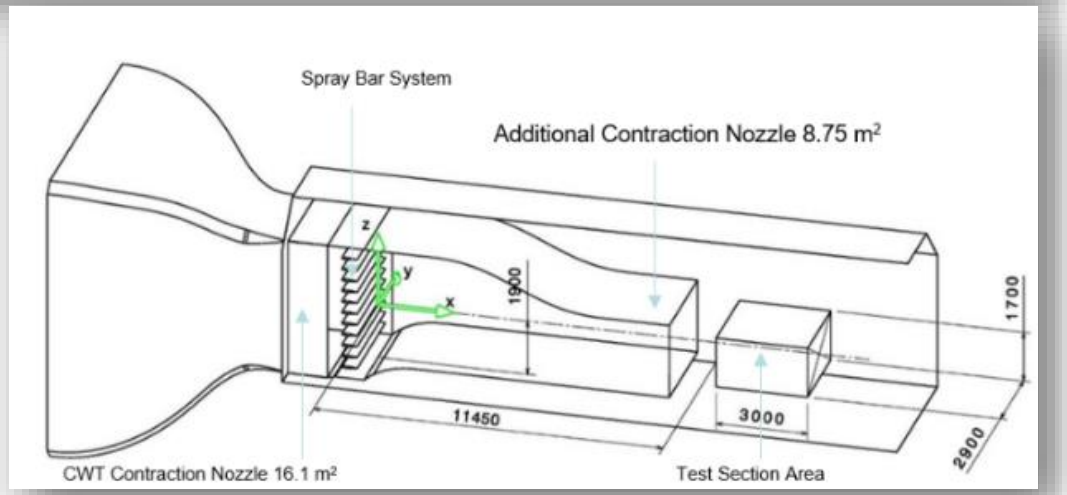


Figure 8: RTA Icing Wind Tunnel schematic of the "High-Speed Configuration" with the additional contraction nozzle

CALIBRATION ACTIVITIES

- **PSD centreline measurements**
  - **FZDZ MVD < 40 µm**
    - 4 spray nozzle settings have been analysed in detail
    - Measurement data from **Malvern Spraytec** available from previous campaigns
    - **CAPS** measurements were performed supported by DLR
  - **FZDZ MVD > 40 µm**
    - 4 spray nozzle settings have been analysed in detail
      - Bimodal / only small mode / only large mode
    - Measurement data from **Malvern Spraytec** and **FCDP/2D-S** available from previous campaigns
    - **CAPS** measurements were performed supported by DLR

$$MVD = MVD_s * \frac{lwc_s}{lwc_s + lwc_l} + MVD_l * \left(1 - \frac{lwc_s}{lwc_s + lwc_l}\right)$$

Figure 9: DLR CAPS in the RTA IWT

CALIBRATION ACTIVITIES

- **PSD measurements**
  - **FZDZ MVD < 40 µm**
    - MVDs in the range of 18 to 26 µm have been measured
    - Maximum diameter ~ 200 µm
    - Good agreement between Malvern and CAPS PSDs

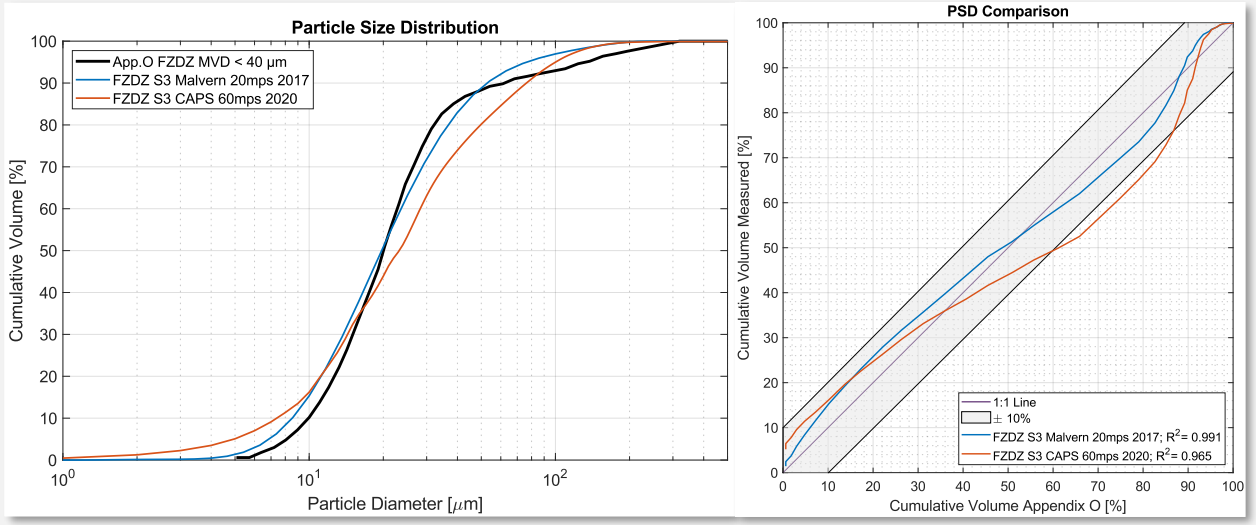


Figure 10: Measured PSDs for FZDZ S3 compared to Appendix O requirements, cumulative volume (left), q - q plot (right)

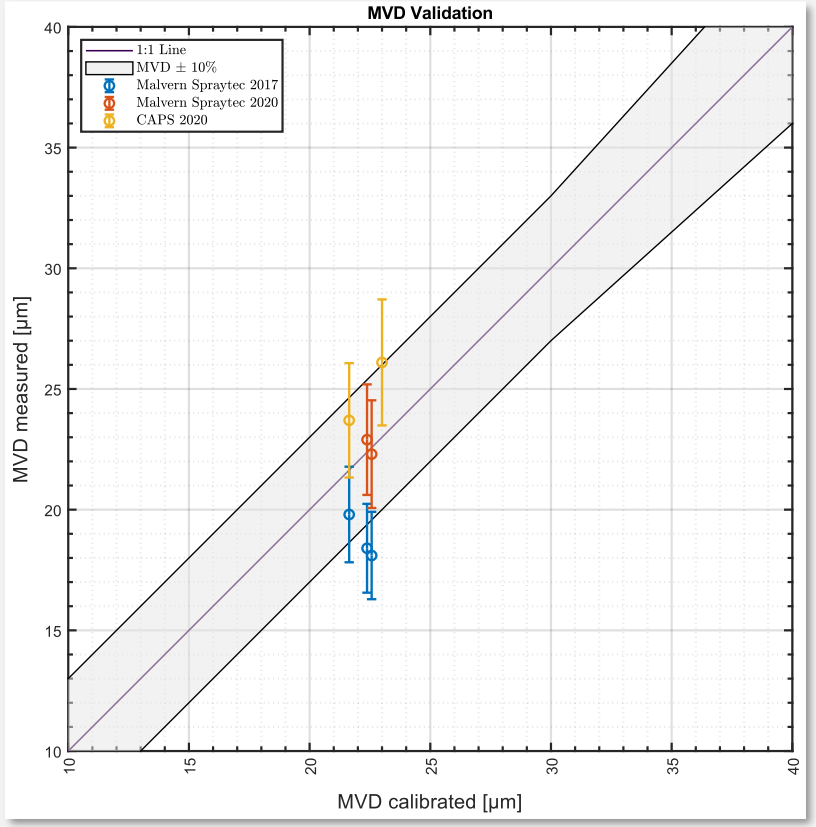


Figure 11: Comparison of calibrated and measured MVDs for FZDZ MVD < 40 µm

CALIBRATION ACTIVITIES

- **PSD measurements**
  - **FZDZ MVD > 40 µm**
    - MVDs in the range of 83 to 110 µm have been measured
    - Maximum diameter ~ 550 µm
    - Good agreement between Malvern, FDCP/2D-S and CAPS PSDs

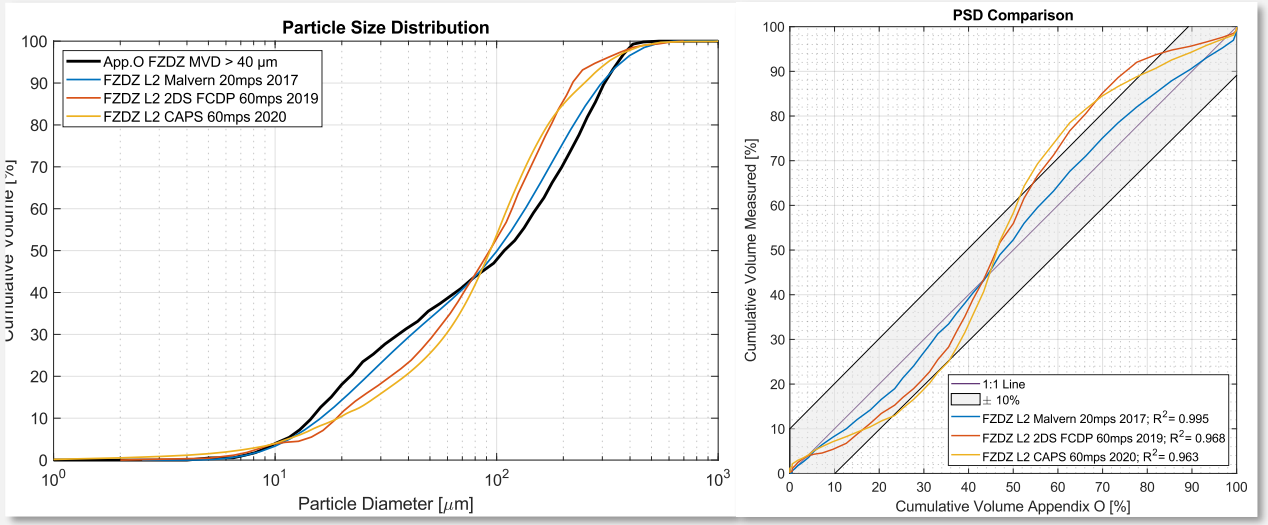


Figure 12: Measured PSDs for FZDZ L2 compared to Appendix O requirements, cumulative volume (left), q - q plot (right)

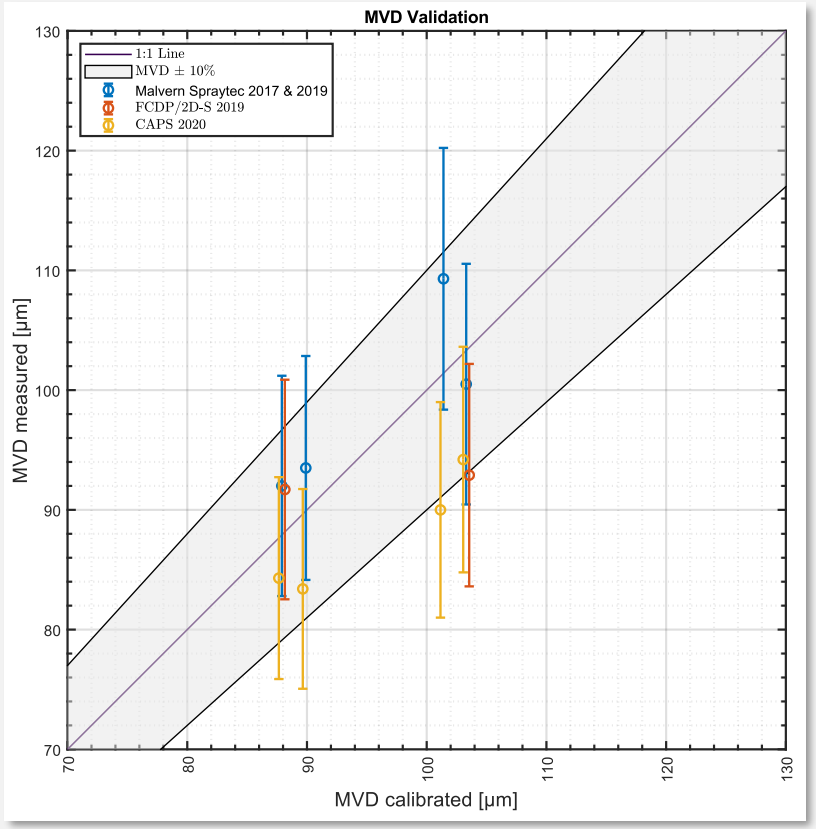


Figure 13: Comparison of calibrated and measured MVDs for FZDZ MVD > 40 µm

CALIBRATION ACTIVITIES

LWC centreline measurements

- **FZDZ MVD < 40 µm**
  - 4 spray nozzle settings have been analysed in detail
  - Measurement data from **Icing Blade** and **waterflow investigations**
  - LWC derived from **CAPS** measurements
- **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 performed supported by DLR

$$LWC = \frac{lwc_{cal\ small} + lwc_{cal\ large}}{TAS}$$

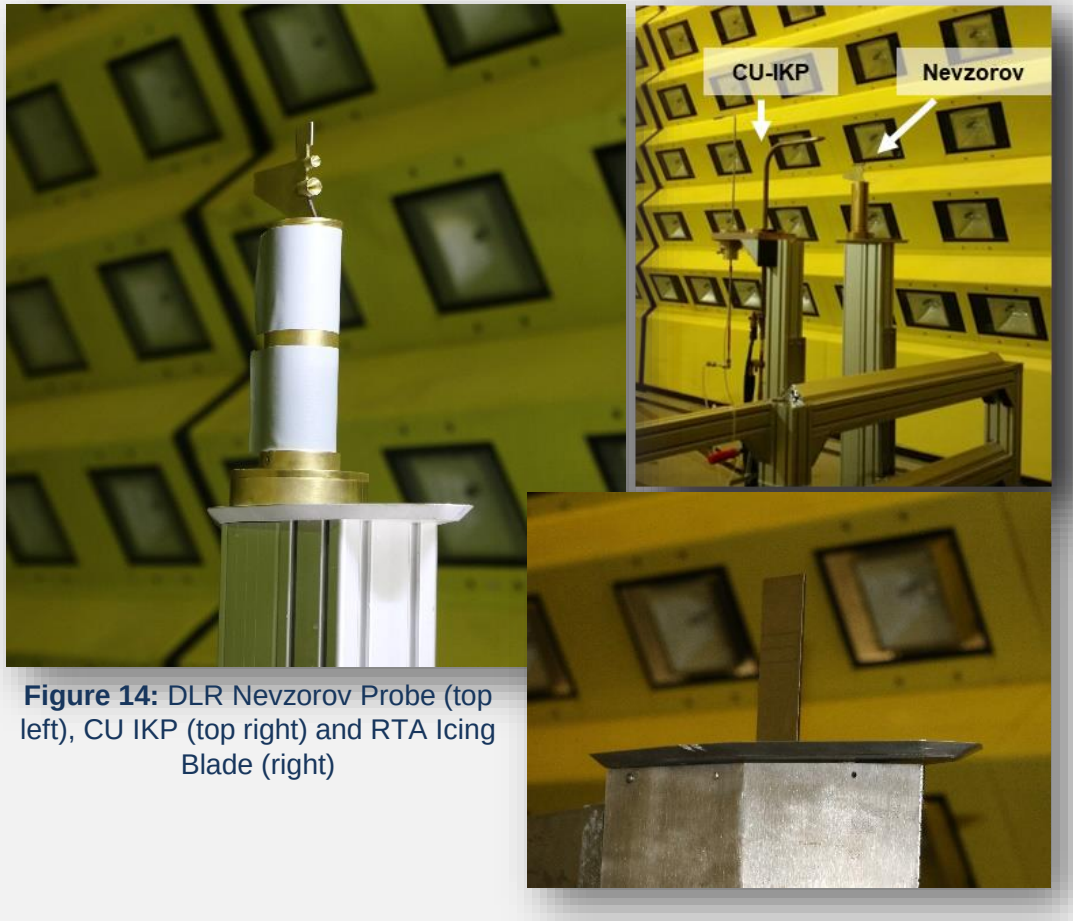


Figure 14: DLR Nevzorov Probe (top left), CU IKP (top right) and RTA Icing Blade (right)

CALIBRATION ACTIVITIES

- **LWC measurements**
  - **FZDZ MVD < 40 µm**
    - Calibration based on Icing Blade measurements (only one Mode)
    - Agreement within ± 20%
  - **FZDZ MVD > 40 µm**
    - Calibration based on average of all instruments small mode + large mode
    - Agreement within ± 20%

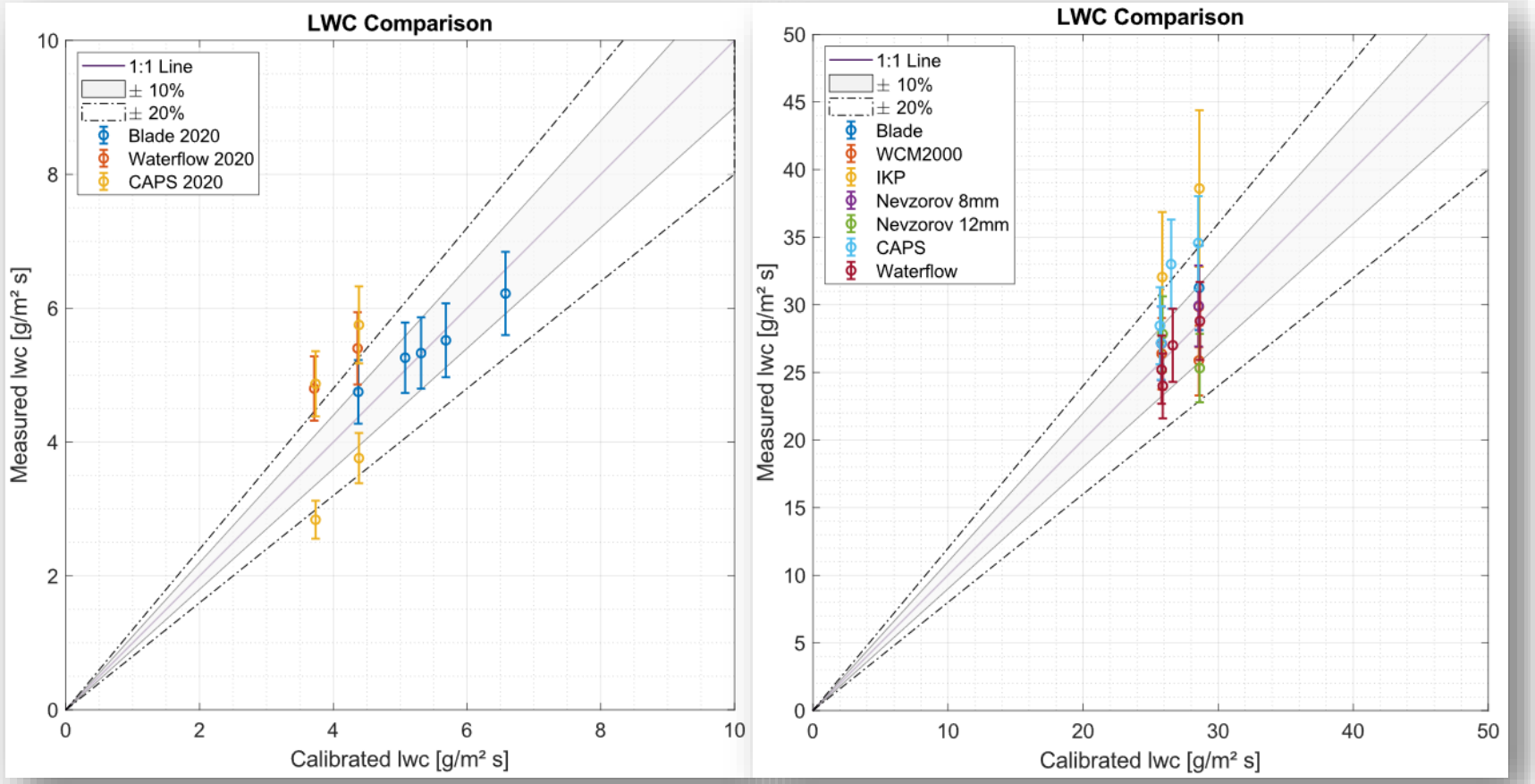


Figure 15: Comparison of calibrated and measured liquid water contents for FZDZ MVD < 40 µm (left) and FZDZ MVD > 40 µm (right)

CALIBRATION ACTIVITIES

- **PSD uniformity measurements**
  - Measured with **CAPS** supported by DLR
  - **FZDZ MVD < 40 µm**
    - No mappings performed
  - **FZDZ MVD > 40 µm**
    - 2 PSD uniformity mappings were performed
    - 49 positions
    - Vertical spacing was adjusted for individual runs

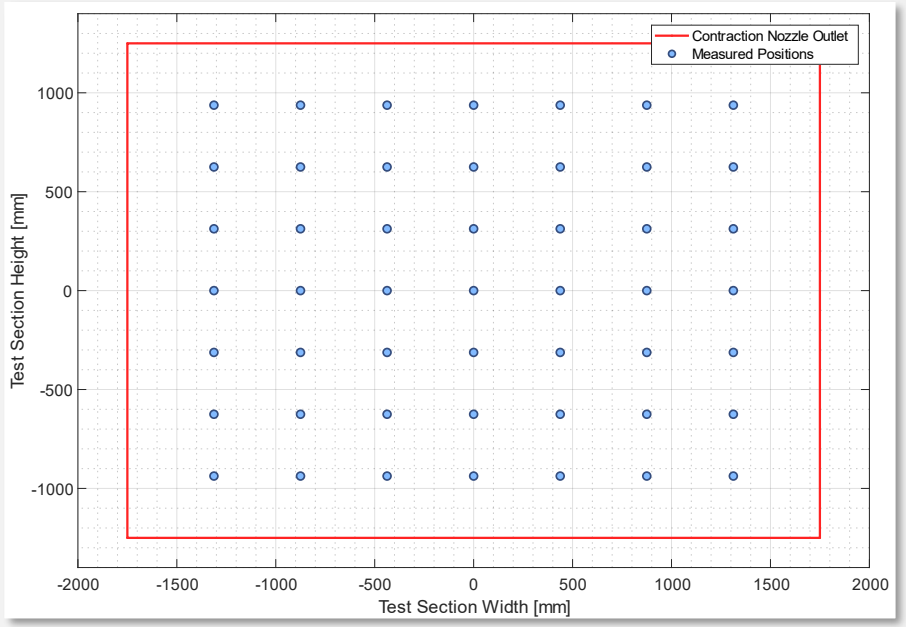


Figure 16: Measurement positions for 2D test section mapping

Figure 17: DLR CAPS Probe mounted on traversing system in the RTA IWT

CALIBRATION ACTIVITIES

- **FZDZ MVD > 40 µm**
  - PSD Uniformity
  - DLR CAPS TS mapping

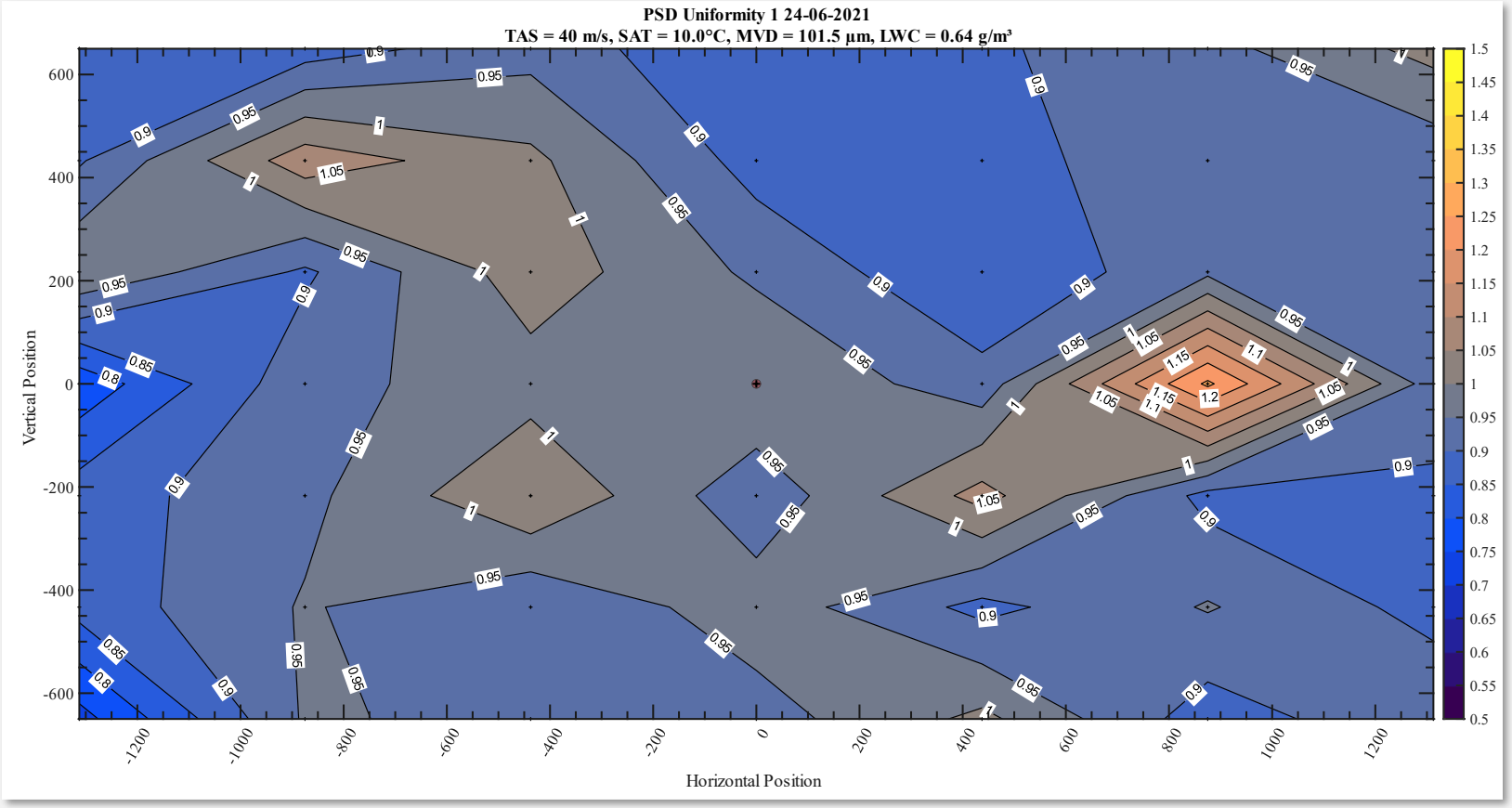


Figure 18: MVD Uniformity for "FZDZ L4" at a test section airspeed of 40 m/s, test section mapping with CAPS Probe, spray bars 3-11 were active

CALIBRATION ACTIVITIES

- **LWC uniformity measurements**
  - Measured with **Nevzorov Probe** supported by DLR (as WCM-2000 was not available)
  - Ice accretion grid measurements available from previous research
  - **<u>FZDZ MVD < 40 µm</u>**
    - 1 mapping performed on 49 positions at a test section airspeed of 40 m/s
  - **<u>FZDZ MVD > 40 µm</u>**
    - 4 PSD uniformity mappings with 49 positions were performed
      - 3 bimodal at 40 m/s and 60 m/s
      - Only large mode at 40 m/s

Figure 19: DLR Nevzorov Probe mounted on traversing system in the RTA IWT

FZDZ ENVELOPES

- **FZDZ MVD < 40 µm**
  - LWC Uniformity
  - DLR Nevzorov Probe TS mapping

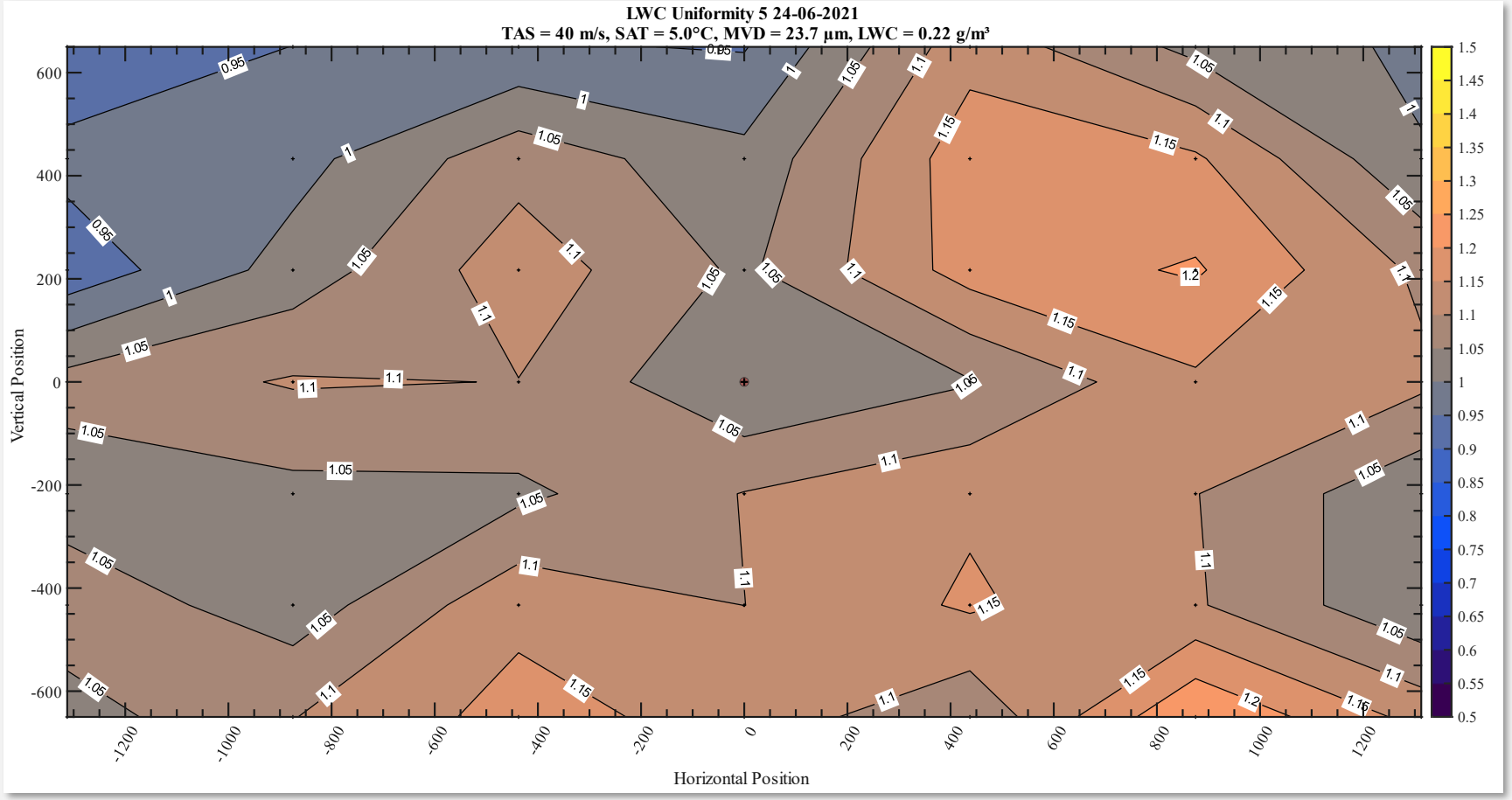


Figure 19: LWC Uniformity measured with Nevzorov probe on traversing system, spray bars 3-11 were active

FZDZ ENVELOPES

- **FZDZ MVD > 40 µm**
  - LWC Uniformity
  - DLR Nevzorov Probe TS mapping

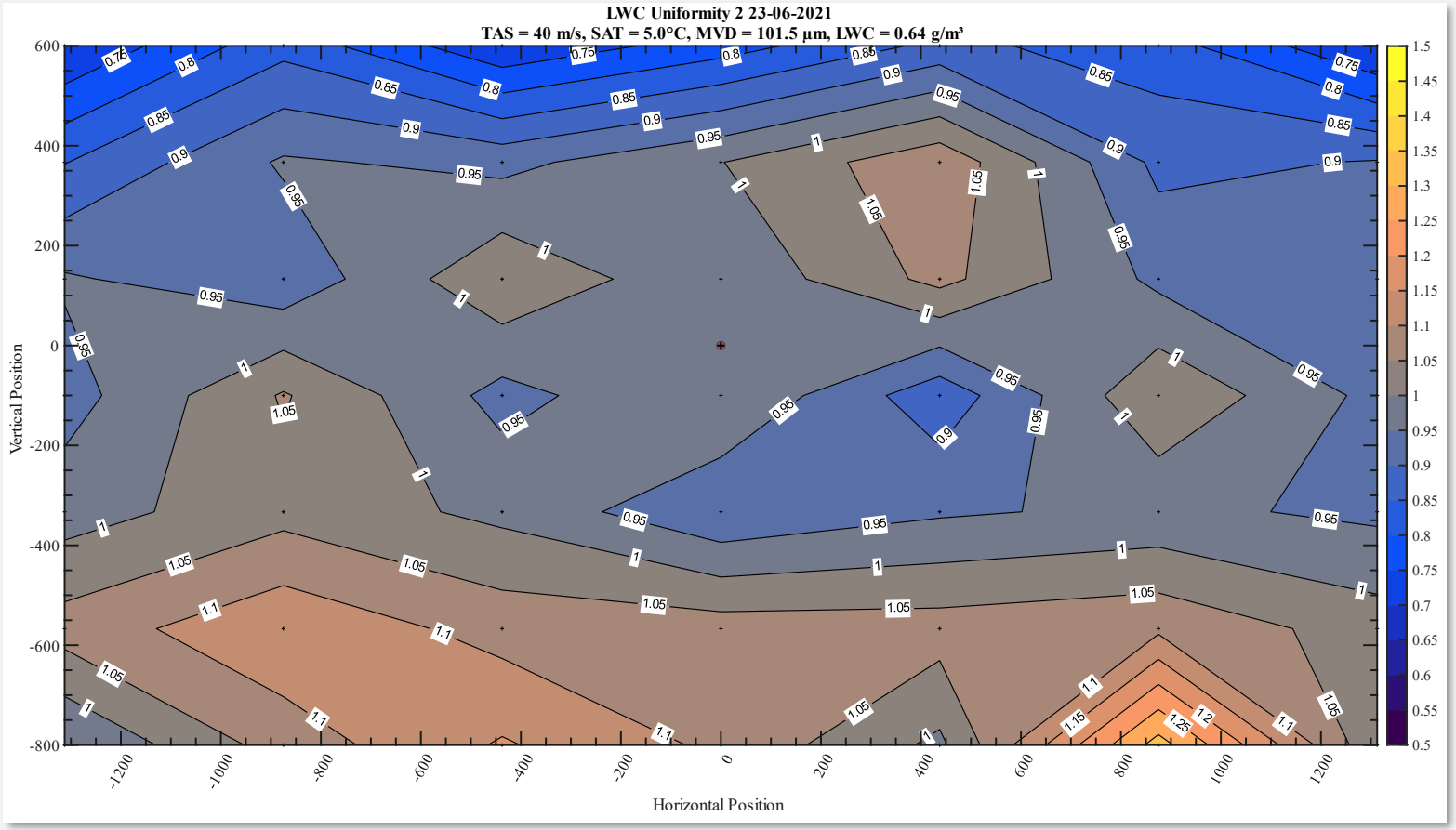
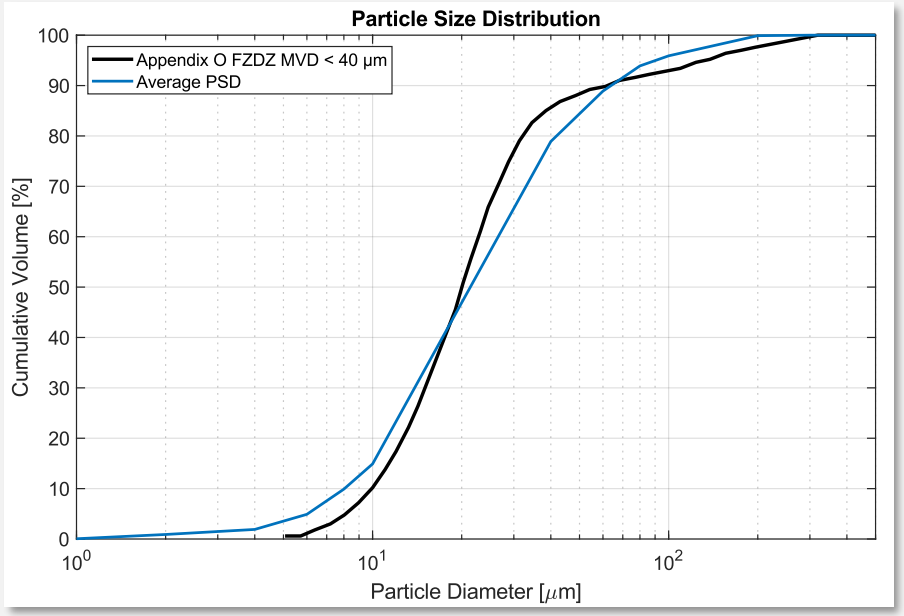


Figure 20: LWC Uniformity for "FZDZ L4" at a test section airspeed of 40 m/s, test section mapping with Nevzorov Probe, spray bars 3-11 were active

FZDZ ENVELOPES

- **FZDZ MVD < 40 µm**
  - **MVD:** 18 – 26 µm
  - **LWC:** 0.05 – 0.35 g/m³ (depending on airspeed)



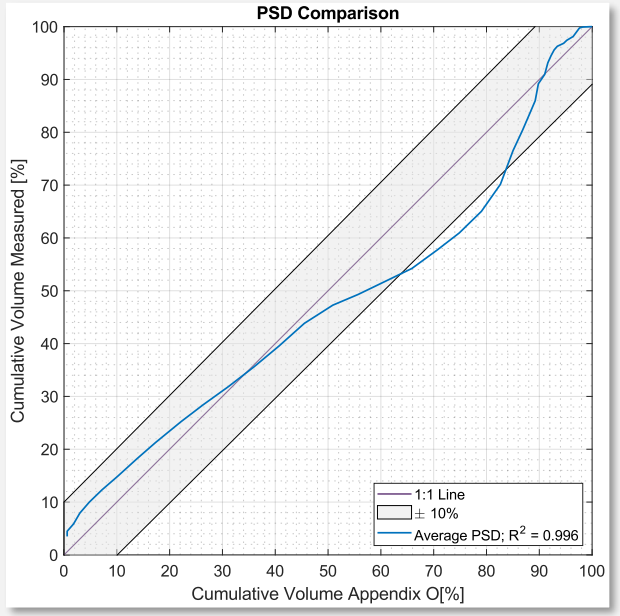


Figure 21: Average PSDs for FZDZ MVD < 40 µm compared to Appendix O requirements, cumulative volume (left), q - q plot (right)

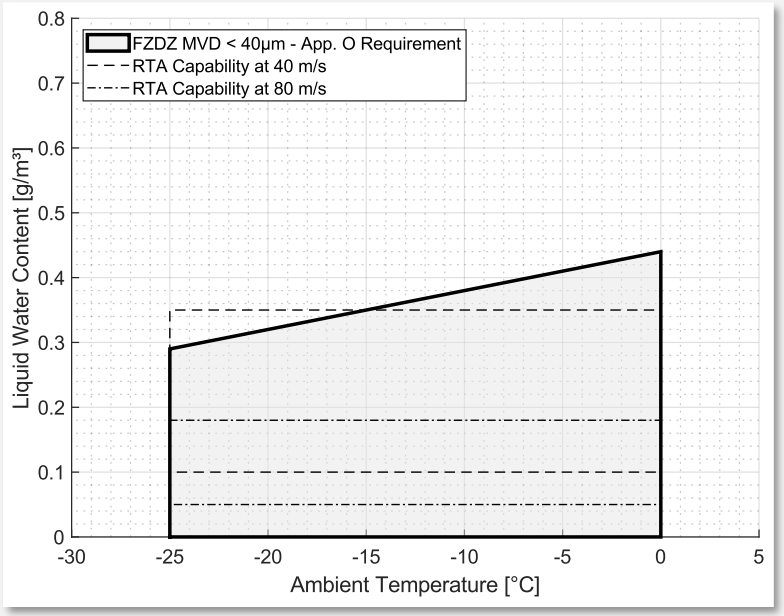
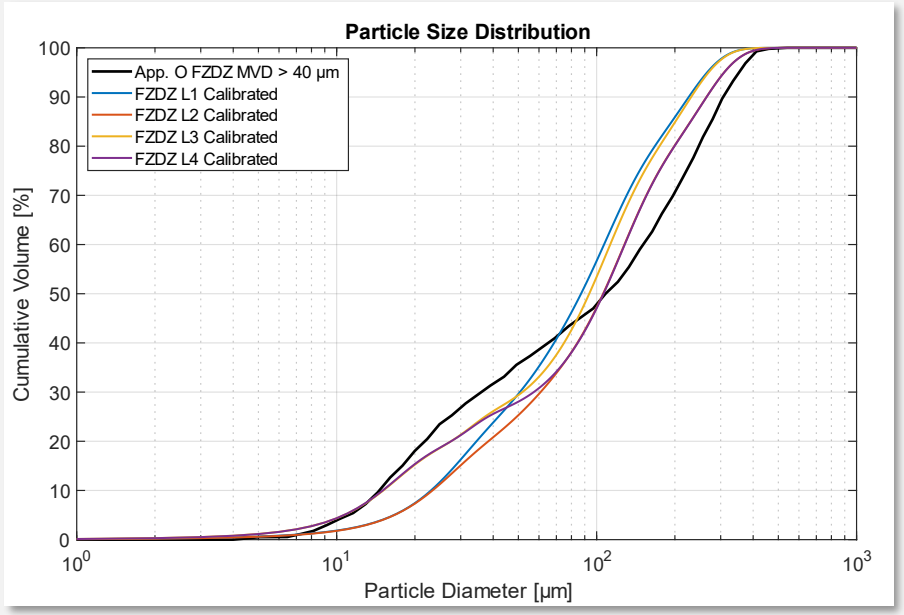


Figure 22: FZDZ < 40 µm, LWC envelope

FZDZ ENVELOPES

- **FZDZ MVD > 40 µm**
  - **MVD:** 85 – 105 µm
  - **LWC:** 0.32 – 0.71 g/m³ (depending on airspeed and MVD)



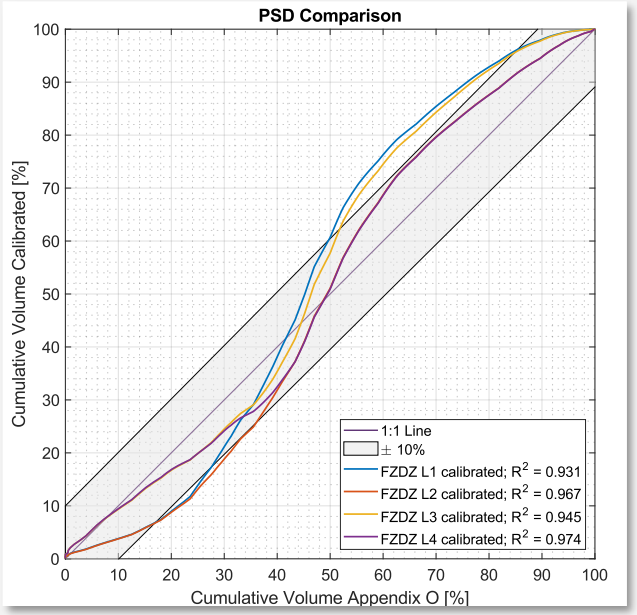


Figure 23: Average PSDs for FZDZ MVD > 40 µm compared to Appendix O requirements, cumulative volume (left), q - q plot (right)

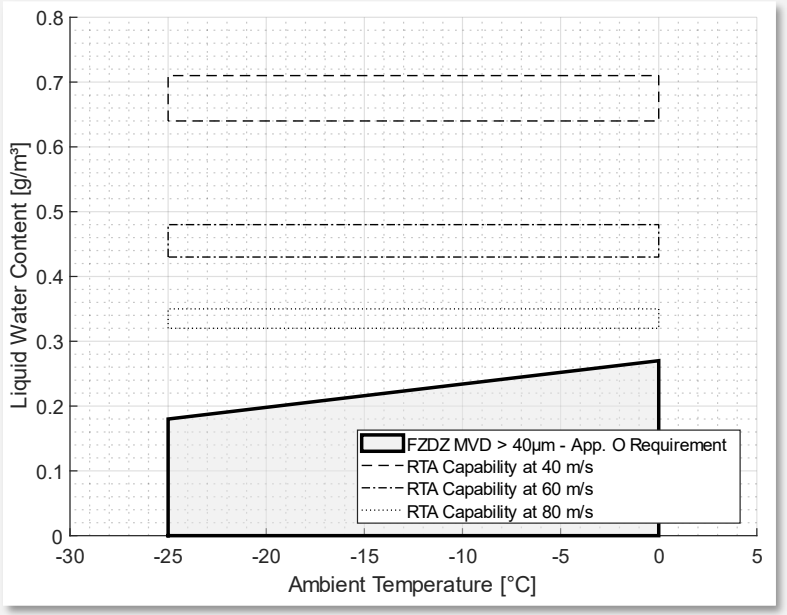


Figure 24: FZDZ > 40 µm, LWC envelope

FZDZ ENVELOPES

FZDZ MVD > 40 µm (AoA = 0°, SAT = -10.0°C, V = 60 m/s, LWC = 0.50 g/m³, 455 s)

Figure 25: FZDZ MVD > 40 µm, ice accretion on NACA0012 wing section

FZRA CAPABILITY ASSESSMENT

- **FZRA MVD > 40 µm**
  - Bimodal distribution
  - **PSD calibration**
    - Malvern Spraytec,
    - FCDP / 2D-S / PIP
  - **LWC calibration**
    - WCM2000, IKP, Nevzorov
  - **LWC Uniformity**
    - Ice accretion grid / NACA0012

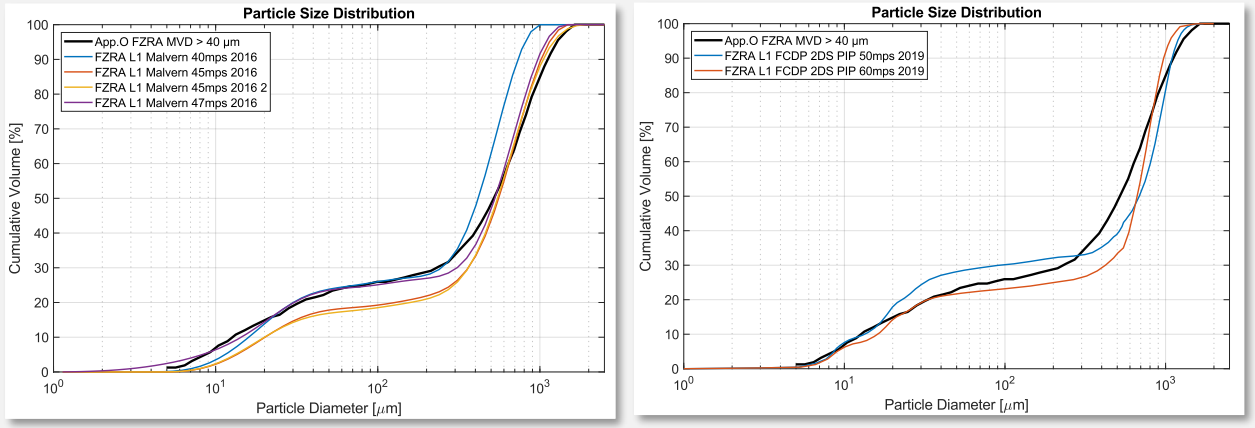


Figure 26: Measured PSDs for FZRA MVD > 40 µm, Malvern Spraytec (left), FCDP / SD-S / PIP (right)

Figure 27: Photograph of FZRA ice shape on NACA0012 wing section

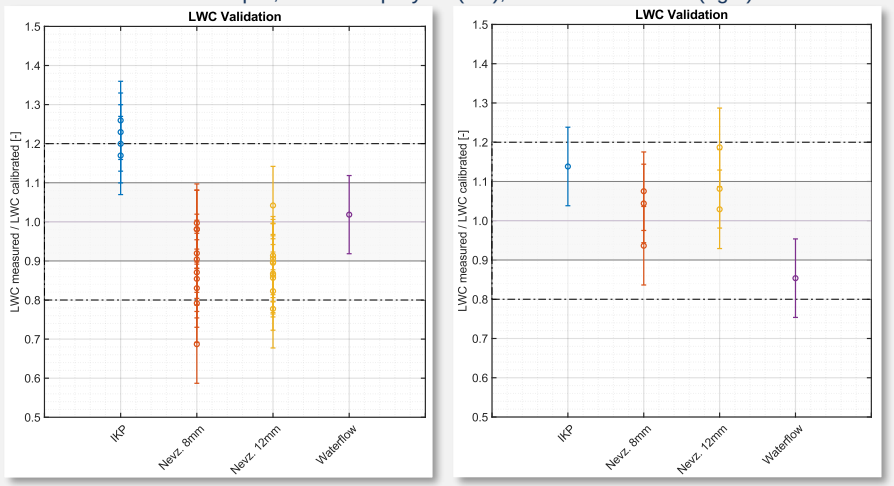
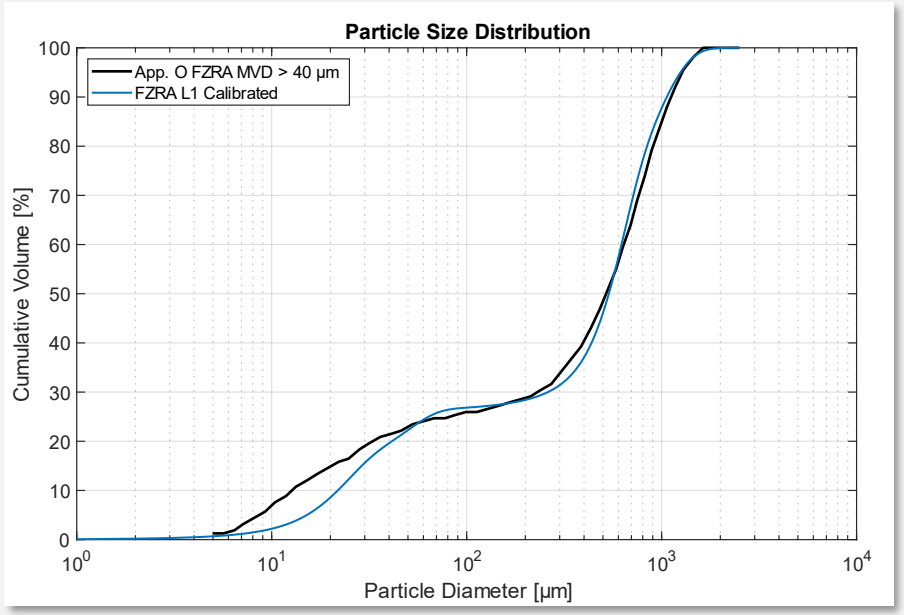


Figure 28: LWC comparison for FZRA MVD > 40 µm, full bimodal distribution (left), only large (right)

FZRA CAPABILITY ASSESSMENT

- **FZRA MVD > 40 µm**
  - **MVD:** 535 µm
  - **LWC:** 0.25 – 0.40 g/m³ (depending on airspeed)



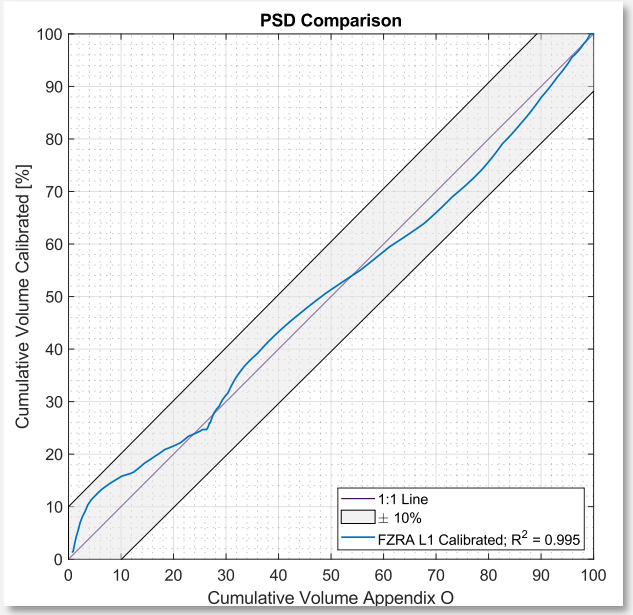


Figure 29: Average PSDs for FZDZ MVD < 40 µm compared to Appendix O requirements, cumulative volume (left), q - q plot (right)

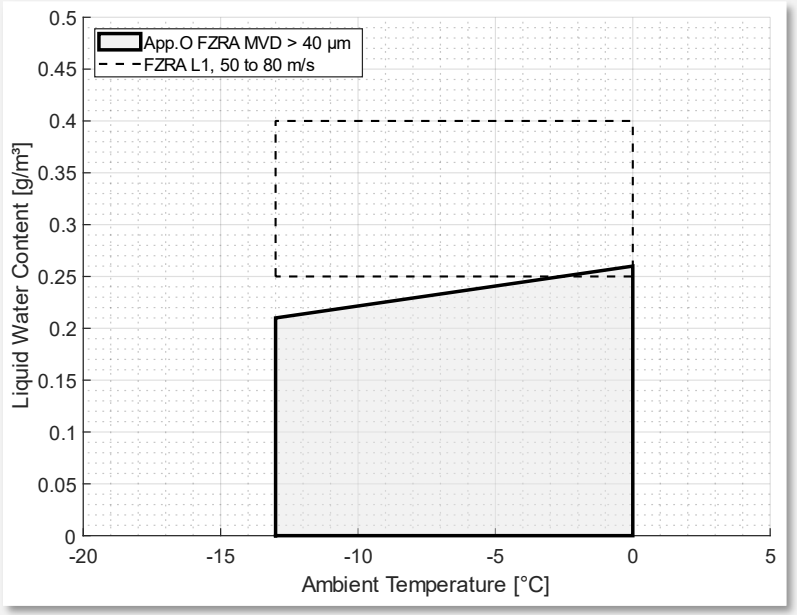


Figure 30: FZDZ < 40 µm, LWC envelope

CONCLUSIONS

- **Calibration for FZDZ conditions completed**
  - ✓ **PSDs** within 10% cum. volume can be created for FZDZ MVD < 40 µm and FZDZ MVD > 40 µm
  - ✓ **MVD** within 10% of Appendix O requirements for FZDZ MVD < 40 µm and FZDZ MVD > 40 µm
  - ✓ **LWC Uniformity** within ±20% over a large area
  - ✓ Droplet temperature investigated → large droplets are supercooled when reaching the test section
  - – **LWC** for FZDZ MVD < 40 µm slightly lower than requirements depending on airspeed
  - – **LWC** for FZDZ MVD > 40 µm higher than requirements depending on airspeed
- **ICE GENESIS TRL3**, **TRL4** and **TRL5** passed succesfully
- **FZRA capabilities were assessed**
  - PSD, and LWC content can be generated close to requirements
  - Limitations on airspeed and ambient temperature

QUESTIONS

THANK YOU

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