SENS4ICE

SENSORS AND CERTIFIABLE HYBRID ARCHITECTURES FOR SAFER AVIATION IN ICING ENVIRONMENT

# SENS4ICE project overview including flight campaigns

October 2023

Carsten Schwarz (DLR)

SAE AC-9C Aircraft Icing Technology Committee Meeting #78, October 23-25, 2023

Milwaukee (including online presentations)

This project has received funding from European Union's Horizon 2020 research and innovation programme under grant agreement n° 824253

# SENS4ICE Project Overview

## SENSors and certifiable hybrid architectures for safer aviation in ICing Environment

- JAN 2019 - DEC 2023 (extended, originally DEC 2022)
- 17 Consortium partners including coordinator DLR
- Budget:
  - total estimated eligible costs — 8.7 M EUR
  - max. EU contribution — 6.6 M EUR
  - project effort in person-months approx. — 800 PM
- https://www.sens4ice-project.eu
- #sens4iceproject on LinkedIn

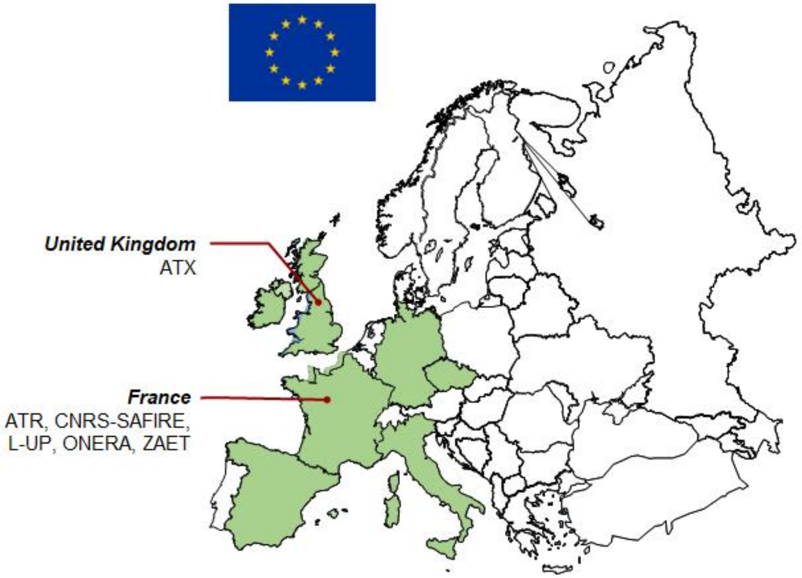
# SENS4ICE Consortium Partners

1) DEUTSCHES ZENTRUM FUER LUFT - UND RAUMFAHRT e.V. (DLR)
2) AVIONS DE TRANSPORT REGIONAL (ATR)
3) AEROTEX UK LLP
4) CENTRO ITALIANO RICERCHE AEROSPAZIALI SCPA (CIRA)
5) CENTRE NATIONAL DE LA RECHERCHE SCIENTIFIQUE (CNRS)
6) EMBRAER SA
7) HONEYWELL INTERNATIONAL SRO
8) INSTITUTO NACIONAL DE TECNICA AEROESPACIAL ESTEBAN TERRADAS (INTA)
9) LEONARDO - SOCIETA PER AZIONI
10) L-UP SAS
11) OFFICE NATIONAL D'ETUDES ET DE RECHERCHES AEROSPATIALES (ONERA)
12) TECHNISCHE UNIVERSITAET BRAUNSCHWEIG
13) COLLINS AEROSPACE IRELAND, LIMITED
14) SAFRAN AEROSYSTEMS
15) HONEYWELL INTERNATIONAL INC
16) COLLINS AEROSPACE
17) NATIONAL RESEARCH COUNCIL CANADA



BACKUP

# SENS4ICE international collaboration and cooperation


- InCo – international cooperation flagship: Aviation International Cooperation Flagship "Safer and Greener Aviation in a Smaller World"
- 17 project parties (10 countries)
  - 13 European/4 international
  - 6 research centers, 1 university, 9 industrial partners (OEMs and system developers and one SME), 1 SME consultancy partner
- Advisory Board (9 members)
  - aviation certification authorities (EASA, FAA, ANAC)
  - manufacturing (Bombardier, Gulfstream, Airbus DS, DAHER)
  - research (ITA, NLR)
  - operations (VC - *Vereinigung Cockpit*, German Pilot’s Association)
- Coordination with EU icing projects ICE GENESIS and MUSIC-haic
- Cooperation with SAE AC-9C Aircraft Icing Technology Committee

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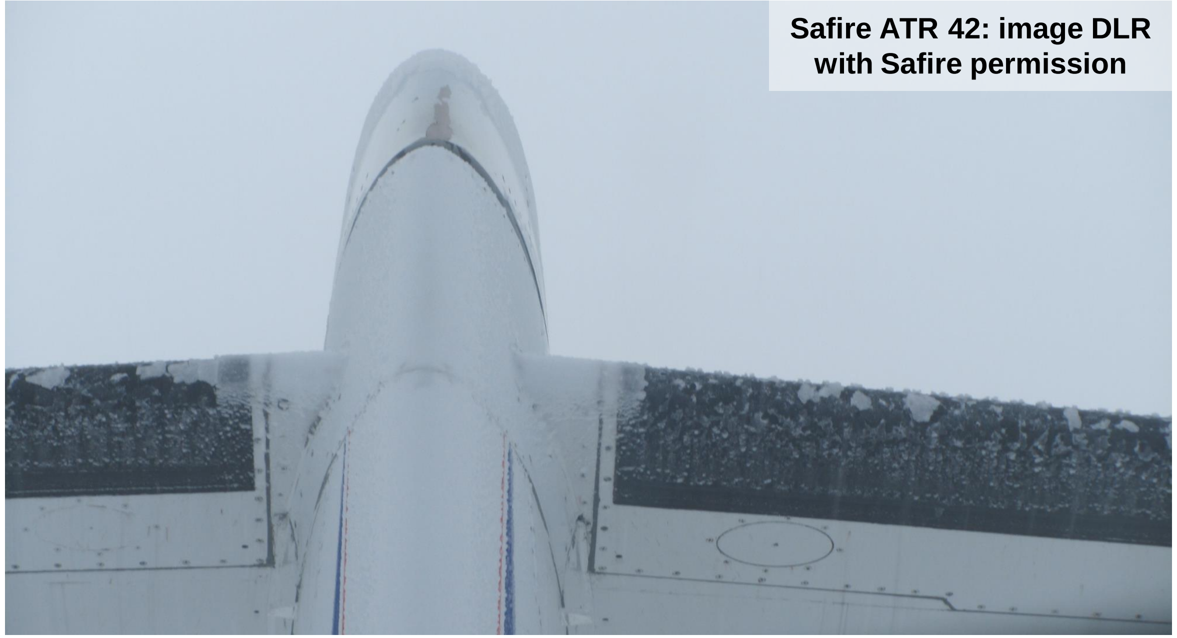
# Aircraft Icing Phenomena
# Natural Ice Shapes






- hazardous effects on aircraft
  - performance
  - dynamic behavior and
  - controls
- adaptation of operational limits required

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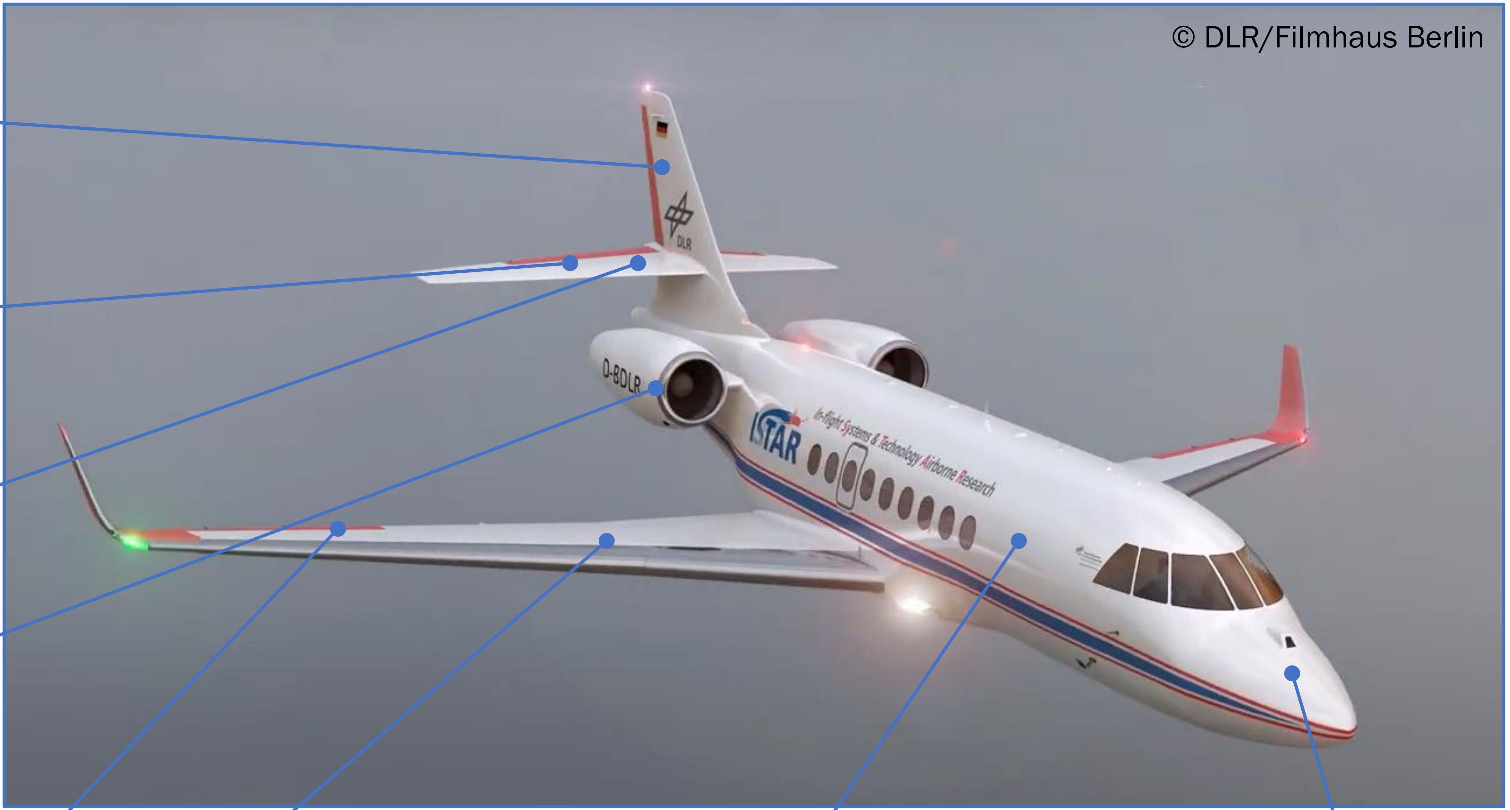
# Dangers of Icing in Flight




**Vertical Tail Plane**
- Control degradation
- Drag increase

**Elevator Gap**
- Control degradation

**Stabilizer**
- Control degradation
- Drag increase

**Engines**
- Danger of flameout or damage due to contaminants

**Aileron Gap**
- Control degradation

**Wing**
- Performance loss
- Control degradation

**Fuselage**
- Drag increase
- Collected contaminant ice layer

**Sensors**
- Malfunction
- Blockage



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# SENS4ICE Goal/ Impact

Problem

- Detect icing conditions
- Including SLD (supercooled large droplets) / App. O (CS-25 / 14 CFR Part 25) icing
- Detection very challenging

Solution

- 10 direct detection technologies
- Hybrid approach – fusion of input data: sensor(s) and indirect detection

Benefits

- Operational benefits:
  - activate anti-/de-icing
  - avoid/ leave icing conditions
- Certification process benefits – flights in App. O/ SLD icing
  - safety risk due to severe and unknown aircraft icing
  - online evaluation of safety margins during flight tests/ certification flights

# SENS4ICE
# Scope and Positioning

- SENS4ICE fills the gap of SLD icing detection (App. O)
  → hybridisation of different detection techniques
- Technology development, test, validation and maturation
  with specific regards to integration of hybrid system architectures
  → TRL 5 of hybrid system at the end of SENS4ICE
- Technology demonstration in relevant icing conditions:
  - icing wind tunnels
  - flight test
  
  → SENS4ICE will provide large data base of icing conditions
- Close cooperation with regulation authorities
  for development of new certifiable hybrid ice detection system
  → SENS4ICE will provide an acceptable means of compliance

**→ SENS4ICE contributes to increase aviation safety in SLD icing conditions**

TRL: Technology readiness level

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# Expected Impact

- Contribute to **increased flight safety**
  by fewer accidents and less in-flight events worldwide
- Contribute to **reduce costs** for all stakeholders
  by improved and internationally accepted certification rules, standards and means of compliance, covering all types of icing hazards
- Contribute to **decrease delays** in operations
  thanks to more efficient avoidance of icing hazards and to fewer damages in need of inspection and repair



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# Layered Approach on Ice Detection

SENS4ICE will address this challenge of reliably detecting and avoiding App. O SLD conditions with a unique layered safety approach:

**Strategic:** flight planning based on **new enhanced weather forecast.**

**Tactical: new nowcasting** to enhance actual situational awareness in avoidance of hazardous icing conditions.

**In situ: new hybrid detection of icing** conditions and accretion to trigger IPS and safe exit strategy

**Contingency: new detection of reduction in aircraft flight envelope** (loss of control prevention)

→ Hybrid ice detection is central technology and key to this approach

# SENSors and certifiable hybrid architectures for safer aviation in ICing Environment
# SENS4ICE

## WP 1 – Direct and indirect ice detection for App. O
- Task 1.1 – Direct ice detection sensors
- Task 1.2 – Icing wind tunnel testing and evaluation of direct ice detection sensors
- Task 1.3 – Selection of sensor technology for hybridization & airborne demonstration
- Task 1.4 – Indirect ice detection
- Task 1.5 – Remote detection of icing conditions
- Task 1.6 – Maturation of sensor technologies for airborne demonstration

## WP 2 – Hybrid ice detection architectures
- Task 2.1 – Hybrid ice detection system specification & requirements
- Task 2.2 – Means of compliance for certification
- Task 2.3 – Ice detection system implementation

## WP 3 – Airborne demonstration and atmosphere characterization
- Task 3.1 – Specification for sensor integration
- Task 3.2 – HW and SW integration on ATR platform + flight test preparation
- Task 3.3 – HW and SW integration on EBM platform + flight test preparation
- Task 3.4 – Airborne demonstration in natural icing with ATR platform
- Task 3.5 – Airborne demonstration in natural icing with Embraer platform
- Task 3.6 – Atmosphere characterization

## WP 4 – Technology evaluation
- Task 4.1 – Individual technology evaluation and roadmap for future developments
- Task 4.2 – Evaluation of hybrid ice detection
- Task 4.3 – Overall evaluation of flight test campaigns
- Task 4.4 – Evaluation of project developments and results

## WP 5 – Project management and international cooperation
- Task 5.1 – Project progress monitoring and interfacing with international partners
- Task 5.2 – Administrative, financial and quality management

## WP 6 – Communication, dissemination and exploitation
- Task 6.1 – Dissemination activities and Action Plan
- Task 6.2 – Communication
- Task 6.3 – IPR, exploitation and certification



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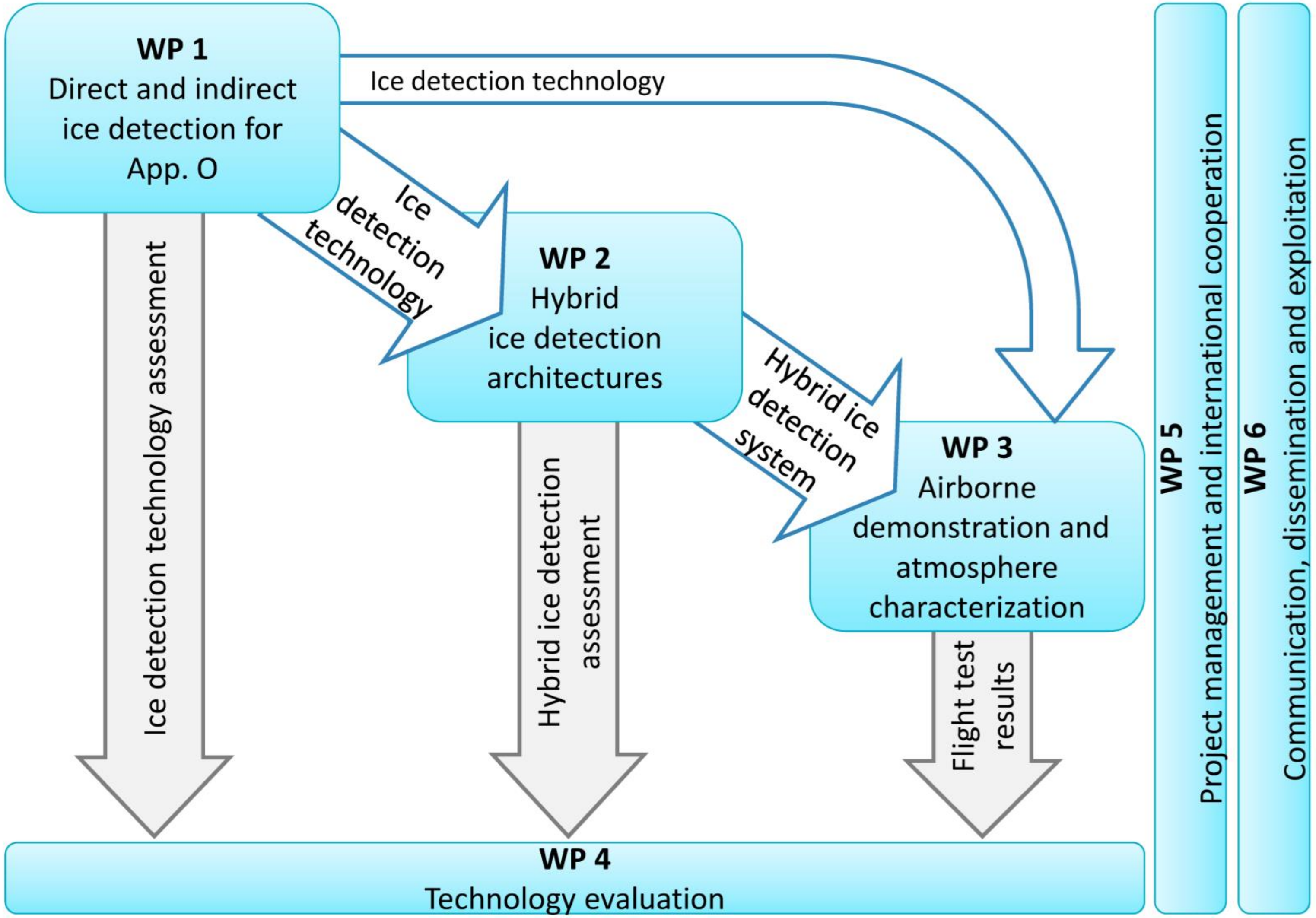
# Technical Work Packages Interrelation



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# SENS4ICE Timeline – Focus Flight Test Analysis

Develop sensors/ technologies for App. O detection

Upgrade icing wind tunnels for App. O

Icing wind tunnel testing

Sensor technology evaluation and selection

Indirect ice detection

Hybrid ice detection

Flight test preparation

Flight testing

FEB/MAR 2023

Copyright © Embraer

APR 2023

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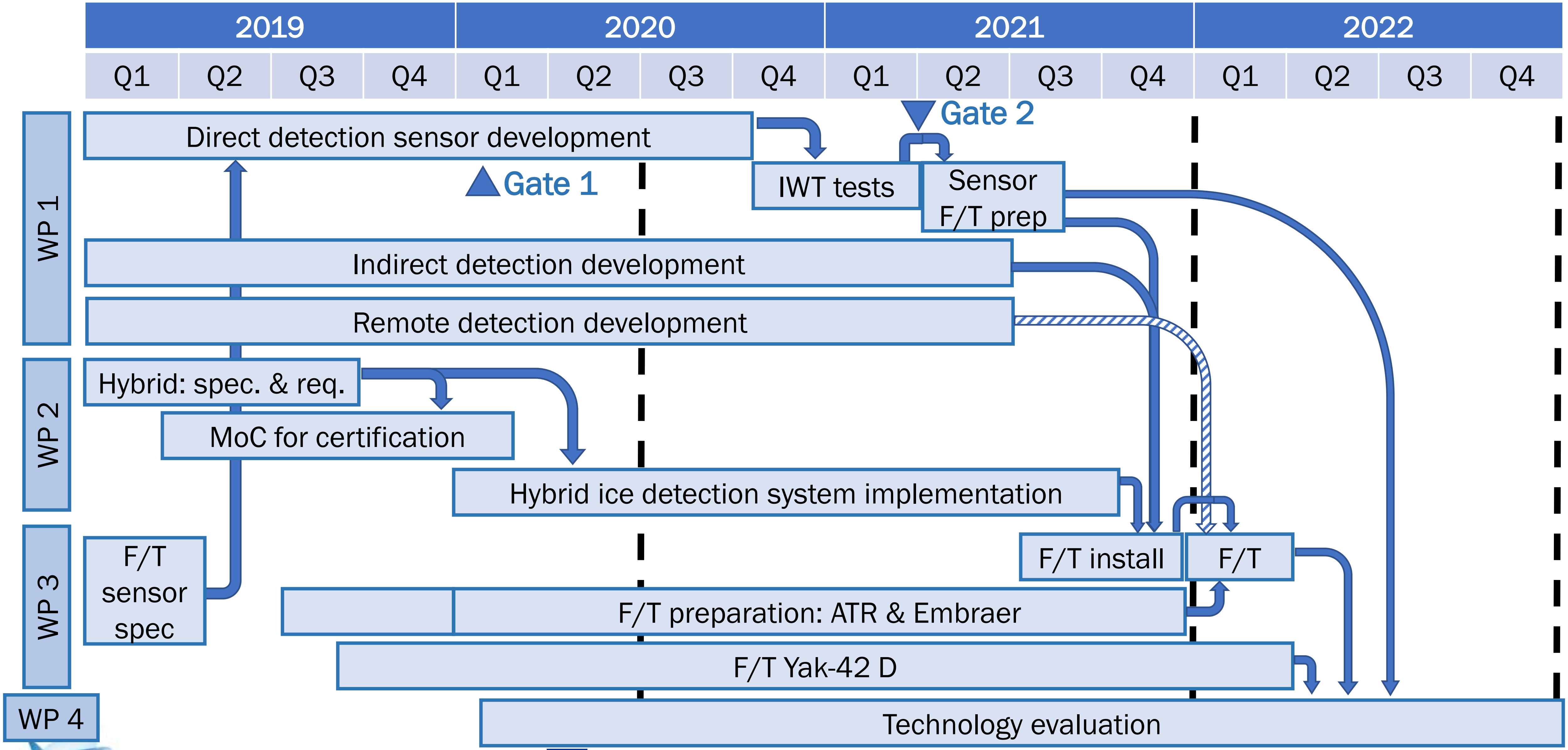
Flight test analysis

Commu-nication, Dissem-ination, Exploi-tation

**2019 - 2020** **2021** **2022** **2023**

# SENS4ICE Timescale (simplified Gantt – original/ 4 years)



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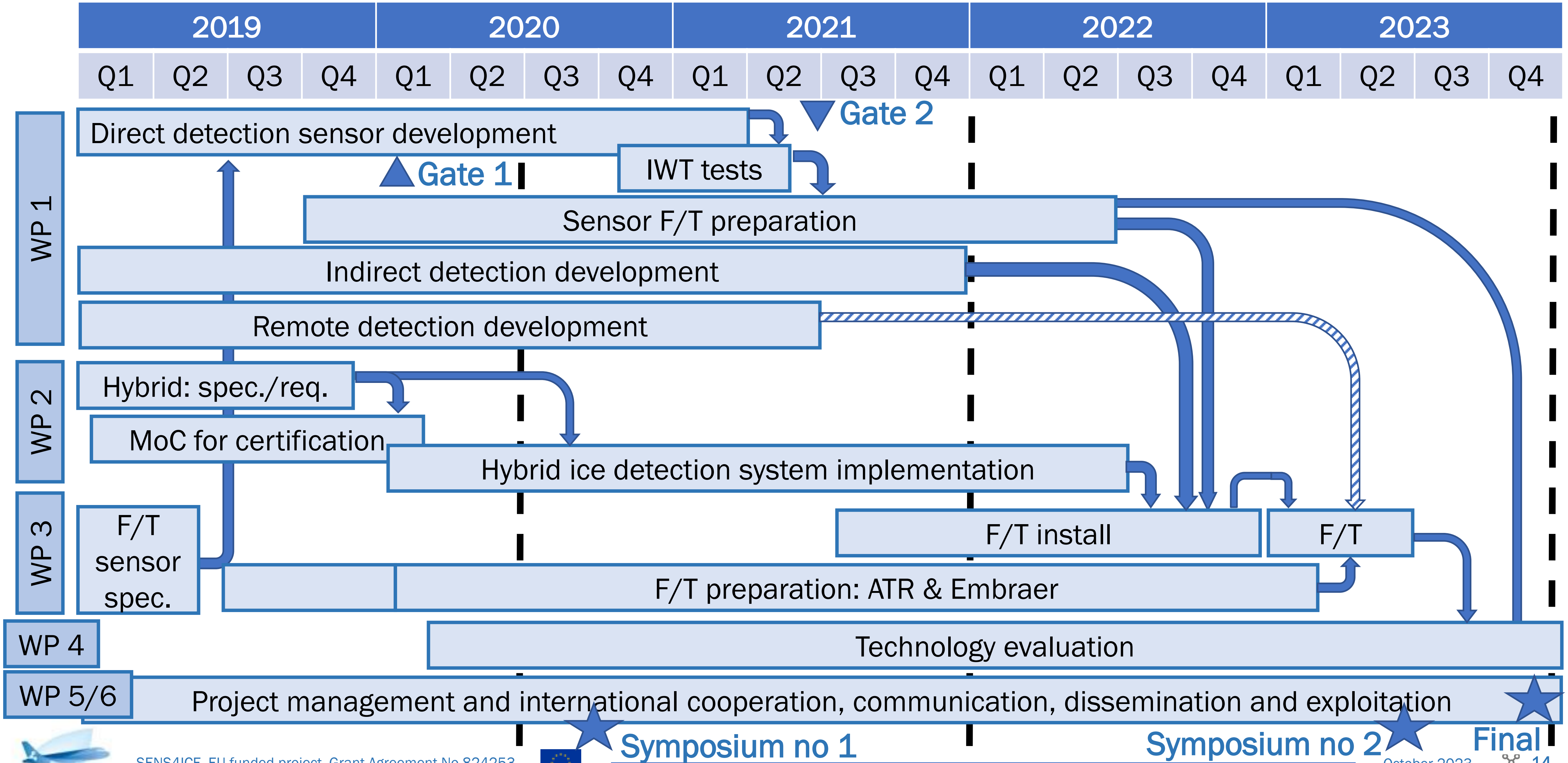
# SENS4ICE Timescale (simplified Gantt – extended/ 5 years)

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# WP1: Direct and Indirect Ice Detection for App. O High Level Objectives

Main Objective: Develop technologies capable of detecting App. O icing conditions using a three-pronged approach:

- Direct detection: development of *in situ* sensors capable of ice detection
  - 10 technologies under EU-funded development representing a variety of physical detection principles
  - Evaluation in icing wind tunnel tests under simulated App. O conditions – three tunnel facilities/total of 16 weeks testing time
  - Two-stage evaluation/selection process to ensure most promising sensors advance to flight test (WP3)
- Indirect detection: utilising existing sensor information and aircraft performance reference data for early detection of airframe icing
- Remote detection: development of methods to detect App. O conditions before the aircraft enters the hazard area
  - Detection and Nowcasting: development of algorithms that combine meteorological factors retrieved from satellite data to detect and forecast (very short-term range) icing threats in App. O conditions
  - Polarimetric weather radar: development of algorithms to classify icing threats and identify App. O conditions



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# SENS4ICE sensor technologies overview, sensor types and principles

| Developer | Sensor | Sensor Type | Sensor Principle |
|---|---|---|---|
| AeroTex | AIP - Atmospheric Icing Patch | Atmospheric | Isothermal with inertial separation at different sensors along aircraft |
| Collins | IDS - Ice Detection System | Atmospheric | Thermal response to heat impulse |
| DLR | LILD - Local Ice Layer Detector | Accretion | Ultrasonic wave attenuation / phase change |
| Honeywell | SRP - Short Range Particulate | Atmospheric | Collecting backscattered light from particles |
| INTA | FOD - Fiber Optic Detector | Accretion | Latent heat measured with fiber optic |
| ONERA | AHDEL - Atmospheric Hydrometeor Detector based on Electrostatics | Atmospheric | Particle charging and subsequent measurement of the charge |
| ONERA | AMPERA - Atmospheric Measurement of Potential and ElectRic field on Aircraft | Atmospheric | Measurement of aircraft electric potential |
| SAFRAN | AOD - Appendix O Discriminator | Atmospheric | Shadowgraphy |
| SAFRAN | PFIDS - Primary in-Flight Icing Detection System | Accretion | Optical reflection from accretion |
| DLR | CM2D - Cloud Multi-Detection Device [BCPD - Backscatter Cloud Probe with Polarization Detection] | Atmospheric | Single particle optical backscatter |
| DLR | CM2D - Cloud Multi-Detection Device [Nevzorov] | Atmospheric | Isothermal measurement of water content |



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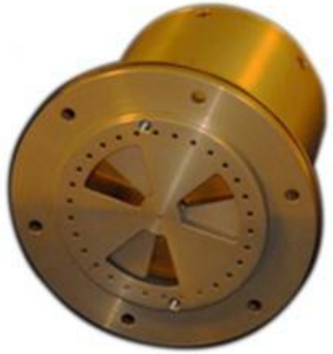
# SENS4ICE sensor technologies for direct sensing of atmospheric icing conditions or ice accretion detection (1/2)

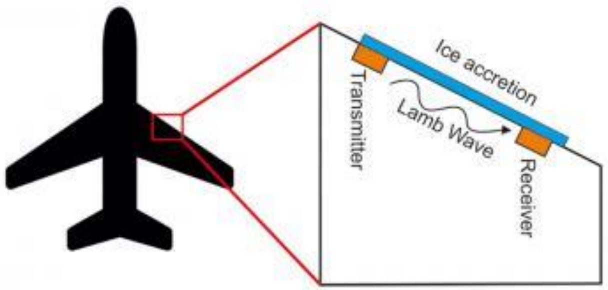
Name: *Short Range Particulate (SRP)*
Project partner: *Honeywell*
Copyrights: © Honeywell

Name: *Collins Ice Detection System (IDS)*
Project partner: *Collins Aerospace*
Copyrights: © Collins

Name: *Atmospheric Hydrometeor Detector based on Electrostatics (AHDEL)*
Project partner: *French Aerospace Lab (ONERA)*
Copyrights: © French Aerospace Lab (ONERA)



Name: *AMPERA*
Project partner: *French Aerospace Lab (ONERA)*
Copyrights: © French Aerospace Lab (ONERA)




Name: *Local Ice Layer Detector (LILD)*
Project partner: DLR (*German Aerospace Center)*
Copyrights: © DLR (German Aerospace Center)



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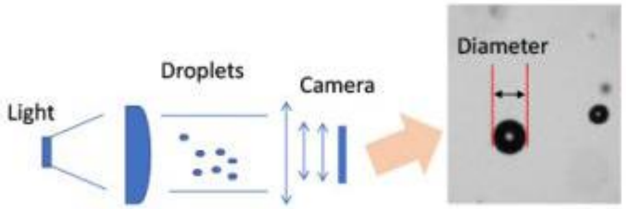
# SENS4ICE sensor technologies for direct sensing of atmospheric icing conditions or ice accretion detection (2/2)




Name: *Appendix O Discriminator (AOD)*
Project partner: *SAFRAN*
Copyrights: © SAFRAN

Name: *Atmospheric Icing Patch (AIP)*
Project partner: *AeroTex UK*
Copyrights: © AeroTex UK LLP

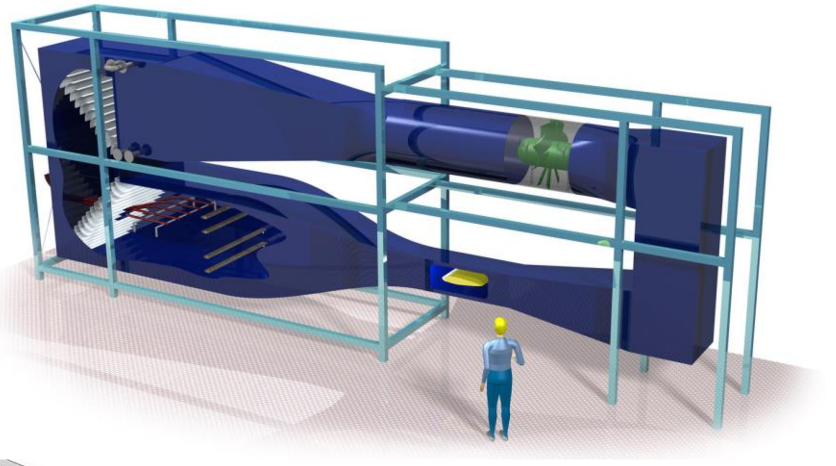
Name: *Fiber Optic Detector (FOD)*
Project partner: *INTA*
Copyrights: © INTA

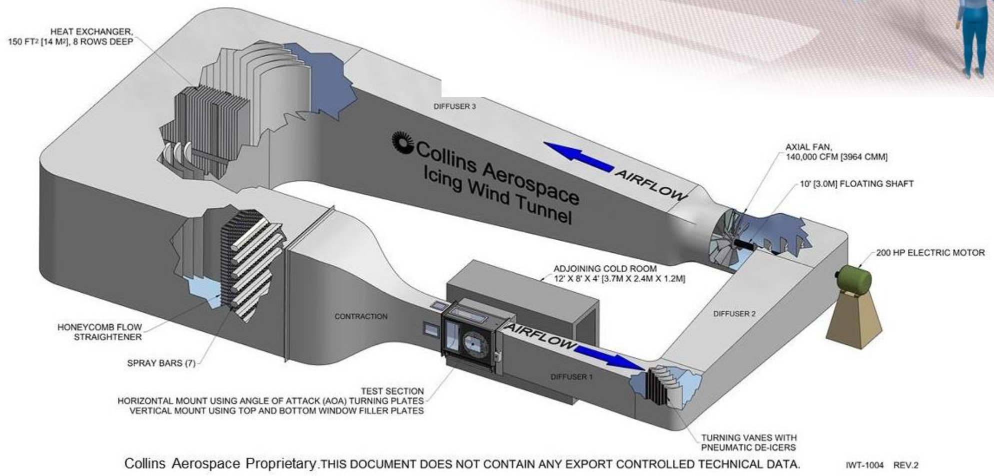
Name: *PFIDS (Primary in-Flight Icing Detection System)*
Project partner: *SAFRAN*
Copyrights: © SAFRAN

Name: *Nevzorov Probe and Backscatter Cloud Probe with Polarization Detection (BCPD)*
Project partner: *DLR (German Aerospace Center)*
Copyrights: © Skytech and © DMT

# SENS4ICE Research Facilities: Icing Wind Tunnels

- TU Braunschweig
    - SLD capabilities available and enhanced during SENS4ICE
- Collins Aerospace
    - SLD capabilities available and enhanced during SENS4ICE
- National Research Council Canada
    - SLD capabilities available
- Total testing time: 16 weeks
- Planned time frame: NOV 2020 – MAR 2021





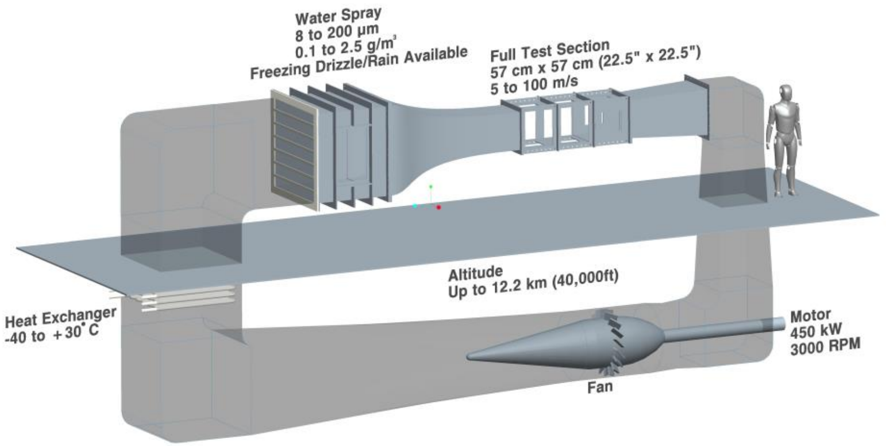
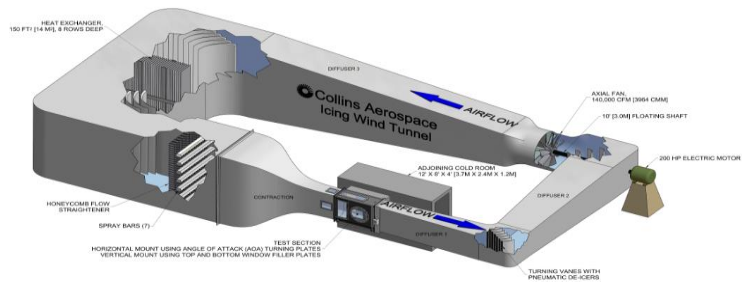




Image Credits TU Braunschweig/ Collins Aerospace/ NRC

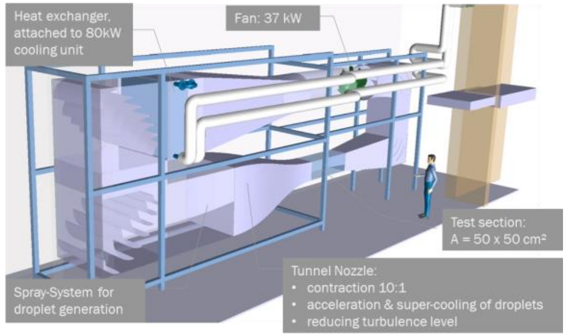
# Overview of SENS4ICE IWT Capabilities

## Collins Aerospace, USA



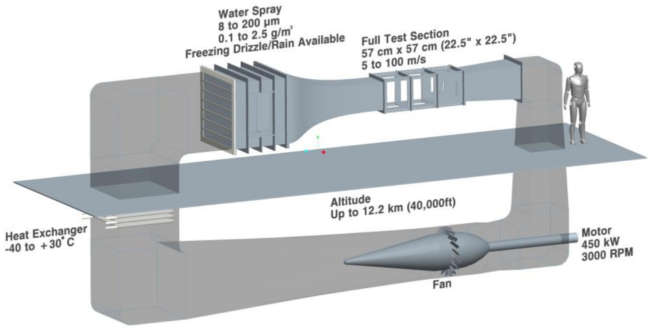

- 5-147 micron droplets
- LWC between 0.1 and 3 g/m3
- Temperature 0°C to -30°C
- Sustained speed 13-103 m/s
- Test section: 152×56×112 cm3
- Calibrated per SAE ARP 5905
- Compliant with AS9100C
- Controls and power supplies can simulate aircraft controls

## TU Braunschweig, Germany




- MVD 9-200 micron droplets
- LWC between 0.1 and 1.5 g/m3
- Temperature 30°C to -20°C
- Sustained speed 10-40 m/s
- Test section: 150×50×50 cm3
- Calibrated per SAE ARP 5905
- Short spray transients ~ 15s
- Bi-modal SLD and mixed phase capability

## NRC, Canada




- 8-200 micron droplets
- LWC between 0.1 and 2.5 g/m3
- Supercooled Water: 10 to > 200 µm (incl. SLD bi-modal)
- Temperature +30°C to -40°C
- Sustained speed 5-100 m/s
- Test section: 57×57 cm2 (52x33 cm2 with insert)
- Sea level < Altitude < 40,000ft
- Calibrated per SAE ARP 5905

- Dedicated common test points defined for all involved SENS4ICE IWT



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# Common Test Points Between IWT Facilities TUBS, Collins and NRC

| IWT | App C | | | | | |
|---|---|---|---|---|---|---|
| | Total Test Points | Common with 3 IWT | Common with 2 IWT | Only at 1 IWT | CM Test Points | IM Test Points |
| TUBS | 19 | 4 | 1 | 14 | 10 | 9 |
| Collins | 18 | 4 | 3 | 10 | 9 | 9 |
| NRC | 19 | 4 | 4 | 11 | 9 | 10 |
| | App O | | | | | |
| | Total Test Points | Common with 3 IWT | Common with 2 IWT | Only at 1 IWT | Total Points [unimodal] | Total Points [bimodal] |
| TUBS | 18 | 0 | 1 | 17 | 0 | 18 |
| Collins | 6 | 0 | 1 | 5 | 6 | 0 |
| NRC | 17 | 0 | 2 | 15 | 4 | 13 |

# Collins IWT SENS4ICE Test Matrix

| Case | Condition | Airspeed | Static Temp. | MVD | LWC |
|---|---|---|---|---|---|
| [-] | [-] | [m/s] | [deg. C] | [µm] | [g/m^3] |
| 1 | LW-C CM | 40 | -20 | 15 | 0.30 |
| 2 | LW-C CM | 40 | -10 | 20 | 0.42 |
| 3 | LW-C CM | 40 | -1 | 23 | 0.54 |
| 4 | LW-C CM | 67 | -2 | 15 | 0.80 |
| 5 | LW-C CM | 67 | -20 | 18 | 0.25 |
| 6 | LW-C CM | 67 | -10 | 20 | 0.42 |
| 7 | LW-C CM | 85 | -30 | 17 | 0.17 |
| 8 | LW-C CM | 85 | -20 | 15 | 0.30 |
| 9 | LW-C CM | 85 | -10 | 23 | 0.34 |
| 10 | LW-C IM | 40 | -20 | 22 | 1.50 |
| 11 | LW-C IM | 40 | -1 | 20 | 2.50 |
| 12 | LW-C IM | 40 | -10 | 28 | 1.20 |

| Case | Condition | Airspeed | Static Temp. | MVD | LWC |
|---|---|---|---|---|---|
| [-] | [-] | [m/s] | [deg. C] | [µm] | [g/m^3] |
| 13 | LW-C IM | 67 | -2 | 23 | 2.00 |
| 14 | LW-C IM | 67 | -20 | 30 | 0.80 |
| 15 | LW-C IM | 67 | -10 | 25 | 1.40 |
| 16 | LW-C IM | 85 | -30 | 20 | 1.00 |
| 17 | LW-C IM | 85 | -20 | 23 | 1.30 |
| 18 | LW-C IM | 85 | -10 | 32 | 0.80 |
| 19 | unimodal | 76 | -17.7 | 122.3 | 0.46 |
| 20 | unimodal | 76 | -17.7 | 189.5 | 0.56 |
| 21 | unimodal | 76 | -17.7 | 169.1 | 0.78 |
| 22 | unimodal | 76 | -17.7 | 183.8 | 0.78 |
| 23 | unimodal | 76 | -17.7 | 155.4 | 0.94 |
| 24 | unimodal | 76 | -17.7 | 163.5 | 0.82 |



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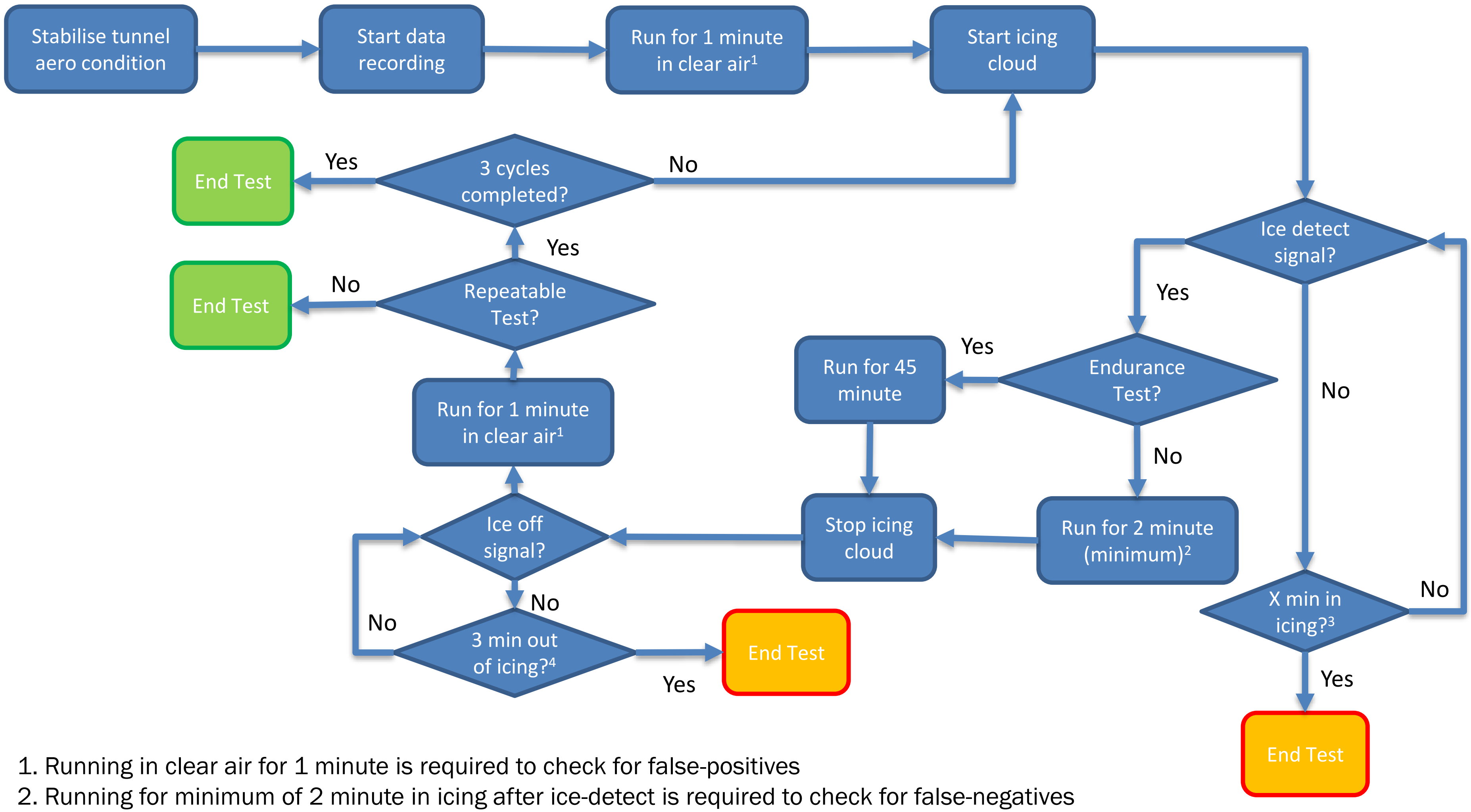
# IWT Test Procedures – App C Conditions



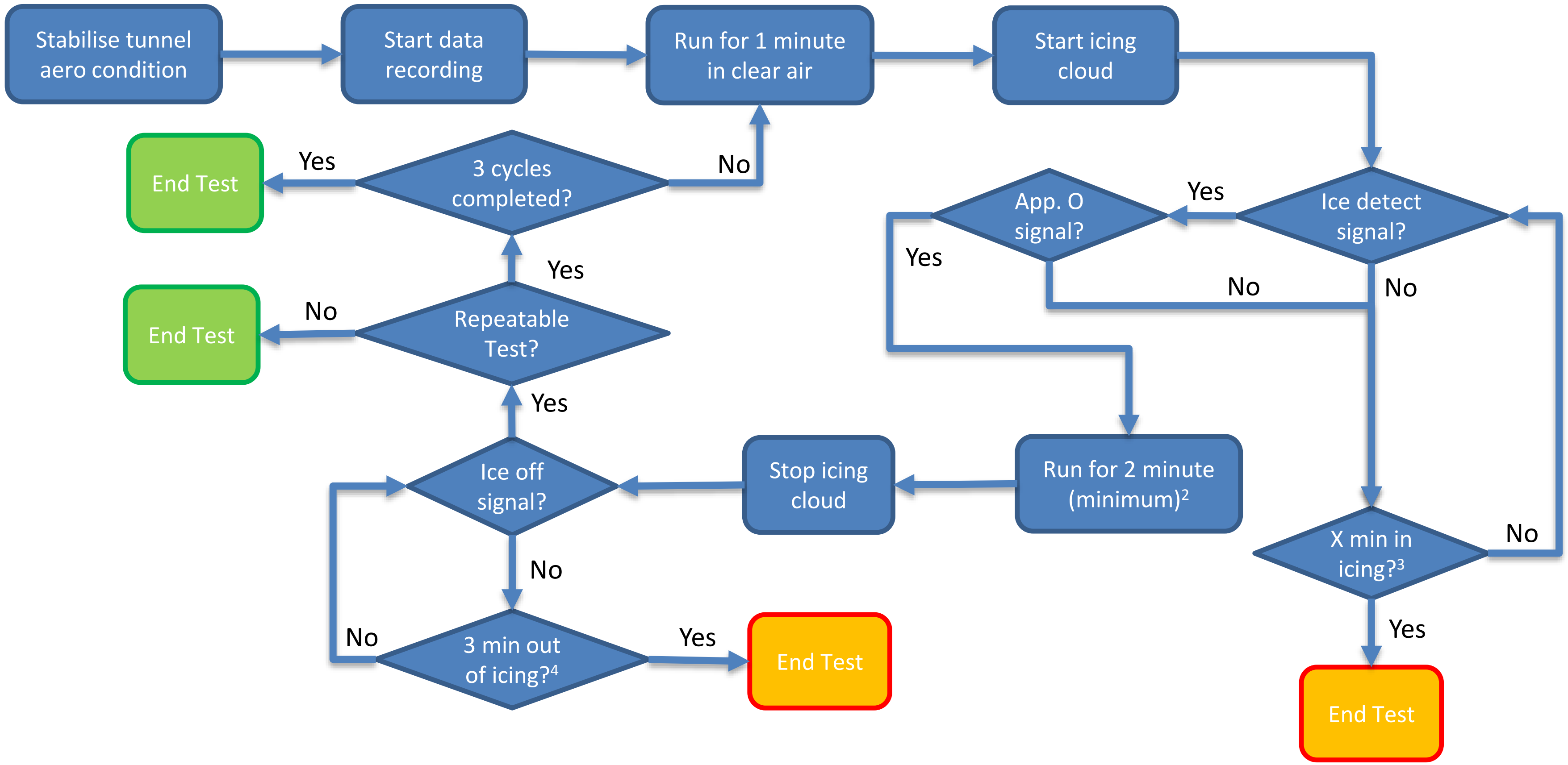

Notes:

1. Running in clear air for 1 minute is required to check for false-positives
2. Running for minimum of 2 minute in icing after ice-detect is required to check for false-negatives
3. X is the target calculated detection time + 1 minute
4. Based on AS5498A time to detect exit being a maximum of 3 minutes



**BACKUP**

# IWT Test Procedures – App O Conditions




Notes:
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4. Based on AS5498A time to detect exit being a maximum of 3 minutes

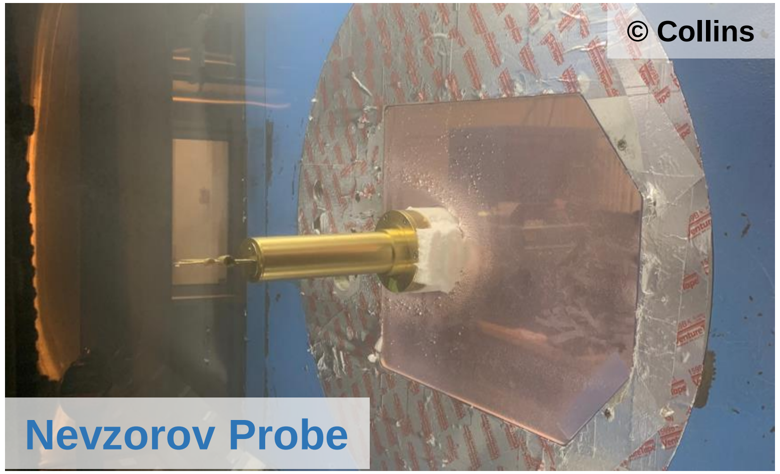


BACKUP

# SENS4ICE Reference Measurements
# CCP & Nevzorov Probes at Collins Icing Wind Tunnel

- Nevzorov probe
  2 days of testing at Collins
  - Completed entirety of App C and App O test matrices

- Cloud Combination Probe (CCP) probe
  3.5 days of testing at Collins
  - Completed entirety of App. C and App O. test matrices
  - During test only one of CCP probe's measurement volumes could be positioned in tunnel centerline at a time
  - For that reason, many test conditions were repeated in two configurations so that data could be collected with each measurement volume centered in the tunnel.




Nevzorov Probe


CCP Probe

[El Hassan Ridouane (Collins), SENS4ICE Icing Wind Tunnel Capabilities and Test Procedures, SENS4ICE first public project symposium, SAE AC-9C Aircraft Icing Technology Committee Meeting 22 OCT 2020]





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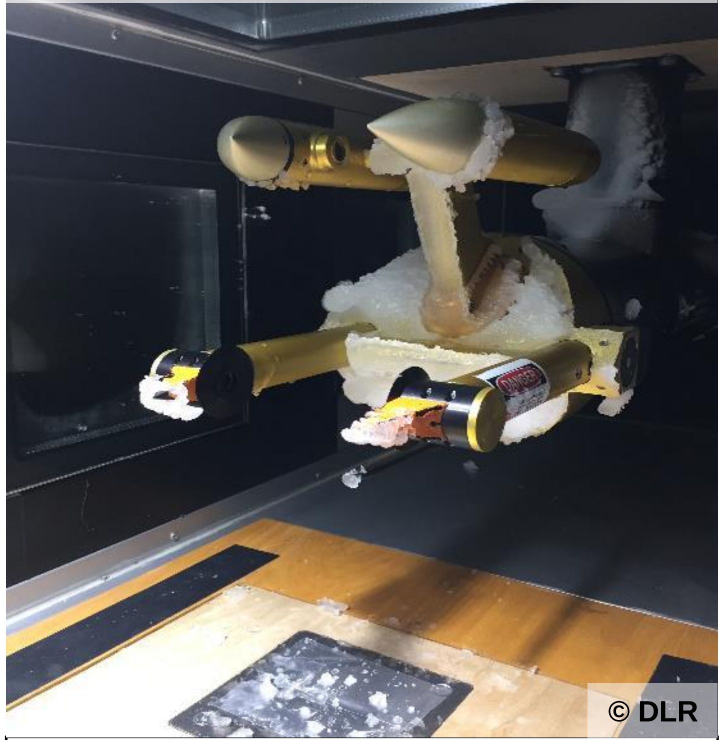
# SENS4ICE Reference Measurements
## CCP (CDP & CIP) & Nevzorov Probes at TUBS Icing Wind Tunnel

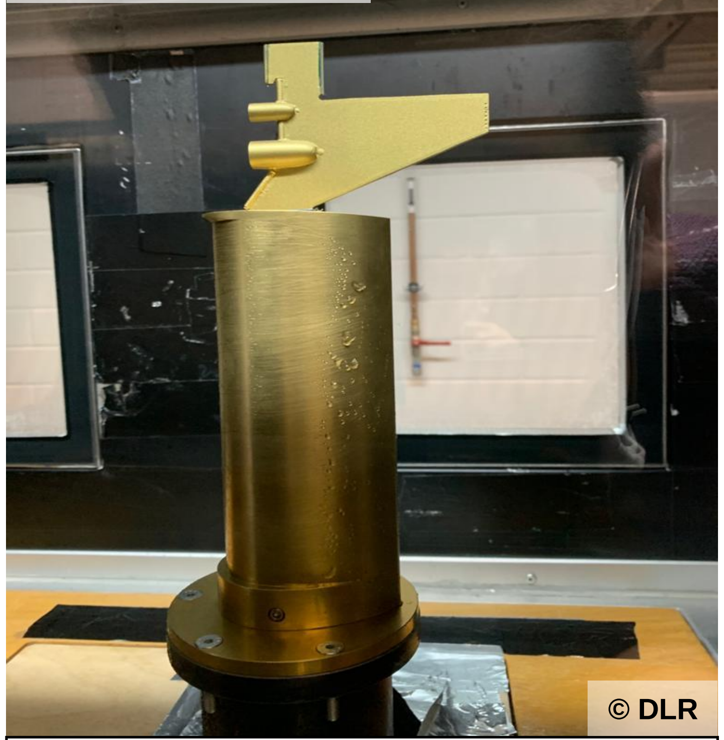
Reference measurement wind tunnel testing in Appendix C and O conditions was conducted during three weeks in January and July 2020

### Cloud Combination Probe (CCP)




CDP size range : 2 – 50 µm
CIP size range: 15 – 950 µm

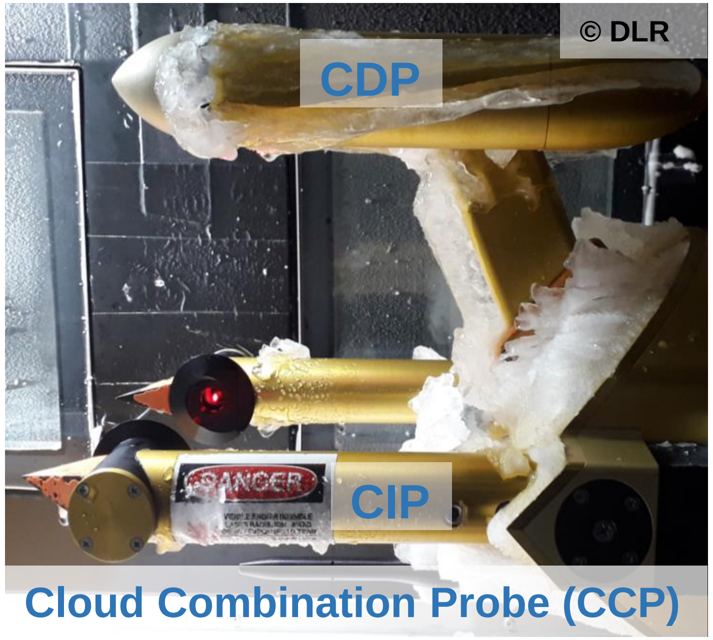
### Nevzorov Probe

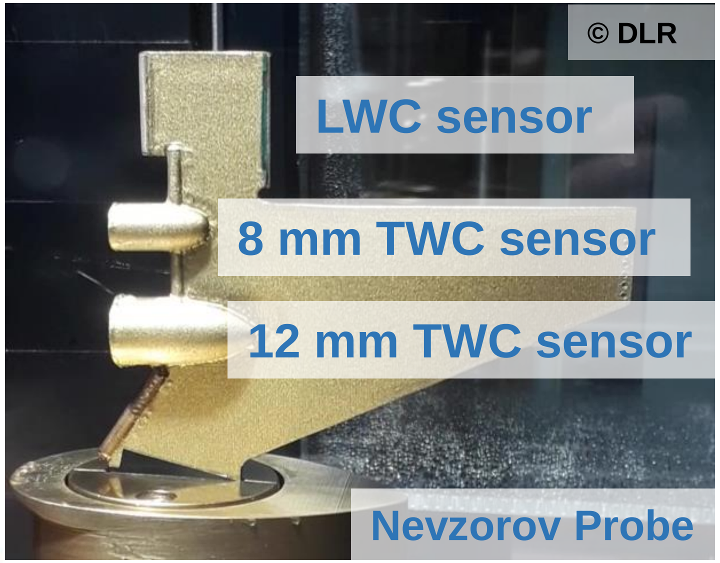



LWC sensitivity: 0.003 g/m³
Air speed range: 10 – 180 m/s

BACKUP

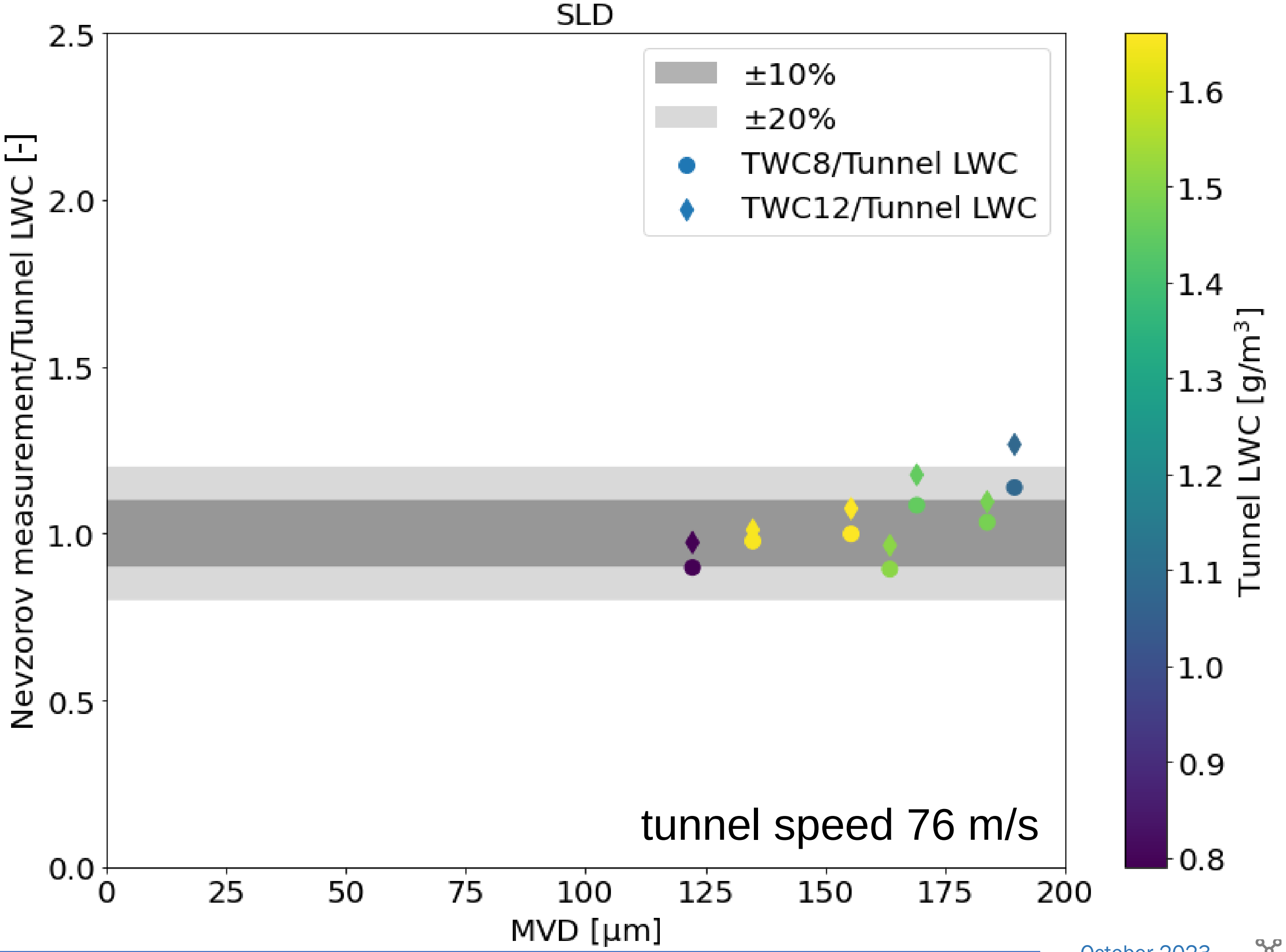
# Reference Instrumentation & Measurements




Reference measurements (Nevzorov probe) in SLD conditions

- generally good agreement with tunnel LWC data (SEA probe)
- for MVDs < 180 µm, Nevzorov and SEA probe agree within 20%

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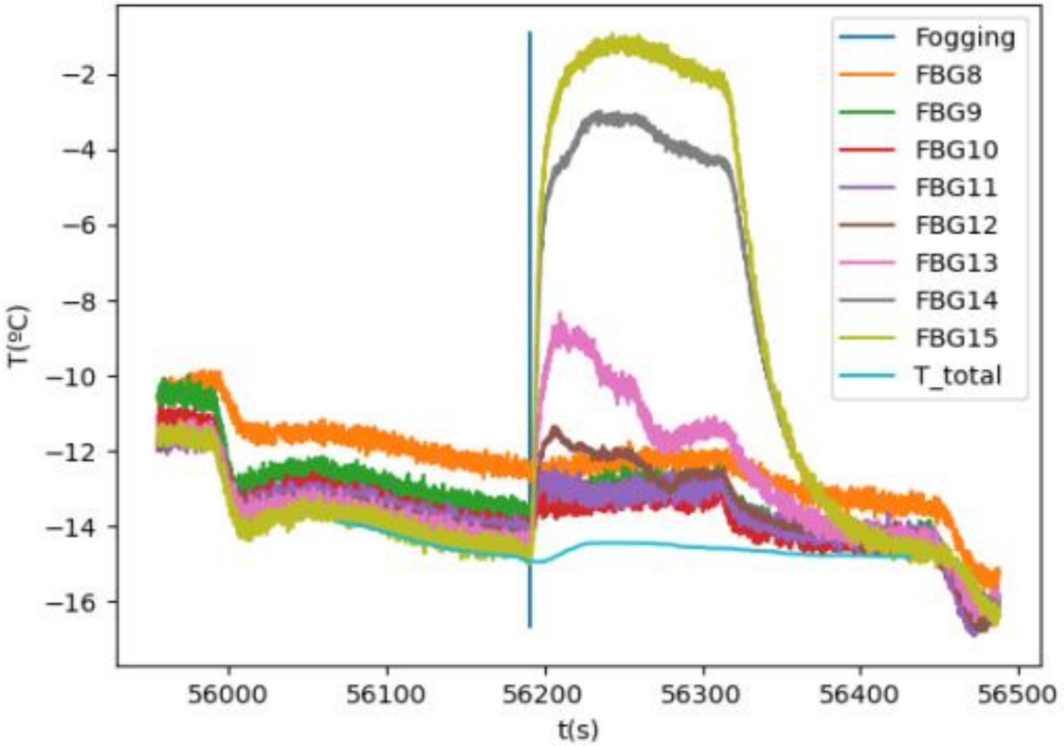
# FOD (Fiber Optic Detector) – using Fiber Bragg Grating Sensors (FBGSs)

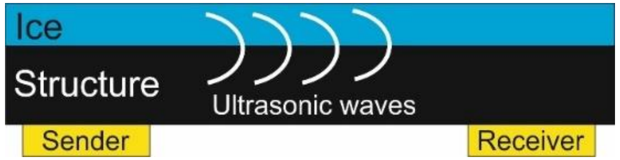
- FBGS are integrated in the surface of an airfoil to provide temperature measurements over the chord.
- Measurements are compared with a heat and mass balance model.
- Based on this a prediction for liquid water content (LWC) and ice accretion rate (IAR) is generated.
- IWT results show a good correlation with theoretical calculations. The following capabilities have been demonstrated: detect beginning and end of ice accretion, LWC and IAR quickly and with good precision.
- The different measurement locations over the cord of the airfoil allow to clearly distinguish the temperature distribution.



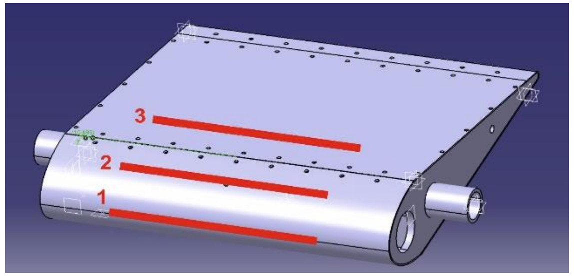

FOD temperature time histories at NRC AIWT for different measurement locations over the airfoil chord (“FBG 8 – 15") and the total temperature for Appendix O conditions (LWC = 0.82 g/m^3, MVD = 163.5 µm; V = 76 m/s, start time of icing cloud marked by a vertical line “Fogging”)

**BACKUP**

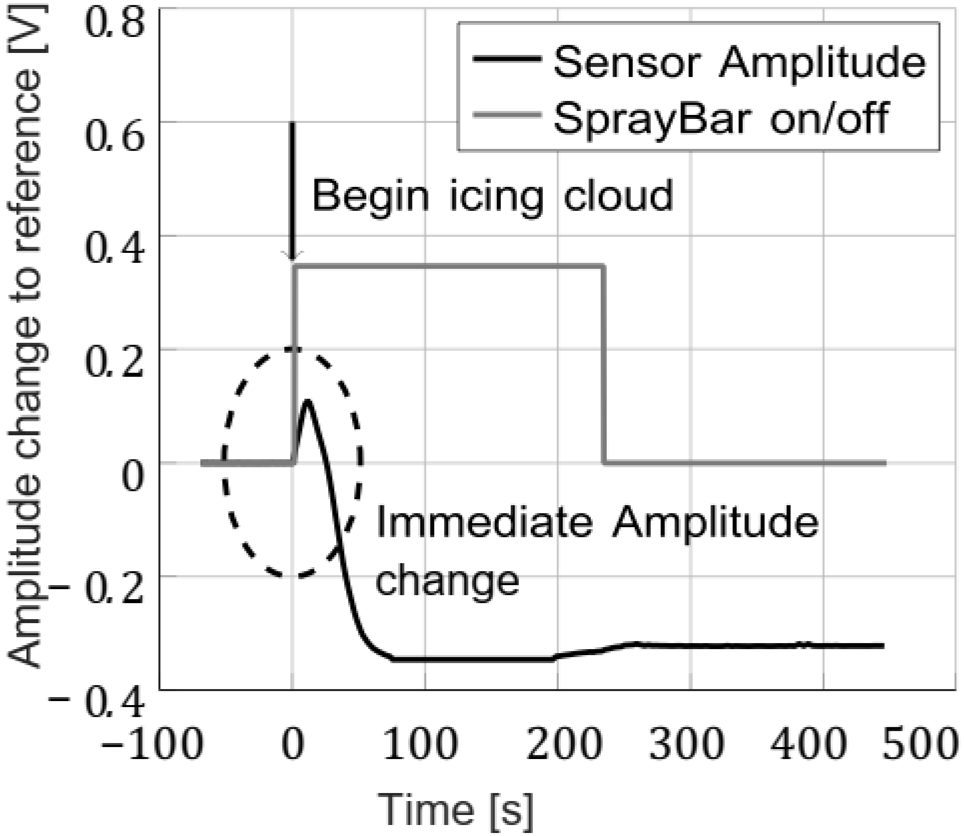
# Local Ice Layer Detector (LILD)



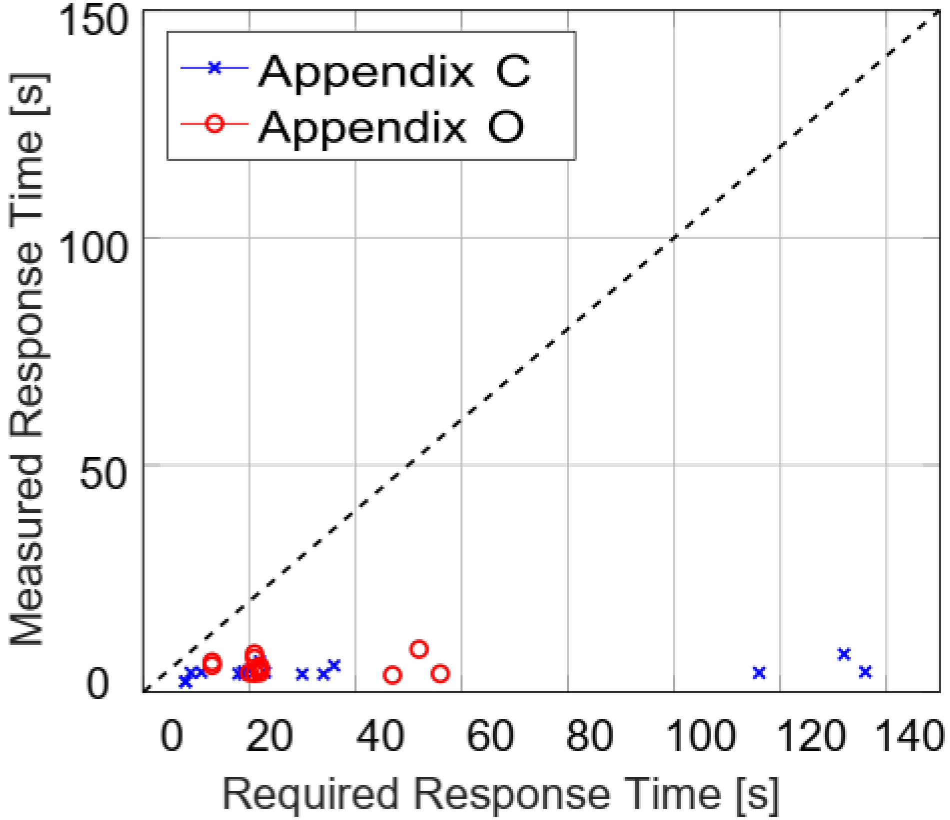

LILD principle of travelling ultrasonic lamb waves




Lamb wave measurement channels marked in red for IWT test




LILD immediate lamb wave amplitude reaction of the received pulse upon icing conditions start for exemplary Appendix C test case (MVD = 21.1 µm, LWC = 0,98 g/m^3, T = -10 °C)



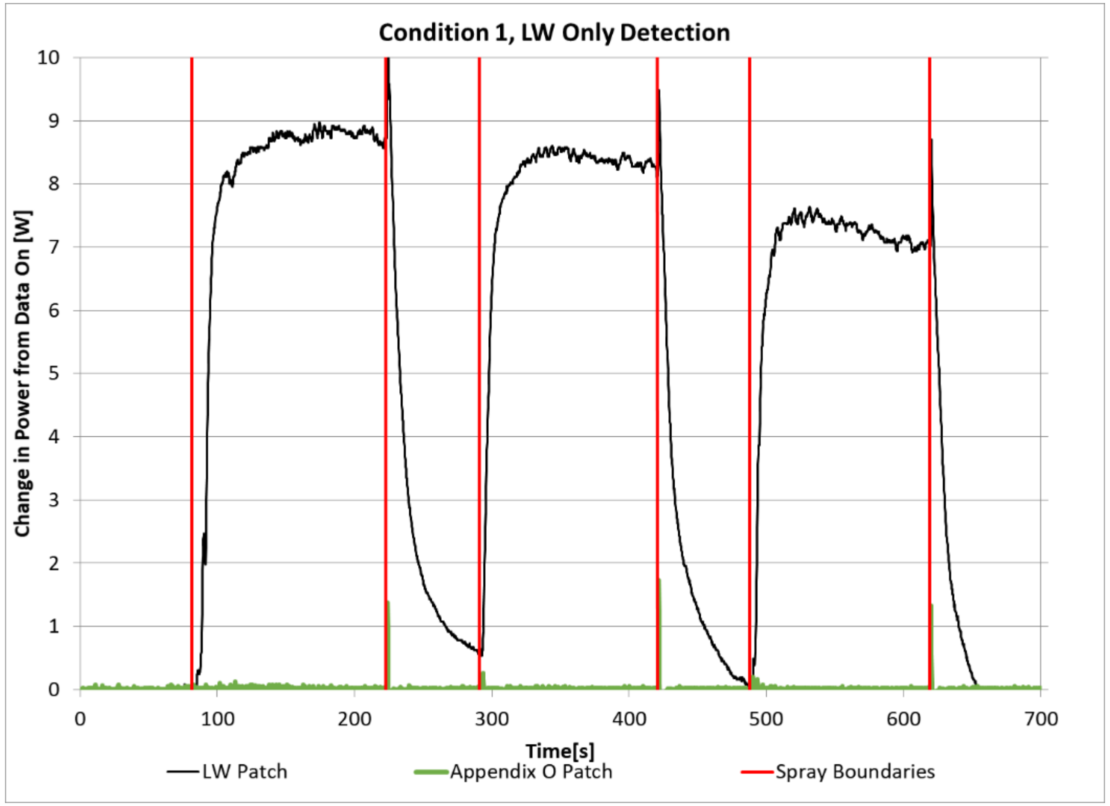

LILD response times for Appendix C and O conditions measured at BIWT compared to the required response time



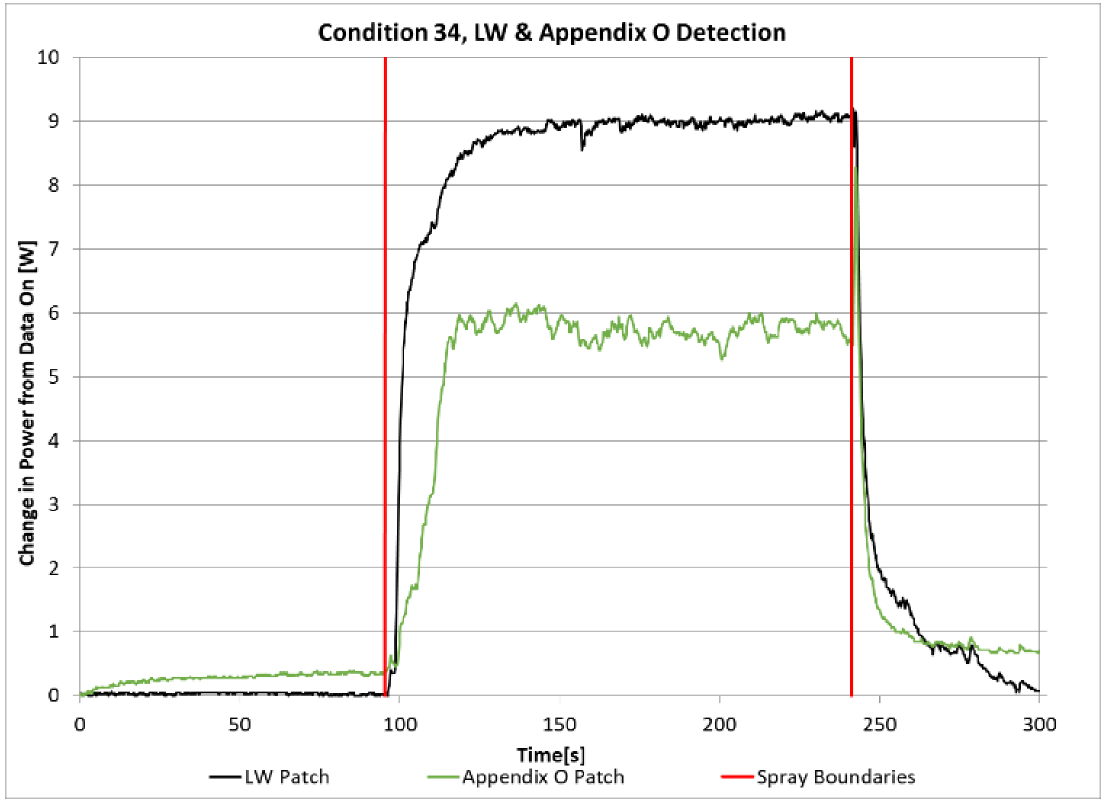
**BACKUP**

# Atmospheric Icing Patch – AIP

## consisting of an array of low power (< 28W) iso-thermal ice detection sensors

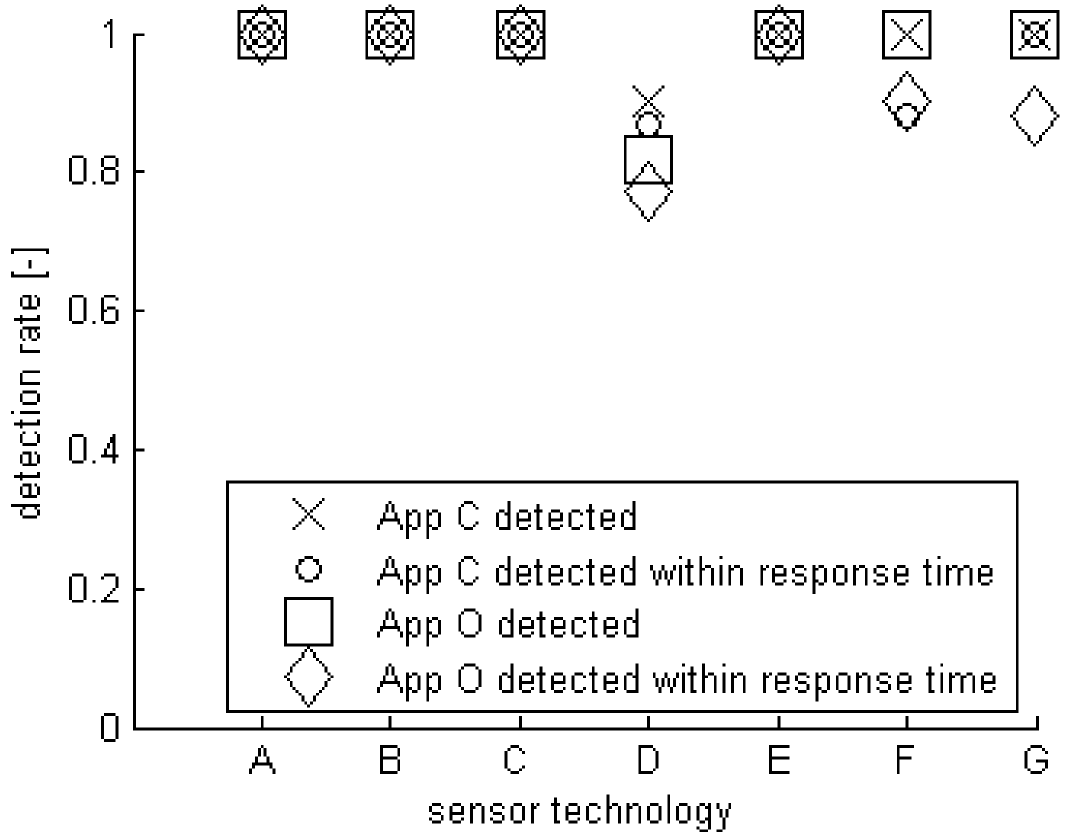



Example of AIP patch power response in small droplet icing conditions (note Appendix O patch shows no response)




Example of AIP patch power response in large droplet icing conditions (note Appendix O patch response)

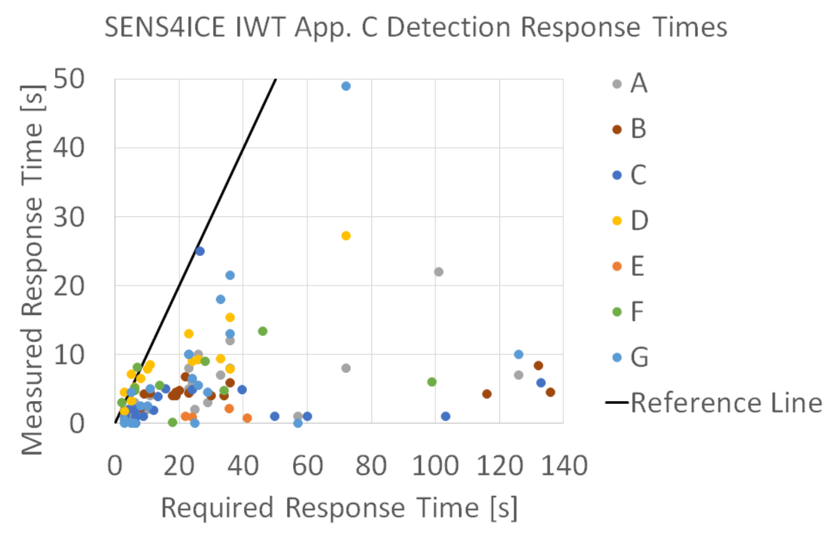
# SENS4ICE sensor technologies IWT testing detection rates for App. C and O icing condition test points

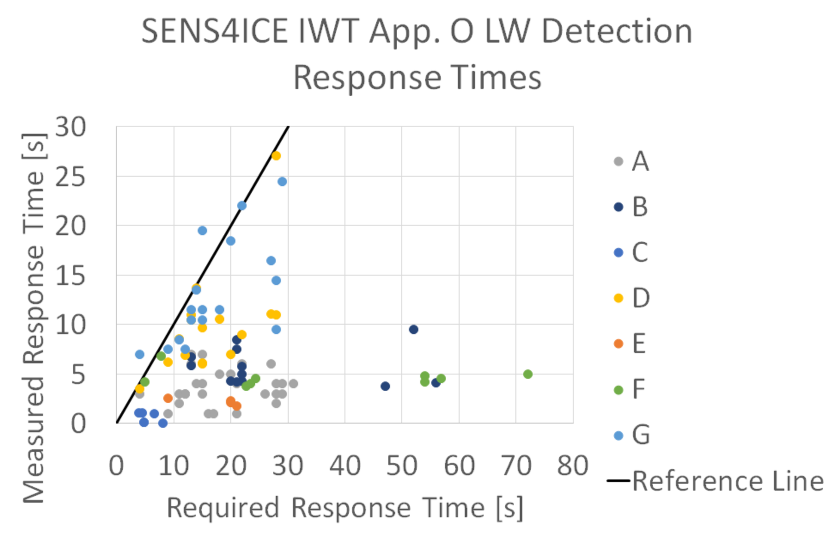


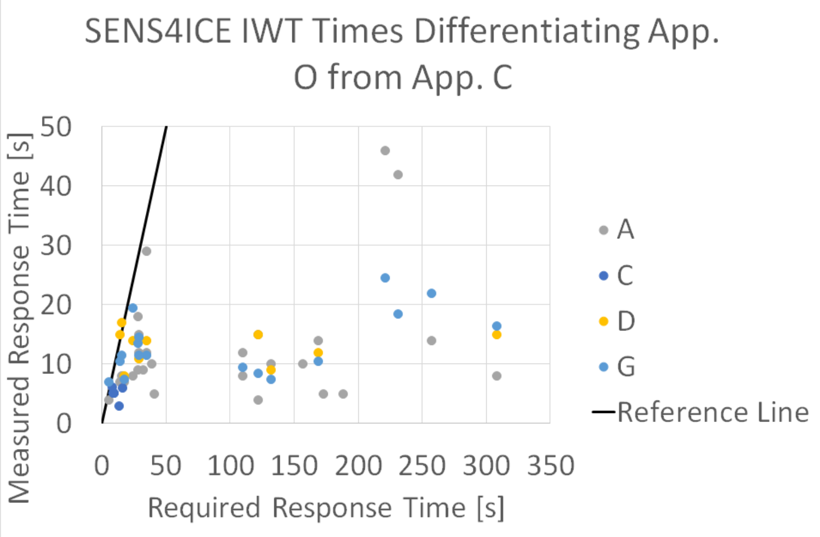

- anonymised overview of detection rates
  - test cases successfully detected related to total number of test cases
  - excluding CM2D scientific/reference sensor and one other sensor that was withdrawn from IWT testing in the context of Covid-19 related delays
- several sensors have correctly detected 100% of test points for Appendix C and also for Appendix O
- also within required maximum response time
  - as per EUROCAE inflight icing systems standard ED-103
  - maximum response time depending on icing condition

# SENS4ICE sensor technologies IWT measured sensor response times compared to required response times

- anonymised results
- required maximum response time as per EUROCAE inflight icing systems standard ED-103 (depending on icing condition)
- App. C test points liquid water (LW) detection
- App. O test points liquid water (LW) detection
- differentiating App. C conditions from App. O conditions (for sensors providing differentiation information)



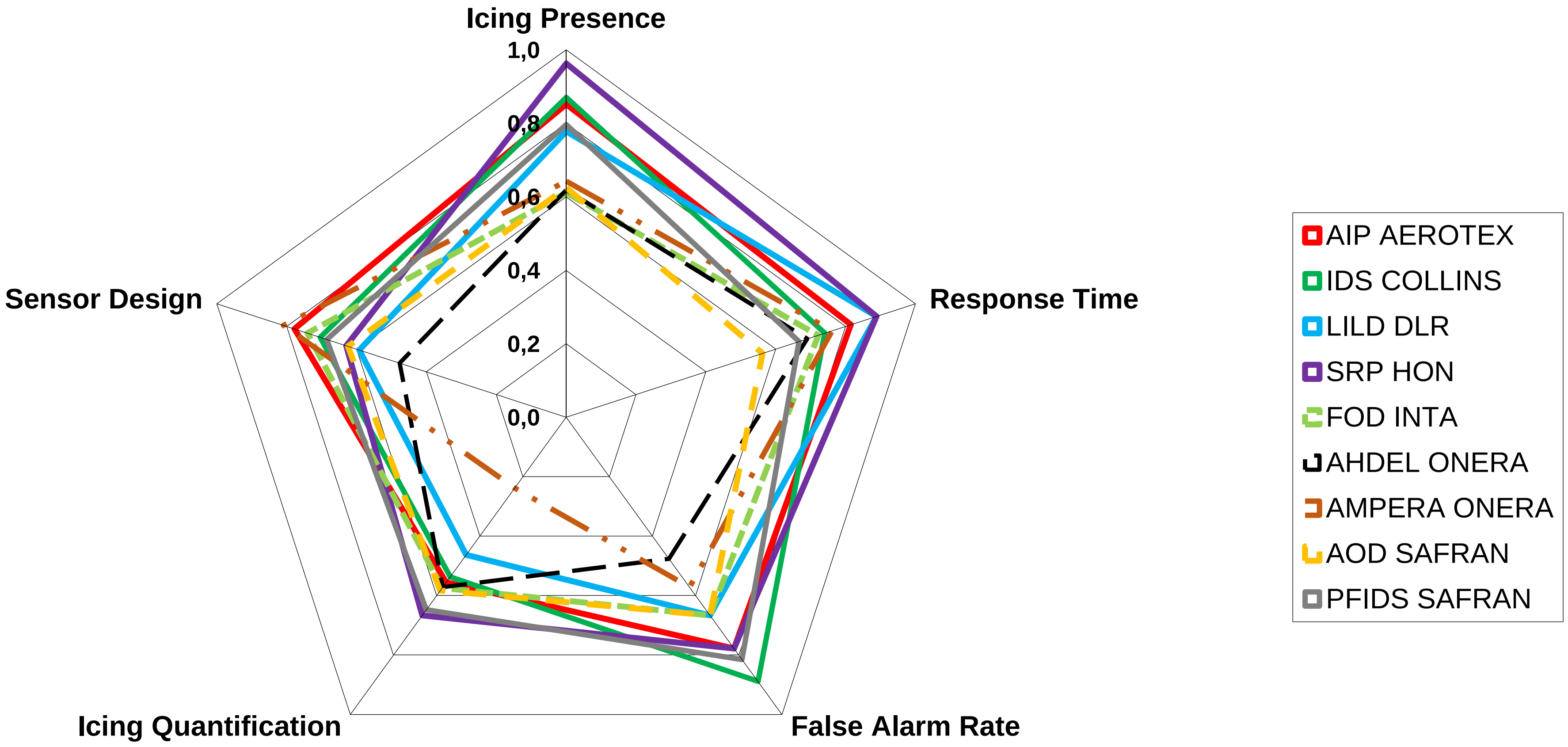
# Technology evaluation criteria and weighting factors

| Technology evaluation criteria | Weighting factor |
|---|---|
| **Icing (ice accretion) / Icing condition presence detection capability** (for App. C (required) and App. O (primary project goal, hence App. O capabilities are more relevant)) | 0.35 |
| **Response time** (for providing Icing/Icing Condition Presence) | 0.20 |
| **False alarm rate** (i.e., detection of icing in non-icing conditions) | 0.10 |
| **Icing quantification and contributing factors for severity determination**, mainly with regard to App. O (discrimination App. C/O, icing, icing condition characteristics, either of those outputs can contribute to a good rating, while not all are required) | 0.30 |
| **Sensor design**: weight/integration/power (expected once technology is matured) | 0.05 |

# SENS4ICE Advisory Board evaluation ratings for sensor technologies

## averaged for all Advisory Board members for evaluation criteria

## (averaged ratings between 0 and 1, normalised, best rating 1)

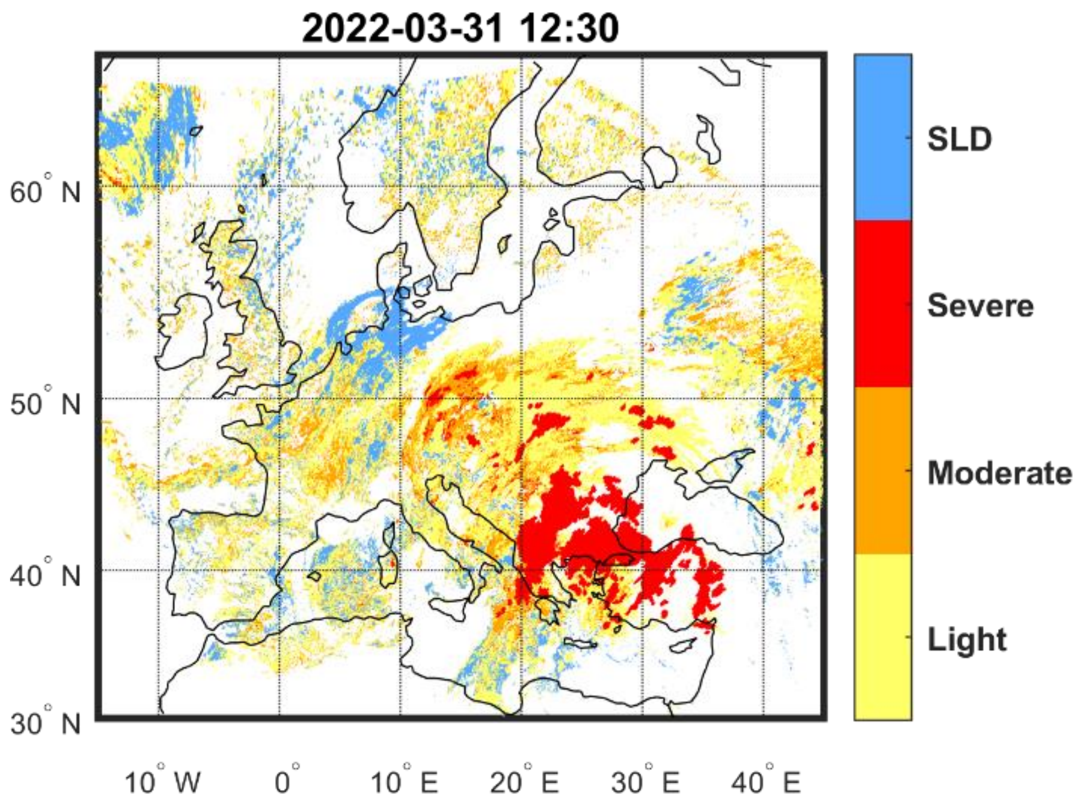




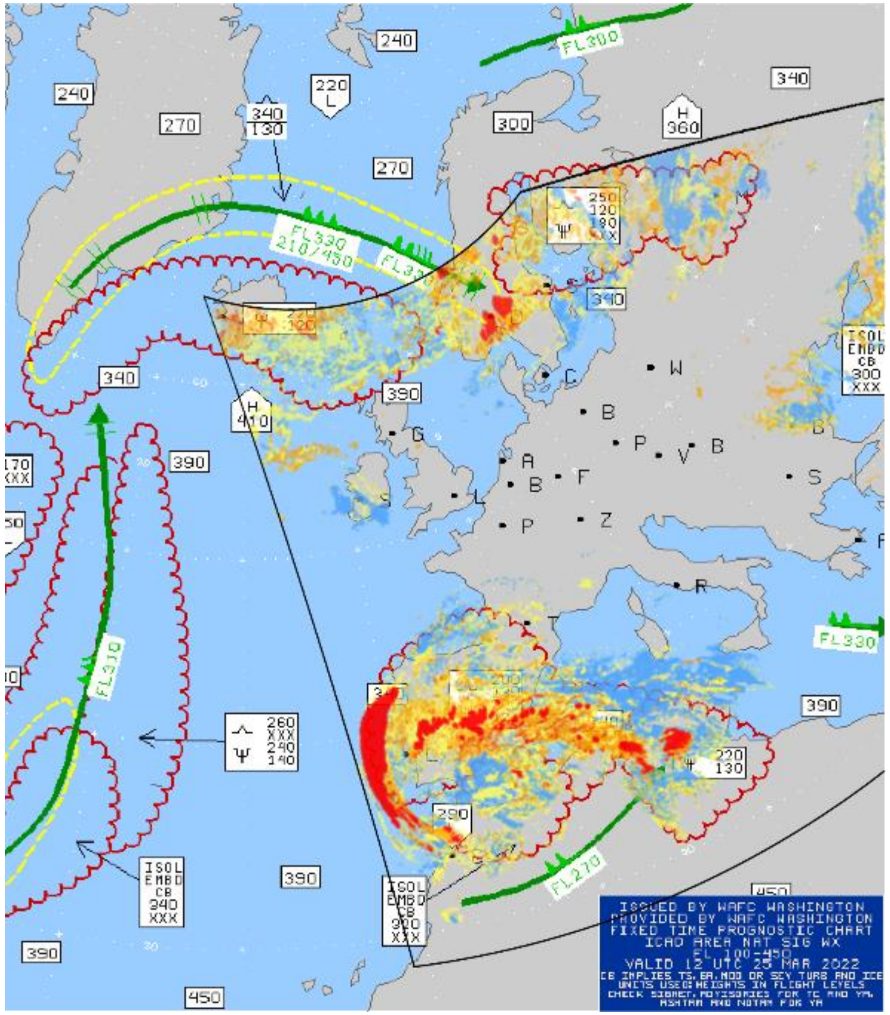

**BACKUP**

# Remote Ice Detection

- CIRA enhanced and matured existing satellite data based icing detection algorithm to consider SLD icing conditions
- main factors: liquid water content (LWC), temperature, droplet size and cloud type




CIRA remote icing detection algorithm output for 31 MAR 2022 12:30 UTC



CIRA remote icing detection validation example (comparison with SIGWX chart)



BACKUP

# WP2: Hybrid Ice Detection

**Robust Hybrid Ice Detection:**

different techniques for **direct sensing** of atmospheric conditions and/or ice accretion

+

**indirect** techniques to detect change of aircraft characteristics with ice accretion on airframe

**Development, test, validation and maturation** of different technologies for

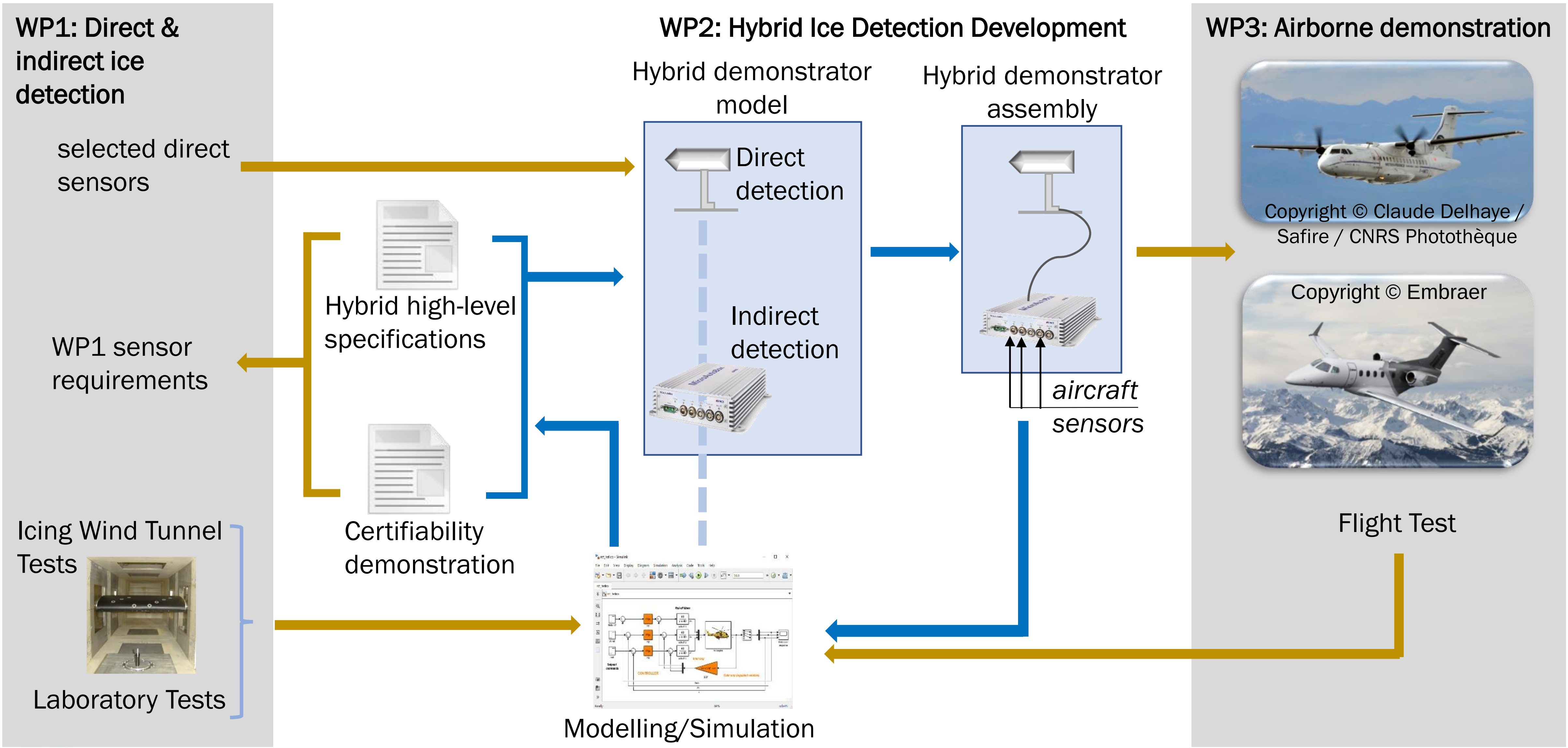
- direct ice detection
- indirect ice detection

**Objectives for hybrid ice detection**

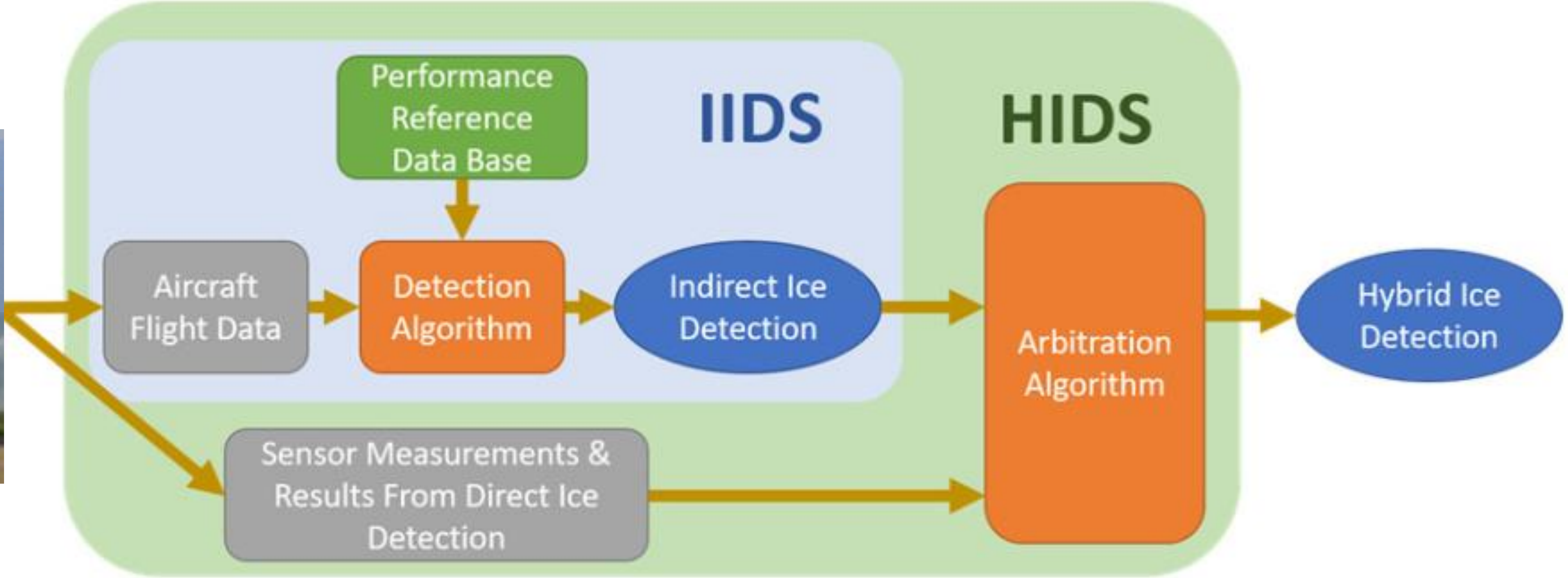
1. Hybrid ice detection system specification
2. Certification programme for hybrid ice detection system
3. Hybrid ice detection system modelling
4. Hybrid ice detection design, build & assembly (+ TRL 5 review)

in **close cooperation with OEMs and certification authorities** during SENS4ICE

# WP2: Hybrid Ice Detection – Development Workflow



# Hybrid Ice Detection System (HIDS) concept including Indirect Ice Detection System (IIDS)

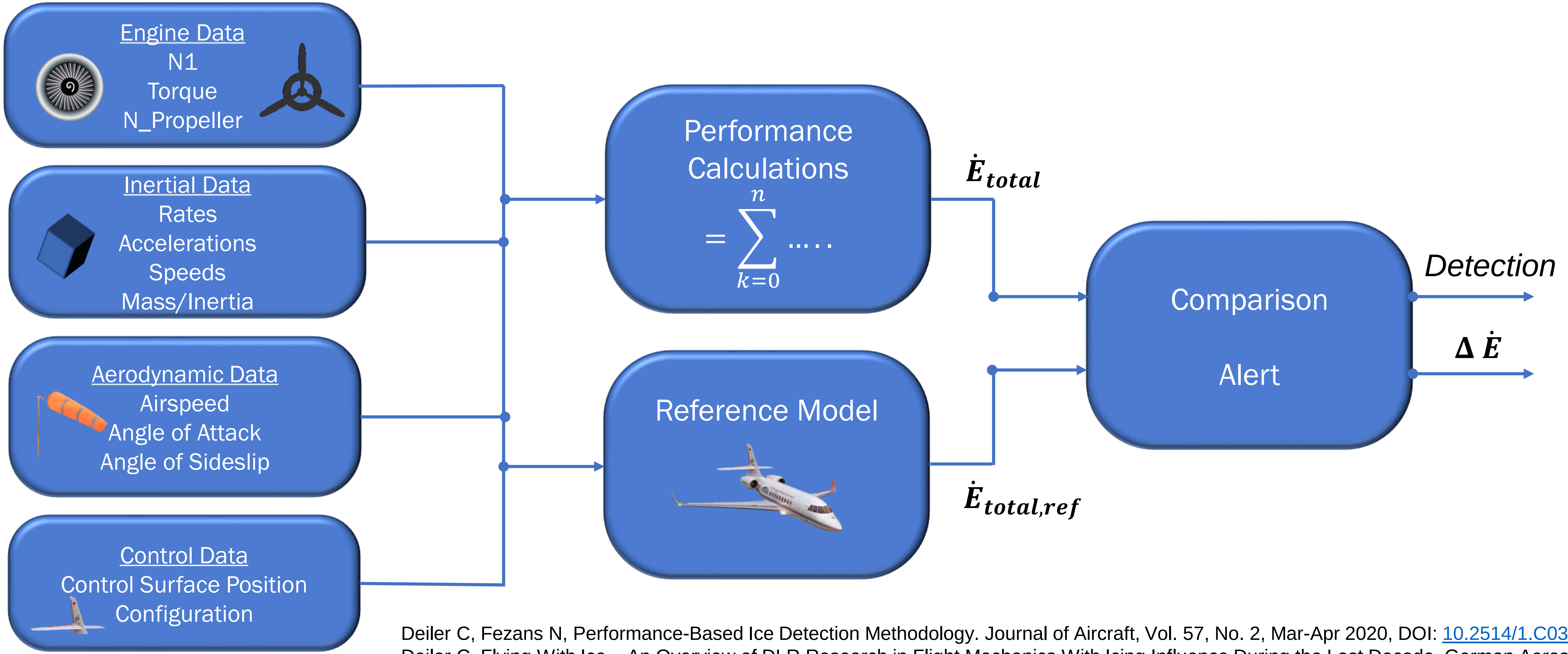



[Orazzo, A., Thillays, B., "Hybrid Ice Detection System development and validation", SAE International Conference on Icing of Aircraft, Engines, and Structures 2023, Vienna, Austria, 20 – 22 June 2023, 23ICE-0049]

[Christoph Deiler, Falk Sachs (2023) Design and Testing of an Indirect Ice Detection Methodology SAE International Conference on Icing of Aircraft, Engines, and Structures 2023, 20-22 June 2023, Vienna, Austria]

Image Credit
DLR/EMBRAER/SAFIRE

# DLR's Indirect Ice Detection – based on aircraft performance System Design





Deiler C, Fezans N, Performance-Based Ice Detection Methodology. Journal of Aircraft, Vol. 57, No. 2, Mar-Apr 2020, DOI: 10.2514/1.C034828

Deiler C, Flying With Ice – An Overview of DLR Research in Flight Mechanics With Icing Influence During the Last Decade. German Aerospace Conference DLRK 2021, Bremen and online, DOI: 10.25967/550008




**BACKUP**

# Indirect Ice Detection – System Performance

Conflicting demands

**Detection time** ⟷ Trade-Off ⟷ **Detection accuracy/reliability**

- Early detection information
- Enable early countermeasures
- Faster than any hazardous effects could occur

- Prevent false alarms
- Increase reliability of detection information
- Increase situational awareness
- Basis for automatic system response

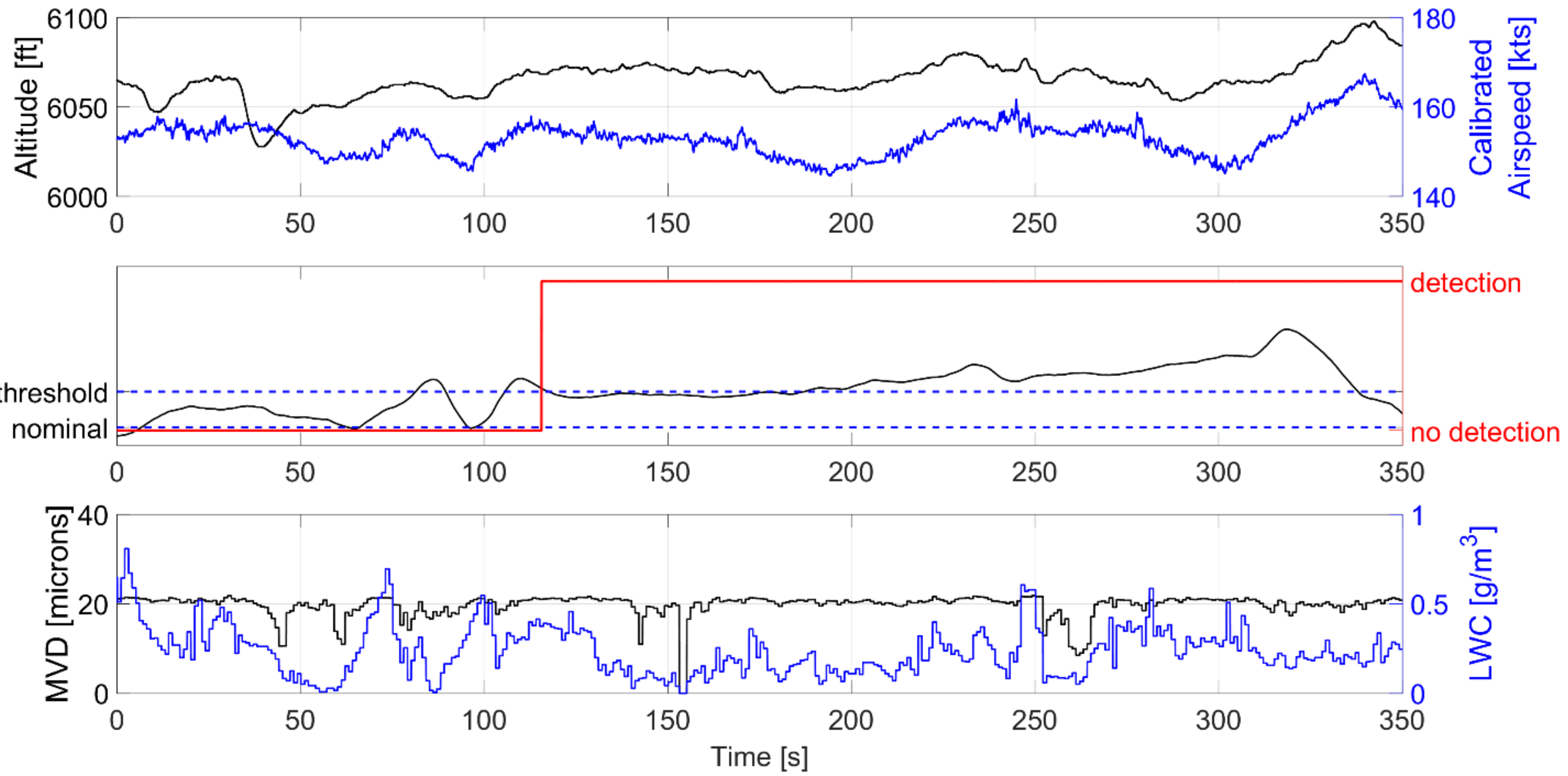
System is based on ice accretion effects on performance (continuous change, no significant step)

→ Determine a threshold that represents the necessary compromise



**BACKUP**

# Indirect Ice Detection – Flight Test Data Initial Results




Indirect ice detection results based on pre-existing natural icing flight test data exhibiting relative drag increase above detection threshold [Embraer flight test data]



**BACKUP**

# WP3: Airborne Demonstration and Atmosphere Characterisation

## dedicated to airborne technology demonstration in relevant icing conditions

Objectives

- Issue main requirements and constraints
  for integration of sensors and probes on flight test platforms
- Release flight test program
  for testing new individual and hybrid technologies in distinct icing conditions
- Perform airborne demonstration in natural icing conditions:
  - in Europe with the French ATR 42 environmental research aircraft of Safire
  - in North America with Embraer Phenom 300
- Characterisation of atmosphere from flight test campaigns in App. O conditions

Guidance by special Flight Test Committee (FTC) formed by platform providers and leaders of WP1, WP2 and WP4 to ensure harmonised preparation and execution of individual flight test campaigns



BACKUP

# SENS4ICE Flight Campaigns

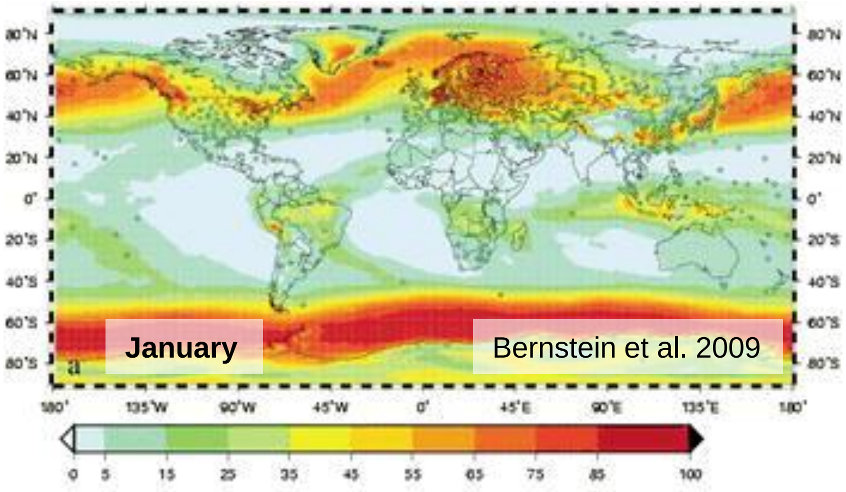
- Total flight test time: 75h in natural icing conditions
- North America
  - February/March 2023
  - Embraer Phenom 300 operated by Embraer
  - **15 flights** with a total of **25 flight hours** (including ferry and check flights) successfully conducted targeting natural liquid water icing conditions and in particular SLD conditions
- Europe
  - April 2023
  - French ATR 42 environmental research aircraft of Safire
  - **15 flights** with a total of **about 50 flight hours** successfully conducted targeting natural liquid water icing conditions and in particular SLD conditions

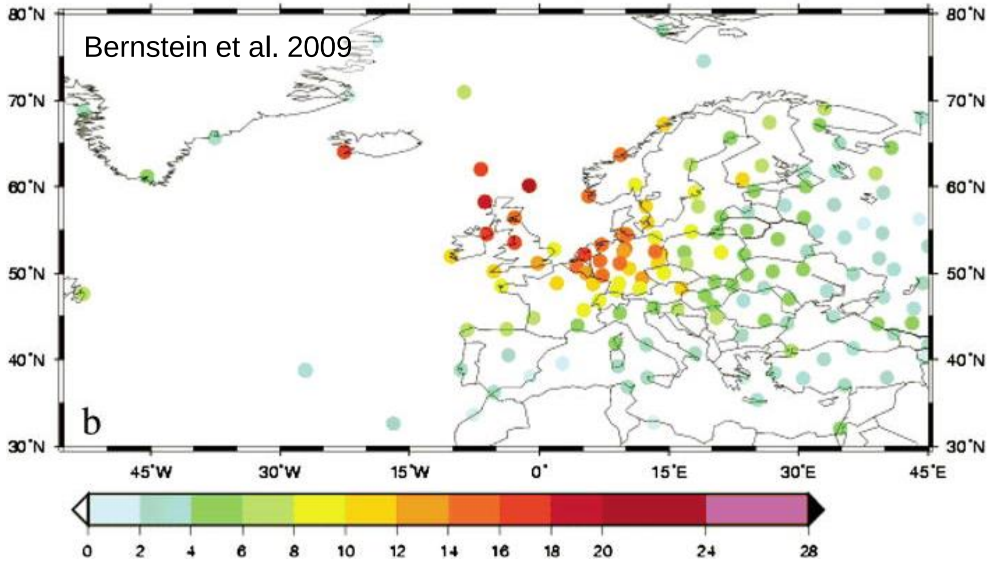
**Embraer Phenom 300**

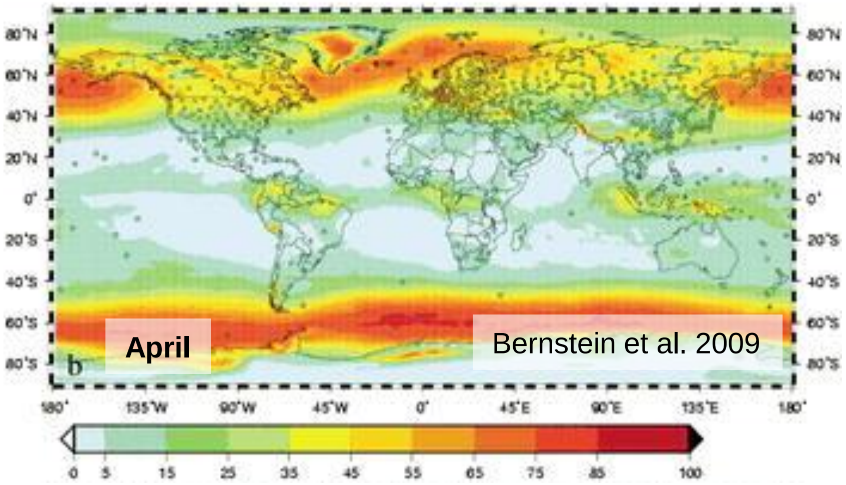


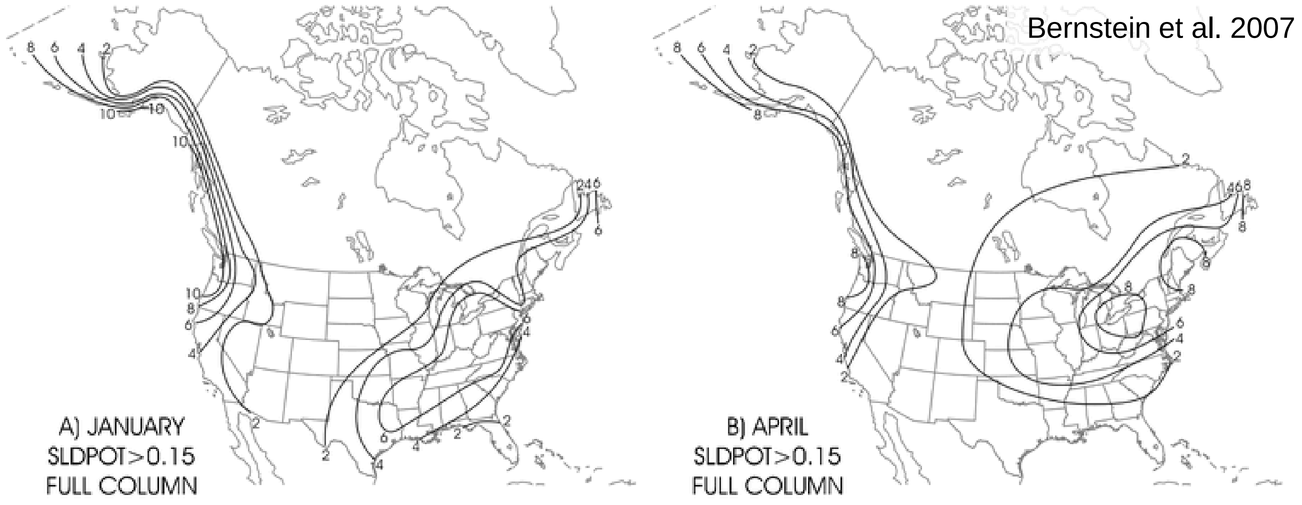
**SAFIRE ATR 42**

# Icing Frequencies Analysis



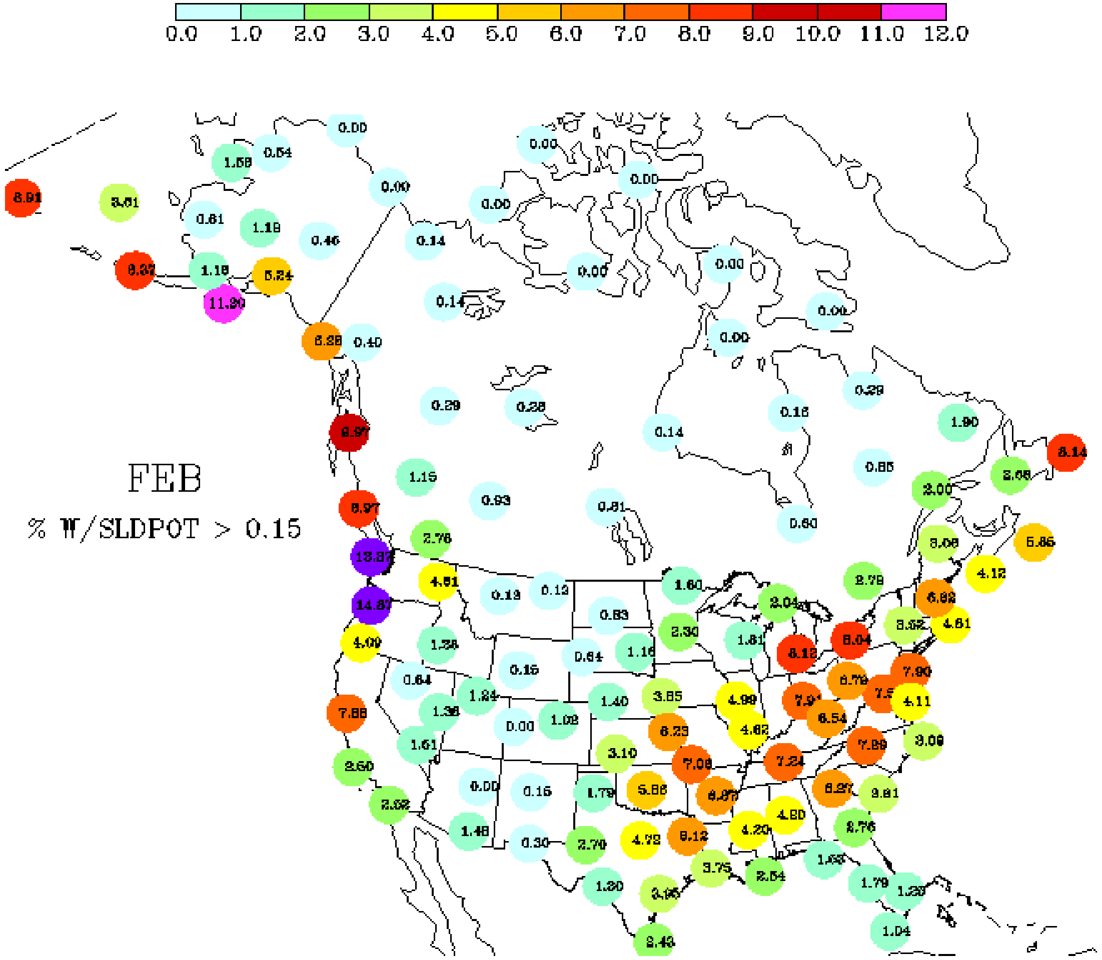

**Bernstein et al. 2007**: Bernstein, B. C., Wolff, C. A., & McDonough, F. (JAMC 2007). An Inferred Climatology of Icing Conditions Aloft, Including Supercooled Large Drops. Part I: Canada and the Continental United States. DOI: 10.1175/2007JAMC1607.1, **Bernstein et al. 2009**: Bernstein, B. C., & Le Bot, C. (JAMC 2009). An Inferred Climatology of Icing Conditions Aloft, Including Supercooled Large Drops. Part II: Europe, Asia, and the Globe, DOI: 10.1175/2009JAMC2073.1

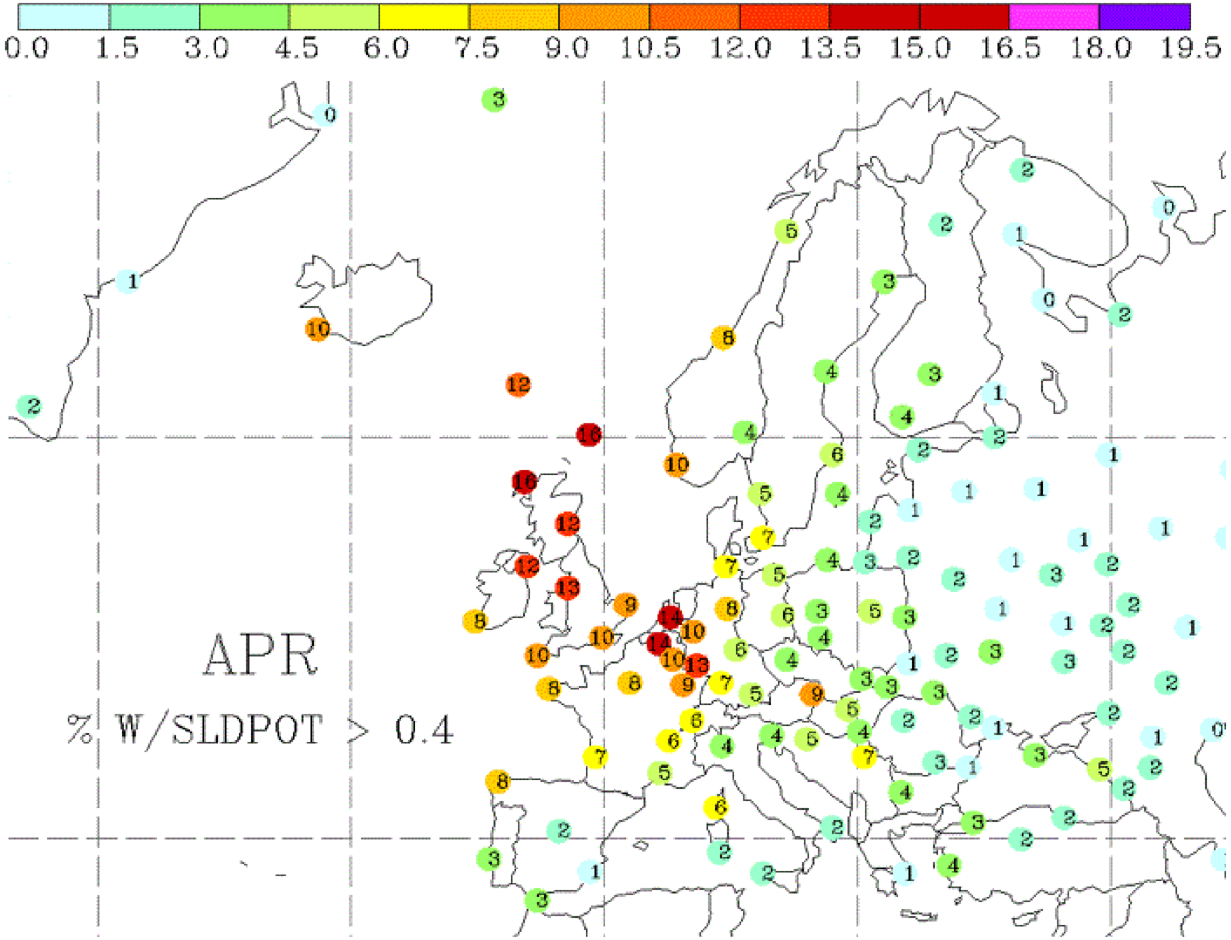


**BACKUP**

# Icing Frequencies Analysis

## Full column frequencies of days with SLD potential [Ben Bernstein]



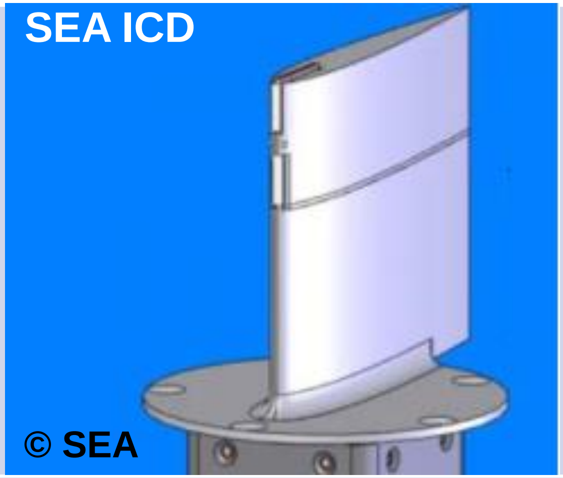




Data analysis process (SLD Potential "SLDPOT" calculated using "CIP-Sonde") based on: Bernstein, B. C., Wolff, C. A., & McDonough, F. (JAMC 2007). An Inferred Climatology of Icing Conditions Aloft, Including Supercooled Large Drops. Part I: Canada and the Continental United States. DOI: 10.1175/2007JAMC1607.1, Bernstein, B. C., & Le Bot, C. (JAMC 2009). An Inferred Climatology of Icing Conditions Aloft, Including Supercooled Large Drops. Part II: Europe, Asia, and the Globe, DOI: 10.1175/2009JAMC2073.1



**BACKUP**

# Airborne Reference Instruments for Icing Atmosphere Characterisation

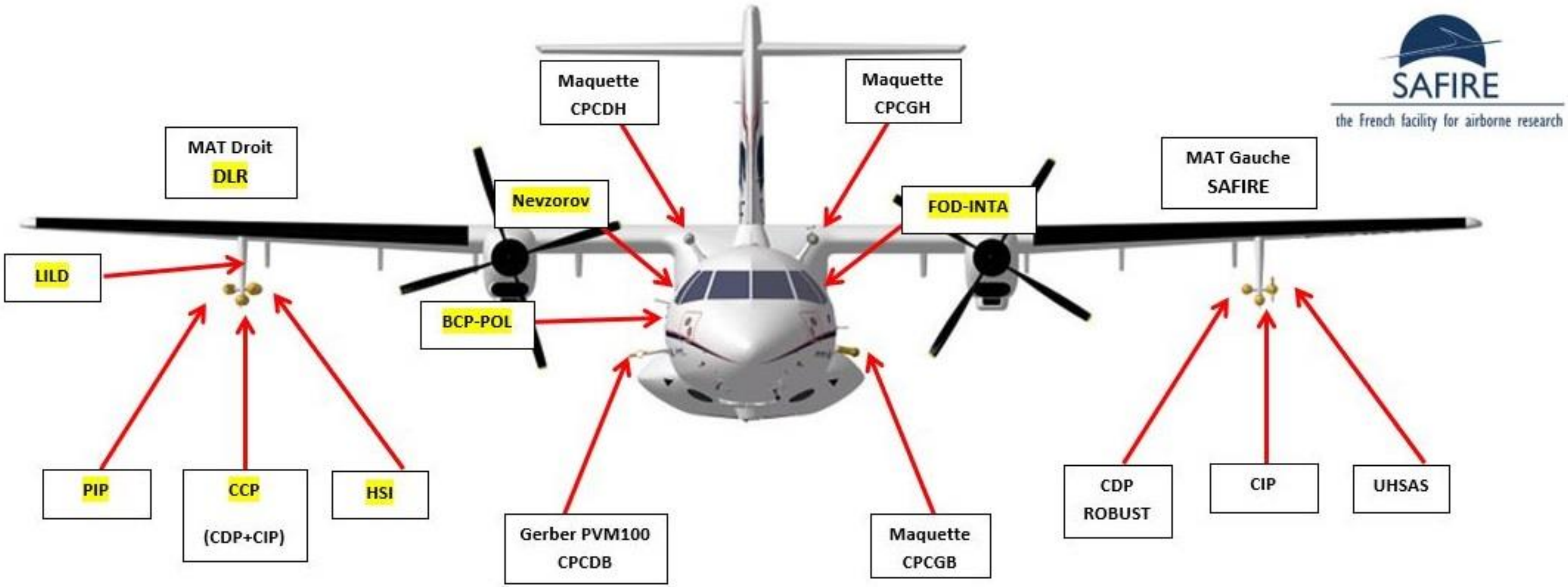
| Instrumentation | Embraer Phenom 300 | Safire ATR 42 |
|---|---|---|
| Hotwire instruments:<br>LWC |   |   |
| Optical instruments:<br>Particle size distributions |   |   |
| Other instruments carried: | | SAFIRE-CDP, SAFIRE-CIP, SAFIRE-UHSAS, SAFIRE-Robust, SAFIRE-GERBER, DLR-PIP, DLR-BCPD, DLR-HSI |

[Lucke, J., et al., "Meteorological conditions and microphysical properties that lead to aircraft icing as observed during the SENS4ICE campaigns", Deutscher Luft- und Raumfahrtkongress (German Aerospace Conference) DLRK 2023, Stuttgart, Germany, September 2023, paper no 0285]



https://www.sens4ice-project.eu/sites/sens4ice/files/media/2023-10/SENS4ICE_DLRK2023_Meteorological_Conditions_DLR_September2023.pdf

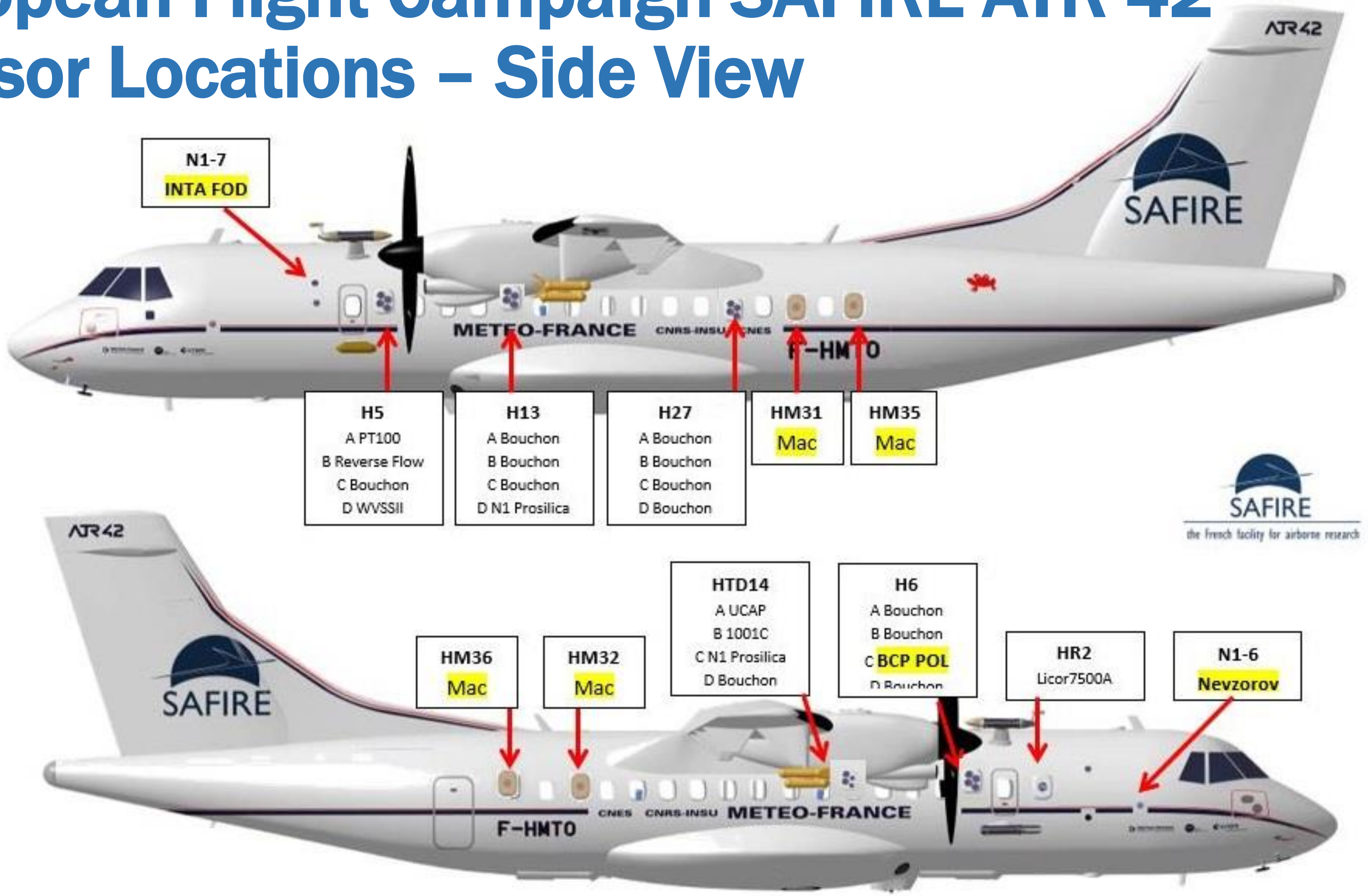
# European Flight Campaign SAFIRE ATR 42 Sensor Locations – Front View




SENS4ICE equipment highlighted in yellow

Image Credit Safire

# European Flight Campaign SAFIRE ATR 42 Sensor Locations – Side View




SENS4ICE equipment highlighted in yellow

Image Credit Safire

BACKUP

# SENS4ICE Airborne Reference Instruments for Icing Atmosphere Characterisation

## Nevzorov Probe installed on SAFIRE ATR 42


## DLR and SAFIRE instruments installed on SAFIRE ATR 42 with ice accretion on the unheated parts while inside supercooled liquid clouds




**BACKUP**

# European Flight Campaign SAFIRE ATR 42 Sensor Installations

- SENS4ICE ice detection technologies tested with SAFIRE ATR 42
  - FOD - Fiber Optic Detector (INTA)
  - AMPERA - Atmospheric Measurement of Potential and ElectRic field on Aircraft (ONERA)
  - LILD - Local Ice Layer Detector (DLR)
  - CM2D - Cloud Multi-Detection Device (DLR)
  - HIDS - Hybrid Ice Detection System (Safran)
  - IIDS - Indirect Ice Detection System (DLR)
- SAFIRE ATR 42 with test sensors and reference instruments


**image DLR with Safire permission**



**BACKUP**

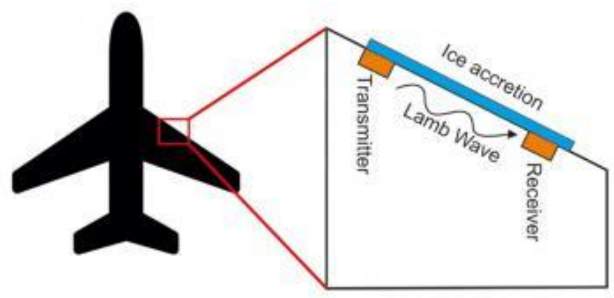
# European Flight Campaign SAFIRE ATR 42 Sensor Installations

- SENS4ICE ice detection technologies tested with SAFIRE ATR 42
  - **FOD** - Fiber Optic Detector (INTA)
  - **AMPERA** - Atmospheric Measurement of Potential and ElectRic field on Aircraft (ONERA)
  - **LILD** - Local Ice Layer Detector (DLR)
  - **CM2D** - Cloud Multi-Detection Device (DLR)
  - **HIDS** - Hybrid Ice Detection System (Safran)
  - **IIDS** - Indirect Ice Detection System (DLR)
- SAFIRE ATR 42 with test sensors and reference instruments

**FOD-INTA**

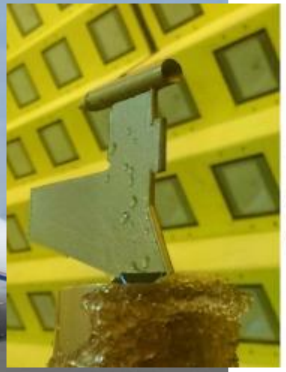
**HIDS-Safran/ IIDS-DLR**

**AMPERA-ONERA**




**LILD-DLR**


**image DLR with Safire permission**



**CM2D-DLR**

# North America Flight Campaign Embraer Phenom 300 Sensor Installations

- SENS4ICE ice detection technologies tested with Embraer Phenom 300
  - **AIP** - Atmospheric Icing Patch (AeroTex)
  - **PFIDS** - Primary in-Flight Icing Detection System (Safran)
  - **IDS** - Ice Detection System (Collins)
  - **SRP** - Short Range Particulate (Honeywell)
  - **HIDS** - Hybrid Ice Detection System (Safran)
  - **IIDS** - Indirect Ice Detection System (DLR)


© Embraer

# North America Flight Campaign Embraer Phenom 300 Sensor Installations

- SENS4ICE ice detection technologies tested with Embraer Phenom 300
  - **AIP** - Atmospheric Icing Patch (AeroTex)
  - **PFIDS** - Primary in-Flight Icing Detection System (Safran)
  - **IDS** - Ice Detection System (Collins)
  - **SRP** - Short Range Particulate (Honeywell)
  - **HIDS** - Hybrid Ice Detection System (Safran)
  - **IIDS** - Indirect Ice Detection System (DLR)



HIDS-Safran/
IIDS-DLR

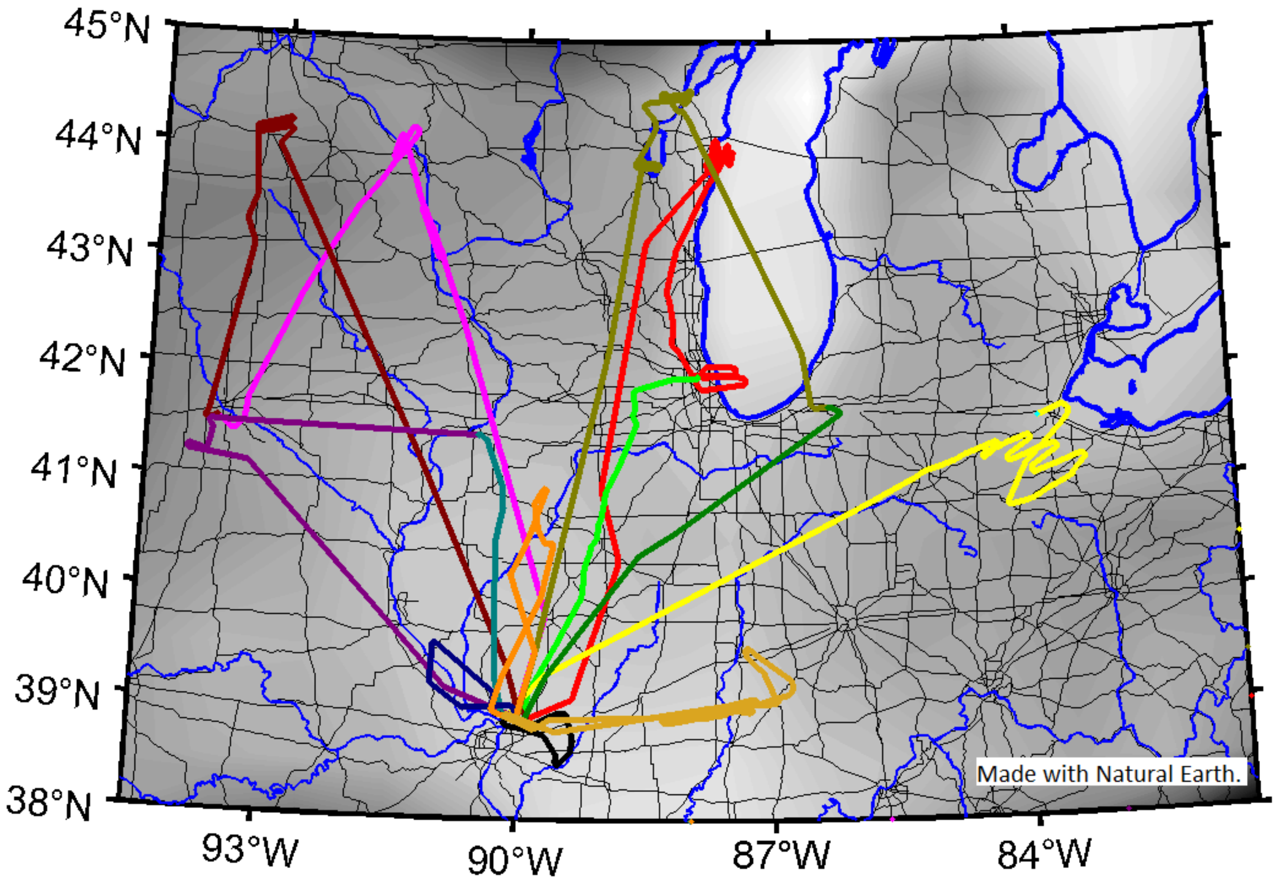
# SENS4ICE Flight Campaign North America

- February/March 2023
- Embraer Phenom 300 operated by Embraer
- **15 flights** with a total of **25 flight hours** (including ferry and check flights) successfully conducted targeting natural liquid water icing conditions and in particular SLD conditions
- total of **55 encounters** with icing clouds flown, ranging from about 2 min to about 7 min duration
- the higher the LWC the lower the exposure time
- icing encounters intended to be relatively short for safety reasons
- preliminary analysis: 
  about 20% of flight time in icing conditions
- initial detailed analysis: 264 min in icing conditions, 37 min Appendix O conditions

| No | Date | Flight duration [hrs] | Comment |
|---|---|---|---|
| 1 | 22 FEB 2023 | 0:39 | Check flight |
| 2 | 23 FEB 2023 | 2:45 | Appendix O |
| 3 | 23 FEB 2023 | 1:12 | Appendix C |
| 4 | 25 FEB 2023 | 2:03 | Appendix O |
| 5 | 25 FEB 2023 | 1:37 | Appendix C |
| 6 | 01 MAR 2023 | 2:45 | Appendix O |
| 7 | 01 MAR 2023 | 2:12 | Appendix O |
| 8 | 06 MAR 2023 | 1:07 | Appendix C |
| 9 | 06 MAR 2023 | - | Dry Air |
| 10 | 08 MAR 2023 | 2:21 | Appendix O |
| 11 | 08 MAR 2023 | 0:40 | Return to base |
| 12 | 08 MAR 2023 | - | Check flight |
| 13 | 09 MAR 2023 | 1:23 | Appendix C |
| 14 | 10 MAR 2023 | 2:15 | Appendix O |
| 15 | 10 MAR 2023 | 1:08 | Appendix C |

# SENS4ICE Flight Campaign North America Ground Tracks

- Aircraft located in Alton, Illinois, along the border between Illinois and Missouri
- Operating in regions of flat terrain to the west and south of the Great Lakes



# SENS4ICE Flight Campaign North America
# Icing Encounter Statistics

| Date | Flight ID | App. C encounters [-] | App. O encounters [-] | App. C duration [mm:ss] | App. O duration [mm:ss] |
|---|---|---|---|---|---|
| 23 FEB 2023 | F1475-1 | 20 | 5 | 20:18 | 09:03 |
| 23 FEB 2023 | F1475-2 | 4 | 0 | 19:59 | 00:00 |
| 25 FEB 2023 | F1476 | 20 | 7 | 38:47 | 22:24 |
| 01 MAR 2023 | F1477-1 | 17 | 3 | 31:03 | 03:55 |
| 01 MAR 2023 | F1477-2 | 9 | 8 | 14:30 | 07:31 |
| 06 MAR 2023 | F1478 | 11 | 4 | 43:24 | 04:20 |
| 09 MAR 2023 | F1481 | 11 | 3 | 15:51 | 02:46 |
| 10 MAR 2023 | F1482 | 23 | 0 | 79:59 | 00:00 |

Microphysics data analysis DLR Institute of Atmospheric Physics

# SENS4ICE Flight Campaign North America

- Ice accreted on windshield after leaving clouds with supercooled liquid water

Image Credit Embraer

# SENS4ICE Flight Campaign North America

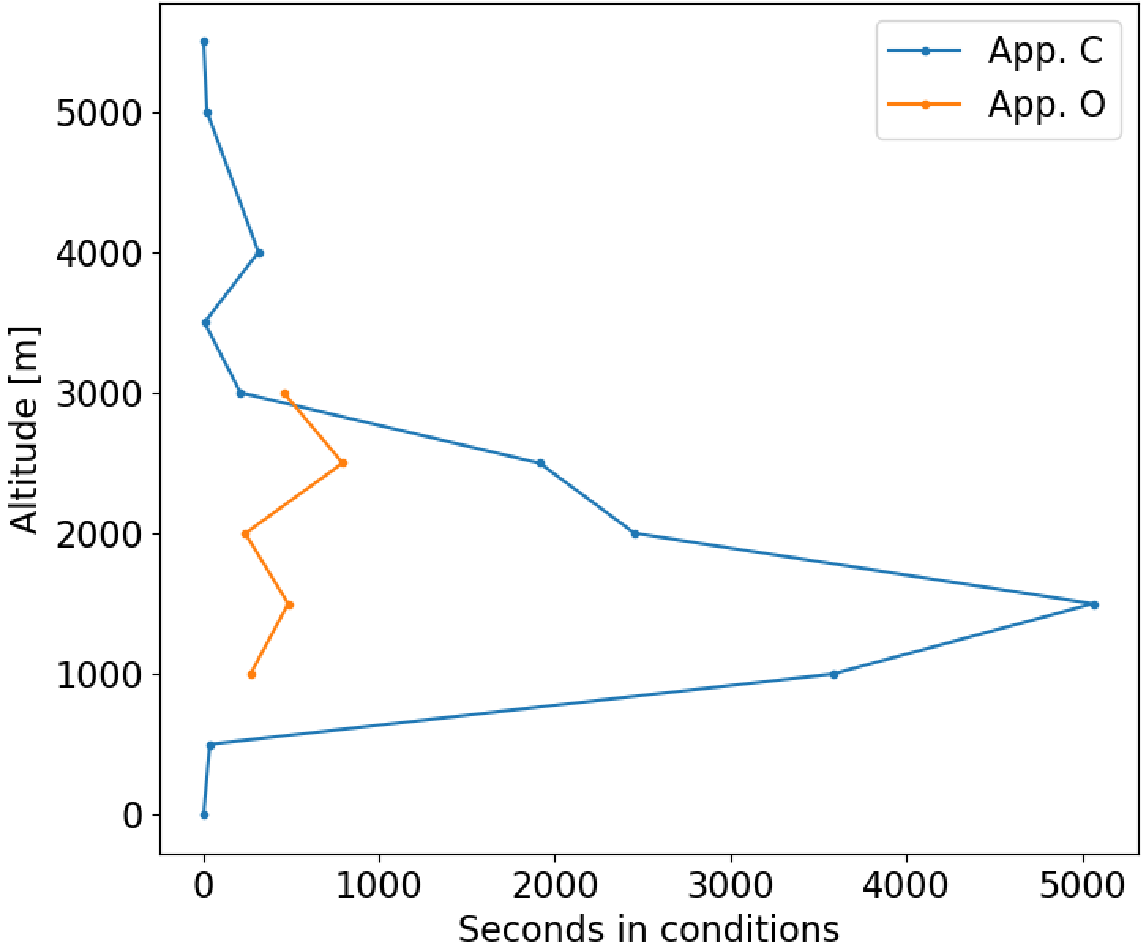
- Ice accretion on windshield during SLD cloud encounter

time-lapse video - Credit Embraer



BACKUP

# SENS4ICE Flight Campaign North America
# Altitude of Icing Conditions




- Icing conditions encountered mainly between 500 m and 3000 m, with a maximum around 1500 m
- Appendix O conditions encountered between 1000 m and 3000 m

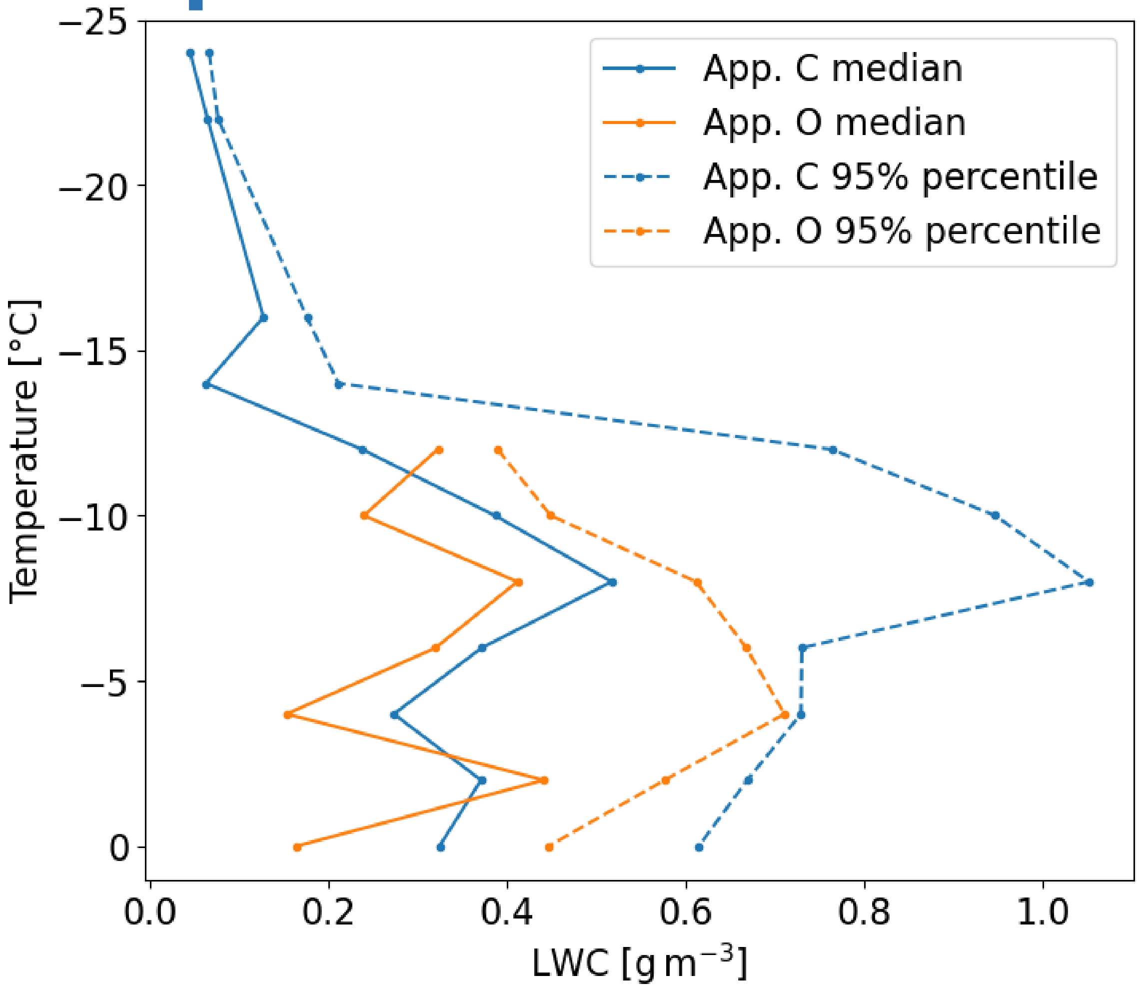
Microphysics data analysis DLR Institute of Atmospheric Physics

[Lucke, J., et al., “Meteorological conditions and microphysical properties that lead to aircraft icing as observed during the SENS4ICE campaigns”, Deutscher Luft- und Raumfahrtkongress (German Aerospace Conference) DLRK 2023, Stuttgart, Germany, September 2023, paper no 0285]



https://www.sens4ice-project.eu/sites/sens4ice/files/media/2023-10/SENS4ICE_DLRK2023_Meteorological_Conditions_DLR_September2023.pdf

# SENS4ICE Flight Campaign North America
# Temperature distribution of Appendix C and O conditions




- Appendix O conditions were encountered from -12°C upwards.
- For Appendix C conditions median liquid water content much lower below -13°C.
- Appendix C LWCs are larger than Appendix O LWCs

Microphysics data analysis DLR Institute of Atmospheric Physics

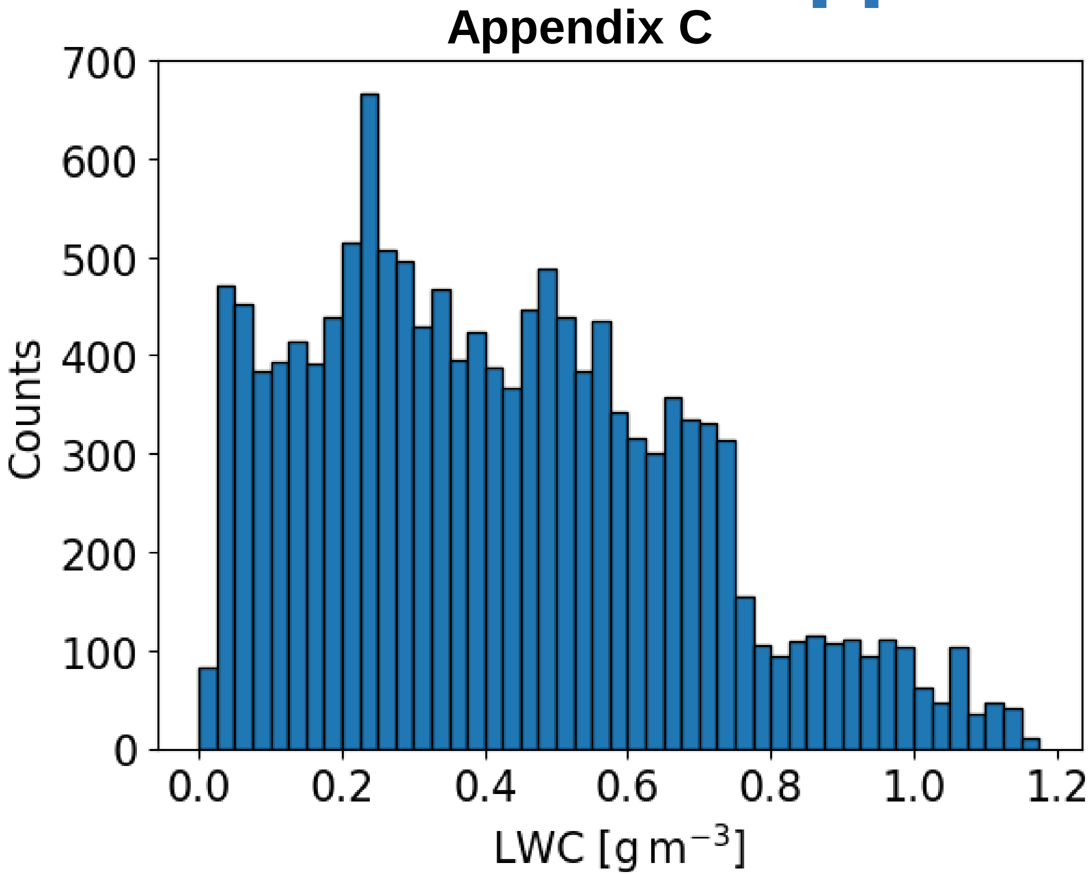
[Lucke, J., et al., “Meteorological conditions and microphysical properties that lead to aircraft icing as observed during the SENS4ICE campaigns”, Deutscher Luft- und Raumfahrtkongress (German Aerospace Conference) DLRK 2023, Stuttgart, Germany, September 2023, paper no 0285]

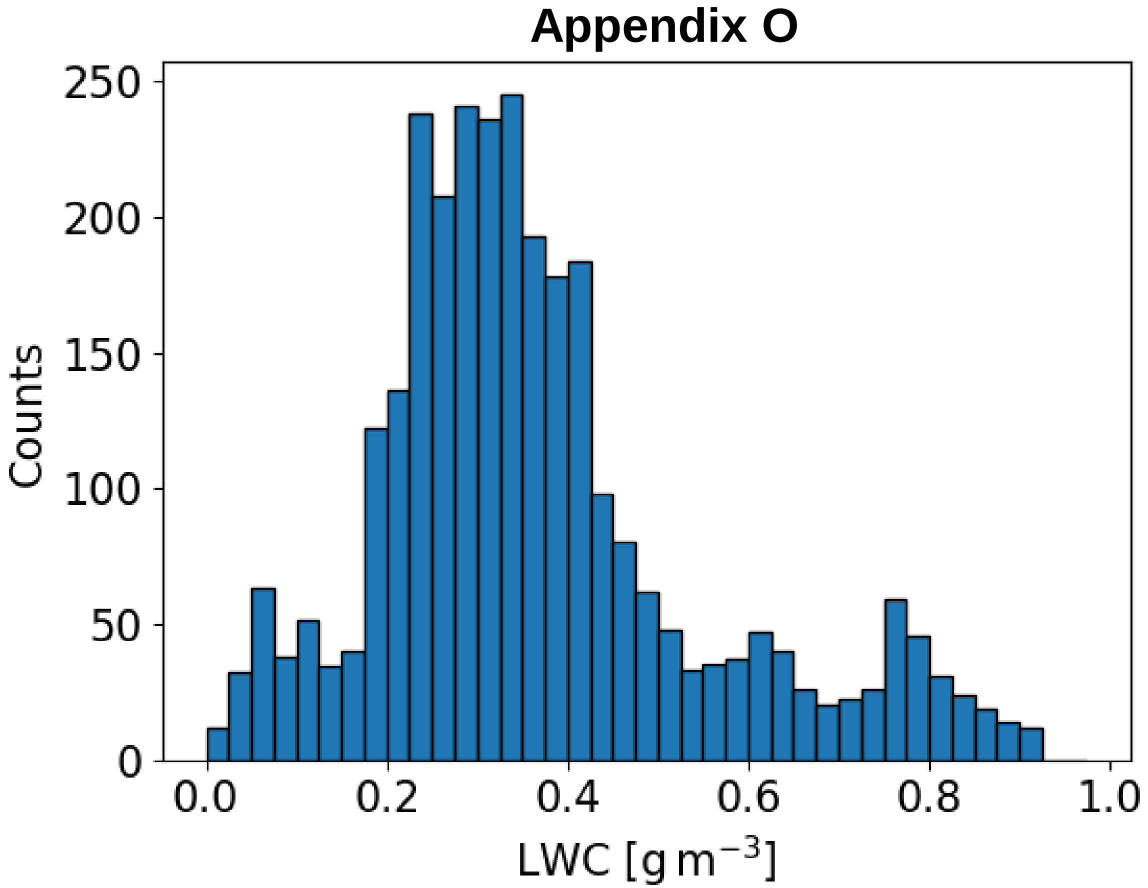


https://www.sens4ice-project.eu/sites/sens4ice/files/media/2023-10/SENS4ICE_DLRK2023_Meteorological_Conditions_DLR_September2023.pdf

# SENS4ICE Flight Campaign North America
# LWC distribution of Appendix C and O conditions






- Appendix C conditions frequently reached LWCs up to about 0.8 g/m³
- Appendix O conditions peaked around 0.3 g/m³, but in few cases reached up to 0.9 g/m³

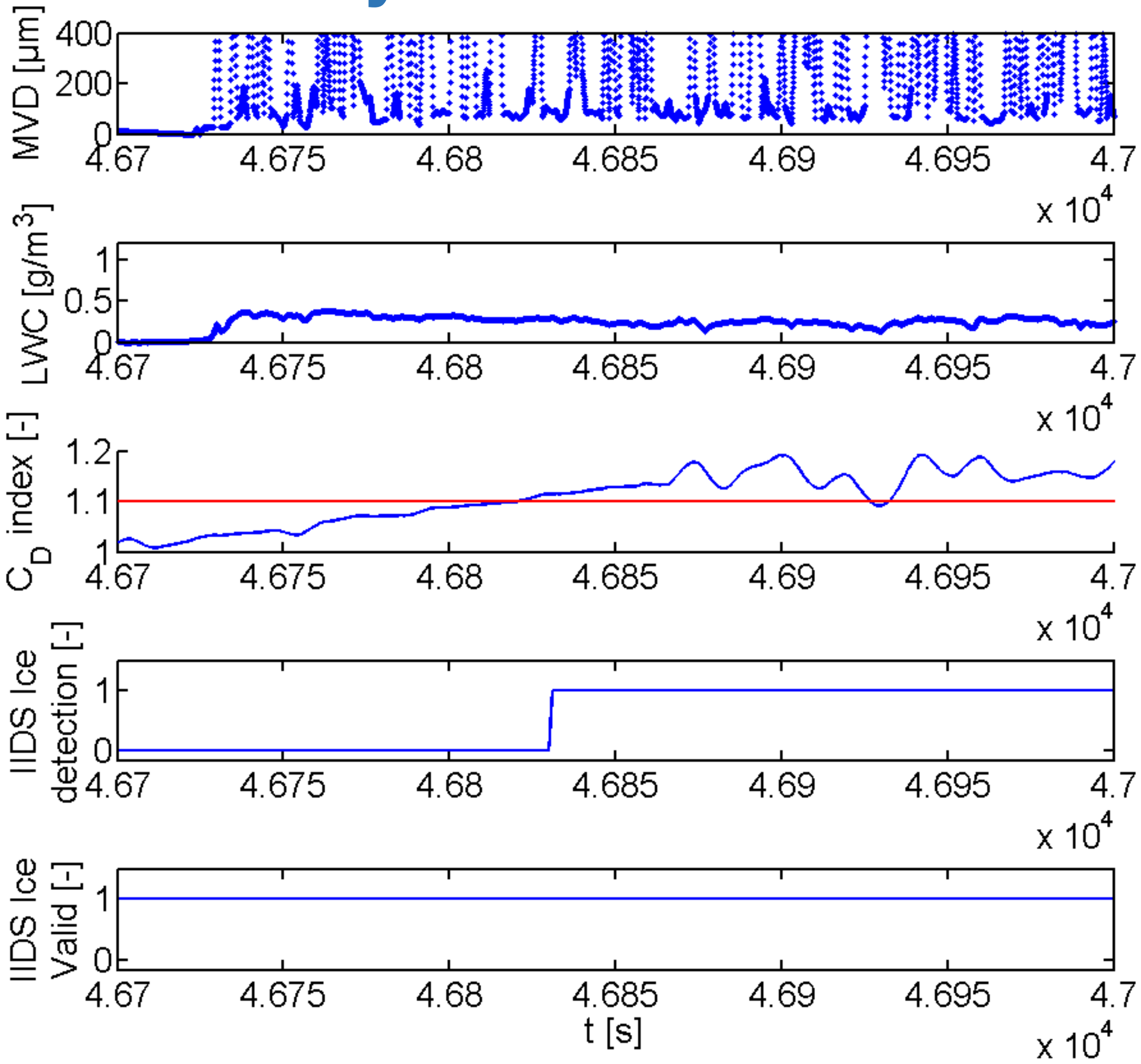
[Lucke, J., et al., "Meteorological conditions and microphysical properties that lead to aircraft icing as observed during the SENS4ICE campaigns", Deutscher Luft- und Raumfahrtkongress (German Aerospace Conference) DLRK 2023, Stuttgart, Germany, September 2023, paper no 0285]



https://www.sens4ice-project.eu/sites/sens4ice/files/media/2023-10/SENS4ICE_DLRK2023_Meteorological_Conditions_DLR_September2023.pdf

# SENS4ICE Flight Campaign North America
# Indirect Ice Detection – Preliminary Results

- flight test 25 Feb 2023
- outcome example based on preliminary analysis and compared to preliminary results for MVD and LWC

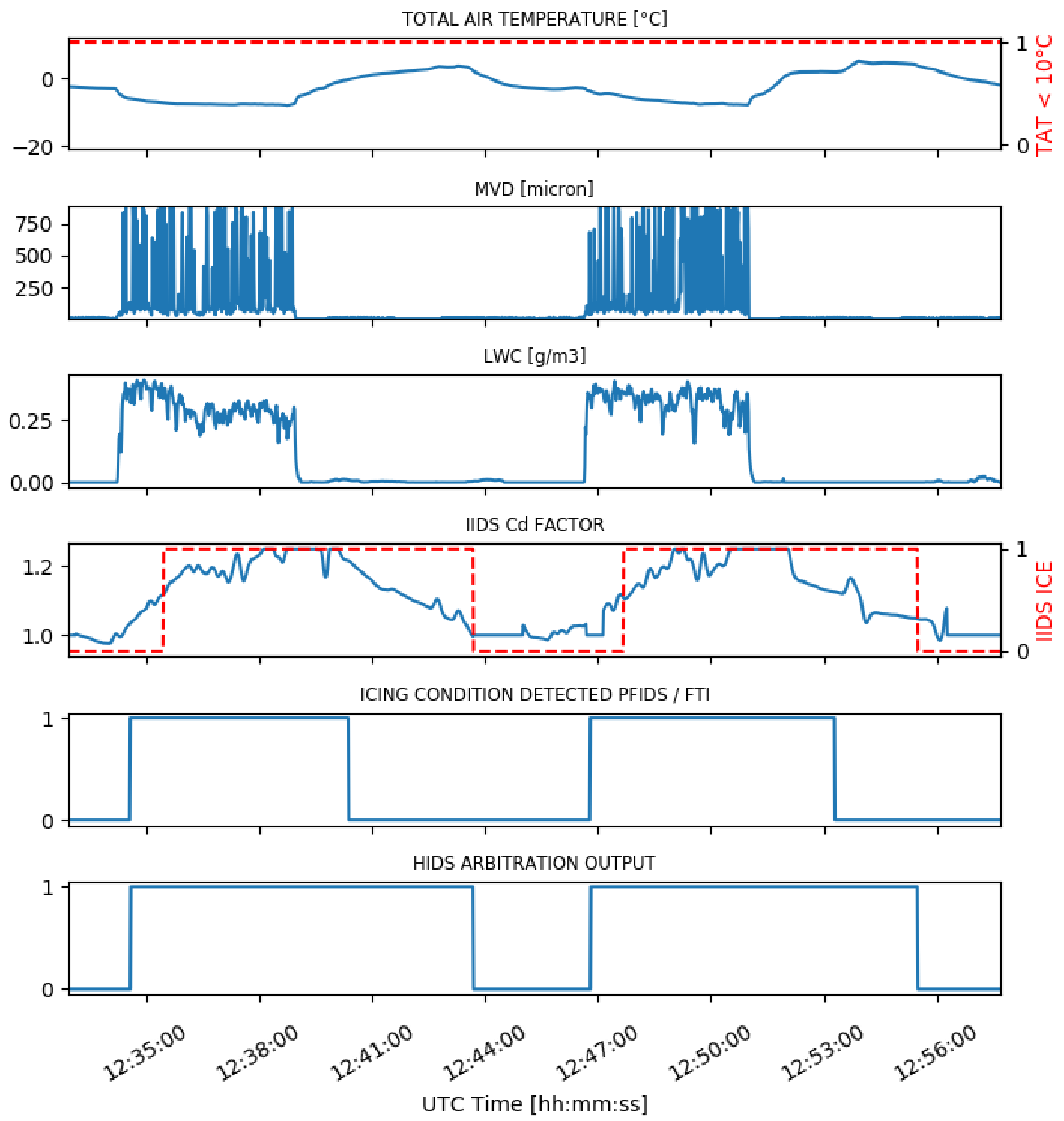





BACKUP

# SENS4ICE Flight Campaign North America Hybrid Ice Detection – Preliminary Results

- HIDS (Hybrid Ice Detection System), including IIDS (Indirect Ice Detection System), flight test 25 Feb 2023 outcome example based on preliminary analysis and compared to preliminary results for MVD and LWC






BACKUP

# SENS4ICE Flight Campaign Europe

| SENS4ICE Flight No | Safire Flight ID | Date | Takeoff (UTC) | Landing (UTC) |
|---|---|---|---|---|
| 1 | as230009 | 2023-04-03 | 2023-04-03 at 06:08:24 in Francazal | 2023-04-03 at 09:37:52 in Francazal |
| 2 | as230010 | 2023-04-04 | 2023-04-04 at 11:38:45 in Francazal | 2023-04-04 at 12:53:28 in Hyeres |
| 3 | as230011 | 2023-04-04 | 2023-04-04 at 13:11:38 in Hyeres | 2023-04-04 at 14:30:24 in Francazal |
| 4 | as230012 | 2023-04-06 | 2023-04-06 at 07:14:08 in Francazal | 2023-04-06 at 07:40:33 in Francazal |
| 5 | as230013 | 2023-04-14 | 2023-04-14 at 04:36:47 in Francazal | 2023-04-14 at 09:29:43 in Francazal |
| 6 | as230014 | 2023-04-15 | 2023-04-15 at 06:03:41 in Francazal | 2023-04-15 at 08:19:53 in Francazal |
| 7 | as230015 | 2023-04-18 | 2023-04-18 at 13:56:21 in Francazal | 2023-04-18 at 17:05:24 in Francazal |
| 8 | as230016 | 2023-04-20 | 2023-04-20 at 10:40:09 in Francazal | 2023-04-20 at 13:20:12 in Francazal |
| 9 | as230017 | 2023-04-22 | 2023-04-22 at 06:03:10 in Blagnac | 2023-04-22 at 08:52:02 in Blagnac |
| 10 | as230018 | 2023-04-24 | 2023-04-24 at 12:22:37 in Francazal | 2023-04-24 at 16:52:22 in Francazal |
| 11 | as230019 | 2023-04-25 | 2023-04-25 at 11:03:45 in Francazal | 2023-04-25 at 15:54:11 in Francazal |
| 12 | as230020 | 2023-04-26 | 2023-04-26 at 06:30:55 in Francazal | 2023-04-26 at 08:54:07 in Francazal |
| 13 | as230021 | 2023-04-26 | 2023-04-26 at 13:34:05 in Francazal | 2023-04-26 at 17:08:11 in Francazal |
| 14 | as230022 | 2023-04-27 | 2023-04-27 at 06:33:18 in Francazal | 2023-04-27 at 09:58:29 in Francazal |
| 15 | as230023 | 2023-04-27 | 2023-04-27 at 12:07:20 in Francazal | 2023-04-27 at 15:46:36 in Francazal |

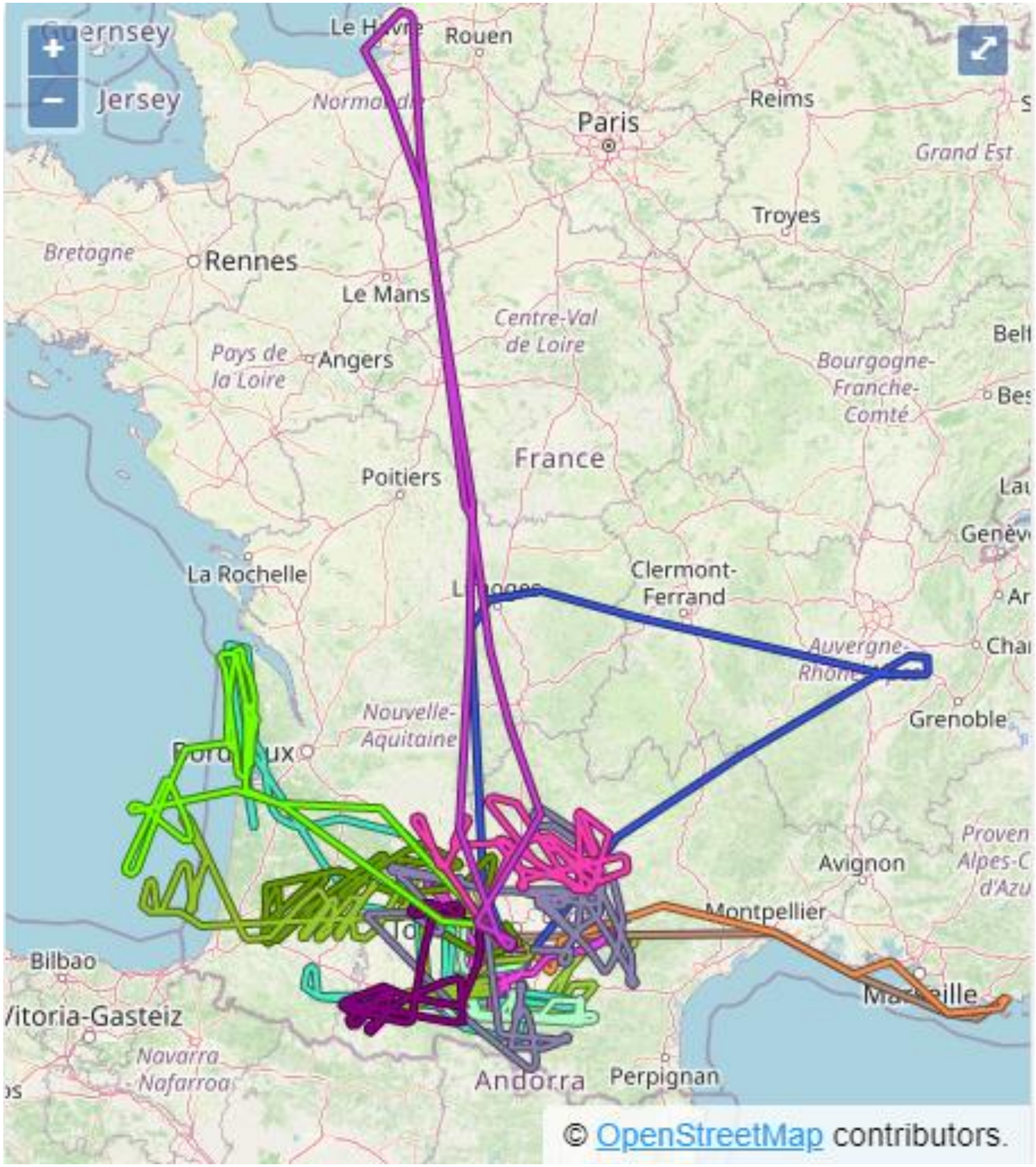
- based on public Safire website https://safireplus.aeris-data.fr/data-access

Airborne data was obtained using the aircraft managed by Safire, the French facility for airborne research, an infrastructure of the French National Center for Scientific Research (CNRS), Météo-France and the French National Center for Space Studies (CNES). Distributed data are processed by SAFIRE.

# SENS4ICE Flight Campaign Europe Ground Tracks

- April 2023
- French ATR 42 environmental research aircraft of Safire
- **15 flights** with a total of **about 50 flight hours** successfully conducted targeting natural liquid water icing conditions and in particular SLD conditions

- Source: https://safireplus.aeris-data.fr/data-access
- Airborne data was obtained using the aircraft managed by Safire, the French facility for airborne research, an infrastructure of the French National Center for Scientific Research (CNRS), Météo-France and the French National Center for Space Studies (CNES). Distributed data are processed by SAFIRE.
- Map Data From OpenStreetMap https://www.openstreetmap.org/copyright/en licensed under the Open Database License



# SENS4ICE Flight Campaign Europe Icing Encounter Statistics

| Date | Flight ID | App. C duration [mm:ss] | App. O duration [mm:ss] |
|---|---|---|---|
| 2023-04-03 | 1 | 90:13 | 01:26 |
| 2023-04-04 | 2 | 10:42 | 00:11 |
| 2023-04-04 | 3 | 12:14 | 01:39 |
| 2023-04-15 | 6 | 40:37 | 13:35 |
| 2023-04-18 | 7 | 72:01 | 00:00 |
| 2023-04-20 | 8 | 02:38 | 00:00 |
| 2023-04-22 | 9 | 34:07 | 00:00 |
| 2023-04-24 | 10 | 90:57 | 26:35 |
| 2023-04-25 | 11 | 90:14 | 19:31 |
| 2023-04-26 | 12 | 13:42 | 00:00 |
| 2023-04-26 | 13 | 52:20 | 04:53 |
| 2023-04-27 | 14 | 62:42 | 03:12 |
| 2023-04-27 | 15 | 42:09 | 07:31 |

Microphysics data analysis

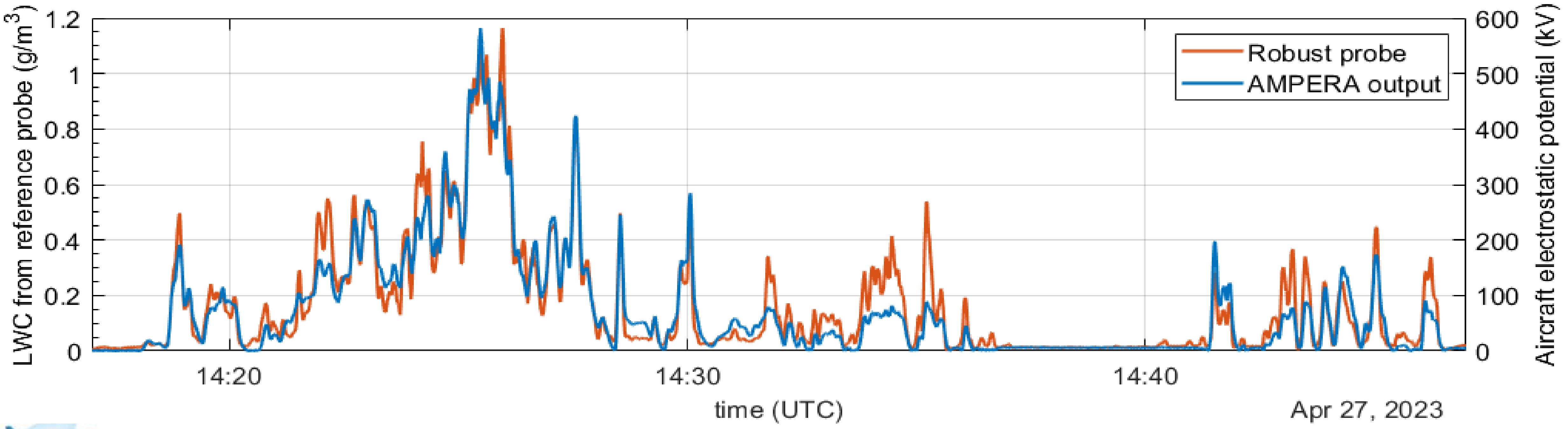
DLR Institute of Atmospheric Physics

# SENS4ICE Flight Campaign Europe

- SAFIRE ATR 42 horizontal tail with ice accretion [image DLR with Safire permission]

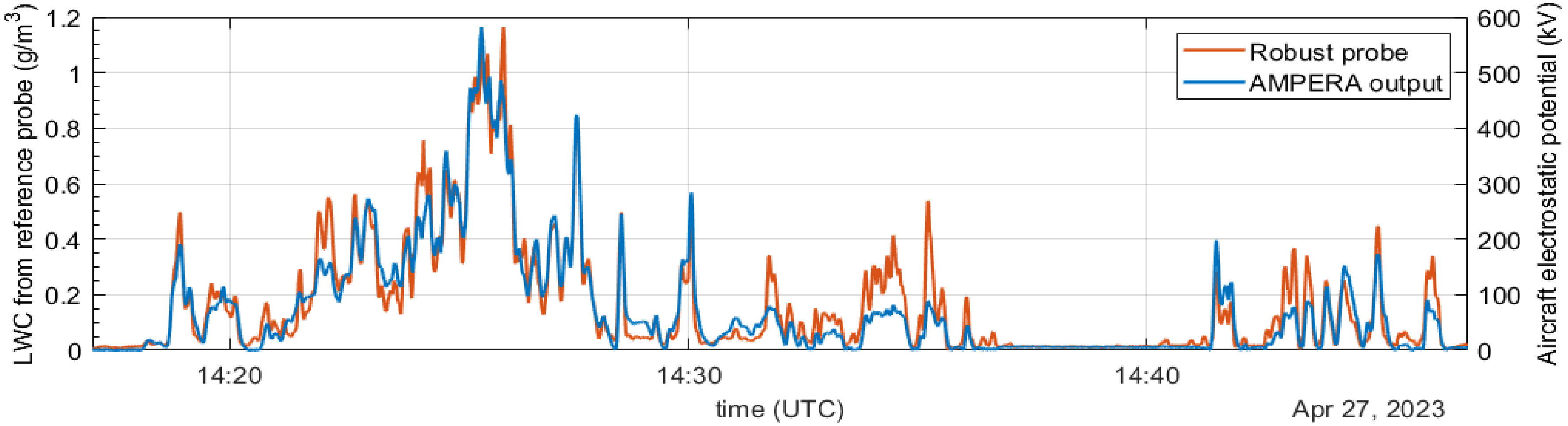
# SENS4ICE Europe Flight Campaign
# AMPERA / ONERA

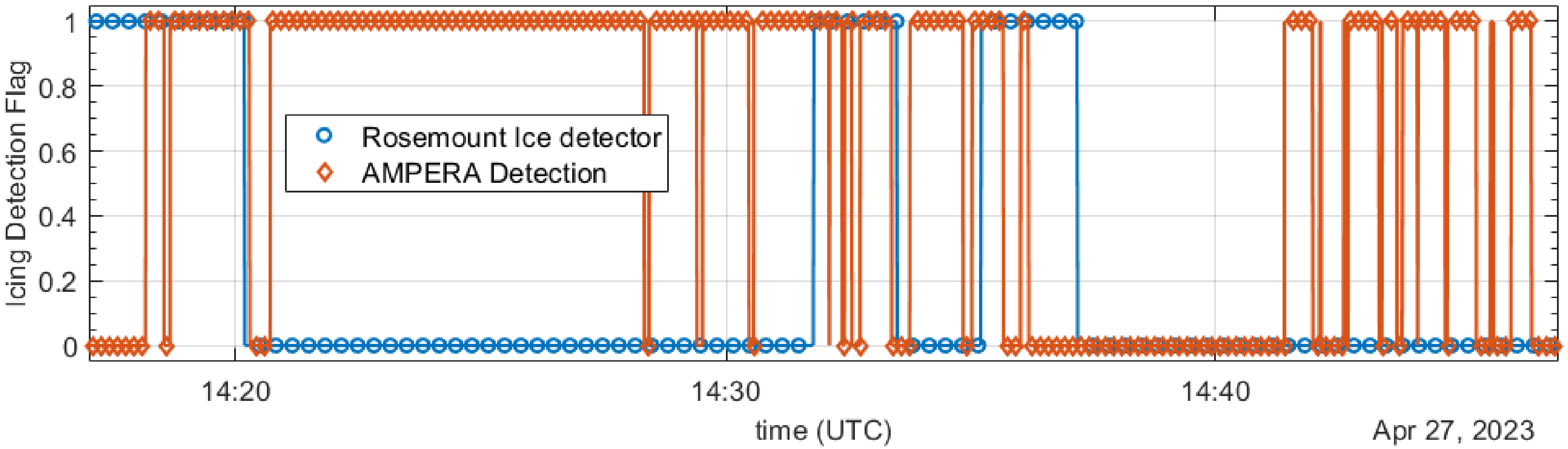
- LWC and Aircraft electrostatic potential comparison – strong correlation (upper figure)
- very robust measurement
- response time of about 1s (enter/exit clouds)
- [SAE 2023 23ICE-0108 Martins et al.]



# SENS4ICE Europe Flight Campaign
# AMPERA / ONERA

- LWC and Aircraft electrostatic potential comparison – strong correlation (upper figure)
- AMPERA atmospheric icing flag and Rosemount Ice accretion flag – good agreement / higher sensitivity (lower figure)
- very robust measurement
- response time of about 1s (enter/exit clouds)
- [SAE 2023 23ICE-0108 Martins et al.]

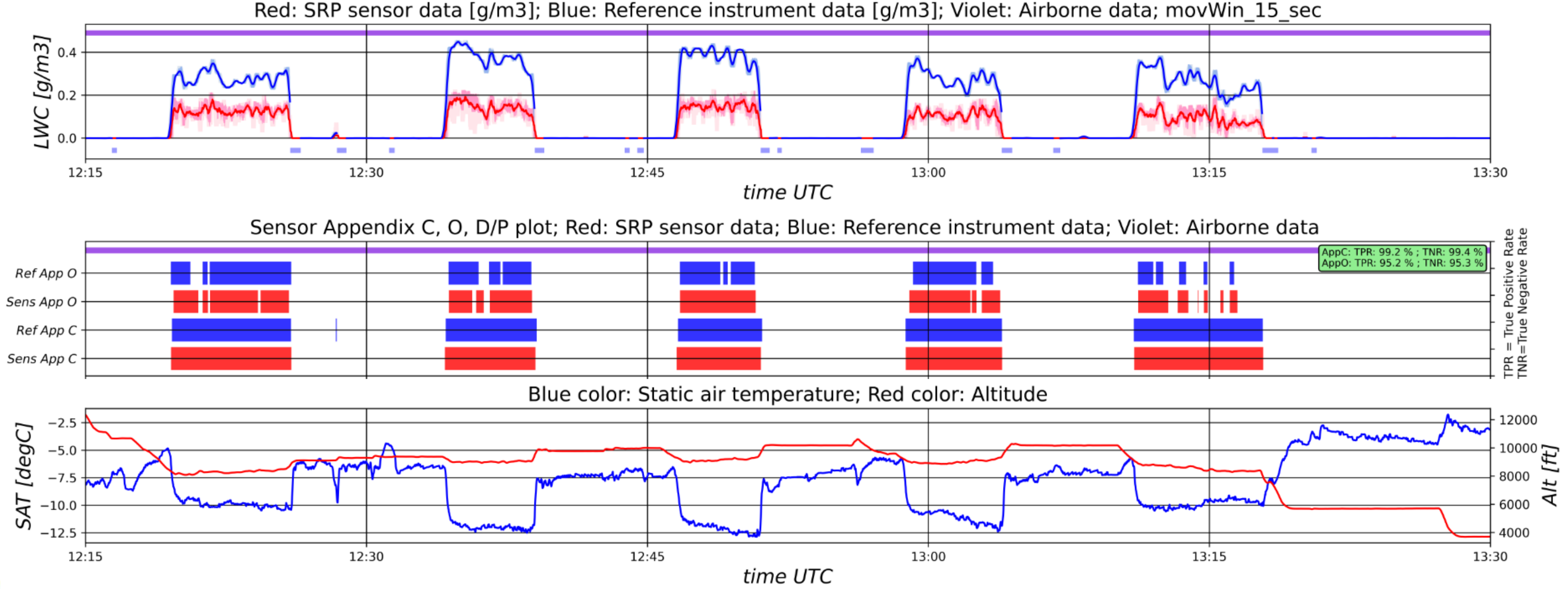



BACKUP

# SENS4ICE North America Flight Campaign
# SRP / Honeywell optical sensor data analysis

- Flight 1476 [SAE 2023 23ICE-0105 Hamada] [Figure courtesy of Honeywell]
- No collection efficiency / sensor non-linearities corrections not applied, better results expected

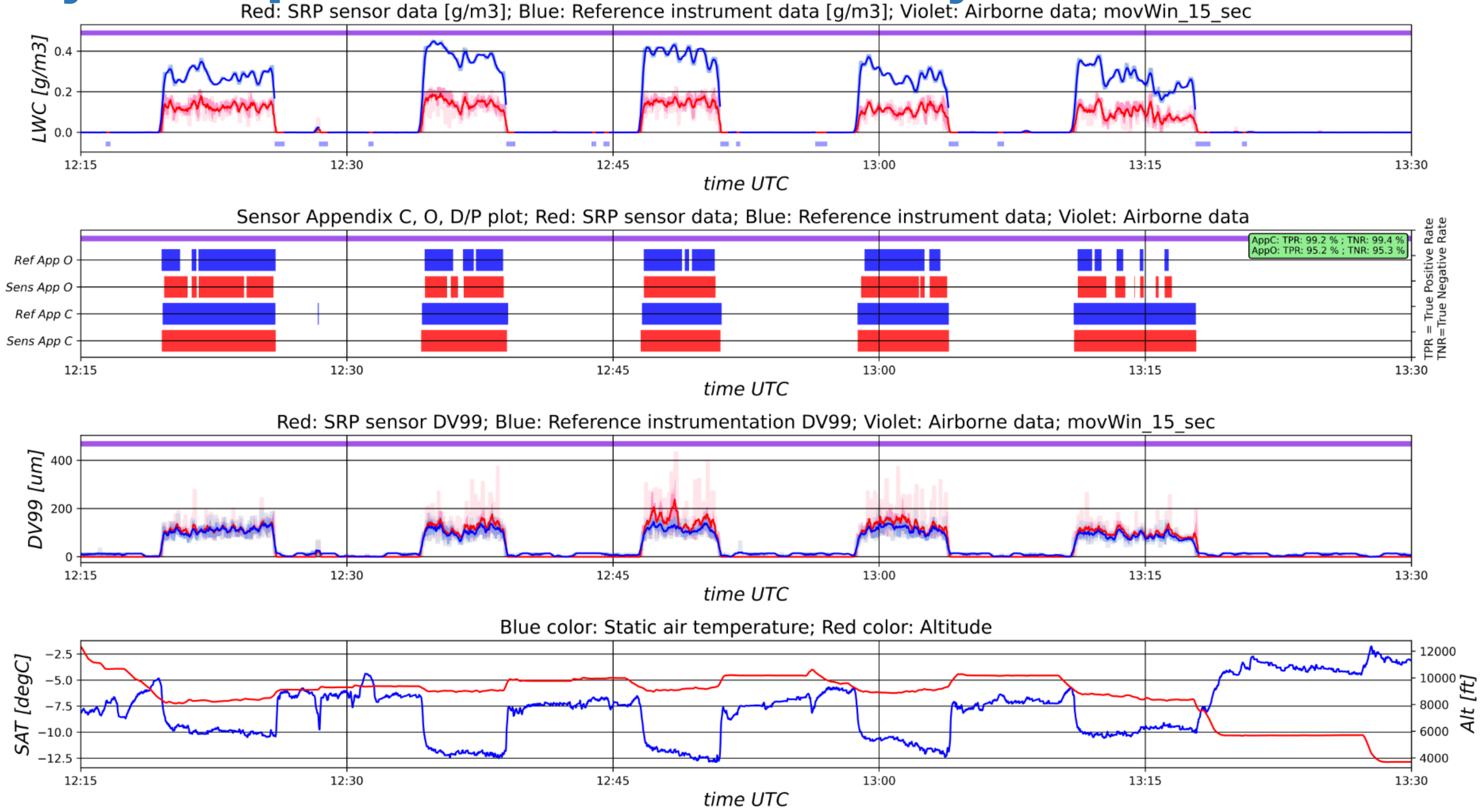





**BACKUP**

# SENS4ICE North America Flight Campaign
# SRP / Honeywell optical sensor data analysis

- Flight 1476
- No collection efficiency corrections applied, sensor non-linearities corrections not applied, better results expected
- [SAE 2023 23ICE-0105 Hamada]
- [Figure courtesy of Honeywell]



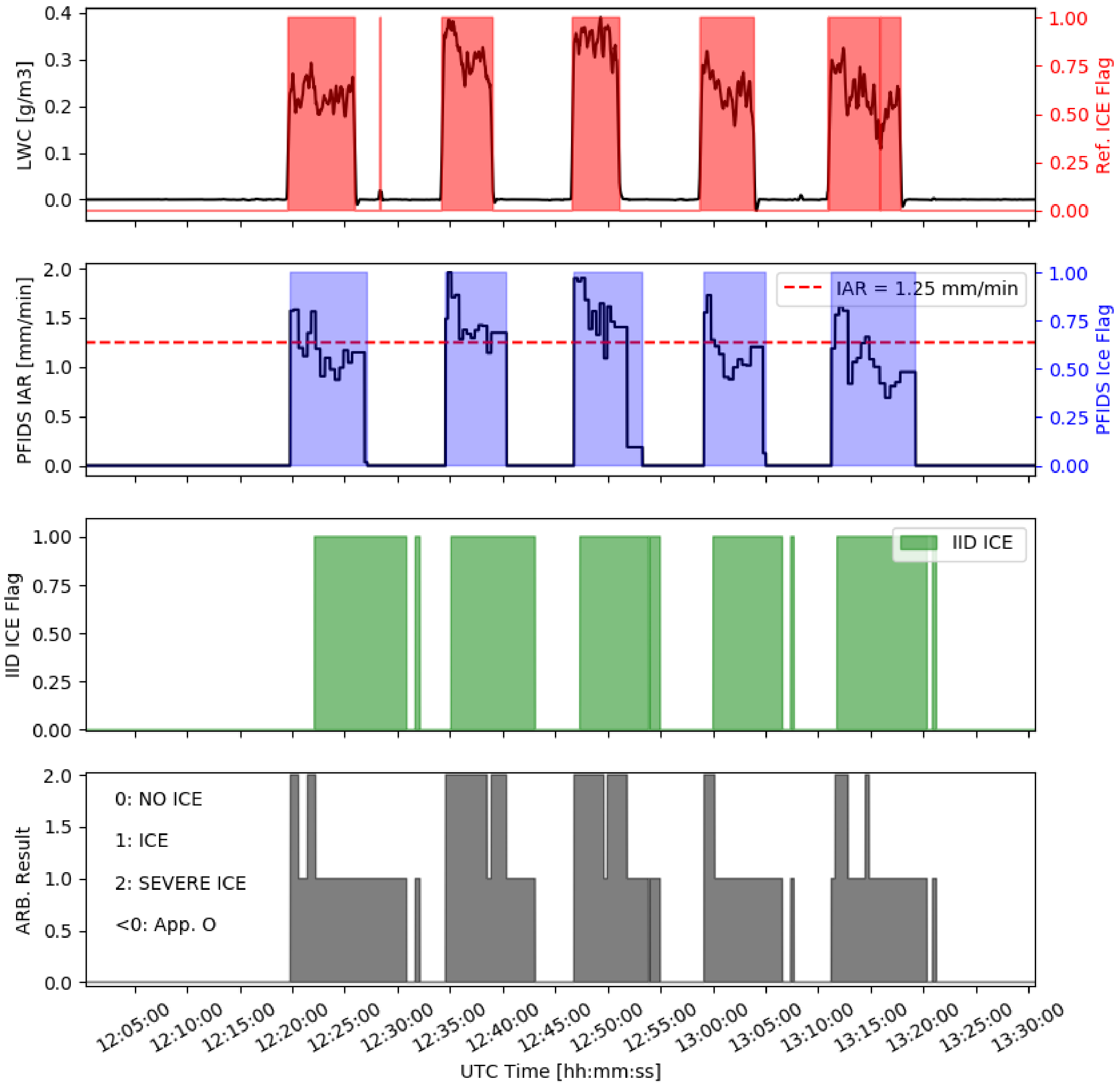



BACKUP

# SENS4ICE North America Flight Campaign HIDS with IID

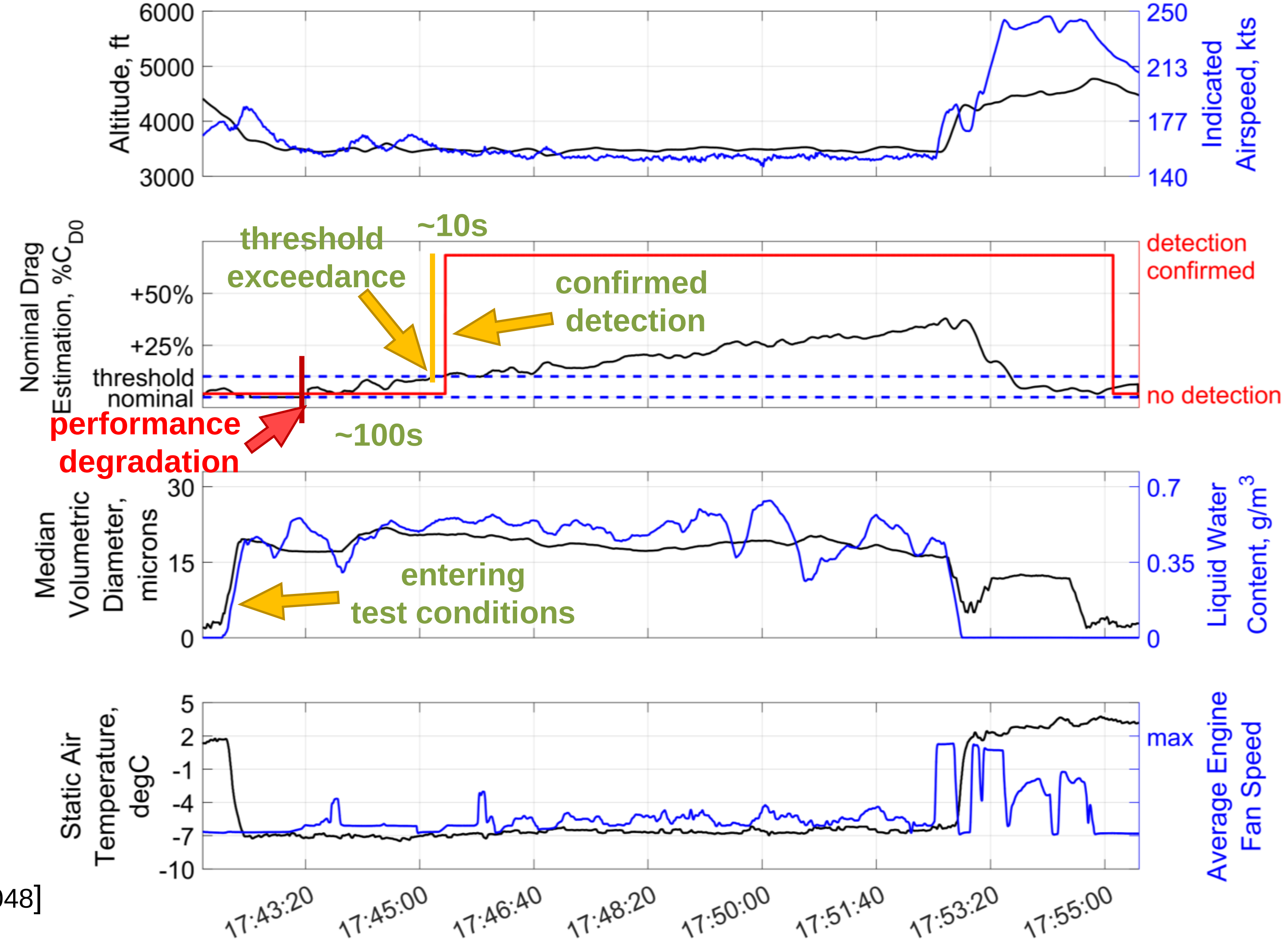
- Flight 1476-1
- Figure 1: LWC (liquid water content) curve and microphysics reference ICE FLAG
- Figure 2: PFIDS (direct ice sensor) IAR (ice accretion rate) and ICE Flag
- Figure 3: IID (indirect ice detection) Validated ICE Flag (i.e. IID reliable and TAT < 5°C)
- Figure 4: HIDS PFIDS/ IID arbitration output

[Courtesy of SAFRAN Aerosystems]



# SENS4ICE North America Flight Campaign
# Indirect Ice Detection Performance

- example 23 FEB 2023, 17:41:49 UTC - 17:55:29 UTC
- figure 1: altitude and indicated airspeed
- figure 2: nominal drag estimation and IIDS detection output
- figure 3: MVD and LWC of encountered icing conditions
- figure 4: static air temperature and average engine fan speed
- detection threshold at 10 % relative drag increase




[Deiler, C., "Testing of an Indirect Ice Detection Methodology in the Horizon 2020 Project SENS4ICE", Deutscher Luft- und Raumfahrtkongress (German Aerospace Conference) DLRK 2023, Stuttgart, Germany, 09/2023, paper no. 0048]

# Summary

- EU project SENS4ICE: increase flight safety in icing / especially SLD conditions and enhance knowledge base for Appendix O conditions
- Icing detection technologies developed specifically aiming at Appendix O icing conditions
- Icing wind tunnels enhanced capabilities for representing Appendix O conditions
- Direct ice detection sensors tested successfully in icing wind tunnels under both Appendix O and Appendix C conditions
- Hybrid ice detection system under development, incorporating a performance-based indirect ice detection
- Two flight campaigns successfully conducted early 2023
  - test ice detection technologies under natural icing conditions
  - focus on Appendix O
  - promising initial results: encountered icing conditions, sensor detection behavior and hybrid ice detection system performance including indirect ice detection system

# SENS4ICE Final Public Dissemination Event

- 29th of November 2023
- Brussels, Belgium
- Further details see
  - https://www.sens4ice-project.eu
  - https://www.linkedin.com/company/sens4ice-project

This project has received funding from European Union’s Horizon 2020 research and innovation programme under grant agreement n° 824253.

If not acknowledged, images courtesy of the consortium partners.



SENS4ICE

https://www.sens4ice-project.eu

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