SENS4ICE

SENSORS AND CERTIFIABLE HYBRID ARCHITECTURES
FOR SAFER AVIATION IN ICING ENVIRONMENT

SENS4ICE Aircraft Icing Hybrid Detection Flight Demonstration Results

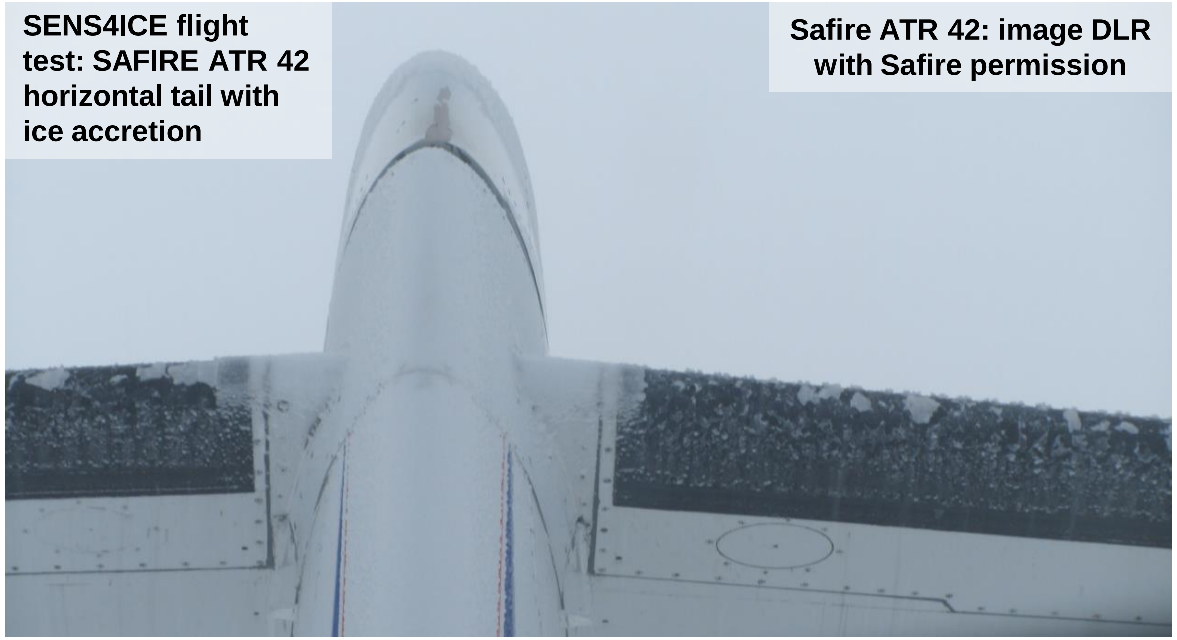
November 2024

Carsten Schwarz (DLR)

EASN Research Webinars
15 November 2024

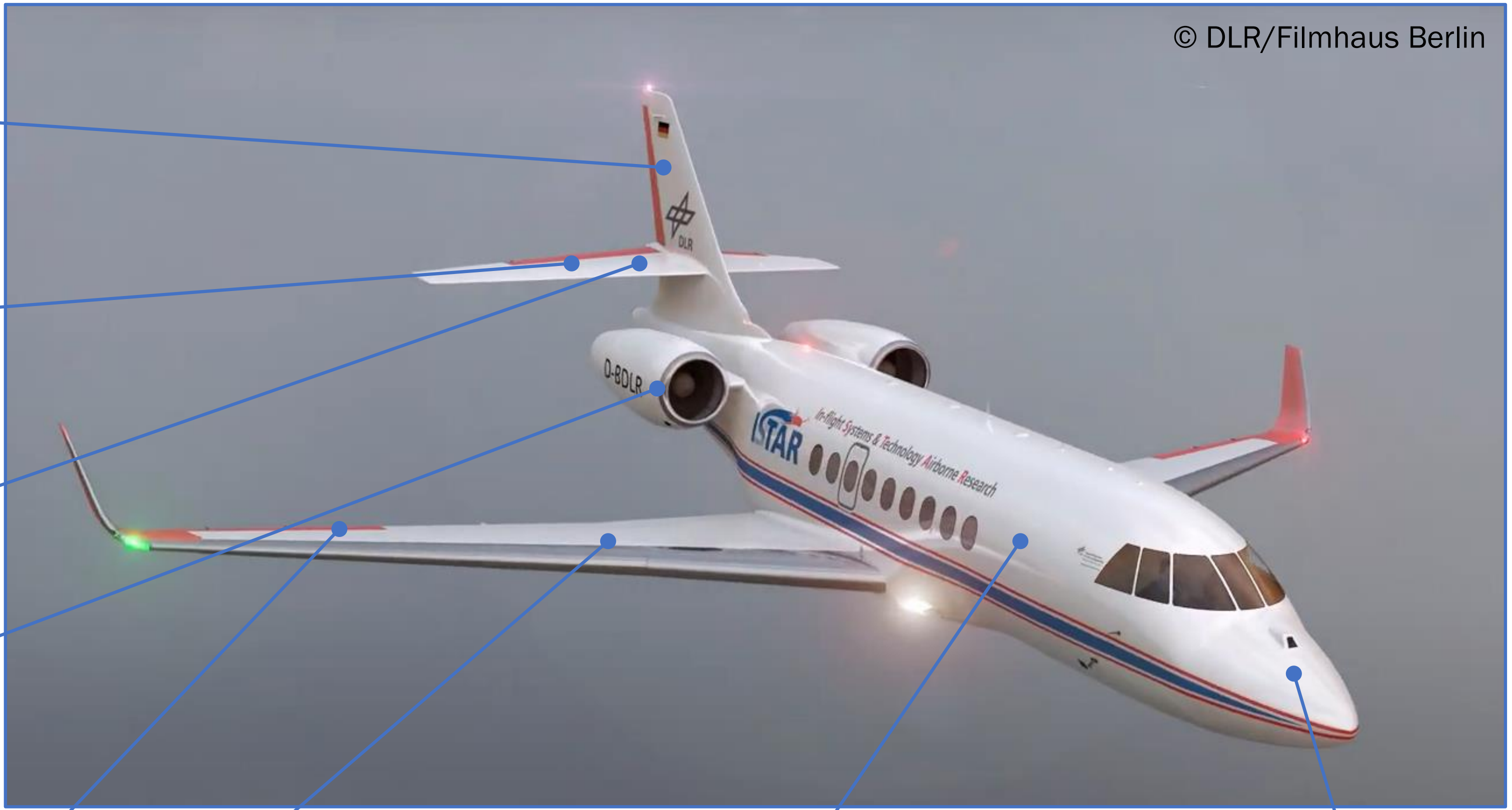
This project has received funding from European Union's Horizon 2020 research and innovation programme under grant agreement n° 824253

Aircraft Icing Phenomena Natural Ice Shapes



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

Safety Risks 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

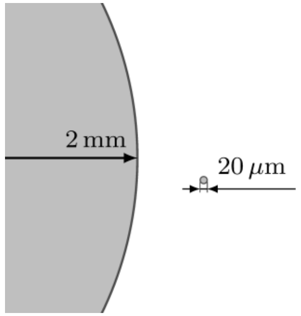
Fuselage
- Drag increase
- Collected contaminant ice layer

Sensors
- Malfunction
- Blockage

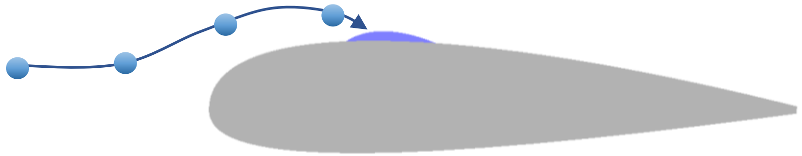
[Falk Sachs (DLR), Indirect ice detection for the hybrid ice detection system, SENS4ICE first public project symposium, SAE AC-9C Aircraft Icing Technology Committee Meeting 22 OCT 2020]

Supercooled Large Droplet (SLD) Icing - Challenges

Supercooled **Large** Droplets: > 50 µm



- Impingement behind the leading edge

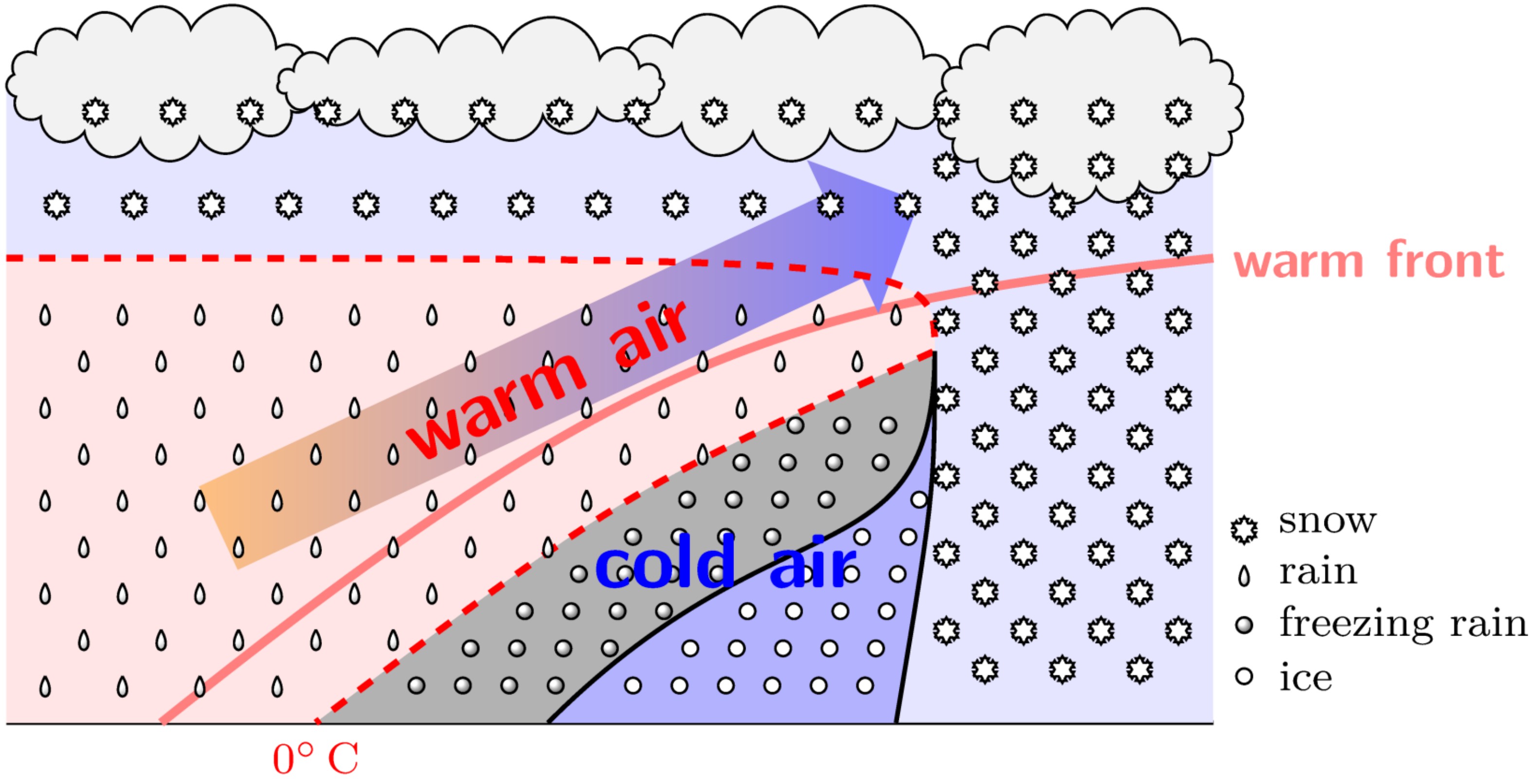


- Supercooled water running downstream

→ SLD icing conditions > safety of flight > certification
(Certification specifications Appendix O: CS-25 / 14 CFR Part 25)

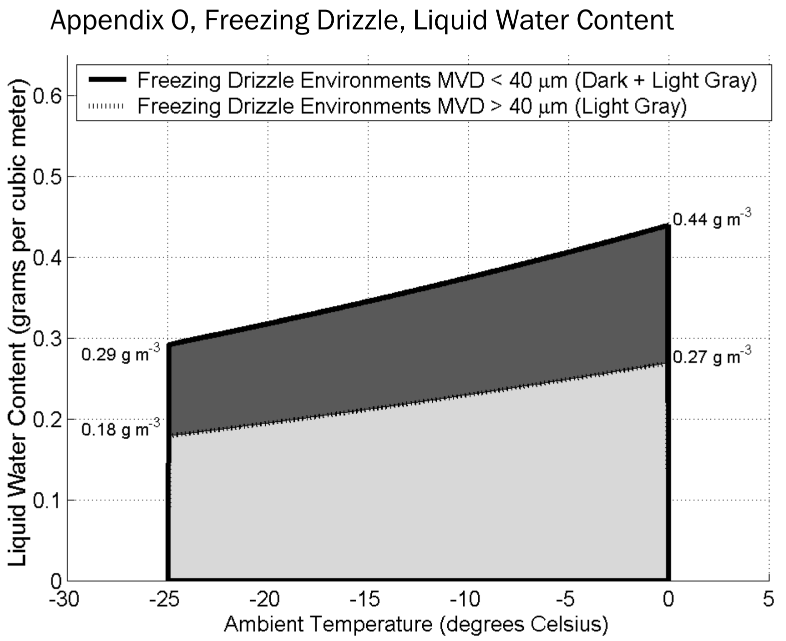
Supercooled Large Droplets (>50 µm)

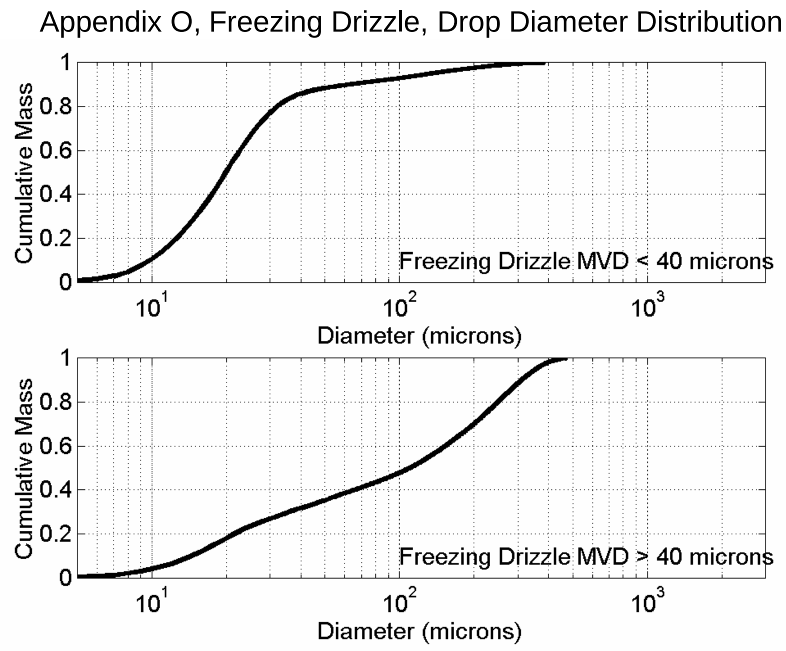
- High reaching clouds containing snow, which is melting in the warm air to large drops
- Part of large droplets falling down being supercooled in cold air
- Without nucleus for crystallization, SLD from freezing drizzle or freezing rain



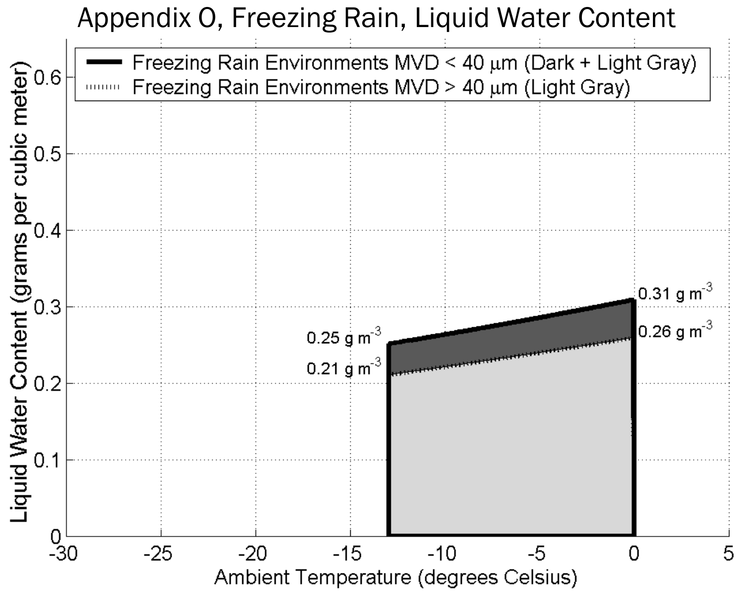
EASA/FAA Certification Specifications Appendix O envelope

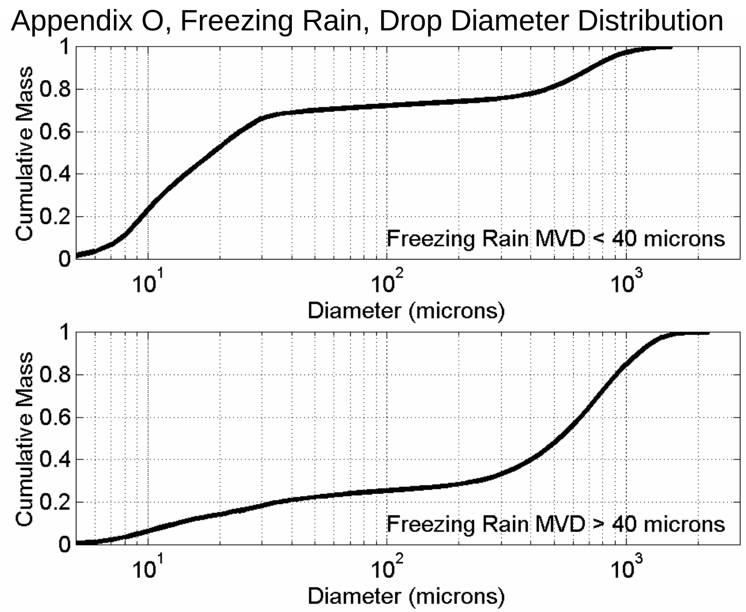
- Freezing Drizzle
- Freezing Rain





CS-25 BOOK 1 (CS-25 Amendment 21, Annex to ED Decision 2018/005/R), Appendix O, Figure 1 & 2





CS-25 BOOK 1 (CS-25 Amendment 21, Annex to ED Decision 2018/005/R), Appendix O, Figure 4 & 5

BACKUP

SENS4ICE Project Overview

SENSors and certifiable hybrid architectures for safer aviation in ICing Environment

- EU Horizon 2020 research and innovation programme
- 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

DLR
LEONARDO AIRCRAFT
UP
ATR PROPELLING THE NEXT CONNECTION
AeroTex UK LLP
ONERA THE FRENCH AEROSPACE LAB
CIRA Centro Italiano Ricerche Aerospaziali
Technische Universität Braunschweig
Collins Aerospace
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EMBRAER
Collins Aerospace
Honeywell THE POWER OF CONNECTED
INTA
National Research Council Canada
Conseil national de recherches Canada

SENS4ICE Challenge – Detect SLD Icing Conditions

Problem: Detection very challenging (very few very large droplets)

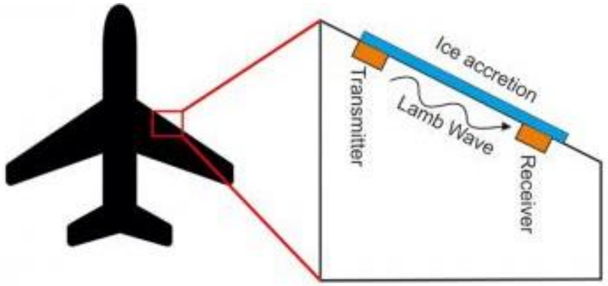
Solution/Innovation:

- 8 direct detection technologies matured & flight test demonstrated
- Hybrid approach – fusion of complementary input data: sensor(s) and indirect ice detection (IID)

Benefits:

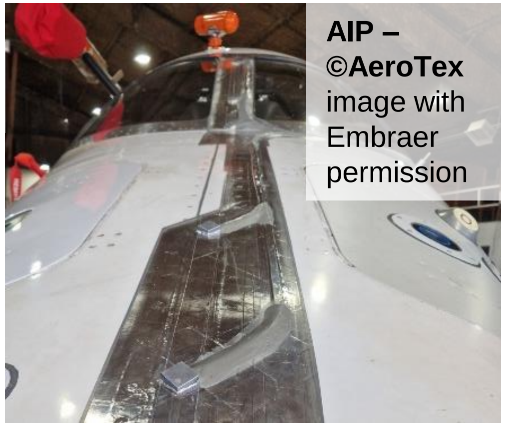
- Operational safety (activate anti-/de-icing, avoid/ leave icing conditions)
- Certification support (enabling technologies) for Appendix O/ SLD icing


HIDS-Safran/ IID-DLR

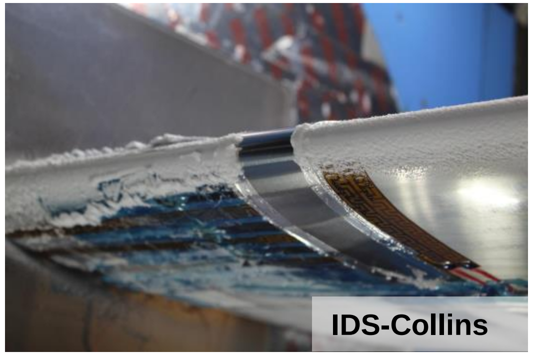


LILD-DLR


PFIDS-Safran


AIP – ©AeroTex image with Embraer permission

AMPERA-ONERA image with Safire permission


IDS-Collins


SRP–Honeywell image © Embraer


CM2D-DLR image DLR


FOD-INTA image with Safire permission

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

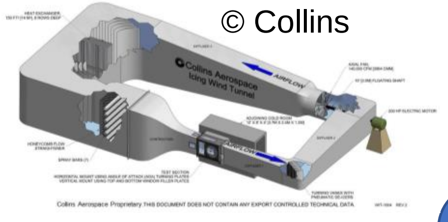
Contingency: new detection of reduction in aircraft flight envelope (loss of control prevention)

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

SENS4ICE Timeline / Summary / Achievements

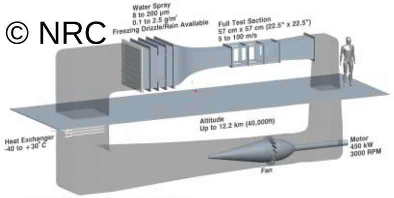
Upgrade icing wind tunnels for App. O

Develop sensors/ technologies for App. O detection

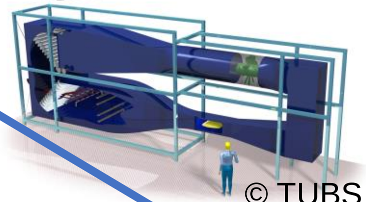


© Collins

Icing wind tunnel testing



© NRC



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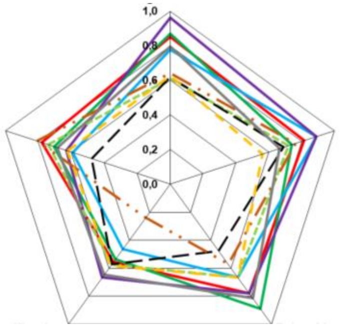
Sensor technology evaluation and selection



Hybrid ice detection

Indirect ice detection

Flight test preparation

Flight testing

FEB/MAR 2023

Copyright © Embraer

APR 2023

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Flight test analysis/ techno-logy evalua-tion

Commu-nication, Dissem-ination, Exploi-tation

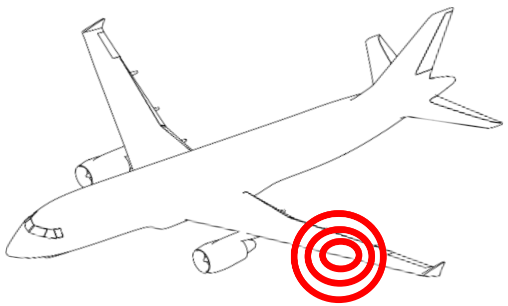
2019 - 2020 **2021** **2022** **2023**

8.7 M EUR including 6.6 M EUR EU contribution

Hybrid Ice Detection Approach

Direct ice detection

Local detection (ice detector): presence of ice accretion/icing condition.



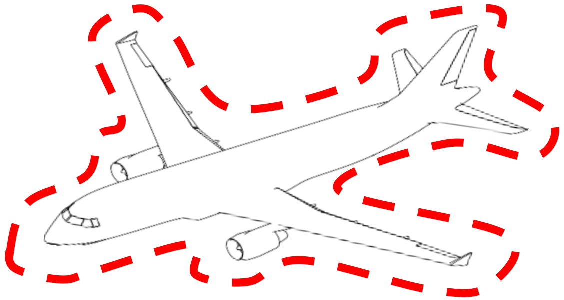
Hybrid ice detection

Combination of Direct and Indirect Detection.

- Flight safety increase
- False alarms reduction
- A/C performance monitoring
- Improved situational awareness

Indirect ice detection

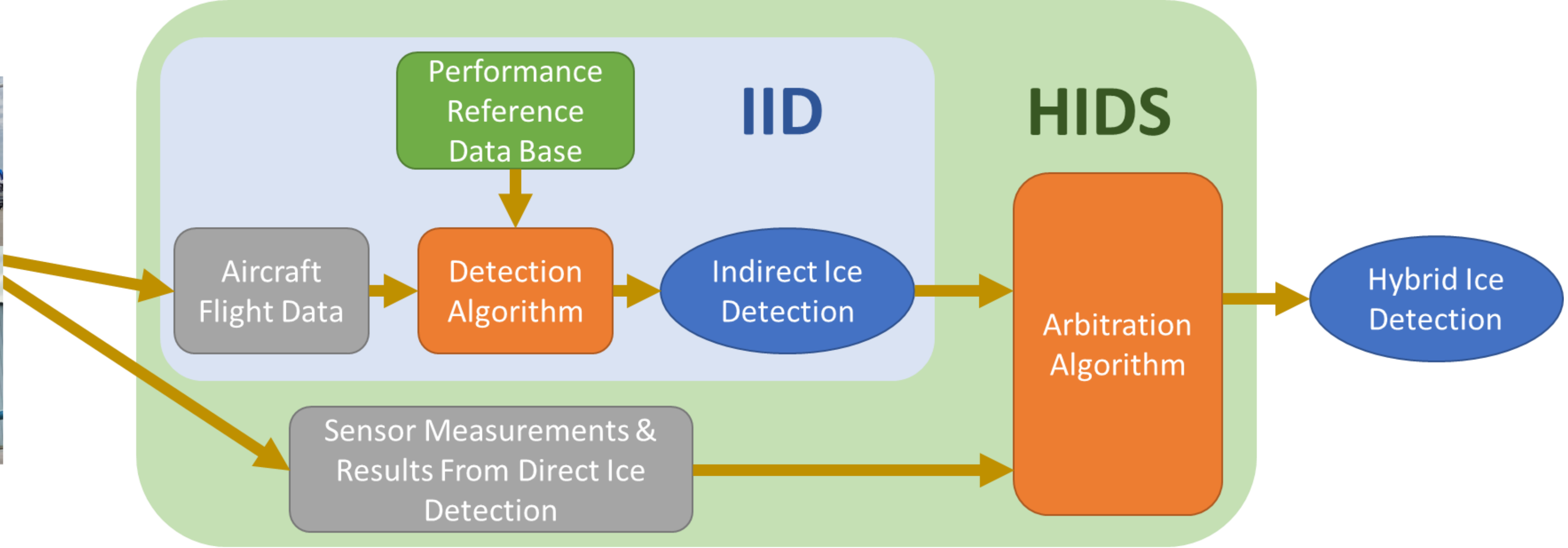
Global detection: effects of ice accretion.



SENS4ICE goals

- define hybrid detection specifications
- develop Hybrid Ice Detection System (HIDS) demonstrator for flight campaign

Hybrid Ice Detection System (HIDS) concept including Indirect Ice Detection (IID)

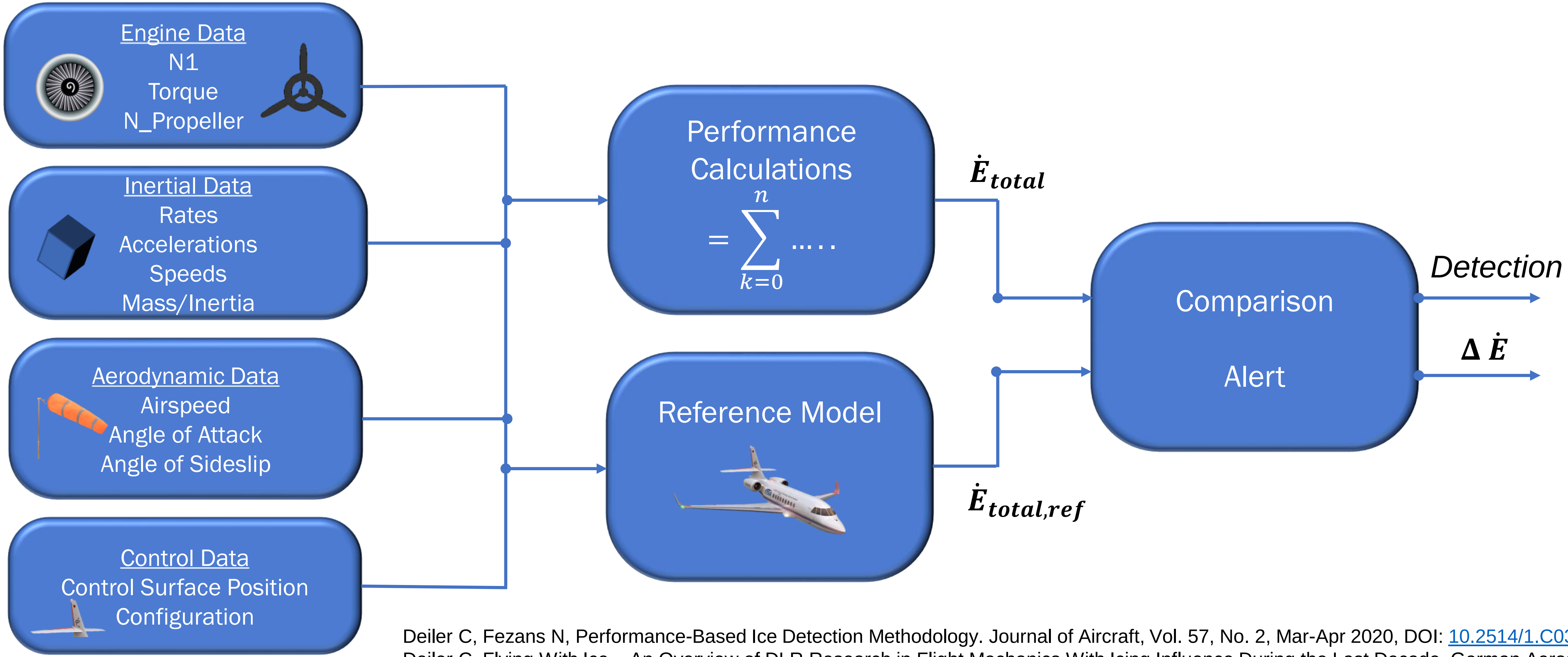


[Orazzo, A., Thillays, B., "Hybrid Ice Detection System development and validation", SAE International Conference on Icing of Aircraft, Engines, and Structures 2023, Vienna, Austria, 20 – 22 June 2023, 23ICE-0049]

[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

SENS4ICE Flight Campaigns - Overview

- Total flight test time: 75h aiming at 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
  - 260+ min in App C and 50 min in App O
- 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
  - 610+ min App C and 150+ min App O

Embraer Phenom 300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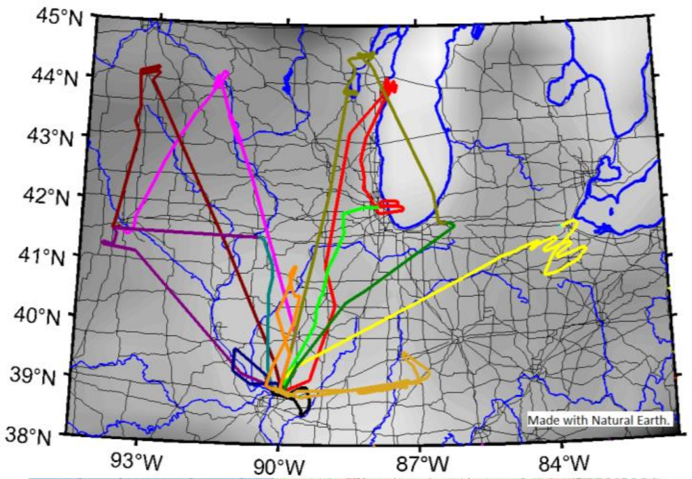
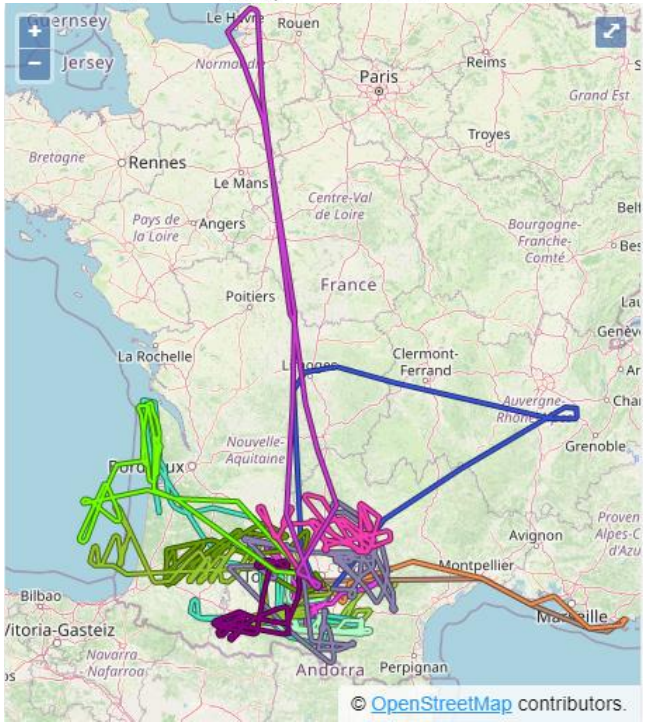


SAFIRE ATR 42

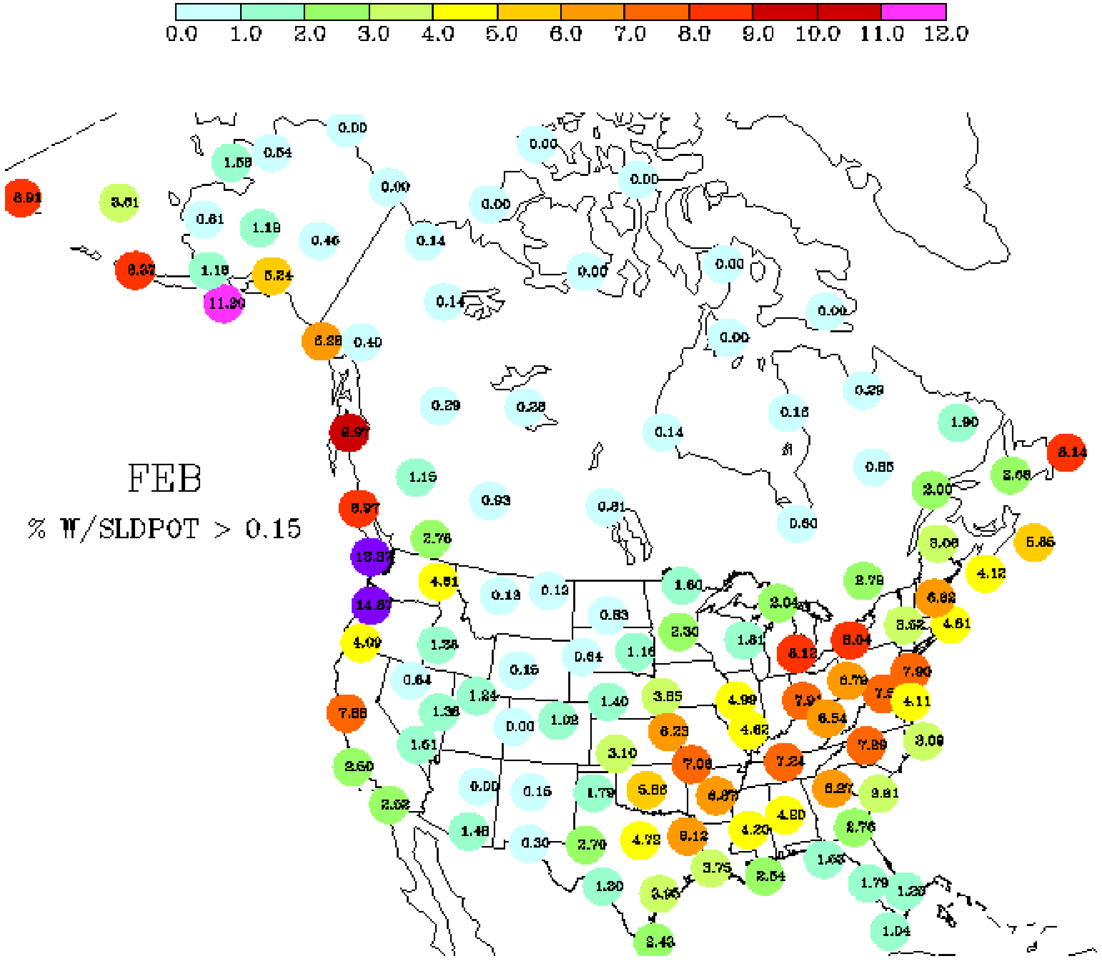

Copyright SAFIRE

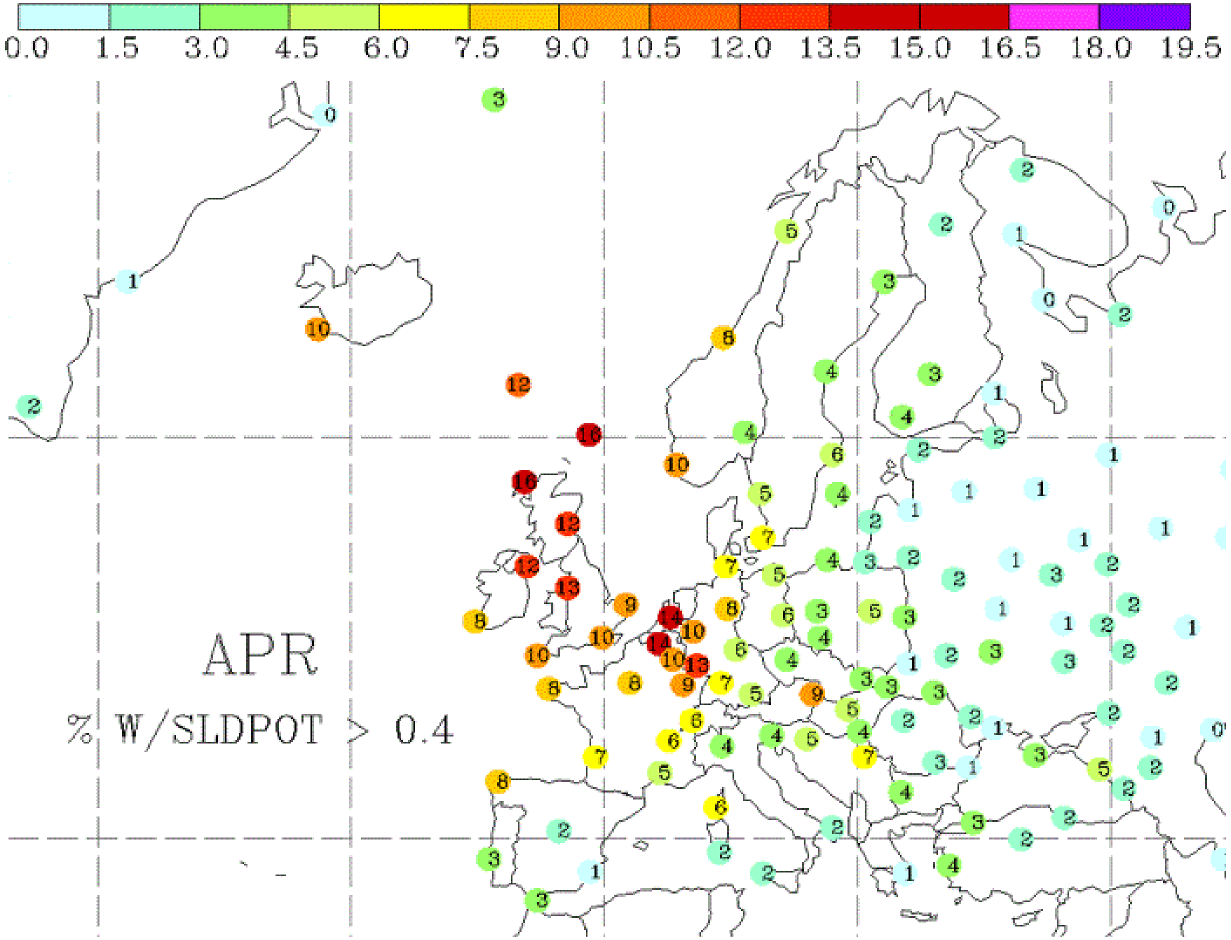


SAFIRE atmospheric reference data publicly available
https://safireplus.aeris-data.fr/data-access

Icing Frequencies Analysis

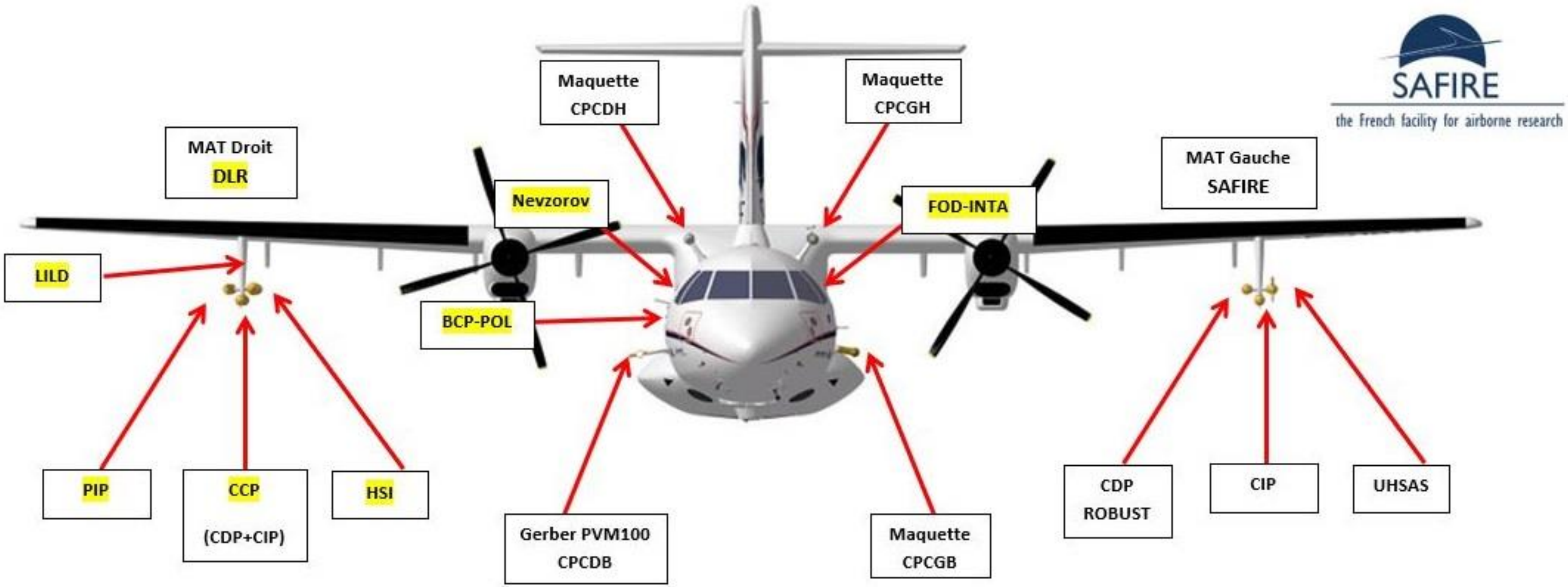
Full column frequencies of days with SLD potential [Ben Bernstein]





<u>Data analysis process (SLD Potential "SLDPOT" calculated using "CIP-Sonde") based on</u>: 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](https://doi.org/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](https://doi.org/10.1175/2009JAMC2073.1)

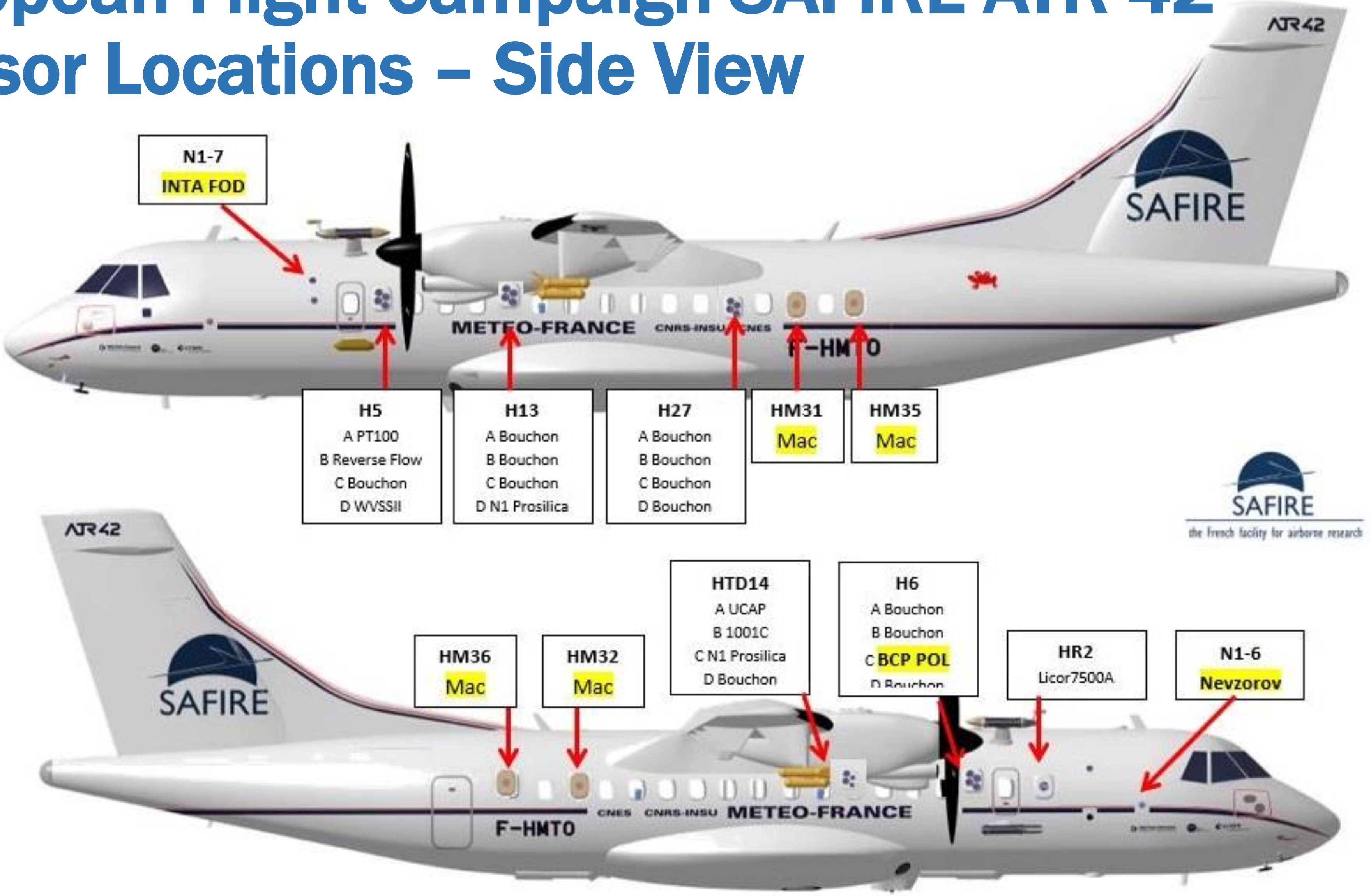
European Flight Campaign SAFIRE ATR 42 Sensor Locations – Front View



SENS4ICE equipment highlighted in yellow

Image Credit Safire

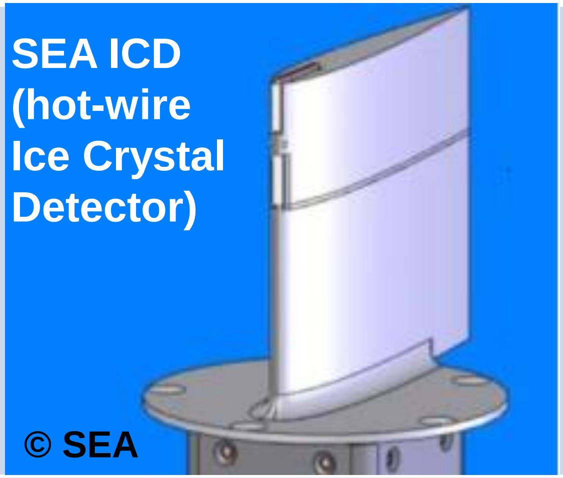
European Flight Campaign SAFIRE ATR 42 Sensor Locations – Side View



SENS4ICE equipment highlighted in yellow

Image Credit Safire

Airborne Reference Instruments for Icing Atmosphere Characterisation

Instrumentation	Embraer Phenom 300	Safire ATR 42
Hotwire instruments: LWC (liquid water content)		
Optical instruments: Particle size distributions		DLR-PA CCP (Cloud Combination Probe)
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 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)

HIDS-Safran/ IIDS-DLR

- SAFIRE ATR 42 with test sensors and reference instruments

LILD-DLR

image DLR with Safire permission

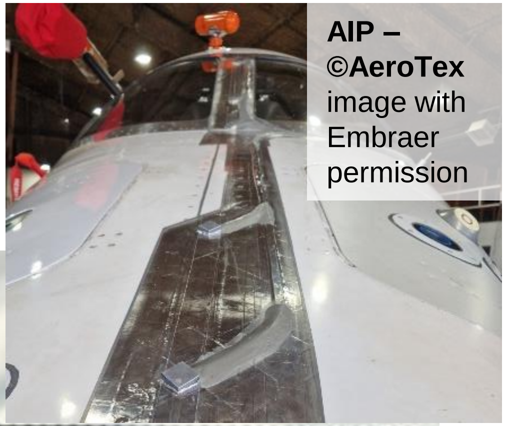
AMPERA-ONERA
image with Safire permission

FOD-INTA
image with Safire permission

CM2D-DLR image 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)



AIP – ©AeroTex image with Embraer permission

© Embraer

PFIDS-Safran

SRP–Honeywell image © Embraer

IDS-Collins

HIDS-Safran/ IIDS-DLR

North America Flight Campaign Embraer Phenom 300 Impressions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SENS4ICE Flight Campaign North America
Time-lapse video - Credit Embraer

- Ice accretion on windshield during SLD cloud encounter
- Entering cloud from above

SENS4ICE Flight Campaigns

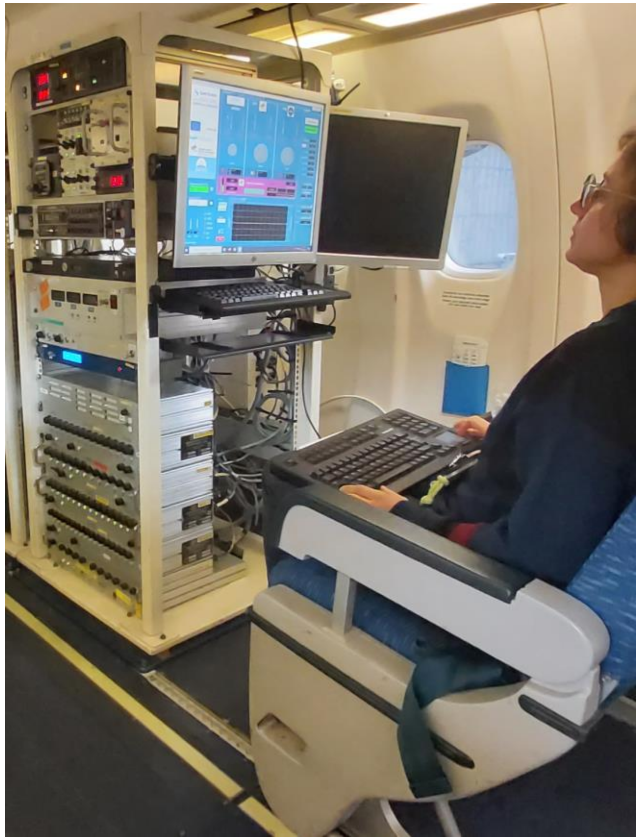
North America

- Ice accretion on windshield after SLD cloud encounter
- [image credit Embraer]

Europe

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

SENS4ICE Flight Campaign Europe
Impressions

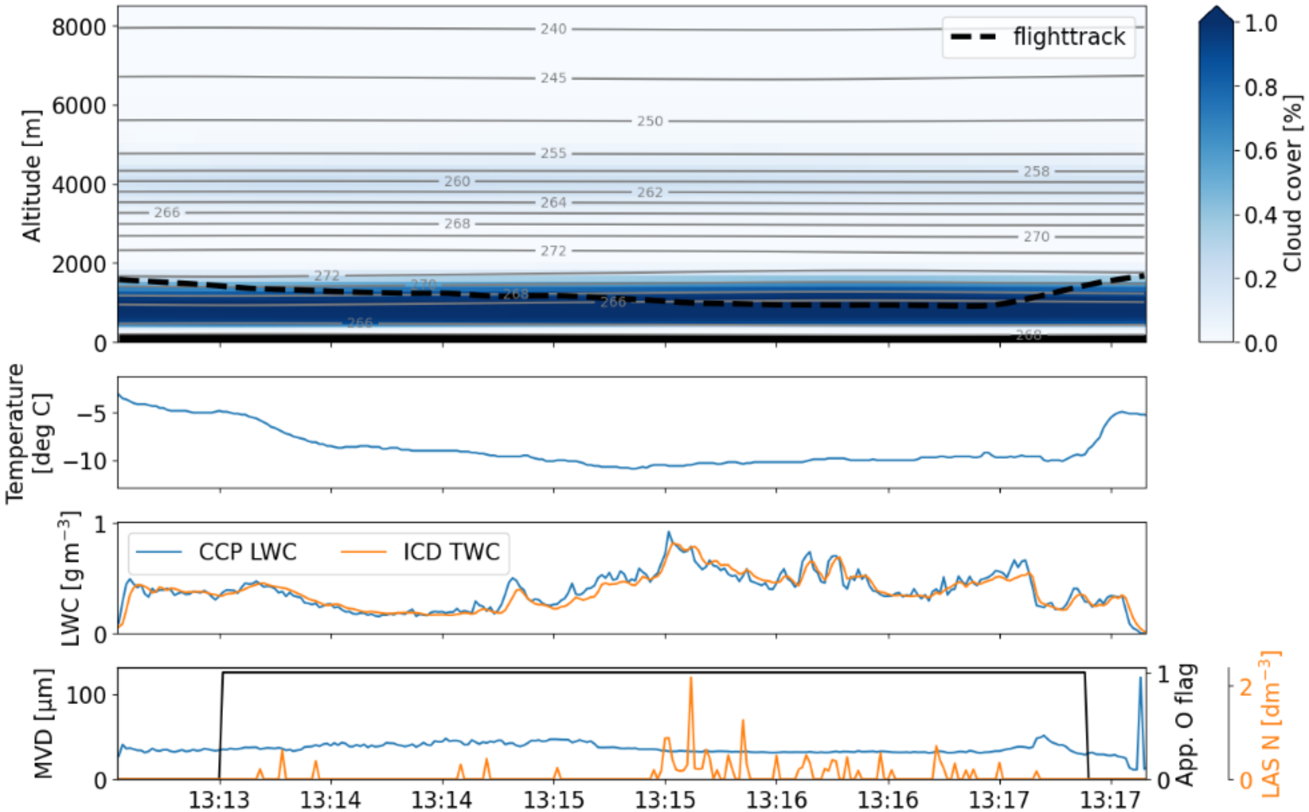


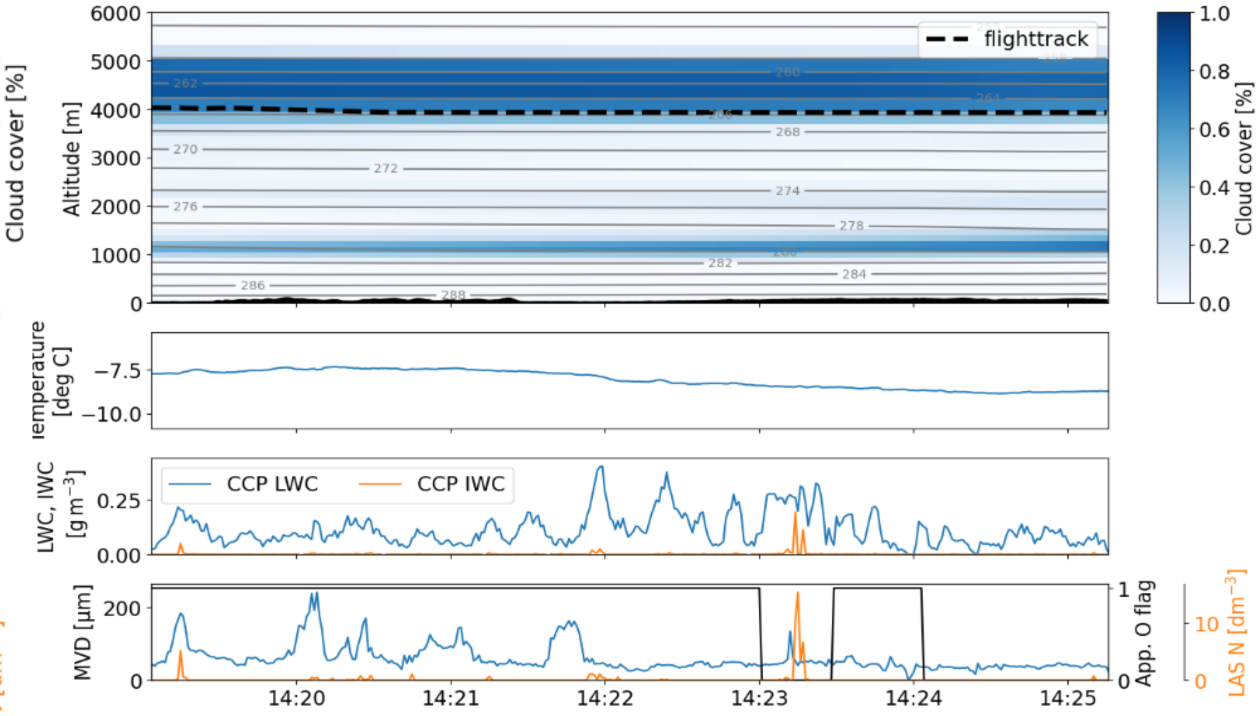
Operator working with HIDS PC.
(credit SAFRAN)

Reference sensors with ice accretion
[image DLR with Safire permission]

Appendix O Example Encounters

BACKUP





North America Campaign

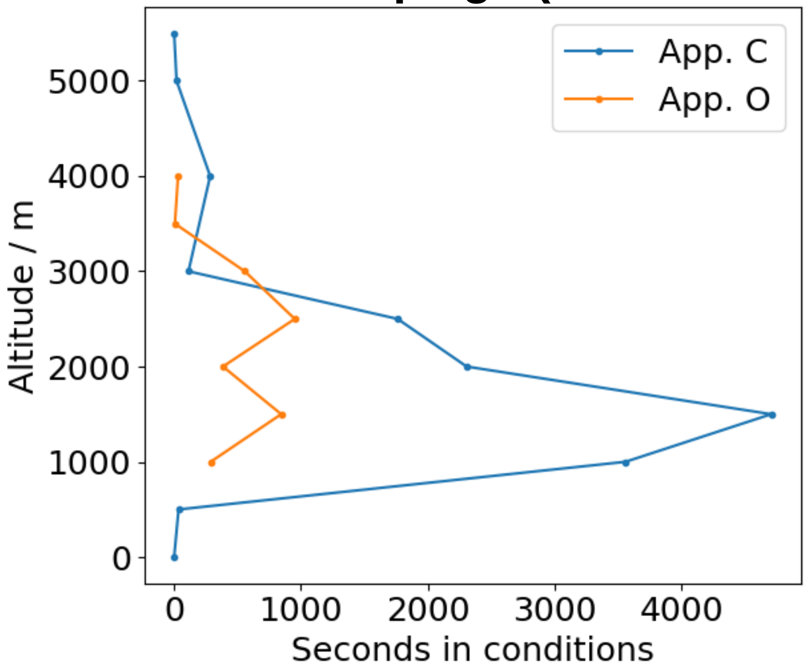
- Clouds most often closed stratus decks
- Appendix O encountered above a stable layer
- Typically cloud approached from top

Europe Campaign

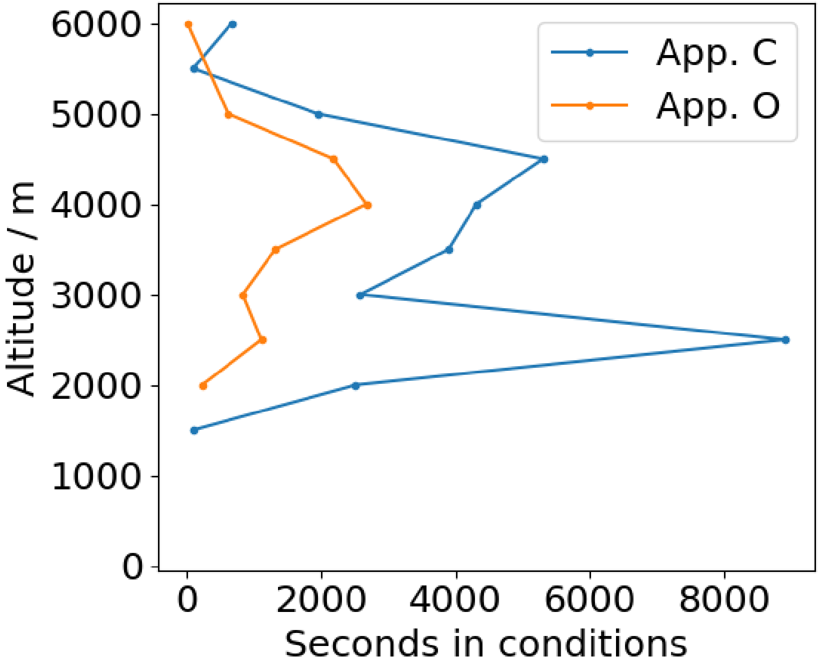
- Cloud consisted of multiple layers, not separately resolved in ERA5 cloud cover data
- Clouds thinner and patchier, large variation of LWC within clouds

Altitude of Icing Conditions

North American campaign (Feb/March 2023)



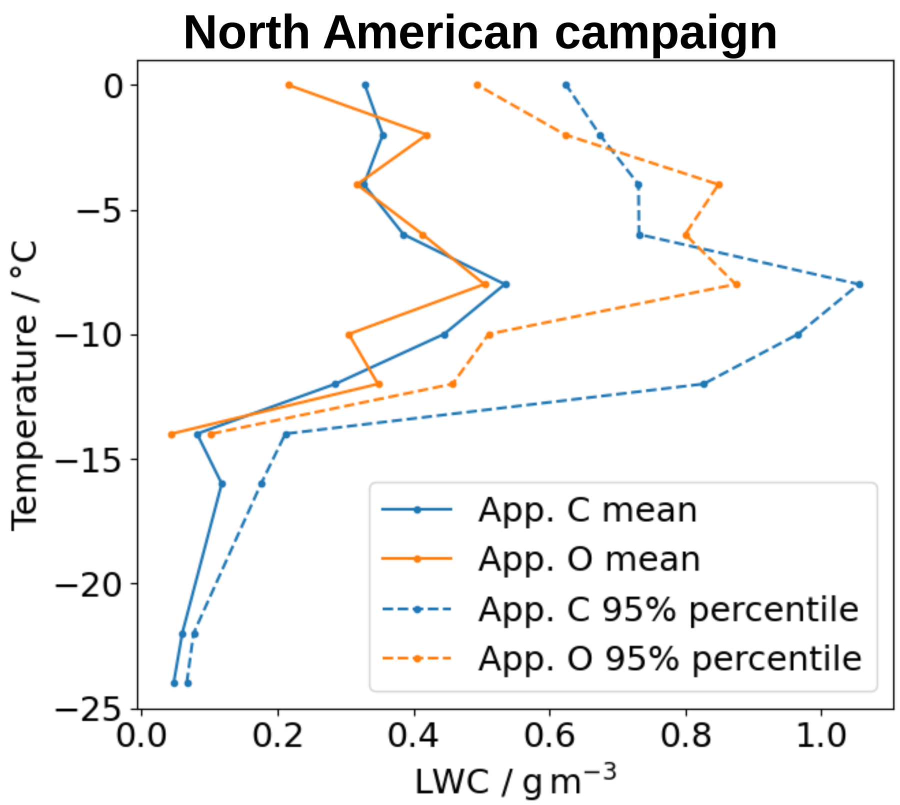
European campaign (April 2023)

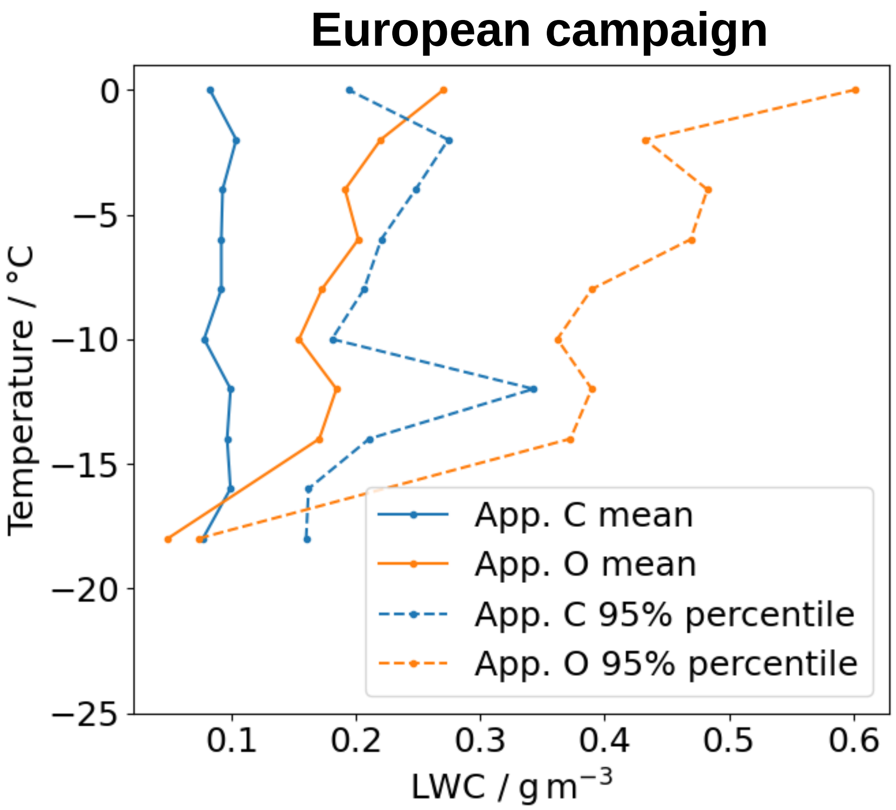


- North American campaign: Icing conditions mostly 1000 - 3000 m
- European campaign: Most icing conditions 2500 - 5000 m
- Most Appendix O conditions during European campaign 3500 - 5000 m
- Different altitudes reflect different seasons during which campaigns occurred

[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

LWC of Icing Conditions





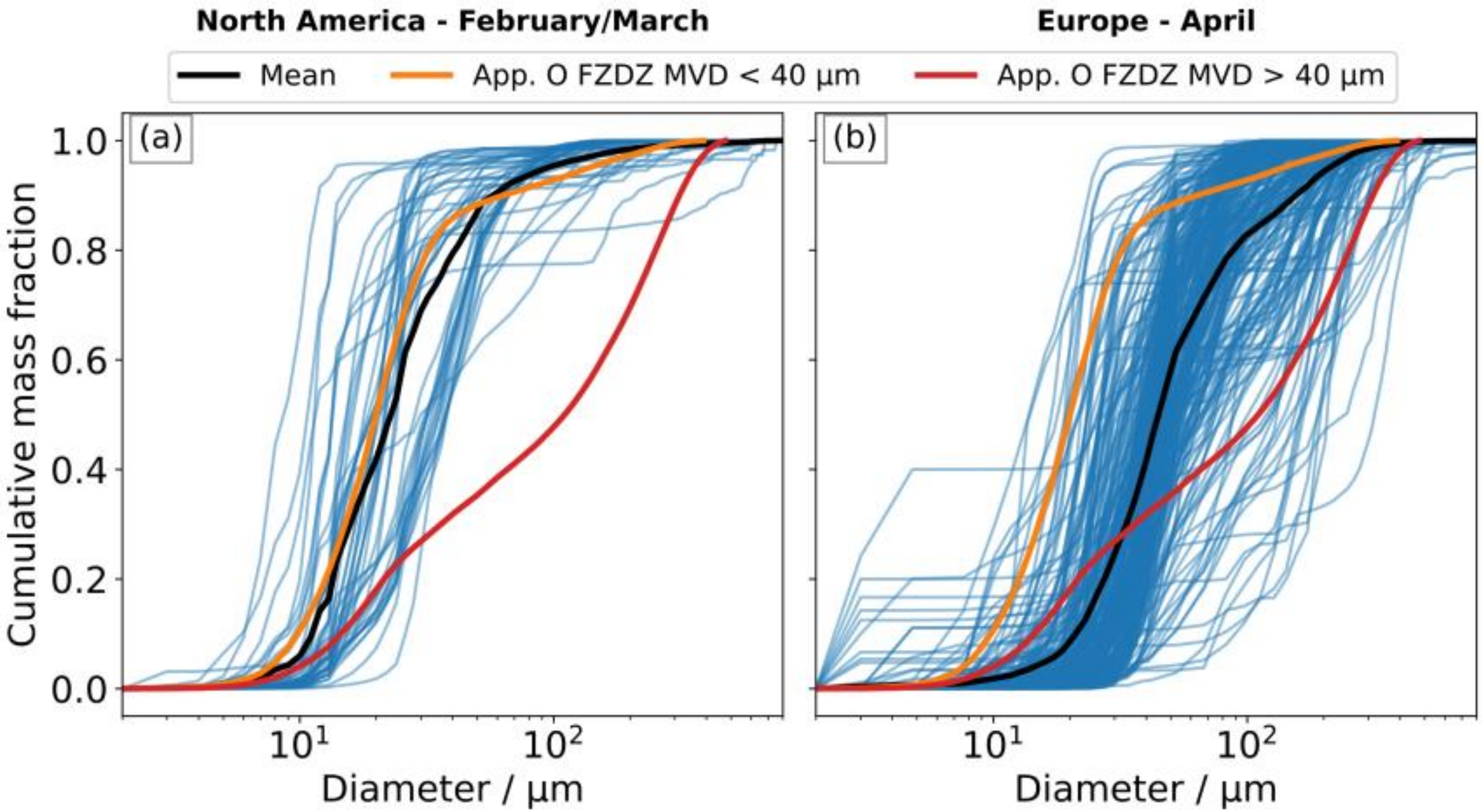
- LWCs higher during North American campaign
- North American campaign: LWCs in Appendix C and O conditions are similar.
- European campaign: LWCs in Appendix O significantly higher than in Appendix C

BACKUP

[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

Cumulative mass distributions

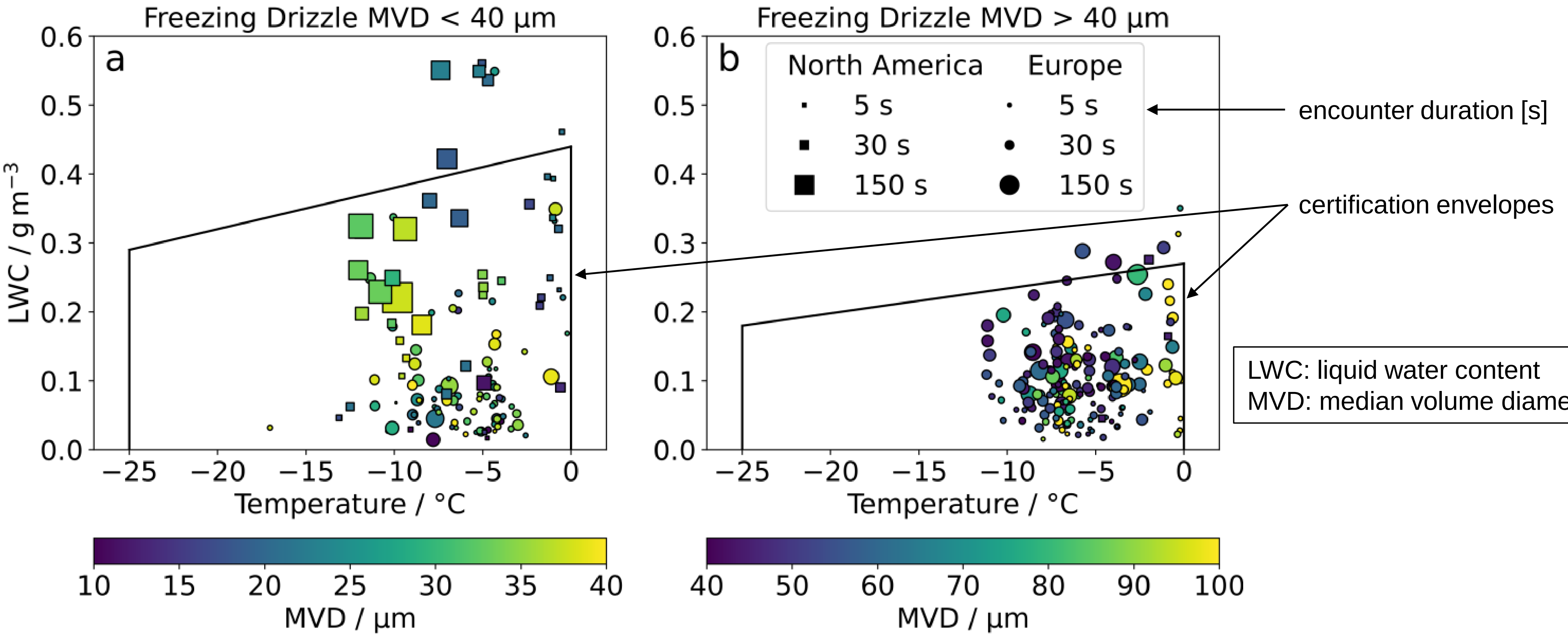
BACKUP



- North America average MVD ≈ 23 µm
- Europe average MVD ≈ 45 µm

SENS4ICE Flight Campaigns: **Comparison with App O LWC Envelopes**

- Shorter sampling distance of LWC values accounted for with scaling factor
- Only encounters exceeding 30 s used for this analysis
- Certification envelopes represented well by measurements, only few encounters outside

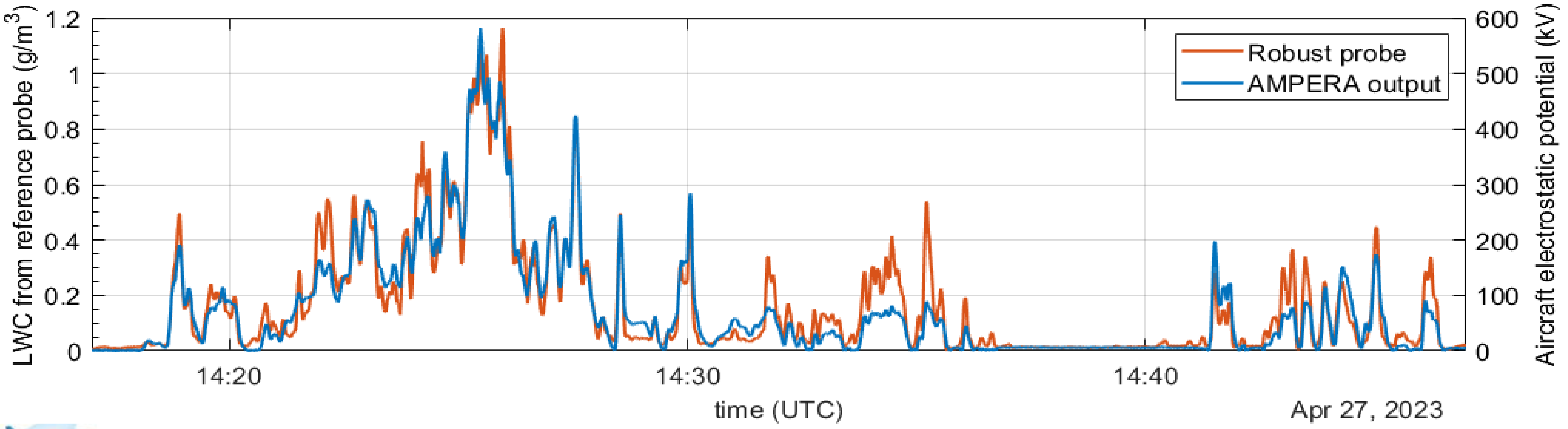


LWC: liquid water content
MVD: median volume diameter

Microphysics data analysis DLR Institute of Atmospheric Physics
[Lucke, J., et al., AIAA AVIATION 2024, Las Vegas, NV, USA]

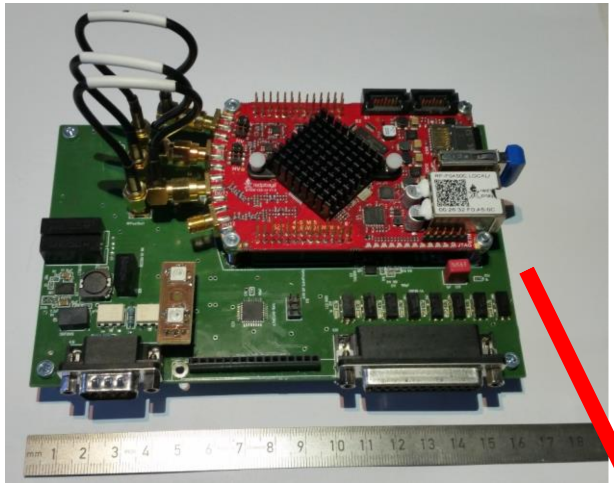
SENS4ICE Europe Flight Campaign AMPERA / ONERA

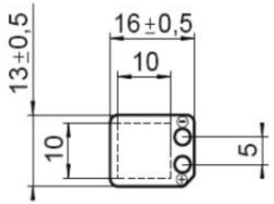
- LWC and Aircraft electrostatic potential comparison – strong correlation
- very robust measurement
- response time of about 1s (enter/exit clouds)
- [SAE 2023 23ICE-0108 Martins et al.]

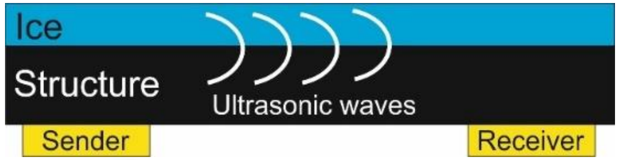


Local Ice Layer Detector (LILD / DLR)
Preparing the flight test

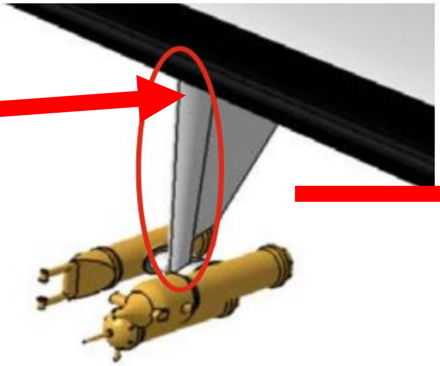
- Sensor integration for flight tests in March/April 2023

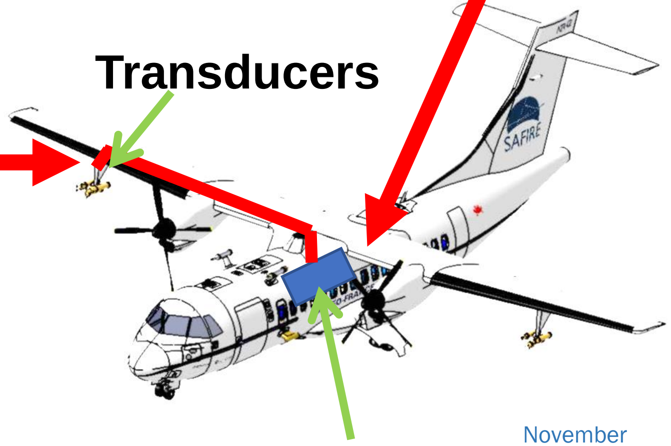






LILD principle of travelling ultrasonic lamb waves



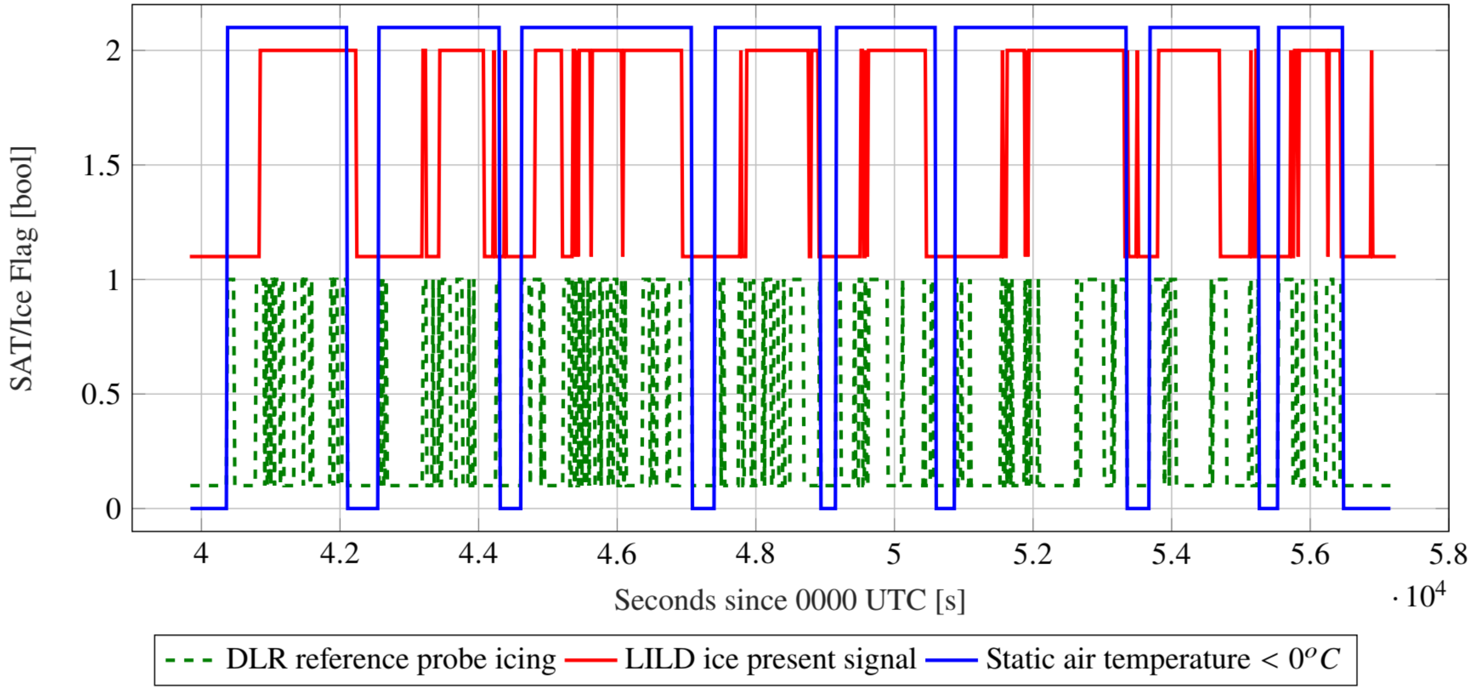


BACKUP

ATR 42 image © Safire

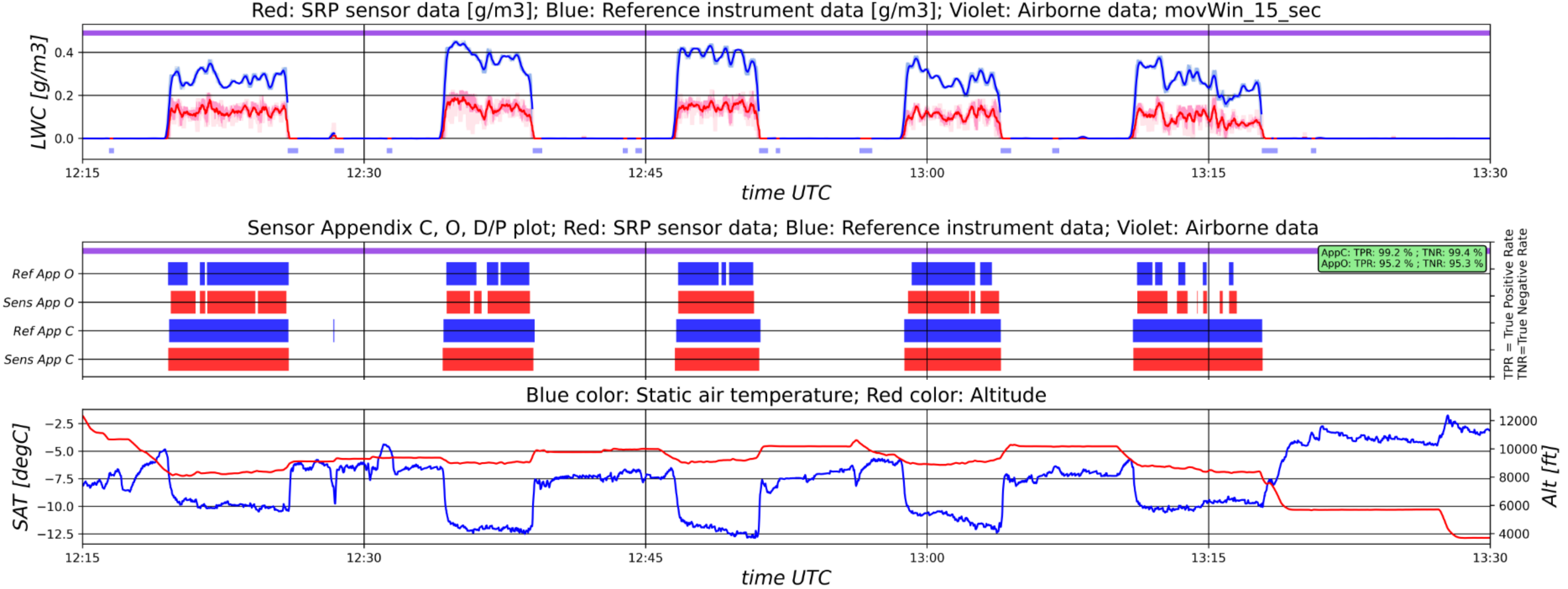
Local Ice Layer Detector (LILD / DLR)
Flight test results

- One exemplarily test flight: 25 APR 2023 in the vicinity of TLS (Toulouse airport)
- Ice Status: LILD and DLR atmospheric reference probe signal with static temperature<0°C indication
- LILD detects icing slightly later than atmospheric reference
- All icing encounters detected ☺



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



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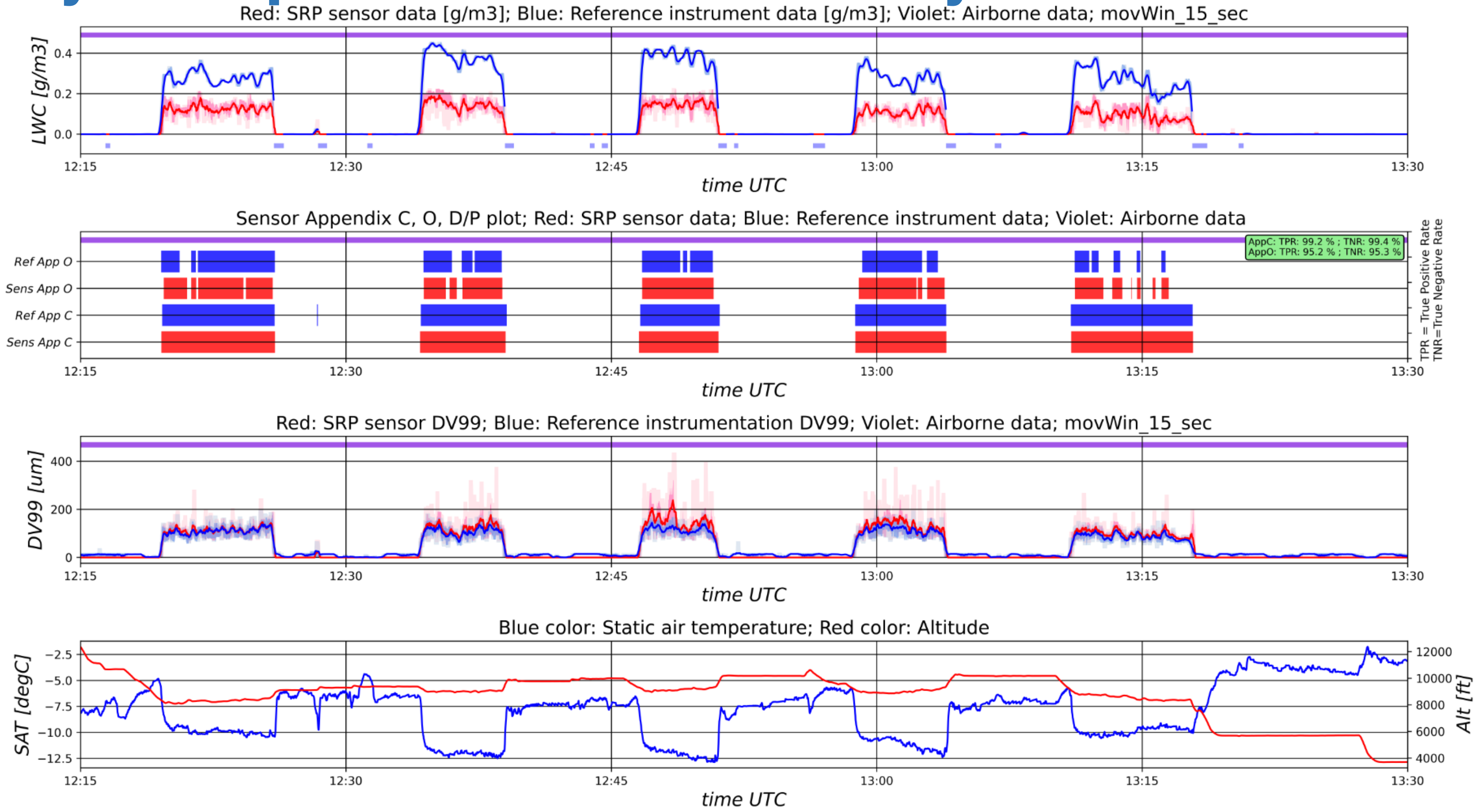
SENS4ICE North America Flight Campaign
SRP / Honeywell optical sensor data analysis

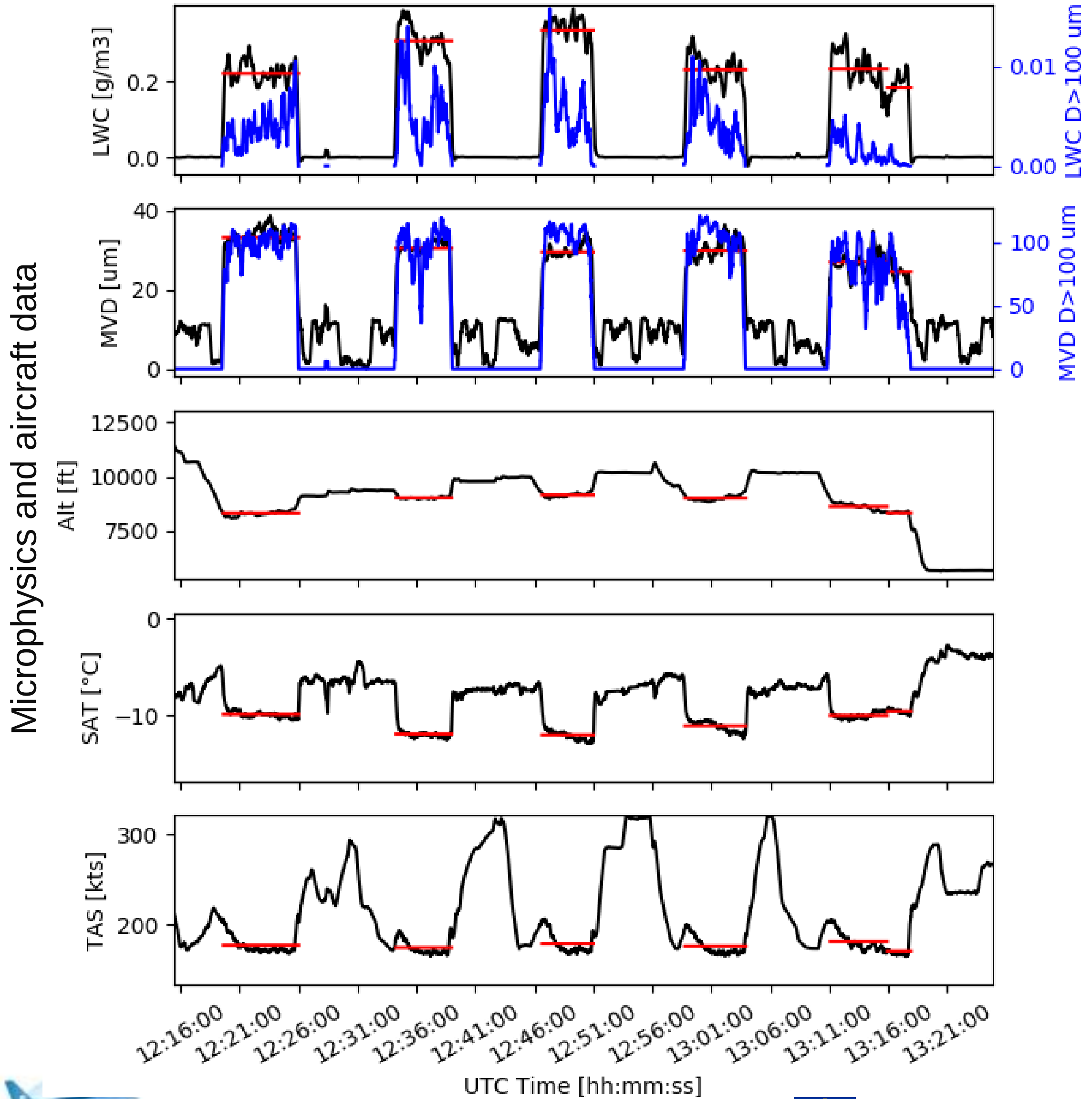
- Flight 1476
- No collection efficiency corrections applied, sensor non-linearities corrections not applied, better results expected
- [SAE 2023 23ICE-0105 Hamada]
- [Figure courtesy of Honeywell]

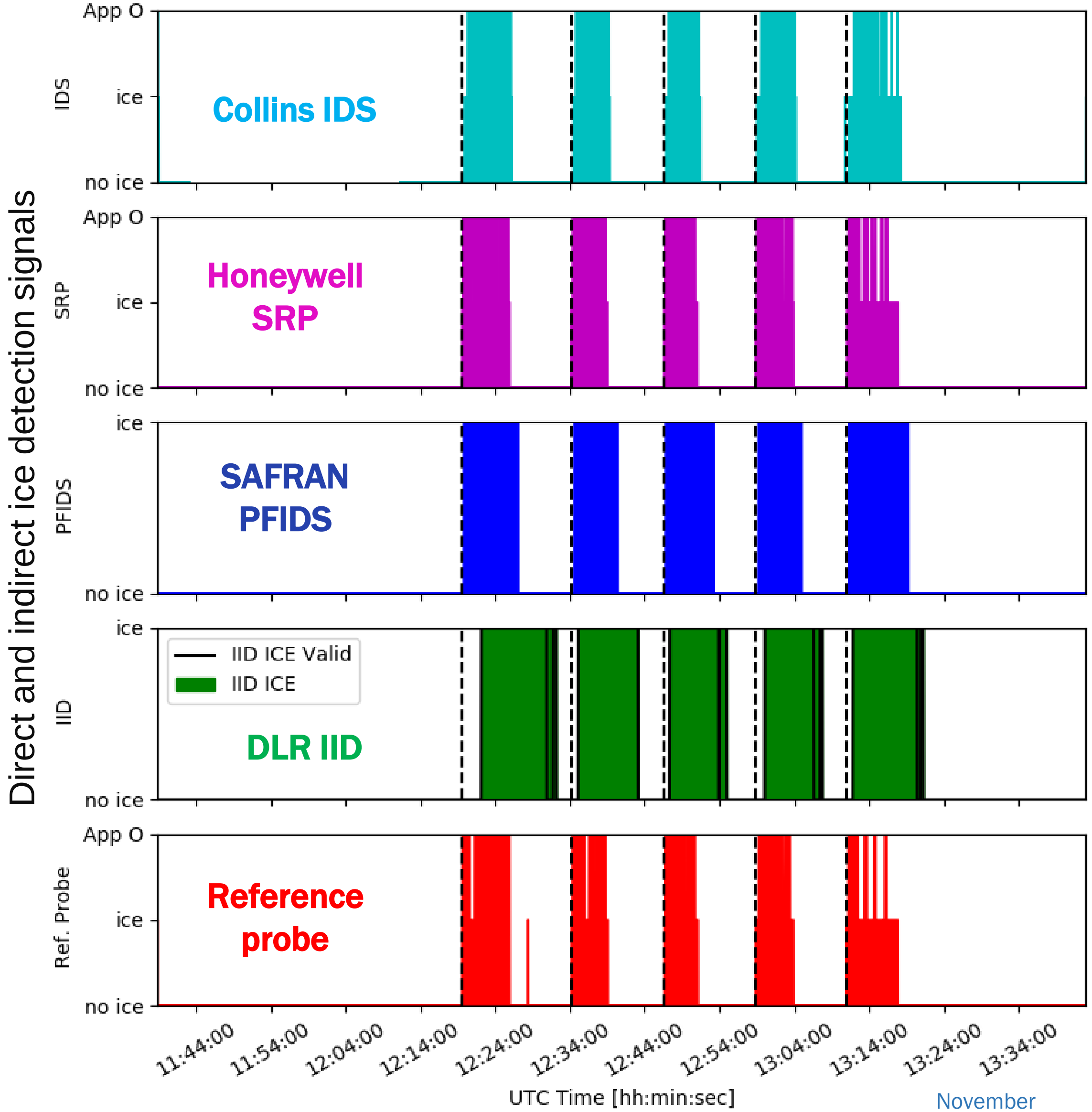


BACKUP

HIDS North America Flight Campaign Results

Flight 1476 – Direct and Indirect Ice detection in **App O conditions**

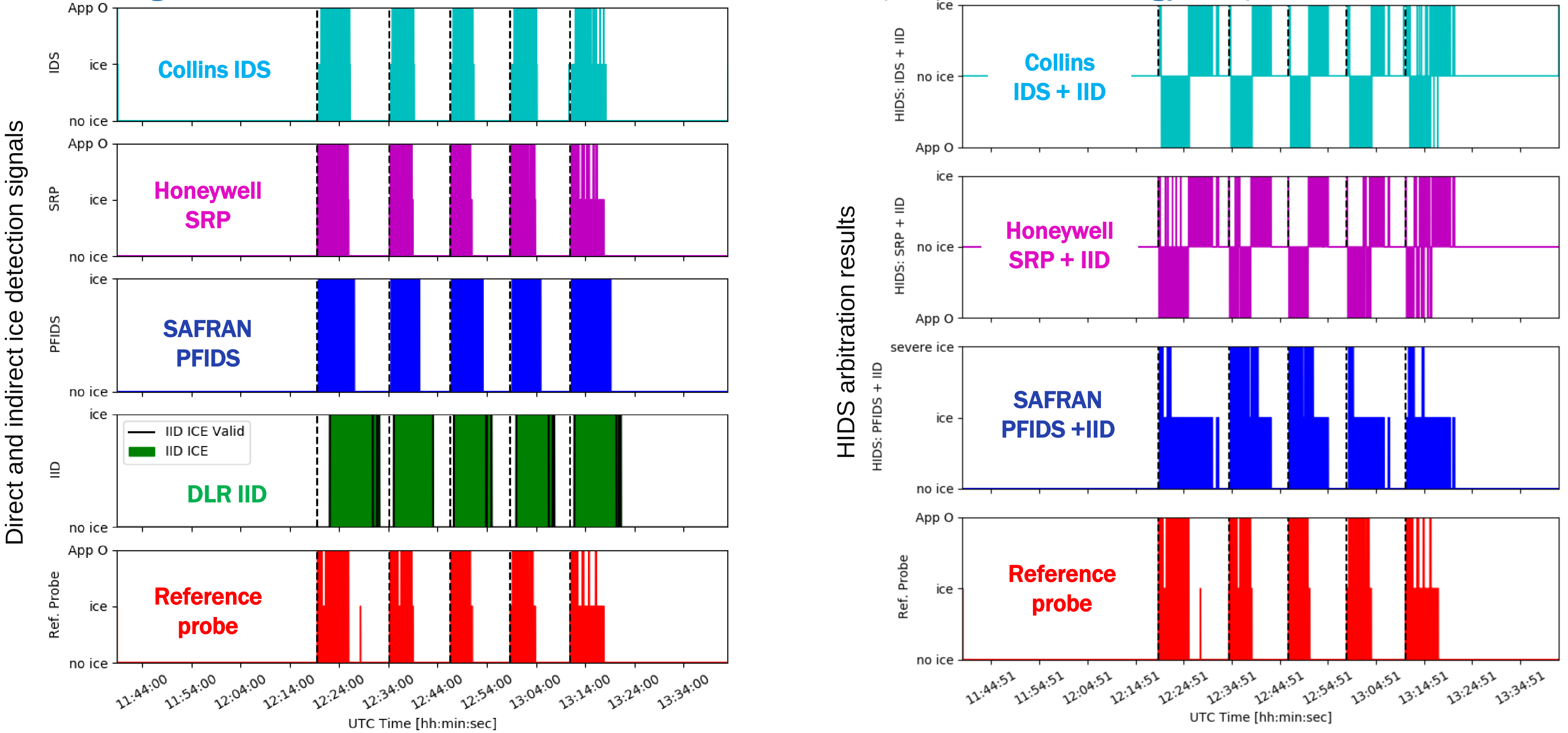




Hybrid ice detection data analysis by SAFRAN

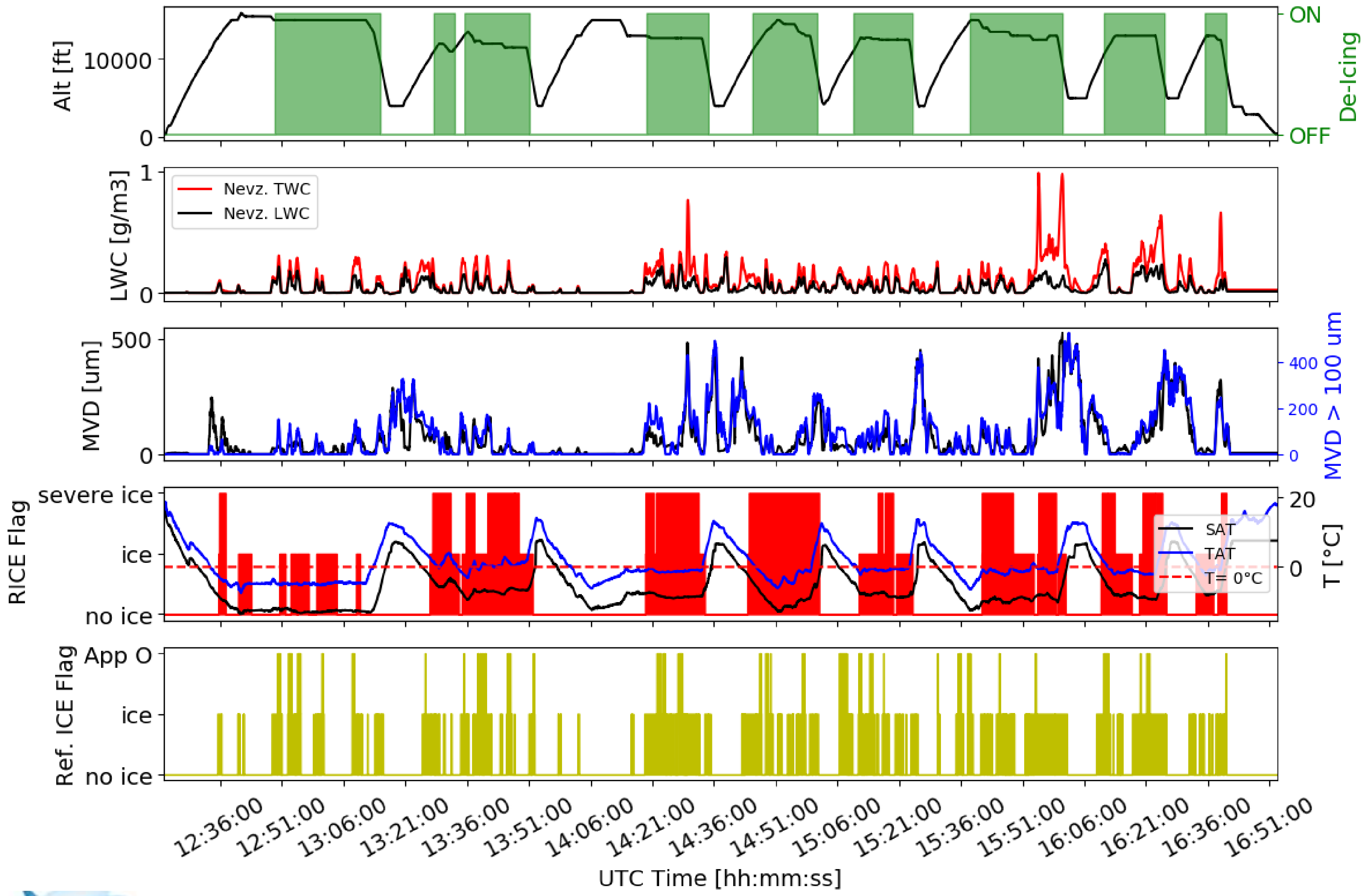
HIDS North America Flight Campaign Results

Flight 1476 – HIDS arbitration results for each direct/indirect technology couple



HIDS Europe Flight Campaign Results

Flight as230018: Microphysics and aircraft data



Several icing conditions encountered

- 9 activations of IPS
- 20 RICE reference detections
- 251 Microphysics probes detections
  - SLD presence
  - Ice Crystals presence
  - Lower LWC w.r.t. North America flight campaign

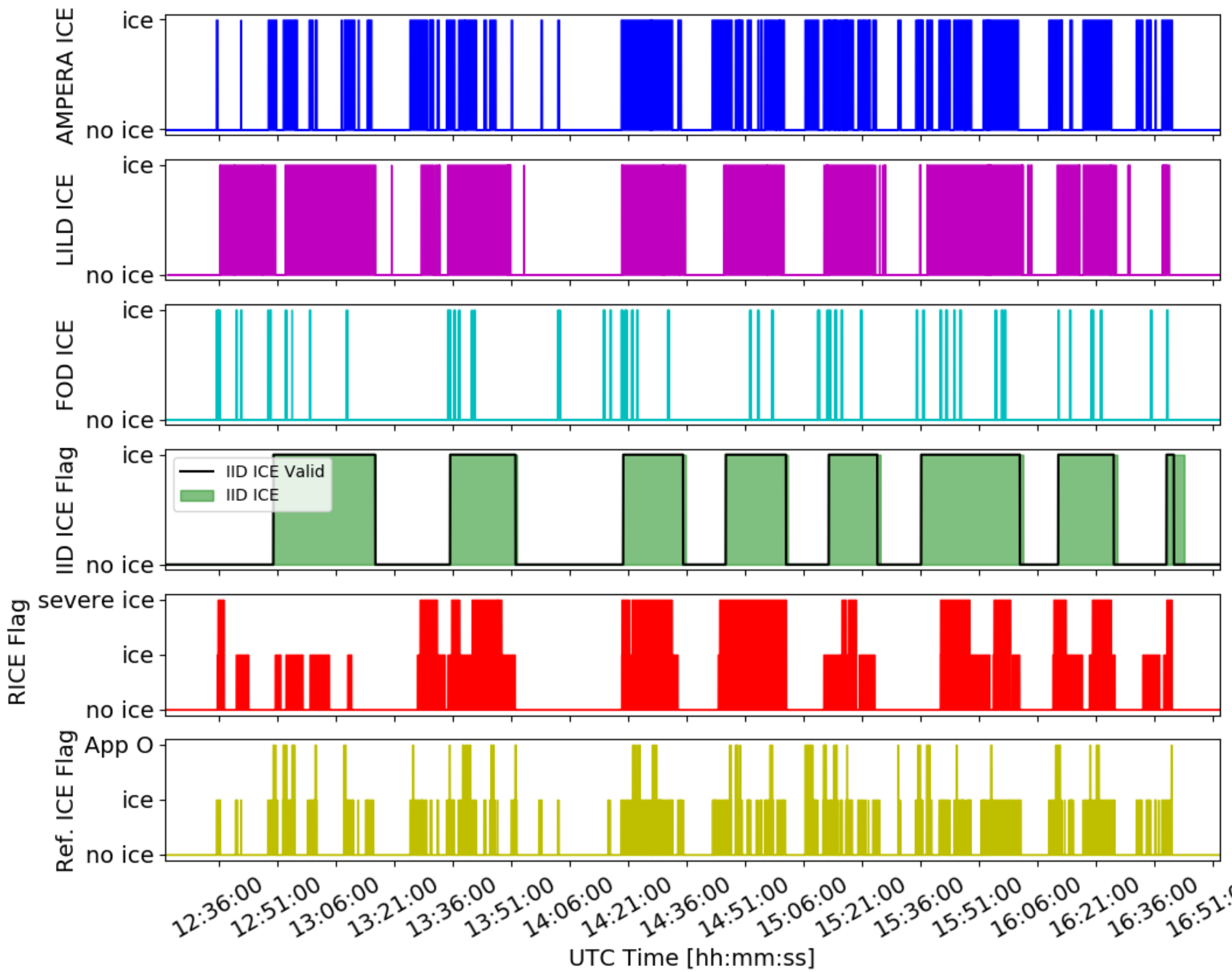
Difficult characterization of icing conditions!

Hybrid ice detection data analysis by SAFRAN

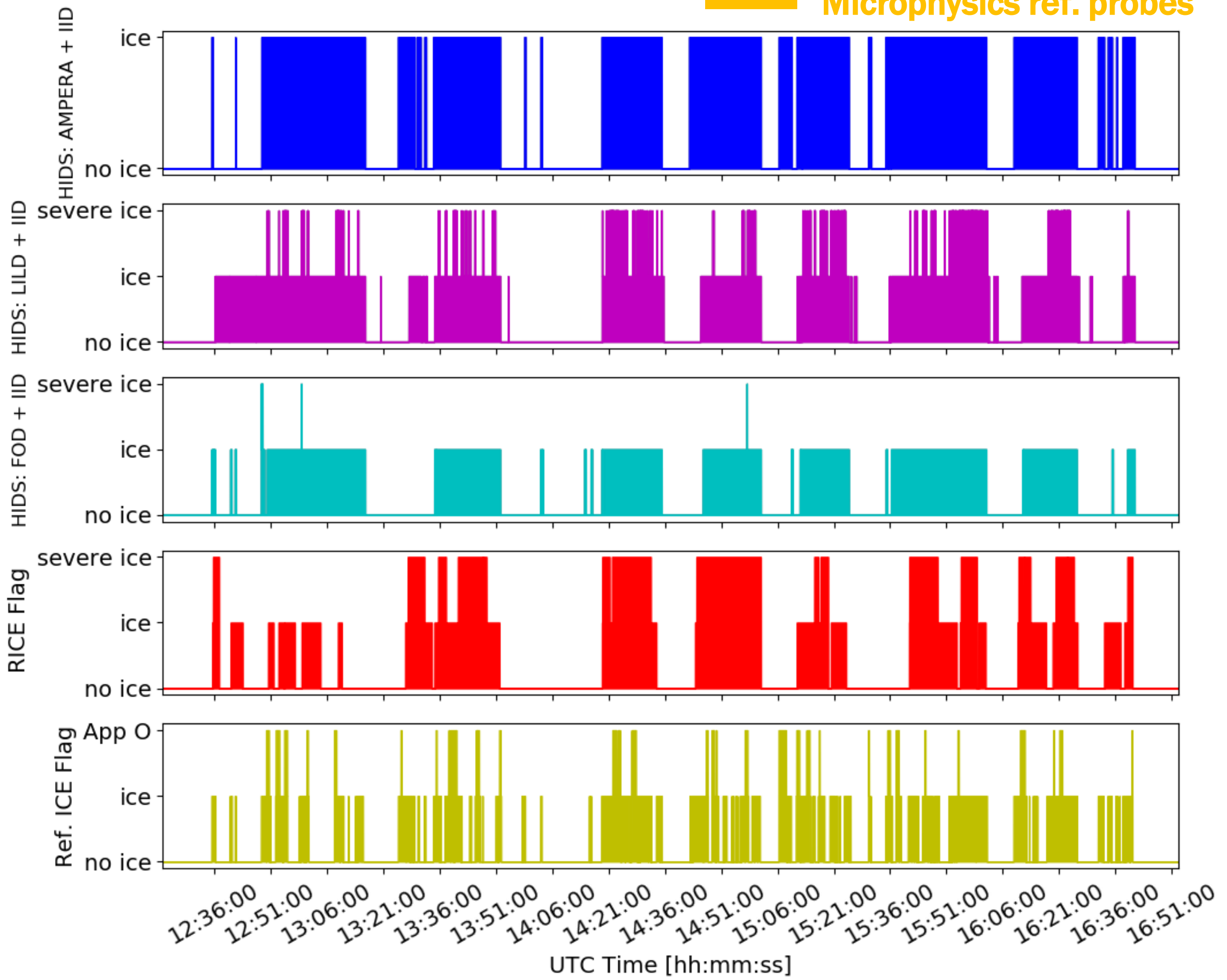
HIDS Europe Flight Campaign Results

Flight 24 APR 2023 (as230018): Ice detection results

Direct and indirect ice detection signals

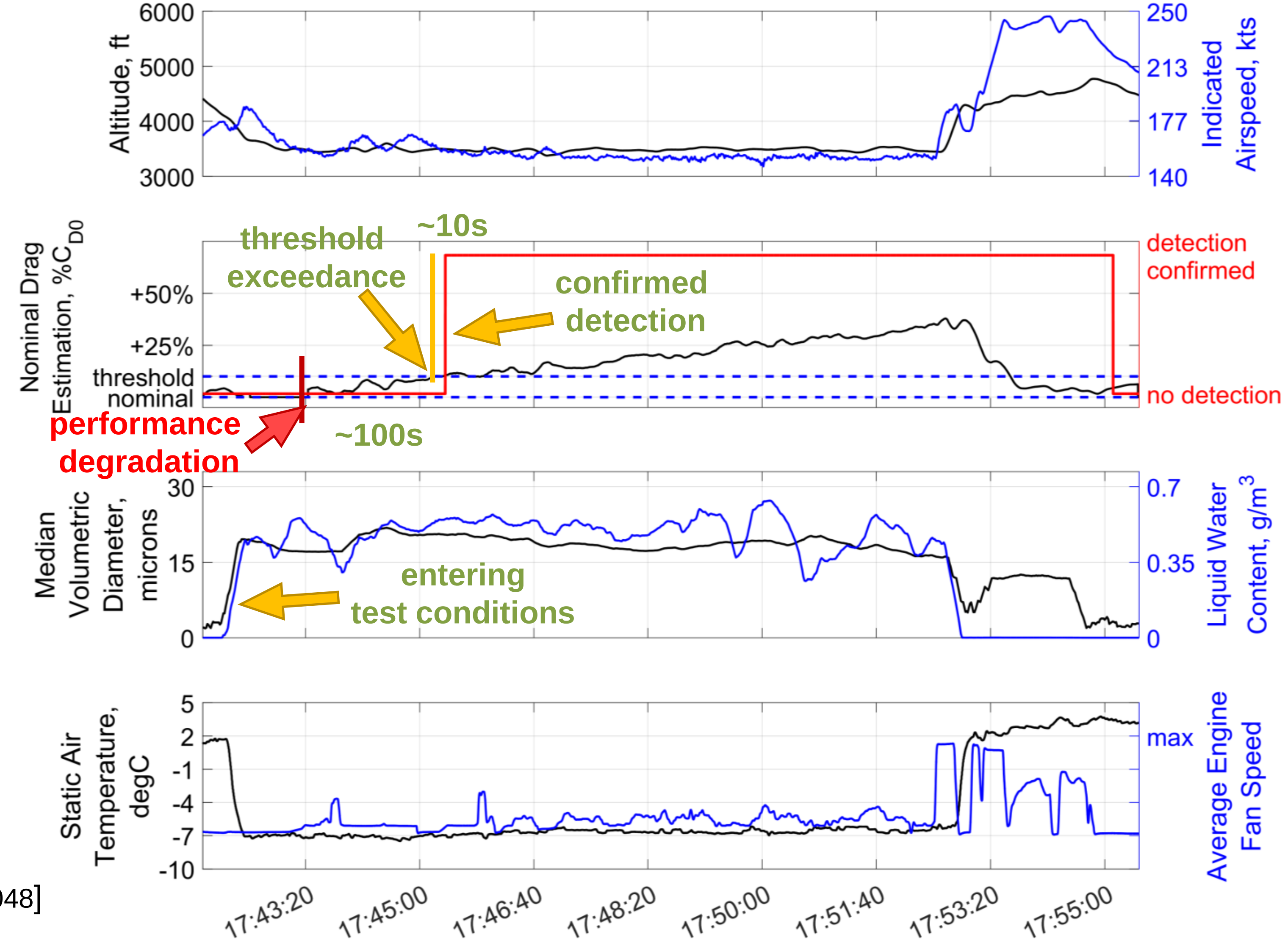


HIDS arbitration results



SENS4ICE North America Flight Campaign
Indirect Ice Detection Performance

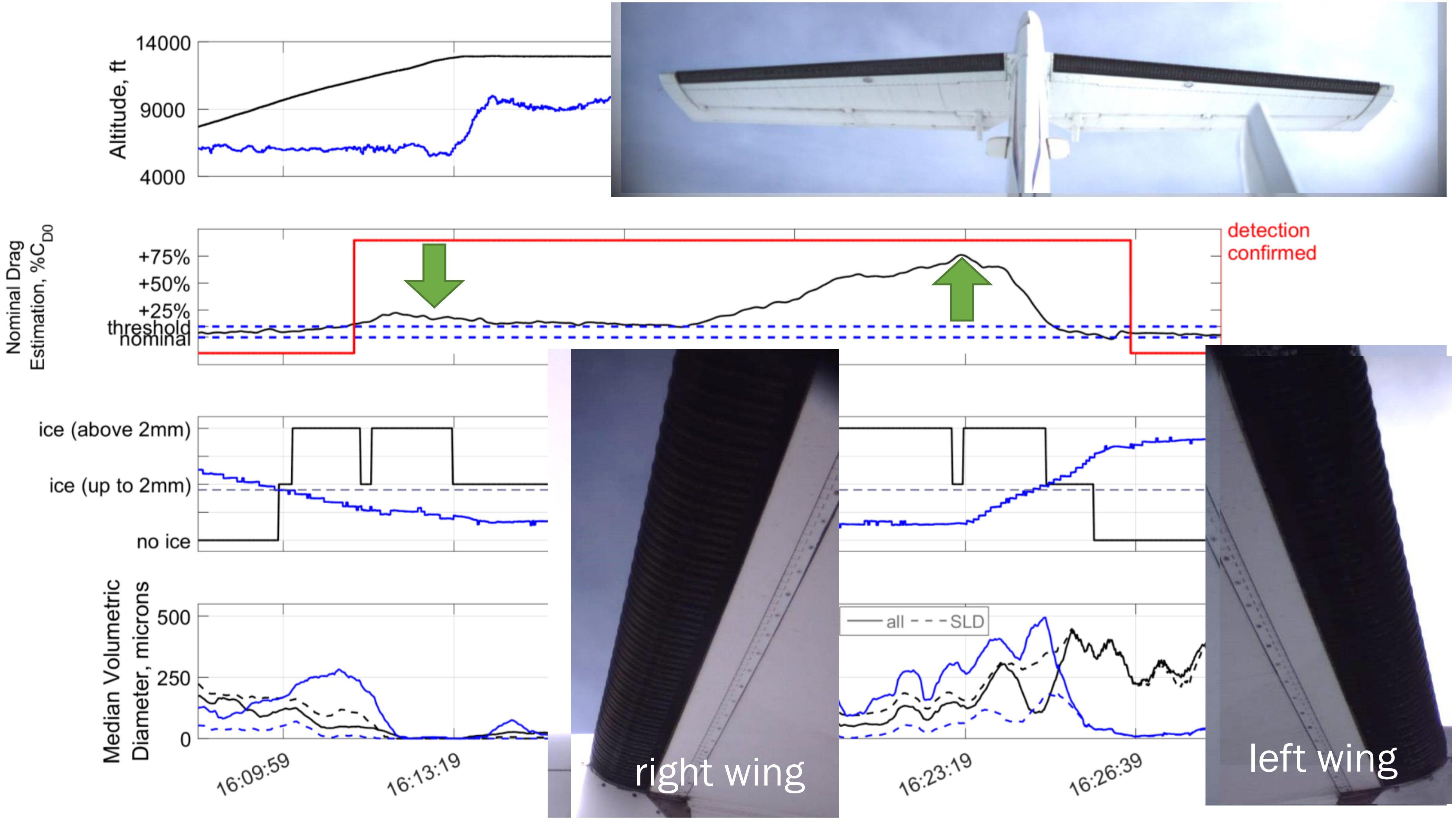
- example 23 FEB 2023,
  17:41:49 UTC - 17:55:29 UTC
- figure 1: altitude and indicated airspeed
- figure 2: nominal drag estimation and IIDS detection output
- figure 3: MVD and LWC of encountered icing conditions
- figure 4: static air temperature and average engine fan speed
- detection threshold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

SENS4ICE Europe Flight Campaign
Indirect Ice Detection Detailed Example Results

Flight 24 APR 2023 (as230018): single icing encounter

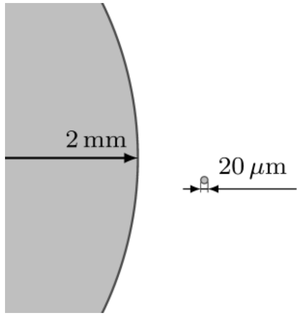


SENS4ICE Challenge/Outcome

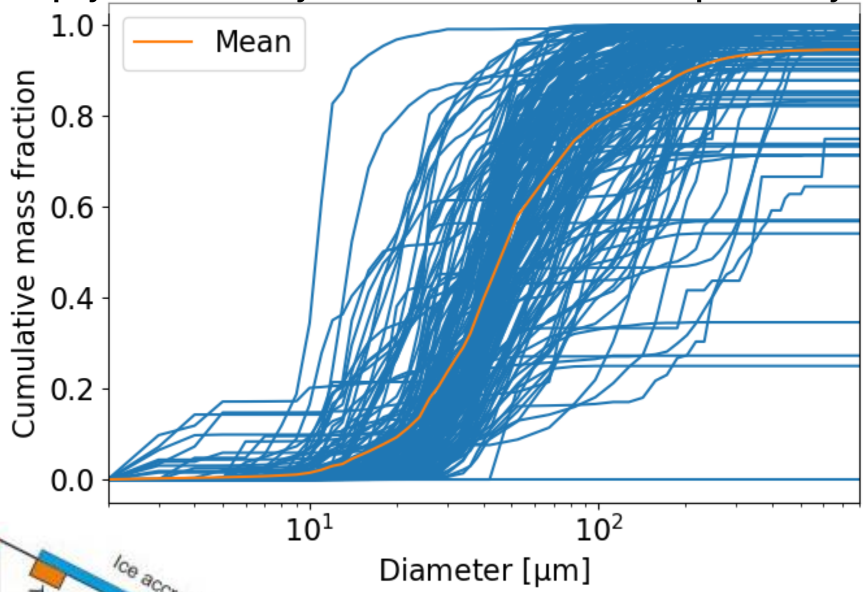
- Detect icing conditions – challenge: SLD

Solution/Innovation

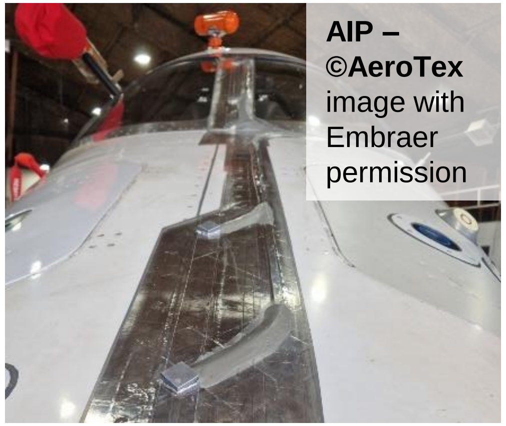
- 8 direct detection technologies matured & flight test demonstrated (many TRL6)
- Hybrid approach (TRL5) – fusion of input data: sensor(s) and indirect detection



SENS4ICE Flight Campaign Europe
Cumulative mass distribution of Appendix O conditions
Microphysics data analysis - DLR Institute of Atmospheric Physics

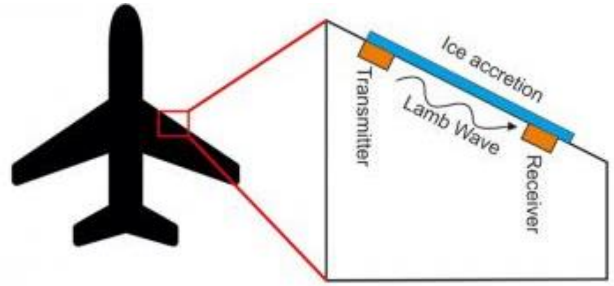


HIDS-Safran/ IID-DLR



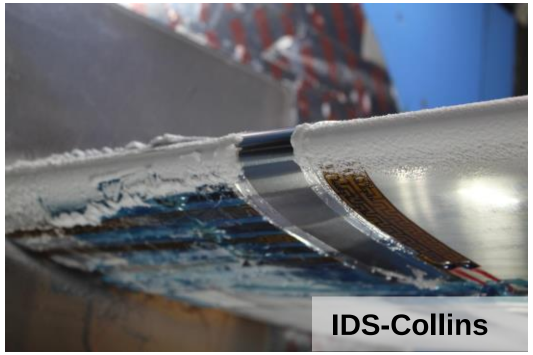
AIP – ©AeroTex image with Embraer permission

PFIDS-Safran



LILD-DLR

AMPERA-ONERA image with Safire permission



IDS-Collins

SRP–Honeywell image © Embraer

CM2D-DLR image DLR

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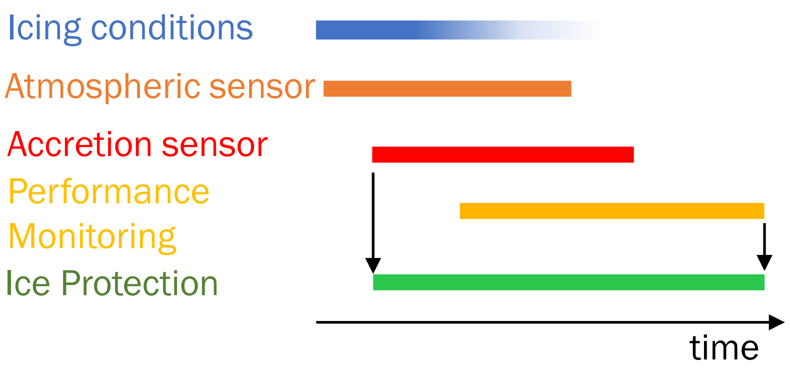
SENS4ICE EU Project
Conclusion & Outlook - Research Gaps

- game changer **hybrid solution** for SLD detection
  - benefits of quick warnings and continuous ice accretion and flight performance monitoring
  - enabling IPS efficiency/energy optimisation
- identifying path for certification



- improve understanding of icing effects on aircraft
  - for rare and safety/certification relevant icing conditions (Appendix O/ SLD)
  - to enable certification and safe operations for new aircraft/vehicle designs
- further research/development/testing required for maturing icing detection & discrimination technologies
  - in enhanced icing wind tunnels and in natural icing conditions in flight
  - covering the full range of App O, specifically freezing rain
- dedicated research and development for smart ice protection technologies with high efficiency e.g. for
  - greener aviation high aspect ratio aircraft and
  - small/ low speed/ low altitude/ unmanned vehicles

SENS4ICE follow-on activities
Small/ low speed/ low altitude/ unmanned vehicles

- lower atmosphere icing conditions characterization
- understanding small/ low speed vehicle icing, i.e. for typical configurations/ geometries
- dedicated ice detection and protection technologies for unmanned vehicles
  - automated
  - low power
  - low weight
  - low size
  - including performance monitoring, envelope protection and loss-of-control prevention
- possible instruments to consolidate research needs
  - SAE AC-9C
  - NATO AVT-388 (Applied Vehicle Technology Panel)
  - UAV Icing Workshop www.uavicingworkshop.com
  - possible future research projects including EU projects


Credit: DLR (CC-BY 3.0)


Credit: © DLR

https://www.sens4ice-project.eu

SENS4ICE
Final Public Dissemination

Final Public Dissemination Event

- November 2023, Brussels, Belgium
- Presentations download
  - https://www.sens4ice-project.eu/publications-presentations > section Presentations

Final Public Project Reports

- D4.1 Sensor evaluation results and final roadmaps for future technology development and exploitation
- D4.2 Final report on hybrid ice detection development
- D4.3 Final report on airborne demonstration and atmospheric characterisation
- D4.4 Final report on evaluation of technologies developed in SENS4ICE and technical project results
- Reports download
  - https://www.sens4ice-project.eu/publications-presentations > section Publications

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

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