SENS4ICE

SENSORS AND CERTIFIABLE HYBRID ARCHITECTURES
FOR SAFER AVIATION IN ICING ENVIRONMENT

SENS4ICE Conclusions and Way Forward

October 2024

Carsten Schwarz (DLR)

SAE AC-9C Aircraft Icing Technology Committee Meeting #81

October 21-22, 2024 – Ottawa

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

- 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

SENS4ICE Challenge – Detect SLD Icing Conditions

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

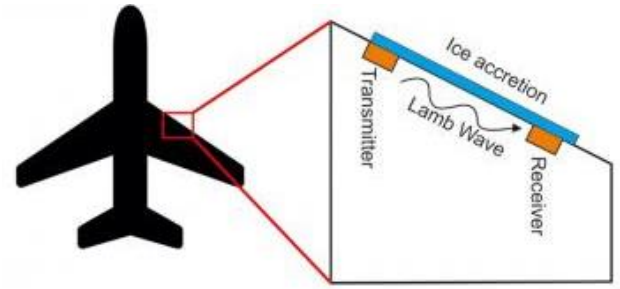
Solution/Innovation:

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

Benefits:

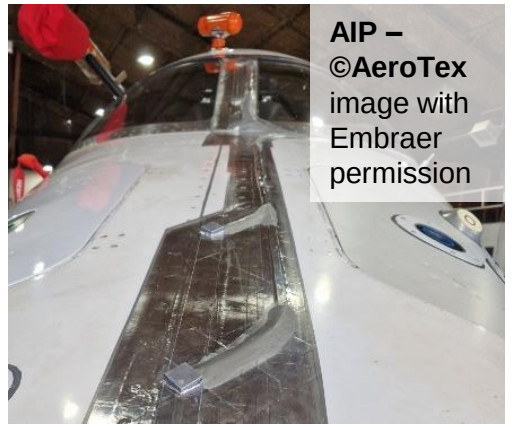
- Operational safety (activate anti-/de-icing, avoid/ leave icing conditions)
- Certification support (enabling technologies) for Appendix O/ SLD icing

HIDS-Safran/ IID-DLR



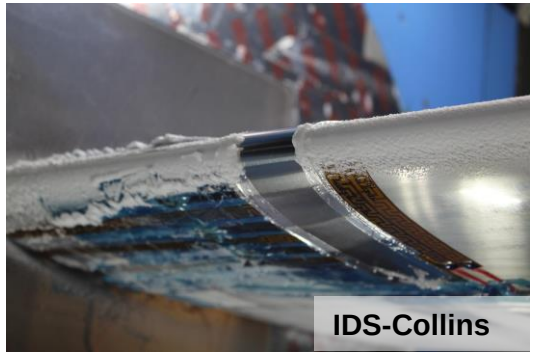
LILD-DLR

PFIDS-Safran



AIP – ©AeroTex image with Embraer permission

AMPERA-ONERA
image with Safire permission



IDS-Collins

SRP–Honeywell image © Embraer

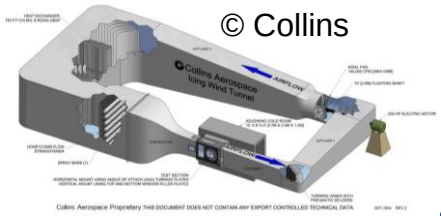
CM2D-DLR image DLR

FOD-INTA
image with Safire permission

SENS4ICE Timeline / Summary / Achievements

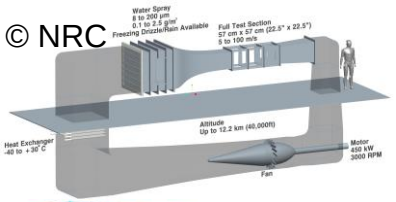
Upgrade icing wind tunnels for App. O

Develop sensors/ technologies for App. O detection



© Collins

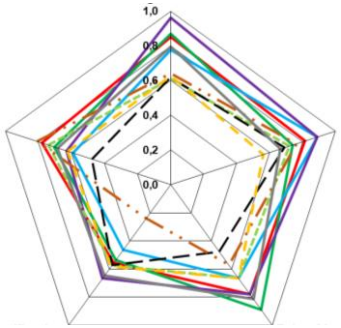
Icing wind tunnel testing



© NRC


© TUBS

Sensor technology evaluation and selection



Hybrid ice detection

Indirect ice detection

Flight test preparation

Flight testing

FEB/MAR 2023


Copyright © Embraer

APR 2023


Copyright © Claude Delhaye / Safire / CNRS Photothèque

Flight test analysis/ techno-logy evalua-tion

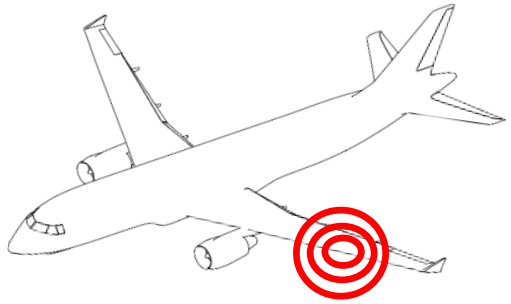
Commu-nication, Dissem-ination, Exploi-tation

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

Hybrid Ice Detection Approach

Direct ice detection

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



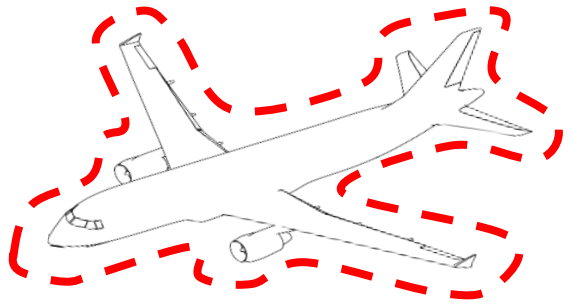
Hybrid ice detection

Combination of Direct and Indirect Detection.

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

Indirect ice detection

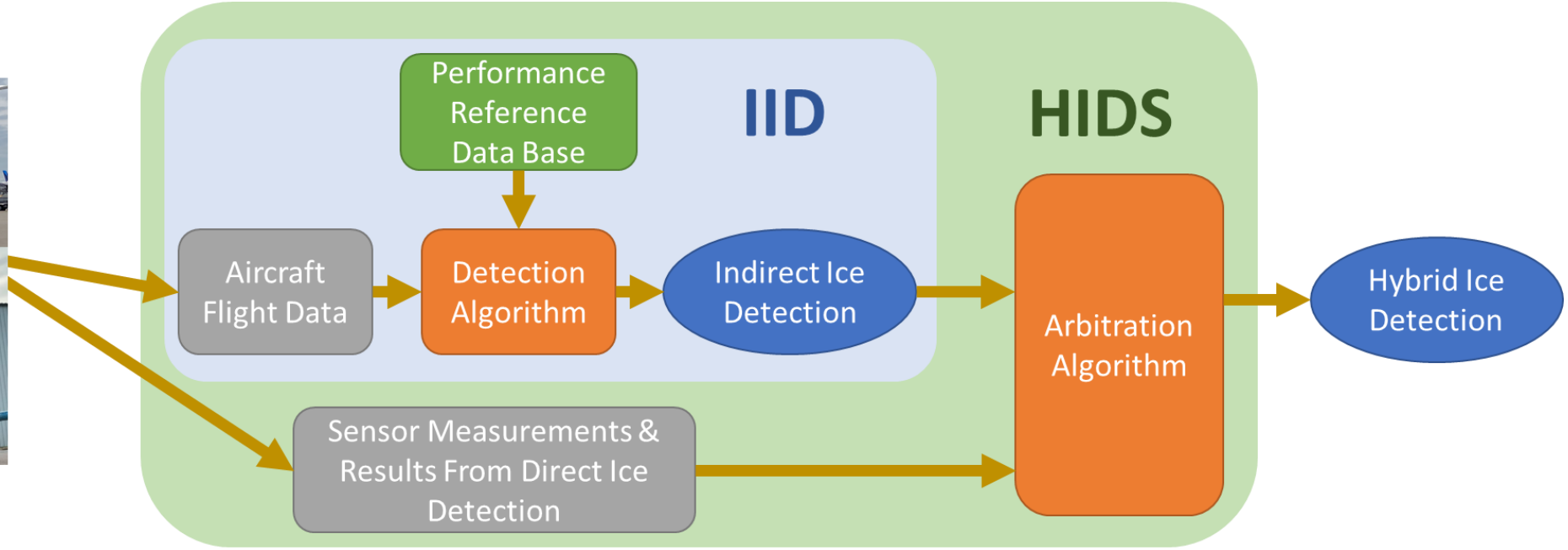
Global detection: effects of ice accretion.



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)

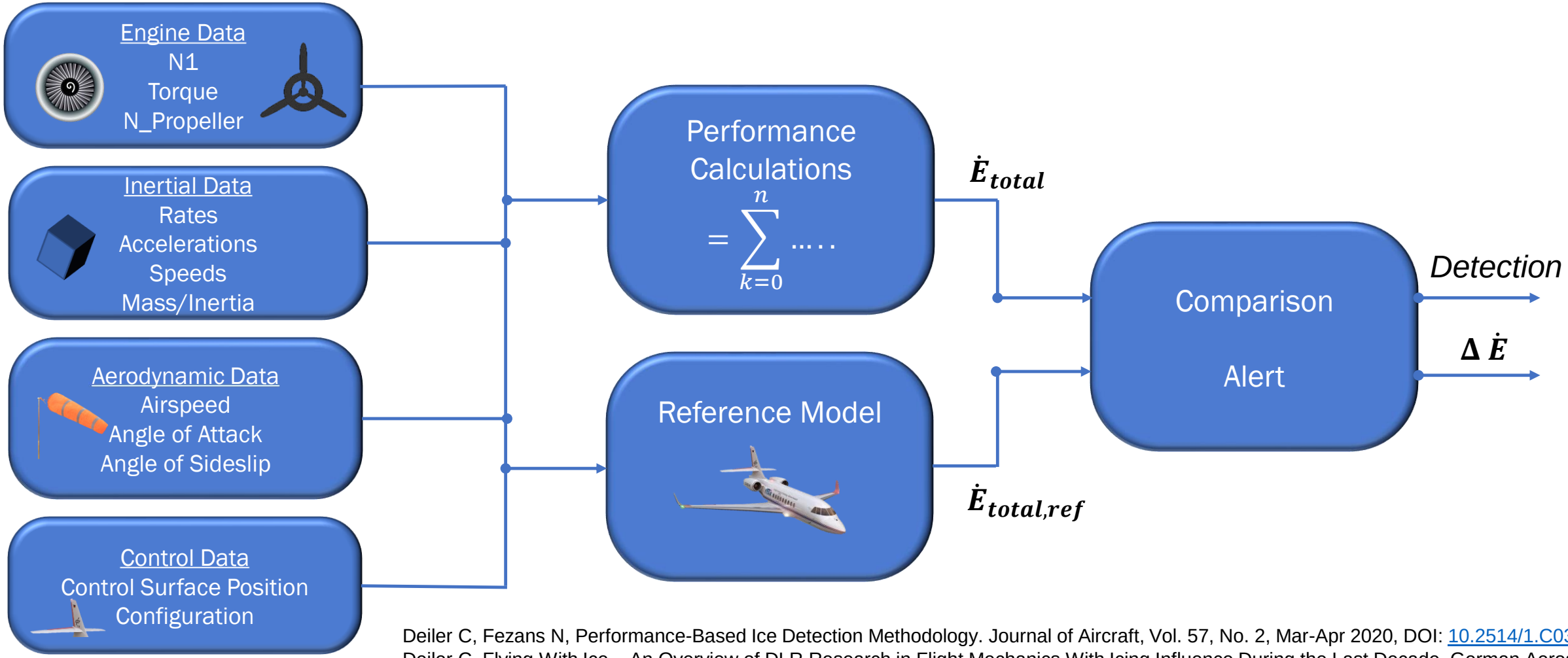


[Orazzo, A., Thillays, B., “Hybrid Ice Detection System development and validation”, SAE International Conference on Icing of Aircraft, Engines, and Structures 2023, Vienna, Austria, 20 – 22 June 2023, 23ICE-0049]

[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

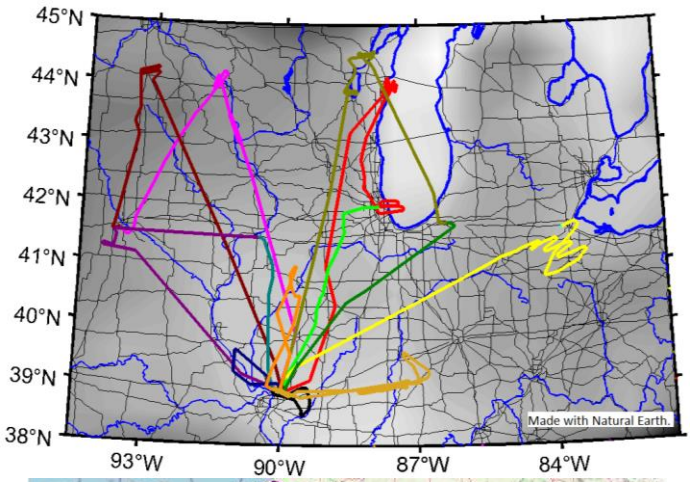
BACKUP

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

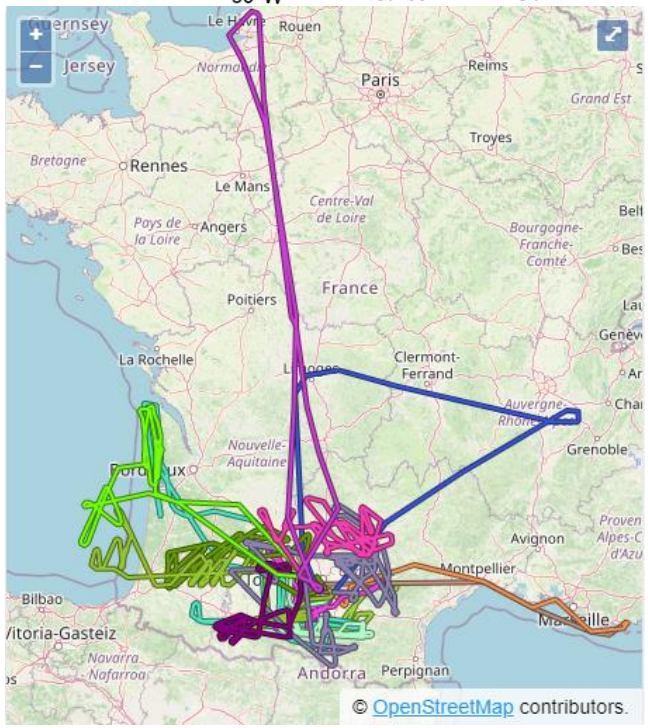
Embraer Phenom 300


Copyright West Star Aviation with Embraer permission



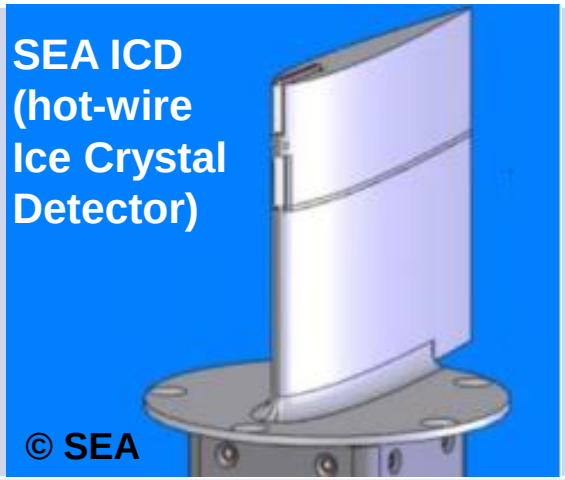
SAFIRE ATR 42


Copyright SAFIRE



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

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		
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]

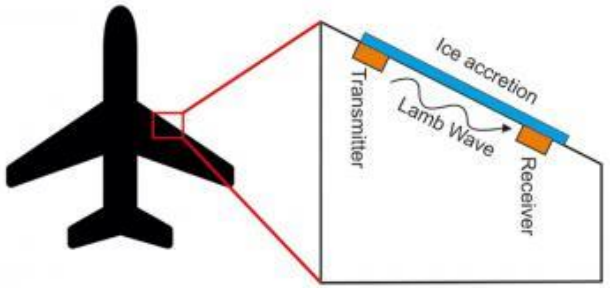
https://www.sens4ice-project.eu/sites/sens4ice/files/media/2023-10/SENS4ICE_DLRK2023_Meteorological_Conditions_DLR_September2023.pdf

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)
- SAFIRE ATR 42 with test sensors and reference instruments

HIDS-Safran/ IIDS-DLR

FOD-INTA
image with Safire permission



LILD-DLR

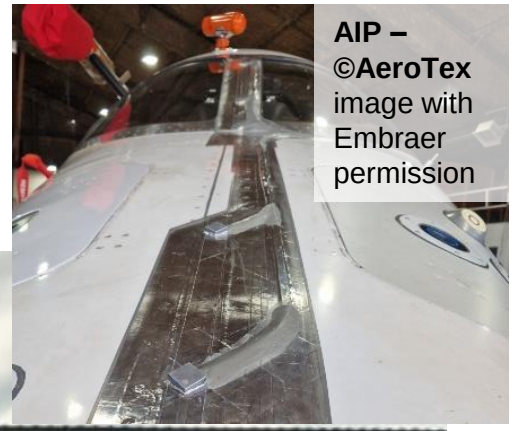
image DLR with Safire permission

AMPERA-ONERA
image with Safire permission

CM2D-DLR image DLR

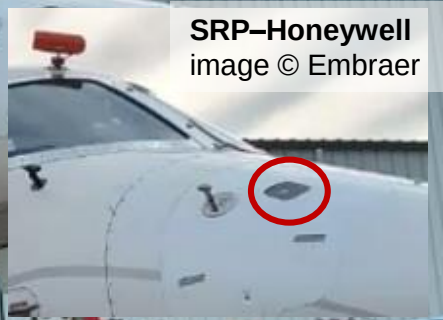
North America Flight Campaign Embraer Phenom 300 Sensor Installations

- 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

PFIDS-Safran



SRP–Honeywell image © Embraer

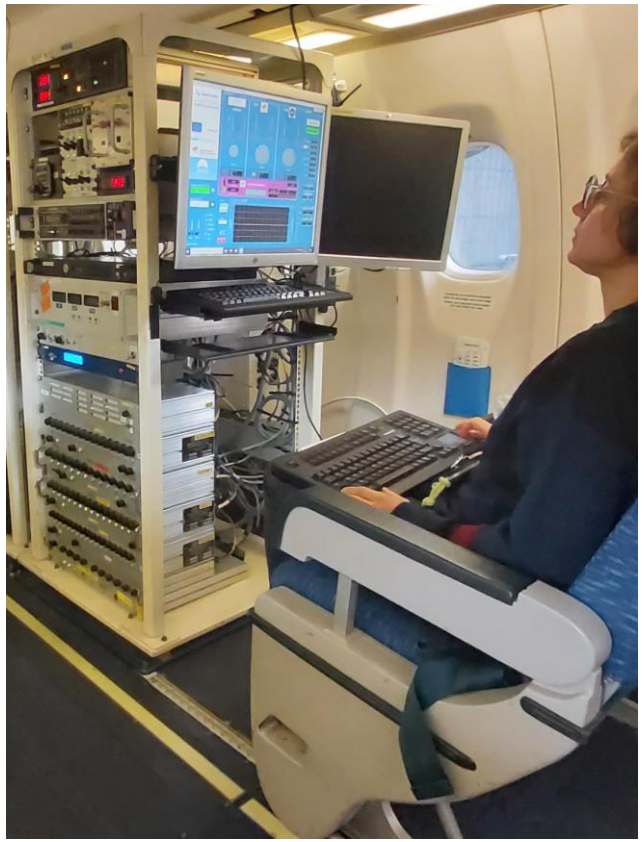
© Embraer

IDS-Collins

HIDS-Safran/ IIDS-DLR

North America Flight Campaign Embraer Phenom 300 Impressions

SENS4ICE Flight Campaign Europe
Impressions



Operator working with HIDS PC.
(credit SAFRAN)

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

SENS4ICE Flight Campaigns

North America

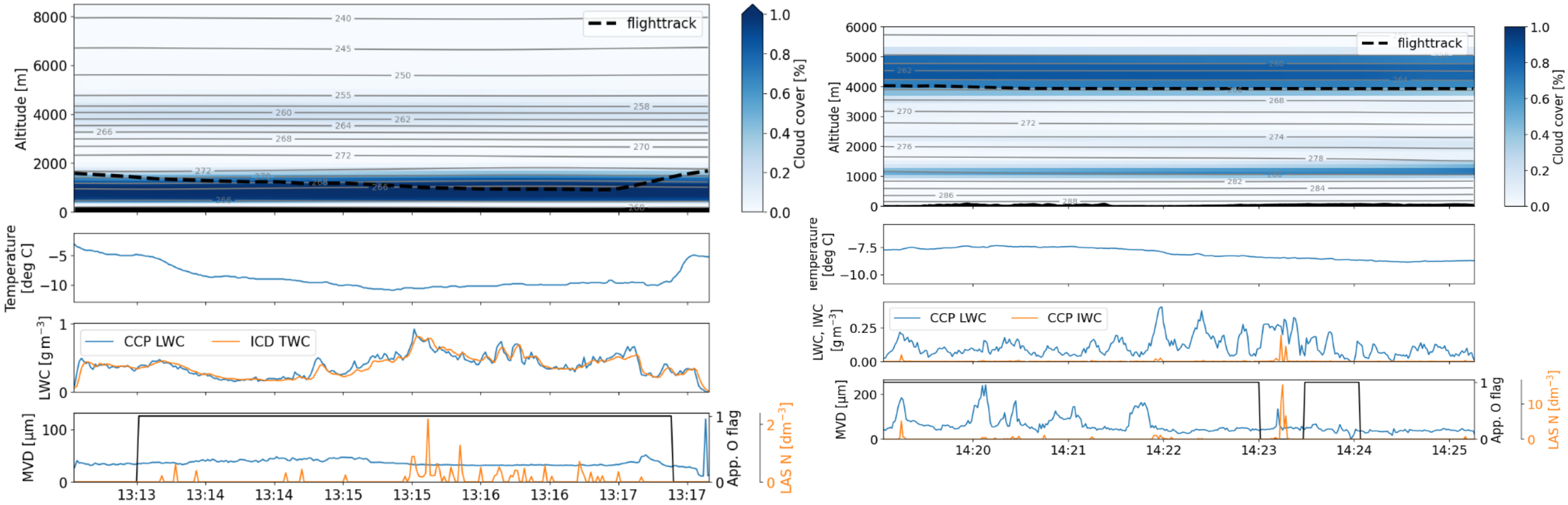
- Ice accretion on windshield after SLD cloud encounter
- [image credit Embraer]

Europe

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

Appendix O Example Encounters

BACKUP



North America Campaign

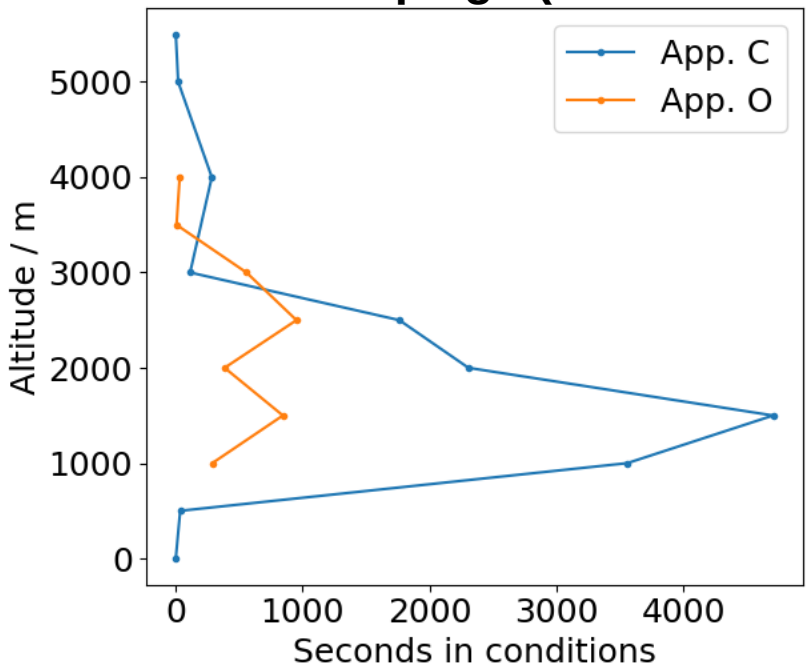
- Clouds most often closed stratus decks
- Appendix O encountered above a stable layer
- Typically cloud approached from top

Europe Campaign

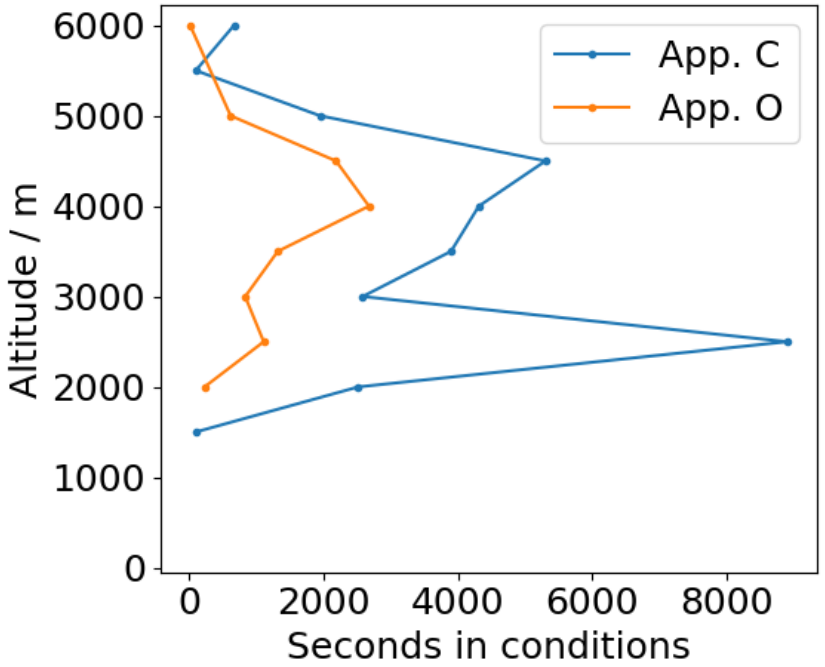
- Cloud consisted of multiple layers, not separately resolved in ERA5 cloud cover data
- Clouds thinner and patchier, large variation of LWC within clouds

Altitude of Icing Conditions

North American campaign (Feb/March 2023)



European campaign (April 2023)

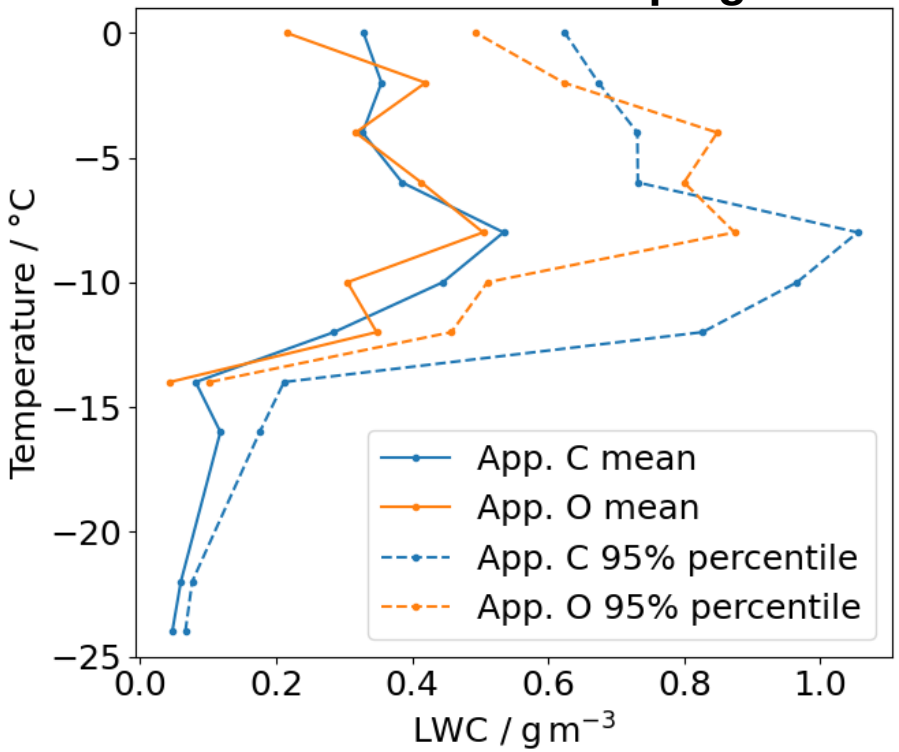


- North American campaign: Icing conditions mostly 1000 - 3000 m
- European campaign: Most icing conditions 2500 - 5000 m
- Most Appendix O conditions during European campaign 3500 - 5000 m
- Different altitudes reflect different seasons during which campaigns occurred

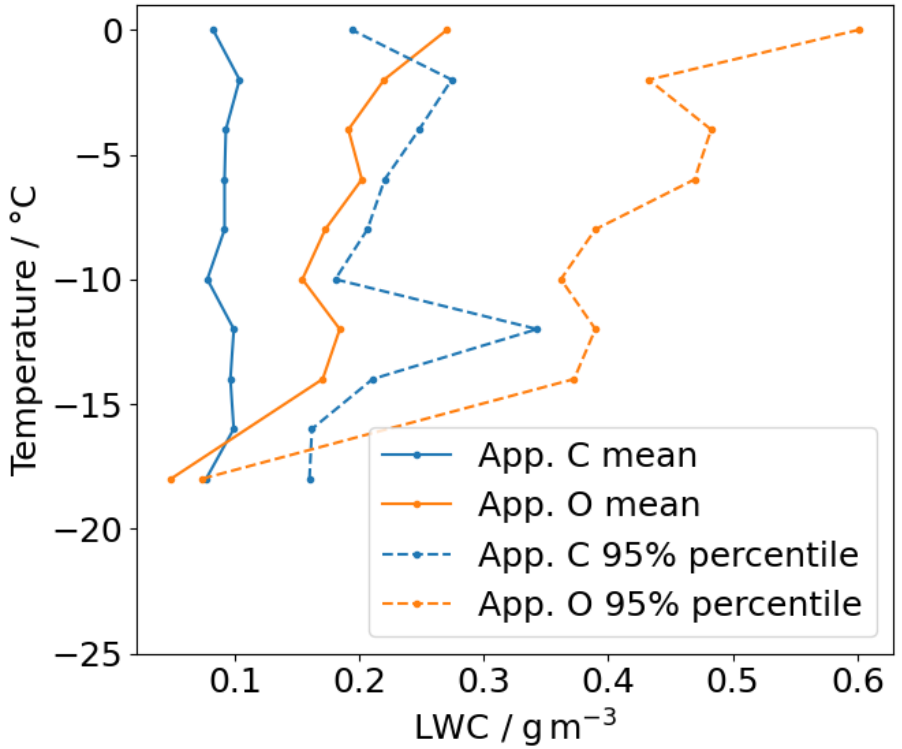
[Lucke, J., et al., “Meteorological conditions and microphysical properties that lead to aircraft icing as observed during the SENS4ICE campaigns”, Deutscher Luft- und Raumfahrtkongress (German Aerospace Conference) DLRK 2023, Stuttgart, Germany, September 2023, paper no 0285]

LWC of Icing Conditions

North American campaign



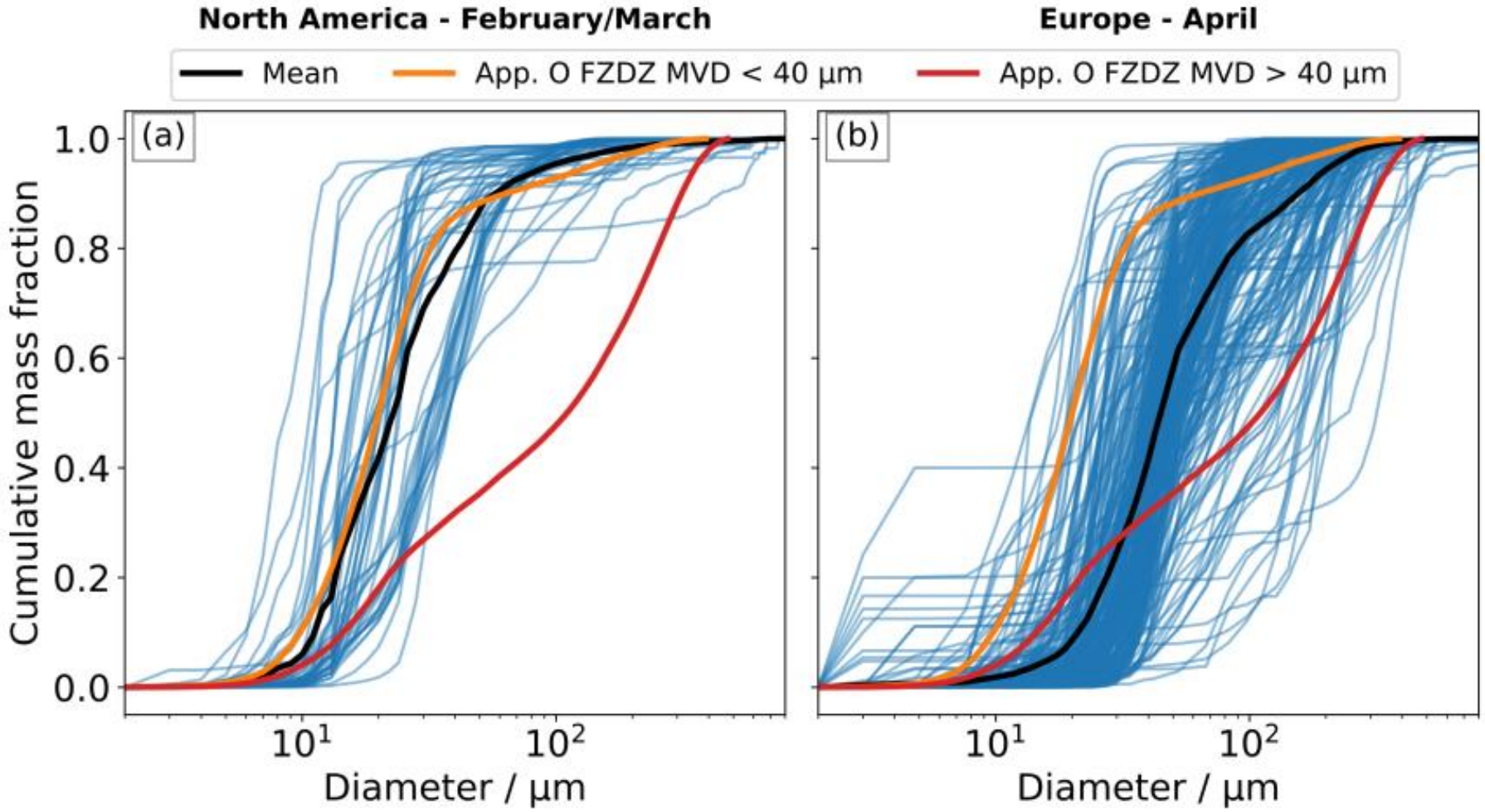
European campaign



- 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

[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]

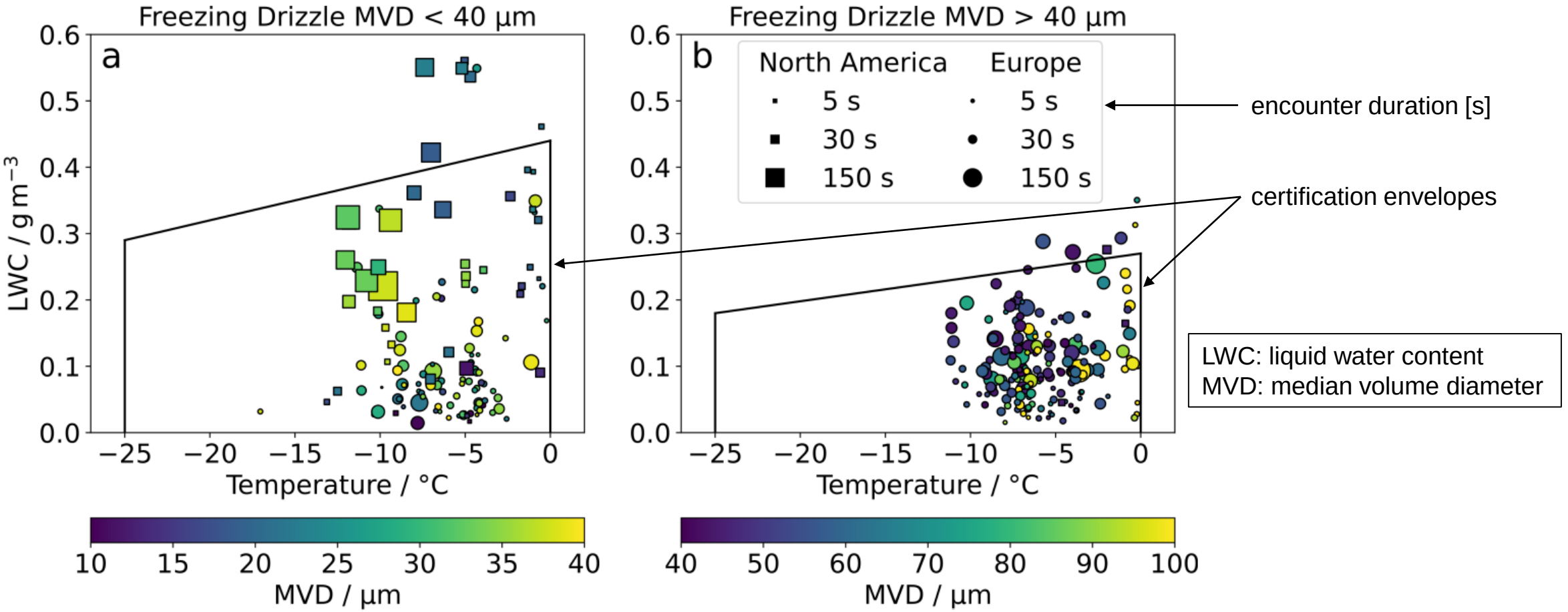
Cumulative mass distributions



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

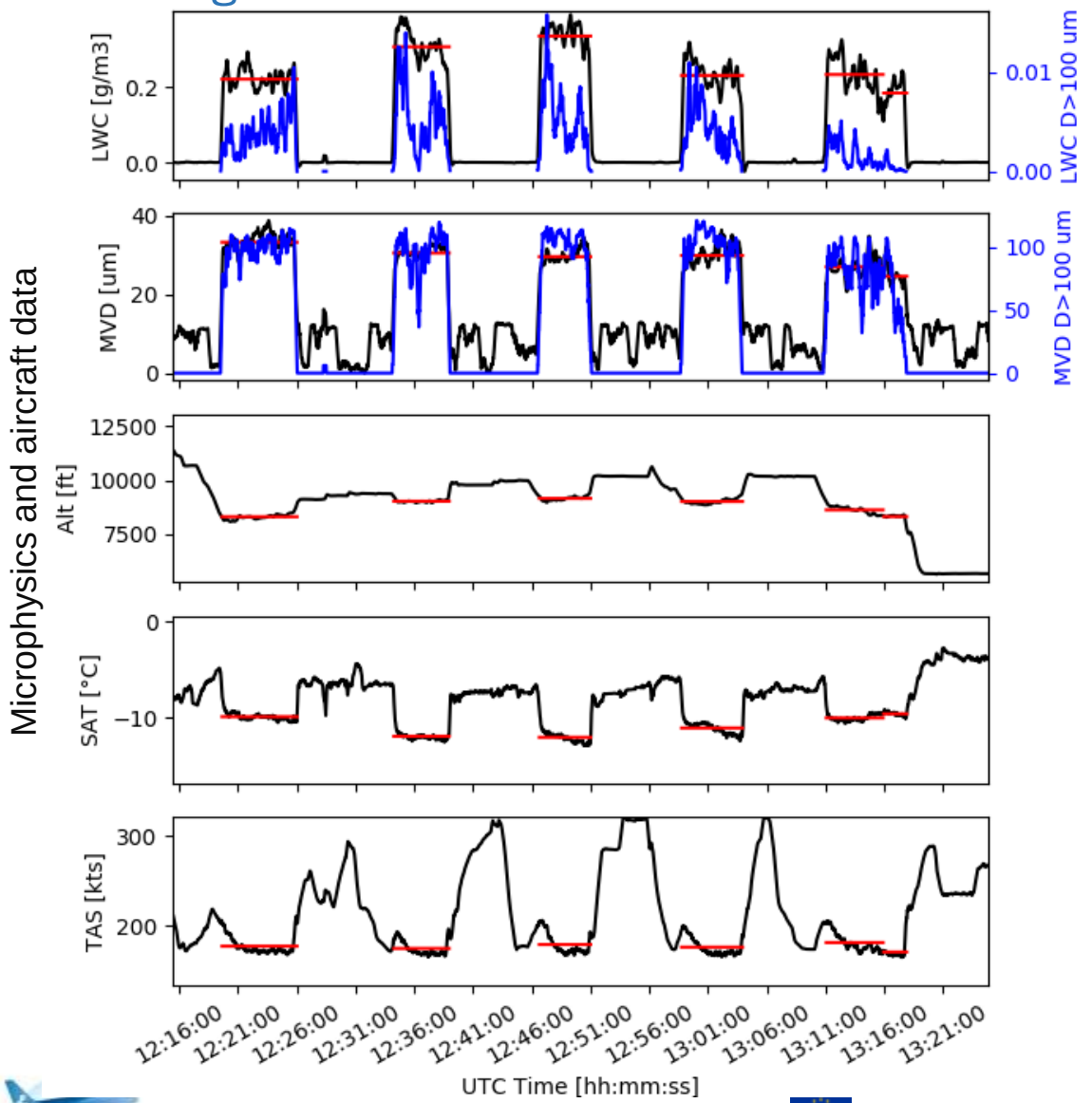
SENS4ICE Flight Campaigns: Comparison with App O LWC Envelopes

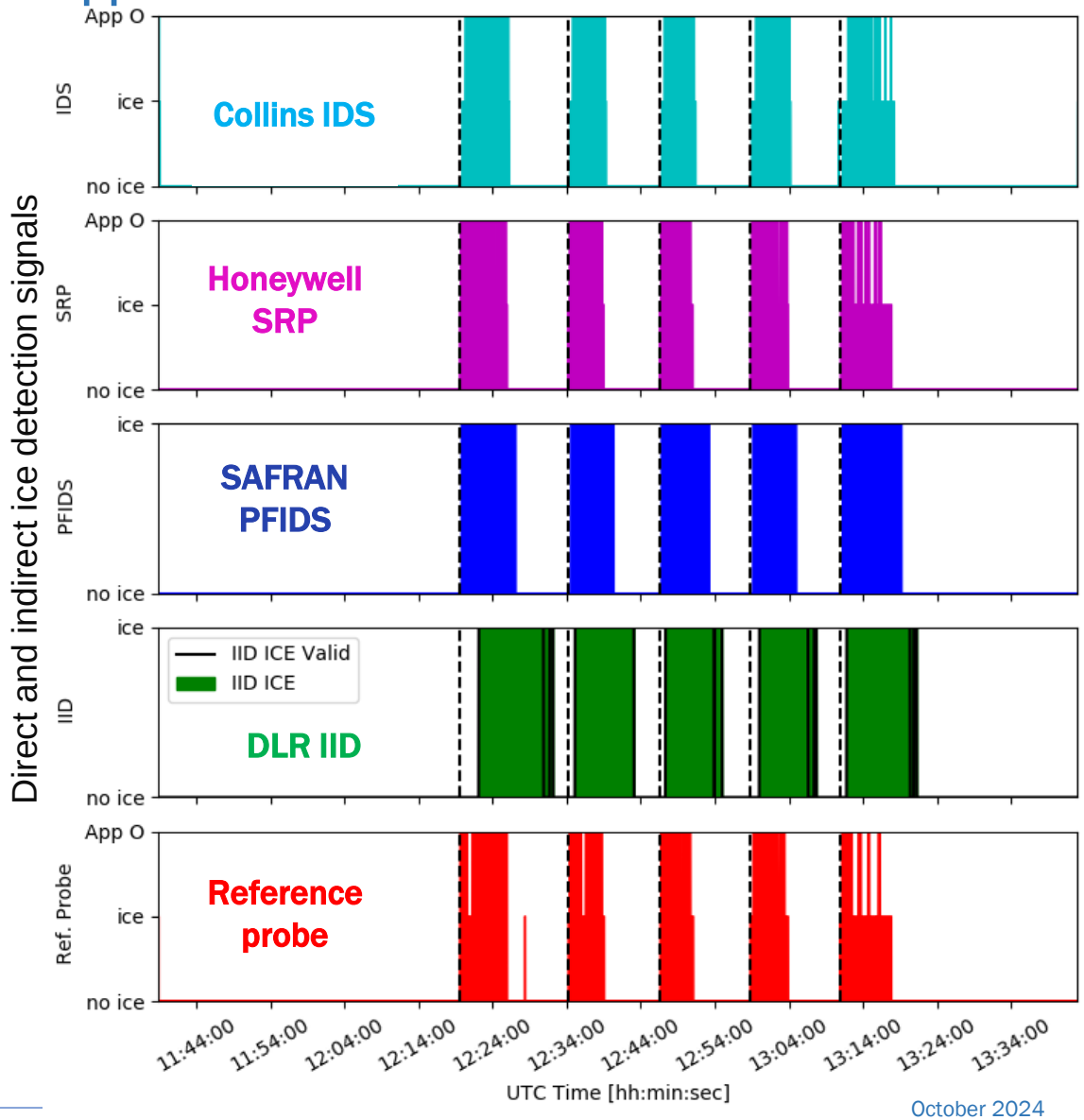
- Shorter sampling distance of LWC values accounted for with scaling factor
- Only encounters exceeding 30 s used for this analysis
- Certification envelopes represented well by measurements, only few encounters outside



HIDS North America Flight Campaign Results

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



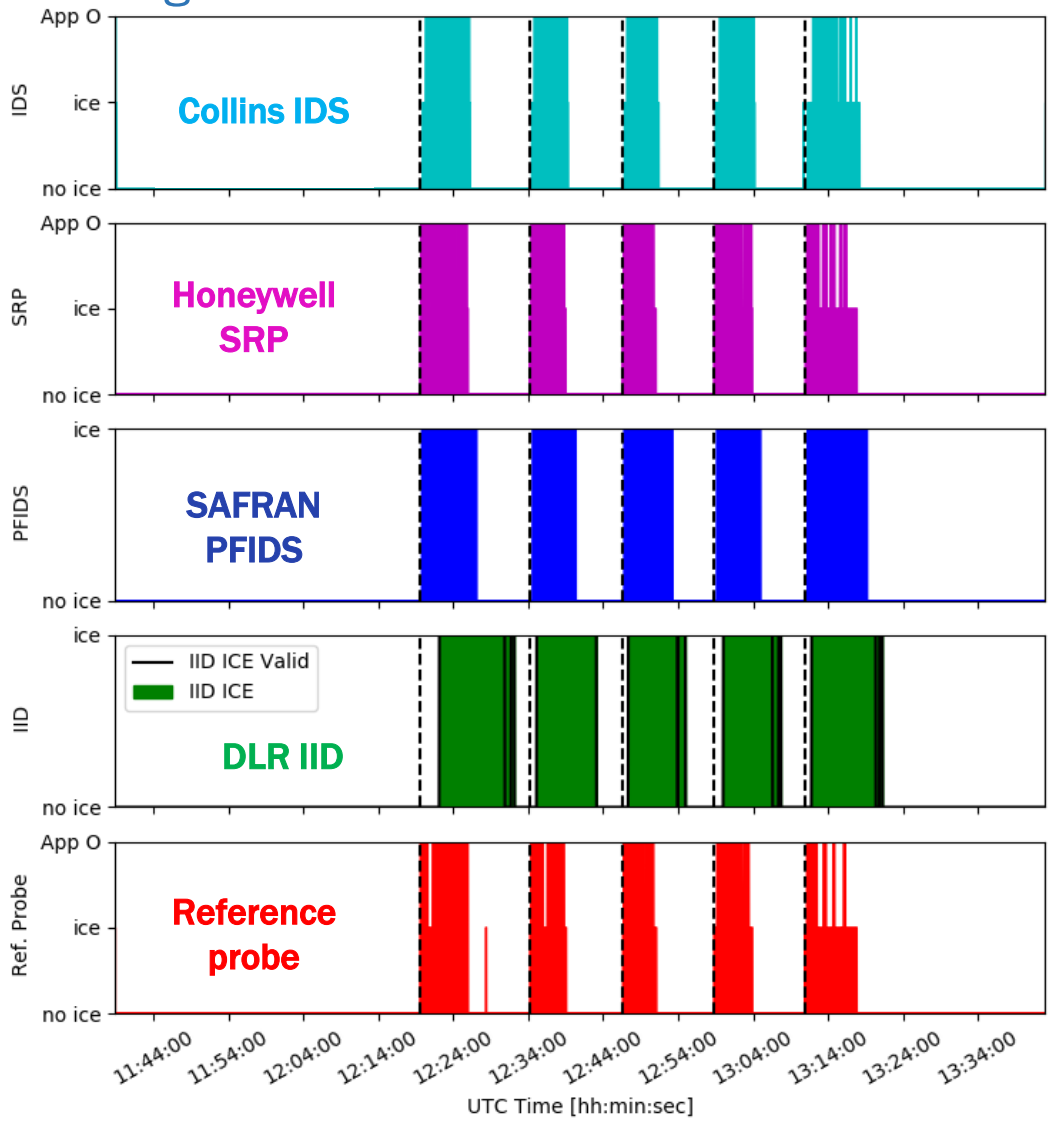


Hybrid ice detection data analysis by SAFRAN

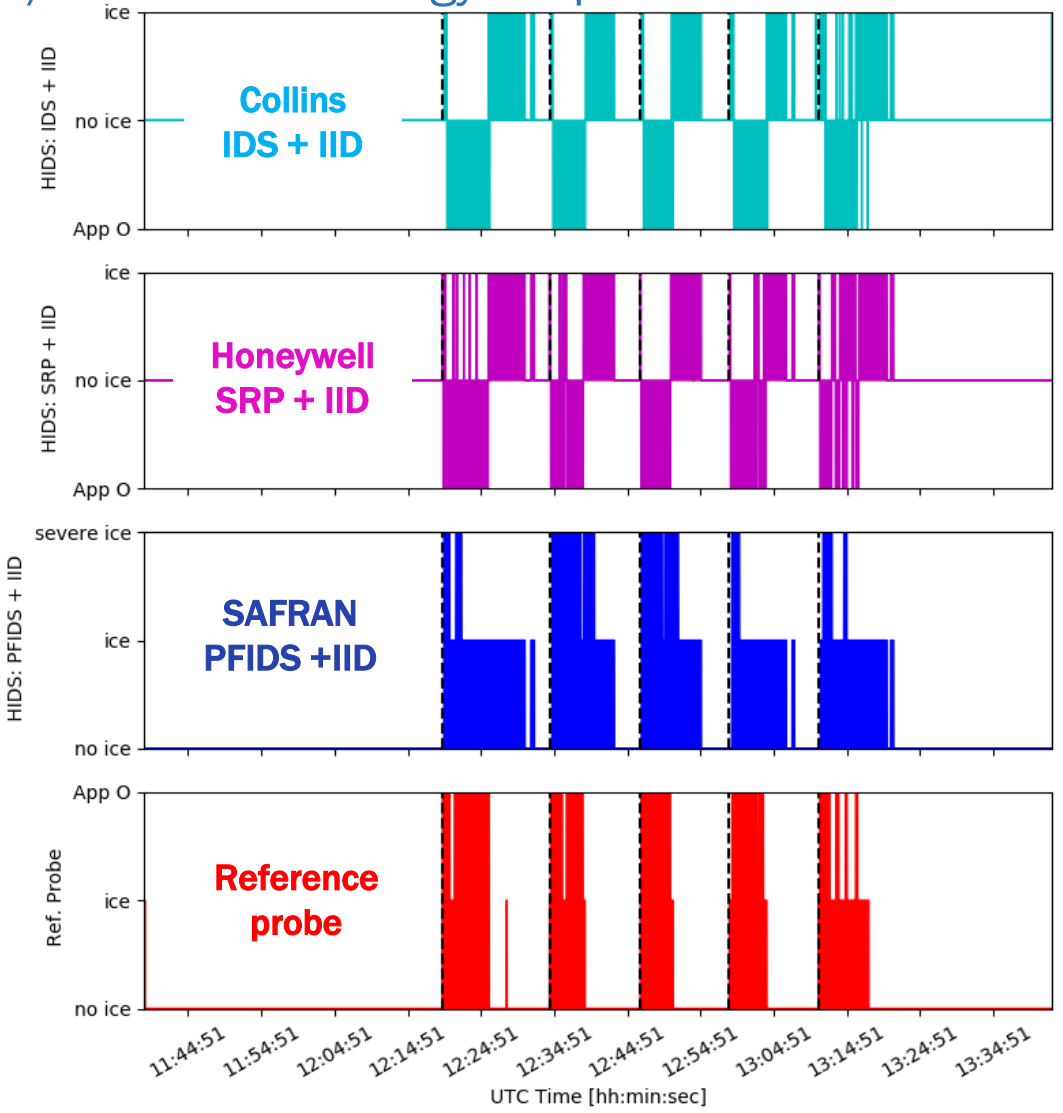
HIDS North America Flight Campaign Results

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

Direct and indirect ice detection signals

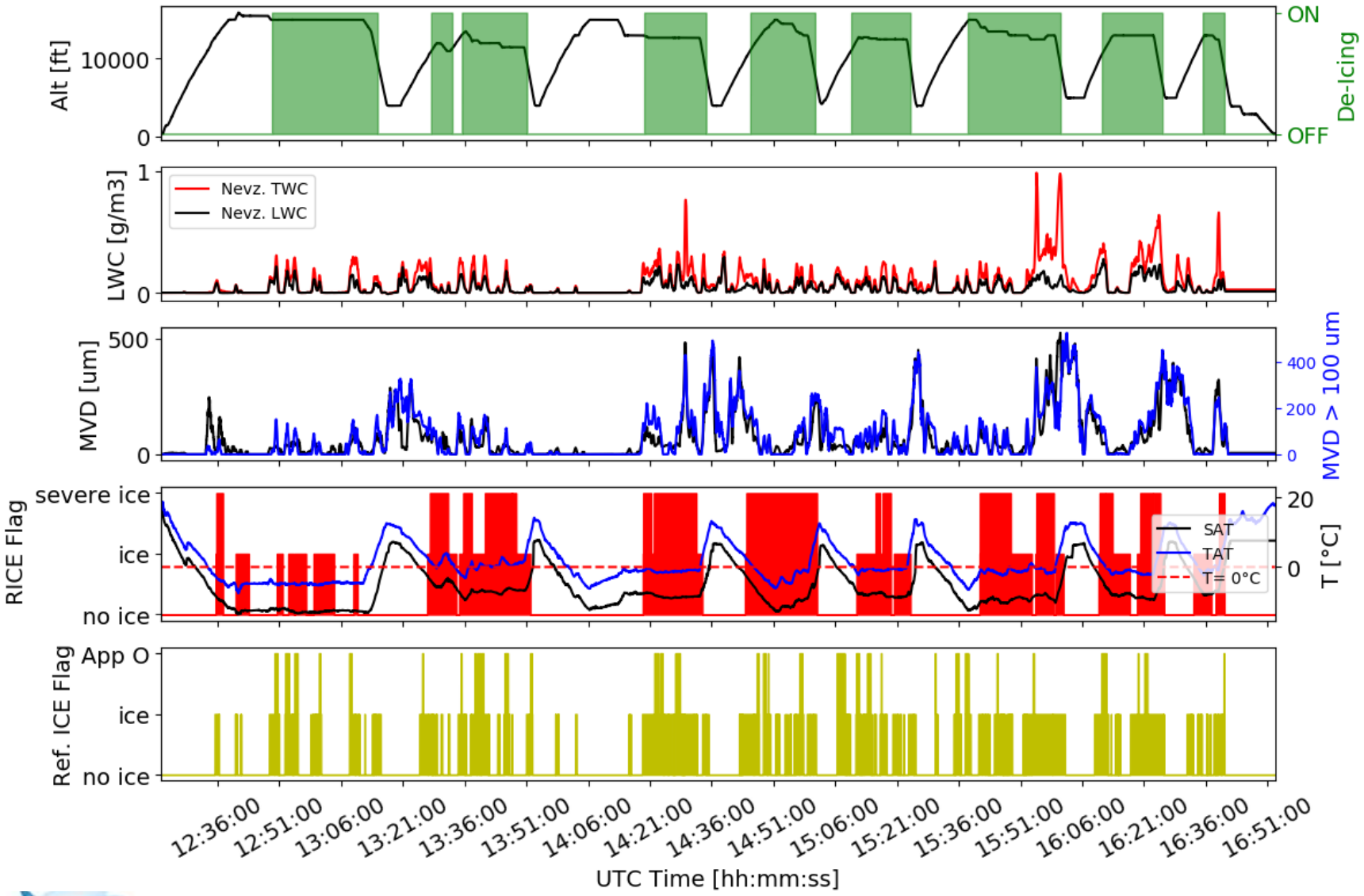


HIDS arbitration results



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

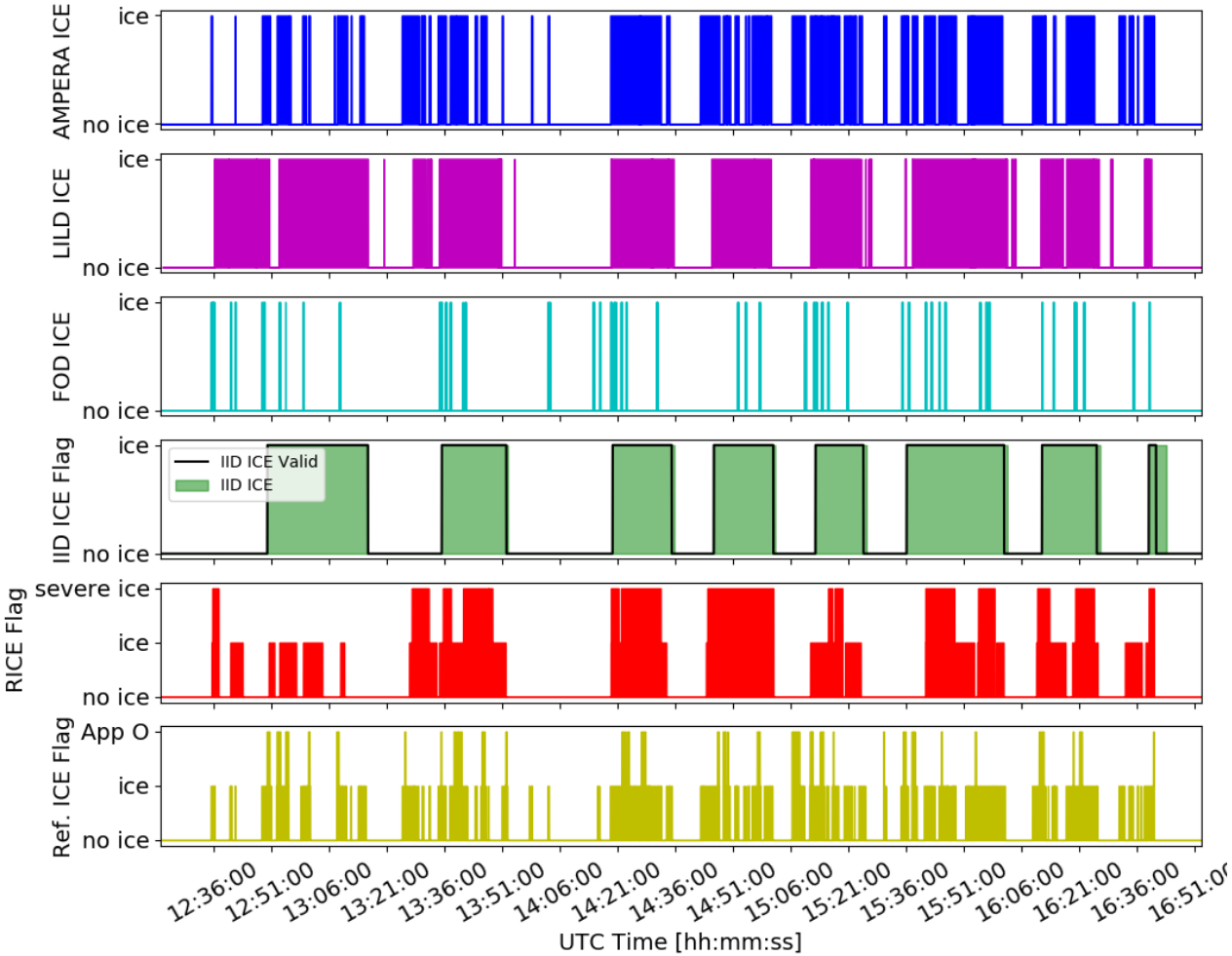
Difficult characterization of icing conditions!

HIDS Europe Flight Campaign Results

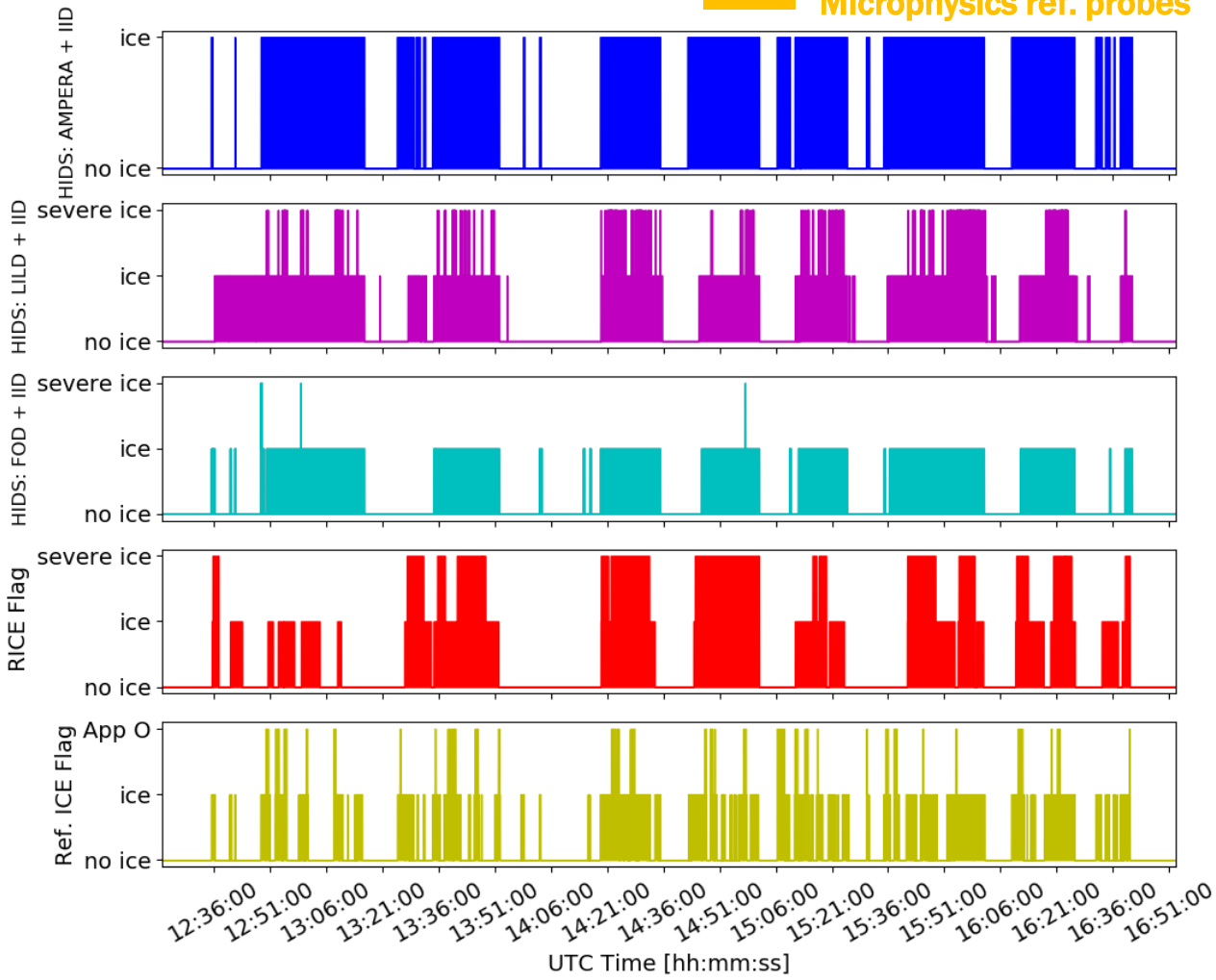
Flight 24 APR 2023 (as230018): Ice detection results

ONERA AMPERA
DLR LILD
INTA FOD
DLR IID
RICE reference probe
Microphysics ref. probes

Direct and indirect ice detection signals

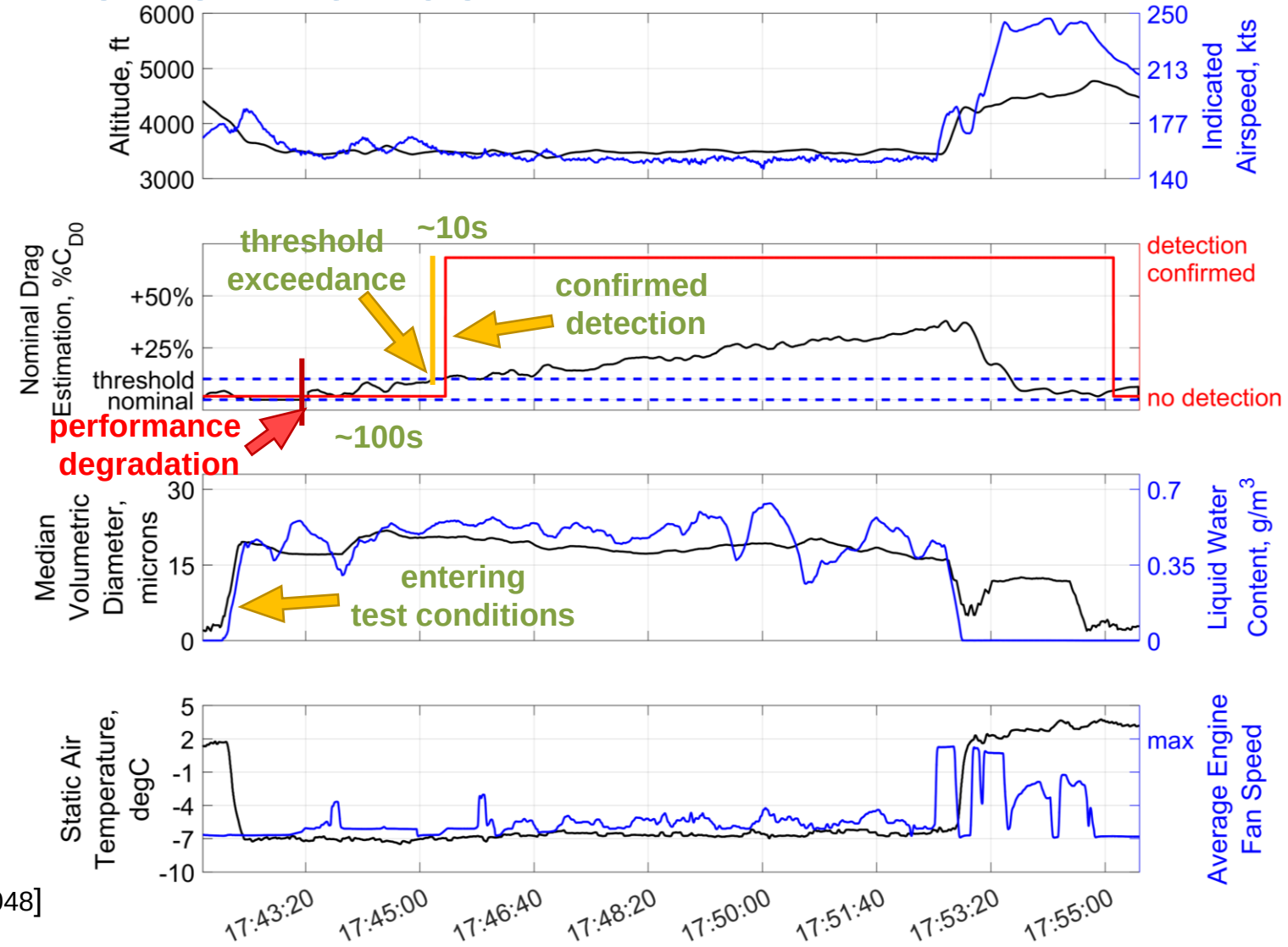


HIDS arbitration results



SENS4ICE North America Flight Campaign
Indirect Ice Detection Performance

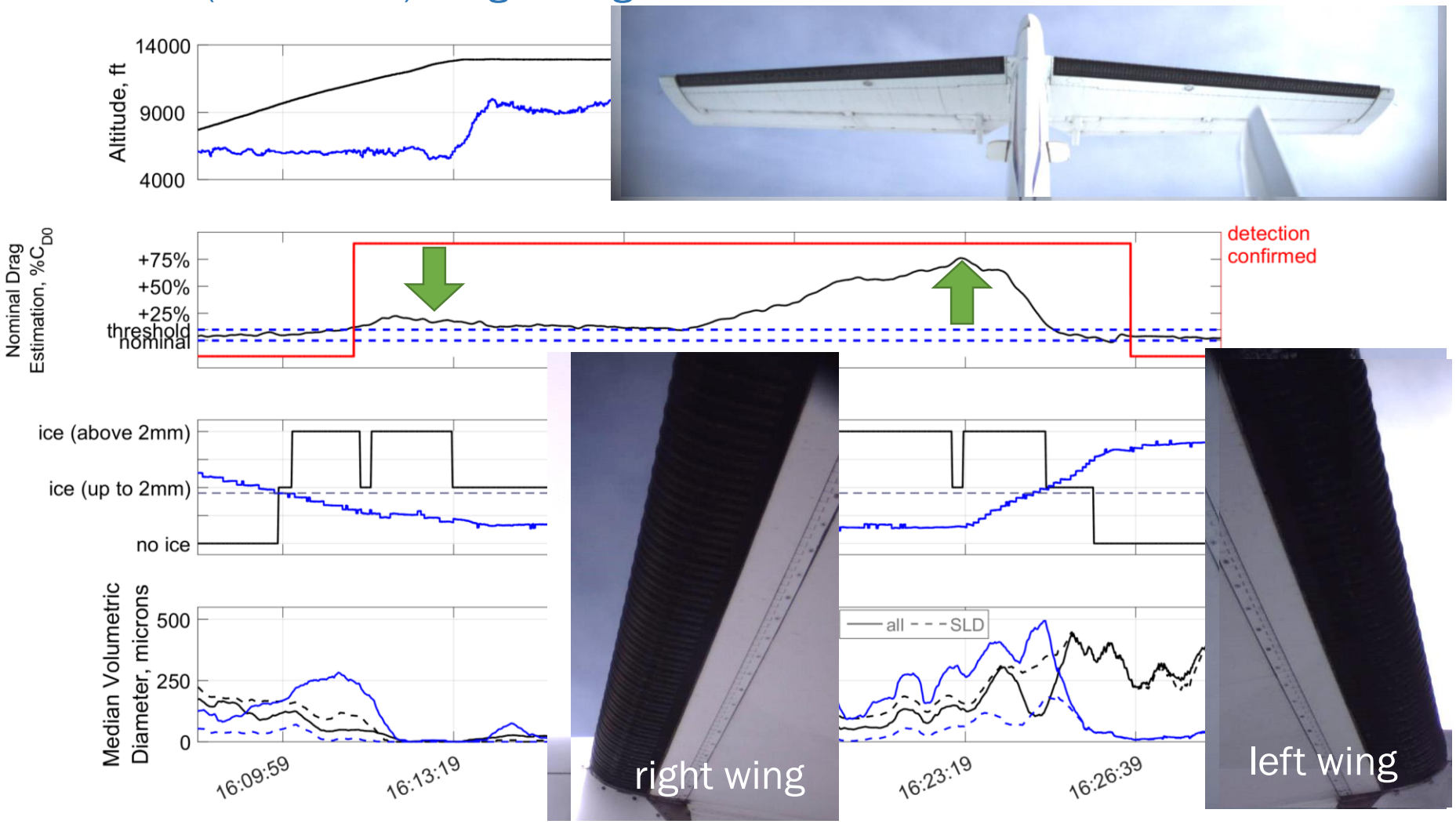
- example 23 FEB 2023, 17:41:49 UTC - 17:55:29 UTC
- figure 1: altitude and indicated airspeed
- figure 2: nominal drag estimation and IIDS detection output
- figure 3: MVD and LWC of encountered icing conditions
- figure 4: static air temperature and average engine fan speed
- detection threshold at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

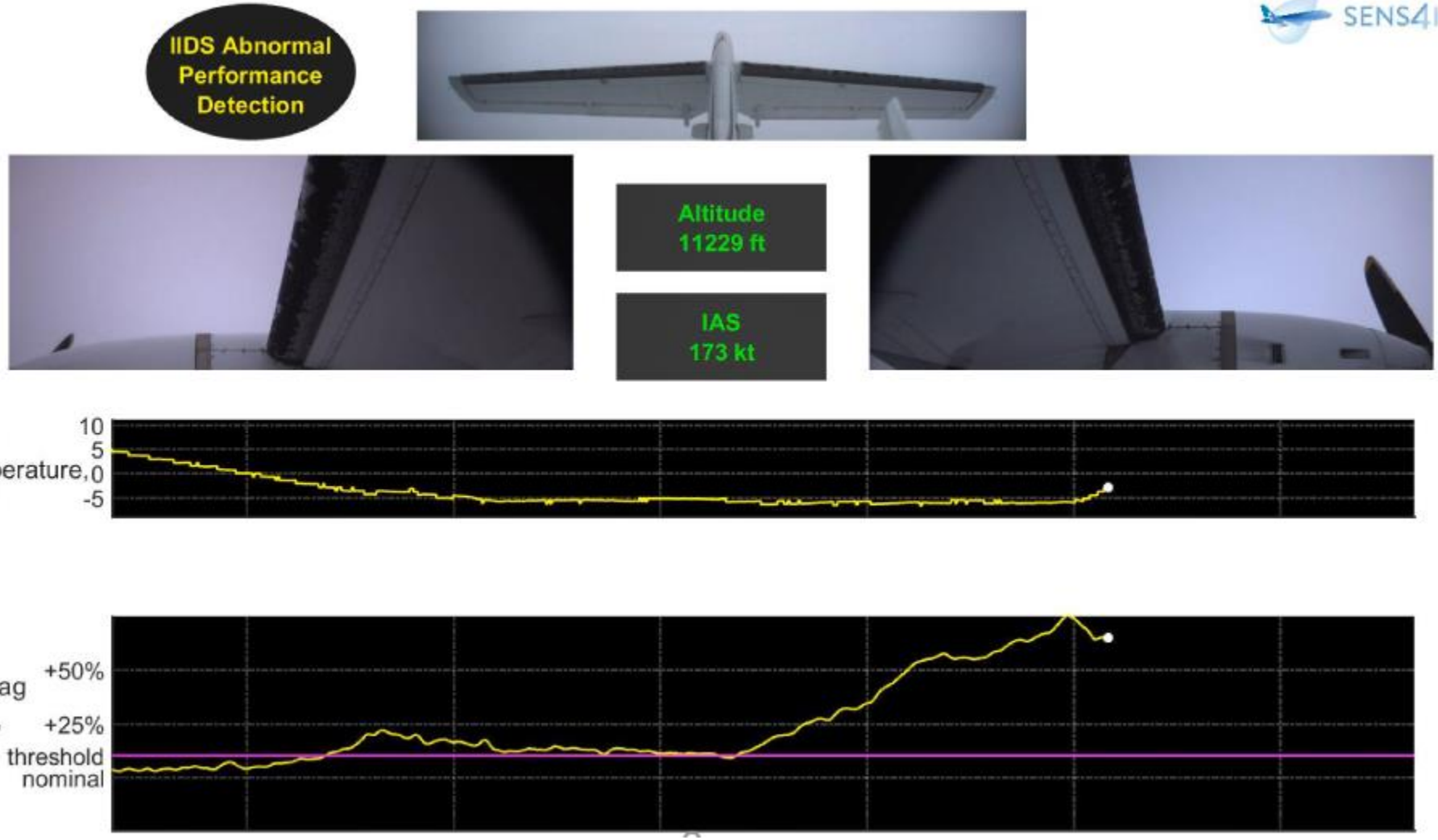
SENS4ICE Europe Flight Campaign
Indirect Ice Detection Detailed Example Results

Flight 24 APR 2023 (as230018): single icing encounter



Example on detailed indirect ice detection results

Flight 24 APR 2023 (as230018): single icing encounter (video snapshot)

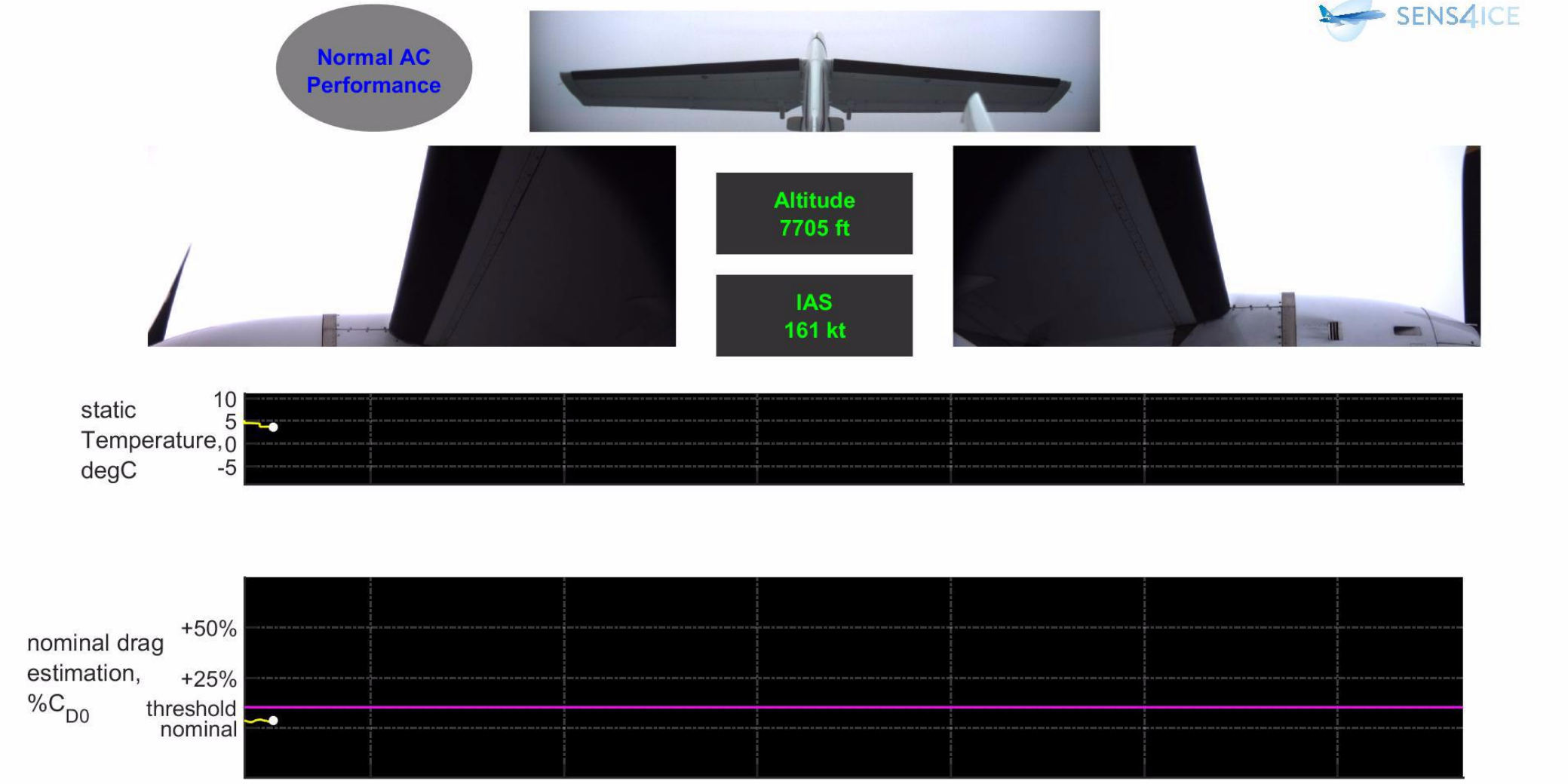


$$\frac{C_D - C_{D,ref}}{C_{D0,ref}}$$

BACKUP

Example on detailed indirect ice detection results

Flight 24 APR 2023 (as230018): single icing encounter (time-lapse video)



$$\frac{C_D - C_{D,ref}}{C_{D0,ref}}$$

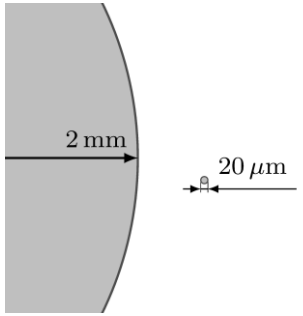
BACKUP

SENS4ICE Challenge/Outcome

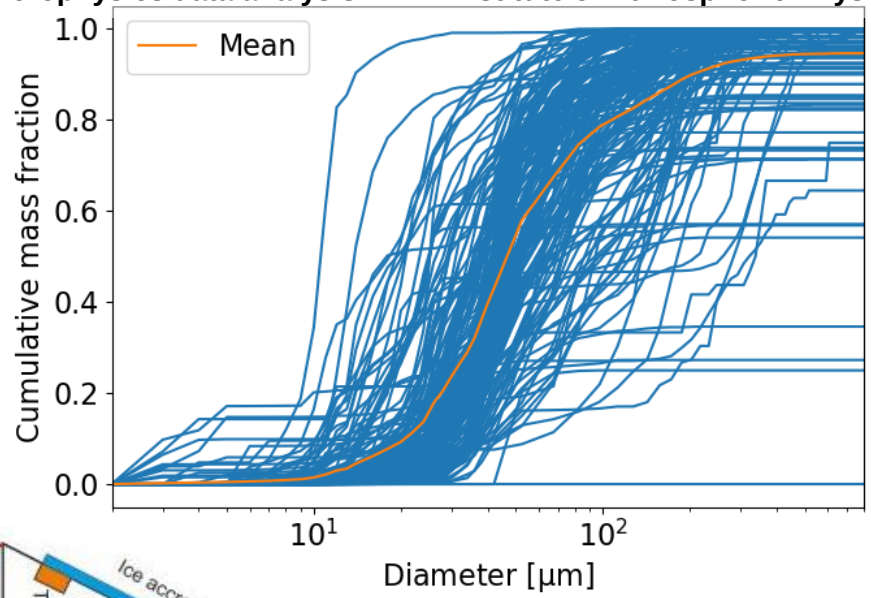
- Detect icing conditions – challenge: SLD

Solution/Innovation

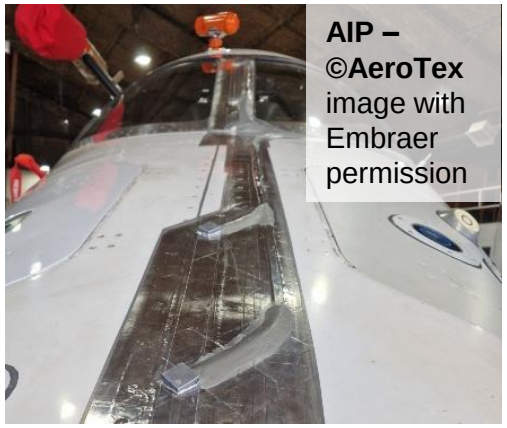
- 8 direct detection technologies
  matured & flight test demonstrated (many TRL6)
- Hybrid approach (TRL5) – fusion of input data:
  sensor(s) and indirect detection



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

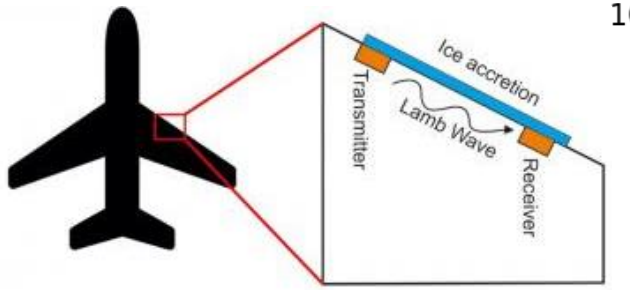


HIDS-Safran/ IID-DLR



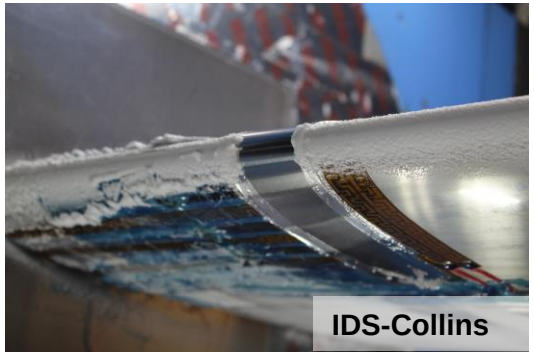
AIP – ©AeroTex image with Embraer permission

PFIDS-Safran



LILD-DLR

AMPERA-ONERA
image with Safire permission



IDS-Collins

SRP–Honeywell image © Embraer

CM2D-DLR image DLR

FOD-INTA
image with Safire permission

SENS4ICE
Final Public Dissemination

https://www.sens4ice-project.eu

Final Public Dissemination Event

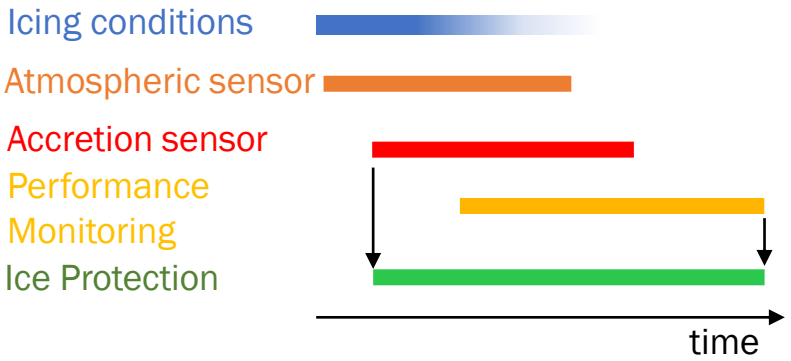
- 29 November 2023, Brussels, Belgium
- Presentations download
  - https://www.sens4ice-project.eu/publications-presentations > section Presentations

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

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

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

https://www.linkedin.com/company/sens4ice-project