SENS4ICE

SENSORS AND CERTIFIABLE HYBRID ARCHITECTURES
FOR SAFER AVIATION IN ICING ENVIRONMENT

EU Project SENS4ICE Hybrid Ice Detection Architectures Demonstration Results

April 2024

Carsten Schwarz (DLR)

ACGSC Meeting #132, Salt Lake City, Utah, USA, 17-19 April 2024

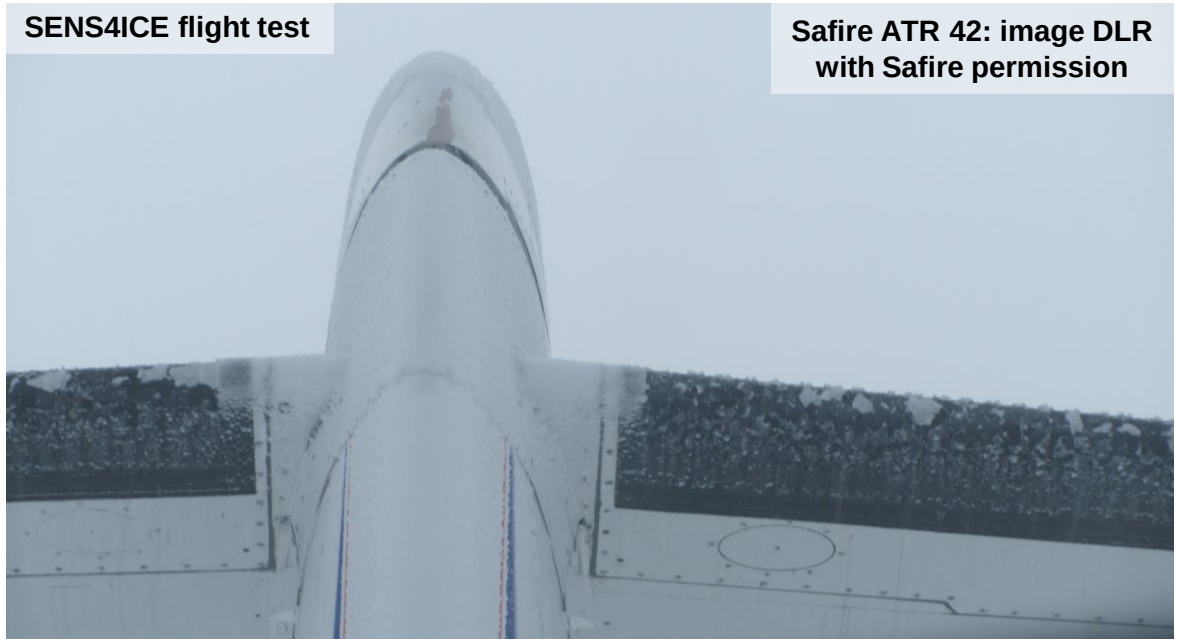
This project has received funding from European Union's Horizon 2020 research and innovation programme under grant agreement n° 824253

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

Aircraft Icing Phenomena
Natural Ice Shapes



SENS4ICE flight test

Safire ATR 42: image DLR with Safire permission

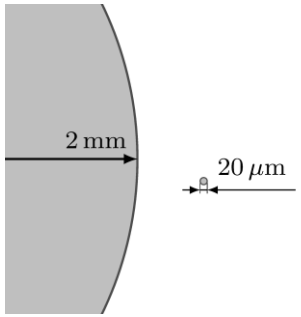
Credit: **NASA** (GRC), general permission for usage for educational and informational purposes (NASA Media Usage Guidelines), https://www.nasa.gov/sites/default/files/thumbnails/image/36_anti_icing_technology.jpg

Credit: **BFU**, Interim Report BFU CX001-13

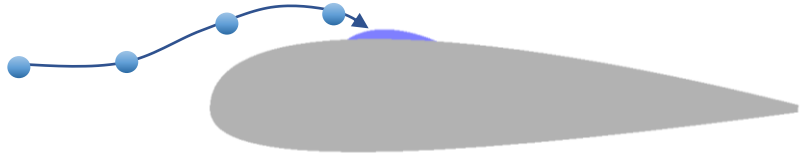
- hazardous effects on aircraft
  - performance
  - dynamic behavior and
  - controls
- adaptation of operational limits required

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

Credit: DLR (C. Raab)

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

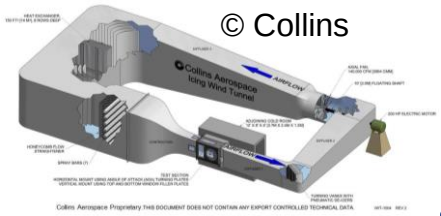
Benefits

- 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 Timeline / Summary / Achievements

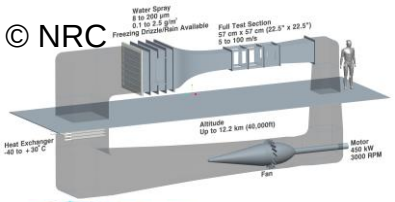
Upgrade icing wind tunnels for App. O

Develop sensors/ technologies for App. O detection



© Collins

Icing wind tunnel testing



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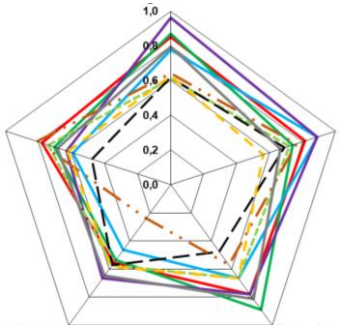
© TUBS

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

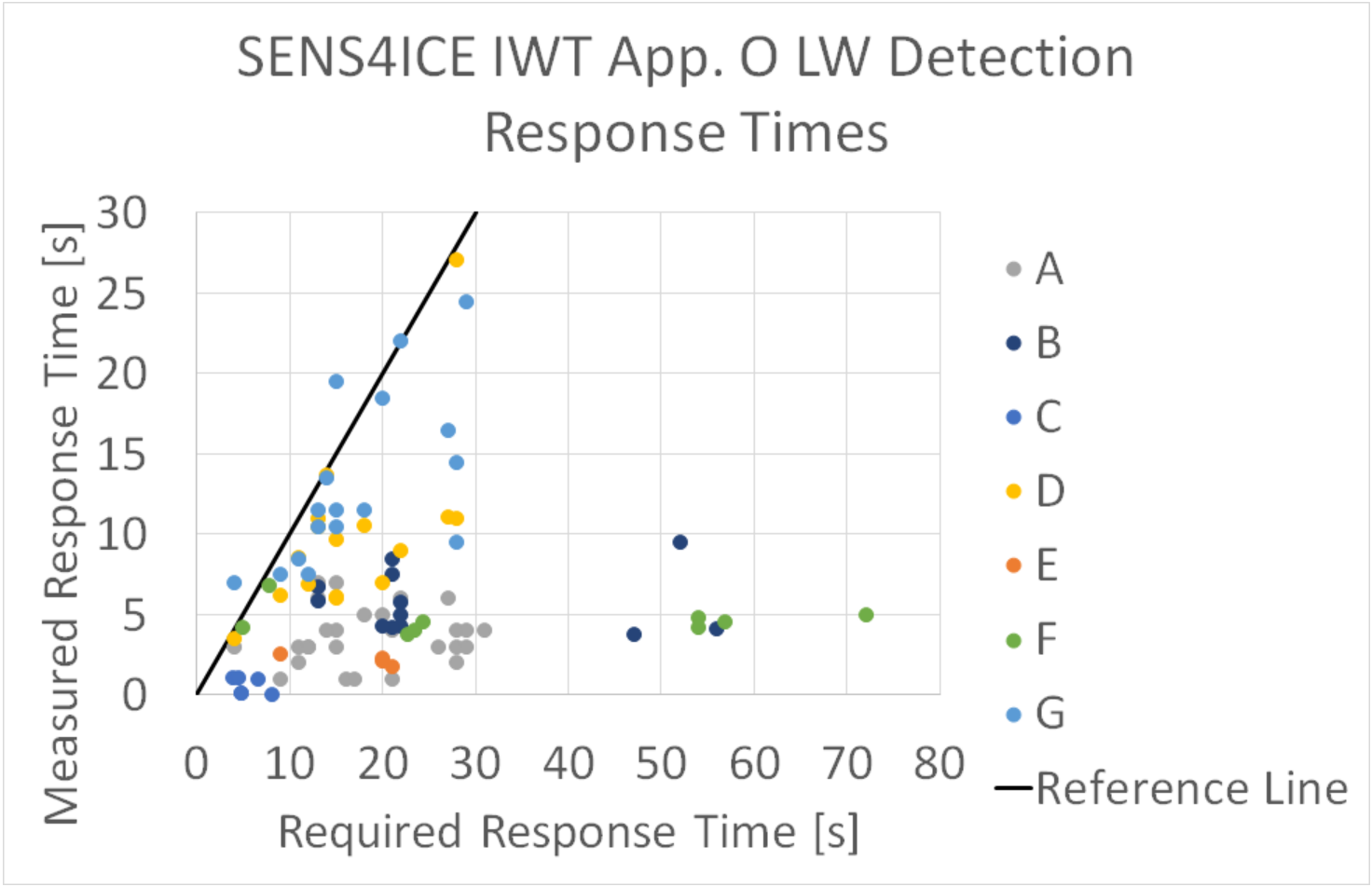
Flight test analysis/ techno-logy evalua-tion

Commu-nication, Dissem-ination, Exploi-tation

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

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

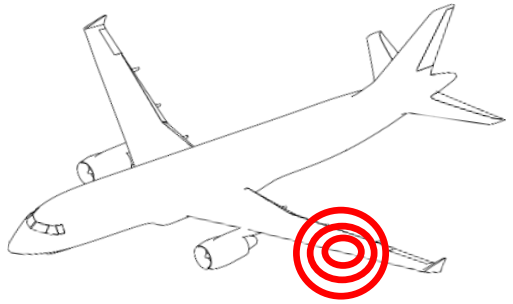
- anonymised results
- required maximum response time as per EUROCAE inflight icing systems standard ED-103 (depending on icing condition)
- App. O test points liquid water (LW) detection



Hybrid Ice Detection Approach

Direct ice detection

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



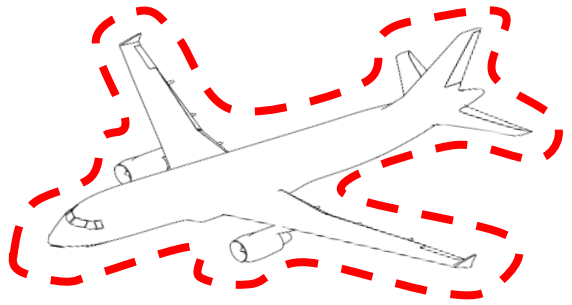
Hybrid ice detection

Combination of Direct and Indirect Detection.

- Flight safety increase.
- Better availability.
- False alarms reduction.
- Detailed information about the icing encounter.
- Continuous monitoring of A/C performance.
- Pilots better reaction.

Indirect ice detection

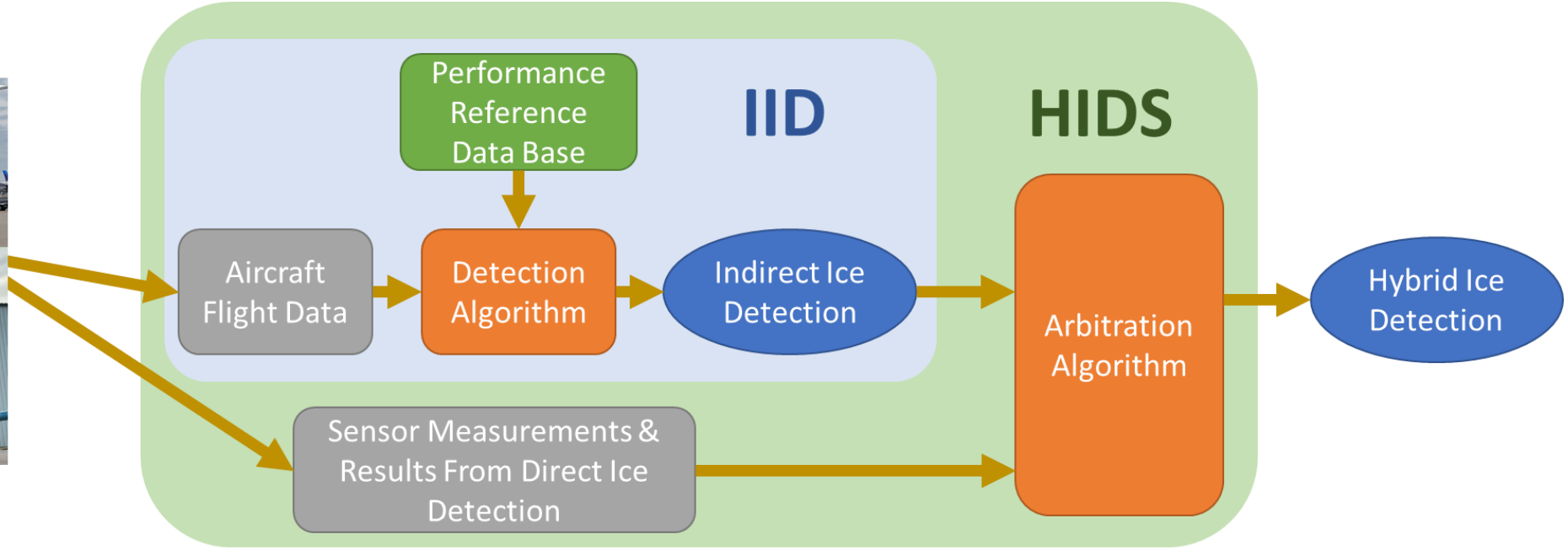
Global detection: effects of ice accretion.



SENS4ICE goals

- To define the specifications and needs for Hybrid Detection approach
- To develop Hybrid Ice Detection System (HIDS) demonstrator for FT campaign

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

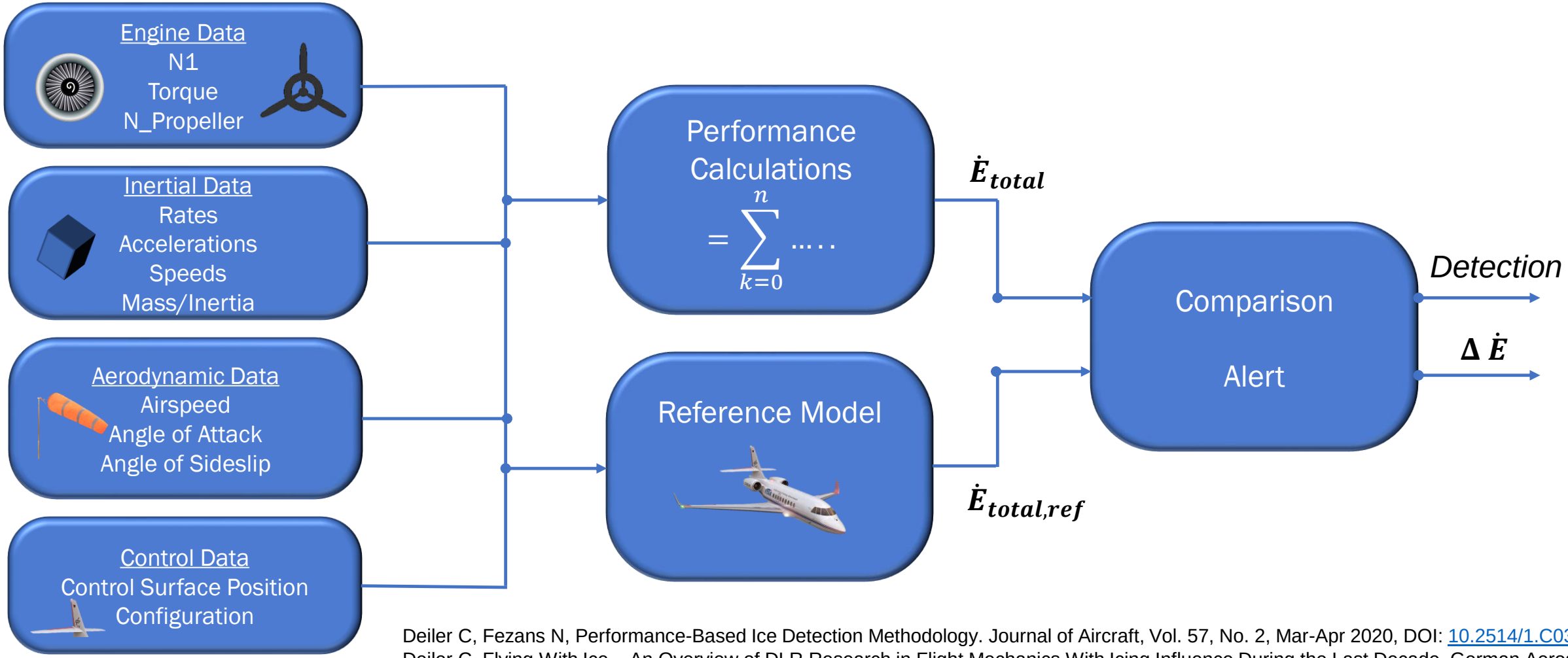


[Orazzo, A., Thillays, B., "Hybrid Ice Detection System development and validation", SAE International Conference on Icing of Aircraft, Engines, and Structures 2023, Vienna, Austria, 20 – 22 June 2023, 23ICE-0049]

[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

Performance Based (Indirect) Ice Detection

Abnormal Aircraft Performance Monitoring:

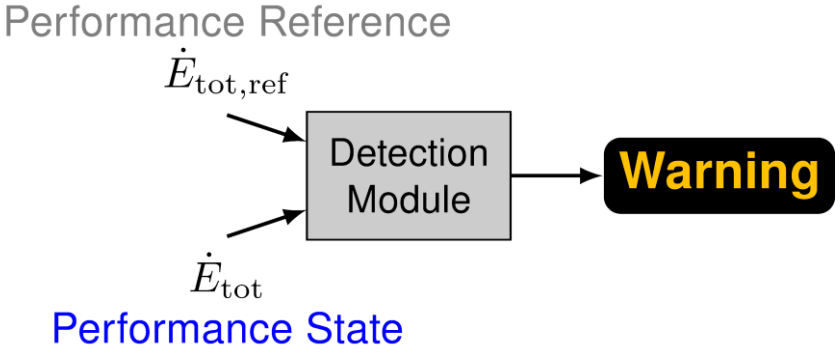
- Total Energy:

$$E_{tot} = \frac{1}{2} \cdot m_{AC} \cdot V_{TAS}^2 + m_{AC} \cdot g \cdot H$$

- Power Imbalance:

$$\dot{E}_{tot} = V_{TAS} \cdot \dot{V}_{TAS} \cdot m_{AC} + \frac{1}{2} \cdot V_{TAS}^2 \cdot \dot{m}_{AC} + g \cdot \dot{H} \cdot m_{AC} + g \cdot H \cdot \dot{m}_{AC}$$

- Detection Principle



- Performance variation as equivalent drag coefficient

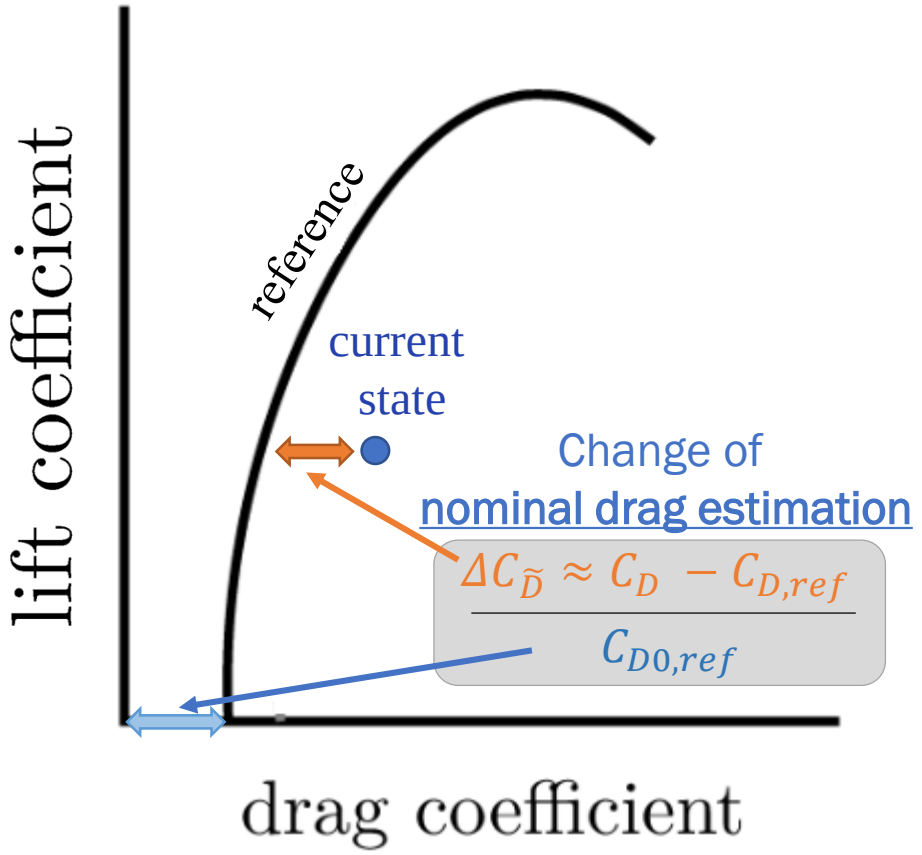
$$\Delta C_{\tilde{D}} \approx \frac{\dot{E}_{tot,ref} - \dot{E}_{tot}}{V_{TAS} \cdot \overline{q} \cdot S}$$

with $\dot{E}_{tot,ref}$ subject to further corrections

Credit: DLR

Flight Performance Reference Data Base

- Reference data required to compute the reference power imbalance $\dot{E}_{tot,ref}$
- Must include the aircraft performance
  - e.g., via multi-dimensional model for $\dot{E}_{tot,ref}$ (e.g. table)
  - aerodynamic reference and engine thrust model → used for SENS4ICE
- Reference could be based on flight data or only preliminary design data for new aircraft
- For SENS4ICE flight test:
  - Specific adaption of reference required due to significant aircraft modifications



SENS4ICE Flight Campaigns

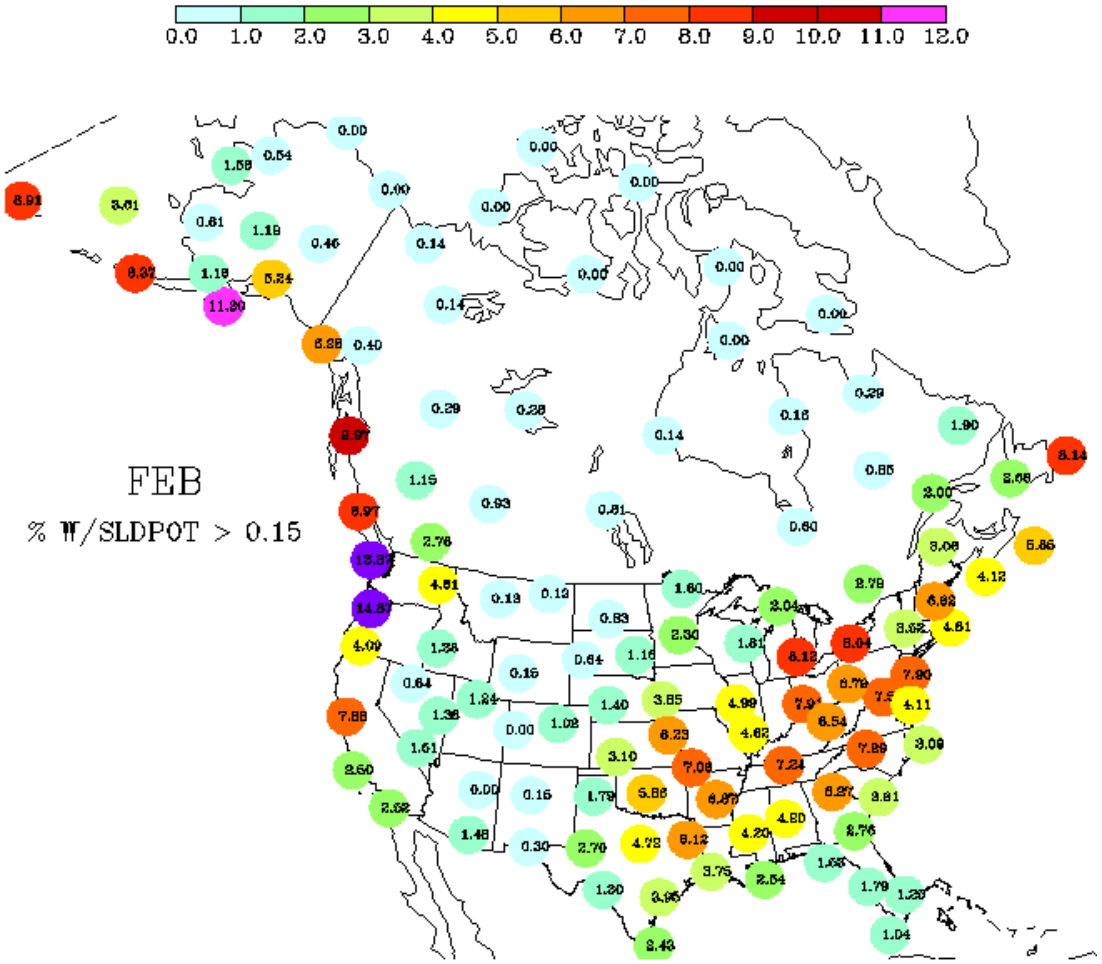
- Total flight test time: 75h in natural icing conditions
- North America
  - February/March 2023
  - Embraer Phenom 300 operated by Embraer
  - **15 flights** with a total of **25 flight hours** (including ferry and check flights) successfully conducted targeting natural liquid water icing conditions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

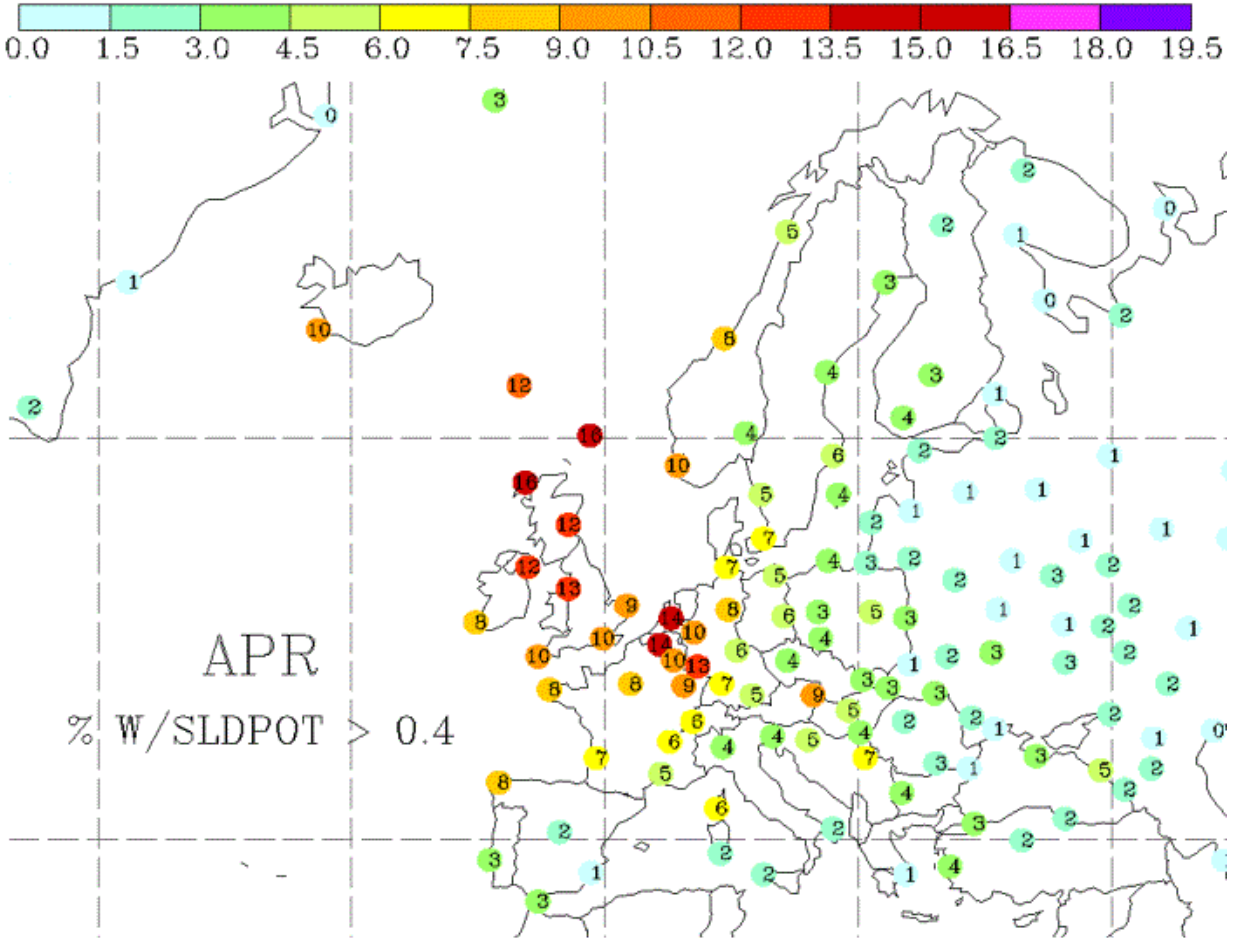
Embraer Phenom 300

SAFIRE ATR 42

Icing Frequencies Analysis

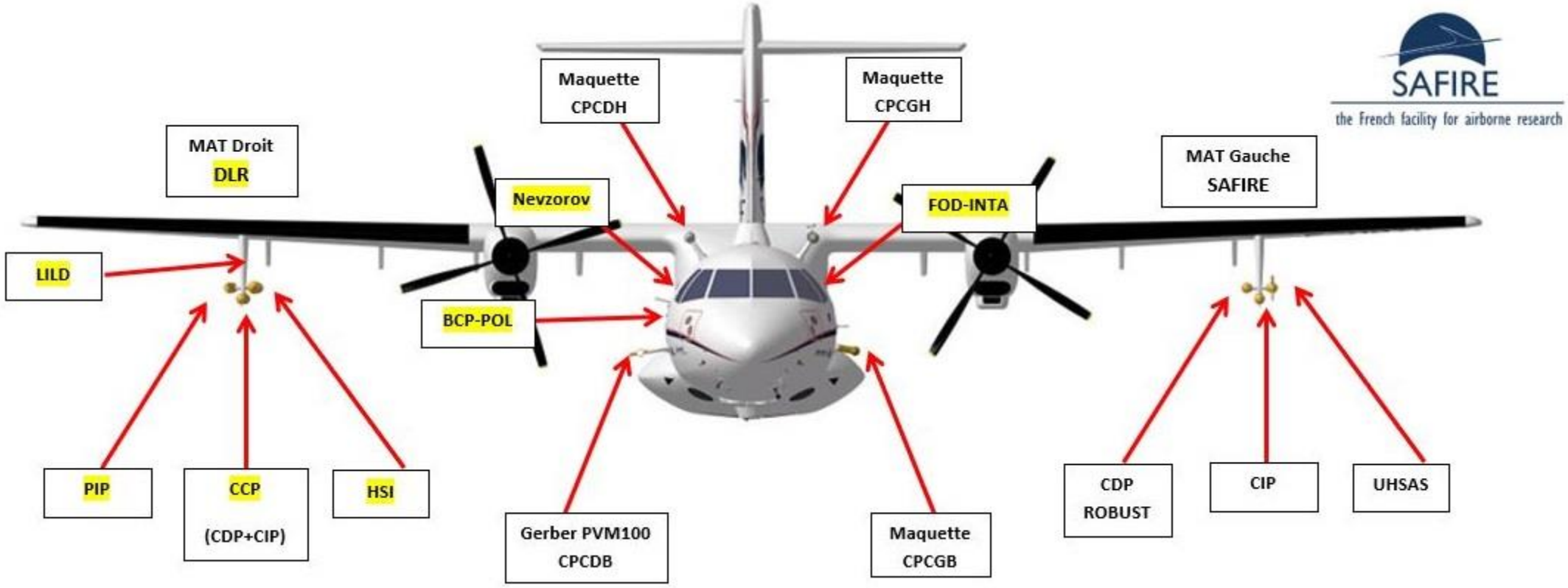
Full column frequencies of days with SLD potential [Ben Bernstein]





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

European Flight Campaign SAFIRE ATR 42 Sensor Locations – Front View



SENS4ICE equipment highlighted in yellow

Image Credit Safire

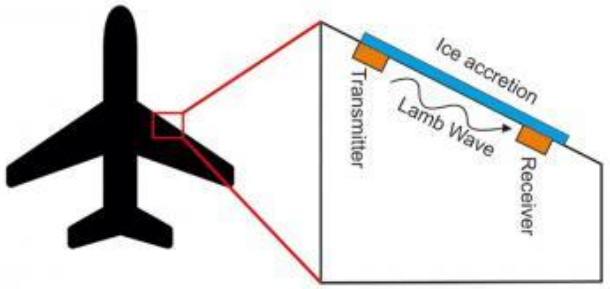
European Flight Campaign SAFIRE ATR 42 Sensor Installations

- 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

AMPERA-ONERA



LILD-DLR

image DLR with Safire permission

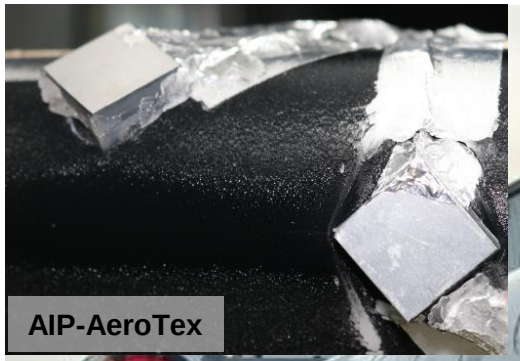
CM2D-DLR

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)

HIDS-Safran/
IIDS-DLR

PFIDS-Safran



AIP-AeroTex

IDS-Collins

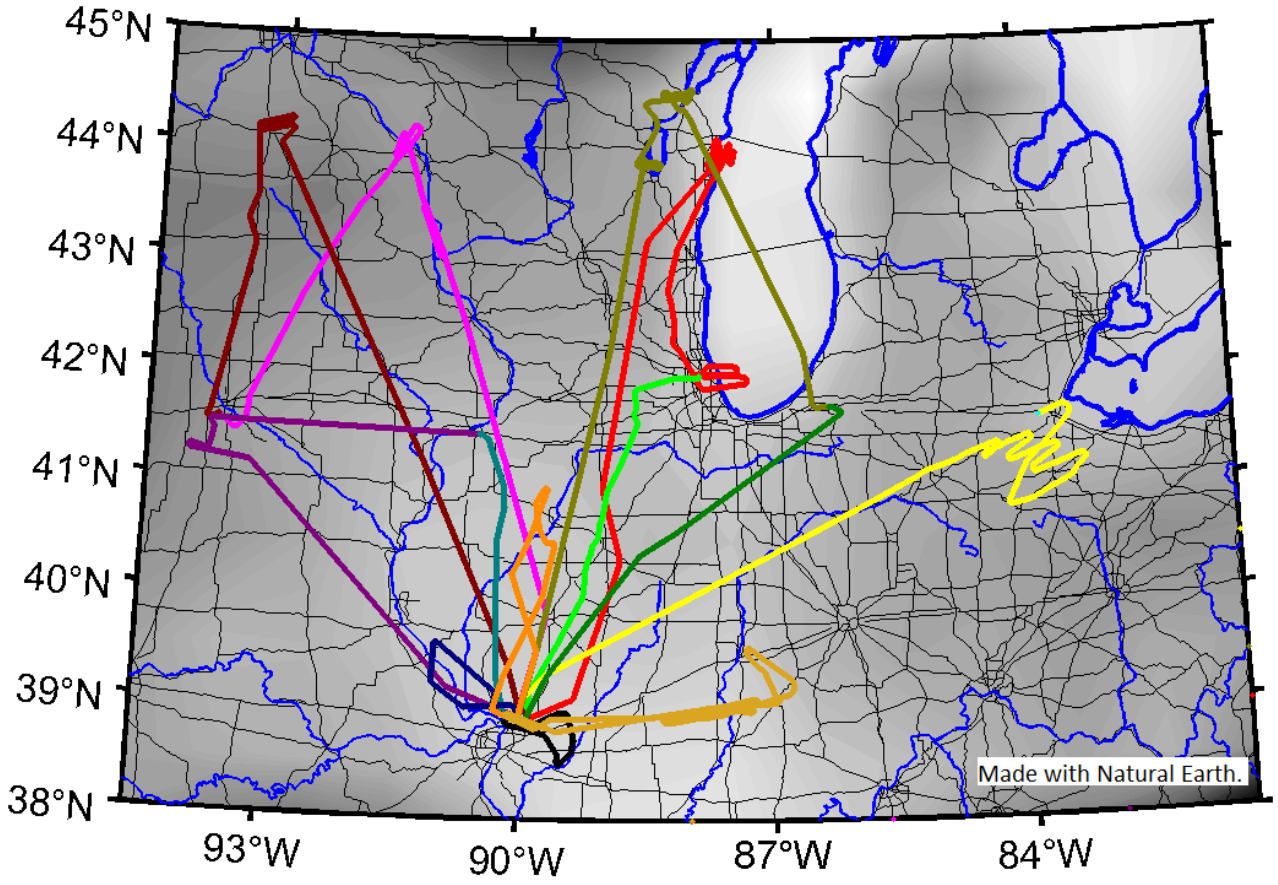
SRP-Honeywell

© Embraer

North America Flight Campaign Embraer Phenom 300 Impressions

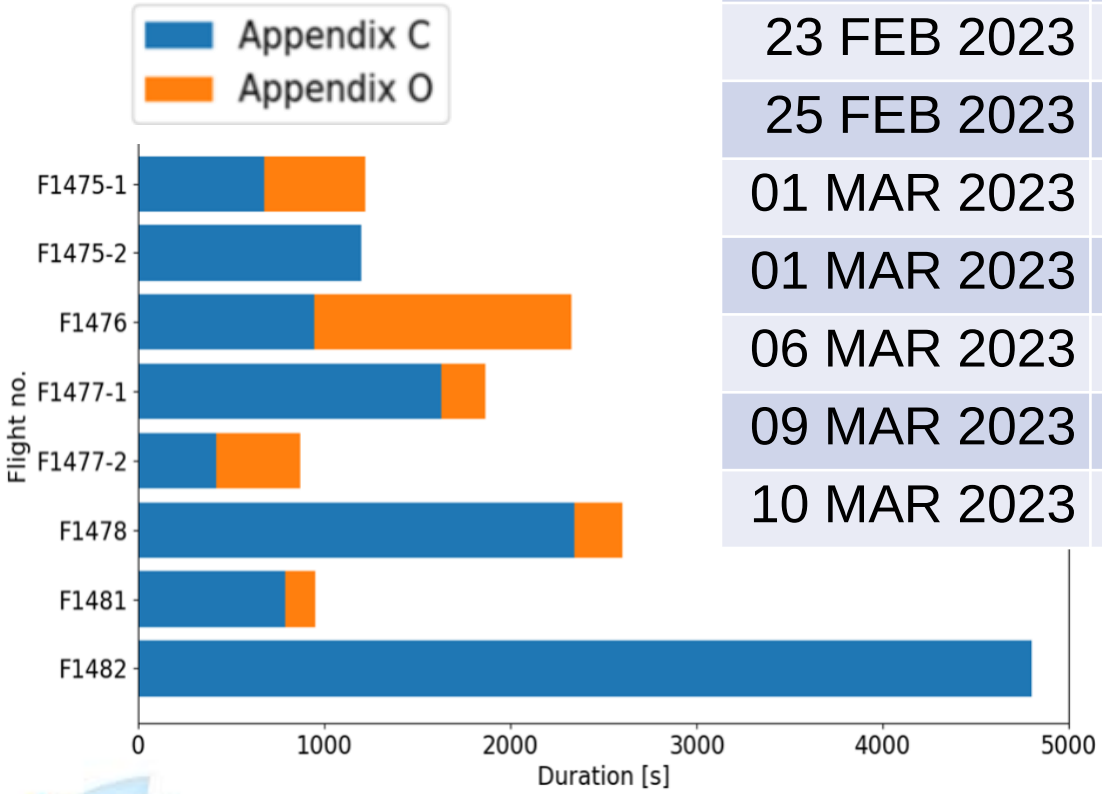
SENS4ICE Flight Campaign North America Ground Tracks

- 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



- 260+ min in App C and 50 min in App O

Microphysics data analysis DLR Institute of Atmospheric Physics

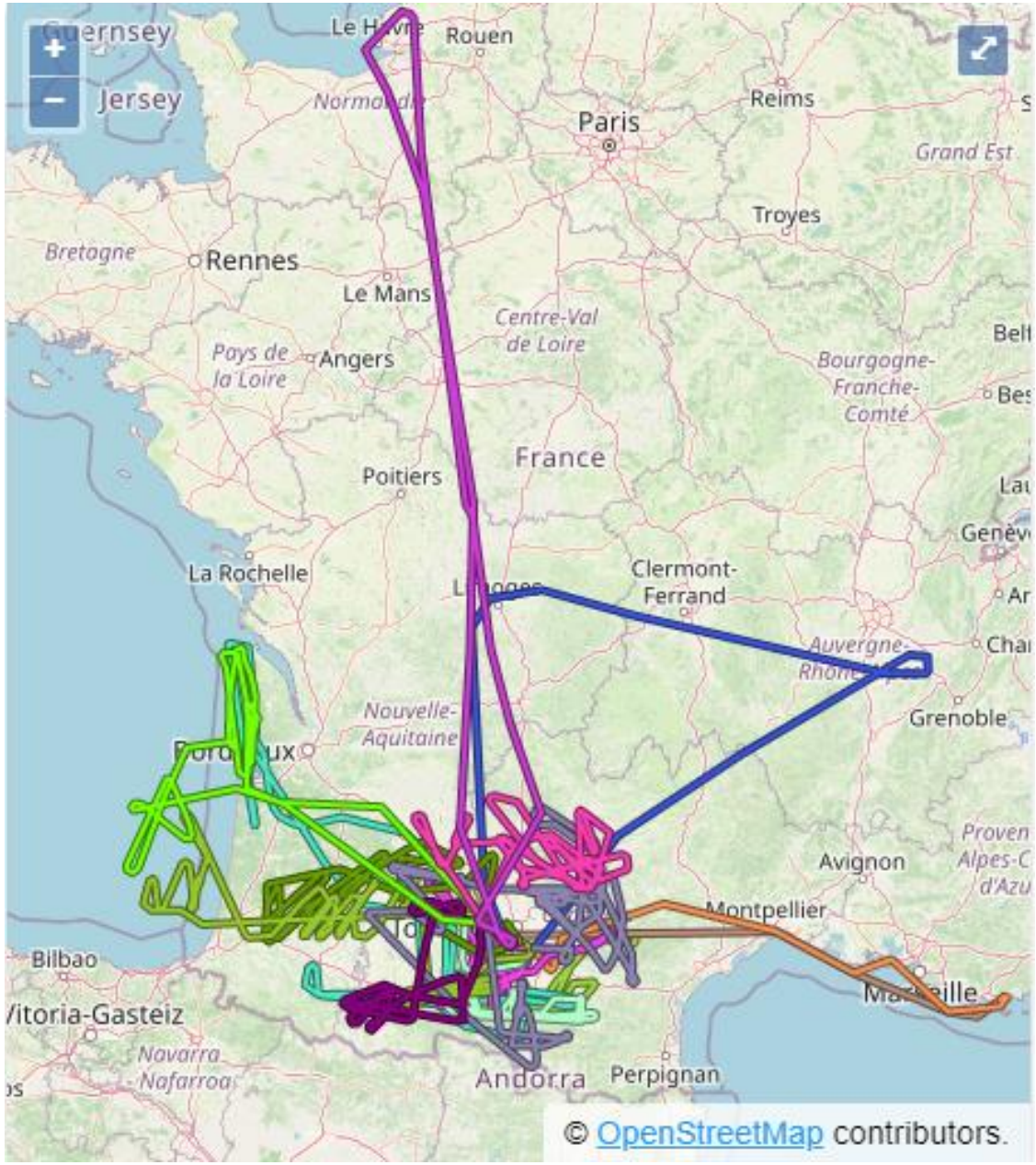
SENS4ICE Flight Campaign North America

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

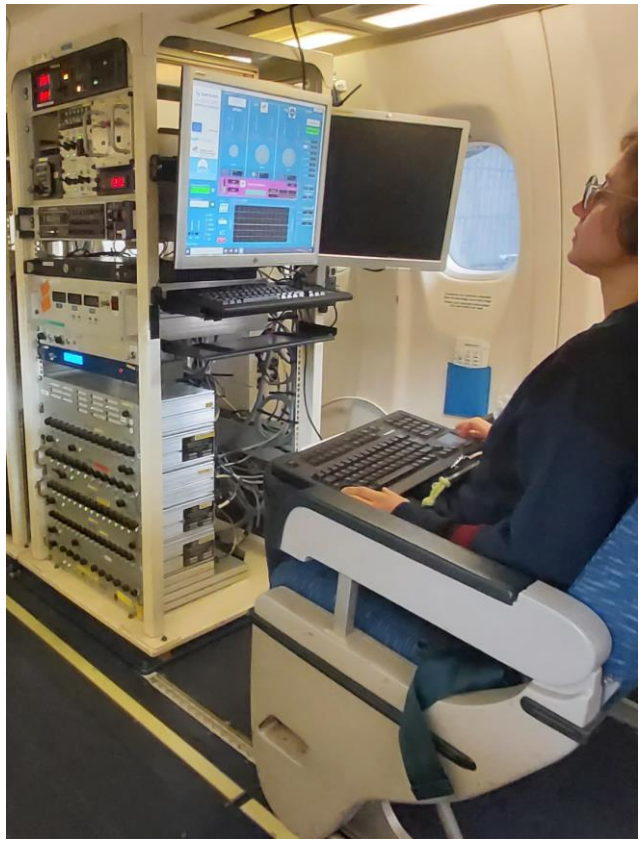
Image Credit Embraer

SENS4ICE Flight Campaign 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
- Access to Data from CNRS/Safire sensors and probes (atmosphere characterization) is public: https://safireplus.aeris-data.fr/data-access
  (link is available from SENS4ICE website and LinkedIn profile)
- 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
Impressions



Operator working with HIDS PC.
(credit SAFRAN)

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

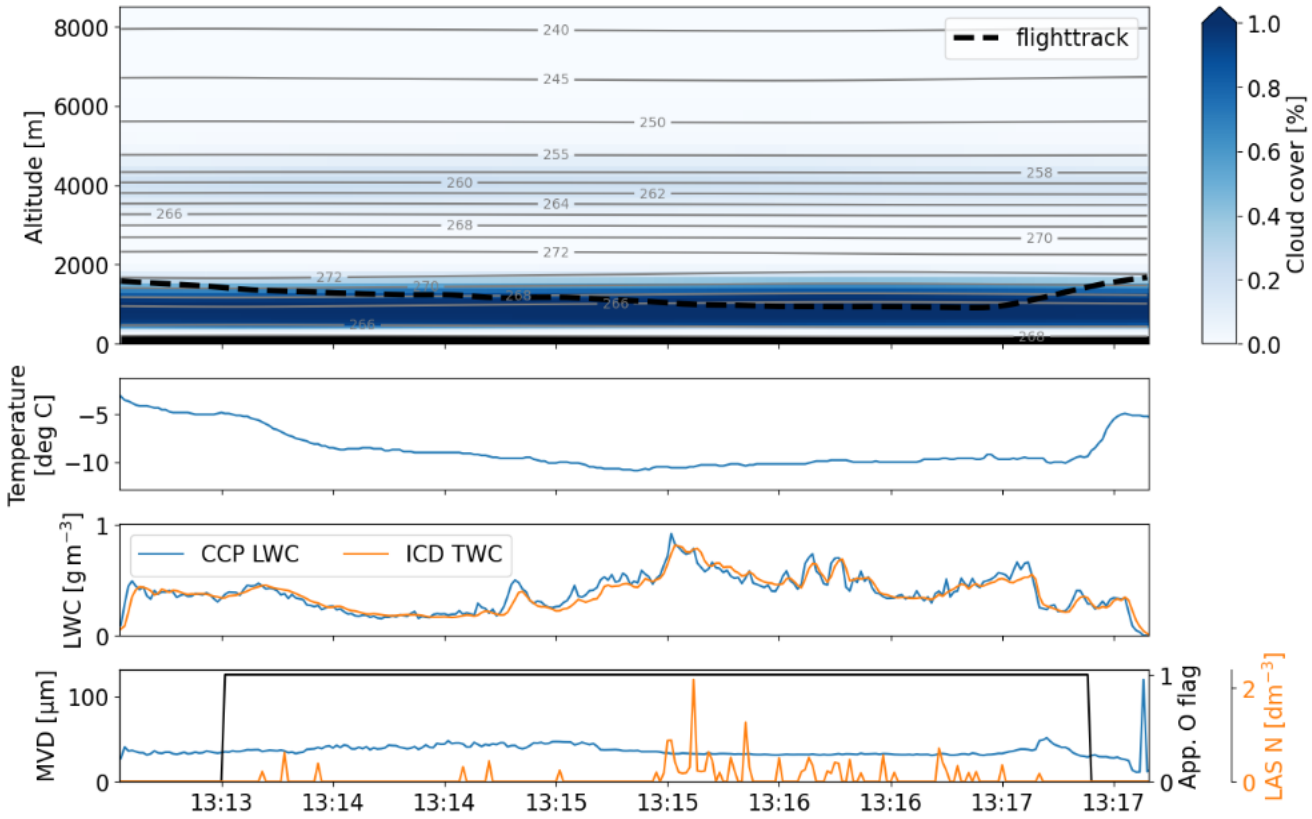
SENS4ICE Flight Campaign Europe Icing Encounter Statistics

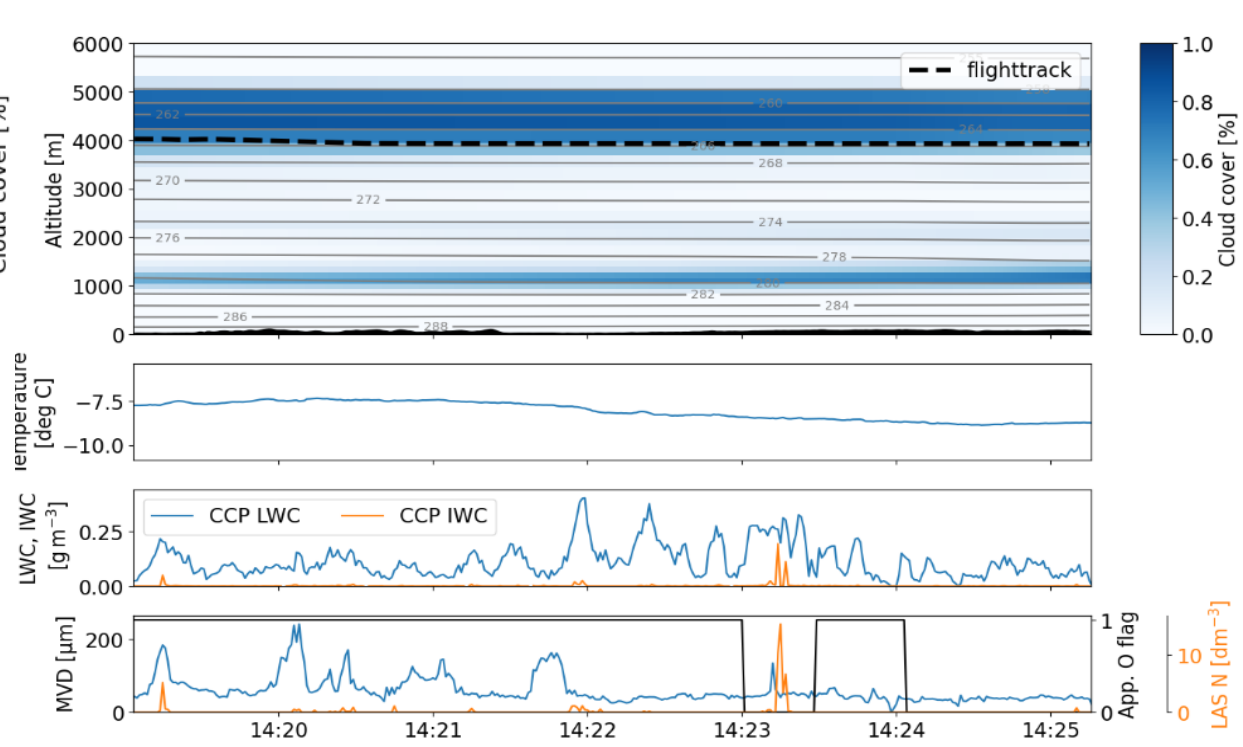
Safire ATR 42: image DLR with Safire permission

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

Appendix O Example Encounters





North America Campaign

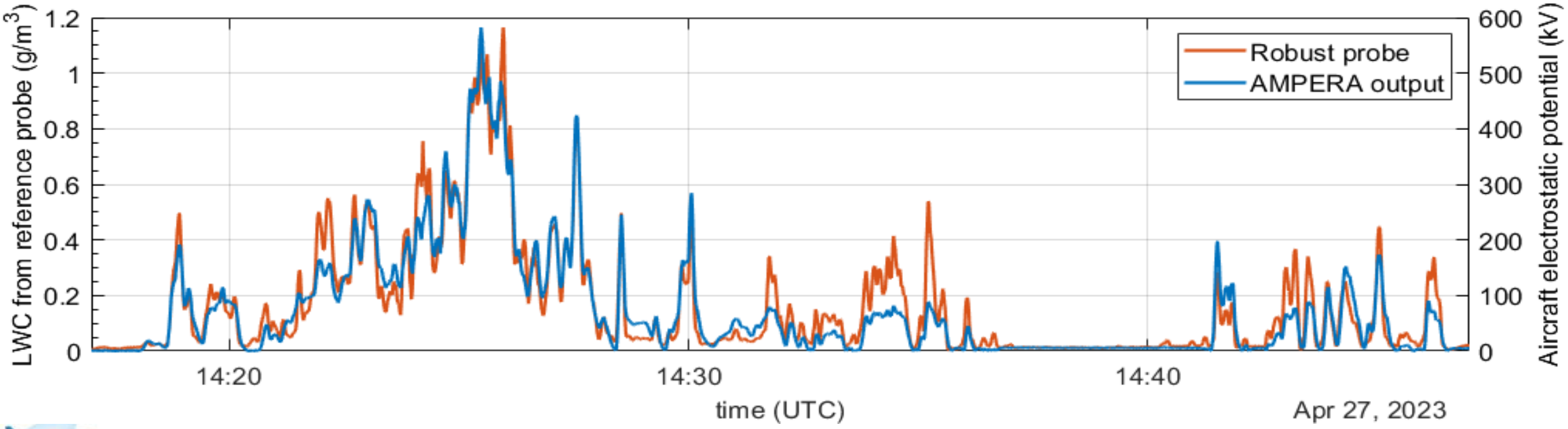
- Clouds most often closed stratus decks
- Appendix O encountered above a stable layer
- Typically cloud approached from top

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

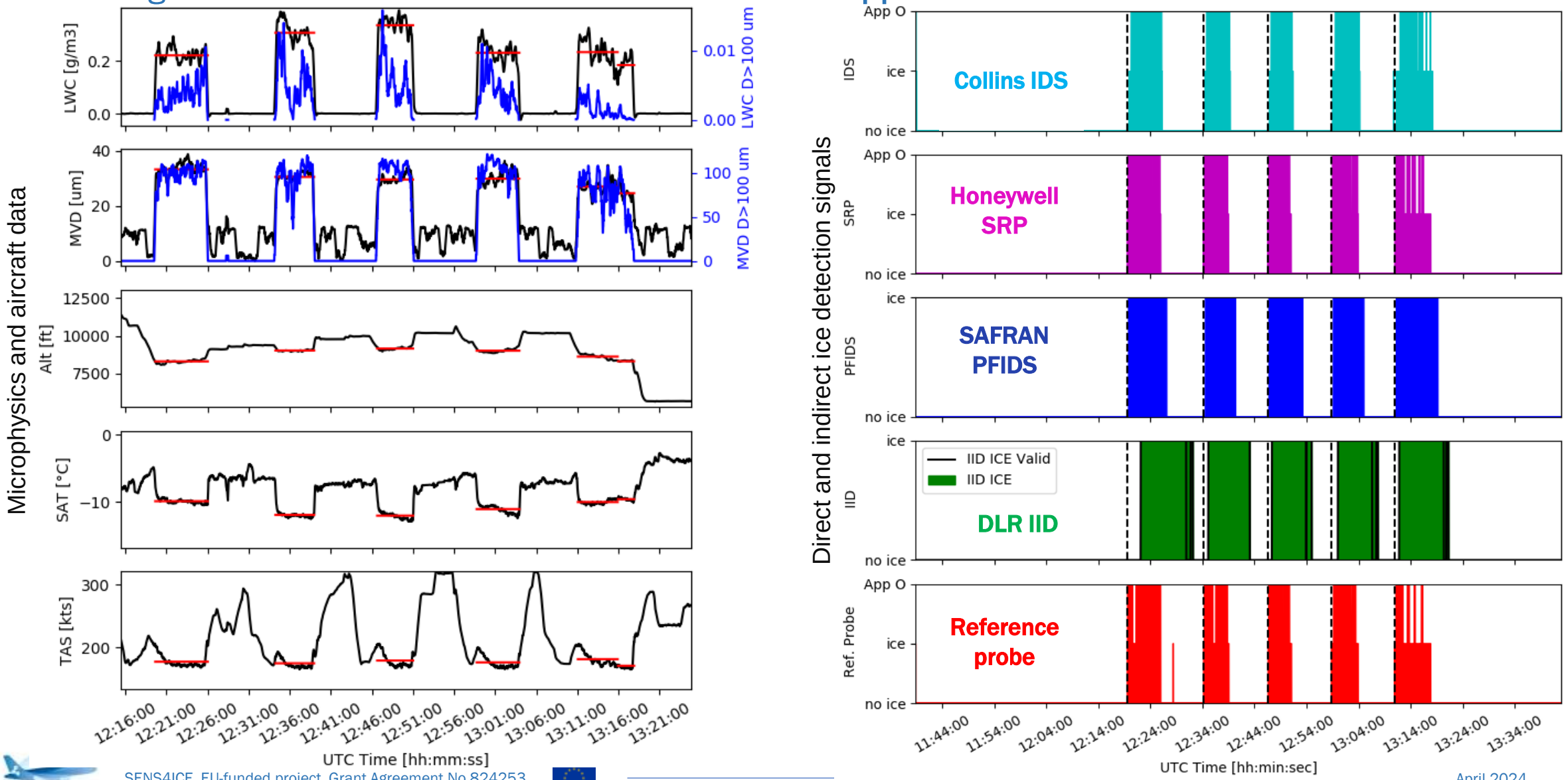
SENS4ICE Europe Flight Campaign
AMPERA / ONERA

- 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.]



HIDS North America Flight Campaign Results

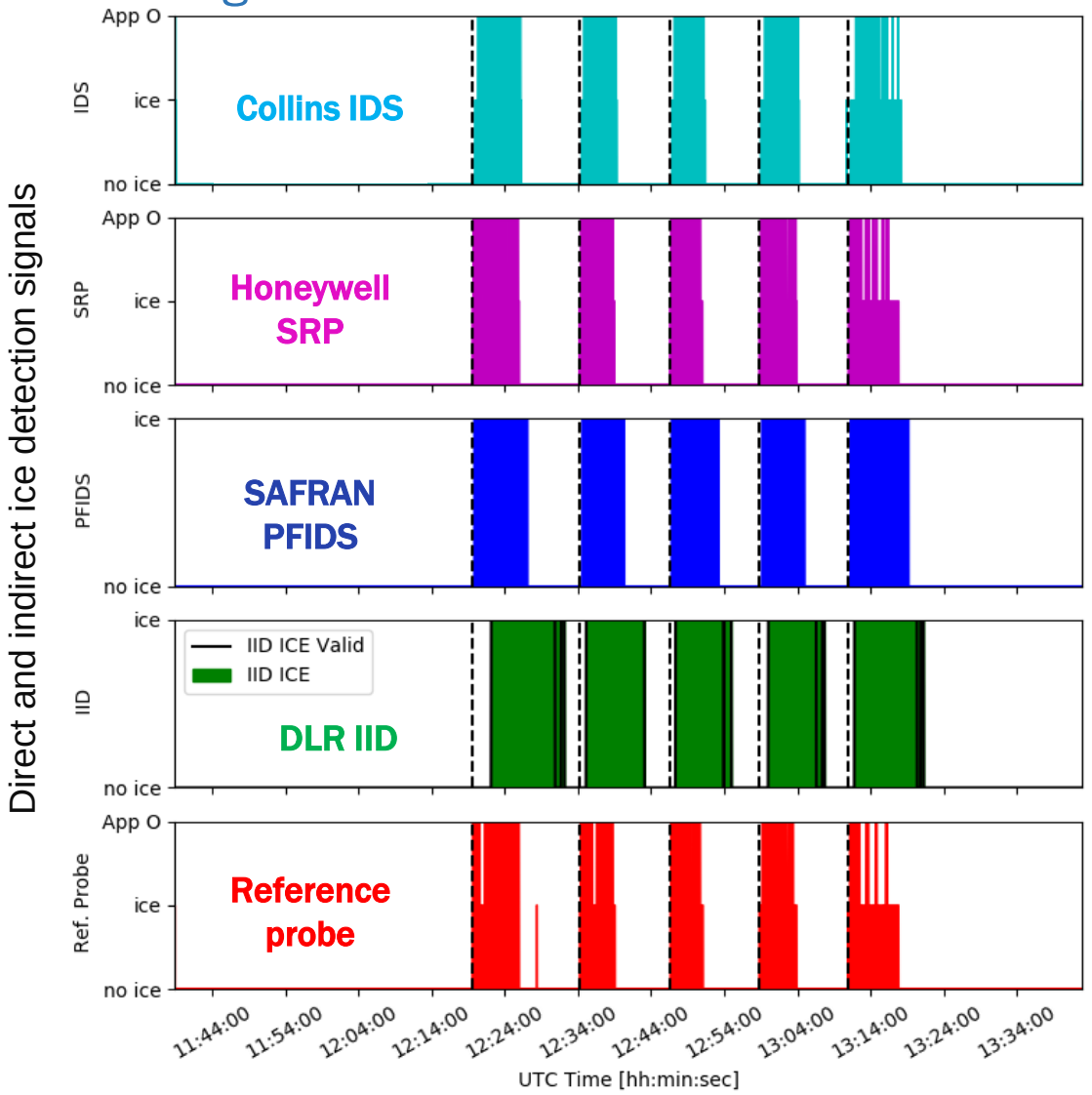
Flight 1476 – Direct and Indirect Ice detection in App O conditions

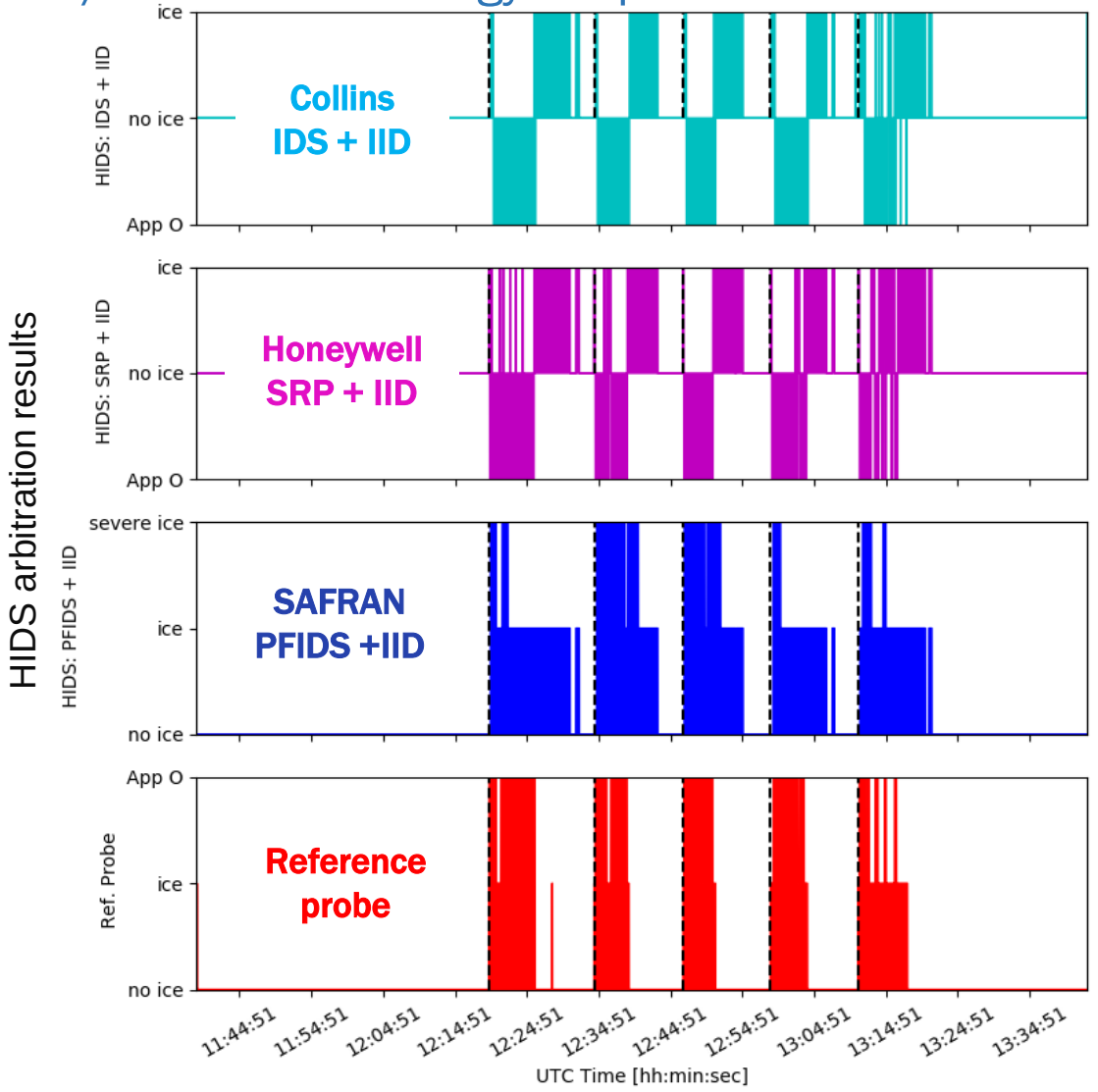


Hybrid ice detection data analysis by SAFRAN

HIDS North America Flight Campaign Results

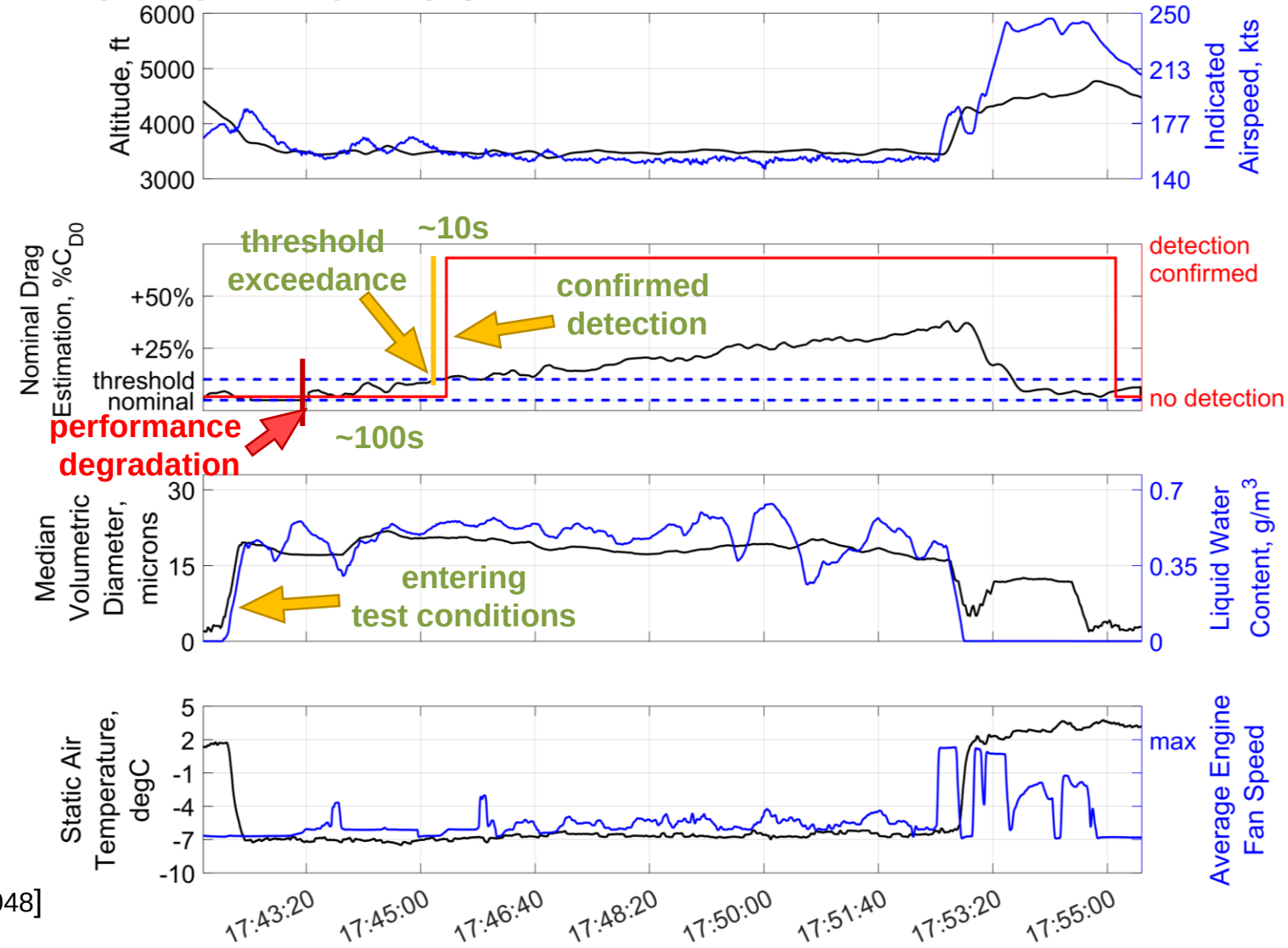
Flight 1476 – HIDS arbitration results for each direct/indirect technology couple





SENS4ICE North America Flight Campaign
Indirect Ice Detection Performance

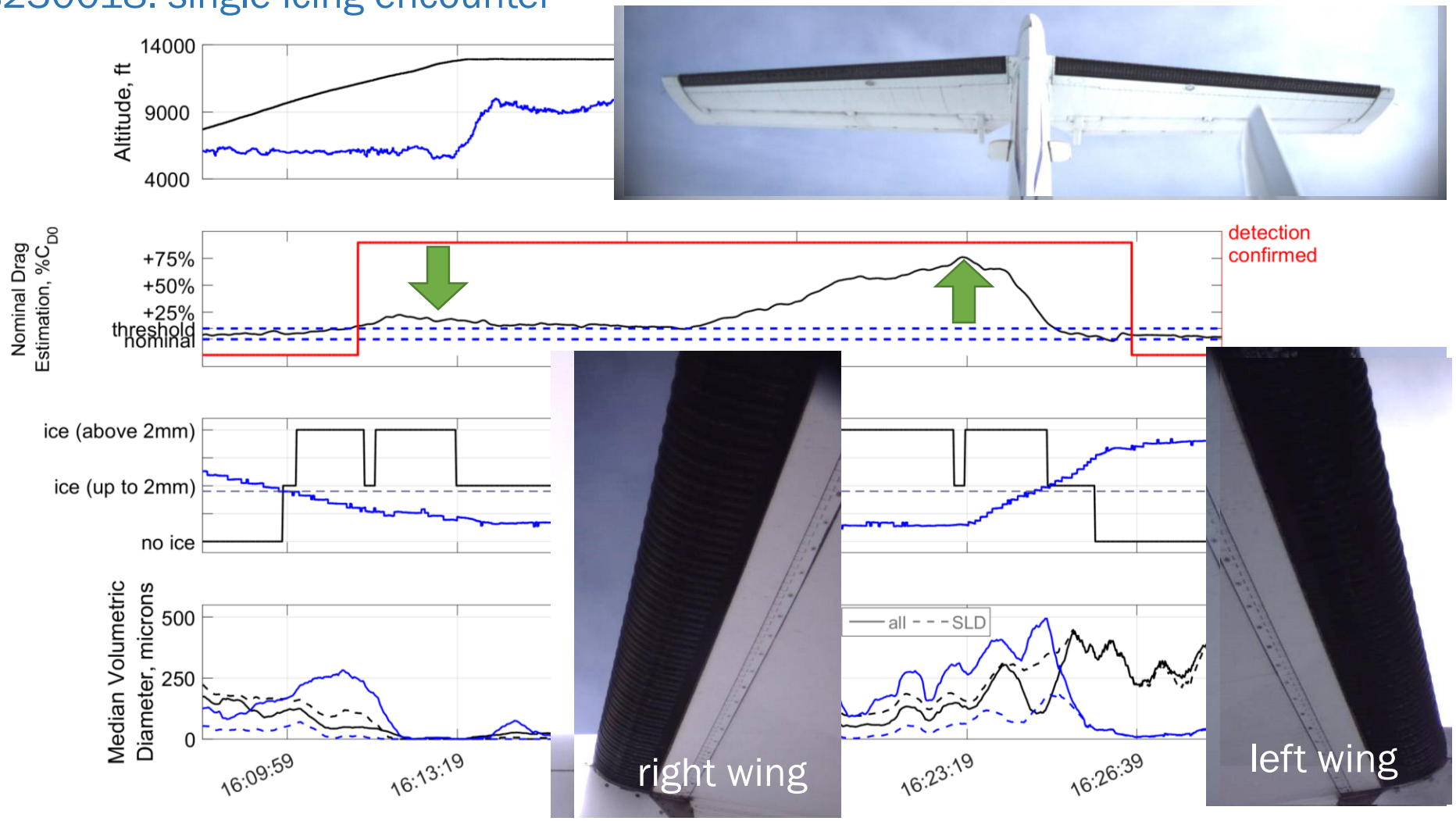
- example 23 FEB 2023, 17:41:49 UTC - 17:55:29 UTC
- figure 1: altitude and indicated airspeed
- figure 2: nominal drag estimation and IIDS detection output
- figure 3: MVD and LWC of encountered icing conditions
- figure 4: static air temperature and average engine fan speed
- detection threshold at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

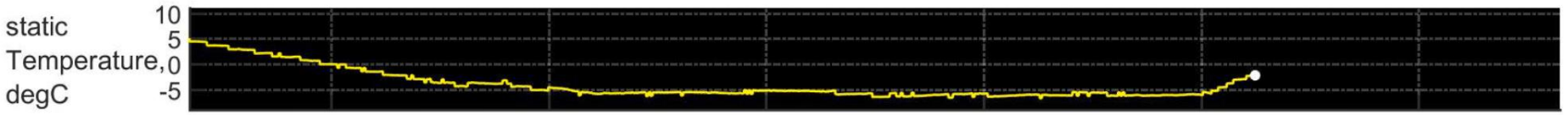
SENS4ICE Europe Flight Campaign
Indirect Ice Detection Detailed Example Results

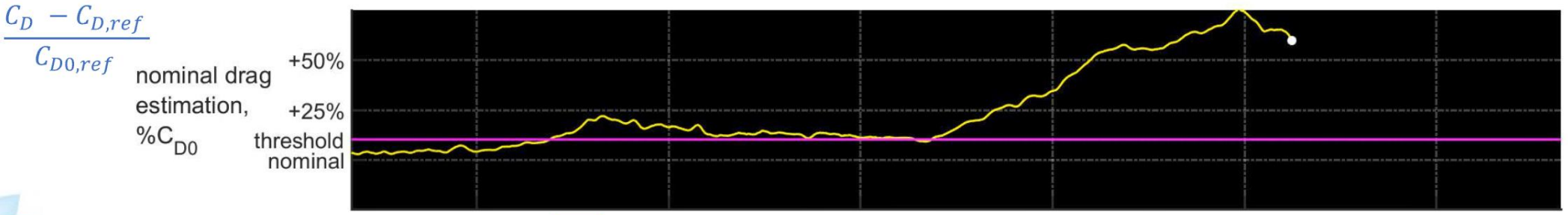
Flight as230018: single icing encounter



Example on detailed indirect ice detection results

Flight as230018: single icing encounter



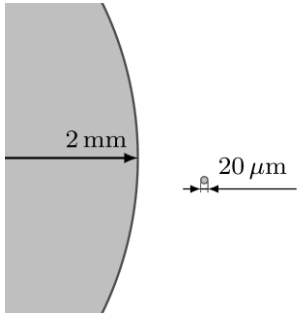


SENS4ICE Challenge/Outcome

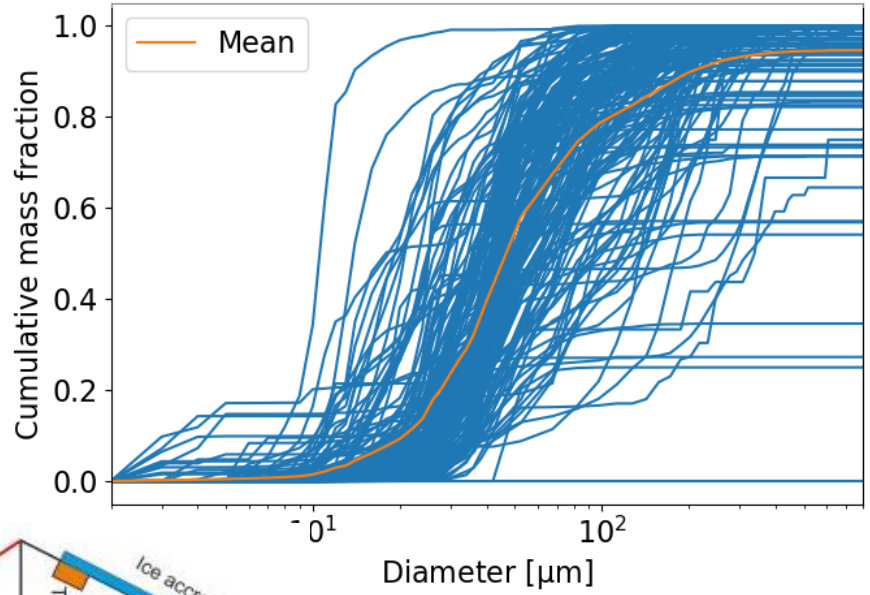
- Detect icing conditions – challenge: SLD

Solution/Innovation

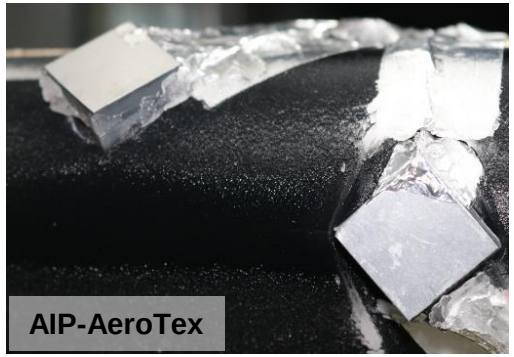
- 8 direct detection technologies matured & flight test demonstrated
- Hybrid approach – fusion of input data: sensor(s) and indirect detection



SENS4ICE Flight Campaign Europe - Droplet diameter distribution
Microphysics data analysis - DLR Institute of Atmospheric Physics

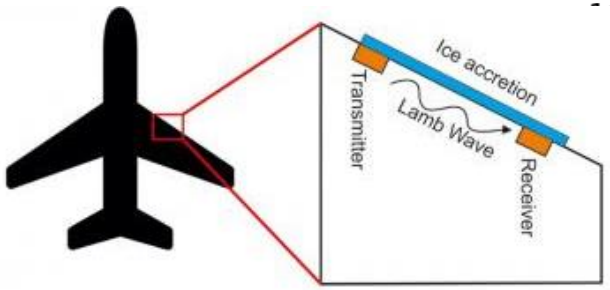


HIDS-Safran/ IIDS-DLR



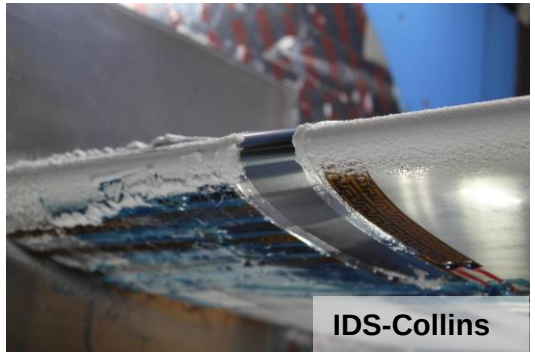
AIP-AeroTex

PFIDS-Safran



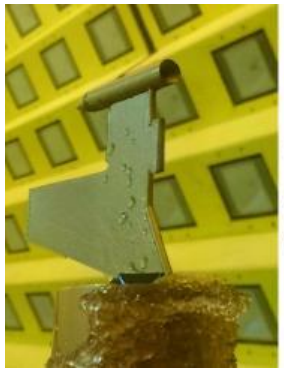
LILD-DLR

AMPERA-ONERA



IDS-Collins

SRP-Honeywell



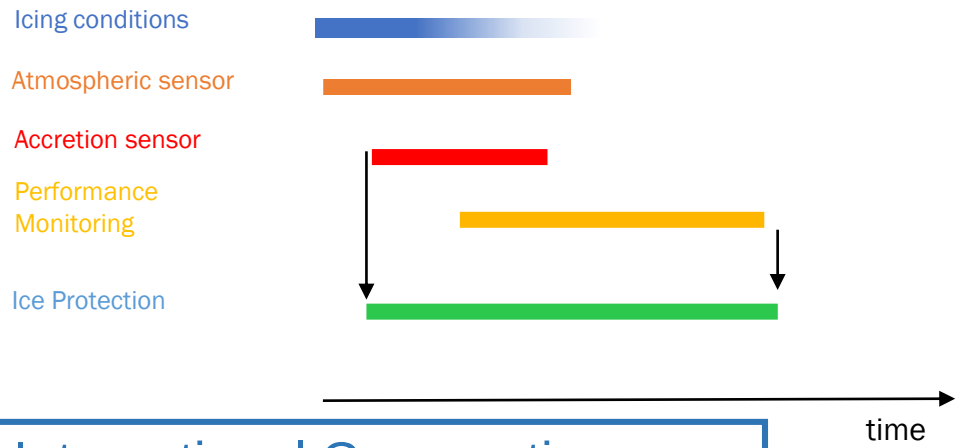
CM2D-DLR

FOD-INTA

EU Project SENS4ICE - Results

SENSors and certifiable hybrid architectures for safer aviation in ICing Environment

- **Direct, indirect and remote ice detection technologies particularly for SLD** (Supercooled Large Droplets) icing
- successfully demonstrated in operational environment (many technologies TRL 6)
  → while certification envelope is multi-dimensional and much larger
- **Broad and promising technology application** for different purposes/vehicles
- Game changer **hybrid solution** for challenging task of SLD detection
  - successfully tested/demonstrated in two flight campaigns (TRL 5 reached)
  - benefits of quick warnings and continuous ice accretion and flight performance monitoring
  - IPS efficiency optimisation



- Excellent Fruitful International Cooperation
- Outstanding Communication and Dissemination

SENS4ICE Final Public Dissemination

Final Public Dissemination Event

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

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If not acknowledged, images courtesy of the consortium partners.

SENS4ICE

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