



SENS4ICE

SENSORS AND CERTIFIABLE HYBRID ARCHITECTURES
FOR SAFER AVIATION IN ICING ENVIRONMENT

SENS4ICE - Aircraft Icing Detection Research

November 2022

Carsten Schwarz (DLR)

DWD International Icing Seminar, online - 02 NOV 2022

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

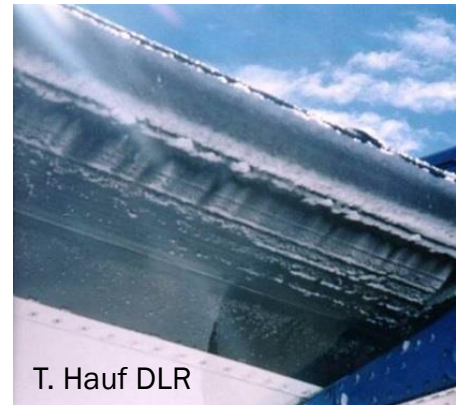


Credit: BFU, Interim Report BFU CX001-13

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



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



T. Hauf DLR



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

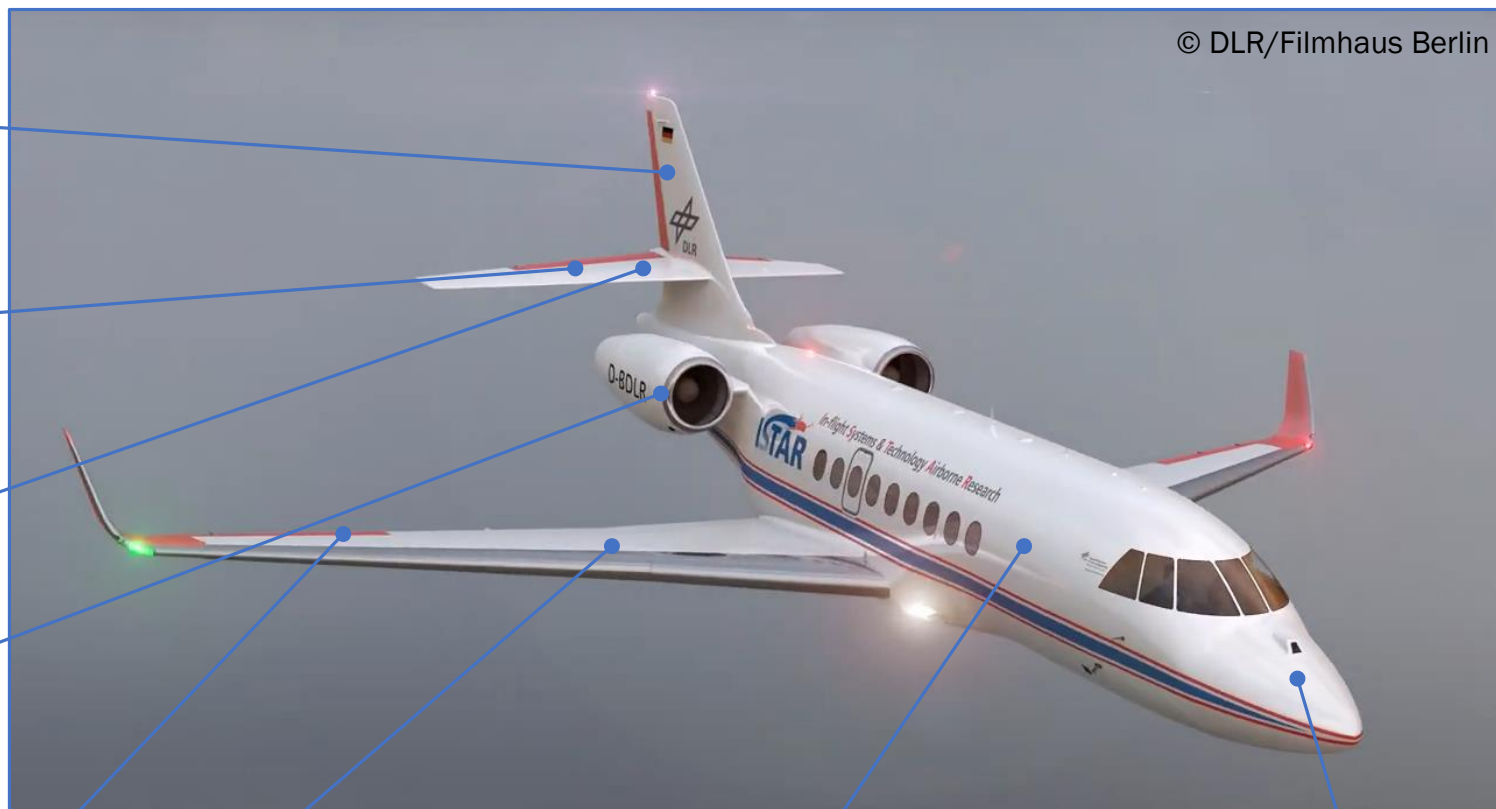
- Performance loss
- Control degradation

Fuselage

- Drag increase
- Collected contaminant ice layer

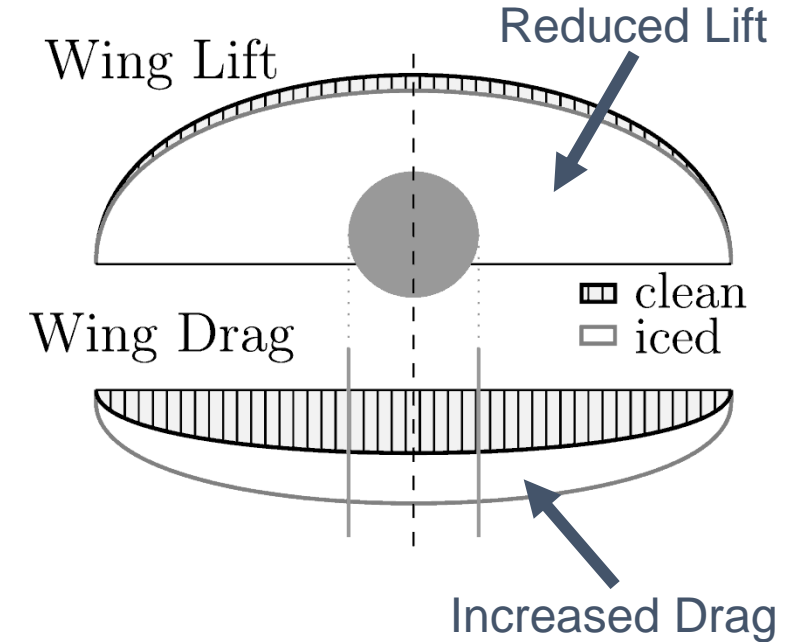
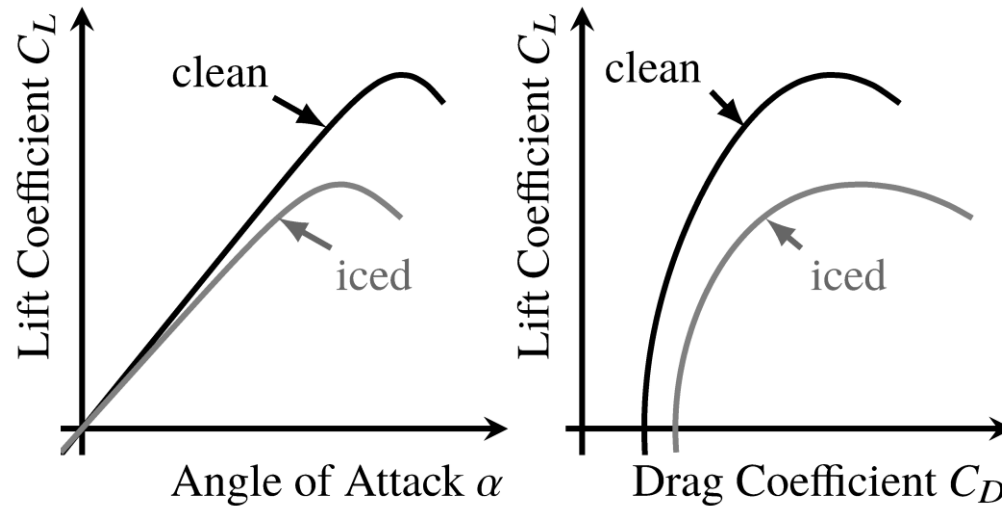
Sensors

- Malfunction
- Blockage



[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]

General Expected Aerodynamic Degradation due to Icing



Degrading effects of wing ice:

- 💧 reduced maximum angle of attack
> decreased maximum lift
- 💧 slight change in lift curve slope
- 💧 significant increase of zero-lift drag
- 💧 noticeable drag increase at medium and high lift coefficients

DLR@TUBS SuLaDI project

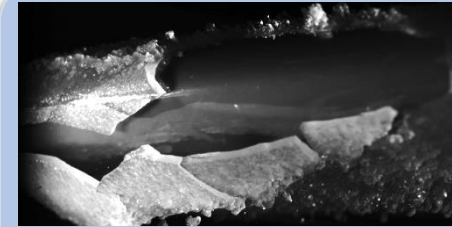
Supercooled Large Droplets Icing

- DLR/ TUBS university cooperation project
- 5 years
10/2011-09/2016
- German national funding (HGF)
5.8 M EUR
- Fundamental research of aircraft icing under specific focus on the process of contamination with Supercooled Large Droplets (Water droplet diameter $> 50 \mu\text{m}$)

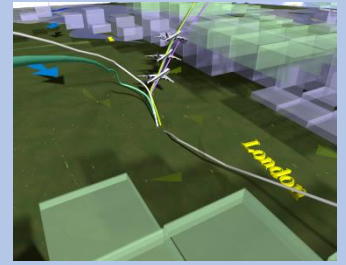
[Christoph Deiler (DLR), Aerodynamic Modeling, System Identification and Analysis of Iced Aircraft Configurations, AIAA AVIATION 2016, 13 - 17 JUN 2016]



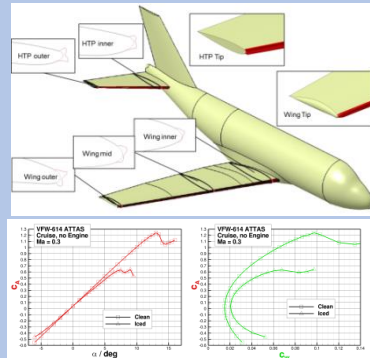
Icing Wind Tunnel
(TUBS)



Low Frequency De-Icing
(TUBS)



Flight Guidance
(DLR)



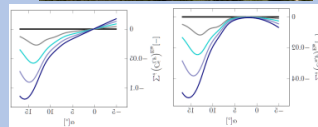
CFD Results
(DLR)



Supercooled Large
Droplets Icing



Electro Impulse De-Icing
(TUBS)



Flight Dynamics
& Control

AVES (Air Vehicle Simulator)



EMBRAER



SENS4ICE Project Overview

SENSors and certifiable hybrid architectures for safer aviation in ICing Environment

💧 JAN 2019 - DEC 2023 (extended, originally DEC 2022)

💧 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

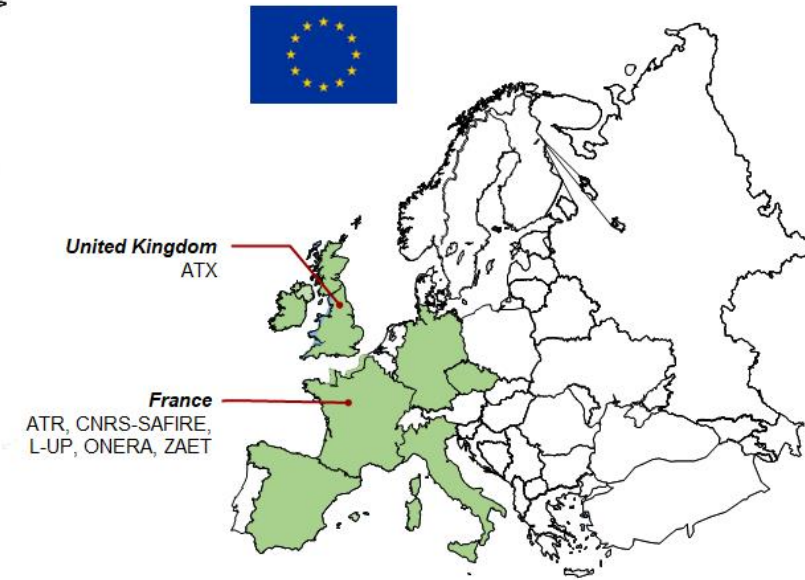


National Research
Council Canada

Conseil national de
recherches Canada



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



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. 0)
 - 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



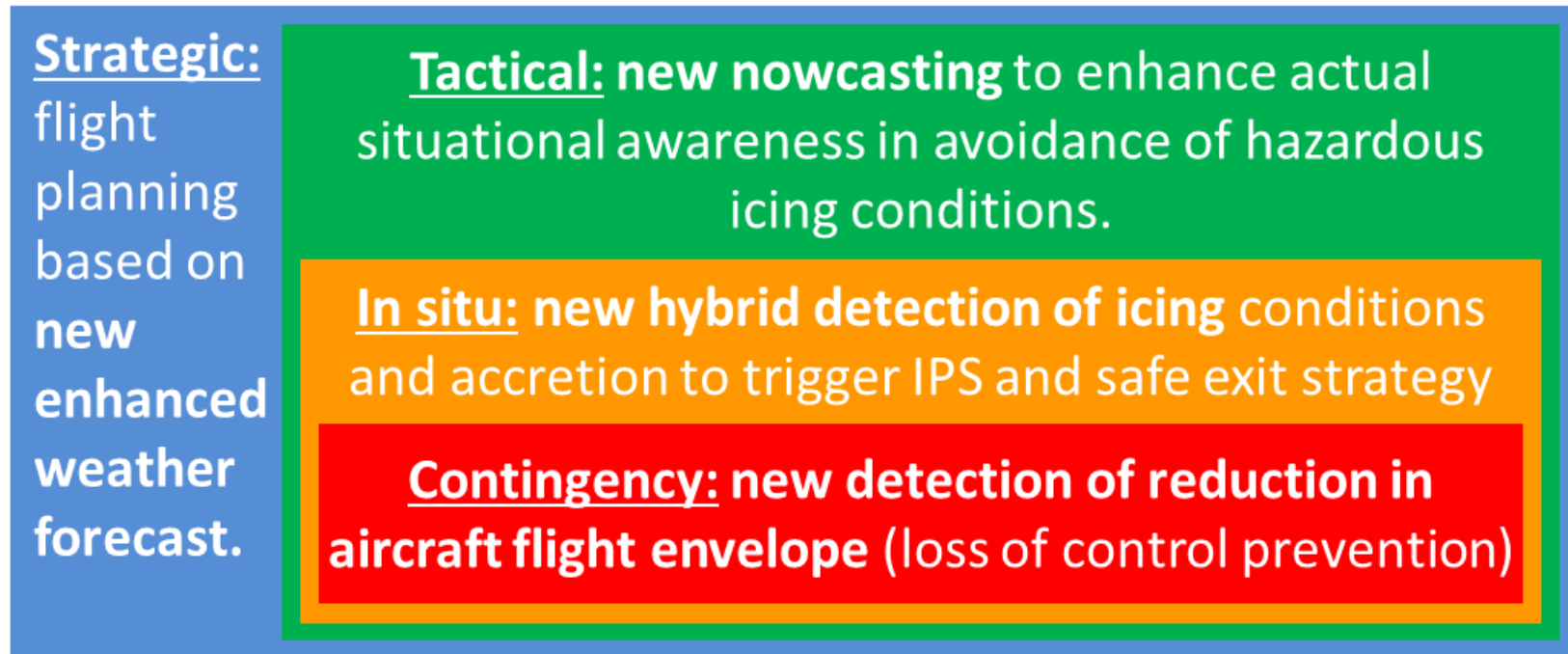
Expected impact

- 💧 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



Layered Approach on Ice Detection

SENS4ICE will address this challenge of reliably detecting and avoiding App. 0 SLD conditions with a unique layered safety approach:

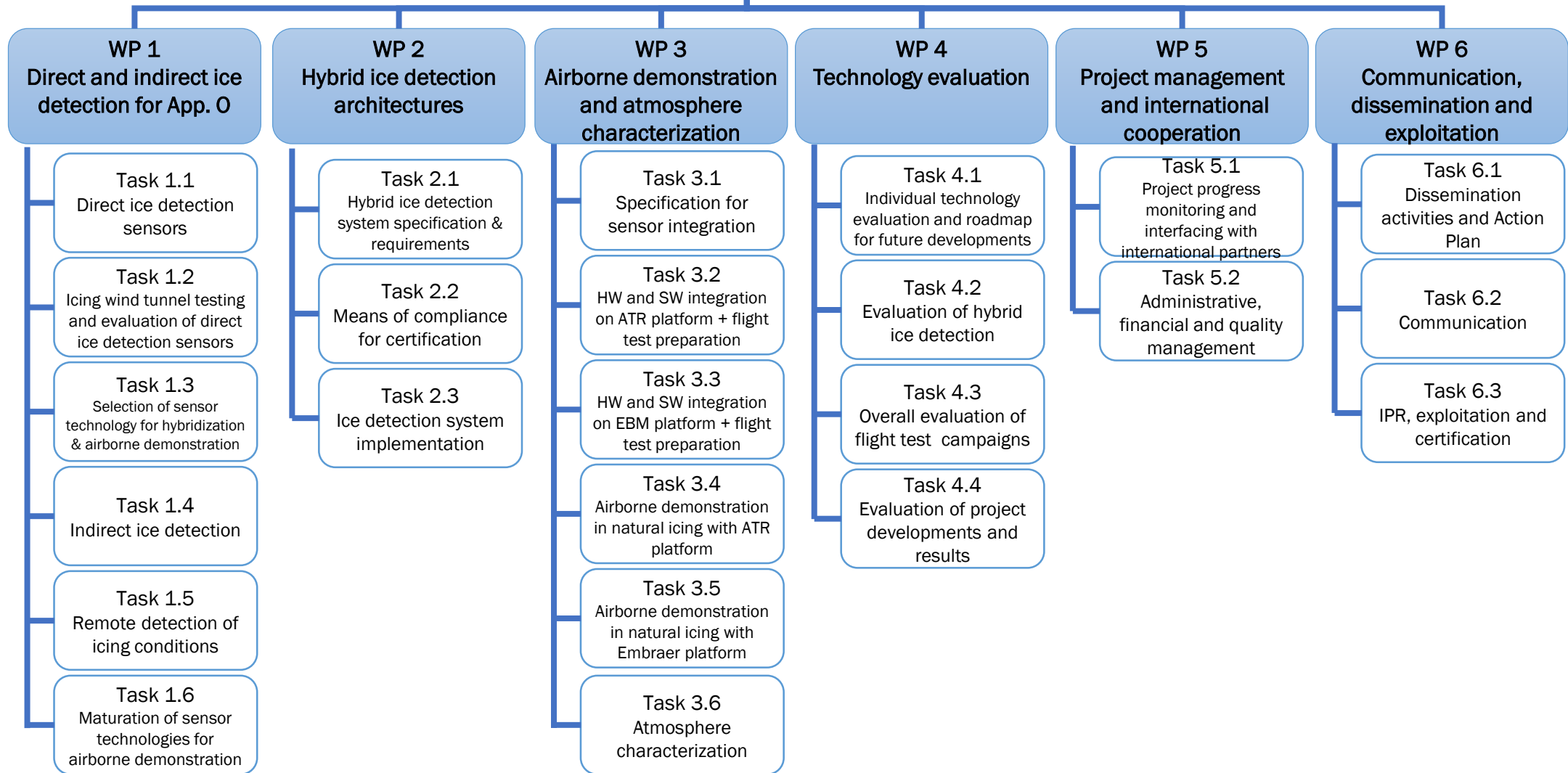


→ Hybrid ice detection is central technology and key to this approach

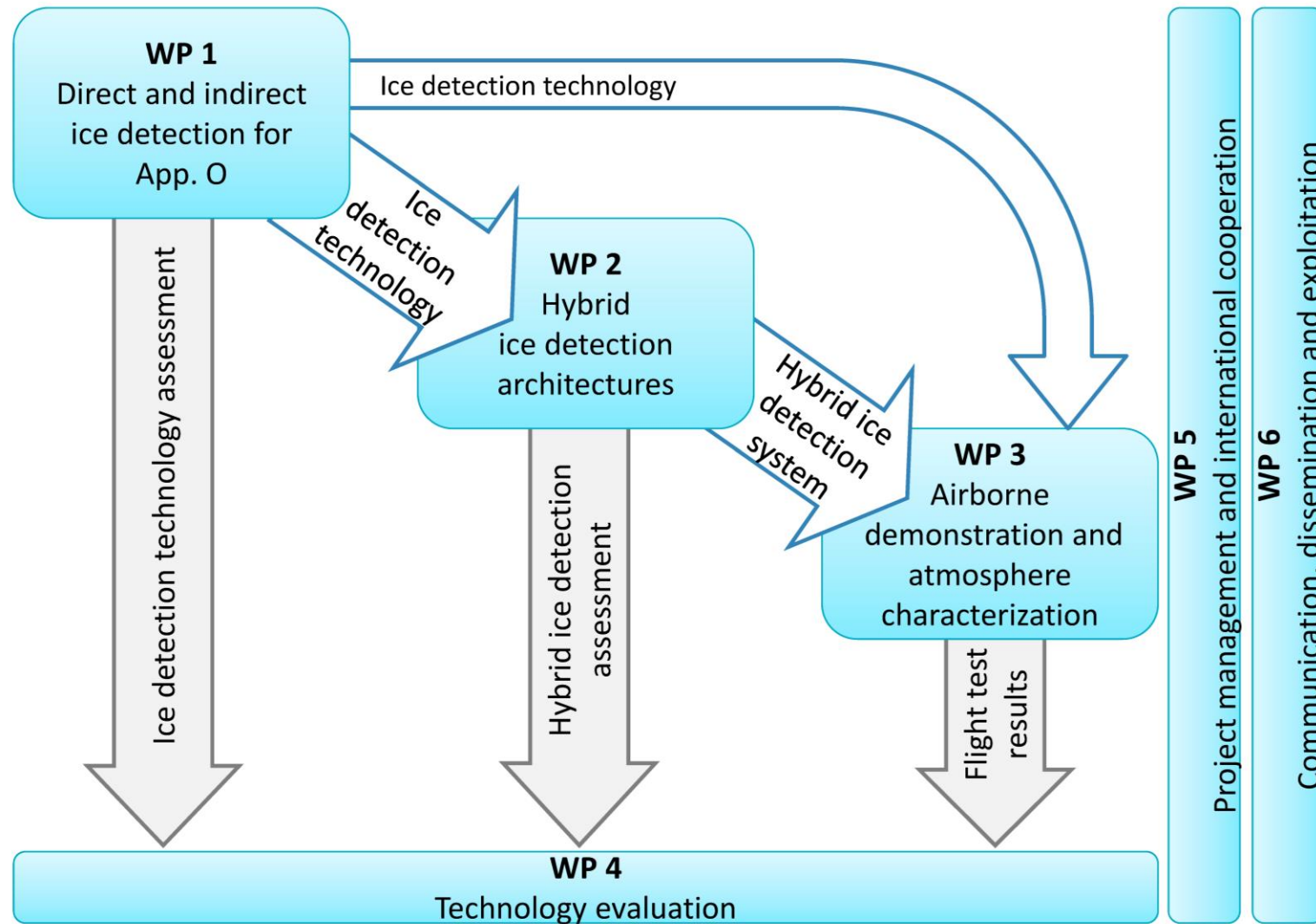


SENSors and certifiable hybrid architectures for safer aviation in ICing Environment

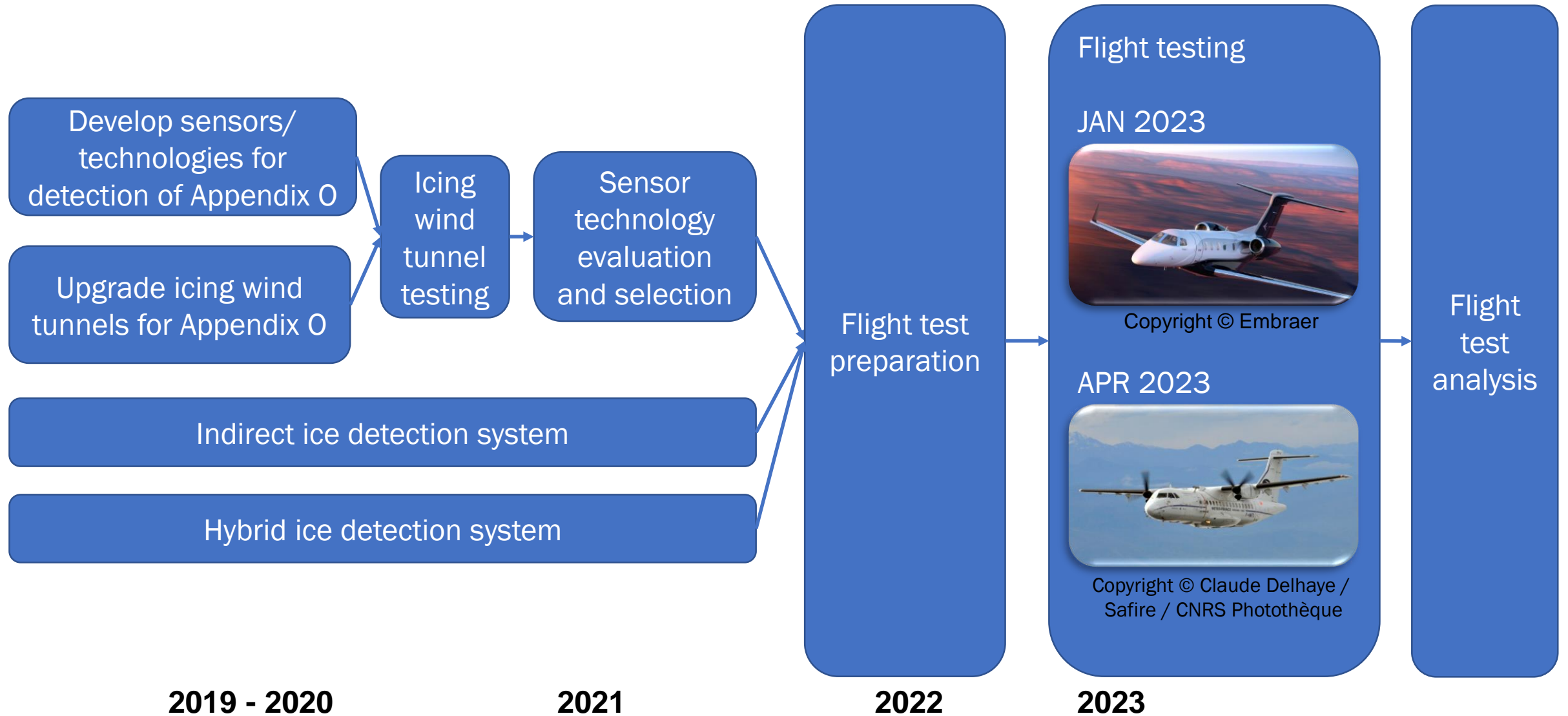
SENS4ICE



Technical Work Packages Interrelation



SENS4ICE Timeline – focus flight testing



WP1: Direct and indirect ice detection for App. 0

High Level Objectives

Main Objective: Develop technologies capable of detecting App. 0 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. 0 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. 0 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. 0 conditions
 - 💧 Polarimetric weather radar: development of algorithms to classify icing threats and identify App. 0 conditions



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	Atmospheric	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



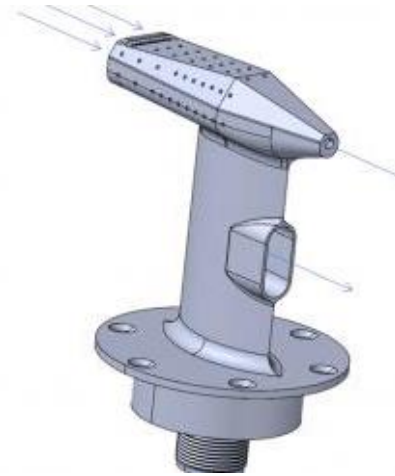
SENS4ICE sensor technologies for direct sensing of atmospheric icing conditions or ice accretion detection (1/2)



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



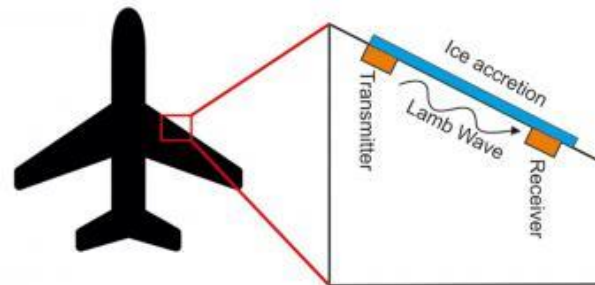
Name: *Collins Ice Detection System (IDS)*
Project partner: *Collins Aerospace*



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



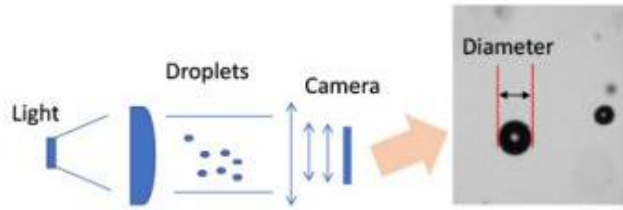
Name: *AMPERA*
Project partner: *French Aerospace Lab (ONERA)*
Copyrights: © French Aerospace Lab (ONERA)



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



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



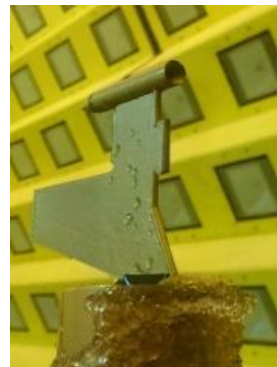
Name: *Atmospheric Icing Patch (AIP)*
Project partner: *AeroTex UK*
Copyrights: © AeroTex UK LLP



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

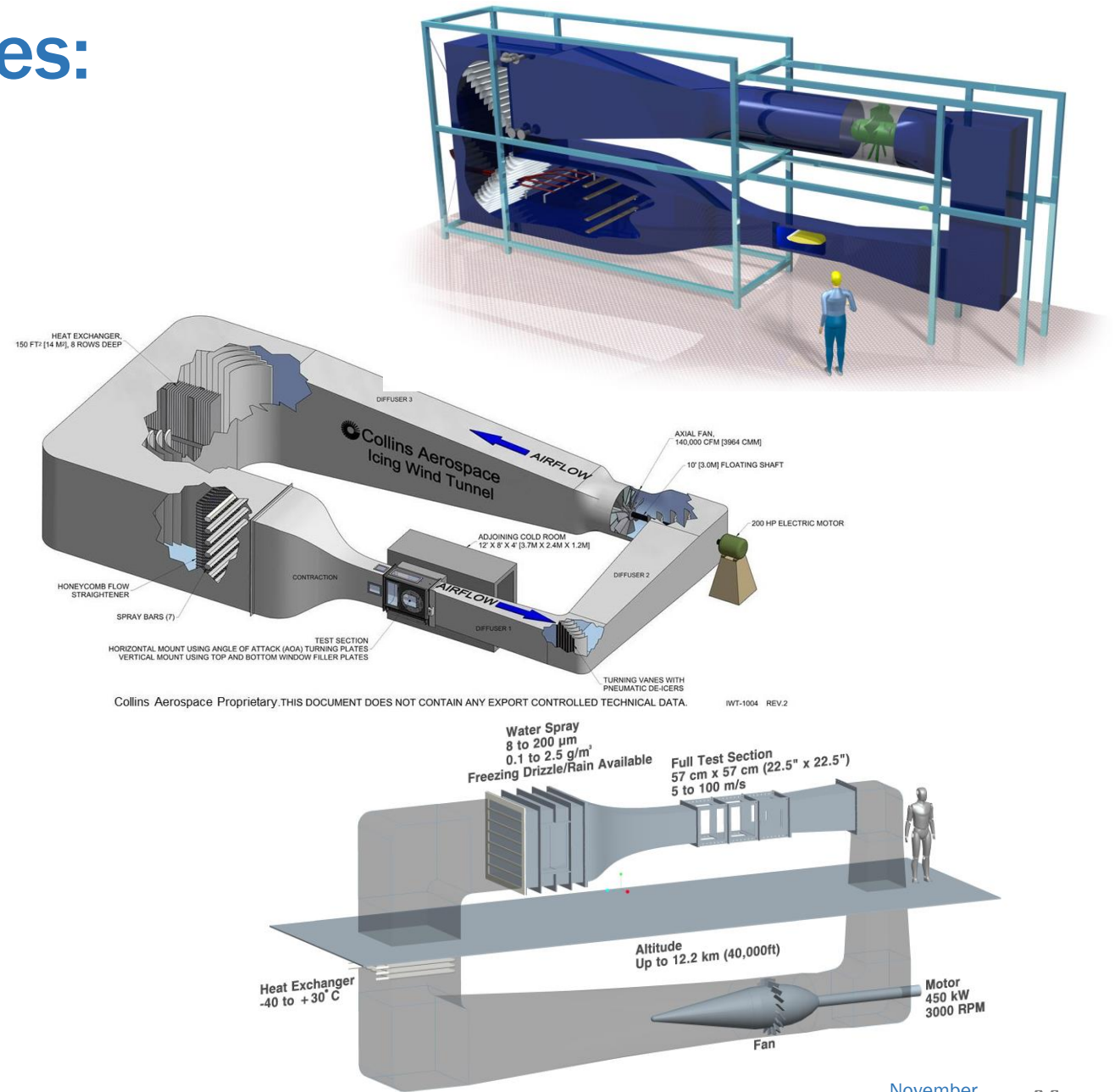
💧 SLD capabilities available and enhanced during SENS4ICE

💧 National Research Council Canada

💧 SLD capabilities available

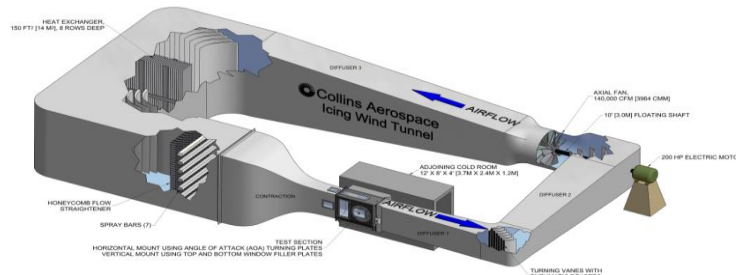
💧 Total testing time: 16 weeks

💧 Planned time frame: NOV 2020 – MAR 2021



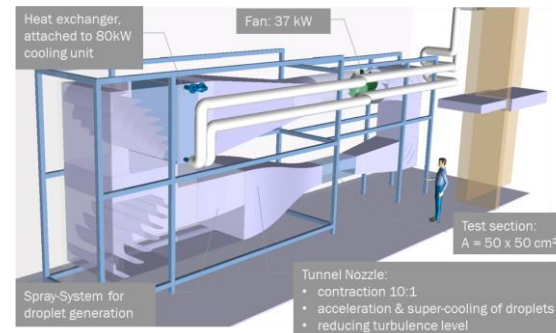
Overview of SENS4ICE IWT Capabilities

Collins Aerospace, USA



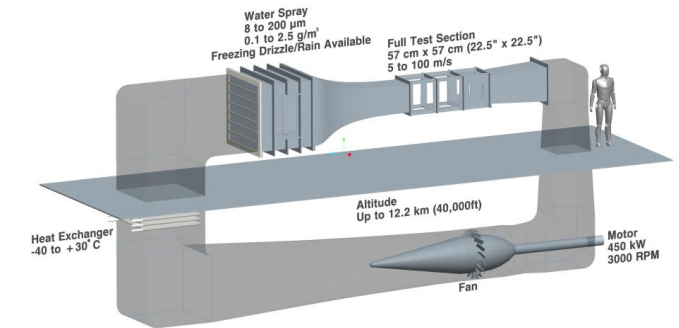
- 5-147 micron droplets
- LWC between 0.1 and 3 g/m³
- Temperature 0°C to -30°C
- Sustained speed 13-103 m/s
- Test section: 152x56x112 cm³
- Calibrated per SAE ARP 5905
- Compliant with AS9100C
- Controls and power supplies can simulate aircraft controls

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: 150x50x50 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: 57x57 cm² (52x33 cm² with insert)
- Sea level < Altitude < 40,000ft
- Calibrated per SAE ARP 5905

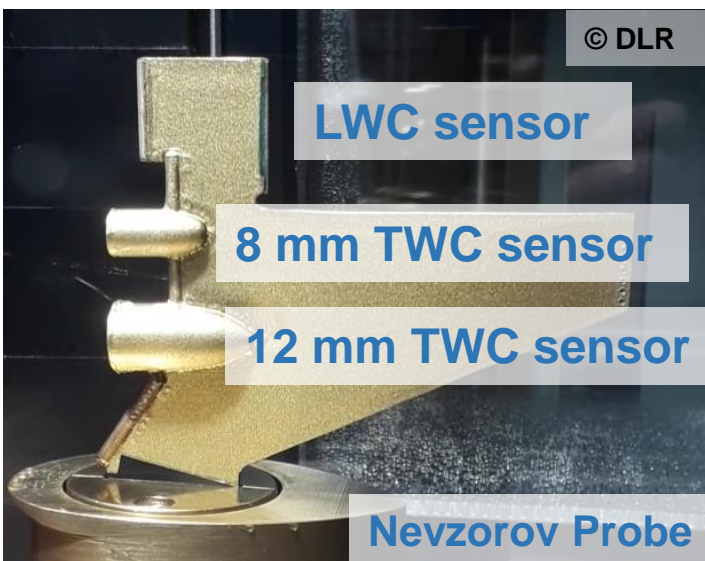
💧 Dedicated common test points defined for all involved SENS4ICE IWT



Reference Instrumentation & Measurements

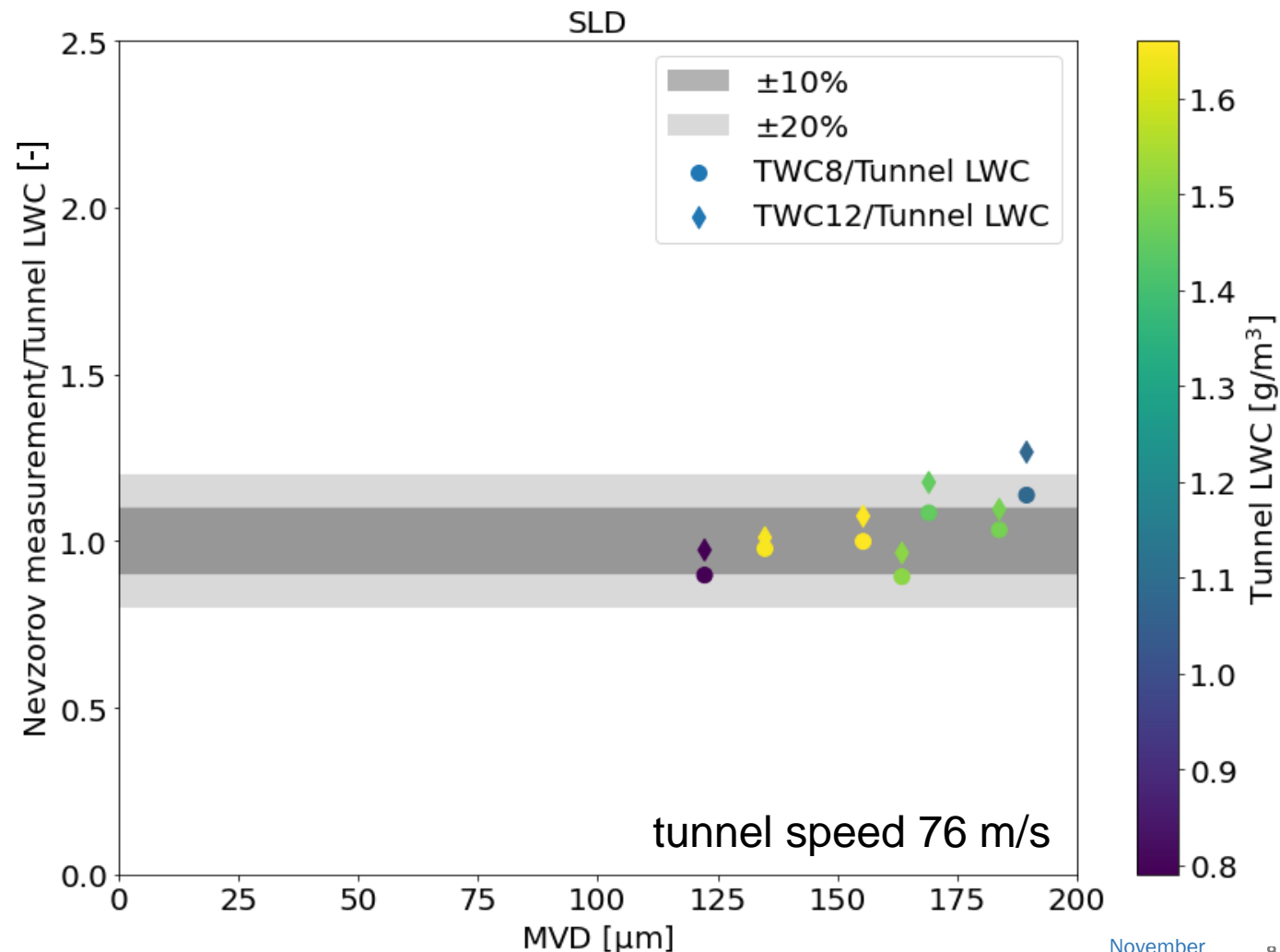


Cloud Combination Probe (CCP)



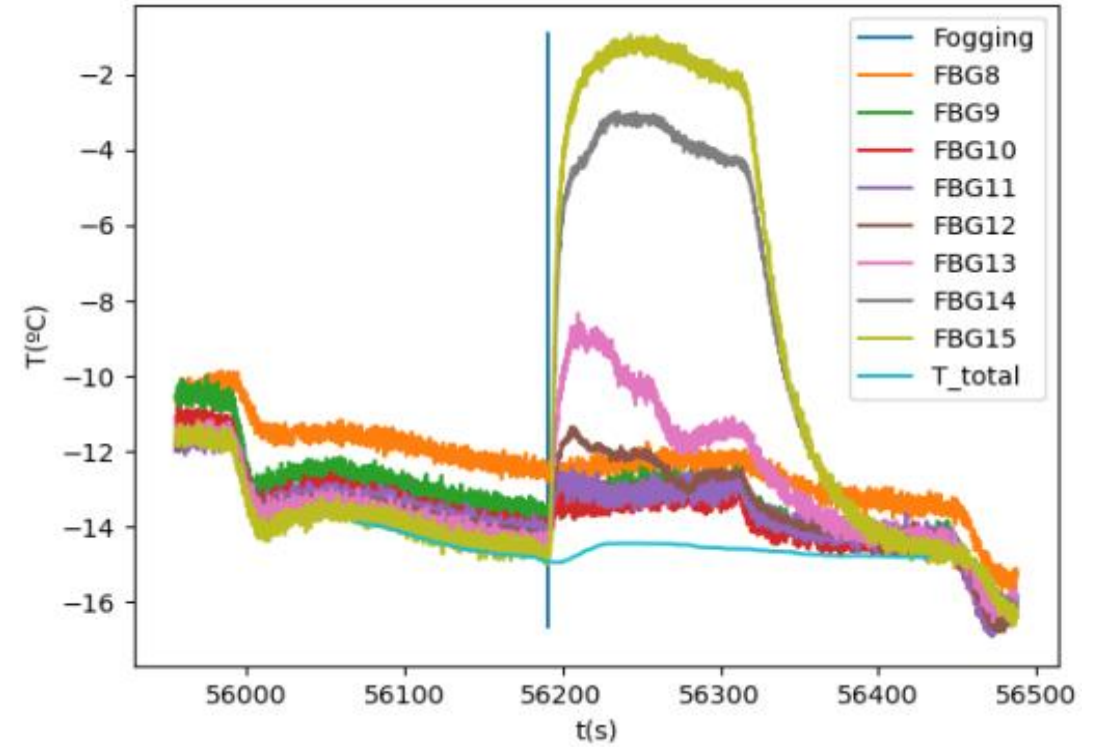
Nevzorov Probe

- Reference measurements (Nevzorov probe) in SLD conditions
- 💧 generally good agreement with tunnel LWC data (SEA probe)
 - 💧 for MVDs $< 180 \mu\text{m}$, Nevzorov and SEA probe agree within 20%



FOD (Fiber Optic Detector) – using Fiber Bragg Grating Sensors (FBGs)

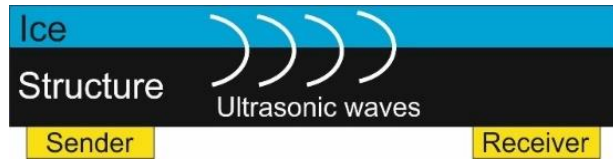
- 💧 FBGS are integrated in the surface of an airfoil to provide temperature measurements over the chord.
- 💧 Measurements are compared with a heat and mass balance model.
- 💧 Based on this a prediction for liquid water content (LWC) and ice accretion rate (IAR) is generated.
- 💧 IWT results show a good 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.



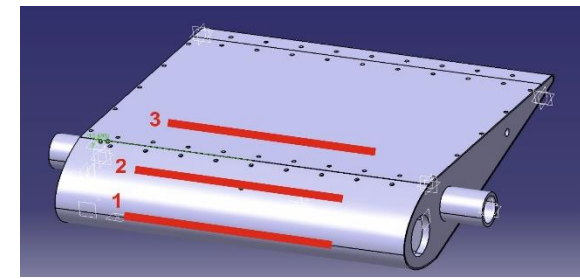
FOD temperature time histories at NRC AIWT for different measurement locations over the airfoil chord (“FBG 8 – 15”) and the total temperature for Appendix O conditions (LWC = 0.82 g/m³, MVD = 163.5 μm; V = 76 m/s, start time of icing cloud marked by a vertical line “Fogging”)



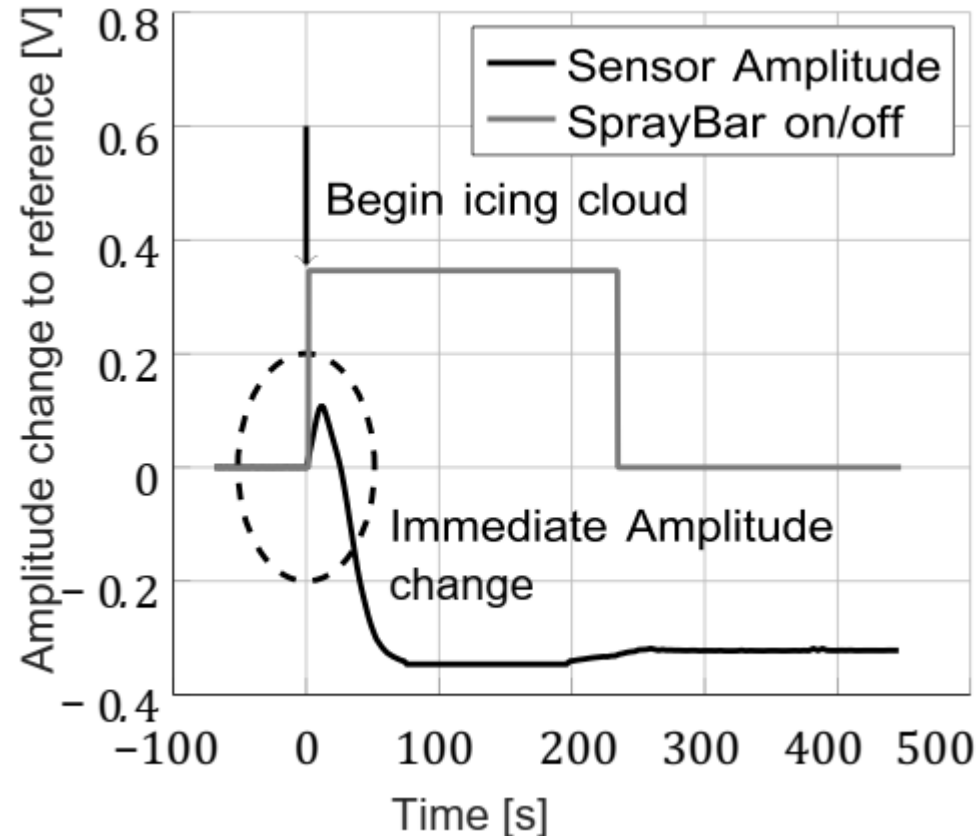
Local Ice Layer Detector (LILD)



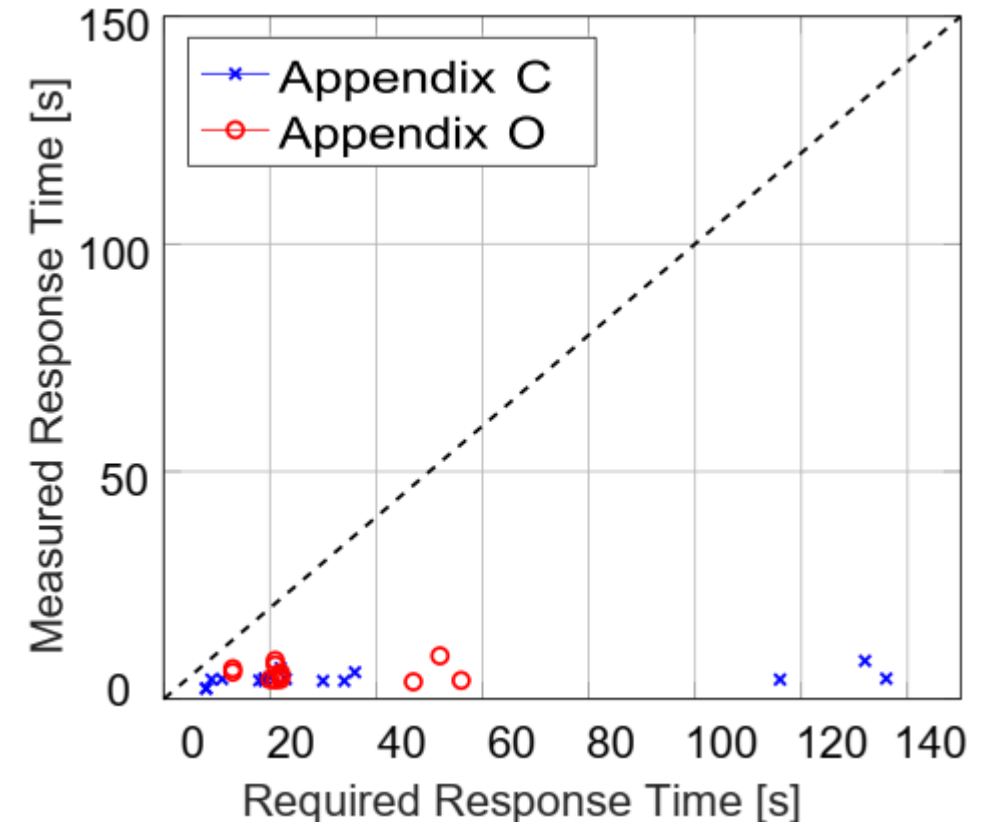
LILD principle of travelling ultrasonic lamb waves



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)

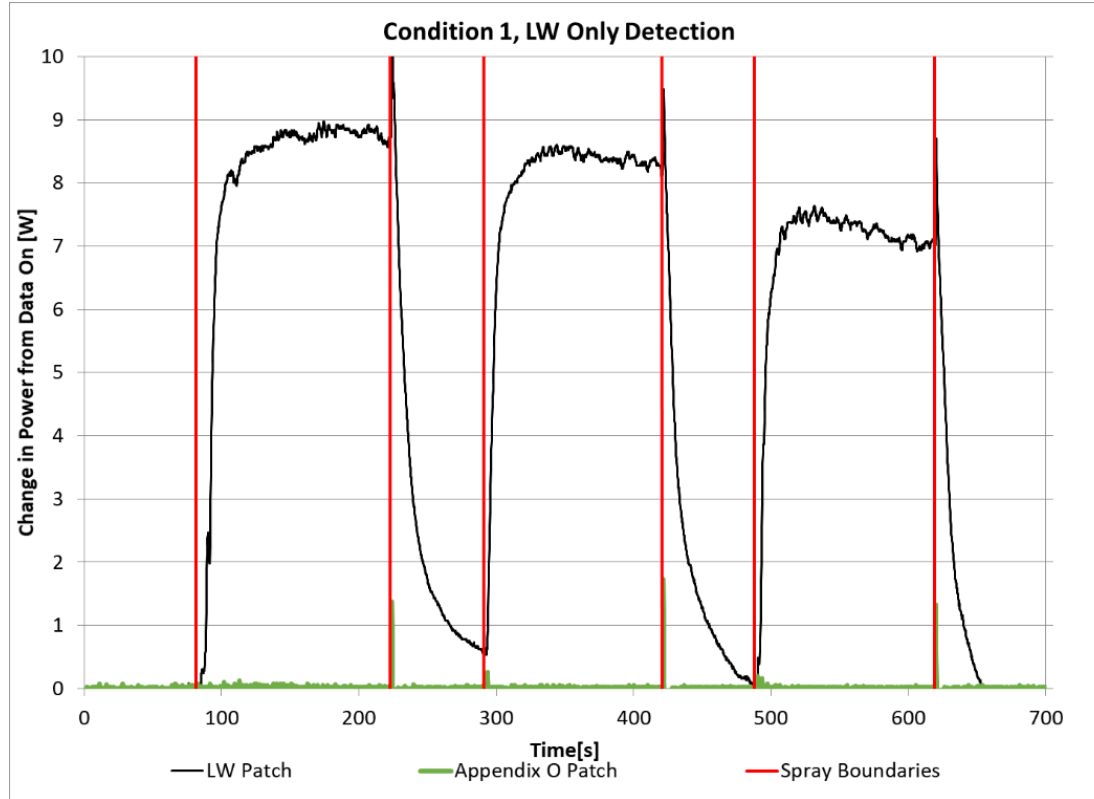


LILD response times for Appendix C and O conditions measured at BIWT compared to the required response time

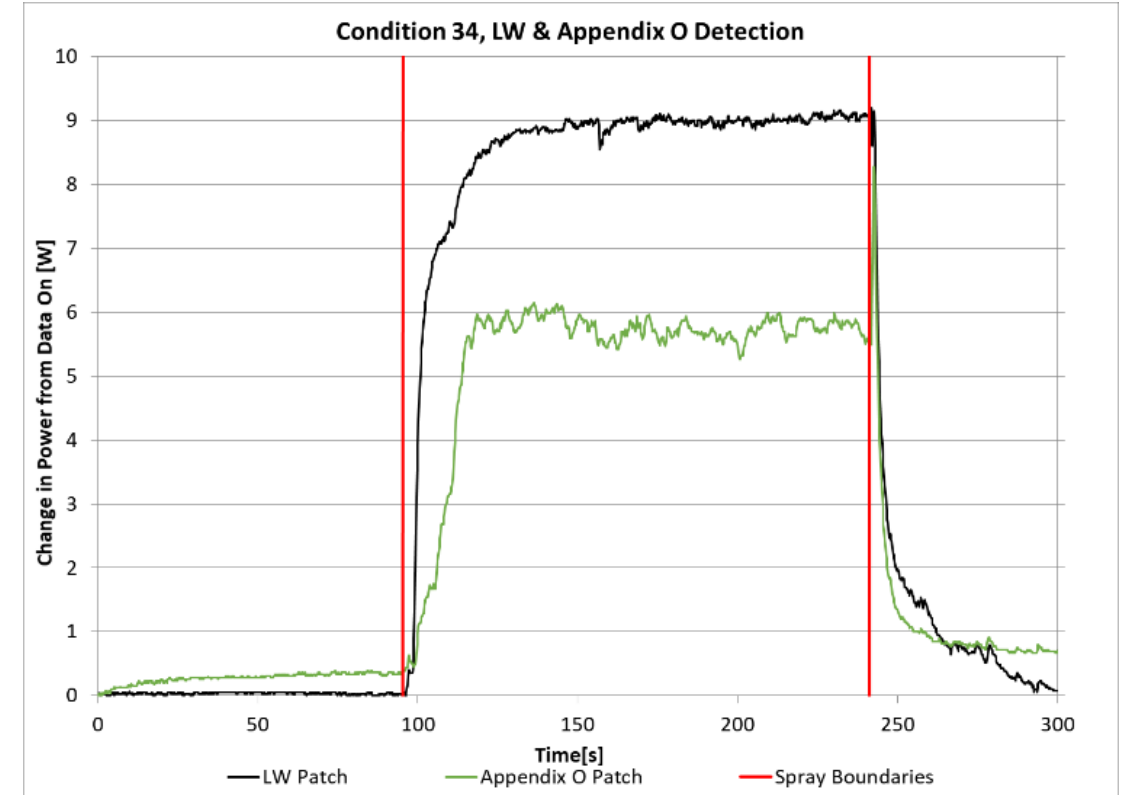


Atmospheric Icing Patch – AIP

consisting of an array of low power ($< 28\text{W}$) iso-thermal ice detection sensors



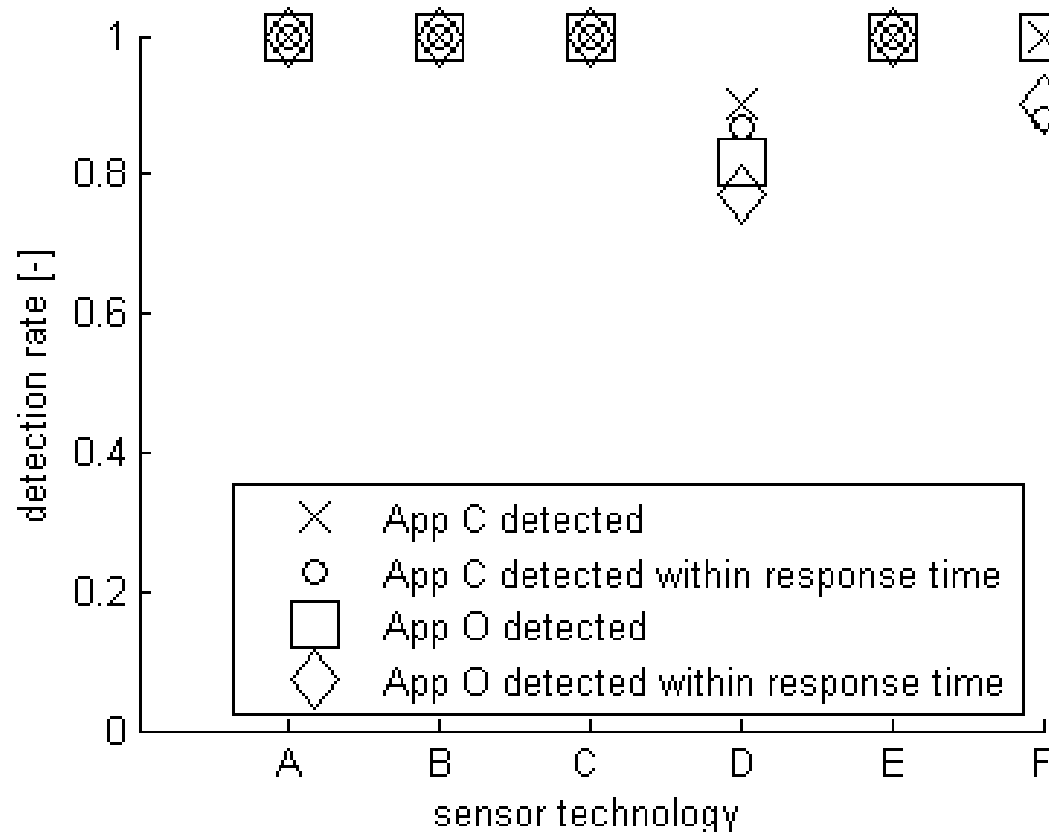
Example of AIP patch power response in small droplet icing conditions (note Appendix O patch shows no response)



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 DLR's CM2D scientific/reference sensor and another sensor with results subject to export control restrictions
- 💧 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

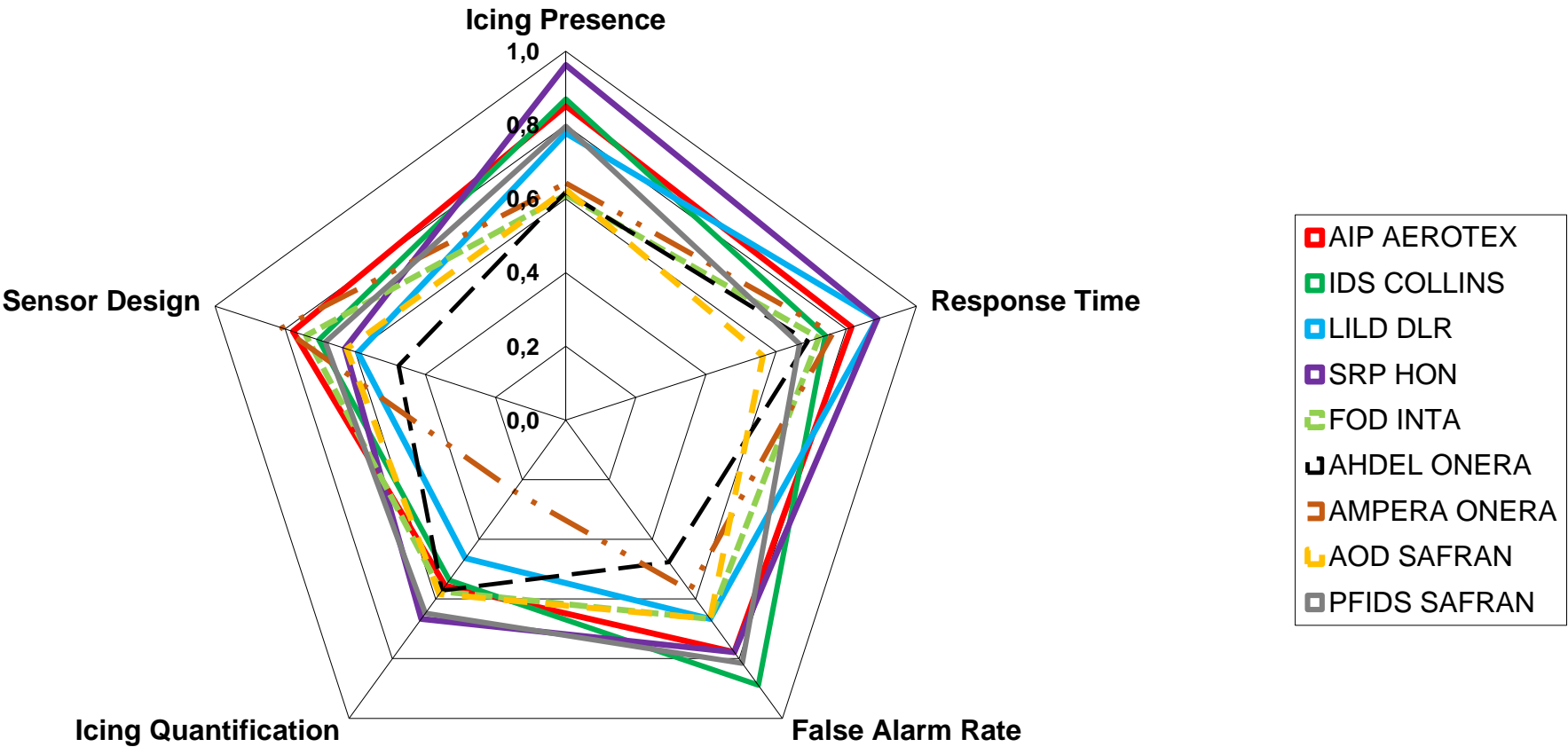


Technology evaluation criteria and weighting factors

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

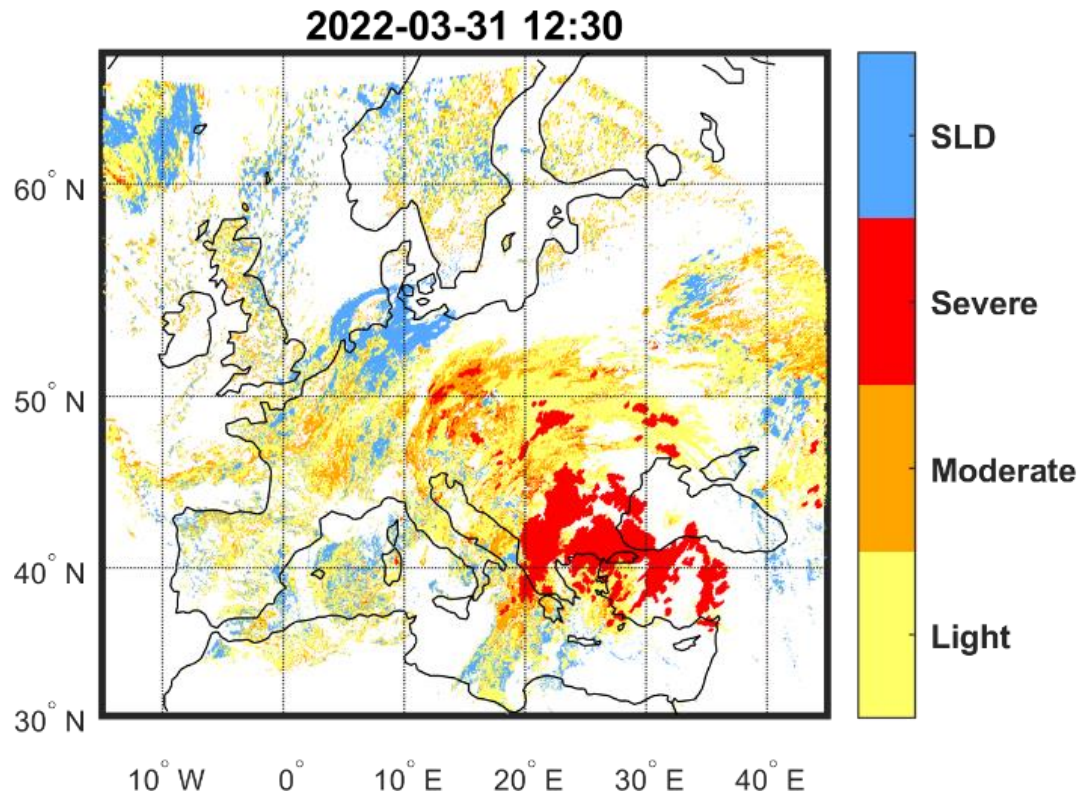


SENS4ICE Advisory Board evaluation ratings for sensor technologies averaged for all Advisory Board members for evaluation criteria (averaged ratings between 0 and 1, normalised, best rating 1)

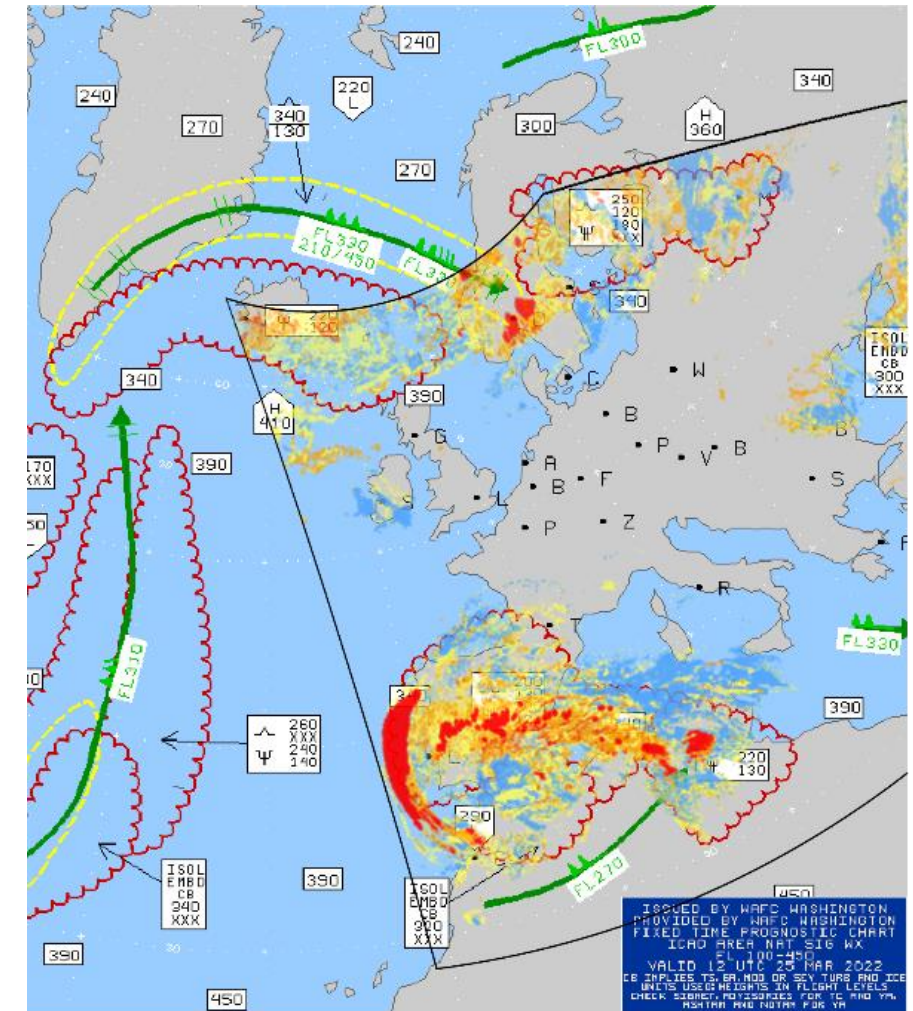


Remote Ice Detection

- ❖ 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)



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

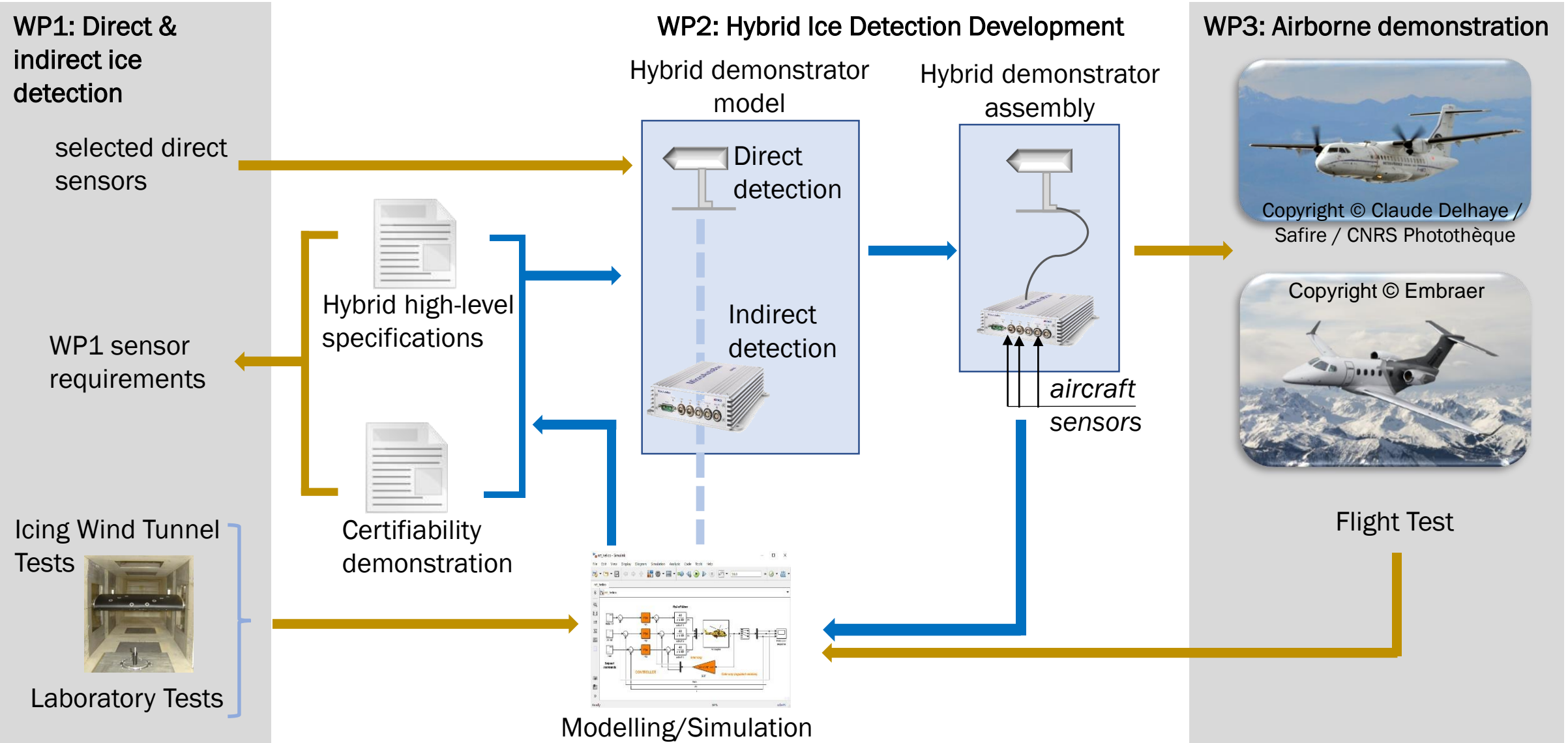
Objectives for hybrid ice detection

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

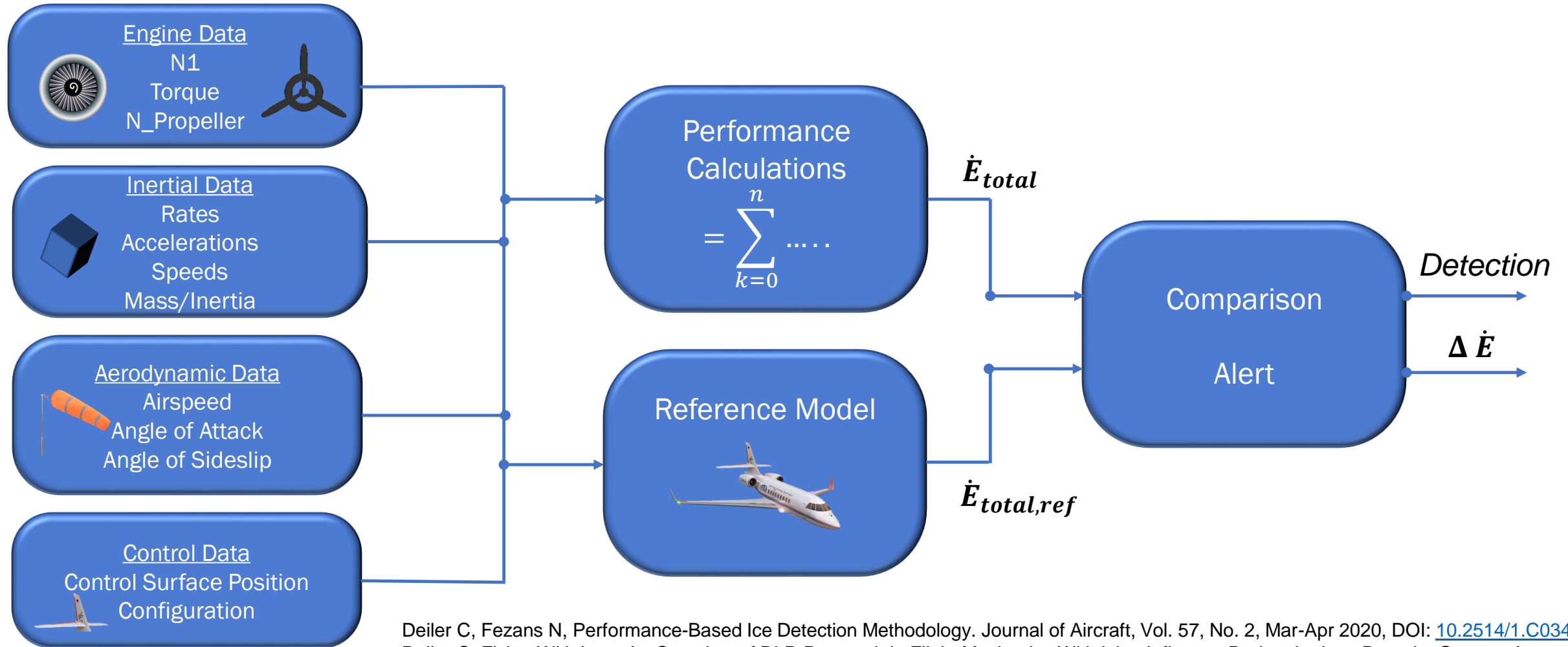


WP2: Hybrid Ice Detection – Development Workflow



DLR's Indirect Ice Detection – based on aircraft performance

System Design

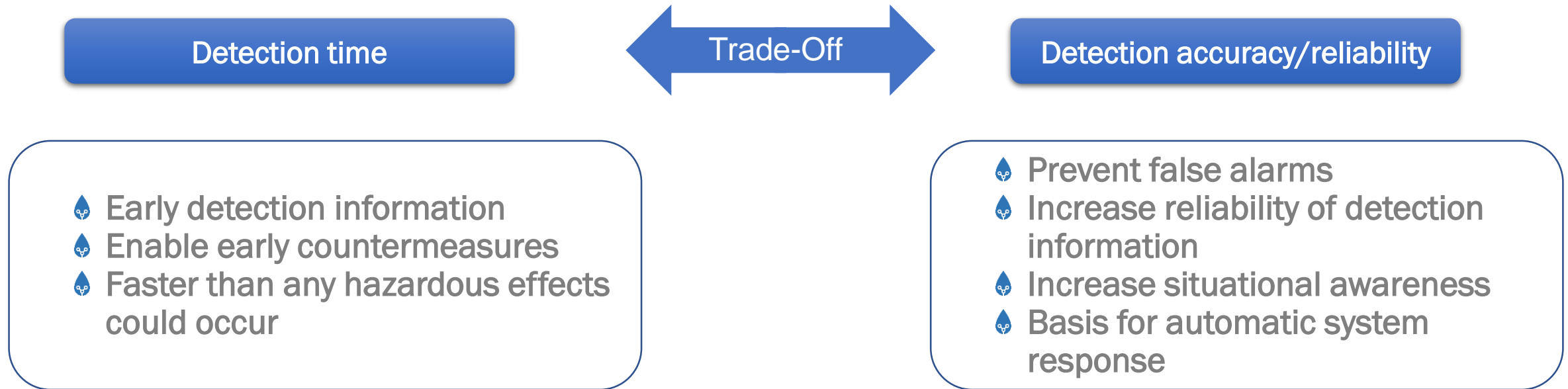


Deiler C, Fezans N, Performance-Based Ice Detection Methodology. Journal of Aircraft, Vol. 57, No. 2, Mar-Apr 2020, DOI: [10.2514/1.C034828](https://doi.org/10.2514/1.C034828)
Deiler C, Flying With Ice – An Overview of DLR Research in Flight Mechanics With Icing Influence During the Last Decade. German Aerospace Conference DLRK 2021, Bremen and online, DOI: [10.25967/550008](https://doi.org/10.25967/550008)



Indirect Ice Detection – System Performance

Conflicting demands

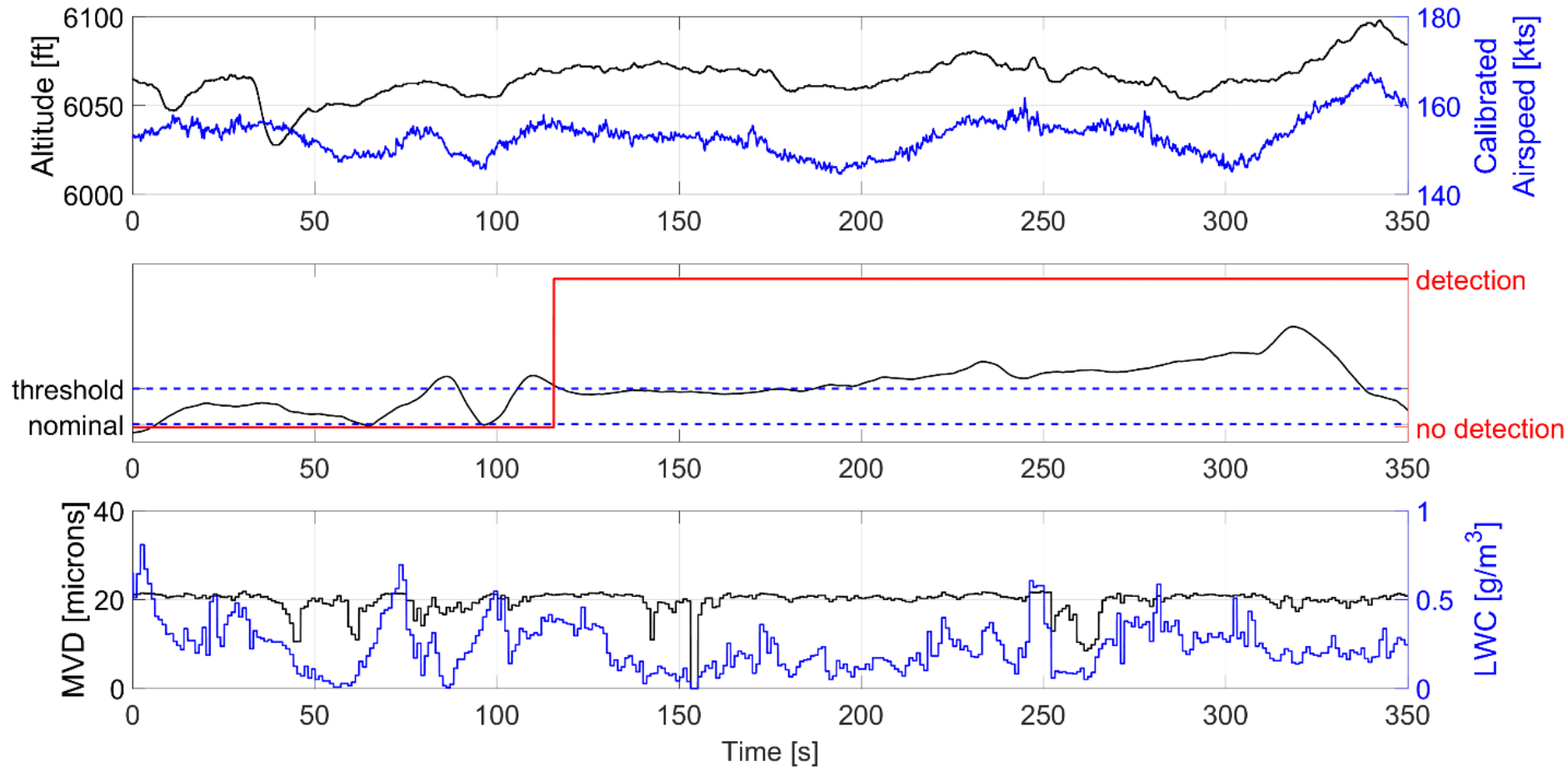


System is based on ice accretion effects on performance (continuous change, no significant step)

→ Determine a threshold that represents the necessary compromise



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]



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 CNRS/SAFIRE ATR-42
 - ◆ in North America with Embraer Phenom 300
- ◆ Characterisation of atmosphere from flight test campaigns in App. 0 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



SENS4ICE research facilities: Flight Test Platforms

- total flight test time: 75h in natural icing conditions
- planned main time frame: JAN and APR 2023

SAFIRE ATR-42



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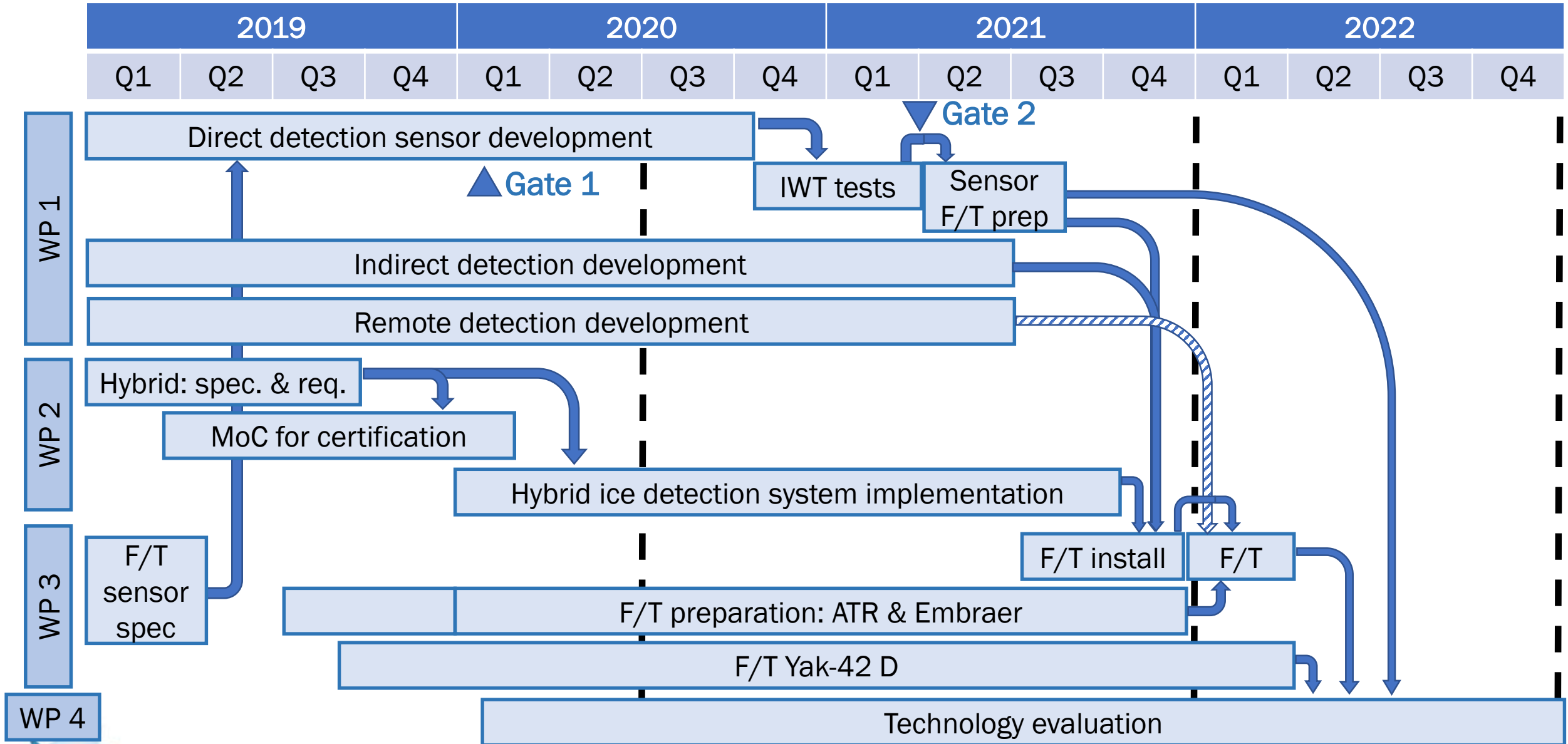
Embraer Phenom 300



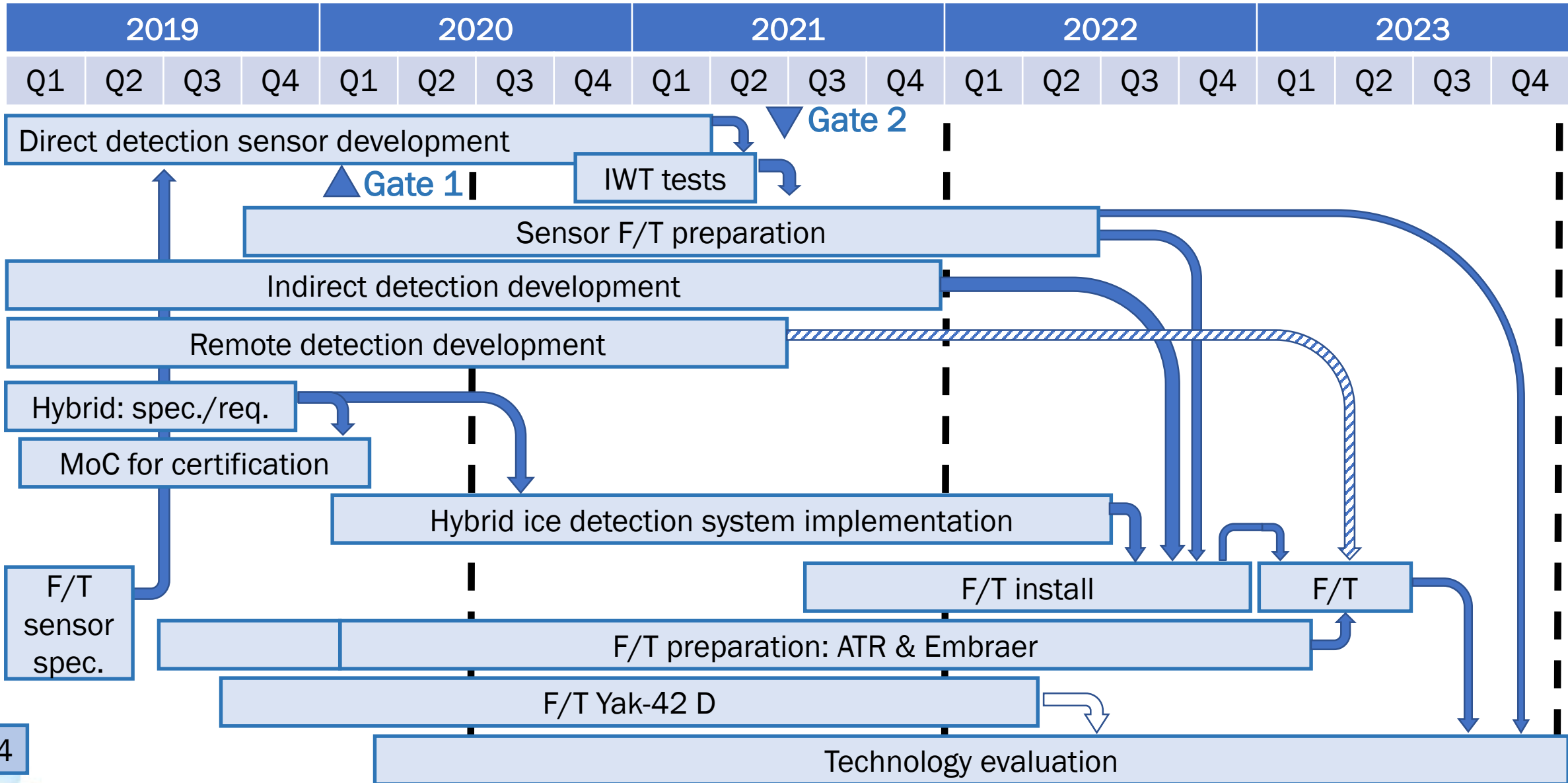
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SENS4ICE Timescale (simplified Gantt – original/ 4 years)



SENS4ICE Timescale (simplified Gantt – extended/ 5 years)



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