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The SENS4ICE EU project – SENSors and certifiable hybrid architectures for safer aviation in ICing Environment – Project Overview and Initial Results

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Abstract

The EU-funded project SENS4ICE addresses reliable detection and discrimination of supercooled large droplets (SLD) icing conditions. These conditions are considered as particularly safety relevant and have been included in airplane certification specifications. The SENS4ICE project comprises technology development, icing wind tunnel upgrading/testing and flight testing. A novel hybrid approach for icing detection combines direct sensing (atmospheric conditions / ice accretion) with indirect techniques based on changing aircraft characteristics.

Keywords: aircraft icing, SLD icing, supercooled large droplets, hybrid ice detection

Nomenclature

AHDEL	Atmospheric Hydrometeor Detector based on Electrostatics
AIP	Atmospheric Icing Patch
AIWT	Altitude Icing Wind Tunnel
AMPERA	Atmospheric Measurement of Potential and ElectRic field on Aircraft
AOD	Appendix O Discriminator
BCPD	Backscatter Cloud Probe with Polarization Detection
BIWT	Braunschweig Icing Wind Tunnel
CCP	Cloud Combination Probe
CFR	Code of Federal Regulations
CIRA	*Centro Italiano Ricerche Aerospaziali* (Italian Aerospace Research Center)
CM	Continuous Maximum
CM2D	Cloud Multi-Detection Device
CS	Certification Specifications
DLR	*Deutsches Zentrum für Luft- und Raumfahrt* (German Aerospace Center)
FAR	Federal Aviation Regulations
FBG	Fiber Bragg Grating
FBGS	Fiber Bragg Grating Sensor
FOD	Fiber Optic Detector
HIDS	Hybrid Ice Detection System
IAR	Ice Accretion Rate
IDS	Ice Differentiator System
IIDS	Indirect Ice Detection System
IM	Intermittent Maximum
INTA	*Instituto Nacional de Técnica Aeroespacial* (National Institute of Aerospace Technology)
IPS	Ice Protection System
IWT	Icing Wind Tunnel
LILD	Local Ice Layer Detector
LW	Liquid Water
LWC	Liquid Water Content
MRO	Maintenance, Repair and Overhaul
MVD	Median Volume Diameter
NRC	National Research Council Canada
ONERA	*Office national d'études et de recherches aérospatiales* (The French Aerospace Lab)
SENS4ICE	SENSors and certifiable hybrid architectures for safer aviation in ICing Environment
PFIDS	Primary in-Flight Icing Detection System
SIGWX	Significant Weather Chart
SLD	Supercooled Large Droplets
SRP	Short Range Particulate
t	time
T	Temperature
TUBS	*Technische Universität Braunschweig* (Technical University Braunschweig)
UTC	Coordinated Universal Time
V	speed

1. Introduction

Modern airplanes are well equipped to cope with most common icing conditions, which are defined in Appendix C of CS-25 [1] / 14 CFR Part 25 (formerly known as FAR 25) [2]. However, some conditions consisting of supercooled large droplets (SLD, with a diameter larger than 100 µm) have been the cause of several accidents over the last three decades. It became obvious that there are certain types of airplanes which are not robust against these SLD conditions as ice can form on unprotected areas of the lifting surfaces (e.g. behind the leading edge and/or related to runback icing) leading to loss of control. Consequently, authorities addressed these safety concerns by issuing new certification rules under Appendix O (CS-25 [1] / 14 CFR Part 25 [2]) to ensure that future airplanes remain controllable in these conditions and can exit safely upon detection. Hence, the key to increasing overall aviation icing safety is the early and reliable detection of icing conditions to allow the necessary actions to be taken by the flight crew. The EU-funded project SENS4ICE directly addresses this need for reliable detection and discrimination of icing conditions [3].

Although much progress has been made on icing detection, there are considerable gaps specifically regarding the different icing conditions. This is in the focus of the novel approach of the SENS4ICE project. An intelligent way to cope with the complex problem of ice detection is the hybridization of different detection techniques. Direct sensing of atmospheric conditions and /or ice accretion on the airframe may be combined with indirect techniques in which the change of aircraft characteristics with ice accretion on the airframe is detected. Combining several complementary solutions will serve the goal of providing a more robust and reliable detection for a wide range of icing conditions.

SENS4ICE is addressing development, test (icing wind tunnel and in flight), validation, and maturation of different detection principles and the hybridisation approach, as well as the final airborne demonstration of technology capabilities in relevant natural icing conditions [4]. The hybridisation activities particularly are conducted in close cooperation with regulation authorities in order to develop acceptable means of compliance.

SENS4ICE is addressing this challenge with a unique layered safety approach (Figure 1) [5]:

Strategic and tactical icing assessment: Improved icing condition predictions (based on satellite or weather radar data) serve to provide information and warnings before entering an area. In addition to flight planning on a strategic level, nowcasting weather forecasting can support situational awareness and decision making on a very short term basis, e.g. for up to one or two hours in advance even during flight. Furthermore, atmospheric measurements specifically with an emphasis on SLD conditions will result in a better understanding and improved prediction models and methods. This will improve safety and avoid unnecessary diversions and fuel consumption.

In-situ ice detection: The hybrid ice detection approach is designed to reliably detect icing conditions during both entry and flight through different icing conditions including SLD. This will provide a better situational awareness for pilots to changing conditions and optimised activation of ice protection system, reducing energy consumption and emissions contributing to greener aviation.

Contingency: Prevention of icing-induced loss of control events as a contingency to safely exit icing conditions. Complementary to the increased situational awareness of icing conditions, the detection of a reduced aircraft flight envelope provides the necessary information to alert the crew of the reduced aircraft capabilities as ice forms on the airframe.

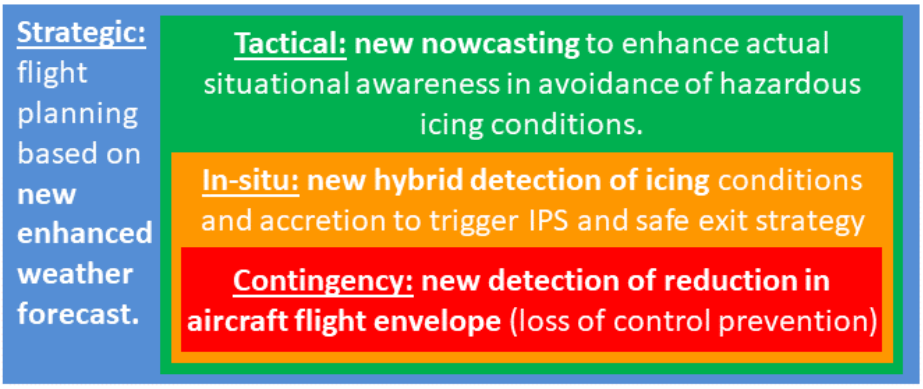


Figure 1 SENS4ICE layered safety concept for liquid water icing [5]

The expected impact of the project is to contribute to the key societal challenges of smart, green and integrated transport, considering the challenges of its competitiveness, performance and sustainability. SENS4ICE is tackling these challenges by contributing to increased passenger safety, decreased cost by improving certification rules, and increasing aviation efficiency by avoidance of icing hazards and lowering inspection and MRO operations [6].

2. Sensor Technology Development

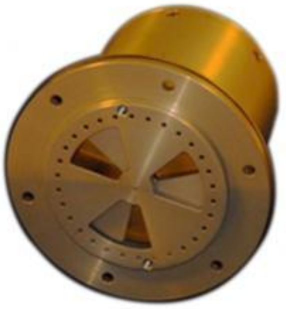
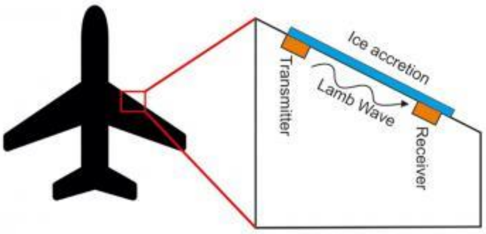
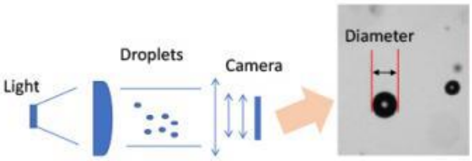
The first part of the project was mostly devoted to the development and maturation of icing detection technologies, with a focus on Appendix O icing conditions (as defined in [1] and [2]).

Ten different technologies with various physical principles for directly detecting icing conditions have been developed and matured with EU funding. At the project start, the sensor technologies had different levels of technology readiness, some at the early stages of the design process and some at a higher level of maturation and testing. In the first part of the project, all sensors reached the status to be ready for icing wind tunnel testing.

One of the technologies (CM2D, combining the Nevzorov Probe and the Backscatter Cloud Probe with Polarization Detection (BCPD)) aspires to improve airborne scientific and reference measurements. The other nine are aiming at applications for operational air transport. The sensor technologies can be grouped into two types, atmospheric sensors, that are measuring the atmospheric conditions, and accretion sensors, that are measuring ice accretion on the aircraft. Table 1 provides an overview of the icing sensor technologies under development in the SENS4ICE project and Figure 2 illustrates the sensor technologies.

Table 1 SENS4ICE sensor technologies overview, sensor types and principles

Developer	**Sensor**	**Sensor Type**	**Sensor Principle**
AeroTex	AIP	Atmospheric	Isothermal with inertial separation at different sensors along aircraft
Collins	IDS	Atmospheric	Thermal response to heat impulse
DLR	LILD	Accretion	Ultrasonic wave attenuation / phase change
Honeywell	SRP	Atmospheric	Collecting backscattered light from particles
INTA	FOD	Accretion	Latent heat measured with fiber optic
ONERA	AHDEL	Atmospheric	Particle charging and subsequent measurement of the charge
ONERA	AMPERA	Atmospheric	Measurement of aircraft electric potential
SAFRAN	AOD	Atmospheric	Shadowgraphy
SAFRAN	PFIDS	Atmospheric	Optical reflection from accretion
DLR	CM2D [BCPD]	Atmospheric	Single particle optical backscatter
DLR	CM2D [Nevzorov]	Atmospheric	Isothermal measurement of water content

 Name: Short Range Particulate (SRP) Project partner: Honeywell Copyrights: © Honeywell	 Name: Collins Ice Differentiator 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: German Aerospace Center (DLR) Copyrights: © German Aerospace Center (DLR)	 Name: Appendix O Discriminator (AOD) Project partner: SAFRAN Copyrights: © SAFRAN
 Name: PFIDS (Primary in-Flight Icing Detection System) 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: Nevzorov Probe and Backscatter Cloud Probe with Polarization Detection (BCPD) Project partner: DLR Copyrights: © Skytech and © DMT

Figure 2 – SENS4ICE sensor technologies for direct sensing of atmospheric icing conditions or ice accretion detection

As an example for the SENS4ICE sensor technologies, FOD (Fiber Optic Detector) is using Fiber Bragg Grating Sensors (FBGSs) to identify icing conditions [7]. 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 [7]. FOD IWT testing in SENS4ICE was prepared with the INTA Icing Wind Tunnel (IWT) and then conducted at the NRC Altitude Icing Wind Tunnel (AIWT) (see also next section). IWT results for FOD 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 [7].

Figure 3 shows FOD temperature time histories at NRC AIWT for Appendix O conditions (LWC = 0.82 g/m^3, MVD = 163.5 um; V = 76 m/s) [8]. The different measurement locations over the cord of the airfoil allow to clearly distinguish the temperature distribution.

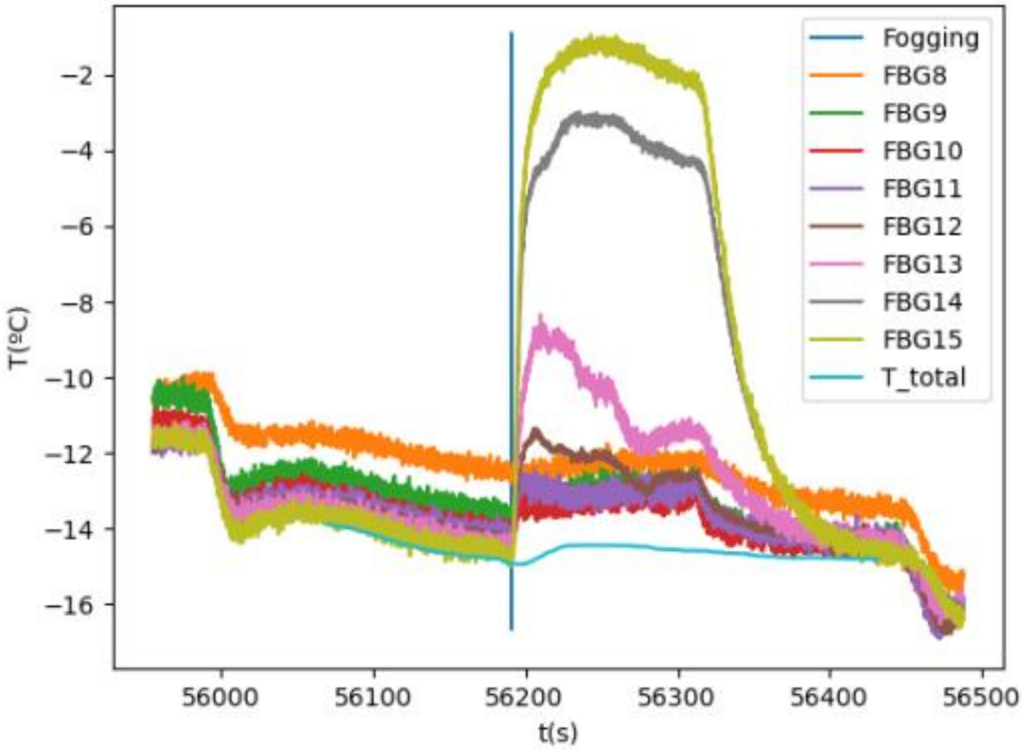


Figure 3 FOD temperature time histories at NRC AIWT for different measurement locations over the airfoil chord (“FBG 8 – 15") and the total temperature for Appendix O conditions (LWC = 0.82 g/m^3, MVD = 163.5 µm; V = 76 m/s, start time of icing cloud marked by a vertical line “Fogging”) [8]

Another example for the SENS4ICE sensor technologies is the Local Ice Layer Detector (LILD). This technology uses travelling ultrasonic lamb waves, that are sent through the structure which may be affected by icing (Figure 4). Presence of ice changes the waveguide behaviour of the underlying structure, which can be detected [9]. For SENS4ICE IWT tests at the TUBS BIWT (see also next section), LILD was applied on an airfoil section. Various Appendix C and O icing conditions have been tested with the goal to detect the beginning of icing conditions and ice accretion with an adequate response time. Figure 5 shows an example of an immediate lamb wave amplitude reaction compared to the timely evolution of the IWT icing cloud. Figure 6 depicts LILD response times for Appendix C and O conditions measured at BIWT compared to required response time [9]. All response times are relatively short within a range of a few seconds and meet the required response times as per inflight icing systems standard ED-103 [10] in all test cases.

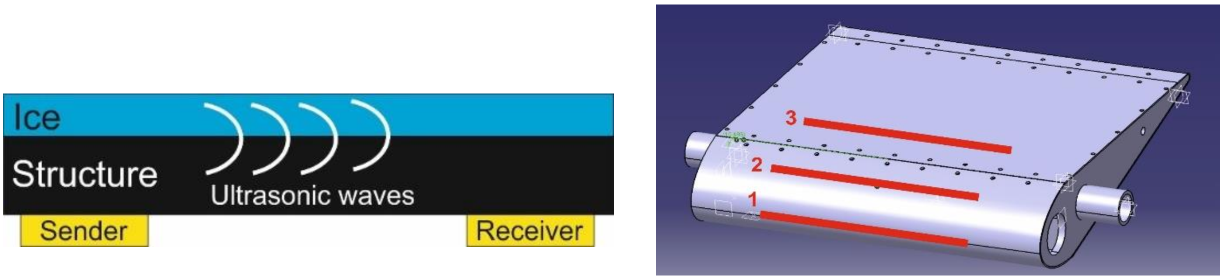


Figure 4 LILD principle (left) and Lamb wave measurement channels marked in red for IWT test (right) [9]

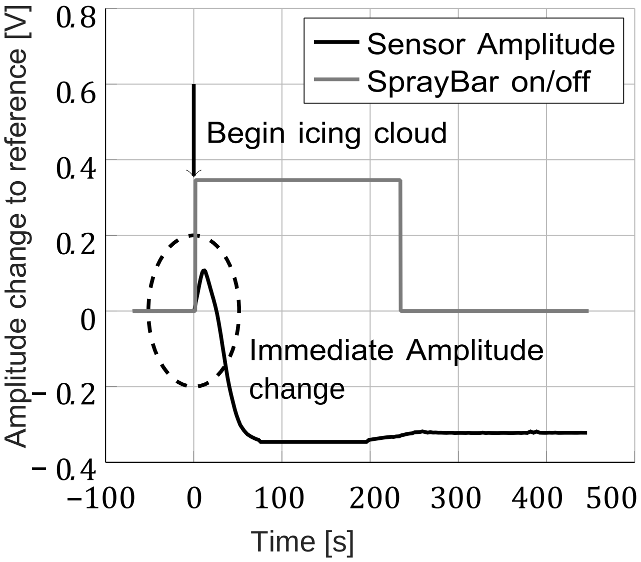


Figure 5 LILD immediate lamb wave amplitude reaction of the received pulse upon icing conditions start for exemplary Appendix C test case (MVD = 21.1 µm, LWC = 0,98 g/m^3, T = -10°C) [image Martin Pohl, DLR]

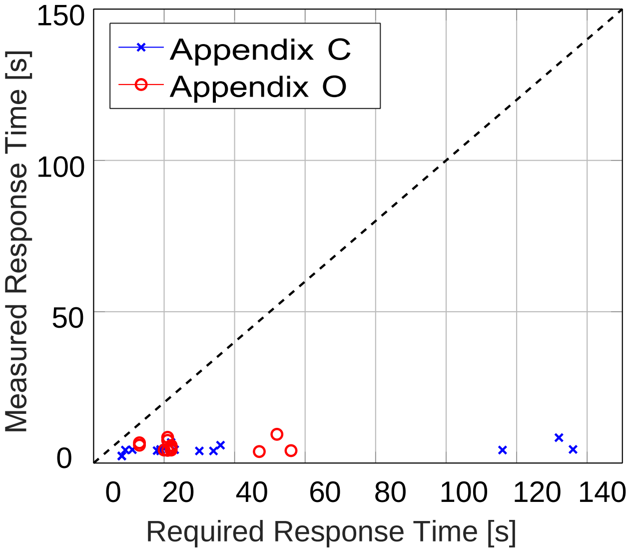


Figure 6 LILD response times for Appendix C and O conditions measured at BIWT compared to the required response time [9]

A final example of SENS4ICE technology consists of an array of low power (< 28W) iso-thermal ice detection sensors: Atmospheric Icing Patch – AIP. The small iso-thermal sensor patches are operating at a constant high temperature and the change in power drawn under icing conditions compared to dry conditions indicates the presence of water. By positioning the patches at different locations on the aircraft, the presence of different diameter droplets can be discriminated and the icing severity (LWC) assessed [11].

IWT tests provided measurements for the change in power for various liquid water conditions including Appendix O conditions. Examples of the power response of the heaters in small and large droplet conditions are shown in Figure 7 and Figure 8 respectively, demonstrating detection of spray boundaries for start and end of the icing conditions and differentiation between droplet size.

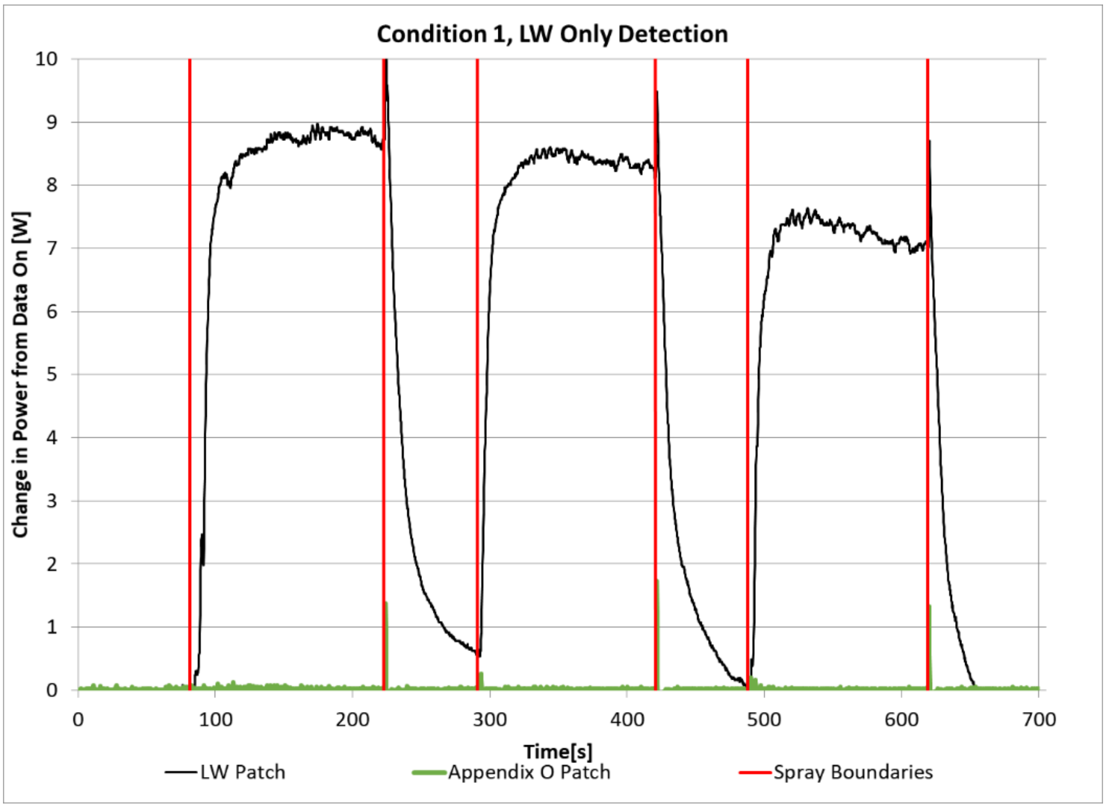


Figure 7 Example of AIP patch power response in small droplet icing conditions (note Appendix O patch shows no response) [11]

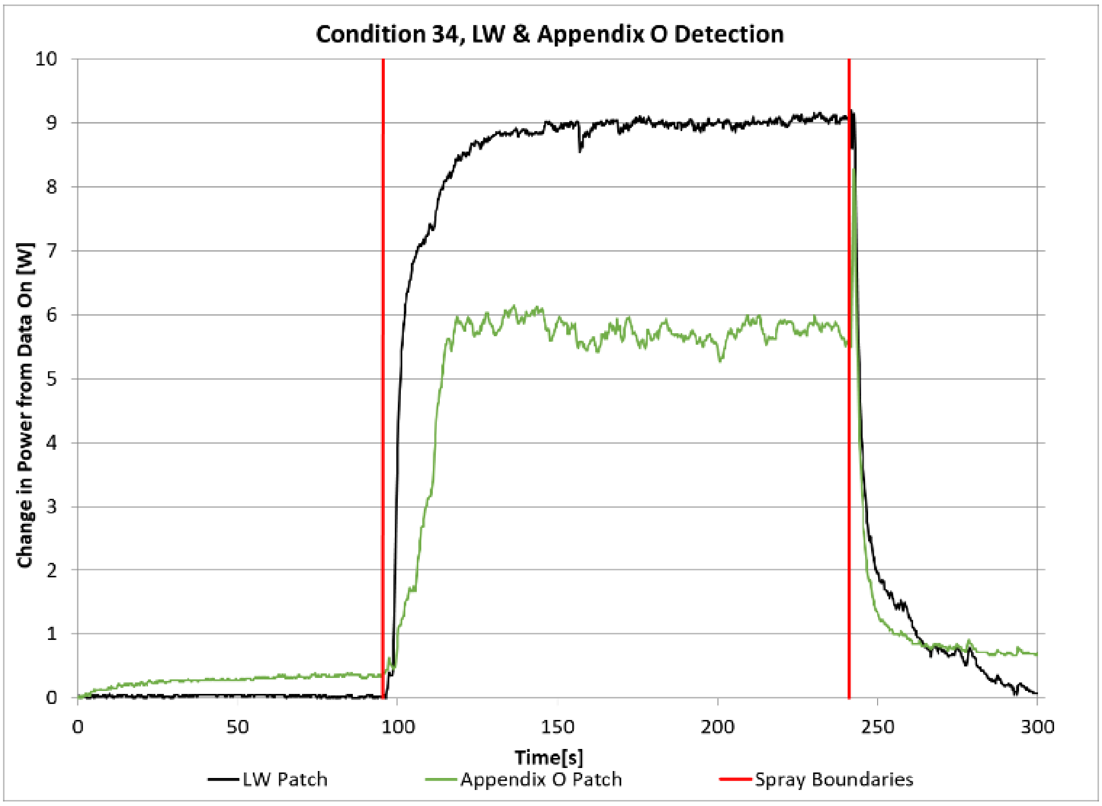


Figure 8 Example of AIP patch power response in large droplet icing conditions (note Appendix O patch response) [11]

3. Icing Wind Tunnel Testing

Three icing wind tunnel (IWT) test facilities were used by the sensor developers to conduct the SENS4ICE IWT testing for EU funded sensor technologies:

- Collins Aerospace Icing Wind Tunnel
- TUBS BIWT (Braunschweig Icing Wind Tunnel) [12]
- National Research Council (NRC): Altitude Icing Wind Tunnel (AIWT) [13].

3.1 Icing Wind Tunnel Upgrading and Reference Measurements

While the NRC AIWT already provide the capability to achieve SLD in full bimodal freezing drizzle conditions, the other involved icing wind tunnel facilities have improved their capabilities to represent Appendix O conditions.

The extension of the wind tunnel capabilities towards the Appendix O icing regime was accompanied by the effort to precisely characterize the generated droplet sprays. However, as of now, no standardized procedure for the measurement of Appendix O conditions exists, hence wind tunnel operators utilise a wide range of different instruments. This raised the question, to what extent the results of SENS4ICE sensors that measured in different wind tunnels are comparable. To ensure comparability between results obtained in the different IWTs, reference measurements with a common set of established airborne instruments were conducted in the three IWTs. Reference measurements of LWC were conducted in the three IWTs with a Nevzorov probe, which had been modified with a second total water content collector cone (with an increased diameter of 12 mm alongside the standard 8 mm cone, Figure 9). This has been found to be generally suitable for the collection of SLD [14]. In addition, at Collins and at the BIWT, a Cloud Combination Probe (CCP) was used for IWT reference measurements (Figure 10).

Dedicated reference measurement results are compared with specifications and IWT data for specific test points. Figure 11 shows a comparison of Nevzorov LWC measurements with IWT data for different MVD at a tunnel speed of 76 m/s. Generally, there is good agreement. For MVDs of less than 180 µm the Nevzorov and IWT data agree within 20% for all cases except one.

Icing wind tunnel conditions and comparison are deemed fully sufficient for SENS4ICE project purposes of testing icing sensors as part of the sensor technology development and maturation process. From the icing wind tunnel perspective it is concluded that further collaborative efforts are needed for product development and certification in standardised SLD conditions. International exchange and collaboration will be particularly useful to achieve this goal.

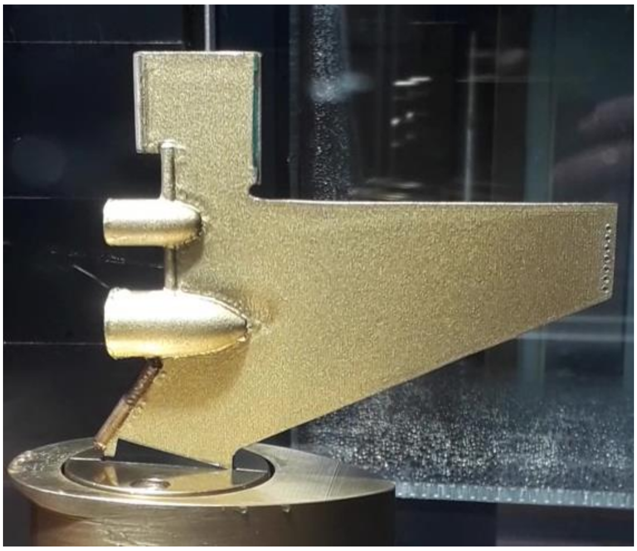


Figure 9 Nevzorov probe with new sensor head with hotwire (top), 8 mm total water content collector cone (middle) and new 12 mm total water content collector cone (bottom)

Figure 10 Cloud Combination Probe (CCP) developed by DLR Institute of Atmospheric Physics and used to characterise icing in wind tunnels

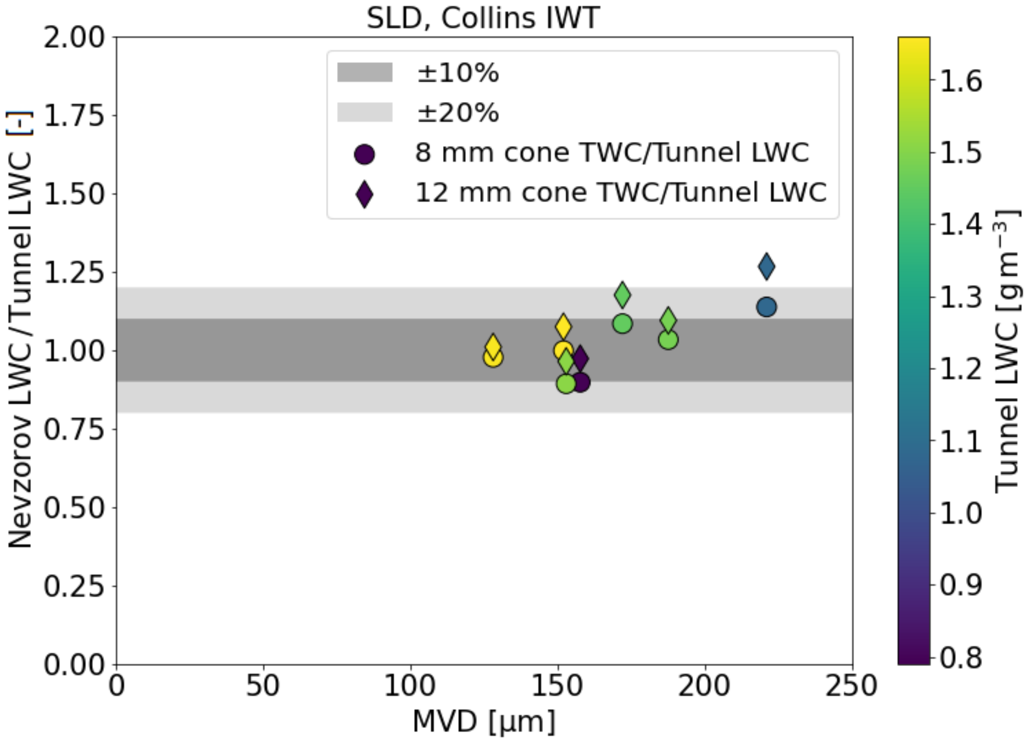


Figure 11 Comparison of Nevzorov LWC reference measurements (8 mm and 12 mm cones) with Collins IWT LWC data for a tunnel speed of 76 m/s and for different MVD [15]

3.2 Icing Wind Tunnel Testing

Significant effort was devoted to the development of test matrices for each IWT facility following the guidelines of ED-103 [10]. It is important to note that, due to the capabilities of each IWT facility, icing envelopes differ from one IWT facility to another with very limited overlap. This overlap was leveraged to define common test points between all or some of the facilities (Table 2).

Table 2 Common test points between IWT facilities TUBS, Collins and NRC

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

Test matrices for each IWT define details of the test points. Such details include air speed, MVD, LWC, required response time as per ED-103, and other relevant parameters. Test for different sensors and different test points were standardised to ensure comparability: 1) start data recording, 2) record data for 1 min in clean air, 3) start the icing cloud, 4) once an icing signal is detected, run for 1 min, 5) stop the icing cloud [16]. For a selected subset of the test points, 3 cycles of icing have been completed (to test repeatability to the extent possible with the available IWT time). In order to test sensor ability to maintain its functionality over an extended period, one Appendix C test point was selected for endurance. This test point was tested with the icing cloud turned on for a duration of 45 minutes.

Eight technologies have provided testing results in different icing wind tunnels in Appendix C and O conditions. As the sensor technology AMPERA uses the aircraft as a sensor (measurement of aircraft electric potential), IWT testing is not feasible. Instead, flight test data from previous projects were analysed to investigate the correlation between the electrostatic field and the total water content [17]. Most sensor technologies have been able to demonstrate with IWT results the detection of a large portion of the Appendix O test points while at the same time ensuring very good detection capabilities for Appendix C conditions. Several sensors have correctly detected 100% of the test points for

Appendix C and also for Appendix O, also within the required maximum response time as per ED-103. An anonymised overview of the detection rates (test cases successfully detected related to the total number of test cases) is provided in Figure 12, excluding DLR's CM2D scientific/reference sensor and another sensor with results subject to export control restrictions.

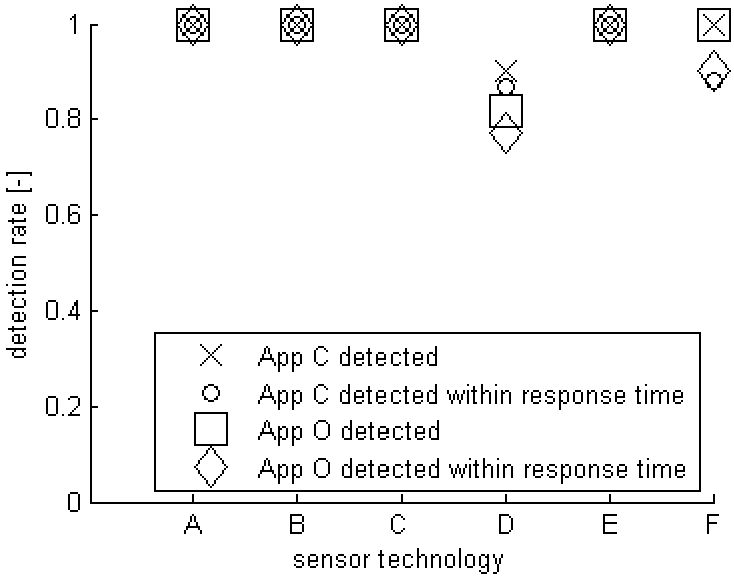


Figure 12 SENS4ICE sensor technologies IWT testing detection rates overview for App. C and O icing condition test points

In addition to detecting icing conditions, some sensors are capable of providing specific relevant icing parameters like liquid water content (LWC) and median volume diameter (MVD), which is considered as very beneficial especially as input for the hybrid ice detection system.

SENS4ICE sensor IWT testing provided valuable results for the sensor technology development process and demonstrated overall that the technologies under development can be considered as promising. Furthermore, IWT test results constituted a profound basis for the project internal technology evaluation and selection process, as described in the following section.

4. Sensor Technology Evaluation

The primary goal of the SENS4ICE project is to develop a hybrid system for detecting liquid water icing including Appendix C and particularly Appendix O conditions. While the development of direct detection sensors is considered critical for this effort, the development of sensors for stand-alone applications is considered an important secondary goal. The SENS4ICE project was developed with a two-stage selection process for the direct detection sensors. For the flight testing within the SENS4ICE project it has to be noted that there is a limited budget dedicated for the flight test preparation. So, in case all or many sensors were ready for flight test, not all sensors can receive part of the dedicated budget for flight test preparation. To support the sensor technology evaluation, an external Advisory Board was set up. The Advisory Board is composed of aviation certification authorities, aircraft manufacturers, pilot representatives and research institutions. The project members of the SENS4ICE Advisory Board provided helpful input for this evaluation.

About one year after the project start, it was found with a first round of technology evaluation that no major issues were identified and that no particular sensor technology was clearly falling behind, while no sensor technology was standing out either. The second sensor technology evaluation was conducted in May 2021 and selection for flight testing was mainly based on IWT test data generated as part of the SENS4ICE project.

The primary project goal to be considered for the technology evaluation is to provide icing detection capabilities for Appendix O (as this is not operationally available). In the scope of this project these newly developed icing detection capabilities shall also be able to detect Appendix C conditions. Furthermore, the approach of the project is to develop a hybrid icing detection system. Individual direct icing sensors are evaluated regarding benefits for the hybrid system and not primarily as stand-alone sensors (although this will clearly be a spin-off). The basic idea of the hybrid system is: The hybrid system offers the possibility to combine multiple sensors and their specific strengths. In addition a good combination of sensors and the information/data they are providing might be more promising than stand-alone solutions of other sensors.

Five evaluation criteria have been developed, associated with weighting factors in order to obtain overall ratings for each sensor, as shown in Table 3.

Table 3 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

The very comprehensive Advisory Board evaluations, including ratings for the five evaluation categories (averaged for all Advisory Board members in Figure 13) and general comments, constituted a profound basis for the sensor technology evaluation and selection. Also highlighting individual sensor technology particular strengths and weaknesses is particularly valuable for integration in to the HIDS and also to focus future development.

No sensor technology received a very low overall Advisory Board rating. All sensor technologies have made substantial progress and are considered promising by the Advisory Board. As two sensors (AHDEL/ ONERA and AOD/ SAFRAN) were withdrawn from flight testing due to low maturity, it was decided to select all other sensors for flight testing.

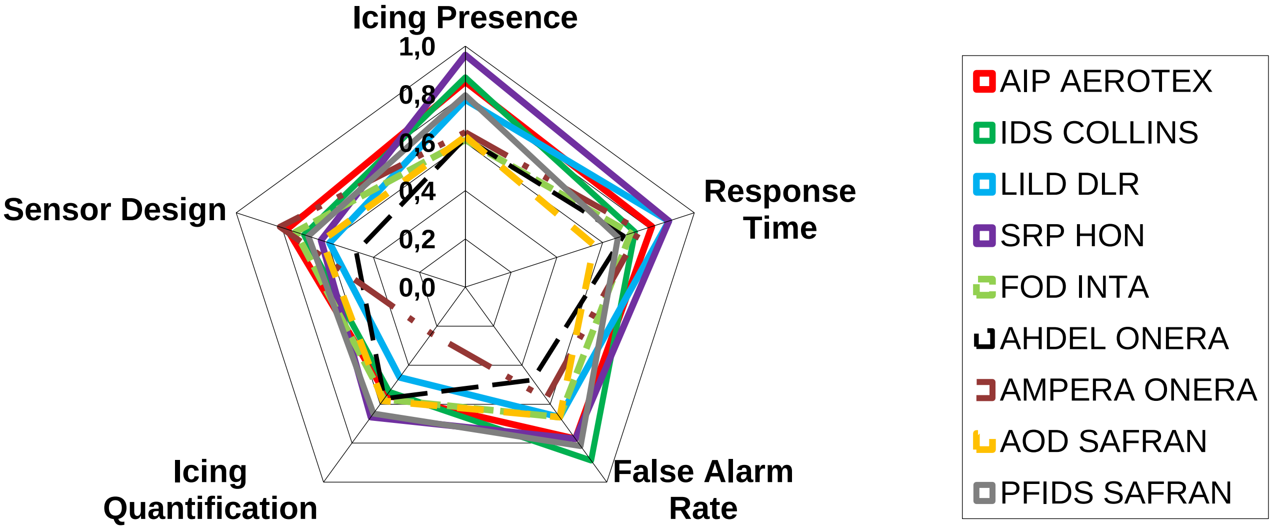


Figure 13 SENS4ICE Advisory Board evaluation ratings for sensor technologies averaged for all Advisory Board members for evaluation criteria (averaged ratings between 0 and 1, normalised, best rating 1)

5. Remote Ice Detection

Remote icing detection technologies have been investigated, based on satellite data or airborne weather radar data. Both approaches have shown promising results and strengths and weaknesses were identified.

The remote detection based on satellite data was presented by CIRA at the EGU22 (European Geosciences Union) General Assembly [18]. A previously developed icing detection algorithm was enhanced and further matured in order to consider SLD icing conditions (see example output Figure 14). The main meteorological factors considered for determining the icing condition are liquid water content (LWC), temperature, droplet size and cloud type, with a specific focus on mean effective drop diameter as retrieved from satellite data.

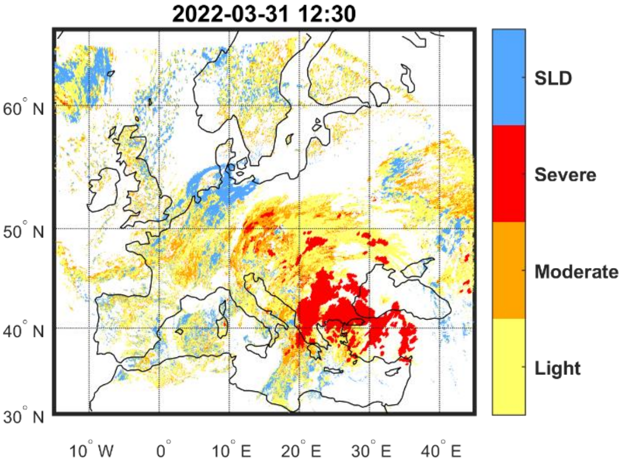


Figure 14 CIRA remote icing detection algorithm output for 31 MAR 2022 12:30 UTC [18]

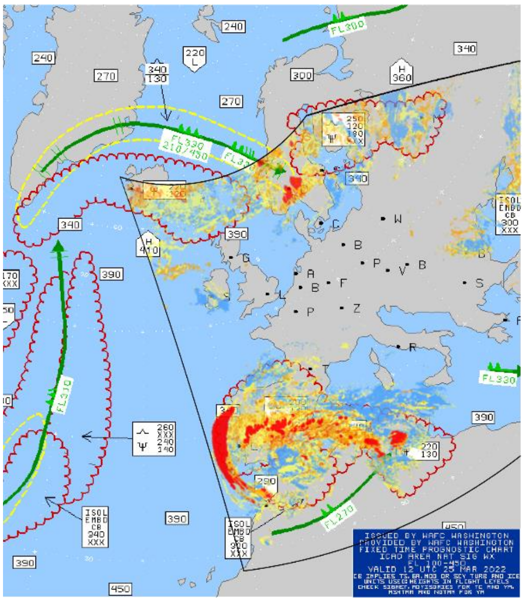


Figure 15 CIRA remote icing detection validation example (comparison with SIGWX chart) [18]

A complete validation of the results is very challenging, but a qualitative comparison with Mid-Level Significant Weather (SIGWX) Charts shows a quite good agreement of regions affected by icing conditions (see validation example Figure 15). Further performance evaluations for the algorithm are still ongoing. Based on the icing detection method a nowcasting tool was developed based on the extrapolation in time of the current weather conditions detected by satellite data, by estimating speed and direction of movement of the current icing conditions.

Overall, remote icing detection technologies appear to be promising and bear the potential for providing benefits during operational application for aviation.

6. Hybrid Ice Detection

For the hybrid ice detection system (HIDS), developed by SAFRAN, various technologies utilizing different physical principles can be combined in order to use each individual technologies' advantages and mitigate individual sensor limitations. For example, a combination of technologies to detect icing conditions in the atmosphere, ice accretion on the aircraft's surfaces, or the change of aircraft characteristics due to ice accretion can be part of the hybrid solution. More generally, the hybrid system will combine several individual technologies with the aim of providing a more robust and reliable detection.

6.1 HIDS Development

In the first project phase the hybrid ice detection system was specified. Initial considerations of certification aspects have been discussed in close cooperation with aviation certification authorities, aircraft manufacturers, pilot representatives and research institutions. Subsequently a suitable hardware and software architecture was developed in order to test in flight. Particularly the interfaces with the basic aircraft data system and direct and indirect ice detection systems have been detailed. By combining the various input sources, the HIDS will derive an overall output signal for icing detection. The HIDS will be part of two flight test campaigns in 2023 and is adapted to meet specific test aircraft system architecture requirements.

6.2 Indirect Ice Detection

As part of the hybrid approach, a performance-based indirect ice detection system (IIDS) is developed and matured by DLR, able to early detect even relatively light ice accretion on the airframe by utilising fundamental knowledge about the changes of aircraft characteristics under icing conditions, specifically flight performance degradation [19], [20]. The methodology is energy based and considers aircraft body and engine effects on flight performance. The detection reliability is robust for manoeuvring flight, wind shear, turbulence, and sideslip as well as for sensor failure scenarios [19].

The system utilizes flight parameters and information normally available on modern aircraft, e.g. aircraft parameters, air data, and inertial data. In addition, a database of pre-defined aircraft characteristics is necessary to compare the detected aircraft characteristics to the nominal behaviour and derive the icing status.

Extensive analysis was conducted with flight test data to identify applicable thresholds for specific aerodynamic aircraft parameters. Preliminary results based on the existing data from flights in natural icing conditions (App. C icing conditions) show, that a fast and reliable detection behaviour could be achieved. Figure 16 depicts IIDS ice detection results based on pre-existing Embraer natural icing flight test data exhibiting relative drag increase above detection threshold. It is expected that this behaviour will be somewhat similar for flights in App. O conditions.

As the IIDS is part of the HIDS, it will be also part of the two SENS4ICE flight test campaigns in 2023 and is adapted accordingly.

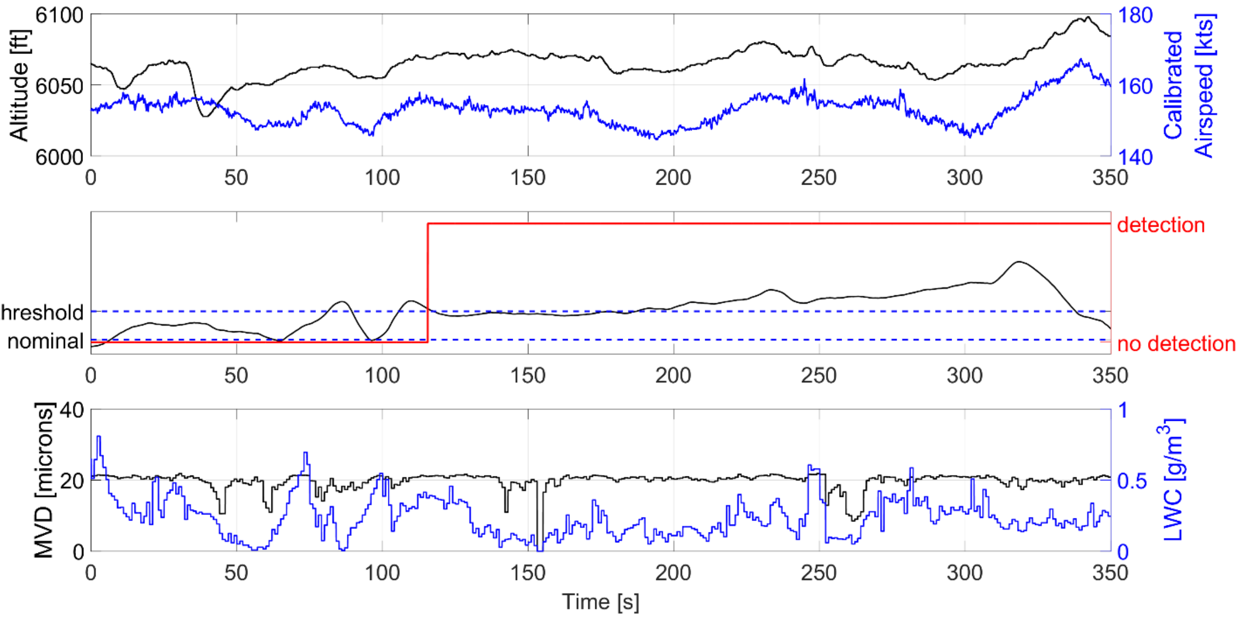


Figure 16 IIDS ice detection results based on pre-existing natural icing flight test data exhibiting relative drag increase above detection threshold [image Christoph Deiler DLR, flight test data Embraer]

7. Flight Testing

First flight tests have already been carried out in the first phase of the project and a comprehensive characterisation of various icing conditions was provided. Further flight tests are planned for 2023 to test and demonstrate eight of the direct ice detection technologies under development and in addition the hybrid ice detection system including the indirect ice detection system. The following campaigns are planned for the last project year 2023:

- JAN 2023, North America, Embraer Phenom 300 operated by Embraer (Figure 17)
- APR 2023, Southern Europe, ATR-42 operated by CNRS/SAFIRE (Figure 18)

Figure 17 Embraer Phenom 300 (Copyright © Embraer)

Figure 18 SAFIRE ATR-42 (Copyright © SAFIRE/JC Canonici)

Interface definition, preparation and integration activities are performed for flight testing the direct, indirect and hybrid detection technologies. Critical Design Reviews have been conducted successfully for all relevant systems. Particular focus was put on selecting suitable aircraft locations for mounting external sensors in order to allow for good icing detection conditions. Close collaboration between all involved partners, specifically including detection technology developers, aircraft operators and aircraft manufacturers, is paramount in order to allow for successful flight testing. Further emphasis is on ensuring adequate reference measurements as a profound basis for analysis of flight test data and technology evaluation.

Aircraft specific safety requirements have been developed, including minimum altitudes for natural icing flight tests. This is reducing the likelihood to encounter relevant icing conditions. Hence, extensive meteorological and climatological analysis is underway in order to have the best chances to encounter icing conditions including Appendix O conditions.

8. Summary and Conclusion

The objectives of the EU-funded project SENS4ICE are to increase flight safety in icing conditions and especially for SLD conditions and to contribute to increase the knowledge base on the formation and occurrence of Appendix O conditions.

In the first part of the project, icing detection technologies have been developed specifically focusing on Appendix O icing conditions. Icing wind tunnels have upgraded their capabilities for representing Appendix O conditions. Direct ice detection sensors have been tested in icing wind tunnels under both Appendix O and Appendix C conditions. A hybrid ice detection system is under development, including a performance-based indirect ice detection system. The second part of the project is devoted to the preparation of several flight test campaigns in order to test ice detection technologies under natural icing conditions, with an emphasis on Appendix O. These flight tests are planned for 2023.

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11. Copyright Statement

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