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SENS4ICE EU PROJECT
ICING DETECTION TECHNOLOGIES EVALUATION

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Abstract

The EU Horizon 2020 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 encompasses 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 an indirect technique based on changing aircraft characteristics. In the first part of the project icing detection technologies were developed and matured, with a focus on Appendix O icing conditions (14 CFR Part 25 and CS-25). Moreover, several icing wind tunnel facilities have enhanced capabilities to represent Appendix O conditions. Icing wind tunnel testing (including Appendix O) of several icing detection sensors developed in SENS4ICE completed the first part of the project. In this paper a summary of IWT results is given. The second part of the project is dedicated to flight test evaluation of icing technologies in natural icing conditions including Appendix O. Two flight test campaigns in early 2023 served to test and demonstrate eight of the direct ice detection technologies under development as well as the hybrid ice detection system, including indirect ice detection. Extensive meteorological support allowed to encounter icing conditions of interest including Appendix O conditions in flight. Initial flight test results are promising with regard to sensor detection behavior and hybrid ice detection system performance including indirect ice detection.

1. INTRODUCTION

Current airplanes have well established means to handle 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, particular conditions consisting of supercooled large droplets (SLD, with a diameter larger than 50 µm) have been a contributing factor in several accidents over the last three decades [3]. It became apparent that there are specific scenarios where some airplanes are not robust against these SLD conditions as ice can form on unprotected areas of the lifting surfaces (e.g. behind the leading edge or related to runback icing) leading to loss of control. Therefore, authorities have issued specific certification rules under Appendix O (CS-25 [1] / 14 CFR Part 25 [2]) to help to ensure safety of flight in these conditions. Essential for increasing overall aviation icing safety is the early and reliable detection of icing conditions to facilitate the necessary actions to be taken by the flight crew. The EU-funded Horizon 2020 project SENS4ICE directly approaches this need for reliable detection and discrimination between Appendix C and O icing conditions [4].

While substantial progress has been made on icing detection, there are significant challenges specifically regarding particular icing conditions like Appendix O. This is in the focus of the novel approach of the SENS4ICE project [5]. An intelligent way to tackle the complex problem of ice detection is the hybridization of different detection techniques [6]. Direct sensing of atmospheric conditions and 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 allows to provide a more robust and reliable detection for a wide variety of icing conditions. This integrated solution aims not only to deliver fast and reliable information about icing conditions and ice accretion on the airframe in order to activate the countermeasures but also may provide valuable information to pilots about the aircraft performance status.

SENS4ICE is encompassing development, test (icing wind tunnel and in flight, in both cases with a focus on freezing drizzle and without addressing freezing rain conditions), validation, and maturation of different detection principles and the hybridization approach, including the final airborne demonstration of technology capabilities in relevant natural icing conditions [7]. In particular, hybridization activities are conducted in close cooperation with regulation authorities supporting the development of acceptable means of compliance.

2. ICING WIND TUNNEL UPGRADING AND REFERENCE MEASUREMENTS

For testing the novel ice detection technologies developed and matured in the SENS4ICE project specifically in SLD conditions, three icing wind tunnel (IWT) test facilities were involved:

- Collins Aerospace Icing Wind Tunnel
- TUBS Braunschweig Icing Wind Tunnel (BIWT) [8]
- National Research Council (NRC): Altitude Icing Wind Tunnel (AIWT) [9].

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While the NRC AIWT already provided the capability to achieve SLD in full bimodal freezing drizzle conditions, the other two icing wind tunnel facilities enhanced their capabilities to represent Appendix O conditions in the framework of SENS4ICE. These improvements mainly included adapting the spray nozzle setup and were aiming at freezing drizzle conditions. Details of the bimodal freezing drizzle cloud calibration for TUBS Braunschweig Icing Wind Tunnel (BIWT) can be found in [10]. Testing freezing rain conditions was out of the scope for the SENS4ICE project.

No standardized procedure exists for the measurement of Appendix O conditions. In order to compare test points from the different tunnels, reference measurements with established airborne instrumentation were performed in each tunnel. The reference instrumentation consisted of a Nevzorov probe for liquid water content (LWC) measurements and a Cloud Combination Probe (CCP) [11] for measurements of the droplet size distribution. The Nevzorov probe was modified with a second total water content collector cone (with an increased diameter of 12 mm alongside the standard 8 mm cone) that is suitable for the capture of SLD [12]. Dedicated reference measurement results were compared with specifications and IWT data for specific test points. 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 [12]. From the icing wind tunnel perspective, it is concluded that cooperation and exchange was very fruitful and further collaborative efforts are required for product development and certification in standardized SLD conditions. Further international exchange and collaboration will especially beneficial to support addressing these needs.

3. DIRECT ICE DETECTION TECHNOLOGY DEVELOPMENT

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

Ten different technologies with various physical principles for directly detecting icing conditions have been developed and/or advanced with EU funding. At the project beginning, the sensor technologies had different levels of technology readiness, some very low and others having had already passed steps of technology testing. In the first project phase, all sensors reached the status to be ready for icing wind tunnel testing. More details are provided in the next section Direct Ice Detection Technology IWT Testing and Evaluation.

One particular technology (CM2D, combining the Nevzorov Probe and the Backscatter Cloud Probe with Polarization Detection (BCPD)) strives to improve airborne scientific and reference measurements. The other nine are targeting applications for operational air transport. The sensor technologies can be grouped into two categories: atmospheric sensors (measuring the atmospheric conditions) and accretion sensors (measuring ice accretion on the aircraft). TAB 1 provides an overview of the icing sensor technologies under development in the SENS4ICE project.

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

TAB 1 SENS4ICE sensor technologies overview, sensor types and principles

4. DIRECT ICE DETECTION TECHNOLOGY IWT TESTING AND EVALUATION

A first principal technology evaluation was undertaken based on IWT results. A project internal standardized testing procedure and partly common test points between the different icing wind tunnels served for adequate comparability of the results.

Substantial emphasis was dedicated to the development of test matrices for each involved IWT facility following the guidelines of ED-103 [13]. As the setup and capabilities of each IWT facility differ, icing envelopes deviate from one IWT facility to another with very limited overlap. This effect was leveraged by establishing a common test procedure and by selecting common test points between all or some of the facilities (TAB 2) [14].

Apart from reference instruments, eight technologies have generated IWT results in Appendix C and O conditions. Due to the fact that the sensor technology AMPERA from ONERA measures the electrical potential of the whole aircraft in flight, IWT testing is not feasible. Instead, flight test data from previous projects were assessed to investigate the correlation between the electrostatic field and the total water content [15]. During the IWT tests most sensor technologies have been able to demonstrate 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. Moreover, some sensors are capable of providing specific relevant icing parameters like liquid water content and median volume diameter, which is deemed as very valuable as input for the hybrid ice detection system (see next section). Example results for the technologies FOD (INTA), LILD (DLR) and AIP (AeroTex) for detecting small and large droplet conditions have been shown in [11] and in more detail in [16], [17] and [18].

IWT						
App C	Total Test Points	Common with 3 IWT	Common with 2 IWT	Only at 1 IWT	CM Test Points	IM Test Points
TUBS BIWT	19	4	1	14	10	9
Collins Aerospace IWT	18	4	3	10	9	9
NRC AIWT	19	4	4	11	9	10
App O	Total Test Points	Common with 3 IWT	Common with 2 IWT	Only at 1 IWT	Total Points [uni-modal]	Total Points [bi-modal]
TUBS BIWT	18	0	1	17	0	18
Collins Aerospace IWT	6	0	1	5	6	0
NRC AIWT	17	0	2	15	4	13

TAB 2 Common test points between IWT facilities TUBS, Collins and NRC (test points common with 2 or 3 IWT or only applicable for one IWT)

Sensor technologies performed generally very well in IWT tests and 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 shown in FIG 1, excluding DLR's CM2D scientific/reference sensor and one other sensor that was withdrawn from IWT testing in the context of Covid-19 related delays.

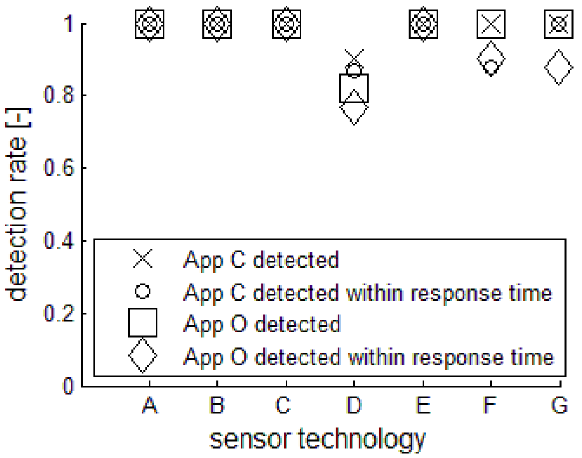

FIG 1 SENS4ICE sensor detection rates overview for App. C and O icing condition IWT test points for seven detection technologies

A qualitative overview (anonymised) of measured sensor response times compared to required response times as per ED-103 is shown in FIG 2 for App. C icing condition test points. In almost all cases the response times for the detection technologies are within the requirements.

Measured sensor response times compared to required response times for detecting liquid water icing conditions for App. O IWT test points are shown in FIG 3.

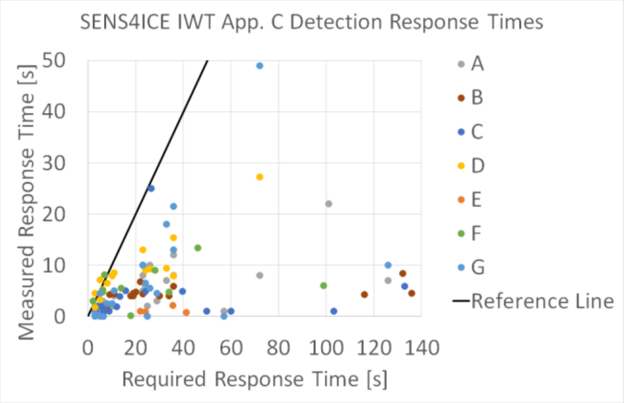

FIG 2 Measured sensor response times compared to required response times for App. C IWT test points

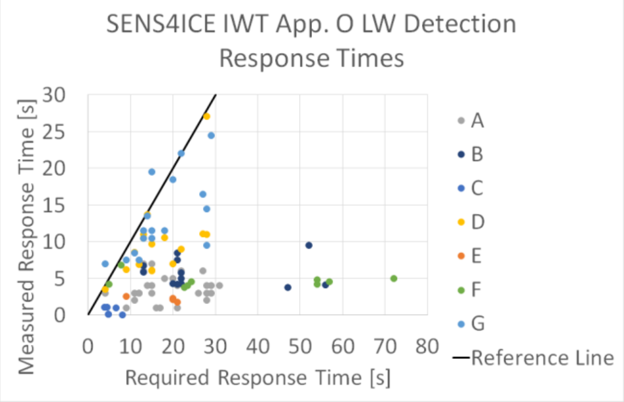

FIG 3 Measured sensor response times compared to required response times for detecting liquid water (LW) icing conditions for App. O IWT test points

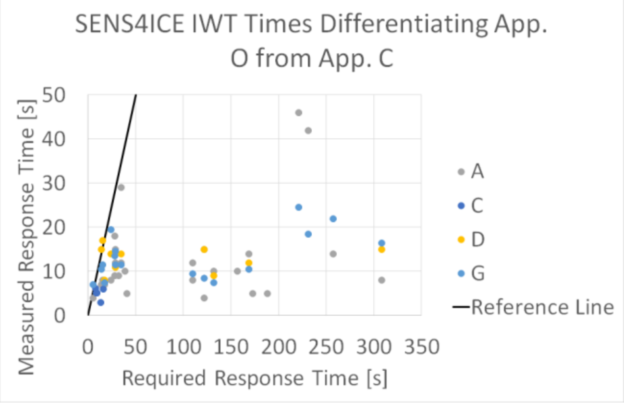

FIG 4 Measured sensor response times compared to required response times for differentiating App. C conditions from App. O conditions in IWT (for sensors providing differentiation information)

Measured sensor response times compared to required response times for differentiating App. C conditions from App. O condition are shown in FIG 4. Note that not all sensor technologies have provided differentiation information for the IWT tests.

SENS4ICE sensor IWT testing provided valuable results for the sensor technology development indicating that the technologies under development can generally be considered as promising. Moreover, IWT test outcomes excellently facilitated the project internal technology evaluation and selection process.

For the evaluation of the sensor technologies it is important to note that the principal objective of the SENS4ICE project is to develop a hybrid system for detecting liquid water icing including Appendix C and particularly Appendix O conditions (see next section). While the development of direct detection sensors is deemed essential for this effort, the development of sensors for stand-alone applications constitutes an important secondary goal. Emphasis was not only put on stand-alone performance of sensors but also on the potential benefit to contribute to a hybrid system, e.g. by compensating for possible weaknesses of other elements of the hybrid systems e.g. in terms of response time or detection rates.

A multi-level evaluation process with dedicated technology evaluation criteria was developed [9], and additionally general comments including highlighting strengths and weaknesses have been received and perceived as very worthy for the subsequent technology development work. Technology evaluation was tremendously supported by the SENS4ICE Advisory Board comprising aviation certification authorities, aircraft manufacturers, pilot representatives and research institutions. No sensor technology received a very low overall Advisory Board rating. All sensor technologies have made considerable progress and are judged as 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.

5. HYBRID ICE DETECTION

The solution of the hybrid ice detection system (HIDS), primarily developed by Safran in SENS4ICE, is to combine diverse technologies utilizing different physical principles in order to benefit from each individual technologies' advantages and mitigate individual sensor limitations. This may include 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 to be part of the hybrid solution. More generally speaking, the hybrid system approach combines several individual technologies with the aim to provide a more robust and reliable detection (FIG 5).

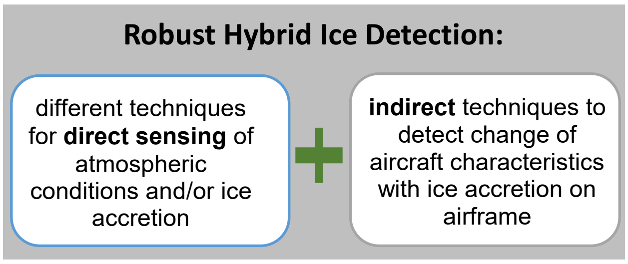

FIG 5 Robust hybrid ice detection concept depiction

5.1. HIDS Development

In the initial project phase the requirements for the hybrid ice detection system were collected and the specification derived. Initial questions for certification aspects have been discussed in close cooperation with aviation certification authorities, aircraft manufacturers, pilot representatives and research institutions. Based on this an appropriate hardware and software architecture was established in order to test the system in flight. Particularly, the interfaces with the basic aircraft data system and direct and indirect ice detection systems have been specified and tailored solutions have been implemented to meet specific test aircraft system architecture requirements for the flight campaigns with an Embraer Phenom 300 and an ATR 42. The HIDS is composing an overall output signal for icing detection by merging information from the various input sources (FIG 6).

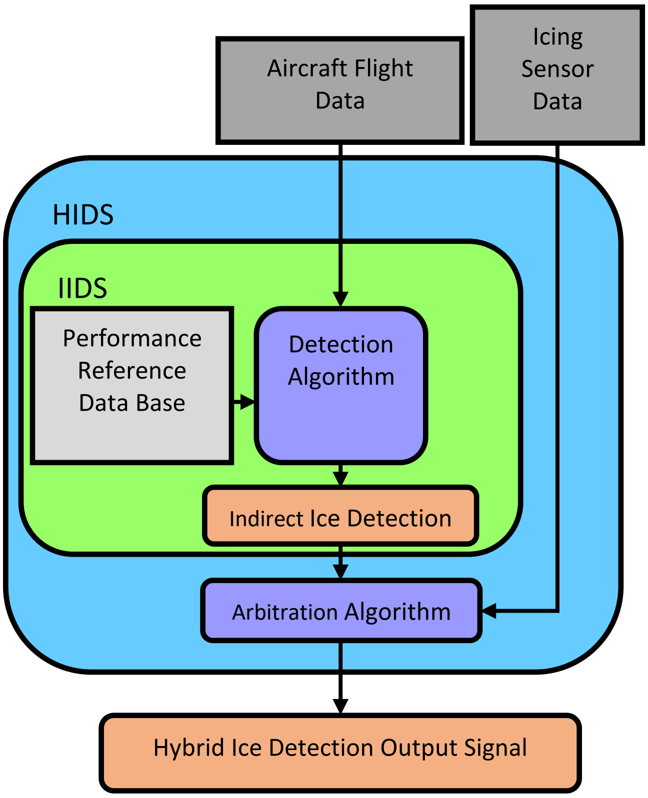

FIG 6 HIDS concept including indirect ice detection system IIDS (based on [19])

5.2. Indirect Ice Detection

As a fundamental part of the hybrid approach, a performance-based indirect ice detection system (IIDS) is developed and matured by DLR, designed to early detect even relatively light ice accretion on the airframe by applying fundamental knowledge about the changes of aircraft characteristics under icing conditions, primarily flight performance degradation [20], [21]. Extensive analysis was conducted with flight test data to identify applicable thresholds for specific aerodynamic aircraft parameters. Preliminary results based on data from previous flights in natural icing conditions (specifically Appendix C) indicate that a fast and reliable detection behavior could be achieved [19]. These preliminary studies supported the expectation that the approach may be successfully applied for flights in Appendix O conditions, which were conducted subsequently in the project, see following sections.

6. NATURAL ICING FLIGHT CAMPAIGNS

Technology testing in natural in-flight icing conditions allows to increase the Technology Readiness Level (TRL) for the technologies under development and to progress towards industrialization and operational application and also to facilitate future aircraft certification activities. Two flight campaigns with a total flight test time of about 75 hrs. have been conducted in 2023 to test and to demonstrate eight of the direct ice detection technologies under development and in addition the hybrid ice detection system including the indirect ice detection in particular in Appendix O/ SLD icing conditions:

- February/March 2023, North America, Embraer Phenom 300 operated by Embraer,
- April 2023, Southern Europe, French ATR 42 environmental research aircraft of Safire.

In addition to aircraft interface definitions for direct, indirect and hybrid detection technologies, specific emphasis was devoted to selecting suitable aircraft locations for installing external sensors in order to allow for good icing detection. Furthermore, ensuring adequate reference measurements is highly important. These reference measurements are a profound basis for analysis of flight test data and technology evaluation. Aircraft specific safety requirements and flight procedures have been established, including minimum altitudes for natural icing flight tests. This is reducing the likelihood to encounter relevant icing conditions, as only icing conditions above a certain altitude can be encountered during measurement flights. Hence, extensive meteorological and climatological analysis was conducted in order to identify suitable regions to encounter icing conditions including Appendix O conditions, as described in more detail in the next section.

6.1. Icing Occurrence Analysis

Many statistical and climatological sources for icing frequencies have been assessed, including literature but also discussing with icing meteorology specialists. In particular for SLD occurrence there is no extensive data available, but some specific approaches can be found in literature. In addition, some dedicated analyses have been conducted in the context of the planning of the SENS4ICE icing flight campaigns. This is described in more detail in [22].

Considering not only meteorological, but also operational and safety aspects, the locations for the two flight campaigns were selected. For the flight campaign in North America the aircraft was located in Alton, Illinois, along the border between Illinois and Missouri, allowing to operate in regions of flat terrain to the west and south of the Great Lakes. For the campaign in Europe the aircraft was located in Toulouse, France, aiming at operations in southern France and off the French and Spanish Atlantic and Mediterranean coasts.

6.2. Airborne Reference Measurements Particularly for SLD Icing Atmosphere Characterization

Similar to IWT testing of novel ice detection technologies, detailed reference measurements are of great importance for evaluating sensor performance. The specific challenge for identifying SLD conditions is the combination of many small droplets and potentially only very few large droplets. The range of droplet diameters is very large, from below 10 µm up to more than 1000 µm. This is generally not covered in an appropriate way by a single instrument. Therefore, several instruments were selected in order to adequately cover this range of droplet diameters, described in more detail in [22]. The main reference instruments for the SENS4ICE flight campaigns are listed in TAB 3. Several DLR and Safire reference instruments installed on Safire’s ATR 42 are shown in FIG 7. Parameters of interest include the median volume diameter (MVD), liquid water content (LWC), cumulative mass distribution (CMD) and total water content (TWC).

Instrument	Measured parameter	Range	Reference
Cloud Combination Probe (CCP)	Cloud droplet number and size	2 – 960 µm	[12]
Precipitation Imaging Probe (PIP)	Cloud droplet and ice crystal number and size	100-6400 µm	[23]
High Speed Imager (HIS)	Droplet and Ice particle size and complexity	2-2000 µm	[24]
Nevzorov Probe	LWC and TWC	0.03 –3 g m-3	[12], [25]
Backscatter Cloud Probe with Polarization Detection	Droplet and ice crystal size and asphericity (phase)	2- 42 µm	[26]
Cloud Combination Probe (CCP)	Cloud droplet number and size	2 – 960 µm	[12]
Ice Crystal Detector	LWC and TWC	0.02 –5 g m-3	[27]

TAB 3 Main reference instruments for SENS4ICE European (first five in the list) and North American (last two in the list) flight test campaigns [22]

FIG 7 DLR and Safire instruments installed on Safire’s ATR-42 with ice accretion on the unheated parts while inside supercooled liquid clouds [image DLR]

Scientific reference instruments for detection of cloud particle number, size and phase were used to validate the performance of the new sensors and characterize the atmospheric icing conditions during the flights. The following classifications were applied for Appendix C and

O conditions [28]. The threshold for LWC is driven by the sensitivity of the reference instruments. The selection of the thresholds for maximum diameter D_{max} and temperature are following the approach of Cober and Isaac [29].

- Classification of Appendix C conditions:
  LWC > 0.025 g/m^3, D_{max} < 100 µm and negative temperatures
- Classification of Appendix O conditions:
  LWC > 0.025 g/m^3; D_{max} > 100 µm and negative temperatures

6.3. Meteorological Flight Campaign Support

Support by meteorological experts based on the use of extensive meteorological data is essential for successfully finding and sampling relevant icing conditions and in particular, SLD conditions. This applies both for flight planning and flight guidance. The support was provided externally for the North America campaign by Leading Edge Atmospherics (LEA) and for the Europe campaign by Météo France, DWD German Weather Service and LEA. Input for flight planning and guidance in order to find liquid water icing conditions and particularly SLD conditions included weather model forecasts, as well as tools for the prediction of icing, satellite and radar imagery, surface weather observations, balloon-borne soundings, pilot reports, and synoptic weather charts, as described in [22]. Among others, vertical profiles of temperature and moisture are crucial. In addition, the SENS4ICE project partners provided satellite-based retrievals of the presence of icing conditions including SLD (CIRA) [30] and information of the cloud phase (DLR) derived from Meteosat Second Generation on a nowcasting time scale. An overview of the meteorological conditions during the SENS4ICE airborne test campaigns is given in [31].

6.4. Flight Campaign North America

An Embraer Phenom 300 was equipped with flight test instrumentation including various reference sensors and several cameras for icing monitoring for a flight campaign in natural icing conditions in North America in late February / early March 2023 (FIG 8). In this campaign, four of the icing detection technologies under development in the SENS4CE project have been tested: AIP / AeroTex, IDS / Collins, SRP / Honeywell and PFIDS / Safran. Furthermore, the hybrid ice detection system (HIDS) developed by Safran, combining different detection technologies, was part of the flight testing, including the indirect ice detection system (IIDS) based on online aircraft performance evaluation developed by DLR.

15 flights with a total of 25 flight hours (including ferry and check flights, see TAB 4) have been successfully conducted allowing to target natural liquid water icing conditions and in particular SLD conditions.

The regions of sampling flights were mainly southeast, south and west of Lake Michigan in Northern America. FIG 9 shows a detailed overview of individual flights conducted as part of the campaign between 22 February and 10 March 2023 (not including all check flights). Flights were conducted from Alton/ St. Louis Regional Airport (KALN) and in several cases included refueling stops.

FIG 8 Embraer Phenom 300 with test sensors and reference instruments [image Embraer]

No	Date	Flight duration [hrs:min]	Comment
1	22 FEB 2023	0:39	Check flight
2	23 FEB 2023	2:45	Appendix O
3	23 FEB 2023	1:12	Appendix C
4	25 FEB 2023	2:03	Appendix O
5	25 FEB 2023	1:37	Appendix C
6	01 MAR 2023	2:45	Appendix O
7	01 MAR 2023	2:12	Appendix O
8	06 MAR 2023	1:07	Appendix C
9	06 MAR 2023	-	Dry Air
10	08 MAR 2023	2:21	Appendix O
11	08 MAR 2023	0:40	Return to base
12	08 MAR 2023	-	Check flight
13	09 MAR 2023	1:23	Appendix C
14	10 MAR 2023	2:15	Appendix O
15	10 MAR 2023	1:08	Appendix C

TAB 4 Flight campaign North America overview of flights

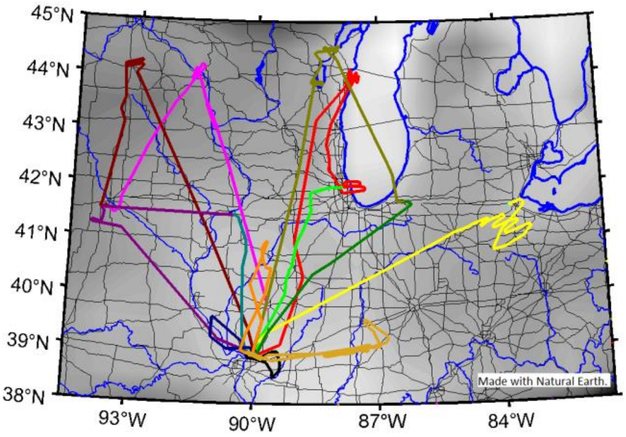

FIG 9 Flight Campaign North America Ground Tracks [Made with Natural Earth[1]]

A total of 55 encounters with icing clouds were flown, ranging from about 2 min to about 7 min duration. Exposure time is a function of LWC, where the higher the LWC the lower the exposure time. Generally, it is important to note that the icing encounters were purposely

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[1] Natural Earth -.Free vector and raster map data @ naturalearthdata.com

intended to be relatively short for safety reasons. Based on preliminary analysis, about 20% of the total flight time was in icing conditions, with about 12% in Appendix C and about 8% in Appendix O conditions. Finding and flying in SLD icing conditions is a challenging task. It appeared that ice visible on the windshield is typically serving as a good indicator for estimating icing conditions and ice accretion on the airframe FIG 10.

FIG 10 Ice accreted on Phenom 300 windshield after leaving clouds with supercooled liquid water [image Embraer]

Further detailed data analysis yields the icing encounter statistics shown in TAB 5 for the number of App. C and App. O encounters. For App. C conditions the liquid water content LWC was found to be below 0.8 g/m^3 in most cases. For App. O conditions encountered the LWC rarely exceeded 0.4 g/m^3 [28].

Further detailed data analysis yields the cumulated icing encounter durations per flight shown in TAB 6. Due to an instrument failure no valid data was acquired with the flight on 08 MAR 2023.

Date	**Flight ID**	**App. C**	**App. O**
23 FEB 2023	F1475-1	20	5
23 FEB 2023	F1475-2	4	0
25 FEB 2023	F1476	20	7
01 MAR 2023	F1477-1	17	3
01 MAR 2023	F1477-2	9	8
06 MAR 2023	F1478	11	4
09 MAR 2023	F1481	11	3
10 MAR 2023	F1482	23	0

TAB 5 Flight campaign North America icing encounter statistics [28]

Date	**Flight ID**	**App. C duration [mm:ss]**	**App. O duration [mm:ss]**
23 FEB 2023	F1475-1	20:18	09:03
23 FEB 2023	F1475-2	19:59	00:00
25 FEB 2023	F1476	38:47	22:24
01 MAR 2023	F1477-1	31:03	03:55
01 MAR 2023	F1477-2	14:30	07:31
06 MAR 2023	F1478	43:24	04:20
09 MAR 2023	F1481	15:51	02:46
10 MAR 2023	F1482	79:59	00:00

TAB 6 Flight campaign North America cumulated icing encounter durations per flight [28]

6.5. Flight Campaign Europe

The French ATR 42 environmental research aircraft of Safire was equipped with flight test instrumentation including various reference sensors and several cameras for icing monitoring for a flight campaign in natural icing conditions in Europe in April 2023 (FIG 11). In this campaign, the following four of the icing detection technologies under development in the SENS4CE project have been tested: FOD / INTA, LILD / DLR, AMPERA/ ONERA and CM2D/ DLR. The hybrid ice detection system (HIDS / Safran), combining different detection technologies, was part of this flight test campaign, including the indirect ice detection (IIDS / DLR).

FIG 11 SAFIRE ATR 42 with test sensors and reference instruments [image DLR]

15 measurement flights (and in addition several check flights) with a total of about 50 flight hours have been successfully conducted targeting natural liquid water icing conditions and in particular SLD conditions (TAB 7 and ground tracks FIG 12).

SENS-4ICE flight no	Safire Flight ID	Date	Flight Du-ration [hrs]	Time (UTC)
1	as230009	2023-04-03	3.5	06:08-09:38
2	as230010	2023-04-04	1.3	11:38-12:53
3	as230011	2023-04-04	1.3	13:11-14:30
4	as230012	2023-04-06	0.4	07:14-07:40
5	as230013	2023-04-14	4.9	04:36-09:29
6	as230014	2023-04-15	2.3	06:03-08:19
7	as230015	2023-04-18	3.2	13:56-17:05
8	as230016	2023-04-20	2.7	10:40-13:20
9	as230017	2023-04-22	2.8	06:03-08:52
10	as230018	2023-04-24	4.5	12:22-16:52
11	as230019	2023-04-25	4.9	11:03-15:54
12	as230020	2023-04-26	2.4	06:30-08:54
13	as230021	2023-04-26	3.6	13:34-17:08
14	as230022	2023-04-27	3.4	06:33-09:58
15	as230023	2023-04-27	3.7	12:07-15:46

TAB 7 Flight campaign Europe overview of flights

Further detailed data analysis yields the cumulated icing encounter durations per flight shown in TAB 8. Note that for some flight no or incomplete data was collected due to technical problems.

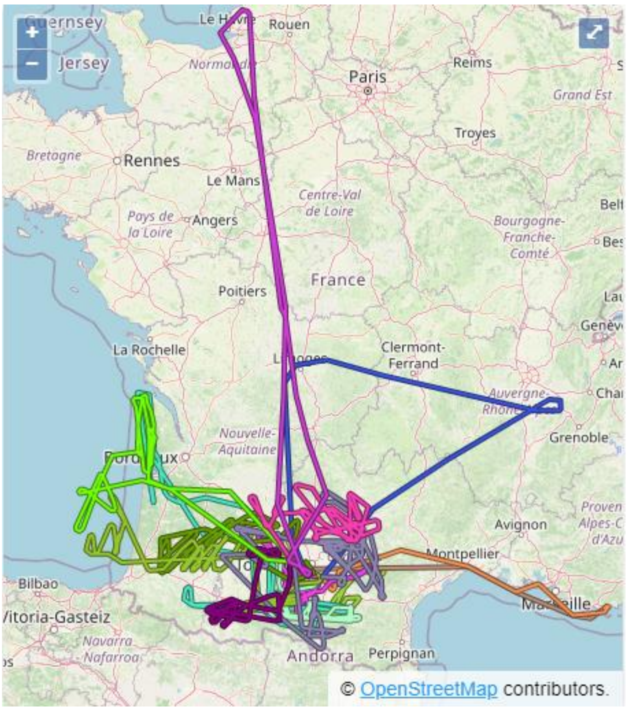

FIG 12 Flight Campaign Europe Ground Tracks [Map Data From OpenStreetMap, image credit SAFIRE]

Date	SENS4ICE flight no	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

TAB 8 Flight campaign Europe cumulated icing encounter durations per flight [28]

7. ICING DETECTION TECHNOLOGIES FLIGHT TEST EVALUATION

Reference measurements with scientific instruments provide precise information about the atmospheric conditions, particularly characterising encountered icing conditions. Based on this, the different ice detection technologies are evaluated, which is comprising the direct ice detection sensors and the hybrid ice detection system including the indirect detection. Only preliminary evaluations are available as the final data analysis is still ongoing. For several detection technologies preliminary results and examples for evaluation are shown in the remainder of this section.

AIP / AeroTex

The AeroTex AIP ice detection concept is described and evaluated in [32]. Flight test results reveal that system capabilities for the detection of icing conditions and the differentiation between small and larger droplet distributions were successfully demonstrated.

IDS / Collins

The Collins Ice Differentiator System (IDS) is described and evaluated in [33]. Flight test results have proven system robustness and demonstrated the capability to successfully detect icing in flight.

SRP / Honeywell

The SRP sensor participated in the SENS4ICE flight campaign performed by Embraer in North America. Reference measurement data for atmospheric conditions was provided by DLR. Eight flights were conducted with SRP with reference measurement data available. Appendix C and Appendix O conditions encountered multiple times. The optical particulate sensor data collection was successful. The 2nd generation version of the optical sensor has the following measurement properties:

- Direct particle sensing for particles of size 50 – 1000 µm
- Background signal analysis for particles of size 5 – 50 µm

The sensor measurement performance was evaluated using reference data provided by DLR. Accurate results were obtained for events in which particulate MVD values exceeded MVD > 25 µm [34]. The sensor underestimates TWC for events in which particulate MVD is lower than MVD < 15-20 µm. Detailed results are provided for Flight 1476 (FIG 13). No collection efficiency corrections applied, sensor non-linearities corrections not applied, better results are expected. A high correlation between reference and optical sensor data is observed (first subplot). Accurate indication of icing conditions and Appendix O conditions is exhibited (2nd subplot). DV99 values are well matched with reference instrumentation data (3rd subplot). Next steps include to integrate the 1st and 2nd generation optical sensor design into a single unit to cover all Icing Appendices (App C, O, D/P).

FOD / INTA

The FOD / INTA sensor has shown an acceptable performance if the LWC reaches a certain point (0.1 g/m3). For this sensor the detection algorithm was defined according to several IWT tests [35], [36]. The atmospheric clouds are not as homogeneous as the icing wind Tunnel clouds, so it would be necessary to redefine the algorithm for inflight conditions. This sensor has the possibility of detecting in different points of the probe, so depending on the conditions, different detection points were activated (if there are Appendix O or glaze conditions).

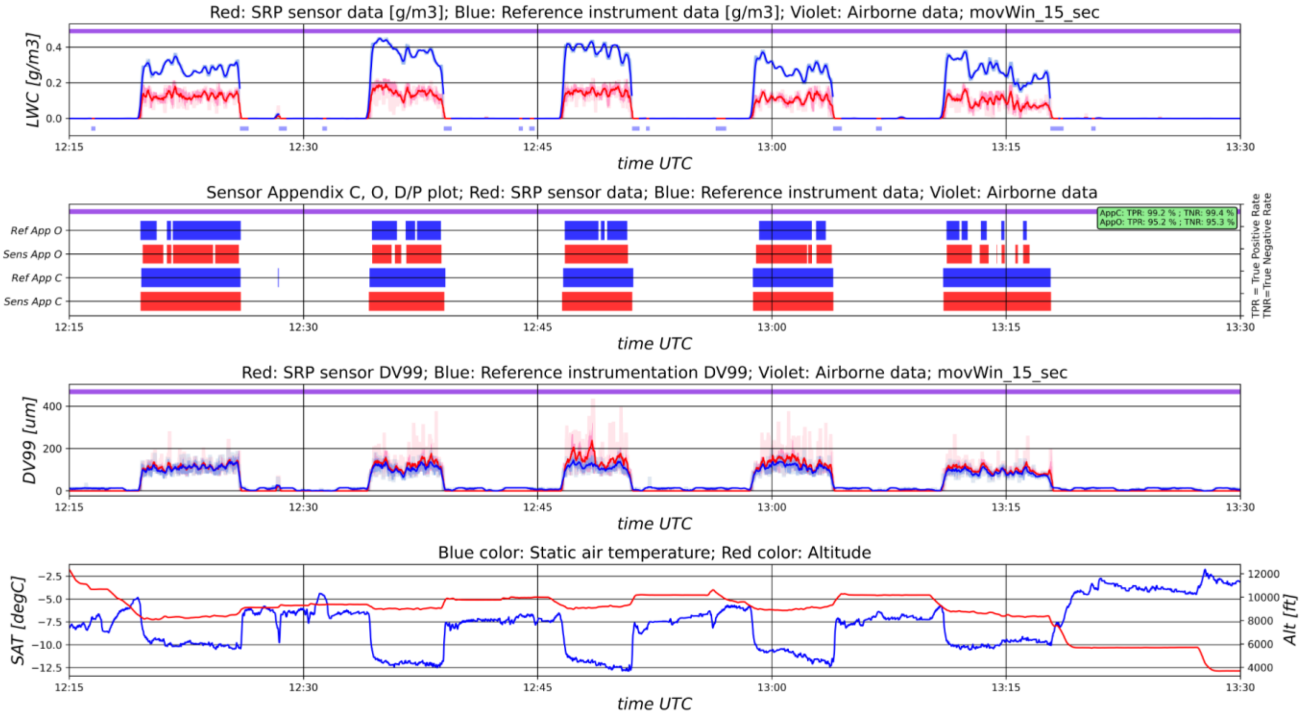

FIG 13 SRP / Honeywell optical sensor data analysis SENS4ICE North America flight campaign flight 1476 [Courtesy of Honeywell]

LILD / DLR

The DLR LILD sensor ice present signal has shown a very good correlation with the DLR microphysics icing flag in terms of detecting a beginning ice accretion at a clean airfoil. The delay was very minimal and even very thin ice layers with minimal LWC were detected. After the ice accretion was detected, the ice present signal stayed high until the aircraft was deiced by descending into a warm layer of air. The measurement of the ice thickness and accretion rate is currently associated with uncertainties since the temperature cross influence to the sensor signal is not yet fully compensated. More information concerning LILD can be found in [37].

AMPERA/ ONERA

Throughout the European SENS4ICE flight campaign, the AMPERA system exhibited exceptional robustness, with no observed technical issues in either the hardware or the software components. The system exhibited a response time of approximately one second when entering and exiting clouds with particles and the measurements inside the clouds were at least two orders of magnitude higher compared to the baseline measurements in clear air. Preliminary analysis and comparisons conducted with the reference probe revealed a strong correlation between the measured LWC and the electrostatic potential, as well as good agreement in icing flag detection.

The preliminary analysis and comparisons conducted with the reference probe have shown a strong correlation between the shape and variations of the measured LWC and the electrostatic potential [38]. FIG 14 depicts the comparison between the AMPERA output and the “Robust” reference probe from SAFIRE, highlighting a significant agreement between the two signals. In order to calculate a real-time atmospheric icing detection flag, ONERA proposed, during the flight campaign an “AMPERA flag” derived from three parameters: the aircraft potential, the static temperature and dew point temperature.

When comparing this flag with the airframe ice accretion flag obtained from the Rosemount Ice detector, it was observed that the AMPERA flag demonstrates higher sensitivity. This is because the AMPERA flag considers the specific atmospheric conditions encountered by the aircraft during flight, while the Rosemount flag primarily accounts for ice accretion.

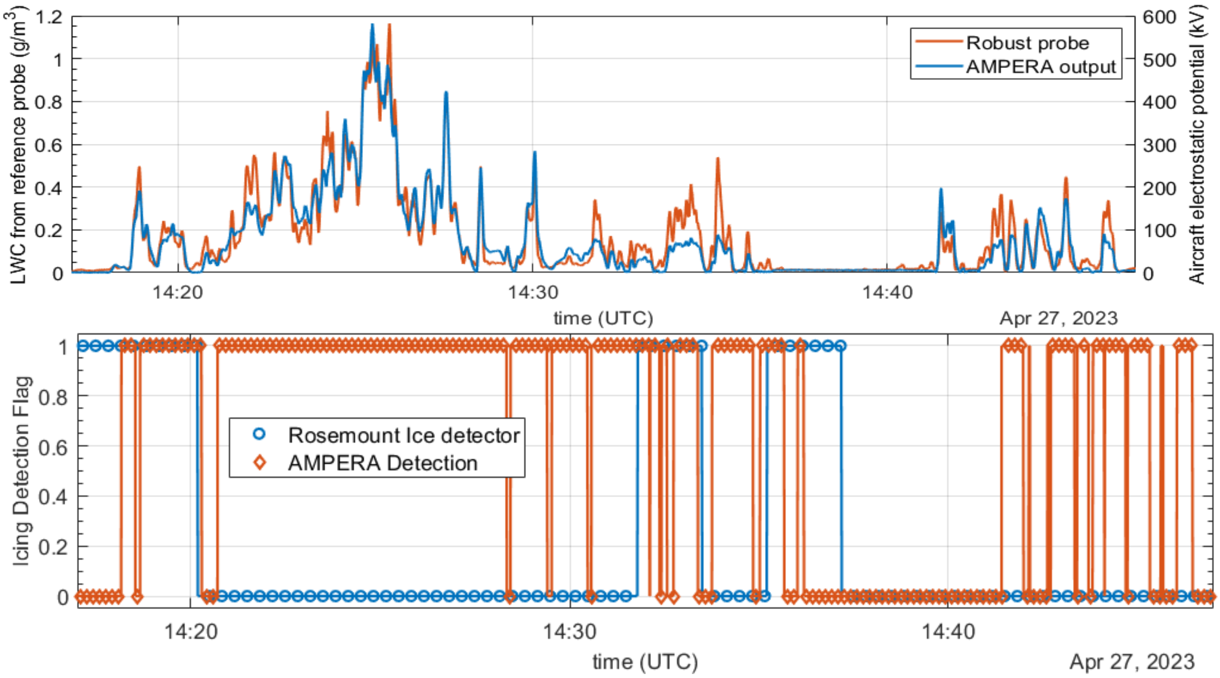

FIG 14 LWC and Aircraft electrostatic potential comparison (upper) and AMPERA atmospheric icing flag and Rosemount Ice accretion flag (lower) (Courtesy of ONERA)

IIDS / DLR

The performance-based (indirect) ice detection methodology is one pillar of the hybrid ice detection approach and based on the changes of airplane flight characteristics under icing influence. During the two campaigns and the various icing encounters the IIDS was able to reliably detect the aircraft flight performance degradation caused by ice accretion on the aircraft after the icing conditions were encountered. Postflight analysis of the data for both campaigns reveal that the IIDS implementation could be even enhanced by slight modification of the detection algorithm or even a reduction of the detection threshold to provide an even faster response to icing-induced performance degradation. The IIDS implementation further proved the expected retrofit capabilities of the method as a simple software solution providing a highly beneficial information about the remaining aircraft capabilities for safe aircraft operations [39]. FIG 15 shows the time history of IIDS system performance during a specific icing encounter from one example flight of the North America flight test campaign with the Phenom 300 prototype. Once liquid water icing conditions are present, as indicated by MVD and LWC reference measurements, the estimated drag is increasing and an icing detection is confirmed subsequently. Respectively, once the temperature is increasing above zero degree Celsius, the estimated drag is decreasing and subsequently no icing is indicated.

HIDS / Safran

FIG 16 shows HIDS preliminary results for the combined PFIDS / IIDS for the flight 1476-1 of the North America flight campaign. During this flight 5 App O conditions were encountered. Both PFIDS and IIDS were able to detect these conditions. In particular, PFIDS detected each icing encounter very fast, within 10-15s, and the provided IAR, measured on the PFIDS target, is well correlated to the ICD probe LWC signal [40]. Note that further studies are needed to correctly estimate the PFIDS installation factor (IF) in order to evaluate the icing condition LWC thanks to the PFIDS IAR measures

$$LWC = IAR_{PFIDS} \cdot \rho_i / (TAS \cdot IF).$$

Indirect Detection, instead, need some ice accretion on the airframe to detect a performance degradation, for this reason, the response times are of the order of one minute. It is interesting to note that if the PFIDS ICE Flag stops to indicate ice once the aircraft exits the icing cloud, the IIDS continues to detect a performance degradation possibly due to some residual ice on the airframe. This could indicate an insufficient airframe de-icing process.

HIDS, via the Arbitration function, associates direct and indirect detections, check the availability of the two sources and provides a synthetic. The HIDS ICE flag, indeed, encloses PFIDS and IIDS ICE Flags in order to assure a fast ice detection and the monitoring of A/C performance. Moreover, thanks to the detector IAR or LWC measures, HIDS is able to provide information about the severity of the encountered condition. For the analysed flight, when the $IAR_{PFIDS} > 1.25$ mm/min, a standard threshold coming from the pilot classification of icing conditions, the HIDS ICE Flag goes from 1 to 2. Note that such IAR threshold can be defined together with the aircraft manufacturer in order to be adjusted for aircraft characteristics.

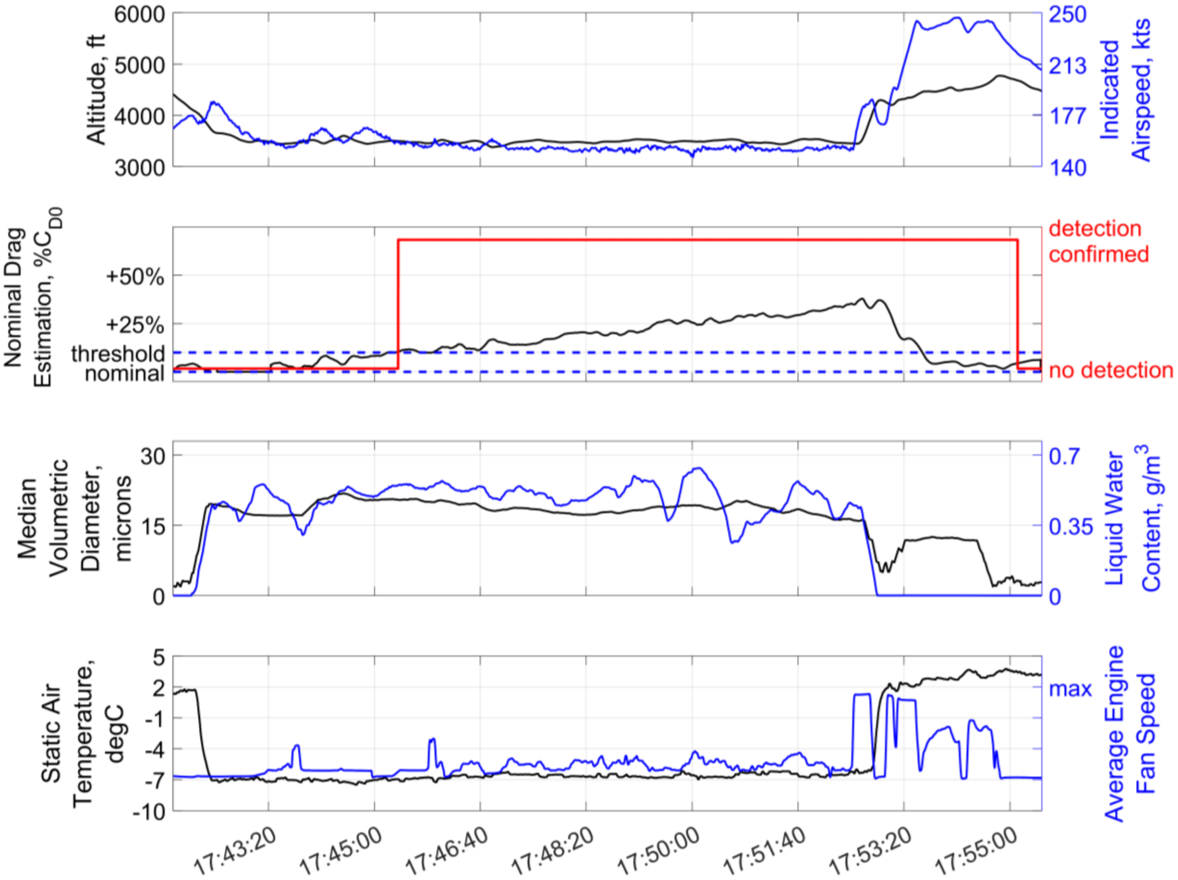

FIG 15 Time history of IIDS system performance during specific icing encounter from one example flight of the North America flight test campaign with the Phenom 300 prototype (February 23rd, 2023, 17:41:49 UTC to 17:55:29 UTC): altitude and indicated airspeed (top), nominal drag estimation and IIDS detection output (second plot), and MVD and LWC of encountered icing conditions (third plot), and static air temperature and average engine fan speed (bottom); detection threshold at 10 % relative drag increase [39].

8. SUMMARY AND CONCLUSIONS

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

In the first part of the project, icing detection technologies have been developed specifically aiming at Appendix O icing conditions. Icing wind tunnels have improved their capabilities for representing Appendix O conditions. Direct ice detection sensors have been tested successfully in icing wind tunnels under both Appendix O and Appendix C conditions. A hybrid ice detection system is developed, containing a performance-based indirect ice detection. The second part of the project is dedicated to two flight campaigns in order to test ice detection technologies in natural icing conditions, with a focus on Appendix O. These flight tests have been conducted in early 2023 showing promising initial results in terms of encountered icing conditions, sensor detection behavior and hybrid ice detection system performance including the indirect ice detection. Generally, the SENS4ICE icing detection technologies have demonstrated to detect relevant liquid water icing conditions in real-time in real flight. The final data evaluation is still ongoing. Final project results will be released by the end of the project end of 2023.

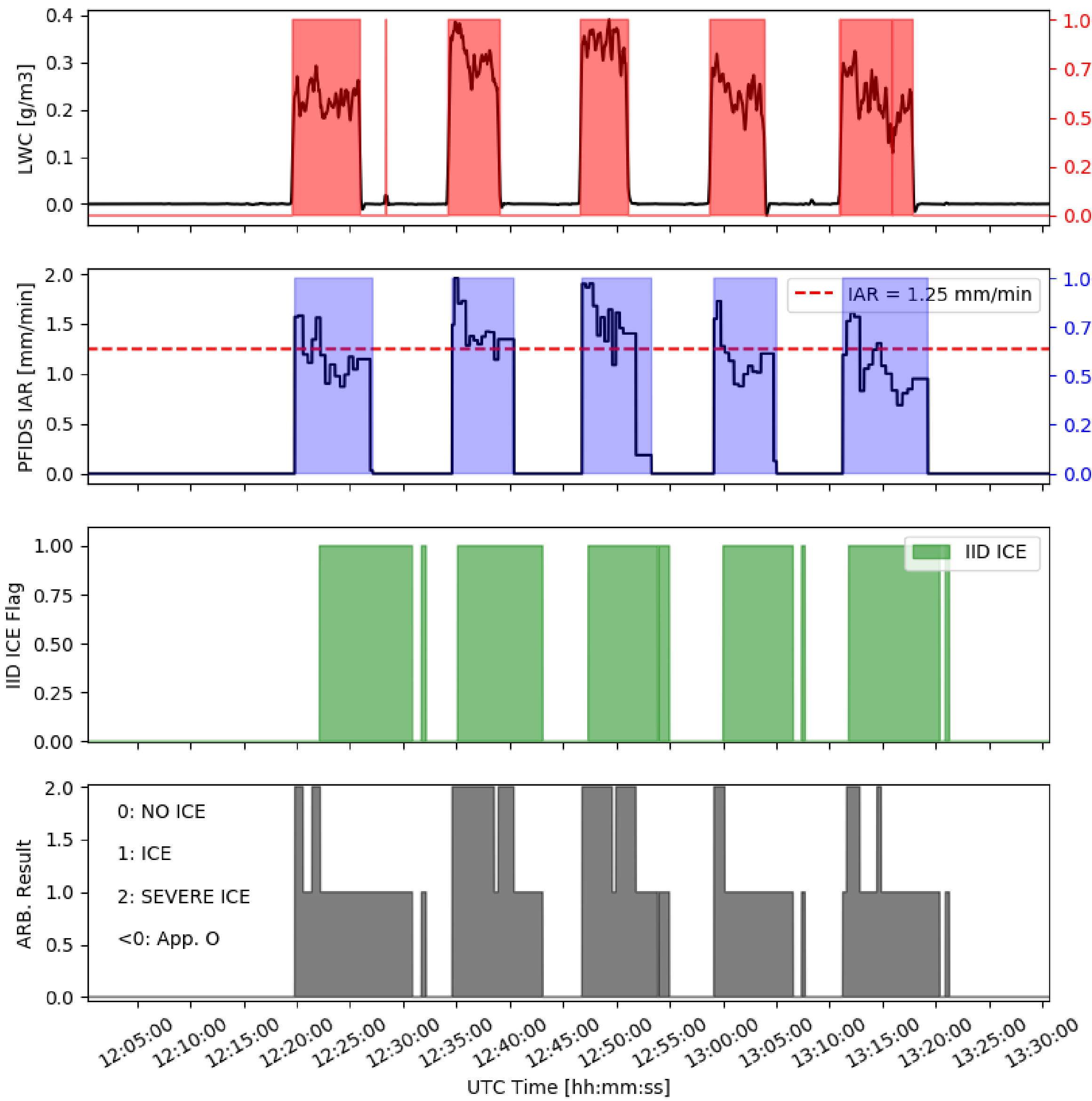

FIG 16 HIDS results for the couple PFIDS/HIDS for the North America FT 1476-1. From the top to the bottom: LWC curve and microphysics reference ICE FLAG; PFIDS IAR and ICE Flag; IID Validated ICE Flag (i.e. IID reliable and TAT<5°C); HIDS PFIDS/ IIDS arbitration output. [Courtesy of SAFRAN Aerosystems]

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DISCLAIMER

The Phenom 300 flight test data analyzed is based on an experimental prototype. This aircraft prototype has embedded additional flight test instrumentation and features that do not represent any certified Phenom 300 aircraft model. Therefore, the analysis and performance estimations assessed in the study environment, and performed by the SENS4ICE project team, do not represent the Phenom 300’s certified performance.

DEFINITIONS/ABBREVIATIONS

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
CNRS	*Centre national de la recherche scientifique* (French National Centre for Scientific Research)
CS	Certification Specifications
DLR	*Deutsches Zentrum für Luft- und Raumfahrt* (German Aerospace Center)
D_{max}	Maximum diameter
DWD	*Deutscher Wetter Dienst* (German Weather Service)
FAR	Federal Aviation Regulations
FOD	Fiber Optic Detector
HIDS	Hybrid Ice Detection System
ICD	Ice Crystal Detector
IDS	Ice Differentiator System
IIDS	Indirect Ice Detection System
IM	Intermittent Maximum
INTA	*Instituto Nacional de Técnica Aeroespacial* (National Institute of Aerospace Technology)
IWT	Icing Wind Tunnel
LEA	Leading Edge Atmospherics
LILD	Local Ice Layer Detector
LW	Liquid Water
LWC	Liquid Water Content
MVD	Median Volume Diameter
NRC	National Research Council Canada
ONERA	*Office national d’études et de recherches aérospatiales* (The French Aerospace Lab)
PFIDS	Primary in-Flight Icing Detection System
PIP	Precipitation Imaging Probe
SAFIRE	*Service des Avions Français Instrumentés pour la Recherche en Environnement* (The French facility for airborne research)
SEA	Science Engineering Associates
SENS4ICE	SENSors and certifiable hybrid architectures for safer aviation in ICing Environment
SLD	Supercooled Large Droplets
SRP	Short Range Particulate
TUBS	*Technische Universität Braunschweig* (Technical University Braunschweig)
TWC	Total Water Content
UTC	Coordinated Universal Time