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SENS4ICE EU project preliminary results

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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 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 an indirect technique based on changing aircraft characteristics. The first part of the project was devoted to the development and maturation of icing detection technologies, with a focus on Appendix O (of 14 CFR Part 25 and CS-25) icing conditions. Furthermore, several icing wind tunnel facilities have improved capabilities to represent Appendix O conditions. Icing wind tunnel testing (including Appendix O) of several icing detection sensors developed in the SENS4ICE project concluded the first part of the project. An overview of initial results is provided. The second part of the project is dedicated to flight testing 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 the indirect ice detection system. Extensive meteorological and climatological analysis was done in order to have the best chances to encounter icing conditions including Appendix O conditions.

Introduction

Modern airplanes have well established means 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, 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. It became obvious that there are certain 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 and/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 ensure safety of flight in these conditions. A 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 Horizon 2020 project SENS4ICE directly approaches this need for reliable detection and discrimination between Appendix C and O icing conditions [3].

While considerable progress has been made on icing detection, there are substantial gaps specifically regarding the different icing conditions. This is in the scope of the novel approach of the SENS4ICE project [4]. A smart way to tackle the complex problem of ice detection is the hybridization of different detection techniques [5]. 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 serves to provide a more robust and reliable detection for a wide range of icing conditions. This integrated approach aims not only to provide 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 addressing 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, as well as the final airborne demonstration of technology capabilities in relevant natural icing conditions [6]. In particular, hybridization activities are conducted in close cooperation with regulation authorities aiming at the development of acceptable means of compliance.

Icing Wind Tunnel Upgrading and Reference Measurements

In order to test the novel ice detection technologies developed/matured as part of the SENS4ICE project in particular in SLD conditions, three icing wind tunnel (IWT) test facilities were involved:

- Collins Aerospace Icing Wind Tunnel
- TUBS BIWT (Braunschweig Icing Wind Tunnel) [7]
- National Research Council (NRC): Altitude Icing Wind Tunnel (AIWT) [8].

While the NRC AIWT already provided the capability to achieve SLD in full bimodal freezing drizzle conditions, the other two icing wind tunnel facilities improved their capabilities to represent Appendix O conditions in the scope of the SENS4ICE project. These improvements mainly included adapting the spray nozzle setup and were aiming at freezing drizzle conditions, while 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 be able 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) [9] 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 [9]. 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 [10]. From the icing wind tunnel perspective, it is concluded that further collaborative efforts are needed for product development and certification in standardized SLD conditions. International exchange and collaboration will be particularly useful to achieve this goal.

Direct Ice Detection Technology Development

The first part of the project was mainly dedicated to 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 diverse 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 at very low levels and others having had already passed steps of technology testing. In the first phase of the project, all sensors reached the status to be ready for icing wind tunnel testing, see 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)) aims to improve airborne scientific and reference measurements. The other nine are targeting applications for operational air transport. The sensor technologies can be clustered into two categories, atmospheric sensors, that are measuring the atmospheric conditions, and accretion sensors, that are measuring ice accretion on the aircraft. Table 1 gives an overview of the icing sensor technologies under development in the SENS4ICE project.

Table 1 SENS4ICE sensor technologies overview, sensor types and principles

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

Direct Ice Detection Technology IWT Testing and Evaluation

A first major technology evaluation was conducted based on IWT results. A standardized testing procedure and partly common test points between the different icing wind tunnels serve for adequate comparability of the results.

Significant emphasis was put on the development of test matrices for each involved IWT facility following the guidelines of ED-103 [11]. As the setup and capabilities of each IWT facility vary, icing envelopes differ 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 (Table 2).

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

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

Apart from the reference instruments, eight technologies have provided testing results in different icing wind tunnels in Appendix C and O conditions. Due to the fact that the sensor technology AMPERA (ONERA) uses the aircraft as a sensor (measurement of aircraft electric potential), 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 [12]. 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. Furthermore, some sensors are capable of providing specific relevant icing parameters like liquid water content and median volume diameter, which is considered as very beneficial 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 [9] and in more detail in [13], [14] and [15].

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 1, excluding DLR's CM2D scientific/reference sensor, one sensor that completed a more basic test matrix due to technical problems and another sensor with results subject to export control restrictions.

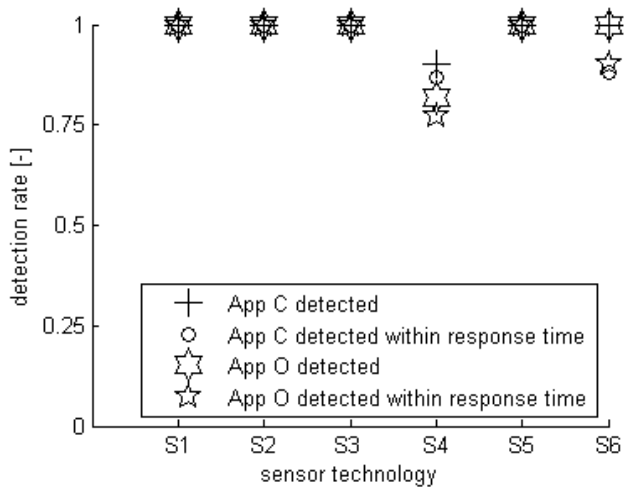

Figure 1 SENS4ICE sensor technologies IWT testing detection rates overview for App. C and O icing condition test points

SENS4ICE sensor IWT testing provided valuable results for the sensor technology development and revealed that the technologies under development can be considered as promising. Furthermore, IWT test results established a profound basis for the project internal technology evaluation and selection process.

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 (see next section). 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.

Technology evaluation was greatly supported by the SENS4ICE Advisory Board composed of aviation certification authorities, aircraft manufacturers, pilot representatives and research institutions. A multi-stage 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 valuable for the further technology 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.

Hybrid Ice Detection

The idea for the hybrid ice detection system (HIDS), mainly developed by Safran in SENS4ICE, is to combine various technologies utilizing different physical principles in order to use 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 intention to provide a more robust and reliable detection (Figure 2).

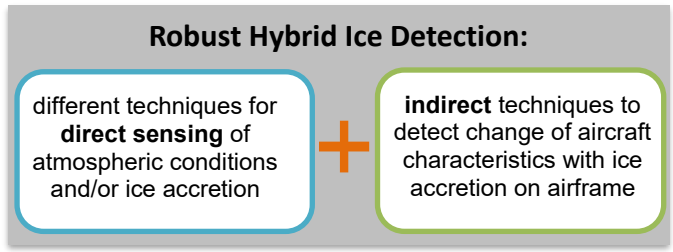

Figure 2 Robust Hybrid Ice Detection Concept Depiction

HIDS Development

In the first 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 a suitable 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 dedicated 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 deriving an overall output signal for icing detection by combining the various input sources (Figure 3).

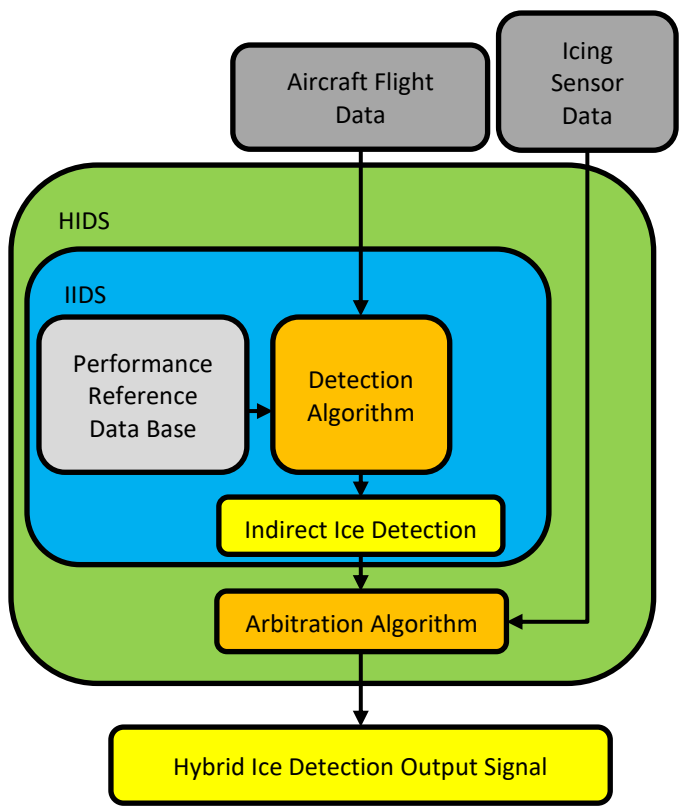

Figure 3 HIDS concept including indirect ice detection system IIDS [based on 16]

Indirect Ice Detection

As an integral 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 [17], [18]. 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 [16]. This leads to the expectation that the behavior may be similar for flights in Appendix O conditions.

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 pave the way towards industrialization and operational application and also to support 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 demonstrate eight of the direct ice detection technologies under development and in addition the hybrid ice detection system including the indirect ice detection system 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

Apart from aircraft interface definitions for direct, indirect and hybrid detection technologies, particular focus was put on selecting suitable aircraft locations for mounting external sensors in order to allow for good icing detection. Further emphasis was put on ensuring adequate reference measurements. These reference measurements serve as a profound basis for analysis of flight test data and technology evaluation. Aircraft specific safety requirements and flight procedures have been developed, 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 undertaken in order to select suitable regions to encounter icing conditions including Appendix O conditions, as described in more detail in the next section.

Icing Frequencies Analysis

Various statistical and climatological sources for icing frequencies have been consulted, including literature but also discussion with icing meteorology specialists. In particular for SLD occurrence there is no extensive data available, but some specific approaches can be found in literature.

Bernstein et al. [19] and Bernstein and Le Bot [20] used a method called CIP-sonde to determine the potential for icing and SLD icing (ICEPOT and SLDPOT) using coincident observations from balloon-borne soundings and surface stations, with the output provided on a scale of 0 (no icing/SLD evident) to 1 (icing/SLD very likely). A value of 0.15 was deemed suitable to represent conditions to have "at least some chance" for icing/SLD to be present. In [20], the Météo France SIGMA icing index was also applied to assess the potential presence of icing based on a gridded, global re-analysis of temperature and relative humidity. The icing index used these fields to indicate the chances for icing from 0 (no icing) to 10 (icing very likely). This analysis, as well as ICEPOT results from CIP-Sonde, indicated that both North America and Europe have regions with icing frequencies high enough to be of interest for natural icing flight campaigns.

In an unpublished study, the CIP-Sonde technique described in [19 and 20] was used to assess the monthly frequency of SLD potential using North American data from 1997 to 2001. Figure 4 shows the frequency of SLDPOT ≥ 0.15 in the column for February 1997-2001. There are two distinct maxima present. One along the Pacific Coast from Alaska to Oregon, and the other in a broad swath from northeastern Texas through the Appalachians to the coasts of New England and southeastern Canada.

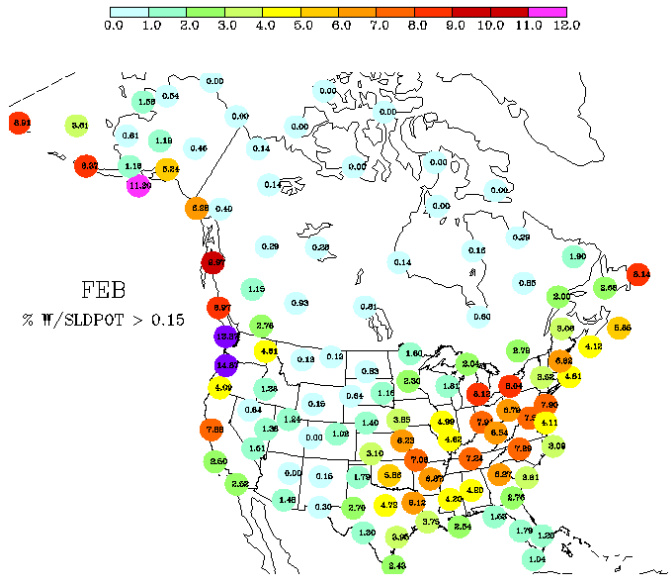

Figure 4 Full column frequencies of days with SLD icing occurrence (CIP-sonde) for North America for February 1997-2001, using an SLDPOT threshold of 0.15 [image provided by Ben Bernstein]

For Europe, the frequency of SLD was estimated using an SLDPOT threshold of 0.4 in [20] to represent a higher chance for SLD to be present. Here it was found that in April, SLDPOT ≥ 0.4 was indicated more than 8% of the time found in the northwestern part of Europe (see Figure 5). Lower SLD frequencies were found in parts of southwestern Europe, but frequencies were still 3-8% in some cases.

Based on this approach, additional and more detailed analyses including icing frequencies depending on locations and time of the year have been conducted with several partners based on different data sources as described in [21]. 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.

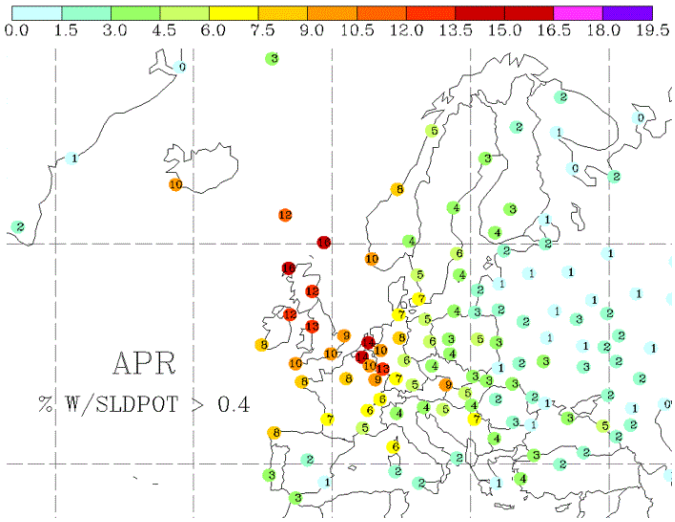

Figure 5 Full column frequencies of days with SLD potentials (SLDPOT) ≥0.40 as described in [20] [image provided by Ben Bernstein].

Airborne Reference Instruments Particularly for SLD Icing Atmosphere Characterization

Similar to IWT testing of novel ice detection technologies, detailed reference measurements are of high importance in order to evaluate sensor performance. The particular 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 a suitable way by a single instrument. Therefore, several instruments were selected in order to appropriately cover this range of droplet diameters, described in more detail in [21]. Parameters of interest include the median volume diameter (MVD), liquid water content (LWC), cumulative mass distribution (CMD) and total water content (TWC). A variety of instruments have been provided by the project partners Embraer (Phenom 300 operator), CNRS/SAFIRE (ATR 42 operator) and DLR and as an external partner for the Phenom 300 flight tests SEA. This is described in further detail in [21] and for example includes the flight proven instruments Nevzorov Probe (Figure 6, modified with an additional 12 mm TWC sensor [22]), Precipitation Imaging Probe (PIP), Cloud Combination Probe (CCP) with Cloud Droplet Probe (CDP, Scattering probe for particle size measurements from 2 – 50 µm) and Cloud Imaging Probe (CIP, Optical array probe for particle size measurements from 15 – 950 µm) and Ultra-High Sensitivity Aerosol Spectrometer (UHSAS). SEA provided a hot-wire Ice Crystal Detector (ICD) [23, 24].

Figure 6 Nevzorov Probe installed on SAFIRE ATR 42 (image DLR)

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 [21]. 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) [25] 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 [26].

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. 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) have been successfully conducted allowing to target natural liquid water icing conditions and in particular SLD conditions. 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 intended to be relatively short for safety reasons. Based on preliminary analysis, about 20% of the flight was in icing conditions, with about 12% in Appendix C and about 8% in Appendix O conditions. 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.

The regions of sampling flights were mainly southeast, south and west of Lake Michigan in Northern America. Figure 7 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.

Preliminary results generally suggest that the different icing detection technologies have been able to detect relevant conditions [27, 28, 29].

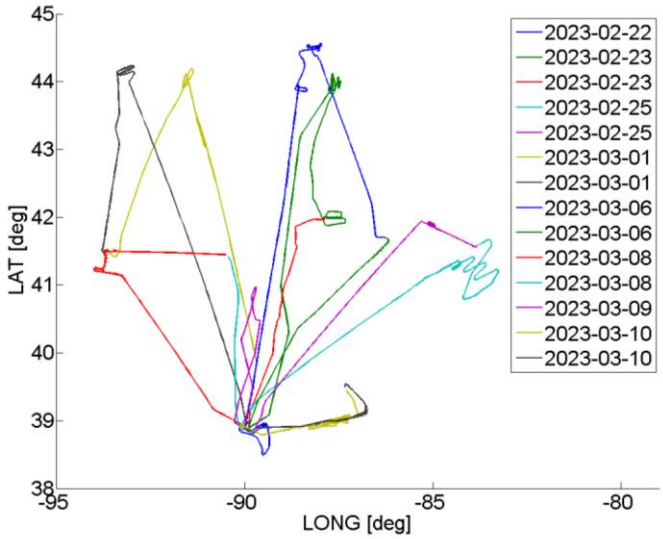

Figure 7 SENS4ICE flight campaign North America February/March 2023 overview of flight tracks for flights in natural icing conditions

In order to apply the IIDS for the considerably modified test aircraft, an updated aircraft performance reference model was estimated based on previous clean air flights of the aircraft with the specific flight campaign modifications, which is therefore only applicable for the specific experimental prototype and not representative for the certified aircraft model (see section Disclaimer below). Based on preliminary flight data analysis the IIDS was tuned to detect icing on the Phenom 300 aircraft. Hence the IIDS was able to reliably detected the icing influence on the aircraft during the icing cloud encounters, both in Appendix C and O conditions. Figure 8 shows preliminary evaluation results of an example encounter. Once the reference instruments detect liquid water due to noticeable MVD (only instantaneous and non-filtered values without any postprocessing shown here) and LWC values the performance indicator parameter starts to increase. After passing a threshold and based on a confirmation time, the IIDS ice detection signal is triggered within about 100 s.

In a preliminary application scenario shown here as an example, the HIDS is combining the IIDS with one direct ice detection sensor (PFIDS). As the reference instruments indicate significant MVD and LWC values, the hybrid system triggers an ice detection signal based on the combined analysis of the individual detection signals (Figure 9).

Based on initial analysis the SENS4ICE North America flight campaign provides a very good amount of measurements of liquid water icing conditions and SLD conditions in particular. Preliminary assessment of ice detection technologies shows that successful detections have been achieved, while detailed evaluations are still ongoing.

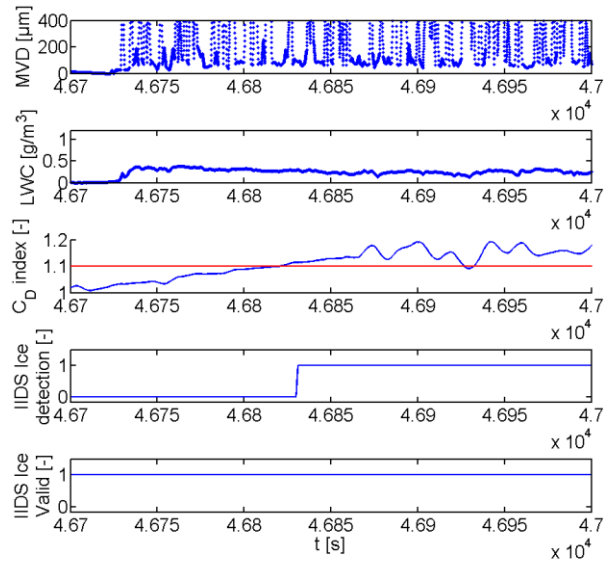

Figure 8 IIDS flight test 25 Feb 2023 outcome example based on preliminary analysis and compared to preliminary results for MVD and LWC

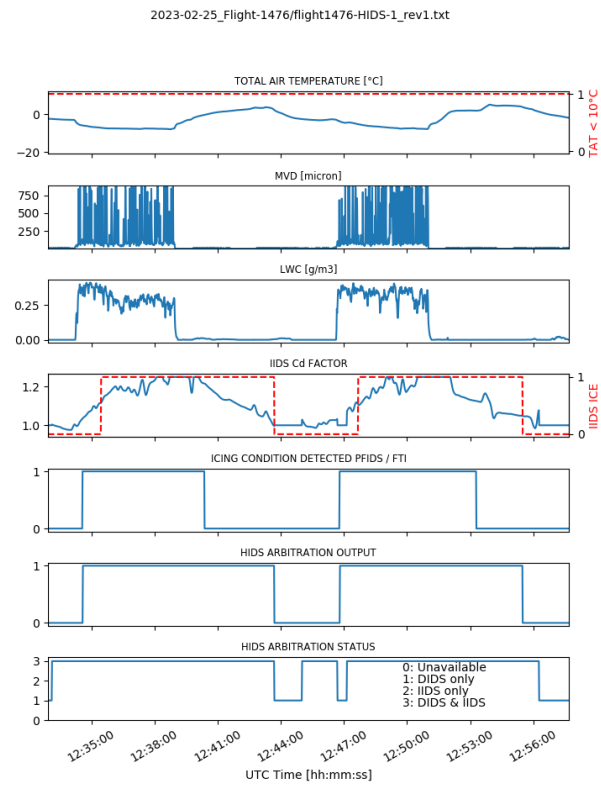

Figure 9 HIDS flight test 25 Feb 2023 outcome example based on preliminary analysis and compared to preliminary results for MVD and LWC

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 (Figure 10). 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 system (IIDS / DLR).

Figure 10 SAFIRE ATR 42 with test sensors and reference instruments [image DLR]

Figure 11 shows the approximated possible measurement flight region for the instrumented Safire ATR 42 aircraft based at Francazal airport (LFBF). It is important to note that airspace structure implications may limit the selection of flight areas.

Figure 11 Approximated possible measurement flight region for European SENS4ICE flight campaign with aircraft based at Francazal airport (Toulouse, France)

15 flights with a total of about 50 flight hours have been successfully conducted targeting natural liquid water icing conditions and in particular SLD conditions. Figure 12 shows an example of the SAFIRE ATR 42 horizontal tail with ice accretion.

Based on initial analysis the SENS4ICE Europe flight campaign provides extensive measurements of liquid water icing conditions including SLD conditions and the preliminary assessment of ice detection technologies shows that promising detection results have been achieved, while detailed evaluations are still ongoing.

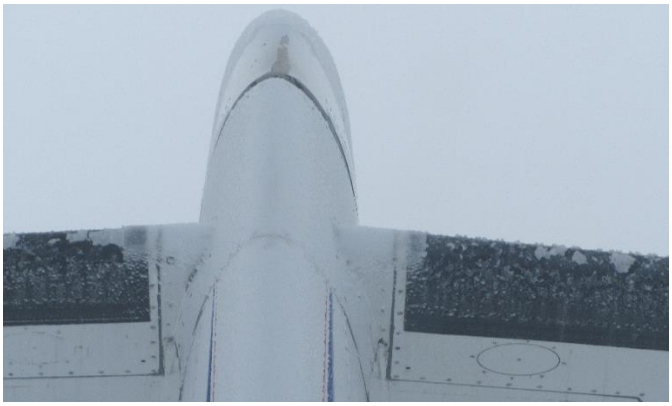

Figure 12 SAFIRE ATR 42 horizontal tail with ice accretion [image DLR]

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 enhanced 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 under development, incorporating a performance-based indirect ice detection system. The second part of the project is devoted to two flight campaigns in order to test ice detection technologies under 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 system. The final data evaluation is still ongoing. Final project results will be released by the end of the project end of 2023.

References

1. European Aviation Safety Agency, Certification Specifications and Acceptable Means of Compliance for Large Aeroplanes CS-25 Amendment 22, 5 November 2018.
2. Federal Aviation Administration, Code of Federal Regulations (CFR) Title 14 Aeronautics and Space Chapter I Federal Aviation Administration, Department of Transportation Subchapter C Aircraft Part 25 Airworthiness Standards: Transport Category Airplanes.
3. CORDIS EU Research and Development Information Service: SENS4ICE project profile https://cordis.europa.eu/project/id/824253 (accessed 05 MAY 2023)
4. SENS4ICE project website https://www.sens4ice-project.eu (accessed 05 MAY 2023)
5. Schwarz, C., Ohme, P., Deiler, C., "The SENS4ICE EU project – SENSors and certifiable hybrid architectures for safer aviation in Icing Environment", SAE Icing Conference on Icing of Aircraft, Engines, and Structures 2019, Minneapolis, MN, USA, 17 – 21 JUN 2019.
6. Schwarz, C., "The SENS4ICE EU project – SENSors and certifiable hybrid architectures for safer aviation in Icing Environment – A project midterm overview" 6th International

Conference "Prospects of Civil Avionics Development", online / Moscow, Russia, GosNIIAS, July 22, 2021.
7. Bansmer, S. E., Baumert, A., Sattler, S., Knop, I., Leroy, D., Schwarzenboeck, A., Jurkat-Witschas, T., Voigt, C., Pervier, H., and Esposito, B., "Design, construction and commissioning of the Braunschweig Icing Wind Tunnel", Atmos. Meas. Tech., 11, 3221–3249, DOI: 10.5194/amt-11-3221-2018, 2018.
8. Orchard, D. M., Clark, C., Chevrette, G., "Measurement of Liquid Water Content for Supercooled Large Drop conditions in the NRC's Altitude Icing Wind Tunnel", SAE Icing Conference on Icing of Aircraft, Engines, and Structures 2019, Minneapolis, MN, USA, 17 – 21 JUN 2019.
9. Schwarz, C., "The SENS4ICE EU project – SENSors and certifiable hybrid architectures for safer aviation in Icing Environment – Project Overview and Initial Results", International council of the aeronautical sciences (ICAS), Stockholm, Sweden, September 2022. https://doi.org/10.5281/zenodo.7105074
10. Lucke, J., Jurkat-Witschas, T., Heller, R., Hahn, V., Hamman, M., Breitfuss, W., Reddy Bora, V., Moser, M., and Voigt, C., Atmos. Meas. Tech., 15, 7375–7394, DOI: 10.5194/amt-15-7375-2022, 2022
11. EUROCAE, ED-103A/B Minimum operational performance standard for inflight icing detection systems. November 2017. http://www.eurocae.net
12. Bouchard, A. et al., "Relationship between airborne electrical and total water content measurements in ice clouds", Atmospheric Research, Vol 237, 103836, 2020, DOI: 10.1016/j.atmosres.2019.104836
13. del Val, M. G. and Frovel, M., "Fiber Bragg Grating Sensors ice detection: Methodologies and performance", (2022) DOI: 10.1016/j.sna.2022.113778
14. Pohl, M., Feder, J., Riemenschneider, J., "Lamb-wave and impedance based ice accretion sensing on airfoil structures", SPIE Sensors and Smart Structures Technologies for Civil, Mechanical, and Aerospace Systems 2023, Paper 12486-37, Long Beach, CA, USA, 13 – 16 March 2023
15. Roberts, I., "AIP – Atmospheric Icing Patches – A distributed system for ice detection", SENS4ICE 1st Project Symposium co-hosted by SAE AC-9C Aircraft Icing Technology Committee Meeting OCT 2021, online. https://www.sens4ice-project.eu/sites/sens4ice/files/media/2020-10/SENS4ICE_SAE_Symposium_Atmospheric%20Icing%20Patches_ATX_20201022.pdf (accessed 05 MAY 2023).
16. Deiler, D., Sachs, F., "Design and Testing of an Indirect Ice Detection Methodology", SAE International Conference on Icing of Aircraft, Engines, and Structures 2023, Vienna, Austria, 20-22 June 2023, 2023-01-1493.
17. Deiler, C., Fezans, N., "Performance-Based Ice Detection Methodology", Journal of Aircraft, Vol. 57, No. 2, March – April 2020, DOI: 10.2514/1.C034828
18. Deiler, C., "Flying With Ice – An Overview of DLR Research in Flight Mechanics With Icing Influence During the Last Decade", Deutscher Luft- und Raumfahrtkongress (German Aerospace Conference) 2021, Bremen and online, 2021, DOI: 10.25967/550008
19. Bernstein, B. C., Wolff, C. A., and McDonough, F. "An Inferred Climatology of Icing Conditions Aloft, Including Supercooled Large Drops. Part I: Canada and the Continental United States", JAMC 2007, DOI: 10.1175/2007JAMC1607.1
20. Bernstein, B. C. and Le Bot, C., „An Inferred Climatology of Icing Conditions Aloft, Including Supercooled Large Drops, Part II: Europe, Asia, and the Globe", JAMC 2009, DOI: 10.1175/2009JAMC2073.1
21. Jurkat-Witschas, T., et al., "Overview on the cloud microphysical properties during the SENS4ICE airborne test campaigns in contrast to climatological expectations", SAE International Conference on Icing of Aircraft, Engines, and Structures 2023, Vienna, Austria, 20 – 22 June 2023, 2023-01-1491.
22. Lucke, J., et al., "Characterization of atmospheric icing conditions during the HALO-(AC)³ campaign with the Nevzorov probe and the Backscatter Cloud Probe with Polarization Detection", SAE International Conference on Icing of Aircraft, Engines, and Structures 2023, Vienna, Austria, 20 – 22 June 2023, 2023-01-1485.
23. Lilie, L., Bouley, D., Sivo, C., and Ratvasky, T., "Test Results for the SEA Ice Crystal Detector (ICD) under SLD Conditions at the NASA IRT," AIAA 2021-2654. AIAA AVIATION 2021 FORUM. August 2021, DOI: 10.2514/6.2021-2654.
24. Esposito, B. et al., "Comparability of Hot-Wire Estimates of Liquid Water Content in SLD Conditions", SAE International Conference on Icing of Aircraft, Engines, and Structures 2023, Vienna, Austria, 20 – 22 June 2023, 2023-01-1423.
25. Zollo A L, Montesarchio M, Bucchignani E, In-flight icing: a remote detection tool based on satellite data. EGU22 European Geoscience Union General Assembly, 2022.
26. Jaron, O., Bernstein, B., "Overview on the meteorological conditions during the SENS4ICE airborne test campaigns", SAE International Conference on Icing of Aircraft, Engines, and Structures 2023, Vienna, Austria, 20 – 22 June 2023, 23ICE-0125.
27. Roberts, I., "Development of the Atmospheric Icing Patch (AIP) under the SENS4ICE programme", SAE International Conference on Icing of Aircraft, Engines, and Structures 2023, Vienna, Austria, 20 – 22 June 2023, 2023-01-1488.
28. Hamman, M., Gelao, G., Ridouane, El H., Chabukswar, R., Botura, G., "Development and Validation Testing of the Collins Ice Differentiator System in App C and App O Icing Conditions", SAE International Conference on Icing of Aircraft, Engines, and Structures 2023, Vienna, Austria, 20 – 22 June 2023, 2023-01-1490.
29. Orazzo, A., Thillays, B., "Hybrid Ice Detection System development and validation", SAE International Conference on Icing of Aircraft, Engines, and Structures 2023, Vienna, Austria, 20 – 22 June 2023, 23ICE-0049.

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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
CDP	Cloud Droplet Probe
CFR	Code of Federal Regulations
CIRA	*Centro Italiano Ricerche Aerospaziali* (Italian Aerospace Research Center)
CIP	Cloud Imaging Probe
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)
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
SIGMA	System of Icing Geographic identification in Meteorology for Aviation
SLD	Supercooled Large Droplets
SRP	Short Range Particulate
t	Time
TRL	Technology Readiness Level
TUBS	*Technische Universität Braunschweig* (Technical University Braunschweig)
TWC	Total Water Content
UHSAS	Ultra-High Sensitivity Aerosol Spectrometer
UTC	Coordinated Universal Time