SENS4ICE EU Project Hybrid Ice Detection Architectures Demonstration Results

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Abstract

A novel hybrid approach for icing detection was developed and demonstrated combining direct sensing (atmospheric conditions / ice accretion) with indirect techniques based on changing aircraft characteristics. This approach is specifically aiming at reliable detection and discrimination of supercooled large droplets (SLD) icing conditions, which are potentially safety critical and particularly difficult to detect. As part of the EU-funded project SENS4ICE two demonstration flight campaigns were conducted. Relevant icing conditions have been encountered and successfully detected. This enables a wide range of aviation applications.

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
ATC	Air Traffic Control
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
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
MVD	Median Volume Diameter
NRC	National Research Council Canada
ONERA	*Office national d'études et de recherches aérospatiales* (The French Aerospace Lab)
RICE	Rosemount Icing Detector
SENS4ICE	SENSors and certifiable hybrid architectures for safer aviation in ICing Environment
PFIDS	Primary in-Flight Icing Detection System
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

Today's airplanes have well established means to handle most typical icing conditions, which are defined in Appendix C of CS-25 / 14 CFR Part 25 (formerly known as FAR 25) [1],[2]. However, specific conditions that contain supercooled large droplets (SLD, with a diameter larger than 100 µm) have been a contributing factor in several accidents over the last three decades. It became apparent that scenarios exist where some airplanes may not be sufficiently protected against these SLD conditions as ice can form on unprotected areas of the lifting surfaces (e.g. aft of the leading edge or in runback icing situations) leading possibly to loss of control. Therefore, authorities have issued dedicated certification rules under Appendix O (CS-25 / 14 CFR Part 25). Essential for increasing overall aviation icing safety is the early and reliable detection of icing conditions to support the required actions to be taken by the flight crew (or by automated systems). The EU-funded Horizon 2020 project SENS4ICE (2019-2023) directly addressed this need for robust and reliable detection and discrimination between Appendix C and O icing conditions [3]. Novel instruments for the detection of these rare conditions were developed and tested in icing wind tunnels and flight campaigns in relevant (natural) icing conditions [4].

A smart way to approach the challenging problem of SLD ice detection is the hybridization of different detection techniques: Direct sensing of atmospheric conditions and/or ice accretion on the airframe is combined with an indirect technique, which detects changes of the aircraft flight characteristics caused by ice accretion on the airframe [5]. The indirect ice detection relies solely on aircraft parameters without requiring information about atmospheric data/ microphysical cloud parameters such as droplet diameters or the liquid water content. This indirect ice detection is a performance monitoring concept with a well-defined reference of the aircraft performance in all nominal conditions. Combining this and one or several other complementary solutions results in a robust and reliable hybrid detection for a vast variety of icing conditions. This integrated "hybrid ice detection" solution as developed in SENS4ICE is not only aiming 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.

2. Direct Ice Detection Technologies and Icing Wind Tunnel Testing

Ten novel SLD ice detection technologies with various physical principles for directly detecting ice accretion or atmospheric icing conditions have been developed and matured. In a first step the sensor technologies were tested in different icing wind tunnels (Table 1) particularly in Appendix O conditions (in freezing drizzle conditions, while freezing rain was not in the scope) [6]. Some of the icing wind tunnel facilities have enhanced their capabilities to produce Appendix O conditions. As no standardised procedure exists for icing wind tunnels to provide Appendix O icing conditions, calibration and reference measurement activities across wind tunnels have resulted in valuable insights and knowledge gain. Dedicated common test points have been defined for all involved SENS4ICE IWT [7] based on the EUROCAE standard for inflight icing detection systems ED-103 [8].

Table 1 SENS4ICE icing wind tunnel facilities

IWT facility	**Speed range (sustained)**	**Temperature range**	**Test section**
Collins Aerospace Icing Wind Tunnel	13-103 m/s	0°C to -30°C	152×56×112 cm^3
TUBS Braunschweig Icing Wind Tunnel (BIWT) [9]	10-40 m/s	30°C to -20°C	150×50×50 cm^3
National Research Council (NRC): Altitude Icing Wind Tunnel (AIWT) [10]	5-100 m/s	+30°C to -40°C	57×57 cm^2 (52x33 cm^2 with insert)

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 [11],[12]. 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 2 provides an overview of the icing sensor technologies under development in the SENS4ICE project and Figure 1 is showing the sensors demonstrated in flight.

Table 2 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	Accretion	Backscattering from ice accretion
DLR	CM2D [BCPD]	Atmospheric	Single particle optical backscatter
DLR	CM2D [Nevzorov]	Atmospheric	Isothermal measurement of water content

CM2D-DLR image DLR **LILD-DLR**

Figure 1 SENS4ICE icing sensors demonstrated in flight

Dedicated reference measurement results were compared with specifications and IWT data for specific test points. Icing wind tunnel conditions were covering a considerable range e.g. for MVD and LWC which was useful for SENS4ICE project purposes of testing icing sensors as part of the sensor technology development and maturation process [14].

Apart from reference instruments (including CCP and Nevzorov [14], [10]), 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 to be 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 [16] and in more detail in [17], [18] and [19].

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 overview of the detection rates (test cases successfully detected related to the total number of test cases) is shown in Figure 2, excluding the CM2D scientific/reference sensor and the AOD sensor that was withdrawn from IWT testing in the context of Covid-19 related delays.

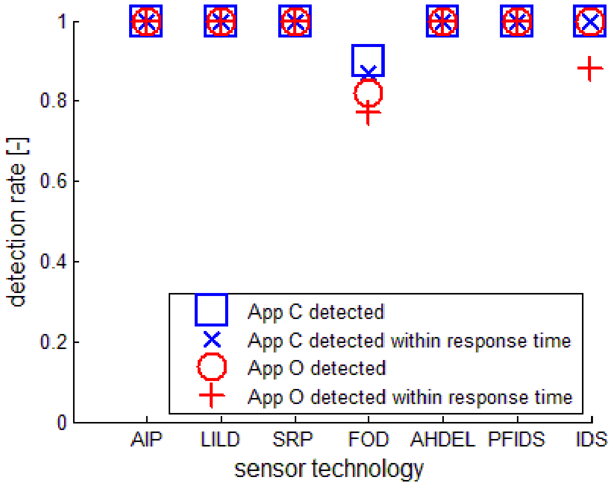

Figure 2 SENS4ICE sensor detection rates overview for App. C and O icing condition IWT test points for seven direct ice detection technologies (while detecting App. O refers to the capability to differentiate from App. C conditions)

An (anonymised) comparison of measured icing wind tunnel sensor response times compared to required response times as per ED-103 is shown in Figure 3 for App. O icing condition test points. In almost all cases the response times for the detection technologies are within the requirements. This was also the case for App. C conditions as was shown in [20]. Some sensor technologies have also provided differentiation information for the IWT test conditions. These measured sensor response times were compared to ED-103 required response times for differentiating App. C conditions from App. O conditions and were mostly within required limits, too [20].

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 [16]. Based on detailed analysis and evaluation of IWT results, eight ice detection sensor technologies were selected for flight testing and subsequently integrated in the flight demonstration aircraft.

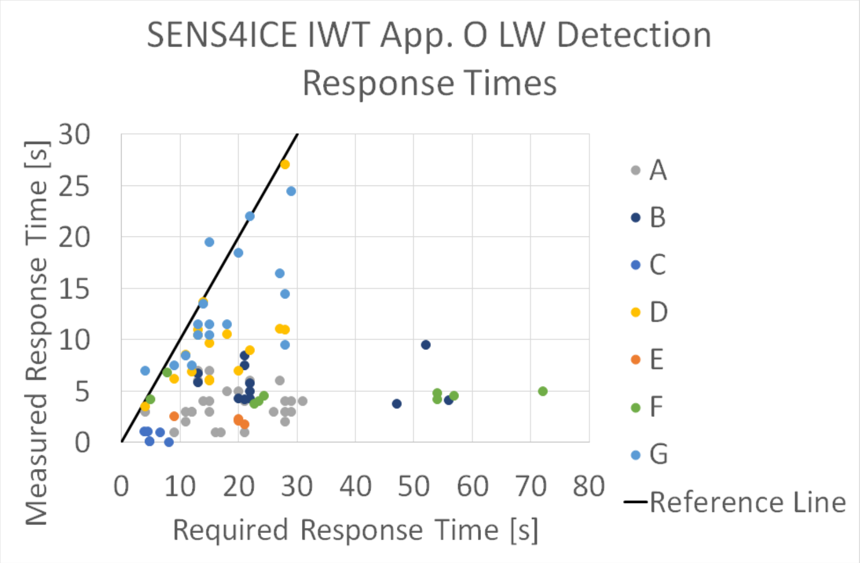

Figure 3 Measured sensor response times compared to required response times for detecting liquid water (LW) icing conditions for App. O IWT test points (sensors anonymised A-G)

3. Hybrid Ice Detection

The hybrid ice detection approach combines direct technologies using various physical principles, e.g. thermal, optical or electrical sensors, but also an indirect ice detection method based on the change of aircraft characteristics due to ice accretion. This combination allows to benefit from individual advantages of different technologies like fast detection or low false alarm rate. This provides a more robust and reliable overall detection. The concepts and the flight demonstration results are described in detail in SENS4ICE public deliverable D4.1 [21].

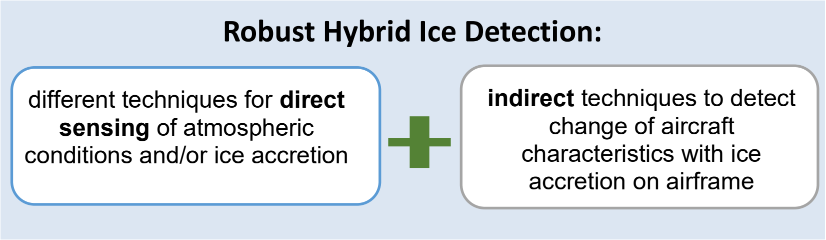

Figure 4 Robust hybrid ice detection concept

3.1 Hybrid Ice Detection System

The SENS4ICE hybrid ice detection system (HIDS) was developed by SAFRAN. In the first project phase the system was specified and initial considerations of certification aspects were discussed in close cooperation with aviation certification authorities, aircraft manufacturers, pilot representatives and research institutions. Subsequently a suitable hardware and software architecture was established for flight testing. 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 is deriving an overall output signal for icing detection. The HIDS was adapted to meet specific test aircraft system architecture requirements. It was demonstrated in the two SENS4ICE flight campaigns in 2023 with an Embraer Phenom 300 and an ATR 42. A detailed description including flight demonstration results is available in [22] and in SENS4ICE public deliverable D4.2 [23].

3.2 Indirect Ice Detection

An essential element of the hybrid approach is a performance-based indirect ice detection (IID) as developed and matured by DLR. The IID is applying fundamental knowledge about the changes of aircraft characteristics under icing conditions, namely flight performance degradation [24], [25]. This approach 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 [24].

The system utilizes flight parameters and information normally available on modern aircraft, namely aerodynamic, inertial, engine and control data. In addition, a database of pre-defined aircraft characteristics is used to compare the detected aircraft characteristics to the nominal behaviour and derive the icing status.

Extensive preliminary studies were conducted with pre-existing flight test data to identify applicable thresholds for specific aerodynamic aircraft parameters. As the IID is part of the HIDS, it was also demonstrated in flight in the two SENS4ICE flight test campaigns in 2023. For more detailed flight data analyses see [26], [27].

4. SLD Icing Flight Campaigns

Both SENS4ICE natural icing flight campaigns are described in detail in SENS4ICE public deliverable D4.3 [29] and in [30].

The first SENS4ICE flight campaign took place 23 February - 10 March 2023, based in Alton, Illinois, USA. The second flight campaign took place 3 – 27 April 2023, based in Toulouse, France. The campaigns are therefore referred to as the North American and the European flight test campaign. Prior to the campaigns, different models and satellite observations on icing occurrence above Europe and North America were analysed to find the best region with the highest occurrence rate of icing in general and SLD in particular, given the different safety constraints on the flight manoeuvres. The overview and conclusions of the analysis are summarized in [28] and [29].

The reference instruments for the characterization of microphysical properties of the clouds encountered were of highest importance for both flight campaigns. The North American flight test campaign used an Embraer Phenom 300 aircraft as the measurement platform (see Figure 5). The Phenom carried a Cloud Combination Probe (CCP) [31],[32],[33], owned by Embraer and manufactured by Droplet Measurement Technologies for the measurement of particle size distributions. For the measurement of liquid water content (LWC) and total water content (TWC), the Phenom 300 also carried a SEA ice crystal detector (ICD) manufactured and operated by Science Engineering Associates (SEA) [34]. Figure 6 shows an example of ice accretion on the wing tip of the Embraer Phenom 300.

Figure 5 North American flight campaign Embraer Phenom 300 aircraft [copyright Embraer]

Figure 6 Embraer Phenom 300 with ice accretion on wing tip [copyright Embraer]

For the European flight campaign, an ATR 42 aircraft of the French facility for airborne research (SAFIRE) was used (see Figure 7). A large suite of reference instruments was installed on the plane, for more details see SENS4ICE deliverable D4.3 [29]. To maintain consistency with the American flight test campaign data, only measurements of the CCP and the Nevzorov probe were used for the European campaign data. In the future, more detailed microphysical analyses and instrument comparisons will also consider the data from the other instruments. Figure 8 shows an example of ice accretion for the SAFIRE ATR 42 horizontal tail.

Figure 7 European flight campaign SAFIRE ATR 42 environmental research aircraft [image DLR/ SENS4ICE project with SAFIRE permission]

Figure 8 SAFIRE ATR 42 horizontal tail with ice accretion [image DLR/ SENS4ICE project with SAFIRE permission]

The reference measurements of both campaigns can be grouped into particle size measurements and bulk LWC and TWC measurements. Particular processes were applied to derive reliable reference measurement results. Details of the evaluation steps necessary for both types of instruments are described in SENS4ICE public deliverable D4.3 [29].

4.1 Flight Campaign North America

In the North America campaign, four of the icing detection technologies under development in the

SENS4CE project were tested: AIP / AeroTex, IDS / Collins, SRP / Honeywell and PFIDS / Safran. 15 flights with a total of 25 flight hours (including ferry and check flights) were successfully conducted allowing to target natural liquid water icing conditions and in particular SLD conditions (Figure 9). Nine measurement flights were performed as part of the North American flight test campaign, which are listed in Table 3. A total of 4 hours and 23 minutes were spent in icing conditions, 50 minutes of which were in Appendix O icing conditions, based on the definitions in SENS4ICE public deliverable D4.3. A detailed meteorological analysis of selected flights is available in [35].

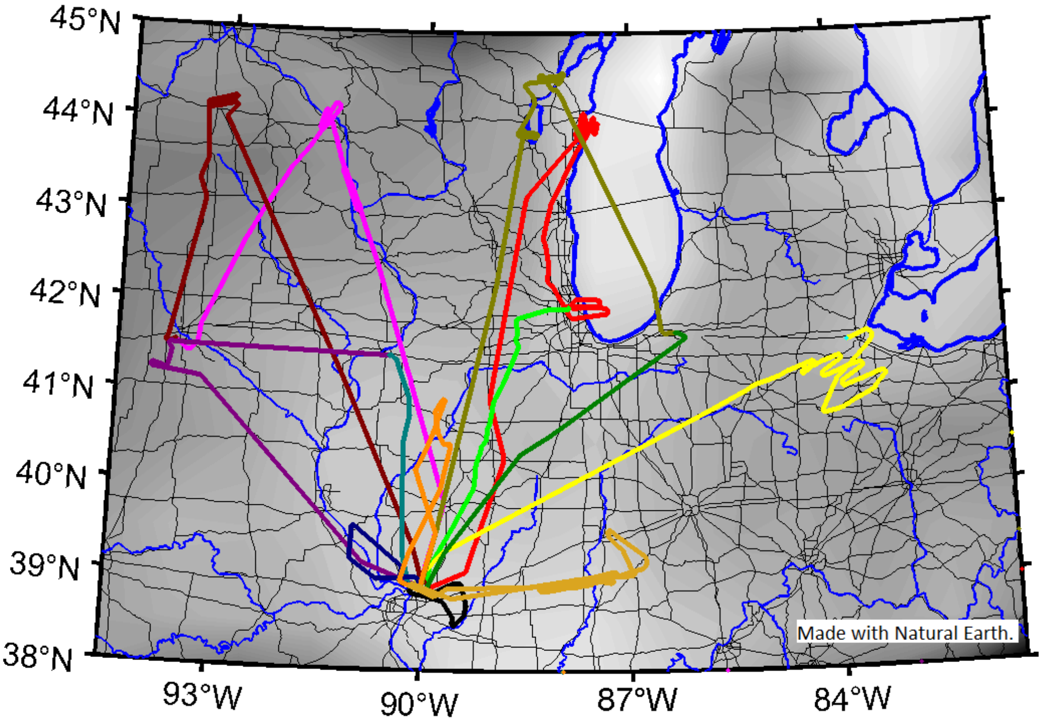

Figure 9 Ground tracks of SENS4ICE North America campaign in February/March 2023 [credit DLR/ SENS4ICE project made with Natural Earth]

Table 3 Flights of SENS4ICE North America flight campaign

Flight	Day	Flight time UTC	Time in Icing conditions [mm:ss]	Time in Appendix O conditions [mm:ss]
F1475-1	23/02/2023	11:43-14:29	20:18	9:03
F1475-2	23/02/2023	17:18-18:33	19:59	0:00
F1476	25/02/2023	11:38-13:43	38:47	22:24
F1477-1	01/03/2023	11:38-13:48	31:03	3:55
F1477-2	01/03/2023	16:56-18:34	14:30	7:31
F1478	06/03/2023	11:46-14:18	43:24	4:03
F1479	08/03/2023	Instrument failure	-	-
F1481	09/03/2023	12:01-13:13	15:51	2:46
F1482	10/03/2023	12:08-17:40	79:59	0:00

4.2 Flight Campaign Europe

The flights of the European flight test campaign were either performed as airways flights or (preferably) as CER flights. CER (Contrôle Essais Réception / Dedicated ATC for tests & acceptance) refers to specifically designated areas reserved for test aircraft. Flights in these areas were controlled by a dedicated controller, which provides a lot of flexibility for adjusting the flight plan. However, only a few CER zones were available for this flight campaign. If no suitable weather conditions were predicted for these regions, airways flights were conducted instead. These had basically no flexibility to make changes in the horizontal flight path.

The direct detectors tested in this campaign, together with HIDS/IID, are INTA FOD, DLR LILD, ONERA AMPERA and DLR CM2D. Note that the latter sensor, which is considered as a scientific reference probe, was not used for hybridization with indirect detection.

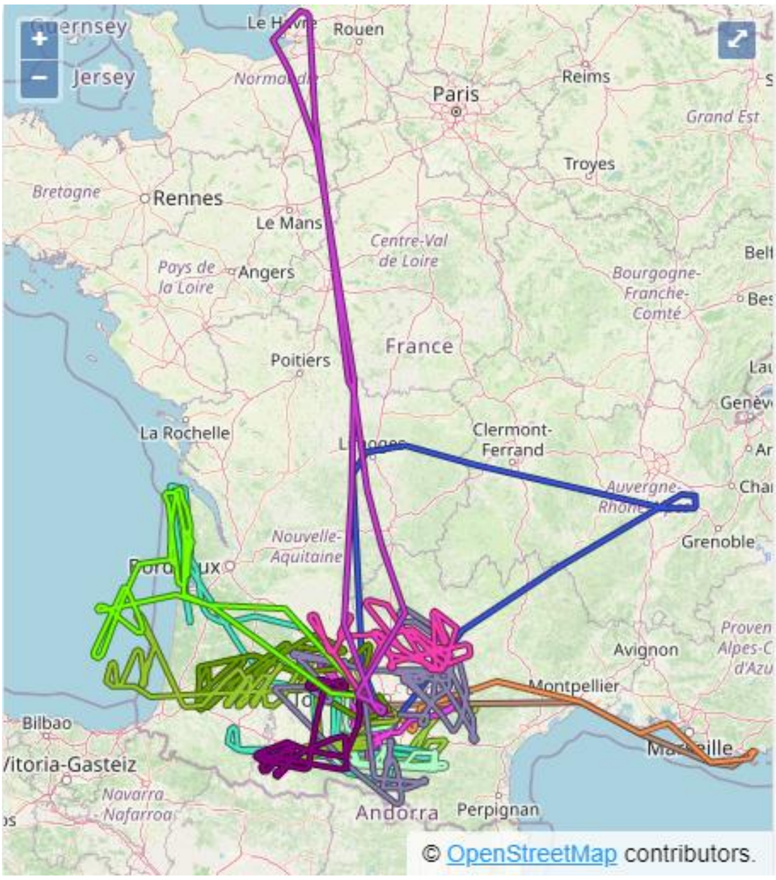

Figure 10 Flight campaign Europe April 2023 ground tracks [credit SAFIRE/ SENS4ICE project, Map data from OpenStreetMap]

Fifteen scientific flights were performed within the European flight test campaign. Aircraft and instrument issues were encountered during observational flights (OFs) 3 and 4, respectively so these flights were subsequently not evaluated. On flight OF1 to OF8 the Nevzorov data was considered unreliable and is hence not used. The LWC and derived parameters, such as icing flags, stem from the CCP for these flights.

Table 4 Flights of SENS4ICE Europe flight campaign

Flight	SAFIRE flight number	Day	Flight time (UTC)	Time in Icing conditions [mm:ss]	Time in Appendix O conditions [mm:ss]
OF1	as230009	03/04/2023	05:47-09:35	90:13	1:28
OF2 pt1	as230010	04/04/2023	11:12-12:52	10:42	0:11
OF2 pt2	as230011	04/04/2023	13:05-14:29	12:14	1:48
OF3	as230012	06/04/2023	Flight aborted	n/a	n/a
OF4	as230013	14/04/2023	Instrument failure	n/a	n/a
OF5	as230014	15/04/2023	05:24-08:11	40:37	12:40
OF6	as230015	18/04/2023	13:04-17:01	72:01	0:00
OF7	as230016	20/04/2023	09:43-13:17	2:38	0:00
OF8	as230017	22/04/2023	05:16-08:47	34:07	0:00
OF9	as230018	24/04/2023	12:24-16:47	90:57	59:48
OF10	as230019	25/04/2023	10:06-15:51	90:14	43:01
OF11	as230020	26/04/2023	05:56-08:52	13:42	0:00
OF12	as230021	26/04/2023	12:37-17:04	52:20	14:01
OF13	as230022	27/04/2023	05:50-09:57	62:42	6:14
OF14	as230023	27/04/2023	11:28-15:43	42:09	13:39

Based on 13 evaluated flights, in total more than 10 hours were spent in icing conditions, and particularly in Appendix O conditions more than 2 hours.

4.3 Atmosphere Characterisation

A detailed analysis of the meteorological conditions and microphysical properties encountered is described in [36].

The altitude of the icing conditions encountered is shown in Figure 11 for both flight campaigns.

For the North American campaign, the icing conditions mostly were encountered in 1000 - 3000 m altitude and for the European campaign a significant portion of icing conditions was in 3500 - 5000 m. Most Appendix O conditions during the European campaign were encountered in 3500 - 5000 m. The different altitudes reflect different seasons during which campaigns occurred.

Conditions like those encountered during the European campaign haven't been measured much before. The flight campaigns which were made to establish Appendix O were flown in conditions similar to those of the American campaign.

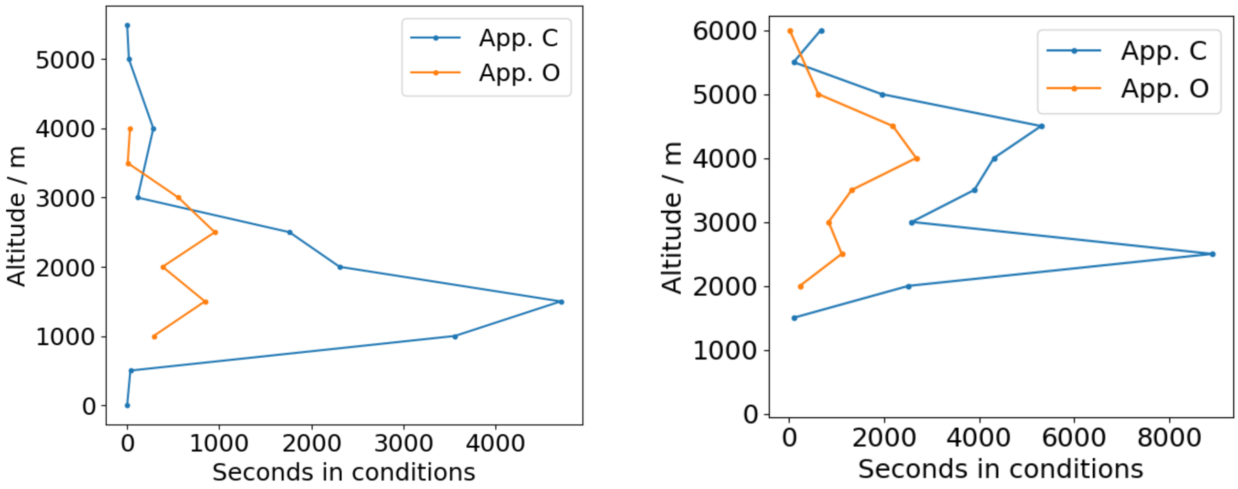

Figure 11 Altitude of icing conditions: left – North America campaign, right – Europe campaign

The LWC is shown in Figure 12 for both flight campaigns. The LWC values were generally higher during North American campaign. For the European campaign the LWC values in Appendix O were significantly higher than in Appendix C. While during the North American campaign Appendix O conditions tended to have lower LWC than Appendix C conditions, during the European campaign the LWCs in Appendix C and Appendix O conditions were approximately equal.

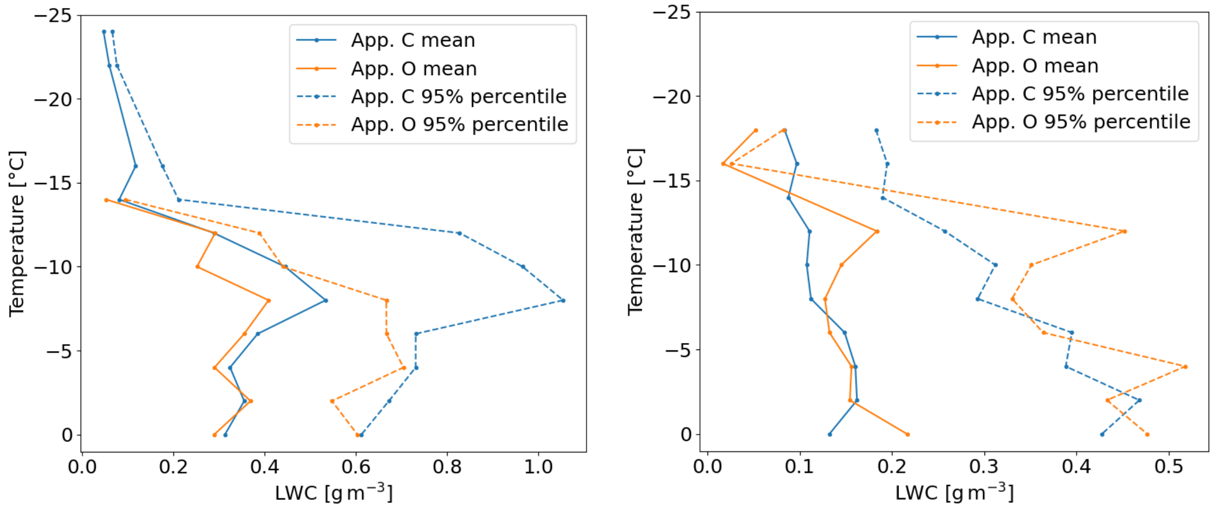

Figure 12 LWC of icing conditions: left – North America campaign, right – Europe campaign

LWC and temperature data is compared with App O certification envelopes (Figure 13). Shorter sampling distance of LWC values are accounted for with a scaling factor [29]. Only encounters exceeding 30 s are used for this analysis. Only few encounters are exceeding the LWC-temperature envelope. Given 95% confidence interval based on the Cober Isaac study [37] the encounters are matching the envelopes reasonably well.

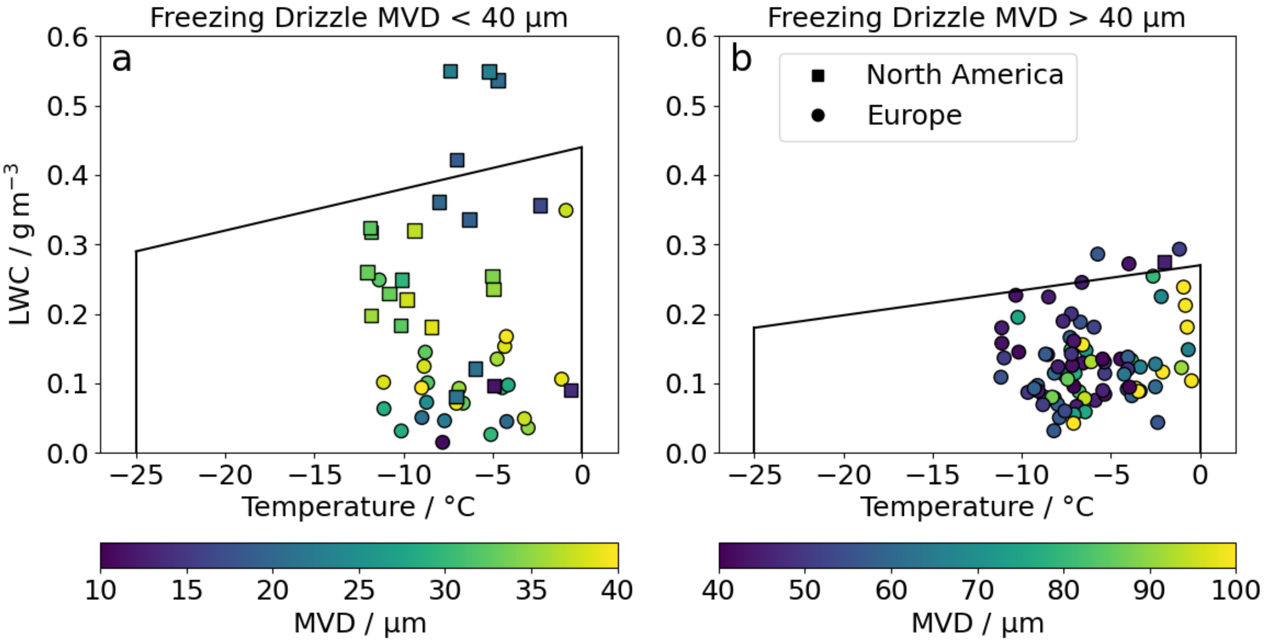

Figure 13 LWC and temperature data compared with App O certification envelopes for a) MVD < 40 µm and b) MVD > 40 µm

5. Satellite-based detection and nowcasting of icing conditions

One of the objectives of the SENS4ICE project was to increase pilot awareness of icing threats through the development of a remote detection technology. In the first phase of the project, the Meteorology Laboratory of CIRA developed a satellite-based tool for detection and nowcasting of icing conditions[38], which was tested during the European flight campaign [39]. During the campaign, data on monitoring and nowcasting of icing conditions relying on the developed tools was provided in pre-flight phase and updated in near-real time, i.e., with a delay of a few tens of minutes due to the time of receiving and processing satellite data. This information was useful for the planning of the research flights.

The satellite-based nowcasting was compared to the SENS4ICE flight data. In general, the results are confirmed well by the flight data, particularly also including Appendix O encounters [29],[40].

The flight demonstration results regarding the evaluation of the detection tool in relevant icing conditions are promising, suggesting that this satellite-based approach can be exploited for applications supporting aviation meteorology. Indeed, additional investigations are ongoing with the aim of performing a more detailed validation to identify the strengths and weaknesses of the tool and the needed steps for its future exploitation.

6. Hybrid Ice Detection Technologies Flight Demonstration

DISCLAIMER: the assessment of icing severity used in this section is only for research and development purposes based on engineering science judgement but not related to the aircraft operations.

All detection technologies performed well during the flight demonstrations and generally exhibited robust and timely ice detection behaviour. The technology readiness level (TRL) was increased up to TRL 5 in several cases and even TRL6 for many of the technologies [41], [21]. Particularly the hybrid ice detection approach showed the capability to provide both early detection and a continuous monitoring of ice accretion on the aircraft [23].

Example results are shown for each of the flight campaigns. The results of the analyses shown hereinafter are obtained by replaying offline the whole flight test scenario by using post-processed data for the indirect detection, the microphysics and direct sensors.

As displayed in Figure 14, North America campaign flight 1476 was characterized by five icing conditions classified as App. O encounters. The detection signals of direct ice detection sensors and indirect ice detection are compared with the reference microphysics ice flag in Figure 14: the detectors were able to detect the five conditions and SRP and IDS, which can discriminate between App. C and App. O, considered the five encounters as App. O conditions. Unfortunately, during this flight Aerotex AIP faced some issues, for this reason its data are not available for this flight. Figure 16 shows the results of the HIDS arbitration for each couple of the direct sensors IDS, SRP and PFIDS with the indirect ice detection IID.

The HIDS arbitration function checks the reliability of direct sensors and IID, and, in order to keep an early ice detection and to monitor the A/C performance even when the A/C exits the icing clouds, the arbitration ice flag encloses perfectly both direct sensors and IID ice flags (Figure 16). Moreover, the HIDS output can provide information about the severity of the encountered icing conditions based on direct sensors outputs (IAR or LWC, for more details see [23]).

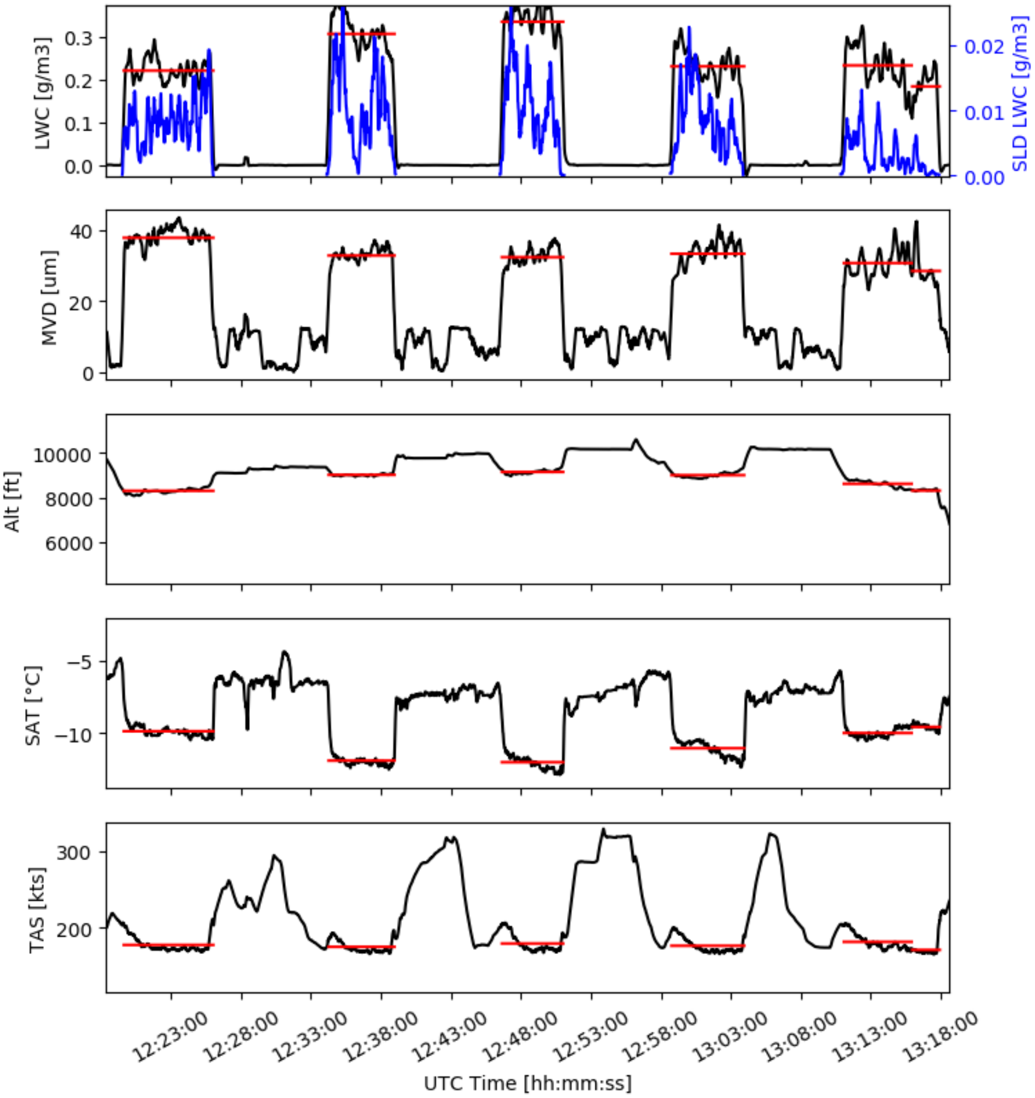

Figure 14 Microphysics and aircraft data North America flight 1476 (liquid water content LWC, median volume diameter MVD, altitude Alt, static air temperature SAT, true airspeed TAS; red lines represent calculated average values during icing encounters)

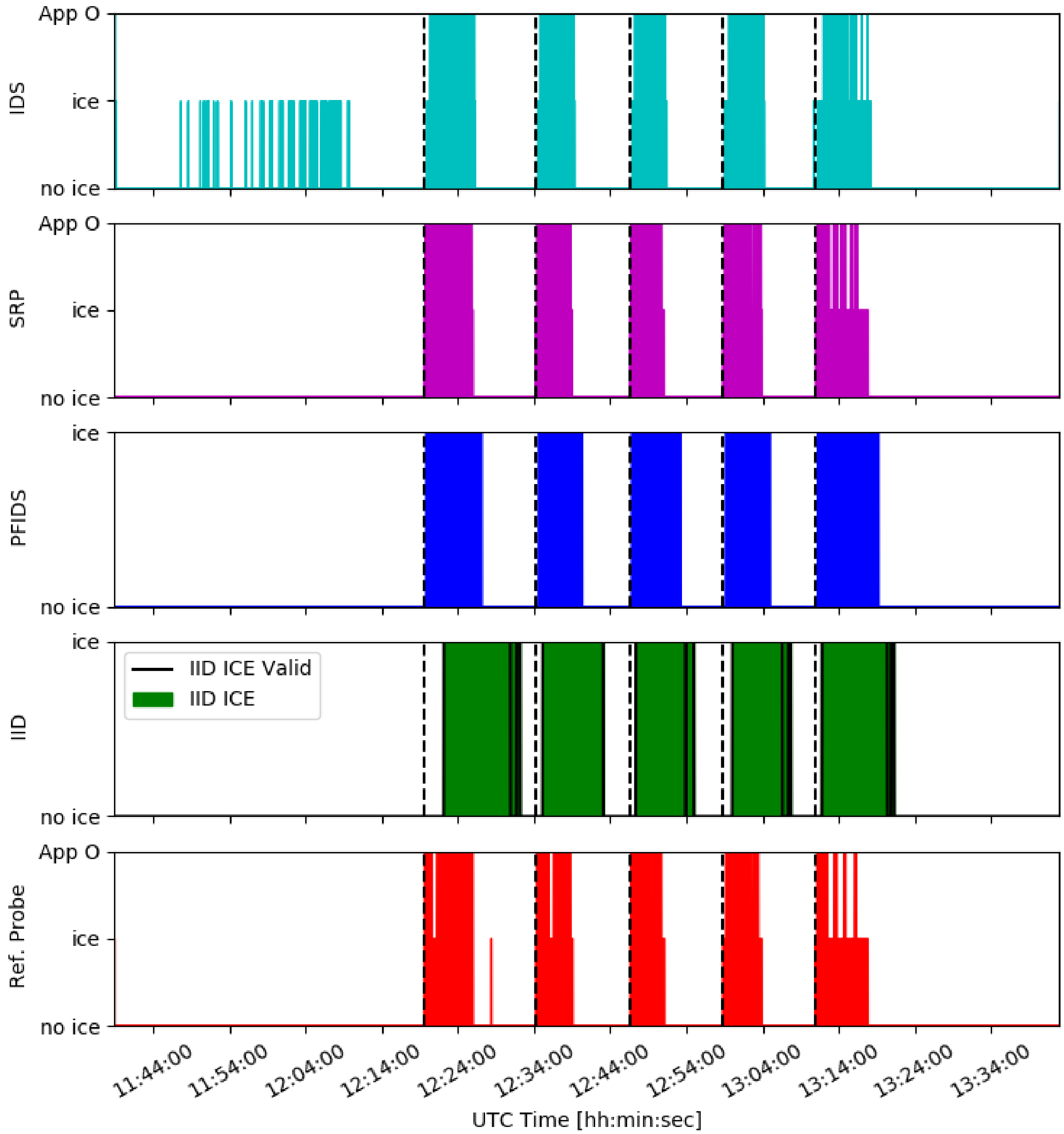

Figure 15 Direct and indirect ice detection signals North America flight 1476

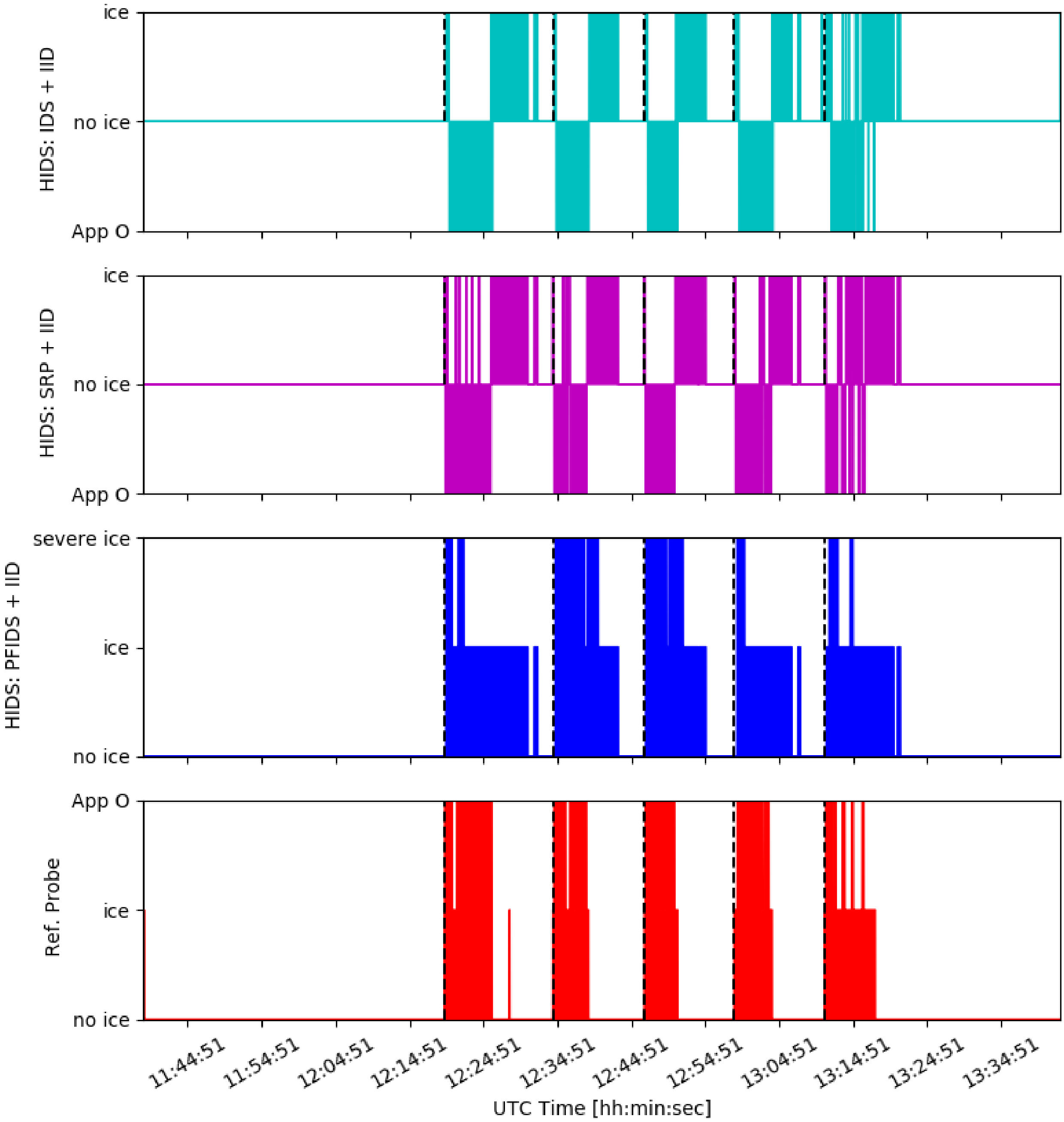

Figure 16 HIDS arbitration results North America flight 1476

For the European flight campaign flight as230018 is shown exemplarily. The flight lasted more than 4 hours and several icing clouds were encountered as demonstrated by the RICE probe (Rosemount Icing Detector, a magnetostrictive oscillation probe), the standard ice accretion detector for the test aircraft, and the microphysics analyses. Moreover, during this flight, the ATR42 flew through some clouds characterized by the presence of SLD. Figure 17 shows aircraft data, microphysics data and reference ice detection. Between icing encounters the altitude was reduced in order to reach temperatures above freezing level and to completely deice the aircraft. As illustrated in Figure 18, all the direct ice detection sensors were able to detect the icing encounters. As expected according to the different measurement principles, the AMPERA output is well correlated with the microphysics icing flags, while LILD and IID, which are ice accretion sensors, match up the RICE ice accretion signals. The FOD detected as well several icing encounters, in agreement with the microphysics flags, but it was not able to hold the ice signal and to properly detect the exit from the cloud because of the heterogeneous nature of the encountered icing clouds. Neither LILD, nor FOD, detected the presence of SLD during this flight.

Figure 19 shows the results of the HIDS arbitration for each couple of the direct sensors AMPERA, LILD and FOD, with the indirect ice detection IID. As for the North America flight test campaign, HIDS ice flag encloses perfectly the direct sensor and IID ice flags, in order to guarantee a fast ice detection, thanks to very reactive direct detectors, and to provide information about aircraft performance degradation even when it exits the clouds. Such coupling improves the ice detection capability and, as shown in Figure 19, a better matching with the reference signal is obtained.

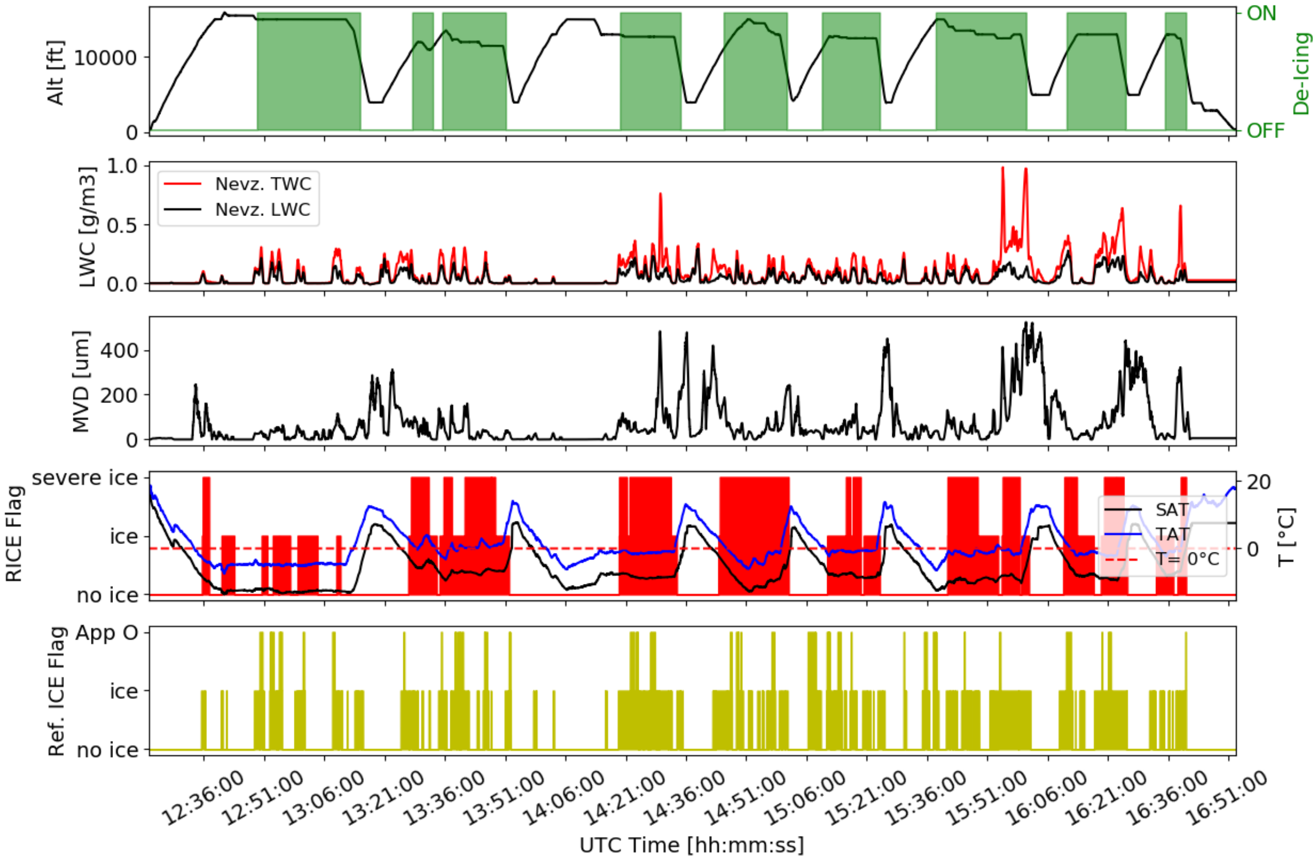

Figure 17 A/C data, microphysics data and reference icing flags for Europe flight as230018. From top to bottom: A/C altitude and IPS activation; Nevzorov measurements of LWC and TWC; Temperature (both SAT and TAT) and RICE reference probe ice flags; microphysics ice flags.

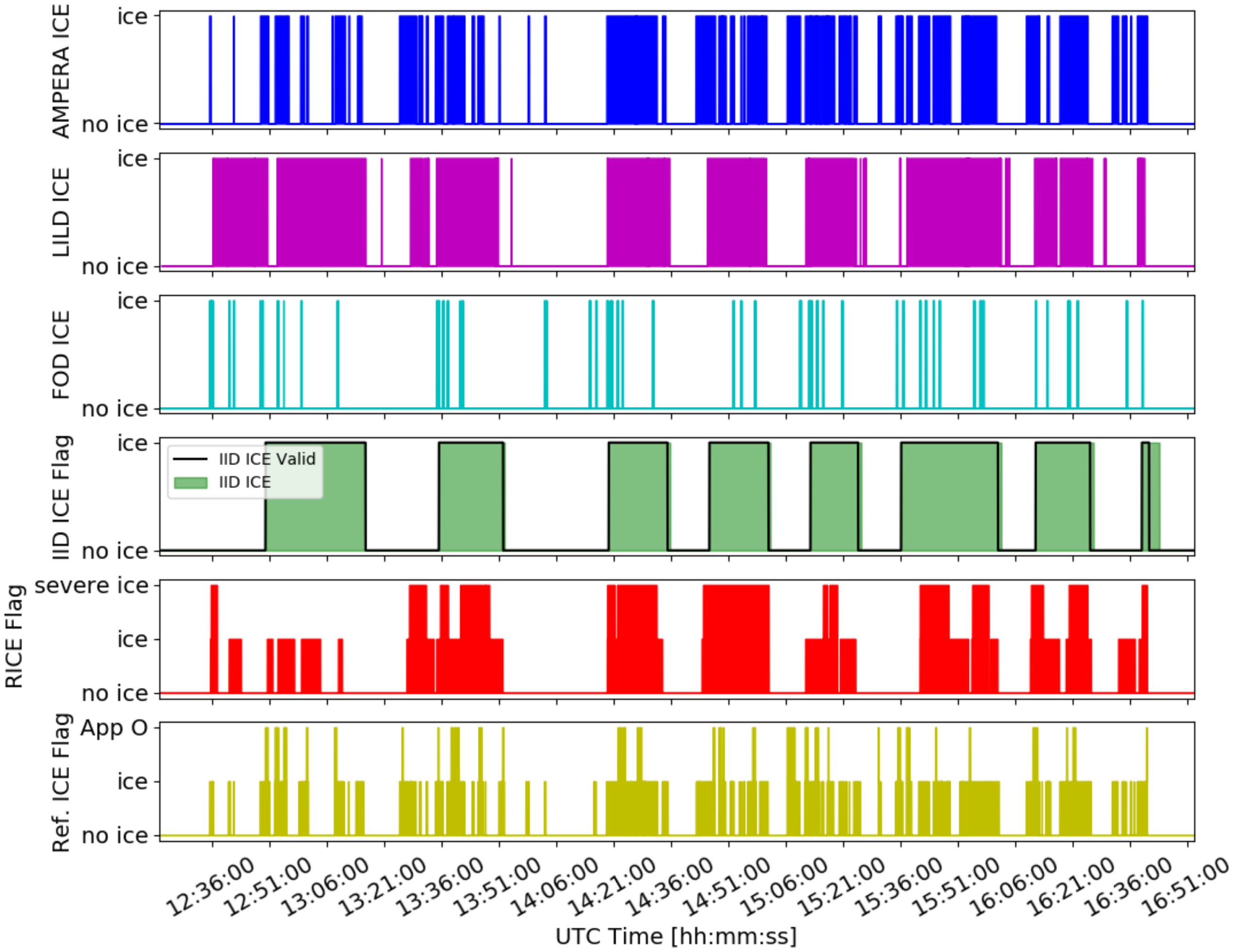

Figure 18 Ice Detection signal of direct ice detection sensors and indirect ice detection (IID) for the icing encounters of flight as230018. From the top to the bottom: AMPERA, LILD, FOD, IID, RICE (reference), microphysics ice flag

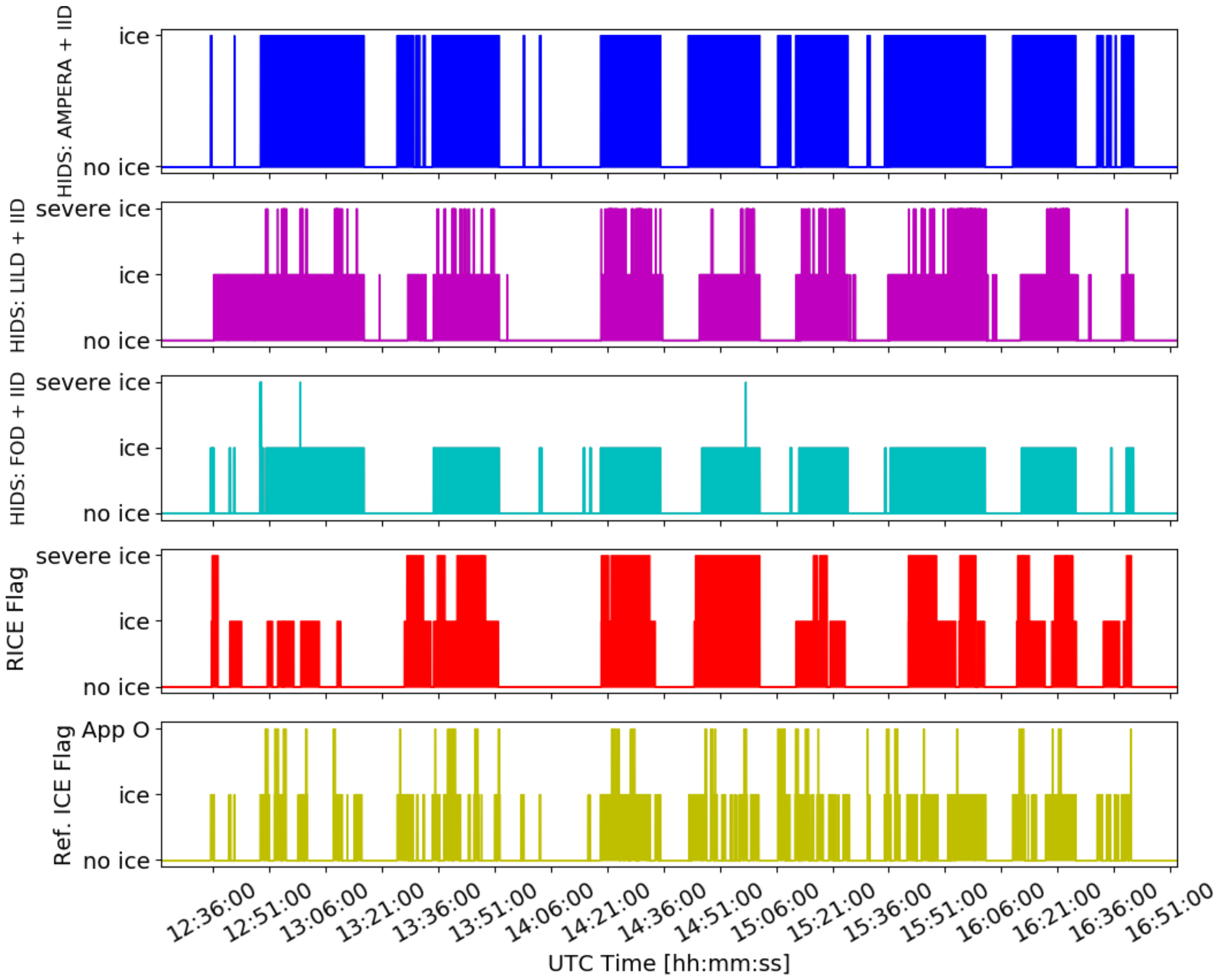

Figure 19 HIDS arbitration results flight as230018

7. Summary and Conclusion

Direct, remote, indirect and hybrid ice detection technologies particularly for SLD icing were further developed, considerably matured and successfully demonstrated, for the direct sensors in icing wind tunnels (IWT) and for direct and remote ice detection in natural icing conditions flight campaigns. Significant coverage of relevant icing conditions was achieved for IWT and flight campaigns including valuable SLD encounters, while the certification envelope for Appendix O is multi-dimensional and much larger. All detection technologies performed well during the flight demonstration and generally exhibited robust and timely ice detection behaviour, particularly also the hybrid including the indirect detection. For the satellite-based approach the evaluation of the detection tool in relevant icing conditions is promising, suggesting that this remote approach, after further maturation, can be exploited for applications supporting aviation meteorology. A major step for increasing technology readiness (TRL) for almost all technologies under development was achieved. The TRL was increased up to TRL5 in several cases and even TRL6 for many of the technologies. The demonstrated novel ice detection technologies facilitate broad and promising applications for many different air vehicle types (including UAV, UAM and any unconventional future air vehicles including greener aviation commercial transport aircraft) and several applications including ensuring operational safety and supporting certification activities. This is particularly the case for many of the novel technology due to low size/ low weight/ low power properties, or even a software solution in case of the indirect detection.

Furthermore, the novel detection technologies support the efficiency optimization for future smart ice protection systems. This can enable to reduce energy consumption. Once icing conditions are encountered, this may typically be quickly detected by atmospheric sensors. If ice is accreting on the aircraft, this may be detected by accretion sensors. Based on this information the ice protection can be activated. The online performance monitoring can detect any significant impact on the aircraft overall performance state including drag increase. When the icing conditions are left, the performance monitoring can indicate when there is still a performance reduction due to residual ice on the airframe, caused by SLD or runback ice. This way the pilots are aware of the actual performance state of the aircraft, and can apply corrective actions if needed (Figure 20).

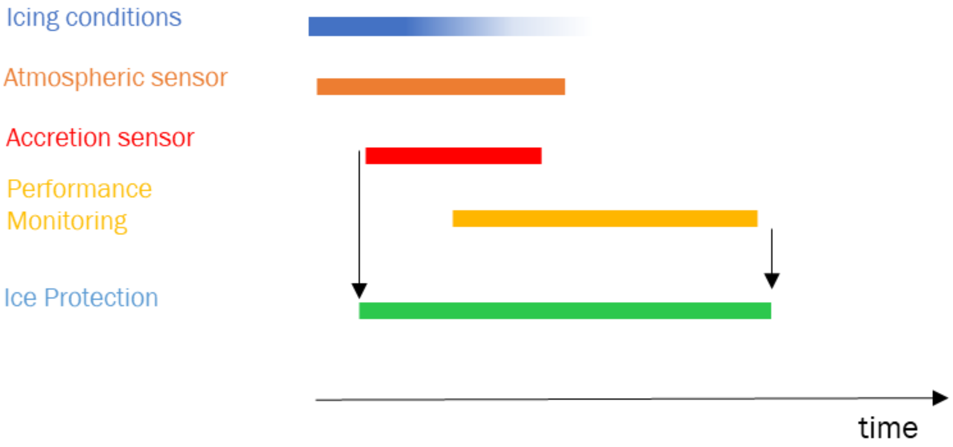

Figure 20 Hybrid ice detection optimising ice protection

However, further research/ development/ testing in enhanced icing wind tunnels and in natural icing conditions in flight is required for covering the full range of App O, specifically freezing rain, for maturing icing detection and discrimination technologies and identifying path for certification.

One important finding of the flight test campaigns is that for ensuring safety and certification for icing conditions, not only the atmospheric conditions and the local effects on the aircraft like ice shapes have to be considered. It is also crucial to analyse the overall effects on the aircraft including performance and stability aspects, including operational envelopes like stall speed and maximum angle of attack. This outcome may shed a new light on the ways to approach the means for complying with certification requirements. However, based on the knowledge gain and successful technology demonstrations with the natural icing flight campaigns it is also apparent that additional research for further maturation is required as the new technologies are currently only tested for a (very relevant) part of the Appendix O envelope, while a wide part has not been considered yet. Additional flight tests are required to better understand the typical SLD conditions occurring during flight and the specific impact on the aircraft flight characteristics.

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The Phenom 300 flight test data analysed 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 within the SENS4ICE project do not represent the Phenom 300’s certified performance.

The SENS4ICE European flight campaign airborne data was obtained using the aircraft managed by Safire, the French facility for airborne research, and infrastructure of the French National Center for Scientific Research (CNRS), Météo-France and the French National Center for Space Studies (CNES).

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10. Copyright Statement

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