Performance-Based Ice Detection
First Results from SENS4ICE European Flight Test Campaign

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Supercooled large droplets (SLD) icing conditions have been the cause of severe aircraft accidents over the last decades. As existing countermeasures even on modern aircraft are not necessarily effective against the resulting ice formations, the detection of SLD conditions is crucial and required for future transport aircraft certification. The EU funded Horizon 2020 project SENS4ICE focused on new ice detection approaches and innovative sensor hybridization to target a reliable SLD-ice detection. The performance-based (indirect) ice detection methodology is key to this approach and based on the changes of airplane flight characteristics under icing influence. This paper provides a short overview on the development and implementation of the indirect ice detection system (IIDS) algorithms in SENS4ICE. Furthermore, it gives first exemplary results on the IIDS performance during the SENS4ICE European flight test campaign conducted in April 2023 around Toulouse, France. These initial results are discussed and the consequences for the future flight campaign analysis are outlined.

Nomenclature

C_D	=	drag coefficient
C_{D0}	=	zero-lift drag coefficient
$\Delta C_{\tilde{D}}$	=	equivalent drag coefficient
ΔISA	=	temperature offset to standard atmosphere, K
E	=	energy J
$\dot{E}_{\text{tot}}$	=	energy change / power imbalance W
$\dot{E}_{\text{tot,ref}}$	=	reference power imbalance W
f, b	=	engine model adjustment factor and bias 1,N
H	=	altitude, m
k_1, k_2	=	drag coefficient equation factors
m_{AC}	=	aircraft mass, kg
$\mathcal{P}$	=	percentile/ quantile
$\overline{q}$	=	dynamic pressure, Pa
S_{Wing}	=	wing surface area, m^2
T	=	engine thrust force, N
V_{TAS}	=	true airspeed, m/s
α	=	angle of attack, rad

Acronyms

ATR	=	Avions de Transport Régional
HIDS	=	Hybrid Ice Detection System
IIDS	=	Indirect Ice Detection System
IPS	=	Ice Protection System
SLD	=	Supercooled Large Droplets

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I. Introduction

Icing can have hazardous effects on airplane performance characteristics and can be a limiting factor for the safe flight envelope. The change of the dynamic behavior and potential premature stall raise the need for pilot situational awareness and an adaption of control strategy. Different accidents worldwide have shown the criticality of icing related aircraft characteristics degradations, e.g., Refs. [1–4], especially when caused by supercooled large water droplets (SLD). Although in most cases the involved aircraft were equipped with state-of-the-art ice protection systems, the hazardous effects of SLD ice accretion led often to catastrophic events. These icing conditions can pose a high risk to the aircraft, crew and passengers, which requires specific detection and countermeasures to assure aircraft safety during flight. The certification of (modern) transport aircraft for flight into (known) icing conditions was mainly based on the certification requirements given in the so-called App. C to e.g., CS-25. But with the identified hazard to fixed-wing aircraft resulting from SLD the certification requirements were extended by the new App. O including SLD ice. From now on, manufacturers must prove that a newly developed airplane is also safe for flight into the even more hazardous SLD icing conditions. For flight safety it is now mandatory to detect the presence of SLD icing early. Furthermore, monitoring the aircraft's remaining capabilities during the further flight (in icing conditions) would give a relevant information to the pilots about the required adaption of operation, e.g., urgent need to enter warm air in order to melt the ice accretion on the aircraft if the aerodynamics are significantly degraded. As a complicating fact, predicting the distinct change of aircraft characteristics caused by SLD ice formation is challenging and still topic of current aviation research.

Today, the existing ice protection systems (IPS) require an significant amount of energy provided on board. Thermal ice protection systems usually rely on bleed air, which reduces the engine effectiveness and increases fuel consumption. Using such a system preventively has a direct impact on fuel consumption an therefore aircraft emissions and operation cost. A more deliberate activation of the IPS can lead to more efficient flight operations but therefore a reliable information about the current degradation and safety risk is required to decide for the need to activate the IPS. Hence, the design of new IPS with different power consumption depending on its effectiveness against the current icing encounter would be beneficial for the operations of future new aircraft designs. The information required for this could be provided by suitable ice detection methods giving a hint about the presence of icing conditions, actual ice formation on the airframe and the effect on the flight characteristics [5, 6]. Moreover, it would also open possibilities for the modification of existing systems by modulating the thermal power according to the current need on existing aircraft, directly reducing their energy consumption and increasing the efficiency: on the one hand, if e.g., the aircraft flight characteristics are not changing during icing encounter it indicates that the IPS is effective; on the other hand, if there is rapid change in aircraft characteristics noticeable indicating higher icing severity, the IPS power could be increased to counteract the ice accretion, whereas the power could be maybe decreased if the severity is low.

The goal of the European Union Horizon 2020 Project "'SENSors and certifiable hybrid architectures for safer aviation in ICing Environment"' (SENS4ICE) project was to provide a more comprehensive overview on the icing conditions, ice formation and aircraft degradation status including the aircraft's remaining capabilities (icing-related change in aircraft flight physics, i.e., degraded aircraft performance) [7, 8]. In a layered approach a hybrid ice detection system (HIDS) is forming the core function accompanied by additional new nowcasting and enhanced weather forecasting. The latter allows to initially prevent the flight through hazardous icing conditions from a strategic and tactical point of view, whereas the hybrid detection architecture provides the necessary information to the flight crew for the IPS activation and the execution of safe exit strategies, when required. It combines in-situ measurement from various ice detection sensor technologies based on different physical principles (optical or remote sensing and ice accretion detection) with an indirect detection methodology. Hence, the HIDS allows to give a more general overview on the current aircraft icing than an individual system alone. In addition, the indirect detection methodology monitoring the current aircraft flight characteristic reveals the degraded aircraft flight envelope, which is essential for loss of control prevention. An overview on the layered safety concept is given in Fig. 1. The concept targets a general application and safety enhancement for fixed-wing aircraft icing and is not only dedicated to aircraft already certified for flight into known icing conditions (App. C). It intentionally goes beyond current certified aircraft systems proving safe operations in icing conditions.

This paper is focused on the "indirect ice detection system" (IIDS), which is a novel methodology and system for the on-board surveillance of aircraft flight performance used for ice detection purposes. The base formulation of the idea was already presented in Ref. [5] and its application in SENS4ICE as one important project pillar in Ref. [6]. It utilizes the effect of aircraft performance degradation due to ice accretion and is not restricted to an application on large transport aircraft but can also enable a reliable ice detection for aircraft systems, such as small UAV, which currently have no ice detection system but operate in hazardous environments with very different icing conditions.

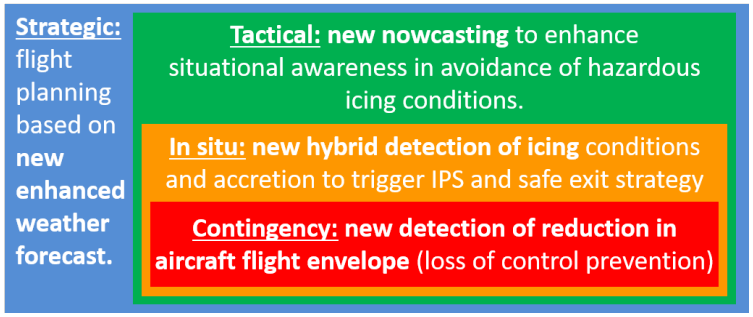

Fig. 1 SENS4ICE layered safety concept

The SENS4ICE project contained two major icing flight test campaigns: the North America campaign using an Embraer Phenom 300 prototype aircraft and the European campaign with an ATR 42-320 environmental research aircraft operated by Safire (Service des Avions Francais Instrumentés pour la Recherche en Environnement) [8, 9]. This paper presents first results of the evaluation of flight test results from the European fight test campaign in April 2023 with a focus on the IIDS ability to reliably detect the performance degradation caused by icing during several example ice encounters.

The paper is structured as follows:

- a brief description of the indirect ice detection methodology based on the observed aircraft flight performance variation is given in section II;
- section III contains the specific implementation of the detection algorithm for the SENS4ICE purpose with focus on the Safire ATR 42 test aircraft;
- exemplary flight test data analysis from SENS4ICE Europen icing flight test campaign reflecting the system performance with regard to the ability of reliable ice detection in section IV.

Finally, a summary with initial conclusions as well as an outlook are given.

II. Airframe Ice Detection through Flight Performance Monitoring

One major effect of aircraft ice accretion is a significant drag increase due to surface roughness changes, parasitic influence of ice protuberances, and local flow separation. Another effect of icing is a change of the aircraft lift behavior, causing e.g., earlier or more abrupt flow detachment with increasing angle of attack and/or a reduction in aircraft lift slope. Both together significantly alter the aircraft flight performance which can be monitored during flight. Figure 2 illustrates the typical icing-induced change of the lift and drag curves as generally described e.g., in the AGARD report 344 [10]. Icing will also change the aircraft's flight dynamics (e.g., pitching and rolling moment). Also the control characteristics are negatively affected by icing and change the aircraft dynamics differently according to the specific occurrence of ice accretion. But these changes are very difficult to detect during flight, for what the IIDS relies on the icing related change of aircraft flight performance [5, 6].

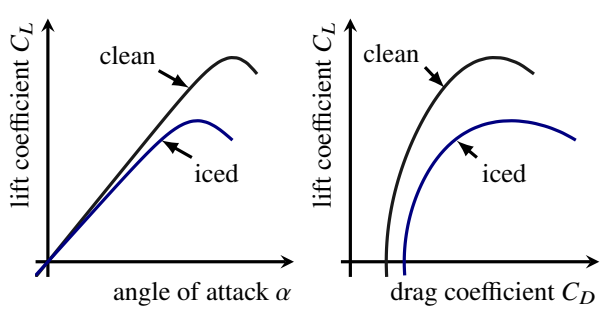

Fig. 2 Expected influence of icing on aircraft aerodynamics (lift and drag coefficient); adapted from [10]

Hence, aircraft flight performance monitoring can provide crucial information to the pilots about the current (limited/degraded) aircraft capabilities while only requiring the sensor information that is available on all modern

airliners and business jets. The advantage of the developed methodology is that it relies only on the change in flight performance (i.e., steady flight states) contrary to the many failed attempts (e.g., in Refs. [11–16]) based on the estimation of changes in the aircraft's dynamic behavior or a combination of both. The change/degradation in the flight performance is an indicator of ice accretion that is both robust and highly available: unlike the approaches based on the detection of changes in the aircraft dynamical behavior, it can be used also during steady flight conditions (most of an operating flight) and can detect icing effects significantly before entering into stall. Although other direct ice measuring approaches for the detection of icing conditions or ice accretion on the airframe could deliver a partly similar information, the indirect detection using the performance monitoring approach would not require (potentially costly) modifications of existing and future aircraft. It is important to highlight that the method within the IIDS is focused on the flight performance changes with a need of any additional dynamic aircraft excitation. Such an excitation is not acceptable during normal operations as stated in Ref. [13] and especially not when flying with an aircraft that has a reduced (unknown) maximum-lift angle of attack due to icing.

Key to the indirect ice detection using performance monitoring is the assumption that the performance variation of a single aircraft over lifetime in service or within a fleet of aircraft of same type – where flight performance characteristics of each individual aircraft slightly differ – is well distinguishable from the performance variation caused by icing. Some of the factors causing the flight performance variations across airplanes from the same type are production tolerances, aircraft skin repairs, aircraft skin contamination (e.g., dirt), engine aging causing reduced efficiency, or engine contamination. In order to be able to detect icing through the detection of flight performance changes, the other factors not related to icing must be significantly lower or significantly slower in degradation rate than the degradations caused by icing. The aircraft flight performance can be seen as follows:

$$\begin{aligned}\textbf{Flight Performance} = \;& \text{Nominal Aircraft Performance}\\ &+ \text{Expectable Variation}\\ &+ \textit{Variation to be detected}\end{aligned}$$

whereby the "Expectable Variation" part gathers the effects mentioned previously and the "*Variation to be detected*" is subject to the indirect ice detection approach. The first step is to determine the typical and most extreme flight performance variation ("Expectable Variation") encountered during regular airline operations (due to a real performance variation or sensor errors). There are different approaches to reveal this variation from operational flight data. In Refs. [5, 17] the determination of the performance variation from 75,689 flights with Boeing B737-700 and B737-800 aircraft operated by a German airline is presented. The results unterpinned the above assumption and revealed that is possible to successfully monitor the aircraft performance using the regular sensors and with a level of precision that permits to detect the performance degradation that is induced by the ice accretion at a very early stage (before this degradation of the performance reaches a critical level).

Fig. 3 Safire ATR 42-320 flight test bench (MSN 78): aircraft with all modification for the SENS4ICE European flight test campaign at Toulouse/Francazal airport; credit DLR/Safire.

The flight data for the Safire ATR 42 test aircraft (Fig. 3) serving as flight test bench in SENS4ICE European flight test campaign were processed to obtain the measured performance variation during flight. The resulting performance variation (without icing) is given in Fig. 4 for the Safire ATR 42 test bench. The measured performance

variation in this case results from the non-filtered measurements which are also not corrected for external disturbances. Therefore, the measured variation does include (external) effects on the aircraft, e.g., resulting from encountered atmospheric disturbances or conducted maneuvers, together with additional influences on the performance calculation like measurement noise.

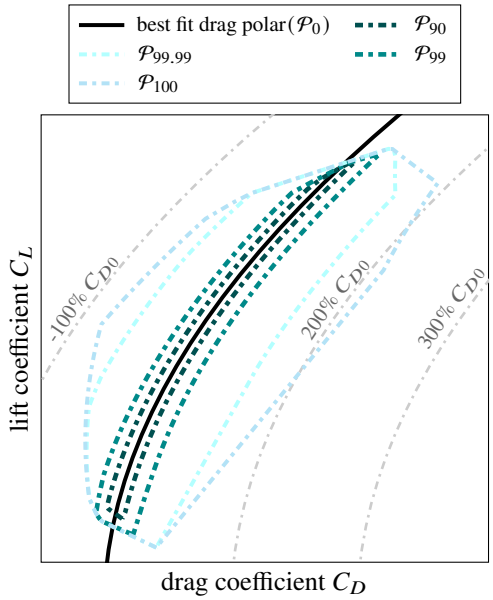

Fig. 4 Measured aircraft performance variation based on Safire ATR 42-300 flight test data at several flight conditions (1.45 million data points): estimated drag polar and convex hulls ($\mathcal{P}_{90}$, $\mathcal{P}_{99}$, $\mathcal{P}_{99.9}$ & $\mathcal{P}_{100}$).

This is in contrast to the results given in Refs. [5, 17], where the data were corrected for most of these effects. But for the design of the IIDS, it is essential to also evaluate the measured performance variation of a single aircraft, which is mainly the variation between the actual aircraft and the reference model together with the named additional influences. Hence, in this case the 90% quantile is more relevant than the higher ones, because it can be reliably assumed that the variation above results from the external influence which can be ignored for the ice detection and circumvented (e.g., for large scale atmospheric disturbances or dynamic maneuvers) or filtered (e.g., for measurement noise) within the designed algorithm.

Hence, if the measurements of the flight condition are available with high frame rate above e.g., 20 Hz and are not filtered or corrected for e.g., measurement noise, the IIDS must account for a higher observed performance variation ("Expectable Variation") but is assumed to be able to reliably detect a performance degradation due to icing fast. But if the measurement frame rate is significantly lower (e.g., 5 Hz) and/or the data are already low-pass filtered, the IIDS will observe a smaller performance variation and the detection of the degradation might be slower than for the higher measurement rate case. Hence, for any given application of the IIDS approach a trade-off between the detection speed and accuracy and the quality of the flight data measurements is required. Nevertheless, the results of the specific flight data analysis given above led to the guess that the detection threshold for the Safire ATR 42 test bench should be defined between 10% and 15% deviation of the zero-lift drag in order to provide a good sensitivity and reliability. As no information about the Safire ATR 42 flight performance degradation caused by icing was available for the IIDS design in SEN4ICE a conservative definition of the threshold at 15% drag increase seemed reasonable. Note that if no aircraft data are available for this kind of evaluation, e.g., for new aircraft designs, the manufacture's design performance data will also be suitable, eventually together with an increased more conservative threshold.

The basic idea of the performance-based ice detection method is to compare the current (possibly ice-influenced) aircraft flight performance characteristics with a known reference (see Fig. 5). The flight performance can be defined as a power imbalance (change of total energy) $\dot{E}_{tot}$ for the current state and the reference, which allows representing the change of aircraft characteristics in a sole value. Consequently, this reduces the complexity of the detection algorithm. It further combines the individual parts of the aircraft performance related to aerodynamics and engines in a single

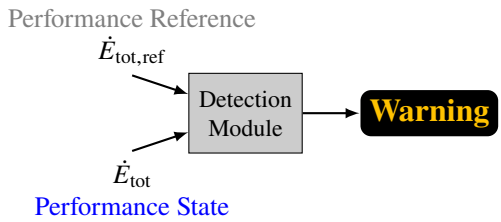

Fig. 5 Basic principle of the IIDS method based on the aircraft power imbalance; from [5]

observation. The power imbalance $\dot{E}_{tot}$ can be formulated as

$$\dot{E}_{\text{tot}} = V_{\text{TAS}} \cdot \dot{V}_{\text{TAS}} \cdot m_{\text{AC}} + \frac{1}{2} \cdot V_{\text{TAS}}^2 \cdot \dot{m}_{\text{AC}} + g \cdot \dot{H} \cdot m_{\text{AC}} + g \cdot H \cdot \dot{m}_{\text{AC}} \,, \tag{1}$$

with the altitude change (with respect to time) $\dot{H}$ referenced to the surrounding air and the speed change (with respect to time) $\dot{V}_{\text{TAS}}$. The change of aircraft mass $\dot{m}_{\text{AC}}$ corresponds to the engine fuel consumption for normal civil aircraft operations, which are considered as main application of the presented method. Note that the gravitational acceleration is assumed to be constant and its variation with time can be neglected for the calculation of the power imbalance. To convert the power imbalance into an equivalent drag coefficient variation, which is more easy to assess from an engineering point of view, the formulation from [5] is used:

$$\Delta C_{\bar{D}} \approx \frac{\dot{E}_{\text{tot,ref}} - \dot{E}_{\text{tot}}}{V_{\text{TAS}} \cdot \overline{q} \cdot S_{\text{Wing}}} \tag{2}$$

This non-dimensional equivalent drag coefficient is calculated by comparison of the current determined power imbalance $\dot{E}_{\text{tot}}$ and a predefined reference value $\dot{E}_{\text{tot,ref}}$. The performance reference value is a function of the aircraft flight state defined by parameters like altitude, speed and load factor, and also the aircraft configuration (e.g., mass, high lift system configuration) and propulsion system state. If required, some corrections for additional influences, e.g., flight with side slip condition could be applied[5]. The equivalent drag coefficient is well comparable to a predefined threshold value and indicates an abnormal performance variation when exceeding. This is further independent from any flight point. Note that a drag coefficient value is well interpretable in terms of aerodynamics and flight mechanics by aerospace engineers and allows a direct assessment of the magnitude of aerodynamic degradation caused by icing.

A simple way for the definition of the aircraft flight performance reference is the usage of a multi-dimensional table including the different above-mentioned states and conditions as dimension. Interpolation within the table will then allow a quick access to the current reference power imbalance value. The table approach has also the advantage that the performance reference can be easily adapted to a specific aircraft over life time: this will cover the "Expectable Variation" described above and will further ensure a constantly high sensitivity of the IIDS with very low likelihood for false alarms. Another way is to calculate the reference power imbalance from an aerodynamic data base and engine thrust model, if both are available. But using these as source for the performance reference could make the adaptation to a specific aircraft more difficult. In such case it must be determined if the variation in the reference power imbalance results from changes of the aircraft aerodynamics or the engine performance. For the implementation in SENS4ICE an engine thrust model was available and the reference power imbalance can be formulated as a function of flight condition, aircraft configuration (using a reference aerodynamic model representation) and the current predicted engine thrust. For example, a methodology to adapt flight performance models from operational flight data is given in Ref. [18], which could be relevant for the adaptation of the performance reference with separated models (aerodynamics and engine thrust).

The airspeed V_{TAS} is derived from several measurements and contains a combination of aircraft flight path velocity and wind speed (both to be understood as 3D vectors). The true airspeed time derivative $\dot{V}_{\text{TAS}}$ contains a component related to the change of inertial velocity vector as well as a component related to the change of wind vector. For the present case, only the first of these components $\dot{V}_{\text{TAS},\dot{\vec{V}}_{\text{k}}}$ is relevant as it directly affects the aircraft performance. The second component should be ignored in order to prevent it from falsifying the performance estimate. A variable wind-corrected energy change $\dot{E}_{\text{tot,corr}}$ results from Eq. (3) using $\dot{V}_{\text{TAS},\dot{\vec{V}}_{\text{k}}}$ as airspeed change:

$$\dot{E}_{\text{tot,corr}} = V_{\text{TAS}} \cdot \dot{V}_{\text{TAS},\dot{\vec{V}}_{\text{k}}} \cdot m_{\text{AC}} + \frac{1}{2} \cdot V_{\text{TAS}}^2 \cdot \dot{m}_{\text{AC}} + g \cdot \dot{H} \cdot m_{\text{AC}} + g \cdot H \cdot \dot{m}_{\text{AC}}. \tag{3}$$

III. Implementation of the Indirect Ice Detection Algorithm

The indirect ice detection is implemented as a modular set of functions, including the core detection algorithm, the required data preprocessing and a subsequent detection result filtering to prevent false detections. The latter also guarantees the necessary system robustness and consequently reliability. Within SENS4ICE, the indirect ice detection is part of the HIDS and allows with its specific implementation detecting performance degradations and therefore the ice accretion (see Fig. 6). The HIDS implementation is designed to be applicable to both flight test benches used for SENS4ICE flight test campaigns, which are very different aircraft configuration: a light business jet aircraft (Embraer Phenom 300) and a regional class turbo-prop aircraft (ATR 42). This applicability is possible through the generic formulation of the detection methodology itself, not relying in specific information about the aircraft: the required aircraft-specific adaption of the detection is achieved by considering the aircraft-specific reference, which is an input to the algorithm and not part of the core implementation.

The IIDS formulation of the detection methodology is a significant advantage for prototyping the specific system implementation compared to more integrated approaches which would require more specific information about the aircraft inside the core detection algorithm. But, there are still several needs for adjustments inside the IIDS for a specific aircraft type, which concern

- the flight data preprocessing,
- the flight performance reference data base,
- the indirect ice detection threshold and confirmation times,
- the detection reliability conditions,

which are briefly outlined detailed below and further detailed in Ref.[6]. These adjustments are mainly part of the "Aircraft Flight Data" and "Performance Reference Data Base" blocks in Fig. 6.

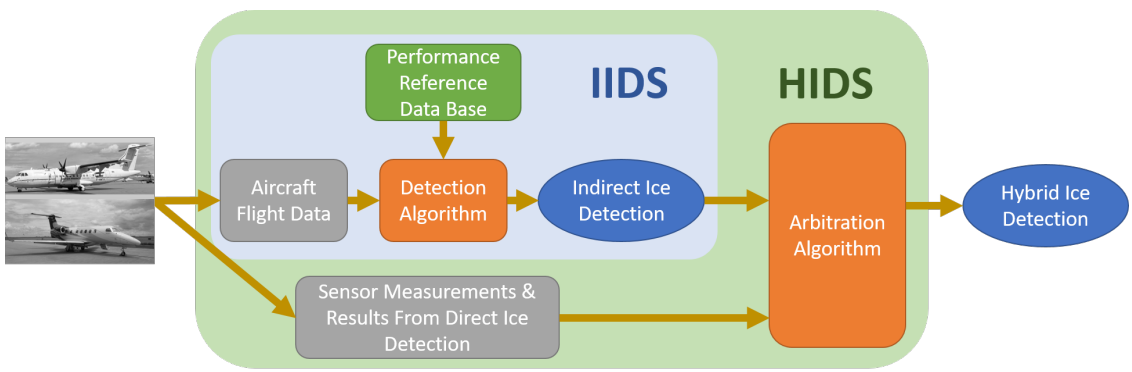

Fig. 6 Visualization of HIDS concept used within SENS4ICE; pictures credit DLR / Embraer / Safire.

The IIDS is currently implemented in MATLAB®/Simulink because a very agile prototyping and dynamic testing was required. The HIDS runs on a dSpace MicroAutoBox in real time for the flight tests, and the Simulink model can be easily transferred to the hardware including a full intellectual property protection required for several parts of the IIDS. Future exploitation will presumably provide a code implementation running with aircraft avionic systems.

A. Flight Data Preprocessing

The available measurements about the aircraft's current flight state, the configuration and the atmospheric conditions are significantly aircraft dependent. Nevertheless, for modern transport aircraft, there is a minimum set of required measurements, e.g., for indication in the cockpit or use in flight controllers, which is almost sufficient for the IIDS calculations. Within the flight data preprocessing a data selection for the required data sets must be performed, treating, e.g., specifically the data from the different propulsion systems to calculate engine thrust. For the IIDS it is essential to have all measurements about the flight state referenced to the current center of gravity position, which means that accelerations and flow measurements must be corrected for position offsets. Consequently, this is a part of the IIDS which requires a deeper insight in the aircraft and avionics system but the necessary effort for development is not different as for any other aircraft-specific avionic functions (e.g., flight management system or flight control functions).

For example, the IIDS requires the following information about the current aircraft state

- acceleration, rotational rates and attitude,
- atmospheric conditions, altitude, airspeed, inflow angles,

- engine (and propeller) state,
- aircraft configuration and weight and balance,

which is processed and provided to the detection algorithm in a fixed format. For an ideal implementation of the IIDS, a high sample rate for high resolution data measured with high accuracy is of course favorable to ensure a highly reliable and fast detection of the flight performance degradation. But also lower sample rate with less accurate measurements can be used to predict the degraded flight performance, as in the presented case for the Safire ATR 42 which provides mainly measurements with sample rates between 1 Hz and 8 Hz. Nevertheless, as performance degradation is a low frequency process, the reduced measurement sample rates might / will only affect the IIDS reactivity to icing.

B. Flight Performance Reference Data Base

The IIDS relies on an accurate flight performance reference which allows to compute an expected current flight performance to be compared to the measured one within the detection module. As discussed above, the reference data base must allow to compute the reference power imbalance $\dot{E}_{\text{tot,ref}}$ and is not restricted to a certain type of implementation. In Ref. [5] a multi-dimensional table was found to be the most suitable way but for the SENS4ICE project a different implementation was chosen for several reasons. For the presented case the IIDS consist of a performance reference data base splitting engine and aerodynamic influence into individual parts. Having this separation, it was more easy to adapt the reference aerodynamics to the specific conditions given by the flight test benches having several external probes attached to the test aircraft influencing the aircraft's flight performance.

The flight test case-specific adaption of the aerodynamic performance reference is formulated as an additional part to the "base" aircraft reference, which allowed a very fast adaption of the reference data base prior to the icing flight tests. For the European flight test campaign, the final configuration of the aircraft with all modifications, i.e. external sensors and pods mounted on wing pylons or at the fuselage, was available for check flights two week before the campaign start in mid March 2023. With two specific test flight on March 22nd and 23rd, 2023, the corresponding changes of the aerodynamic compared to the "base" aircraft aerodynamics were determined. The latter were already available through the extensive flight data evaluation of Safire's ATR 42-320 (MSN 78, see Fig. 3). Using a kind of delta approach to the aerodynamic reference, it could be shown that the performance reference was successfully adapted to the modified aircraft. This was done with small but very specific information available from an initial test flight in dry air. Note, that this is a special condition and therefore not contrary but complementary to the argumentation in Ref. [5] being in favor of an integrated multi-dimensional reference table for a tail number-specific implementation of the performance reference in an aircraft fleet of similar type.

Having a representation of the aircraft drag polar given by

$$C_D = C_{D0} + k_1 \cdot C_L + \cdot C_L^2 \,, \tag{4}$$

a linear parameter extension was already foreseen in the IIDS implementation allowing the adaptation of the aircraft aerodynamics to the SENS4ICE aircraft modifications:

$$C_D = \left(C_{D0,\text{ref}} + \Delta C_{D0}\right) + \left(k_{1,\text{ref}} + \Delta k_1\right) \cdot C_L + \left(k_{2,\text{ref}} + \Delta k_2\right) \cdot C_L^2 \,. \tag{5}$$

Figure 7 shows the drag polar calculated from flight test data of the clean air flights with the aircraft in campaign configuration together with the pre-campaign reference used to design the IIDS and the modified drag polar used for the icing flight tests. The corresponding parameters to shift the drag polar from MSN 78 pre-campaign reference to EU icing flight test campaign reference using the formulation in Equation (5) are given in Table 1.

zero-lift drag coefficient modification parameter	ΔC_{D0}	0.0014
linear drag change with lift	Δk_1	0.0
quadratic drag change with lift	Δk_2	0.0021

Table 1 Parameters for change of aerodynamic reference according to the SENS4ICE aircraft modifications; Safire ATR 42-320 flight test bench used for European flight test campaign.

Moreover, for both flight test benches ATR and Embraer delivered detailed information about the propeller respectively engine thrust based on the inflight measurements of propeller and engine states. Consequently, the flight performance reference consists of different data bases and reference model formulations adapted to the SENS4ICE

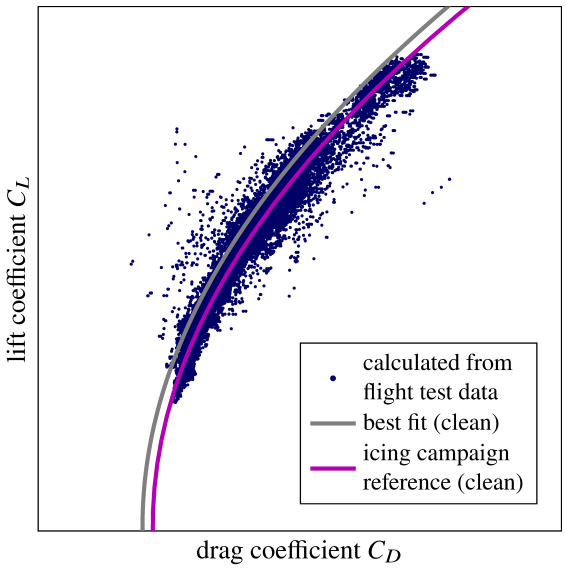

Fig. 7 Aircraft drag polar for Safire ATR 42-320 (MSN78) used for the SENS4ICE European icing flight test campaign: calculated lift and drag coefficient from flight test data (blue dots), pre-campaign reference drag polar (gray line, no SENS4ICE aircraft modification) and adapted campaign reference drag polar considering aircraft modifications (magenta line); clean air flights in final aircraft configuration with all modification required for SENS4ICE on March 22nd and 23rd, 2023.

purposes, but is still generally valid for different aircraft implementation if required. Note that the flight performance reference in SENS4ICE is based on certain a priori knowledge and information obtained from a specific flight data evaluation. But for new aircraft designs it could also be on the design models and initial prototype flight test results.

C. Detection Threshold and Confirmation Time

Abnormal flight performance can result from different sources as initially discussed. But if resulting from ice accretion on the airframe it is assumed to be persistent and constantly increasing. In this case, the flight performance degradation is leading to the indirect ice detection, but must not be subject to false alarms. Therefore, a detection threshold on the equivalent drag coefficient has to be defined which ensures that the degradation is significant and critical for the further flight. For practical reasons, the detection is not done on the absolute value of the equivalent drag increase but on a relative value with the zero-lift drag coefficient as base. In a nominal case, the additional drag coefficient is zero and there is no relative change to the normal drag condition.

During normal operation flight there is a constant fluctuation of measured flight performance, sometimes also exceeding the threshold. Hence, detection algorithm has to account for these by providing a suitable low-pass filtering function preventing any false-positive detection. In addition, the implementation of a confirmation time allows to further prevent false alarms cause by short-time threshold exceeding if set large enough. Furthermore, it makes the IIDS output more robust to cases where the performance degradation leads to oscillations around the threshold which would lead to multiple triggers of the detection if not considered properly. Hence, the detection is only triggered once if confirmed during the defined confirmation time. The confirmation time is chosen in accordance with the modeling accuracy of the whole IIDS system chain and quality of flight data. A high quality and accuracy of flight data measurements together with a highly accurate performance reference data base can lead to relatively short confirmation times whereas lower data quality and/or performance reference accuracy must lead to longer confirmation times in order to prevent false detections. To ensure that the equivalent drag exceeds the threshold most of the time (more than 50%) within a considered time frame weighted moving averages are used. These are based on a certain confirmation time frame and different for the positive detection and the reset after leaving the icing situation. For the detection, the confirmation time frame is chosen relatively short to ensure fast response behavior but for reset that confirmation time must be much longer to guarantee the threshold is reliably undershot and the icing-related performance degradation is not present anymore. The corresponding values are given in Table 2.

detection threshold as relative drag coefficient increase (for flight test)	15 %
detection threshold as relative drag coefficient increase (post-campaign)	10 %
confirmation time frame for detection (threshold exceeded more than 50%)	20 s
confirmation time for reset (threshold undershot more than 50%)	180 s

Table 2 Detection threshold values and confirmation time for the IIDS implementation: Safire ATR 42-320 flight test bench for European flight test campaign.

D. Indirect Detection Reliability Conditions

The IIDS is designed to run continuously during the whole flight and to monitor the aircraft flight performance, and a potential degradation, independently from any specific flight phase or maneuver, as discussed in Ref. [5]. The SENS4ICE implementation is experimental and therefore limited to one aircraft specific configuration defined for the flight test in icing conditions. Hence, other aircraft configurations will be detected and the IIDS is designed to freeze and set an unreliability flag allowing the HIDS to discard the current IIDS output. A more detailed description is given in Ref. [6].

IV. Exemplary Results from SENS4ICE European Flight Test Campaign

For this paper an exemplary flight from the European flight test campaign is chosen to provide initial and preliminary results. The selected flight took place in the morning of April 27th, 2023, around Toulouse. The aircraft departed from Toulouse/Francazal airport and searching for icing conditions in the north east of Toulouse. After more the 3 hours of flight, the aircraft returned to Toulouse/Francazal having successfully encountered icing condition several times during flight. An overview on the flight is given in Fig. 8 including the flight track and icing encounters. Note that the information about the icing conditions found is resulting from the Safire icing probe, which is an standard sensor located under the left wing. This information is not cross-referenced with the scientific and/or SENS4ICE icing probes, but gives a very good indication the icing situations present during the flight. The consolidated probe data give three indication about the icing conditions on the aircraft: no ice, ice formation up to 2 mm on the probe, ice formation above 2 mm on the probe. Hence, the current icing intensity can be assessed by the interpretation of the ice formation on the probe.

A. Aerodynamic Degradation due to icing

Figure 9 shows the aircraft drag polar calculated from the measured flight data. Again, the current icing information from the Safire probe is indicated for each data point. It is clearly visible that the aircraft flight performance was significantly degraded during the majority of the ice encounters (green and yellow marks), whereas the aircraft drag coefficient is well comparable to the reference (red line) for the flight without ice (clean aircraft, blue marks). Figure 10 shows again the aircraft drag polar calculated from the measured flight data but now with the indication of the corresponding IIDS calculated relative drag (normalized with base aircraft zero-lift drag). Blue marks indicate a nominal drag estimation / flight performance, which means that there is no increase detected. The more the aircraft is degraded the relative drag increases. For this example flight, the maximum increase was around 25% (light orange marks) which was correctly detected by the IIDS during flight.

In Fig. 11 the calculated aircraft drag polar contains an indication of the IIDS ice detection. Blue marks indicate a nominal drag estimation without any abnormal performance detection. The more the aircraft is degraded the more the drag estimation increases. For this example flight, the maximum increase was around 25% (light yellow marks) which was correctly detected by the IIDS during flight.

B. Indirect Ice Detection System Performance

The IIDS performance during this example flight is further visualized as time history plot in Fig. 12. The top plot contains the altitude and indicated airspeed of the whole flight. It is clearly visible that during the flight the aircraft was intentionally fully de-iced by descending into warmer air and the climbing back to and altitude between FL140 and FL160 where the icing conditions were encountered. The mid plot shows the relative drag coefficient (based on clean aircraft zero-lift drag) and gives a direct impression about the performance degradation during the flight. In parallel the IIDS detection output is given allowing a direct comparison of drag increase and IIDS detection performance. The bottom plot contains the detected ice accretion on the Safire icing probe and the static air temperature. This allows a

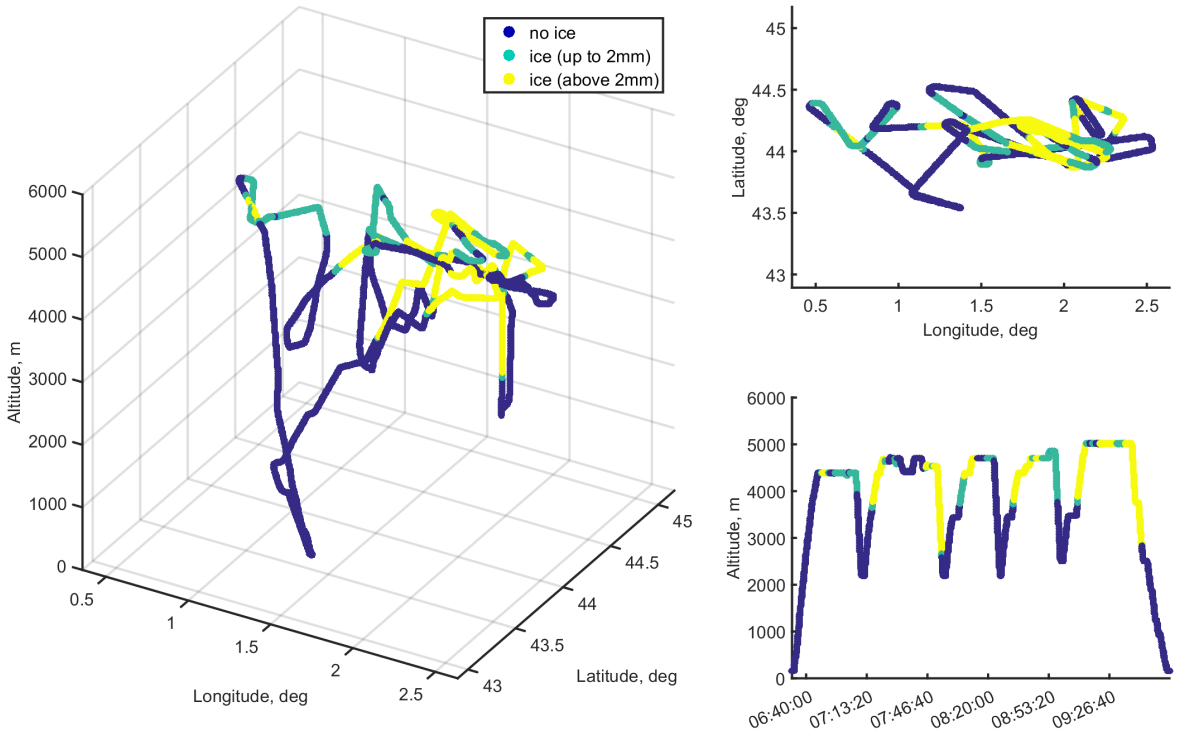

Fig. 8 Flight track from SENS4ICE European icing campaign flight on April 27th, 2023 (morning): geodetic position and altitude with indication of icing encountered; icing information from Safire icing probe.

direct assessment about the icing encountered leading to airframe ice accretion and hence a performance degradation, together with the possibility to cross-check the detection reset with the flight through warm air and consequently de-icing. It can be directly seen, that the threshold of 15% relative drag increase is to conservative to allow a detection of the degradation during the different encounters. Especially during the first quarter of the flight, the performance degradation did not exceed the threshold, which prevented the IIDS from announcing the ice accretion on the airframe.

Figure 13 shows one icing encounter during flight at FL150 and the following de-icing in warmer air. Icing is present until around 08:13 UTC and again between around 08:19 UTC and 08:23 UTC. The aircraft performance is degraded and the drag is increased not exceeding the threshold until around 08:21 UTC resulting then in a IIDS detection output. During descending with higher speed into warmer air, the aircraft is de-iced and the normal aircraft performance is restored resetting the IIDS detection output. The corresponding ice accretion on the airframe is shown in Fig. 14 for different moments during the encounter. Camera views on the left and right wing as well as on the horizontal tail show the evolution of ice accretion on the airframe for the time around the IIDS ice detection output. At 08:20:45 UTC visible ice formation is present on the wings' leading edge, which is more and more removed during the following 3 minutes. During the descent at 08:23:47 UTC the ice formation on the wings is almost gone.

Another longer icing encounter leading to a stronger performance degradation respectively aircraft drag increase is given Fig. 15. There is a detection of icing by the aircraft icing probe during the climb to FL160, but the air temperature is relatively still high and the ice formation on the airframe almost not detectable. A slight increase of relative drag can be observed when the aircraft reaches FL160 (around 09:14 UTC), but without any significant effect on the aircraft performance. With the indication of another icing encounter after 09:17 UTC the aircraft drag increases due to light ice accretion on the aircraft. Around 09:21 UTC another icing encounter leads to a rise in measured relative drag exceeding the threshold and triggering the IIDS detection output. After the icing encounter the aircraft drag is lightly reduced leading the IIDS to reset the detection around 09:34 UTC but exceeding the threshold again shortly after triggering the IIDS detection output again. This exemplary encounter reveals the already discussed challenge of selecting the IIDS detection and reset confirmation times together with the detection threshold in order to prevent false alarms and frequent

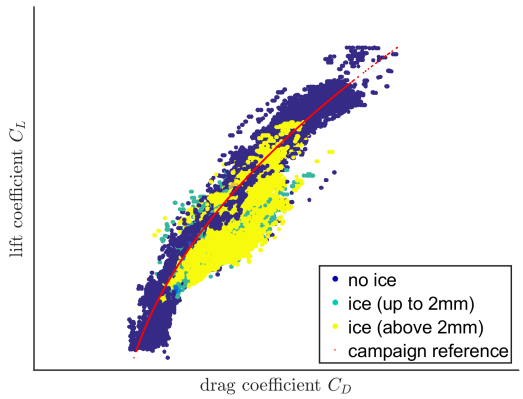

Fig. 9 Aircraft drag polar from SENS4ICE European icing campaign flight on April 27th, 2023 (morning): calculated drag coefficient from flight data measurements and drag polar reference (red line) for the Safire ATR 42 with SENS4ICE modifications (high-lift devices and gear retracted); drag coefficient data including the indication of icing encountered; icing information from Safire icing probe.

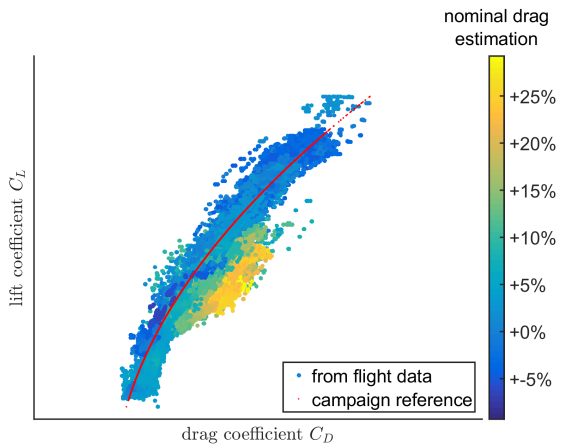

Fig. 10 Aircraft drag polar from SENS4ICE European icing campaign flight on April 27th, 2023 (morning): calculated drag coefficient from flight data measurements and drag polar reference (red line) for the Safire ATR 42 with SENS4ICE modifications (high-lift devices and gear retracted); drag coefficient data including the indication of nominal drag estimation calculated by IIDS.

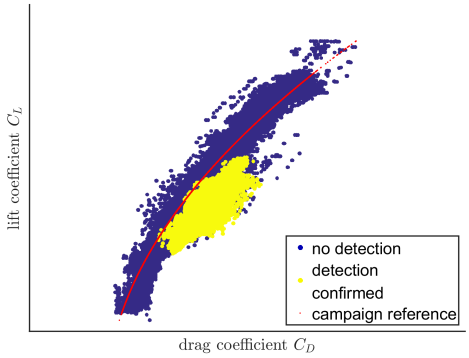

Fig. 11 Aircraft drag polar from SENS4ICE European icing campaign flight on April 27th, 2023 (morning): calculated drag coefficient from flight data measurements and drag polar reference (red line) for the Safire ATR 42 with SENS4ICE modifications (high-lift devices and gear retracted); drag coefficient data including the indication of IIDS abnormal flight performance detection related to airframe ice accretion.

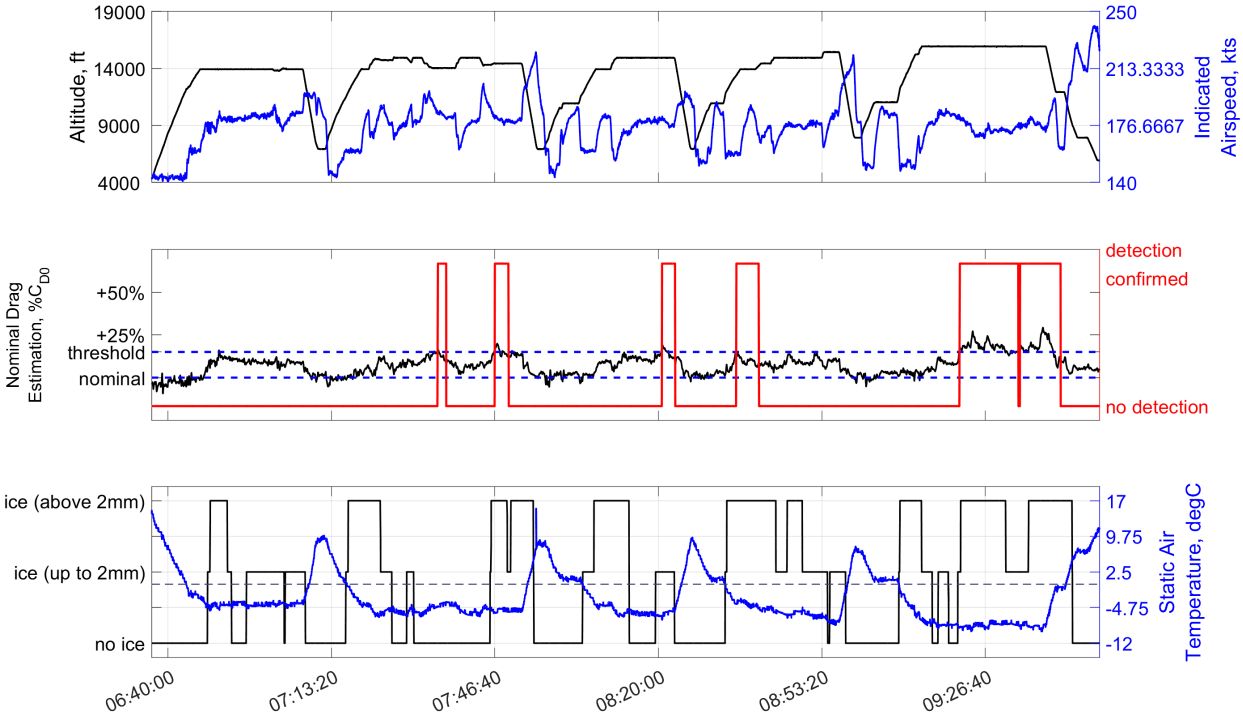

Fig. 12 Time history of IIDS system performance during whole example flight from SENS4ICE European campaign flight on April 27th, 2023 (morning): altitude and indicated airspeed (top), relative drag coefficient and IIDS detection output (mid), and detected icing and static air temperature (dashed line 0 degC) (bottom); flight campaign detection threshold of 15% relative drag increase.

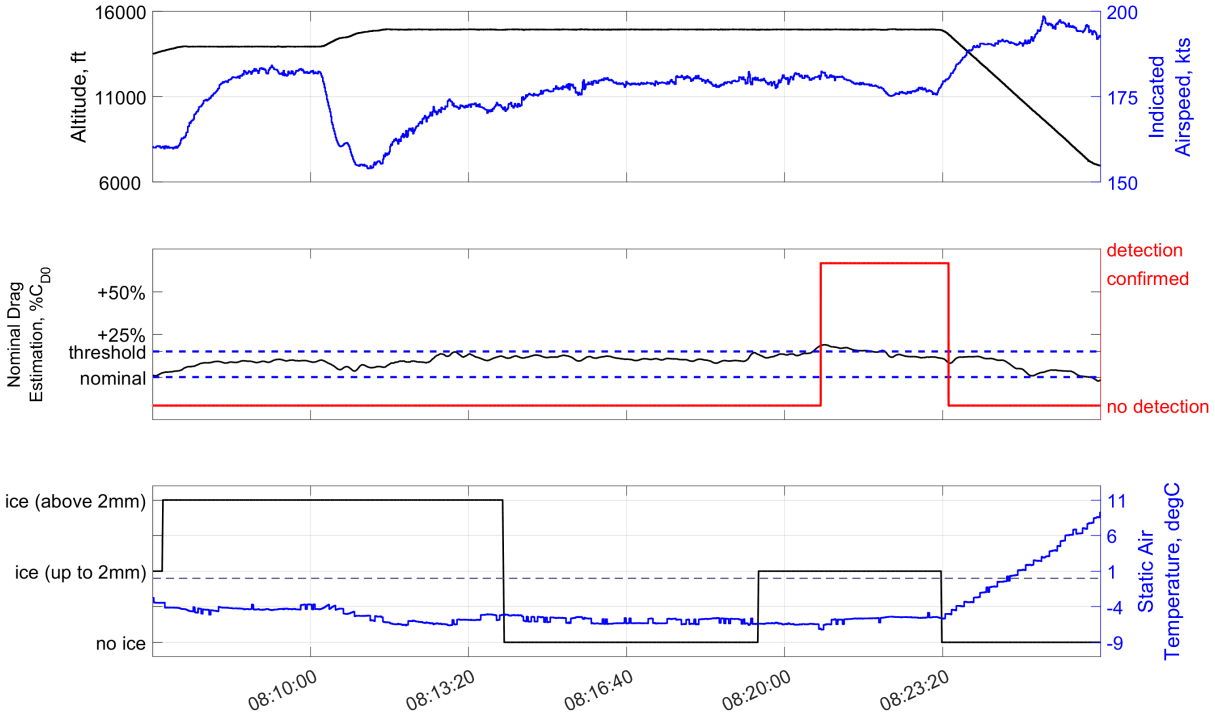

Fig. 13 Time history of IIDS system performance during specific icing encounter from the example flight (08:06 UTC to 08:26 UTC): altitude and indicated airspeed (top), relative drag coefficient and IIDS detection output (mid), and detected icing and static air temperature (dashed line 0 degC) (bottom); flight campaign detection threshold of 15% relative drag increase.

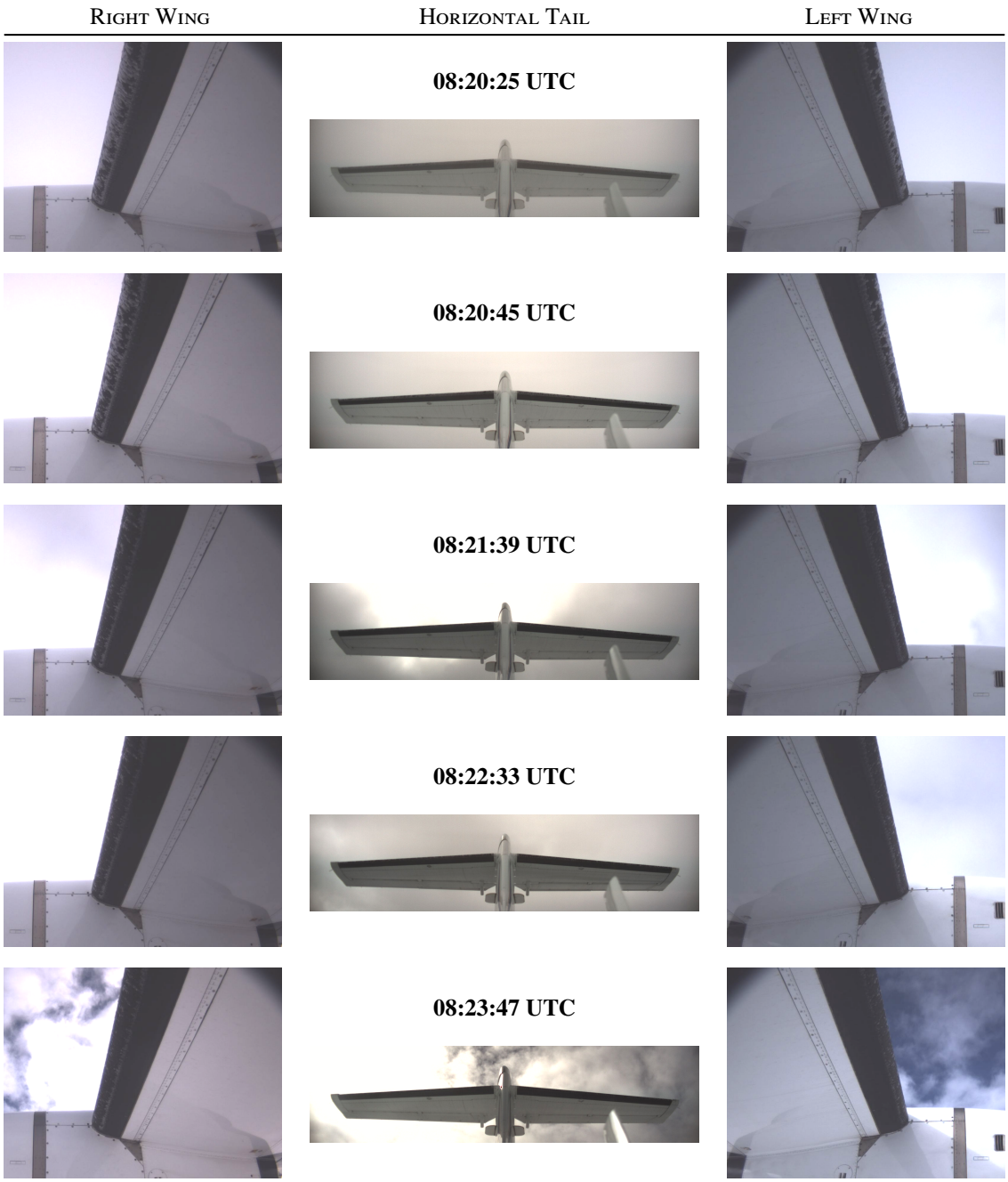

Fig. 14 Evolution of ice accretion on the airframe during icing encounter: camera views on left & right wing and horizontal tail for specific moments during flight (increased brightness and contrast); corresponding to encounter and IIDS detection given in Fig. 13; credit Safire / SENS4ICE project.

changes of detection output but guarantee a fast response to changing conditions (airframe icing and de-icing). After descending into warmer air, the aircraft is de-iced and the detection output is reset. Pictures from the corresponding ice accretion on the aircraft's wings and horizontal tail are given in Fig. 16.

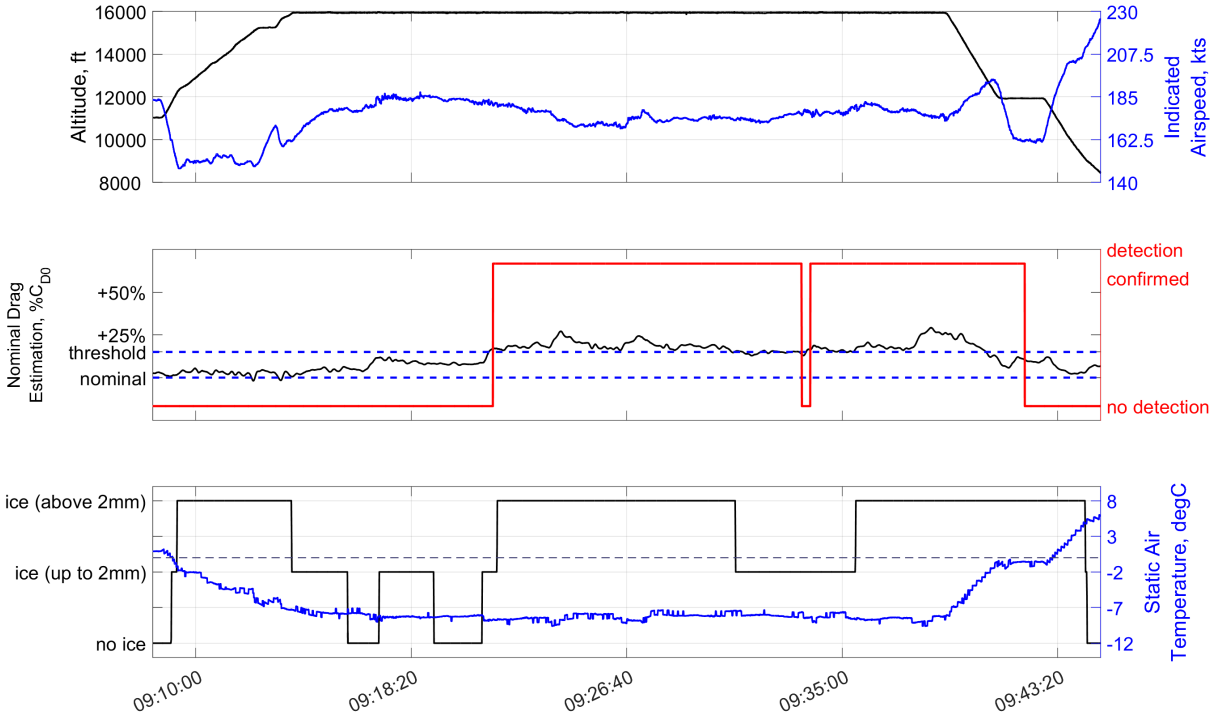

Fig. 15 Time history of IIDS system performance during specific icing encounter from the example flight (09:08 UTC to 09:44 UTC): altitude and indicated airspeed (top), relative drag coefficient and IIDS detection output (mid), and detected icing and static air temperature (dashed line 0 degC) (bottom); flight campaign detection threshold of 15% relative drag increase.

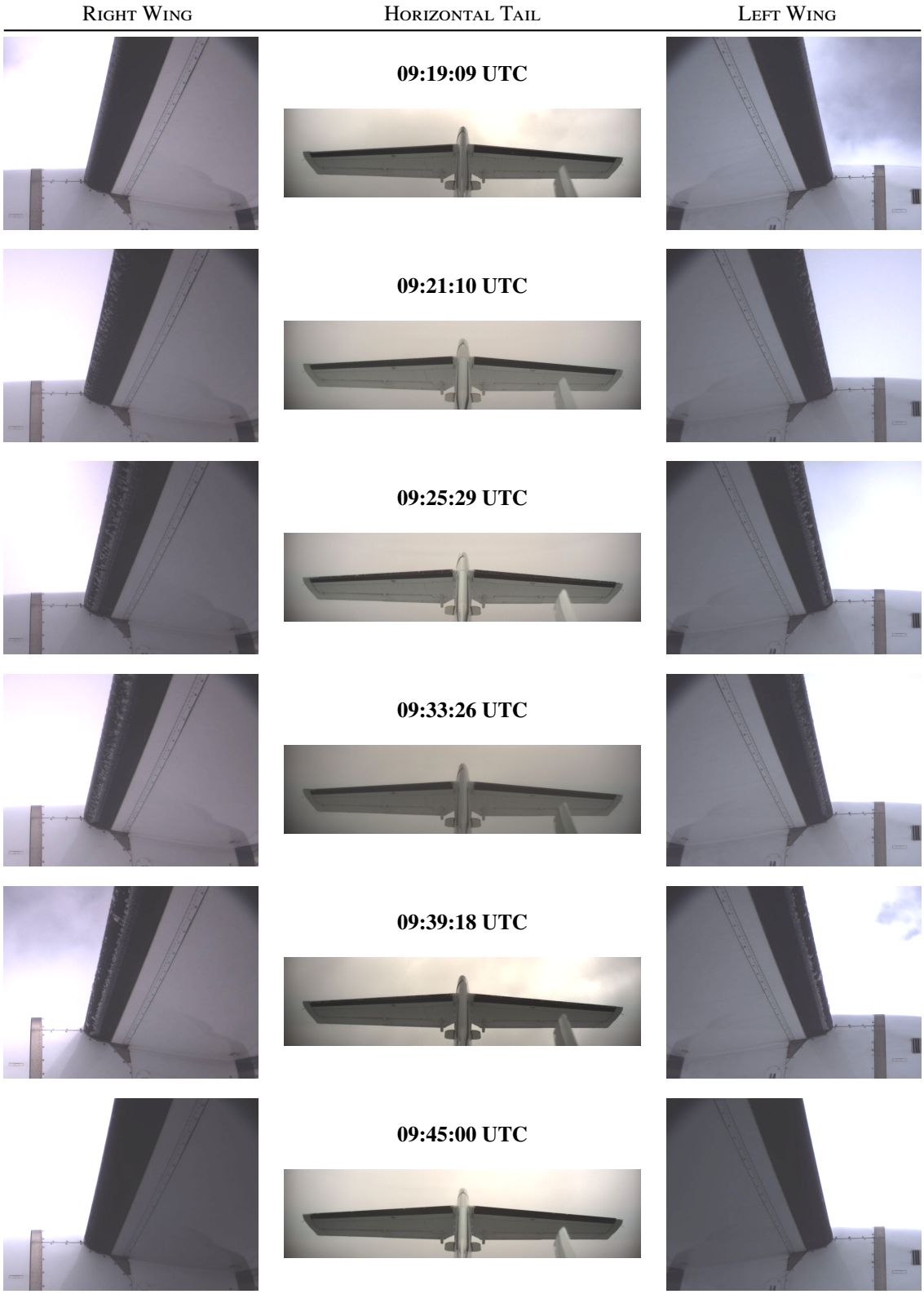

Fig. 16 Evolution of ice accretion on the airframe during icing encounter: camera views on left & right wing and horizontal tail for specific moments during flight (increased brightness and contrast); corresponding to encounter and IIDS detection given in Fig. 15; credit Safire / SENS4ICE project.

C. Post-Flight Test Ice Detection System Evaluation with Reduced Detection Threshold

The initial IIDS performance evaluation during the flight test campaign reveal that the detection threshold of 15% relative drag increase was chosen too conservative. This is underpinned by the above given example, especially in the first half hour of the flight where the drag increase did not reach the 15% threshold but icing conditions were present and the influence on the flight performance well noticeable (see Fig. 12). Note that the threshold was initially chosen more conservative because of the relevant information about the aircraft performance degradation due to ice accretion was missing for this specific. With the initial evaluation of the SENS4ICE flight test data and initial campaign results the use of a reduced threshold similar to the one used in the SENS4ICE North America flight test campaign [6] of 10% relative drag increase seems more reasonable also for the Safire ATR 42. Consequently, the example flight from April 27th was replayed and the IIDS performance recorded for the reduced detection threshold without any further change of IIDS configuration. The results are given in Fig. 17 for the whole flight. The comparison of these results with the flight test recordings provided in Fig. 12 reveals the advantage of the reduced threshold while not increasing any risk for false alarms on this specific example. Now the IIDS is also able to announce the degraded aircraft performance during the light icing encounters and/or earlier during moderate icing encounters. Especially during the first half hour of the flight the icing related performance degradation is now correctly detected.

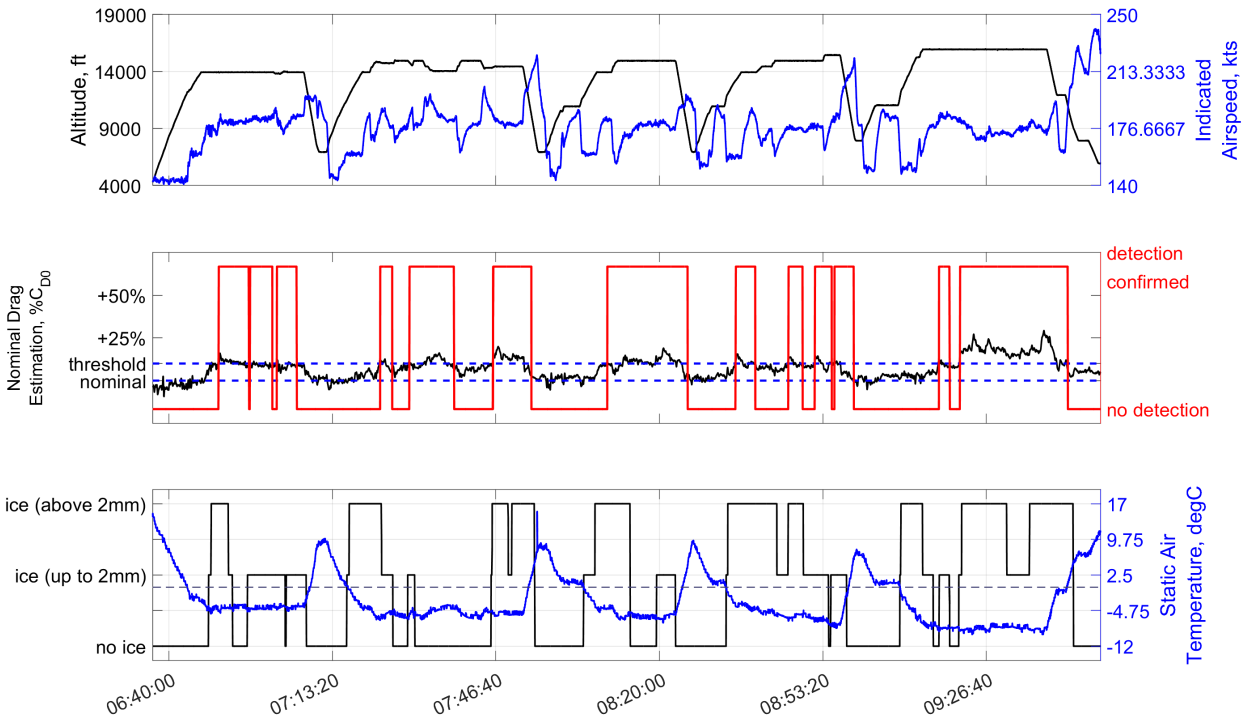

Fig. 17 Time history of IIDS system performance for the example flight replay (SENS4ICE European campaign flight on morning April 27th, 2023): altitude and indicated airspeed (top), relative drag coefficient and IIDS detection output (mid), and detected icing and static air temperature (bottom); *reduced* detection threshold of 10% relative drag increase compared to Fig. 12.

Figure 18 shows the IIDS performance with a reduced detection threshold during the icing encounter given in Fig. 13. The degraded performance is detected right after the encounter started, announcing the drag increase caused by light ice accretion on the wing. The outside view on the airframe for the beginning of this encounter is given in Fig. 19. The IIDS now detects the degraded performance around 08:09 UTC when some ice accretion is visible on the wings. Around 5 minutes later, less ice is visible but the drag increase is still present (presumably due to ice accretion also present on other parts of the airframe not covered by the cameras during flight) still leading to a positive IIDS detection result. At around 08:20 UTC the drag is further increasing which led to the detection with the flight campaign threshold of 15%.

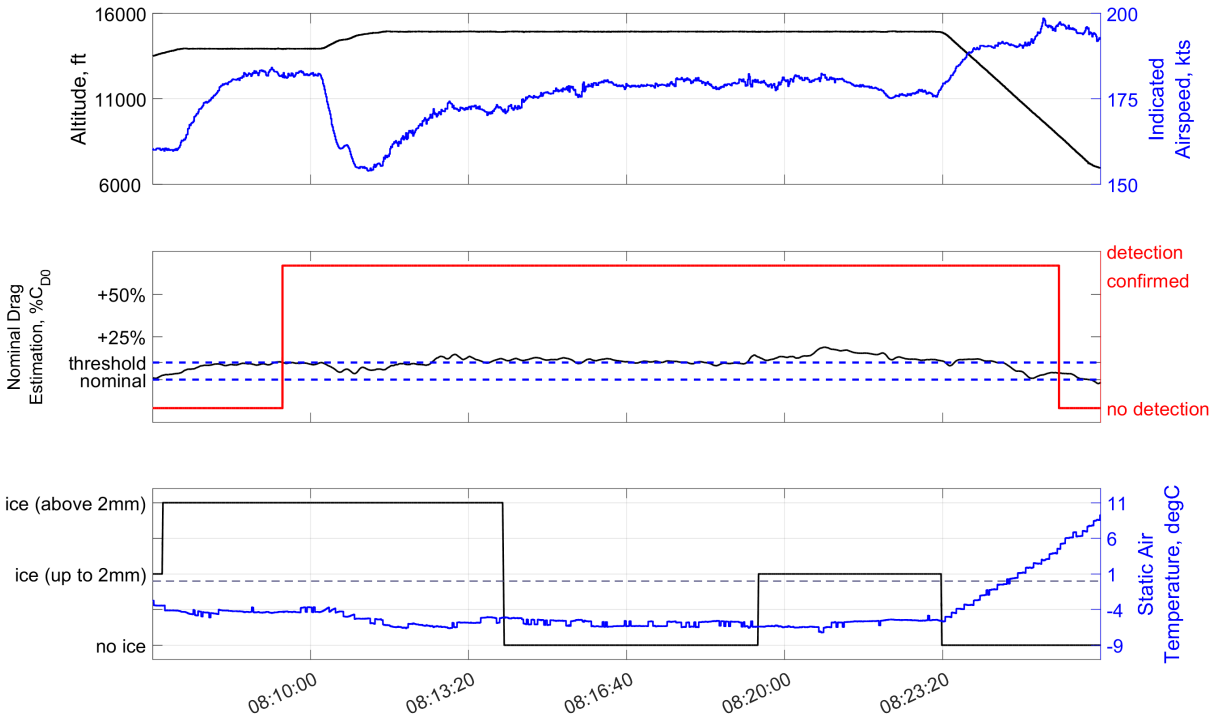

Fig. 18 Time history of IIDS system performance for the example flight replay (SENS4ICE European campaign flight on morning April 27th, 2023; 08:06 UTC to 08:26 UTC): altitude and indicated airspeed (top), relative drag coefficient and IIDS detection output (mid), and detected icing and static air temperature (bottom); *reduced* detection threshold of 10% relative drag increase compared to Fig. 12.

Fig. 19 Evolution of ice accretion on the airframe during icing encounter: camera views on left & right wing and horizontal tail for specific moments during flight (increased brightness and contrast); corresponding to the beginning of the encounter and IIDS detection given in Fig. 18; credit Safire / SENS4ICE project.

Hence, the reduction of the detection threshold enhances the IIDS reactivity to icing related performance degradation which better supports the HIDS arbitration function to provide a more complete overview on the current icing situation to the flight crew as one major results of the SENS4ICE project.

V. Summary and Future Work

The SENS4ICE project is a big step towards successful and reliable detection of different icing conditions including SLD (Appendix O conditions). One key to achieve this goal is the so-called indirect ice detection methodology based on an aircraft performance degradation, which provides several advantages compared to direct detection (ice sensors), which are mainly complementary, e.g., the retrofit capabilities, a simple software solution or the highly beneficial information about the remaining aircraft capabilities for safe aircraft operations. In additions, the indirect ice detection represents a second pillar for ice detection redundancy when hybridized and hence reduces the risk for common cause failures. It is based on the reliable measurements of the aircraft flight condition normally available through modern aircraft avionics. Today, such comprehensive measurements are not only provided to large transport aircraft systems but are also part of smaller aircraft avionics, which also opens up various new possibilities for the performance-based ice detection on this type of vehicles. For example, small unmanned aerial vehicles could not be equipped with large or complex direct ice detection methods but would directly benefit from a reliable and relatively fast software-based indirect ice detection method.

The first results of the SENS4ICE European flight test campaign with a specially equipped ATR 42 aircraft operated by Safire are very promising in order to validate the indirect ice detection methodology and evaluate its performance during flight through natural icing conditions. This paper presents certain preliminary results from the evaluation of one specific test flight on April 27th, 2023, around Toulouse (France). During several icing encounters the IIDS was able to reliably detect the aircraft flight performance degradation caused by ice accretion on the aircraft after it becomes effective. As a first result from the campaign, a reduction of the conservatively chosen detection threshold from 15% to 10% relative drag increase to enhance the IIDS reactivity to light ice accretion was proposed and validated by a post-flight replay with the IIDS. But even without this modification the evaluation of the IIDS performance during this flight showed the system's ability to reliably detect the performance degradation and announce the change of aircraft state very fast after the encounter started.

Future work on the analysis of the SENS4ICE flight test campaigns and the IIDS performance will first be dedicated to a complete evaluation of all test flights. In addition, a comparison of the IIDS performance during the European and North America campaign will further reveal the IIDS performance for icing encounters with different conditions and the corresponding performance degradation for a business jet and turbo-prop aircraft. The analysis will specifically focus on the performance degradation characteristics related to SLD ice accretion. Also, the minimal reliably detectable ice formation through performance degradation on the different aircraft will be assessed. Furthermore, the IIDS configuration could be optimized by changing, e.g., confirmation times or further reducing the detection thresholds, keeping in mind, that results might only be valid for the flight test benches and encountered icing conditions. But, these results would be valuable for the further definition and design of the IIDS and the system maturation and exploitation for different applications.

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References

[1] Green, S. D., "A Study of U. S. Inflight Icing Accidents and Incidents, 1978 to 2002," 44th AIAA Aerospace Sciences Meeting and Exhibit, American Institute of Aeronautics and Astronautics, Inc. (AIAA), Reno, Nevada, USA, 2006. doi:10.2514/6.2006-82.

[2] Green, S. D., "The Icemaster Database and an Analysis of Aircraft Aerodynamic Icing Accidents and Incidents," Technical Report DOT/FAA/TC-14/44, R1, Federal Aviation Administration, Atlantic City, NJ, USA, Oct. 2015.

[3] Anon., *Final Report (BFU 5X011-0/98)*, German Federal Bureau of Aircraft Accident Investigation, Braunschweig, Germany, April 2001.

[4] Anon., *Aircraft Accident Report (NTSB/AAR-96/01, DCA95MA001), Safety Board Report*, National Transportation Safety Board (NTSB), Washington, DC, USA, July 9th 1996.

[5] Deiler, C., and Fezans, N., "Performance-Based Ice Detection Methodology," *Journal of Aircraft*, Vol. 57, No. 2, 2020, pp. 209–223. doi:10.2514/1.C034828.

[6] Deiler, C., "Design and Testing of an Indirect Ice Detection Methodology," SAE International Conference on Icing of Aircraft, Engines, and Structures, SAE International, Paper 2023-01-1493, Vienna, Austria, 2023.

[7] Schwarz, C. W., "The SENS4ICE EU project – SENSors and certifiable hybrid architectures for safer aviation in ICing Environment – Project Overview and Initial Results," 33th Congress of the International Council of the Aeronautical Sciences (ICAS), Stockholm, Sweden, 2022. URL `https://icas.org/ICAS_ARCHIVE/ICAS2020/data/papers/ICAS2022_0794_paper.pdf`.

[8] Schwarz, C. W., "SENS4ICE EU Project Preliminary Results," SAE International Conference on Icing of Aircraft, Engines, and Structures, SAE International, Paper 2023-01-1496, Vienna, Austria, 2023.

[9] Jurkat-Witschas, T., Lucke, J., Schwarz, C. W., Deiler, C., Sachs, F., Kirschler, S., Menekay, D., Voigt, C., Bernstein, B., Jaron, O., Kalinka, F., Zollo, A., Lilie, L., Mayer, J., Page, C., Vié, B., Bourdon, A., Pereira Lima, R., and Vieira, L., "Overview of Cloud Microphysical Measurements During the SENS4ICE Airborne Test Campaigns: Contrasting Icing Frequencies from Climatological Data to First Results from Airborne Observations," SAE International Conference on Icing of Aircraft, Engines, and Structures, SAE International, Paper 2023-01-1491, Vienna, Austria, 2023.

[10] Anon., "Ice Accretion Simulation," AGARD Advisory Report 344, Advisory Group for Aerospace Research & Development (AGARD) - Fluid Dynamics Panel Working Group 20, North Atlantic Treaty Organization (NATO), Neuilly-Sur-Seine, France, December 1997.

[11] Bragg, M. B., Perkins, W. R., Sarter, N. B., Başar, T., Voulgaris, P. G., Gurbacki, H. M., Melody, J. W., and McCray, S. A., "An Interdisciplinary Approach to Inflight Aircraft Icing Safety," 36th AIAA Aerospace Sciences Meeting and Exhibit, American Institute of Aeronautics and Astronautics, Inc. (AIAA), Reno, Nevada, USA, 1998. doi:10.2514/6.1998-95.

[12] Myers, T. T., Klyde, D. H., and Magdaleno, R. E., "The Dynamic Icing Detection System (DIDS)," 38th AIAA Aerospace Sciences Meeting and Exhibit, American Institute of Aeronautics and Astronautics, Inc. (AIAA), Reno, Nevada, USA, 1999. doi:10.2514/6.2000-364.

[13] Melody, J. W., Başar, T., Perkins, W. R., and Voulgaris, P. G., "Parameter Identification for Inflight Detection and Characterization of Aircraft Icing," *Control Engineering Practice*, Vol. 8, No. 9, 2000, pp. 985–1001. doi:10.1016/S0967-0661(00)00046-0.

[14] Bragg, M. B., Başar, T., Perkins, W. R., Selig, M. S., Voulgaris, P. G., Melody, J. W., and Sater, N. B., "Smart Icing Systems for Aircraft Icing Safety," 40th AIAA Aerospace Sciences Meeting and Exhibit, American Institute of Aeronautics and Astronautics, Inc. (AIAA), Reno, Nevada, USA, 2002. doi:10.2514/6.2002-813.

[15] Aykan, R., Hajiyev, C., and Caliskan, F., "Aircraft Icing Detection, Identification and Reconfigurable Control Based on Kalman Filtering and Neural Networks," AIAA Atmospheric Flight Mechanics Conference and Exhibit, American Institute of Aeronautics and Astronautics, Inc. (AIAA), San Francisco, California, USA, 2005. doi:10.2514/6.2005-6220.

[16] Gingras, D. R., Barnhart, B. P., Ranuado, R. J., Ratvasky, T. P., and Morelli, E. A., "Envelope Protection for In-Flight Ice Contamination," 47th Aerospace Sciences Meeting, American Institute of Aeronautics and Astronautics, Inc. (AIAA), Orlando, Florida, USA, 2009. doi:10.2514/6.2009-1458.

[17] Deiler, C., "Evaluation of Aircraft Performance Variation During Daily Flight Operations," Deutscher Luft- und Raumfahrtkongress, Deutsche Gesellschaft fur Luft- und Raumfahrt (DGLR), Friedrichshafen, Germany, 2018. doi:10.25967/480025, URL `https://elib.dlr.de/121521/`.

[18] Deiler, C., "A Smart Data Approach to Determine an Aircraft Performance Model From an Operational Flight Data Base," AIAA Scitech Forum, American Institute of Aeronautics and Astronautics, Inc. (AIAA), National Harbor, Maryland, USA, 2023. doi:10.2514/6.2023-0797.