This paper was presented at: SAE Icing Conference, 20.-22. Jun. 2023, Vienna, Austria. doi: 10.4271/2023-01-1493

Design and Testing of an Indirect Ice Detection Methodology

Christoph Deiler, Falk Sachs
DLR - German Aerospace Center

Abstract

Distinct atmospheric conditions containing supercooled large droplets (SLD) have been identified as cause of severe accidents over the last decades as existing countermeasures even on modern aircraft are not necessarily effective against SLD-ice. Therefore, the detection of such conditions is crucial and required for future transport aircraft certification. However, the reliable detection is a very challenging task. The EU funded Horizon 2020 project SENS4ICE targets this gap with new ice detection approaches and innovative sensor hybridization. The indirect ice detection methodology presented herein is key to this approach and based on the changes of airplane flight characteristics under icing influence. A performance-based approach is chosen detecting an abnormal flight performance throughout the normal operational flight. It is solely based on a priori knowledge about the aircraft characteristic and the current measurable flight state. This paper provides a proof of concept for the performance-based ice detection: starting with the evaluation of operational flight data for different example aircraft the expectable flight performance variation within a fleet of same type is shown which must be smaller than the expected icing influence for reliable detection. Next, the implementation of the indirect ice detection system (IIDS) algorithms in SENS4ICE is detailed with certain regard to the flight test implementation for final validation. Finally, the initial methodology verification and validation results are presented and discussed.

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. Various accidents worldwide have shown the severity of icing related degradations, e.g., Refs. [1, 2, 3, 4], especially when caused by supercooled large water droplets (SLD) although involved aircraft were equipped with state-of-the-art ice protection systems. 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 CS-25. But with the identified hazard to fixed-wing aircraft resulting from SLD the aviation agencies issued the new App. O to the certification requirements. From now on, manufacturers must prove that a newly developed airplane is also safe for flight into the even more hazardous SLD icing conditions. 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. Hence, it is mandatory to detect the presence of especially SLD icing early and to also monitor the aircraft's remaining capabilities during the further flight. 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.

Furthermore, all different existing ice protection systems (IPS) require an significant amount of energy provided on board. In case of thermal protection systems usually bleed air is used, which causes a reduction of the engine effectiveness and an increased fuel consumption. A deliberate activation of the IPS is necessary for efficient flight operations, which raises the demand for a reliable information about the current degradation, safety risk, and therefore need to activate the IPS. The design of new IPS with different power consumption depending on its effectiveness against the current icing encounter will 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.

The "SENSors and certifiable hybrid architectures for safer aviation in ICing Environment" (SENS4ICE) project aims 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) [5, 6]. 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 facilitates in-situ measurement from different ice detection sensor technologies as well as an indirect detection methodology resulting in a novel detection of the degraded aircraft flight envelope, which is essential for loss of control prevention. An overview on the layered safety concept is given in Figure 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. Apart from the safety improvements provided by the SENS4ICE ice detection architecture, a more efficient use of energy-consuming devices such as anti-ice systems could possibly be enabled by monitoring the IPS efficiency: on the one hand, if e.g., the aircraft flight performance is not changing during icing encounter it indicates that the IPS is effective; on the other hand, if the ice detectors and e.g. a rapid change in flight performance indicate higher icing severity, the IPS power could be increased to counteract the ice accretion, whereas the power could be maybe

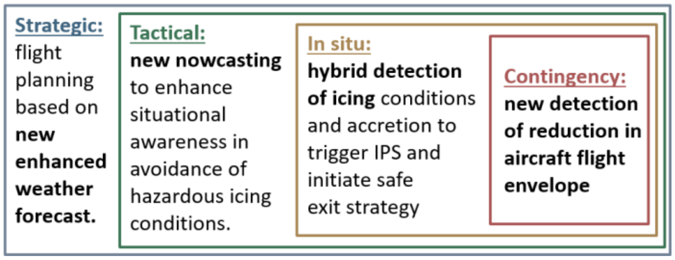

Figure 1. SENS4ICE layered safety concept, adapted from [5].

decreased if the severity is low. Hence, SENS4ICE developments enable potentials even beyond the project scope.

This paper presents one main core of the hybrid ice detection architecture: the implementation of a novel methodology and system for the on-board surveillance of aircraft flight performance used for ice detection purposes named the "indirect ice detection system" (IIDS). A base formulation of the idea was already presented in Ref. [7], and built one important pillar for the definition of the SENS4ICE project in 2018. Figure 2 illustrates the typical estimated icing-induced change of the lift and drag curves as generally described e.g., in the AGARD report 344 [8]. 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, with nonlinearities in the lift curve (e.g., earlier or more abrupt flow detachment with increasing angle of attack). Both together significantly change the aircraft flight performance. This is utilized for the IIDS. Moreover, icing will also alter the aircraft's flight dynamics, e.g., characteristics of pitching and rolling moment. Especially the response to control inputs and also the control efficiencies are affected by icing and change the aircraft dynamics differently according to the specific occurrence of ice accretion on the aircraft's surfaces. But these changes are very difficult to detect during flight, for what the IIDS relies on the icing related change of aircraft flight performance. In addition, the IIDS concept can 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.

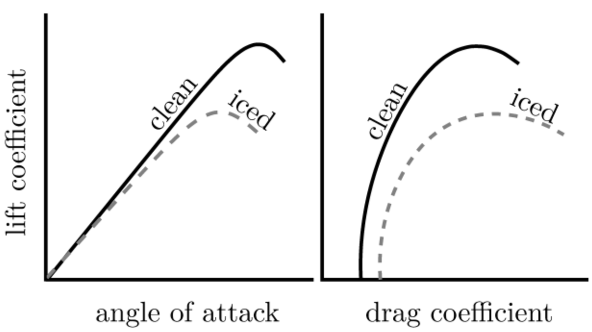

Figure 2. Expected aerodynamic degradation due to icing; adapted from [8].

The paper is structured as follows: a detailed description of the indirect ice detection methodology based on the observed aircraft flight performance variation is given first. Second, the specific implementation of the detection algorithm for the SENS4ICE purpose is presented. It is followed by the analysis of results reflecting the system performance with regard to the ability of ice detection using emulated and real icing flight data. Finally, a conclusion as well as an outlook are given.

Flight Performance Monitoring for Airframe Ice Detection

The 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. [9, 10, 11, 12, 13, 14]) 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.

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:

$$\begin{aligned}\boldsymbol{Flight\ Performance}\\ &= Nominal\ Aircraft\ Performance\\ &+ Expectable\ Variation\\ &+ Variation\ to\ be\ detected\end{aligned} \tag{1}$$

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. [7, 15] 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. Without any information about the aircraft engine thrust characteristics in the recorded flight data, a specific energy-based approach was used to extract the performance variation.

The methodology used to derive the aircraft performance from the recorded data is based on the energy of the airplane or rather its time derivative. The total energy of the aircraft is

$$E_{tot} = \frac{1}{2} \cdot m_{AC} \cdot V_{TAS}^2 + m_{AC} \cdot g \cdot H \tag{2}$$

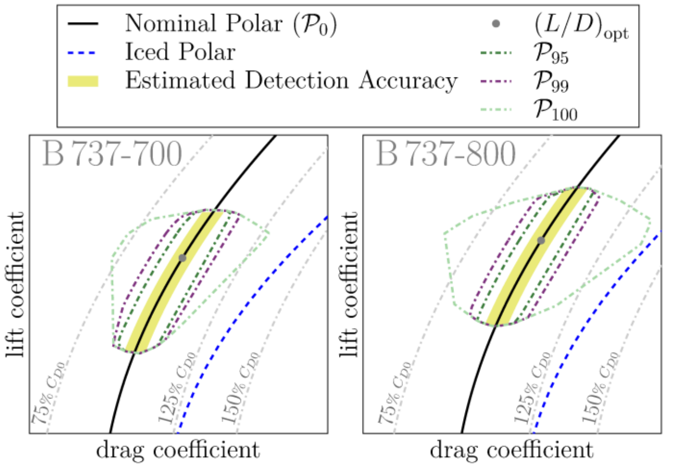

Figure 3. Aircraft performance variation within two aircraft fleets determined from operational flight data records: convex hulls (P_{95}, P_{99} & P_{100}) of obtained equivalent drag coefficient, adapted from [7].

and the time derivative of the energy $\dot{E}_{tot}$ describes the aircraft's real power imbalance. The total energy level is increasing, for instance, due to an excess of engine thrust for the current flight situation.

Figure 3 shows the aircraft flight performance variation within the fleet of Boeing B737-700 (left) and B737-800 aircraft (right). In order to reduce data (millions of data points) convex hulls (shape including the corresponding subset of data) in the [C_D, C_L]-plane corresponding to several quantiles of the data were computed and plotted. On these individual figures,

1. the black line represents the nominal drag polar of the aircraft;
2. the dot-dashed gray lines are defined by shifting the nominal drag polar by steps of 25% C_{D0} and serve as grid in this figure;
3. the dashed blue line represents an expectable drag polar with moderate ice accretion;
4. the yellow area represents schematically the accuracy that was (very conservatively) expected to be reached with performance monitoring system, in this case IIDS;
5. the areas defined by the dash-dotted dark green, dash-dotted purple, and dash-dotted light green polygon lines are the convex hulls of the selected data quantiles (95%, 99%, and 100%).

The results of this initial big data analysis support the underlying assumption that it 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). This makes the implementation of the IIDS within the HIDS approach possible. The potential ice (accretion) detection based on the flight performance change in the IIDS is maybe not comparable to other direct sensing technologies in terms of fast detection of icing conditions or very small accretions, but will deliver a reliable information about the aircraft's restricted envelope with only a short delay. As an initial guess a drag increase of more than 30% zero-lift drag was conservatively defined as minimum detection threshold. This definition was updated later on for the specific implementation. Moreover, the threshold can be also altered in order to obtain a much faster IIDS response once the system is verified and properly tuned.

In a second step, flight data for the Embraer Phenom 300 prototype (Figure 4, see also disclaimer below) and the ATR 42 test aircraft (Figure 5) serving as flight test benches in SENS4ICE were processed to obtain the measured performance variation during flight. The

Figure 4. Embraer Phenom 300 prototype for SENS4ICE SLD-ice flight test campaign in North America (credit DLR/EMBRAER).

Figure 5. SAFIRE ATR 42-320 flight test bench for SENS4ICE SLD-ice flight test campaign in Europe (credit DLR/SAFIRE).

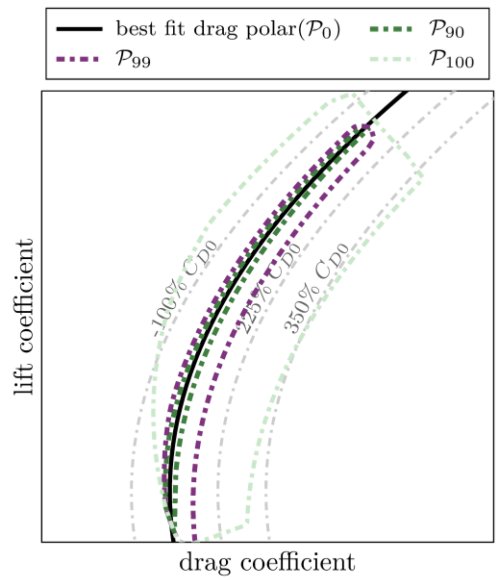

Figure 6. Measured aircraft performance variation based on dynamic Phenom 300 flight test data throughout a large flight envelope (2.2 million data points): estimated drag polar and convex hulls ($P_{90}, P_{99}, P_{99.9}$ & P_{100}).

resulting performance variation (without icing) is given in Figure 6 for the Phenom 300 and in Figure 7 for the 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.

This is in contrast to the results given in Figure 3, 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.

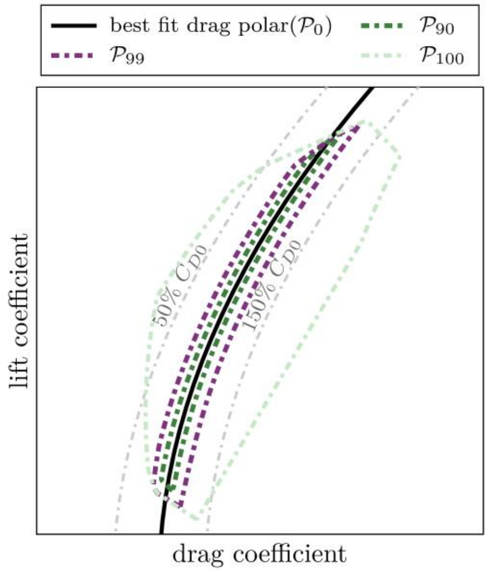

Figure 7. Measured aircraft performance variation based on ATR 42 flight test data at several flight conditions (1.45 million data points): estimated drag polar and convex hulls (P_{90}, P_{99}, $P_{99.9}$ & P_{100}).

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 also able to reliably detect a performance degradation due to icing fast during dynamic maneuvers. In contrast, if the measurements are only available with low frame rate (e.g., 5 Hz) and/or already low-pass filtered, the IIDS will observe a smaller performance variation and the detection of the degradation might be slower. Consequently, there must be a trade-off for any given application of the IIDS approach regarding the detection speed and accuracy and the quality of the flight data measurements. Nevertheless, the results of the specific flight data analysis for the two flight test benches revealed that the detection threshold for the icing flight test campaigns should be defined by around 10% to 15% deviation of the zero-lift drag in order to provide a good sensitivity and reliability. Looking at the results of a specific evaluation of (artificial) icing cases for the Phenom 300 in Refs. [16, 17, 18] this definition of the threshold for the Phenom 300 is practical and justifiable with the flight data evaluation results. Unfortunately, such an extensive analysis about the expectable icing impact on the ATR 42 was not available, but the conservative definition of the threshold at 15% drag increase seems reasonable. The validation of the thresholds will finally result from the flight test data analysis at the end of SENS4ICE and an evaluation of the false alarm rate can be made. 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 threshold.

In contrast to other approaches to detect icing on changes of the dynamic aircraft behavior [9, 10, 11, 12, 13, 14, 19], the method within the IIDS is focused on the flight performance changes. Icing mainly affects the aircraft's drag (see Figure 2), but none of these proposed methods is based on this effect. A major advantage of "only" monitoring flight performance characteristics and not the aircraft's dynamic behavior is that no (additional) dynamic excitation is required. Such an excitation is not acceptable during normal operations as stated in Ref. [11] and especially not when flying with an aircraft that has a reduced (unknown) maximum-lift angle of attack due to icing, as indicated in Figure 2.

The basic idea of the herein-proposed detection method is to compare the current (possibly ice-influenced) aircraft flight performance characteristics with a known reference, as schematically represented in Figure 8.

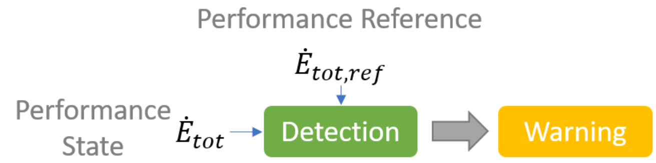

Figure 8. Basic principle of the IIDS method based on the aircraft power imbalance; adapted from [7].

The flight performance can be formulated as a power imbalance (change of total energy) $\dot{E}_{tot}$ in both cases (current state and reference), which allows to represent the changed aircraft characteristics in only one significant value and reduces the detection module complexity. Moreover, it combines the influences of aerodynamics and engines on the aircraft performance. The power imbalance $\dot{E}_{tot}$ is analytically derived through

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

with the altitude change (with respect to time) $\dot{H}$ referenced to the surrounding air and the speed change (with respect to time) $\dot{V}_{TAS}$. 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. The following scaling/conversion of this power imbalance into an equivalent drag coefficient variation according to Ref. [7] is used:

$$\Delta C_{\tilde{D}} \approx \frac{\dot{E}_{tot,ref} - \dot{E}_{tot}}{V_{TAS} \cdot \overline{q} \cdot S} \tag{4}$$

This nondimensional value is well comparable to a predefined threshold and indicates an abnormal performance variation when exceeding the threshold value, independent from any flight point. Moreover, it 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 within the IIDS. The equivalent drag coefficient is calculated by comparison of the current determined power imbalance $\dot{E}_{tot}$ and a predefined reference value $\dot{E}_{tot,ref}$. The latter is a function of certain aircraft flight parameters like altitude, speed and load factor, the aircraft configuration (e.g., mass, high lift system configuration) and propulsion system state. Furthermore, some corrections for additional influences, e.g., flight with side slip condition, might be necessary [7].

There are different possibilities to define the reference. A simple way is the definition of a multi-dimensional table using 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. Furthermore, such table approach has the advantage that the reference data can be easily adapted to a specific aircraft over life time covering the "*Expectable Variation*" and hence ensure a high sensitivity of the IIDS. Another way is to calculate the reference power imbalance from an aerodynamic data base and an engine model, if both are available. Using these the adaptation to a specific aircraft could be more difficult, because it must be determined if the variation in the reference power imbalance results from changes of the aerodynamics or the engine performance. Nevertheless, if the engine thrust model is available, as for the herein presented implementation in SENS4ICE, the reference power imbalance can be formulated as a function of the flight condition, the aircraft configuration and the current predicted engine thrust.

The true airspeed time derivative $\dot{V}_{TAS}$ contains a component related to the change of inertial velocity vector as well as a component related to the change of wind vector. But only the first of these two components $\dot{V}_{TAS,\dot{\vec{V}}_k}$ is relevant for the aircraft performance, and the second component should be ignored in order to prevent it from falsifying the performance estimate. A variable wind-corrected energy change $\dot{E}_{tot,corr}$ results from equation (3) using $\dot{V}_{TAS,\dot{\vec{V}}_k}$ as airspeed change:

$$\dot{E}_{tot,corr} = V_{TAS} \cdot \dot{V}_{TAS,\dot{\vec{V}}_k} \cdot m_{AC} + \frac{1}{2} \cdot V_{TAS}^2 \cdot \dot{m}_{AC} + g \cdot \dot{H} \cdot m_{AC} + g \cdot H \cdot \dot{m}_{AC} \quad (5)$$

With the above correction, the energy change and the corresponding equivalent drag coefficient variation are available and can be used for abnormal flight performance detection. However, depending on the formulation of the performance reference model ($\dot{E}_{tot,ref}$) additional corrections might be necessary for e.g., asymmetric flight conditions if the reference model does not account for angle of sideslip influences on the aircraft drag. A detailed description of such corrections is given in Ref. [7].

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 filtering also helps to achieve the necessary system robustness and 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 on the two very different testing aircraft (see Figure 9). This 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.

With regard to a highly adaptable use of the IIDS for different aircraft types, this formulation of the detection methodology is a significant advantage for prototyping the specific system implementation compared to more integrated approaches. Such implementations would require more specific information about the aircraft inside the core detection algorithm. Hence, there are still several needs for adjustments inside the IIDS for a specific aircraft type, which concern

1. the flight data preprocessing,
2. the flight performance reference data base,
3. the indirect ice detection threshold and confirmation times,
4. the detection reliability conditions,

which are further detailed below.

The IIDS is currently implemented in MATLAB®/Simulink including several parts formulated in code originating from SENS4ICE project partners. Basically, the methodology can be implemented in different formats depending on the framework to run with. For SENS4ICE a very agile prototyping and dynamic testing was required for which MATLAB®/Simulink is very handy. Furthermore, for flight testing the HIDS runs on a dSpace MicroAutoBox in real time, and the Simulink model can be easily transferred to the hardware including a full

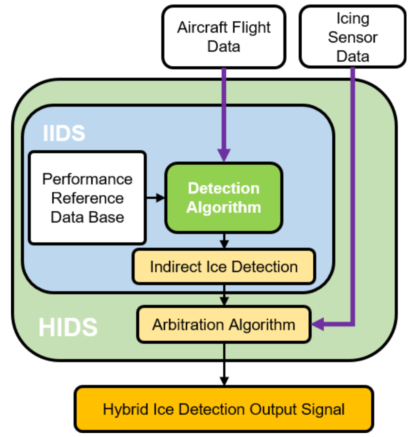

Figure 9. Visualization of HIDS concept used within SENS4ICE

intellectual property protection required for several parts of the IIDS. Future exploitation will presumably provide a code implementation running with aircraft avionic systems.

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. But the number measurements, the units and their quality are different for different aircraft: for example, modern highly automated aircraft are equipped with doubled or tripled sensor systems in order to provide a fail-safe avionics system for automatic flight control, whereas older aircraft might only provide a minimum set of sensors sufficient for manual flight controls. Another example are the different propulsion systems, which require a different treatment of measured data for calculating the total aircraft thrust.

Hence, within the flight data preprocessing a data selection for the required data sets must be performed. 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. For the specific implementation in the SENS4ICE project, two individual data preprocessing functions are used, providing mutual parts but also aircraft-specific implementations reflecting the different propulsion systems of the ATR 42 (turboprops) and the Phenom 300 (jet engines) or the individual sensor positions of the different sensor equipment. 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. The highest available sample time, e.g., commonly available for the acceleration measurements, defines the overall sample time for the IIDS input data, knowing that some data will not be updated between different time stamps in the input data. Nevertheless, normally the low sampled data also reflects slow processes or dynamics, which makes this acceptable. But 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.

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 $\dot{\mathrm{E}}_{\mathrm{tot,ref}}$ and is not restricted to a certain type of implementation. In Ref. [7] 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. In SENS4ICE, the IIDS consist of a performance reference data base splitting engine and aerodynamic influence into individual parts. Having this separation, it will be 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 performance reference in SENS4ICE is based on certain a priori knowledge and information obtained from a specific flight data evaluation. Using existing and well-known aircraft types eases off course the flight performance reference generation in the presented case. Nevertheless, for new aircraft designs or the application of the IIDS to other aircraft types, the performance reference can be based on the design models and initial prototype flight test results. This means, that the IIDS implementation does not require an existing aircraft fleet but can be part of the aircraft design and certification process from the beginning with a validation during e.g., first production flights.

The flight test case-specific adaption of the aerodynamic performance reference is formulated as an additional part to the "base" aircraft reference, which allows a very fast adaption of the reference data base prior to the icing flight tests. Having the final configuration of the aircraft only available a few days before the icing flight test campaign and with only one initial test flight to retrieve the aerodynamic changes compared to the "base" aircraft aerodynamics already available through the extensive flight data evaluation, this is the most practical and suitable approach. Using only a kind of delta approach to the aerodynamic reference, the performance reference is highly adaptable with the small but very specific information available from an initial test flight in dry air with dedicated test conditions prior to the campaign. Note, that this is a special condition and therefore not contrary but complementary to the argumentation in Ref. [7] 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.

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. Note, that in case of the Phenom 300 a numerical engine thrust model was shared which does not represent the correct engine performance but provides a sufficient estimation for the IIDS implementation. Having this available for SENS4ICE, the definition of a different reference model formulation for the propulsion system influence on the reference flight performance is of no additional value. Consequently, the flight performance reference consists of different data bases and reference model formulations adapted to the SENS4ICE purposes, but is still generally valid for different aircraft implementation if required.

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. One simple reason is that the data used for the detection is processed online in near real time and therefore affected by measurement noise which is not filtered although the measurements are calibrated and corrected for constant known errors. To reduce the overall effort of the data processing and computations necessary for detection the input data are not filtered for noise but the equivalent drag coefficient is. A low-pass filtering allows to remove the higher frequency fluctuations resulting from noise. Furthermore, flight performance is also affected by atmospheric disturbances, which are accounted for by monitoring the performance in the aerodynamic frame, but this relies on an accurate measurement of the inflow with high resolution. This is commonly not available on transport aircraft because e.g., the flight control system does not require those. Hence, the measured flight performance will also contain some fluctuations for which a reliable detection algorithm has to account for. As these will also lead to a short-time exceedance of the detection threshold from time to time, the detection module requires the implementation of a confirmation time, which is set large enough to prevent a false detection resulting from other effects leading to a threshold exceedance.

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 1.

Table 1. Detection threshold values and confirmation time for the different IIDS implementations for the SENS4ICE flight test benches.

	SAFIRE ATR 42-320	**Embraer Phenom 300**
detection threshold as relative drag coefficient increase	15%	10%
confirmation timeframe for detection (threshold exceeded more than 50%)	20 s	20 s
confirmation time for reset (threshold undershot more than 50%)	180 s	180 s

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. [7]. This also includes considering different aircraft configurations for different settings of the high lift system and gear extension. Nevertheless, the implementation in SENS4ICE is currently experimental and limited to one aircraft configuration without flaps or gear extended because of the flight test in icing conditions being only performed in this configuration for flight safety reasons. For all other aircraft configurations, the IIDS is designed to detect that the configuration is not reflected in the current implementation, freeze and set an unreliability flag allowing the HIDS to discard the current IIDS output. Freezing in this case allows to not load the moving average filters with unreliable data leading to a false positive detection when the IIDS is reactivated after a configuration change. A similar procedure is applied for short-term effects on the flight performance not included in the reference flight performance data base to reduce the overall effort for calculations in the IIDS like the use of speed-brakes. During these phases, the IIDS also freezes and the output unreliability is set.

IIDS Test Results on Icing Flight Data

For the IIDS verification and validation several data sets from Embraer and ATR were made available through SENS4ICE. For verification both ATR and Embraer data sets were used to ensure the correct implementation of the algorithm in MATLAB®/Simulink by comparison with the results of a different implementation of required calculations as reference. For validation, there was the advantage of real icing flights in App. C conditions including atmospheric condition measurements from a previous Embraer flight test campaign with the Phenom 300 prototype also used for the SENS4ICE flight tests.

Consequently, the herein presented validation results are based on several examples for Phenom 300 flights through natural icing conditions, during which ice was accreted on several parts of the aircraft, for which the IPS was in a special condition. The available flight data sets include more data than actually required for the IIDS input. They include measurements of 1) translational accelerations; 2) rotational rates; 3) aircraft attitude; 4) true airspeed, angle of attack, and angle of sideslip; 5) geographic position and altitude; and 6) control surface deflections. The flight data sets are comprised of whole flights which had been searched first for icing conditions to extract the relevant parts for the validation. After specific data selection, the relevant IIDS input data are composed and also stored for HIDS verification. The advantage of the available flight data sets is the knowledge that ice was accreted on the airframe accompanied by a significant drag increase. Hence, any detectable flight performance change can be directly related to icing. Note that the use of the specific flight test data allows to exclude any other source for changed flight performance.

Figure 10 provides the results of the aerodynamic coefficient calculation from flight data together with the best fit polar for the clean aircraft also given in Figure 6. In addition, the detection threshold related to a zero-lift drag change is also included to reflect the foreseen IIDS accuracy. It is clearly visible that the majority of data reflecting the aircraft performance characteristics during the ice encounters is shifted to the right (higher drag) directly indicating a performance degradation. Hence, with these results it is highly expectable that the defined IIDS threshold will allow to reliably detect the icing-related performance degradation. The corresponding atmospheric conditions

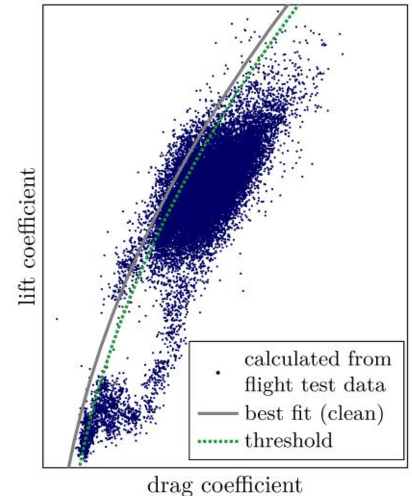

Figure 10. Example of lift and drag coefficient calculated from Phenom 300 flight test data: natural icing flight test results with visible shift of flight performance respectively drag increase (121,000 data points).

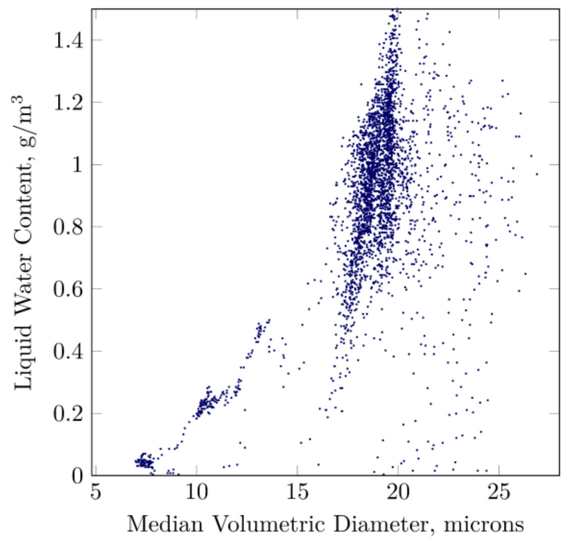

Figure 11. Example of atmospheric parameters (liquid water content and medium volumetric diameter) from Phenom 300 flight test data: natural icing flight test in Appendix C conditions related to aerodynamic parameters in Figure 10 (121,000 data points).

are given in Figure 11 (liquid water content and medium volumetric diameter) and Figure 12 (liquid water content and air temperature).

Running these data sets through the developed IIDS implementation generates time histories of the detection algorithm output. The results for three example data sets are given in Figure 13 to Figure 15. Each time history plot provides an information about speed and altitude at the top, the IIDS output in the middle and the icing conditions at the bottom. Note that the cloud data are provided with lower time resolution (1 Hz) than the aircraft data. The aircraft is flying with relatively constant speed (around 160 kts calibrated airspeed) through the icing conditions at an altitude of about 6000 ft. Each time segment begins with a phase of near nominal flight performance during which the drag increase is small or performance degradation starts slowly. After the calculated drag increase passes the detection threshold, the detection is confirmed several seconds later. The first example in Figure 13 shows a case where the performance degradation constantly occurs resulting in an IIDS detection confirmation at about 75 s. During the next 100 s, the drag is not much increased and stays around

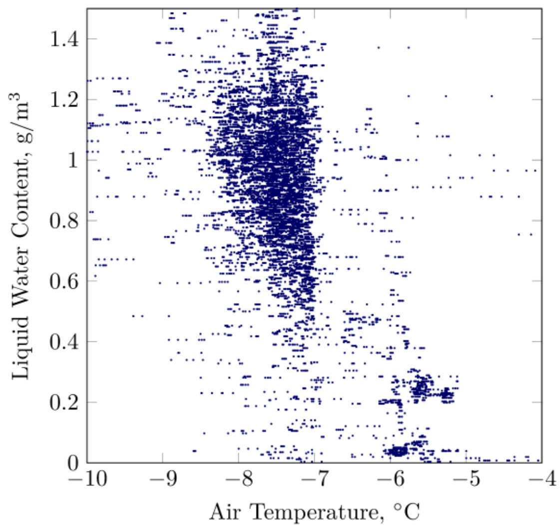

Figure 12. Example of atmospheric parameters (liquid water content and static air temperature) from Phenom 300 flight test data: natural icing flight test in Appendix C conditions related to aerodynamic parameters in Figure 10 (121,000 data points).

the threshold even falling two times below. But due to the different confirmation times for detection and reset, the IIDS output remains set and there is no misleading switching of the IIDS detection result.

The second example in Figure 14 shows a different case, where the calculated drag first passes the threshold (at about 30 s), falls below (at about 40 s), passes the threshold again (at about 55 s) and then falls below again (at about 70 s) to stay slightly below the threshold for about 70 s. After that, the calculated drag further increases significantly. This case demonstrates the need for the weighted moving average filters and different confirmation times in the detection module to prevent the IIDS from switching between the detection states and not maintaining the states for a certain time. In this example specifically the first threshold passing does not trigger the detection, because it was too short, but after the second exceedance the detection was confirmed. Having a longer period slightly below the threshold should also not reset the IIDS too early, which is clearly demonstrated in this example as well. Figure 15 provides the third example also showing a slow and moderate calculated drag increase in the beginning of the data segment. The detection threshold is passed the first time at about 25 s and the detection is confirmed 10 s later in the IIDS as designed. Afterwards, the calculated drag remains near the threshold falling slightly below and passing it again for another 60 s showing again the need for the implemented moving average criterion with the long reset time to prevent a too early all-clear signal.

All in all, these initial results for validation are very encouraging for the SENS4ICE flight test campaign and the successful integration of the IIDS integration within the HIDS. Moreover, the ice detection capabilities of the IIDS provided show the potential of this methodology for applications where no direct sensing technology can be applied but still providing a reliable information in an acceptable time.

Conclusion

The SENS4ICE project is a big step towards successful and reliable detection of different icing conditions including supercooled large droplets and the atmospheric condition envelope defined by Appendix O to the certification regulations of large transport aircraft. The indirect ice detection methodology based on an aircraft performance degradation is one key to success and provides several advantages compared to direct detection, which are mainly complementary, e.g., the retrofit capabilities, a simple software solution or the highly beneficial information about the remaining aircraft capabilities for the subsequent flight execution through icing conditions. The IIDS further provides some redundancy for the ice detection when hybridized and hence reduces the risk for common cause failures. The methodology requires precise measurements of the aircraft flight condition which are normally available for modern aircraft as these are also relevant for flight control systems and autopilots. Hence, the methodology also opens up various new possibilities for the ice detection on smaller aircraft which could not be equipped with large or complex direct ice detection methods such as small unmanned aerial vehicles. The successful verification and validation of the newly developed indirect ice detection system on the bases of ATR 42 and Phenom 300 flight data, including natural icing flight tests in Appendix C conditions, is an important milestone for the further system maturation. Nevertheless, the limited number of flight data sets from flights in natural icing conditions available for the initial verification and validation tests presented herein makes it necessary to conduct more tests with additional data. More flight data from different icing conditions resulting in different ice accumulations and shapes on the airframe and also more information about the flight performance degradation during the ice built-up will lead to a better definition of the detection threshold and the confirmation times. This will allow to further mature the IIDS with a high reliability and no false detections. With the given results the IIDS is ready for the system demonstration in the following SENS4ICE SLD icing flight test campaigns which will result in unique and very important data about the aircraft performance degradation caused by different icing conditions, especially SLD. Having the flight test campaign data available, the IIDS approach can be also further compared to direct sensors in terms of, e.g., reliability and detection response time. Furthermore, the direct comparison of flight through App. C and App. O conditions will allow conclusions on the IIDS' capabilities to discrimination between the impact of the different icing conditions on the aircraft performance. With expecting a much stronger and faster impact of SLD icing conditions and corresponding ice accretion on aircraft performance, the IIDS result might allow to reveal the difference in aircraft performance degradation related to the icing conditions. This is subject to future work data analysis.

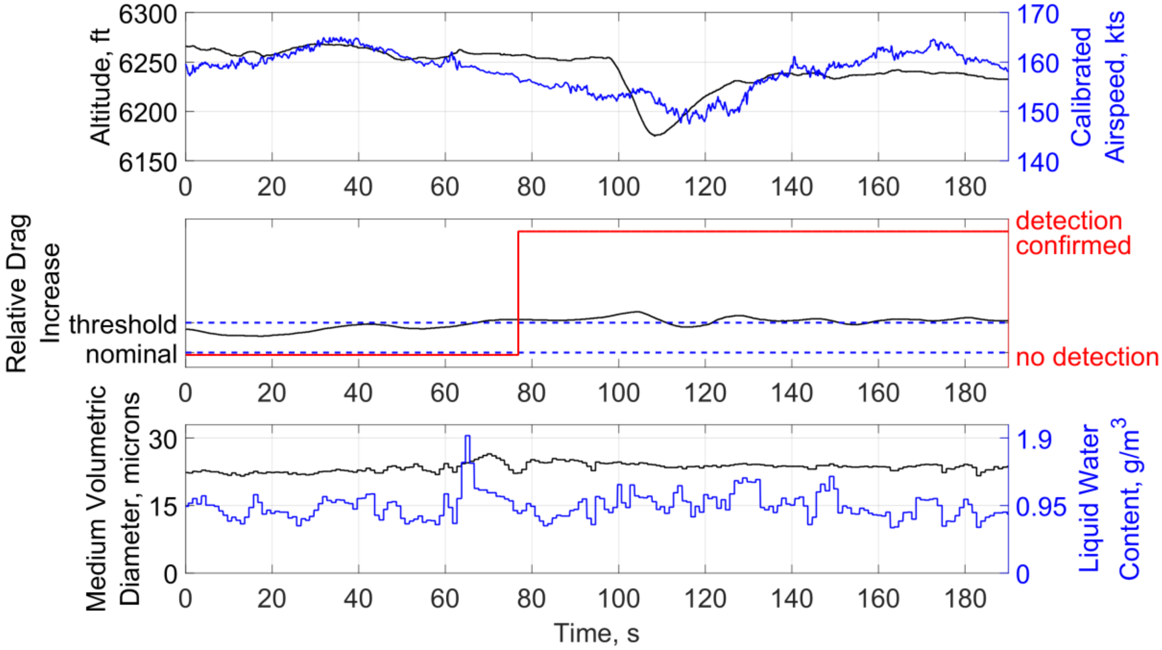

Figure 13. First example on IIDS behavior with real ice flight data from Embraer Phenom 300 flight test available for IIDS tuning and design in SENS4ICE

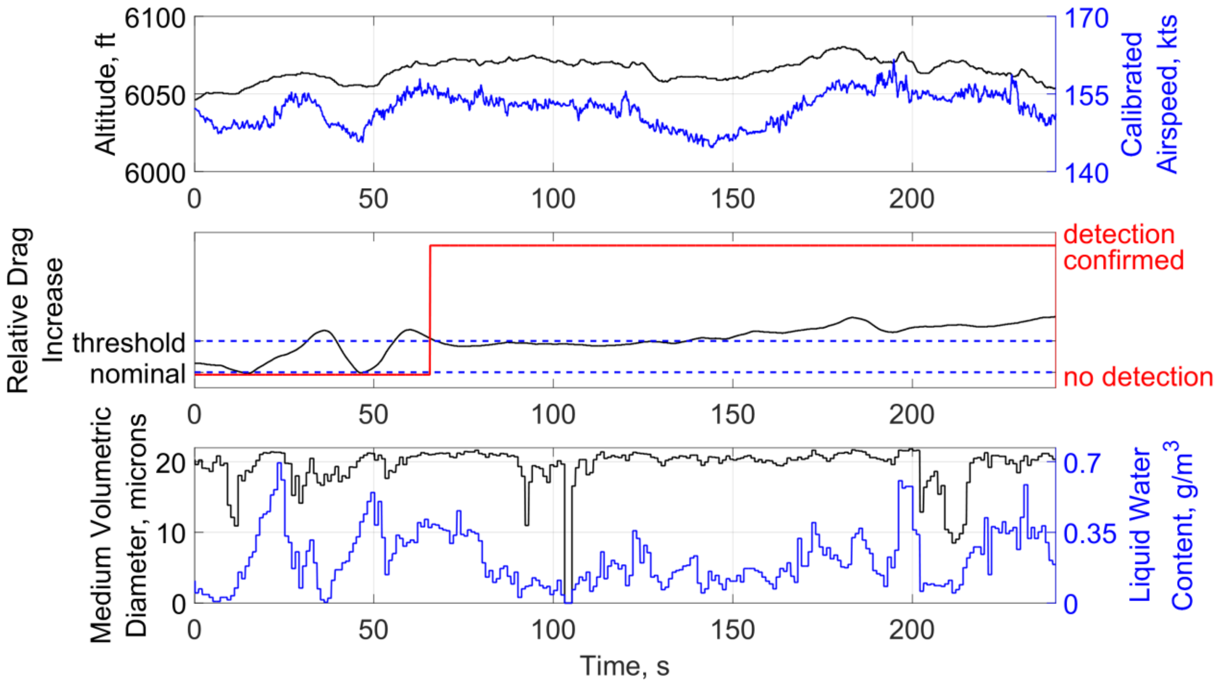

Figure 14. Second example on IIDS behavior with real ice flight data from Embraer Phenom 300 flight test available for IIDS tuning and design in SENS4ICE

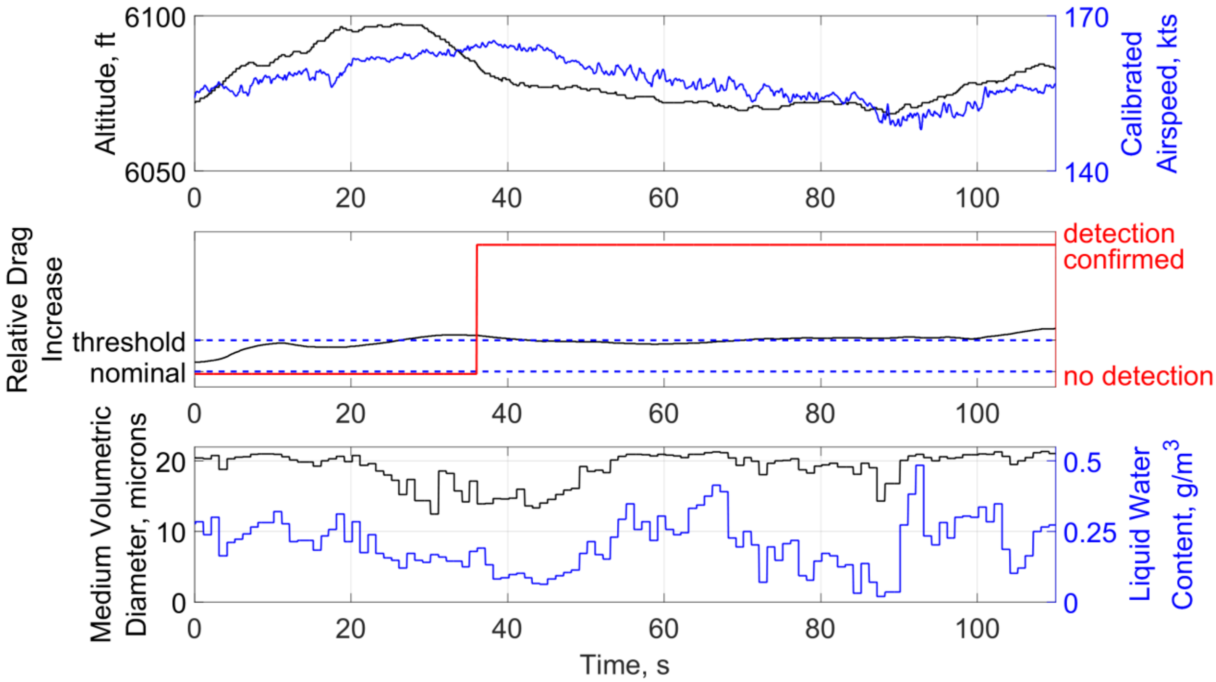

Figure 15. Third example on IIDS behavior with real ice flight data from Embraer Phenom 300 flight test available for IIDS tuning and design in SENS4ICE

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Contact Information

Christoph Deiler
German Aerospace Center (DLR),
Institute of Flight Systems,
Department Flight Dynamics and Simulation,
Lilienthalplatz 7,
Braunschweig, 38108, Germany
christoph.deiler@dlr.de

Acknowledgments

The "SENSors and certifiable hybrid architectures for safer aviation in ICing Environment" (SENS4ICE) project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N° 824253.

Disclaimer

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

Definitions/Abbreviations

DLR	German Aerospace Center
SENS4ICE	SENSors and certifiable hybrid architectures for safer aviation in ICing Environment
IPS	ice protection system
SLD	supercooled large droplets
TAS	true airspeed
HIDS	hybrid ice detection system
IIDS	indirect ice detection system
$C_{\tilde{D}}$	equivalent drag coefficient
C_D	drag coefficient
C_{D0}	zero-lift drag coefficient
C_L	lift coefficient
E_{tot}	total energy
$\dot{E}_{tot}$	power imbalance, total energy time derivative
$\dot{E}_{tot,ref}$	reference power imbalance
g	gravitational acceleration
H	altitude
$(L/D)_{opt}$	optimal lift-to-drag ratio
m_{AC}	aircraft mass
P	percentile / quantile
$\bar{q}$	dynamic pressure
S	reference surface
V	airspeed
$\dot{V}_{TAS,\dot{\vec{V}}_k}$	Change of true airspeed due to a change of flight path-dependent speed