NRC Particle Detection Probe: Transition from Test Cell to Flight Operation

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ABSTRACT

High Altitude Ice Crystals are causing in-service events in excess of one per month for commercial aircraft. The effects include preventing the air data probes (pitot pressure and total air temperature in particular) from functioning correctly and engine roll back and shut down. The National Research Council Canada (NRC) has developed a particle detection probe (PDP) that mounts on the fuselage of aircraft to sense and quantify the ice crystals in the environment. The probe is low-power and non-intrusive. This paper describes the multi-year process of developing the NRC PDP from a test cell sensor for detecting contaminants in engine exhaust to an aircraft ice-crystal detection probe. The probe was demonstrated on the NRC Convair and Airbus A340 research aircraft as part of the European Union high altitude ice crystal program (HAIC). The probe was ruggedized, adapted for easy installation in standard aircraft fittings, and tested in a variety of conditions for longevity and endurance. Efforts to achieve the safety requirements for flight on aircraft are discussed in detail. The challenges, surprises and opportunities for testing that the development group capitalized on are also presented. The work included over 20 flight tests on NRC aircraft and the Airbus HAIC test program. It was demonstrated that the detectors give signals proportional to the ice crystal content of clouds and results demonstrating the functionality of the probe are presented.

1.0 INTRODUCTION

Until the 1990s it was believed that a gas turbine with a straight "pitot" inlet could operate safely in ice crystal conditions. Evidence to the contrary was gathered from the mid-1990s to mid-2000s. Lawson et. al. discussed the types of cloud particles in the anvils of thunderstorms that could be causing engine rollbacks in a 1996 conference paper (republished as [1]). Investigations by manufacturers and the Ice Protection Harmonization Working Group indicated that ice crystals were the probable cause of rollbacks, and could affect any type of gas turbine engine and some critical aircraft sensors. In 2006, Mason et. al. noted that although general recommendations could be made to plan flight paths well clear of convective cells likely to contain areas of high ice crystal concentration, pilots and ground control would have a limited ability to determine acceptable routes in areas with high traffic and frequent thunderstorms [2]. In the following years, the priority of the research increased as reports of probe failures and engine issues indicated that the problem was growing with increased traffic through regions with high humidity and active weather. Figure 1 shows the frequency of ice-crystal conditions over tropical and near-tropical zones, and Figure 2 is a map of known Ice Crystal Icing (ICI) event locations up to 2002.

By 2010 it was clear that a method of detecting high ice crystal content in the flight path or the immediate airspace around the aircraft was needed. Forward-looking radar gets little or no return signal from ice crystals. Angling the radar downward would detect the water content at lower altitudes, but not provide a direct warning to the pilot. The Particle Detection Probe (PDP) non-intrusively measures the concentration of ice crystals in the air stream passing over it. It has the potential to improve flight safety by providing information on the concentration of ice crystals around an aircraft. The sensor is lightweight, low-power, flush mounted and has been demonstrated on three aircraft. This paper is the story of the PDP development for ice crystal detection on board commercial aircraft. The outcome of this phase of the work was to flight test it on a research aircraft operated by Airbus to demonstrate the feasibility of use on board a commercial fleet. This paper concentrates on demonstrating flight readiness and lessons learned from the internal National Research Council Canada (NRC) flight tests and the Airbus high altitude ice crystal (HAIC) flight test campaign.

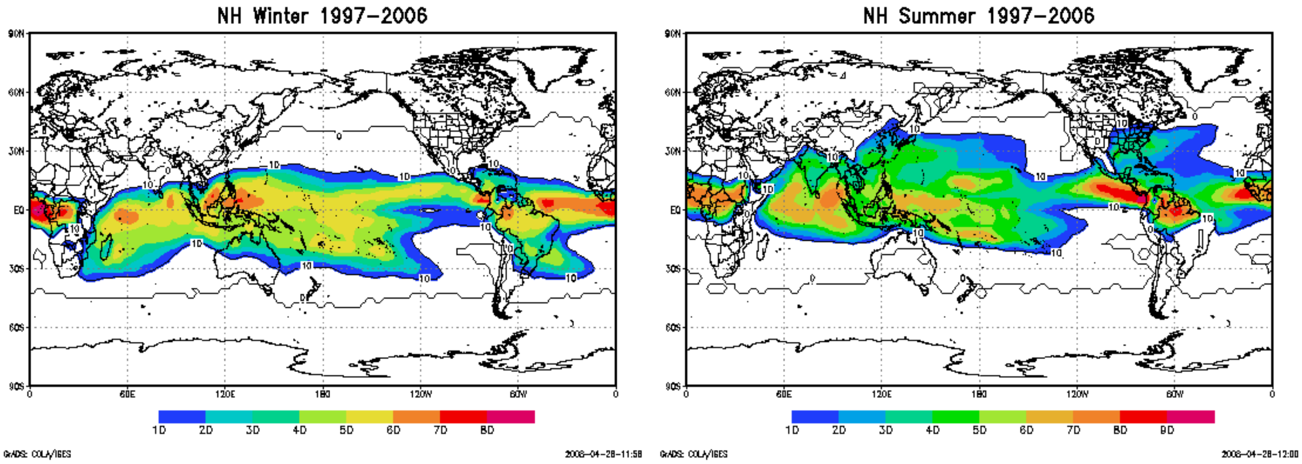


Figure 1: "Percentage of time that NCEP-NCAR Reanalysis grid points had favorable conditions for the development of convection associated with engine events." [3]

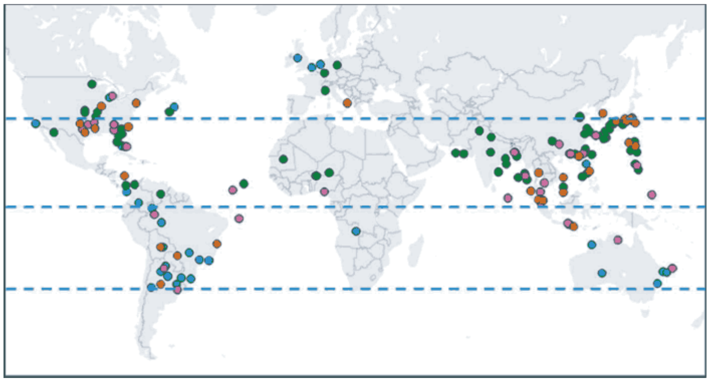


Figure 2: "Map of Boeing ICI encounters" [4]

Figure 3 is a flowchart outlining the process from the start of development of the probe for ice crystal detection through to the conclusion of flight testing and preparation for commercialisation of the PDP. Possible paths not taken are shown in grey. Solid black paths are routes the development process followed. Inputs came from wind tunnel tests, technical requirements for probe functioning, flight worthiness requirements and requirements for the probe to be a viable commercial product. Flight worthiness requirements were supplied by experts at NRC and Airbus. The requirements for a commercial product were primarily supplied by Airbus. Several of the development stages were iterative as testing revealed new opportunities for improvement.

The process started with existing NRC technology being piggy backed on existing test programs to minimise the cost of demonstrating the concept. After the proof of concept, the development of the probe was sponsored by the

Canadian Department of National Defence (DND), for use in detecting dust and sand, and by an internal NRC HAIC program. After the initial testing stages, DND identified other priorities and NRC funded the PDP development. The first iterative stage shown in Figure 3 involved testing in several wind tunnels and primarily helped improve the technical aspects of the PDP. The technology readiness levels (TRL) provided in the flowchart were supplied by Airbus and had to be achieved to continue in the HAIC program and eventually fly on Airbus's A340 flight test aircraft.

Table 1 provides the TRL definitions. The TRL 3 level had been achieved prior to NRC joining the HAIC program so development at this point was beyond that required for the TRL 3 gate. After passing the TRL 2 gate, the testing and probe improvement continued. At this stage it included testing in an altitude wind tunnel and initial flight tests. Both of these near real world environments provided valuable feedback on the improvements required to produce an effective product. After the TRL 3 gate the PDP was considered viable for testing on NRC's Convair flight test aircraft that was participating in a high ice water campaign in French Guiana. This campaign in actual high ice water conditions confirmed the effectiveness of the probe and provided data for algorithm and software development to improve its function. The final TRL gate prior to installation and flight on the Airbus A340 required further airworthiness testing.

The following sections of this report discuss some of the steps in the process in more detail. The extensive development effort on the path from test cell operation to flights on NRC aircraft and finally to flights on the Airbus A340 will be discussed. Results from the wind tunnel and flight campaigns will be presented. The final section will examine the lessons learned from the test campaigns and present the future plan for the probe.

Table 1: Outline of technology readiness levels used to define acceptance gates for ice crystal detector

TRL:	1	2	3	4	5	6
Description	Basic principles observed and reported	Technology concept and/or application formulated	Analytical and experimental critical function and/or characteristic proof of concept	Component and/or breadboard validation in laboratory environment	Component and/or breadboard validation in relevant environment	System/subsystem model or prototype demonstration in a relevant environment
Definition	Lowest level of technology readiness. Scientific research begins to be translated into applied research and development.	Invention begins. Once basic principles are observed, practical applications can be invented. The application is speculative and there is no proof or detailed analysis to support the assumption.	Active research and development is initiated. This includes analytical studies and laboratory studies to physically validate analytical predictions of separate elements of the technology.	Basic technological components are integrated to establish that the pieces will work together. This is relatively "low fidelity" compared to the eventual system.	Fidelity of breadboard technology increases significantly. The basic technological components are integrated with reasonably realistic supporting elements so that the technology can be tested in a simulated environment.	Representative model or prototype system, which is well beyond the breadboard tested for TRL 5, is tested in a relevant environment. Represents a major step up in a technology's demonstrated readiness.

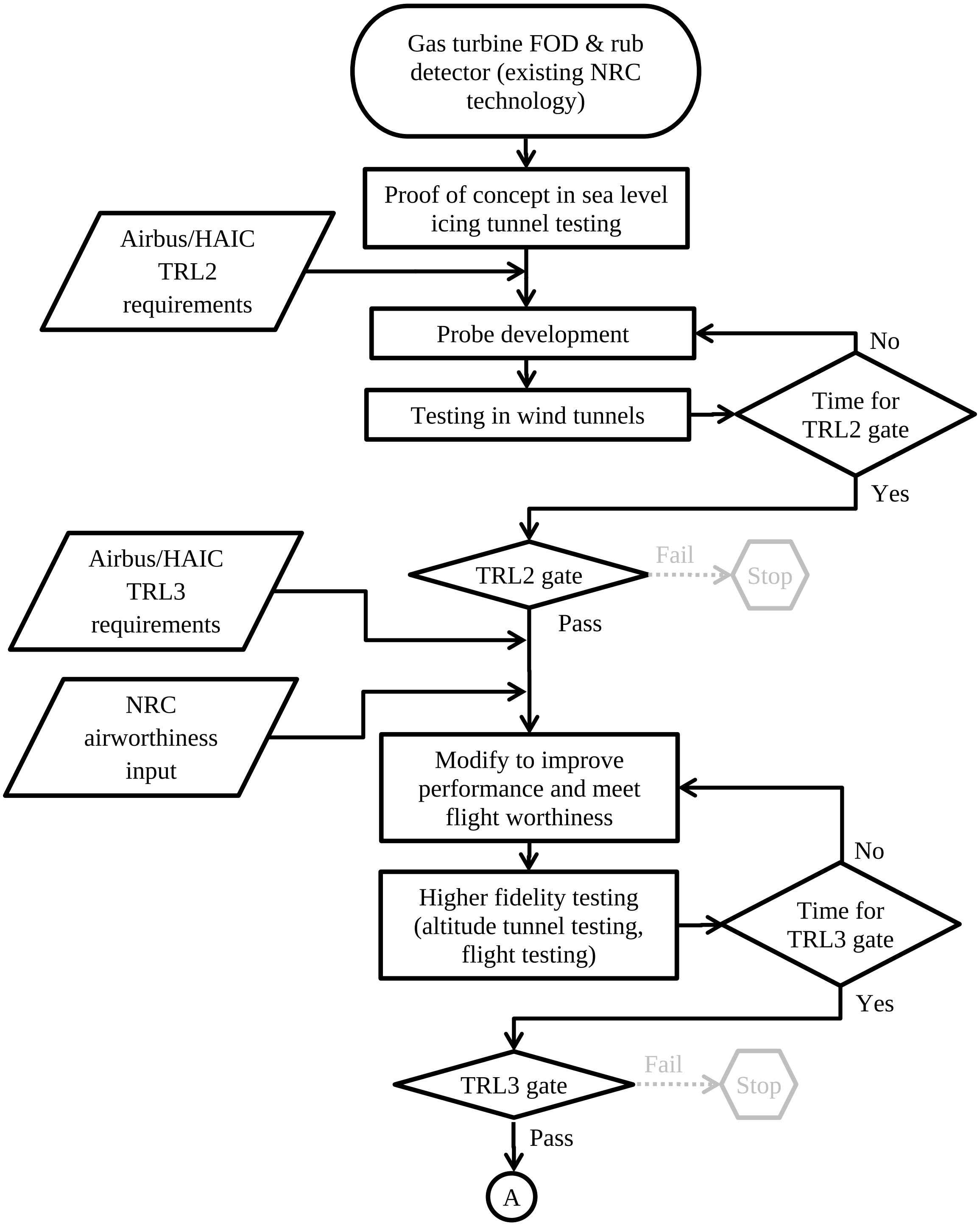


Figure 3: (continued on next page): Development process for NRC particle detection probe for on-aircraft detection of airborne particles

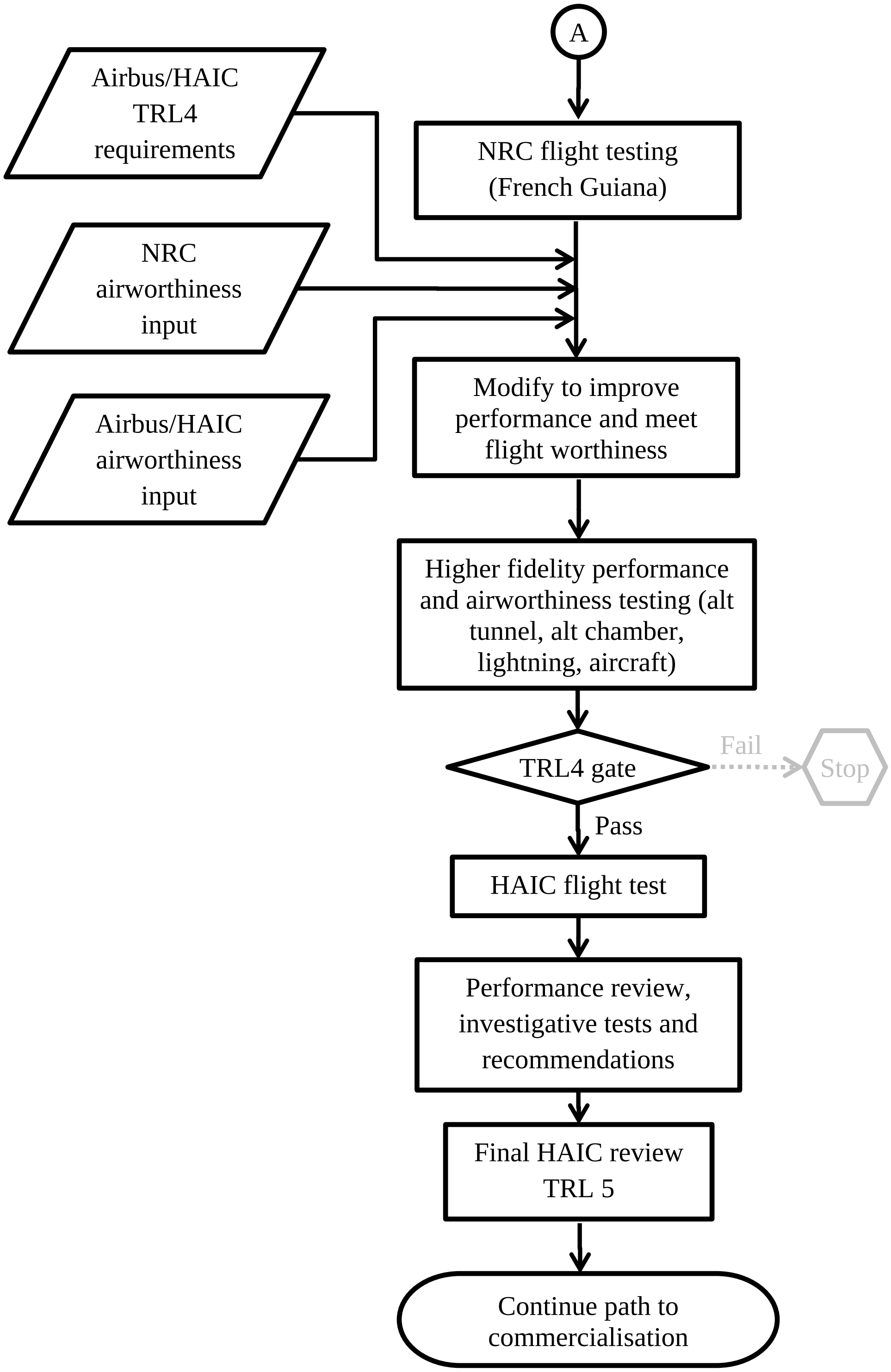


Figure 3: (continued): Development process for NRC particle detection probe for on-aircraft detection of airborne particles

2.0 BACKGROUND AND CONTEXT

The NRC had experience with ice crystal research going back to the 1950s [5]. When the HAIC program was starting, the NRC had led the development a total water content isokinetic probe (IKP) for quantification of ice crystals [6]. This was a research probe and not appropriate for use on commercial aircraft due to the complexity, size, drag and power required. It did, however, provide a knowledge base in developing a probe for use in flight. NRC had also developed both a sea level and altitude wind tunnel for ice crystal testing. [7, 8]

The fundamental PDP technology had been tested in the NRC gas turbine lab for detecting engine debris during engine endurance campaigns since the early 1990s [9]. The sensor technology non-intrusively detects particles by measuring the changes in electrical characteristics in the local atmosphere. The detection systems were low-weight and low-power, both distinct advantages for a commercial system.

In its most basic form, the PDP consists of a sensing surface, signal conditioner and a voltmeter. The probe itself, not including data acquisition and signal conditioning equipment, is shown in Figure 4. The flight test version included an array of sensing surfaces to quantify particle charges and velocities, variable amplification units, an anti-icing power supply and a full data acquisition system (DAS) with a solid-state hard drive. The final flight test version also included a self-diagnostic system or Built in Test Equipment (BITE). It is expected that a commercialised flight version would only require a single sensing surface, and a data processing chip. It is possible that anti-ice heating will be required in-flight, depending on the probe location on the aircraft.

The sampling head shown in Figure 4 is designed to withstand the atmospheric conditions encountered in flight by commercial aircraft. The flight test probe orientation identified in the diagram is important for particle tracking and charge measurement but not for bulk measurement. The array portion of the probe, used for particle tracking, is on the trailing edge of the probe. The leading edge of the probe was identified by markings on the probe flange. In addition, the surface of the probe should be approximately parallel to the flow as particles impacting the probe can generate noise. The sample volume, in which the probe can detect particles, extends approximately 5 cm (2 inches) from the aircraft skin. Thus the probe cannot be installed in a region shadowed from ice crystals. Additionally, the probe cannot be installed where fluids could collect as they would change the measurement sensitivity and generate confounding signals.

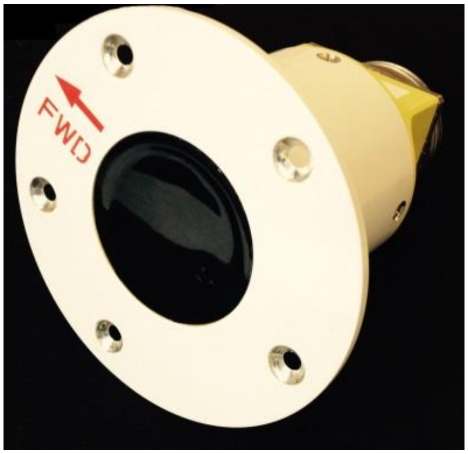


Figure 4: NRC particle detection probe for HAIC flight testing (black electrode diameter 1.85 inches)

3.0 PROBE DEVELOPMENT PROCESS AND TESTING

The PDP is an attractive solution to the problem of detecting ice crystals because it is flush with the fuselage which does not increase drag, minimises susceptibility to icing from super-cooled water, and presents less opportunity for foreign object damage (FOD) or to create FOD hazards to the rest of the aircraft. Development of a system specifically to detect ice crystals was started with an internal NRC New Initiatives application in 2008. Figure 3 illustrates the highly iterative nature of the development process. Testing was carried out, modifications made and testing repeated. Early tests were performed in an NRC sea level icing wind tunnel that could produce ice particles. This led to the development of a flush mountable probe. The flush mountable probe was tested in a sea level facility with sand and dust and an altitude facility with ice crystals. At the time there was a clear need for a sensor to quantify ice crystals so that was the development path taken, but the results from the sand testing were valuable in understanding the response of the probe to environments it would encounter. The sensor can detect and estimate the concentration of the following conditions, so calibration and operating experience in these environments was important.

- Ice crystals/particles
- Mixed phase
- Sand
- Ash

Versions of the sensor were also piggybacked on flight test campaigns exposing it to icing conditions on the NRC Convair 580, Figure 10, and engine emission particulate measurements on the NRC CT-133 aircraft (a version of a Lockheed T-33), Figure 9 [10]. The results of these campaigns demonstrated the viability of the PDP to operate in extreme flight environments including a wide range of weather conditions, altitudes, temperatures and speeds. It also demonstrated that the sensor and its DAS did not interfere with aircraft systems or vice-versa. The results of these campaigns provided valuable information on the sensor's high sensitivity and identified some changes required to improve its robustness. After further wind tunnel testing and development, including significant efforts towards airworthiness, the PDP was again flown on the Convair, this time in a flight campaign dedicated to ice crystal conditions. This campaign was successful but identified a few more modifications to improve the performance and reliability of the PDP. The sections below provide more details on some of the significant milestones in the development of the PDP.

3.1 Preliminary Test Cell Work

The original technology used on gas turbine inlets and exhausts was installed in a sea-level icing wind tunnel as a proof of concept. The tunnel uses a saw system to generate ice crystals from blocks of ice. More details about the tunnel can be found in the papers by Strapp et. al. [8] and Davison et. al. [11] Figure 5 shows the response of the proof of concept PDP to ice crystals in the tunnel. The initial increase in feed rate does not correspond to ice entering the tunnel. Initially the ice block is being moved through empty space towards the saw. Ice engagement can be identified by the drop in feed rate due to the added resistance of the saw. The probe response increases when the ice engages and decreases when the feed rate is decreased. However, the probe also had a response to the feed system being activated. This is shown by the response that is already occurring when recording was begun. At the end a similar response is seen. When the feed rate is reduced the response rapidly drops, but not to zero. The spikes at the end are likely due to ice being cleared out of the system but they appear to be superimposed on a baseline greater than zero.

The results of this initial work indicated that the probe did respond to ice crystal content but that it was susceptible to interference from other inputs. These results were adequate to justify further funding of the probe development. While the results specifically applied to ice crystals they also applied more generally to any airborne particulates. The next stages of the work received funding from both the Canadian Department of National Defence (DND), who were interested in quantifying sand clouds that helicopters are exposed to, and the NRC who were interested in the commercial application of quantifying ice crystals. As both organisations are part of the Canadian Government intellectual property issues did not arise and both projects benefited from the work in the other.

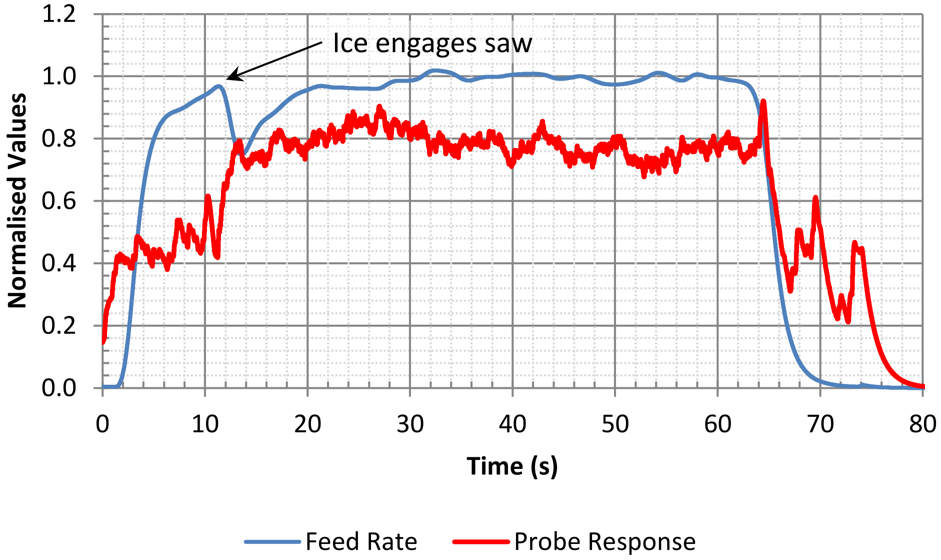


Figure 5: Response of proof of concept PDP to feed rate of ice in sea level ice crystal tunnel

3.2 Airbus High Altitude Ice Crystal Program

In 2012, NRC was approached by Airbus during the planning phase of the HAIC project to be a contributor to the ice crystal detector development task. The goal of the project was to improve aircraft safety in mixed phase and ice crystal conditions. The more detailed sub-goals of the project are provided in [12]. The relevant sub-goal for the PDP was to develop technologies to alert the flight crew of the hazard using on-board detectors for high ice water content.

The project was executed over 5 years, with a capstone flight test campaign to boost technologies to TRL5 and beyond. At that point in time, NRC had completed proof of concept tests showing the NRC probe design was capable of detecting airborne ice particles and working in flight. The HAIC project defined a series of TRL reviews to ensure the various detection technologies were advancing sufficiently and allowed the identification of technologies that would be removed from the project before flight testing. The TRL gates used in this project to evaluate the PDP are defined in Table 1. As NRC is a research organisation, input from an air framer on the requirements for a commercial probe were very valuable and greatly increased the chances of success.

The proof of concept tests completed by the NRC before 2012 were well beyond what would be expected for the TRL2 level expected at the first HAIC review. The tests provided excellent information on the challenges in aircraft installations including isolating the probe from signal noise due to the aircraft electrical systems, using research DAS components in an unpressurized compartment, and the effect of super-cooled liquid water reducing the probe’s ability to measure. In addition, the NRC airworthiness team reviewed the probe design and recommended a modification for a failsafe design. Solutions to address the identified shortcomings were built into a probe design for the tests to demonstrate conformity with the TRL3 and 4 gate requirements.

3.2.1 Industry-led project requirements – retrofit and BITE

One advantage of an industry-led project was that the requirements for commercial implementation were provided and had to be met. One requirement was identifying how this sensor could potentially be retrofitted onto existing aircraft. This led to the static port variant seen in Figure 6, which could be retrofit into existing static ports on an aircraft.

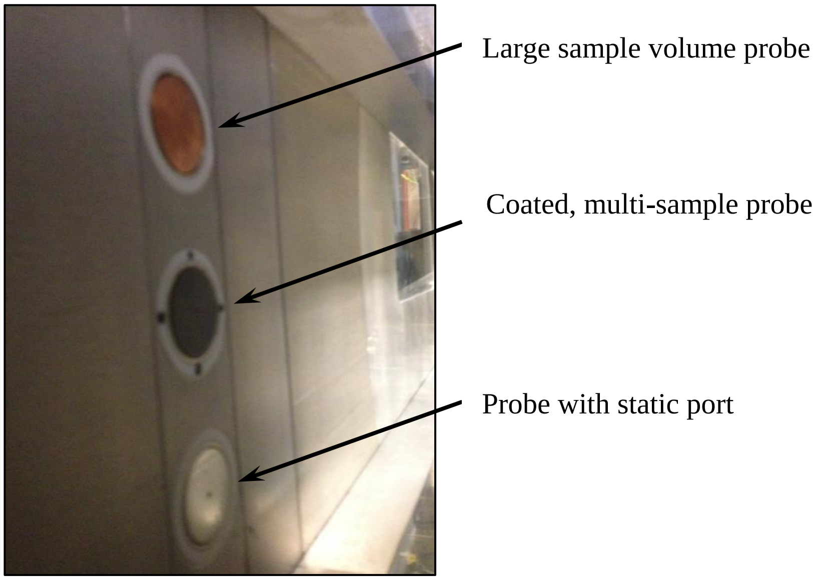
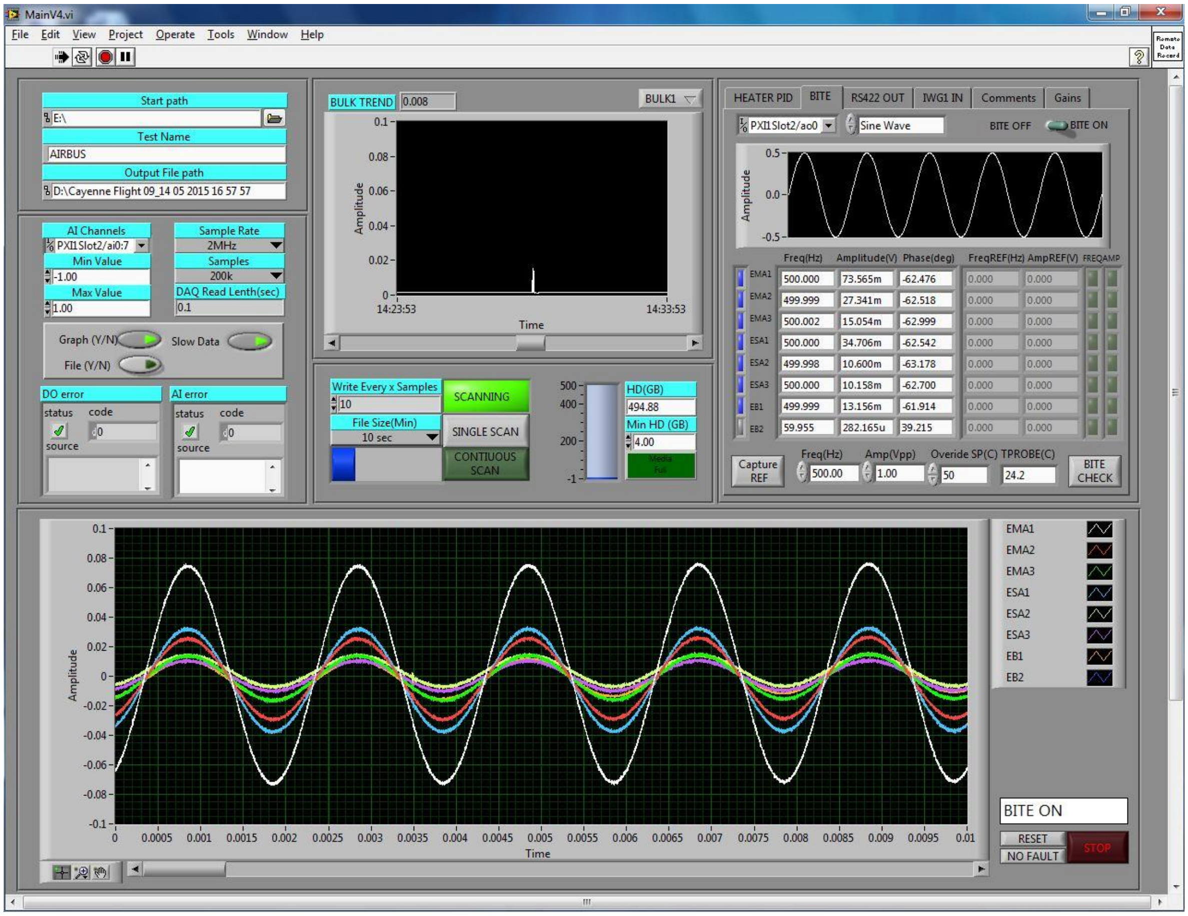


Figure 6: PDP variants installed in the RATFac ice crystal cascade rig

Another industry-driven requirement was the ability to detect sensor faults using built-in test equipment (BITE). To meet this requirement for the TRL4 review and beyond, NRC developed an end-to-end check. The check is completed by sending a reference signal to the probe on a line independent of the sensing system. The sensor response is then compared to the reference signal as shown in Figure 7. This test required only a few seconds to conduct and verified that the response phase and amplitude were consistent with healthy values for the wiring, amplification and data acquisition components. While the signals could be manually compared, as in Figure 7, an algorithm was also developed to automatically evaluate the signal and provide a go/no-go status.



Start path: E:\
Test Name: AIRBUS
Output File path: D:\Cayenne Flight 09_14 05 2015 16 57 57
AI Channels: PXI1Slot2/ai0:7
Sample Rate: 2MHz
Min Value: -1.00
Samples: 200k
Max Value: 1.00
DAQ Read Lenth(sec): 0.1
Graph (Y/N)
Slow Data
File (Y/N)
DO error: status ✓ code 0 source
AI error: status ✓ code 0 source
BULK TREND: 0.008
Write Every x Samples: 10
File Size(Min): 10 sec
HD(GB): 494.88
Min HD (GB): 4.00
PXI1Slot2/ao0
Sine Wave

	Freq(Hz)	Amplitude(V)	Phase(deg)	FreqREF(Hz)	AmpREF(V)
EMA1	500.000	73.565m	-62.476	0.000	0.000
EMA2	499.999	27.341m	-62.518	0.000	0.000
EMA3	500.002	15.054m	-62.999	0.000	0.000
ESA1	500.000	34.706m	-62.542	0.000	0.000
ESA2	499.998	10.600m	-63.178	0.000	0.000
ESA3	500.000	10.158m	-62.700	0.000	0.000
EB1	499.999	13.156m	-61.914	0.000	0.000
EB2	59.955	282.165u	39.215	0.000	0.000

Freq(Hz): 500.00
Amp(Vpp): 1.00
Overide SP(C): 50
TPROBE(C): 24.2
BITE ON

Figure 7: PDP development interface showing built in end-to-end BITE system

3.2.2 Airworthiness

Both NRC and HAIC have airworthiness requirements for their test aircraft but the initial requirements for HAIC were extensive and well beyond those NRC would normally see in a research and development flight test program. After extensive discussion between NRC and Airbus, a much smaller scope of requirements was defined, with consideration given to the amount of tunnel and flight testing that NRC had conducted. It was agreed that the primary requirement was to ensure that a failure of the probe would not deleteriously affect the aircraft. As the PDP was non-essential equipment, it could be turned off if its operation posed a hazard to the aircraft. A reduced list of outstanding requirements was agreed upon and the resolutions are provided in Table 2.

This resolution resulted in additional design reviews, which identified one new flight safety test, requiring the probe to be exposed to a simulated lightning strike. For this test, a high direct current voltage was applied above the PDP electrode to create an arc as shown in Figure 8. The test was performed by Lightning Technologies, a company with expertise in designing and testing equipment to withstand lightning strikes aboard aircraft. Six PDPs were tested a minimum of three times each and the results showed no punctures in the coating and no current was measured leaving the sense cabling. The results of these tests helped develop requirements for shielding and grounding on the aircraft installation.

At this point, the design was close to a commercial-style probe, including details such as commercial connectors, installation markings, traceable materials, and a mounting bolt pattern with an offset to ensure correct positioning when installed. This probe is shown in Figure 4 and was implemented on the HAIC A340 flight test.

Table 2: Reduced Airworthiness Requirements

Requirement	Resolution and Details
Power Input & Voltage spikes	NRC described the electrical aspects of the system. The design was tolerant of power and voltage spikes though incorporation of appropriate wire size and circuit protective devices, but was not formally tested to prove this was the case. NRC is not qualified to carry out and report on tests to the Airbus or DO160G standards specified. However, the design had been successfully installed and operated in two NRC aircraft, and powered by the ships' 28 VDC systems without adverse effects. The installation was not capable of generating significant power or voltage spikes that could be hazardous to the aircraft.
Flammability/ Heat Release/ Smoke Density/ Toxicity	All NRC wiring follows generally-accepted aircraft practices for gauge, type, insulation and installation practices in accordance with FAA Advisory Circular (AC) 43.13-1B/2B and believed to be generally compliant with ABD0100.1.6 Sections 4.5 and 4.6. However, commercial of the shelf (COTS) components included in the design at its current level of maturity may have included materials that were not compliant. Materials and Workmanship were documented in a Modification Card to quality standards expected for installation on NRC experimental aircraft. Installation guidance was provided in the system description document.
Emission of Radio Frequency- Energy	PDP system electromagnetic interference (EMI) was not quantified by NRC and several COTS items did not meet applicable aerospace standards. NRC carried out EMI/electromagnetic compatibility (EMC) "source-victim" tests on previous installations in the NRC Convair 580 and Canadair CT-133 aircraft with the PDP system acting as the "source" of radio frequency (RF) emissions, and the aircraft acting as the "victim". NRC recommended that Airbus carry out EMI/EMC source-victim tests following installation of the PDP sensor in the Airbus test aircraft to demonstrate compliance with ABD0100.1.2 G. During the test aircraft navigation, communication and other essential systems should be monitored for adverse effects while switching the NRC PDP equipment on and operating it in all available modes.

Requirement	Resolution and Details
Temperature, Temperature Variations and Altitude/Pressure	All NRC and COTS electronics were housed inside a heated and pressurized avionics bay, with a cabin pressure altitude of 8,500 feet or less for normal operations. With the PDP installed, the Convair was operated in a tropical convective environment in heavy precipitation and ice crystals at altitudes up to 23,000 feet during HAIC flight trials in Cayenne, French Guiana. The flush mount PDP sensor installation was proof pressure tested on two separate occasions to pressure differentials of 11.1 and 8.9 psi and documented in NRC internal Test Reports. NRC was confident that the sensor could safely withstand Airbus cabin pressure differential loads to the Part 25 airworthiness requirements.
Vibrations, Waterproofness, Icing, Hail	The PDP had already been flown under these conditions with no adverse effect.
Lightning	NRC contracted Lightning Technologies to review the design and prepare a report addressing these requirements (see text for details).

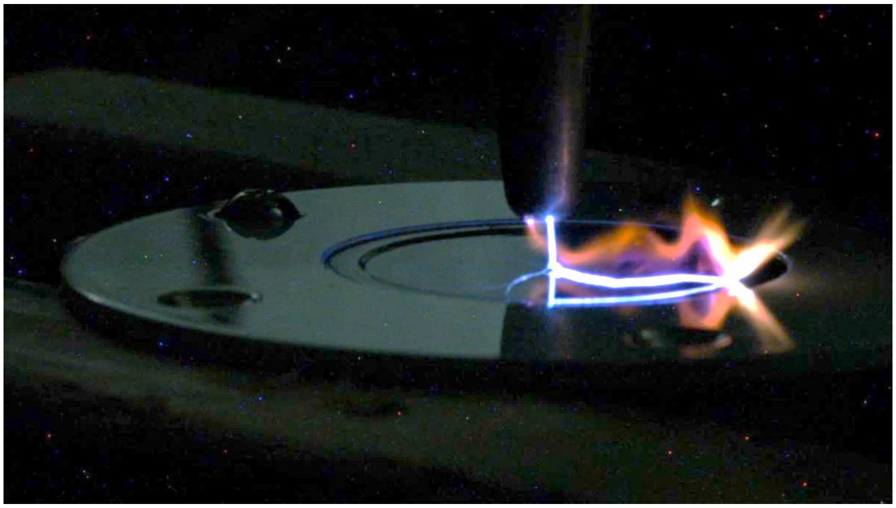


Figure 8: Lightning strike simulation test on a PDP

3.3 Development Flight Tests

The PDP was installed on the NRC Convair 580 for a super-cooled LWC flight campaign out of Ottawa, Canada. This campaign highlighted functional issues with operation in liquid environments. This was one of the iterative steps in moving from a wind tunnel capable probe to a flight ready version. The PDP was further tested by installing it on the NRC Canadair (Lockheed) CT-133 flight test aircraft to detect exhaust particles. Flight preparation included demonstrating that the amplifiers could function consistently at temperatures and altitudes representative of flight conditions, using a bench-top environmental chamber, and ensuring that the data system could fit within the available space.

During the flights, the electronics were installed in an unheated and unpressurised avionics bay. The aircraft flew up to 11,600 m (38,000 feet) in relatively benign meteorological conditions, including cirrus cloud encounters. The aircraft was subject to dynamic manoeuvres as it was flown in the wake of large airliners. The PDP operated reliably throughout the flight test campaign and it detected and measured changes in ice water content (IWC) within the cirrus cloud it passed through. Ice crystal concentrations in the cirrus cloud were estimated to be less than 0.01 g/m3 with particle sizes below 10 microns, which showed that the PDP is extremely sensitive to ice particles.

Figure 9: PDP probe installed on NRC CT-133 Aircraft

3.4 Altitude Icing Cascade Testing

The PDP was tested in the laboratory at NRC under glaciated, mixed and liquid phases with independent control for liquid water content (LWC) and IWC. This work was pursued with an ice crystal icing (ICI) system and cascade rig set-up in the Research Altitude Test Facility (RATFac) at the NRC [13]. This facility allows for the control and measurement of a wide range of critical ICI parameters including altitude, TWC, total air temperature (TAT), Mach number and particle size, as summarized in Table 3.

Testing the probe in this facility showed the sensitivity of the PDP to TWC and confirmed a high signal-to-noise ratio. Good facility accessibility and long campaigns of daily tests allowed simultaneous investigation of probe design variations as shown in Figure 6, and iterative improvement of the signal-to-noise ratio.

Table 3: General cascade rig operating envelope1 for ice crystal icing testing at NRC RATFac

Parameter	Min.	Max.	Unit
T_0	-50	+40	°C
P_0	1.9	14.3	PSIA
Mach #	0.15	0.8	
IWC	0.4	20	g/m^3
$MVD_{ice}{}^2$	20	700	µm
LWC	0.25	5	g/m^3
$MVD_{water}{}^2$	15	200	µm
RH	1	100	%
[1] Depends on specific test point and test article geometry [2] At tunnel inlet			

3.5 Convair 580 Cayenne ice crystal flight

The next flight campaign was also on the Convair 580 but in Cayenne, French Guiana in January 2015. This campaign encountered a wide range of conditions including:

- Rain in warm conditions
- Super-cooled large droplet, freezing rain and freezing drizzle liquid and ice crystals, but super-cooled liquid observations were patchy
- Small ice crystals up to 4 g/m^3 with sustained conditions of 1-2 g/m^3. Ice sizes ranged from tens of micrometres to centimetre sized aggregates
- Altitudes up to 7,000 m (23,000 feet) and temperatures ranging from above 30°C to -17°C

The primary objective of this flight campaign was to characterise the high ice water content conditions and the aircraft was fully equipped with an array of instruments to measure the properties of the cloud. The baseline TWC was measured using an isokinetic TWC probe known as the IKP2. This is a research probe specifically designed and tested to measure TWC in ice crystal conditions [14, 15]. The IKP was mounted under the wing, sampling the free stream conditions. The aircraft was also equipped with hot wire probes useful for discriminating mixed and liquid phase environments, particle sizing probes, radar and other probes for atmospheric characterization.

The NRC ice crystal flight campaign was the first time the PDP was flown in conditions for which it was designed. The PDP hardware had been tested in multiple wind tunnels and on-board the CT-133. The technicians in the NRC Gas Turbine Laboratory and Flight Research Laboratory invested a lot of time installing and checking the PDP on the aircraft prior to deployment. The result of this preparation was near flawless performance of the hardware during the campaign.

The location of the PDP is shown in Figure 10. It is flush with the fuselage just upstream of the front door. This location minimises the chance of particles impacting the probe but does not sample the freestream ice crystal concentration. The front of the aircraft acts like a snowplough pushing ice crystals to the side and around the aircraft. The ratio of the ice crystals at any location to that in the freestream is called the concentration factor. The concentration factor for the location of the PDP on the Convair was never calculated so the response of the probe cannot be connected to an ice crystal concentration but the relative response can be correlated.

Figure 10: PDP installed on NRC Convair 580 Flight Test aircraft

The successful functioning of the hardware allowed the controls and data processing to be developed during this campaign. This was the first flight campaign under typical conditions the PDP would be expected to measure, and the control systems responses had to be tuned for these conditions. In addition, amplification levels had to be determined. Too low an amplification level reduces the resolution of the probe but too high causes the probe to saturate and stop responding for a period of time.

The response of the installed system was checked with a signal generator that simulated the field produced by the ice crystals. The generated signal was then compared to the response of the PDP. The functioning of the PDP was confirmed with this method during the initial commissioning in French Guiana and subsequently used prior to each flight to confirm the probe functionality.

A sample of the results is given in Figure 11, which compares the TWC measured by the PDP and IKP. These are the results as gathered during the campaign, therefore the IKP results are processed by one of the authors of this paper based on the best information available at the time. Further processing was done by the lead partners in the campaign, NRC Flight Research Laboratory and Environment and Climate Change Canada. Based on other instruments, three periods were identified that likely had a significant portion of the TWC in liquid form. The PDP responds much more weakly to liquid water which explains why the PDP underestimates TWC in these conditions. The PDP TWC was based on a preliminary filtering algorithm and a linear correlation between the IKP TWC and the PDP TWC from a previous flight. In other periods the PDP overestimates the TWC but no clear reason for this was evident. One possibility is installation effects. The concentration factor at the probe location may depend on particle size so if the particle size changes the response of the PDP may change due to a change in concentration at the probe even though the free stream concentration has not changed. Another possibility is that the baseline correlation had liquid water mixed in reducing the PDP response. This highlights an issue with flight testing under complex atmospheric conditions. It is hard to fully characterise the conditions being measured at the PDP location and hence difficult to draw decisive correlations.

Figure 12 shows the unfiltered data for both the PDP and IKP for the same time period as Figure 11. Both have a data point every second. The IKP samples at 1 Hz but the geometry of the IKP likely provides some physical filtering of the response. The PDP was sampled for 0.1 s per second at a rate of the 2 MHz. This data was averaged to produce the data point for that second. Removing the filtering caused the variation in both the IKP and PDP to increase by approximately the same amount. This indicates that the "noise" in the PDP is actually variations in the environmental conditions. It is still obvious that the PDP is tracking the IKP. The agreement between the PDP and IKP TWC was excellent in ice water conditions. This successful flight campaign confirmed that the PDP was ready for the HAIC flight test.

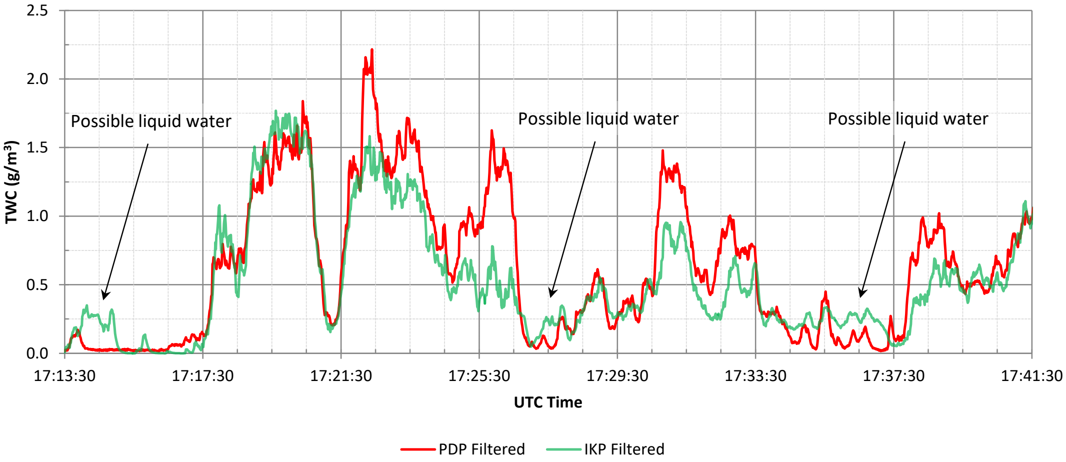


Figure 11: Comparison of filtered TWC measured by PDP and IKP during the Flight Campaign in French Guiana on the NRC Convair

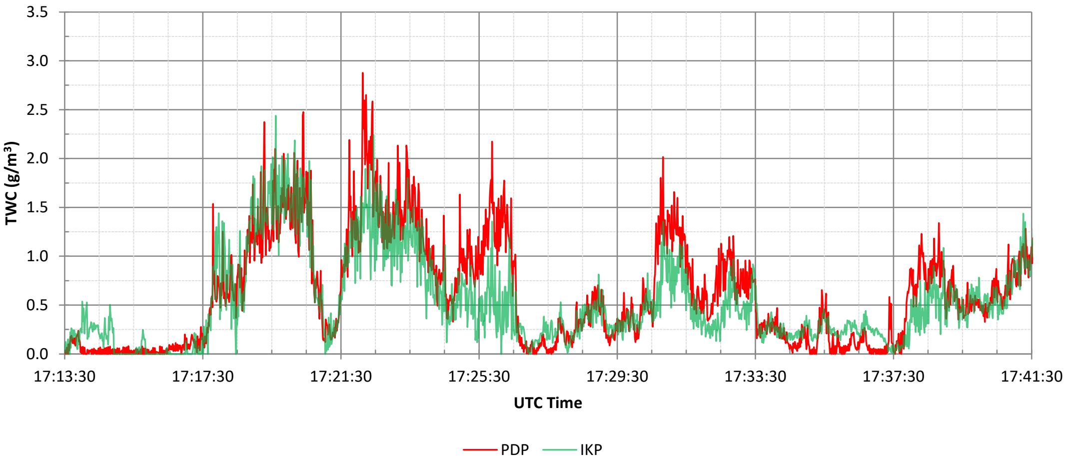


Figure 12: Comparison of TWC measured by PDP and IKP during the Flight Campaign in French Guiana on the NRC Convair

3.6 HAIC Airbus Flight Campaign in Darwin and Reunion Island

The HAIC flight campaign took the PDP to a much higher altitude than the NRC Convair 580 campaign. While the Convair did not fly above 23,000 feet, the Airbus A340 flew up to 40,000 feet covering the typical altitude range of commercial aircraft. It was frequently in fully glaciated conditions. The PDP was installed on the lower side of the nose of the A340, as shown in Figure 13, a zone with a concentration factor in the order of 2.5 as verbally indicated by Airbus. As can be seen, this installation was at an angle to the flow, so unlike the Convair location, the ice crystals did not just flow past the PDP but impacted on the surface. Ideally the probe would have been installed on the tail or in a window where particles would not have impacted the surface. However, no window locations were available and installation in the tail would have been too difficult to implement.

Figure 13: PDP installed on A340 flight test aircraft with inset zoomed in to show details

Particles impacting the surface affected the probe response and durability. The paint on the probe was eroded by the ice crystals. It was suitable for airframe exterior surfaces and was effective on metallic surfaces but erosion was initiated on a small plastic strip as seen in Figure 14. Once initiated the paint removal continued onto the metallic zone of the probe. Once the metallic zone is exposed the probe no longer functions correctly. Further development requires changing the surface preparation and primer, and possibly the substrate material. During the flight campaign, however, it was not possible to repaint the probe so a heavy duty plastic tape was used to protect the probe. The ice crystals also eroded the tape as shown in Figure 15. It appeared that the erosion began at the edge of the probe so aluminium tape, shown in Figure 16, was added around the edge to try to prevent the initiation. Although it did not completely prevent the erosion, replacing it after each flight protected it for the majority of each. This iterative process was a microcosm of the overall PDP development.

Figure 14: PDP with initial paint erosion due to particle impact

Figure 15: Erosion of protective covering

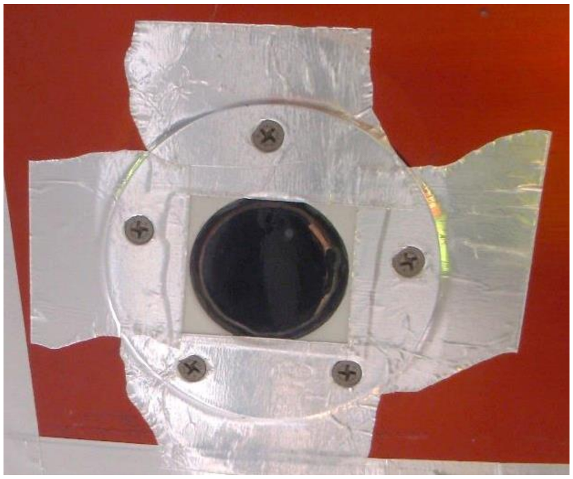


Figure 16: Final protective covering

Figure 17 shows the filtered results for the PDP and the SEA Robust probe, which was the baseline comparison probe for this campaign. The filtering algorithm was significantly advanced from the French Guiana campaign. Based on the damage in Figure 15 it is not surprising that when a particle hits the surface it generates a response much stronger than caused by a particle passing by. The characteristics of the signal are also different which added a new variable into the correlation between response and ice concentration. Not only does the response due to impact have to be accounted for but differences in impact force due to angle, speed and size will also alter the response. The system configuration also had to be altered due to this effect. If the amplified signal is too large the system saturates and cannot sense for a period of time while it recovers. This meant that the amplification had to be reduced to prevent this effect which reduces the resolution under normal operation.

Figure 18 shows the unfiltered data for the same time period as Figure 17. Unlike the unfiltered data in Figure 12 the deviation in the PDP increased significantly more than the baseline probe. This seems to indicate that the deviation is caused by something other than the changes in the environmental conditions. It was hypothesised that this was due to the particles impacting on the probe.

The location the PDP was installed on the A340 was not considered ideal. During initial discussions with Airbus other locations were discussed that NRC felt would provide better data but even on research aircraft, especially one the size and complexity of the A340, location is limited by aircraft safety and other priorities for the flight campaign. Although not ideal, the results taught us a lot. The additional noise and interference forced us to develop techniques to manage high levels of noise including a physical redesign of the probe. These techniques will improve the reliability of the probe even when installed in a preferred location.

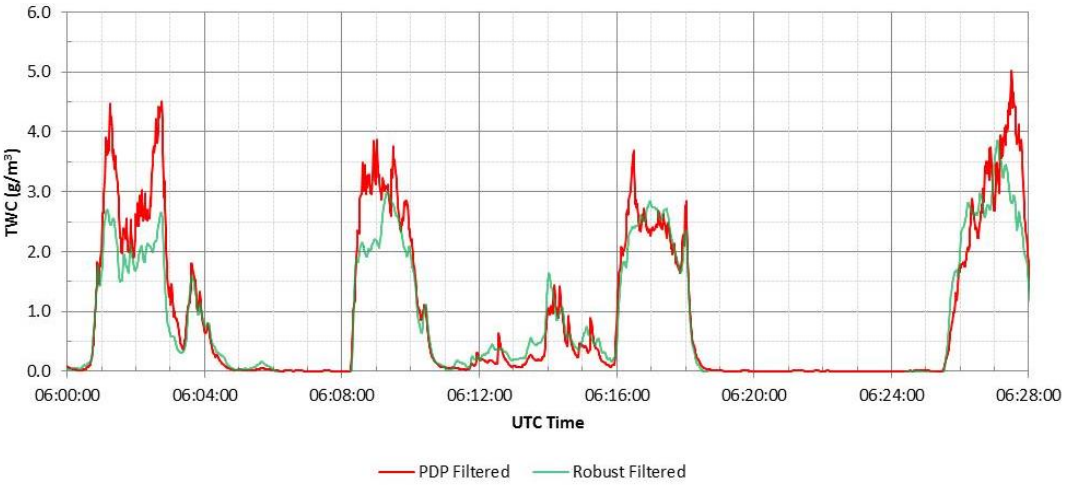


Figure 17: Comparison of filtered TWC measured by PDP and IKP during the Flight Campaign in Reunion Island on the Airbus A340

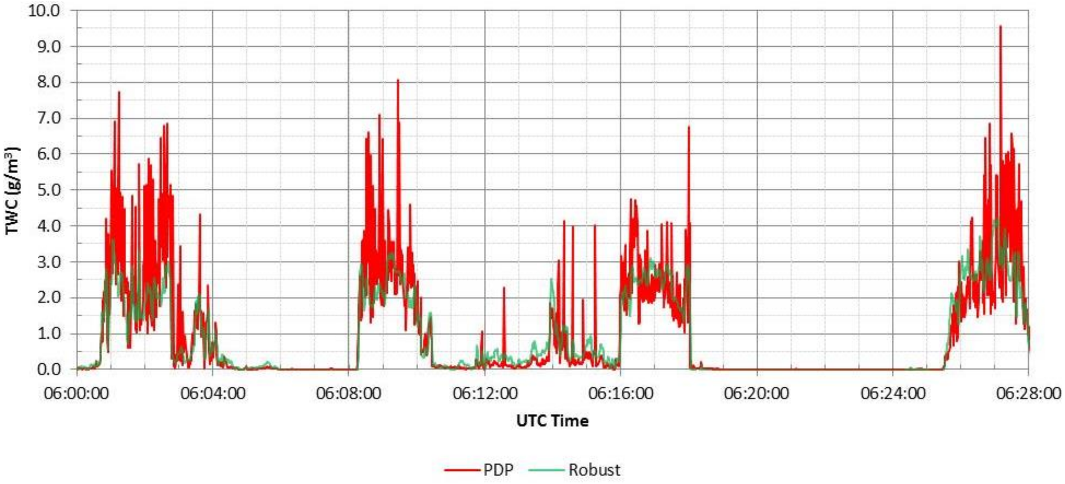


Figure 18: Comparison of TWC measured by PDP and IKP during the Flight Campaign in Reunion Island on the Airbus A340

3.7 Post-Flight Wind Tunnel Tests

Soon after the HAIC flight campaign the sea level ice crystal tunnel used in the preliminary work was available for testing the PDP. The compact IKP was installed in the center of the tunnel as a baseline comparison. The ice distribution over the tunnel cross section is known to be very non-uniform so the TWC at the center is not the TWC at the probe location but provides a baseline for comparison. This is similar to the concentration factor seen on the aircraft. The wind tunnel testing had to be completed before the DAS equipment used in the flight campaign was able to be returned to NRC so an earlier, less advanced, system was used.

The object of the test was to examine the effect of the ice impacts on the probe. The PDP was installed flush to the tunnel wall as shown in Figure 19 as a baseline and at 30° to the wall as shown in Figure 20 to determine the effect of the impacts. Also a re-designed probe, that was expected to be less susceptible to impacts than the painted version, was tested. The re-designed PDP was developed prior to the flight campaign but insufficient time was available to test and certify it before the flight. Three variations of the PDP were tested: painted probe to compare to the standard probe used in French Guiana and for HAIC; taped probe to compare to repaired probe used for HAIC; and the new probe to determine if it was a further improvement.

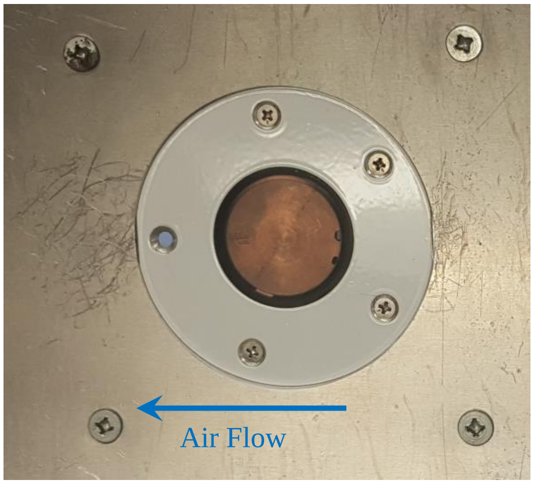


Figure 19: PDP installed in tunnel at 0°

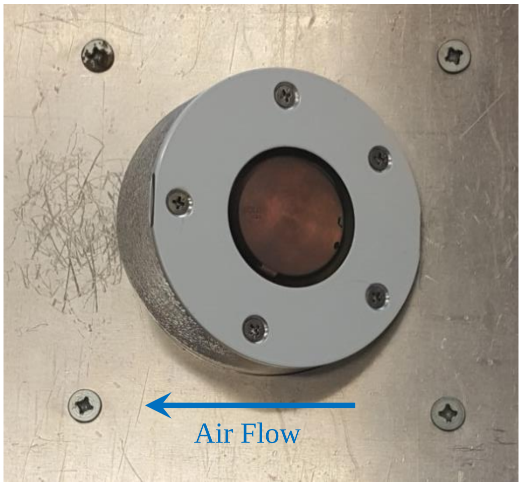


Figure 20: PDP installed in tunnel at 30°

Figure 21 displays some of the results from the sea level tests. It compares the three variations of PDP. The painted version shows the strongest response as was expected since the other versions had more physical shielding between the sensor and the airstream. The painted version also showed the greatest variation in repeat points. The taped version showed a weaker response than the painted version but also had less variation in repeat points. By the end of the test the tape had started to erode, exposing part of the painted surface, which might explain the variation in results. The new probe had a weaker response than the painted but almost the same as the taped. The new, however, showed much less variation in the repeat test points than either the painted or taped.

At a 0° angle of attack (AOA) the response rate of the painted and new probes was much lower than at 30° and the response of the new probe is lower than the painted. The taped probe was not tested at 0° since it was not used at this AOA in flight and was never intended to be a permanent design. The variation in repeat points relative to the response was about the same for both the painted and new probes. The new design, therefore, may be advantageous in installations that are not flush to the airstream.

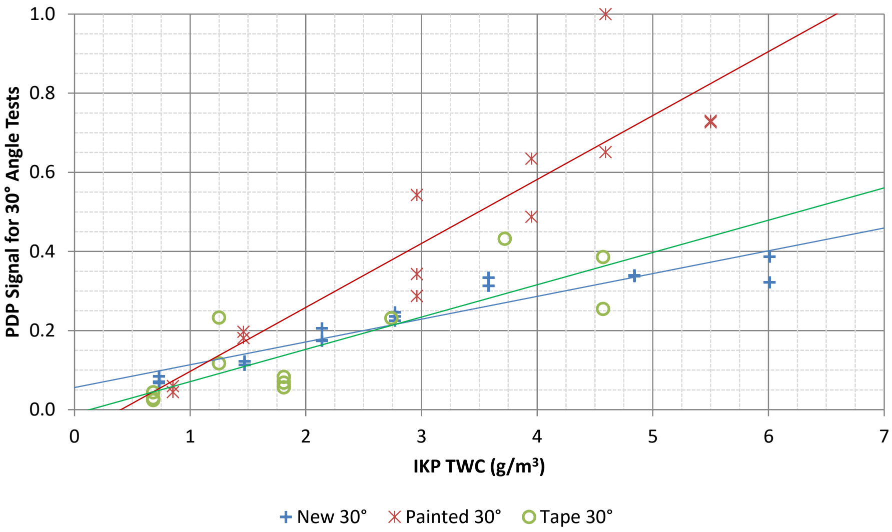


Figure 21:PDP results from post-flight tests in sea level ice crystal wind tunnel showing data points and least squares regression lines with probes installed at 30° to the 150 m/s airflow

4.0 CONCLUSIONS AND FUTURE STEPS

The HAIC campaign was very successful and a large amount of data was recorded. The findings were presented as part of the final TRL5 review. The results showed that the probe was effective in not only detecting the presence of ice crystals, but also estimating the TWC in flight. All other systems worked reliably, although there was coating degradation, which was not seen in the NRC flights or ICI tunnel tests. It is likely this installation produced a harsher environment due to a more forward-facing location than the NRC tests and high flights speeds. Process changes were identified to address this problem.

After approximately 750 hours of altitude icing wind tunnel testing, around 90 hours of flight testing, on three different aircraft, in five separate campaigns, and exposure to glaciated, mixed phase and super-cooled liquid water environments, the NRC PDP was the only probe to successfully pass the HAIC TRL5 review. In fact, the system met every TRL6 criteria, except that a non-commercial DAS was used. This was necessary to allow flexibility in control and data acquisition during the flight test.

The process from an initial test cell probe used for engine testing to a flight-worthy probe was a long and involved process. The inclusion of NRC flight test engineers with expertise in airworthiness was critical for success. The participation of Airbus in the development process was also invaluable providing guidance on the requirements for a commercially viable probe.

The next steps require the development of the PDP to a commercial probe. This requires the signal conditioning and data processing to be incorporated into the probe. It also requires the probe to meet further airworthiness requirements, especially if it is used as a warning system for the pilots to take action. The probe also needs to be manufactured and maintained once in service. None of these activities fall within the expertise of NRC and NRC intends to partner with a commercial company to complete the journey towards incorporation on commercial aircraft.

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