INNOVATIVE MOISTURE/ICING-RESISTANT FLUSH AIR DATA SYSTEM

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Abstract

Bombardier Aerospace contracted the Flight Research Laboratory of the National Research Council of Canada (NRC) to develop a Flush Air Data System (FADS) capable of operation following transit through adverse weather conditions for use on Bombardier's test aircraft. The NRC's existing FADS design was modified to incorporate water traps at the inlet of each of the four pressure ports to prevent moisture ingestion into the pressure lines. A heating system was designed to reduce moisture condensation in the pressure lines. After fabrication of the final prototype was completed, experimental bench tests were performed to demonstrate that the FADS had met the performance requirements for flight through adverse conditions and that the system was safe for flight. The FADS was then sent to Bombardier Flight Test Centre and installed on a Bombardier Global 5000 aircraft for flight testing. To evaluate the FADS performance, manoeuvres were performed where the FADS was exposed to adverse weather conditions; the FADS angle of attack and angle of sideslip measurements were unaffected by these conditions during the tests. The FADS was calibrated using NRC's GPS-based Simultaneous Calibration of Air Data Systems (SCADS) technique by developing angle of attack and angle of sideslip calibration coefficients. The calibration coefficients were then validated across the aircraft's flight envelope and weather requirements. From the results of the bench tests and flight tests, it was concluded that the new FADS was able to measure angles of attack and sideslip after flight through adverse weather conditions accurately.

1 Introduction

The Flight Research Laboratory at the National Research Council of Canada's Institute for Aerospace Research (NRC-IAR-FRL), was contracted by Bombardier Aerospace (BA) to develop a non-intrusive Flush Air Data System (FADS) capable of operation following transit through certain adverse weather conditions for use on Bombardier's test aircraft. The existing NRC FADS design used differential pressure measurements across vertical and horizontal pairs of pressure ports on the aircraft nose radome to obtain angle of attack (AOA) and angle of sideslip (AOS) measurements respectively

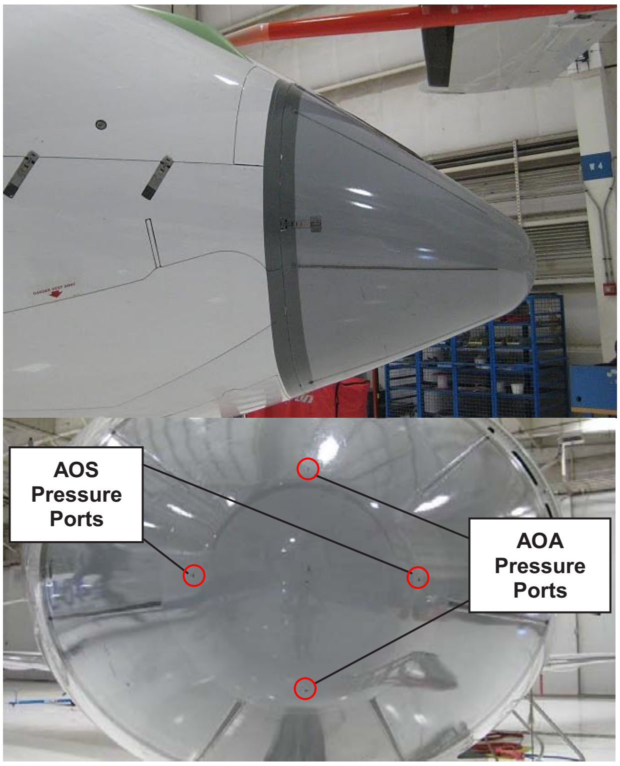

Figure 1: FADS installed on Nose Cone of Bombardier's Global 5000 Aircraft

(see Figure 1). In NRC's past flight test programs using the original FADS, adverse weather conditions such as rain and clouds were completely avoided to prevent moisture accumulation in the pressure lines. When flight through these conditions was unavoidable to reach the flight test area, it was necessary to cover the pressure ports, fly through the adverse weather condition, and land before flight testing to remove the covers. This wasted valuable time during tight flight testing schedules. In certain circumstances, the original FADS was flown through clouds during an aircraft descent. In these situations, the angle of attack and angle of sideslip measurements failed because of excessive moisture ingestion through the pressure ports that blocked the pressure lines. Thus, NRC's existing FADS design was modified to provide the capability to collect data after transiting through particular adverse weather-related environments.

2 Operational Design Requirements

Operational design requirements were established by BA and NRC concerning weather conditions that the FADS was expected to withstand. These requirements are listed below:

1. Operation in ambient pressures up to 51,000 ft
2. Operation in flight in ambient temperatures from 15°C to -56°C
3. Operation on ground in temperatures ranging from 50°C to -40°C
4. Unrestricted operation following flight through
    a. clouds
    b. moderate or heavy rain
    c. light snow or trace icing[1]
5. Exposure to rain or snow while the aircraft is taxiing on the tarmac
6. Ability to withstand transit through moderate icing without damage

In addition, the modified FADS was not to degrade the performance of the aircraft's weather radar, glideslope antenna, or other aircraft systems below an acceptable level defined by the flight crew.

3 Design Research and Development

To develop the optimal design, research was conducted into previous design concepts, the main environmental threats to the FADS, and the potential for the FADS to affect the performance of other aircraft systems. This is discussed in the following sections.

3.1 Environmental Conditions

Environmental conditions that the FADS would be exposed to were studied in detail to ensure that the FADS design would be robust. Two primary factors threatened its performance: the first significant threat to the FADS was moisture ingestion as a result of descent through clouds. During descent, a pressure gradient between the ambient air and the air inside the pressure lines is created, forcing the moist ambient air into the pressure lines. Typical moisture content of different cloud species was studied to determine the amount of moisture that the FADS would have to be able to withstand. The second threat was condensation in the pressure lines during aircraft descent. Condensation would occur when the dew point temperature of the air in the pressure lines exceeded the temperature of the pressure lines. This was a result of poor thermal conductivity of the pressure lines, causing the temperature of air in the pressure lines to increase faster than the temperature of the pressure lines during descent.

3.2 Electrostatic Discharge

In one of NRC's past flight test programs using the original FADS, an electrostatic buildup occurred on the tip of the radome due to ice and water particles in the atmosphere colliding with the aircraft. This electrostatic charge propagated inside the radome through metallic components at the pressure port interfaces on the front of the nose cone and burned a hole in one of the pressure lines. Thus, it was important to use an insulating material at the radome interface during design of the new FADS to avoid creating a pathway for discharge.

[1] Where trace icing is defined by FAR AIM Chapter 7

4 Final Modified FADS Design

The following design was developed to meet the defined requirements. To prevent the ingestion of moisture during flight through rain or clouds, water traps were designed and installed at the inlet of each of the pressure ports. Each of these water traps contained sponges inside a polycarbonate housing, located between each of the pressure ports and their corresponding pressure lines. The top pressure port was the most vulnerable to moisture ingestion because of its orientation, causing the moisture to be drawn inside by gravity. Thus, the top water trap was redesigned and a water reservoir connected to the bottom of the water trap to collect ingested moisture, and the pressure line was connected to an orifice on the top of the water trap. Figure 2 shows the layout of the water trap for the top pressure port.

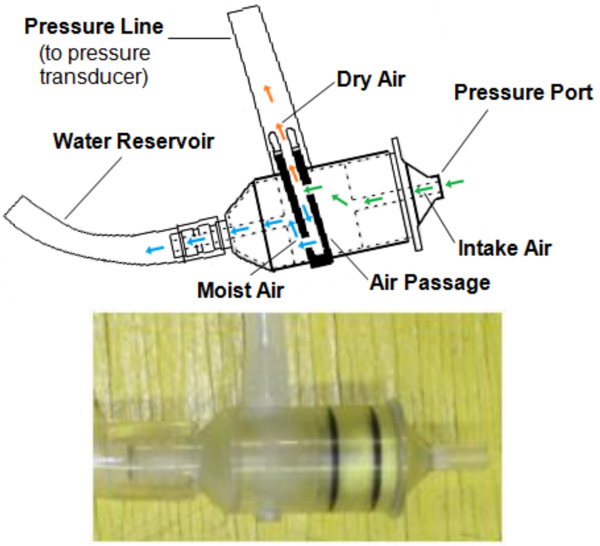

Figure 2: Configuration of the Water Trap for the Top Pressure Port (Sponges Shown as Dotted Lines)

To prevent condensation inside the pressure lines as the aircraft descends, a heating system was designed to maintain the temperature of the pressure lines above the dew point temperature of the air in the pressure lines. This heating system contained a heating box that blew hot air in a closed loop circuit through conduits which contained the pressure lines. The heating box contained the pressure transducers, four ceramic heaters, a fan, a temperature sensor, and two thermostats.

The heating box, powered by the host aircraft, was mounted below the glideslope antenna at the back of the radome on an aluminum honeycomb panel. The temperature sensor was used to monitor the performance of the FADS heating system. The thermostats were used to regulate the heaters and fan to prevent the system from overheating.

The pressure transducers were located in the heating box to create a temperature gradient in the pressure lines between the pressure transducers and the ambient air. As the pressure lines were heated, the air inside was heated and expanded out of the pressure ports, expelling moist air from the pressure lines in the process.

The fan in the heating box was a brushed electric motor, an interference threat for other aircraft signals due to its electromagnetic noise. Thus, a low pass four element LC (inductor capacitor) filter was installed on the fan.

A 2-inch conduit, carrying the four pressure lines from the heating box, transitioned into four 1-inch conduits through a composite manifold. These 1-inch conduits led each of the pressure lines to their respective pressure ports to the nose of the radome. Similarly, four 1-inch conduits carried the cold air return to the heating box via a composite manifold transitioning to a 2-inch conduit, completing the closed-loop circuit. The complete layout of the modified FADS is shown in Figure 3.

To prevent interference with the weather radar and glideslope antenna signal, it was critical that no metallic components were used at the front of the radome. Corrugated flame resistant FEP Teflon tubing was selected for the 2-inch and 1-inch conduits. This material was non-metallic, and was able to maintain flexibility and structural integrity at very high and low temperatures. These conduits were also covered in insulation to minimize heat loss. The composite manifolds consisted of an insulated foam core encased in carbon fiber housing.

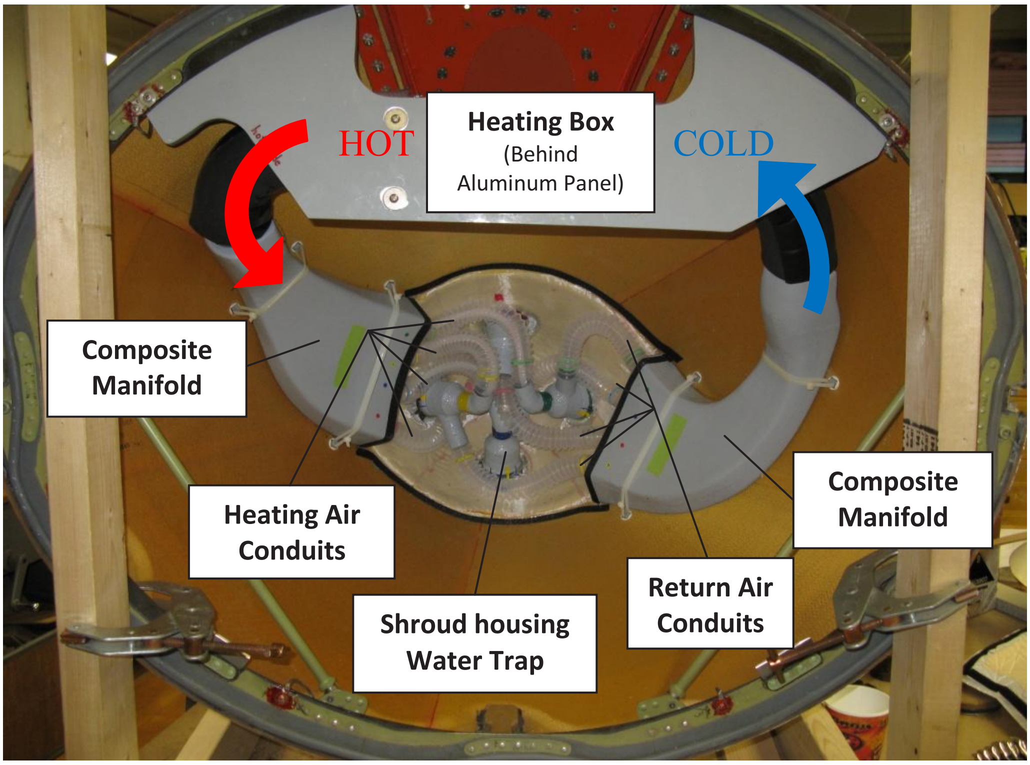

Figure 3: Complete Layout of the Modified FADS

A maintenance apparatus was designed to efficiently remove accumulated moisture from the sponges in the four water traps and the water reservoir in the top water trap. This apparatus consisted of a loop of tubing with four evenly spaced thin tubes attached. Air was blown through one end of this loop of tubing using a pressurized air source, and extracted from the four thin tubes. The loop of tubing was hung over the radome nose, and each of the four thin tubes was inserted into one of the pressure ports. As the air exiting the thin tubes blew past the sponges, it dried any moisture contained in them. Also, any accumulated moisture in the water reservoir of the top water trap was syringed out. This system ensured minimum inspection was required between flights, and allowed for a quick and effective moisture cleanup of the sponges.

5 FADS Testing Results

After design and construction, the FADS endured a series of meticulous experimental bench tests to demonstrate that the performance requirements were met and that the system was safe for flight. The FADS was then installed on a Global 5000 aircraft for flight testing to further test the performance of the FADS after flight through adverse conditions. These tests were used to determine if the FADS interfered with any aircraft systems, and to calibrate the angle of sideslip and angle of attack measurements. The following subsections describe the results of the bench and flight tests of the FADS.

5.1 FADS Bench Testing Results

Experimental bench tests were comprised of structural load, heating system airworthiness and performance tests. The results of these tests are described in the following sections.

5.1.1 Structural Airworthiness Tests

Static load tests were conducted on the aluminum honeycomb panel used to mount the FADS heating box to demonstrate compliance with longitudinal and vertical design load requirements.

The maximum design loads that the aluminum panel was expected to withstand were specified by the NRC FRL airworthiness group of 9g and 2g in the vertical and longitudinal directions respectively, which were chosen to exceed realistic load conditions by a factor of 1.5.

For the vertical load test, weights were suspended from the centre of the aluminum panel for about one hour. For the longitudinal load test, the radome was placed nose down and weights were applied to the centre of the panel for about 15 minutes simulating a longitudinal load. For each test, the deformation in the panel was measured after this time period. After inspecting the panel at the conclusion of each test, it was found that the panel did not noticeably deform or show any sign of failure.

5.1.2 Heating System Airworthiness Tests

Airworthiness tests were performed to demonstrate that a failure of the FADS heating system would not result in a safety hazard for the test aircraft. Potential failure cases were identified to be the following:

(1) A fan failure preventing hot air from circulating throughout the system, causing the heating box to overheat
(2) A failure of one of the thermostats, causing the temperature of the system to rise above a safe temperature
(3) A rapid aircraft ascent resulting in a pressure build-up in the heating system, causing the conduits to become disconnected

To test failure case (1), the fan was disabled while the FADS heating system was running. Failure case (2) was tested by disabling each thermostat while the heating system was running. During both tests, thermocouples were placed throughout the heating system in areas where the temperature could reach a critical level. The maximum temperature in each of these areas was recorded and compared to the maximum exposure temperature of these components. The FADS passed these safety tests after the results showed that the critical temperatures in each of the respective critical areas were below the maximum exposure temperatures by a safety margin of at least 10°C.

Failure case (3) was tested in a Tenneystrat environmental chamber in which the ambient temperature and pressure could be varied. Altimeters were used to measure ambient chamber pressure altitude and the pressure altitude inside the FADS heating system. The pressure in the environmental chamber was then dropped rapidly to simulate an aircraft in rapid ascent. The test showed that the pressure in the FADS heating system dropped at the same rate as the ambient pressure in the chamber demonstrating that the heating system was not susceptible to pressure build-ups.

5.1.3 Performance Tests

Performance tests were performed to demonstrate that the FADS met the requirements pertaining to tolerance of weather conditions and operating environments. Several specific critical conditions were defined as potential situations when the FADS would be most likely to fail. These are listed as follows:

(1) Flight at 51,000 ft where the ambient temperature is -56°C, which is the maximum altitude that the FADS is required to operate at
(2) Operations on the ground at -40°C, the minimum temperature on ground that the FADS must be able to operate at
(3) During descents from 15,000 ft where the FADS must pass through moist air in clouds, resulting in condensation inside the system
(4) Operations on ground or during flight in heavy rain
(5) Flight through an icing encounter

Failure cases (1) and (2) addressed concerns of whether or not the FADS heating system would be able to sufficiently heat the pressure lines in very low temperatures and pressures. If the heating system was not able to maintain the pressure lines at a sufficiently high temperature, there was a risk of moisture condensing and blocking the pressure lines. To demonstrate that the FADS would not fail in either of these situations, the FADS heating system was placed in a Tenneystrat environmental chamber, and operated in each of the respective ambient conditions. Note that due to space limitations, only the heating system and pressure lines were placed in the environmental chamber (independent of the radome).

Failure case (3) was tested by setting the conditions in the environmental chamber to those at 15,000 ft, and then observing whether or not the heating system was able to reach a temperature greater than the temperature at ground level.

During each of the three tests, thermocouples were installed throughout the heating system to monitor its performance. All three tests demonstrated that the FADS heating system was sufficient to prevent condensation.

The ground operations in heavy rain threat described by failure case (4) was tested by spraying water over the nose cone using a shower head and a specially selected metal screen to disperse the stream into small droplets. The experimental setup is shown in Figure 4. Exposure to heavy rain during flight was tested using a paint spray gun to apply high speed water directly at the ports. Although actual aircraft speeds could not be simulated, the test served as a proof of concept. Both tests showed that as long as the pressure lines were sealed at the back by the pressure transducers, water was prevented from entering the pressure ports by the air trapped inside.

Figure 4: Experimental Setup to test Operations in Heavy Rain

Exposure to icing was the last failure condition that was tested. The main threat during an icing encounter is when ice covering the nose cone begins to melt, and the water enters one of the pressure ports, causing a blockage. This was tested by covering one of the pressure ports with a block of ice to simulate an ice build-up on the nose cone. The test showed that as the block of ice melted, the melted ice was prevented from entering the pressure ports by the air trapped in the pressure lines.

To conclude, all performance tests showed that the FADS met the established requirements for operation in adverse weather conditions.

5.2 FADS Flight Testing Results

Once the final bench testing of the FADS was complete, the FADS was sent to the Bombardier Flight Test Centre in Wichita, Kansas where it was installed on a Bombardier Global 5000 aircraft for flight testing (see Figure 1). The purpose of flight testing the FADS was to determine whether or not the FADS interfered with any aircraft systems, to demonstrate its ability to withstand encounters with adverse weather in flight conditions, and to calibrate the angle of attack and angle of sideslip measurements.

5.2.1 Instrumentation

In addition to the FADS, which was used to measure the aircraft angle of attack and sideslip, a DGPS was installed on the aircraft to measure groundspeeds and altitude, and the LTN-90-100 IRU and the Novatel SPAN INS were used to measure aircraft attitudes, angular rates, and accelerations. Impact pressure, static pressure, and total air temperature were recorded from the aircraft air data computer.

5.2.2 Flight Test Plan

First, glideslope antenna and weather radar evaluation manoeuvres were performed to determine if components of the FADS interfered with the operation of either system during flight. Manoeuvres which involved flying through the atmospheric conditions listed in the performance requirements were flown to test the ability of the FADS to operate following flight through these conditions. Next, wind boxes were flown and were used in NRC's state of the art Simultaneous Calibration of Air Data System (SCADS) technique to calibrate the FADS angle of attack and angle of sideslip and the dynamic and static pressure measured by the aircraft's pitot-static system. An extensive flight test plan covering a wide spectrum of manoeuvres was developed to validate the FADS measurements, calibration and ability to withstand the weather requirements. These manoeuvres included 2-3-1-1s (large, alternate step inputs to excite the angles of attack and sideslip), steady-heading sideslips, straight and turning stalls, Dutch rolls, and OEI go-arounds.

5.2.3 Glideslope Antenna and Weather Radar Interference Evaluation

To begin the flight test, manoeuvres were performed to ensure the FADS did not mechanically or electrically interfere with the weather radar or glideslope antenna mounted inside the nose cone. A weather radar sweep was performed during flight to confirm this. However, glideslope antenna evaluations during runway approach indicated that the antenna did not lock until the aircraft was within 1.5-2.5 nm of the runway. This problem was caused by the metallic components in the heating box which interfered with the signal. To correct this problem, the heating box and aluminium panel were moved to the side of the radome. The glideslope antenna evaluation manoeuvres were then repeated; during these tests the glideslope antenna signal was able to successfully lock onto the runway. Thus, it was successfully demonstrated that the FADS did not interfere with the aircraft's glideslope antenna and weather radar.

5.2.4 Flight into Atmospheric Conditions

Manoeuvres were performed where the FADS was flown through adverse atmospheric conditions to test the ability of the FADS to withstand these conditions during flight. A set of 2-3-1-1 manoeuvres were performed before and after each encounter with an atmospheric condition; the data from these 2-3-1-1s were compared to determine if the FADS angle of attack and angle of sideslip measurements had been affected by exposure to the adverse weather conditions.

First, the FADS was flown through heavy rain. No moisture was detected inside the FADS during ground inspection after the flight. Analysis of the 2-3-1-1 data collected afterward showed that the FADS was unaffected by the rain. This confirmed the results of the experimental spray tests which also showed that the FADS could withstand a rain encounter.

Second, the FADS was flown through clouds with icing. Since ice accumulation was observed on the wing tips of the aircraft, it was assumed that ice build-up occurred on the nose cone as well. After the aircraft landed, no moisture accumulation was detected inside the pressure lines. The 2-3-1-1 data also showed that the FADS was unaffected by the icing encounter. This test confirmed the results from the icing build-up bench test performed earlier which demonstrated that the FADS was capable of successfully transiting through icing.

Last, the FADS was flown through cloud moisture during an aircraft descent. As with the other tests, no moisture was detected inside the FADS after inspection on the ground. The 2-3-1-1 data collected after this test was unaffected. Thus, it was demonstrated that the FADS was able to successfully fly through cloud moisture.

The average root mean square (RMS) error of the angles of attack and sideslip measurements during the 2-3-1-1s performed before and after atmospheric encounters was unchanged and remained below 0.5° throughout the envelope of the flight test plan. Therefore, it was concluded that the FADS was able to successfully transit through these conditions without being affected by them. It should be noted that these tolerances adhere to Federal Aviation Administration's (FAA) Flight Qualification Test Guide approved Level D standards making it an ideal choice for high fidelity flight test data gathering applications.

5.2.5 FADS Flight Data Calibration

The angles of sideslip and attack measured by the FADS were calibrated using NRC's GPS-based Simultaneous Calibration of Air Data

Systems (SCADS) technique. SCADS is a technique developed by NRC to correct angle of sideslip, angle of attack, dynamic pressure, and static pressure for errors that are caused by changes in the free-stream flow as it approaches the aircraft, commonly known as the position error correction (*PEC*). A special manoeuvre, denoted as a SCADS wind box, is performed covering operational altitudes up to 50,000 ft at various flap settings.

The first two legs of the box consist of rapid level acceleration and deceleration (120-400 knots in approximately 2 minutes) to cover the speed envelope and angle of attack envelope of the aircraft for calibration of the static and dynamic pressure measurements and angle of attack. The next two legs consist of an angle of sideslip sweep at a higher and lower speed for calibration of the angle of sideslip.

Table 1: FADS and Pitot-Static Calibration Coefficients

	Aircraft Flap Configuration: IN/0	Aircraft Flap Configuration: OUT/15 & OUT/30
C_{p0}	-0.01047	0.01971
C_{p1}	0.01333	-0.02819
$C_{\alpha 0}$	7.095	6.675
$C_{\alpha 1}$	13.160 (Mach ≤ .0486) 22.5*Mach^2 – 21.5*Mach + 18.3 (0.486 < Mach < 0.626) 7.109*Mach + 9.1908 (Mach ≥ 0.626)	12.349
$C_{\beta 0}$	0.104	0.173
$C_{\beta 1}$	16.787 (Mach ≤ .0478) 38.1*Mach^2 – 35.8*Mach + 25.2 (0.478 < Mach < 0.600) 10.467*Mach + 11.144 (Mach ≥ 0.600)	16.961

The box shape of the manoeuvre allows for an optimum estimate of the wind based on a comparison between the aircraft airspeed and groundspeed. The data collected during the SCADS wind box manoeuvre was analyzed using NRC's SCADS optimization software. A linear time-varying wind was calculated based on the airspeed and groundspeed. The remaining error between the airspeed and groundspeeds was minimized by an optimization routine which calculated optimum calibration coefficients; these coefficients were applied to the air data measurements using the equations below [1].

$$\alpha = C_{\alpha 0} + C_{\alpha 1} \cdot \frac{P_\alpha}{P_d} \quad (1)$$

$$\beta = C_{\beta 0} + C_{\beta 1} \cdot \frac{P_\beta}{P_d} \quad (2)$$

$$PEC = C_{p0} + C_{p1} \cdot Pd \quad (3)$$

$$Pd = Pd + PEC \quad (4)$$

$$Ps = Ps - PEC \quad (5)$$

The pitot-static and flow angle calibration coefficients derived from the SCADS identification process are shown in Table 1.

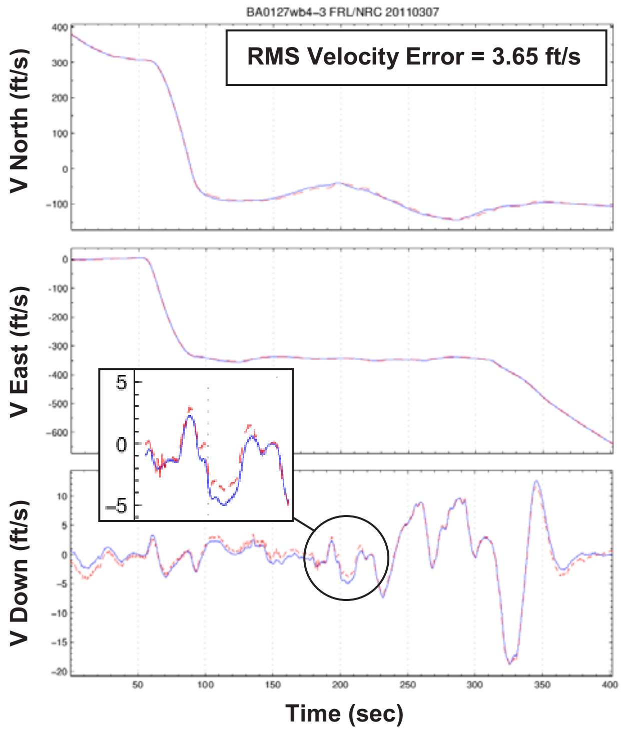

Figure 5: Measured Groundspeed (blue) plotted against Groundspeed calculated using Calibrated Air Data (red)

SCADS was carried out for each flap and landing gear configuration of the aircraft since these changes influence the free-stream flow approaching the aircraft. Wind boxes were also performed at various altitudes to account for the effects of flow compressibility on the air data calibration because of the Global 5000's capability to fly at high subsonic Mach numbers.

Figure 5 illustrates a sample SCADS validation which demonstrates successful transit of the FADS through adverse weather conditions during gusty and very high wind conditions [2] (up to 50 knots). The angles of attack and sideslip accuracy is unaffected. The graph plots measured groundspeeds against groundspeeds calculated from calibrated air data.

The high altitude, high speed SCADS runs were used to determine the Mach effects of the calibration coefficients. The calibrated angles of attack and sideslip exhibited proportionality to Mach number due to the flow compression that occurs as Mach number increases, changing the flow slipstream as it approaches the aircraft, thereby affecting the calibration [3].

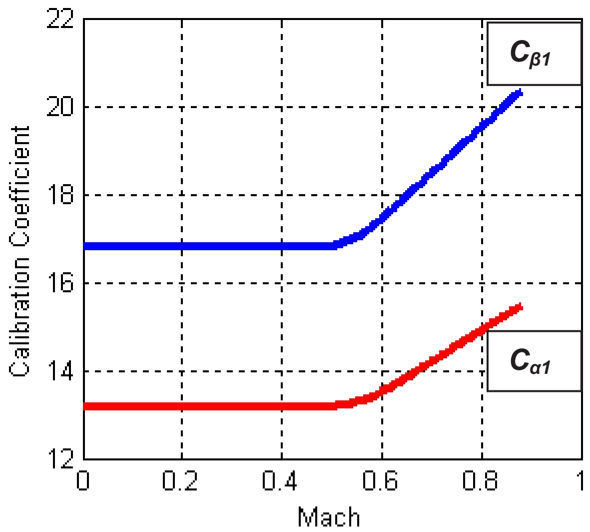

Figure 6: Mach Number Relationships of $C_{\alpha 1}$ and $C_{\beta 1}$ for the IN/0 Flap Configuration

In particular, $C_{\beta 1}$ and $C_{\alpha 1}$ revealed linear Mach number relationships above 0.5 Mach, further described in [4]. Sample curves for the clean flap configuration are shown in Figure 6.

5.2.6 Validation of the FADS Calibration Coefficients

The FADS calibration coefficients were validated by comparing the calibrated data collected during Dutch rolls, stalls, steady heading sideslips, and 2-3-1-1s to Flight Path Reconstructed (FPR) angle of attack and angle of sideslip from the LTN-90-100 IRU and using GPS groundspeeds with the wind

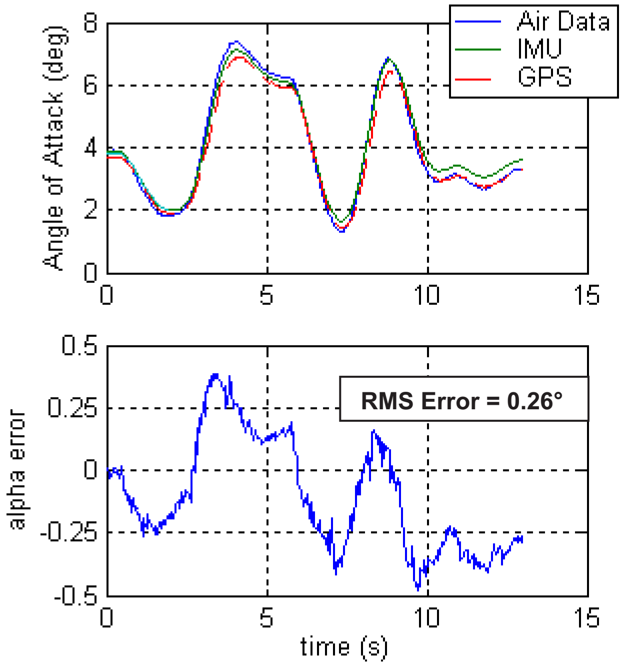

Figure 7: Plot of Calibrated FADS Angle of Attack Data against Reconstructed Angle of Attack from IMU and GPS Data during an Elevator 2311 Manoeuvre. Error Computed using IMU Data.

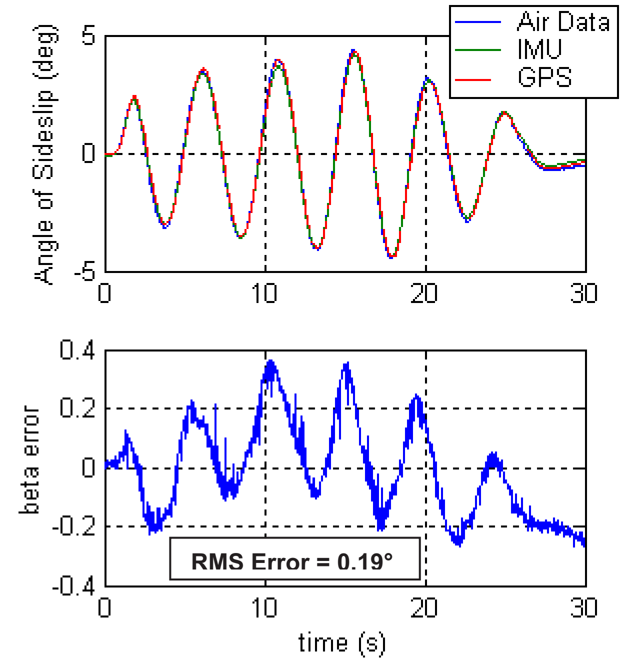

Figure 8: Plot of Calibrated FADS Angle of Sideslip Data against Reconstructed Angle of Sideslip from IMU and GPS Data during a Dutch Roll Manoeuvre. Error Computed using IMU Data.

component removed. Figure 7 and Figure 8 show example plots comparing the calibrated and reconstructed flow angles from Dutch roll and Elevator 2311 manoeuvres respectively. Typical RMS errors for the various manoeuvres flown are tabulated in Table 2. These values adhere to FAA's Flight Qualification Test Guide approved level D standards of 0.5° tolerance; thus, the FADS was successfully calibrated with the calibration coefficients developed using the SCADS technique.

Table 2: Root Mean Square Errors for Angles of Attack and Sideslip

Manoeuvre	AOA RMS	AOS RMS
Straight Stall	0.1389°	-
Turning Stall	0.5453°	-
Rudder 2311	-	0.1949°
Elevator 2311	0.1644°	-
Aileron 2311	0.2557°	0.2499°
AOS Demonstration	-	0.1850°
Dutch Roll	-	0.2126°

6 Conclusions

An innovative Flush Air Data System capable of operation following transit through adverse weather conditions including flight through clouds, heavy rain, snow, and icing was successfully developed for use on test aircraft. The current NRC FADS was modified by adding water traps at the inlet of each of the four pressure ports to limit moisture ingestion, and a heating system was designed to maintain the temperature in the pressure lines to prevent condensation.

Experimental bench tests demonstrated that the performance requirements had been met and the FADS was safe for flight. Weather radar and glideslope antenna evaluation manoeuvres performed during flight demonstrated the FADS did not interfere with this system after modifications. The FADS angles of attack and sideslip measurements were successfully calibrated using NRC's Simultaneous Calibration of Air Data Systems technique to generate calibration coefficients based on GPS measurements. The maintenance schedule designed for the FADS minimized inspection time, while providing efficient cleanup of the sponges between flights. The FADS performed manoeuvres which involved flight through adverse atmospheric conditions and no degradation in the flow angle measurements was observed after transiting through these conditions. Throughout the validation manoeuvres, the angles of attack and sideslip measurements adhered to FAA's Flight Qualification Test Guide Level D standards.

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