Validation of the Simultaneous Calibration of Aircraft Position Error and Airflow Angles Using a Differential GPS Technique on a Helicopter

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1.0 SUMMARY

This paper describes the validation of a technique for the simultaneous determination of pitot-static position error and the calibration curves for angle of attack and sideslip sensors. The SCADS (simultaneous calibration of airdata system) technique involves flying the aircraft in a "wind box" pattern while recording a suite of standard flight test parameters and Differential Global Positioning System (DGPS) measurements. This simultaneous calibration technique combines the calibration procedure for both position error and airflow angle calibration, and eliminates the need for flying close to the ground during the tests. During the development of this technique using the NRC Falcon 20 aircraft, the results demonstrated that accurate calibrations could be obtained with reduced flight time and cost over conventional calibration techniques. The present paper describes the application of the SCADS technique to the NRC Bell 206B helicopter. The calibration results are presented and are compared with data from other standard calibration methods and verified with maneuvers not used in the model development. The results from using the SCADS technique have demonstrated better efficiency and accuracy.

2.0 INTRODUCTION

CAE Electronics, Montreal, and the Flight Research Laboratory (FRL) of the National Research Council Canada (NRC) have conducted several joint programs to develop Level D flight simulators. These programs have involved the use of a leased aircraft to gather the flight test data for the simulator mathematical model development. To minimize the cost of this and other projects, the FRL has concentrated on increasing the efficiency of the flight tests. One area of emphasis has been the development of a more efficient method of calibrating airdata systems.

The current FRL method of calibrating airdata systems is a two-step process. The first step is to obtain the position error correction (PEC) and flight data by:

1) stopping at a reference position on a runway to record baseline position and pressure data;
2) performing a single, low altitude fly-by down the runway to provide a single calibrated point of the airdata system; and
3) performing a series of fly-bys over a relatively flat surface, such as a lake, to gather additional "pseudo-tower-fly-by" data.

The PEC coefficients are then determined using the flight data, as collected above, and the standard atmosphere equations.

The second step is to obtain the calibration curves for the angles of attack and sideslip; and the FRL flight path reconstruction (FPR) technique is used for this purpose with a variety of flight test maneuvers such as trim points and beta sweeps. This technique has been used successfully on flight test programs for several types of aircraft, and requires a fully calibrated airspeed system. Even though these methods of calibration have been proven to be accurate, they are tedious and complex. The two processes cannot be flown simultaneously, and the requirement to fly the test points in series results in additional flight test time and cost. The total flight test time required for this calibration is about five hours. Additional drawbacks of this technique are that the FPR process requires high accuracy inertial measurements and assumes the angle of sideslip to be zero during trim points. These drawbacks have led to a search for improved methods of calibrating airspeed and airflow angles.

Recent advances in the Global Positioning System (GPS), in terms of accuracy and price, have made it possible to use this system in the calibration of aircraft airdata systems. Other agencies have used GPS for airspeed calibration. Kimberlin showed in 1992 that the use of GPS for the pitot-static system calibration gave results similar to the two conventional methods, namely the "Speed Course" and "Tower-Fly-By" methods. This project was conducted on the Princeton University in-flight simulator (a Ryan Navion aircraft).

FRL has developed a process based on GPS, error modelling and minimization techniques to calibrate airdata systems in a single step. This technique has been named SCADS (Simultaneous Calibration of Airdata System). Hui, Srinivasan and Baillie showed in 1996 that the SCADS technique provided accurate results on the NRC Falcon 20 aircraft. The airdata measurements were obtained from a project-dedicated pitot-static system, while nosecone differential pressure ports provided angle of attack and sideslip measurements.

Future FRL plans include the requirement for numerous helicopter flight tests. With the recognition that the nosecone differential pressure technique is not applicable to helicopters, and that airdata measurement errors are more difficult to determine for helicopter than for fixed-wing aircraft, a validation of the SCADS technique on a helicopter with a noseboon installation was required.

This paper reviews the development of the airdata aerodynamic model algorithms, and the flight test maneuvers for calibration using the SCADS technique, and focuses on the validation of the SCADS technique for helicopter applications. In particular, the paper will describe:

1) position error characteristics and calibration methods;
2) flow angle modelling for a noseboon installation;
3) effects of wind on airdata calibrations;
4) the SCADS technique and the specific details for the helicopter application;
5) the NRC Bell 206B and its instrumentation and
6) the results of a SCADS flight test on the NRC Bell 206B.

3.0 POSITION ERROR CHARACTERISTICS AND CALIBRATION METHODS

Brown\textsuperscript{1} has described that the flow field around an aircraft in flight is distorted and, in turn, the local static pressure usually differs from that at infinity. The magnitude of this error generally increases with speed in proportion to aerodynamic forces and compressibility effects, and is also strongly affected by the location of the pressure sensor source on the aircraft.

Gracey\textsuperscript{7} showed that it is generally possible to design a pitot tube installation to avoid measurable total pressure error for typical flight conditions. As a result, to produce accurate airspeed and altitude data on most aircraft, a calibration is only needed for the static pressure source position error. References 6 through 10 discuss pitot-static calibration techniques, specific procedures and expected accuracies. Some references also include the analysis of airflow angle calibration methods. These methods include the ground speed course, trailing bomb, pacer method, tower-fly-by method and Radar techniques. These methods fall into three general categories, namely (1) the direct speed reference methods which depend on favourable wind conditions, (2) methods which do not require any special atmospheric measurements, and (3) radar methods using atmospheric measurements or meteorological analysis for the reference pressure altimetry.

4.0 FLOW ANGLE MODELLING

The vanes on the noseboom measure the angles between the local velocity vector and the noseboom axes. These two angles are defined in Etkin\textsuperscript{3} as angle of attack and flank angle of attack. In this paper, the subscript of the noseboom was dropped for the angles of attack and sideslip, flank angle of attack and the true airspeed vector and its components.

Angle of attack: \( \alpha = \tan^{-1} \left( \frac{w}{u} \right) \)

Flank angle of attack: \( \beta_F = \tan^{-1} \left( \frac{v}{u} \right) \)

where \( u, v, w \) are the three components of the true airspeed vector while \( U \) is the magnitude of the true airspeed vector and

Angle of sideslip: \( \beta = \sin^{-1} \left( \frac{v}{U} \right) \)

Traditionally, flank angle of attack, \( \beta_F \), is equated to angle of sideslip, \( \beta \); however, these two quantities are not exactly the same. Flank angle of attack is the rotation of the freestream velocity vector about the body Z axis. Angle of sideslip is the rotation of the freestream velocity vector about the stability Z axis. Corrections for the following must be applied to the measured angles \( \alpha_m, \beta_{fm} \), to obtain the true angles of attack and sideslip: 1) noseboom misalignment, 2) noseboom bending, 3) upwash and sidewash, 4) transformation of flank angle of attack to angle of sideslip and 5) aircraft angular rate.

4.1 Noseboom Misalignment Corrections

The Bell 206B noseboom was installed with misalignments on the order of 0.1 - 0.3 degrees from the aircraft axis system. Fortunately, for misalignments of this magnitude, the significant terms in the axis transformation occur as minor biases and scale factor errors which may be implicitly included in the upwash/sidewash corrections to be discussed in an upcoming section.

4.2 Noseboom Bending Corrections

During elevated-g manoeuvring, the noseboom will deflect with the increasing load. For the wind box manoeuvre and most flight test manoeuvres of interest, the g-loading is either small or short-lived; therefore, the noseboom bending effect was ignored in this application.

4.3 Effects of Aircraft Induced Upwash and Sidewash

This is the aerodynamic effect that the helicopter and/or the noseboom induces on the local velocity vector. The vanes on a noseboom measure the effective angle of attack and flank angle of attack \( (\alpha_m, \beta_{fm}) \), not the free-stream angles of attack and sideslip \( (\alpha, \beta) \). The difference between these angles is defined as the upwash or sidewash. To adjust the flow angle model for this difference let:

\[
\Delta \alpha = \alpha_m - \alpha = (1-m) \alpha_m + m \beta_{fm} + \beta_{fm} \\
\Delta \beta_F = \beta_F - \beta = (1-n) \beta + n \beta_{fm} + \beta_{fm}
\]

For both \( \alpha \) and \( \beta \) ranging between +/- 20 degrees, Moes and Whitmore\textsuperscript{13} showed that the up- and side- wash correction terms for a wingtip boom mounted on a fixed-wing aircraft are:

\[
\Delta \alpha = m \alpha_m + \alpha_{int} \\
\Delta \beta_F = n \beta_{fm} + \beta_{fm} 
\]

where \( m \) (upwash factor) and \( n \) (sidewash factor) are approximately constant at low speeds and less than 1.0. With this as a basis, the vane calibration equations can be rearranged into the form:

\[
\alpha = (1-m) \alpha_m + \alpha_{int} \\
\beta_F = (1-n) \beta_{fm} + \beta_{fm}
\]

This form of correction will be assumed for the helicopter noseboom case presented here.

4.4 Transformation of Flank Angle of Attack to Angle of Sideslip

The transformation of the flank angle of attack to angle of sideslip is governed by the following equation:

\[
\beta = \tan^{-1} \left( \tan(\beta_F) \cos(\alpha) \right)
\]

For small angles of attack, less than +/- 10 degrees, the difference between \( \beta \) and \( \beta_F \) is minimal and, therefore, can be neglected. For larger angle of attack ranges, however, this nonlinear term must be included in the corrections.

4.5 Aircraft Angular Rate Corrections

Since the noseboom is not located at the aircraft centre of gravity, any aircraft angular rate will induce an additional airspeed at the vane location. The noseboom components of velocity must be corrected to the centre of gravity (CG) of the aircraft. These corrections are presented in detail in Reference 5. As an example, for a centreline-mounted \( \alpha \)-vane, this correction is given by the equation:

\[
\alpha = \tan^{-1} \left[ \left( \frac{u \tan \alpha + Q x_i}{u - Q z_i} \right) \right]
\]

where \( u = U \cos \alpha \cos \beta \);

\( \alpha \) is the true angle of attack at the CG of the aircraft;

\( x_i, z_i \) are the distances from the centre of gravity of the aircraft to the noseboom and

\( Q \) is the pitch rate of the aircraft.

5.0 EFFECTS OF WIND ON AIRDATA CALIBRATION

During a flight research program, Eberberger\textsuperscript{14} acquired and analyzed a set of wind variation data. These data indicated
that wind variations are often larger than airdata calibration accuracy standards (typically 0.003 Mach). Ehemberger's data showed typical variations in wind of 0.075 Knots/mile and typical RMS values of 6 Knots over a 3.5 hour time period. His results agreed reasonably well with wind variability determined from larger data sets produced by the National Meteorological Center and the USAF Global Weather Center.

Chan did a similar study of a vertical wind. For turbulent flight, it was possible to have large excursions in vertical wind data (+/- 6 knots peak-to-peak in two minutes) during a 20-min session, with the vertical wind returning to a mean value (2 knots) after the perturbation. Chan also concluded that, for most of the flight, the atmosphere was smooth, and the vertical winds generally averaged zero over a long period of time. In consideration of the above data, the SCADS technique employs a wind model which can vary linearly with time.

6.0 THE SCADS TECHNIQUE

The purpose of the flight test maneuver in the SCADS technique is to create an aircraft time history for which the errors in the airdata system are independent of wind speed and direction. The standard method of eliminating the correlation between wind speed and pitot-static errors is to fly the aircraft on reciprocal headings. This approach does not, however, adequately discern errors in the measurement of sideslip angle. In the SCADS technique, therefore, the aircraft is flown in a wind box pattern (see Figure 1). To further produce variation in angles of attack and sideslip and, therefore, to improve the information content of the time history, variations in airspeed and beta sweep maneuvers have been incorporated in the various "legs" of the wind box.

Figure 1 Typical Wind Box Pattern

According to the SCADS results from previous flight tests on the NRC Falcon 20, a wind box with an acceleration/deceleration maneuver in the first two legs of the wind box was better than a wind box flown at a single constant speed. In the present work, the requirement for a variation in airspeed over the SCADS maneuver was met by accelerating or decelerating the aircraft either on straight segments or during turns. For all wind boxes, a gradual sideslip change with constant track was executed in both directions (known as a beta sweep) on the third and last legs of the wind box. Each wind box covered the entire airspeed envelope of the helicopter. All wind boxes were performed within 25 km of the GPS reference station to maintain the optimum GPS measurement accuracy.

The general equations for SCADS were presented in Reference 5. Some of the equations specific to the SCADS application in helicopters will be listed below. The equations for the position error correction (ΔP), true dynamic pressure (Pd) and true static pressure (Ps) of the Bell 206B helicopter are approximated by:

\[\Delta P = C_{p_d} + C_{p_s} * P_d + C_{p_s} * P_s^2\]

\[P_d = P_i + \Delta P\]

where \(P_i\) are the indicated dynamic and static pressures.

The second order error term is uniquely used in this application on a Bell 206B. The helicopter up- and side-wash effects, as previously discussed in Section 4.0, 'Flow Angle Modelling', may be implicitly expressed in the vane calibration equations as:

\[\alpha = C_{\alpha d} + C_{\alpha s} \cdot \alpha_m\]

\[\beta = C_{\beta d} + C_{\beta s} \cdot \beta_m\]

where the terms \(C_{\alpha d}\) and \(C_{\alpha s}\) reflect the sum of biases from the misalignment of the noseboom plus the up- or side-wash effects \(C_{\alpha s}\) and \(C_{\beta s}\) are sensitivity factors, and \(\alpha_m\) and \(\beta_m\) are the geometric or static angle of attack and flapping angle of attack measures.

To summarize the SCADS technique, the following parameters were measured during the wind box maneuver:
- dynamic pressure, static pressure, 3 attitudes (θ, φ, ψ),
- total temperature, 2 noseboom vane deflections,
- 3 angular rates (P, Q, R), 3 GPS ground speeds (V_on, V_off, V_g), and GPS altitude (Z_g).

The aircraft ground speed vector for the maneuver is calculated from the true airspeed vector and an assumed wind model. The Direct Search Complex Algorithm method varies the coefficients of 1) the position error correction equations, 2) the airflow angle model and 3) the wind model in order to minimize the weighted sum of the errors between the GPS-measured ground speed vector and the calculated ground speed vector. The minimization also considers the difference between calculated pressure altitude and GPS-derived altitude.

7.0 AIRCRAFT DESCRIPTION

The validation of the SCADS technique was performed using the NRC Bell 206B JetRanger (see Figure 2). This aircraft is a single engine utility-type helicopter. The main rotor is a two-bladed, semi-rigid see-saw type. The main rotor blades are of all-metal construction of aluminum alloy monocoque type. The diameter of the main rotor is 33 ft 4.0 in and the length of the chord is 13 inches.
8.0 INSTRUMENTATION SYSTEM

For the SCADS validation project, a Litton LTN-90-100 Inertial Reference System (IRS) and the FRL high-accuracy portable instrumentation system and a data acquisition system (Micropak) were installed in the Bell 206B. This system included:
1) sensors for measuring the aircraft’s inertial parameters,
2) a noseboom airdata system, with potentiometer measurements for the airflow angle vanes, and
3) a PC-mounted GPS receiver.

The time-coded parameters were recorded onboard the helicopter at 64 Hz.

8.1 Inertial Parameters

Because the Litton IRS was designed for the navigation role on commercial aircraft, its parameters, especially normal accelerations, are heavily low pass filtered. For this reason, the measures of aircraft acceleration and angular rate were taken from the thermally-modelled accelerometers and rate sensors of the Micropak while attitude measures were obtained from the IRS.

8.2 Airdata System

Prior to this experiment, a swivelling pitot-static noseboom system, a Space Age Control, self-aligning airdata probe, was installed on the NRC Bell 206B helicopter for project purposes (Figure 3). The swivelling probe was separate from the pitot/co-pilot systems and consisted of a combined pitot-static tube with four fins attached to the end of the tube to allow for aerodynamic alignment of the probe with the local flow. There were six static orifices placed at 60-degree intervals around the tube. The swivelling probe was designed to align itself with the local flow to effectively eliminate total and static pressure losses as a result of local angles of attack and sideslip effects. The nose pitot section was mounted to permit a 21 degree swivel in any direction. Manufacturer’s data suggests that the vanes can maintain their accuracy up to +/-40 degrees of angles of attack and sideslip. The static and differential pressure transducers were PanScienfific “intelligent” transducers which are thermally modelled, and accurate to within 0.01 percent. A Rosemount total temperature probe was mounted vertically behind the sideslip vane and below the boom.

8.3 Global Positioning System

A NovAtel 3151 GPS PC card receiver was installed in the test aircraft, with a model 511 antenna mounted atop the fuselage behind the main rotor of the helicopter. The unit was a single frequency (L1 at 1575.42 MHz) receiver card mounted in the backplane of a 486-computer system. The Differential mode of the GPS was used to obtain accurate measures of aircraft position and ground speed. The GPS reference station included a NovAtel 501 antenna with a choke-ring mounted atop the FRL hangar and a 3151 GPS PC card receiver. GPS data and status information could be displayed and controlled on either PC system by a NovAtel program called Winsat.

The GPS data post-processing software used ambiguity resolution and cycle slip handling techniques developed by GeoNav System for single and dual frequency systems. For this experiment, with single-frequency observations, this GPS post-processing software, called P-RTK, was expected to generate its best accuracy for baselines (distance between the aircraft and the ground station) of 25 km or less. The combination of P-RTK and the NovAtel 3151 compatible receiver was expected to produce position accuracies of 2 cm + 2ppm (i.e., 2 mm error for every km) for fixed-wing aircraft when at least four satellites were observed. The time-coded GPS data, processed with the P-RTK software, provided measures of longitude, latitude, height and the three components of velocity with respect to the ground. The WGS-84 convention was used to convert the longitude, latitude and height into local Cartesian coordinates.

The use of GPS in the helicopter environment is not as advanced as in fixed-wing applications. One problem for helicopters is that the rotor blades momentarily blank off the satellites. This blocking effect lowers the signal-to-noise level of the satellite measurements. With low signal-to-noise level, the occurrence of what are known as cycle-slips becomes much prevalent. These complications made the processing of helicopter GPS measurements more difficult.

At the beginning of the SCADS validation flights, the NovAtel GPS receiver was configured to track ephemeris and the satellite pseudoranges with options that were validated in previous fixed-wing studies. This setup resulted in GPS data which was unusable. Newer options for the NovAtel configuration were tried and much improved data resulted. Attention was also paid to the manner in which the helicopter was flown. High quality GPS data was finally achieved by using the newer configuration options and by flying the helicopter with the following limitations/procedures:

- Position the helicopter at a location where no obstacles block the signal from the satellites
- Set 100% Nr (rotor RPM)
- Start Winsat and wait until at least 4 satellites are tracked before starting the data log
- Collect 5 minutes of GPS data prior to moving the helicopter
- Climb to the test altitude gradually
- Limit turns to less than 40 deg bank and limit roll/yaw angular rates to less than 30 deg/sec
- Return to the starting location and, with Nr =100%, record 3 more minutes of GPS data.

All GPS data used in this paper were collected in the above manner and resulted in an integer ambiguity solution with no special user interaction.
9.0 SCADS FLIGHT TEST ON THE BELL 206B

The NRC Bell 206B SCADS flight test comprised 3.7 flight hours in 3 flights over a 3 day period. The objectives of this flight test were to optimize the SCADS manoeuvre for the helicopter application, to calibrate the Bell 206B airdata system using the SCADS technique and to assess the accuracy of that calibration by collecting and analyzing time histories of other types of aircraft manoeuvres. The following sections will summarize the results and discuss them in relation to these objectives. Wind conditions for the three flights are described in Table 1.

9.1 Summary of Results

The downwash from the main rotor clears the noseboom-vanes when the helicopter exceeds a forward speed of 20 Knots. Therefore, most of the SCADS wind box manoeuvres were performed within an IAS range of 40 to 110 Knots. The wind boxes were performed at altitudes of either 1000 ft or 5000 ft and in one of three wind conditions; calm, strong and steady, or moderate and turbulent. The SCADS-derived airdata calibration coefficients are presented in Table 1. The File designator indicates the wind conditions (i.e., S - Steady strong wind of 15 Knots, U - Moderate but turbulent wind of 7 Knots and C - Calm wind of 1.5 Knots). The Type designator indicates how the variation in airspeed was accomplished: L - Acceleration/deceleration within the first two legs of the wind box, T - the acceleration/deceleration within the turns and T2 - similar to T except the last leg has a different constant speed. All airdata calibration coefficients are relatively consistent in value. The values of the airdata calibration coefficients have the best agreement for calm wind cases. The predicted wind magnitudes for all cases agree to within 1-2 knots. The calculated wind direction is also relatively consistent. These wind magnitudes and directions also agree well with the actual and predicted weather measures over the Ottawa/McDonald Carier International airport.

9.2 Comparison of Results from Different SCADS Manoeuvres

Inspecting the values presented in Table 1, with consideration of the acceleration/deceleration type, leads to the conclusion that the T2 manoeuvre type is slightly superior. Unfortunately, T2 manoeuvres were only flown in calm conditions; therefore, the comparison may be misleading. From a qualitative consideration of the more uniform distribution of angle of attack achieved during T2 manoeuvres it is felt, however, that the T2 manoeuvre is slightly superior to others.

9.3 Bell 206 Airdata Calibration

The airdata calibration coefficients for the Bell 206B are summarized in Table 2. These coefficients were sorted by meteorological wind conditions. The overall values reflect an average of airdata calibration coefficients which were derived from all the available cases. The range of deviations from the average value for the calm air condition group were significantly lower than for the other two groups. Under these conditions, the wind is more repeatable and the airdata coefficients are more robust. Based upon the consistency of the calm air coefficients and the wind data, on a case by case basis, the averaged calm air coefficients were chosen as the final NRC Bell 206B calibration. Note that this choice represents only 0.6 hours of flight data, including aircraft transit time.

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<table>
<thead>
<tr>
<th>Designators</th>
<th>Position Error Correction</th>
<th>α</th>
<th>β</th>
<th>Resulting Wind Model</th>
</tr>
</thead>
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<td>IAS Kr</td>
<td>Type</td>
<td>C₀₀</td>
<td>C₀₁</td>
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Table 1 Results from the Eleven Wind Box Manoeuvres
Table 2 Summary of Airdata Calibration Coefficients

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<tr>
<th>Group</th>
<th>$C_{p0}$ +/- range</th>
<th>$C_{p1}$ +/- range</th>
<th>$C_{p2}$ /psi $/C_{a0}$ +/- range</th>
<th>$C_{a1}$ +/- range</th>
<th>$C_{a0}$ +/- range</th>
<th>$C_{b1}$ +/- range</th>
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<tbody>
<tr>
<td>Strong and Steady</td>
<td>0.0105 +/- 0.0025</td>
<td>-0.0597 +/- 0.0107</td>
<td>0.6579 +/- 0.0756</td>
<td>0.2711 +/- 0.0954</td>
<td>0.9106 +/- 0.1046</td>
<td>-0.2862 +/- 0.3961</td>
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<tr>
<td>Moderate and Turb.</td>
<td>0.0089 +/- 0.0014</td>
<td>-0.0574 +/- 0.0094</td>
<td>0.7647 +/- 0.1632</td>
<td>0.3124 +/- 0.2750</td>
<td>0.7466 +/- 0.0812</td>
<td>-0.0106 +/- 0.5384</td>
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<td>Calm</td>
<td>0.0100 +/- 0.0005</td>
<td>-0.0458 +/- 0.0031</td>
<td>0.7254 +/- 0.0469</td>
<td>0.5443 +/- 0.1304</td>
<td>0.7457 +/- 0.0238</td>
<td>0.2453 +/- 0.0718</td>
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<tr>
<td>Overall</td>
<td>0.0096 +/- 0.0018</td>
<td>-0.0548 +/- 0.0103</td>
<td>0.7249 +/- 0.1273</td>
<td>0.3644 +/- 0.2322</td>
<td>0.7911 +/- 0.1072</td>
<td>0.1498 +/- 0.4386</td>
</tr>
</tbody>
</table>

9.4 Typical SCADS Identification Results

Figure 4 shows the typical error between the GPS-measured ground speed/altitude time histories and those calculated from a SCADS estimation, in this case run CO2. The significant features of this plot are:

1) Groundspeed and altitude errors are small during constant heading sections;
2) These errors are large during turns (turn data is not used in the SCADS minimization routine).

9.5 Verification of Bell 206 PEC Calibration with Standard Calibration Techniques

The Bell 206B was flown up and down the runway in calm air conditions at different speeds using a ground speed course (GSC) technique. The runway was 9651 ft long. The PEC coefficients derived from this method and those from the SCADS estimation are listed in Table 3. The large difference between the estimated PECs at the lowest airspeed is attributable to a decrease in accuracy in the GSC method at lower speeds. In such cases, a small variation in wind will cause a large percentage variation in the PEC estimate.

![Figure 4 Typical SCADS Identification Results]

Table 3 PEC Coefficient Comparison SCADS Vs GSC

<table>
<thead>
<tr>
<th>Approximate IAS</th>
<th>Avg Indicated Pd</th>
<th>GSC - PEC</th>
<th>SCADS - PEC</th>
<th>(SCADS-PEC) / Pd percent difference</th>
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<td>Kt</td>
<td>psi</td>
<td>psi</td>
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<td>0.00962</td>
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<td>0.09240</td>
<td>0.01428</td>
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<td>0.16670</td>
<td>0.02063</td>
<td>0.02253</td>
<td>1.14</td>
</tr>
</tbody>
</table>
Table 4 Two Cases of SCADS Results for PEC Verification

<table>
<thead>
<tr>
<th>Case</th>
<th>Leg Segment</th>
<th>Wind Magnitude f/s</th>
<th>Wind Direction deg</th>
<th>North Wind f/s</th>
<th>East Wind f/s</th>
<th>Aircraft Heading deg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calm</td>
<td>1</td>
<td>2.47</td>
<td>-34.3</td>
<td>1.16</td>
<td>-0.79</td>
<td>341.3</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>2.61</td>
<td>1.33</td>
<td>0.16</td>
<td>68.3</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>2.92</td>
<td>2.34</td>
<td>0.95</td>
<td>155.9</td>
<td></td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>3.82</td>
<td>2.57</td>
<td>1.52</td>
<td>246.7</td>
<td></td>
</tr>
<tr>
<td>Moderate</td>
<td>1</td>
<td>10.65</td>
<td>271.9</td>
<td>0.3</td>
<td>-10.5</td>
<td>337.0</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>10.78</td>
<td>3.5</td>
<td>-10.0</td>
<td>70.3</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>12.63</td>
<td>4.6</td>
<td>-11.5</td>
<td>160.7</td>
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<tr>
<td></td>
<td>4</td>
<td>13.32</td>
<td>4.8</td>
<td>-11.9</td>
<td>250.5</td>
<td></td>
</tr>
</tbody>
</table>

9.6 Verification with Flight Data

Verification of the SCADS-produced Bell 206B airdata calibration was performed by using flight records which were not used in the development of the PEC. Two cases were chosen: a constant airspeed wind box flown in calm wind conditions and a wind box with airspeed changes during the turns flown in moderate and turbulent wind conditions. For each of the manoeuvres, the SCADS-derived calibrations were applied to the airdata measurements, and the wind was determined from the difference between the measured/calibrated airspeed vector and the GPS-measured groundspeed vector. The mean value of the horizontal wind vector for each wind box leg gives an estimate of the accuracy of the airspeed. Table 4 shows these mean values.

A second verification can be performed by inspecting the calculated wind for correlation with variations in angle of attack and sideslip. Figure 5 shows a minimal correlation in calculated wind with \( \beta \). Attributing all East wind variation (approximately equivalent to body axis lateral wind) to errors in the \( \beta \) calibration results in a worst case error of 0.21° over the range of \( \pm 13.5° \). A similar look at vertical wind variation correlated to angle of attack change produced a maximum angle of attack error of 0.31° over a range of \( \pm 3.5° \).

10.0 CONCLUSIONS

A simultaneous calibration of the airdata system (SCADS) technique was validated using the NRC Bell 206B helicopter. Flight test results from the SCADS technique were compared to other standard calibration methods and matched well. The following specific conclusions can be reached:

- Calm weather conditions are preferable for the calibration of a helicopter airdata system.
- The SCADS technique provides better efficiency and accuracy than previous FRL methods.
- The SCADS method provided an airspeed calibration to within 0.75 Knots, and airflow angle calibrations to within 0.31° for \( \alpha \) and 0.21° for \( \beta \).

The aircraft instrumentation included a swivelling pitot-static noseboom with airflow vanes, a NovAtel DGPS and inertial sensors. The aircraft was flown in a wind box pattern with gradual beta sweeps and in an acceleration/deceleration fashion. The initial airdata aerodynamic model was devised from the empirical formulation based on the position error characteristics, noseboom airflow modelling, and atmospheric analysis for an airdata calibration. The SCADS technique allowed a simple and accurate calibration of aircraft PEC and airflow angles. This technique was validated by modelling the Bell 206B helicopter airdata system in the IAS range of 40 to 110 Knots.

11.0 ACKNOWLEDGMENTS

We wish to acknowledge the contributions of Stephane Carignan, pilot of the NRC Bell 206B helicopter, who performed and developed the flight test procedures which ensured an integer ambiguity solution for the GPS.
12.0 REFERENCES


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