Investigation Of Global Positioning System Use For Air Data System Calibration

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Abstract ----- This paper is based on the results of flight testing on the air data systems of two general aviation aircraft performed by the USAF Test Pilot School [1]. The objective was to compare data collected from commercial GPS receivers to data from classical pitot-static calibration flight test techniques. The results showed that GPS receivers can be used for air data system calibrations even with selective availability active.

INTRODUCTION

Aircraft performance testing has always made up a large portion of developmental flights. Although flight testing the integrated avionics systems on board may validate the mission suitability of the aircraft, initial flight tests normally deal with the traditional questions of how fast and how high. A critical part of determining such airspeed and altitude performance is the calibration of the air data system (ADS). Usually the air data system consists of a pitot-static system with one instrument measuring the total pressure on the aircraft and another instrument measuring the static pressure. For general aviation aircraft, the ADS may consist of a pitot tube under the wing and a static source flush with the fuselage. On aircraft with complex shapes, like the B-2 bomber, a computer calculates the total pressure using a series of static pressure ports.

For some simple ADS designs, the error in the system can be considered negligible. However, the placement of the static pressure ports may cause enough of an error to provide inaccurate airspeed and altitude readings. If the errors are not found and accounted for, performance data will also be in error. Several flight test methods can be used to determine the static pressure source position error. The methods compare aircraft airspeed and altitude with airspeed and altitude truth sources. Some of the classical truth sources include the flyby tower, pacer aircraft and the ground speed course, while other modern sources include radar, laser and cinetheodolite tracking. The drawback to some of the modern truth sources is the time and expense to gather and reduce the data.

To avoid some of that expense the F-22 Combined Test Force asked the USAF Test Pilot School (TPS) to investigate using Global Positioning System (GPS) as a truth source. The test team performed an ADS calibration of an F-16B using a differential GPS pod [2]. The ADS on the aircraft was calibrated at the Air Force Flight Test Center, Edwards AFB, California, using the both radar and flyby tower assets. While flying with radar tracking or by the flyby tower a differential GPS pod collected position and velocity data. The investigation concluded that unaided GPS precision (P) code receiver data were sufficient to calibrate an F-16B ADS within the accuracy of current truth sources (radar). After those encouraging results and those published by the University of Tennessee Space Institute [3], another team from TPS used both GPS P and coarse acquisition (C/A) code receivers to establish methods and a level of GPS accuracy needed during a calibration of the ADS on a general aviation (GA) aircraft. This paper discusses the results of that investigation.

TEST ITEM AND INSTRUMENTATION

Two different aircraft with two respectively different pitot static systems on were used during this investigation. The Aerospatiale TB 10 Tobago was a low wing, four-place GA aircraft. The production ADS consisted of a pitot tube located under the left wing and flush static sources located on either side of the fuselage. A sensitive airspeed indicator and a
sensitive total temperature probe were installed to improve data accuracy during collection. The Rutan Long EZ was an experimental, pusher-propeller, tandem-seat, swept-wing, forward-canard aircraft. The pitot static system on the Long EZ used an unheated pitot tube in the nose of the aircraft and a flush static port on the left fuselage under the canard. A detailed account of the resolutions and accuracies for the instrumentation on both aircraft can be found in the flight test report [1].

The primary GPS receiver used during flight test was the Garmin GPS AVD 100 manufactured by Garmin International. This portable system could track up to eight satellites on one channel and used Garmin MultiTrac software to calculate the navigation solution. This receiver could only pick up the C/A code from the GPS satellites which resulted in a 100 meter horizontal and 140 meter vertical error. The Garmin could display position, estimated location error, groundspeed along a track, as well as other navigation data [4].

The other receiver used was a portable lightweight GPS receiver (PLGR+) made by the Collins Avionics Division of Rockwell Aerospace. The PLGR+ could receive the encrypted precision code for improved geometric position accuracy. This receiver was used because it conservatively simulated the accuracies predicted for the Wide Area Augmentation System (WAAS), scheduled to be operational by 2001 [5]. The published accuracy for the PLGR+ was 21 meters horizontally and 28 meters vertically. The unit was a five-channel receiver that automatically picked the best four satellites to calculate a position solution. However, the PLGR+ received only the L1 frequency from the GPS satellites which increased the error from ionospheric effects as compared to a two-frequency receiver. The receiver could also display position, groundspeed along a track, estimated location error, as well as other navigation data [6].

**TEST PROCEDURES**

The TB 10 Tobago was flown using two low altitude flight test techniques (FTTs) to collect data for an ADS calibration. In addition, an all-altitude airspeed comparison technique was developed to collect calibration data using a portable, civil GPS receiver. During all flights the TB 10 was flown in the cruise configuration with flaps retracted and pitot heat in the OFF position. In the final phase of the project, the all-altitude velocity comparison method was used to calibrate the ADS of a Long EZ aircraft. The Long EZ was also flown in the cruise configuration with nosewheel and landing brake retracted.

The first phase of flight testing consisted of using the altitude comparison method or tower flyby (TFB) FTT and the groundspeed course (GSC) FTT to collect pitot-static data on the TB 10. The aircraft was flown past the flyby tower at approximately 10 knot increments over a range of 70 knots indicated to the maximum velocity attained in level flight. Data tolerance required the aircraft to be climbing or descending less than ± 50 feet per minute and at least one wingspan (32 feet) above the ground. Theodolite data were used along with pressure altitude readings in the tower and the aircraft to calculate static position error corrections.

During the flyby tower passes altitude data from GPS receivers in the aircraft and the tower were collected. A pair of commercially available Garmin GPS 100s were used to collect C/A code data, while a pair of PLGR+ receivers provided data using the P code. The GPS receivers were used in accordance with relative GPS theory which states that two receivers in different locations, looking at the same satellites would provide an accurate measurement of the distance between them [7]. The difference in altitude measurements from the GPS receivers in the aircraft and the tower provided the same function as the theodolite in the flyby tower.

For slower velocity aircraft, the GSC usually provides more accurate data for the calculation of velocity static position error correction compared to the flyby tower. This project attempted to use that advantage by flying the TB 10 over the four statute mile course at approximately 10 knot increments over a range of 70 knots indicated to the maximum velocity in level flight. By flying both up and down the course, distance over time measurements were used to calculate an average ground velocity. The ground velocity was then assumed to be the aircraft true velocity through the airmass. The true velocity could then be used with indicated altitude, velocity and temperature measurements to determine the static position error.
During the GSC runs, the two different types of GPS receivers were used to provide a groundspeed from the Doppler shift of the GPS signal [8]. The GPS groundspeed was also assumed to be the true velocity and was used in the calculation of the static pressure source position error. This assumption was possible since data tolerances were: airspeed within ±1 knot indicated over a one mile section of the course, altitude higher than one wingspan above the ground and winds less than 10 knots.

The second phase of testing provided a way to collect data for an ADS calibration without the need for external facilities like a flyby tower or a surveyed ground course assuming that the GPS groundspeed could be used as the truth source. After validating GPS data as a truth source, the all-altitude airspeed comparison method was flown at 5,000 and 10,000 feet pressure altitude (PA).

Basically, this technique came down to determining the direction of the winds aloft and then flying perpendicular to the winds. The critical parameter needed during this method was true velocity with wind effects reduced as much as possible. The only data available from the GPS receivers were groundspeed and groundtrack. The difference between the heading flown and the track gave an indication of wind direction and crosswind magnitude. The difference between the GPS groundspeed and a calculated true velocity gave an indication of head or tailwind magnitude.

A straightforward approach was used to determine the winds aloft using the GPS receiver data. The forecasted winds aloft at 5,000 or 10,000 feet were first corrected to magnetic heading and were assumed to be correct. A true airspeed was calculated based on the outside air temperature and indicated airspeed. The Tobago was then flown in a slow turn starting parallel to the direction of the wind at the specified altitude and airspeed until the GPS groundspeed was equal to the calculated true airspeed. The aircraft was then rolled level, groundspeed noted and then flown on the reciprocal heading. The GPS groundtrack and groundspeed were compared for the two directions. If the aircraft was flown perpendicular to the wind, the groundspeeds would be equal and the absolute difference between the groundtracks and headings flown would be equal. If that data were different, the general direction of the wind could be determined from the data and the heading corrected. To prevent infinite iterations, a difference of five knots in groundspeed between the two directions was determined to be acceptable [1].

The all-altitude technique could also be thought of as a variation on the groundspeed course method. The groundspeed course requires flying back and forth along the course to find groundspeed. That groundspeed corrected for drift angle was assumed to be true airspeed and then the two passes averaged. At altitude, flying perpendicular to the wind minimizes the head and tailwind components allowing the assumption that groundspeed corrected for drift was true airspeed. The final true airspeed was determined by flying the direction normal to the wind for a one minute period and along the reciprocal heading then averaging the groundspeeds. The one minute of data collection provided a sanity check to verify that the winds were not varying greatly in magnitude or direction.

For this method data tolerances were: altitude within 100 feet of the goal altitude, airspeed within ±1 knot indicated of the goal and within two degrees of the desired heading during a test point. If the GPS groundspeed varied more than five knots during a run or the track varied more than five degrees the data were discarded.

The final phase of flight testing was performed on a Rutan Long EZ to validate the portability of the technique to other GA aircraft and compare calibration results from an earlier US Army flight test program. The Army performed a partial airspeed calibration of a Long EZ using the pacer aircraft method. An ADS calibration was conducted at 4,000 and 10,000 feet PA using the all-altitude airspeed comparison method described in the previous paragraphs. The aircraft was flown over a velocity range of 80 knots indicated to the maximum velocity in level flight. Data tolerances were: altitude within ±100 feet of the goal altitude and airspeed ±1° of the desired heading during a test point.

Data reduction was accomplished using the standard pitot-static equations found in Herrington’s Flight Test Handbook [9]. Data were entered into a spreadsheet after each flight and the embedded equations automatically calculated and plotted the static pressure source position error. The primary goal for data reduction routines was for them to be simple and portable.
RESULTS AND CONCLUSIONS

In this section the results and analysis of the data gathered for each method will be discussed in turn. Within each section, a general conclusion is made about the feasibility of using commercial GPS receiver data as part of an air data system calibration. The results from the flyby tower indicate that the data from the commercial receivers were not as accurate as the flyby tower theodolite. However, other commercial receivers with differential or carrier phase tracking abilities would be more accurate. The groundspeed course results were encouraging enough to use GPS groundspeed data as a truth source. In the final phase of flight testing, the all-altitude airspeed comparison method worked well enough to be used in place of the flyby tower and groundspeed course. In summary, coarse acquisition coded, commercial GPS receiver data were satisfactory for the purpose of ADS calibrations on general aviation aircraft.

Tower Flyby

The altitude position error correction determined from both GPS and flyby tower theodolite are presented in Figure 1. The data measured with the P code receiver compared somewhat favorably with data from the flyby tower. The published altitude position error correction uncertainty for the TFB was ± 26 feet [10]. That value was the approximate scatter of the data shown in Figure 1. The scatter from the P code receiver was on the same order as flyby tower data but the results from the C/A code data were much more dispersed.

Both coarse acquisition and precision coded GPS receiver data were used to determine a height above the flyby tower during this altitude comparison method. The commercially available C/A code receiver was not as accurate as the flyby tower theodolite. Although the receiver in the aircraft and the tower were used according to relative GPS theory, the user segment / receiver errors were well above that of the flyby tower theodolite. Therefore, the C/A code receiver was not suitable for determining the altitude position error correction for the Tobago ADS via the altitude comparison method. As stated before, the P code data produced a height above the tower which was comparable to the theodolite.

One possible explanation for the variety of data seen in Figure 1 might have been the inability of both of the similar receivers, one in the aircraft and the other in the tower, to use the same satellites in the same way. Thus, the relative GPS theory assumption that both receivers were using the same satellites to calculate a navigation solution was in error. In conclusion, the C/A coded receiver data were not suitable for use in the altitude comparison method. However, increasing the accuracy of GPS altitude measurements could render a flyby tower obsolete.

Several easy fixes are available for increasing the accuracy of GPS altitude measurements. Most involve buying GPS receivers with more capabilities. Using GPS receivers equipped to receive differential corrections or process carrier wave data are a couple of choices. Another method, using a suitable receiver and compatible computer could allow post-processing of the GPS data so that both receivers are using the same satellites at the same time to compute altitude. With an increase in altitude measurement accuracy using one of the choices above, the altitude comparison method may be possible without the need for a flyby tower.

Groundspeed Course

The groundspeed course provided the most promising results for use with GPS. During the early morning flights with calm winds, the aircraft predicted true velocity was comparable to the GPS groundspeeds.

The C/A and P code receivers provided groundspeed data while flying over the Air Force Flight Test Center groundspeed course. Even though selective availability was active, the C/A code and P code receiver groundspeed values were always comparable. The measured groundspeeds from the receivers were always within one knot of each other. Based on that velocity accuracy, only the commercial C/A code receiver data were used for comparison to the GSC data.

The GPS groundspeeds were also comparable to the groundspeed calculated from the distance and time flown over the groundspeed course. Therefore, when the position error corrections were calculated from the groundspeed course data, the data from the GPS and distance over time measurements produced similar scatter bands.
The results from the GSC runs are shown in Figure 2. The TB 10 was flown over the course to collect at least six points per airspeed from 70 to 120 knots indicated. The velocity and altitude static pressure source position error corrections derived from the GPS groundspeed data were comparable to those found from the distance over time data from the GSC for both velocity and altitude position error corrections. When Figures 1 and 2 are compared, the scatter between the GSC and GPS data was much less than scatter between the TFB theodolite and GPS data.

The groundspeeds obtained from the Doppler shift of the GPS signals were accurate enough to provide static pressure source position error correction curves without the need of a groundspeed course or other support aircraft as long as wind effects are minimized. The accuracy was also good enough to allow the GPS groundspeed to be used as a velocity truth source.

**All-Altitude Method**

The results from the all-altitude airspeed comparison method in the TB 10 are presented in Figure 3. Based on the results of the GSC testing, the GPS groundspeed data was considered to be the measurement truth source. In the plot of velocity position error correction, no breakout can be seen for the altitudes flown. The lack of a breakout indicated negligible pressure field effects around the side fuselage static ports at the two altitudes.

The final phase of flight testing calibrated the air data system of a Long EZ. A partial airspeed calibration was performed by the US Army on a Long EZ with a similar pitot-static system. The Army data was collected via a pacer aircraft. That allowed even another comparison of the GPS data with a classical FTT. The velocity correction results shown in Figure 4 were compared to a limited ADS calibration performed by the Army on another Long EZ with a similar pitot static system [11]. The data follow the same trend showing that the Long EZ requires notable corrections at the slow end of its envelope. More importantly, the comparison validates the GPS technique since the GPS results closely match the Army results.

In addition to the comparison to the Army data the all-altitude airspeed comparison method was used to calibrate the Long EZ ADS at 4,000 and 10,000 feet PA. Comparison of the altitude and velocity position error corrections at 4,000 and 10,000 feet PA indicated negligible pressure field effects. The all-altitude airspeed comparison method developed for and used in this project was determined to be adequate for calibrating the ADS of general aviation aircraft.

**IMPACT ON FLIGHT TESTING**

The impact of using GPS for future performance flight testing is not small. Both GA and military flight testing can benefit from the results presented here. For the experimental aircraft builder, pitot-static designs for kit aircraft are not always the standard seen on production GA aircraft. Some designs create a situation, as seen here with the Long EZ data, where airflow adversely affects the static pressure source during critical phases of flight. Data from GPS receivers can be used to identify how far an airspeed indicator or altimeter might be in error during landing or at high angles of attack.

With current state of the art receivers using differential or carrier phase tracking capabilities, future high performance aircraft can use the methods presented here and in Reference 2 to reduce flight test costs incurred from ground support equipment such as tracking radars and flyby towers. Even without the differential or carrier phase corrections, this GPS method has been recently considered for possible use on unmanned aerospace vehicles (UAVs) and cruise missiles. If feasible the GPS method would allow those platforms to calibrate their air data systems without the need for pacer aircraft or radar tracking. In addition this method has been considered for possible use with USAF Academy and US Coast Guard motor gliders for spot checking the pitot-static errors in various phases of flight.

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Figure 1 Tobago Altitude Correction Comparison of Flyby Tower and GPS Data

Figure 2 Tobago Velocity Correction Comparison of Groundspeed Course and GPS Data
Figure 3 Tobago Velocity Position Error Correction

Figure 4 Comparison Between Army Pacer and GPS Data