ASSESSMENT OF A NON-DEDICATED GPS RECEIVER SYSTEM FOR PRECISE AIRBORNE ATTITUDE DETERMINATION

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ABSTRACT

The use of a non-dedicated GPS receiver system for attitude determination was assessed in airborne mode through a test conducted at Sandia National Laboratories. Four independent NovAtel GPSCard™ receivers were installed in Sandia's Twin Engine Otter with two antennas mounted on the fuselage and two on the wing tips at separations of 6 to 18 m. A strapdown INS *was* also on board the aircraft in order to provide an independent attitude reference at rates between 4 and 10 Hz. During the multi-day test, GPS measurements were recorded between 1 and 10 Hz. Carrier phase measurements were post-processed using a double difference approach developed at The University of Calgary in which integer ambiguities were resolved in seconds using the known antenna separations as constraints. The tracking capability of the system is demonstrated under dynamics consisting of roll and pitch angles up to 45 and 12 degrees, respectively. Comparisons between the GPS and INS attitude angles are presented for two of the test days and show agreement at the several arcminute level. Conclusions are made with respect to system accuracy and performance in an operational airborne environment.

INTRODUCTION

The ability of GPS to provide accurate attitude components has been demonstrated using several platforms and a variety of operational conditions. Many of the tests that have been conducted to date utilize a dedicated attitude determination system comprised of a multichannel receiver which has a bank of channels dedicated to each of the supported antennas, which is typically four (e.g. Ferguson et al., 1991). The advantage of this type of system is that all channels are driven from the same oscillator which means that all carrier phase measurements have a common clock offset to provide an additional degree of freedom in the determination of attitude. Results using these dedicated attitude determination systems show that arcminute-level accuracies can be achieved depending on antenna separation, e.g. van Graas and Braasch (1991), Cohen and Parkinson (1992) and Schade et al. (1993).

An alternative to the above is to use a non-dedicated attitude determination system comprised of three or more independent GPS receivers mounted on the platform. One advantage of such a system is flexibility since the receivers can be used for a variety of applications in addition to attitude determination, e.g. Sun (1994). Cost-effectiveness may also be gamed through the utilization of low-cost GPS receivers which output the carrier phase observable. Marine tests conducted with this type of system confirm an achievable accuracy of 1 to 2 arcminutes for antenna separations of up to 40 m (Lachapelle et al., 1994) and several arcminutes for shorter separations (Lu et al., 1993; McMillan et al., 1994).

The objective of this paper is to assess the performance of a non-dedicated GPS attitude determination system in an operational aircraft environment. Comparisons are made between GPS attitude components and those obtained from an INS which was also installed in the aircraft.

TEST DESCRIPTION

A series of flight tests were conducted by Sandia in early February, 1994 near their facility located on Kirtland Air Force Base in Albuquerque, New Mexico. The tests used a DeHavilland Twin Otter aircraft operated for Sandia by the Department of Energy's Ross Aviation. The Twin Otter has been used for a variety of navigation and radar flight tests and is equipped with flight racks that can house computer and navigation equipment. For this series of tests, three single frequency GPS antennas were installed on the aircraft, one on each wing and one near the tail, in addition to the dual frequency GPS antenna already in place just aft of the cockpit. The locations of the four GPS antennas, as measured by a theodolite, are shown in Figure 1.

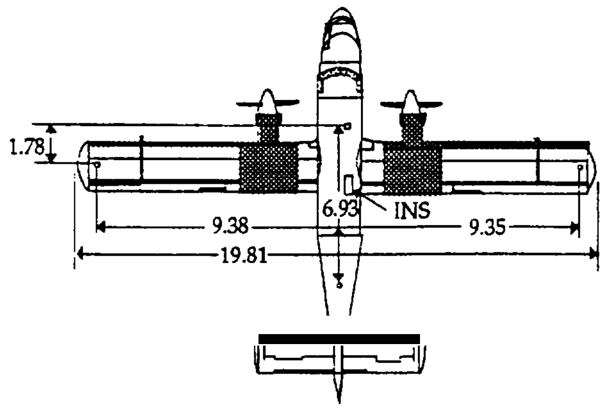

Figure 1
Aircraft Antenna Locations

The suite of test equipment included: 1) six Novktel GPSCard™ receivers, each housed in a portable personal computer, four in the aircraft and two on the ground; 2) a Honeywell ring laser gyro assembly (RLGA) inertial measurement unit (IMU); 3) a Sandia Airborne Computer (SANDAC) to implement the navigation equations; and 4) a Texas Instruments (TI) embedded P-code GPS receiver integrated with the SANDAC. The RLGA IMU and SANDAC were mounted on the floor of the aircraft just forward of the main cabin door, see Figure 2. The RLGA has long term drift rates commensurate with 1 to 2 nautical miles per hour navigation accuracy, with individual gyro specifications of: 0.01 deg/hr bias, random walk less than 0.008 $deg/\sqrt{h}$ and scale factor less than 1 part-per-million.

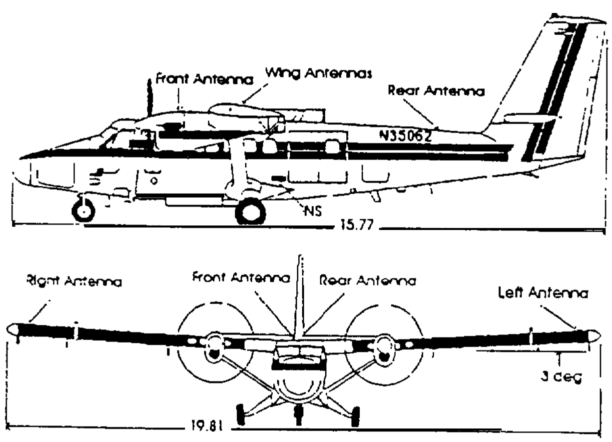

Figure 2
Aircraft Installation

Four portable computers containing the GPSCards™ were mounted in the flight racks, with each receiver connected to one of the four GPS antennas. The TI embedded P-code receiver was connected to the dual frequency forward fuselage GPS antenna in parallel with one of the NovAtel receivers. The Tl receiver's 1 pulse per second interrupt was used to time tag the SANDAC/RLGA navigation and attitude measurements to GPS time to an accuracy of a few milliseconds.

Two NovAtel ground station receivers were set up for kinematic testing purposes, e.g. Sun (1994). One antenna was mounted on an airport hangar while the second was set up at a surveyed benchmark approximately seven kilometers from the airport. These sites are indicated on Figure 3.

A static test was performed in order to compute the relative positions between the four aircraft antennas. Four flight tests were conducted as part of this experiment and two were selected for attitude post-processing. The test characteristics for these days, herein denoted as Day 3 and Day 4, are given below.

Day 3 Flight Test: Several high dynamic maneuvers were undertaken and midway into the flight, the airborne receivers were intentionally shut down and re-booted to assess the in-flight acquisition performance and to collect data to look at in-flight on-the-fly ambiguity resolution for kinematic positioning. GPS data was logged at 10 Hz and IMU data was logged at 10 2/3 Hz. The flight trajectory that was used in the analysis is shown in Figure 3 which indudes the first part of the flight before the intentional shutdown. Roil, pitch and heading as estimated from GPS are shown in Figure 4. Pitch varied from 0 to 12 degrees while roll maneuvers were in the -30 to +20 degree range. The number of satellites tracked ranged from 4 to 7 during the segment of flight data that was analysed.

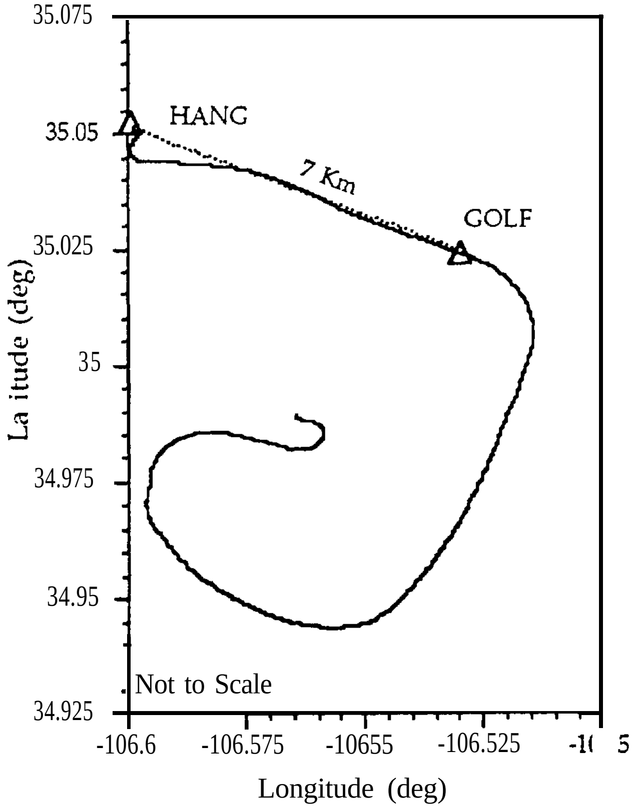

Figure 3
Aircraft Trajectory on Day 3

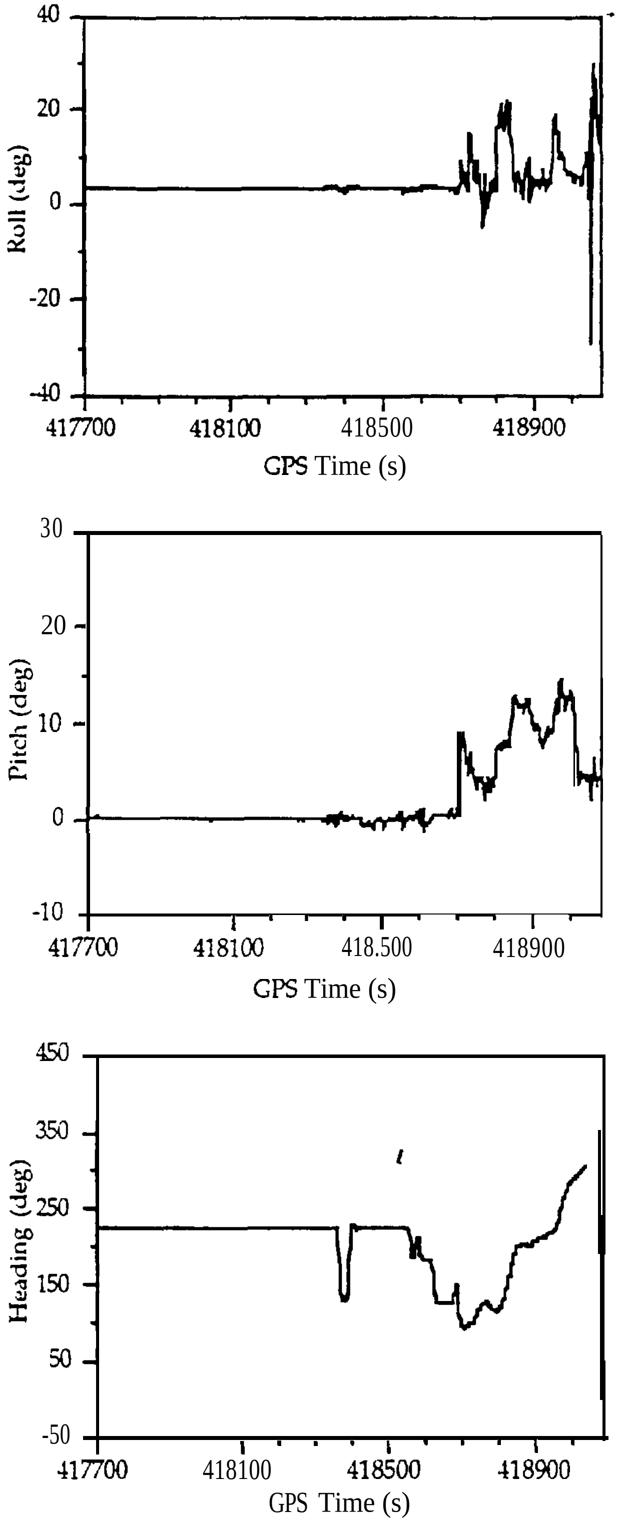

Figure 4
Aircraft Roll, Pitch and Heading on Day 3 Estimated from GPS

Day 4 Flight Test For this test, the aircraft operated using low dynamic flight parameters. The flight's purpose was primarily to test the kinematic position performance over long baselines with multiple monitor stations and multiple aircraft receivers and antennas. GPS data was logged at 5 Hz and IMU data was logged at 8 Hz. The flight trajectory is shown in Figure 5 and the GPS attitude components are given in Figure 6. In this test, aircraft roll ranged from 40 to +45 degrees and pitch ranged from -5 to +12 degrees. Four to eight satellites were observed during the mission.

The flight tests also included 30 to 45 minutes of static data before a flight and 20 to 25 minutes after a flight. After each day's flight test, the data was recovered from the aircraft and monitor station computers and a "quick look" was done during the evening to insure that the data was acceptable and a decision was made as to whether to proceed to the next day's objectives. During the data collection, all the GPS receivers, the IMU, and SANDAC performed well, with the only casualty being a hard disk drive that failed on one of the aircraft portable computers just before a takeoff, causing a short delay until it was replaced.

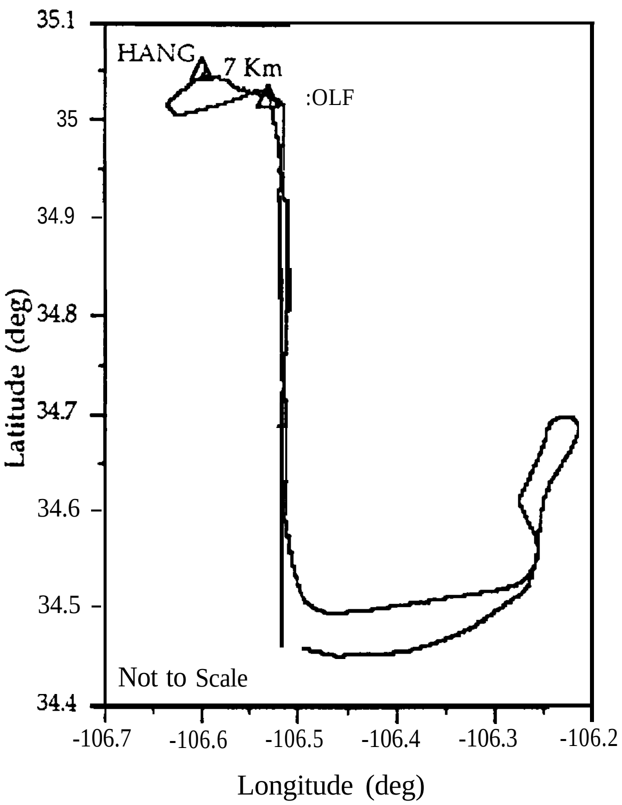

Figure 5
Aircraft **Trajectory on Day** 4

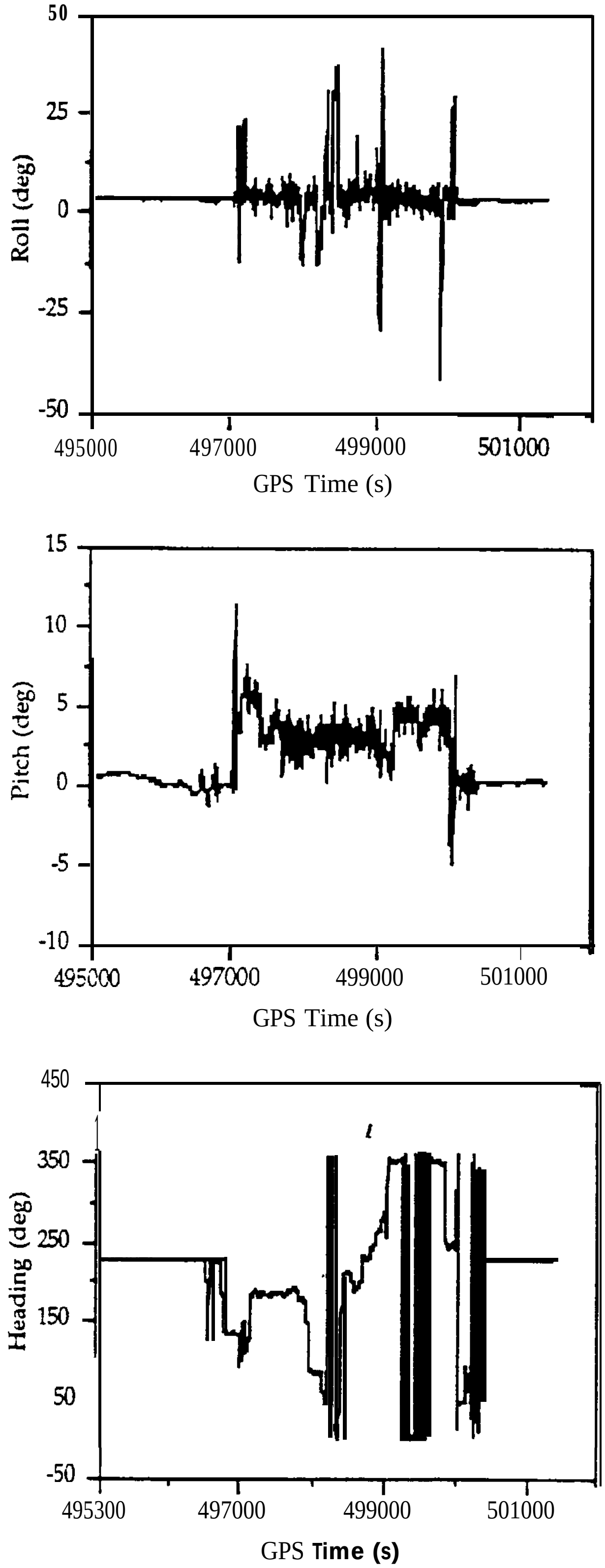

Figure 6
Aircraft Roll, Pitch and Heading on Day 4 **Estimated from GPS**

METHODOLOGY

GPS Attitude Estimation

The GPS data was processed using The University of Calgary's MULTINAV™ software program which estimates roll, pitch and heading using carrier phase measurements from three or more antennas. The body frame, which is needed for definition of the aircraft attitude, was realized by three antennas, namely the aft, forward and port antennas. These are shown on Figure 7 below.

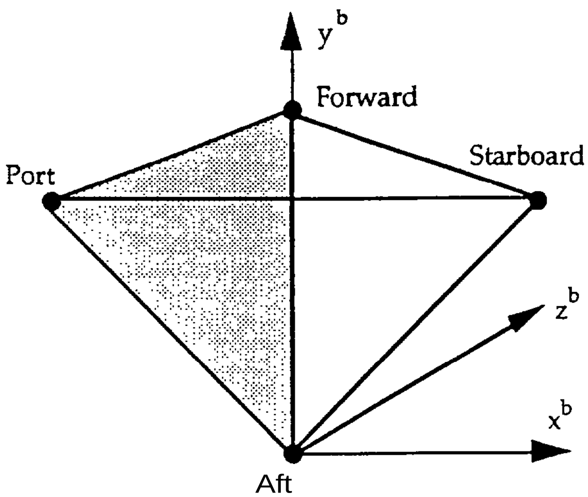

Figure 7
Body Frame Defined by GPS Antennas

The body frame can be measured directly using a theodclite cr can be determined by GPS initialization, which is typically more convenient. In the present case, the body frame was determined through a two hour static GPS survey when the aircraft was located on the tarmac prior to take-off. The resulting body frame coordinates are shown in Table 1. Distances between the GPS antenna pairs were estimated to about the 1 cm level and were used as constraints in the **attitude** determination algorithm to eliminate incorrect carrier phase integer ambiguities during the **search phase.**

Table 1
Antenna Body Frame Coordinates

Antenna	x (m)	y (m)	z (m)
1 (aft)	0.0000	0.0000	0.0000
2 (forward)	0.0000	6.9222	0.0000
3 (port)	-9.5141	4.8085	0.0000
4 (starboard)	9.1555	5.5115	0.9335

Attitude components, i.e. roll, pitch and heading, are estimated via a least squares approach using the interstation vectors between antennas as quasi-observables. Suppose $r_i^b = (x_i^b, y_i^b, z_i^b)^T$ are the body-frame coordinates of the i-th antenna which were previously estimated. The measurements are $r_i^n = (x_i^n, y_i^n, z_i^n)^T$, the local level coordinate of the i-th antenna, which are determined from the differential GPS carrier phase solution. These coordinates satisfy the following equation

$$\begin{pmatrix} r_2^b \\ r_3^b \\ r_4^b \end{pmatrix}^T = R_n^b(\varphi,\theta,\psi) \begin{pmatrix} r_2^n \\ r_3^n \\ r_4^n \end{pmatrix}^T \qquad (1a)$$

where $R_n^b(\varphi,\theta,\psi)$ is the transformation matrix between the body-frame coordinates and the local-level frame coordinates, and

$$R_n^b(\varphi,\theta,\psi) = \qquad (1b)$$

$$\begin{pmatrix} c(\psi)c(\varphi)-s(\psi)s(\theta)s(\varphi) & s(\psi)c(\varphi)+c(\psi)s(\theta)s(\varphi) & -c(\theta)s(\varphi) \\ -s(\psi)c(\theta) & c(\psi)c(\theta) & s(\theta) \\ c(\psi)s(\varphi)+s(\psi)s(\theta)c(\varphi) & s(\psi)s(\varphi)-c(\psi)s(\theta)c(\varphi) & c(\theta)c(\varphi) \end{pmatrix}$$

where c() is a cosine function and s() is a sine function. When there are three antennas on the platform, a unique solution is generated, whereas a fourth antenna provides redundancy. These equations can be solved using a least squares adjustment model by minimizing the cost function

$$J(\varphi,\theta,\psi) = \left\| (r^b - R(\varphi,\theta,\psi) r^n \right\|^2 \qquad (2)$$

The least squares method has many advantages over other methods such as a direction computation of attitude (Lu **et al.,** 1993). It can easily accommodate more antennas and attitude is less effected by multipath from a single antenna since it is based on a least squares fit of all antenna positions.

Further details on the methodology used in the attitude determination algorithms **are** given in Lachapelle et al. (1994) and Lu (1994).

Wing Flexure Modeling

Due to wing flexure of the aircraft, the body-frame defined above is not a fixed rigid body frame. Since the frame is changing with the wing flexure, the derived attitude is relative to a different coordinate frame. In order to obtain attitude with respect to one fixed coordinate frame, the wing flexure has to be removed before attitude is computed. A wing flexure model was considered here. Wing flexure is constrained in the z- component in **the** body frame. That is

$$r_i^b = r_i^{b0} - B_f f \qquad (3)$$

where

$$Bf = (0,0,1)^T \qquad (4)$$

and f is a scalar amount which is estimated in the least square adjustment.

When considering all four antennas, the body frame coordinates and the local level coordinates should satisfy the following relation

$$\begin{pmatrix} r_2^b \\ r_3^b \\ r_4^b \end{pmatrix}^T = \begin{pmatrix} r_2^{b0} \\ r_3^{b0} \\ r_4^{b0} \end{pmatrix}^T - \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 1 & 0 & 1 \end{pmatrix} f \ . \qquad (5)$$

The solution is obtained by minimizing the cost function

$$J(\varphi,\theta,\psi,f) = \left\|(r^{b0} - Bf) - R(\varphi,\theta,\psi)r^n\right\|^2 . \qquad (6)$$

Refer to Cohen et al. (1993) for a similar approach to flexure modeling.

INS Attitude Reference

The INS attitude parameters were collected to provide a reference for the analysis of the non-dedicated GPS attitude system. Roll, pitch and heading which were output from the real-time navigation filter were used for this purpose. The accuracy of the roll and pitch reference values are at the level of 1 arcminute given the system installed on the aircraft, whereas the heading accuracy is accurate to 4-5 arcminutes. It should be noted that the heading error is generally a bias and is removed when comparison with the GPS heading is done by the development of a rotation matrix as discussed below.

GPS - INS Comparison Strategy

In order to compare the GPS and INS attitude parameters, errors in the alignment of one system with respect to the other must be taken into account. These misalignment errors are inevitable **due to the difficulties in mounting the systems in the aircraft.**

The rotation matrix that represents the mounting error is R_I^G which is the rotation required to transform the INS attitude parameters to the GPS body frame. It is computed as

$$R_I^G = R_I^n R_n^G \qquad (7)$$

where R_I^n is the INS to local level transformation which can be formed using the INS output attitude parameters while R_n^G is the local level to GPS body frame transformation matrix which can be formed using attitude parameters computed from the GPS multi-antenna system. The matrix RF is determined at each epoch **of the** flight data and then a mean transformation for the mission is determined. This transformation matrix was determined separately for each flight, however the agreement between the two days is at the 10 arcsec level which verifies the comparison strategy

Results presented below are therefore the remaining differences between GPS and INS once the above rotation matrix has been applied. A similar implementation of Equation (7) for GPS and INS comparisons can be found in Lachapelle et al. (1994).

WING FLEXURE RESULTS

In order to assess the impact of wing flexure modeling, comparisons are first made between the INS and GPS attitude parameters without the model being applied. Data from Day 4 was selected for this analysis.

Figure 8 gives the difference4 in roll, pitch and heading between the two systems for the entire mission. Results for the pitch and heading components are generally centered around zero, while the roll differences exhibit two clear discontinuities. Correlating these discontinuities with the vertical velocity profile in Figure 9, it shows that they occur when the aircraft takes off and lands and thus is most likely due to wing flexure. **Due** to the low **correlation of wing flexure** versus pitch and heading, no significant effects **are** present.

The GPS attitude data was then re-processed with the flexure model implemented. Estimated wing flexure from the model is shown **in** Figure 10 and demonstrates flexure at the level of 12 cm. The plot in this figure is highly correlated to the roll differences shown in Figure 8, which confirms that the discontinuities are in fact due to flexure.

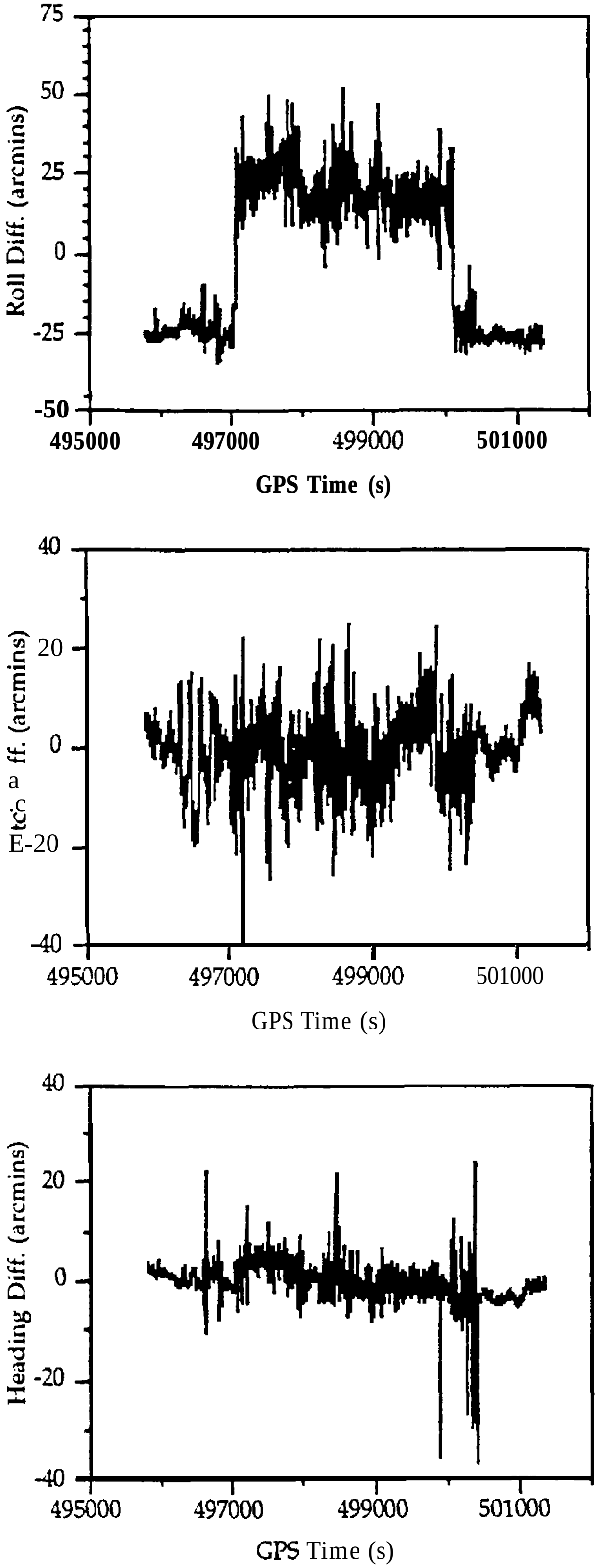

Figure 8
GPS-INS **Attitude Differences on Day 4**
without Wing Flexure Model

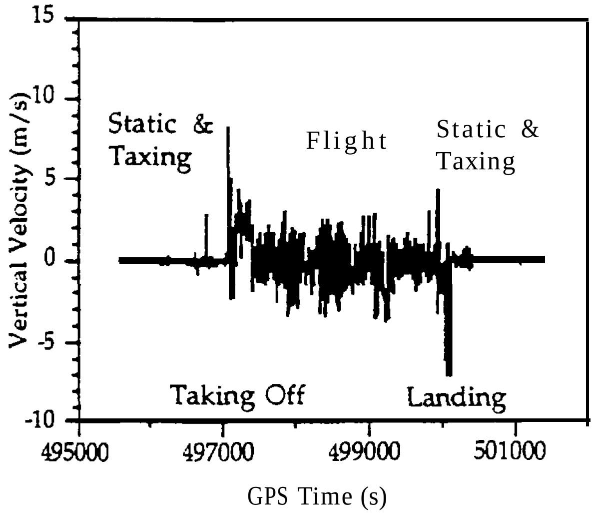

Figure 9
Vertical Aircraft Velocity on Day 4

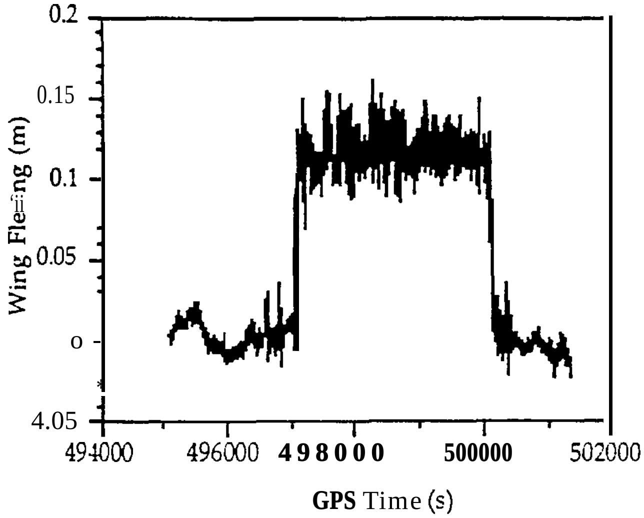

Figure 10
Estimated Wing Flexure on Day 4

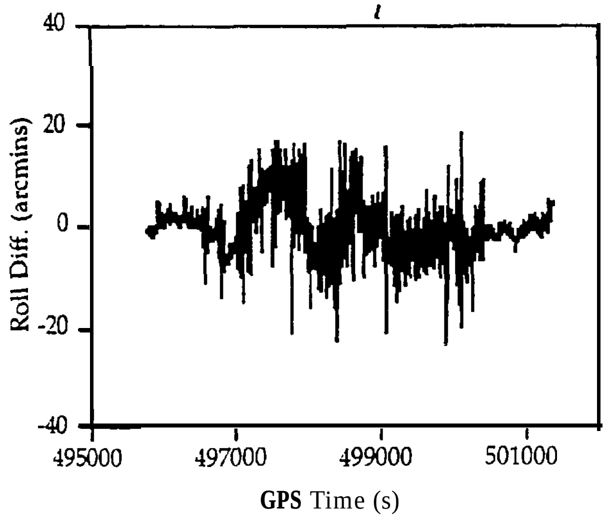

Figure 11
GPS-INS Roll Differences on Day *4*
with **Wing Flexure Model**

A comparison of the re-processed roil component with wing flexure removed is plotted in Figure 11. The discontinuities are eliminated and the remaining errors are thus carrier phase noise and multipath. The effect of multipath has an amplitude of 10-12 arcminutes in terms of roll. These results, along with those obtained for the Day 3 test are discussed in further detail below.

GPS-INS AGREEMENT

From Figure 11, the most significant remaining errors are the carrier phase noise as well as mulitpath. Additional errors are due to high frequency wing vibration and small time tagging errors between the GPS and INS systems.

Figure 12 shows the estimated wing flexure for the Day 3 test. At approximatelt 418700 s the aircraft takes off and the wings flex about 10 to 12 cm as in the Day 4 case.

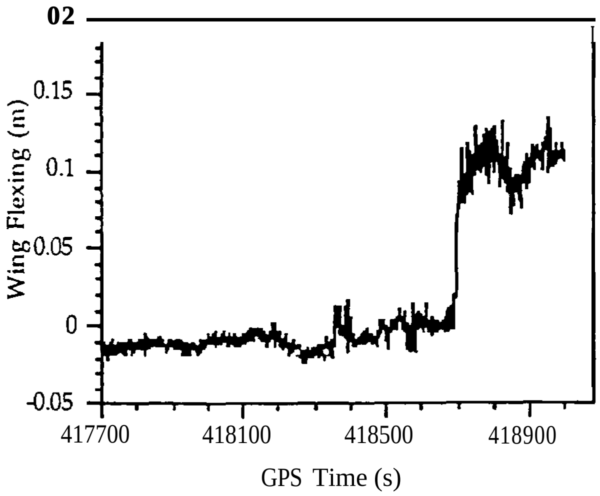

Figure **12**
Estimated Wing Plexure on Day 3

Plotted in Figure 13 are the GPS versus INS differences with the wing flexure model applied. As in the Day 4 results, remaining errors are most likely due to noise and multipath. At time 418350 s there is a fluctuation in the agreement at the level of +/- 20 arcminutes which occurs when the aircraft makes a sharp turn on the ground before take-off. A similar phenomenon occurs in the Day 4 results at time 500400 s after the aircraft lands (see Heading plot in Figure 8). This also coincides with a sharp turn on the ground after landing.

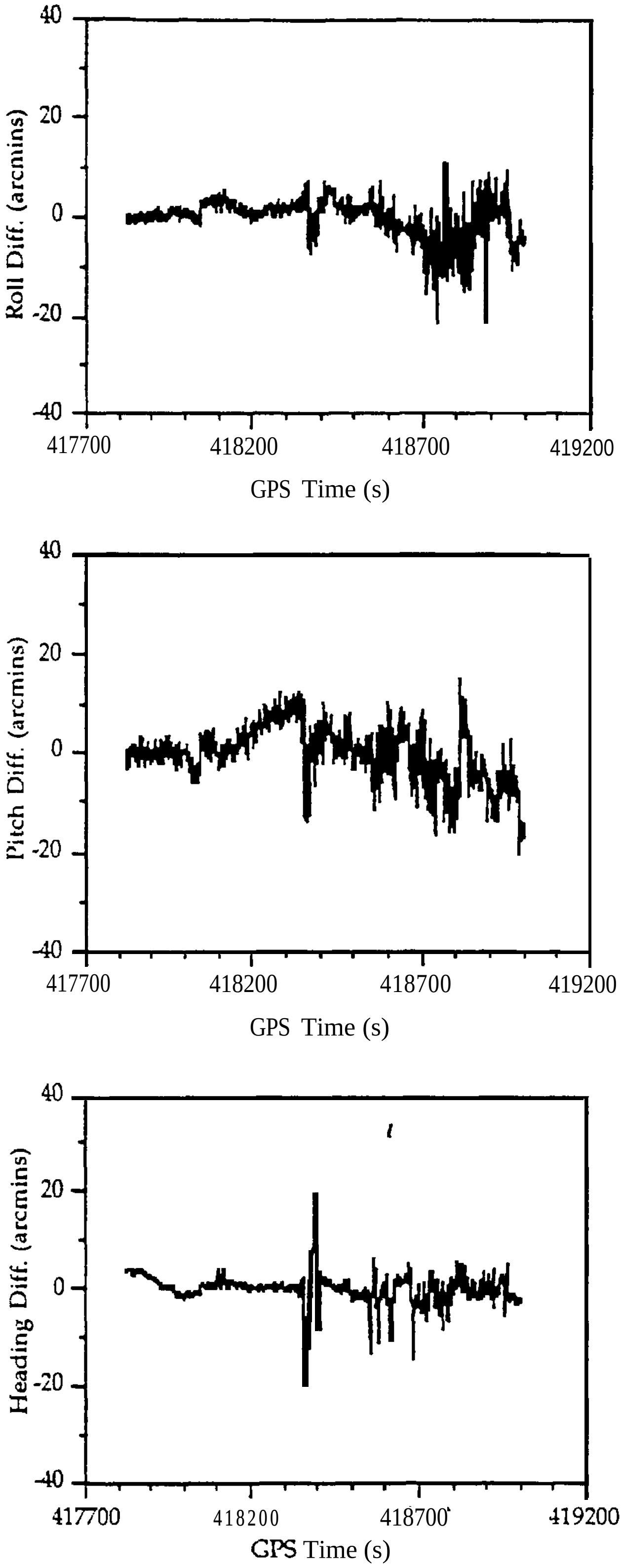

Figure 13
GPS-INS Differences on Day 3 with Wing Flexure Model

Table 2 summarizes the statistics of the GPS-INS differences. Agreement is at the level of 3.1 to 6.6 arcminutes for the three components which agrees well previous results using a nondedicated GPS attitude determination system, e.g. Lu et al. (1993), as well as those obtained from fully dedicated systems, e.g. Schade et al. (1993). Results for the Day 4 test are slightly degraded with respect to those from Day 3 which is due to the shorter flight segment on Day 3 (i.e. more static data is inlcuded in the results).

Table 2
RMS of the Differences Between
GPS and INS Attitude

Session	RAMS (arcrnins)		
	Roll	Pitch	Heading
Day 3	3.6	5.0	3.1
Day 4	5.0	6.6	3.9

CONCLUSIONS

Several flight tests have been conducted using a non-dedicated GPS attitude determination system consisting of four NovAtel GPSCard™ receivers installed in a Twin Otter aircraft. An INS was also mounted in the aircraft to provide an attitude reference at the level of 1 arcminute. Roll and pitch angles ranged from -5 to 12 degrees and -40 to +45 degrees, respectively during the tests.

In order to properly compare the GPS and INS attitude parameters, a wing flexure model was introduced into the GPS model. Flexure was then estimated at each measurement epoch. The most significant effects were found at take-off and during landing when the flexure reached approximately 12 centimeters.

Once flexure was taken into account the agreement between GPS and INS attitude was at the level of 3-7 arcminutes. Given that the distances between the antennas ranged from 7 to 10 m, this level of compatibility agrees with previous flight tests using dedicated systems, as well marine tests using a similar nondedicated approach discussed above.

The advantages of the dedicated approach, is twofold; firstly to provide flexibility in the installation and usage of the GPS receivers, and secondly to provide a cost-effective system which can use emerging low-cost GPS receivers which output the carrier phase observable.

ACKNOWLEDGMENTS

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