FLIGHT TEST RESULTS OF AN INTEGRATED GPS/INS/PSEUDOLITE SYSTEM FOR AIRCRAFT PRECISION APPROACH AND LANDING

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Abstract

The Satellite Navigation and Positioning Group (SNAP) at the University of New South Wales and the DSO National Laboratories, Singapore, have jointly collaborated in the development of an integrated GPS, INS and pseudolite system for aircraft precision approach and landing. Flight tests were carried out in April/May 2003 to study the overall performance, and associated limitations, of such an integrated system. This paper describes the test results, which indicate that: (a) there is significant geometry enhancement in the vertical component, resulting in an improvement in the aircraft's altitude determination; and (b) notable reliability improvement (especially with respect to the external reliability of the vertical component determination).

KEYWORDS: GPS/INS/Pseudolite Integration, Flight Test, Precision Landing and Appraoch

1. INTRODUCTION

The performance of integrated GPS/INS systems relies heavily upon the quality of the GPS measurements and the geometry of the satellite constellation. In most airborne applications, however, there are stringent requirements in terms of positioning accuracy, availability and integrity that cannot always be met. For instance, due to the limited number of GPS satellites, a sufficient number of 'visible' satellites cannot be guaranteed at all times and at all locations. Even when some low elevation satellites are tracked, relatively high atmospheric noise effects contaminate the observations to these satellites. Therefore, such an intrinsic shortcoming of satellite-based navigation systems leads to, for example, poor accuracy in the vertical component, which is approximately three times worse than that of the horizontal components. Research has shown that these drawbacks can be addressed by the integration of GPS with other sensors and/or GPS augmentation using airport pseudolites (Elrod and Barltrop, 1994; Hein et al., 1997)

Airport pseudolites are ground-based GPS-like signal transmitters which can be readily installed wherever they are needed. Hence, a pseudolite-augmented GPS/INS system (i.e., GPS/INS/Pseudolite integration) will be able to improve system performance in terms of availability, accuracy, and integrity under a wide variety of adverse operational scenarios (Wang et al., 2001; Lee, 2002). Availability is increased because the airport pseudolite(s) provide additional ranging source(s) to augment the GPS satellite constellation. Navigation accuracy improvement will occur due to better local geometry, as measured by a lower vertical dilution of precision (VDOP), which is crucial in aircraft precision approach and landing applications. In addition, integrity enhancement is achieved by the additional redundant measurements.

In this paper the issue of the integration of pseudolites with GPS/INS for aircraft precision approach and landing will be discussed. A prototype airport pseudolite has been configured for this application. To evaluate overall navigation performance, flight tests were carried out in April/May 2003 at the Wedderburn Airfield, Sydney, Australia. An overview of the equipment will be first presented. This is followed by a description of the flight tests and the preliminary results.

2. SYSTEM ARCHITECTURE

2.1 Ground Subsystem

A ground subsystem comprises a pseudolite and a ground reference system. The prototype pseudolite consists of a GPS signal generator with low noise amplifier and a rubidium frequency reference clock. The pseudolite signals are generated by a Spirent Communications GSS4100P single-channel signal generator pulsing at a 1/11 duty cycle, with a 10MHz oven-controlled crystal oscillator frequency reference.

The reference station consists of a NovAtel Millennium receiver with Leica AT504 choke-ring antenna, and a wireless data-link transmitter. Note that use of the choke-ring is for the mitigation of GPS/pseudolite multipath. Raw measurements from the GPS/pseudolite signals tracked on the reference receiver are recorded using a laptop computer, simultaneously output over a serial communications interface and broadcast over the wireless data-link.

2.2 Airborne Subsystem

The airborne system comprises two GPS/pseudolite receivers (NovAtel Millennium) including antennas (#1 and #2), a main processor, an Inertial Navigation System (INS) and a wireless data-link receiver/antenna. The INS is the Boeing C-MIGITS II system. The airborne subsystem has two GPS antennas mounted on the aircraft - upward- and downward-looking antennas attached on top and bottom of the aircraft.

3. FLIGHT EXPERIMENT DESIGN

The Satellite Navigation and Positioning (SNAP) group at The University of New South Wales (UNSW) and DSO National Laboratories, Singapore, carried out flight tests at Wederburn Airfield, Sydney, in April/May 2003. Figure 1 illustrates the setup of the ground subsystem around the runway.

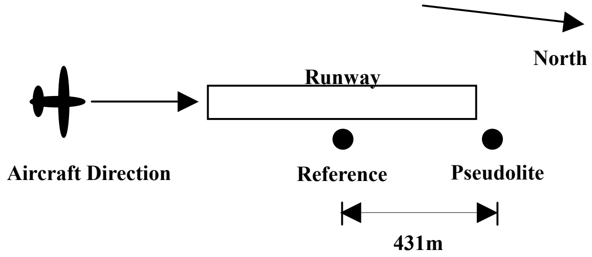

Figure 1. Wederburn Airfield ground configuration

The ground reference station was set up approximately 431.0m away from the pseudolite transmitting system. The power level for the pseudolite transmissions was able to support an operational range of approximately 10 – 15km. However, the power level was reduced due to the proximity of the pseudolite signal transmitter to the reference station, since high-level power transmission could interrupt the reference station's ability to track GPS signals.

The flight test aircraft used was a Beech Duchess aircraft from the Department of Aviation, UNSW. Data was collected for three flight days of the test period (29th April, 6th May and 8th May 2003). During these days no changes were made to the ground configuration.

The raw INS sensor and GPS carrier phase measurements from the NovAtel Millennium receivers were processed using an in-house software package - a modified version of the AIMS^{TM} navigation processing software (see Lee et al., 2003). The system accuracy cannot be directly evaluated in the kinematic mode, as an accurate reference trajectory is not available. Alternatively, a comparison with the independent trajectory obtained by dual-frequency GPS post-processing using the GrafNav/GrafNet software and the double-differenced (DD) residuals computed from INS-predicted GPS antenna positions are used to analyse the prediction accuracy of the INS. In addition, the RMS errors of the estimated navigation parameters from the Kalman filter (Lee, 2002) are analysed in order to evaluate the performance of the integrated system. The satellite measurements were processed to generate the independent trajectory. However, in the integrated GPS/INS/Pseudolite processing, only five of these satellites and one pseudolite was used to simulate a harsh operational environment.

4. FLIGHT TEST RESULTS

A specified period within the data sets, which was from start of the approach (the highest altitude) to the lowest altitude, was selected for processing. The highest altitude (ellipsoidal height) of the aircraft at the starting point of the approach is approximately 850 metres and the lowest point is about 290 metres. In addition, tracking of the pseudolite signal began at an altitude of 480.5 metres, at a distance of 3.8 km from the reference station.

Figure 2 shows the Relative Dilution of Precision (RDOP) values during the aircraft approach, with/without the pseudolite. It can be seen that the RPDOP value is significantly reduced when the pseudolite observable is introduced into the navigation solution. It is interesting to note that the greatest reduction occurs in the RVDOP value, indicating that in the case of an airborne application, the inclusion of the pseudolite observable largely affects the estimated vertical component Figure 3 illustrates the positioning performance of the GPS/INS and GPS/INS/Pseudolite integrations, obtained from a comparison of the positioning results provided by each of the systems against the reference trajectory obtained from dual-frequency GPS carrier phase processing. Carrier phase integer ambiguities are resolved using the technique proposed by Lee et al. (2003). Overall results show that the position differences in both the systems are within a few centimetres, and the differences in the vertical component fluctuate more than the horizontal component (note that different sets of satellites are used in the integrated processing). Two interesting points can be observed from these results. One is the position differences with/without the pseudolite augmentation; the differences in the vertical component are larger than those of the horizontal components, which means the inclusion of pseudolites largely impacts the vertical positioning performance (as demonstrated in the geometric analysis shown in Figure 2). The other point to be made from Figure 3 is that the position difference with/without the pseudolite increases as the aircraft gets closer to the runway (i.e., to the pseudolite signal transmitter). The mean and standard deviation of the positioning differences obtained from the two different system configurations are given in Table 1. It can be seen that a slight improvement in the vertical component (of the order of one centimetre) is achieved with the inclusion of pseudolite observables.

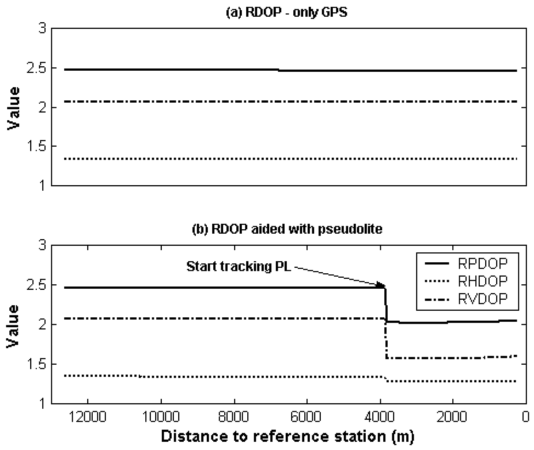

Figure 2. RDOP changes of an approach

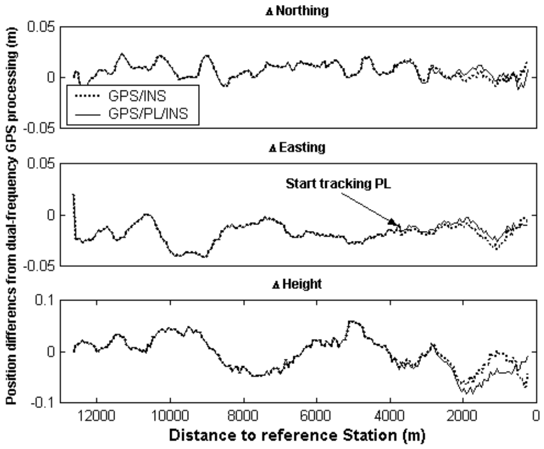

Figure 3. Position differences of GPS/INS and GPS/INS/PL systems from the dual-frequency GPS processing

Table 1. Comparison of positioning results of GPS/INS and GPS/INS/PL systems (unit: cm)

	GPS/INS		GPS/INS/PL	
	Ave.	Std.	Ave.	Std.
ΔN	0.3	0.7	0.4	0.6
ΔE	-1.3	0.5	-1.7	0.7
ΔH	3.7	2.4	2.5	2.0

Figure 4 depicts the double-differenced carrier phase residuals for the three satellite pairs computed using the INS-predicted coordinates. Similar to Figure 3, these results show that the difference in the two residual sequences obtained from the GPS/INS and GPS/INS/Pseudolite configurations becomes larger as the aircraft approaches the pseudolite. Table 2 shows the statistics of the residuals. In general these results indicate that the residuals of the GPS/INS/Pseudolite system are slightly better than those of the GPS/INS system (i.e., closer to the zero value).

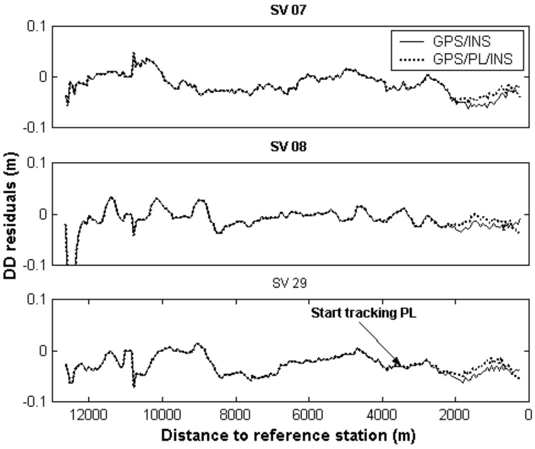

Figure 4 DD carrier phase residuals of the three highest satellites in GPS/INS and GPS/PL/INS systems

Table 2. Comparison of DD carrier phase residuals from the three highest satellites (unit: cm)

	GPS/INS		GPS/INS/PL	
	Ave.	Std.	Ave.	Std.
SV 07	-1.5	1.9	-1.4	1.4
SV 08	1.2	1.1	-1.0	1.1
SV 29	2.9	1.0	-2.7	1.0

Considering the results presented in Figures 3 & 4 as well as Tables 1 & 2, it can be concluded that the positioning accuracy obtained from the GPS/INS/Pseudolite system is slightly better than that of the GPS/INS system. However, the accuracy improvement is not as much as has been expected from the satellite/pseudolite geometric analysis. This is due to the pseudolite residual errors mainly being contaminated by multipath.

Figure 5 shows the Root-Mean-Square (RMS) error differences between the GPS/INS and GPS/INS/Pseudolite systems in the position, velocity, and attitude components, indicating the pseudolite contribution to the Kalman filter estimation procedure. The actual values can be calculated by subtracting the RMSs of the GPS/INS/Pseudolite from those of the GPS/INS. Therefore, if the performance of the GPS/INS/Pseudolite system were better than that of GPS/INS, the values would be positive, otherwise they would be negative. Note that the RMS values are obtained from the diagonal components of the integration filter's covariance matrix. It can be seen from the figure that the pseudolite augmented results are slightly better (i.e. more precise), the greatest improvement is observed in the vertical position component.

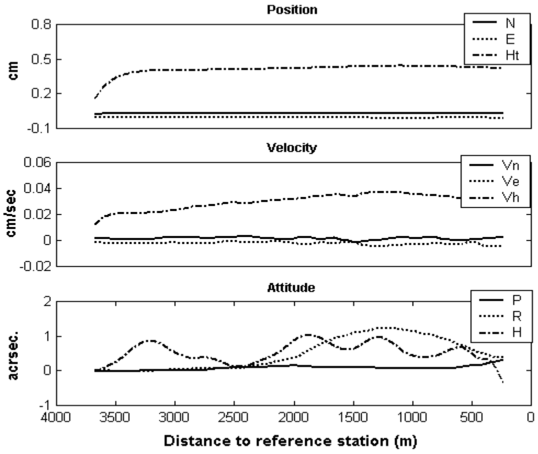

Figure 5 RMS difference between the GPS/INS and GPS/PL/INS systems in the navigation error estimates

In addition to the solution accuracy and precision, reliability should be considered in a navigation system design and implementation. The reliability has two distinct forms: internal and external reliability (Hewitson et al., 2004). The internal reliability is the ability of a system to detect biases in the observations. These biases are referred to as Minimal Detectable Bias (MDB), which describes the size of model errors that can be detected using the appropriate test statistics. On the other hand, the external reliability is the effect of undetected biases on positioning, which can be computed by propagating the effect of each MDB in the solution. Both of the reliabilities are critical for monitoring the navigation solution integrity. Figure 6 illustrates the internal and external reliability changes. Even though the inclusion of pseudolite observables enhances both reliabilities, it is important to note that a significant improvement (e.g., from 28 cm to 6 cm) of the external reliability is in the vertical component. Such an enhancement in reliability can be attributed to increased redundancy in the navigation solution. The greater redundancy, the easier it is to detect outliers due to less correlation among the test statistics (see Hewitson et al., 2004).

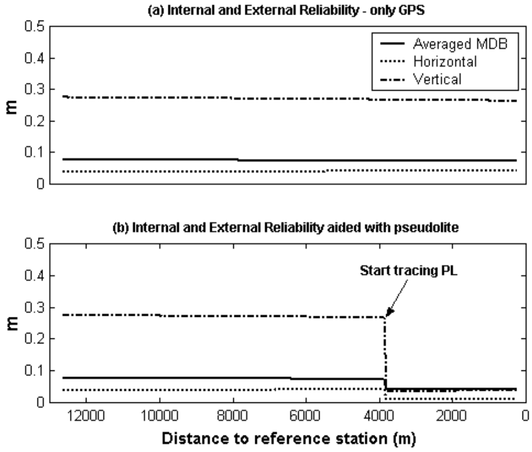

Figure 6 Internal and external (horizontal and vertical) reliability values during the approach

5. CONCLUDING REMARKS

The precision and reliability of a satellite-based navigation system to support aircraft precision approach and landing is dependent on both the number of visible GPS satellites and their geometric distribution. Integrating a pseudolite with GPS/INS is one option to improve system performances, particularly in adverse operational environments.

The flight results of GPS/INS/Pseudolite integration have shown that the pseudolite observables can strengthen the signal availability and the satellite geometry. Significant geometry enhancement was observed in the vertical component, resulting in an improvement in the aircraft's estimated altitude. However, the actual positioning accuracy improvement in the vertical component was not as much as had been expected from the satellite/pseudolites geometry (e.g., RVDOP), and was smaller than the improvement in the filter estimation precision (e.g., RMS errors). This contradiction seems to be attributed to the impact of pseudolite measurement residual errors, mainly caused by multipath. Hence, if such errors are mitigated and/or modelled, it is expected that the positioning accuracy can be further improved.

Reliability parameters are critical as they provide measures for monitoring the navigation solution integrity. The results from the tests have revealed that the inclusion of pseudolite observables enhances both the internal and external reliabilities due to the increased number of redundant measurements. A dramatic improvement in the external reliability for the estimated vertical component was observed.

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