Flight Test Results of Precision Approach and Landing Augmented by Airport Pseudolites

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BIOGRAPHY

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ABSTRACT

In this paper preliminary flight tests results are presented for a feasibility study of using differential GPS precision approach and landings augmented with pseudolites. Flight tests have been carried out by the DSO National Laboratories, Singapore, and the Satellite Navigation and Positioning (SNAP) group of the University of New South Wales. Trials were carried out in April/May 2003, at the Wedderburn Airfield, Australia, to assess the capabilities and limitations of an integrated differential GPS/pseudolite navigation system.

The results of the tests indicate that carrier-smoothed code-phase differential GPS/pseudolite can satisfy

vertical and lateral accuracies consistent with RNP for CAT III landing.

INTRODUCTION

With full GPS operational capability declared in the mid-1990s, research has been ongoing in the development of a local area augmentation system, that can fulfill the Required Navigation Performance (RNP) parameters (accuracy, availability, integrity and continuity) for CAT II/III aircraft precision approach and landing, as a replacement for the Instrument Landing System (ILS) and Microwave Landing System (MLS). Standalone GPS and conventional code-phase differential GPS are unable to meet the stringent navigation requirements in most airborne applications, because the performance of satellite-based navigation systems are dependent on both the number and geometric distribution of satellites tracked by the receivers. Due to the limited number of GPS satellites, a sufficient number of visible satellites cannot be guaranteed everywhere, 24 hours a day. Even when some low elevation satellites can be tracked, the measurements from these satellites are contaminated by relatively high atmospheric noise. Therefore, this intrinsic shortcoming of satellite-based positioning systems results in poor accuracy in the vertical component, which is typically about three times worse than that of the horizontal components.

Studies have shown that some means of augmentation can address these drawbacks in order to meet the specified requirements. Airport pseudolites have been suggested as a means of satisfying the stringent performance requirements of CAT II/III approach systems [4][5][8].

Airport pseudolites are ground-based transmitters that emit GPS-like signals; enhancing GPS navigation by providing increased accuracy, availability and integrity. Navigation accuracy improvement can 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. Accuracy and integrity enhancement can also be achieved by using an airport pseudolite's integral data link to support differential modes of operation and timely transmission of integrity warning information. Availability is increased because airport pseudolites provide additional ranging sources to augment the GPS constellation.

In order to realize an increase in availability with the addition of an airport pseudolite(s) to a local area augmentation system, the airport pseudolite must be of high quality and able to be used as a ranging source. A prototype airport pseudolite has been configured for this application, and it consists primarily of a GPS signal generator with power amplifier and rubidium reference clock. The airport pseudolite signal generator is a modified Spirent Communications single-channel GPS simulator (GSS4100P) with pulsing function.

The SNAP group at The University of New South Wales, Australia, and the DSO National Laboratories, Singapore, are jointly developing a local area augmentation system able to provide high accuracy navigation for aircraft precision approach and landing. The SNAP group has for several years been involved in the development of integrated GPS and pseudolite systems for airborne applications, such as for airborne mapping, aircraft automatic landing, and positioning and navigation services using high altitude platforms.

Although the use of airport pseudolites offers many potentially benefits for GPS airborne applications, there are a number of technical issues, which must be addressed. Some of the main issues are ground multipath, and the 'near-far' problem where large power level variation is expected over the final approach path. More importantly, the number and the geometric distribution of the airport pseudolites on the ground will have a significant impact on the performance of an augmented system in terms of the positioning accuracy, integrity and reliability of the ambiguity resolution. Multipath is also expected to be the largest error source for the ground reference station [6].

The first phase of the development consisted of a post-processed GPS carrier-smoothed code-phase differential software system. The next phase of the development has focused on improving the accuracy, availability and integrity of the system with the addition of one or more airport pseudolites. This has resulted in the development of an integrated GPS/Pseudolite carrier-smoothed code-phase differential system.

Flight tests were carried out in April/May 2003 at the Wedderburn Airfield, Australia, in which a total of 40 approach and landings were performed.

This paper provides an overview of the technical considerations that need to be addressed to use pseudolites as additional ranging sources for augmenting DGPS to meet the requirements for precision landing. The next section provides an overview of the equipment used for the flight tests. This is followed by a description of the flight tests, and the results that were obtained.

PSEUDOLITE SYSTEM CONCEPT

Pseudolites are ground-based transmitters, which can be configured to broadcast GPS-like signals with code-phase, carrier-phase and navigation messages with the same timing as the satellite signals and with nearly the same format. A GPS receiver acquires this signal and derives code-phase pseudoranges or carrier-phase measurements that can be used in a navigation algorithm. Pseudolites are usually set up wherever the coverage with GPS signals is not sufficient (e.g. in aviation application during precision approaches/landings, some open pit mines, which may have an elevation mask angle greater than 45° or in urban canyon environment where GPS signal maybe completely blocked).

They *augment* GPS by providing increased accuracy, integrity and availability. Significant improvements in vertical position accuracy become possible due to better local geometry, as indicated by a lower Vertical Dilution of Precision (VDOP), especially for applications in which pseudolites may be placed below an aircraft during precision approach and landing. Integrity enhancement can be achieved by employing a pseudolite's integral data link to support differential (DGPS) modes of operation and timely transmittal of integrity warning information [13].

This method is attractive because the user's navigation receiver already contains all the hardware necessary to tune and demodulate the data signal; it requires only a software upgrade. If one uses the traditional GPS signal format, the data rate for a single pseudolite signal is only 50bps. Simple modifications of this format, however, could increase the data rate to as high as 1000bps. Availability is increased because each additional pseudolite provides an additional (local) ranging source to augment the GPS ranging signals.

Although the use of pseudolites potentially offers significant benefits, there are still a number of technical issues which must be addressed. Other issues include deployment requirements, signal data rate, signal integrity monitoring, and user antenna location and sensitivity.

Near-Far Problem

One of the problems a user may encounter is the near-far problem, i.e. large variation in signal reception power due to relatively small changes in distance between user and pseudolite. Three signal diversity techniques have been proposed to minimize the interference to the signal reception of GPS satellites [12]:

- Pulsed signals with random or fixed cycle rates, a TDMA variation.
- Signals transmitted at a frequency offset from L1 (1575.42MHz), but within the same frequency band as GPS, a variation of frequency division multiple access (FDMA).
- Alternative codes that have a longer sequence than the existing GPS codes, a variation of CDMA.

Pseudolite Tropospheric Delay

For GPS signals, the tropospheric delay can be estimated by using a model such as the Saastomoinen, Hopfield or Black models. The delay estimated from these models is very dependent on the GPS satellite elevation angle. The standard tropospheric models cannot be used to compensate for pseudolite tropospheric delay. In [11], a simple tropospheric delay was proposed, where the refractivity n at the base of the atmosphere is described as a function of the meteorological parameters:

$$N = (n-1).10^{6}=77.6[(P-e)/T] + 71.98(e/T) + 375000(e/T^{2})$$

where P is the air pressure in hectopascals, e is the partial pressure of the water vapor in hectopascals, and T is the absolute temperature in degree Kelvin. The partial pressure of the water vapor can be estimated via the relative humidity (RH):

$$e = RH.exp(-37.2465 + 0.2133T - 0.0002569T^{2})$$

With the assumption that the meteorological parameters are the same, the tropospheric delay after between-receiver single-differencing can be represented by [10]:

$$\Delta\delta_{trop}=77.6(P/T) + 5.62(e/T) + 375000(e/T^{2}).10^{-6}\ \Delta p$$

where Δp is the difference in geometric ranges between the pseudolite transmitter and the two receivers. For the standard meteorogical parameters (P = 1013mPa, $T = 20^{\circ}$, RH = 50%), the tropospheric delay correction can reach 320.5ppm. Under some weather conditions, the influence of the pseudolite tropospheric delay can reach up to 600ppm. Similar conclusions have been drawn by [11]. Clearly the local weather conditions have a significant effect on the magnitude of the correction.

Effects of Orbital Errors

The orbit errors (or errors in the coordinates of the phase centers of the transmitter antennas) are one of the major biases in satellite/pseudolites-based positioning. In GPS relative positioning the impact of the satellite orbital errors on baseline component accuracy is severely mitigated. However, as pseudolites are close to users, the impact of these 'orbital errors' on the differenced range becomes double in the worst case scenario. Good selection of pseudolite location can mitigate the effect of this bias. It should be emphasized that the pseudolite antenna locations must be surveyed accurately.

Multipath

If one or more reflected signals arrive at the receiver antenna in addition to the direct signal, multipath will be present in both the code and carrier measurements. The effect of multipath on code observations is two orders of magnitude larger than on the carrier phase observations. The theoretical maximum multipath bias that can occur in pseudorange data is approximately half a chip length of the code, that is, 150m for C/A code ranges and 15m for the P(Y) code ranges. Typical errors are much lower (generally <10m). The carrier-phase multipath for undifferenced measurements does not exceed about one-quarter of the wavelength (5-6cm for L1 or L2) [7].

Compared with multipath from GPS signals, the pseudolite multipath has some unique characteristics. First is the effect of the pseudolite multipath error on a ground reference station receiver. Since the pseudolite and receiver are both stationary, the multipath bias will be a constant. Hence the influence of multipath from a pseudolite cannot be mitigated and reduced to the same extent over time as in the case of GPS. Secondly, during an approach the ground serves as the main surface from which the signal may be reflected. Because approach trajectories are not exactly repeatable, it is difficult to correlate user multipath errors with geometry. So multipath will significantly increase the noise level of the measurement in a dynamic environment. Therefore the primarily means of mitigating pseudolite multipath must be to reduce the gain of the transmission towards the ground. This was accomplished by means of a large antenna ground plane for the pseudolite system and using choke-ring antenna for the ground-based GPS reference station receiver.

FLIGHT TEST SYSTEM ARCHITECTURE

A brief description of the various elements of the flight test system is presented in this section.

Pseudolite System

A prototype pseudolite system intended for airborne/land applications was configured as shown in Figures 1 & 2. The pseudolite system consists primarily of a GPS signal generator with low noise amplifier (LNA) and a rubidium frequency reference clock. The pseudolite signal is provided by a Spirent Communications GSS4100P single-channel signal generator pulsing at a 1/11 duty cycle, with a 10MHz oven-controlled crystal oscillator (OCXO) frequency reference.

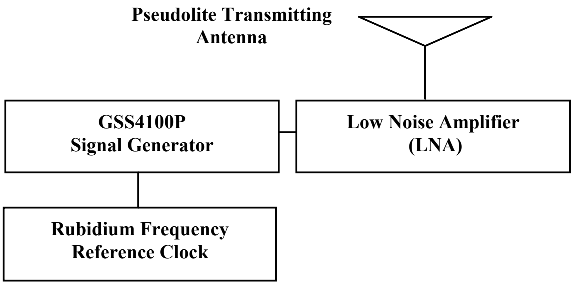

Figure 1. L1 C/A pseudolite configuration block diagram.

Figure 2. L1 C/A pseudolite physical configuration.

The pseudolite signal is compatible with the SPS GPS signal, i.e. a 1575.42 ± 20MHz carrier coherently modulated with a C/A code (1.023MHz) and a navigation message (50bps).

Ground Reference Subsystem

The reference subsystem consists of a GPS/pseudolite receiver and choke-ring antenna, and a wireless data-link transmitter. Raw measurements from the GPS/pseudolite signals tracked by the reference receiver are output over a serial communications interface and broadcast over the wireless data-link.

Airborne Subsystem

The block diagram of the airborne subsystem is shown in Figure 3. It consists of two GPS/pseudolite receivers, a main processor, an INS and a wireless data-link receiver. The subsystem has two GPS antennae mounted on the aircraft; one upward-looking antenna is mounted on top of the aircraft, whereas the second is attached to a downward-looking antenna mounted on the belly of the aircraft. Both antennas can be used to track signals from the GPS satellites and pseudolites. There are a few configurations in which the subsystem functions as a navigation system:

- An integrated GPS/pseudolite/INS system using only the top-mounted antenna for tracking both GPS and pseudolites.
- An integrated GPS/pseudolite/INS system using only the top-mounted antenna for GPS and bottom-mounted antenna for pseudolite, and only using the INS as an attitude data source which is required to resolve the vector between the upper and lower antenna (as this changes with variations in aircraft orientation).
- An integrated GPS/pseudolite system using the top-mounted antenna for both GPS and pseudolite tracking.

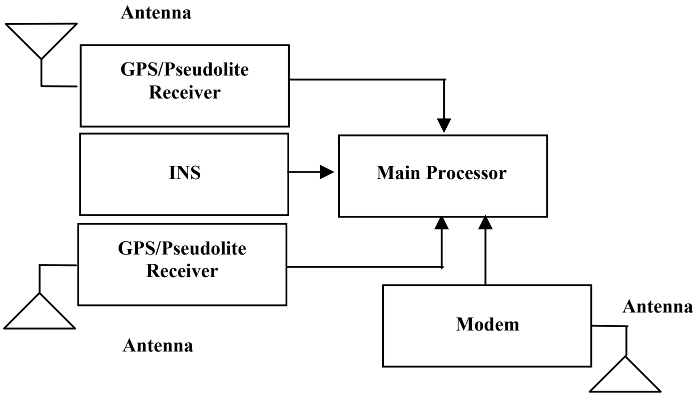

Figure 3. Airborne subsystem block diagram.

Flight test results presented in this paper are processed using the GPS and pseudolite measurements from the receiver connected to the top-mounted antenna only.

Measurement Processing

Combining the noisy-but-unambiguous GPS/pseudolite code measurements with the precise-but-ambiguous carrier-phase measurements leads to carrier smoothing of the code, and hence a reduction in the level of noise. At first the pseudorange measurements were smoothed using carrier-phase measurements consistent with the LAAS recommended smoothing algorithm [3]:

$$PR_S(t_i)=\alpha(t_i)PR(t_i)-[1-\alpha(t_i)]\{PR_S(t_{i-1})+[\phi_m(t_i)-\phi_m(t_{i-1})]\lambda\}$$

where PR_S is the smoothed pseudorange measurement, PR is the raw pseudorange measurement, α is the filter constant, ϕ_m is the accumulated Doppler range, and λ is the carrier wavelength.

The above algorithm weights the carrier-phase measurements more heavily than the code phase measurements. However, in this smoothing filter, code-carrier divergence poses a threat because of ionospheric effects. Hence instead the single-difference code-based pseudoranges between the reference station and the user are smoothed [1].

$$\rho_{s,ru}(t_i) = (1/M)\rho_{ru}(t_i) + [(M-1)/M][\rho_{s,ru}(t_{i-1}) + \lambda(\phi_{ru}(t_i) - \phi_{ru}(t_{i-1}))]$$

where $\rho_{s,ru}$ is the smoothed pseudorange difference, M is the measurement epochs, λ is the wavelength and ϕ_{ru} is the carrier-phase difference.

The advantage of implementing carrier-smoothed code using single-differences is that ionospheric divergence is contained. As a result, longer smoothing durations may be used than if raw measurements were smoothed by the ground and airborne subsystems separately.

FLIGHT TEST DESCRIPTION

Flight tests were conducted at the Wedderburn Airfield, within the Sydney basin area, Australia. Figure 4 shows the setup of ground subsystems at the runway.

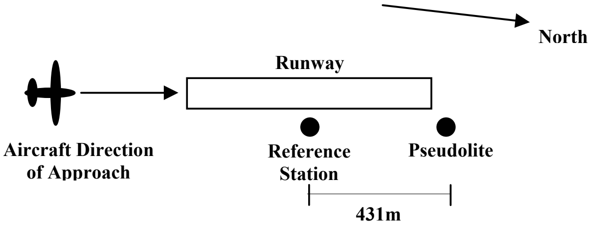

Figure 4. Wedderburn Airfield ground configuration (Not to scale).

The location of the pseudolite transmission antenna and the GPS reference antenna were precisely surveyed using NovAtel Millennium dual-frequency GPS receivers, post-processed using the GrafNav/GrafNet software. The ground reference station was set up approximately 431.0m away from the pseudolite system. The power level for the pseudolite transmission was able to support an operational range of approximately 10 – 15km. At this power level, and with pulsing, the reference receiver experienced no interference while tracking the GPS satellites. During most of the flight approaches, the airborne subsystem was able to lock-on to the pseudolite signal as far as 15km away from the reference station.

The flight test aircraft used is a Beech Duchess aircraft from the University of New South Wales Aviation Department, as show in Figure 5. Data were analyzed for three flight days of the test period, which was 29th April 2003, 6th May 2003 and 8th May 2003. During these days no changes were made to the ground configuration.

Figure 5. Beech Duchess aircraft from the UNSW Aviation Department.

Truth System

The truth trajectories were generated during the trials using Waypoint Consulting Inc's GrafNav/GrafNet Ver. 6.01 GPS post-processing software package. One NovAtel Millennium dual-frequency GPS receiver was located on the ground at a known location, as a reference receiver, while the remote receiver was installed within the aircraft. In kinematic mode, achievable accuracies of 2cm + 1ppm can be obtained by post-processing the GPS data collected from both the reference and remote GPS receivers for baselines of length less than about 5km.

FLIGHT TEST RESULTS

A total of 40 approaches were flown over a period of four days from 29th April 2003 to 8th May 2003. Post-processed data were analyzed in terms of along-track, cross-track and vertical accuracies.

Figure 6 shows the typical trajectory of the aircraft approach during the flight tests, with each circuit taking approximately 6-8min to complete.

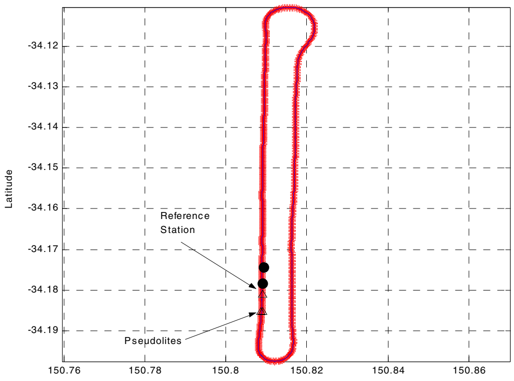

Figure 6. Plan view of the flight trajectory.

Figure 7 shows the typical magnitude of the VDOP values when the pseudolite is integrated into the differential position solution. The plot shows one of the approaches on 29th April 2003. No attempt was made to optimize the siting of the pseudolite transmitter to maximize the signal availability. Nor was the time of the day for the flight tests chosen to minimize the VDOP. The VDOP was reduced to less than 1.0 with the integration of the pseudolite into the solution.

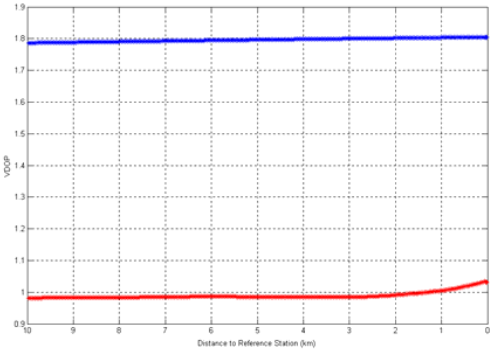

Figure 7. Typical VDOP of an approach with and without pseudolite in the positioning solution (RED: with pseudolite, BLUE: without pseudolite).

Figure 8 shows the typical DGPS/DPL solution errors over the final phase of an approach. These errors are the carrier-smoothed DGPS solution error without pseudolite substracted from the carrier smoothed DGPS/DPL solution with the pseudolite (The absolute DGPS error with respect to the truth reference generated using GrafNav/GrafNet GPS post-processing software package was submeter in accuracy).

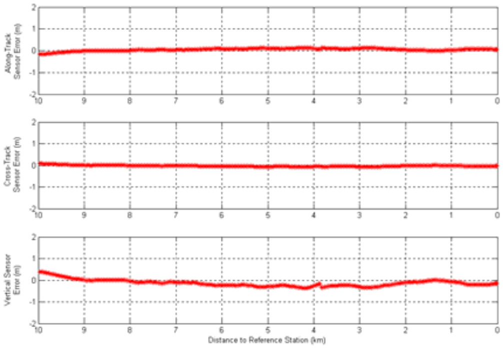

Figure 8. Typical difference between the GPS only DGPS position errors and GPS/PL DGPS/DPL position errors.

Figures 9 through 11 show the flight test results compared with the post-processed 'truth' reference data over the 3 flight days. The horizontal axes show the distance with respect to the ground reference station.

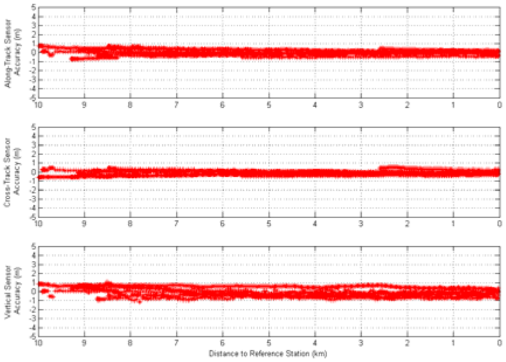

Figure 9. Flight test results on 29th April 2003.

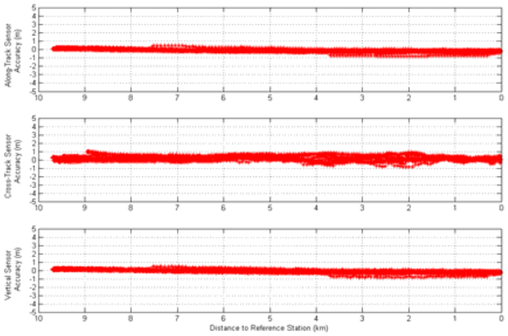

Figure 10. Flight test results on 6th May 2003.

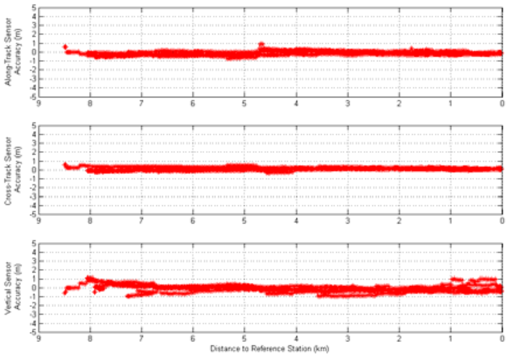

Figure 11. Flight test results on 8th May 2003.

The performance of the flight test at the 100 feet decision height: along-track sensor accuracy of 0.5115m (95%), cross-track sensor accuracy of 0.320m (95%) and vertical sensor accuracy of 0.770m (95%).

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CONCLUSION

The reliability and accuracy of a satellite-based positioning system to support aircraft precision approach and landing is very dependent on both the number of visible GPS satellites and their geometric distribution. The integrated processing of measurements made on pseudolite and GPS signals is one option for improving system performance, particularly in poor operational environments.

A system overview and preliminary flight test (post-processed) results are presented. The airborne subsystem was able to track the pseudolite signal as far as 15km away from the ground reference station during approach. Vertical sensor accuracies of 0.770m (95%) and lateral accuracies of 0.603m (95%) were achieved at a height of 100 feet above the ground; but there is still potential for further improvement to these accuracies.

The development of this system is still on-going, with further flight tests scheduled for November/December 2003. This time with a real-time integrated GPS/pseduolite flight system.

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