GPS/Pseudolite/INS Integration: Concept and First Tests

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ABSTRACT

This paper discusses the introduction of pseudolites (ground-based GPS-like signal transmitters) into existing integrated GPS/INS systems in order to provide higher availability, integrity and accuracy in a local area. Even though integrated GPS/INS systems can overcome inherent drawbacks of each component system (line-of-sight requirement for GPS, and INS errors that grow with time), performance is nevertheless degraded under adverse operational circumstances. Some typical examples are when the duration of satellite signal blockage exceeds an INS bridging level, resulting in large accumulated INS errors that are not able to be calibrated by GPS. Such a scenario is unfortunately a common occurrence for certain kinematic applications. To address such shortcomings, both pseudolite/INS and GPS/pseudolite/INS integration schemes are proposed here. Typically the former is applicable for indoor positioning where the GPS signal is unavailable for use. The latter would be appropriate for system augmentation when the number and geometry of visible satellites is not sufficient for accurate positioning or attitude determination. In this paper, some technical issues concerned with implementing these two integration schemes are described, including the measurement model, and the appropriate integration filter for INS error estimation and correction through GPS and pseudolite (PL) carrier phase measurements. In addition, the results from the *processing of simulated measurements, as well as field experiments, are presented in order to characterize the system performance. As a result, it has been established that the GPS/PL/INS and PL/INS integration schemes would make it possible to ensure centimetre level positioning accuracy even if the number of GPS signals is insufficient, or completely unavailable.*

INTRODUCTION

An Inertial Navigation System (INS) can provide position, velocity and attitude information at a high output rate. The system, however, is prone to time-dependent errors when operated in the stand-alone mode, without appropriate error calibration. In contrast, GPS provides accurate position, velocity and time information without any dependence on mission length or time. The main factor limiting the use of GPS is the requirement for line-of-sight between the receiver antenna and the satellites. Additional shortcomings include the comparatively low data output rate and the need to deploy more than one GPS antenna to obtain attitude information. In order to overcome the inherent drawbacks of each system, integrated GPS/INS systems have been developed. In such integrated systems, high accuracy GPS measurements are used to estimate, and to correct, the error states of the INS by means of Kalman filtering. High data rate INS measurements can then provide accurate position and attitude information between the GPS updates. In addition, redundant precise positional information from the INS can be used for ancillary tasks such as GPS cycle slip detection and repair, one of the limitations of high accuracy GPS in the stand-alone mode (Cannon, 1991). It is, however, necessary to note that satisfactory results cannot generally be provided in the free navigation mode during periods of GPS signal outage because the INS errors increase rapidly with time. More severely, if the blockage continues longer than the INS bridging level, it would be very difficult to recover correct GPS ambiguities due to the significantly increased INS position errors. In this research, pseudolites deployed at appropriate locations can improve an integrated GPS/INS system through overcoming not only the aforementioned GPS and INS drawbacks, but existing GPS/INS shortcomings, so that accurate position and attitude information can be obtained for a wide variety of operational scenarios.

Pseudolites are ground-based GPS-like signal transmitters, which can improve the 'open air' signal availability, or even replace the GPS satellites constellation for some indoor applications (Wang et al., 2001). They typically transmit signals at the GPS frequency L1 or L2. Both pseudo-range and carrier phase measurements can be made on the pseudolite signals. In fact, during the 1970's, even before the launch of the GPS satellites, pseudolites were used to test the initial GPS user equipment (Harrington & Dolloff, 1976). With the development of the pseudolite techniques and GPS user equipment during the last decade, pseudolites can be used to enhance the availability, reliability, integrity and accuracy for many applications, such as aircraft landing (Hein et al., 1997), land vehicle navigation in urban environments (Christian, 1999), for deformation monitoring applications (Dai et al., 2001, 2002), Mars exploration (Lemaster & Rock, 1999).

This paper will discuss the concepts, and benefits, of the employment of additional pseudolite signals within an integrated GPS/INS system. Some technical issues necessary for system implementation, such as the measurement models and the Kalman filtering scheme, are also described. In addition, the results of simulation tests and a field experiment will be presented.

CONCEPT OF GPS/PSEUDOLITE/INS INTEGRATION

In order to satisfy the objective of this research – to provide high availability, integrity and positioning accuracy at all times in a local area – an integrated GPS/Pseudolite/INS system, and an alternative integrated Pseudolite/INS system, are proposed. (In practice, the latter is a special case of the former, for cases where all GPS signals are blocked.) The pseudolites play three different roles in the proposed integration scheme, depending on the operational conditions.

Firstly, in the case of 'normal' kinematic GPS operation where there are no signal blockages, and more than five satellites are available, additional pseudolites strengthen the GPS satellite-pseudolite geometry. FIGURE 1 shows the variations of the RDOP values, together with the horizontal and vertical components, for both the GPS-only and GPS/Pseudolite scenario. The DOP values are computed for a 24 hour period and two pseudolites which have 5 and 10 degree elevation angle as well as 25 and 50 meters apart from the receiver respectively are assumed. It can be seen that the precision of all position components is significantly improved by the inclusion of additional pseudolite signals.

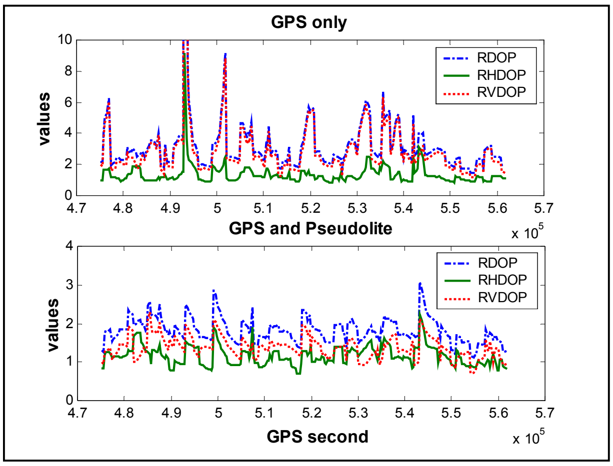

FIGURE 1. Geometric comparision between GPS-only and augmented GPS with Pseudolites

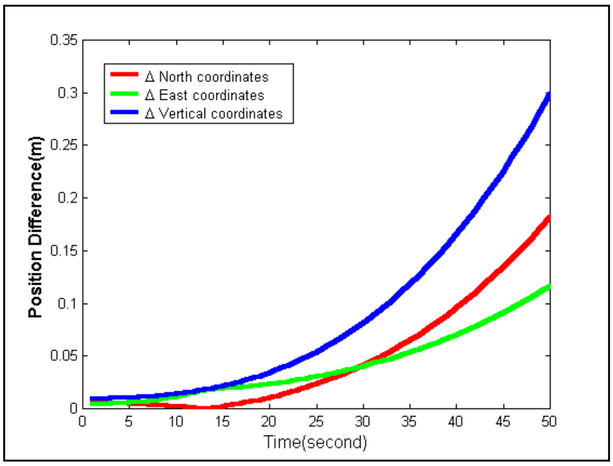

FIGURE 2. INS error behaviour without GPS calibration

Secondly, in the case when there are adverse GPS operational conditions, pseudolites can also help. There are two typical situations. One is when the number of GPS signals is insufficient to generate a reliable position result. Although the advantage of a tightly integrated system is to provide Kalman filter updates even when there are less than four satellite signals, integer ambiguities must be resolved at the beginning of the positioning mission, and when cycle clips occur in the carrier phase measurements. The other is the case when the duration of satellite signal blockage is excessive, longer than the INS bridging level, resulting in large accumulated INS errors that cannot be calibrated by GPS. Even though signal lock may subsequently be recovered, incorrect integer ambiguities could be introduced owing to the large INS position errors. The critical duration of signal outage varies as a function of the quality of the Inertial Measurement Unit (IMU). For example, it could be a couple of seconds for a low-grade IMU, and a few tens of seconds for navigation-grade IMUs. FIGURE 2 shows the simulated 50 second Strapdown Inertial Navigation System (SDINS) error behaviour of a navigation-grade if double-differenced GPS measurements are unavailable. A good example of GPS positioning in a harsh environment is presented in Stone et al. (1998), where the operational time of a GPS-only system can be reduced to 20% if the obstruction angle is up to 45°. The sky masking at construction or mining sites results in significantly reduced satellite availability, and as a consequence reliability and geometry is degraded. In such a case, one or more pseudolites deployed at appropriate locations can be used to improve the availability of measurements. Another benefit of such a system is an improvement of the ambiguity search performance as the initial coordinate from the calibrated INS solution is more accurate than that of the GPS-only pseudo-range solution.

In the third case, GPS signals are completely unavailable, such as when operated indoors. In such cases GPS measurements cannot be used in the Kalman filter update and the accumulated INS error increases exponentially (see FIGURE 2). However, the pseudolites can replace the satellite constellation, and hence be used to calibrate the INS error states. This is the pseudolite-only positioning concept, which has been proposed for indoor positioning (Kee et al., 2000). An important issue in this scenario is the locations of the pseudolite transmitters, since the positioning results are affected by the measurement geometry. A geometric simulation has been carried out when five pseudolites are deployed as indicated in Figure 3. RDOP values for a rover moving around on the floor of the room are shown in Figure 4. The optimum selection of pseudolite location(s) is an important consideration in the case of the pseudolite-based positioning. This issue will be discussed in more detail in the following section.

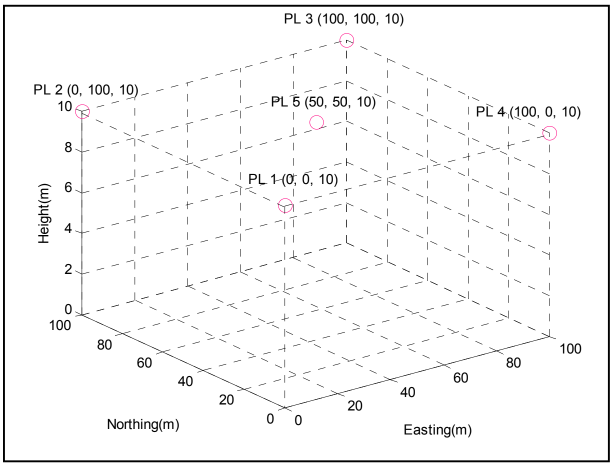

FIGURE 3. Pseudolite positions in the indoor case

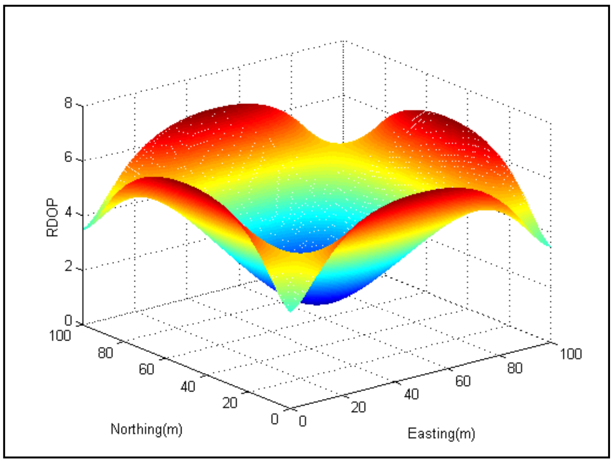

FIGURE 4. RDOP in the indoor case for a receiver on the floor with PLs asindicated in Figure 3

Integrating GPS and pseudolite measurements is relatively straightforward because the pseudolites can be considered simply as extra GPS satellite signals (if the pseudolites transmit signals on the GPS L1 or L2 frequency). Consequently, a system based on GPS/Pseudolite/INS sensor technology can be designed, using a 'tightly coupled' integration strategy. (The benefit of such an approach relative to a 'loosely coupled' one is better accuracy and less sensitivity to satellite dropouts.) Therefore, the proposed integration approach can be a useful tool to alleviate adverse GPS geometry in the following applications.

Land vehicle control and guidance is a challenging application, especially for construction plant, because many obstructions will cause GPS signal blockage. Some examples include drills, shovels, excavators and trucks. Such machinery can be currently controlled through laser guidance systems, or more recently using kinematic GPS techniques. Whilst the laser system can only provide height information, the added benefit of a GPS system is that it provides 3-dimensional coordinates. However, the GPS system cannot give orientation information (with one GPS antenna), and its usage is restricted by the requirement for unobstructed line-of-sight between satellite and receiving antenna (accuracy is dependent on satellite geometry). Unfortunately, it is difficult to ensure good satellite geometry and signal availability on construction sites, open-cut mines, highways, dam construction, etc., where steep pit walls or local terrain may mask some of the GPS signals. The proposed integrated GPS/Pseudolite/INS system provides, in principle, an effective solution for such applications. In addition to land vehicle control and guidance, Surveying & Mapping has benefited enormously from GPS's ability to provide fast and accurate positioning. The GPS/Pseudolite/INS system described here is able to deliver further benefits by providing accurate attitude information even without satellite signals. The system can provide precise exterior orientation parameters (i.e. position and attitude information) for mobile mapping applications. Hence it is possible to perform direct geo-referencing without Ground Control Points (GCP). In principle, the application of mobile mapping systems can therefore be extended to indoors, and even underground. Another application is the measurement of railtrack irregularities (Lück et al., 1999). A GPS/Pseudolite/INS system mounted on a monitoring car can offer an elegant solution to the problem of measuring track geometry in tunnels.

INTEGRATION FILTER

Pseudolite measurement model

Without loss of generality, in an analogous manner to the GPS satellite measurements, the mathematical models for the pseudolite pseudo-range and carrier phase observations are (Wang et al., 2001b):

$$R_k^p = \rho_k^p + c \cdot (dt^p - dt_k) + T_k^p + dr_k^p + dm_k^p + \varepsilon_{\mathrm{k}}^{\mathrm{p}} \tag{1}$$

$$\phi_k^p = \frac{\rho_k^p}{\lambda_p} + \frac{c}{\lambda_p} \cdot (dt^p - dt_k) + N_k^p + \frac{T_p}{\lambda_p} + \frac{dr_k^p}{\lambda_p} + (dm_K^P + e_k^p) \tag{2}$$

where k and p denote the receiver and pseudolite respectively. R_k^p and $\phi_{\mathrm{k}}^{\mathrm{p}}$ are the pseudo-range and carrier phase measurements respectively. λ_p is the wavelength of the carrier frequency, ρ_k^p is the topocentric distance, and dt^p and dt_k are the clock errors respectively. T_k^p is the tropospheric delay, dr_k^p is the pseudolite location error, and dm_k^p and δm_k^p are multipath errors in the pseudo-range and carrier phase measurements respectively. ε_k^p and e_k^p are the pseudo-range and carrier phase measurement errors respectively. In the above observation equations, note that there are no signal-propagation correction terms for the ionosphere. This is because pseudolite (PL) signal transmitters and the user receiver antenna are both on the ground. Hence the PL signal will not propagate through the ionosphere.

Error State Model

For a short baseline application, as assumed in the following simulations and as is the case for the field experiments, the residual GPS measurement errors are small when the double-differenced carrier phase observable model is used – the common error sources between reference and rover receivers are reduced or eliminated. Hence, the error state vector of the Kalman filter only includes the parameters of the navigation solution, and the accelerometer and gyroscope error states. Here, the following complete terrestrial INS psi-angle error model is used (Bar-Itzhack & Berman, 1988):

$$\delta\dot{v} = -(\omega_{ie} + \omega_{in}) \times \delta v - \psi \times f + \delta g + \nabla \tag{3}$$

$$\delta\dot{r} = -\omega_{en} \times \delta r + \delta v \tag{4}$$

$$\dot{\psi} = -\omega_{in} \times \psi + \varepsilon \tag{5}$$

where $\delta v, \delta r,$ and $\delta\psi$ are the velocity, position, and attitude error vector respectively; ∇ is the accelerometer error vector; δg is the error in the computed gravity vector; and ε is the gyro drift vector.

An exact expression for the system equation for the Kalman filter depends on what error states are chosen and what kind of models are used to describe them. In this study twenty one error states are selected, namely the error state vector, which includes nine navigation solution errors with respect to positions (δr), velocities (δv) and attitude angles $(\delta\psi)$, six accelerometer measurement errors (biases (∇_b) and scale factors (∇_f)), three gyro drifts (ε_d), and three gravity uncertainty errors (δg) (see equations 6-10). The model has the following form.

$$\begin{bmatrix} \dot{x}_{Nav} \\ \dot{x}_{Acc} \\ \dot{x}_{Gyro} \\ \dot{x}_{Grav} \end{bmatrix} = \begin{bmatrix} F_{11} & F_{12} & F_{13} & F_{14} \\ 0 & F_{22} & 0 & 0 \\ 0 & 0 & F_{33} & 0 \\ 0 & 0 & 0 & F_{44} \end{bmatrix} \begin{bmatrix} x_{nav} \\ x_{Acc} \\ x_{Gyro} \\ x_{Grav} \end{bmatrix} + \begin{bmatrix} w_{Nav} \\ w_{Acc} \\ w_{Gyro} \\ w_{Grav} \end{bmatrix} \tag{6}$$

where x_{Nav}, x_{Acc}, x_{Gyro}, and x_{Grav} are the error vectors of inertial navigation solutions, the accelerometer measurements, the gyro measurements, the gravity uncertainty . A detailed expression of the matrix F are provided in Da (1997). Finally, w_{Nav}, w_{Acc}, w_{Gyro}, and w_{Grav} are all zero-mean Gaussian white noise vectors.

$$x_{nav} = [\delta r_N, \delta r_E, \delta r_D, \delta v_N, \delta v_E, \delta v_D, \delta\psi_N, \delta\psi_E, \delta\psi_D]^T \tag{7}$$

$$x_{Acc} = [\nabla_{bx}, \nabla_{by}, \nabla_{bz}, \nabla_{fx}, \nabla_{fy}, \nabla_{fz}]^T \tag{8}$$

$$x_{Gyro} = [\varepsilon_{dx}, \varepsilon_{dy}, \varepsilon_{dz}]^T \tag{9}$$

$$x_{Grav} = [\delta g_N, \delta\delta_E, \delta\delta_D]^T \tag{10}$$

For a more detailed discussion of such a model see, for example, Grejner-Brezinska (1998a, 1998b) and Da (1997).

Measurement Update and Error Correction

Tightly coupled integration, adapted in this research (see FIGURE 5), treats GPS/Pseudolite and INS not as navigation systems, but as *sensors*. A single filter is applied to process all the measurements, and hence raw GPS/Pseudolite measurements are used. In this study, double-differenced carrier phase measurements are used in the filter. Therefore integer ambiguities have to be fixed by an efficient method, before filter updating. An 'on-the-fly' searching method is applied, and ambiguity searching is carried out efficiently because the search space is considerably reduced due to the use of very accurate initial coordinates from the INS, and the line-of-sight vector between epochs changes by a large angle (which results in a well-conditioned matrix of ambiguity parameters). In addition, the closed-loop update technique is used to correct the estimated INS errors, as indicated in FIGURE 5. The estimated errors are fed back to update the inertial solution and sensor measurements. The closed-loop update limits the inertial position errors to the centimetre level.

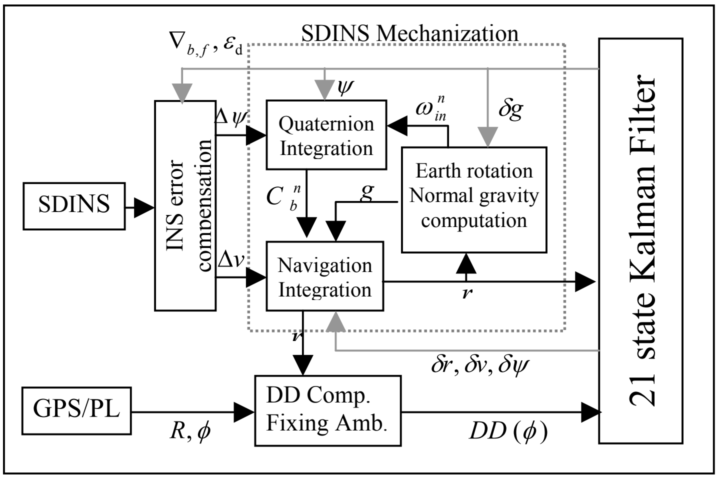

FIGURE 5. Tightly coupled GPS/PL/INS integration

SIMULATIONS

During the early stages of the development of an integrated sensor system it is necessary to test the components, assess the behaviour of the various integration strategies and to verify the performance of the system algorithms. It is often not practical to collect data under all possible scenarios. Furthermore, in many kinematic scenarios the true trajectory is not known precisely. By processing simulated data a reference trajectory can be generated, and then compared with results from the integrated system.

Measurement Simulation

For this study, integrated GPS/Pseudolite/SDINS measurement simulation software has been developed. The software comprises three components: the trajectory profile, and the SDINS and GPS/PL measurement simulation modules. Both the GPS/Pseudolite and the SDINS data simulation require a reference trajectory (a flight profile) for the moving vehicle or platform. The reference trajectory is defined by time, and the coordinate, velocity and attitude angle values. The inputs for the software include the initial coordinates, velocity, attitude, update rate, starting and ending time. Moreover, to define the vehicle's movement change, segment parameters, for example acceleration, velocity and heading changes, need to be defined. The generated trajectory profile is output with a 1Hz rate.

In the case of the SDINS, specific force (acceleration) and angular velocity is first generated, based on the given trajectory profile, and then related sensor errors, accelerometer/gyro bias, scale factor and noise, as well as effects associated with Earth rotation and gravity, are computed and added to the 'true' measurements. All data so generated are output in a binary format with a rate of 64Hz.

GPS/PL data generation begins with the computation of the coordinates of the satellites. While GPS satellite coordinates are computed using an ephemeris data file (based on an almanac file), those for the pseudolites need to be provided by the user. Subsequently, based on the coordinates of the receiver antenna and the satellites, the distance between the two points in space is computed. The biases, errors and measurement noise defined by the appropriate models (1.0 m for pseudo-range and 2 cm for carrier phase measurement), are then added. Multipath is not taken into account in this simulation study. Some points need to be made at this stage. One is the lack of an ionospheric delay model for the pseudolite measurements, see equations 1 & 2. Secondly, a different tropospheric delay model must be used for pseudolites, as the standard GPS tropospheric models cannot compensate for the pseudolite tropospheric delay. In this study a simple troposphere model, as described in Dai et al. (2001), has been used. A GPS/PL simulation output rate of 1Hz was used. The simulated data is output in the RINEX V2 format.

Trajectory and Measurements

The reference trajectory is generated with 62 segments and for a total time period of 1120 seconds, as shown FIGURE 6. The first segment is stationary, for the purpose of initial INS alignment, and then the vehicle moves with a constant acceleration of 0.15m/sec^2. The vehicle then moves with a constant velocity of 5.9m/sec (21.2km/h) for the remainder of the trajectory. The heading and roll were changed 11 times, whereas the pitch and height were both changed 5 times. It was assumed that the velocity component along the Z-(Down) axis of the navigation frame was zero m/sec. However, when the pitch and roll angles are changed, the actual Z-axis velocity component may not be zero.

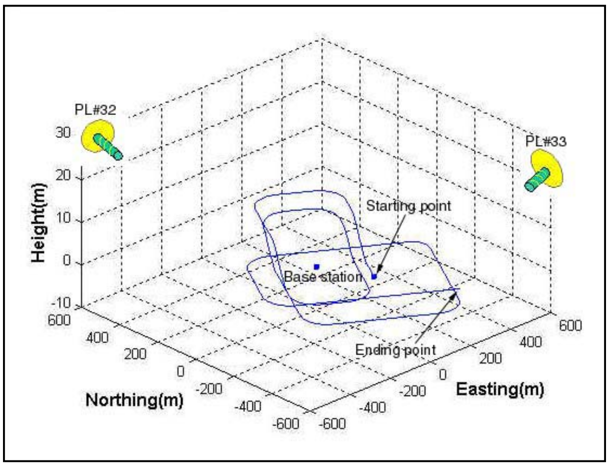

FIGURE 6. Reference trajectory for the testing

Test Case	Testing Scenarios	Num. Of SVs	Mean PDOP	Data sets
I	GPS/INS	5	3.4	①
	GPS/PL/INS	5(1-4)	0.8-2.1	②
II	GPS/INS	5-3	3.6	①
	GPS/PL/INS	5-3(2)	1.7	②
III	GPS/PL/INS	3(2)	2.3	③
IV	PL/INS	(5)	4.7	④
	PL/INS	(5)	2.1	⑤

TABLE 1. Simulated data sets for testing

Using the measurement simulation software described above, the GPS/PL base and 'rover' receiver measurements, as well as the SDINS measurements, were generated. While five GPS/PL data sets were simulated by assuming different positioning scenarios, see Table 1, only one SDINS data set was simulated. In the Table 1, the figures in the brackets of the third columns refer to the number of pseudolites used in measurement simulation.

TESTINS AND RESULTS OF THE SIMULATED MEASUREMENTS

As shown in Table 1, five different GPS/PL data sets, based on a variety of positioning scenarios, were simulated in order to assess the performance of such integrated systems. Four different simulation tests will be discussed, illustrating the different role that can be played by a pseudolite when integrated with a GPS/INS system. In these tests the software package AIMS^{TM} (Airborne Integrated Mapping System), developed by the Center for Mapping of the Ohio State University (Grejner-Brzezinska, 1997; Grejner-Brzezinska et al., 1998), was used for data processing. This software has been modified at The University of New South Wales to include the capability of processing pseudolite measurements.

Normal operational environment (Test case I)

This test was to compare the accuracy of standard GPS/INS with a GPS/PL/INS system, as well as to evaluate the accuracy of the integrated GPS/PL/INS system as a function of the number of pseudolites used. To this end, GPS measurements from five satellites were used under normal operational conditions, whilst an additional four pseudolite measurements were included.

To assess the system accuracy, a comparison between positions on the reference and computed trajectory is made in FIGURE 7. As mentioned in the previous section, the reference trajectory in the simulation studies provides the best means of analysing achievable accuracy and system performance. In addition, standard deviations of the double-differenced (DD) residuals of the three highest satellites in each epoch are compared as well (see FIGURE 8). As illustrated in FIGURE 1, the addition of pseudolites strengthens the existing GPS satellite geometry, that is PDOP falls from 3.7 without pseudolite to 0.8-2.1 (depending on the number of pseudolites used). The enhanced geometry results in accurate INS error estimation in the integration filter, and subsequently improved accuracy for the integrated system. Comparing the standard deviation values of the differences in both the horizontal and vertical components, and the double-differenced residuals, it can be seen that the addition of pseudolites has improved the accuracy in the GPS/INS system. Therefore, it should be noted that the deployment of the pseudolites, such as number and position, should be carefully done via a geometric simulation process.

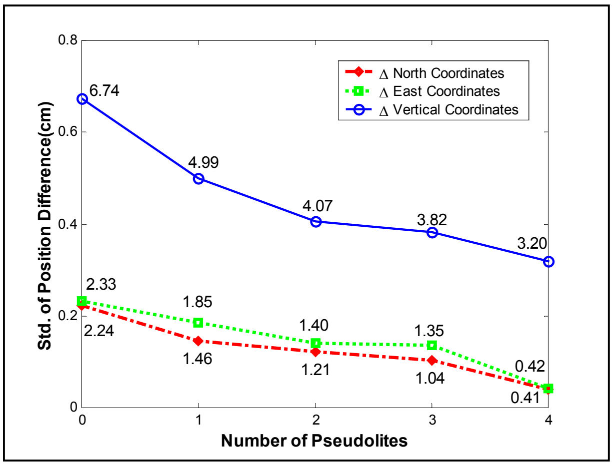

FIGURE 7. Standard deviation of coordinate differences in the GPS/PL/INS system as a function of the number of pseudolites

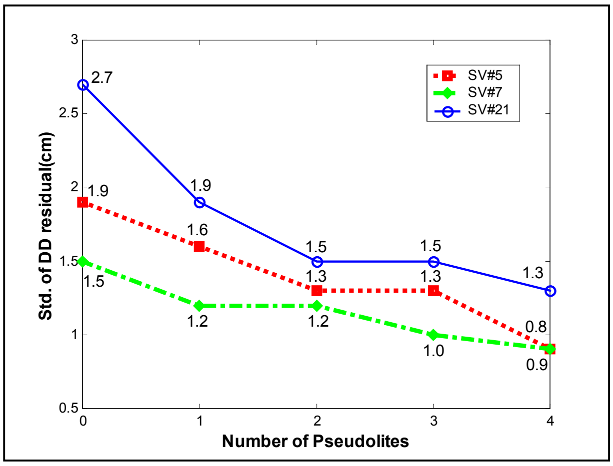

FIGURE 8. Standard deviation of DD residuals of the three highest satellites as a function of the number of pseudolites

Adverse operational environment (Test case II & III)

The first test (Case II) in this case was carried out assuming the blockage of signals from satellites 5 and 30, simulated three times for 10, 20, and 40 second periods to analyse the system error behaviour during these outages. The results using GPS/INS and GPS/PL/INS is compared. FIGURE 9 shows the number of SVs tracked and the associated RDOP values. It can be seen that two pseudolites enhance the geometry significantly. The arrows in the lower graphs of FIGURES 10 and 11 indicate the results during the periods of GPS signal blockage.

Even though measurements from the other visible satellites during these periods are not enough to update the Kalman filter (two GPS DD measurements) in the case of GPS/INS integration, the results in FIGURE 10 indicate that there is no significant error increase – remaining in the range of a few millimetres to centimetres – except for the third blockage period (40 seconds duration). This is possible because of the capability of the INS to continue providing accurate output results over short time intervals, as well as the tightly coupled integration filter permitting an update of the filter with only a few GPS measurements. However, the conclusions would be different if the signal blockage periods are longer, and/or a different type of IMU is used. The former issue will be dealt with later. In the case of GPS/PL/INS integration, the upper and lower graphs in FIGURE 11 show almost identical results. This means that the additional pseudolite signals can play a significant role in maintaining stable system accuracy. In addition, comparing FIGURE 10 with FIGURE 11, it can be seen that the results of GPS/PL/INS are better than that of GPS/INS in terms of accuracy and stability.

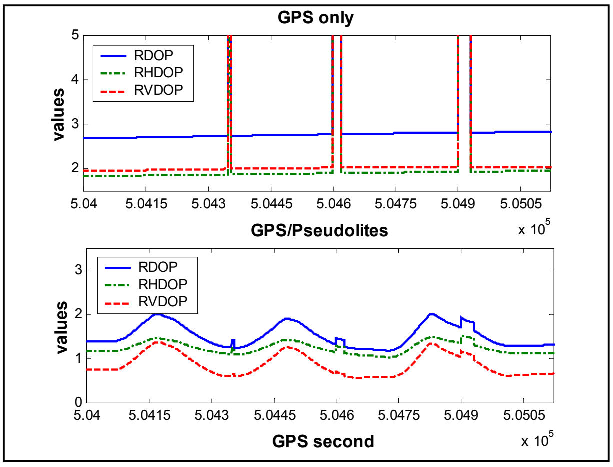

FIGURE 9. RDOP changes in Test case II

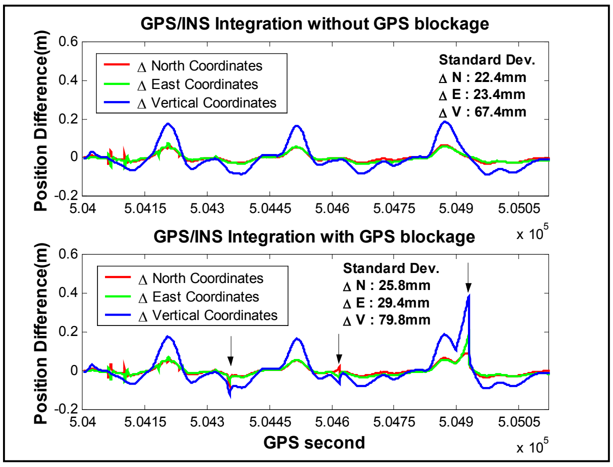

FIGURE 10. Differences between reference and computed position with/without satellite blockage (GPS/INS – Test case II)

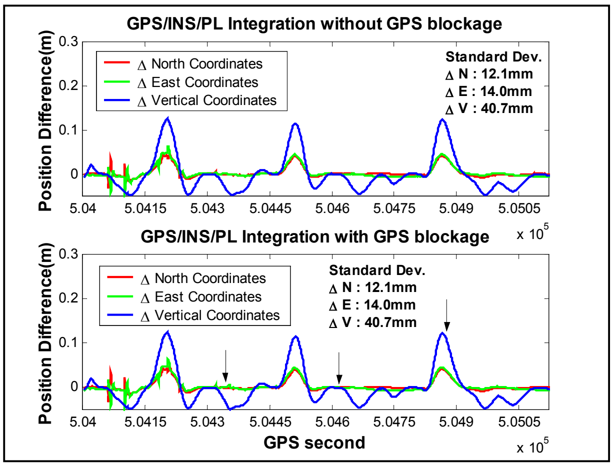

FIGURE 11. Differences between reference and computed position with/without satellite blockage (GPS/PL/INS – Test case II)

The second (Case III) is a scenario where the number of visible GPS satellites is less than five. When using double-differenced carrier phase observables for updating the INS error estimation within a Kalman filter, an important issue is to fix the ambiguities correctly. By and large, more than five satellites are recommended for on-the-fly (OTF) ambiguity resolution algorithms (at the beginning of data processing and/or after the occurrence of cycle slips). This means that using double-differenced observables without the correct ambiguities makes it impossible to accurately estimate (and correct in the feedback loop) the accumulated INS errors. The first test in this session (Case II) showed that a few seconds of GPS data loss did not affect the rate of INS accuracy degradation if a high-grade IMU is used. However, even a few seconds of signal loss could significantly degrade the accuracy of the system if a low-grade IMU was used. FIGURE 2 shows the INS error behaviour if the double-differenced observables were not available due to an insufficient number of tracked satellites. More severely, the longer the signal blockage, the larger the accumulated INS errors. Under these circumstances the existing GPS/INS integration configuration cannot give high positioning accuracy, especially with a low-cost IMU. As shown in the upper graph of FIGURE 12, three GPS and two pseudolite measurements are generated for this test. Although only three GPS measurements are used, the mean RDOP value is still at the 2.3 level. Moreover, note that centimetre level positioning accuracy is achievable in the simulation test even if the number of tracked satellite is less than five, using an OTF algorithm. Note the magnitudes of the standard deviations in each of the FIGUREs.

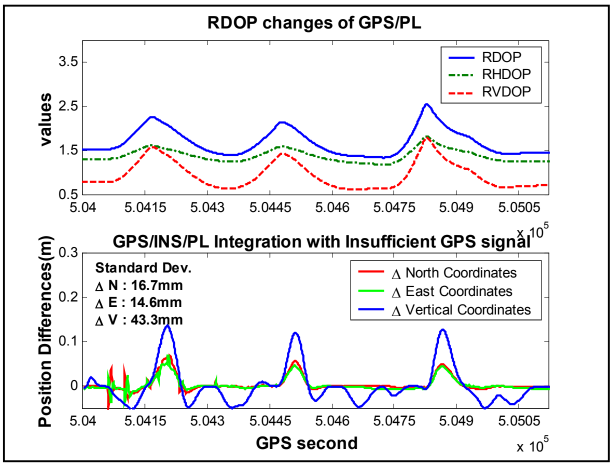

FIGURE 12. RDOP change, and position differences in the case of GPS/PL/INS integration

Pseudolite/INS integration for indoor applications

So far the simulation tests have assumed both sufficient and insufficient GPS measurements in order to assess the contribution of pseudolites to current GPS-only and integrated GPS/INS systems, with respect to geometric strength and accuracy. This test is, however, the 'harshest' GPS operating environment, namely indoor positioning. The test assumed five pseudolites in an integrated PL/INS configuration, and applied the same methodology as in the previous test. It has already been shown that, in the case of satellite-based positioning, the reliability and accuracy of pseudolite-augmented systems, i.e. GPS/PL and GPS/PL/INS, is very dependent on the geometric strength of the configuration. In this test, two measurement sets, for different PL constellations, were simulated to evaluate how variations in pseudolite deployment will affect the accuracy of such a system. The constellations were chosen based on insight obtained from the results of the simulation analysis shown in FIGURE 4. For example, the higher the elevation angle and the farther apart the pseudolite locations, the more accurate is the result obtained, see FIGURE 13.

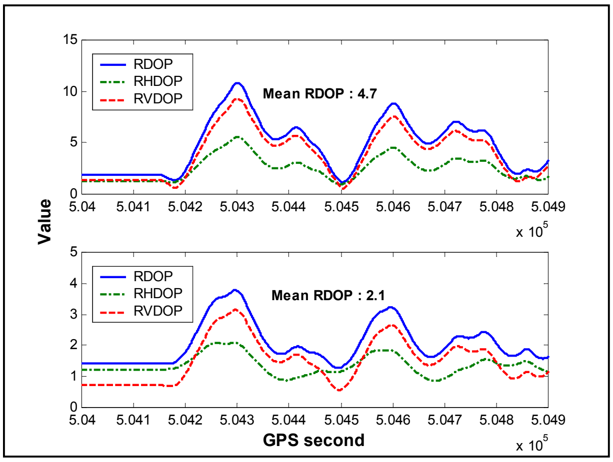

FIGURE 13. Geometry changes in the simulated PL measurement sets

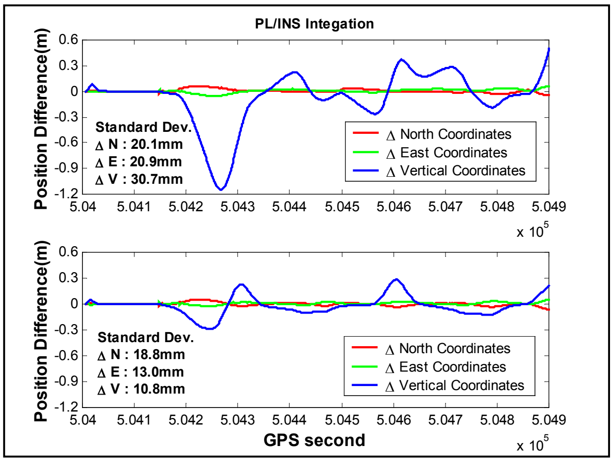

FIGURE 14. Difference between reference and computed position in the case of PL/INS integration

As expected, the accuracy of both the horizontal and vertical components is considerably improved (see FIGURE 14) when good geometry is assumed. In particular, the improvement in the vertical component accuracy is such that it is now better than the horizontal components (when the geometry is good). This is in contrast to the results generally obtained from GPS-only positioning, and can be attributed to the use of low elevation pseudolite signals. It could be concluded from these simulation results, irrespective of the pattern of deployment of the pseudolites (the RDOP remains below 5), that the achievable accuracy of the system is at the centimetre level.

EXPERIMENT AND RESULTS

A real kinematic experiment was carried out to investigate the performance of an integrated GPS/Pseudolite/INS system. This was done in cooperation with the Center for Mapping, of the Ohio Sate University, in May 2001. The system consisted of two NovAtel Millennium GPS receivers, a Litton LN-100 strapdown INS, and an IntegriNautics IN200 pseudolite. The data was collected for twenty minutes, including an eight minute period with the system in the static mode.

All data was processed with the modified version of AIMS^{TM} software referred to earlier. In the data processing, only L1 measurements were used for the Kalman filter update. (The pseudolite used in this experiment could only transmit on the L1 frequency.) To investigate the pseudolite signal contribution to the integrated system, measurements on four GPS satellites were selected for data processing, even though there were six visible satellites above the cut-off angle of 15°. As indicated in the upper graph of FIGURE 15, the average GPS-only RDOP value is 3.2, while the satellite geometry is strengthened (average RDOP 2.1) when the single pseudolite signal in included. Typically more than five satellite measurements are necessary to fix integer ambiguity by means of OTF searching methods. In this experiment, with four GPS measurements and one PL measurement per epoch, ambiguities could be successfully resolved within a few seconds (despite one signal outage simulated for ten seconds). In addition, another contribution of the peudolite in ambiguity resolution is the reduction in search time, because in the kinematic mode the line-of-sight vector between epochs changes by a large angle, which results in a well-conditioned matrix for the ambiguity parameters.

The accuracy cannot be directly assessed in the kinematic mode because an accurate reference trajectory is not available. A comparison is made with the independent trajectory obtained by GPS-only processing, as well as an analysis of the standard deviations of the estimated navigation parameters (El-Sheimy et al, 1995) and the filter predicted double-differenced residuals (Grejner-

Brzezinska et al, 1994). Firstly, GPS L1/L2 measurements were processed using the Leica SKI-Pro commercial software. The differences between the trajectories are of the order of a few centimetres. As shown in the lower graph of FIGURE 15, the standard deviations of the differences are 3.1cm, 1.5cm and 3.3cm in the north, east, and height component respectively. It should be pointed out that there were no big differences despite the GPS signal blockage owing to the INS bridging capability (note, a high quality IMU was used). FIGURE 16 depicts the RMS values derived from the covariance matrix, and the velocity and attitude angle estimation. The estimated values are several centimetres for position, better than 0.002cm/sec for velocity and around 10 arc-seconds for attitude angle estimation after filter initialization.

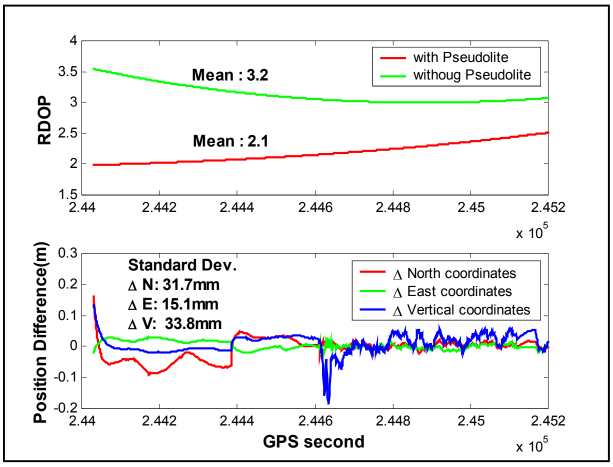

FIGURE 15. RDOP change, and position differences between GPS/PL/INS integration and Leica SKI-Pro solution

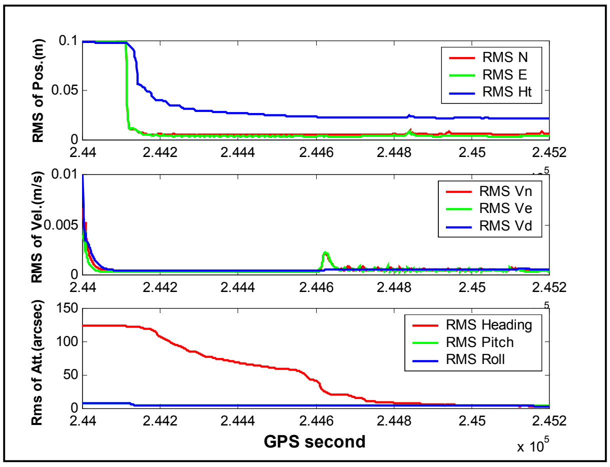

FIGURE 16. Root-Mean-Square for Kalman filter estimation

FIGURE 17 shows the double-differenced residuals computed from the INS-predicted positions in the filter for the satellite (upper graph) and pseudolite (lower graph) measurements while operating in the kinematic mode, except during the GPS blockage period. The satellite measurement residuals are around a couple of centimeters, while those of the pseudolite are much larger and noisier. The residuals show the effect of unmodelled measurement errors in the data processing. In this result, it is suspected that such large pseudolite residuals are because the measurements are contaminated by multipath. Clearly, pseudolite measurements are more severely affected by multipath than GPS signals because the multipath is not only due to reflected signals from surfaces, but also from the pseudolite transmitter itself (Ford et al., 1996). In addition, the elevation angle of the pseudolite signals is generally very low, of the order of a couple of degrees (about 1.7° in this experiment). If the pseudolite and the receiver were both staionary, the multipath error would be a constant (Dai et al., 2001, 2002). Hence, the multipath *bias* can be easily accounted for. However, in a kinematic environment, a different solution to this problem needs to be found, such as improvements in hardware design (including receivers, GPS antenna and pseudolite transmitter antenna), as well as software-based multipath mitigation techniques. These issues are the subject of further research.

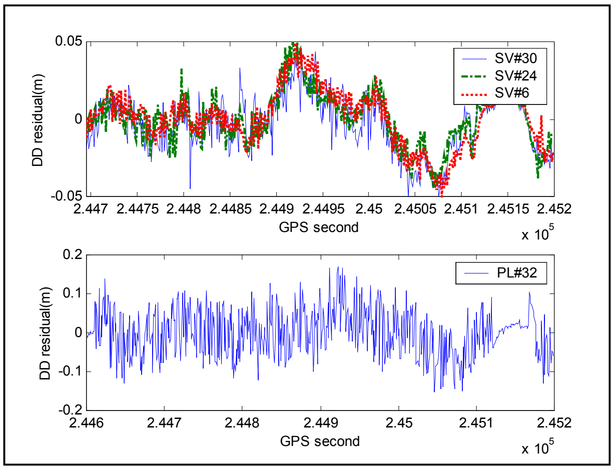

FIGURE 17. Filter predicted double-difference residuals in kinematic environment.

CONCLUDING REMARKS

A system integration concept based on two or more of the following: GPS receiver, pseudolite transmitter and INS technologies, has been described in this paper. GPS/Pseudolite/INS and Pseudolite/INS integration schemes are proposed in order to overcome the shortcomings of existing GPS/INS systems. In addition, some technical issues concerned with implementing there two integration schemes are described, including the measurement model, and the appropriate integration filter for INS error estimation based on GPS and pseudolite carrier phase measurements. In order to assess and demonstrate the performance of different system configurations and operational scenarios, a variety of simulation tests, as well as a field experiment, have been carried out. It has been found that appropriately located pseudolites can strengthen the GPS satellite/Pseudolite transmitter geometry, and therefore ensure improved accuracy for different positioning scenarios. In addition, it has been demonstrated that GPS/PL/INS and PL/INS integration would make possible centimetre-level positioning accuracy even if there are insufficient GPS signals available. More research on mitigating pseudolite multipath, and further tests with different SDINSs, will be carried out in the near future.

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