

High-Accuracy Airborne GPS/INS Positioning Augmented by Pseudolite

Jianguo Jack Wang, Jinling Wang
*School of Surveying and Spatial Information Systems
University of New South Wales, Sydney, Australia*

David Sinclair, Leo Watts
QASCO Surveys Pty. Limited, 41 Boundary St. South Brisbane, Qld, 4101

BIOGRAPHY

Jianguo Jack Wang is a PhD student at the School of Surveying & SIS, The University of New South Wales, Sydney, Australia since November 2003. He received his B.Sc. in Physics and M.E. in Electrical and Information Engineering. His current research interests include precision kinematic positioning and navigation sensor integration.

Jinling Wang is a senior lecturer in the School of Surveying & Spatial Information System at the University of New South Wales. He is a member of the editorial board for the international journal GPS SOLUTIONS, and Chairman of the international study group on pseudolite applications in positioning and navigation within the International Association of Geodesy's Commission 4. He was 2004 President of the International Association of Chinese Professionals in Global Positioning Systems (CPGPS), He holds a PhD in GPS/Geodesy from Curtin University of Technology, Australia.

David Sinclair is a licensed surveyor in four Australian states, having gained a Bachelor of Applied Science (Surveying) in 1975. He is the Director and General Manager of QASCO in Australia, which is the pioneer in Australia using airborne GPS for Mapping. David currently holds the position of Chairman of the Board of Consulting Surveyors Quality Corporation.

Leo Watts is a surveyor by profession and Queensland Manager of QASCO. He concerns particularly with aerial photography, aerial surveying and mapping, and engineer surveying.

ABSTRACT

GPS/INS integrated systems have been used in mapping applications for direct geo-referencing, which needs very accurate position and attitude solutions. However, due to the limited constellation of GPS satellites and their geometric distribution, the accuracy of GPS positioning

cannot meet the requirements of large scale aerial photogrammetry.

A GPS/INS integrated system with pseudolite (PL) augmentation for large scale airborne surveying is introduced in this paper. Comprehensive analysis is conducted for geometry design of the integrated system for airborne surveying. Only appropriately located PL can strengthen the GPS satellite geometry significantly, and minimize the impacts of PL location errors and the tropospheric delay modelling error at the same time.

As PLs are comparatively close to receivers, the unit vectors from a PL to the reference and rover receivers can be significantly different. Tropospheric delay modelling error cannot be effectively mitigated in the differencing procedure. PL signals only propagate through the lower troposphere, where it is very difficult to model the signal delay due to spatial variations of atmospheric parameters and dense water vapour. Several models are introduced and evaluated in this paper for accurately estimating the PL tropospheric delay. Estimation of the PL troposphere modelling errors in a Kalman filter can improve position accuracy further.

An extended Kalman filter is applied to process INS raw measurements and GPS/PL carrier phase data for system integration. Carrier phase ambiguities are estimated using the combination of GPS and PL code and phase observations. Double differenced GPS and PL measurements are processed to get initial positioning results. Computed positions based on fixed ambiguities, together with initial Kalman filter parameters are used to initialize the tightly coupled integrated system. Close-loop update in the system corrects INS errors, as the estimated errors are fed back to the inertial solutions. The inertial position errors are limited to the centimeter level. The INS measurement processed by the filter provides the relative movement during each GPS epoch and can be used to detect and repair GPS/PL cycle slips. The integer ambiguities are fixed by an OTF searching method before the filter updating.

INTRODUCTION

GPS aided positioning systems have been widely applied for airborne surveying, which can reduce the number of ground control points dramatically (Abdullah et al., 2002; Kwon and Jekeli, 2001; Lapine, 1996). Whilst GPS pseudo-range positioning is utilized for real time navigation during aerial image acquisition, carrier phase differential GPS positioning is applied for the camera exposure station location in a post-processing mode. However, even if decimetre level accuracy can be achieved by airborne carrier phase DGPS in an ideal situation, the accuracy of camera exposure positions is normally much worse than it. The accuracy of the camera exposure positions getting from GPS is limited by a number of factors, such as GPS positioning accuracy and data rate, lever arm and airplane attitude variation etc.

GPS/INS integrated systems are also being introduced to minimize positioning error and for direct geo-referencing, which needs very accurate position and attitude solutions (Cramer, 2003; Grejner-Brzezinska, 1997; Kwon and Jekeli, 2001). In GPS/INS integrated systems, high accuracy GPS measurements are used to estimate and 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, INS can provide short time precise position, which can be used for GPS cycle slip detection and repair. However, due to the limited constellation of GPS satellites and their geometric distribution, GPS has limited positioning accuracy, availability and integrity. The accuracy of GPS positioning in vertical coordinate is much worse than that of the horizontal coordinate components. This cannot meet the requirement of direct geo-referencing for large scale aerial photogrammetry.

This problem can be handled by the inclusion of additional ranging signals transmitted from ground-based pseudolite (PL). PLs are transmitters that broadcast GPS (or similar) signals. Ground-based PLs can strengthen the measurement geometry dramatically for airborne GPS based geo-referencing systems (Lee et al., 2002). As a result, positioning accuracy and reliability can be improved, especially in the vertical component. PL signals can also support integer ambiguity resolution (Lee et al., 2003), which is the key for carrier phase based precise positioning. As PLs are comparatively close to the user receivers, some challenging issues in systematic error analyses and modelling need to be investigated.

A GPS/INS integrated system with PL augmentation for large scale airborne surveying is introduced in this paper. PL modelling and geometry design are discussed. Comprehensive analysis is conducted for geometry design of the integrated system for airborne surveying, aiming to

optimally strengthen GPS satellite geometry, and minimizing impacts of PL location error and tropospheric delay modelling error at the same time. Several models are introduced and evaluated in this paper for improving PL tropospheric delay estimation. As PLs are comparatively close to receivers, the unit vectors from a PL to the reference and rover receivers can be significantly different. Tropospheric delay modelling error cannot be effectively mitigated in the differencing procedure. Adaptive estimation for PL troposphere modelling error is needed in the integration to improve position accuracy. A tightly coupled extended Kalman filter is applied to process INS raw measurement and GPS/PL carrier phase data for filter measurement update and estimating airborne camera position and attitude.

GPS/INS/PL INTEGRATED SYSTEM

The basic structure of the proposed GPS/INS/PL integrated system is expressed in Figure 1. It includes two GPS/PL receivers (NovAtel OEM4, which can track both GPS and PL signals) used as the base and the rover receiver, and a medium accuracy high reliability strapdown INS (Boeing C-MIGITS II). Differential GPS and PL phase observations and high data rate IMU measurement are used to achieve high accuracy. As Kalman filtering is the most suitable method to combine INS and GPS/PL measurements, it is applied in the system. However, adequate dynamics and measurement covariance models for both INS and GPS/PL systems are required to achieve the potential system performance.

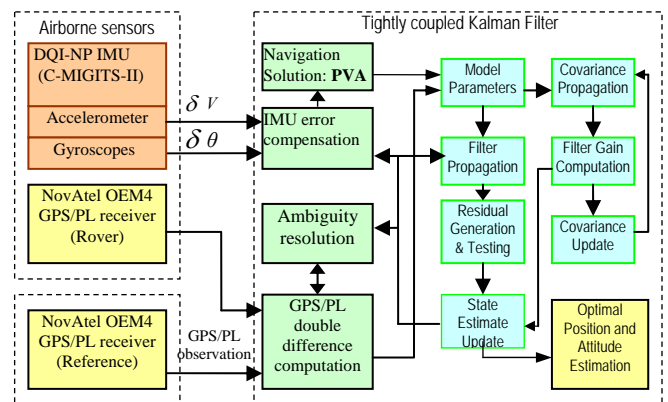


Fig. 1 PL augmented GPS/INS integration scheme

Data processing model of the integrated system is based on a tightly coupled extended Kalman filter (EKF) as used in the AIMS system (Brzezinska and Toth, 1999). Double differenced GPS and PL measurements are processed to get initial positioning results. Wideline and geometry-free ambiguities are estimated using GPS and PL code and phase observations. Computed positions based on fixed ambiguities, together with EKF initial parameters are used to initialize the integrated system. Then an extended Kalman filter is applied to process INS

raw measurement and GPS/PL carrier phase data with a tightly coupled algorithm.

After initialization, the EKF uses INS raw measurements and GPS/PL carrier phase data for the filter measurement update. A close-loop update corrects INS errors, as indicated in Figure 1. The estimated errors are fed back to update the inertial solutions. The close-loop update technique can limit the inertial position errors to the centimeter level when healthy GPS/PL signals can be received. The INS measurements processed by the filter provide the relative movement information during each GPS epoch and can be used to detect and repair GPS/PL cycle slips. The GPS/PL integer ambiguities are fixed by an OTF searching method before the filter updating. The ambiguities for satellites/PL whose tracking starts during the flight are also resolved OTF, using continuous positioning estimates from the Kalman filter. The ambiguity searching is done quickly because the searching space is considerably reduced due to the use of accurate initial coordinates from the INS, and the quick change of PL line-of-sight vector between epochs, which results in a well-conditioned matrix of ambiguity parameters (Lee et al., 2002).

Adequate mathematical models for the GPS/PL and INS are required to combine inertial and GPS measurements with EKF. The INS psi-angle error model is applied, which describe IMU sensor measurement errors, as well as the gravity anomaly and deflections. Both the accelerometer and gyro errors are modeled as random walks and the gravity uncertainty are modeled as first-order Markov process. GPS/PL measurement error states are also in the filter as random walks, because tropospheric delay modeling errors may be significant for GPS/PL measurements. The GPS/PL antenna lever arm errors are also estimated in the filter. State equations are expressed as Equation (1). The matrices F_{11} , F_{12} , F_{13} , F_{14} and F_{22} connect the sensors error sources and navigation solution errors. Details of the matrices can be found in Da et al. (1996). The number of states equals to 24, plus the number of double differences if GPS/PL measurement error states are included.

$$\begin{bmatrix} \dot{\mathbf{x}}_{Nav} \\ \dot{\mathbf{x}}_{Grav} \\ \dot{\mathbf{x}}_{Acc} \\ \dot{\mathbf{x}}_{Gyro} \\ \dot{\mathbf{x}}_{Ant} \\ \dot{\mathbf{x}}_{GPS} \end{bmatrix} = \begin{bmatrix} F_{11} & F_{12} & F_{13} & F_{14} & 0 & 0 \\ 0 & F_{22} & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} \mathbf{x}_{Nav} \\ \mathbf{x}_{Grav} \\ \mathbf{x}_{Acc} \\ \mathbf{x}_{Gyro} \\ \mathbf{x}_{Ant} \\ \mathbf{x}_{GPS} \end{bmatrix} + \begin{bmatrix} \mathbf{w}_{Nav} \\ \mathbf{w}_{Grav} \\ \mathbf{w}_{Acc} \\ \mathbf{w}_{Gyro} \\ 0 \\ \mathbf{w}_{GPS} \end{bmatrix} \quad (1)$$

where \mathbf{x}_{Nav} , \mathbf{x}_{Grav} , \mathbf{x}_{Acc} , \mathbf{x}_{Gyro} , \mathbf{x}_{Ant} and \mathbf{x}_{GPS} are the error vectors of the inertial navigation solution (position, velocity and attitude), the gravity anomaly and deflections errors, the accelerometer measurement errors (bias and

scaling factor), the gyro measurement error (drift), the antenna lever arm errors, and GPS/PL tropospheric delay errors, respectively; \mathbf{w}_{Nav} , \mathbf{w}_{Acc} , \mathbf{w}_{Gyro} , \mathbf{w}_{Grav} and \mathbf{w}_{GPS} are all zero-mean Gaussian white noise vectors.

In order to optimally apply PL augmentation for airborne GPS/INS integrated systems, it is necessary to analyse PL modelling and geometry design, especially the impact of the PL tropospheric delay modelling, the number of GPS satellites and their geometry change. The sensitivity of PL augmentation results with respect to the change of flight height is also investigated.

GEOMETRY ANALYSIS

It is well known that the geometry of GPS satellites can be enhanced with PL augmentation, especially in the vertical component. This is more obvious for airborne applications because a negative elevation angle is observed from the airborne receiver to a PL. A comprehensive analysis is conducted for the site design of PL augmented airborne surveying (Wang et al., 2004). Appropriately located PL can strengthen GPS satellite geometry and minimize the impacts of PL location error and the tropospheric delay modelling error at the same time. Consequently it makes a large improvement on the reliability and accuracy of the final positioning solution. The best PL location at a certain time also depends on the GPS satellite constellation and the rover receiver moving range. The reference receiver location is also important for PL augmentation. In general, locating the reference receiver at the centre of a surveying area and the PL outside it at a proper direction and a distance can minimize impacts of PL location error and the tropospheric delay modelling error, and reduce the DOP value at the same time (Wang, 2005).

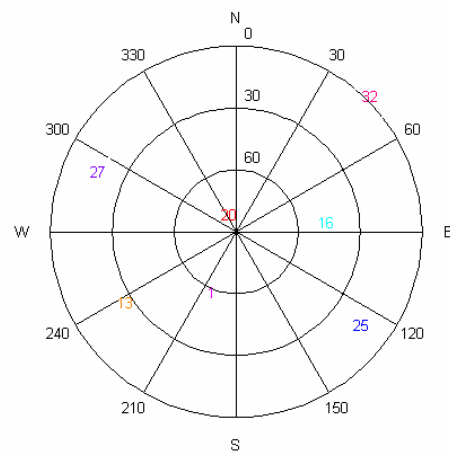


Fig. 2 Sky plot for GPS and PL

PL augmentation for large scale airborne surveying scenario is analysed. As shown in Figure 2, one PL (PRN 32) is located at north-east relative to the reference

receiver, which is the optimal location for augmenting the GPS satellite constellation in Figure 2. The positioning results with and without PL augmentation at different flight height with different number of GPS satellites are analysed.

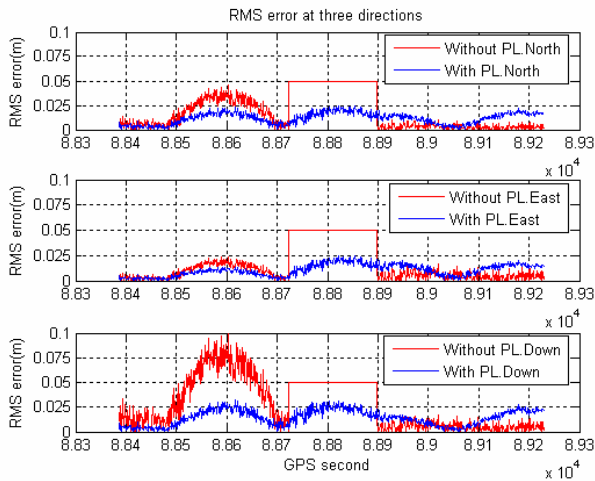


Fig. 3 The RMSs of positioning results by GPS and GPS/PL with 4 to 5 GPS satellites at flight height 450m

Figure 3 shows the RMS of positioning results at three directions with 4 to 5 GPS satellites at 450 meter flight height. As shown in the figure, the RMSs of GPS only positioning is very sensitive to the satellite geometry change. There are five GPS satellites from 8.84 to 8.87 ($\times 10^4$ GPS second) but the geometry is getting worse, so the RMSs are high. Only four satellites available from 8.87 to 8.89 ($\times 10^4$ GPS second) thus no RMS can be calculated. A constant value of 5cm is displayed in the figure. Five satellites with a better geometry can be observed from 8.89 to 8.92 ($\times 10^4$ GPS second) so the RMSs are quite small. The RMS of vertical component is much worse than horizontal components. With PL augmentation, on contrast, the RMSs remain relatively stable during the whole period, and the vertical component is improved significantly.

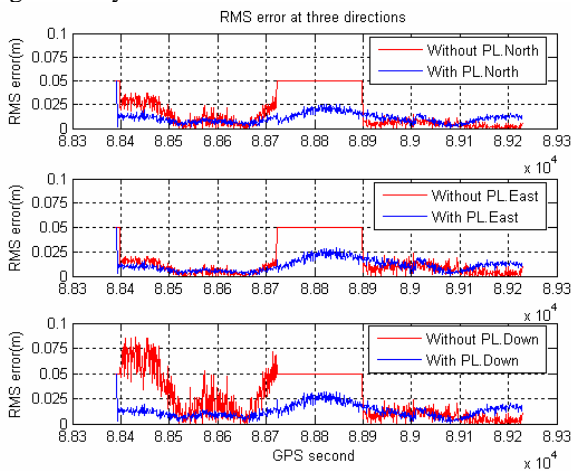


Fig. 4 The RMSs of positioning results by GPS and GPS/PL with 4 to 5 GPS satellites at flight height 3000m

Figure 4 shows the RMSs of positioning results at 3000m flight height, which is more or less similar to Figure 3. This means that the PL augmentation results do not heavily depend on the change of flight height of airborne surveying. The same geometry design can be used to different flight heights.

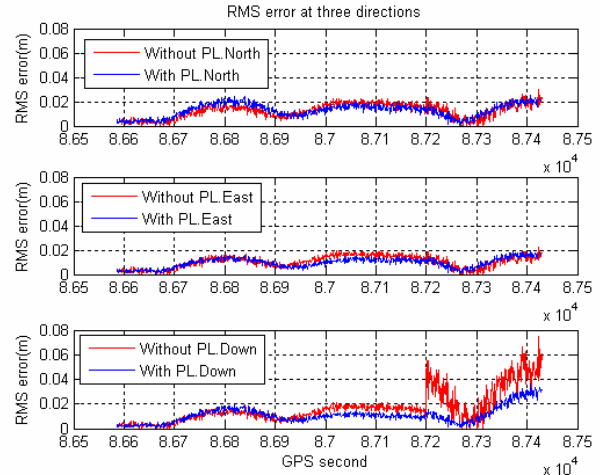


Fig. 5 The RMSs of positioning results by GPS and GPS/PL with 5 to 6 GPS satellites at flight height 450m

Figure 5 shows the results with 5 to 6 GPS satellites at flight height 450m. PL augmentation is very effective when only five satellites are available (from 8.72 to 8.75 $\times 10^4$ GPS second), but not for six or more satellites.

Obviously, it can be concluded from the above analysis that PL can augment airborne GPS positioning effectively, particularly when the number of GPS satellites is less than six or their geometry is weak. With PL augmentation, positioning accuracy of the vertical component is improved evidently, even better than corresponding horizontal components. The RMSs of positioning results are improved with PL augmentation and remain stable when the GPS constellation changes. Furthermore, PL augmentation results are not sensitive to the flight height of airborne surveying.

PL TROPOSPHERIC DELAY MODELLING

GPS tropospheric delay can be effectively mitigated in differencing procedure. This is due to the fact that signal propagation paths from a satellite to a ground reference station and a user receiver are largely the same. For a ground based PL, however, the paths from it to a reference and a user receiver can be significantly different. Accordingly PL tropospheric delay cannot be effectively mitigated in differencing procedure. Furthermore, it is very difficult to model PL tropospheric delay due to spatial variations of atmospheric parameters and dense water vapour in lower troposphere, where PL signals propagate through. The variation in atmospheric condition can easily change the differential tropospheric

delay on the order of ± 20 cm (Barltrop et al., 1996). Even more momentous for airborne applications, tropospheric delay is also strongly dependent on vertical differences. Therefore, an advanced PL tropospheric delay estimation strategy has to be applied in a PL augmented GPS/INS system for high accuracy positioning.

In principle, tropospheric delay is the integration of local refraction index along a signal path. However, as it is impossible to measure local meteorological data or refraction index continuously along a signal path, all the models compute the delay with meteorological data at one point (receiver), which varies slowly and may not reflect the troposphere condition along the signal path.

The typical approach for tropospheric correction is to use a model to estimate the delay. Several models, grouped into two methods, have been introduced and evaluated for estimating PL tropospheric delay (Wang et al., 2004a). One method is to compute the delay as a function of the local refraction index along the signal path. Another method utilizes single-differenced GPS tropospheric delay models, which are relatively well developed and can reach very high accuracy, but may have large biases at low elevation angles.

The tropospheric delay models as a function of local refraction index (Biberger et al., 2003; Bouska and Raquet, 2003; RTCA, 2000) consist of a dry (hydrostatic) and a wet component, which can be determined separately by Equation (2) :

$$\Delta_*^{trop} = 10^{-6} \cdot N_{*,0} \cdot R_r \cdot F(h_r, h_{PL}, h_{*,0}) \quad (2)$$

The “*” in Equation (2) expresses the parameters for dry and wet respectively. The receiver height h_r and PL height h_{PL} in Equation (2) declare the importance of the vertical distance for troposphere modeling while R_r is the slope distance between the receiver and PL. The $h_{*,0}$ is defined as the upper boundaries for dry or wet troposphere refraction. It is empirically fixed height in a model or as a function of temperature in other models (Zhang and Barton, 2005). The refraction index N_* is determined by local meteorological data with Equation (3):

$$N_{dry,0} = 77.6 \cdot \frac{P}{T} \quad \text{and} \quad N_{wet,0} = 22770 \cdot \frac{f}{T^2} \cdot 10^{\frac{7.4475 \cdot (T-273)}{T-38.3}} \quad (3)$$

where T is temperature (K), f is the relative humidity (%) and P is the atmospheric pressure (mb) measured at the station.

The models derived from the single-differenced GPS tropospheric delay models, such as Saastamoinen model (Remond, 2000) and NMF model (Niell, 1996), are empirically based on the zenith angle, atmospheric

pressure, water vapour pressure, height of the observing site, the latitude and even the day of the year.

The impact of the local meteorological data for GPS and PL tropospheric delay estimation is demonstrated in Figure 6. It compares the carrier phase double difference between two GPS satellites (SV28 & SV7) and between a PL (SV12) and the reference GPS satellite (SV28), with short baseline flight test data. Different relative humidity was applied in both GPS and PL tropospheric delay models. It is obvious that the PL tropospheric delay is much more sensitive to local meteorological data. Therefore PL tropospheric delay estimation requires more accurate meteorological data than GPS satellites.

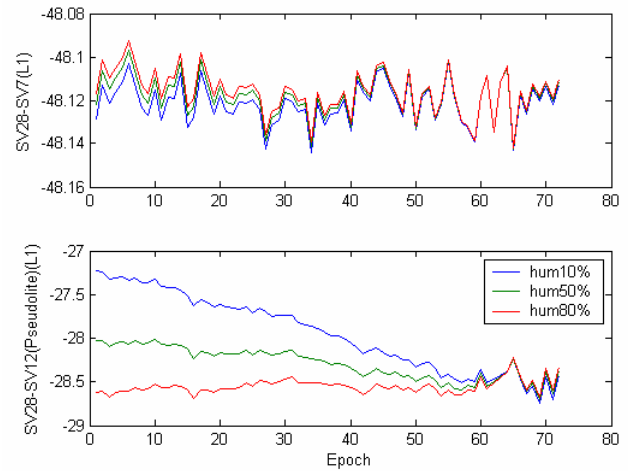


Fig. 6 Carrier phase double difference results of different meteorological data applied to Tropospheric delay models.

Local refraction index or local meteorological data should be estimated as slowly varying parameters. For differential positioning, local refraction index at a reference receiver can be estimated with a proper tropospheric model, and then it can be used to correct rover tropospheric delay on both PL and GPS signals. This method eliminates the need to obtain local meteorological data. A simple model was introduced for PL tropospheric delay estimation (Barltrop et al., 1996; Farrell and Barth, 1999) and claimed the estimation error less than 10 cm over a distance of 10 km compared to 1 m using a season model. Another method uses real-time meteorological based troposphere (RMT) models to provide troposphere error corrections. The meteorological data can be measured from a reference station or user if equipped. Otherwise, the data can be estimated from a nearby network site. All the models introduced above, except NMF, can use this method. Another RMT model introduced by Zhang and Barton (2005) consists of a Hopfield (wet and dry) zenith troposphere delay models and a Chao mapping function.

In brief, PL tropospheric delay is more sensitive to local meteorological data, and has higher modelling error compared to GPS measurements. Moreover, differential process cannot effectively reduce PL tropospheric delay modelling error for airborne applications even with proper geometry design. Thus further improvement is required to estimate PL tropospheric delay modelling error in the integrated system. As mentioned in Equation (1), the estimation of PL and GPS tropospheric modelling errors in EKF is applied to improve PL augmented positioning accuracy, with details in the following section.

SYSTEM TEST

In order to evaluate the performance of the integrated system, GPS, INS and PL measurements were simulated and processed. The AIMS software from the Centre for Mapping at Ohio State University was modified to include the PL data. GPS/PL, GPS/INS and GPS/INS/PL integrated positioning results were obtained and compared with true trajectory. Primary test results demonstrate the benefit of PL augmentation for a GPS/INS integrated system in large scale airborne surveying scenario.

Figure 7 plots the true trajectory together with the measured trajectories of GPS/PL/INS, GPS/INS and GPS/PL integrated systems respectively. It is obvious that positioning accuracy and measurement noise of vertical component is improved dramatically by PL augmentation for both GPS/PL and GPS/PL/INS integration, comparing with GPS/INS integration.

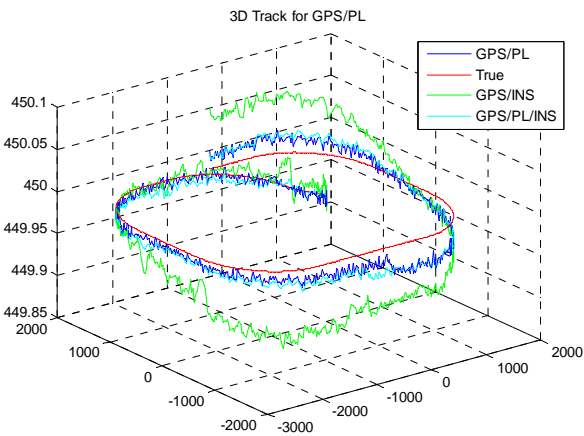


Fig. 7 Trajectory comparison integration scheme

Table 1 lists the STD of the positioning errors at three directions with different positioning procedures. As shown in Table 1, GPS only and GPS/INS integrated system have similar performances. The accuracy of vertical component was much worse than that of the horizontal components. With PL augmentation, however, positioning accuracy of vertical component was improved dramatically in both GPS/PL and GPS/PL/INS cases,

even better than corresponding horizontal components. GPS/PL/INS integration has the best performance among all the procedures though GPS/PL positioning result is also competitive. It should be noticed that the above tests are based on ideal GPS PL measurements without tropospheric delayed applied.

STD (cm)	GPS/PL/INS	GPS/PL	GPS/INS	GPS
North	1.47	1.79	2.34	2.35
East	1.55	1.97	1.63	1.64
Down	1.29	1.43	4.31	4.36

Table 1 STD of positioning results with different integration systems

In order to evaluate the effect of estimation of PL and GPS tropospheric modelling errors in EKF of the integrated system, The EKF processes the GPS/PL double differenced phases combined with the inertial solution with two methods. One method uses the first 24 states in Equation (1) without GPS/PL tropospheric modelling errors error states; the other one includes them. As PL tropospheric delay is much more sensitive to local meteorological data, and has higher modelling error compared to GPS measurements, states estimation bias of PL tropospheric delay in the EKF are set five times larger than that of GPS. These biases can also be changed according to the altitude difference between reference and user receivers.

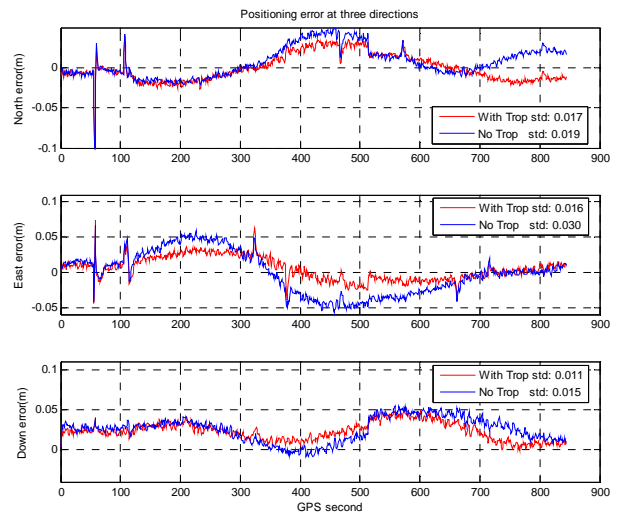


Fig. 8 Error of integrated solutions with and without tropospheric delay error states in EKF.

The Positioning errors of PL augmented airborne GPS/INS system with and without tropospheric delay error states in the EKF are shown in Figure 8. Some improvement was achieved by adding the tropospheric error states in the EKF at all the three directions. The small sparks in the North and East directions are mainly due to the airplane horizontal maneuver. Further

investigation for the EKF adjustment and modification will be conducted to get better position results.

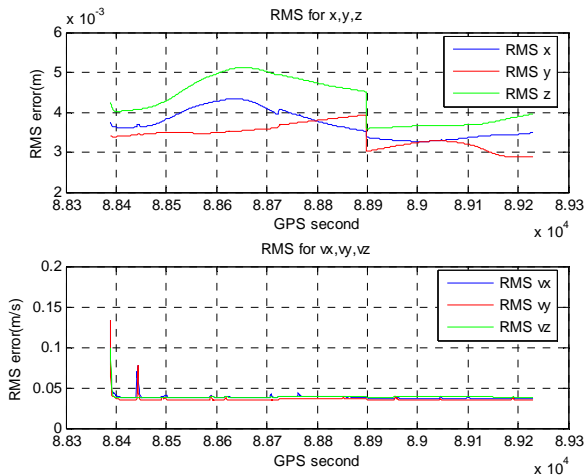


Fig. 9 The RMSs of position and velocity estimated by the integrated GPS/INS/PL system

Figure 9 displays the RMSs of position and velocity processed by the GPS/INS/PL system with tropospheric delay error states in the EKF. The RMS of position results was at the millimeter level and the RMS of velocity estimation was converged quickly to about 0.04m/s.

CONCLUDING REMARKS

An integrated airborne GPS/INS/PL system is introduced in this paper, mainly focusing on PL augmentation. The algorithm and software structure, and initial testing results are described. The impact of PL augmentation on airborne GPS/INS positioning is demonstrated by analysing test results of GPS/INS, GPS/PL and GPS/PL/INS integration. PL can augment airborne GPS positioning effectively when the number of GPS satellites is less than six or the satellites geometry is weak. The positioning accuracy of the vertical component is improved evidently. With PL augmentation, the RMSs of positioning results can be improved and remain stable when GPS constellation changes. PL augmentation results are not sensitive to the flight height of airborne surveying.

Test results have demonstrated that the PL tropospheric delay is very sensitive to local meteorological data, and has higher modeling error compared to GPS satellites. As differential process cannot effectively reduce PL tropospheric delay modeling errors, accurate tropospheric delay model and local meteorological data are required for the PL measurements. Further improvement for PL tropospheric delay estimation in the EKF has been achieved by introducing tropospheric delay error states in the filter. The performance of the proposed PL augmented airborne GPS/INS integrated system has been evaluated through simulations, indicating the potential to meet the

requirements for large-scale airborne surveying or aircraft landing with proper modelling and processing strategies.

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