ARTIFICIAL SATELLITES, Vol. 46, No. 2 - 2011
DOI: 10.2478/v10018-011-0010-6

PRECISE POINT POSITIONING IN THE AIRBORNE MODE

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ABSTRACT. The Global Positioning System (GPS) is widely used for positioning in the airborne mode such as in navigation as a supplementary system and for geo-referencing of cameras in mapping and surveillance by aircrafts and Unmanned Aerial Vehicles (UAV). The Precise Point Positioning (PPP) approach is an attractive positioning approach based on processing of un-differenced observations from a single GPS receiver. It employs precise satellite orbits and satellite clock corrections. These data can be obtained via the internet from several sources, e.g. the International GNSS Service (IGS). The data can also broadcast from satellites, such as via the LEX signal of the new Japanese satellite system QZSS. The PPP can achieve positioning precision and accuracy at the sub-decimetre level.

In this paper, the functional and stochastic mathematical modelling used in PPP is discussed. Results of applying the PPP method in an airborne test using a small fixed-wing aircraft are presented. To evaluate the performance of the PPP approach, a reference trajectory was established by differential positioning of the same GPS observations with data from a ground reference station. The coordinate results from the two approaches, PPP and differential positioning, were compared and statistically evaluated. For the test at hand, positioning accuracy at the cm-to-decimetre was achieved for latitude and longitude coordinates and doubles that value for height estimation.

Keywords: Precise Point Positioning, GPS, aviation, navigation.

1. INTRODUCTION

The use of the global navigation satellite systems (GNSS) for navigation in civil aviation is expanding. It is estimated that from 2015, most new commercial aircraft will be fitted with a GNSS system to enhance precise navigation and make it safer (Pedreira, 2009). At the moment, GPS is approved as a stand-alone aid for non-precision approaches (Radišić, 2010), e.g. as a supplementary navigation system, and for positioning of non safety-of-life applications such as aerial mapping. Due to the presence of satellite, media and receiver errors, a GPS system in a standalone mode can generally produce positioning with accuracy from 1 to 10 m using phase-smoothed code observations. Therefore, some techniques are required to reduce measurement errors in order to use the system for applications demanding better accuracy, such as aerial mapping in post-mission processing, or aviation in real time. For instance, in CAT-I phase of aviation, which includes enroute flying, positioning by GPS is dependent on receiving corrections from Satellite Based Augmentation Systems (SBAS), such that a positioning accuracy at the range 1-3 m can be achieved. However, in CAT-III, which is a more demanding phase in aviation as the aircraft gets into the final approach and landing, accuracy better than 0.6m is usually required in estimation of the height and 3 m in horizontal coordinates. It is proven with the continuous development of real-time single or network reference systems that with a good set of phase-measurement corrections, such required accuracy and precision can be met (El-Mowafy, 2008). However, other factors, such as integrity, availability and reliability need to be addressed when considering GPS in the airborne navigation.

Traditionally, GPS positioning errors are reduced by double differencing of the rover measurements with observations from a reference station of known coordinates, making centimetre-accuracy positioning possible. The shortcoming of this approach is the need to use synchronous measurements at the reference and the rover, and that the reference-to-rover distance should typically be less than 30 km. Currently, in the airborne mode, these two conditions are hard to achieve all the time, particularly for aviation, as firstly, it is expensive to send the reference station data in real time to the aircraft, and technically, it is hard to maintain receiving the corrections without experiencing some breaks. Secondly, finding a reference station that is located within a reasonable range might be difficult for cases such as emergency landing or rescue operations.

An alternative method of processing GNSS measurements is the PPP approach, which is based on the processing of un-differenced observations from a single GPS receiver, and employing precise satellite orbits and clock corrections. Therefore, no reference stations are needed. However, to reach sub-decimetre positioning accuracy, the phase measurements should be used, and thus, their ambiguities should be determined. Typically, they are computed as float ambiguities with real values along with the positioning unknowns (Kouba and Héroux, 2001). As a result, a long time is needed, typically from 15 to 30 minutes, for the solution to converge before a reliable estimate of the float ambiguities can be determined (Ge *et al*., 2008). In this paper, a brief presentation of the PPP method and its application in the airborne mode is given. Results of an airborne test using PPP for positioning of a fixed-wing aircraft will be presented and discussed.

2. FUNCTIONAL MODELLING OF THE PPP METHOD

The code and phase observation equations of the GPS can be formulated in metre units as follows:

$$\rho_{(t)} = r_{(t,\, t-\tau)} + ds_{(t-\tau)} + cdT_{(t)} - cdt_{(t-\tau)} + d_{iono} + d_{tropo} + \varepsilon(\rho) \quad (1)$$

$$\phi_{(t)} = r_{(t,\, t-\tau)} + ds_{(t-\tau)} + cdT_{(t)} - cdt_{(t-\tau)} - d_{iono} + d_{tropo} + \lambda N + \varepsilon(\phi) \quad (2)$$

where $\rho_{(t)}$ and $\phi_{(t)}$ are the pseudo-range code and the phase measurements, respectively, at the time of receiving the data (t), $(t-\tau)$ denotes the satellite time, where τ refers to the travel time between the satellite and the receiver. $r_{(t,\, t-\tau)}$ is the true geometric range, ds is the orbital error, c denotes the speed of light, dT and dt are the receiver and satellite clock errors, d_{iono} and d_{tropo} are the ionosphere and troposphere delays, respectively. λ denotes the carrier-phase wavelength, N is the integer phase ambiguity, and ε denotes the measurement noise, including multipath and the antenna phase centre variation.

To reduce orbital errors in the PPP approach, the user needs to utilize precise orbits. In addition, due to the fact that GPS satellite clocks are difficult to be modelled; corrections to satellite clocks are used. The precise orbits and clock corrections can be obtained from the International GNSS Service (IGS) via the internet. Table 1 gives an overview of IGS currently available satellite products, which shows the accuracy, expected latency in updating these products, frequency of updates, and sample interval (Van Bree *et al*., 2009). In general, best results can be obtained using the Final IGS products; however, this is only applicable for post-processing applications. For real-time applications, a communication link is needed to download the products, and under the Real Time (RT)-IGS pilot project, ‘near’ real-time products are currently being developed with an accuracy and sampling interval that give the user the possibility to obtain results near the results obtained with Rapid IGS products. For the user that has no real-time communication link, the Predicted IGS orbits can be used; however, they give the least accuracy. A few organizations are currently developing real-time products, such as the REal-Time system for CLock Estimation (RETICLE) by the German Space Operations Centre of DLR, The NASA Global Differential GPS (GDGPS) System, and Natural Resources Canada (NRCan).

Table 1. Precise orbits and clock corrections available

GPS Satellite Ephemerides / Clock Corrections	Accuracy Orbits/Clocks	Latency	updates	Sample Interval
Broadcast	100 cm/ 2.5ns	Real time	daily	2 hr
Ultra Rapid (predicted)	5 cm/ 1.5ns	Real time	at 03, 09, 15, 21 UTC	15 min
Rapid	2.5 cm/ 25ps	17-41 hr	at 17 UTC	15 min/ 5min
Final	2.5 cm/ 20ps	13-18 days	Thursdays	15 min/ 30 sec
RETICLE (FTP)	2.5 cm/ 0.5ns	5 sec	10 sec	10 sec

The ionosphere can be considered the dominant source of error in GPS positioning. Since the ionosphere is dispersive, i.e. frequency dependent, the most common method of PPP is to use a combination of dual frequency observations to eliminate the first-order ionospheric error, which accounts for more than 99% of this error. In addition, to minimize the impact of noise from code measurements, a code-phase combination in the form of their average can be used for the two frequencies (Shen, 2002). This significantly helps in convergence of the PPP solution if the value of the remaining errors is small enough, particularly while solving for the float ambiguities. The ionosphere has the same value for the code and phase measurements but with the opposite sign, thus, their average eliminates the ionosphere error. The observation equations then read:

$$\rho^{IF}_{Li(t)} = \frac{P(Li)+\phi(Li)}{2} = r_{(t,\,t-\tau)} + ds_{(t-\tau)} + cdT_{(t)} - cdt_{(t-\tau)} + d_{tropo} + 0.5\,\lambda_i\,N_i + 0.5(\varepsilon(\rho(Li)+\phi(Li)) \tag{3}$$

$$\phi^{IF}_{(t)} = \frac{f_1^2.\phi_1 - f_2^2.\phi_2}{f_1^2 - f_2^2} = r_{(t,\,t-\tau)} + ds_{(t-\tau)} + cdT_{(t)} - cdt_{(t-\tau)} + d_{tropo} + \frac{c.f_1.N_1 - c.f_2.N_2}{f_1^2 - f_2^2} + \varepsilon(\phi^{IF}) \tag{4}$$

where IF denotes the ionosphere free operator, f_1 and f_2 are the frequencies of the carrier waves L1 and L2, respectively, *i* is the frequency operator, where *i*=1 for L1 and i=2 for L2. The total tropospheric range delay resulting from propagation of the satellite signals through the neutral atmosphere is expressed as the sum of the hydrostatic and wet components. Range delays resulting from the hydrostatic component of the dry troposphere, which is the major part of tropospheric error, can be computed with an accuracy of a few millimetres using empirical models (e.g. Saastamionen, Hopfield, etc.). In addition, a good mapping function is required to project the satellite-to-user troposphere delay into the zenith direction, such that only one troposphere unknown is considered for all observed satellites. The wet part of the troposphere (approximately 2-10% of the total) is hard to model as it needs wet vapour measurements, which are usually not available to normal users. Thus, in PPP, if detailed values of the wet troposphere zenith delay are not available from a local network, this error is taken as an additional unknown.

The estimation of un-differenced ambiguities in PPP can be carried out using an on-the-fly approach in the standalone mode. However, a non-zero initial phase bias is experienced due to the un-synchronization of the satellite-transmitted and receiver-generated signals. Accordingly, the ambiguities in PPP are real numbers (Gao, 2006). This bias is usually cancelled out in the traditional double-differencing approach. Thus, in PPP integer un-differenced ambiguities can first be estimated as constants. Next, they are adjusted to their float numbers as the data accumulate and the processing filter converges to a stable condition. This convergence process usually takes several minutes (typically 15 to 30 minutes) leading to one of the main limitations of PPP. With the addition of the initial phase bias, the iono-free phase observation can be re-written as follows:

$$\phi^{IF}_{(t)} = \frac{f_1^2.\phi_1 - f_2^2.\phi_2}{f_1^2 - f_2^2} = r_{(t,\ t-\tau)} + ds_{(t-\tau)} + cdT_{(t)} - cdt_{(t-\tau)} + d_{tropo} + \frac{c.f_1.(N_1 + \phi_{1r}(t_o) - \phi_{1s}(t_o)) - c.f_2.(N_2 + \phi_{2r}(t_o) - \phi_{1s}(t_o))}{f_1^2 - f_2^2} + \varepsilon(\phi^{IF}) \quad (5)$$

Where ($\phi_{1r}(t_o)$, $\phi_{2r}(t_o)$) and ($\phi_{1s}(t_o)$, $\phi_{2s}(t_o)$) are the receiver and satellite initial phase biases for the L1 and L2 frequencies respectively. Since the phase bias for a particular satellite is the same for all receivers, a method to estimate the satellite initial phase bias has been proposed in Ge *et al.*, 2008 based on network processing. The long term stability of the satellite initial phase bias makes its determination in advance and broadcast along with clock corrections an acceptable approach. In this case, PPP ambiguity solution at the user end deals only with estimation of the receiver initial phase bias. Some techniques were proposed for such ambiguity estimation; see for instance Abdel-Salam 2005, Wang and Gao 2006-2007, and Banville *et al.* 2008.

The main vector of unknowns in PPP processing typically includes the three position coordinate parameters $(x, y, z)_u$, a receiver clock offset parameter, the Zenith Wet tropospheric component (*ZWD*), where the hydrostatic component of d_{tropo} is modelled out, and the float ambiguities. The state vector can be formulated as (El-Mowafy, 2007):

$$\bar{X}_u = [\ (x, y, z)_u, c\ dT_{(t)}, ZWD, (N)_{1 \ldots n}\ ]^T \quad (6)$$

Where n is the number of observed satellites. One however should note that since positioning is performed without differencing, some errors that are mostly eliminated in the differential approach have to be modelled out in the PPP approach. These errors are basically attributed to physical phenomena, and include:

- relativity error, which is a function of the satellite motion and the Earth's gravity;
- Sagnac delay caused by the Earth's rotation during the transition time of the satellite signal;
- phase wind up, due to the relative motion and rotation of the satellite and receiver;
- inter-frequency bias, resulting if using L1 or L2 alone.

Some information about the definition and modelling of these errors are given in Abdel-Salam 2005, Lahaye *et al.* 2008. In the airborne mode, errors such as earth tide and ocean tide loading, which are considered for land applications, are ignored.

3. STOCHASTIC MODELLING IN PPP

Obtaining a consistent stochastic model is important in the estimation process. However, such a task is still a challenge. An incorrect stochastic model makes it difficult to estimate good float ambiguities, and accordingly inaccurate positioning. A good stochastic modelling should involve representation of stochastic behaviour of single measurement errors, their possible cross-correlation and temporal correlation. An example of stochastic modelling used in PPP in the airborne mode is given in Table 2 (El-Mowafy, 2009).

Table 2. Example of Stochastic modeling in PPP

Component	**Stochastic model**	**Assumed initial stochastic parameters**
Measurements	Uncorrelated individual code and phase measurements.	weight is a function of satellite elevation angle
Position	random-walk process	spectral density= 10^5 m^2/s
Receiver clock error	random-walk / white noise process	spectral density= 10^5 m^2/s
wet troposphere	first order Gauss-Markov process	correlation time can be taken as several minutes. Spectral density = 8 $x10^{-12}$ m^2/s
Ambiguities	constant	-
Initial phase biases	constant	-

4. SOME ASPECTS IN USING PPP IN THE AIRBORNE MODE

Applying PPP in post-mission data processing can without difficulty be performed in the airborne mode if data longer than 20-30 minutes can be collected, which is the time needed to estimate good real values for the ambiguities. Thus, PPP can be implemented in aerial mapping and post-mission surveillance. While positioning can be carried out as usual after determination of the ambiguities, a position solution accurate to the sub-decimetre level can be obtained for the period taken for ambiguity determination by backward processing of data.

For real-time applications, such as aviation and real-time surveillance, obtaining the precise orbits, satellite clock corrections or atmospheric corrections can represent a problem. Technically, this information can be received through the internet via satellite communication. However, this is an expensive option. The cheaper option is to get the precise orbits and satellite clock corrections through dedicated “free-to-air” satellite signals, such as the LEX signal of the Japanese system Quasi-Zenith Satellite System (QZSS). The operational phase of the signal has started in June 2011.

The available IGS predicted part of the Ultra-Rapid clock corrections, as compared to the Final clock errors increases almost linearly with time from the beginning of the predicted part, reaching several nano seconds (Van Bree *et al.* 2009). Currently, near real-time clock products can be obtained from the Real-Time Clock Estimation (RETICLE) system, developed at German Space Operation Centre. These clock products are globally valid. Van Bree *et al.* (2009) showed that the RETICLE corrections, available as SP3c file, which can be accessed for a relaxed time user from an FTP server with 10 seconds intervals and 5 minutes updates, can achieve clock accuracies of a sub-nano second level. Alternatively, a much shorter latency of approximately 5 seconds can be achieved by receiving the RETICLE corrections via Networked Transport of RTCM via Internet Protocol (NTRIP)-Stream from a caster either in a binary format with compressed data of 5 seconds intervals and 10 seconds updates, or an ASCII format including the last 8 epochs in SP3-format (Van Bree *et al.* 2009). The NASA Global Differential GPS (GDGPS) System is another alternative, which provides 1 Hz corrections to the GPS spacecraft position and clock state that are globally and uniformly valid. Adding the corrections to the broadcast ephemerides gives the precise orbit and clock state of the spacecraft, accurate to better than 20 cm 3D RMS (Bar-Sever, 2011). The system has 4-6 seconds latency with orbits and clocks frequencies of 30 seconds and 1 second, respectively.

For use in real-time applications, such precise orbits and clock corrections have to be extrapolated (predicted). Prediction of orbits is not a critical task as they are usually stable. However, in PPP, prediction of satellite clock corrections has to be accounted for properly for each satellite as the change of drift rate varies among different satellites over time. In general, the Cesium clocks on the old block II/IIA of satellites perform worse than the Rubidium clocks used onboard the new satellites. For illustration, Figure 1 shows the change of the drift rate (in Ps/s) for 6 satellites over a period of 8 hours. The changes are computed referenced to the start of the 8 hour period, which is selected at the same date (1-11-2007) of the airborne test to be discussed in the next section. As shown from the figure, the drift rate of all satellites changes almost linearly with time, but with significant variation for different satellites. This makes prediction process of clock corrections an acceptable process over a few seconds. For the interested reader, a number of prediction methods for satellite clock corrections in the kinematic mode were discussed in El-Mowafy, 2008.

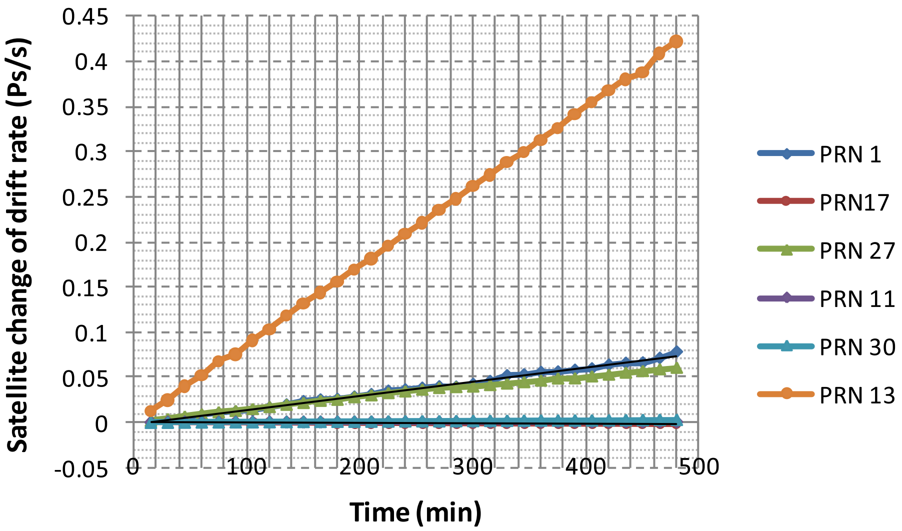

Fig 1. Satellite changes of drift rate over time (1-11-2007)

Due to the problem of current long convergence time of float ambiguities, the use of low accuracy clock corrections, as well as errors associated with the prediction of clock corrections, real-time PPP is still in the testing phase. In addition, taken into considering the integrity and availability concerns, in the mean time, PPP can only be used for airborne navigation in non-safety of life applications and not during CAT II or III. For instance, PPP can be used as a pack up positioning system during enroute flying and for airport surface navigation on low dynamics.

5. TESTING PPP IN THE AIRBORNE MODE

To evaluate the performance of PPP in the airborne mode, data from an airborne test conducted in Delft, Holland on 1st November, 2007, were processed and analysed. The data are provided courtesy of The Mathematical Geodesy & Positioning group, the Delft Institute of Earth Observation and Space Systems, Delft University of Technology, Netherlands. A Septentrio PolarRx2 dual-frequency receiver was used for GPS data collection, where the antenna was mounted on a small fixed-wing aircraft. The flight period was from 10:06:15 to 14:00:00 and the data were recorded at a sampling interval of 10 Hz.

The airborne data were first post processed using the PPP approach utilizing the online service provided by the Precise Point Positioning Software Centre (Banville *et al.*, 2009). The centre process data using different engines, including the Geodetic Survey Division (GSD) of Natural Resources Canada known as the Canadian Spatial Reference System PPP (CSRS-PPP), Automatic Precise Positioning Service (APPS) by Jet Propulsion Laboratory (JPL), GPS Analysis and Positioning Software (GAPS) by University of New Brunswick, and magicGNSS by GMV company. A comparison between the performances of different engines is not considered into the scope of this study. For consistency purpose, the main results presented here are obtained from APPS (Bar-Sever, 2011) and CSRS-PPP (Lahaye *et al.*, 2008). The computed positions are presented in the International Terrestrial Reference Frame (ITRF), Altamimi *et al.*, 2010. Since the data were collected in 2007, PPP processing used the final IGS satellite products. The processing also included cycle-slip filtering, applying satellite and receiver antenna phase centre offsets, and a reference frame transformation. The statistical information computed from PPP processing such as standard deviations will be shown to present precision of the method.

For accuracy assessment, the same GPS data of the aircraft receiver were processed in a differential mode with data from a ground reference station, collected at 1 Hz sampling rate. The PPP solution was compared with the solution of the differential positioning, where the latter was taken as the reference for comparison. This is due to the fact that differential positioning is a well established technique that can give mm to cm positioning accuracy as the ambiguities are fixed to their integer values and most errors are reduced or cancelled. The reference station was selected almost at the middle of the flying course to have the shortest distance possible to the terminal points, which are the most critical, range-wise. Since the rover data were collected at 10 Hz intervals, the rover solution was decimated to 1 Hz intervals for comparison with the differential solution.

Table 3 summarizes the precision obtained from the PPP solution in terms of the average and maximum values of the standard deviation (STD) for the whole data set for the unknowns: latitude and longitude coordinates, ellipsoidal height, receiver clock error, and Zenith dry+wet “Total” troposphere Delay (ZTD). The table also gives STD of point Cartesian coordinates (X, Y, Z). The coordinates were computed in the ITRF2005 at GPS observation epoch. As the Table 3 shows, the average values of standard deviations for point coordinates were at the sub-decimetre level. For most aerial mapping applications such precision is acceptable. The table also shows that maximum values of the standard deviations can reach a couple of decimetres. Figures 2 to 6 show the time series of the computed STD (denoted as σ) of the PPP computed unknowns. Note the change of vertical scale among these figures. Figures 7 and 8 illustrate the time series of the computed ZWD and ZTD, respectively. Results show that the solution has been stabilized with converged float ambiguities after approximately 16 minutes. GAPS solution can also provide the ionosphere estimation using a geometry-free carrier-phase observation model, solved connected to the PPP estimation filter (Leandro *et al.*, 2007). The estimated ionosphere is depicted in Figure 9.

Table 3. STD of the PPP solution for the unknowns

	σ LAT(m)	σ LON(m)	σ HGT(m)	σ CLK(ns)	σ TZD(m)
Average	0.044	0.028	0.0668	0.1614	0.003
Maximum	0.227	0.176	0.425	0.584	0.005
	σ X(m)	σ Y(m)	σ Z(m)		
Average	0.088	0.059	0.040		
Maximum	0.334	0.178	0.140		

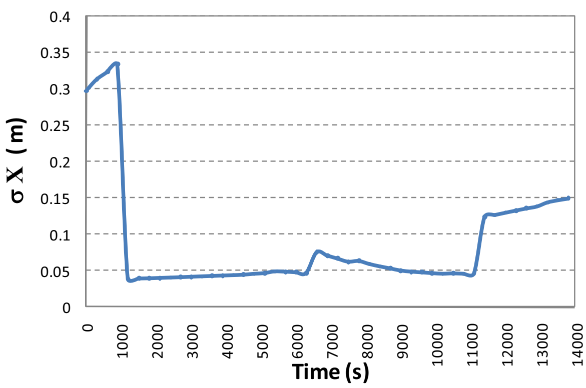

Fig 2. STD of the X coordinate

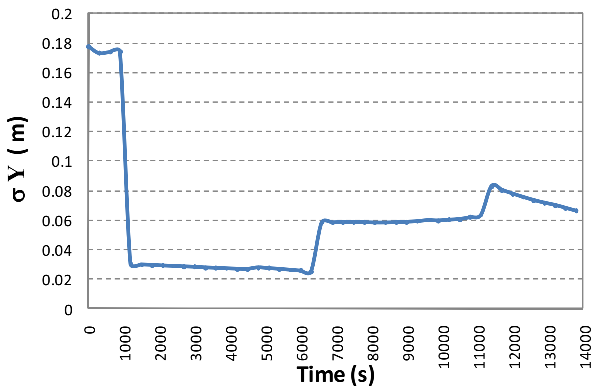

Fig 3. STD of the Y coordinate

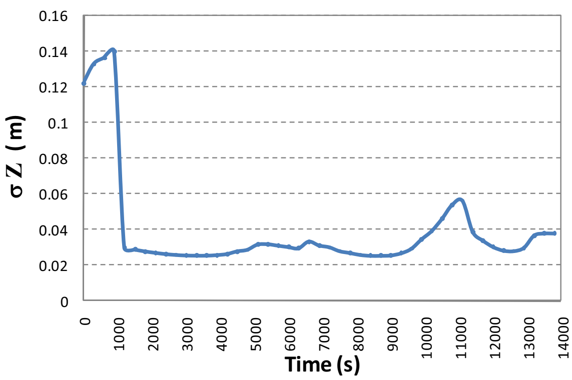

Fig 4. STD of the Z coordinate

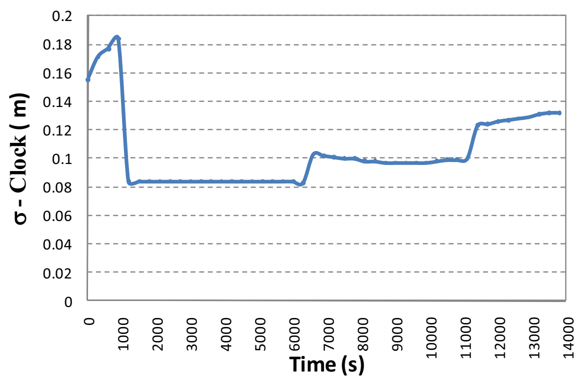

Fig 5. STD of Receiver clock error

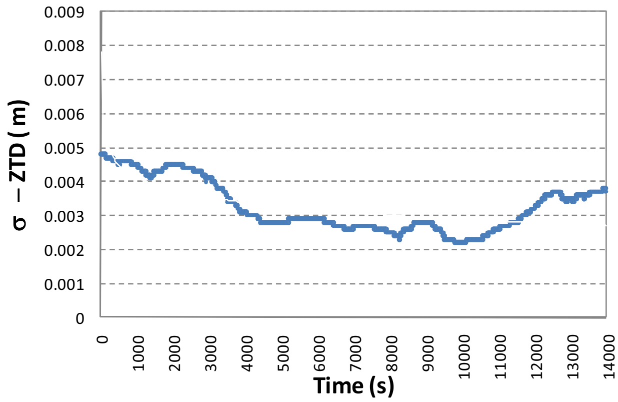

Fig 6. STD of ZWD,

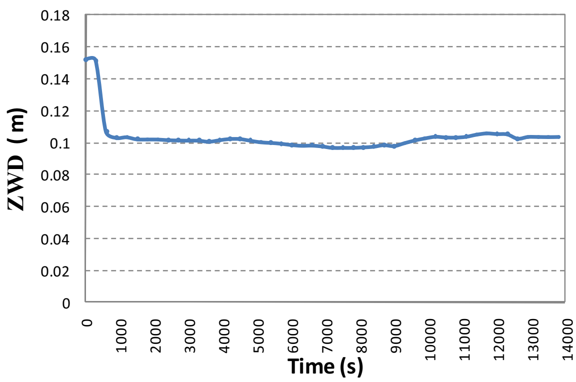

Fig 7. Computed ZWD

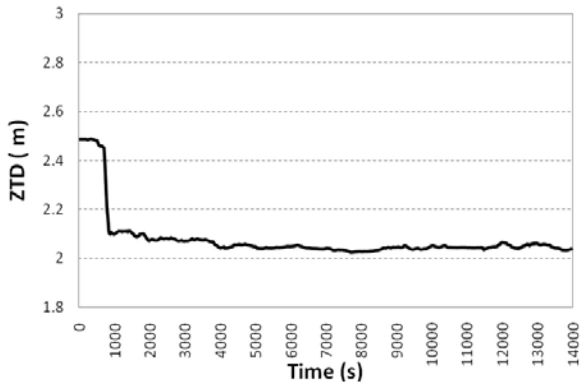

Fig 8. Computed ZTD

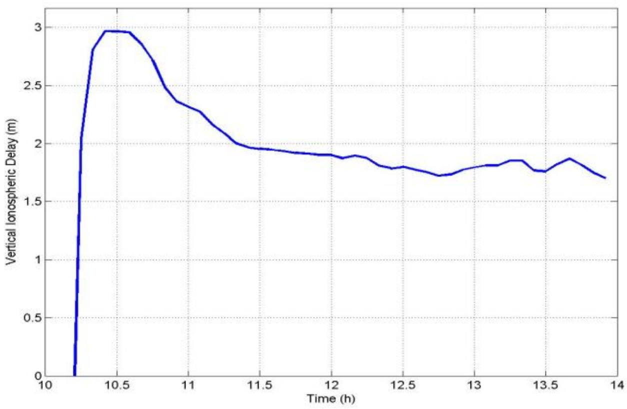

Fig 9. Estimated Ionospheric Delay

Since zenith wet delay varies slowly with time, it can be estimated at a low frequency, e.g. every 30 seconds, to increase the degrees of freedom in the solution by one. During this period either the last obtained ZTD value can be used or troposphere gradients are estimated along with the wet troposphere delay and applied to the estimated troposphere delay during the extrapolation period. Figures 10 and 11 show the toposphere gradients along the North and East directions estimated by the APPS solution.

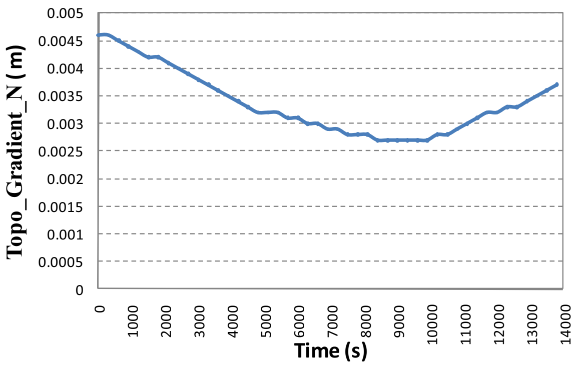

Fig 10. Tropo gradient along North

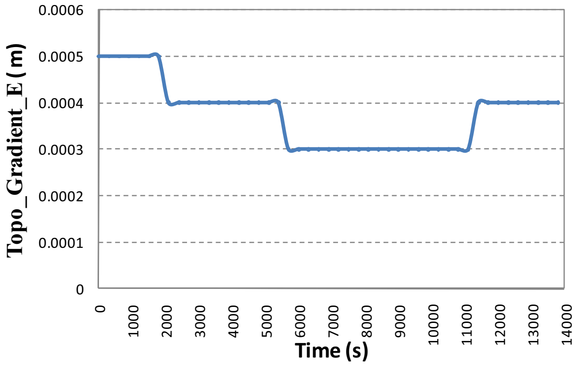

Fig 11. Tropo gradient along East

For accuracy assessment of the PPP, the post-mission differential processing of data used as the reference for comparison with the PPP solution was performed using commercial software (Sokkia Spectrum, version 4.22). The fixed-ambiguity differential solution gave excellent standard deviations of 0.018m, 0.009m, and 0.026m, on average, for the whole test period for the latitude, longitude and height components, respectively.

Due to flight manoeuvre, the data were lost for a period of 13 seconds and at some other epochs the data of L2 was not recorded. Thus, the comparison between the PPP and the differential solution was made for the period from 10:44:18 to 13:16:56, which comprised 9,145 epochs of data, mainly including the enroute flying phase. Results of 10 epochs of anomalous differences between the two solutions were excluded from the comparison where the differences reached several metres. These differences can be attributed to observing only 4 satellites with bad geometry due to aircraft turning, resulting in wrong ambiguity determination in the PPP solution.

The differences between PPP and the differential solutions for the coordinate components are given in Table 4 and their time series are plotted in the Figures 12, 13 and 14. As the table and the figures show, the differences were at the decimetre level for the latitude and the cm level for the longitude. This can be partially explained by the good distribution of the GPS satellites along the longitude direction compared with their distribution along the latitude direction. Figure 12 shows that there could be a shift in latitude results of approximately 0.13 m. This shift can be attributed to the float ambiguity estimation in the PPP, which can bias the output more than a decimetre. The difference between the float solution and the correct integer values varies between satellites, and can be aligned in one direction than the other. In addition, the coordinates of the reference station used in the differential processing were computed in ITRF2005 by using the AUSPOS web processing service involving long baseline processing with known IGS stations. This process contributes to about 0.012 cm in the difference budget between the two methods as the PPP results are based on an autonomous solution. The differences of the ellipsoidal heights were at 1.5 decimetre, on average. The change in differences in the middle of the trajectory can be attributed to a loss of observations for the mentioned period of 13 seconds, which requires re-initialization of the ambiguities. To examine the impact of loss of lock on the solution, no backward positioning of the PPP after solving for the ambiguities was applied in this case. As shown from the figures, the period involving convergence of the PPP ambiguities, which last for almost 30 minutes, suffered from positioning inaccuracy from 2 to 2.5 decimetres for latitude and longitude, and up to 1 m in height.

Table 4. Differences between PPP and differential positioning results

	LAT(m)	LON(m)	HGT(m)
Average	0.134	0.007	-0.168
Maximum	0.513	0.040	0.640
STD	0.161	0.018	0.373

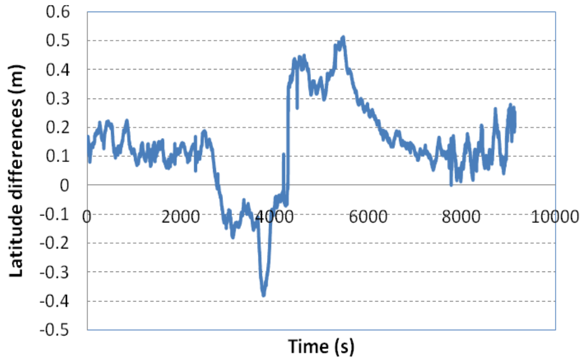

Fig 12. PPP-differential latitude discrepancies

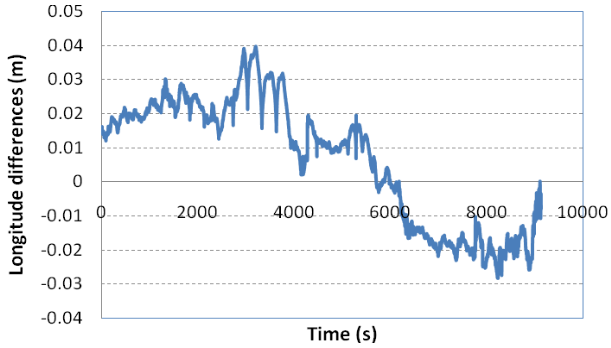

Fig 13. PPP-differential longitude discrepancies

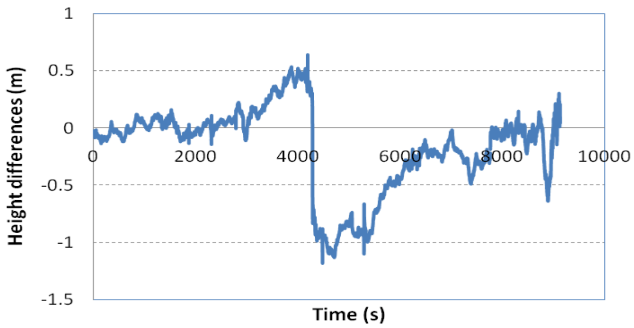

Fig 14. PPP-differential Height discrepancies

6. CONCLUSIONS

The paper shows that the PPP method has a reasonable performance suitable for many post mission or near real time airborne applications. Solving the satellite and receiver initial phase biases is vital to improve ambiguity estimation, solution convergence and precision of the PPP. Various available online web-based PPP post-mission processing engines provide a convenient tool to users. For the airborne test given in the paper, the PPP determined position components were precise at a few centimetres and it was double this value for height determination. The accuracy of PPP was within a few millimetres to 1.5 decimetre compared with a differential GPS solution that was based on a fixed ambiguity resolution approach. These result were achieved with a sufficient data length that allows the float ambiguities computed in the PPP approach to converge to stable values.

Acknowledgements. The Mathematical Geodesy & Positioning group, the Delft Institute of Earth Observation and Space Systems, Delft University of Technology, Netherlands, is acknowledged for providing the airborne data used.

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Received: 2011-07-01,

Reviewed: 2011-10-03, by M. Bakuła,

Accepted: 2011-10-07.