Journal of Global Positioning Systems (2008)
Vol. 7, No. 1 : 62-71

Journal of Global Positioning Systems
2008
© CPGPS

An Evaluation of Various Ionospheric Error Mitigation Methods used in Single Frequency PPP

S. Choy, K. Zhang, and D. Silcock
Royal Melbourne Institute of Technology (RMIT) University, Melbourne, Australia.

Abstract

Precise Point Positioning (PPP) using dual frequency GPS receivers is capable of providing centimetre level point positioning accuracy anywhere around the world, without the need for a base station. However, when using single frequency GPS receivers, the accuracy of the positioning decreases, particularly in the height component. One main factor for this degradation in accuracy is the unmodeled ionospheric error.

This paper investigates the performance of three different ionospheric error mitigation methods used in single frequency PPP in the Australian Region. They are the GRAPHIC (GRoup And PHase Ionospheric Correction) algorithm, the Global Ionospheric Maps (GIMs) and the Klobuchar model. Numerical results show that the GRAPHIC and GIMs methods are able to provide point positioning accuracy better than 1m for session duration less than an hour using geodetic quality single frequency receivers. For 12 to 24 hours data sets, the positioning accuracy can be as good as <0.1m.

Keywords: Single Frequency, PPP, Ionospheric Error

1 Introduction

Global Positioning System (GPS) is currently one of the most popular satellite positioning systems due to the global availability of GPS signal and performance. Centimetre level positioning accuracy is now achievable using carrier phase-based Differential GPS (DGPS) technique, in which two or more geodetic quality GPS receivers are deployed and two or more frequencies are used to alleviate ionospheric effects (Wang et al., 2004, Wu et al., 2006). This technique is able to provide high accuracy solution because common errors, such as satellite and receiver clock errors are cancelled out in short baselines or the errors are dramatically reduced in long baselines (Witchayangkoon, 2000, Zhang et al., 2007).

The coordinates of a point can also be determined by absolute point positioning technique using a single GPS receiver (Hofmann-Wellenhof et al., 2001). However, this technique using code observations is only capable of providing positioning accuracy in the level of a few metres. Such performance is due to the nature of code observations, as well as, the lack of knowledge about the satellite clock error and the noise affecting code observations (Kwon et al., 2001). Therefore, the absolute positioning technique is often not suitable for applications that require highly precise and accurate solutions.

Since 1994, the International GNSS Service (IGS) has been providing precise GPS orbit and satellite clock corrections to the GPS community. This has pushed absolute point positioning technique to a new era, whereby users can accurately obtain their positions without the need to process their data with any base station. This new technique is known as Precise Point Positioning (PPP). PPP uses undifferenced code and carrier phase observation from a single receiver, in addition to the precise satellite orbit and clock correction products for high accuracy point positioning. Recent research has demonstrated that PPP is capable of providing centimetre level point positioning for static applications and decimetre level for kinematic applications using a dual frequency, geodetic quality receiver (Hèroux et al., 2004; Abdel-salam, 2005). As for single frequency observations, the accuracy of the estimated point positioning decreases (Yuan *et al.*, 2007), particularly in the height component. One main factor for this degradation in accuracy is the effect of unmodeled ionospheric error.

The objective of this paper is to investigate the accuracy of single frequency PPP as a function of various observation durations, using the Australian Regional GPS Network (ARGN) stations. Single frequency GPS receivers are the most widely used tools for tracking, navigation and geo-referencing. It is estimated that 75 percent of all GPS receivers used globally are single frequency receivers (Arbesser-Rastburg, 2006, Wyllie et al., 2006). Thus, any accuracy improvement on the point positioning algorithm will clearly be of great practical importance. Different ionospheric error mitigation methods will also be assessed and their accuracy compared. Three methods were used in this investigation: the single frequency ionospheric-free code and phase delay known as GRAPHIC (GRoup And PHase Ionospheric Correction) algorithm (Yunck, 1993), the IGS rapid Global Ionospheric Maps (GIMs) and the Klobuchar model together with the broadcast ionospheric coefficients.

This paper first presents a brief overview of the basic PPP observation equations. Secondly, a description of the GRAPHIC, GIMs and Klobuchar models will be given. Absolute point positioning at eight ARGN sites with accurately known International Terrestrial Reference Frame 2000 (ITRF00) coordinates is carried out using single frequency GPS observations with different ionospheric error mitigation methods. The performance of the algorithms is evaluated based on the accuracy and precision of the derived solutions, as well as the time required for the solutions to converge. Numerical results clearly demonstrates that the GRAPHIC and GIMs methods are able to provide point positioning accuracy better than 1m for session duration less than an hour using geodetic quality single frequency receivers. For 12 to 24 hours data sets, the positioning accuracy can be as good as a few centimetres (approximately <0.1m under favourable conditions).

2 GPS Observation Equations

The basic GPS observation equations can be written and expressed as follows (Chen and Gao, 2005):

$$\mathrm{Pr} = p_r^s + c.(dt_r - dT^s) + dorb + dion + dtrop + drel + \varepsilon(\mathrm{Pr}) \tag{1}$$

$$\Phi_L = p_r^s + c.(dt_r - dT^s) + dorb - dion + dtrop + \lambda_L.N_L + drel + dpw + \varepsilon(\Phi_L) \tag{2}$$

where,

Pr	: measured pseudorange on L1 (m)
Φ_L	: measured carrier phase range, L1 or L2 (m)
p_r^s	: true geometric range between the GPS receiver and the satellite (m)
c	: speed of light (m/s)
dt_r	: receiver clock error (s)
dT^s	: satellite clock error (s)
$dorb$	: satellite orbit error (m)
$dion$	: ionospheric error (m)
$dtrop$	: tropospheric error (m)
$drel$	: relativistic effects (m)
dpw	: phase windup error on the carrier phase measurements (m)
λ_L	: wavelength of the carrier phase, L1 or L2 (m/cycle)
N_L	: phase ambiguity including the initial phase bias on the carrier phase, L1 or L2 (cycle)
$\varepsilon(.)$	: noise including multipath (m)

The satellite orbit error ($dorb$) and clock error (dT^s) can be eliminated by applying the precise orbit and clock correction products from the IGS. The tropospheric error ($dtrop$) can be corrected at decimetre and even centimetre level, using existing models and meteorological measurements. The relativistic effects ($drel$) and the phase windup (dpw) can be corrected to centimetre level accuracy using existing correction models (Chen and Gao, 2005).

Consequently, equations (1) and (2) can be expressed as,

$$\mathrm{Pr} = p_r^s + c.dt_r + dion + M.ZPD + \varepsilon(\mathrm{Pr}) \tag{3}$$

$$\Phi_L = p_r^s + c.dt_r - dion + M.ZPD + \lambda_L.N_L + \varepsilon(\Phi_L) \tag{4}$$

It should be noted that the original tropospheric error ($dtrop$) is now expressed in equations (3) and (4) as a function of the tropospheric Zenith Path Delay (ZPD) with Mapping function (M) relating the tropospheric error to the elevation angle of the satellite.

Equations (3) and (4) are known as the basic PPP observation equations. From Equation (3) and (4), the ionospheric error becomes a major source of error in single frequency PPP. Note that there are two observation equations for single frequency data, one code measurement and one carrier phase measurement for each satellite observed per epoch.

3 Ionospheric Error Mitigation Methods

There are a number of different mitigation methods for single frequency GPS users to correct for the ionospheric error. The simplest and most widely used method to correct for the ionospheric error is to utilise the Klobuchar model together with the eight ionospheric coefficients broadcast as part of the navigation message. During normal operation, the parameters of the model are updated at least once every six days (ARINC Research Corporation, 2000; Øvstedal, 2002). This algorithm can be used in real-time and it was designed to provide a correction for approximately 50 percent Root Mean Square (RMS) of the ionospheric range delay (Klobuchar, 1987). Since mid July 2000, the Centre for Orbit Determination in Europe (CODE) has been providing post-fit Klobuchar ionospheric coefficients that best fit the GIMs data estimated by CODE. Øvestedal (2002) has shown that the post-fit coefficient is able to provide more consistent results than the broadcast Klobuchar model. Currently, the post-fit Klobuchar ionospheric coefficients have a latency of several days. Thus, for the purpose of this investigation, the Klobuchar model with the broadcast ionospheric coefficients was used instead. It is worth noting that the CODE has also been estimating predicted Klobuchar-style coefficients. However, the improvement was found to be not as significant as the post-fit coefficients (Chen and Gao, 2005; CODE, 2007).

Alternatively, single frequency GPS users may fully exploit the state of the art ionospheric model provided by IGS and other organisations, such as the Jet Propulsion Laboratory (JPL) and the CODE. Currently, four IGS Ionosphere Associate Analysis Centres (IAACs) provide two-dimensional GIMs in IONosphere map EXchange (IONEX) format (Schaer et al., 1998) that refer to a 450 km shell height. The four IGS IAACs are CODE, European Space Operations Centre of ESA (ESOC), JPL, and Technical University of Catalonia (UPC) (Hernández-Pajares, private communication). Each IAAC sets up a daily IONEX file that has 13 GIMs, which contains Total Electron Content (TEC) values and a set of Differential Code Biases (DCBs) values for that day. These products are contributed to the IGS Ionosphere Working Group in order to generate the combined IGS final and rapid GIMs. In April 2003, the IGS final GIMs in IONEX format became an official IGS product, which has a latency of 11 days. Meanwhile, a rapid version of the GIMs with a delay of less than 24 hours is made available to the public since December 2003. Both final and rapid GIMs have a temporal resolution of 2 hours and a spatial resolution of 5˚ in longitude (λ) and 2.5˚ in latitude (ϕ). According to the products accuracy specifications, the rapid and final GIMs have an accuracy level of 2 TEC Unit (TECU) to about 8-9 TECU (IGS, 2007), in which 1 TECU corresponds to 0.163m range error on L1 frequency (Øvstedal, 2002; Chen and Gao, 2005). The combined IGS rapid GIMs were used in this investigation due to its shorter latency. The characteristics of the GIMs are shown in Table 1.

Table 1 IGS Ionospheric Correction Products (IGS, 2007).

Product	Accuracy	Latency	Updates	Sample Interval
Rapid Ionospheric TEC Grid	2-9 TECU	<24 Hours	Daily	2 Hours; 5˚ (λ) x 2.5˚ (ϕ)
Final Ionospehric TEC Grid	2-8 TECU	~11 Days	Weekly	2 Hours; 5˚ (λ) x 2.5˚ (ϕ)

Perhaps the least appreciated technique for single frequency GPS users to correct for the ionospheric error is by using the GRAPHIC method. The ionosphere delays the code measurements and advances the carrier phase measurements, thus making it possible to eliminate this error by taking the simple average of the code and carrier phase delay observables (Yunck, 1993; Montenbruck, 2003; Simsky, 2006).

Upon adding and averaging the code and carrier phase range, the combined GRAPHIC measurement (ignoring the higher-order ionospheric error terms) can be written in a simplified manner as follows,

$$\begin{aligned} P^{CA\&L1} &= \frac{\Pr + \Phi_{L1}}{2} \\ &= p_r^s + c \cdot dt_r + M \cdot ZPD + \frac{\lambda_{L1} N_{L1}}{2} \\ &\quad + \frac{\varepsilon(\Pr)}{2} + \frac{\varepsilon(\Phi_{L1})}{2} \end{aligned} \tag{5}$$

In Equation (5), one should note that the combined measurement no longer depends on the ionospheric delay and exhibits a noise, which is half the code and carrier phase noise values. However, since the bandwidth limitations keep the carrier phase observables typically 100 times more precise than the code, the noise affecting the GRAPHIC method is mainly dominated by the code measurement error (Yunck, 1993). The term GRAPHIC was first introduced by Yunck (1993) for single frequency ionospheric-free code and phase delays. Since then, various authors have addressed the potential of using GRAPHIC method in post-processing and real-time single frequency PPP (Montenbruck, 2003; Muellerschoen et al., 2004; Simsky, 2006).

4 Differential Code Biases (DCBs)

It is important for single frequency PPP users to apply the L1-L2 DCBs along with the above-mentioned ionospheric error mitigation methods. For both the broadcast and precise satellite clock corrections, the offset of the satellite clocks is always referred to the ionosphere-free linear combination of the L1 and L2 frequency. For dual frequency PPP, no such DCBs calibrations are required to be applied. However, single frequency PPP users must apply the satellite DCBs as the satellite clock corrections are consistent with the satellite L1-L2 DCBs convention (Kouba, 2003; Le, 2004). The satellite DCBs can be found from the GIMs in IONEX format as they are constantly computed by IAACs as part of their global ionospheric delay corrections, as well as from the broadcast navigation message. In this research, the DCBs from the GIMs were used.

Due to the effects of Anti-Spoofing, some civilian GPS receivers do not output P1 code but C/A code instead, which has a different hardware delay than the P1 code. Therefore, data from these receivers must be corrected using the P1-C1 DCBs in order to achieve full consistency with the P1-P2 data and the satellite clock corrections. The RINEX conversion utility "cc2noncc.f" can be used to transform given C/A code measurements to be consistent with the P1-P2 data and satellite clock corrections. The "cc2noncc.f" conversion utility is available at the IGS Clock Products Working Group website (U.S. Naval Research Lab, 2007). Alternatively, the P1-C1 DCBs can be obtained as a separate file from the CODE website (CODE, 2007).

5 Numerical Results and Analysis

The CSRS-PPP software package was used to facilitate single frequency GPS data processing (Hèroux et al., 2004). This software package is capable of processing both dual and single frequency data, using either the broadcast or precise satellite ephemerides. After considering the accuracy and latency of these products, the IGS rapid satellite orbit and clock corrections were used in this investigation for both the GRAPHIC and GIMs methods. As for the Klobuchar model, the broadcast ephemerides were used instead. Currently, the IGS rapid orbit and clock corrections are accurate better than 5cm and 0.1ns respectively, and have a latency of 17 hours (IGS, 2007). Details of the various IGS products can be found at the IGS website (IGS, 2008).

Precise satellite orbits provided by the IGS ephemerides do not refer to the antenna phase centre, but instead, they refer to the centre of mass. As all GPS range observations are measured from the satellite transmitting antenna to the electrical phase centre of the receiving antenna, single frequency PPP users are required to apply the satellite phase centre corrections to account for the offsets. The relative GPS antenna phase centre offsets and variations contained in the *igs_01.pcv* file (IGS, 2007) were used in this research, as the GPS data were collected prior to 5 November 2006. However, one should note that the IGS has adopted the absolute antenna phase centre offsets and variations for its routine generation of the precise satellite orbits on the 5 November 2006 (Gendt, 2006). Thus, users should use the absolute antenna phase centre corrections for all GPS data processing using observations data collected after the 5 November 2006.

A static test was performed on 7th July 2006, using eight selected ARGN GPS stations. They are Hobart, (HOB2), Mount Stromlo (STR1), Alice Springs (ALIC), Yaragadee (YAR2), Ceduna (CEDU), Townsville (TOW2), Darwin (DARW) and Cocos Island (COCO) stations. The location of these stations is shown in Fig. 1. 24 hours data from these eight stations were downloaded from the Scripps Orbit and Permanent Array (SOPAC) website (SOPAC, 2008). These data were windowed into 15 minutes, 30 minutes, 1 hour, 2 hours, 4 hours and 12 hours, starting from 00:00 GPS time. These stations are equipped with dual frequency, geodetic quality GPS receivers, but only observations on L1 were used in the data processing. The time interval of the collected data is 30 seconds. A 5° cut-off elevation angle was applied to all datasets.

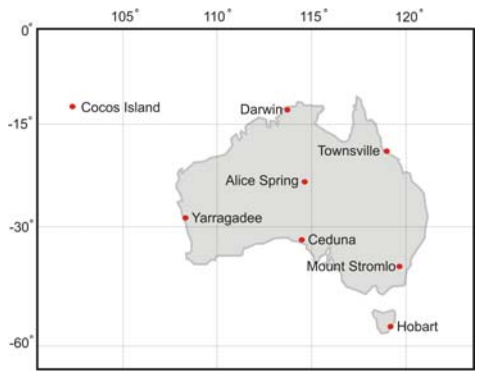

Fig. 1 The location of the eight ARGN stations.

One of the general rules of single frequency PPP algorithm is to set a realistic a priori code and carrier phase sigma values, which will adequately reflect the actual measurements noise including multipath. Since the noise on L1 code is unknown, it is a challenge to produce realistic error estimates which reflect the measurement noise. The parameter statistics are often biased, especially for a short observation period because multipath does not average out (Hèroux, private communication). Therefore, the measurement sigmas used in this investigation were based on the standard values widely used in GPS processing. In fact, the values themselves are not of great importance; only the fact the sigma values for the code measurement should be greater (approximately 4 times) than the carrier phase measurements (Simsky, 2006). In this research, a priori code and carrier phase sigma values were set to 4m and 0.03m, respectively.

These data were post-processed using the above three different ionospheric error mitigation methods and the estimated coordinates were compared to the accurately known ITRF00 coordinates for the eight ARGN stations. L1 code and carrier phase measurements were used in the GRAPHIC and IGS rapid GIMs algorithms; while only L1 code measurements were used in the Klobuchar model method. This was done to provide an indication of the achievable point positioning accuracy using the classical single frequency code-based processing with the broadcast ionospheric coefficients. The coordinate differences between the estimated and the known values are plotted as a function of various observation periods.

The results for STR1 station point estimations are presented in Fig. 2 and 3, respectively. Fig. 2 shows error values of the east, north and height components based on the three ionospheric error mitigation processing methods, over the first 12 hours (00:00-12:00 GPS time; Greenwich Meridian Time (GMT) +10 hours). The east, north and height component errors were computed by subtracting the accurately known reference coordinates with the estimated position values. Fig. 2 presents an example of coordinates convergence of a 12 hours solution for each methods. Fig. 3 provides a more detailed outlook of the position error at specific observation period.

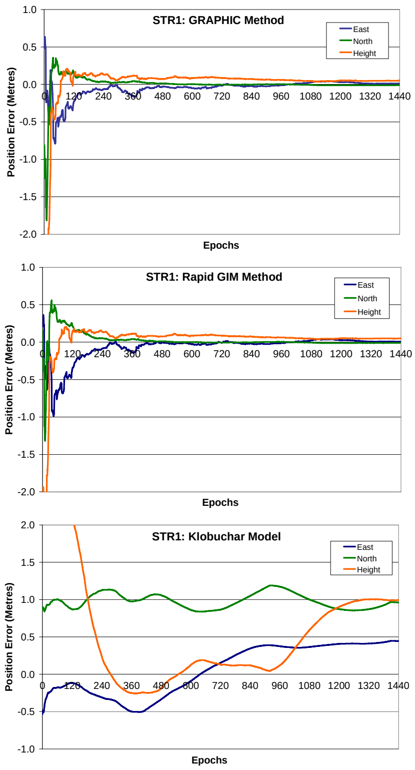

Fig. 2 Position errors with respect to the accurately known coordinates for STR1 station (sample rate: 1 epoch = 30 seconds).

It can be clearly seen from these figures that the GRAPHIC and GIMs methods follow a similar long-term pattern, whereby both methods provide comparable positioning accuracy. Both methods are able to provide horizontal accuracy better than 0.5m after an hour observation period (120 epochs). Only after 4 hours observations, the position estimates from these two methods converge to approximately 8cm of the known values. This is because the ambiguity term in L1 measurement is not known, and the multipath effect on the pseudorange measurement typically sets the accuracy limit for single frequency PPP, especially for short observation sessions. As predicted, the broadcast Klobuchar model has the least accurate positioning results.

In order to have representative data from the low or near equatorial region where ionospheric activities are considerably higher and complex than the mid latitude region, COCO station situated at latitude 12˚11'S has been selected. Fig. 4 and 5 present the position errors using the three different ionospheric error mitigation methods. Similarly, the GRAPHIC and GIMs provide similar positioning accuracy over 24 hours observation period. While, the Klobuchar model only provides comparable position estimates accuracy between 00:00 to

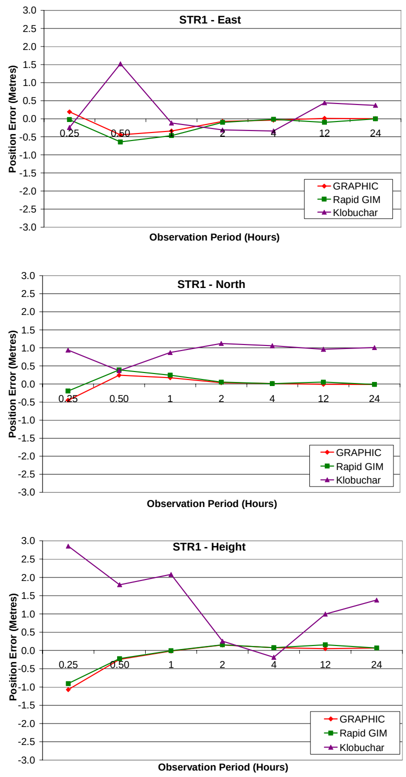

Fig. 3 A detailed outlook of the position errors for STR1 station at 0.25, 0.50, 1, 2, 4, 12 and 24 hours observation periods.

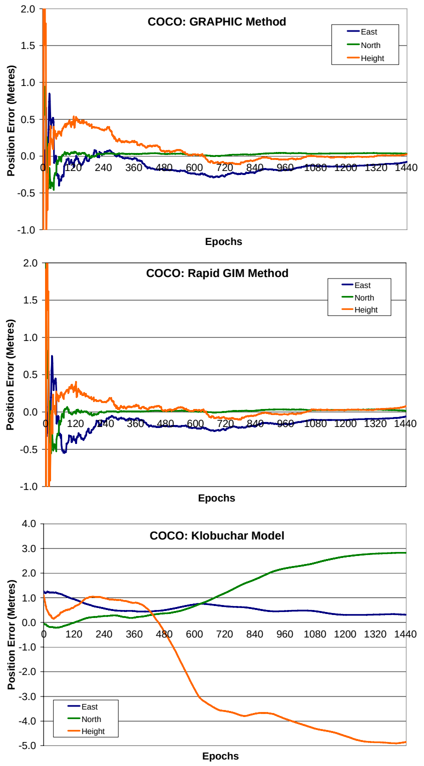

Fig. 4 Position errors with respect to the accurately known coordinates for COCO station (sample rate: 1 epoch = 30 seconds). Note the different y-axis scale on the Klobuchar model plot.

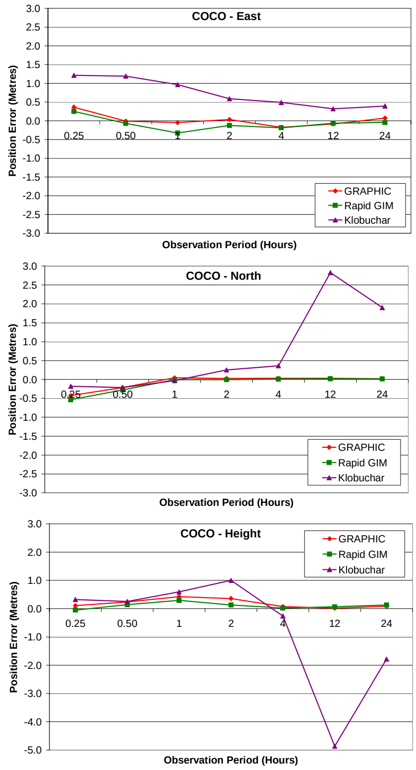

Fig. 5 A detailed outlook of the position errors for COCO station at 0.25, 0.50, 1, 2, 4, 12 and 24 hours observation periods. Note the different y-axis scale on the height component plot.

03:00 GPS time (GMT +6.5 hours), where the ionospheric activity is considered at its minimum. The Klobuchar model is unable to provide consistent and accurate solutions especially in the height estimations, over 24 hours observation period. This is mainly due to the increase of TEC in the atmosphere and the broadcast ionospheric coefficients failed to account for the sudden variation. Both the GRAPHIC and GIMs methods are not significantly affected by this phenomenon.

Another point worth noting is that the height component for this station using GRAPHIC and GIMs methods takes longer time to converge than STR1 station. This is probably caused by the software failure to account for the residual ionospheric range delay effectively, thus disabling the fixing of ambiguity over short observation period.

Fig. 6 and 7 illustrate the position estimate errors for DARW station. DARW station is situated approximately 70km away from Darwin, in the Northern Territory of Australia. Similarly, DARW station is located in the low latitude region 12˚50'S.

It can be inferred from Fig. 4, 5, 6, and 7 that the DARW position estimates based on the three algorithms are not as accurate and consistent as those of COCO station, even though both stations are located in the same latitudinal region. Two reasons that may cause this: first, the geometric factors of the satellites, and second, the multipath effects and/or the undetected cycle clips of the carrier phase measurements at DARW station. To verify this, the datasets of these stations were checked for its data quality using TEQC (Translating/Editing/Quality Control) software. It was found that the multipath effects affecting L1 frequency is more significant at DARW than COCO station. The number of cycle slips and outliers are also higher at DARW station, resulting in less accurate position solutions. Fig. 8 and 9 are the images of the COCO and DARW stations.

Tables 2 and 3 summarise the combined mean and RMS values based on the eight ARGN stations over various observation periods, i.e. 0.25 (15m), 0.50 (30m), 1, 2, 4, 12 and 24 hours. The GRAPHIC method was abbreviated in the table as "GHIC", and the Klobuchar model was abbreviated as "Klob model".

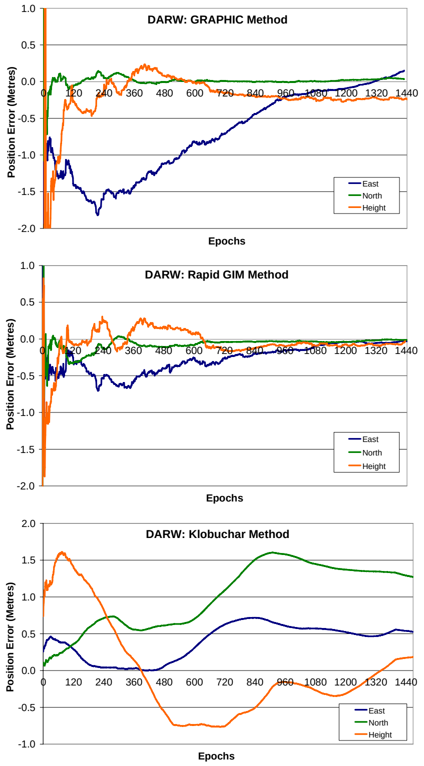

Fig. 6 Position errors with respect to the accurately known coordinates for DARW station (sample rate: 1 epoch = 30 seconds).

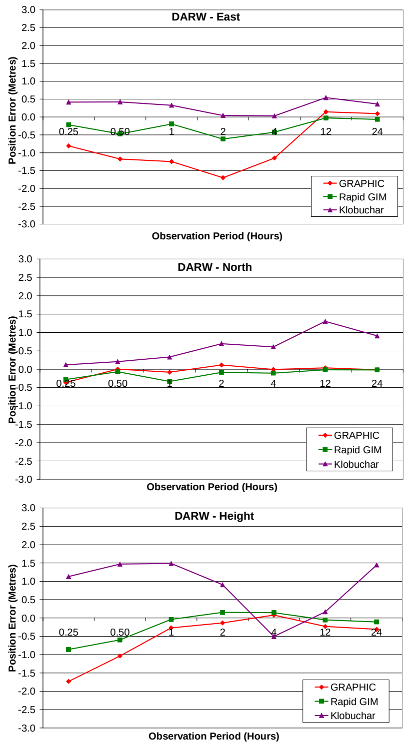

Fig. 7 A detailed outlook of the position errors for DARW station at 0.25, 0.50, 1, 2, 4, 12 and 24 hours observation periods.

Fig. 8 COCO station is equipped with an ASHTECH UZ-12 GPS receiver with an AOAD/M_T antenna type. This station is located within the perimeter of Cocos Island Airport and it offers unobstructed visibility of the sky (Geoscience Australia, 2007).

Fig. 9 DARW station is equipped with an ASHTECH UZ-12 GPS receiver with an ASH700936D_M antenna type. This station is located at an old abandoned seismic station at Manton Dam and is surrounded by trees and a building (Geoscience Australia, 2007).

Table 2 The combined mean for the three ionospheric error mitigation methods, based on GPS data collected at the eight ARGN stations.

Combined Mean (unit: m)								
		15m	**30m**	**1hr**	**2hr**	**4hr**	**12hr**	**24hr**
GHIC	**E**	-0.05	-0.27	-0.29	-0.38	-0.35	0.06	0.05
	N	-0.42	-0.13	-0.12	0.01	0.00	0.00	-0.01
	H	-0.69	-0.14	0.06	0.21	0.22	0.03	0.03
Rapid GIMs	**E**	0.02	-0.10	-0.05	-0.10	-0.07	-0.01	-0.01
	N	-0.12	0.00	-0.03	-0.02	-0.02	0.00	0.00
	H	-0.14	0.08	0.25	0.18	0.14	0.09	0.08
Klob model	**E**	0.27	0.48	0.20	-0.14	-0.18	0.41	0.34
	N	0.56	0.53	0.64	0.88	0.74	1.20	1.03
	H	1.71	1.63	1.51	0.67	0.04	0.01	1.03

Table 3 The combined RMS values for the three ionospheric error mitigation methods, based on GPS data collected at the eight ARGN stations.

Combined RMS value (unit: m)								
		15m	**30m**	**1hr**	**2hr**	**4hr**	**12hr**	**24hr**
GHIC	**E**	0.42	0.71	0.85	0.77	0.57	0.10	0.07
	N	0.44	0.31	0.23	0.09	0.05	0.04	0.03
	H	1.37	0.50	0.30	0.33	0.32	0.13	0.15
Rapid GIMs	**E**	0.30	0.45	0.32	0.33	0.21	0.05	0.07
	N	0.25	0.27	0.17	0.09	0.06	0.04	0.03
	H	0.91	0.36	0.37	0.23	0.18	0.14	0.12
Klob model	**E**	0.52	0.75	0.41	0.36	0.37	0.41	0.34
	N	0.71	0.68	0.73	0.94	0.77	1.36	1.09
	H	1.88	1.74	1.58	0.81	0.49	1.87	1.49

As expected, the Klobuchar model solution gives the least accurate positioning solutions. The bias particularly in the height component is larger using this model than the GRAPHIC and GIMs methods. The GIMs method generally provides better point positioning accuracy and precision especially for shorter observation period, as their combined mean and RMS values are the lowest among the three algorithms tested. Although the GRAPHIC provides less accurate solutions over short observation periods, this algorithm is still capable of providing high accuracy point positioning solution over longer observation periods, without the aid of any ionospheric correction products. The GIMs method and GRAPHIC method are remarkably similar especially after a few hours. This is because the use of the GIMs improves the accuracy of the code-based single frequency PPP, but this has impact only on the initial portion of the solutions. After the ambiguities are stabilized, the solutions will follow the more precise carrier phase measurements and the code measurements will only have marginal effect.

6 Discussions

The ionospheric coefficients of the Klobuchar model are transmitted as part of the satellite navigation message, and are available for all single frequency GPS users in real-time. The Klobuchar model was designed to minimise users' computational complexity, while having the potential to correct for at least 50 percent RMS of the ionospheric range error (Klobuchar, 1987). The Klobuchar model based on code solution could provide metre level positioning accuracy using good quality single frequency observations. However, the solutions, particularly in the height component are often not accurate and precise enough for many GPS applications.

Alternatively, single frequency users may fully exploit the IGS combined GIMs to correct for the ionospheric effects. The IGS GIMs come in two products, final and rapid GIMs, and their characteristics have been outlined in Table 1. Currently, the IGS ionospheric products provide accuracy of 2 to 9 TECU at grid points, in which 1 TECU corresponds to 0.16m range error on L1 measurement (Øvstedal, 2002; Chen and Gao, 2005). Users should however note that the accuracy of the map degrades for interpolated points, as the maps are constructed with a spatial resolution of 5˚ in longitude and 2.5˚ in latitude and a temporal resolution of 2 hours. Therefore, the performance of the GIMs for stations located within a grid will not be as optimal for stations located at grid points.

The IGS rapid GIMs and GRAPHIC methods provide comparable point positioning accuracy over long observation sessions (e.g. >12 hours). As for shorter observation session, the GIMs method performs better. Although the GIMs method using L1 code and phase measurement is more robust, one limitation of using this method is that the IGS GIMs are currently not available in real-time (as at February 2007). Therefore, this method is not applicable for real-time single frequency PPP.

On the other hand, the GRAPHIC algorithm is based on the single frequency ionospheric-free linear combination of L1 code and carrier phase measurements. This algorithm takes advantage of the fact that the ionosphere affects the code (delay) and carrier phase (advance) at the same magnitude but opposite in sign (Yunck, 1993; Montenbruck, 2003; Muellerschoen et al., 2004; Simsky, 2006). Limitation of using this method is that the carrier phase ambiguity is required to be estimated and the noise level of this combination is largely dominated by the code measurement noise (Chen and Gao, 2005). This means that the accuracy of the point positioning solutions using GRAPHIC is highly dependent on the L1 code measurements noise. In addition, an estimation process using cumulative measurements has to be applied and a long period of several hours is also required for the float ambiguity parameters to converge (Hèroux et al., 2004; Chen and Gao, 2005). This slow ambiguity convergence issue continues to limit the applicability of single frequency PPP for short occupancy, real-time use, and thus requires further research (Hèroux et al., 2004). Nevertheless, the uniqueness of GRAPHIC algorithm is that it has the obvious advantage of eliminating the first-order ionospheric error in real-time, while being able to provide high accuracy point positioning solutions after long observation sessions, typically more than 12 hours.

7 Conclusions

Different ionospheric error mitigation methods for single frequency PPP have been described, compared and evaluated. It has been shown that both GRAPHIC and GIMs methods are capable of providing high accuracy point positioning solutions to single frequency PPP users. The accuracy of the improved absolute positioning can be confirmed at a sub-metre to metre level for less than 1-hour observation sessions, using high quality single frequency GPS receivers. After 12 to 24 hours, the accuracy of the solution can be as good as a few centimetres (under favourable condition, e.g. low multipath). For short observation sessions, the GIMs method performs better than the GRAPHIC and Klobuchar model. It is expected that the effects of ionosphere will be more pronounced at stations located in the low latitude regions, and that the results obtained from the mid to high latitude stations tend to be more accurate and consistent. However, the effects of the station location on positional accuracy using both GRAPHIC and GIMs methods seem unclear as a result of the test compiled for this paper. Further research will be undertaken on both ionospheric quiet and disturbed days and their results compared.

One of the limitations using single frequency PPP approach is that the phase ambiguities on L1 are not of integer values, as in double-difference. This is because they are corrupted by the satellite and receiver initial phase biases. PPP technique also requires a long initialization time, typically more than 30 minutes to 2 hours for the float solution to converge (Gao and Garin, 2006). The PPP convergence time varies based on the number and geometry of visible satellites, observation sampling rate and quality, as well as users' defined environment. Therefore, further investigation on the ambiguity convergence time and cycle slips detection algorithm is recommended to improve the robustness of PPP for real-time applications.

Acknowledgements

The authors would like to thank the Geodetic Survey Division of Natural Resources Canada (NRCan) for kindly providing the CSRS-PPP software package and Mr. François Lahaye from NRCan for answering questions concerning the usage of the software. The first author would also like to thank Mr. Pierre Héroux from NRCan for his useful information and valuable technical discussion regarding PPP. The helpful comments and suggestions from the two anonymous reviewers are gratefully acknowledged.

References

Abdel-salam M. (2005) ***Precise Point Positioning Using Un-Differenced Code and Carrier Phase Observations***. PhD Dissertation, The University of Calgary, Canada.

Arbesser-Rastburg B. (2006) ***The Galileo Single Frequency Ionospheric Correction Algorithm***, <http://sidc.oma.be/esww3/presentations/Session4/Arbesser.pdf> (January 2007).

ARINC Research Corporation (2000) ***GPS Interface Control Document ICD-GPS-200 (IRN-200C-004): Navstar GPS Space Segment and Aviation User Interfaces***. CA, USA.

Chen K. and Gao Y. (2005) ***Real-Time Precise Point Positioning Using Single Frequency Data***. Proceedings of the ION GNSS 18th International Technical Meeting of the Satellite Division, Long Beach, CA, 13-16 September, 1514-1523.

CODE (2007) ***Global Ionosphere Maps Produced by CODE***. <http://www.aiub.unibe.ch/content/research/gnss/code___research/igs/global_ionosphere_maps_produced_by_code/index_eng.html> (January 2007).

Gao Y. and Garin L. (2006) ***GNSS Solution: Precise Point Positioning and Its Challenges, Aided-GNSS and Signal Tracking***. <http://www.insidegnss.com/pdf/12-06-GNSSSol.pdf> (December 2006).

Gendt G. (2006) ***[IGSMAIL-5438]: IGS Switch to Absolute Antenna Model and ITRF 2005***. <http://igscb.jpl.nasa.gov/mail/igsmail/2006/msg00161.html> (November 2006).

Geoscience Australia (2007) ***Australian Regional GPS Network***. <http://www.ga.gov/au/geodesy/argn/> (January 2007).

Hernández-Pajares, M. (2007) ***Private Communication***. Group Astronomy and Geomatics, Technical University of Catalonia.

Hèroux P., Gao Y., Kouba J., Lahaye F., Mireault Y., Collins P., Macleod K., Tétreault P. and Chen K. (2004) ***Products and Applications for Precise Point Positioning - Moving Towards Real-Time***. Proceedings of the ION GNSS 17th International Technical Meeting of the Satellite Division, Long Beach, CA, 21-24 September, 1832-1843.

Hèroux P. (2006) ***Private Communication***. Geodetic Survey Division of Natural Resources Canada.

Hofmann-Wellenhof B. Lichtenegger H. and Collins J. (2001) ***GPS Theory and Practice***. (5th edition) Springer-Verlag Wien New York.

IGS (2007) ***International GNSS Service***. <http://igscb.jpl.nasa.gov/> (January 2007).

Klobuchar J.A. (1987) ***Ionospheric Time-Delay Algorithm for Single-Frequency GPS Users***. IEEE Transactions on Aerospace and Electronic Systems, AES-23(3), 325-331.

Kouba J. (2003) ***A Guide to using International GPS Service (IGS) Products***. <ftp://igscb.jpl.nasa.gov/igscb/resource/pubs/GuidetoUsingIGSProducts.pdf> (April 2006).

Kwon J.H., Kim J.W. and Lee D.C. (2001) ***Absolute Kinematic GPS Positioning for Remote Area***. Proceedings of the IEEE Geoscience and Remote Sensing Symposium (IGARSS) 2001, Sydney, Australia, 9-13 July, 2067-2069.

Le A.Q. (2004) ***Achieving Decimetre Accuracy with Single Frequency Standalone GPS Positioning***. Proceedings of the ION GNSS 17th International Technical Meeting of the Satellite Division, Long Beach, CA, 1881-1891.

Montenbruck O. (2003) ***Kinematic GPS Positioning of LEO Satellites Using Ionosphere-Free Single Frequency Measurements***. Aerospace Science and Technology, 7, 396-405.

Muellerschoen R., Iijima B., Meyer R., Bar-Sever Y. and Accad E. (2004) ***Real-Time Point-Positioning Performance Evaluation of Single-Frequency Receivers Using NASA's Global Differential GPS System***. Proceedings of the ION GNSS 17th International Technical Meeting of the Satellite Division, Long Beach, CA, 21-24 September, 1872-1880.

Øvstedal O. (2002) ***Absolute Positioning with Single-Frequency GPS Receivers, GPS Solutions***. 5(4), 33-44.

Schaer S., Gurtner W. and Feltens J. (1998) ***IONEX: The IONosphere Map EXchange Format Version 1***. Proceedings of the IGS AC Workshop, Darmstadt, Germany, 9-11 February.

Simsky A. (2006) ***Standalone Real-Time Navigation Algorithm for Single-Frequency Ionosphere-Free Positioning Based on Dynamic Ambiguities (DARTS-SF)***. Proceedings of the ION GNSS 18th International Technical Meeting of the Satellite Division, Fort Worth, Texas, 301-308.

SOPAC (2007) ***Scripps Orbit and Permanent Array Center***. <http://sopac.ucsd.edu/> (January 2007).

U.S. Naval Research Lab (2007) ***IGS Clock Products Working Group***. <https://goby.nrl.navy.mil/IGStime/ cc2noncc/> (August 2007).

Wang Z., Wu Y., Zhang K. and Meng Y. (2004) ***Triple Frequency Method for High-order Ionospheric Refractive Error Modelling in GPS Modernization,*** J of Global Positioning Systems Vol. 4, No.1+2, 291-295.

Witchayangkoon B. (2000) ***Elements of GPS Precise Point Positioning***, PhD Dissertation, The University of Maine, USA.

Wu S., Yuan Y., Zhang K. and Grenfell R. (2006) ***Temporal and Spatial Variations of the Ionospheric TEC over Victoria for GPSnet-based Real-time Positioning***, J of Global Positioning Systems, Vol.5, No.1-2, pp.52-57.

Wyllie S., Zhang K. and Talbot N. (2006) ***An Analysis of the Temporal Correlation of the Ionospheric Bias Affecting GPS Carrier Phase Observations,*** Proceedings of IGNSS Symposium. Holiday Inn Surfers Paradise, Australia, 17–21 July (79).

Yuan Y., Huo X. and Ou J. (2007) ***Models and Methods for Precise Determination of Ionospheric Delay using GPS***. Progress in Natural Science, 2(17), 187-196.

Yunck T. (1993) ***Coping With the Atmosphere and Ionosphere in Precise Satellite and Ground Positioning***. Geophysical Monograph 73, 13.

Zhang K.; Wu S. and Wu F. (2007) ***The Latest Development of a Network-based RTK System in Australia***, International Journal of Science and Research, Vol. 2(1), pp.87-94.