Real-Time Precise Point Positioning Using Single Frequency Data

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BIOGRAPHY

Kongzhe Chen is now a senior software engineer at Centrality Communications, Inc. He has received a BSc and an MSc of Electrical and Computer Engineering from Wuhan University. He has been involved in GPS research since 1996. He recently received a PhD from The University of Calgary.

Dr. Yang Gao is an Associate Professor in Department of Geomatics Engineering at The University of Calgary. His research focuses on the development of innovative methods and applications using GNSS and other enabling sensors. His research work has contributed to the development of public services and commercial products for GPS applications. A software system developed for precise point positioning by his research group has been licensed to worldwide users. He is Chair of the International Association of Geodesy's Sub-Commission 4.5: Next Generation RTK and a Luojia Chair Professor at Wuhan University.

ABSTRACT

Precise Point Positioning (PPP) has begun to receive increased interests within the GPS community for a number of reasons: simplified operation, cost-effective and no base stations required. PPP with dual-frequency receivers and precise GPS products have demonstrated centimeter to decimeter positioning accuracy (Zumberge et al., 1997; Kouba and Héroux, 2001, Gao and Shen, 2002). Using real-time GPS products, the accuracy is also obtainable in real-time (Chen, 2004).

This paper investigates PPP using single-frequency data which will be of interest to a broad range of applications as the majority of GPS users are using single-frequency GPS receivers. Since the ionospheric effect will be the biggest error source for a single-frequency receiver based PPP system, different methods for ionospheric effect mitigation will be assessed and compared, from the use of IGS precise ionosphere products to estimation via modeling, so that sub-meter positioning accuracy becomes obtainable.

INTRODUCTION

With the advent of precise GPS orbit and clock products, precise point positioning (PPP) began to receive increased interests within the GPS positioning and navigation community for its simplified operation, cost-effectiveness and improved positioning accuracy. PPP performs position determination by processing un-differenced dual-frequency code and carrier-phase measurements from a dual-frequency receiver coupled with precise GPS orbit and clock products and has been widely demonstrated capable of providing accurate position solutions at sub-decimeter level for kinematic positioning and at sub-centimeter level for static positioning (Zumberge et al., 1997).

Since the majority of GPS users however are using single-frequency GPS receivers, PPP using a single-frequency GPS receiver therefore will be of interest to a broad range of applications. So far only accuracy at several meters has been demonstrated for point positioning using a single-frequency GPS receiver. This is because the ionospheric effect, which is the dominant error source in point positioning after the application of precise GPS orbit and clock products, cannot be mitigated effectively using single-frequency measurements. As a result, how to mitigate the ionospheric effects in un-differenced single-frequency measurements is the key in order to develop single-frequency PPP systems.

There exist different methods for ionospheric effect mitigation. The simplest way would be to directly use the Klobuchar model with ionospheric coefficients broadcast from the GPS satellites. But it can only mitigate 50~60% of the total ionospheric effects (Klobuchar, 1996). On the other hand, the International GNSS Service (IGS) has been providing the total electron content of ionosphere on a global scale since 1998 (Schaer et al., 1998) which can also be applied. As reported in Ovstedal (2002), the IGS model known as Global Ionospheric Model (GIM) could provide better results than the Klobuchar model using the same GPS dataset and ephemeris. But only a couple of meters position accuracy has been obtained since only the code measurements were used. The use of the GIM model will also be limited by the low spatial and temporal resolution and significant latency. To be independent on any models, the ionosphere-free observable known as GRAPHIC (GRoup And PHase Ionospheric Correction) (Yunck, 1996) can be formed via a combination of the code and phase observations. Positioning accuracy of 1.5m has been demonstrated for LEO (Low Earth Orbit) satellite orbit determination in Montenbruck (2003). Recently, the method to estimate the ionospheric effect within the positioning model has also been investigated. Beran et al. (2003) shown positioning accuracy at a couple of meters using single-frequency observations from a static geodetic receiver with one or two (a bias and a drift) zenith ionospheric parameters being estimated.

In this research, the abovementioned models will be assessed and compared for their achievable accuracy. An ionospheric estimation model proposed by Chen and Gao (2005), which can account for ionosphric gradients and can be implemented in real-time, will also be assessed and compared. The real-time tests using this model and the Internet-based Global Differential GPS (IGDG) products from JPL have demonstrated kinematic positioning accuracy at a couple of decimeters level using single-frequency GPS measurements collected at mid-latitude stations. Since the performance of ionospheric modeling for position determination will be correlated with the ionospheric activities as well as the user's geographic locations, datasets from different user locations (equatorial region, mid- and high-latitude regions) and different ionospheric conditions (ionospheric quiet and disturbed days) will be used in assessing the performance of different ionospheric models. Different from the research in the past, both code and carrier phase measurements will be used. Sub-meter position accuracy has been demonstrated from the numerical analysis using PPP with single-frequency measurements.

IONOSPHERE MITIGATION FOR SINGLE-FREQUENCY PPP

For single-frequency GPS data, the code and phase observation equations can be written as

$$C_1 = \rho_r^s + c(dt_r - dt^s + T_{gd}) + d_{orb} + d_{trop} + d_{ion} + d_{rel} + \varepsilon(C_1) \quad (1)$$

$$\Phi_1 = \rho_r^s + c(dt_r - dt^s) + d_{orb} + d_{trop} - d_{ion} + d_{rel} + d_{w1} + \lambda_1 N_1 + \varepsilon(\Phi_1) \quad (2)$$

where

C_1	is the measured C/A-Code pseudorange (m);
Φ_1	is the measured L_1 carrier phase (m);
ρ_r^s	is the true geometric range (m);
c	is the speed of light (m/s);
dt^s	is the satellite clock error (s);
dt_r	is the receiver clock error (s);
d_{orb}	is the satellite orbit error (m);
d_{trop}	is the tropospheric delay (m);
d_{ion}	is the ionospheric delay on L_1 (m);
d_{rel}	is the relativistic effects (m);
d_{w1}	is the phase windup on L_1 (m);
λ_1	is the wavelength on L_1 (m/cycle);
N_1	is the phase ambiguity including initial phase bias on L_1 (cycle);
T_{gd}	is the group delay of satellite (s);
$\varepsilon(.)$	is the noise including residual multipath (m).

For sub-meter accurate positioning using PPP with precise orbit and clock precise products from organizations such as IGS and JPL, the orbit error d_{orb} and clock error dt^s can be eliminated. The trop delay effect can also be corrected at decimeter even centimeter level using existing models and meteorological measurements. The relativistic effects d_{rel} and the phase windup d_{w1} can be modeled to centimeter level accuracy. As the clock corrections in broadcast ephemeris or IGS precise clocks are fully consistent to P1/P2 code measurements, the group delay T_{gd}, which is available from the navigation message, should be applied for single-frequency measurements. There are also differential code biases between P_1 and C_1 measurements, which are satellites related (Jefferson et al. 2001) and correction should also be applied. As a result, the observation equation (1) and (2) can be reduced to the following:

$$C_1 = \rho_r^s + cdt_r + d_{ion} + \varepsilon(C_1) \quad (3)$$

$$\Phi_1 = \rho_r^s + cdt_r - d_{ion} + \lambda_1 N_1 + \varepsilon(\Phi_1) \quad (4)$$

From equations (3) and (4), the ionosphere effect becomes the major error source in the un-differenced code and phase measurements and they must be mitigated as precise as possible. As indicated earlier, the following methods can be applied:

a) Using broadcast Klobuchar ionospheric model (Klobuchar, 1996);
b) Using Global Ionosphere Map provided by IGS and other organizations (Schaer et al., 1999);

c) Using single-frequency ionosphere-free combination (Montenbruck, 2003);

d) Estimating ionospheric effects as unknowns (Beran et al., 2003).

The first and likely the most popular method, is using the Klobuchar model with broadcast ionospheric coefficients (Klobuchar, 1996). This method can be implemented in real-time. The drawback of the Klobuchar model with broadcast ionospheric coefficients is that it can only mitigate 50~60% of the total ionospheric effect (Klobuchar, 1996). Even using precise orbit and clock products, the position solutions can only be accurate to a couple of meters (Ovstedal, 2002). Post-fit ionospheric coefficients have been developed that can help improve the performance of the Klobuchar model. Since the middle of July 2000, CODE has been providing Klobuchar-style ionospheric coefficients on a regular basis that best fit its IONEX data. The post-fit coefficients have demonstrated much better performance than the coefficients broadcast by the GPS satellites (Ovstedal, 2002). Currently, CODE post-fits coefficients have latency of several days so that they can only be used in post-mission. CODE is also computing predicted Klobuchar-style coefficients, but the improvement was found not as significant as the post-fit ones.

The second method is to use the Global Ionospheric Model (GIM) provided by IGS and other organizations (Schaer et al., 1998). Since 1998, IGS has provided ionospheric TEC grid parameters with latency of about 11 days. Currently, the IGS ionospheric products can provide accuracy of 2 TECU (1 TECU corresponds to 0.163 m range error in C_1) at grid points (Ovstedal, 2002). But the accuracy does degrade for interpolated points as their temporal resolution is 2 hours and spatial resolution is 5 degrees (longitude) x 2.5 degrees (latitude) (IGS website, 2004). This method could provide better results than the Klobuchar model using the same GPS dataset and ephemeris (Ovstedal, 2002). Since only code measurements were processed, the achievable position accuracy however is limited to a couple of meters. The model is also limited by the 11 days' latency of the IGS ionospheric products. In this research, this model will be assessed using both code and phase measurements to further exploit the potential of the IGS ionospheric products.

The third method is based on the use of a single-frequency ionosphere-free combination (Montenbruck, 2003). The single-frequency ionosphere-free combination, which averages the code and carrier-phase measurements on the same frequency, has been known as GRAPHIC (Group And Phase Ionospheric Correction) and can be written as follows (Yunck, 1996):

$$\frac{C_1+\Phi_1}{2}=\rho+cdt_r+\frac{\lambda_1 N_1}{2}+\frac{\varepsilon(C_1)+\varepsilon(\Phi_1)}{2} \tag{5}$$

Though the first-order ionospheric error can be completely removed by the code and phase combination, the phase ambiguity needs to be estimated and further the noise level of this combination is dominated by the code measurement noise. With this model, the position coordinate and ambiguity parameters can not be determined using a single epoch of observations. An estimation process using cumulative measurements has to be applied and a long time period of 2~4 hours is also required for the float ambiguity parameters to converge (Heroux et al., 2004). This method is suitable for post-mission applications where long data tracking sessions are available. Montenbruck (2003) has demonstrated 1.5 m 3D positioning accuracy in determining orbits of LEO satellites. Because this research is focused on real-time applications, this model will not be used.

The last method is to estimate the zenith ionospheric delay using code and/or phase observations (Beran et al., 2003). Mapping functions are used to map the zenith ionospheric delay to slant delays. Using post-mission precise GPS orbits and clocks, an accuracy of a couple of meters with meter level biases has been demonstrated using single-frequency observations from a static geodetic receiver with one or two (a bias and a drift) estimated ionospheric parameters. This method is also applicable to real-time navigation using real-time precise GPS orbit and clock products. However, the zenith ionospheric delays for different satellites at different ionospheric pierce points would vary significantly. It is therefore not adequate to model ionospheric delays for all satellites using only one zenith delay and one mapping function. The limitations of using one zenith delay and one mapping function have been investigated in Klobuchar et al. (1993) who indicated that applying mapping function to regions with large horizontal electron density gradients would lead to errors of several TECU. Therefore, overall this model does not show any improvement over the simple Klobuchar model (Beran et al., 2003). More sophisticated ionospheric models are therefore needed to account for the ionospheric variations which will be addressed in the next section.

Except the third method, all methods need to use ionospheric mapping functions. Several mapping functions are used with only slight difference at low elevations. These mapping functions include the broadcast mapping function, Single Layer Model (SLM) and Modified Single Layer (MSLM) mapping functions. Details of those mapping functions can be found in Schaer (1999). In this research, the broadcast mapping function will be used along with the Klobuchar model. When using GIM and the ionospheric delay estimation model, SLM will be used.

IONOSPHERE GRADIENTS ESTIMATION FOR SINGLE FREQUENCY PPP

Ionospheric horizontal gradients have been demonstrated by researchers for years. The most typical gradients are the general equatorward increase of total electron content (TEC) in mid-latitudes during daytime, the west to east increase of TEC in morning in all seasons, the east to west increase in the afternoon in winter. Though some models, such as the Klobuchar model, have considered these gradients, but the actual gradients can differ considerably from average values because of a substantial day-to-day variability of the ionization (Leitinger, 1993). Normally, people use TECU/km to denote electron content changes versus distance or TECU/deg to denote electron content changes versus latitude or longitude. Vo and Foster (2001) have shown TEC gradients are correlated with the background TEC. High gradients values occurred in the sunlit sector with TEC gradients up to 10 TECU/deg found in the post-noon ionosphere. Hernández-Pajares et al. (1998) suggested a 2 TECU/deg gradient with low solar activity for tomographic modeling.

Horizontal electron density gradients have been described as a common phenomenon in middle-latitude region (Gail et. al., 1993), but they have also been investigated in other regions (Huang, 1997; Ohta and Hayakawa, 2000). Schaer et al. (1999) and Bock et al. (2000) attempted to introduce ionospheric gradient parameters in GPS network processing, and they found these parameters might absorb part of the satellite- and epoch-specific biases. Dai et al. (2001) have also made similar attempts to estimate ionospheric gradient parameters for ambiguity resolution in the hopes that the ionospheric gradient parameters could absorb a significant amount of the spatially correlated ionospheric biases. No work has been reported on estimating ionospheric gradient parameters using un-differenced single-frequency GPS data.

IGS Final ionospheric TEC grids in GIM, which are accurate up to 2 TECU or even better at grid points (Ovstedal, 2002), can be used to demonstrate the gradients numerically. The IGS Final ionospheric TEC grids for December 31st, 2003 were used for this purpose. The Ap index of that day is 19, which means a typical ionospheric condition. A mid-latitude IGS station, AMC2 (38.8° N, 104.5° W), was selected to evaluate the ionospheric gradients. The ionospheric TEC grids were interpolated to the ionospheric pierce points for satellites observed at AMC2 with different azimuth and elevation angles.

Figures 1 to 4 show VTEC at ionospheric pierce points for satellites observed by AMC2 at different azimuth and elevation angles. The VTEC shown in these figures is consistent with the three types of gradients discussed above. In Figure 1, VTEC was interpolated to the ionospheric pierce points for satellites in the north (0° azimuth) and south (180° azimuth) with elevation angles from 0° to 90° at 16:00 local time. It presents the equatorward increase of TEC in the mid-latitudes during daytime. In Figure 2, VTEC was interpolated to the ionospheric pierce points for satellites in the east (90° azimuth) and west (270° azimuth) with elevation angles from 0° to 90° at 6:00 local time. It highlights the west to east increase of TEC in the morning. In Figure 3, VTEC was interpolated to the ionospheric pierce points for satellites in the east (90° azimuth) and west (270° azimuth) with elevation angles from 0° to 90° at 18:00 local time. It illustrates the east to west increase of TEC in the afternoon. In Figure 4, VTEC was interpolated to the ionospheric pierce points for satellites at an elevation angle of 30° with azimuth angles from 0° to 360° at different local time. It shows the general TEC changes against the azimuth angles at different local time periods. To improve the accuracy of modeling the ionospheric effects and subsequently the positioning accuracy, an ionospheric estimation model has been proposed to estimate the ionospheric horizontal gradients along with the zenith delay and implemented into the position determination using PPP (Chen and Gao, 2005). The advantage of estimating ionospheric gradients can be clearly seen from the following numerical analysis results.

NUMERICAL RESULTS AND ANALYSIS

Several positioning results using JPL real-time precise products and single-frequency observations will be presented, including both real-time and post-mission. Currently, JPL real-time precise products, which are accurate up to 18 cm for orbits and 0.5 ns for clocks, can be received with about 4 seconds latency. Details of JPL real-time precise products have been described in Muellerschoen et al. (2000, 2001). A PPP software package P$^{3®}$ developed at The University of Calgary is used to facilitate the numerical computation, which is capable of real-time and post-mission PPP positioning using single- or dual-frequency observation.

Static Positioning Results

A real-time positioning test was conducted on December 3, 2003 on the roof of Engineering Building at the University of Calgary. Ionosphere is quiet on that day with an Ap index of 4. A Javad Legacy receiver was used in the test along with a Javad JPSLEGANT antenna. The antenna was set up on a pillar on the roof with precisely known coordinates. JPSLEGANT is an antenna with a flat ground plane so it can partly mitigate the multipath effects. Data interval is 10 seconds. The processing was done in a computer connected to the GPS receiver and the Internet to receive JPL real-time GPS precise orbit and clock corrections.

The positioning errors and zenith ionospheric delay estimates using the estimation model are shown in Figure 5 and 6. The dataset was also post processed using the Klobuchar and GIM models and the JPL real-time GPS precise orbit and clock corrections (saved). The accuracy statistics was shown in Table 1. As shown in Table 1, the accuracy obtained in real-time using ionospheric estimation model is better than the post-mission accuracy obtained using the Klobuchar model or even the GIM model. Half-meter level accuracy was achieved.

Airborne Positioning Results

To test the performance of these ionospheric models in kinematic positioning, one airborne dataset was also processed with JPL real-time precise products (saved).

The airborne dataset was collected on August 28, 2004 at 40 kilometers north of Halifax, Nova Scotia. The Ap index is 7 in that day. A Novatel Black Diamond unit with antenna of model 512 was set up on a helicopter. The sample rate of the two GPS receivers was 1 Hz.

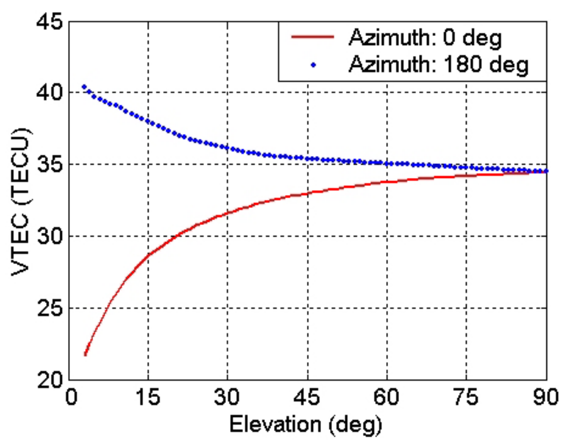

Figure 1. The equator toward increase of TEC at local time 16:00

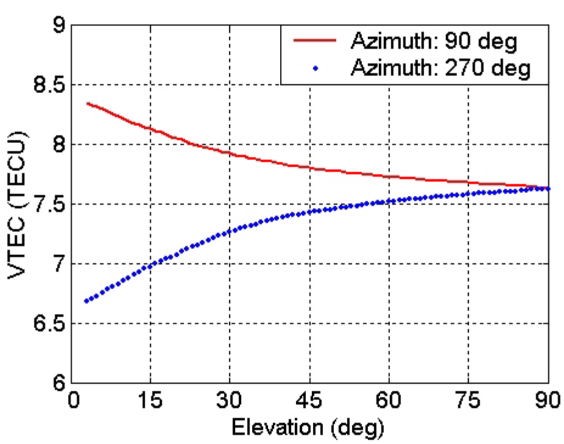

Figure 2. The west to east increase of TEC at local time 6:00

The helicopter was typically flying at an altitude of 250 meters above ground level at 50 knots. Another NovAtel DL-4 receiver and antenna with ground plane were used as the base station. The distance between the rover and base is less than 10 kilometers. The double-differenced with ambiguity-fixed trajectory was applied as the reference.

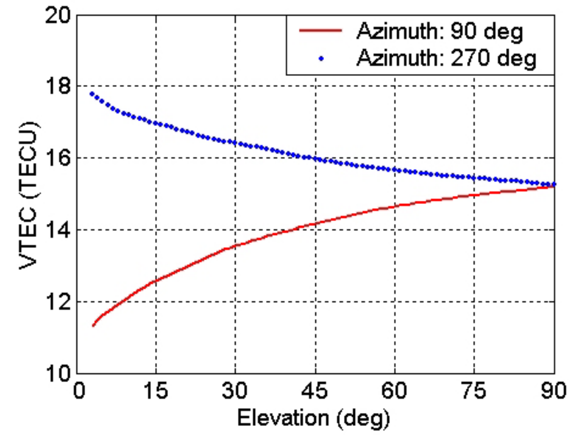

Figure 3. The east to west increase of TEC at local time 18:00

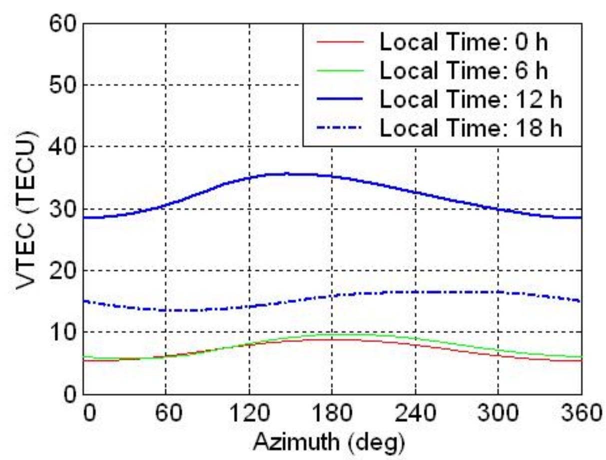

Figure 4. The VTEC at sub-ionospheric pierce point for satellites at 30° elevation and different azimuth

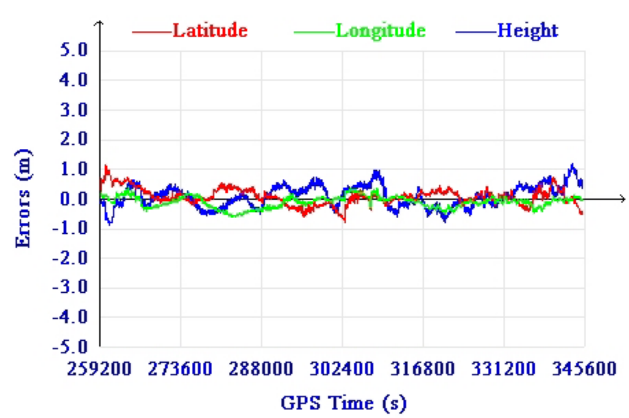

Figure 5. Positioning errors using ionospheric estimation model

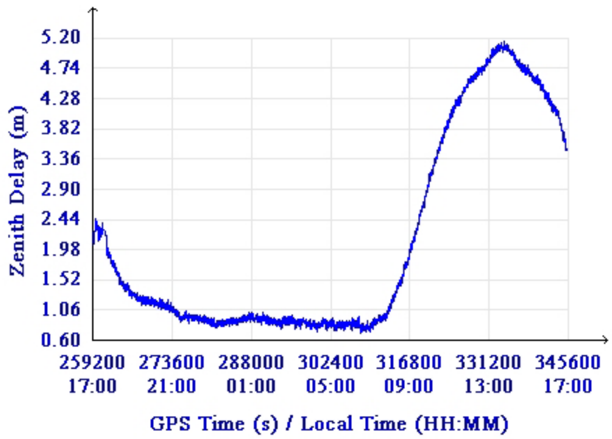

Figure 6. Zenith ionospheric delay estimates

Table 1. Static positioning accuracy (Unit: m)

	Iono Estimation	Klobuchar	GIM
Latitude	0.277	1.088	0.366
Longitude	0.223	0.611	0.274
Height	0.371	1.504	0.443

Figure 7 shows the trajectory. Figures 8 to 10 show the positioning errors in each positioning component using different models. The accuracy statistics for all processing is shown in Table 2. From Figure 8 to 10, we can see it takes about 10 to 20 minutes for the positioning errors to converge to a sub-meter level. Using ionospheric estimation model and GIM, the positioning errors kept within sub-meter level after the ambiguity convergence.

As shown in Table 2, about 30 cm accuracy was obtained in each positioning component using the ionospheric estimation model and GIM model. The accuracy is much worse when using the Klobuchar model, but still at meter level. With JPL real-time precise orbits and clocks, the accuracy from using the ionospheric estimation model and the Klobuchar can be obtained in real-time.

Positioning Results under Different Ionospheric Conditions

The positioning results presented above are all obtained at mid-latitudes and quiet ionospheric conditions. In the following, data from 3 stations located at different ionospheric regions (see Table 3) and collected under different ionospheric conditions (see Table 4), are processed with JPL real-time precise products. The station S1 is on the roof of Engineering Building at the University of Calgary as a mid-latitude station, GLPS and FAIR are two IGS stations as equatorial and high-latitude stations, respectively.

Given in Tables 5 are the accuracy statistics, arranged in an ascending order according to Ap values, using the ionospheric estimation model. From the tables, we can see the ionospheric estimation model can provide meter level accuracy at all stations and for all testing days. In ionospheric quiet days at mid- and high- latitude stations, half meter level accuracy was obtained.

The performance of the ionospheric estimation model is strongly correlated with the ionospheric conditions. The position accuracy is higher in ionospheric quiet days than

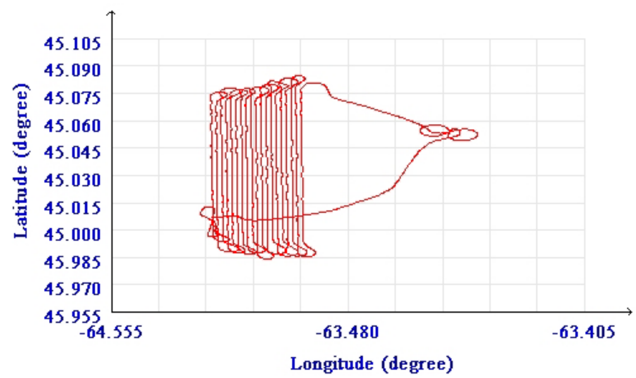

Figure 7. Trajectory of aircraft

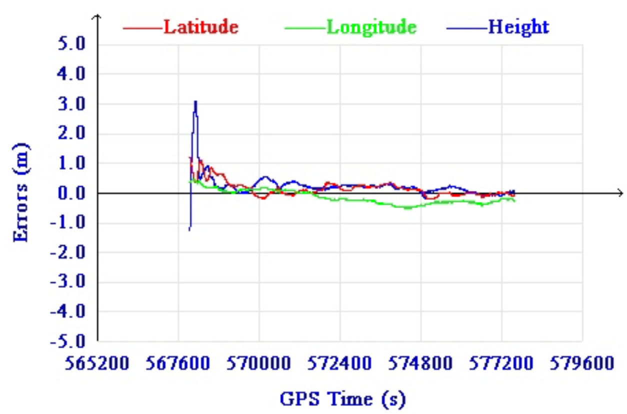

Figure 8. Positioning errors using ionospheric estimation model for airborne dataset

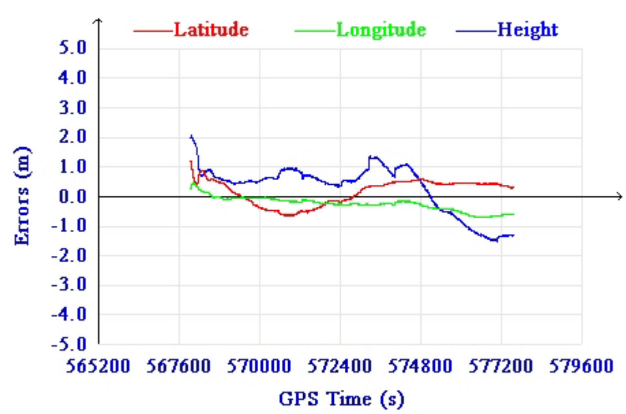

Figure 9. Positioning errors using Klobuchar model for airborne dataset

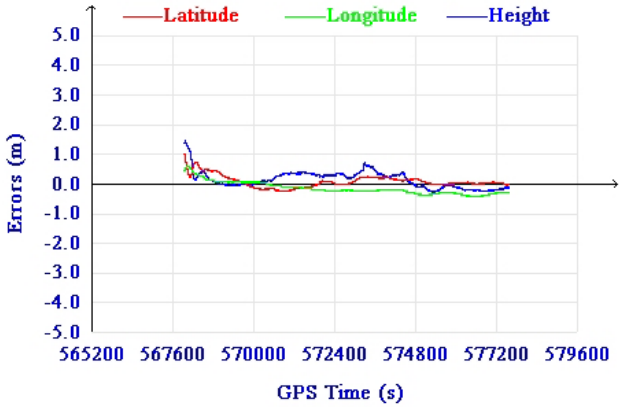

Figure 10. Positioning errors using GIM model for airborne dataset

in disturbed days. Accuracy is best at mid-latitude, worst at the equatorial regions and in the between at high-latitude, which is consistent with the ionospheric conditions in these regions. In the equatorial region, the peak electron density values are the highest among the three regions while they are least variable at the mid-latitude ionosphere (Komjathy, 1997). The ionospheric activity is usually more complicated in high-latitude region than mid-latitude regions (Skone, 1999; Komjathy, 1997).

Table 2. Kinematic positioning accuracy (Unit: m)

	Iono Estimation	Klobuchar	GIM
Latitude	0.154	0.418	0.131
Longitude	0.271	0.347	0.243
Height	0.217	0.840	0.262

Table 3. Station Coordinates

	GLPS	S1	FAIR
Latitude	-00° 44’ 35”	51° 04’ 46”	64° 58’ 41”
Longitude	-90° 18’ 13”	-114° 07’ 58”	-147° 29’ 57”
Height	1.8	1116.6	319.0

Table 4. Ap indices in August 2004

Date	4	8	24	3	19	14	20	10	21	31	30
Ap	3	3	3	3	4	7	15	16	16	28	42

Table 5. Positioning with ionospheric estimation model (Unit: m)

Date	GLIP			S1			FAIR		
	Lat	Lon	H	Lat	Lon	H	Lat	Lon	H
Aug 4	0.167	0.396	0.451	0.259	0.295	0.364	0.176	0.191	0.415
Aug 8	0.270	0.286	0.532	0.237	0.281	0.406	0.231	0.207	0.686
Aug 24	0.289	0.472	0.740	0.281	0.247	0.342	0.233	0.222	0.605
Aug 3	0.111	0.359	0.485	0.314	0.322	0.398	0.231	0.258	0.456
Aug 19	0.189	0.695	0.740	0.319	0.276	0.407	0.246	0.302	0.631
Aug 14	0.421	0.820	0.734	0.306	0.308	0.392	0.388	0.410	0.702
Aug 20	0.190	0.352	0.532	0.325	0.260	0.621	0.457	0.563	0.741
Aug 10	0.262	0.348	0.497	0.363	0.293	0.520	0.483	0.339	0.628
Aug 21	0.282	0.853	1.006	0.260	0.399	0.434	0.279	0.240	0.749
Aug 31	0.286	0.556	0.735	0.205	0.253	0.547	0.300	0.248	0.652
Aug 30	0.369	0.772	0.917	0.449	0.270	0.636	0.494	0.319	1.057

Shown in Tables 6 are the accuracy statistics for the three stations using the Klobuchar model over the 11 days. Compared to the ionospheric estimation model, the accuracy from the Klobuchar model is much worse; only 1 to 3 meters accuracy was obtained. But the Klobuchar model is not as sensitive to ionospheric conditions as the ionospheric estimation model. Unlike the ionospheric estimation model, the Klobuchar model provides the best results at the high-latitude station FAIR, though it still provides better results at the mid-latitude station S1 than the equatorial station GLPS. This may be due to the fact that the Klobuchar model just uses 8 coefficients to fit the ionospheric activity on a global scale. The coefficients perform better at some regions, which may not be characterized with more quiet ionospheric conditions, than other areas.

Table 6. Positioning with Klobuchar model (Unit: m)

Date	GLIP			S1			FAIR		
	Lat	Lon	H	Lat	Lon	H	Lat	Lon	H
Aug 4	0.477	1.551	1.927	0.703	0.516	1.095	0.253	0.187	0.865
Aug 8	0.701	0.894	2.836	0.764	0.761	1.609	0.388	0.236	0.885
Aug 24	1.483	1.084	1.818	0.523	0.534	1.352	0.499	0.465	0.987
Aug 3	0.757	0.712	1.154	0.335	0.477	0.669	0.357	0.290	0.820
Aug 19	0.906	1.519	2.069	0.527	0.588	2.097	0.462	0.362	1.147
Aug 14	1.058	1.186	2.254	0.536	0.627	0.874	0.647	0.362	1.313
Aug 20	0.756	1.093	1.890	0.734	0.470	1.287	0.482	0.280	0.768
Aug 10	0.989	1.183	2.338	0.412	0.572	0.838	0.432	0.367	0.740
Aug 21	1.022	1.141	1.772	0.607	0.574	1.071	0.388	0.295	1.074
Aug 31	1.158	0.980	2.187	0.422	0.411	1.009	0.358	0.307	0.824
Aug 30	0.745	1.290	3.225	0.498	0.400	0.927	0.652	0.548	1.335

Given in Tables 7 are the accuracy statistics (RMS) for the three stations using the GIM over the 11 days. The GIM provides much better results at all stations than the Klobuchar model. It can even provide slightly better results than the ionospheric estimation model at the high latitude station, though the latter is much better at the equatorial station. The accuracy of the GIM is meter or even sub-meter level at mid- and high-latitude stations but it is about 1.5 meters at equatorial stations.

Like the ionospheric estimation model, the GIM provides the best results at mid-latitude stations and performs the worst at equatorial stations. This is consistent with the ionospheric conditions and the performance of the IGS ionospheric products in these regions. The IGS tracking network, which is used to create the ionospheric products, is unevenly distributed (Fedrizzi et al., 2002). It is much denser in the mid-latitude region than in the equatorial region (Komjathy, 1997). Also, the resolution of the IGS final ionospheric TEC grids, which is 5 deg (longitude) x 2.5 deg (latitude) at a 2-hour' interval, is not high enough to recover TEC at any given location and time in the equatorial region. This is because the vertical TEC can change up to 20-TECU within one hour or several degrees in this region.

Table 7. Positioning with GIM model (Unit: m)

Date	GLIP			S1			FAIR		
	Lat	Lon	H	Lat	Lon	H	Lat	Lon	H
Aug 4	0.364	0.309	0.980	0.188	0.215	0.355	0.145	0.165	0.371
Aug 8	0.432	0.790	1.026	0.245	0.219	0.474	0.199	0.205	0.621
Aug 24	0.636	0.644	1.001	0.238	0.281	0.494	0.248	0.228	0.551
Aug 3	0.260	0.323	1.341	0.243	0.290	0.270	0.200	0.171	0.407
Aug 19	0.594	0.645	1.456	0.256	0.263	0.466	0.186	0.211	0.505
Aug 14	0.598	0.960	1.406	0.279	0.363	0.403	0.333	0.278	0.824
Aug 20	0.360	0.336	1.185	0.324	0.244	0.540	0.355	0.218	0.574
Aug 10	0.431	0.517	1.035	0.241	0.228	0.442	0.338	0.278	0.658
Aug 21	0.363	0.522	1.349	0.469	0.289	0.654	0.234	0.186	0.724
Aug 31	0.663	0.625	1.252	0.322	0.236	0.671	0.285	0.230	0.656
Aug 30	0.346	0.603	0.979	0.308	0.199	0.523	0.481	0.327	0.880

CONCLUSIONS AND FUTURE WORKS

Different ionospheric models have been compared in this research for precise point positioning using single-frequency data. The performance of all ionosphere models is correlated with the ionospheric conditions. For each model, the positioning accuracy is higher on ionospheric quiet days than on disturbed days, and is better at mid- and high-latitude stations than at equatorial stations. At mid- and high-latitude stations, almost all models can provide meter-level accuracy on ionospheric quiet days.

At equatorial stations, even the best model can only provide accuracy of about one meter during ionospheric disturbed periods.

The ionospheric estimation model with horizontal gradients estimated and GIM offer better performance than the Klobuchar model. The ionospheric estimation model and GIM provide comparable accuracy at mid-latitude stations. The former can be implemented in real-time mode while the latter is obtainable only in post-mission using IGS Final ionospheric products with latency of currently 11 days. GIM is slightly more accurate at high-latitude stations while the ionospheric estimation model is much better at equatorial stations. Precise ionospheric effect estimation method and high temporal and spatial resolution ionospheric TEC grids with short latency should be further investigated in the future.

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