Development of a Real-Time Single-Frequency Precise Point Positioning System and Test Results

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BIOGRAPHY

Dr. Yang Gao is a 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. He has developed a precise point positioning software with users worldwide. He is Chair of the International Association of Geodesy's Sub-Commission 4.5: Next Generation RTK and Luojia Chair Professor at Wuhan University. Drs Yufeng Zhang and Kongzhe Chen are post-doctoral fellows in the same department.

ABSTRACT

Precise Point Positioning (PPP) has received wide attention in the past several years as one of the next generation RTK technologies. PPP can offer great flexibility and cost-saving to field positioning work as it can eliminates the need to deploy base stations. Centimetre to decimetre accurate positioning accuracy has been widely demonstrated for PPP using a dual-frequency GPS receiver. The requirement of a dual-frequency GPS receiver in PPP is for the elimination of the ionospheric effect, currently the largest error source in GPS measurements. Considering the fact that the majority of GPS receivers in use are single-frequency type, it is beneficial to investigate methods and algorithms for PPP using only a single-frequency GPS receiver. The emergence of precise ionospheric products has also pushed for research work on this direction.

The major objective of this paper is to describe the development of a real-time single-frequency PPP system and test results under road and marine conditions. The paper will begin with an outline of the real-time single-frequency PPP system including the observation and positioning models and error mitigation strategies which are essential to achieve the best position accuracy possible. Due to significant horizontal gradients in ionospheric densities, ionospheric gradient has been taken into account in the position determination and can be estimated in addition to zenith ionospheric parameters.

Road testing of the real-time single-frequency PPP system has been conducted to assess its performance. The road environments include signal attention, blockage as well as multipath which represent real application environments. The marine tests were conducted independently by a third party under operational conditions. Both test results have demonstrated decimetre to sub-metre accuracy which is very encouraging since so far only accuracy at sub-metre to several metres has been demonstrated for point positioning using a single-frequency GPS receiver.

INTRODUCTION

Precise Point Positioning (PPP) is a next generation positioning technology which has received increased interests within the GPS positioning and navigation community for its simplified operation, cost-effectiveness and improved positioning accuracy (Gao and Shen, 2002). Using a dual-frequency GPS receiver, PPP has been widely demonstrated to be capable of providing accurate position solutions at sub-decimetre level for kinematic positioning and at sub-centimetre level for static positioning (Zumberge et al., 1997, Heroux et al., 2004 Gao et al., 2005). Considering the fact that the majority of the GPS users are using single-frequency GPS receivers, a method has been developed by Chen and Gao (2005) for PPP to perform position determination using a single frequency GPS receiver. Since the dominant error source in point positioning after the application of precise GPS orbit and clock products is the ionospheric effect, how to mitigate the ionospheric effects in un-differenced single-frequency measurements is the key in order to develop single-frequency PPP systems. Applying an ionospheric estimation model which can account for ionosphric gradients and a positioning mode which uses both code and carrier phase measurements as principle observables, sub-metre position accuracy has been demonstrated from the numerical analysis using PPP with single-frequency measurements (Chen and Gao, 2005). Such system will be of great interest to a broad range of applications such as marine navigation and GIS applications since so far only accuracy at several metres has been demonstrated for point positioning using a single-frequency GPS receiver.

In this research, our focus is the implementation of the methods and algorithms that have been reported in Chen and Gao (2005) into a real-time system aimed to support commercial product development and the assessment of the system's performance in both road and marine environments. The real-time tests using the Internet-based Global Differential GPS (IGDG) products from JPL have demonstrated kinematic positioning accuracy at decimetre to sub-metre level using a single-frequency GPS receiver under operational conditions.

A SINGLE-FREQUENCY PRECISE POINT POSITIONING METHOD

The code and phase observation equations from a single-frequency GPS receiver can be written as

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

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

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);
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).

After the application of real-time precise orbit and clock products from organizations such as JPL, equations (1) and (2) can be reduced to the form of

$$C_1 = \rho_r^s + c(dt_r + T_{gd}) + d_{trop} + d_{ion} + \varepsilon(C_1) \tag{3}$$

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

As to the troposphere delay effect, it can be corrected at decimetre even centimetre level using models and meteorological measurements and therefore it can be eliminated from the equations for single-frequency PPP aimed for supporting sub-metre level applications, namely,

$$C_1 = \rho_r^s + c(dt_r + T_{gd}) + d_{ion} + \varepsilon(C_1) \tag{5}$$

$$\Phi_1 = \rho_r^s + cdt_r - d_{ion} + \lambda_1 N_1 + \varepsilon\ (\Phi_1) \tag{6}$$

As the clock corrections in broadcast ephemeris or IGS precise clocks are fully consistent to P1/P2 code measurements, the group delay T_{gd} should be removed using the navigation message. Finally the observation equation (1) and (2) can be reduced to the following form:

$$C_1 = \rho_r^s + cdt_r + d_{ion} + \varepsilon\ (C_1) \tag{7}$$

$$\Phi_1 = \rho_r^s + cdt_r - d_{ion} + \lambda_1 N_1 + \varepsilon\ (\Phi_1) \tag{8}$$

Since the ionosphere effect now becomes the major error source in the un-differenced code and phase measurements in equations (7) and (8), methods therefore must be developed to facilitate real-time high precision modeling and estimation of ionosphere for single-frequency PPP system.

Precise ionospheric modeling requires the consideration of the horizontal gradients. 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. To demonstrate this, Figures 1 to 4 shows VTEC at ionospheric pierce points for satellites observed by an IGS station AMC2 at different azimuth and elevation angles using IGS Final ionospheric TEC grids in GIM (Ovstedal, 2002). Figures 1 and 2 have demonstrated the increase of TEC in the directions of equatorward and west to east at different local times. Figure 3 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, a method has been proposed in Chen and Gao (2005) to estimate the ionospheric horizontal gradients along with the zenith delay for position determination using PPP.

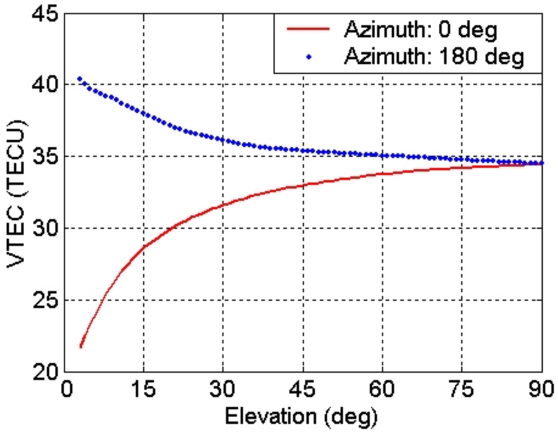

Figure 1. Equator toward increase of TEC at local time 16:00

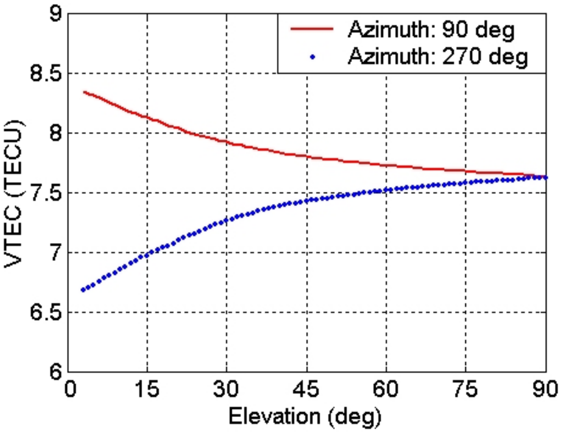

Figure 2. West to east increase of TEC at local time 6:00

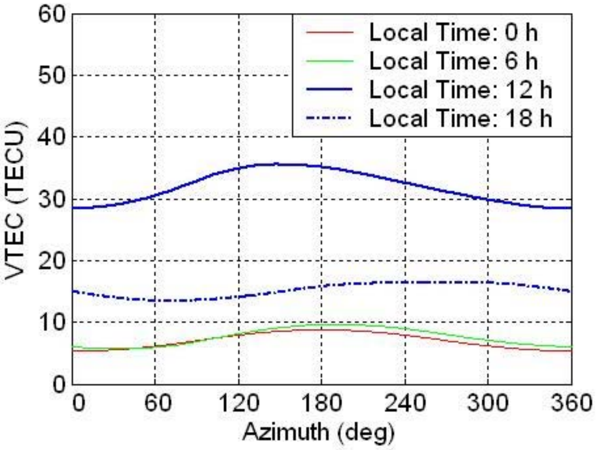

Figure 3. VTEC at sub-ionospheric pierce point for satellites at 30° elevation and different azimuth

DEVELOPMENT OF A REAL-TIME SINGLE-FREQUENCY PPP SYSTEM

A real-time single-frequency PPP (SFP3) system has been developed at The University of Calgary, implementing the methods and algorithms described in Chen and Gao (2005). The major system component is a software engine for wireless data communication and precise point positioning using a single GPS receiver. As to data communication, the system is able to receive the GPS observations from a directly connected GPS receiver or via Internet from a remote GPS receiver. The system can also access real-time precise orbit and clock correction data via Internet from organizations such as JPL and NRCan.

TESTS UNDER URBAN AND MARINE ENVIRONMENTS AND RESULTS

Several positioning results under urban and marine environments using JPL real-time precise orbit and clock corrections and single-frequency observations will be presented. 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). Various tests have also demonstrated that there is no significant difference in terms of positioning accuracy between using IGS final products and JPL real-time precise orbit and clock correction data (Chen, 2004; Dixon, 2006). This provides great promise to develop commercial real-time PPP products by the industry.

Road Test Results

The system configuration for the road test under urban environment is given in Figure 4. The test was conducted on January 15, 2006 in Calgary for about 4 hours on the road. The test used a NovAtel single-frequency receiver (FLEXPAK-G2L-GENERIC) and a dual-frequency antenna (GPS 702). A Sony Ericsson GPRS (GC82 EDGE) PC Card was used to connect the Internet to receive the precise orbit and clock corrections from JPL. A Javad dual-frequency receiver (LEGACY) was setup on the roof of Engineering Building at The University of Calgary as a base station to derive a reference trajectory using double difference positioning techniques. Figure 5 and 6 show the hardware setup in the test vehicle and the antenna location on the roof of the test vehicle.

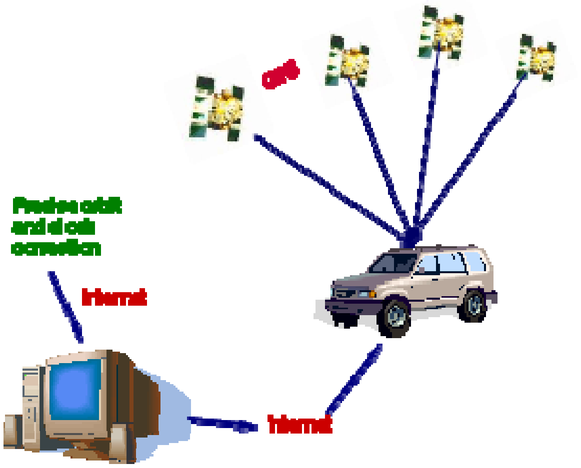

Figure 4. Road test system configuration

Figure 5. Equipment setup in the test vehicle

Figure 6. Antenna setup on the roof of the test vehicle

Shown in Figure 7 are the position differences between the real-time single-frequency PPP solutions and the post-mission double difference solutions with centimetre accuracy. From Figure 8, we can see that it takes about 10 to 20 minutes for the position solutions to converge to a sub-metre level. Note that for post-mission applications, this convergence time or initialization time is not a concern because a backward or inverse processing, which is feasible in post-mission, can be applied to ensure all position solution points at the same accuracy level. Although the positioning errors kept within sub-metre level after the position convergence (initialization), there were several big jumps in position errors at some epochs. After examining the road conditions for those places, we found that the big errors at #1 occurred before the position convergence, #2 occurred when the vehicle went through a heavy trees area (see Figure 8), #3 and #7 occurred when the vehicle went through two overpasses (see Figure 9), #4 occurred when the vehicle was in an area with tall buildings along the road, #5 occurred when the vehicle did a U-Turn with heavy surrounding trees, #6 occurred in a resident area with only 5 satellites visible and PDOP >7.

If we consider only the position solutions after the position has been converged and also remove those 7 solutions with big position errors, we recalculate the accuracy statistics and show them in Table 1. The results demonstrate that sub-metre level position accuracy was indeed obtainable in real-time using the developed single-frequency PPP system.

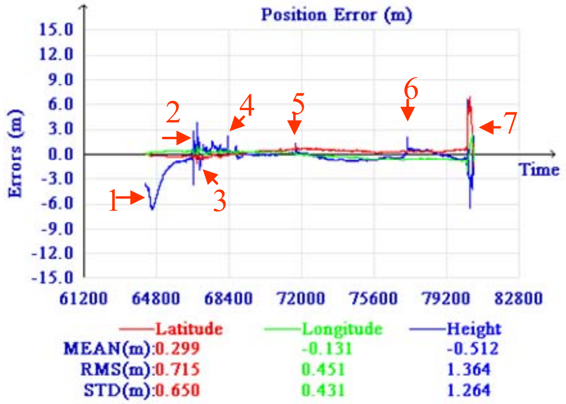

Figure 7. Time epochs with significant position errors

Figure 8. Heavy trees causing big position error at time epoch #2

Figure 9. One of the overpasses causing big position error at time epoch #3

Table 1. Positioning accuracy after convergence (m)

	Latitude	Longitude	Height
Mean	0.389	-0.283	-0.213
STD	0.418	0.453	0.460
RMS	0.153	0.353	0.407

Marine Test Results

The system configuration for tests under the marine environment is given in Figure 10. The real-time single-frequency system was installed on a commercial vessel. The GPS receiver was a C-Nav dual-frequency GPS receiver unit but only the observations at L1 were used for real-time positioning determination. Figure 11 shows the antenna setup. The JPL real-time correction data was broadcast to the vessel using satellite communication link (VSAT LEE). The GPS raw measurements and real-time position solutions from the real-time single-frequency PPP system (SFP3) were saved by the navigation center computer and made available to the University of Calgary for system performance analysis. Since there was no a land base GPS receiver station available near the vessel, the reference position trajectory has been generated by processing the dual-frequency GPS observations from the C-Nav receiver and the IGS Final products using P3® software. P3® is a dual-frequency PPP software package developed at The University of Calgary and it can provide a reference trajectory with centimetre accuracy.

A total of more than 40 hours data from September 11 to 13, 2006 have been acquired with a sampling rate of 1 Hz. In the following, the position solutions over the three days are presented separately although the real-time system was operated on a continuous basis.

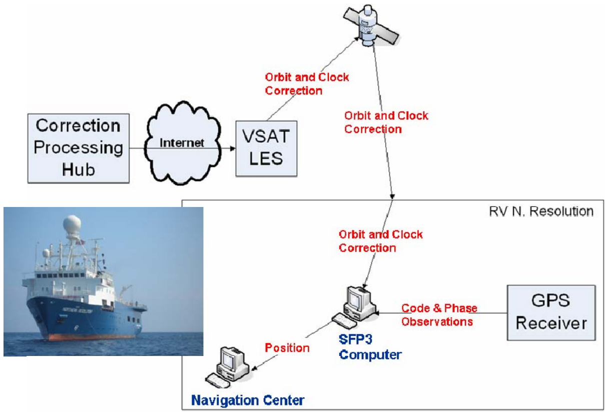

Figure 10. Marine test system configuration

Figure 11. Antenna setup

Shown in Figure 12 is the vessel trajectory on September 11, 2006. Figure 13 shows the position difference between the post-mission dual-frequency PPP solutions (as the reference) from the P3® and the real-time single-frequency PPP solutions sent back from the SFP3 system installed on the vessel. The accuracy statistics are given in Table 2.

From Figure 13, we notice that there is a bias (about -0.7m) in the height component. This could be likely due to errors in the estimation of the ionosphere zenith delays and the corresponding gradients. Although the ionosphere conditions were typical during the test period but the test site located in lower latitude region. An improvement to better follow the ionosphere variations is needed in order to reduce the position bias. Another potential cause for the bias is the residual tropospheric effect since it was mitigated only by a model using fixed default meteorological parameters. Note that the height component is more sensitive to the residual tropospheric effect. Further improvement can be expected after an improvement to the tropospheric effect calculation.

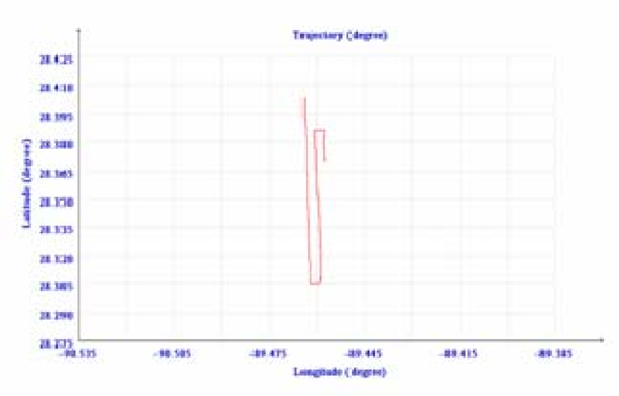

Figure 12. Vessel trajectory (Sept 11/06)

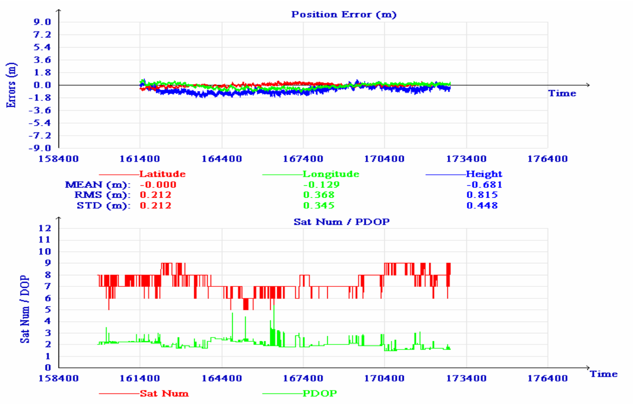

Figure 13. Positioning geometry and errors (Sept 11/06)

Table 2. Positioning accuracy (m) (Sept 11/06)

	Latitude	Longitude	Height
Mean	-0.000	-0.129	-0.681
RMS	0.212	0.368	0.815
STD	0.212	0.345	0.448

Shown in Figure 14 is the vessel trajectory on September 12, 2006. Figure 15 shows the position difference between the post-mission dual-frequency PPP solutions (as the reference) from P3® and the real-time single-frequency PPP solutions from SFP3. The positioning accuracy statistics are given in Table 3.

Figure 15 indicates some direct correlation between bad satellite geometry and greater position error. We also notice that greater position error may take the system filter some times before they converge to higher accuracy. This indicates the potential to further improve the filter design especially the ionosphere zenith delay and gradient estimation. Improved quality control to detect poor solutions due to poor geometry and data quality would also help further enhance the overall performance of the developed system for real-time applications.

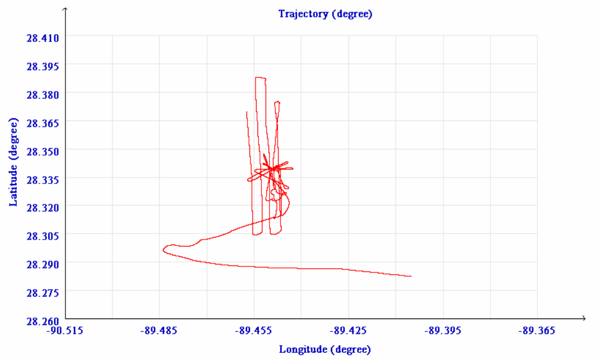

Figure 14. Vessel trajectory (Sept 12/06)

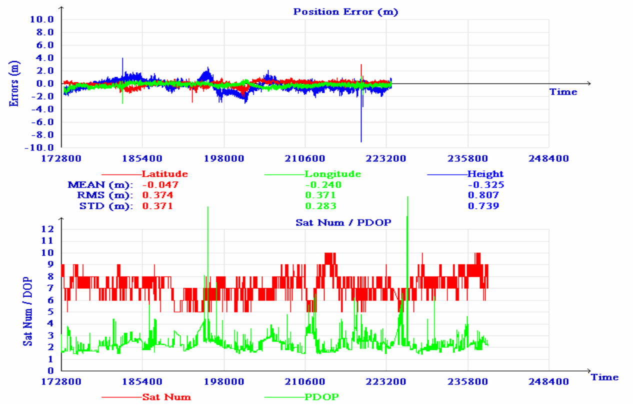

Figure 15. Positioning geometry and errors (Sept 12/06)

Table 3. Positioning accuracy (m) (Sept 12/06)

	Latitude	Longitude	Height
Mean	-0.047	-0.240	-0.325
RMS	0.374	0.371	0.807
STD	0.371	0.283	0.739

Shown in Figure 16 is the vessel trajectory on September 13, 2006. Figure 17 shows the position difference between the post-mission dual-frequency PPP solutions (as the reference) from P3® and the real-time single-frequency PPP solutions from SFP3. The positioning accuracy statistics are given in Table 4.

From Figure 17, we have seen again the slow convergence of the position errors in the height component and also in the longitude component in a relatively smaller scale. As the variations are of systematic nature, this confirms that further improvement can be made by the refinement of the ionospheric modeling and more precise tropospheric effect computation. Again an improved quality control scheme could eliminate the only significant position error jump in the position solutions.

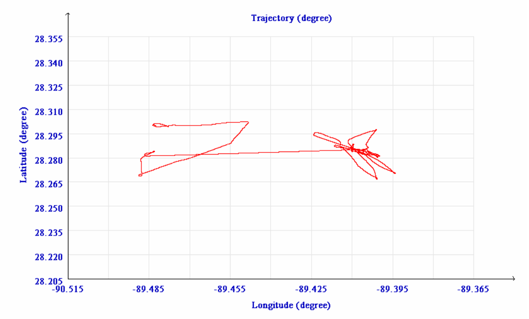

Figure 16. Vessel trajectory (Sept 13/06)

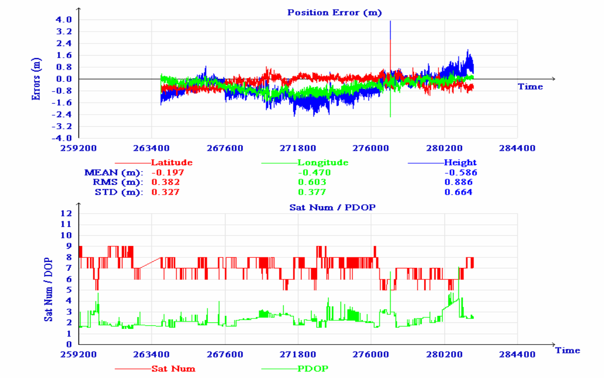

Figure 17. Positioning geometry and errors (Sept 13/06)

Table 4. Positioning accuracy (m) (Sept 13/06)

	Latitude	Longitude	Height
Mean	-0.197	-0.470	-0.586
RMS	0.382	0.603	0.886
STD	0.327	0.377	0.664

CONCLUSIONS

A real-time single-frequency precise point positioning (PPP) system has been developed at The University of Calgary and can be used to support commercial product development. After extensive post-mission tests, a number of real-time tests have been conducted to assess the performance of the developed system. Two tests under urban and marine environments have been presented in this paper to demonstrate that decimetre to sub-metre level accuracy is obtainable using PPP approach with a single-frequency GPS receiver.

Several areas for further improvement have been identified. For instance further improvement to the system can be made to refine the ionospheric modeling and estimation method, the tropospheric effect computation as well as the system quality control.

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REFERENCES

Chen, K. (2004). Real-Time Precise Point Positioning and Its Potential Applications. *Proceedings of ION GNSS 2004*, Long Beach, California, September 21-24, 2004.

Chen, K. and Gao, Y. (2005). Real-Time Precise Point Positioning Using Single Frequency Data", *Proceedings of ION GNSS 2005*, Long Beach, California, September 13-16, 2005.

Dixon, K. (2006). StarFire: A Global SBAS for Sub-Decimeter Precise Point Positioning, *Proceedings of ION GNSS 2006*, Fort Worth, Texas, September 26-29, 2006.

Gao, Y. and Shen, X. (2002). A New Method for Carrier Phase Based Precise Point Positioning, *Navigation, Journal of the Institute of Navigation*, Vol. 49, No. 2.

Gao, Y., Wojciechowski, A. And Chen, K. (2005). Airborne Kinematic Positioning Using Precise Point Positoning Methodology", *Geomatica*, Vol. 59, No. 1.

Heroux, P., Gao, Y., Kouba, J., Lahaye, F., Mireault, Y., Collins, P., Macleod, K., Tetreault, P. and Chen, K. (2004), Products and Applications for Precise Point Positioning - Moving Towards Real-Time. Proceedings of ION GNSS 2004, Long Beach, CA, September 21-24, 2004.

Muellerschoen, R.J., Bertiger, W.I. and Lough, M.F. (2000). Results of an Internet-Based Dual-Frequency Global Differential GPS System, *Proceedings of IAIN World Congress*, San Diego, CA, June 2000.

Muellerschoen, R.J., Reichert, A., Kuang, D., Heflin, M., Bertiger, W. and Bar-Sever, Y.E. (2001). Orbit Determination with NASA's High Accuracy Real-Time Global Differential GPS System, *Proceedings of ION GPS-2001,* Salt Lake City, UT, September 2001.

Ovstedal, O. (2002). Absolute Positioning with Single Frequency GPS Receivers, GPS Solutions, Vol. 5, No. 4.

Zumberge, J.F., Heflin, M.B., Jefferson, D.C., Watkins, M.M. and Webb, F.H. (1997). Precise point positioning for the efficient and robust analysis of GPS data from large networks. *Journal of Geophysical Research*, Vol. 102, 5005-5017.