Some Recent Advances in GPS Precise Point Positioning

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Abstract

Global Positioning System (GPS) surveying has traditionally been carried out in the relative (differential) positioning mode. This is mainly due to the higher positioning accuracy obtained with relative positioning in comparison with point, or standalone, GPS positioning. A major disadvantage of GPS relative positioning, however, is its dependency on the measurements or corrections from a reference receiver or network; i.e. two or more GPS receivers are required to carry out the job. New developments in GPS positioning show that a user with a standalone GPS receiver can obtain positioning accuracy comparable to that of relative positioning. Such technique is known as precise point positioning (PPP).

A major drawback of PPP, however, is that about 30 minutes or more is currently required to achieve centimetre- to decimetre-level accuracy. This relatively long convergence time results from remaining un-modelled GPS residual errors. This article discusses some recent developments in PPP, which are carried out by the Global Navigation Satellite System (GNSS) research group at Ryerson University.

Introduction

Differential carrier-phased-based GPS techniques have traditionally been used in high-accuracy surveying applications. These techniques inherit their high accuracy from the fact that GPS receivers in close proximity share, to a high degree of similarity, the same errors and biases. The shorter the receiver separation is, the more similar the errors and biases. As such, for those receivers, a major part of the GPS error budget can simply be removed by combining their GPS observables. Unfortunately, as the baseline length increases, the errors at the reference and the rover receivers become less correlated; i.e., they would not cancel out sufficiently through differencing. This leads to unsuccessful fixing for the ambiguity parameters, which in turn deteriorates the positioning accuracy. In addition, a major disadvantage of differential techniques is their dependency on the measurements or corrections from a reference receiver or network (e.g., virtual reference station). This, however, may not be a practical solution in many cases, as a result of, for example, high cost or lack of infrastructure.

With the termination of selective availability (SA) in May 2000 and the production of precise ephemeris and clock data through, e.g., International GNSS Service (IGS), it became evident that centimetre to decimetre positioning accuracy is possible with standalone geodetic-grade GPS receivers. Such technique is commonly known as precise point positioning (PPP). Unlike classical GPS point positioning, PPP attempts to account for all the GPS errors and biases (see El-Rabbany, 2006 for details). In addition to being cost effective, the PPP method provides an accuracy level comparable to that of differential carrier-phase-based positioning (i.e., centimetre- to decimetre-level accuracy).

Typically, in PPP ionosphere-free linear combination of undifferenced code and carrier-phase observations is used to remove the first-order ionospheric effect. This linear combination, however, leaves a residual ionospheric delay component of up to a few centimetres representing higher-order ionospheric terms (Hoque and Jakowski, 2007, 2008). Satellite orbit and satellite clock errors can be accounted for using the IGS precise orbit and clock products. Receiver clock error can be estimated as one of the unknown parameters. Effect of ocean loading, Earth tide, carrier-phase windup, sagnac, relativity, and satellite and receiver antenna phase-center variations can sufficiently be modeled or calibrated. Tropospheric delay can be accounted for using empirical models (e.g. Saastamoinen or Hopfield models) or by using tropospheric corrections derived from regional GPS networks such as the National Oceanic and Atmospheric Administration (NOAA) tropospheric corrections (NOAATrop). The NOAATrop model incorporates GPS observations into numerical weather prediction (NWP) models (Gutman et al., 2003).

At present, the IGS precise orbit and clock products do not take the second-order ionospheric delay into consideration. This leaves a residual error component, which is expected to slow down the convergence time and deteriorate the PPP solution. To overcome this problem, higher order ionospheric delay corrections must be considered when estimating the precise orbit and clock corrections and when forming the PPP mathematical model. In this article we restrict our discussion to the second-order ionospheric delay, which is much higher than all remaining higher order terms (Lutz et al., 2010). This article estimates the second-order ionospheric delay and studies its impact on the accuracy of the estimated GPS satellite orbit, satellite clock corrections, and global ionospheric maps. In addition, the effect of accounting for the second-order ionospheric delay on the PPP solution is examined. It is shown that neglecting the second-order ionospheric delay introduces an error of up to 2 cm in the GPS satellite orbit and clock corrections, based on recent (May 5, 2010) ionospheric and geomagnetic activities. In addition, accounting for the second-order ionospheric delay improves the PPP convergence time by about 15% and the accuracy of the estimated parameters by up to 3 mm.

To further improve the PPP solution convergence, we developed a modified PPP model which uses between-satellite single difference code and carrier-phase measurements. The advantage of this model is that, with the exception of multipath and system noise, all receiver-originating errors and biases are cancelled out. This includes receiver clock error, initial phase bias, and others. Our results indicate that the PPP solution convergence is improved by up to 50% in comparison with the undifferenced PPP model. This is very encouraging as it reduces the station occupation time by up to 50% and is considered a major step towards real-time PPP.

Second-order ionospheric delay

The second-order ionospheric delay results from the interaction of the ionosphere and the magnetic field of the Earth (Hoque and Jakowski, 2008). It depends on the slant total electron content (STEC), magnetic field parameters at the ionospheric pierce point, and the angle between the magnetic field and the direction of signal propagation (Figure 1). STEC values may be obtained from agencies such as the IGS and NOAA. IGS produces global ionospheric maps (GIMs) in the ionospheric exchange (IONEX) format. GIMs are produced with a 2-hour temporal resolution and a 2.5° (latitude) by 5° (longitude) spatial resolution on a daily basis as rapid global maps. NOAA, on the other hand, produces a regional ionospheric model known as the United States total electron content (US-TEC). US-TEC covers regions across the continental US (CONUS), extending from latitude 10° to 60° North and from longitude 50° to 150° West. The US-TEC maps have a spatial resolution of 1°x1° and a temporal resolution of 15 minutes (Rowell, 2005). The maps include both STEC and vertical total electron content (VTEC) for different locations and directions. Alternatively, STEC can be estimated by forming the geometry-free linear combination of GPS pseudorange observables and applying the receiver differential code biases.

The geomagnetic field of the Earth can be approximated by a magnetic dipole placed at the Earth's centre and tilted 11.5° with respect to the axis of rotation. The magnetic field inclination is downwards throughout most of the northern hemisphere and upwards throughout most of the southern hemisphere. A line that passes through the centre of the Earth along the dipole axis intersects the surface of the Earth at two points, referred to as the geomagnetic poles.

A more realistic model for the Earth's geomagnetic field, which is used in this article, is the international geomagnetic reference field (IGRF). The IGRF model is a standard spherical harmonic representation of the Earth's main field. The model is updated every 5 years. The International Association of Geomagnetism and Astronomy (IAGA) has released the 11th generation of the IGRF in December 2009. The coefficients of the IGRF11 model are based on data collected from different sources, including geomagnetic measurements from observatories, ships, aircrafts, and satellites (NOAA, 2011). The relative difference between the dipole and IGRF models ranges from -20% in the east of Asia up to +60% in the so-called south Atlantic anomaly (Hernández-Pajares et al., 2007).

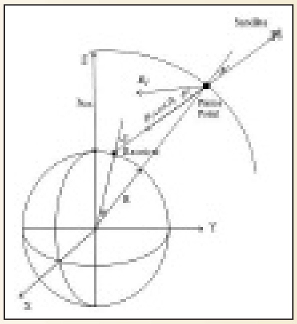

Figure 1. Magnetic Field and Propagation Direction

Effect of second-order ionospheric delay on satellite orbit and clock corrections

To investigate the effect of second-order ionospheric delay on the GPS satellite orbit and clock corrections, Bernese GPS software was used. A well-distributed global cluster of 284 IGS reference stations was formed based on a priori information about the behaviour of each receiver's clock and the total number of carrier-phase ambiguities in the corresponding observation files. GPS measurements collected at the 284 IGS stations were downloaded from the IGS website for May 05, 2010 (DOY125). The raw data were first corrected for the effect of second-order ionospheric delay. The corrected data along with the broadcast ephemeris were used as input to the Bernese GPS software to estimate the satellite orbit and clock corrections. Our study shows that the effect of second-order ionospheric delay on GPS satel-

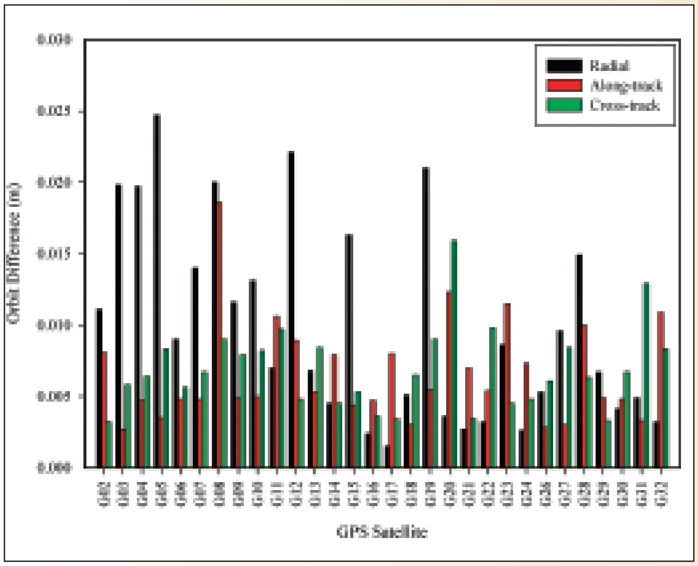

Figure 2: Impact of Second-Order Ionospheric Delay on GPS Satellite Orbit

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lite orbit ranges from 1.5 to 24.7 mm in radial, 2.7 to 18.6 mm in the along-track, and 3.2 to 15.9 mm in cross-track directions, respectively (Figure 2). Satellite clock corrections, on the other hand, show differences within 0.067 ns (2 cm) compared with the final IGS satellite clock corrections. Figure 3 shows that impact of second-order ionospheric delay on GPS satellite clock corrections root-mean-square (RMS). Interested readers should refer to Elsobeiey and El-Rabbany (2011) for more details.

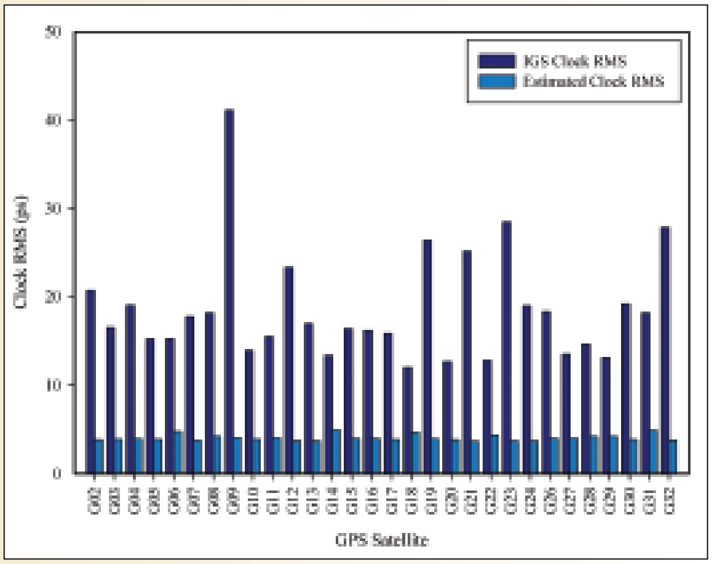

Figure 3: Impact of Second-Order Ionospheric Delay on GPS Satellite Clock Corrections RMS

Results for undifferenced GPS PPP

The GPSPace PPP processing software, which was developed by Natural Resources Canada (NRCan), was modified to accept the second-order ionospheric correction, the NOAA tropospheric correction model, and others. To examine the effect of rigorous error modelling on the undifferenced PPP solution, GPS data from 12 randomly selected IGS stations were processed using the modified GPSPace. The data used were the ionosphere-free (with both first- and second-order corrections included) linear combination of code and carrier-phase measurements. The estimated precise satellite orbit and clock corrections, from the previous step, were used in the data processing. The results show that improvements are attained in all three components of the station coordinates. Figures 4 through 6 show the 3D solution obtained with and without the second-order ionospheric corrections included, for station ALGO (Algonquin Park), as an example. As can be seen, the amplitude variation of the estimated coordinates during the first 15 minutes is reduced when considering the second-order ionospheric delay. In addition, the convergence time for the estimated parameters is reduced by about 15% on average. The final PPP solution shows an improvement in the order of 3 mm in station coordinates. It should be pointed out that the solution improvement is much higher at low latitudes whereas the second-order ionospheric effect is much higher.

Results for between-satellite single-difference model (BSSD)

GPSPace was further modified to perform between-satellite single difference observables. A major advantage of BSSD over the undifferenced mode is that the GPS receiver clock error, receiver hardware delay and non-zero initial phase of the receiver's oscillator are cancelled out. This, however, comes at the expense of introducing mathematical correlations to the BSSD observables. Such mathematical correlation, however, can be easily obtained by applying the law of covariance propagation. To examine our BSSD model, we processed the same data sets at the 12 IGS stations again. The results show that the solution convergence has improved at all stations by 20% to 50%. This improvement is significant and is considered a major step towards real-time PPP. Figures 4 through 6 compare the results obtained for ALGO with both the undifferenced and BSSD modes.

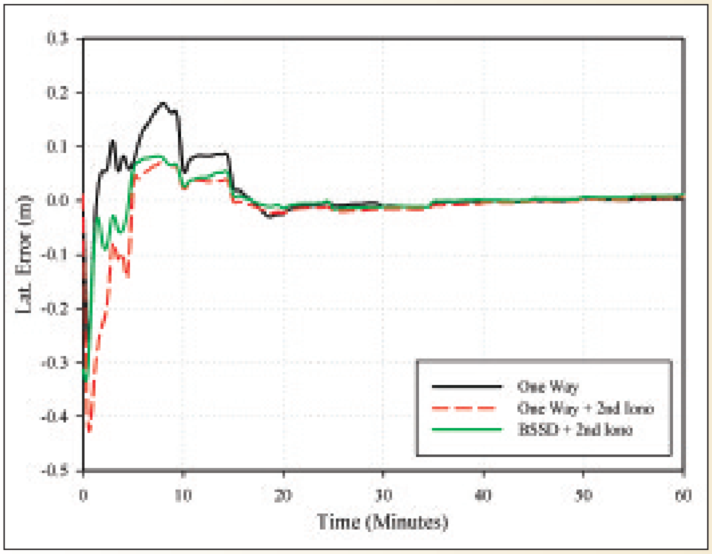

Figure 4: Latitude Improvement Using BSSD and Second-Order Ionospheric Delay vs. Undifferenced Model

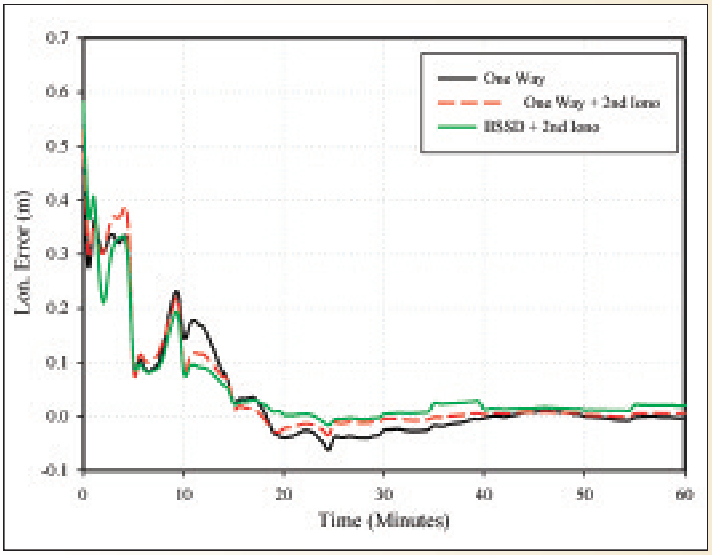

Figure 5: Longitude Improvement Using BSSD and Second-Order Ionospheric Delay vs. Undifferenced Model

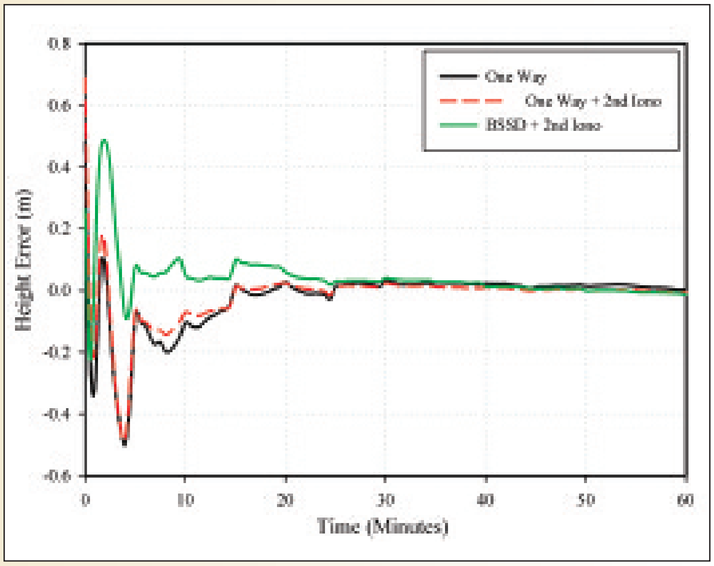

Figure 6: Height Improvement Using BSSD and Second-Order Ionospheric Delay vs. Undifferenced Model

Conclusions and future outlook

It has been shown that rigorous modelling of GPS residual errors can improve the PPP convergence time and solution. It has been shown that neglecting the second-order ionospheric delay can produce an orbital error ranging from 1.5 to 24.7 mm in radial, 2.7 to 18.6 mm along-track, and 3.2 to 15.9 mm in cross-track directions, respectively. In addition, neglecting the second-order ionospheric delay results in a satellite clock error of up to 0.067 ns (i.e. equivalent to a ranging error of 2 cm). Moreover, accounting for the second-order ionospheric delay can improve the final undifferenced PPP coordinate solution by about 3 mm and improve the convergence time of the estimated parameters by about 15%. Further improvements of up to 50% in the PPP solution convergence can be obtained when the BSSD model is used. This is very encouraging and is considered as a major step towards real-time PPP.

Future research will develop a PPP ambiguity resolution technique for precise real-time surveying applications.

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