PPP-based Ionospheric Activity Monitoring

Rodrigo F. Leandro[1,2], Marcelo C. Santos[1], and Richard B. Langley[1]

[1]*Geodetic Research Laboratory, Department of Geodesy and Geomatics Engineering, University of New Brunswick, Fredericton, Canada*

[2]*Trimble Geomatics and Engineering Group – Trimble Terrasat GmbH Hoehenkirchen, Germany*

BIOGRAPHIES

Rodrigo Leandro is a Ph.D. candidate of the Department of Geodesy and Geomatics Engineering, University of New Brunswick (UNB), Canada, where he has been a student since 2004. Mr. Leandro is also a GNSS research and development engineer at Trimble Terrasat GmbH, Germany. He holds an M.Sc.Eng. in civil engineering from the University of São Paulo, in São Paulo, Brazil, and has been involved in research in the fields of geodesy and satellite positioning since 2000. Mr. Leandro has received a best student paper award from the Canadian Geophysical Union and a student paper award from The Institute of Navigation (ION), both in 2004. Mr. Leandro has also received a best presentation award from the ION in 2006.

Marcelo Santos is an associate professor in the Department of Geodesy and Geomatics Engineering at UNB. He holds an M.Sc. in geophysics from the National Observatory in Rio de Janeiro, and a Ph.D. in geodesy from UNB. He has been involved in research in the fields of space and physical geodesy, GNSS, and navigation. He is currently serving as president of the Geodesy Section of the Canadian Geophysical Union. He is also president of International Association of Geodesy Sub-Commission 4.3 on Remote Sensing and Modeling of the Atmosphere.

Richard Langley is a professor in the Department of Geodesy and Geomatics Engineering at UNB, where he has been teaching and managing research since 1981. He has a B.Sc. in applied physics from the University of Waterloo and a Ph.D. in experimental space science from York University, Toronto. Professor Langley has been active in the development of GPS error models since the early 1980s and is a contributing editor and columnist for GPS World magazine. He is a fellow of the ION and was a co-recipient of the ION Burka Award for 2003. He is also a fellow of the International Association of Geodesy and the Royal Institute of Navigation.

ABSTRACT

The ionosphere is inherently associated with GPS, because the refraction it causes on space radiometric measurements is one of the main effects which have to be mitigated in order to determine reliable positions using GPS signals. The ionosphere is a dispersive medium, which means the value of the group delay or phase advance of a radio signal depends on the frequency of the signal. Consequently, GPS signals are broadcast on more than one frequency and, using receivers capable of tracking GPS signals on more than one frequency, we can mathematically eliminate the first order effect of the ionospheric refraction. If on the one hand the ionosphere impacts GPS signals, on the other hand GPS can be used as a sensor of the ionosphere. In this paper we introduce a novel approach for using GPS as an ionospheric sensor.

GPS receiver networks have been used for monitoring the ionosphere for a long time, but our method was created to be suitable for single-receiver operation, as one of the outputs of enhanced precise point positioning (PPP) data processing. The package in which this new technique is implemented is called GPS Analysis and Positioning Software (GAPS), a PPP package developed at the University of New Brunswick. Another characteristic of the novel approach is that only carrier-phase measurements are used, in order to avoid the contaminating effects of pseudorange measurements, such as code multipath. The filter in which the ionospheric delays are estimated is connected to the PPP filter inside GAPS, as we will discuss in this paper. In this paper we will also explain how the ionospheric delay estimation filter work. The goal of this development was to create a procedure for ionospheric delay estimation which would be suitable for single-receiver operation, as mentioned before, and also to be suitable for either static or kinematic scenarios, and eventually real-time applications.

INTRODUCTION

Ionosphere delay is closely related to GPS measurements because it is one of the main effects which have to be mitigated in order to determine reliable positions. The ionosphere is a dispersive medium, which means the value of the delay depends on the frequency of the signal. And as GPS signals are broadcast on more than one frequency, using receivers capable of tracking GPS signals on two frequencies allows us to mathematically eliminate the first order effect of the ionosphere refraction. This is possible by means of a linear combination of the signals on the two frequencies. This combination is widely called the iono-free combination. If on one hand the ionosphere impacts GPS signals, on the other hand GPS can be used as a sensor of the ionosphere.

In this paper we are introducing an approach for using GPS as a sensor of the ionosphere. GPS receiver networks have been used for this purpose for a long time, but this new method was created to be suitable for single-receiver operation. This means that this approach allows the estimated ionospheric delay to be one of the outputs of a PPP package, and in this case it is done in GAPS (GPS Analysis and Positioning Software). Another characteristic is that only carrier-phase measurements are used, in order to avoid effects present on pseudorange measurements. The filter to estimate the ionospheric delays is connected to the PPP filter inside GAPS.

GAPS – GPS data Analysis and Positioning Software

GAPS is a software package for positioning (by means of PPP) and data analysis, which was developed at UNB. The description contained in this section has been also partially shown by Leandro and Santos [2006]. One of the main goals of this development has been to develop a positioning tool; however, GAPS showed itself to be much more versatile than that, allowing innovative data analysis and quality control procedures. GAPS' data processing is done on an epoch by epoch basis, according to:

$$\begin{aligned} & P_{if} - \rho + c \cdot dt - m \cdot T = \\ & A_X \delta_X + A_Y \delta_Y + A_Z \delta_Z + c \cdot \delta_{dT} + m \delta_T \end{aligned} , \tag{1}$$

and

$$\begin{aligned} & \Phi_{if} - \rho + c \cdot dt - m \cdot T - \lambda_{if} N_{if} = \\ & A_X \delta_X + A_Y \delta_Y + A_Z \delta_Z + c \cdot \delta_{dT} + m \delta_T \\ & + \lambda_{if} \delta_N \end{aligned} , \tag{2}$$

where the left-hand side of the equations above contain the common terms of iono-free pseudorange and carrier-phase equations., δ_X, δ_Y, δ_Z, δ_{dT}, δ_T and δ_N are the computed updates for receiver coordinates (X, Y and Z), receiver clock, neutral atmosphere delay and ambiguity parameter, respectively and m is the neutral atmosphere non hydrostatic delay mapping function [Niell, 1996]. The parameters can be set as constant (e.g., ambiguities and coordinates of static positioning), stochastic parameters (e.g., neutral atmosphere delay) or white noise (e.g. receiver clock and coordinates in kinematic positioning). The update vector is computed using a least-squares technique, according to:

$$\underline{\delta} = \left(\underline{A}^t \underline{P} \underline{A} + \underline{C}_x^{-1} \right)^{-1} \underline{A}^t \underline{P} \underline{w} , \tag{3}$$

where $\underline{\delta}$ is the update vector, $\underline{A}$ is the design matrix, $\underline{P}$ is the weight matrix, $\underline{C}_x$ is the parameters' covariance matrix and $\underline{w}$ is the misclosure vector. At every epoch the parameters' covariance matrix is updated according to:

$$\underline{C}_x(t) = \left(\underline{A}^t \underline{P} \underline{A} + \underline{C}_x(t-1)^{-1} \right)^{-1} + \underline{C}_n , \tag{4}$$

where $\underline{C}_n$ is the process noise matrix, for which the values vary depending on the type of parameter, and (t) and (t-1) are epoch indicators of $\underline{C}_x$. The misclosure vector is computed in the same way as on the right-hand side of equations 1 and 2, with the addition of all necessary corrections: earth tides, antenna phase-center offset and variation, satellite code biases (in the case where C/A-code is used), phase wind-up, relativistic effects and so on. A description of most of these corrections has been provided by Kouba [2003] and Tétreault et al. [2005].

A similar model to equations 3 and 4 is used in the ionosphere delay estimation filter of GAPS. A brief overview of GAPS can be found in Leandro et al. [2007].

PPP-BASED IONOSPHERE ACTIVITY ESTIMATION

In this section we introduce an approach to use GPS as a sensor of the ionosphere. GPS receiver networks have been used for this purpose for a long time, but this method was created to be suitable for single-receiver operation. This means that this approach allows the estimated ionospheric delay to be one of the outputs of a PPP package, and in this case it is done in GAPS. Another characteristic is that only carrier-phase measurements are used, in order to avoid effects present in pseudorange measurements. The filter to estimate the ionospheric delays is connected to the PPP filter inside GAPS.

The ionospheric estimation is performed using the following model:

$$\Phi_{gf} = (1-\gamma)MF\left(I_{v,0} + \nabla_{\phi}(\phi_p - \phi_0) + \nabla_{\lambda}(\lambda_p - \lambda_0)\right) + Nb'_{gf} \quad , \tag{5}$$

where Φ_{gf} is the geometry-free carrier-phase observation in length units, MF is the ionosphere mapping function, $I_{v,0}$ is the vertical ionospheric delay at the station position, ∇_{ϕ} and ∇_{λ} are latitudinal and longitudinal gradients, respectively, ϕ_p and λ_p are the geodetic latitude and longitude of the ionospheric piercing point, ϕ_0 and λ_0 are the geodetic latitude and longitude of the station, and Nb'_{gf} is an ambiguity parameter which includes the carrier-phase integer ambiguity plus a collection of biases. The mapping function is based on a spherical ionospheric shell model as shown in Figure 1, and is computed according to:

$$MF = \frac{1}{\sin(\beta)} = \sqrt{1 - \left(\frac{r \cdot \cos(e)}{r + sh}\right)^2} \ . \tag{6}$$

The estimation is performed by means of a least-squares adjustment similar to equations 3 and 4, where the parameters are the ionospheric model elements (vertical delay and gradients) and the ambiguities. With respect to the noise model (used in equation 4), the ionospheric model parameters are treated as stochastic parameters, while the ambiguities are constant (thus no noise is added to them).

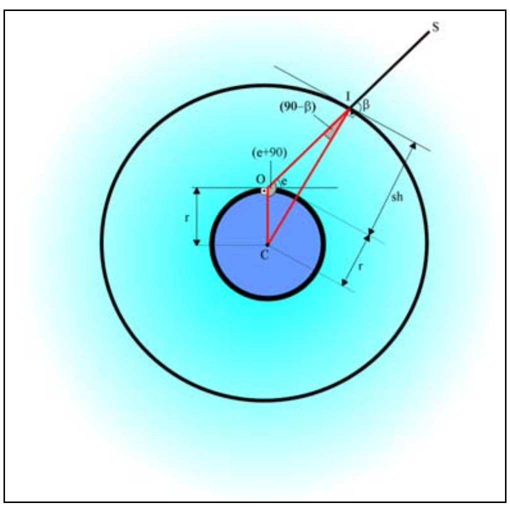

Figure 1. Elements of the ionospheric shell model (not to scale).

Figures 2 and 3 show results of the estimation for station UNB1/UNBJ (at UNB in Fredericton), for a period of low and high geomagnetic activity (these periods were chosen based on Kp index values, obtained from the Space Environment Center, National Oceanic and Atmospheric Administration (NOAA), U.S. Dept. of Commerce, Boulder, CO [Space Environment Center, 2007]).

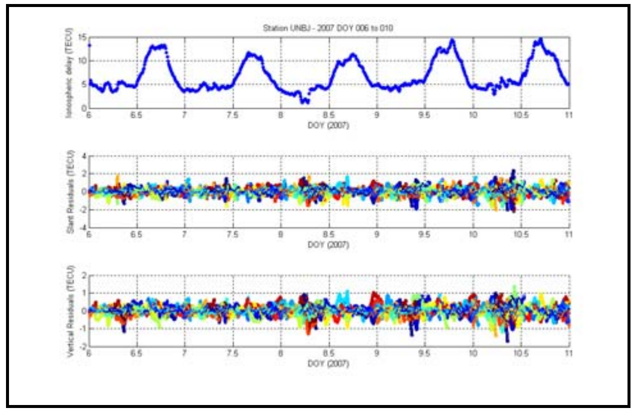

Figure 2. Ionospheric delays and residuals for station UNBJ, 2007 DOY 6 to 10.

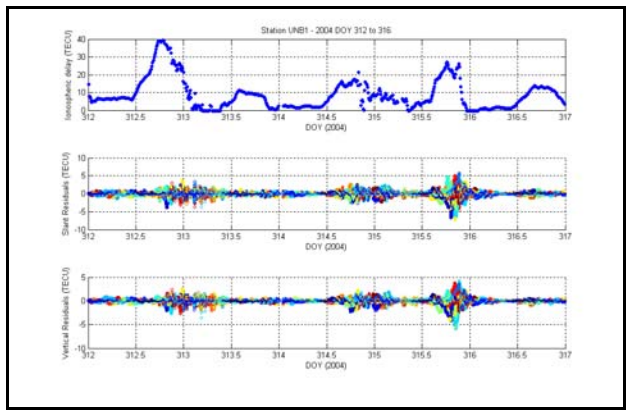

Figure 3. Ionospheric delays and residuals for station UNB1, 2004 DOY 312 to 316.

During the quiet period, the residuals for UNBJ had values usually within 2 and 1 TECU for slant and vertical values, respectively, while for the disturbed period the amplitude of the residuals reached around 5 TECU at certain hours. It can also be seen that the spread of the residuals is reasonably stable over the days of the quiet period, which does not occur during the disturbed period, where variations in residual spread can be easily seen. In the second plot the station name is UNB1 because the observations were made prior the station name change (from UNB1 to UNBJ) which occurred in 2006 [Langley, 2006].

Figures 4 and 5 show a comparison of the ionospheric delays computed with GAPS and those provided by IGS, through final IGS IONEX maps (details about IONEX map generation and format can be found in Schaer et al. [1998]).

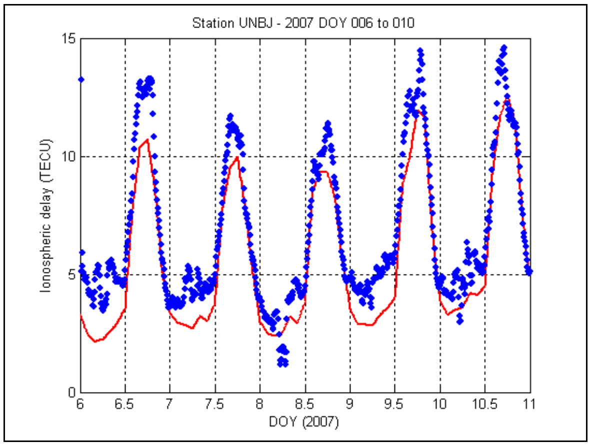

Figure 4. Comparison of results provided by GAPS (blue dots) and IGS (red line) for low activity period.

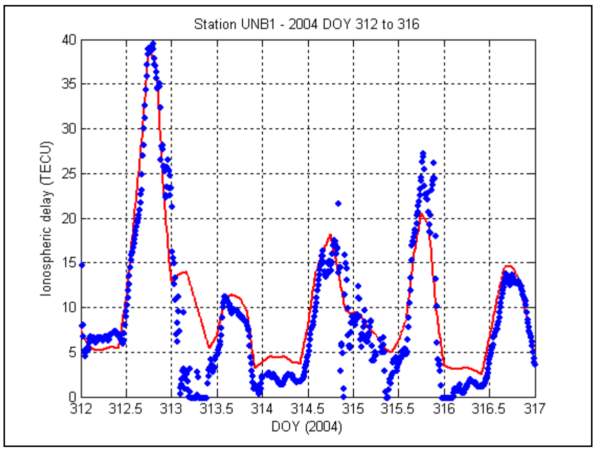

Figure 5. Comparison of results provided by GAPS (blue dots) and IGS (red line) for high activity period.

An effect which can be noticed in the above plots (more clearly in Figure 4) is the bias between the two solutions. This is an effect of a disagreement between the satellite and receiver inter-frequency biases that are determined (explicitly or not) by the two techniques. Even though in the two cases the same effect from inter-frequency biases has to be handled, this is done in a completely different way in each technique, but even then the ionospheric delays, which in theory are bias-free, should match. Table 1 shows the statistics of the comparison for each of the stations.

Table 1. Statistics of GAPS and IGS maps comparison (in the sense GAPS-IGS)

	Bias (TECU)	Std. Dev. (TECU)	RMS (TECU)
Low activity	1.18	0.97	1.52
High activity	-1.54	3.42	3.75

In general, the numbers shown in Table 3.2 are in agreement with the accuracy range claimed by IGS for its ionosphere maps (2-8 TECU for final maps – final maps were used in this analysis). This is a good result in terms of agreement of solutions, given the level of accuracy provided by IGS maps. These numbers become even more meaningful if one considers that we are comparing a station-network technique (IGS), with a single-station technique (GAPS).

Even though the results obtained for station UNB1/UNBJ are very encouraging, there are some cases when there exists a bias of up to around 4 TECU between GAPS and IGS solutions.

CONCLUSIONS AND FURTHER WORK

We have overviewed a novel technique which can be used to estimate ionospheric delays using GPS observations from one single station. The technique, which is implemented in the GAPS PPP software, has a potential to provide un-biased ionospheric delay estimations.

Results for station UNB1/UNBJ show an agreement with values provided by IGS of around 1.5 TECU and 3.5 TECU, for calm and disturbed periods, respectively. These numbers are in a good agreement with the claimed accuracy of the IGS ionospheric maps. We plan to test our procedure with data from stations at other geomagnetic latitudes.

Although results for station UNB1/UNBJ are fairly good, there are occasions when biases of up to about 4 TECU have been found, between GAPS and IGS results. This means that more investigation is required in order to find out what is the reason of such a discrepancy at times. One possible reason is the difference in how the ionosphere is mathematically modeled in the two approaches.

REFERENCES

Kouba, J. (2003). A Guide to Using International GPS Service (IGS) Products. Publication of the IGS Central Bureau. February 2003. Online at <http://igscb.jpl.nasa.gov/igscb/resource/pubs/GuidetoUsingIGSProducts.pdf>.

Langley, R.B. (2006). IGSMAIL-5406: "UNB1 Decommissioned; UNBJ Established." [On–line] Retrieved 10 September 2006 from IGSMAIL, igscb.jpl.nasa.gov, http://igscb.jpl.nasa.gov/mail/igsmail/2006/msg00129.html

Leandro R.F. and M.C. Santos (2006). "Wide Area Based Precise Point Positioning." Proceedings of ION GNSS 2006, Fort Worth, Texas, 26-29 September 2006.

Leandro R.F., M.C. Santos and R.B. Langley (2007). "GAPS: The GPS Analysis and Positioning Software – A Brief Overview." Proceedings of ION GNSS 2007, Fort Worth, Texas, 25-28 September 2007.

Niell, A.E. (1996). "Global Mapping Functions for the Atmosphere Delay at Radio Wavelengths." Journal of Geophysical Research, Vol. 101, No. B2, pp. 3227-3246.

Schaer, S., W. Gurtner, and J. Feltens (1998). "IONEX: The IONosphere Map EXchange Format Version 1". Document available on-line at the International GNSS Service ftp server: ftp://igscb.jpl.nasa.gov/igscb/data/format/ionex1.pdf . Accessed on September 2007.

Space Environment Center (2007). "Indices, Events, and Region Data. Solar, Particle and Geomag. Indices beginning Jan. 1994". http://sec.noaa.gov/ftpmenu/indices/old_indices.html. Web site accessed on 15 February 2007.

Tétreault, P., J. Kouba, P. Héroux, and P. Legree (2005). "CSRS-PPP: An Internet Service for GPS User Access to the Canadian Spatial Reference Frame." Geomatica, Vol. 59, No. 1, pp. 17-28.