GAPS: The GPS Analysis and Positioning Software – A Brief Overview

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BIOGRAPHIES

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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

Precise Point Positioning (PPP) is one of the existing techniques for determining point coordinates using a GPS (Global Positioning System) receiver. In this technique, observations produced by a single receiver are used to determine the three coordinate components, as well as other parameters, such as the receiver clock error and total neutral atmosphere delay. The technique is said to be "precise" because precise information, such as satellite orbit and clock errors, is used in the data processing. More than that, it can also be called precise because the resulting position coordinates are precise (and accurate). The idea behind our present work is that PPP can be used not only for positioning, but for a variety of other tasks, such as signal analysis. The fact that the observation model used in this technique has to take into consideration the several effects present in GPS signals, and that observations are undifferenced (there are no differences between receivers nor between satellite measurements), makes PPP a powerful data analysis tool which is sensible to a variety of parameters. The PPP application developed at UNB, which is called GAPS (GPS Analysis and Positioning Software), has been designed and built in order to be used as a tool for determining parameters other than position, receiver clock error and neutral atmosphere delay. These other estimated parameters include ionospheric delays, code biases, satellite clock errors, and code multipath among others. GAPS is a veritable "Swiss Army knife" for GPS data analysis. In all cases, the procedures were developed in order to be suitable for real-time as well as post-processing applications. Each of the data analysis products listed above will be overviewed in this paper.

INTRODUCTION

GAPS is a software package for positioning (by means of PPP) and data analysis. The description contained in this section has also been partially presented 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.

The algorithms and code structure used in GAPS follows standard GPS PPP approaches but with some important and unique differences.

The ionospheric delay estimation uses a spherical ionospheric shell model, in which the vertical delays are described by means of a zenith delay at the station position and two horizontal gradients. This estimation makes use of carrier-phase measurements only. The ionospheric delay estimation approach will be discussed further, later in this paper.

The code multipath estimation is based on the assumption that the several effects present in code measurements are dealt with within PPP, but strongly based on carrier-phase measurements. Based on this, these effects can be removed from pseudorange measurements, and the leftover effect is essentially the code multipath plus receiver noise. The advantage of this technique is that it potentially can accurately retrieve the mean multipath effect of a satellite arc, in contrast to other inaccurate multipath retrieval techniques.

Another effect which afflicts pseudorange measurements is the code bias. The code biases are important because satellite clock data products are computed using a certain arbitrary convention of observation type, such as P1 code measurements (from semicodeless P(Y) tracking) rather than the C1 code (from C/A-code tracking). If the user´s receiver uses a different observation type than the one which was used to generate the satellite clock error corrections, he (or she) has to apply an offset to the correction, equivalent to the bias between the observations, to be able to use these clock products. One of GAPS' analysis tools produces values of the satellite code biases, based on a positioning observation model, as opposed to being based on a satellite clock estimation observation model as is usually the case when bias values are provided to users. Regarding satellite clock error estimates, GAPS was enhanced in order to provide estimates of satellite clock offsets. This tool was created aiming at a suitable approach for real-time carrier-phase-based satellite clock estimation. The advantages, drawbacks and restrictions of the clock estimation technique used in GAPS are discussed later in this paper.

It is worth mentioning that both code bias and clock error estimations can be improved by using data from several receivers. This is mainly due to multipath effects present in each individual receiver estimate, which are averaged out to a certain degree when combining uncorrelated (site-dependent) multipath effects from different stations. However, even in a case where a combination of several stations is used, single-receiver data processing is still used as an initial step. This is an important aspect in terms of data processing performance, because solving receiver-dependent parameters in a single receiver step and solving network-dependent parameters (only) in a network processing step, speeds up the data processing. GAPS is also available on line via a web interface, through the University of New Brunswick Geodesy and Geomatics Engineering Research and Learning Resources web page, which can be easily run from anywhere, producing all data analysis products discussed in this paper. In addition to signal analysis outputs, GAPS provides state-of-the-art conventional PPP results, including position, receiver clock errors, and neutral atmosphere delays, in either static or kinematic mode. All aspects briefly mentioned above make GAPS a novel application, with innovations mainly in the field of GPS data analysis, available to the user community. In this paper GAPS is presented as an online application available for data analysis and positioning, all procedures used in it are briefly described, the innovating aspects related to each of its procedures are pointed out, and results obtained using it are analyzed and compared with other resources. Further details and data processing examples will be presented in subsequent papers.

STATION COORDINATES ESTIMATION

Station coordinates estimation is carried out in GAPS combining the functional model for pseudorange and carrier-phase measurements. The data processing is done on an epoch-by-epoch basis, according to:

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

and

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

where 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 the ambiguity parameter, respectively and m is the neutral atmosphere non-hydrostatic delay mapping function [Niell, 1996]. The parameters can be set as constants (e.g., ambiguities and coordinates in 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 the least-squares technique, according to:

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

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:

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

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 for $\underline{C}_x$. The misclosure vector is computed in the same way as on the left-hand side of (3) and (4), with the addition of all necessary corrections: earth tides, antenna phase-center offset and variation, satellite code biases (in cases when the C/A-code pseudorange is used), phase wind-up, relativistic effects, and so on. A description of most of these corrections can be found in Kouba [2003] and Tétreault et al. [2005].

PPP-BASED IONOSPHERE ACTIVITY ESTIMATION

In this section, we introduce 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 our 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. Details pertinent to this technique have been presented by Leandro et al. [2007b].

Table 1 shows results of the estimation for station UNB1/UNBJ (Fredericton, Canada), for periods of low and high geomagnetic activity (these periods were chosen based on Kp index values, obtained from the National Oceanic and Atmospheric Administration (NOAA) Space Environment Center, Boulder, CO [Space Environment Center, 2007] as a proxy for ionospheric activity), compared to International GNSS Service (IGS) results.

Table 1. Statistics of the GAPS and IGS map comparisons (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 1 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 the 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).

PPP-BASED CODE BIAS ESTIMATION

The analysis of this section has been explored in detail by Leandro et al. [2007a]. Hardware delay is one of the effects which has to be taken into account when using GPS under certain conditions. These delays can be different for each observable and for each frequency, which means that depending on the signal which is being used in a given application, accounting for the hardware delays might be an ordinary step to achieve the targeted accuracy. The hardware delay is usually determined in a relative sense, where a given observable and frequency (or frequency combination) is used as a standard. Because of this, the values which are determined are usually called biases, because they can bias position or other estimates if not properly accounted for, and can be represented in time or length units. One can separate the instrumental biases into two general classes: the inter-frequency biases, which are the biases between observables on two or more frequencies; and the intra-frequency biases, which are the biases between two observables broadcast on the same frequency.

One simple way of estimating code biases is to compare two different codes simultaneously observed by the same receiver. This technique delivers the receiver-satellite differential bias, which means the receiver part of the estimated quantity still has to be eliminated, in order to obtain the satellite bias. Because the biases can be considered as a constant correction for satellite clock error estimates used for positioning (over typical observation periods), it is desirable that these biases are estimated in a way in which the consistency between biases and clock products is assured. This is usually the case, since the differential satellite biases are generally estimated together with the satellite clocks. This is done, for example, at the Center for Orbit Determination in Europe (CODE) [CODE, 2007]. In the PPP-based technique, we match this approach by using the clock products for estimating the satellite differential biases.

Data from nine receivers distributed worldwide were used to estimate satellite differential P1-C1 biases.

The data was observed between 1 and 10 January 2007, inclusive, and was processed in order to determine the satellite differential P1-C1 biases. The validation of the estimated P1-C1 biases was done by comparing the values with values determined by CODE (Table 2).

Table 2. Statistics of the comparison of P1-C1 bias determinations (GAPS-CODE).

Statistic	*Value (cm)*
Bias	0.74
Standard Deviation	3.63
RMS	3.64
Maximum	7.03
Minimum	-5.52

As can be noticed in the table above, the agreement at one sigma between the two sets of determinations is around 3.6 cm. The maximum difference encountered was around 7 cm, which is also a reasonably small value.

PPP-BASED CODE NOISE ESTIMATION

In this section we briefly mention the approach we use to make estimates of the noise level of pseudorange measurements with GAPS. The main idea of this technique is that inside GAPS there is sufficient information to eliminate most of the effects present in the code measurements in a way that the left-over is purely noise, caused by multipath and other effects (such as receiver noise).

Even though the carrier-phase observable is not directly used in the code-noise observable, the latter depends on parameters such as the zenith neutral atmosphere delay which can only be well determined using carrier-phase measurements. In order to illustrate the outcome of this procedure, we have processed one hour (0h – 1h GPS Time) of data from IGS station ALGO (located in Algonquin Park, Canada), which was observed on 8 January 2007. We computed "mp" values using software TEQC, from UNAVCO, which uses a code and phase differencing approach. More information about TEQC can be found at http://unavco.org/. The comparison between GAPS and TEQC results are shown on Table 3.

Table 3. Code noise level (m).

	Code	*GAPS*	*TEQC*
PRN 6	C1	0.63	0.67
	P2	0.33	0.40
PRN 21	C1	0.20	0.23
	P2	0.07	0.08

As can be seen from the table above, the agreement between the two noise level estimates is around 4 cm, with GAPS results being systematically smaller than values provided by TEQC. This might be an effect of the difference between the state-based noise estimation performed by GAPS, and a pure observation combination (which amplifies noise) performed by TEQC. However, further research is needed to investigate this difference.

CONCLUSIONS AND FURTHER WORK

In this paper we show an overview of GAPS capabilities for positioning and data analysis.

In a comparison with IGS IONEX maps results for station UNB1/UNBJ, we found an agreement of around 1.5 TECU and 3.8 TECU for calm and storm periods, respectively. These results show a great potential for estimating precise un-biased ionospheric total electron count with GAPS.

When using GAPS to compute code biases, we have compared results obtained for P1-C1 bias estimation with numbers provided by CODE. The overall agreement is better than 4 cm, where data of 10 days, observed at 9 GNSS stations was used for GAPS estimation. This result shows that, with our PPP-based technique, we can match other bias estimation techniques at the few cm level.

GAPS is also able to provide estimates of code noise. We have compared our results using this analysis approach with those obtained using software TEQC from UNAVCO. In this comparison, we found an agreement of the pseudorange noise level (which usually ranges from a few centimeters to a couple of meters at times) to better than 5 cm. We have also found that GAPS estimates are systematically smaller than TEQC estimates, due most likely to differences in the two techniques rather than to data editing considerations.

Overall, we have shown that GAPS is a unique software tool which can provide results of several kinds, matching or surpassing the capabilities of other pre-existing well-established techniques.

Further details about GAPS and more illustrative results and comparisons with other techniques will be presented in subsequent publications.

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