Wide Area Based Precise Point Positioning

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BIOGRAPHIES

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ABSTRACT

Precise point positioning (PPP) is a positioning technique in which a single receiver is used to determine its coordinates,using precise products such as orbits and clocks. In this work we are discussing the ambiguity parameter in PPP, which, for several reasons, is not an integer value, as it happens in case of double differenced observations The ambiguity parameter in PPP includes satellite and receiver biases, which have to be adequately separated in order to obtain integer ambiguities, what would allow ambiguities fixing process. In order to do so, a new approach was introduced, called here wide area precise point positioning. The main idea of this new approach the determination of satellite fractional biases using a network of receivers. In order to separate fractional biases from other parameters such as ionospheric delays and ambiguities, a de-correlation filter was created, and in experiments carried out involving nearby stations, the ionospheric delays determined with the de-correlation filter agree very well with each other Differential receiver-satellite fractional biases were determined for former IGS station and PRN 20 at L1 frequency and showed to be stable with a mean value of -0.6 cycles, and standard deviation of around 0.2 cycles. This uncertainty in metric units for L1 frequency is 3.9 cm.

INTRODUCTION

Precise point positioning is a positioning technique in which a single receiver is used to determine its coordinates. It is said to be "precise" because precise products such as orbits and clocks are used in the data processing. More than that, all necessary corrections should be taken into account to achieve the best possible accuracy. Such corrections include tides, relativistic effects, antenna phase center variation among others. Depending on the type of receiver being used (e.g. code only or code and phase; single or dual frequency), some of those corrections can be disregarded, and also further precise products might be needed, such as ionospheric grids in case of single frequency receivers. If the higher possible accuracy is targeted, a "geodetic" receiver is used, with dual frequency measurements of pseudoranges and carrier-phases. In this case, other aspects are also important, such as treating the carrier-phase as an independent measurement (rather than using them to simply filter the pseudoranges), what implicates in ambiguity parameter estimation, and also the estimation of residual neutral atmosphere delays (NAD), since NAD prediction models are not accurate enough for this type of positioning.

The precise point positioning (PPP) observation model is pretty much a standard model nowadays (here we are using the word "standard" because most of PPP packages, such as CSRS-PPP [Tétreault et al. 2005], GAPS, P3 [Gao and Chen, 2004] and Gipsy [Zumberge et al. 1997], use this model, with ionospheric free combination of pseudorange and carrier-phase. A few differences can be found between them, such as the estimation process of NAD (e.g. as random walk, or fixed values for given time intervals). The basic PPP observational model is given by:

$$P_{if} = \rho + c(dT - dt) + T \,, \tag{1}$$

and

$$\phi_{if} = \rho + c(dT - dt) + T + \lambda_{if} N_{if}, \qquad (2)$$

where P_{if} is the ionospheric free combination of pseudorange measurements, ϕ_{if} is the ionospheric free combination of carrier-phase measurements in metric units, ρ is the geometric distance between satellite and receiver antenna phase centers, c is the speed of light, T is the neutral atmosphere delay (where T stands for troposphere), dT and dt are the ionospheric free receiver and satellite clock errors, repectivelly, λ_{if} is the ionospheric free carrier-phase wavelength and N_{if} is the ionospheric free carrier-phase ambiguity parameter. This last term is not simply the combination of ambiguities, but the combination of a few terms, including ambiguities, reason why it is being called here as "ambiguity parameter".

In this work we are discussing the ambiguity term in (2). For several reasons, this term is not an integer value, as it happens in case of double differenced observations, what makes impossible the approach of fixing ambiguities in case of PPP. The motivation of a wide area based PPP (which will be explained later in this paper) is to allow the recovering of integer values for ambiguity parameters.

GAPS – GPS data Analysis and Positioning Software

GAPS (GPS data Analysis and Positioning Software) is a software package for positioning (by means of PPP) and data analysis, which was developed at UNB. One of the main goals of this development has been to allow the investigation of the wide area PPP approach; however GAPS showed to be much more versatile than that, allowing innovating data analysis and quality control procedures. GAPS' PPP uses the functional model given by (1) and (2). The data processing is done in an epoch by epoch basis, according to:

$$\begin{aligned} &A_x\delta_x + A_y\delta_Y + A_z\delta_Z + c\cdot dT + m\delta_t = \\ &P_{if} - \rho + c\cdot dt - m\cdot T \end{aligned}, \qquad (3)$$

and

$$\begin{aligned} &A_x\delta_x + A_y\delta_Y + A_z\delta_Z + c\cdot\delta_{dT} + m\delta_t \\ &+ \lambda_{if}\delta_N = \phi_{if} - \rho + c\cdot dt - m\cdot T - \lambda_{if} N_{if} \end{aligned}, \qquad (4)$$

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 ambiguity parameter, respectively and m is the neutral atmosphere non hydrostatic delay mapping function (Niell [Niell, 1996] mapping function is used in GAPS). The parameters can be set as constant (e.g., ambiguities and coordinates of static positioning), random walk process (e.g., neutral atmosphere delay) or white noise (e.g. receiver clock and coordinates in a kinematic positioning). The update vector is computed using least squares technique, according to:

$$\underline{\delta} = \left(\underline{A}^t \underline{P}\underline{A} + \underline{C}_x^{-1}\right)^{-1} \underline{A}^t \underline{P}\underline{w}, \qquad (5)$$

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:

$$\underline{C}_x(t) = \left(\underline{A}^t \underline{P}\underline{A} + \underline{C}_x(t-1)^{-1}\right)^{-1} + \underline{C}_n, \qquad (6)$$

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 in the right 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 case C/A code is used), phase-wind-up, relativistic effects and sagnac delay. A description of most of these corrections can be found in Kouba [2003] and Tétreault et al. [2005].

In Figure 1 it can be seen a series of seven 24 hour solutions for former IGS station UNB1, using GAPS in static mode. The plot shows the difference between GAPS solution and the reference solution, in this case, the IGS cumulative solution for the same week (considered as "true" here).

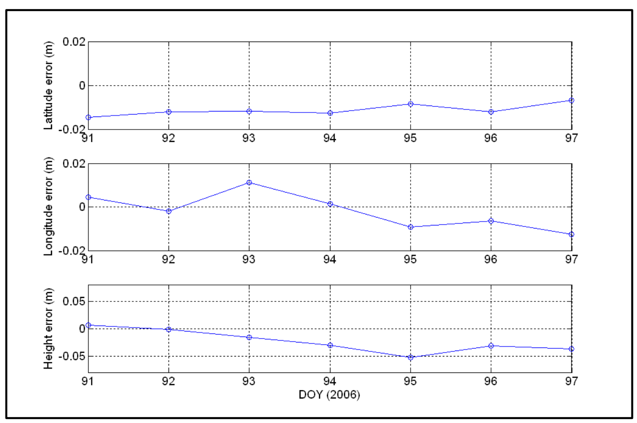

Figure 1. GAPS 24 hour solutions for former IGS station UNB1 (doy 91 to 97).

As it can be seen above, horizontal coordinates have a disagreement of less than 2 cm, and height less than 5 cm.

The rms values for the three components are 1.15 cm, 0.79 cm and 3.01 cm for latitude, longitude and height, respectively.

Figure 2 shows an example of coordinates convergence of a 24 hour solution, in this case for doy 91, station UNB1. As it can be seen, horizontal coordinates better than 5 cm are achieved after around 2 hours of observation in static mode, and it takes a little longer for the height component to achieve the same error level. It can be seen that after 4 hours of observation there is a very small improvement in the horizontal coordinates, while the height component takes longer to fully converge. In the plots of Figure 2, the zero value of the vertical axes is the final value of each component (not the IGS solution, as in Figure 1).

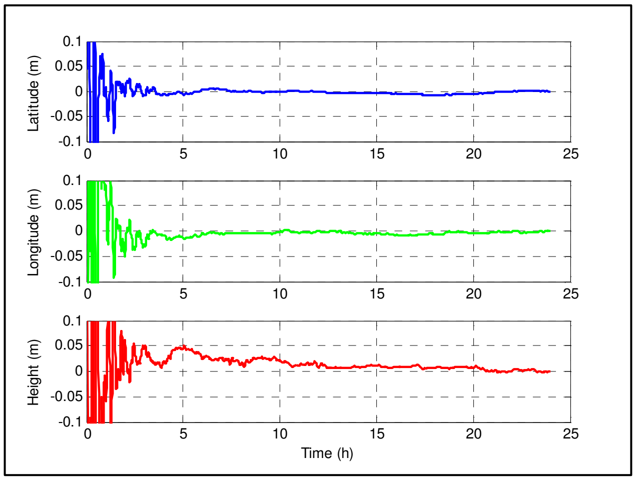

Figure 2. Coordinates convergence in static mode (station UNB1, doy 91).

Figure 3 shows the convergence of the neutral atmosphere delay, as well as its standard deviation. It can be noticed that the neutral atmosphere delay takes several minutes to achieve its convergence.

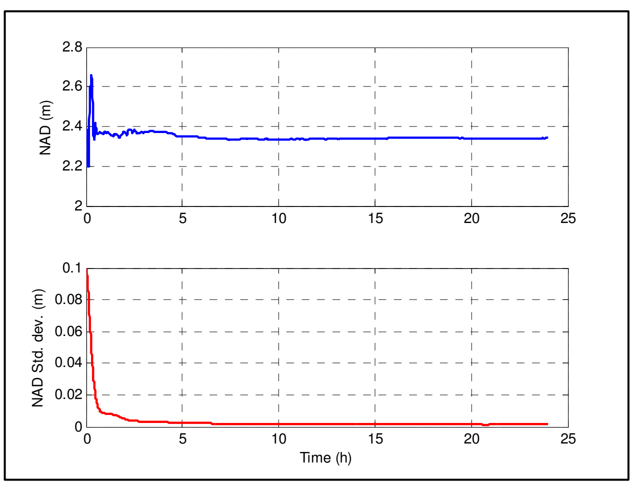

Figure 3. Neutral atmosphere delay convergence with GAPS.

As mentioned before, GAPS has also the option of processing data in kinematic mode. In order to access its accuracy in kinematic mode, data collected during the Princess of Acadia project was used. In this project a receiver placed on board a boat travels between the cities of Saint John and Digby, through the Bay of Fundy [Santos et al. 2004]. Figure 4 shows the trajectory of the boat during the day of analysis. In this analysis the reference solution (considered as “true”) is a multi-baseline baseline solution provided by the software GrafNav version 7.60 from Novatel. In this case, two static stations (in St. John and Digby) are used simultaneously as reference of the baseline, and more weight is given for the nearest station. Figure 5 shows the two solutions (GrafNav, in blue, and GAPS-PPP, in red) for latitude, longitude and height.

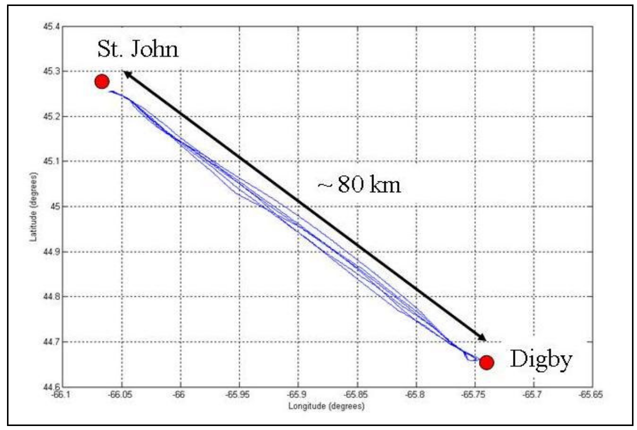

Figure 4. Boat trajectory in the Bay of Fundy.

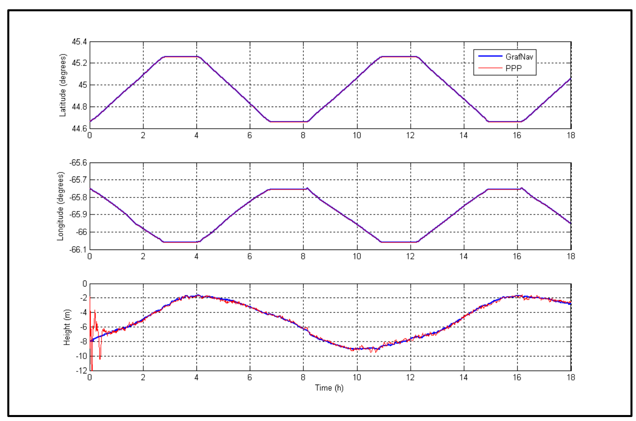

Figure 5. GrafNav (blue) and GAPS-PPP (red) solutions.

Figure 6 shows the difference between the two solutions for latitude, longitude and height. The vertical scale is the same for all three components (-3 m to 3 m). It can be noticed that the height solution is slightly noisier than the horizontal components. It can also be noticed that it takes around one hour to achieve convergence.

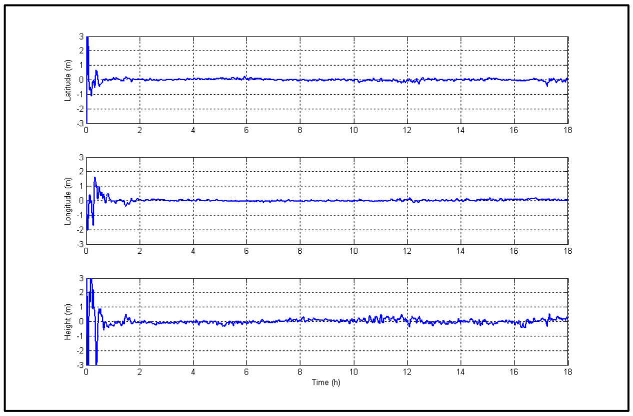

Figure 6. Difference between GAPS and GrafNav solutions.

Figure 7 shows the same results as in 6, however discarding the two first hours and with an enlarged vertical scale (ranging from -0.5 m to 0.5 m). The higher noise of the vertical component can be clearly seen in this figure.

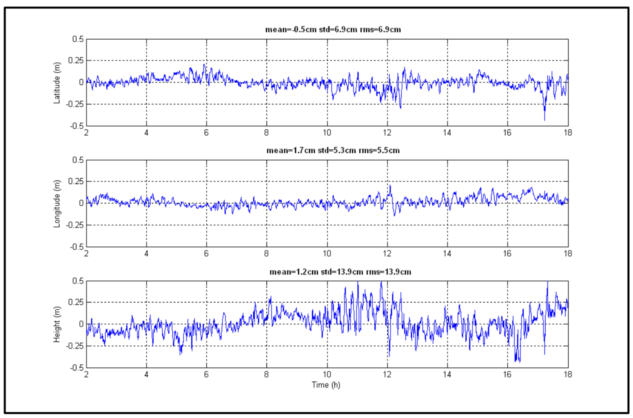

Figure 7. Difference between GAPS and GrafNav solutions.

The rms values of the three components are 6.9 cm, 5.5 cm and 13.9 cm for latitude, longitude and height, respectively. As shown, GAPS provides positioning solutions with the expected accuracy level for a state of art PPP package. This validation is primordial because GAPS is the tool used for the wide area precise point positioning model development, explained in the next sections.

Wide Area based Precise Point Positioning

As mentioned earlier, the main goal of the wide area PPP approach is recovering integer ambiguities parameters in PPP data processing. In order to better understand what is the relation between the integer ambiguities and the PPP functional model, we need to start with the fundamental carrier-phase measurement equation:

$$\phi_r^s = \phi_r(t_r) - \phi^s(t^s) + \lambda N_r^s, \tag{7}$$

where ϕ_r^s is the measured carrier-phase for receiver r and satellite s, $\phi_r(t_r)$ is the receiver phase at reception time, $\phi^s(t^s)$ is the satellite phase at emission time and N_r^s is an integer number of cycles. However what is in fact measured at the receiver is the satellite phase at the reception time, according to:

$$\begin{aligned}\phi_r^s(t_r) &= \phi_r(t_r) - \phi^s(t_r) + \rho \\ &+ b_r - b^s + c(dT - dt) + T - I + \lambda N_r^s,\end{aligned} \tag{8}$$

where receiver and satellite hardware delays (b_r and b^s), clock errors, geometric distance and atmospheric refraction terms have to be considered. Equation 8 is actually very similar to (2), with the inclusion of phase, hardware delays and ionospheric refraction terms (Equation 8 stands for each frequency, while 2 stands for ionospheric free combination). Rearranging (8) similarly to (2) leads to:

$$\begin{aligned}\phi_r^s(t_r) &= \rho + c(dT - dt) + T - I + \lambda N_r^s \\ &+ \left(\phi_r(t_r) + b_r\right) - \left(\phi^s(t_r) + b^s\right).\end{aligned} \tag{9}$$

The above equation can be considered as the basic function model used in PPP, with the addition of the satellite and receiver biases (including hardware delay and phase). In fact we can consider one unique bias which includes the two mentioned effects, since they can not be de-correlated from each other. Because of this, from now on we are going to refer to them as two unique terms, to be called receiver and satellite phase biases hereafter, as shown in (10):

$$\begin{aligned}\phi_r^s(t_r) &= \rho + c(dT - dt) + T - I + \lambda N_r^s \\ &+ b_r - b^s.\end{aligned} \tag{10}$$

Because these two bias terms are not considered in the basic PPP functional model, when an ambiguity parameter is estimated, what is being estimated is in fact the ambiguity plus the receiver and satellite biases. Therefore, if we are using PPP, we do not estimate ambiguities, but ambiguity-like parameters.

As it can be easily noticed, equation 10 can not be solved using an isolated receiver, because of the correlation between bias terms and ambiguities. However the receiver bias can be handled with an isolated receiver, since it is a common value for all satellites. The receiver bias can be either estimated as a parameter or eliminated with single difference between satellites. But before recovering the integer ambiguity the satellite biases (different for each satellite) must be known. The idea behind wide area PPP is the determination of satellite phase biases using a wide area network of receivers. These biases can then be used later for a receiver outside the network (a truly isolated receiver) in order to recover the integer ambiguity values. Figure 8 shows an overall flowchart of the wide area PPP approach.

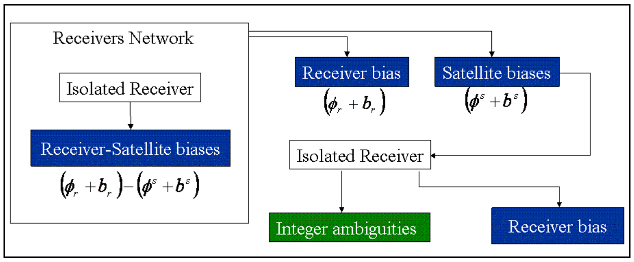

Figure 8. Wide area precise point positioning flowchart.

It is possible to identify two tasks which are not usual in terms of PPP in the flowchart above. One of them is the separation of a combined term, the differential receiver-satellite bias (obtained with one unique receiver), into two terms, for satellite and receiver. This task is not much different from what is done when handling clock biases in a receiver network, or handling network differential code biases in order to estimate ionospheric delays. Therefore this is a task for which the solution is known. The more challenging task in the flowchart above is the determination of the differential biases with an isolated receiver. This task is singularly difficult because of several factors, including the fact that the biases are frequency dependent and they are correlated with ambiguities and ionospheric refraction (see for example equation 9). In order to overcome this difficulty a de-correlation filter has been being developed.

The main task of the de-correlation filter is to separate the receiver and satellite biases from other parameters, such as ambiguities and ionospheric refraction. Because the biases need to be later used with carrier-phase measurements, certain requirements must be satisfied to assure the compatibility between the de-correlation filter and the observables in which the biases derived from that will be applied, in terms of quality. These requirements are (1) the use of un-differenced carrier-phase, what will allow the use of also un-differenced carrier at the isolated receiver end; (2) the use of un-combined carrier-phase, which allows the use of any combination at the positioning side, since biases are determined for each frequency separately; and (3) an estimation independent of pseudoranges, to assure a low noise level and also avoid pseudorange biases.

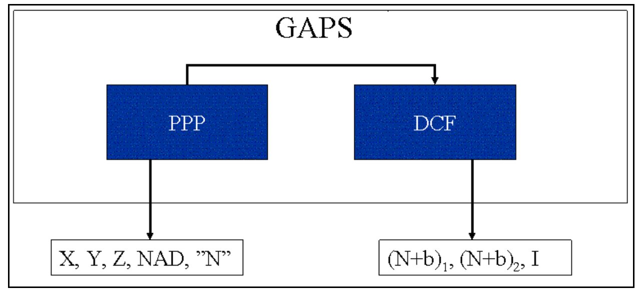

Figure 9. De-correlation filter (DCF) and PPP inside GAPS.

Figure 9 shows the relation between the de-correlation filter (referred to as DCF) and PPP inside GAPS. The filter receives information from PPP solution, and provides the de-correlated information (ambiguities plus biases and ionospheric advances). What is passed on from the PPP to the filter are the adjusted values of the receiver clock offset, neutral atmosphere delay and coordinates. If these terms are considered as known in (10), the following equation is obtained:

$$\phi_r^s(t_r) = -I + \lambda N_r^s + b_r - b^s \,, \qquad (11)$$

which is the functional model of the de-correlation filter. The following steps are the separation of the ionospheric delay (it can be called delay here because it has a negative sign in equation 11) from the other terms, and the latter separation of the integer ambiguities from the differential receiver-satellite bias ($b_r - b^s$). The separation between receiver and satellite biases is done in a network basis, as shown in Figure 8. The way the de-correlation filter works will be explored in detail in future publications, since the main goal of this paper is presenting the overall concept of the wide area based PPP approach.

Assuming the ionospheric delays are successfully de-correlated from the other terms, one can say that the resulting value is an un-biased ionospheric delay. In order to verify this statement, two experiments were made. The first experiment is the data processing of two stations (UNB1 and UNB3), which are actually two receivers sharing the same antenna through a splitter. The idea is that if the ionospheric delays are truly bias-free, the values computed for both stations should be the same. Figure 10 shows the ionospheric delays obtained for the two stations over the day (doy 91).

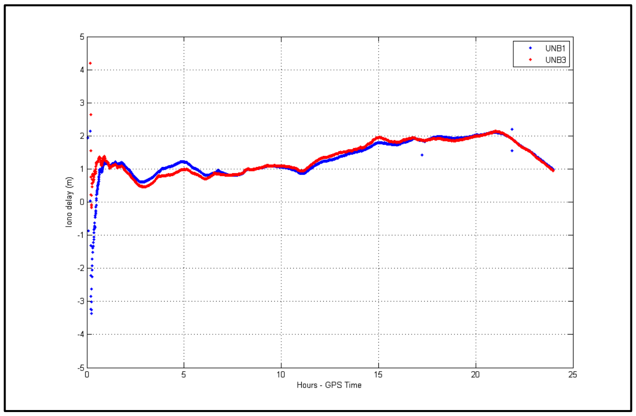

Figure 10. Ionospheric delay for stations UNB1 (in blue) and UNB3 (in red).

As it can be noticed, there is a certain time needed for the convergence achievement, and after that the estimated delays are very similar to each other. The second experiment makes use of two IGS stations (CAGS and NRC1) which are approximately 20 km apart from each other. Figure 11 show the ionospheric delay results for these stations over the day.

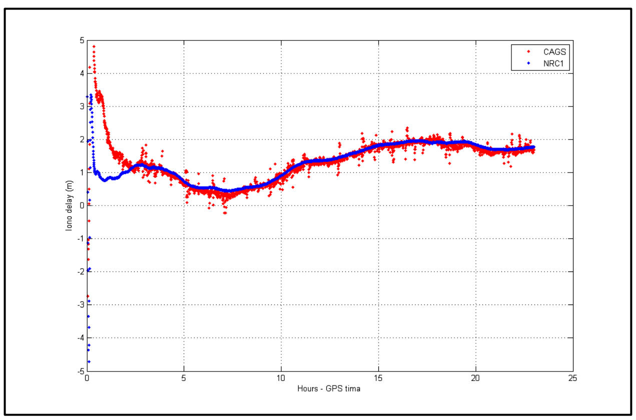

Figure 11. Ionospheric delay for stations CAGS (in red) and NRC1 (in blue).

Similarly to the first experiment, it can be noticed that after convergence the results of the two stations agree very well with each other. These results show that the ionospheric delays derived from GAPS are unbiased, or in other words, that GAPS allows the determination of carrier-phase based, un-biased ionospheric delays.

In order to verify if the fractional biases obtained from the de-correlation filter are meaningful, they were computed for station UNB1 and PRN 20, at every satellite pass from doy 91 to 97. The assumption is that if the biases are being correctly estimated, they should be relatively stable over a few days. This assumption is not entirely true because part of the biases are hardware dependent and should have some day to day variability. Shaer [1999] for example has reported a day-to day repeatability of around 3 cm to 9 cm for the differential code biases of the IGS network receivers. Figure 12 shows the results of the fractional differential biases estimation for L1 frequency.

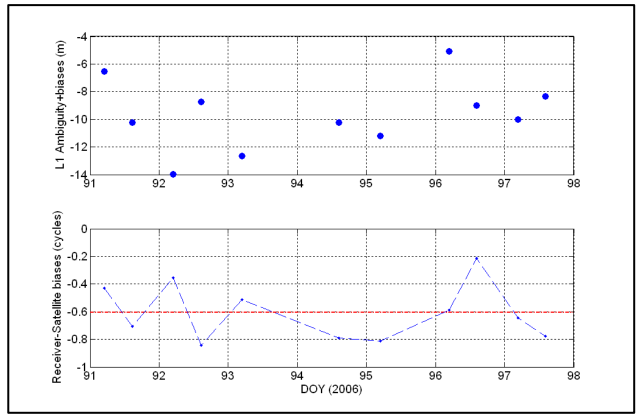

Figure 12. Determination of fractional differential biases for station UNB1 and PRN 20.

In Figure 12 the upper plot shows the integer ambiguity values, represented by blue dots. As it can be seen, the ambiguities assume different values at each satellite passage, with differences of several meters. The lower plot shows the fractional differential biases for the same days, where it can be noticed that the biases have a value fluctuating around a mean value of 0.61 cycles, i.e., around 3.9 cm at L1 frequency. The standard deviation of the mean is 0.21 cycles.

CONCLUSIONS AND FUTURE WORK

In this work a new software package for GPS positioning and data analysis, called GAPS, was introduced. It was shown that GAPS provides positioning results at the expected level for a precise point positioning software, for both static and kinematic positioning. Static data processing (24 hours) showed rms of around 1 cm and 3 cm, for horizontal and height components, respectively. Kinematic positioning uncertainties are around 5 cm for horizontal components and 15 cm for height component.

It was shown that the ambiguity parameter in PPP includes satellite and receiver biases, which have to be adequately separated in order to obtain integer ambiguities, what would allow ambiguities fixing process. In order to do so, a new approach was introduced, called here wide area precise point positioning. The main idea of this new approach the determination of satellite fractional biases using a network of receivers.

In order to separate fractional biases from other parameters such as ionospheric delays and ambiguities, a de-correlation filter was created. In experiments carried out involving nearby stations, and even stations sharing the same GPS antenna, the ionospheric delays determined with the de-correlation filter agree very well with each other. From these experiments we can conclude that GAPS is capable of estimating carrier-phase-based, unbiased ionospheric delays.

Differential receiver-satellite fractional biases were determined for former IGS station and PRN 20 at L1 frequency. In this experiment 7 consecutive days of observations were processed. Ambiguities and fractional biases were determined for each passage of the satellite. Although the ambiguity values are different for each passage, with differences of several meters, the fractional biases showed to be stable with a mean value of -0.6 cycles, and standard deviation of around 0.2 cycles. This uncertainty in metric units for L1 frequency is 3.9 cm, value which is in agreement with previous work in the literature reporting repeatability of receiver dependent biases.

The next step of the research is the refinement of the de-correlation filter, in order to reinforce its current capability of providing reliable differential fractional biases and ionospheric delays, followed by an extensive data processing and results analysis for validation purpouses. Once the computation of fractional biases are validated, the network adjustment will be performed in order to separate the satellite dependent biases, followed by their application in an isolated receiver.

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