Fast Precise Point Positioning for decimeter-error-level navigation for multi and single-frequency users of Global Navigation Satellite Systems

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Summary: This manuscript summarizes the new algorithm of Fast Precise Point Positioning (FPPP) the developed during the projects "Enhanced PPP GNSS multifrequency user algorithm" and “Precise Real Time Orbit Determination and Time synchronisation”, both funded by the European Space Agency (ESA). The main innovations achieved during the overall project comprise the application of precise ionospheric corrections to facilitate the fast resolution of undifferenced carrier phase ambiguities, ambiguity validation and integrity monitoring for both multi- and single-frequency users. Among the integrity, detailed in previous works, the performance of the FPPP algorithm in terms of improved accuracy and convergence time is demonstrated with actual GPS and simulated Galileo data. The 10-centimeters error level real-time kinematic positioning can be achieved in few minutes for dual-and single-frequency users, almost instantaneous for three-frequency users (or once the tropospheric delay is well estimated in few minutes in cold start), and with very limited bandwidth requirements for the FPPP users (less than 300 bps for dual-frequency GPS).

Zusammenfassung: *Schnelle Precise Point Positioning für Dezimeter-error-Level-Navigation für Einzel-und Multi-Frequenz-Nutzer von Global Navigation Satellite Systems.* Dieses Manuskript fasst der neue Algorithmus von Fast Precise Point Positioning (FPPP) entwickelten während der Projekte "Enhanced PPP GNSS Mehrfrequenz Benutzer-Algorithmus" und "Präzise Echtzeit Bahnbestimmung und Zeitsynchronisation", die von der European Space Agency (ESA) bothfunded. Die wichtigsten Neuerungen während der gesamten Projekte erreicht umfassen die Anwendung von präzise ionosphärischen Korrekturen an der schnellen Auflösung der undifferenzierten Träger Phasenmehrdeutigkeiten, Mehrdeutigkeit Validierung und Integrität Überwachung zu erleichtern. Die Leistung des FPPP Algorithmus in Bezug auf die verbesserte Genauigkeit, Konvergenz Zeit und Integrität, mit aktuellen GPS und simulierten Galileo-Daten demonstriert. Dies kann mit sehr begrenzten Bandbreiten-Anforderungen für die FPPP Nutzer (weniger als 300 bps für Dual-Frequenz GPS) erreicht werden.

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1 Introduction

Precise Point Positioning (PPP) is a well-known technique which allows a dual-frequency Global Navigation Satellite Systems (GNSS) user to determine the position at the decimeter (centimeter) error level in kinematic (static) mode with a single receiver. It is based on the ionospheric-free combinations of observables (carrier phases and codes, L_c and P_c), to remove more than 99.9% of the slant ionospheric delay (the first order term), and in the real-time availability of satellite products (GPS clocks and orbits) significantly more precise than those computed by the GPS control segment (by combining data from a denser network and better modeling). The PPP user must model Lc and Pc in a precise way for all the satellites in view, by correcting all the dependencies at centimeter-level, and estimating, in a navigation filter, the remaining relevant unknowns: among 3D position and receiver clock, the phase ambiguities and zenith tropospheric delay.

The main advantages of the basic PPP approach for high precise GNSS navigation are: (1), its simplicity, and (2), the associated low bandwidth message required for satellite clocks and precise predicted orbits (in a similar way to the clock model of the GPS navigation message). But its main drawback is the large convergence time needed by the user to get a good estimation of its position (at least the best part of one before achieving the decimeter level positioning accuracy).

To overcome the limitations of the basic PPP approach we have studied:
(1) The use of precise ionospheric corrections computed and broadcast by a dedicated PPP Central Processing Facility (PPP-CPF), in a similar way as it was done in HERNÁNDEZ-PAJARES ET AL. 2003, 2010.
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(2) The broadcast of satellite fractional part of ambiguities (computed at the CPF level), which allows the user to fix the carrier phase ambiguities improving the positioning solution (see GE ET AL. 2007, LAURISCHESSE ET AL. 2009, MERVART ET AL. 2008, COLLINS ET AL. 2005).
(3) The use of future multifrequency (more than 2) observables and multiconstellation, improving the convergence time and accuracy (note that SANZ ET AL. 2009, suggest that it may be feasible to provide credible integrity monitoring in high-precision GNSS positioning).
(4) The use of precise ionospheric corrections for single-frequency PPP.

2 The basic PPP algorithm

From the first-order ionospheric-free combinations of both carrier phases in unit lengths (L1,L2),and both codes (P1,P2), L_c and P_c respectively:

$$L_c = \frac{f_1^2 L_1 - f_2^2 L_2}{f_1^2 - f_2^2} \qquad (1)$$

$$P_c = \frac{f_1^2 P_1 - f_2^2 P_2}{f_1^2 - f_2^2}$$

the PPP user can estimate its position $\vec{r}_k$, by correcting its a-priori position $\vec{r}_{0,k}$, from the externally provided (CPF) satellite clock error estimates dt^i, and orbits (which allow the computation of the a priori range ρ_0), for all the i=1,..., N_s, satellites in view :

$$\begin{aligned}
&(L_c)_k^i + cdt^i - (\rho_0)_k^i = \\
&= -(\hat{\rho}_0)_k^i \cdot [\vec{r}_k - \vec{r}_{0,k}] + cdt_k + M_k^i \cdot \delta T_k + \\
&+ (B_c)_k^i + \lambda_n w_k + \varepsilon
\end{aligned} \qquad (2)$$

$$\begin{aligned}
&(P_c)_k^i + cdt^i - (\rho_0)_k^i = \\
&= -(\hat{\rho}_0)_k^i \cdot [\vec{r}_k - \vec{r}_{0,k}] + cdt_k + M_k^i \cdot \delta T_k + \varepsilon' ,
\end{aligned} \qquad (3)$$

To get an accurate estimate of $\vec{r}_k$, the PPP user filter has to estimate simultaneously the phase ambiguity B_c (constant per satellite-receiver arch), its clock error dt_k (as white noise process), the (non-hydrostatic) tropospheric correction δT (random walk process) and in kinematic mode the windup w if possible.

3 Improving PPP with ionospheric corrections: the Fast PPP (FPPP)

From Melbourne-Wübbena combination $L_w - P_n$ and ionospheric phase L_I

$$L_w = \frac{f_1 L_1 - f_2 L_2}{f_1 - f_2} \qquad (4)$$

$$P_n = \frac{f_1 P_1 + f_2 P_2}{f_1 + f_2} \qquad (5)$$

$$L_I = L_1 - L_2 \qquad (6)$$

the user can augment the basic PPP equations for L_c and P_c, with the following new equations:

$$(L_w)_k^i - (P_n)_k^i + \frac{\lambda_w \lambda_n}{\lambda_1 \lambda_2} D^i = (B_w)_k^i - \frac{\lambda_w \lambda_n}{\lambda_1 \lambda_2} D_k \qquad (7)$$

$$(L_I)_k^i - S_k^i = \frac{\lambda_1 \lambda_2}{\lambda_w \lambda_n} (B_w - B_c)_k^i \text{ ,} \qquad (8)$$

Where S_k^i is the slant ionospheric delay experienced by the i-th satellite user observation, computed from the precise ionospheric model provided by the PPP CPF in well covered mid latitude regions (such as Europe), together with the satellite interfrequency delay code biases ($(D)_k^i \equiv (D_2)_k^i - (D_1)_k^i$).

In this way B_c can be rapidly derived, thanks to (a) the accuracy of S_k^i, and (b) the very good properties of P_n (noise much lower than P_c). Notice that there is no need of ambiguity fixing, in spite of that ambiguity fixing can help to get certain additional improved performance.

A typical example of the feasibility of FPPP based on actual GPS data is shown in Fig. 1, which summarizes the results obtained for IGS permanent stations MLVL, EUSK and EIJS, treated as actual real-time kinematic users (at 252, 170 and 94 km far, respectively, from the nearest reference receiver BRUS). The full user state was reset every two hours to better characterize the convergence process. In these plots, the horizontal and vertical errors are shown (left and right hand side, respectively) demonstrating the advantage of using precise, real-time ionospheric corrections to speed-up the PPP convergence (Fast PPP). It can be seen that the convergence time (to achieve, for instance, a 10-cm error level) is reduced from about one hour (without ionospheric corrections) to a few minutes.

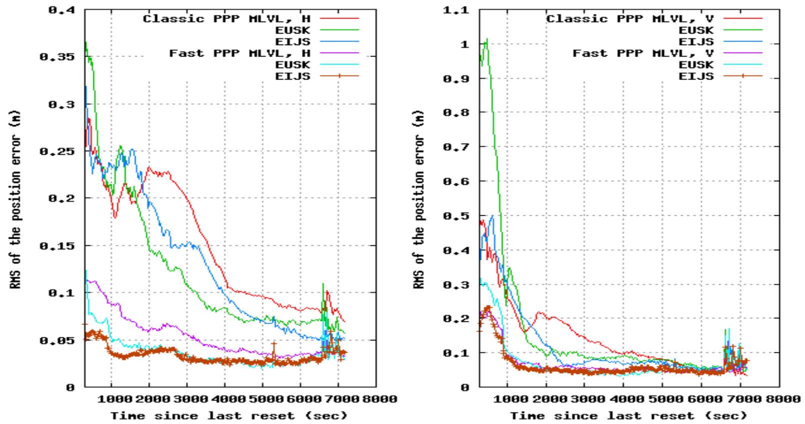

Fig. 1: RMS of the positioning error for the horizontal component (left) and vertical component (right). The classical PPP for the rovers MLVL (red), EUSK (green) and EIJS (blues) is compared with the fast PPP for MLVL (violet), EUSK (light blue) and EIJS (brown).

4 Improving the PPP accuracy: Fixing carrier phase ambiguities

The carrier phase ambiguity $(B_X)^{i,j}_{k,l}$ can be expressed in terms of an integer value $(N_X)^i_k$ of wavelengths (λ_X) and two "fractional parts", $\delta B_X{}^i$ and $\delta B_{X,k}$, for GNSS transmitter i and GNSS receiver k. δB_X are typically stable for times typically larger than the positioning convergence time. In this way any user can apply the following relationship once the satellite fractional part of ambiguities are provided by the CPF:

$$(B_X)^i_k - \delta B_X{}^i = \lambda_X (N_X)^i_k + \delta B_{X,k} \, , \qquad (9)$$

Consequently, from the single difference between satellites, the exact value of the single differences of N_X can be known (it must be integer). Removing this value, like in double-differenced ambiguity fixing, the positioning solution will be improved in the user filter. For this purpose it is necessary an estimation of the fractional part of ambiguities (an example of this estimation is shown in figure Fig. 2).

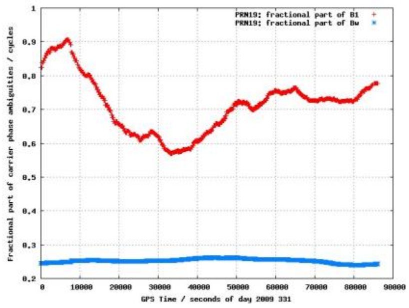

Fig. 2: Fractional part of ambiguities for GPS satellite PRN19 (in cycles) as function of time (in seconds). The wide-lane is shown in blue and the L1 in red. The figure has been extracted from SANZ ET AL. 2011 using the CPF over a global network as mentioned below. The pattern in the figure is due to the correlations with the other parameters in the filter, mainly the satellite clocks.

5 Improving both accuracy and convergence: Multiconstellation and multifrequency scenario

The fast resolution of B_w is the key, jointly with the ionospheric correction, for the fast resolution of B_c (by means of Eq.7 and Eq. 8), and the corresponding prompt decimeter-level GNSS positioning. But in spite of P_n is less noisy than other codes, and λ_w is quite large (~ 0.86 m for GPS frequencies), several minutes are required to achieve a confident value of B_w, which would allow to fix it.

The availability of triple frequency carrier phase measurements offers a geometric- and ionospheric-free estimation of the extra-wide lane ambiguity (which carrier has several meters of wavelength), among the wide-lane ambiguity estimation, which, in the case of availability of precise ionospheric corrections, will accelerate the convergence of precise positioning (from several minutes with GPS to single-epoch with Galileo or modernized GPS). Moreover the coexistence of several constellations provides an additional improvement in positioning through an smaller DOP.

In order to show the expected performance with incoming new GNSS system, several datasets have been generated at signal level in the ESTEC GNSS laboratory, involving the Spirent simulator and three different models of GNSS receivers, gathering L1, L5, E1, E5a, E5b and E6 measurements.

In order to make the simulations more flexible and efficient, the most part of different conditions (satellite clock and orbits quality, ionospheric and tropospheric delay, multipath) are generated by software, except for thermal noise, which corresponds to the actual one (the observations have been gathered from real receivers).

The nominal scenario consists of adding, from the CPF processing with actual data, the following measured carrier phase and pseudorange errors:

(a) a pseudorange multipath error between few decimeters at the zenith direction and meter level at low elevation (based on actual data),

(b) a satellite clock correction with an error of 0.1 ns,

(c) from the exact positions of the GNSS satellites, a correction error of 0.05m in RMS,

(d) Ionospheric Correction Error (after ionospheric model correction): from 0.1 to 0.6 TECU (0.016 m to 0.1 m in L1/P1).

6 3D user positioning error RMS resetting each 900 seconds

To better characterize the convergence time, the user navigation states were reset (to emulate a receiver cold start) every 900 seconds. Moreover, the different working modes considered in the previous sections of this paper (multiconstellation GPS + Galileo vs single GPS constellation, dual-frequency vs. three-frequencies, simple ambiguity fixing vs. LAMBDA ambiguity fixing) were taken into account.

To summarize the performance of each processing mode, the 3D positioning RMS of the eleven time windows (resetting every 900 seconds for 3 hours) is represented in Fig. 3. In this figure, the benefits of using the three PPP improvements proposed in this work (i.e., ionospheric corrections, ambiguity fixing and multiconstellation ; see section II) are clearly seen. The following conclusions, which are specially relevant as relative figure of merit between the different processing mode, arise:

1) The better performance is achieved when the three improvements proposed in this work are simultaneously used.

2) The main factor in the convergence time is the usage of ionospheric corrections. However, if the ambiguities are not fixed, the ionospheric model error limits the accuracy at the end of the convergence period.

3) Finally, the use of the ionospheric correction allows us to achieve the required accuracy to be able to fix the carrier phase ambiguities. Otherwise, without ionospheric corrections, the minimum accuracy needed to fix ambiguities in the 900-second windows would never be achieved.

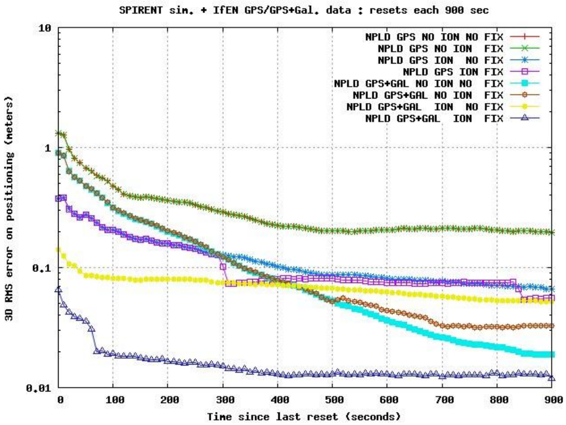

Fig. 3: 3D positioning error RMS for user NPLD considering all of the 900 seconds resets of the user state under nominal conditions for different FPPP user navigation modes: standard PPP for GPS only and GPS + Galileo (red and light blue, respectively); standard PPP + undifferenced carrier phase ambiguity fixing when possible, for GPS (green) and GPS + Galileo (brown); and standard PPP + precise ionospheric corrections + associated undifferenced carrier phase ambiguity fixing, for GPS (purple) and GPS + Galileo (blue with triangles) . For completeness, the results for ionospheric correction without fixing are also shown for GPS only (blue with stars) and GPS + Galileo (yellow).

7 FPPP integrity: First glance

Integrity is the ability of a positioning service to prevent against hazardous anomalies. For instance, the positioning service must guarantee that the probability of positioning errors greater than a certain value (protection levels) is negligible (i.e., 10^{-7}). In this sense, the service provider must transmit not only the corrections but also their confidence levels. Using this information, the user computes its position and the corresponding protection levels. In this sense, integrity is a critical part of the positioning, and the improvement of any solution must take into account the achieved protection level (values and convergence time).

The motivation of this point of study was to check whether the very first results of integrity at the positioning domain could be obtained for FPPP from the simulated datasets. To do that, the same protection levels used in the more extended integrity study recently performed for the WARTK high precise positioning technique (MRS project; see, for instance, SANZ ET AL. 2009) have been used. Indeed, the Vertical Protection Level (VPL) and Horizontal Protection Level (HPL) are defined as VPL=5.33*k*VSigma and HPL=6.2*k*Hsigma, respectively, where VSigma and HSigma are the corresponding Vertical and Horizontal Standard Deviation estimated in the filter, and k is a factor to guarantee the overbounding of the protection levels with respect to the actual errors. The nominal scenario adopted in this point, to have some minimal statistics, was resetting (every 900 seconds) the user navigation filter under a moderate multipath using single constellation (GPS) data for roving user NPLD.

It can be seen in Fig. 4 that the integrity is always maintained (actual errors lower than protection levels), even during the first steps of convergence, after each reset every 900 seconds. In particular, it can be seen that the integrity margin (protection levels minus actual errors) is still larger for dual constellation (Fig. 4, left plot) and is much larger when the ambiguities are fixed thanks to the real-time ionospheric corrections (Fig. 4, right plot).

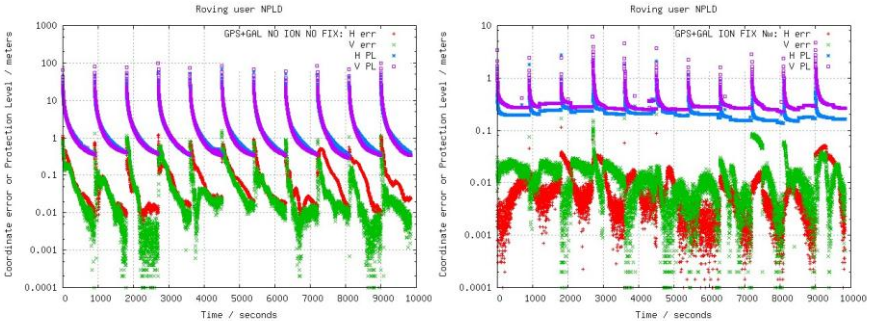

Fig. 4: Horizontal and Vertical protection levels vs. the corresponding horizontal and vertical positioning errors for a NPLD rover in the nominal scenario, resetting every 900 seconds, dual (GPS + Galileo) constellation, three frequency measurements; left: no ionospheric corrections and no fixing ambiguities; right: ionospheric corrections with wide lane ambiguity fixing.

A complete study of the sensitivity to failures can be found in FENG ET AL. 2012 and JUAN ET AL. 2012, confirming the goodness of this new technique, mostly based on the real-time availability of precise ionospheric corrections.

8 Single-frequency FPPP

Another application of the availability of precise real-time ionospheric corrections is for improving the single-frequency GNSS navigation. Indeed, by introducing the external ionospheric delay provided by the CPF as an additional equation per satellite, with a weight corresponding to the estimated standard deviation of the correction, the single frequency GNSS users (improved filter) can quickly navigate with errors of few decimeters, thanks to the accurate FPPP CPF ionospheric model (~10 cm of absolute L1 error close to reference stations). In order to make this possible, the user navigation filter has been rebuilt from the navigation filter with two frequencies, in such a way that the ionospheric delay is now an additional parameter which has to be estimated jointly with the other ones while the external ionosphere is treated as a constraint (with its corresponding weight) for this stochastic parameter. Proceeding in this way makes possible to navigate also without the external ionospheric information, which would be equivalent to employ the GRAPHIC (GRoup And PHase Ionospheric Calibration, YUNCK 1993) combination between L1 and P1.

In Fig. 5 the advantage of applying a ionospheric model is shown in terms of convergence time reduction (for both accurate –PRTODTS- and IGS ionospheric corrections), and also in accuracy (for accurate ionospheric model) in front of not using external ionospheric corrections, i.e. by using the GRAPHIC combination (IGS receiver ZIMM treated as roving user, and place about 200 km from the nearest permanent receiver –PFA2- feeding the CPF).

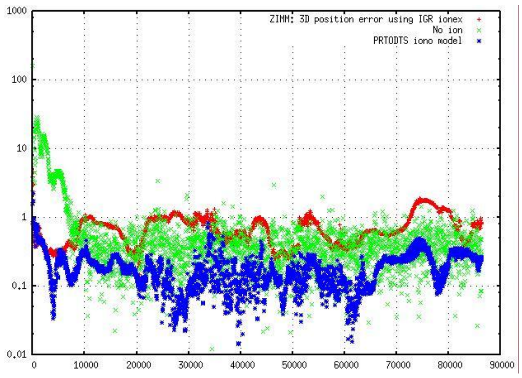

Fig. 5: Single-frequency FPPP: position error using three different modes (ZIMM at 200km from the nearest reference receiver PFA2): Without using iono information (GRAPHIC, green), by using iono information from IGS GIM (red) and using accurate ionospheric information (blue).

The advantage of the presented approach is confirmed after resetting every two hours in next Fig. 6 (left), allowing as well the L1 ambiguity fixation, which introduces a certain extra-improvement in the accuracy (Fig. 6, right). Moreover it allow the extension of the integrity procedures developped for multifrequency users, based as well on the feasibility of precise ionospheric corrections with reasonable error estimates.

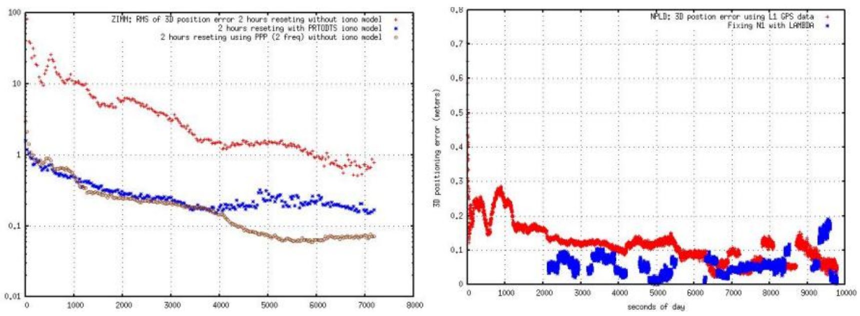

Fig. 6: Left: Single frequency position error resetting (Convergence Time) corresponding to the same FPPP1 experiment: Single frequency receiver (GRAPHIC, red), compared with Single frequency receiver using iono information (blue) and with dual frequency receiver without iono information (classic PPP, brown) . Right: Fixing L1 ambiguity vs. floating, 3D positioning error for NPLD receiver: single frequency mode (red) vs. fixing ambiguities using the Lambda method (blue).

Notice that navigating without external navigation information provides a reasonable good performance after a certain convergence time (of about one hour). This is due to the fact that after such convergence time the user navigation filter is able to separate the carrier phase ambiguities from the stochastic ionospheric delays and, as it shown in Fig. 7, it is able to estimate the ionospheric delays with errors of about 20 cm in L1 delays.

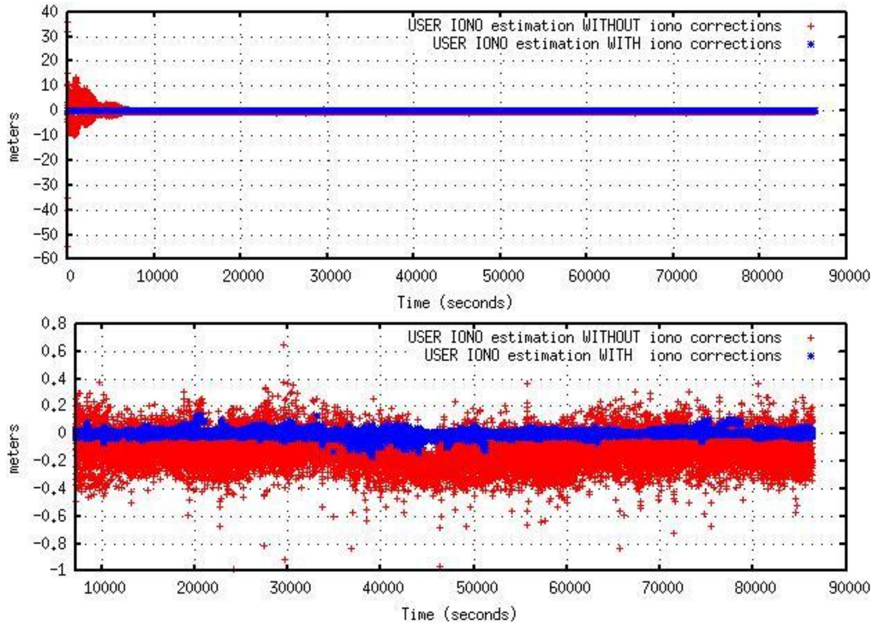

Fig. 7: Error of the user estimated slant ionospheric delay corresponding to the same single frequency FPPP experiment (in meters of LI), when no external ionospheric corrections are available (equivalent to using GRAPHIC, red points) vs. the error when the external ones are used as constraints (blue points), both in terms of time (seconds): Full result during one whole day (top plot) and zoom after the convergence (bottom plot).

9 Conclusions

The main conclusions of this study on new Fast Precise Point Positioning algorithm are:

(1) The feasibility of the proposed FPPP algorithms, in particular the mode with undifferenced ambiguity fixing supported by precise ionospheric corrections, in terms of accuracy (at 10-centimeters error level), convergence time (few minutes in cold start) and message bandwidth (less than 300 bps).

(2) The advantage of undifferenced ambiguity fixing is confirmed, in line with first insights of previous authors.

(3) The integrity monitoring algorithms developed should facilitate the use of PPP to support critical mission applications.

(4) Single frequency GNSS users can quickly navigate with errors of few decimeters, thanks to the accurate FPPP CPF ionospheric model (up to 10 cm of absolute error in L1 close to reference stations).

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