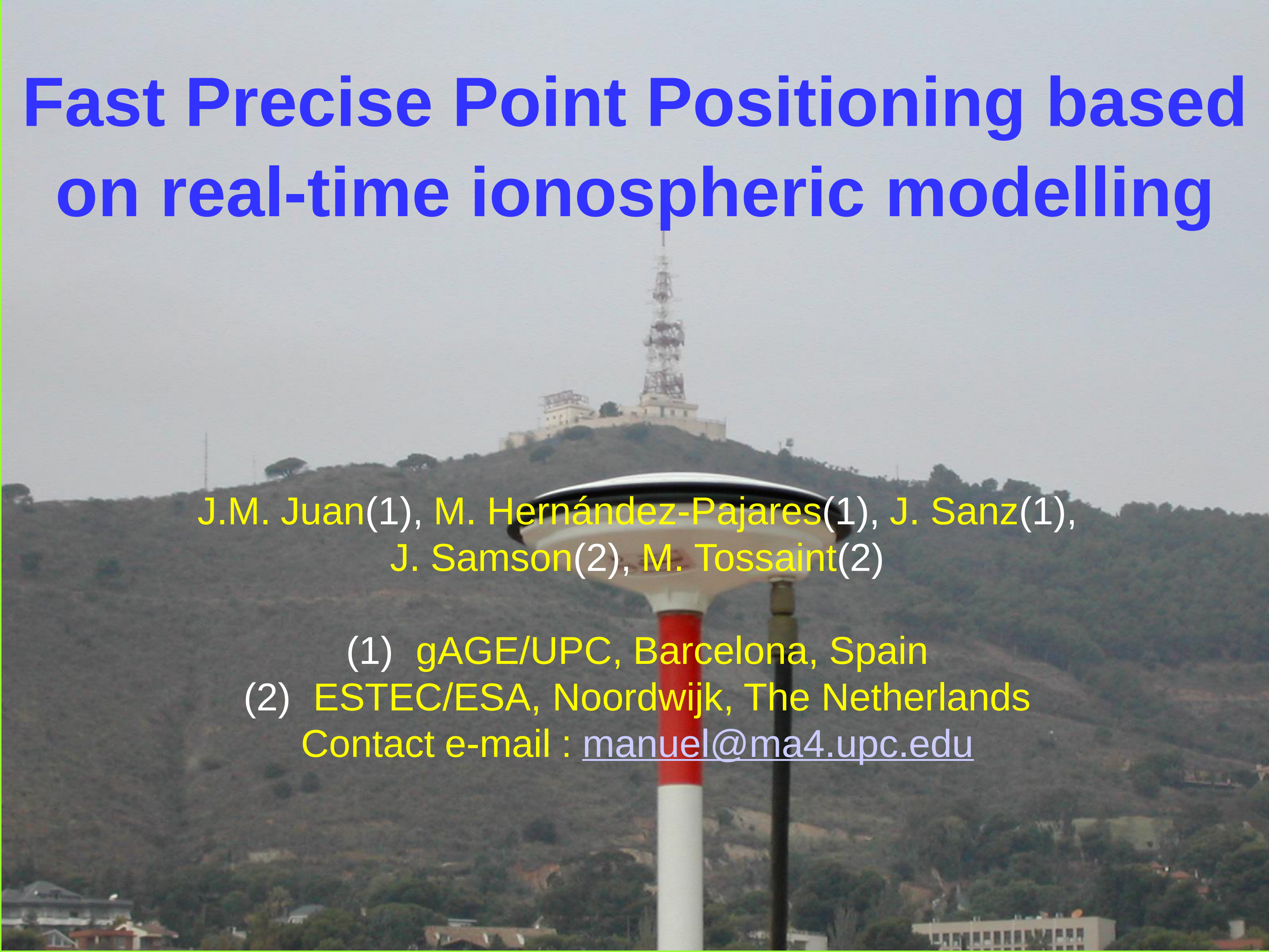
Fast Precise Point Positioning based on real-time ionospheric modelling



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Abstract and outline

-Summary of main results of new technique Fast Precise Point Positioning developed in the framework of the "Enhanced Precise Point Positioning (EPPP) GNSS multifrequency user algorithm" ESA funded project.

-The precise ionospheric corrections facilitate the resolution of undifferenced carrier phase ambiguities, ambiguity validation and integrity monitoring.

-The FPPP performance is shown in terms of accuracy, convergence time and integrity, with actual GPS and simulated Galileo data.

-Very limited bandwidth requirements for future EPPP users (less than 300 bps for dual-frequency GPS data).

I. Introduction
II. Enhanced PPP and results
III. Single-frequency EPPP
IV. Conclusions

I. Introduction

PPP features

1. PRECISE Point Positioning (PPP): allows a dual-frequency GNSS single user to determine the position at the decimeter / centimeter error level in kinematic / static mode.
2. PPP needs the real-time availability of satellite products (GPS clocks & orbits) more precise than those computed by the GPS control segment (denser global network and better modeling).
3. PPP is based on the first order ionospheric-free combinations of observables (carrier phases and codes, Lc & Pc, +99.9% of the slant ionospheric delay is removed).
4. The PPP user must model all the dependencies of Lc & Pc at centimeter-level for all the satellites in view, and estimating, in a navigation filter, the remaining relevant unknowns (3D position & receiver clock, phase ambiguities, zenith tropospheric delay).

Pros, cons & PPP improvements

The main advantages of the basic PPP approach:

(1) Its simplicity

(2) The associated low bandwidth message required (satellite clocks and precise predicted orbits)

Its main drawback is the large convergence time needed by the user to get a good estimation of its decimeter error-level position (~1 hour).

To overcome these 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).

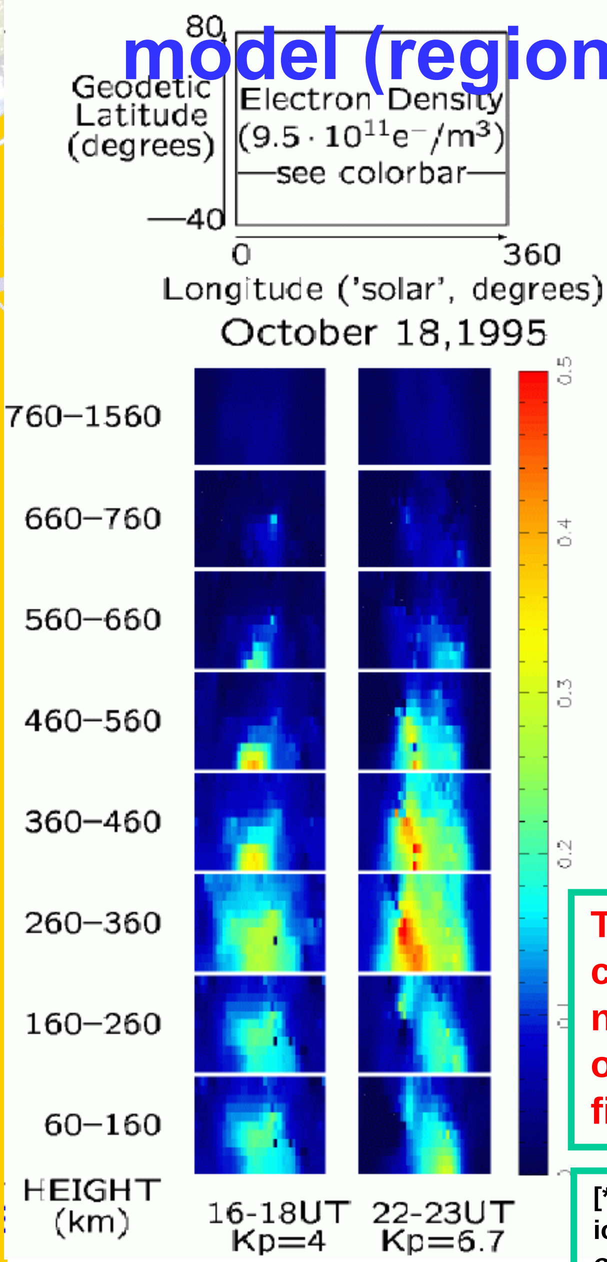
(2) The broadcast of satellite fractional part of ambiguities (computed at the CPF level), which allows the user to fix the carrier phase ambiguities improving the positioning solution.

(3) The use of future multifrequency (more than 2) observables and multiconstellation, improving the convergence time and accuracy.

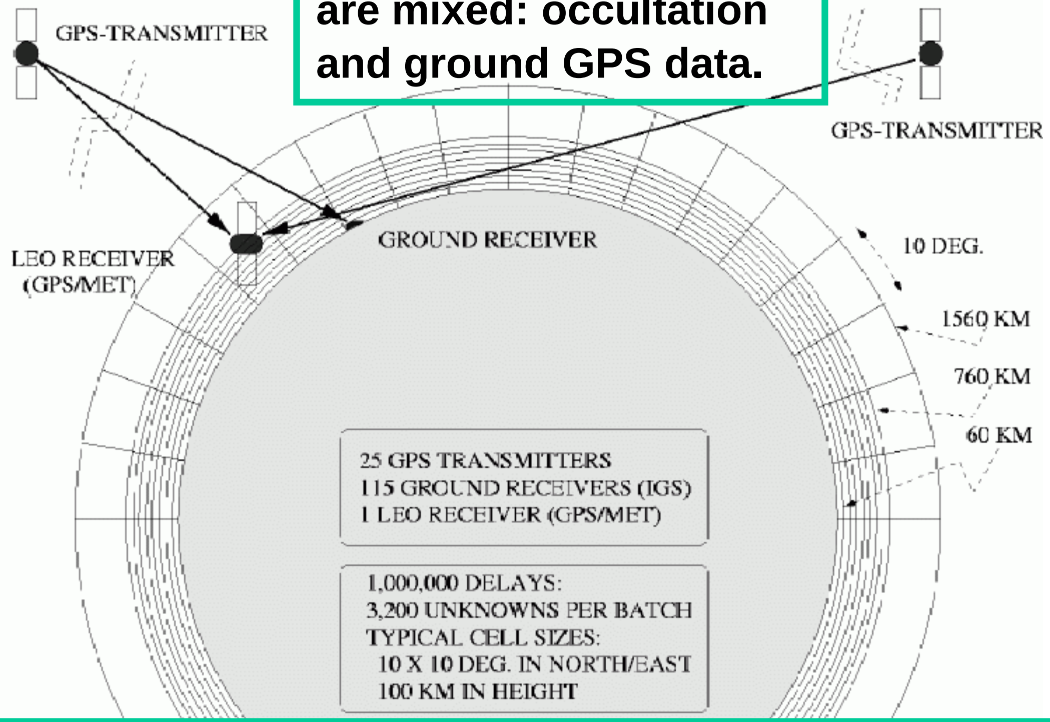
(4) The use of precise ionospheric corrections for single-frequency PPP.

II. Enhanced PPP and results

Estimating electron density in a 3D Voxel model (regional/global) evolving in time…



Different kind of data are mixed: occultation and ground GPS data.

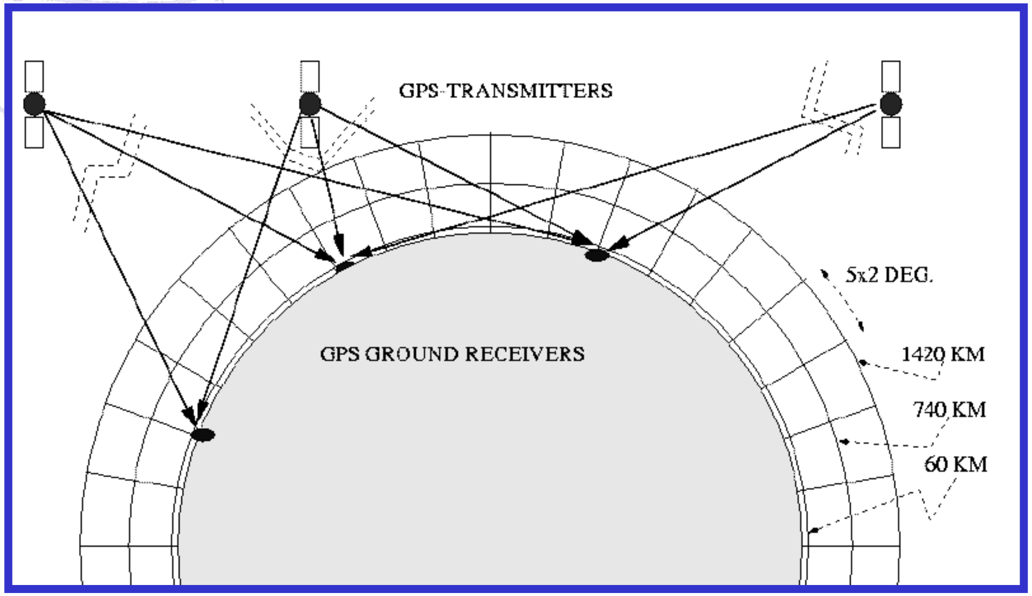


This is an example[*] corresponding to the combination of both complementary type of GPS data (ground-based from IGS network and space-based from GPS/MET LEO) in the framework of a 3D voxel tomographic model solved by means of a Kalman filter (Oct.18, 1995 geomagnetic storm).

[*] Hernández-Pajares M., J.M. Juan, J. Sanz and J.G. Sole, Global observation of the ionospheric electronic response to solar events using ground and LEO GPS data, *Journal of Geophysical Research-Space Physics*, Vol.61, p.1237-1247, 1998.

4D-voxel ionospheric model

(adapted to ground data[*] & ingested in the precise dual-frequency geodetic GNSS model)



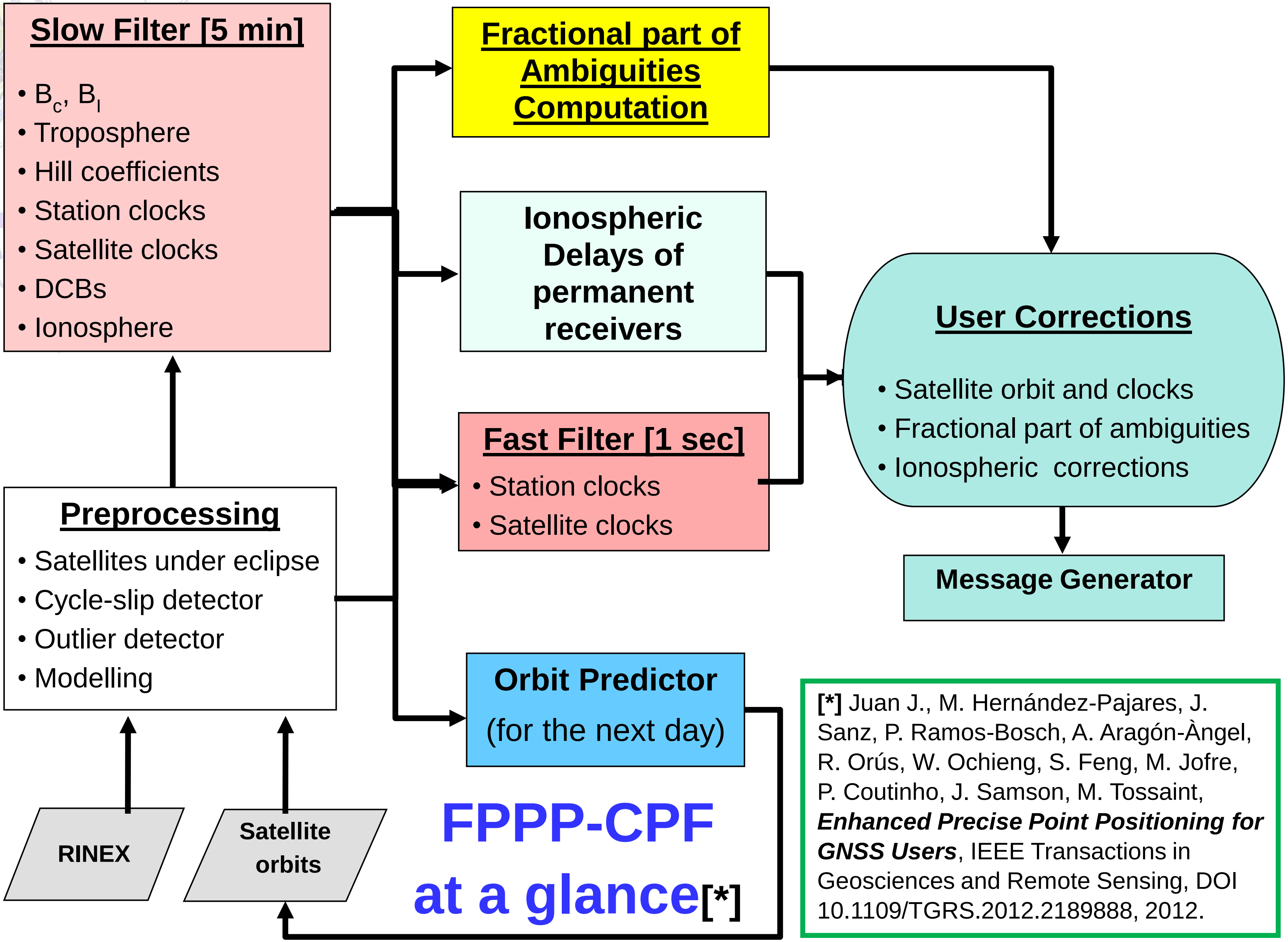
$$\mathrm{L}_I = STEC + B_I = \int_{REC}^{SAT} N_e dl + B_I = \sum_i \sum_j \sum_k (N_e)_{i,j,k} \Delta s_{i,j,k} + B_I$$

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

The carrier phase ambiguities and DCBs are shared between the dual-frequency precise GNSS geodetic model and the 4D iono model, for the overall global network ➔ **Both performances, for geodetic and ionospheric determinations, are improved**

[*] **Hernández-Pajares M., J.M. Juan, J. Sanz and O.L.Colombo, Improving the real-time ionospheric determination from GPS sites at very long distances over the equator, *Journal of Geophysical Research-Space Physics*, Vol.107, p.1296, doi: 10.1029/ 2001JA009203, 2002.**

FPPP-CPF at a glance[*]



Slow Filter [5 min]

- B_c, B_I
- Troposphere
- Hill coefficients
- Station clocks
- Satellite clocks
- DCBs
- Ionosphere

Fractional part of Ambiguities Computation

Ionospheric Delays of permanent receivers

Fast Filter [1 sec]

- Station clocks
- Satellite clocks

User Corrections

- Satellite orbit and clocks
- Fractional part of ambiguities
- Ionospheric corrections

Message Generator

Preprocessing

- Satellites under eclipse
- Cycle-slip detector
- Outlier detector
- Modelling

Orbit Predictor

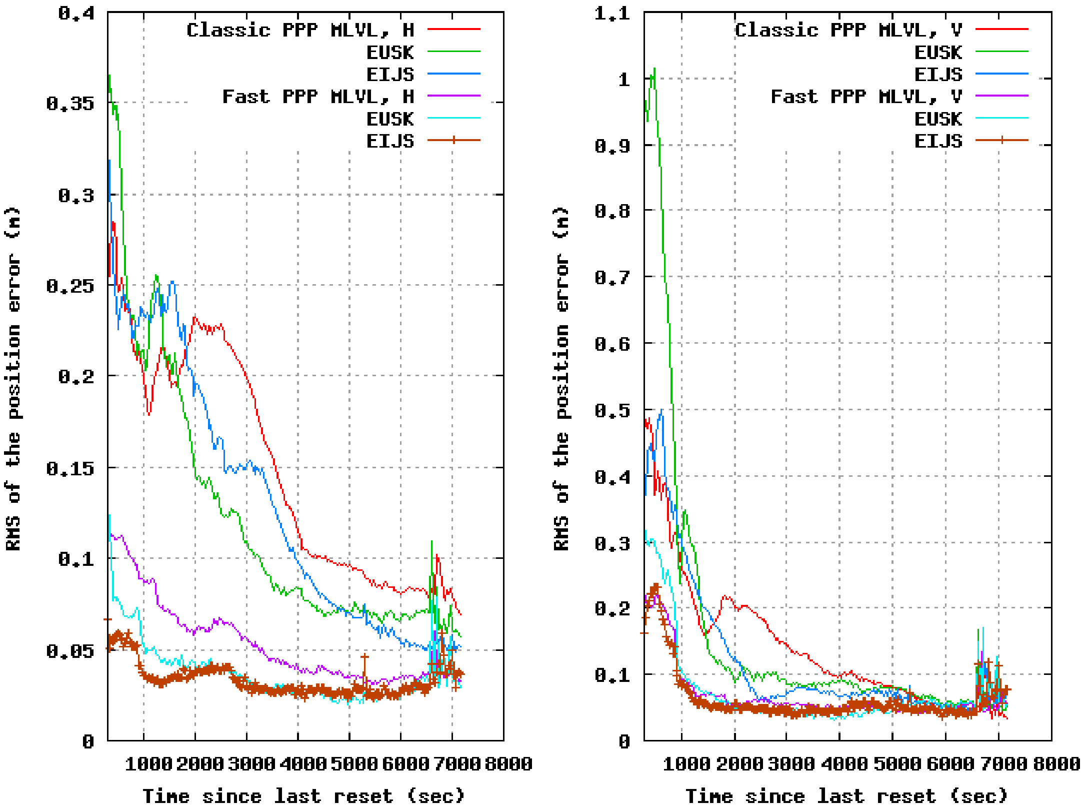
(for the next day)

RINEX

Satellite orbits

[*] Juan J., M. Hernández-Pajares, J. Sanz, P. Ramos-Bosch, A. Aragón-Àngel, R. Orús, W. Ochieng, S. Feng, M. Jofre, P. Coutinho, J. Samson, M. Tossaint, ***Enhanced Precise Point Positioning for GNSS Users***, IEEE Transactions in Geosciences and Remote Sensing, DOI 10.1109/TGRS.2012.2189888, 2012.

FPPP user results with actual GPS



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), at 252, 170 and 94 km respectively far from the nearest reference receiver BRUS .

-The full user state has been reset every two hours to better characterize the convergence process.

-It is shown the advantage of using precise real-time ionospheric corrections in order to speed-up the PPP convergence (Fast PPP).

-The convergence time (to achieve 10-cm error-level) is reduced from ~1 hour (without iono. corrections) up to few minutes.

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) of wavelengths (λ_X) and two "fractional parts", $\delta B_{X,k}$ and δB_X^i, for GNSS transmitter i and GNSS receiver k.

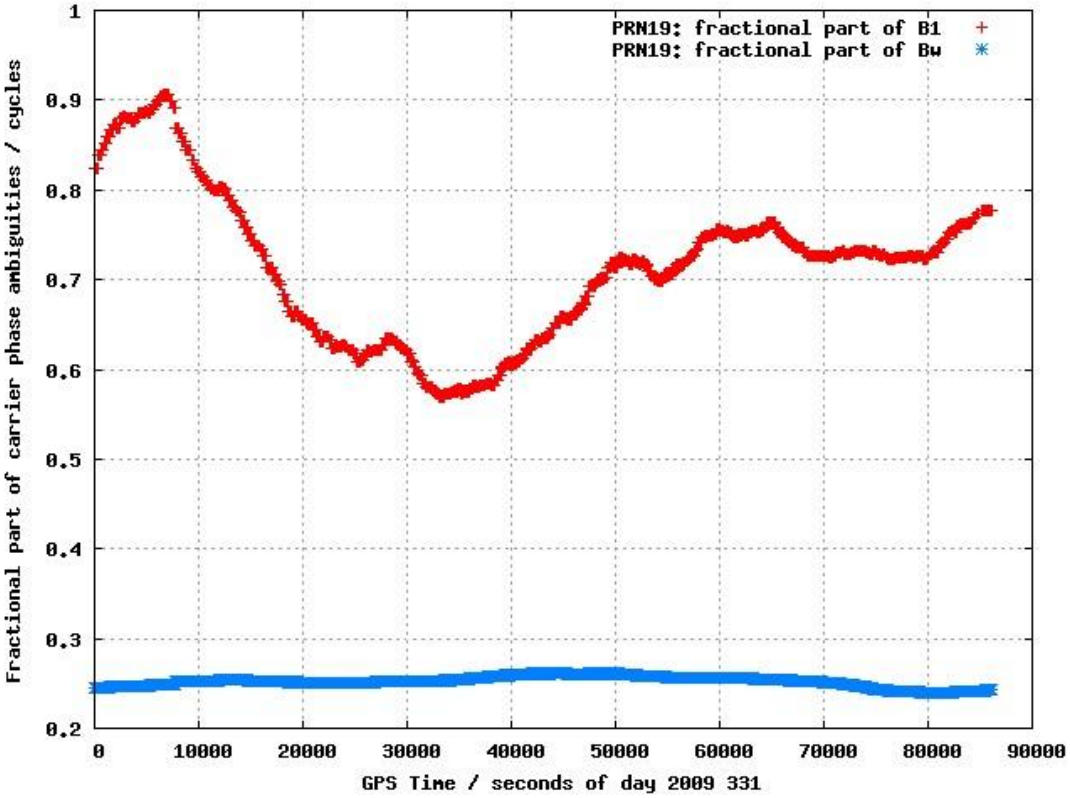
δB_X are typically stable for times typically larger than the positioning convergence time.

In this way any user can apply the following relationship once the satellite fractional part of ambiguities are provided by the CPF:

$$(B_X)^i_k - \delta B_X{}^i = \lambda_X (N_X)^i_k + \delta B_{X,k} \quad \text{(Eq.5)}$$

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.

Example of constancy of fractional part of GPS ambiguities



Fractional part of ambiguities for GPS satellite PRN19 as function of the GPS time, during the day 331 of 2009. The Wide-lane is shown in blue and the L1 in red. The figure has been extracted from Juan et al. 2011 using the CPF over a global network. <u>Vertical axis is shown in cycles and horizontal in seconds of day</u>. The pattern in the figure is due to the correlations with the other parameters in the CPF filter, mainly the satellite clocks.

Improving both accuracy and convergence: Multiconstellation and multifrequency scenario

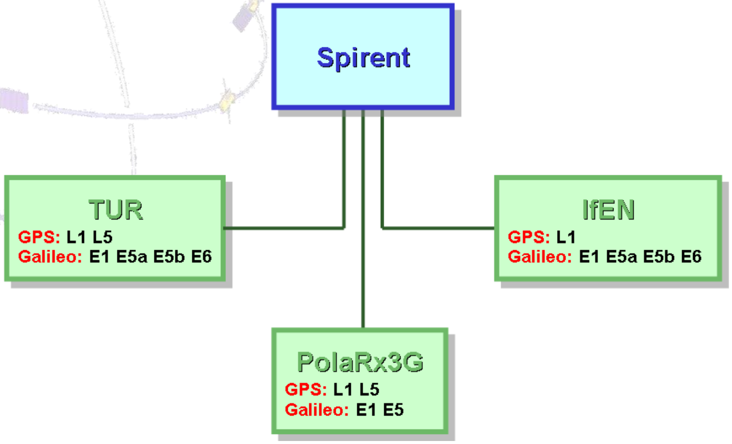
The fast resolution of widelane ambiguity Bw is the key, jointly with the ionospheric correction, for the fast resolution of B_c, and the corresponding prompt decimeter-level GNSS positioning.

But in spite of narrowlane pseudorange Pn 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 Bw, which would allow to fix it.

The availability of triple frequency carrier phase measurements provides an straightforward extra-wide lane (wavelength ~5-10m) and wide-lane ambiguity estimation, which combined with precise ionospheric corrections, accelerate the PPP convergence (up to single-epoch with Galileo or modernized GPS).

Moreover the coexistence of several constellations provides an additional improvement in positioning through an smaller DOP.

Signal simulated GNSS data



-GNSS signal simulation performed at ESTEC/ESA facilities.

-The most part of different conditions (satellite clock and orbits quality, ionospheric and tropospheric delay, multipath) are generated by software.

-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:

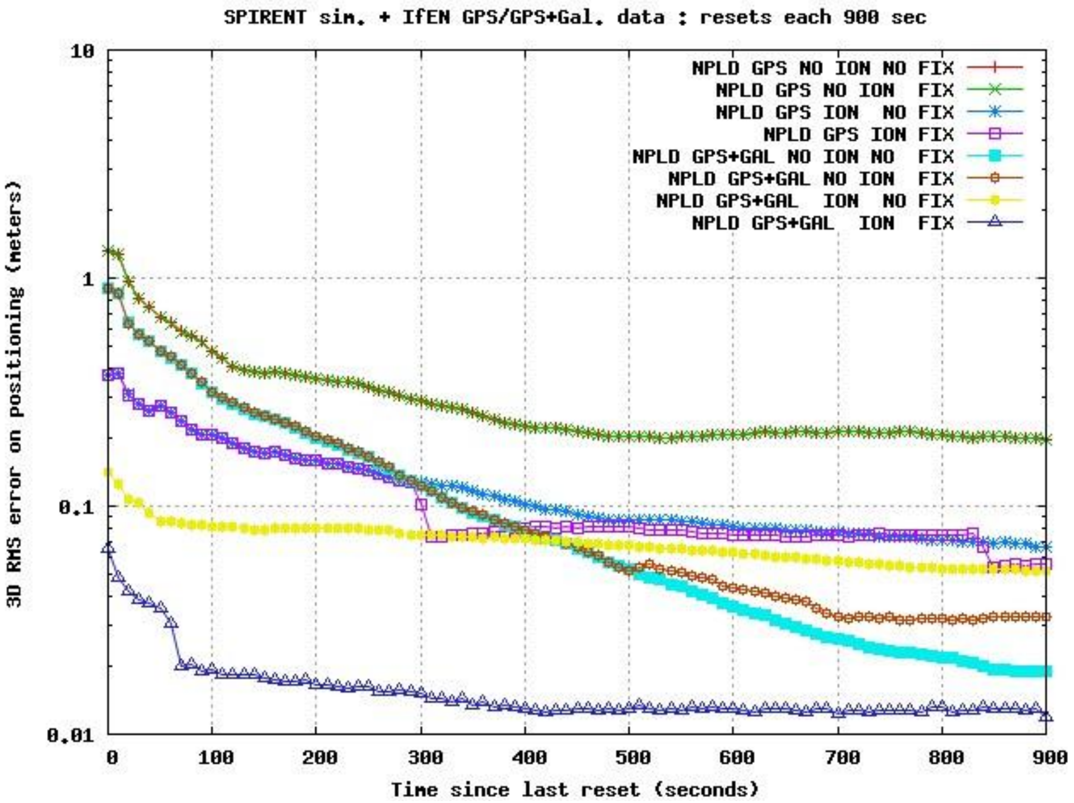
(a) a pseudorange multipath error between few decimeters at the zenith direction and meter level at low elevation (based on actual data),

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

(c) from the exact positions of the GNSS satellites, RMS error of 0.05m.

(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).

3D user positioning error RMS resetting each 900 seconds



1) The **better performance**: using the three improvements proposed in this work, **iono.+amb.fixing+3-freq. data.**

2) The **main driving factor in the convergence time are the ionospheric corrections** (if the ambiguities are not fixed, the ionospheric model error can limit the final accuracy).

3) The **ionospheric corrections allow to fix the carrier phase ambiguities** (otherwise the minimum accuracy needed to fix ambiguities in the 900-second windows would never be achieved).

3D positioning error RMS for user NPLD considering all the 900 seconds resets of the user state, under nominal conditions, for different EPPP 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), standard PPP+precise ionospheric corrections + associated undifferenced carrier phase ambiguity fixing (magenta for GPS and dark blue for GPS+Galileo). For completeness the results for ionospheric correction without fixing are also shown for GPS only (blue) and GPS+Galileo (yellow).*

Integrity

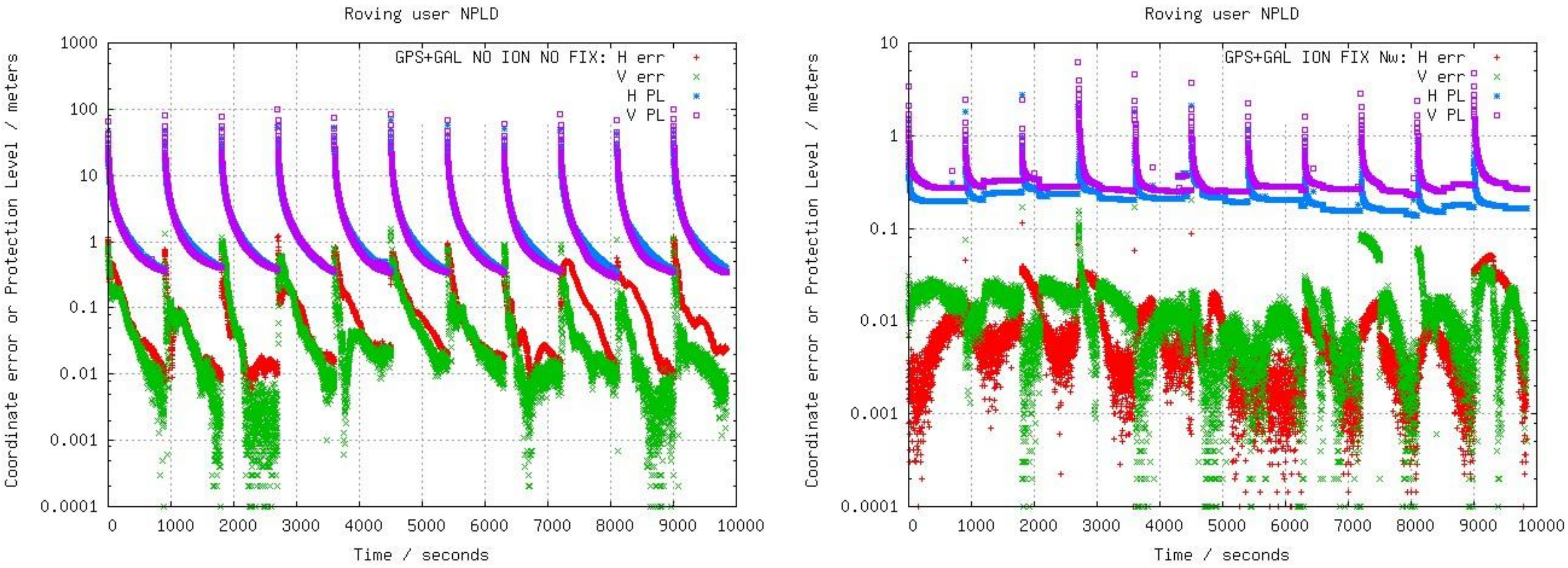
-Integrity is the ability of a positioning service to prevent against hazardous anomalies.

-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 (then the user computes its position and the corresponding protection levels).

-Integrity is an important part of the positioning, and the improvement of any solution must take into account the achieved protection level (values and convergence time).

EPPP integrity: First glance



Horizontal and Vertical protection levels vs. the corresponding horizontal and vertical positioning errors for NPLD rover in reference case with low multipath, resetting each 900 seconds, dual (GPS+Galileo) constellation, three frequency measurements, and without/with ionospheric corrections and no/yes fixing ambiguities (left/right respect.).

-The integrity is always maintained (actual errors lower than protection levels), even right after every resetting each 900 seconds.

-The integrity margin (protection levels minus actual errors) is still larger for dual constellation, and much larger when the ambiguities are fixed thanks to the real-time ionospheric corrections.

III. Single-frequency EPPP

FPPP for single-frequency users

Another application of the availability of precise real-time ionospheric corrections is the single-frequency GNSS navigation improvement.

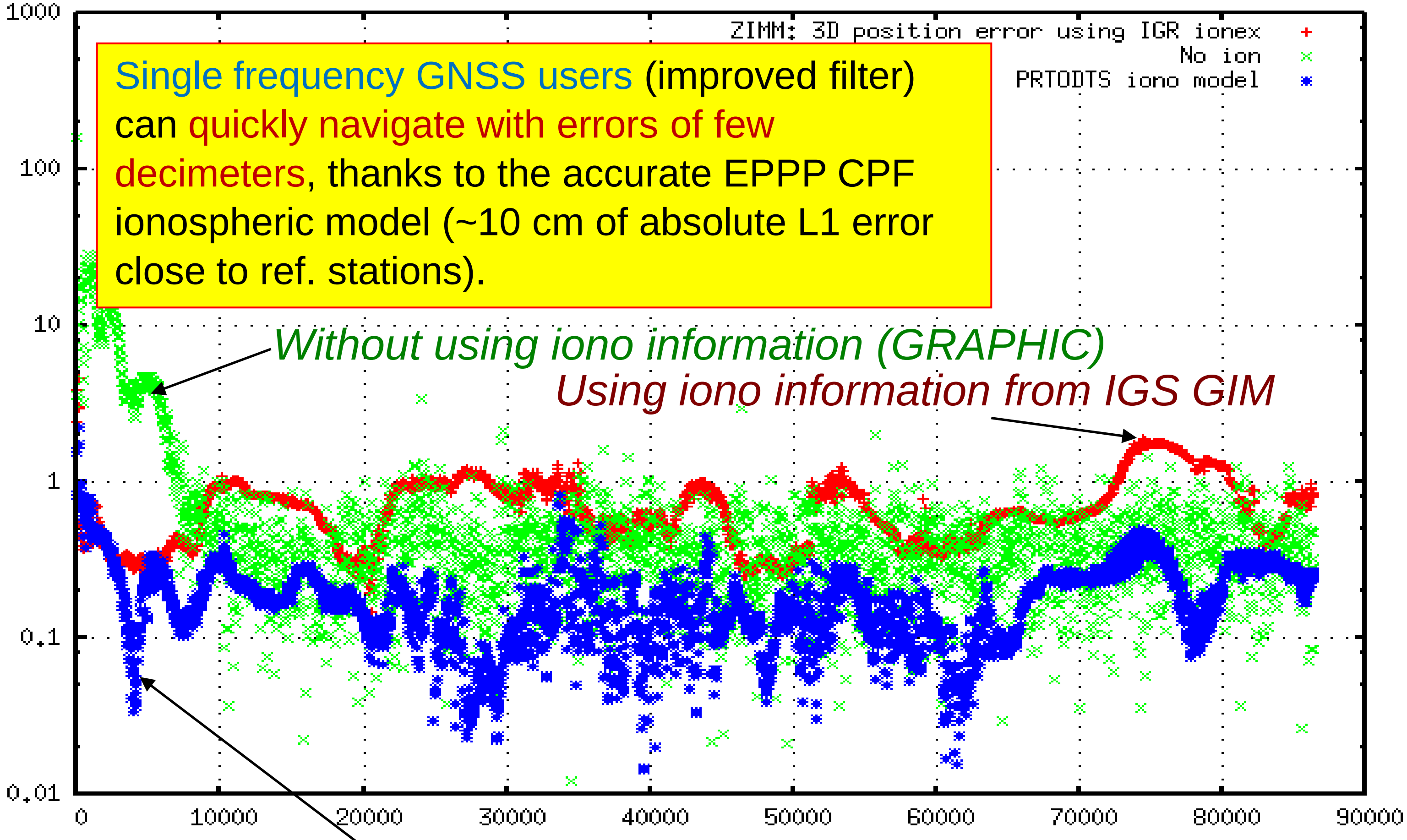
The external ionospheric delay provided by the CPF can be introduced as an additional equation per satellite in the GNSS user filter, with a weight corresponding to the estimated standard deviation of the correction.

In this way, the single-frequency GNSS user 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): **FPPP1**.

This allows to navigate also without the external ionospheric information, which is equivalent to employ the GRAPHIC (GRoup And Phase Ionospheric Calibration, YUNCK 1993) combination between L1 & P1.

FPPP1 positioning error

ZIMM at 200km from the nearest reference receiver



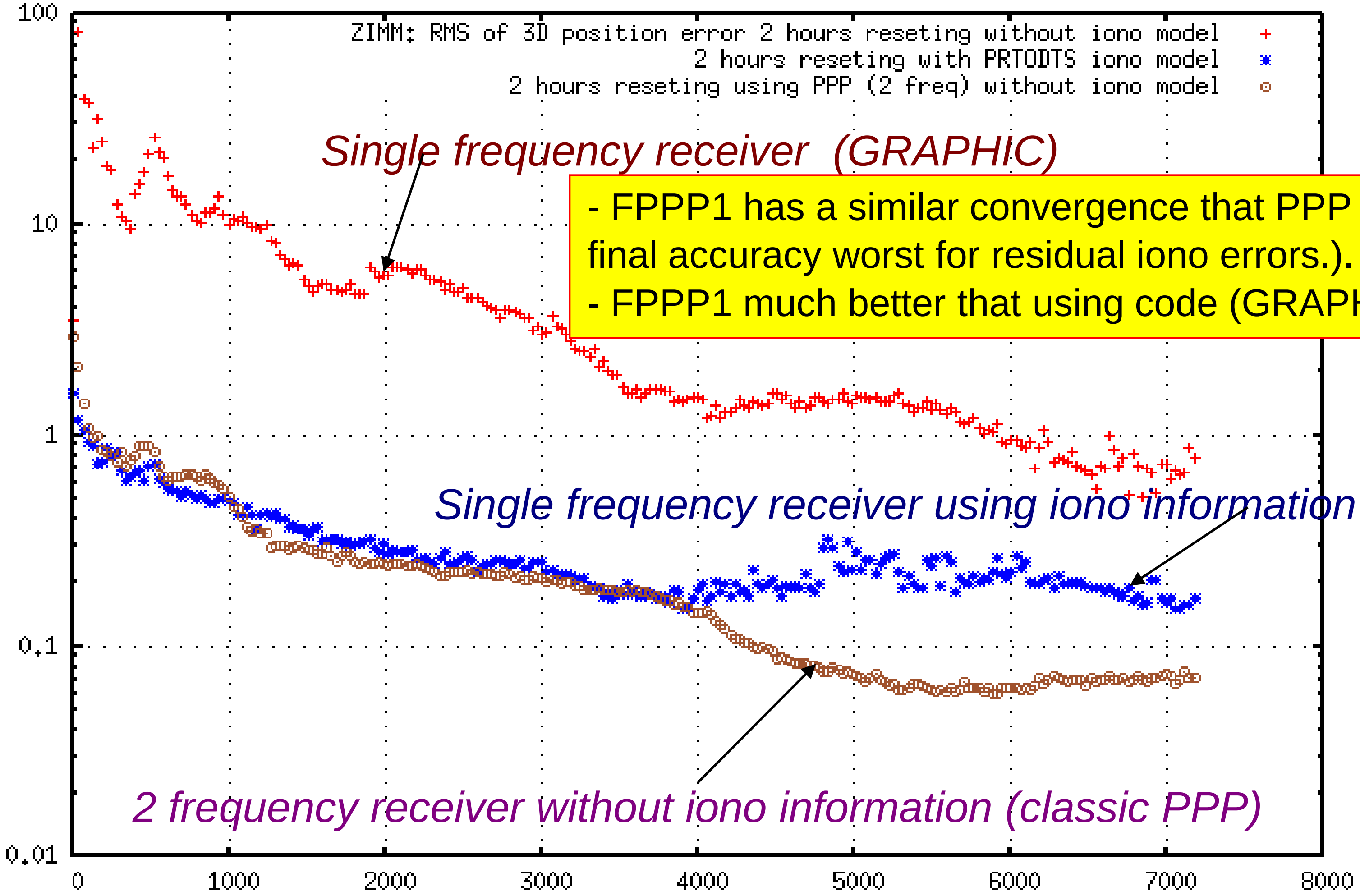
Single frequency GNSS users (improved filter) can quickly navigate with errors of few decimeters, thanks to the accurate EPPP CPF ionospheric model (~10 cm of absolute L1 error close to ref. stations).

Without using iono information (GRAPHIC)

Using iono information from IGS GIM

Using accurate ionospheric information

Single frequency position error resetting (Convergence Time)



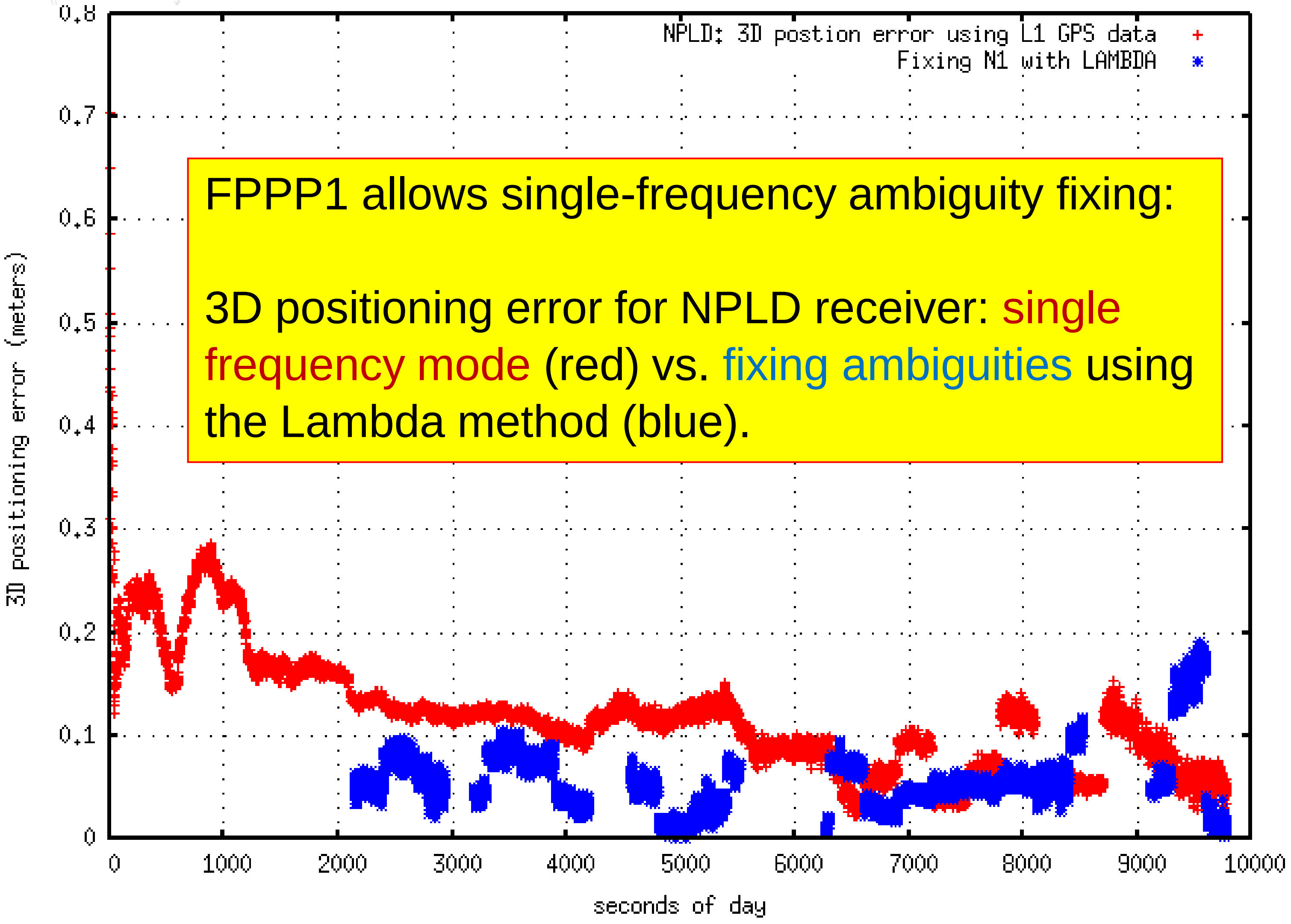
Single frequency receiver (GRAPHIC)

Single frequency receiver using iono information

2 frequency receiver without iono information (classic PPP)

- FPPP1 has a similar convergence that PPP (but final accuracy worst for residual iono errors.).
- FPPP1 much better that using code (GRAPHIC).

FPPP1: Fixing L1 ambiguity vs. floating



FPPP1 allows single-frequency ambiguity fixing:

3D positioning error for NPLD receiver: single frequency mode (red) vs. fixing ambiguities using the Lambda method (blue).

Fast Precise Point Positioning based on real-time ionospheric modelling

IV. Conclusions

(1) The feasibility of EPPP algorithms, in particular the quick decimeter-error-level navigation supported by precise ionospheric corrections, has been shown in terms of accuracy, convergence time, with a limited message bandwidth (< 300 bps/constellation).

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

(3) The expected integrity 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 EPPP CPF ionospheric model (up to 10 cm of absolute error in L1 close to reference stations).

(5) Experimental global RT-IGS VTEC maps are being generated (see tomorrow Agrotis et al.) and first FPPP RT runs are performing well.

More details in:

- Hernández-Pajares, M., Juan J., J. Sanz, J. Samson, M. Tossaint , ***Method, apparatus and system for determining a position of an object having a Global Navigation Satellite System receiver by processing undifferenced data like carrier phase measurements and external products like ionosphere data***, international patent application 2011.

-Juan J., M. Hernández-Pajares, J. Sanz, P. Ramos-Bosch, A. Aragón-Àngel, R. Orús, W. Ochieng, S. Feng, M. Jofre, P. Coutinho, J. Samson, M. Tossaint, ***Enhanced Precise Point Positioning for GNSS Users***, IEEE Transactions in Geosciences and Remote Sensing, DOI 10.1109/TGRS.2012.2189888, 2012.

THANK YOU!

Backup slides

PPP user algorithm at a glance

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

$$L_c = \frac{f_1^{\,2} L_1 - f_2^{\,2} L_2}{f_1^{\,2} - f_2^{\,2}} \qquad P_c = \frac{f_1^{\,2} P_1 - f_2^{\,2} P_2}{f_1^{\,2} - f_2^{\,2}}$$

the PPP user estimates its position r, by correcting its a-priori position $r_{0,k}$, from the satellite clock error estimates $dt^{i,}$ and orbits (computing the apriori range ρ_0), provided by the CPF for all the i=1,…,N, satellites in view :

$$(L_c)_k^i + cdt^i - (\rho_0)_k^i = \\ = -(\hat{\rho}_0)_k^i \cdot [\vec{r}_k - \vec{r}_{0,k}] + cdt_k + M_k^i \cdot \delta T_k + \\ + (B_c)_k^i + \lambda_n w_k + \varepsilon \qquad \text{(Eq.1)}$$

$$(P_c)_k^i + cdt^i - (\rho_0)_k^i = \\ = -(\hat{\rho}_0)_k^i \cdot [\vec{r}_k - \vec{r}_{0,k}] + cdt_k + M_k^i \cdot \delta T_k + \varepsilon' \qquad \text{(Eq.2)}$$

To get an accurate estimate of r, the PPP user filter simultaneously estimates the phase ambiguity B_c (constant per satellite-receiver arch), its clock error dt_k (as white noise), the (non-hydrostatic) tropospheric correction δT_k (as random walk), and in kinematic mode the windup w_k if possible.

Improving PPP user with iono. corr.

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

$$L_w = \frac{f_1 L_1 - f_2 L_2}{f_1 - f_2} \qquad P_n = \frac{f_1 P_1 + f_2 P_2}{f_1 + f_2} \qquad L_I = L_1 - L_2$$

the user can augment the basic PPP equations (Eq.1) and (Eq.2) for L_c and P_c, with the following new equations (Eq.3) and (Eq.4):

(Eq.3)

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

(Eq.4)

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

Where S^i is the i-th satellite slant ionospheric delay provided by the PPP CPF (highly precise in well covered mid latitude regions, such as Europe), together with the satellite interfrequency delay code biases ($D=D_2$-D_1).

In this way B_c can be rapidly derived from (Eq.4), thanks to (a) the accuracy of S, and (b) the very good properties of P_w (noise much lower than P_c): **Fast Precise Point Positioning (FPPP)**.

Notice that there is no need of ambiguity fixing for that, in spite of that ambiguity fixing helps to get additional improved performance.