

Influence of ionospheric perturbations in GPS time and frequency transfer

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Abstract

The stability of GPS time and frequency transfer is limited by the fact that GPS signals travel through the ionosphere. In high precision geodetic time transfer (i.e. based on precise modeling of code and carrier phase GPS data), the so-called ionosphere-free combination of the code and carrier phase measurements made on the two frequencies is used to remove the first-order ionospheric effect. In this paper, we investigate the impact of residual second- and third-order ionospheric effects on geodetic time transfer solutions i.e. remote atomic clock comparisons based on GPS measurements, using the ATOMIUM software developed at the Royal Observatory of Belgium (ROB). The impact of third-order ionospheric effects was shown to be negligible, while for second-order effects, the tests performed on different time links and at different epochs show a small impact of the order of some picoseconds, on a quiet day, and up to more than 10 picoseconds in case of high ionospheric activity. The geomagnetic storm of the 30th October 2003 is used to illustrate how space weather products are relevant to understand perturbations in geodetic time and frequency transfer.

Key words: GNSS, Time and Frequency Transfer, Space Weather

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1 Introduction

Time and frequency transfer (TFT) using GPS (Global Positioning System, (Leick, 2004)) or equivalently GNSS (Global Navigation Satellite System) satellites consists in comparing two remote atomic clocks to the reference time scale of the GPS system (or to another post-processed time scale based on a GPS or GNSS network). From the differences between these comparisons, one gets the synchronization error between the two remote clocks and its time evolution.

GPS TFT is widely used within the time community, for example for the realization of TAI (Temps Atomique International), the basis of the legal time UTC (Universal Time Coordinated), computed by the Bureau International des Poids et Mesures (BIPM). TFT is characterized by its very good resolution (1 observation point/30s or possibly 1 point per second) and a high precision and frequency stability thanks to the carrier phases (uncertainty μA of about 0.1 ns). The present uncertainty in GPS equipment calibration is 5 ns (uncertainty μB -systematic, hence calibration errors- in the BIPM circular T).

The solar activity varies according to the famous *11-year solar cycle*, also called sunspot cycle. An indicator of the solar activity is the number and intensity of solar flare events, as large flares are less frequent than smaller ones and as the frequency of occurrence varies. Solar flares are violent explosions in the Sun's atmosphere that can release as much energy as $6 \cdot 10^{25}$ Joules (more details can be found in (Berghmans et al., 2005)). The X-rays and UV radiation emitted by the strongest solar flares can affect the Earth's ionosphere, modifying the density and the distribution of the electrons within it.

Some solar flares give rise to Coronal Mass Ejections (CMEs), i.e. ejections of plasma (mainly electrons and protons) from the solar corona, carrying a magnetic field and travelling at speeds from about 20 km/s to 2700 km/s, with an average speed of about 500 km/s. Some CMEs reach the Earth as an Interplanetary CME (ICME) perturbing the Earth's magnetosphere and hence the Earth's ionosphere. Consequently, solar flares and associated CMEs strongly influence our terrestrial environment which has an impact on GPS/GNSS signals.

Since ionospheric influence on electromagnetic waves is frequency dependent and since GPS signals are broadcasted in two different frequencies, ionospheric effects are commonly removed through a given combination (named ionosphere-free) of the signals in the two frequencies f_1 and f_2 . However, it is well known that this combination removes only first-order perturbations, which correspond to about 99.9% of the total perturbation. The present study aims at evaluating the impact of the remaining part, concentrating on second- and third-order effects. While Fritsche et al. (2005) and Hernandez-Pajares et al.

(2007) investigated the higher-order ionospheric impact on GPS receiver position, GPS satellite clock or GPS satellite position estimates, in the present paper, we focus on the impact on precise time and frequency transfer using GPS signals.

Second- and third-order ionospheric terms are therefore implemented in the software ATOMIUM (Defraigne et al., 2008), developed at the Royal Observatory of Belgium. ATOMIUM is based on a least-square analysis of dual-frequency carrier phase and code measurements and is able to provide clock solutions in Precise-Point-Positioning (PPP) as well as in single-difference (also called Common-View, CV) mode.

The present paper is organized as follows. The next section recalls the principles of GPS TTT and the ionosphere-free analysis in Precise-Point-Positioning or Common-View mode. In Section 3, the ionosphere-free analysis, as implemented in the ATOMIUM software, is reviewed. In Section 4, the selected method used to implement higher-order ionospheric corrections in the ATOMIUM ionosphere-free analysis is described. Our corresponding results are presented in Section 5, in terms of ionospheric delays of second and third orders compared to first-order ionospheric effects, and then in terms of the impact of higher-order ionospheric delays in the receiver clock solution computed with ATOMIUM. In Section 6, we put our results in perspective with some investigations on related solar flare events and K-index considerations. Conclusions are finally presented in Section 7.

Numerical values in the equations of this paper are provided in SI units.

2 GPS time and frequency transfer

High precision geodetic GPS receivers can lock their internal oscillator on an external frequency, given by a stable atomic clock. The GPS measurements are then based on the clock frequency. Using post-processed satellite orbits and satellite clock products computed by the International GNSS Service (IGS), one can deduce the synchronization error between the external clock and either the GPS time scale or the reference time scale of the IGS, named IGST. The use of GPS measurements made in two stations p and q gives then access to the synchronization error between the two atomic clocks in these stations p and q .

For a station p or similarly q , the GPS measurements, relative to observed satellite i , on the signal code P_k and phase L_k , at frequency k (1 for $f_1 = 1575.42$ MHz or 2 for $f_2 = 1227.6$ MHz) with corresponding wavelength λ_k , can be written in length units as

$$\begin{aligned}
(P_{k=1,2})_p^i &= \rho_p^i + c\Delta t_p + c\Delta\tau^i + \Delta r_p^i + (\varepsilon_{P_k})_p^i + (+I1_k + 2 \cdot I2_k + 3 \cdot I3_k)_p^i \\
(L_{k=1,2})_p^i &= \rho_p^i + c\Delta t_p + c\Delta\tau^i + \Delta r_p^i + N_p^i \lambda_k + (\varepsilon_{L_k})_p^i + (-I1_k - I2_k - I3_k)_p^i
\end{aligned} \tag{1}$$

following Bassiri & Hajj (1993) who considered separately the different orders of the ionosphere impact on GPS code and phase measurements. There, ρ_p^i is the geometric distance i - p ; Δt_p is the station clock synchronization error; $\Delta\tau^i$ is the satellite clock synchronization error; Δr_p^i is the tropospheric path delay for path i - p ; $I1_k$ ($\propto 1/f_k^2$), $I2_k$ ($\propto 1/f_k^3$) and $I3_k$ ($\propto 1/f_k^4$) are the first-, second- and third-order ionospheric delays on frequency k ; N_p^i are the phase ambiguities; $(\varepsilon_{P_k})_p^i$ and $(\varepsilon_{L_k})_p^i$ are the error terms in code P and phase L , respectively, containing noise such as unmodeled multipath, hardware delays (biases from the electronic of the satellite or the station receiver) on the propagation of the modulation/carrier of the signal. In their most general form, the different orders of ionospheric delays ($I1$, $I2$, $I3$) are expressed as integrals along the true path of the signal (including a bending, which is function of the signal frequency, in the dispersive ionosphere), in terms of the signal frequency, of the local electron density in the ionosphere and of the local geomagnetic field along the trajectory (Bassiri & Hajj, 1993).

When a dual frequency GPS receiver is available at station p , the so-called ionosphere-free combination ($k = 3$) is used. This combination is defined as (Leick, 2004):

$$\begin{aligned}
P_3 &\equiv \frac{f_1^2}{(f_1^2 - f_2^2)} P_1 - \frac{f_2^2}{(f_1^2 - f_2^2)} P_2 \\
L_3 &\equiv \frac{f_1^2}{(f_1^2 - f_2^2)} L_1 - \frac{f_2^2}{(f_1^2 - f_2^2)} L_2
\end{aligned} \tag{2}$$

with f_1 and f_2 the two GPS carrier frequencies. This combination removes, from the GPS signal, the first-order ionospheric effect, $I1$, since the latter is proportional to the inverse of the square frequency. The corresponding ionosphere-free observation equations therefore do not contain any first-order ionospheric term, but contain new factors for second- and third-order ionospheric effects (Fritsche et al., 2005) with respect to previous Equation 1:

$$\begin{aligned}
(P_3)_p^i &= \rho_p^i + c\Delta t_p + c\Delta\tau^i + \Delta r_p^i + (\varepsilon_{P_3})_p^i + (+2 \cdot I2_3 - 3 \cdot I3_3)_p^i \\
(L_3)_p^i &= \rho_p^i + c\Delta t_p + c\Delta\tau^i + \Delta r_p^i + N_p^i \lambda_3 + (\varepsilon_{L_3})_p^i + (-I2_3 + I3_3)_p^i
\end{aligned} \tag{3}$$

Note that about 99.9% (Hernandez-Pajares et al., 2008) of ionospheric perturbations are removed with $I1$ in the so-called ionosphere-free combination. Note also that while the first order has the same magnitude on GPS phase and code measurements (but with opposite sign), the impact of second- and third-order effects is larger on code than on phase observations (twice for $I2$, three

times for $I3$). The GPS observation equations given by 3 are directly used in Precise Point Positioning. The clock solution obtained is the synchronization error between the receiver clock and the GPS or IGS Time scale.

For Common-View analysis, one uses the single differences between simultaneous observations of a same satellite i in two remote stations p and q in order to determine directly the synchronization error between the two remote clocks: the observation equations for receivers p and q with satellite i are subtracted. This single difference removes the satellite clock bias in the GPS signal, assuming that the nominal times of observation of the satellite by the two stations are the same. When forming ionosphere-free combinations, the single-difference code and carrier phase equations are:

$$\begin{aligned} (P_3)_{pq}^i &= \rho_{pq}^i + c\Delta t_{pq} + \Delta r_{pq}^i + (\varepsilon_{P_3})_{pq}^i + (+2 \cdot I2_3 - 3 \cdot I3_3)_{pq}^i \\ (L_3)_{pq}^i &= \rho_{pq}^i + c\Delta t_{pq} + \Delta r_{pq}^i + N_{pq}^i \lambda_3 + (\varepsilon_{L_3})_{pq}^i + (-I2_3 + I3_3)_{pq}^i \end{aligned} \quad (4)$$

where, for any quantity X ,

$$X_{pq} \equiv X_p - X_q$$

Now, all the terms in above Equations 1, 3 or 4 can be estimated via an inversion procedure using some a priori precise satellite orbits and satellite clock products. This finally provides the solution for either Δt_p in PPP, i.e. the clock synchronization error between the atomic clock connected to the GPS receiver and the GPS or IGS Time scale at each epoch, or Δt_{pq} in Common View, i.e. the synchronization error between the remote clocks connected to two GPS receivers. In parallel, the station position and tropospheric zenith delays are estimated as a by-product.

3 The ATOMIUM software

The present study on ionospheric higher-order perturbations in TFT is based on the ATOMIUM software (Defraigne et al., 2008), which uses a weighted least-square approach with ionosphere-free combinations of dual-frequency GPS code (P_3) and carrier phase (L_3) observations. ATOMIUM was initially developed to perform GPS PPP, as described in (Kouba & Heroux, 2001), and later adapted to single differences, or Common View (CV), of GPS code and carrier phase observations. In the paragraphs below, we describe ATOMIUM, following the diagram presented in Figure 1. First, GPS ionosphere-free code and phase combinations are constructed according to Equations 2 from L_1 , P_1 ,

L_2 , P_2 observations read in RINEX observation files. By default, the ATOMIUM software uses as a priori the IGS products (IGS data and products, 2009). IGS satellite clocks (tabulated with a 5-minute interval) are used to obtain $\Delta\tau^i$ at the same sampling rate as provided. IGS satellite orbits (tabulated with a 15-minute interval) are used to estimate ρ_p^i (or ρ_{pq}^i) via a 12-points Neville interpolation of the satellite position every 5 minutes. The station position is corrected for its time variations due to degree 2 and 3 solid Earth tides as recommended by the IERS conventions (McCarthy & Petit, 2003, Ch. 7) and for ocean loading according to the FES2004 model (Lyard et al., 2004). The relative (if GPS observations were made before GPS week 1400) or absolute (if after) elevation (no azimuth) and nadir dependant corrections for receiver and satellite antenna phase center variations are read from the IGS atx file available at (IGS atx, 2009). Prior to the least-square inversion, the computed geometric distance is removed from both phase and code ionosphere-free combinations. Those are also corrected for a relativistic (periodic only) delay and an hydrostatic tropospheric delay. Tropospheric delays are modeled as the sum of a hydrostatic and a wet delay, resulting from the product of a given mapping function and of the corresponding hydrostatic or wet zenith path delay (zpd). For the hydrostatic part, we use the Saastamoinen a priori model (Saastamoinen, 1972) and the dry Niell mapping function (Niell, 1996). For the wet part, we use the wet Niell mapping function (Niell, 1996) while the wet zpd is estimated as one point every 2 hour, and modeled by linear interpolation between these points. Carrier phase measurements are further corrected for phase windup (Wu et al., 1993) taking into account satellite attitude and eclipse events. The implementation of additional higher-order ionospheric corrections on phase and code is done at this level, as corrections applied on the code and phase measurements (see Section 4).

The least-square analysis used in ATOMIUM is detailed in (Defraigne et al., 2008). As output, ATOMIUM provides the station p (or relative $p-q$) position for the whole day, the receiver clock p (or relative $p-q$) synchronization error every 5 minutes, tropospheric wet zenith path delays p (and q) at a given rate (2 hours in our case).

4 Corrections for ionospheric delays

First-, second- and third-order ionospheric terms are function of the Slant Total Electron Content (STEC), which is the integrated electron density inside a cylinder column of unit base area between Earth ground and satellite altitude, along the satellite i - station p direction. STEC is function not only of the satellite elevation or station position, but also of the time of the day, of the time of the year, of the solar cycle, and of the particular ionospheric conditions. As the $I1$ term contains 99.9% of the ionospheric perturbations on

the GNSS signal, it can be used to estimate STEC. The second- and third-order terms are then computed using this estimated STEC. The STEC in $I1$ can be determined using the geometry-free combinations of the measurements made on the two GPS frequencies, defined as P_4 and L_4 (Leick, 2004):

$$\begin{aligned} P_4 &\equiv -P_1 + P_2 \\ L_4 &\equiv L_1 - L_2 \end{aligned} \tag{5}$$

The quantities (P_4L_4) only contain a given combination of ionospheric delays on the signals of frequency f_1 and f_2 , plus some constant terms associated with the differential hardware delays (between f_1 and f_2) in the satellite and in the receiver, and the phase ambiguities.

In the following, for a practical and efficient implementation of higher-order ionospheric terms in ATOMIUM, we work in the no-bending approximation, meaning that the trajectory considered to compute those ionospheric corrections on GPS observations is a straight line from satellite i to station p (and q). Indeed, from analytical estimations based on results of Hoque & Jakowski (2008, formula (31)) and Jakowski et al. (1994, formulas (12-13)), we quantified the bending effects in the dispersive ionosphere on the ionosphere-free combinations of GPS measurements. These effects are due to the excess path length for a curved trajectory and to the difference in effective STEC for the two GPS frequencies. Under extreme conditions, i.e. a highly ionized ionosphere together with very low satellite elevations, ionospheric bending effects might reach the level of the third-order ionosphere correction, which turns out to be in the TFT noise as we will show in the following.

We furthermore assume the ionosphere Single Layer Model (SLM) (Bassiri & Hajj, 1993), reducing the whole ionosphere layer through which the GPS signal travels to a single effective sheet at a given height with the equivalent electron content (see Figure 3).

The above assumptions allow to reduce the general integrals for the ionospheric delays to the easily implemented equations given in the following subsections.

4.1 *First-order ionospheric delays*

The first-order ionospheric effect, is given by (Bassiri & Hajj, 1993)

$$I1_k = \alpha 1_k \cdot STEC \tag{6}$$

with the factor for GPS frequencies 1 and 2 being

$$\alpha 1_{1,2} = + \frac{40.3}{f_{1,2}^2} \quad (7)$$

This implies that the corresponding factors for the ionosphere-free ($k = 3$) or geometry-free ($k = 4$) combinations are

$$\begin{aligned} \alpha 1_3 &= 0 \\ \alpha 1_4 &= -40.3 \left(\frac{1}{f_1^2} - \frac{1}{f_2^2} \right) \end{aligned} \quad (8)$$

As announced here above, for each pair of code or phase measurements (on f_1 and f_2), the geometry-free combination can be used to compute the STEC, which is needed in higher-order ionospheric corrections. Neglecting the $I2$ and $I3$ contributions inducing errors in estimated STEC of the order of 0.1 TECU at the most, one gets (Hernandez-Pajares et al., 2007):

$$(STEC)_p^i = \frac{1}{\alpha 1_4} \left[(L_4)_p^i - \left\langle (L_4)_p^i - (P_4)_p^i \right\rangle_{\substack{\text{arc without} \\ \text{cycle slips}}} - c \cdot DCB_p - c \cdot DCB^i \right] \quad (9)$$

In the above formula, $P_1 - P_2$ Differential Code Biases (DCB) are assumed constant during a day, and we read them from the CODE (IGS Analysis Center) IONEX files; $\langle \rangle$ means taking the average.

Alternatively, STEC can be computed using $P_1 P_2$ codes that have first been smoothed with the corresponding phase (Dach et al., 2007),

$$(STEC)_p^i = \frac{1}{\alpha 1_4} \left[\left\{ (P_2)_p^i - (P_1)_p^i \right\}_{\substack{\text{smoothed} \\ \text{with phase}}} - c \cdot DCB_p - c \cdot DCB^i \right] \quad (10)$$

This leads to similar results as those obtained from Equation 9 with respect to the same DCB product.

Within ATOMIUM, STEC is computed, using formula 9, for each satellite-station pair with a sampling rate of 5 minutes. Figure 2 illustrates STEC computed via ATOMIUM for stations BRUS, i.e. Brussels, at latitude $50^\circ 28'$ and longitude $4^\circ 12'$, TLSE, i.e. Toulouse at latitude $43^\circ 20'$ and longitude $1^\circ 17'$, ONSA i.e. Onsala at latitude $57^\circ 14'$ and longitude $11^\circ 33'$. Figure 2a features a quiet-ionosphere day (around a minimum of solar activity), 11th March 2007, with its normal local-noon diurnal maximum of STEC. Figure 2b shows the ionospheric storm of October 30, 2003 and the STEC sensitivity to perturbed ionospheric conditions as induced by solar activity (see Section 6). Since ionospheric effects in GPS are function of STEC, we understand that ionosphere-induced errors will increase in the next few years due to the increasing solar activity associated with the ascending phase of the 24th sunspot cycle (maximum forecast around 2011-2012 depending on the models).

4.2 Second-order ionospheric delays

Whereas the magnitude of $I1$ for a given frequency depends solely on STEC and is always positive, the magnitude and sign of $I2$ depend on the geomagnetic field B values, on STEC and on the i - p signal direction via the angle between B and the Line of Sight (LOS), θ_{B-LOS} (Figure 3). We used the following integrated formula (Hernandez-Pajares et al., 2007)

$$I2_k = \alpha 2_k \cdot B_{IPP} \cdot \cos \theta_{B-LOS} \cdot STEC \quad (11)$$

with frequency factors

$$\alpha 2_3 = -\frac{7527 \cdot c}{2 \cdot f_1 f_2 (f_1 + f_2)} \quad (12)$$

$$\alpha 2_{1,2} = -\frac{7527 \cdot c}{f_{1,2}^3} \quad (13)$$

STEC is obtained from $L_4 P_4$ (Equation 9) and B_{IPP} is computed using the accurate International Geomagnetic Reference (IGR) model (Tsyganenko, 2005), as the latter allows to reduce errors in $I2$ up to 60% with respect to a dipolar model (Hernandez-Pajares et al., 2007, 2008).

4.3 Third-order ionospheric delays

In the third-order ionospheric contribution, the magnetic field term can be safely neglected at sub-millimeter error level, leading to the simple formula (Fritsche et al., 2005)

$$I3_k = \alpha 3_k \cdot STEC \quad (14)$$

with frequency factors also being functions of the electron distribution in the ionosphere:

$$\alpha 3_{1,2} = -\frac{2437 \cdot N_{\max} \cdot \eta}{f_{1,2}^4} \quad (15)$$

$$\alpha 3_3 = -\frac{2437 \cdot N_{\max} \cdot \eta}{3 \cdot f_1^2 \cdot f_2^2} \quad (16)$$

where the shape factor η is taken around 0.66 and the peak electron density along the signal propagation path, N_{max} , can be determined by a linear interpolation between a typical ionospheric situation and a solar maximum one (Fritsche et al., 2005, formula 14 corrected according to a private communication from M. Fritsche, November 2008), using, as interpolation coefficients, the numerical values suggested by Brunner & M. Gu (1991):

$$N_{max} = \frac{[(20 - 6) \cdot 10^{12}]}{[(4.55 - 1.38) \cdot 10^{18}]} \cdot (VTEC - 4.55 \cdot 10^{18}) + 20 \cdot 10^{12} \quad (17)$$

The Vertical TEC (VTEC), which is TEC along a vertical trajectory below the satellite, is taken as the projection, via the Modified Single Layer Model ionosphere mapping function, of $(STEC)_p^i$ from Equation 9 with $\alpha_{MSLM} = 0.9782$, $R_{Earth} = 6371 \cdot 10^3$ m, $H = 506.7 \cdot 10^3$ m as in (Dach et al., 2007):

$$STEC = f_{MSLM}(z) \cdot VTEC \quad (18)$$

$$f_{MSLM}(z) \equiv 1 / \sqrt{1 - \left(\frac{R_{Earth}}{R_{Earth} + H} \right)^2 \cdot \cos^2(\alpha_{MSLM} \cdot z)} \quad (19)$$

Finally, using the above equations for the first-, second- and third-order ionospheric effects on GPS signal propagation, one finds the orders of magnitude of their impact on the code and carrier phase measurements given in Table 1.

5 Quantifying ionospheric effects on TFF

The $I2$ and $I3$ corrections computed according the procedure described above were applied to the ionosphere-free combinations P_3 and L_3 used in ATOMIUM. The present section shows some preliminary results: estimated second- and third-order delays on GPS signals (and on combinations of their measurements) and the impact of these on the time and frequency transfer solutions.

5.1 Ionospheric delays

The first results concern the ionospheric delays as computed with ATOMIUM according to the models detailed in previous section. Firstly, recall that the Total Electron Content of the ionosphere reaches its

maximal value at local noon, on a normal day (Figure 2). Since $I1$, $I2$ and $I3$ are proportional to Slant TEC, the amplitude of ionospheric perturbations in GPS signal reflect this daily variation of TEC.

Secondly, the diurnal TEC maximum is function of the station latitude, so the ionospheric delays in GPS signals follow accordingly.

And finally, for any observed satellite, as the ionospheric thickness crossed by the signal is proportional to the inverse of the sine of the satellite elevation, the STEC during one satellite track, as well as the ionospheric delays, takes the shape of a concave curve.

Figures 6, 7 and 8 illustrate $I1_2$, $I2_3$ and $I3_3$ respectively on a quiet (left) versus an ionosphere-stormy day, the ionospheric storm of October 30, 2003 (right). The selected station in this illustration is Onsala (ONSA). Each point of the curves corresponds to an ionospheric correction on a GPS phase measurement for an observed satellite. The first-order ionospheric perturbations in L_2 can reach about 100 nanoseconds during the storm (Figures 6 a and b), while it is less than 50 nanoseconds in normal times. $I1$ in L_1 is slightly smaller according to factor f_2^2/f_1^2 . The $I1$ effect is removed from the ionosphere-free combination.

The second-order ionospheric perturbation in the ionosphere-free combination (Figure 7 a) is about 3 to 4 orders of magnitude smaller than the first order in L_2 . $I2_3$ can reach about 15 picoseconds during the storm, about the double of its maximum value during a quiet day (Figure 7b compared to 7a). We also recall that, in the ionosphere-free combination, the second-order ionospheric perturbation, $I2_3$, affects twice more the codes than the phases, as seen in Equation 3.

Figure 8 illustrates the third-order ionospheric perturbation which is again an order of magnitude smaller than the second order. Here the effect of the storm is also clear, as the third-order effect in the ionosphere-free combination can reach about 2 picoseconds during the storm (Figure 8b), while its maximum value on a non-stormy day is about 0.14 picoseconds (Figure 8a). Again, the contribution of $I3_3$ is three times more important for codes than for phases, as seen in Equation 3, but remains negligible with respect to the present precision of GPS time and frequency transfer.

5.2 Ionospheric impact on receiver clock estimates from a L_3P_3 analysis

Table 1 and the results presented in the above paragraph illustrate the need to take second-order ionospheric corrections into account in P and L measurements for TFT. However, to be coherent, in addition to the $I2$ (and $I3$) correction(s) on GPS code and phase data, we should also use satellite orbit and clock products computed with $I2$ (and $I3$) correction(s) in order to estimate the impact of the ionosphere on station clock synchronization errors via ATOMIUM. Indeed, Hernandez-Pajares et al. (2007) estimated that

second-order ionospheric effects in satellite clocks were the largest and could be more than 1 centimeter (i.e. ~ 30 picoseconds); the same authors mentioned that the second-order ionospheric effects on the satellite position are of the order of several millimeters only, and consist in a global southward shift of the constellation. Current IGS products do not take $I2$ nor $I3$ into account, this is why we present here the impact of our ionospheric corrections on clock solutions via ATOMIUM in Common-View mode (Figures 9 and 10), as the satellite clock is eliminated in CV. We choose the link BRUS-ONSA, i.e. Brussels-Onsala (Sweden), the day of an ionospheric storm, October 30, 2003, and used GPS observations with a satellite elevation cutoff of 5 degrees. Figure 9 shows the effect of applying the $I2$ corrections on GPS P_3L_3 analysis. We see an effect up to more than 10 picoseconds during the ionospheric storm on the link BRUS-ONSA.

The $I3$ effect shown in Figure 10 is at the present noise level of GPS observations.

Consequently, the residual ionospheric errors in P_3L_3 (when P_3L_3 is not corrected for higher-order effects) are mainly due to the contribution of $I2_3$. A $I2$ delay of 15 picoseconds peak to peak during the storm (Figure 7b) for a given station A induces a variation with the corresponding differential $I2_{3A} - I2_{3B}$ amplitude in CV frequency transfer with station B , as the shape of the curve is determined by the GPS phases for which the $I2$ correction is applied with a factor 1. Furthermore, $I2$ induces twice as much an offset on the absolute time synchronization error (Figure 9), as the calibration of the curve is determined by the code data for which the $I2$ correction is applied with a factor 2 (Equation 3). However, this of course is still well below the present calibration capabilities of GPS equipment.

Note that the results presented here correspond to the time link BRUS-ONSA. It is therefore the differential ionospheric effect between those two stations that matters for the clock solution in Common-View mode. The impact of $I2$ on a clock solution in PPP could therefore be higher and induce larger effects on intercontinental time links. This will be investigated in further studies, when consistent satellite orbits and clock products computed with $I2$ (and $I3$) will be available.

6 Space weather

Solar activity was initially monitored thanks to ground observations (sunspot group evolution). Since recent decades, the Sun is observed via satellites. This opened the field to space weather studies, characterizing the conditions of the Sun, of the space between the Sun and Earth, and on the Earth.

The Geostationary Operational Environmental Satellite (GOES, orbiting the Earth at 35790 km) measures solar flares as X-rays from 100 to 800 picometers

and classifies them as A, B, C, M or X according to their peak flux (in watts per square meter) on a logarithmic scale. Each class has a peak flux ten times greater than the preceding one, with X ones of the order of 10^{-4} W/m^2 . There is an additional linear scale from 1 to 9 inside each class.

Furthermore, the magnetic field of the Earth is characterized (according to Earth latitude) by several indexes. The K index quantifies disturbances in the horizontal component of the Earth’s magnetic field with an integer in the range 0-9. K index is derived from the maximum fluctuations of the Earth geomagnetic field horizontal component observed on a magnetometer during a three-hour interval. The conversion table from maximum fluctuation (in nanoTesla) to K -index, varies from observatory to observatory (NOAA Space Weather Prediction Center, 2009). Hence, the official planetary K_p index is derived by calculating a weighted average of K -indices from a network of geomagnetic observatories. Values of K from 5 and higher indicate a geomagnetic storm which may hamper GPS/GNSS TFT as we shall see.

The previous solar maximum was around 2001. The year 2003 was thus an active period for the Sun, compared to year 2007. For the sake of comparison, we selected a quiet day, March 11 2007, and the very active day of 30th October 2003. Around our quiet test-day, no X and no M flares were observed; only four B-type X-ray events were detected during March 2007. On the other side, the solar activity and Earth geomagnetic conditions were at exceptionally high levels around the 30th October 2003, as can be seen from Figure 4, which lists the solar flare events according to their intensity, together with the Earth geomagnetic index K from Wingst Observatory (K_W in the text) in Germany (at geographic latitude 53.74° and longitude 9.07° , close to Onsala’s latitude). Those events were mostly due to two large solar active regions named NOAA0486 and NOAA0484, which produced numerous solar M-flares and several X-flares. Further insight for Figure 4 can be gained when reading the corresponding SIDC (Solar Influences Data Center) weekly bulletins (SIDC, 2009) on solar activity for weeks 148 and 149 of 2003, corresponding to the range of our plots. We focus on the X-flares accompanied by CME.

On October 28, a X17.2 (thus extremely strong) solar flare occurred from the solar active region NOAA0486 peaking at 11:10 UT. It was accompanied by a CME directed towards the Earth with an estimated plane-of-the-sky speed of about 2125 km/s, first detected at 10:54 UT in the LASCO C2 field of view of the SOHO spacecraft (located at about $1.5 \cdot 10^6$ km from the Earth). As the CME was extremely fast, the shock arrived to the Earth around 06:00 UT on October 29. It produced a severe magnetic storm with K_W index reaching 9. The intensity of the storm decreased slightly to $K_W = 7$ during October 29 as the arriving magnetic cloud was of the north-south type. The main portion of the negative the north-south interplanetary magnetic field component B_z arrived in the trailing part of the cloud at the end of October 29. B_z was

strongly negative during around 8 hours producing the second peak in the K_W index which reached 9 again during 18:00 - 24:00 UT. The K_W index settled down to minor storm conditions ($K_W = 5$) on October 30.

On October 29, the solar active region NOAA0486 produced an X10.1 flare peaking at 20:49 UT, as observed by GOES. It was associated with a CME observed by SOHO/LASCO C2 at 20:54 UT that developed to a full halo CME directed towards the Earth with an estimated plane-of-the-sky speed of about 1950 km/s. The electromagnetic shock of the CME was registered by ACE/MAG around 16:00 UT on October 30. This time the magnetic cloud was of south-north type, so the severe geomagnetic storm started right after the arrival of the shock: the K_W index reached 9 again and stayed at that level during two 3-hour intervals (18:00 - 24:00). The geomagnetic storm finally ended on October 31 - November 1 when the K_W index dropped to 4. From October 30 to November 5 included, several X- and M-class flares occurred in solar active regions NOAA0484, NOAA0486 and NOAA0488.

On November 2, an X8.3 flare was observed by GOES, peaking at 17:25 UT, from the solar active region NOAA0486. A halo CME with estimated plane-of-the-sky speed of about 2100 - 2200 km/s followed. The shock of the arriving CME was recorded in the solar wind on November 4, at 05:53UT. The associated interplanetary magnetic field pointed southward between 07:00 and 9:30 UT. This triggered a geomagnetic storm ($K_W=6-7$), but only for a limited duration: thereafter, the geomagnetic field remained quiet to unsettled.

On November 4, came from NOAA0486 an extreme X17 flare (peaking at 19:53UT), later estimated to have reached an X28 peak flux that saturated the GOES detectors, together with a full halo CME. The shock, corresponding to this CME which arrived sideways on November 6 at 19:37 UT, was relatively weak and only led to a minor storm that lasted until November 7, 00:00 UT. The magnetosphere then remained quiet to unsettled.

By contrast, during the end of the week, the Sun had a very low activity. However, an existing large solar coronal hole gave rise to minor geomagnetic storm ($K_W = 6$) episodes on November 9.

We now come back to our STEC at station Onsala on the 30th October 2003 (Figure 5), estimated using the software ATOMIUM and GPS data. We understand that the huge solar flare event X17.2 of October 28 2003, that was associated with a CME, through the Earth geomagnetic storm it triggered on the 29th October 2003, is responsible for the abnormally high level of STEC at Onsala (and Brussels as well) at early hours of October 30 2003. This explains the correspondingly high first-, second- and third-order ionospheric perturbations computed in Figures 6, 7 and 8, in the first hours of October 30 2003. A small corresponding impact can be seen on the ATOMIUM clock solution in Figure 9.

The major Earth geomagnetic storm that occurred on the 30th October 2003, however, is most probably due to the solar flare event X10.1 of October 29 2003, associated with a CME. This time, the strong signature present in the

STEC estimated with ATOMIUM for Onsala (Figure 5) (and Brussels as well) and computed corresponding first-, second- and third-order ionospheric perturbations on GPS signals (Figures 6, 7 and 8) is clearly visible in the estimated Common-View clock solution of ATOMIUM (Figure 9). This emphasizes the need for higher-order ionospheric corrections on GPS signals in precise time and frequency transfer, as we need to prepare for the next solar maximum.

7 Conclusions

This study aimed at quantifying the impact of second- and third-order ionospheric delays on precise time and frequency transfer using GPS signals.

We used the ATOMIUM software, in which we implemented higher-order ionospheric contributions (second and third orders) in the so-called ionosphere-free combination of GPS codes and phases. We then compared these ionospheric contributions with the first-order ionospheric effect on the GPS dual frequency signal, which is cancelled in ionosphere-free combination. It was shown that the first-order ionospheric delay of several tens of nanoseconds on an ionosphere-quiet day, is doubled in case of ionospheric storms. Though second-order delays in the ionosphere-free combination are about 3 to 4 orders of magnitude smaller than the first-order delays, they can reach about 15 picoseconds on a stormy day, which is significant when performing geodetic time and frequency transfer with very stable clocks. Third-order delays in the ionosphere-free combination are yet an order of magnitude smaller, and are at the level of present noise of GPS observations. The impact of those higher-order delays on ionosphere-free time and frequency transfer clock solutions was estimated for the time link BRUS-ONSA. It reaches more than 10 picoseconds during the ionospheric storm of October 30 2003. Finally, we illustrated the correlations between space weather data (strong solar events, disturbances of the Earth geomagnetic field) and time/frequency transfer performed with GPS signals.

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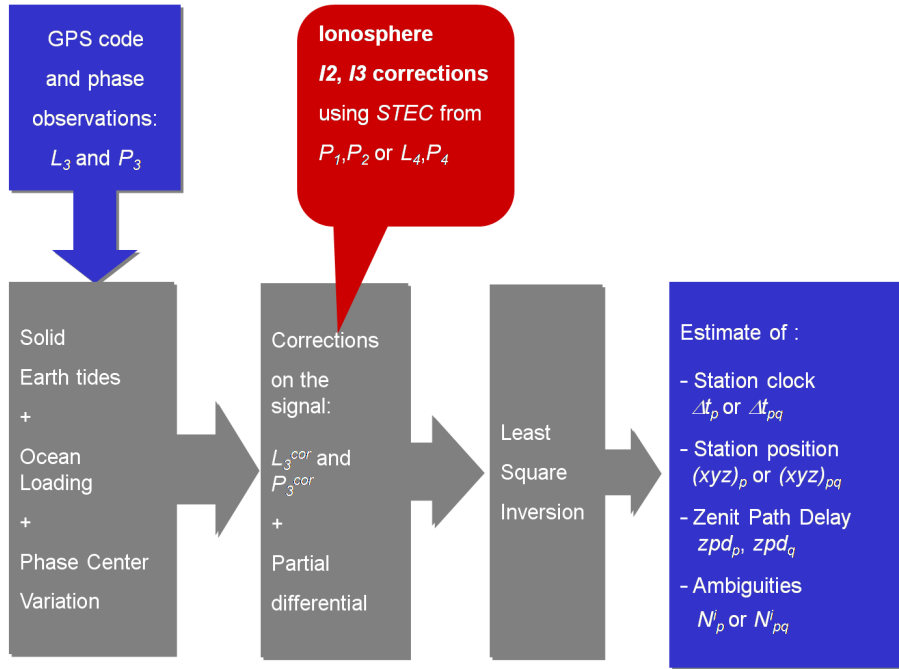


Fig. 1. ATOMIUM software diagram.

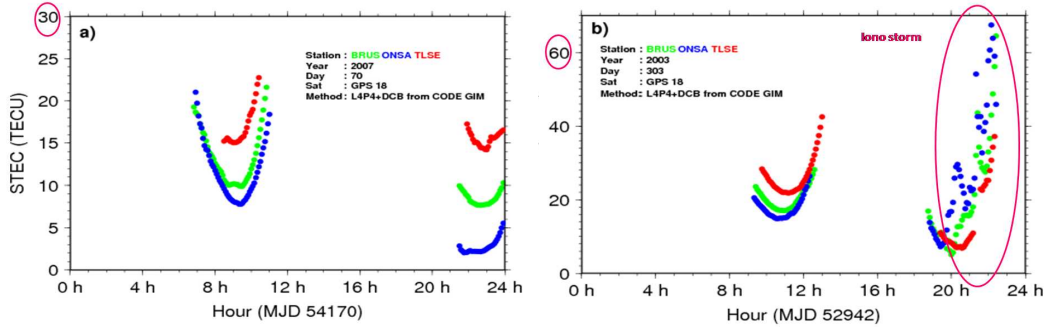


Fig. 2. STEC computed when observing GPS satellite prn 18 with GPS receivers located at Brussels (BRUS), Onsala (ONSA) and Toulouse (TLSE) on an ionosphere-quiet day (11th March 2007), Figure a (left), or on a stormy day (30th October 2003), Figure b (right). STEC was computed with the ATOMIUM software, using Equation (9) and DCBs read from CODE IONEX files. $1 \text{ TECU} = 10^{16} e^-/m^2$.

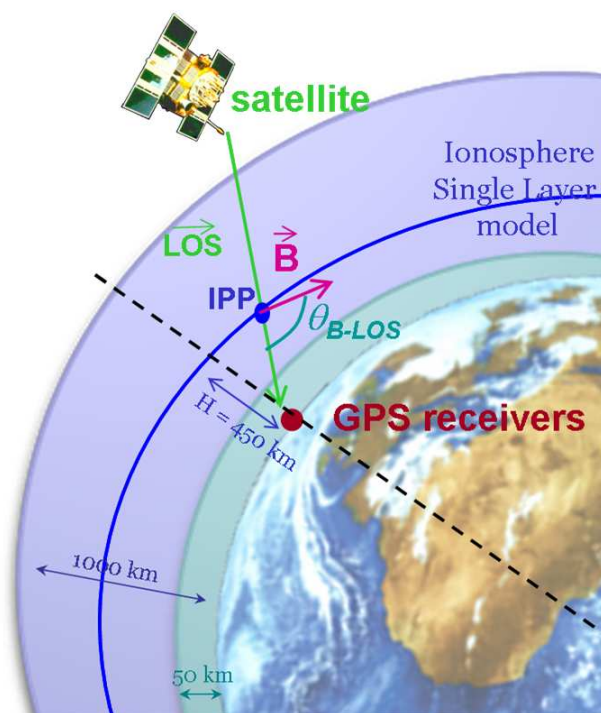


Fig. 3. The second-order ionospheric effect is not only a function of STEC, but it is also function of the angle between the Line Of Sight (LOS) and the geomagnetic field B at the Ionosphere Piercing Point (IPP), and of the magnitude of B at IPP.

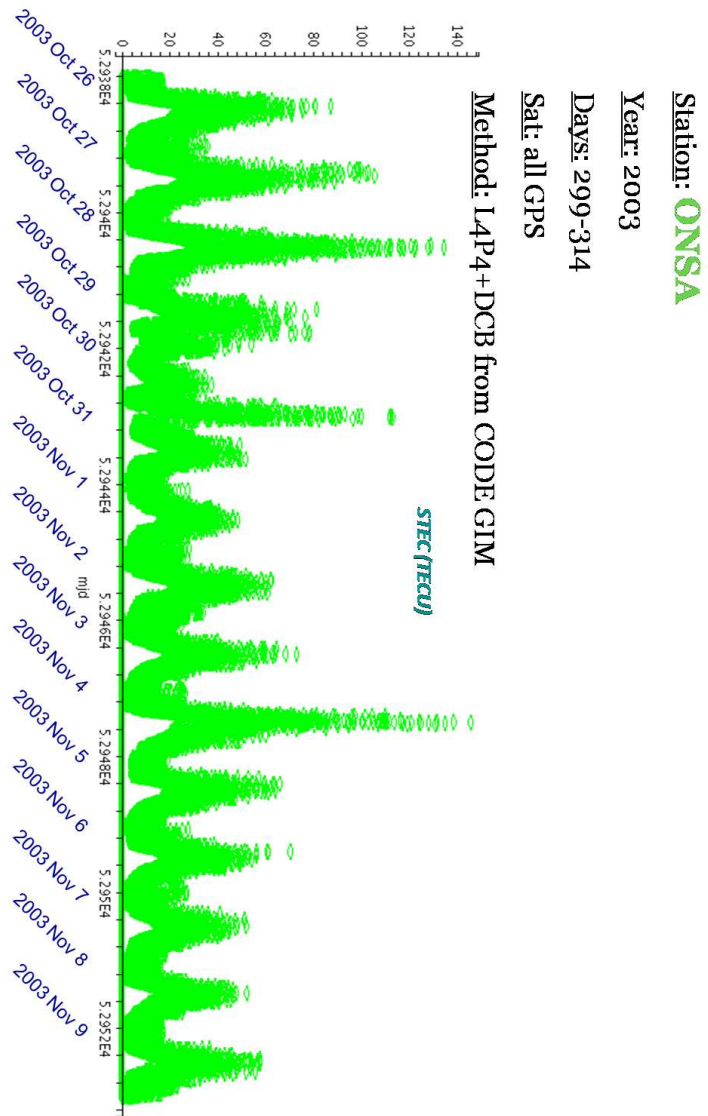


Fig. 5. STEC time series computed with the ATOMIUM software for station Onsala (ONSA), according to Equation 9, from 26th October to 9th November 2003.

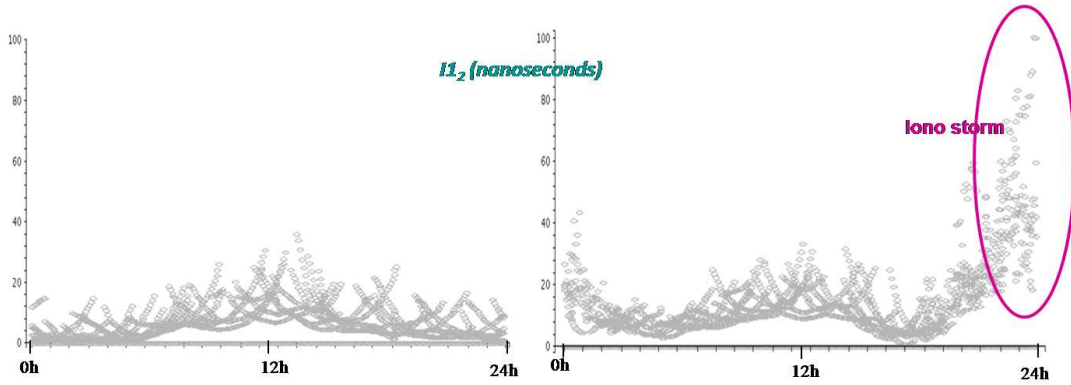


Fig. 6. First-order ionospheric delay in GPS frequency 2, for station Onsala on an ionosphere-quiet day, 11th March 2007 (Figure a, left), versus on an ionosphere-stormy day, 30th October 2003 (Figure b, right).

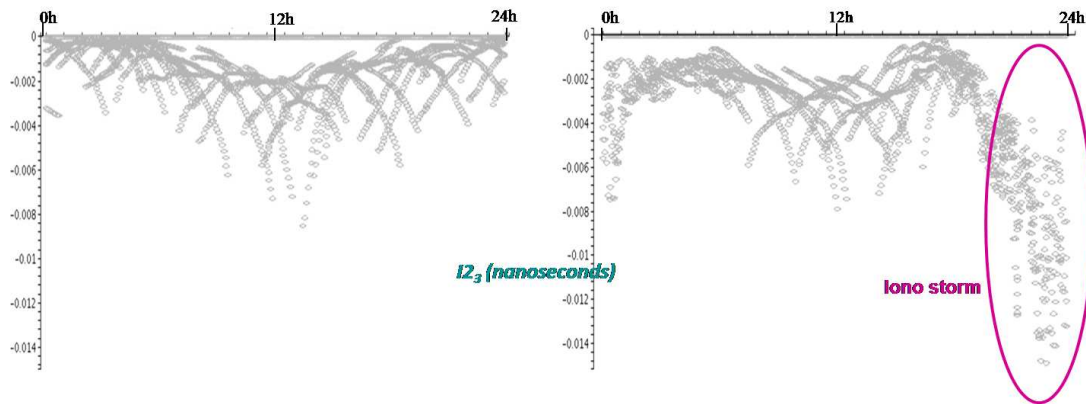


Fig. 7. Second-order ionospheric delay in GPS so-called ionosphere-free combination, for station Onsala on an ionosphere-quiet day, 11th March 2007 (Figure a, left), versus on an ionosphere-stormy day, 30th October 2003 (Figure b, right).

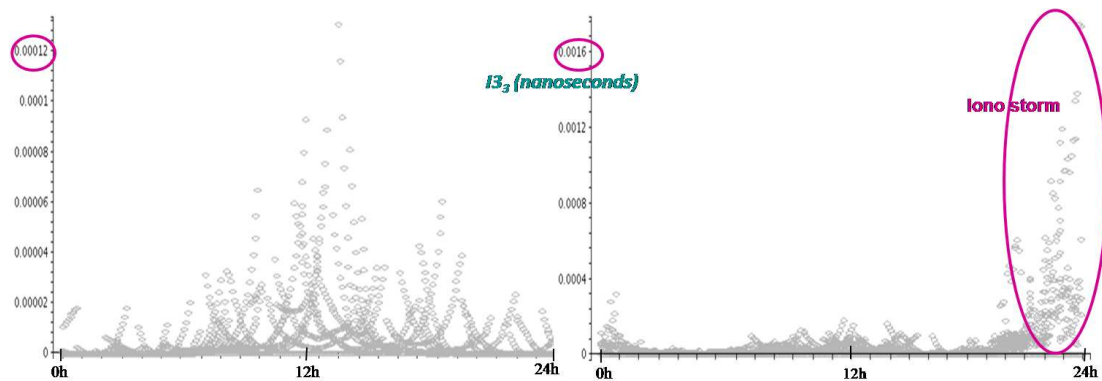


Fig. 8. Third-order ionospheric delay in GPS so-called ionosphere-free combination, for station Onsala on an ionosphere-quiet day, 11th March 2007 (Figure a, left), versus on an ionosphere-stormy day, 30th October 2003 (Figure b, right).

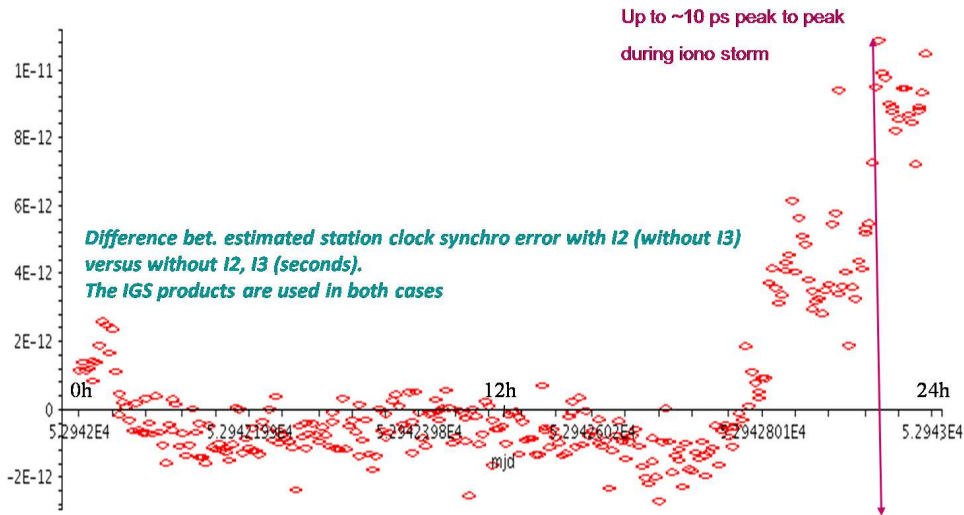


Fig. 9. Effect of taking second-order ionospheric effects, or not, into account in the L_3P_3 GPS measurements for the Brussels-Onsala link, on the ionosphere-stormy day 30th October 2003. The difference is taken between two ATOMIUM estimated station clock solutions, both using IGS products.

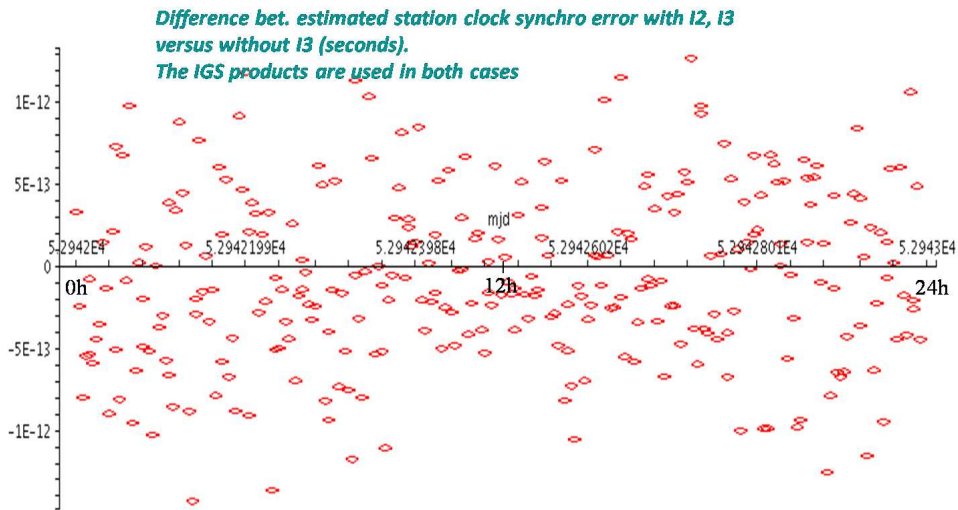


Fig. 10. Effect of taking third-order ionospheric effect, or not, into account in the L_3P_3 GPS measurements for the Brussels-Onsala link, on the ionosphere-stormy day 30th October 2003. The difference is taken between two ATOMIUM estimated station clock solutions, both using IGS products.

Table 1

Orders of magnitude of ionospheric effects $I1$, $I2$ and $I3$ on GPS phase measurements (for codes, see converting factor in code measurement Equations 1, 3, Section 1)

Ionospheric effect (absolute value)	Delay in L_1L_2 per 100 TECU	Delay in L_3 per 100 TECU	Relevance (Hernandez-Pajares et al., 2008)
$I1$	$\sim 30ns - 100 ns$	0	99.9% of $I123$
$I2$	$\sim 0 - 130 ps$	$\sim 0 - 45 ps$	90% of $I23$
$I3$	$\sim 0 - 3 ps$	$\sim 0 - 2 ps$	