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Precise point positioning performance in the presence of the 28 October 2003 Sudden Increase in Total Electron Content

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Abstract

Intense disturbances in the ionosphere may produce perturbations in Global Navigation Satellite System's (GNSS) radio signals that in the most severe cases produce receiver tracking problems, which in turn impact on GNSS positioning accuracy. In this paper we present a case study related to the sudden increase in total electron content (SITEC) induced by the X17.2 solar flare that occurred on 28 October 2003. This is the largest SITEC ever recorded by means of a rate of change of total electron content. A solar radio

burst (SRB) occurred in the same period which caused GNSS signal fading and in some cases complete signal loss. Although SITEC contribution to the signal noise cannot be separated from that of SRB, in this paper we show that accuracy degradation may happen in kinematic precise point positioning (PPP) in several stations of the sunlit hemisphere when 30 s sampling rate data is analyzed. The observed errors in the position are the result of the difficulties that cycle slip (CS) detection strategies have to deal with the observables that have been affected by the SITEC.

1. Introduction

The ionosphere is a dispersive medium for GNSS's (Global Navigation Satellite System) signals. The ionospheric delay produces errors of several tens of meters in the GNSS receiver–satellite range that in first approximation depend on the frequency transmitted and the ionospheric total electron content (TEC). This property makes GNSS a highly useful tool to monitor the ionosphere since dual frequency observations may be used to retrieve the ionospheric delay and TEC [Sardón and Zarraoa, 1997; De Lacy et al., 2005; Ciralo et al., 2007]. The main difficulty lies in solving the inter-frequency bias, but for ionospheric irregularities detection, this obstacle can be overcome using the rate of change of TEC (ROT).

Ionospheric irregularities may produce sudden fast changes in signals carrier's phases that are manifested as large fluctuations of ROT . Diverse techniques based on TEC and ROT have been proposed to detect different scales of plasma structures present in the ionosphere [Wanninger, 1993; Pi et al., 1997; Warnant, 1998; Mendillo et al., 2000; Leonovich et al., 2001; Magdaleno et al., 2011]. These parameters have been widely used for irregularities detection under different solar activity and geomagnetic conditions,

confirming that the irregularity occurrence presents a spatial and temporal variability that depends on local time, season, location, solar activity and Space Weather events.

Disturbances in the ionosphere may produce signal interference and rapid changes in amplitude and phase called scintillation. In the most severe cases, scintillation may cause signal tracking problems such as loss of lock or a complete signal loss [Skone et al., 2001] affecting the cycle slip (CS) detection algorithms [Banville et al., 2010] which in last instance may impact on the GNSS positioning accuracy.

In recent years a number of papers have been published where the accuracy degradation of dual frequency precise point positioning (PPP) under perturbed ionospheric conditions is shown [Moreno et al., 2011; Pi et al., 2013; Jacobsen and Dähnn, 2014; Rodríguez-Bilbao et al., 2015]. In these works PPP is performed by using single-receiver's dual frequency GNSS code and carrier phase un-differenced observations together with precise satellite orbit and clock information to obtain the receiver position with high accuracy [Zumberge et al, 1997; Kouba and Héroux, 2001]. The error contributions to the satellite-receiver range observations such as the atmospheric refraction, the relativistic effects or antennas phase centers are corrected or modeled, and the ionosphere's first order effect is removed by linearly combining the observables in both frequencies [Seeber, 2003]. However, PPP positioning errors still may increase in the presence of ionospheric irregularities but due to the complexity of the scenarios that can occur it is not a trivial task to distinguish between the contributions of each possible source of error to the final accuracy reached. Factors such as dilution of precision, higher order ionospheric effects [Hoque and Jakowski, 2007], diffraction phenomena affecting the ionosphere-free combination [Carrano et al., 2013], solution convergence time after signal loss or the unnecessary ambiguity re-estimation due to the CS false detection

[Banville and Langley, 2013] for each satellite-receiver link can be involved in the problem.

Most of the studies reporting ionospheric irregularity effects on positioning have been so far focused in low- and high-latitude irregularities since these are the zones where radio scintillation is more prone to occur [Aarons, 1982]. Special attention has also been paid to ionospheric disturbances originating under geomagnetically perturbed conditions. In this work we look at a different kind of perturbation, and we analyze the impact of the large sudden increase in TEC (SITEC) induced by the 28 October 2003 X17.2/4B flare on PPP.

A SITEC is produced by the atmospheric extra-ionization due to solar flare radiation emitted in X-ray and Extreme Ultra Violet (EUV). The solar radiation in EUV produces the F region electron density which is the main contributor to the TEC. Therefore a SITEC is largely produced by the ionospheric F region extra-ionization due to the EUV radiation emitted during a flare. A particular characteristic of SITECs is that they are not constricted in latitude and may affect the entire dayside ionosphere. The magnitude of the event depends to a large extent on the flare's location on the sun, the emitted radiation flux and the solar zenith angle (SZA, the angle between the zenith of the site and the line of sight of the Sun [Liou, 2002]). In particular, the ionospheric TEC increases linearly with the cosine of SZA [Wan et al., 2005; Le et al., 2013] and decreases as the distance of the flare from the solar central meridian increases due to the EUV flux absorption by the solar atmosphere [Liu et al., 2006; Qian et al., 2010; Le et al., 2013]. Furthermore, SITECs show seasonal-hemispheric asymmetry related to F region neutral species densities [Tsugawa et al., 2006; 2007].

The 28 October 2003 solar flare is a special event since the EUV radiation emission from near the center of the solar disc produced the increase in the subsolar ionospheric electron

content around 25 TECU in 5 min [Tsurutani et al., 2005]. In terms of ROT this has been the largest SITEC of solar cycle 23 [Liu et al., 2006] which also had an intense response in the dawn and dusk (sunlit) boundary regions [Zhang and Xiao, 2005]. This flare was accompanied by a solar radio burst (SRB) that caused interference to Global Positioning System (GPS) signal jeopardizing signal tracking performance, especially in the L2 frequency by many receivers in the sunlit hemisphere [Chen et al., 2005; Cerruti et al., 2006]. This SRB contained two periods, 11:02-11:12 UT and 11:42-12:00 UT that may have caused interference and signal fading to GPS signals. The first period coincided with the SITEC and previous studies [Chen et al., 2005] claim that SITEC played a secondary role in signal losses. In this work we explore this event's effects on PPP accuracy, and we find position accuracy degradation is attributed to the presence of the SITEC. We make it clear that even if the signal degradation due to the simultaneous effect of SITEC and SRB are behind the observed phenomena, the increase in PPP errors are in most cases a consequence of the data processing strategies.

In order to investigate the impact of the 28 October 2003 SITEC on PPP, position solutions are computed with two different free access tools: the online CSRS-PPP service [Mireault et al., 2008] and gLAB [Sanz et al., 2012]. Each software tackles the SITEC in a different way and therefore provides a different position solution. In this paper we present the influence of the mentioned event on kinematic dual frequency PPP results, and we note the shortcomings of the software when dealing with a phenomenon of this magnitude.

2. Data and observations

For our purpose GNSS data of permanent stations integrated in the International GNSS Service (IGS) are used. The receivers are located at low latitudes at different longitudes

and they have been chosen in order to cover different solar zenith angles, SZA (Table1) as a representative sample of the ionospheric response to the flare. The data correspond to GNSS dual frequency code and phase observations at 30 s sampling rate.

Table 1. IGS stations used in this study^a

ID	Lat. (°N)	Long. (°E)	SZA(°)
NKLG	0.35	9.67	13
ASC1	-7.95	345.59	25
MALI	-3.00	40.19	31
SEY1	-4.67	55.48	45
MAS1	27.76	344.37	48
AREQ	-16.47	288.31	78
BOGT	4.64	285.92	85

^aID, station identification code; Lat., geographic latitude; Long., geographic longitude ; SZA, rounded solar zenith angle estimated for the period of the 28 October 2003 SITEC.

2.1. Procedure used to derive the ionospheric information

A data pre-processing is performed for outliers and phase CS detection. The CSs are not repaired, but a new ambiguity is set up at the corresponding epoch. In the pre-processing, tropospheric delay, satellite and receiver antennas phase centre offsets and variations, phase wind-up and hardware delays are also corrected.

The ionospheric delay on a GNSS signal frequency is estimated by means of a technique based on least squares theory [De Lacy et al., 2005; 2008b] that is implemented in MAP3-1 algorithms [Moreno et al., 2014]. The elevation cut-off applied is 10°, which is the same value as the one used in PPP.

The slant TEC ($sTEC$) for each satellite receiver link is computed in units of TECUs (1 TECU = 10^{16} electrons/m²) by equation (1)

$$sTEC = \frac{J_i \cdot f_i^2}{\alpha \cdot 10^{16}} [TECU] \quad (1)$$

where J_i is the ionospheric delay at frequency f_i for $i = 1, 2$ that correspond to L1 and L2 GPS frequencies and $\alpha = 40.3m^3s^{-2}$. This mathematical expression is obtained by considering only the first two terms in the expansion of the refraction index of the ionosphere. To calculate the equivalent vertical TEC ($vTEC$) a mapping function is applied at the ionospheric pierce point (IPP) by assuming an ionospheric thin layer model [Schaer, 1997]. The expressions used are shown in equation (2) and equation (3)

$$vTEC = sTEC \cdot \cos z_{pp} \quad (2)$$

$$z_{pp} = \sin^{-1} \left(\frac{R}{R_E + H} \sin z \right) \quad (3)$$

where z_{pp} stands for the zenith angle in the IPP, R represents the geocentric distance to the station, R_E the Earth's radius, H the mean value of the height of the ionosphere (in this work 350 km), and z the satellite zenith angle at the observing site. To show how fast the $vTEC$ changes in time while the IPP travels following the satellite movement, the ROT (in units of TECU/30s) is computed arc by arc using the expression shown in equation (4). These ROT values allow us to assess the TEC possible impact on positioning.

$$ROT(t) = (vTEC(t + 30s) - vTEC(t)) \quad (4)$$

2.2. Position determination

The ionosphere-free combinations are the main observables used in dual frequency PPP. The unknowns to be solved in the data processing are the zenith tropospheric delay, the receiver clock error, the ambiguity parameters (integer ambiguity plus biases) and the

position of the receiver. If no signal disruption or CSs occur, the ambiguities keep constant in each data arc. However, they are estimated recursively, which implies a convergence time which can last several minutes (around 30 min) until its final float solution is reached and the final accuracy is achieved: centimeter level in static mode and decimeter level in kinematic [Bisnath and Gao, 2009]. Additionally, in post processing, a backward filtering can be applied which it smooths the PPP results into a more accurate value.

Geometry-Free (GF) and Melbourne-Wübbena (MW) combinations are usually used for outliers and CSs detection [Blewitt, 1990; Dach et al., 2007; de Lacy et al., 2008a]. In the GF combination the carrier phase measurement in the two signals (L1 and L2) are subtracted in order to remove the geometry and the non-dispersive effects of the signal. In general this combination varies smoothly with time, and allows computing the size of CSs easily. However, ionospheric effects and the multipath are not canceled in the combination, and therefore, the use of this combination is only recommended for unperturbed ionospheric conditions since high ionospheric activity conditions can degrade the performance of this detector. Furthermore, if the CSs occur simultaneously in both frequencies, they cannot individually be identified. On the other hand, the MW linear combination is formed as the difference between carrier phase's wide lane (WL) and code's narrow lane (NL) combinations. The MW combination cancels the non-dispersive effects and the ionospheric refraction, however, it does not allow determining which frequency contains the jump, and if the slips in the two frequencies are identical, no CS will be detected.

In this work two different tools have been used to process GNSS dual frequency observations along with IGS precise orbits and clocks [Dow et al., 2009] to get the kinematic PPP solution. Although the receivers are fixed, we assume that they are in

motion in order to analyze the changes in the accuracy epoch by epoch. In both cases an elevation mask of 10° is set.

First, kinematic positioning is carried out by means of the Natural Resources of Canada's free online CSRS-PPP service (Canadian Spatial Reference System Precise Point Positioning, [Mireault et al., 2008]). With this routine, PPP is performed with backward filtering, and NL and WL combinations based CS detection filters by default.

Second, the GNSS-LABoratory (gLAB) tool suite is used for PPP. This resource was developed by the research group of Astronomy and Geomatics from the Universitat Politècnica de Catalunya (gAGE/UPC) [Sanz et al., 2012]. In this PPP routine forward mode has been performed using the default GF and MW CS detection filters.

In the data processing of each software other differences exist in addition to the CS detection filters such as the tropospheric model used and the mapping function applied. The differences that may exist between these two tools will cause the disparities observed in PPP solutions. The positioning results are shown by means of the error in the total distance, denoted $3Derror$ and calculated by the expression given in equation (5)

$$3Derror = \sqrt{\Delta x^2 + \Delta y^2 + \Delta z^2} \quad (5)$$

where $\Delta x, \Delta y$ and Δz correspond to the differences between the estimated Cartesian coordinates and the IGS weekly solution (all referred to IGS05).

3. Testing PPP performance in the presence of the 28 October 2003 SITEC at low latitudes

On 28 October 2003, the TEC experienced a fast enhancement in the 11:00-11:10 UT interval in all stations of the sunlit hemisphere [Tsurutani et al., 2005]. However, in this work we only present the results obtained in seven low latitude stations that cover the effect of different SZA as a sample of what is broadly observed. Figure 1 presents ROT

values for all satellites in view in each of the selected stations from 10:30 to 12:30 UT. This event affects all these satellites simultaneously with nearly identical effects. Figure 2 shows the dependence of ROT with the SZA at 11:02:30 UT. ROT peak values depend on SZA and reach a maximum value of around 4 TECU/30s over the stations with the lowest SZAs. ROT large values observed in figure 1 are the ionospheric response to the increase in the EUV radiation flux due to the flare and the slope of the linear dependence of ROT with $\cos(SZA)$ at each epoch will depend, at least in part, on the impulsive increase of the solar radio flux. In figure 3 the 30s time rate of change of photon flux in EUV and X-rays is presented. Data were obtained by the Solar EUV Monitor (SEM) onboard SOHO (Solar and Heliospheric Observatory) in the 26-34 nm and 0.1-50 nm band passes. These results show that the TEC steps up suddenly every time the flux increases impulsively. The perturbation, characterized by large positive values of ROT , lasted from 11:01 to 11:10 UT, until the EUV flux radiation started to decrease smoothly, although the ionospheric “anomalous TEC” lasted for approximately 3h [Tsurutani et al., 2005].

Figure 1. *ROT* values for each station in the period 10:30-12:30 UT on 28 October 2003.

Each color represents a satellite pass. Receivers are ranged according to the SZA from

bottom (high) to top (low). Satellites above 10° of elevation are only shown.

Figure 2. *ROT* dependence with respect to the SZA in each IPP for each satellite in view

with elevation above 10° at each receiver on 28 October 2003 at 11:02:30 UT.

Figure 3. 30s rate of change of the photon flux measured with SOHO /SEM in the 26-34 nm band pass (gray) and in the 0.1-50 nm band pass (black) for the 10:30-12:30 UT interval on 28 October 2003. http://www.usc.edu/dept/space_science/semdatafolder/.

Figure 4. Number of GPS observables registered at each epoch by each station during 10:30-12:30 UT interval on 28 October 2003. In blue and magenta carrier phases (L1) and codes (P1) in 1.5 GHz respectively, in black and red the carrier phases (L2) and codes (P2) in 1.2 GHz respectively. Satellites above 10° of elevation are only considered.

Note that in figure 1 a discontinuity is observed in NKLG station in the interval coinciding with the SITEC. This gap is due to lack of code and phase observables at L2 (1.2 GHz) in many satellites (in some epochs all of them) in the 11:03:00-11:11:30 UT interval (see figure 4).

Figure 4 shows the number of observables (codes and carrier phases in L1 and L2) registered at each epoch in each receiver. Note that NKLG and ASC1 present the largest tracking problems coinciding with the same day SRB influence periods 11:02 – 11:12 UT and 11:42 -12:00 UT previously reported by Chen et al., [2005]. It is also worth noting

that contrary to NKLG, ASC1 also presented tracking problems in 1.5 GHz, and SEY1 also suffered from signal tracking problems, but only in the period related to the SITEC (i.e. 11:02-11:12 UT). The rest of the receivers do not present the mentioned tracking problems, although signal fading may have been present due to the SRB interference.

Figure 5 shows the $3Derror$ obtained from CSRS-PPP results in the 10:30-12:30 UT interval. The mean value of the $3Derror$ for that day is between 8 cm and 12 cm in all the receivers except for AREQ where 20 cm are reached. The accuracy observed may seem worse than the expected and there are many reasons for that, such as, the poor signal quality in some cases, solution convergence period or the SRB and post-sunset irregularities related phenomena. However the accuracy degradation reaches several meters in the epoch where ROT peaks are present (from 1m in AREQ up to 8m in SEY1).

In addition, NKLG and SEY1 results also show PPP accuracy degradation in the 11:40-12:00 UT interval, which is related to the signal tracking problem shown in figure 4 in the same period of time. Gaps in figures 5 and 6 are the result of no position determination when less than five satellites are available. The big errors present in the period coincident with the SITEC related ROT peak values are the consequence of simultaneous ambiguities reset (figure 6). The combined effect of the signal to noise ratio decrease due to the SRB and the SITEC related increase in observables noise seems to be the source of problems in the NL combination based filters that produced the mentioned ambiguities reset. It is worth mentioning that the signal fading due to the SRB in the 10:40-12:00 UT period, which is not coincident with the SITEC does not cause any positioning problem, except the ones in NKLG and ASC1 which are attributed to signal loss.

Figure 7 shows the number of satellites affected in each epoch by CSs or gaps related problems and NL and WL combination-based filters problems that produced ambiguities to be reset. This plot shows that NL combination related problems stand out with respect

to the other two (CS/gap or WL). However, the ambiguities reset present in NKLG, ASC1, MALI and SEY1 before the SITEC took place seem to be caused by problems with the NL filter performance.

Although the amplitude of the perturbations characterized by *ROT* large values depends on the *SZA*, the accuracy degradation in the same period does not, even if positioning errors coincide with the epochs of high *ROT*. Moreover note that BOGT, the station with the highest *SZA* in this study, is still affected by the SITEC; however, it does not show the accuracy degradation present in the rest. The magnitude of the positioning errors in case of several ambiguity resets in PPP, that is usually related to code noise/multipath errors, in this concrete case, they seems to be related to the increased noise/multipath errors due to a combined effect of the SITEC and the SRB.

Figure 5. The *3Derror* obtained with CSRS-PPP results for each station in the 10:30-12:30 UT interval on 28 October 2003. Receivers are ranged according to the solar zenith angle from bottom (high) to top (low).

Figure 6. Number of satellites with ambiguities reset (red square) and the total number of satellites used in CSRS-PPP at each epoch (black asterisk) for each station in the 10:30-12:30 UT interval on 28 October 2003.

Figure 7. Number of satellites with ambiguities resets due to CS or gap (blue circle), NL combination (black asterisk) and WL combination (red dot) problems for each station in the 10:30-12:30 UT interval on 28 October 2003.

Figure 8. The $3Derror$ determined with gLAB outputs at each station in the 11:00-11:30 UT interval: in black the results after having applied the GF combination and in red the results after having disabled the GF filter.

Due to the online character of CSRS-PPP service, it is not possible to change the parameters involved in the data processing. For that reason, we process the same GNSS data with gLAB because this PPP tool allow us choosing at least some parameters regarding, for example, the filters for cycle slip detection which enables to check what happens when CS detection filters are turned off. Figure 8 shows the $3Derror$ obtained with gLAB results in the 10:30-12:30 UT period. Black color represents the accuracy reached after performing the PPP forward, applying both the GF and the MW combinations to detect the CSs. The PPP performance in all the stations is characterized by a gap in the period where largest values of ROT are present followed by errors of the order of meters. NKLG and ASC1 results also show the problems related to the SRB signal loss in the 11:45-12:05 UT interval. The errors can reach up to 8 m in NKLG, or exceed 2 m in general to gradually decrease until they converge into a more accurate value due to the time needed for ambiguities to reach a steady state. Except for NKLG

the gaps present in black curves in the 11:00-11:15 UT interval are due to data discarding by the filters. The larger the period with high *ROT* the longer the gap is. BOGT, being the station with largest SZA registers the *ROT* smallest values and consequently the gap for the same period lasts less. To prove this statement in a second step no GF filter was applied. Red color represents the results obtained with gLAB with the GF CS detection filter turned off. In the period of the SITEC, no big errors are observed except for NKLG, where the receiver suffered from tracking problems of the code and carrier phase in L2. In this case, disabling the GF CS detection filter implies a better PPP performance in the 10:30-12:30 UT interval because no CSs are mis-detected in the period coinciding with the *ROT* largest values. The stations used in this work are located in low latitudes and most of them present post-sunset irregularities that produce errors enlargement in nighttime period due to the use of the GF CS detection filter. The accuracy degradation is largely produced by false CSs detection due to the large values in *ROT* that characterizes these irregularities. However, real CS may also be present due to scintillation phenomena associated to some of the irregularities present in the signals ray path.

The results obtained with the two tools used in this study show large differences that are related to the data processing methods. For example, one of the characteristics of CSRS-PPP is that backward processing has been performed by default, and therefore, results do not show the convergence time, but only the accuracy reached. Both techniques present difficulties to maintain the expected accuracy due to the SITEC event but in the case of gLAB only when the GF CS detection filter is turned on, since the default threshold values of the MW detection filter seem to be loose enough not to flag the periods with increased noise/multipath caused by the combined effect of the SRB and the SITEC.

4. Discussion and Conclusions

The impact of the 28 October 2003 SITEC on kinematic PPP accuracy has been investigated. The solar flare that hit the Earth's atmosphere that day produced the largest and fastest TEC increase ever recorded by GNSS. The SITEC reached values of around 4 TECU/30s near the subsolar point, and this value gradually decreased to around 1.5 TECU/30s in the sites of the sunlit hemisphere where the SZA was high. This event was accompanied by a SRB which caused interference in GPS signals in two periods: 11:02-11:12 UT and 11:42-12:00 UT. These results show that the large errors observed in PPP during the SITEC are not caused by signal tracking problems related CSs or complete signal loss that have been attributed to a SRB that took place the same day. We blame the SITEC phenomena and not the SRB since this last had a major impact on GPS signal fading in the 11:42-12:00UT interval, and nevertheless, no PPP errors were observed other than those related to signal loss. On the other hand, the SITEC contribution to the noise from the SRB impact in the 11:00-11:15 UT interval cannot be distinguished. The errors observed in this case study are the consequence of a combined effect of the SITEC and SRB influence on GNSS signals and the data processing strategies inside each PPP tool.

The degradation shown in CSRS-PPP results accuracies are well correlated in time with the peak values reached in *ROT*. However the errors observed are due to the simultaneous ambiguities reset induced by the NL combination based filter's problems to deal with the SITEC effect on observables. Except for BOGT (the station with the smallest *ROT* response) and NKLG (the station with the largest *ROT* response and with the most L2 observables losses), the ambiguity parameters are needlessly reset which makes accuracy to drop up to some meters in the epoch where the *ROT* reaches its largest values.

On the other hand, gLAB results show that when the GF CS detection filter is turned on, the large rate of change of this observable combination make the CSs to be flagged at those epochs and the corresponding observables to be rejected from the processing. PPP errors appear after a gap and the accuracy degradation of the order of few meters lasts until the solution converges between 10 and 20 min after the occurrence of the gap. This interruption in the results depends on the ionospheric response to the flare, i.e. the *ROT* value reached, during the SITEC, and the thresholds selected in the filters. These results show a significant accuracy improvement on forward kinematic PPP when the GF filters are turned off since no CS are flagged and therefore no data is discarded. The difficulties to track the L2 signal in the NKLK receiver caused the gap observed in the results. CSs are more prone to occur in the presence of low signal to noise ratio (SNR) especially under strong signal multipath or ionospheric scintillation conditions. Despite the GPS carrier-to-noise ratio fade caused by the same day solar radio bursts [Chen et al., 2005; Cerruti et al., 2006] it is clear that the SITEC disturbed the observables of some of the receivers in the sunlit hemisphere. The PPP accuracy degradation observed in the presence of this particular SITEC is caused by the procedure used for CSs detection. Obviously the GF combination based filters may erroneously detect CSs during the SITEC related carrier phase fast variations. In this concrete case, disabling the GF filters may help to avoid the problem. However the sudden increase in observables noise may also hinder the CS detection in detectors that use other kinds of observables linear combination (e.g., MW or NL combination-based filters), and deactivating completely the CS-s detection filters it is not a real solution since actual CSs may occur. Developing CS detectors that are capable to deal with low-latitudes data are a real challenge due to the presence of scintillation phenomena caused by postsunset irregularities. Even if reached values of ROT may be essentially the same, unlike the SITEC in the presence of

post-sunset irregularities the rapid fluctuations in TEC occur on a particular link and may be accompanied by signal scintillation related CSs. This makes it one of the most difficult situations to detect CSs reliably. To solve the CSs detection failures under disturbed ionospheric conditions, a variety of procedures have been proposed in recent years [Banville and Langley, 2013; Cai et al., 2013; Ji et al., 2013; Zhang et al., 2014], but we ignore if they are able to solve extreme and combined events like the one studied in this work which still can induce errors in PPP. It is noteworthy that in this paper we analyze data with 30s sampling rate and that considering higher rate (e.g.1s) would prevent the SITEC related problems in the CS detection.

In summary, SITECs are not ionospheric events like the low-latitude postsunset irregularities. They cause a simultaneous response in all the sunlit hemisphere and they depend on a specific and uncommon solar episode. Furthermore, they can also be accompanied by SRBs that may cause a simultaneous interference in GNSS signals received in stations that are located in the sunlit hemisphere. As exposed in this work, the SRB itself may produce signal tracking problems and when combined with the SITEC may hinder CS detection algorithms and become a punctual source of error in kinematic PPP.

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References

- Aarons, J. (1982), Global morphology of ionospheric scintillations, in *Proceedings of the IEEE*, 70(4), doi:10.1109/PROC.1982.12314.
- Banville, S., R. B. Langley, S. Saito, and T. Yoshihara (2010), Handling cycle slips in GPS data during ionospheric plasma bubble events, *Radio Sci.*, 45, RS6007, doi:10.1029/2010RS004415.
- Banville, S., and R.B. Langley (2013), Mitigating the impact of ionospheric cycle slips in GNSS observations, *J. Geodes.*, 87(2), 179-193, doi:10.1007/s00190-012-0604-1.
- Bisnath, S., and Y. Gao (2009), Current state of precise point positioning and future prospects and limitations, Observing our Changing Earth, in Proceedings of the 2007 IAG General Assembly, vol. 133, edited by M. G. Sideris, pp. 615-623, doi:10.1007/978-3-540-85426-5_71.
- Blewit, G. (1990), An automatic editing algorithm for GPS data, *Geophys. Res. Lett.*, 17(3), 199-202, doi:10.1029/GL017i003p00199.

452 Cai, C., Z. Liu, P. Xia, and W. Dai (2013), Cycle slip detection and repair for
 453 undifferenced GPS observations under high ionospheric activity, *GPS Solut.*, 17(2), 247-
 454 260, doi:10.1007/s10291-012-0275-7.

455 Carrano, C. S., K. M. Groves, W. J. McNeil, and P. H. Doherty (2013). Direct
 456 measurement of the residual in the ionosphere-free linear combination during
 457 scintillation.in Proceedings of the 2013 International Technical Meeting (ITM) of the
 458 Institute of Navigation, San Diego, CA.

459 Cerruti, A. P., P. M. Kintner, D. E. Gary, L. J. Lanzerotti, E. R. de Paula, and H. B. Vo
 460 (2006), Observed solar radio burst effects on GPS/Wide Area Augmentation System
 461 carrier-to-noise ratio, *Space Weather*, 4, S10006, doi:10.1029/2006SW000254.

462 Ciraolo, L., F. Azpilicueta, C. Brunini, A. Meza, and S. M. Radicella (2007), Calibration
 463 errors on experimental slant total electron content (TEC) determined with GPS, *J.*
 464 *Geodes.*, 81, 111-120, doi:10.1007/s00190-006-0093-1.

465 Chen, Z., Y. Gao, and Z. Liu (2005), Evaluation of solar radio bursts' effect on GPS
 466 receiver signal tracking within International GPS Service network, *Radio Sci.*, 40,
 467 RS3012, doi: 10.1029/2004RS003066.

468 Dach U, U. Hugentobler, R. Fridez, and P. Meindl (2007), Bernese GPS software version
 469 5.0, Astronomical Institute University of Bern.

470 De Lacy M. C., F. Sansó, A. J. Gil, and G. Rodríguez-Caderot (2005), A method for the
 471 ionospheric delay estimation and interpolation in a local GPS network, *Stud. Geophys.*
 472 *Geod.*, 49, 63-84, doi:10.1007/s11200-005-1626-4.

473 De Lacy, M. C., M. Reguzzoni, F. Sansó, and G. Venuti (2008a), The Bayesian detection
 474 of discontinuities in a polynomial regression and its application to the cycle-slip problem,
 475 *J. Geodes.*, 82(9), 527–542, doi:10.1007/s00190-007-0203-8.

476 De Lacy, M. C., A. J. Gil, G. Rodríguez-Caderot, and B. Moreno (2008b), A method to
 477 estimate the ionospheric bias by using the new GNSS frequencies: analysis of its
 478 theoretical accuracy in a PPP context, *Física de la Tierra*, 20, 133–150.

479 Dow, J. M., R. E. Neilan, and C. Rizos (2009), The International GNSS Service in a
 480 changing landscape of Global Navigation Satellite Systems, *J. Geod.*, 83,191–198,
 481 doi:10.1007/s00190-008-0300-3.

482 Hoque, M. M., and N. Jakowski (2007), Higher order ionospheric effects in precise GNSS
 483 positioning, *J. Geodes.*, 81, 259–268, doi: 10.1007/s00190-006-0106-0.

484 Jacobsen, K. S., and M. Dähnn (2014), Statistics of ionospheric disturbances and their
 485 correlation with GNSS positioning errors at high latitudes, *J. Space Weather Space Clim.*,
 486 4, A27, doi:10.1051/swsc/2014024.

487 Ji, S., W. Chen, D. Weng, Z. Wang, and X. Ding (2013), A study on cycle slip detection
 488 and correction in case of ionospheric scintillation, *Adv. Space Res.*, 51, 742-753,
 489 doi:10.1016/j.asr.2012.10.012.

490 Kouba, J., and P. Héroux (2001), Precise point positioning using IGS orbit and clock
 491 products, *GPS Solut.*, 5(2), 12-28, doi:10.1007/PL00012883.

492 Le, H., L. Liu, Y. Chen, and W. Wan (2013), Statistical analysis of ionospheric responses
 493 to solar flares in the solar cycle 23, *J. Geophys. Res. Space Physics*, 118, 576–582,
 494 doi:10.1029/2012JA017934.

495 Leonovich, L. A., A. T. Altynsev, E. L. Afraimovich, and V. V. Grechnev (2001),
 496 Ionospheric effects of the solar flares as deduced from global GPS network data. LANL
 497 e-print archive. [Available at <http://arXiv.org/abs/physics/011006>.]

498 Liou, K. N. (2002), An Introduction to Atmospheric Radiation. 2nd edition, International
 499 Geophysics Series, vol. 84, Academic Press, San Diego, California.

Liu, J. Y., C. H. Lin, Y. I. Chen, Y. C. Lin, T. W. Fang, C. H. Chen, Y. C. Chen, and J.
 J. Hwang (2006), Solar flare signatures of the ionospheric GPS total electron content, *J.*
Geophys. Res., 111, A05308, doi:10.1029/2005JA011306.
 Magdaleno, S., M. Herraiz, and S. M. Radicella (2011), Ionospheric Bubble Seeker: a
 Java application to detect and characterize ionospheric plasma depletion from GPS data,
IEEE Trans. Geosci. Rem. Sens., 50(5), 1719-1727, doi:10.1109/TGRS.2011.2168965.
 Mendillo, M., L. Bosheng, and J. Aarons (2000), The applications of GPS observations
 to equatorial aeronomy, *Radio Sci.*, 35(3), 885-904, doi:10.1029/1999RS002208.
 Mireault, Y., P. Ttreault, F. Lahaye, P. Heroux and J. Kouba (2008), Online precise point
 positioning, *GPS World*, September 2008, 59-64.
 Moreno, B., S. Radicella, M. C. de Lacy, M. Herraiz, and G. Rodrguez- Caderot (2011),
 On the effects of the ionospheric disturbances on precise point positioning at equatorial
 latitudes, *GPS Solut.*, 15, 381–390, doi:10.1007/s10291-010-0197-1.
 Moreno Monge B., G. Rodriguez-Caderot, and M. C. de Lacy (2014), Multifrequency
 algorithms for precise point positioning: MAP3, *GPS Solut.*, 18(3), 355–364,
 doi:10.1007/s10291-013-0335-7.
 Pi, X., A. J. Manucci, U. J. Lindqwister, and C. M. Ho (1997), Monitoring of global
 ionospheric irregularities using the worldwide GPS network, *Geophys. Res. Lett.*, 24(18),
 2283-2286, doi:10.1029/97GL02273.
 Pi, X., A. J. Manucci, B. Valant-Spaight, Y. Bar-Sever, L. J. Romans, S. Skone, L. Sparks,
 and G. M. Hall (2013), Observations of global and regional ionospheric irregularities and
 scintillation using GNSS tracking networks, paper presented at ION Pacific PNT
 Conference, Honolulu, Hawaii.

523 Qian, L., A. G. Burns, P. C. Chamberlin, and S. C. Solomon (2010), Flare location on the
524 solar disk: Modeling the thermosphere and ionosphere response, *J. Geophys. Res.*, 115,
525 A09311, doi:10.1029/2009JA015225.

526 Rodríguez-Bilbao, I., B. Moreno, G. Rodríguez-Caderot, M. Herraiz, and S. M. Radicella
527 (2015), Evaluation of precise point positioning accuracy under large total electron content
528 variations in equatorial latitudes, *Adv. Space Res.*, 55, 605-616,
529 doi:10.1016/j.asr.2014.11.004.

530 Sanz, J., A. Rovira-García, M. Hernandez, J. Juan, J. Ventura-Traveset, C. Lopez, and G.
531 Hein (2012), The ESA/UPC GNSS-Lab Tool (gLAB): An advanced educational and
532 professional package for GNSS data processing and analysis, 6th ESA Workshop on
533 Satellite Navigation Technologies Multi-GNSS Navigation Technologies, Proceedings
534 ISBN: 978-1-4673-2010-8. Noordwijk, the Netherlands, doi:
535 10.1109/NAVITEC.2012.6423100

536 Sardón E., and N. Zarraoa (1997), Estimation of total electron content using GPS data:
537 How stable are the differential satellite and receiver instrumental biases?, *Radio Sci.*,
538 32(5), 1899-1910, doi:10.1029/97RS01457.

539 Schaer, S. (1997), How to use CODE's Global Ionosphere Maps. Astronomical Institute,
540 Univ. of Bern.

541 Seeber, G. (2003), Satellite Geodesy, Walter de Gruyter, Berlin, New York.

542 Skone S., K. Knudsen, and M. de Jong (2001), Limitations in GPS receiver tracking
543 performance under ionospheric scintillation conditions, *Phys. Chem. Earth Pt.A-Solid*
544 *Earth Geod.*, 26(6-8), 613-621, doi:10.1016/S1464-1895(01)00110-7.

545 Tsugawa, T., T. Sadakane, J. Sato, Y. Otsuka, T. Ogawa, K. Shiokawa, and A. Saito
546 (2006), Summer-winter hemispheric asymmetry of sudden increase in ionospheric total

electron content induced by solar flares: A role of O/N₂ ratio, *J. Geophys. Res.*, 111, A11316, doi:10.1029/2006JA011951.

Tsugawa, T., S. R. Zhang, A. J. Coster, Y. Otsuka, J. Sato, A. Saito, Y. Zhang, and L. J. Paxton (2007), Summer-winter hemispheric asymmetry of the sudden increase in ionospheric total electron content and of the O/N₂ ratio: Solar activity dependence, *J. Geophys. Res.*, 112, A08301, doi:10.1029/2007JA012415.

Tsurutani B. T., D. L. Judge, F. L. Guarnieri, P. Gangopadhyay, A. R. Jones, J. Nuttall, G. A. Zambon, L. Didkovsky, A. J. Mannucci, B. Iijima, R. R. Meier, T. J. Immel, T. N. Woods, S. Prasad, L. Floyd, J. Huba, S. C. Solomon, P. Straus, and R. Viereck (2005), The October 28, 2003 extreme EUV solar flare and resultant extreme ionospheric effects: Comparison to other Halloween events and the Bastille Day event, *Geophys. Res. Lett.*, 32, LS03S09, doi:10.1029/2004GL021475.

Wan, W., L. Liu, H. Yuan, B. Ning, and S. Zhang (2005), The GPS measured SITEC caused by the very intense solar flare on July 14, 2000, *Adv. Space Res.*, 36, 2465–2469, doi:10.1016/j.asr.2004.01.027.

Wanninger, L. (1993), Ionospheric monitoring using IGS data, in *Proceedings of the 1993 IGS Workshop*, edited by G. Beutler and E. Brockmann, pp. 351–360, Astronomical Institute, Univ. of Berne, Berne, Switzerland.

Warnant R. (1998), Detection of irregularities in the total electron content using GPS measurements- application to a mid-latitude station, *Acta Geod. Geoph. Hung.*, 33(1), 121–128, doi:10.01007/BF03325529.

Zhang D. H. and Z. Xiao (2005), Study of ionospheric response to the 4B flare on 28 October 2003 using International GPS Service network data, *J. Geophys. Res.*, 110, A03307, doi:10.1029/2004JA010738.

571 Zhang, X., F. Guo, and P. Zhou (2014), Improved precise point positioning in the
572 presence of ionospheric scintillation, *GPS Solut.*, 18, 51–60, doi:10.1007/s10291-012-
573 0309-1.

574 Zumberge, J., M. Heflin, D. Jefferson, M. Watkins, and F. Webb (1997), Precise point
575 positioning for the efficient and robust analysis of GPS data from large networks. *J.*
576 *Geophys. Res.*, 102, B3, 5005–5017, doi:10.1029/96JB03860.