# DETECTION OF SOLAR FLARES BY PROCESSING GLOBAL POSITIONING SYSTEM DATA

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## Abstract

A solar flare detection system has been developed based on the Global Positioning System (GPS), that allows to analyze the ionospheric response to major solar flares with a high simultaneous temporal and spatial resolution. It can be used to look for solar flares backwards or in real time as well. The detector is very simple an and can run in real-time with a very low computational load. It is based on obtaining the variation of the vertical Total Electron Content (TEC) data with respect to the previous sidereal day and then, on performing a second order time difference to obtain the information of the instantaneous TEC changes.

As a first performance evaluation, the technique has been used to detect and analyze two specific flares, the X172 flare on $28^{th}$ October, 2003 and the X57 flare on $14^{th}$ July, 2005. For that purpose, the GPS data of the International GNSS Service (IGS) network with a sampling rate of 30 seconds has been used. The results obtained have been validated with the ones presented previously by different authors, and with the flare records included in the Geostationary Operational Environmental Satellite (GOES) database [2].

## 1 Introduction

Solar flares are huge violent events that are generated near sunspots on the Sun's surface. They are characterized by a sudden increase of the radiation emission in all electromagnetic ranges (mainly in X-rays and ultraviolet) and by an ejection of a great amount of charged particles.

On the one hand, the ejected particles usually take hours or even days to reach the Earth. They can produce geomagnetic storms and thus generate important problems such as satellite damages or interferences in communications. Consequently, the detection of solar flares before the arrival of particles can be really useful. On the other hand, once the radiation reaches the Earth (in about 8 minutes), it produces an overionization of the Ionosphere, which is translated in a sudden enhancement of the ionospheric Total Electron Content ([8]). As the ionization is mainly produced in the Ionosphere, a way to detect solar flares is by monitoring the TEC, present in this part of the atmosphere. And this can be done thanks to the Global Navigation Satellite Systems (GNSS), as for example GPS. Such constellation, of about 30 Medium Earth Orbit transmitters, allows to perform an accurate ionospheric sounding, thanks to the global network of hundreds of permanent dual-frequency recerivers worldwide distributed (International GNSS Service, see for instance [5]).

In this context, the goal of this work is to show a simple and accurate way of detecting solar flares with GPS, which is capable of working in real-time as well. In particular, it can be of interest to warn satellite navigation users about geomagnetic storms that can affect its positioning quality.

## 2 Description of the technique

In order to detect solar flares in a simple way, the following technique is proposed:

First of all, it is necessary to gather the dual-frequency GPS data of a set of stations distributed all over the world. Then, the carrier phase ionospheric combination $L_I$ and the code ionospheric combination $P_I$ (see Equation 1) are calculated for each GPS signal, i.e. for every satellite in view of each of those stations.

$$\begin{aligned} L_I &= L_1 - L_2 \\ P_I &= P_2 - P_1, \end{aligned} \tag{1}$$

After that, the slant TEC (i.e the TEC in the line of sight of the GPS ray path) can be derived from $L_I$ measurements (see Equation 2, in length units), taking into account that the ionospheric bias $B_I$ can be estimated using the computed $P_I$ (see [1] for details). In this context, it is remarkable that the code is much noisier than the carrier phase. As a consequence, working with $L_I$ measurements is much more precise, though the phase ambiguity has to be solved.

$$\begin{aligned} L_I &= STEC + B_I \\ P_I &= STEC + DCB, \end{aligned} \tag{2}$$

where $B_I$ is the phase ambiguity, which is constant within the same continuous carrier phase arch of data, and where $DCB$ is the Delay Code Bias, which is quite constant for each pair satellite-receiver.

From that point and in order to avoid the dependence on the GPS signals inclination, the slant TEC is tranformed into the vertical TEC or VTEC (i.e. in the radial direction regarding to the Earth geocenter) throughout the so-called *mapping function* coefficient. This ionospheric parameter will be useful to monitorize ionization fluctuations, and so, the sudden ionization enhancement expected during solar flares. For that purpose, the mapping function has been applied assuming that the Ionosphere can be modelled as a thin single layer at 450 km height (it is not necessary to use more accurate techniques such as tomographic modelling, see [3]) and we have considered as well an elevation mask of 30 degrees to minimize mapping errors.

In addition, a temporal difference with respect to the previous sidereal day (i.e. substracting the same value but approximately 86160 seconds before current epoch) has been applied in this work. As the line-of-sight geometry is quite similar after this period, many common errors, such as multipath, are significantly mitigated (see [4] for further details). This allows to reduce considerably the ionospheric diurnal and seasonal periodic effects, but not ionospheric unexpected variations such as solar flares. Therefore, the temporal sidereal difference of VTEC (from now on, referred to as $\delta V$) will be obtained by rewriting Equation 2 as follows:

$$\begin{aligned} \delta L_I &= M \cdot \delta V + \delta B_I \\ \delta P_I &= M \cdot \delta V, \end{aligned} \tag{3}$$

where $\delta$ indicates temporal sidereal difference and where it is assumed that $\delta DCB \simeq 0$ due to its repeatability between consecutive days (considering similar equipment conditions). In addition, $M$ is the *mapping function* coefficient.

Furthermore, first and second order time differences of $\delta V$ can be applied between samples separated by a short period of time (in our case, 360 seconds or 12 samples). These differences are computed continuously every 30 seconds, which is the measurement sampling. Due to that, we can focus on high frequency TEC variations (similarly as with the rate of TEC change or rTEC in [7]). In this context, $d\delta V$ and $d^2\delta V$ can be obtained by using Equation 4.

$$\begin{aligned} \delta V(t) &= V(t) - V(t-86160) \\ d\delta V(t) &= \delta V(t) - \delta V(t-360) \\ d^2\delta V(t) &= d\delta V(t) - d\delta V(t-360), \end{aligned} \tag{4}$$

where $t$ is the time expressed in seconds.

Finally, an analysis of the $d^2\delta V$ amplitude values is performed in order to detect solar flares pointing to the Earth. This analysis has been done in two different ways and therefore, two different types of detector have been developed.

In both cases, it is necessary to establish conditions of separability to discard other high frequency TEC variations, as for example the Travelling Ionospheric Disturbances (TIDs) or the Scintillations. Beyond the different spectral characteristics, this can be achieved by taking into account that the solar radiation can only affect the Earth's sunlit Ionosphere and that the other main phenomena to be discarded typically affect it in a more local context.

The first of those detection possibilities is based on searching for the typical overionization pattern (in $d^2\delta V$, an increase is followed by a symmetrical decrease in terms of amplitude, as shown for instance in Figure 1). For that reason and from now on, this solar flare detector will be referred to as TYPical Overionization DETector or abbreviated as TYPODET.

Then, in order to separate the solar radiation overionization from other important ionospheric variations, the following conditions are mandatory to avoid false detections:

1. Focusing on GPS stations in the sunlit region: The overionization should be detected after processing GPS signals of at least $N$ sunlit receivers.

2. Focusing on each of these GPS stations: At least $M$ satellite signals must have a simultaneous TEC increase and with similar amplitudes.

The results presented in this work have been obtained considering a minimum number of five receivers for the first condition, and of three satellite signals for the second one.

Furthermore, the implementation of TYPODET is based on checking sample by sample if $d^2\delta V$ data are above, below or in-between two thresholds of detection (one positive and one negative but with the same absolute amplitude). The transitions between those bands of amplitude must satisfy the above mentioned conditions as well as the expected ionization enhancement shape in $d^2\delta V$ (see [1] for details). In this context, the thresholds of detectability have both been set to 0.2 TEC units or TECUs [1], but with opposite sign.

Also, the detection can also be based on a more general criteria. In this case, only the positive TEC increase in $d^2\delta V$ is searched and the solar zenith angle (*sza*) between the Sun and the Ionospheric Pierce Point (IPP) location becomes of great importance. In this case, we are more interested in enhancing the sensibility of the detector than in searching the typical overionization pattern or its amplitude values. In this case, the detector will be referred to as POsitive INcrease DETector or abbreviated as POINDET.

For the implementation of POINDET, it is necessary to know the number of satellites that detect a $d^2\delta V$ increase above the threshold of detectability (0.2 TECUs, in this work) with respect to the total number of satellites. This proportion (also referred to as *impact coefficient*) is calculated epoch by epoch for three different *sza* bands. For each of them, the *impact coefficient* should be above or below a certain percentage according to the following table.

1. Case $sza \leq THRES1$: *Impact coefficient* $\geq P1\%$

2. Case $THRES1 < sza < THRES2$: *Impact coefficient* $\geq P2\%$

3. Case $sza \geq THRES2$: *Impact coefficient* $\leq P3\%$

In this work, the *sza* thresholds *THRES1* and *THRES2* have been fixed to 40 and 110 degrees (in this case, night conditions), respectively. Regarding *impact coefficients*, percentage *P1* has been initially set to 70% and both *P2* and *P3* to 40%[2].

[1] One TECU is equivalent to $10^{16} el/m^2$.
[2] These percentages are conservative to avoid any false detections.

Additionally, these conditions must be fulfilled during several consecutive epochs to consider that a solar flare has occurred. Appart from that and to declare the results statistically significant, the *impact coefficient* is only calculated when there are more than a minimum number of available satellite observations: three in the first *sza* band, five in the second one and, finally, ten in the third one. In this context, it is important to mention that most of the satellites will have a *sza* greater than 40 degrees. Besides that, it can be noticed that the IPP location is still irradiated by the Sun when the *sza* is above 90 degrees[3].

It must be taken into account that there will be a time difference between POINDET time of detection and GOES time of maximum peak of intensity mainly due to the temporal resolution of the method (see, for instance Figure 1).

It is also remarkable that due to the sidereal day difference applied to GPS data, all ionospheric TEC variations of each day are present after 86160 seconds and therefore, solar flares would be detected twice. However, this can be easily avoided in both detection approaches because the overionization pattern of a solar flare in $d^2\delta V$ is reversed after one sidereal day.

## 3 Computations and results

The results have been obtained using GPS data, with measurement sampling of 30 seconds, of a set of IGS stations distributed regularly over the entire Earth surface, considering that only one station is selected for each cell of 20 degrees per 15 degrees, in longitude and latitude range respectively. This is important in order to be able to detect flares that reach the Earth whenever they happen.

In order to check the technique capabilities using both TYPODET and POINDET detection approaches, two specific days preceding large geomagnetic storms have been analyzed: $28^{th}$ October, 2003 and $14^{th}$ July, 2000.

### *3.1 $28^{th}$ October, 2003*

On $28^{th}$ October, 2003 occurred one of the most powerful flares of the last decade that was classified in terms of irradiance as an X172 flare ([2]). This solar flare has been analyzed in detail by the authors of this work in [1] but also by many other authors, such as [6, 9].

Amplitudes $\delta V$ and $d^2\delta V$ for GPS satellites in sight[4] are plotted in function of UTC time for *asc1* (14W 8S) and *cro1* (65W 18N) IGS receivers in Figure 1. In it, an abrupt overionization can be observed between 11.00h and 11.17h approximately (i.e. 11h00 and 11h10, respectively).

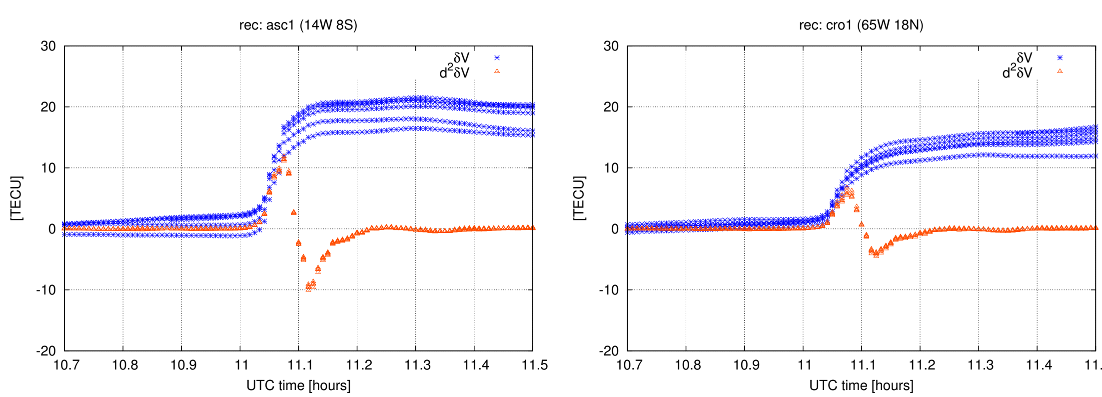


Figure 1: Amplitudes in $\delta V$ and $d^2\delta V$ as function of time obtained from the GPS signals gathered by the IGS receivers *asc1* and *cro1* on $28^{th}$ October, 2003, considering a masking elevation angle of 30 degrees.

When TYPODET was applied, signals from 33 GPS stations (out of more than 90) detected a sudden

[3]As explained before, the Ionosphere is assumed to be a thin single layer model and so the IPPs are located at 450 km above the Earth's surface.

[4]Notice that some plots are superimposed, specially in the case of $d^2\delta V$.

overionization beginning at approximately 11h00m. This overionization, as a $\delta V$ amplitude, was calculated for each pair satellite-receiver for those 33 GPS stations and has been plotted in function of the solar zenith angle (*sza*) from the Ionospheric Pierce Point (IPP) in Figure 2.

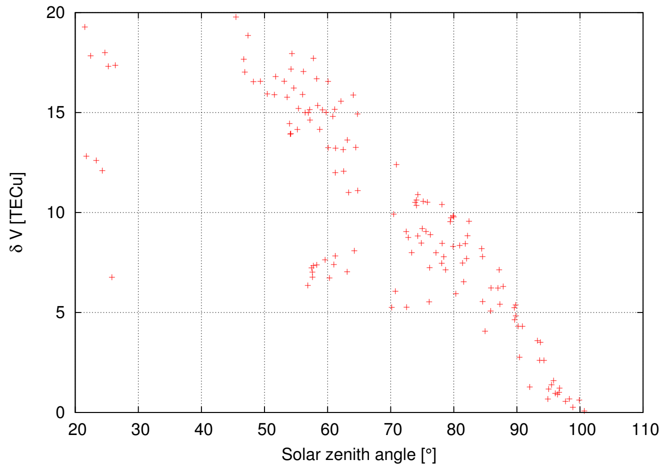


Figure 2: Ionospheric $\delta V$ response in function of the *solar zenith angle* between the Sun and the Ionospheric Pierce Point for each pair satellite-receiver for the X172 solar flare on $28^{th}$ October, 2003.

In Figure 2, the calculated peak of intensity in $\delta V$ reaches almost 20 TECUs near the maximum *sza*. In addition, it can also be seen that the *sza* ranges from 20 to 100 degrees approximately. Therefore, those 33 GPS stations are distributed all over the sunlit region as expected (see section 2).

On the other hand, POINDET has been applied. Its main results for that day have been represented in Figure 3, where the *impact coefficients* for the three distinguished *sza* bands (see section 2) have been plotted for the whole day and for an enlarged view of the period between 10.6h and 11.6h UTC time.

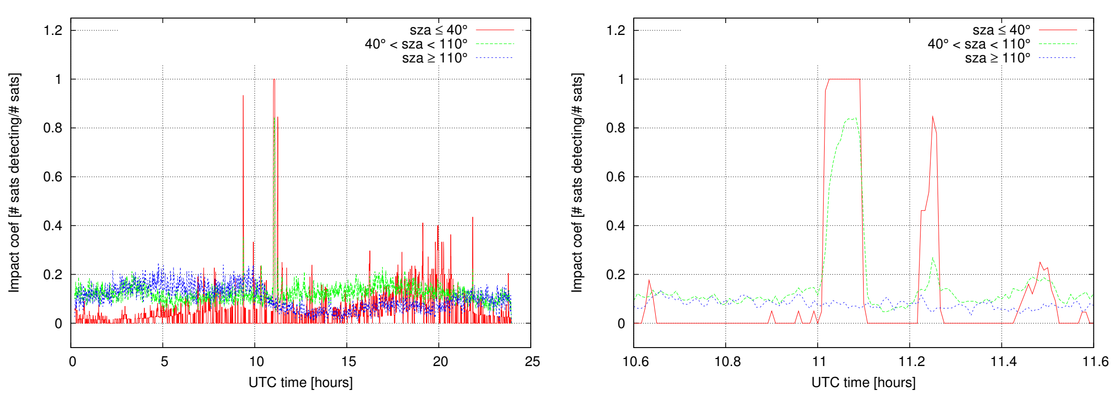


Figure 3: *Impact coefficients* for three different *sza* bands in function of UTC time for the whole day (left hand panel) and focusing on the X172 solar flare (right hand panel) on $28^{th}$ October, 2003.

From the results presented in the left hand panel of Figure 3, the conditions to be fulfilled when applying POINDET, which were also mentioned in the previous section, are satisfied at around 11.08h (i.e. 11h05m) and 11.25h (i.e. 11h15m), and almost satisfied at approximately 9.37h (i.e. 9h22m). Therefore, the detector identifies two possible flares and almost another one.

In order to verify that those results correspond to solar flares, the GOES records ([2]) on that day have been checked and written below in Table 1.

The possible flare detected at 11h05m using POINDET agrees with the last event recorded by GOES on $28^{th}$ October, 2003 (see last row of Table 1). So this flare, classified as an X172 flare, is real and had its

| Start time | End time | Max time | Solar disc location | class |
|---|---|---|---|---|
| 00h41m | 00h48m | 00h45m | N08E08 | C 53 |
| 01h27m | 01h45m | 01h33m | S19E15 | C 75 |
| 05h07m | 05h14m | 05h11m | N06W53 | C 77 |
| 08h35m | 08h44m | 08h39m | | C 87 |
| 09h51m | 11h24m | 11h10m | S16E08 | X172 |

Table 1: Solar flares recorded by GOES on $28^{th}$ October, 2003.

peak of intensity at 11h10m (third column of the previous table)[5]. As for the possible flare which was detected at 11h15m, using POINDET as well, is still below the end time of the X172 flare recorded by GOES (see second column of the X172 flare of Table 1), though it is not distinguished. This lowerer $\delta V$ overionization is slightly visible in Figure 1 after the main enhancement, both in $\delta V$ and $d^2\delta V$ plots for GPS receivers *asc1* and *cro1*.

Finally, in Table 1 it does not appear any flare at around 9h22m. That is because POINDET has detected it due to applying the sidereal day difference to the processed GPS data (see section 2). In fact, this flare is classified by GOES as an M37 and had its peak of intensity at 9h27m[6] on $27^{th}$ October, 2003 ([2]). This effect can be easily filtered out and implemented in a future operative version of this system.

### *3.2 $14^{th}$ July, 2000*

On this day, another strong solar storm occurred near the center of the solar disc, which produced the so-called "La Bastille" geomagnetic storm. In this case, the related solar flare has been classified as an X57 flare with its peak of intensity at 10h24m UTC time, according to GOES results.

This flare is specially interesting because its overionization pattern is not the typical one. As it can be appreciated in Figure 4, where $\delta V$ and $d^2\delta V$ are plotted with respect to time for stations *ammn* and *chum*, the results are quite different from the ones obtained for the X172 flare on $28^{th}$ October, 2003 (see 3.1). In fact and staring at $\delta V$ plot, there are two consecutive sudden enhancements while TEC is increasing instead of one (see also [10]). Therefore, two positive peaks appear in $d^2\delta V$.

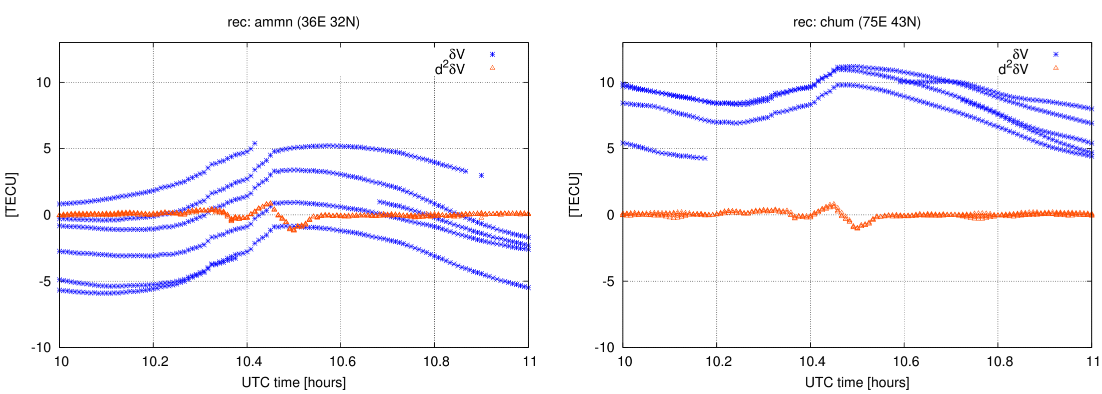


Figure 4: Amplitudes in $\delta V$ and $d^2\delta V$ as function of UTC time obtained from the GPS signals gathered by the IGS receivers *ammn* and *chum* on $14^{th}$ July, 2000, considering a masking elevation angle of 30 degrees.

When applying TYPODET, those two positive peaks in $d^2\delta V$ cannot be detected properly. That is because the shape of both TEC enhancements in $d^2\delta V$ is not symmetrical for almost all the receivers. Nevertheless and from POINDET results, both positive increases are perfectly visible at 10.30h and 10.45h (or at 10h18m and 10h27m) UTC time, when plotting the *impact coefficients* as function of UTC time (Figure 5). Consequently and as conditions assumed in this detection approach are satisfied, both peaks are correctly

[5] As mentioned in section 2, the POINDET time of detection is slightly different from the GOES time of maximum peak of intensity mainly because of the temporal resolution of the method.

[6] Notice that the detection time should also be affected by the difference between 24 hours and the duration of a sidereal day.

distinguished and detected.

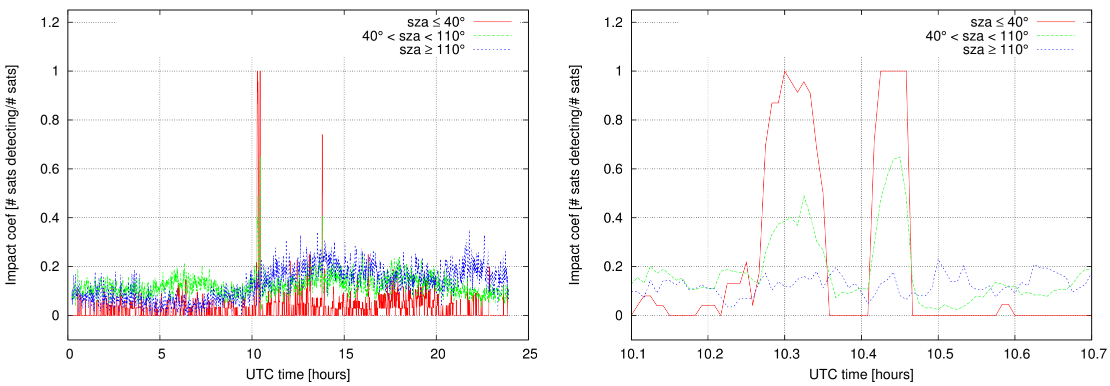


Figure 5: *Impact coefficients* for three different *sza* bands in function of UTC time for the whole day (left hand panel) and focusing on the X57 solar flare (right hand panel) on $14^{th}$ July, 2000.

As shown in the left hand panel of Figure 5, another possible solar flare has been detected at about 13.84h (13h48m) UTC time. However, it does not fulfill the POINDET detection conditions.

In order to verify these results, we can look up the GOES database records. The flare records on $14^{th}$ July, 2000 are included in the following table:

| Start time | End time | Max time | Solar disc location | class |
|---|---|---|---|---|
| 00h20m | 00h26m | 00h23m | | C 49 |
| 00h39m | 00h50m | 00h45m | | M 15 |
| 02h14m | 02h20m | 02h17m | | C 61 |
| 06h52m | 07h05m | 06h57m | | C 71 |
| 09h51m | 09h59m | 09h55m | | C 59 |
| 10h03m | 10h43m | 10h24m | N22W07 | X 57 |
| 13h44m | 14h00m | 13h52m | N20W08 | M 37 |

Table 2: Solar flares recorded by GOES on $14^{th}$ July, 2000.

Comparing GOES results with the ones obtained in this work, it is clear that the flares detected at 10h18m and 10h27m by POINDET are real (see sixth row in Table 2). However, GOES records do not distinguish between both consecutive TEC enhancements and are considered as an X57 flare in terms of amplitude with its peak of intensity at 10h24m.

As for the possible flare that can be seen at about 13h48m in Figure 5, it corresponds to an M37 flare that had its maximum peak at 13h52m (see third column of the last row in Table 2). Therefore, it seems feasible to detect lowerer flares without penalyzing the integrity of the results. However, further studies should be carried confirm this point.

## 4 Conclusions

In this work, the first tests of the detector POINDET have been presented. The analyzed days have been $28^{th}$ October, 2003 and $14^{th}$ July, 2000 because both of them were previously used to test the other detection approach, the so-called TYPODET ([1]). The results have also been validated with external sources of information, such as the GOES X-ray events database ([2]).

First of all, the results of both detection approaches, which can be applied in real-time, agree with the ones presented in recent papers and GOES records, and that POINDET is more sensitive to detect less powerful flares, such as the M37 that occurred on the second of those analyzed days. Moreover, this detection approach is more suitable to detect non typical overionization patterns, such as the X57 class flare on the same day. On the contrary, it is not appropiate to determinate the amplitude enhancement, as TYPODET does. Therefore, the current version of POINDET does not inform about the magnitude of the practical consequences that can arise after the arrival of the flare's charged particles.

In conclusion, the POINDET is able to detect solar flares facing the Earth but it should be combined with amplitude determination procedures to become still more effective to prevent problems.

As for the following steps, a larger test will be performed by using several consecutive days. Then, it will be possible to fix better all the parameters of the POINDET detection conditions in order to detect less intense flares pointing to the Earth. Therefore, further reduction of false detections could be expected, being this an important point in a future real-time operative system with improved sensitivity.

**References**


[1] García-Rigo, A., Hernández-Pajares, M., Juan J.M., et al. Solar flare detection system based on global positioning system data: First results. Adv. Space Res., IRI05-35 (in press).

[2] Coffey, H. Compilation of GOES X-ray events. NOAA Space Environment Center. <ftp://ftp.ngdc.noaa.gov/STP/SOLAR_DATA/SOLAR_FLARES/XRAY_FLARES/>, 7 Dec. 2006.

[3] Hernández-Pajares, M., Juan J.M., Sanz, J., et al., 2002. Improving the real time ionospheric determination from GPS sites at very long distances over the equator. J. Geophys. Res., 107(A10), 1296, doi:10.1029/2001JA009203.

[4] Hernández-Pajares, M., Juan J.M., Sanz, J., 1997. High resolution TEC monitoring method using permanent ground GPS receivers. Geophys. Res. Lett., 24(13).

[5] International GNSS Service (IGS). IGS Central Bureau Information System (CBIS). <http://igscb.jpl.nasa.gov/>, 19 Dec., 2006.

[6] Krankowski, A., Shagimuratov, I.I., Baran, L.W., 2003. Response of the Ionosphere to the great solar flare on October 28, 2003. Poster in: European Geosciences Union, General Assembly.

[7] Liu, J. Y., Tsai, C.H.F., Liou, Y.A., 2004. Ionospheric solar flare effects monitored by the ground based GPS receivers: Theory and observation. J. Geophys. Res., 109(A01307), doi:10.1029/2003JA009931.

[8] Mendillo et al., 1974. Behavior of the ionospheric F region during the great solar flare of August 7, 1972. J. Geophys. Res., 79, 665-672.

[9] Zhang, D.H., Xiao, Z., 2005. Study of the 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.

[10] Zhang, D. H., Xiao, Z., Igarashi, K. et al. , 2002. GPS derived ionospheric total electron content response to a solar flare that occurred on 14 July, 2000. Radio Sci., 37(5), 1086, doi:10.1029/2001RS002542.