The non-usual ionospheric impact and GNSS monitoring of solar flares

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Abstract
The Ionosphere, the partially ionized atmospheric region between about 60 to +1000 km height, is typically affected by spatial and temporal variations, driven by Local Time (solar illumination), Latitude (magnetic field and solar illumination) and time (space weather, among seasonal and solar cycle dependence). And it can be studied by assuming the first order ionospheric delay approximation from the dual L-band frequency GNSS measurements. Nevertheless the Ionosphere can be affected as well by other effects which are not so evident, such as ionospheric waves, higher order ionospheric effects and solar flares. We are going to summarize recent modelling and results associated to the daylight sudden overionization generated by the radiation associated to Solar Flares facing the Earth and its measurement by means of Global Navigation Satellite Systems. This approach has been already implemented in real-time by the authors.

Key words: Ionosphere, Global Navigation Satellite Systems, Solar Flares

Introduction

The Ionosphere can be considered as the region of the Earth atmosphere typically ranging from 50-70 km up to +1000 km, where there is a significant presence of ionized molecules, and free electrons, high enough to affect space-based and ground-based radiofrequency signals, such as those of the Global Navigation Satellite Systems, GNSS (see for instance in Hernández-Pajares et al. 2011 a review describing the main ionospheric effects on GNSS).

The most part of free electrons are generated by the continuous, slowly varying EUV solar radiation flux, which is the most geoeffective and responsible, in particular, of the ionization (and heating) of predominant F, and E regions (see Kelley 2009). From time to time, there are some free electrons quickly generated by the effect of the sudden increase of EUV solar radiation flux during solar flares, which can be used to issue solar flare warnings (see for example García-Rigo et al. 2007), and to indirectly quantify the fast EUV solar radiation flux variation.

Thanks to dual-frequency GNSS measurements at L-band (about 1.6 GHz and 1.2 GHz for GPS for the American GNSS) such electron content can be monitored with an unprecedented temporal and spatial resolution, with tens of MEO transmitters and hundreds of permanent ground receivers involved. The underlying assumption is to approximate the total ionospheric delay of GNSS signals by its first order approximation, being directly proportional to the integrated electron density along the ray path (Slant Total Electron Content, STEC) and inversely proportional to the squared frequency. In spite of this simplification, it becomes an excellent approximation, because such assumption is typically accurate at the level of more
than 99.9%, where the remaining 0.1% approx. is due to the contribution of higher order terms, which impede ultra-precise GNSS applications requiring sub-centimeter error level (such as subsidence monitoring, among other applications of GNSS precise coordinates time series –see King et al. 2011–). Details are provided in a very recent exhaustive study of higher order ionospheric terms by the authors of this manuscript (Hernández-Pajares et al. 2014).

Other non-usual effects on the ionospheric delay, which have been recently characterized at different latitude regions and solar cycle conditions (see Hernández-Pajares et al. 2012b), are the most frequent ionospheric waves: The Medium Scale Travelling Ionospheric Disturbances (MSTIDs), which follow a climatological pattern, and can significantly degrade GNSS precise positioning services like the Real Time Kinematics (RTK) or Wide Area RTK (see Hernández-Pajares et al. 2000, 2006).

In this paper, it will be briefly summarized, how to go beyond one of such typical main scenarios, the generation of the ionospheric free electrons caused by the continuous and slowly varying EUV solar radiation flux. It will be shown how GNSS can provide a useful and accurate way of monitoring solar flares and EUV flux rate by detecting and measuring with GNSS the spatial pattern of the sudden ionospheric overionization, associated to the corresponding prompt EUV solar flux increase (summarizing the method and results obtained in Hernández-Pajares et al. 2012). Such approach has been already implemented by the authors in real-time in the context of MONITOR project (Prieto-Cerdeira & Béniguel 2011), and thanks to the availability of measurements of the International Real-Time GNSS Service (Caissy et al. 2012).

1. Simple model of solar flare sudden ionospheric overionization and GNSS measurement

Due to the short time scale of the impulsive phase of the solar flares, the associated ionospheric overionization can be approximated by the following simple electron production expression, by neglecting transport terms (see, for example, Hernández-Pajares et al. 2012 and associated references):

\[
\frac{\partial V}{\partial t} = \eta' C(\chi') \cdot \Delta I(t) \tag{1}
\]

Where \( V \) represents the vertically integrated ionospheric free electron density (known as Vertical Total Electron Content, Vertical TEC or VTEC), \( \eta' \) stands for the ionization efficiency, \( C(\chi) \) represents the cross section for a solar-zenithal angle \( \chi \), referred to the value \( C(0) \) at the sub-solar point, and \( \Delta I(t) \) is the sudden solar flux increase at the EUV geoeffective band, at time \( t \).

It is going to be shown that such approximation works surprisingly well when it is applied with a simple deprojection factor, \( \cos \chi \), estimating the slope \( a(t) \) (which should be proportional to \( \Delta I(t) \) and the independent term \( b(t) \). This last term takes into account the geometric consequences of the fact that the overionization occurs at few hundreds of kilometers height (and not at the surface).

\[
\frac{\partial V}{\partial t} = a(t) \cos \chi + b(t) \tag{2}
\]

To do that, GNSS like the American Global Positioning System (GPS), offer a unique temporal and spatial resolution and performance to monitor the ionospheric delay. Indeed, taking as basic measurement the difference of dual-frequency L-band carrier phase signals, \( \text{L1-L2 = LI} \) (which removes any non-frequency dependent terms), a very precise measurement of the STEC is directly obtained, typically better than 0.1 TECU=10^{15} electrons/m^2, but affected by an ambiguity term that is constant while the GNSS transmitter signal is being locked by the receiver (see more details in Hernández-Pajares et al. 2011). Thousands of simultaneous STEC measurements are provided each 30 seconds by the hundreds of permanent receivers of networks such as the International GNSS Service (IGS,
see for instance Hernández-Pájares et al. 2009) from the GPS satellites in view (typically 5 to 10). In this way, the VTEC rate values needed to solve at each epoch the slope, a(t), and independent term, b(t), of the previous overionization model, can be easily deduced from the consecutive variation ΔLi in Δt, the deprojection factor from STEC to VTEC (mapping function M), and α=1.05 meters/10 TECU:

$$\frac{\partial V}{\partial t} \approx \frac{\Delta V}{\Delta t} = \frac{1}{M} \frac{\Delta S}{\Delta t} = \frac{1}{\alpha M} \frac{\Delta L_i}{\Delta t}$$ (3)

2. Results

The excellent typical behavior of this overionization model can be seen in Fig.1, where the dependence of VTEC rate, \(\partial V/\partial t\), against the cosinus of the solar-zenith angle, \(\cos \chi\), behaves linearly at the daylight hemisphere, as deduced in previous section.

![Fig. 1. VTEC rate vs. cosinus of solar-zenith angle, during the second 39777 in GPS time scale, of day 301 of 2003, in the impulsive phase of the X-class solar flare producing the Halloween storm Space Weather event.](image1)

![Fig. 2. VTEC rate vs. cosinus of solar-zenith angle, during the second 39777 in GPS time scale, of day 301 of 2003, in the impulsive phase of the X-class solar flare producing the Halloween storm Space Weather event.](image2)
And it can be also appreciated in Fig. 2 the linear relationship of the slope, a(t) (called GNSS Solar Flare Indicator, GSFLAI, and obtained from global GPS measurements looking at the ionospheric overionization spatial pattern), with the EUV solar flux rate, ΔI (directly measured in the EUV band from solar observing satellites), predicted by combining Eq. (1) and (2). The correlation is remarkable, in spite of the different time resolution and completely different observation instrument and environment.

Finally such good relationship has been checked, for almost a Solar Cycle, at the limit of the measurement errors of both compared techniques: the new GNSS-based one, with the direct observation from the Space. This can be clearly seen in Fig.3.

3. Conclusions

The influence of solar flares in the GNSS measurements have been modelled in such a way that a proxy of the solar EUV rate is obtained (GSFLAI), which compares fairly well with direct measurements from solar observation missions on space (such as the SOHO-SEM instrument). Such new solar EUV rate proxy, computed from existing global GNSS networks working in real-time, presents some advantages regarding to solar observing missions, such as its higher rate and especially its immunity to the relativistic electrons, which interrupt and impede the normal recording of solar flux by the spacecraft related instrumentation (see more details in Hernández-Pajares et al. 2012).

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References


