

Detection of solar flare using IGS network stations: case study for September 6, 2017

ABSTRACT

This research shows the viability of using GNSS (Global Navigation Satellite System) stations from IGS (International GNSS Service) network in the detection of solar flare. For this it was considered a flare of class X9.3 occurred on September 6, 2017 as a case study. If the flare is in the direction of Earth, a series of events in the ionosphere may occur, which are called Sudden Ionospheric Disturbances (SID). Among the SID there is the Sudden Increases in the Total Electron Content (SITEC). This immediate variability of the TEC can be estimated from the ROTI index. Since the electromagnetic radiation takes about eight minutes to reach the Earth, the ROTI is presented as a great solar flare detector. In this sense, ROTI was estimated for several IGS stations. It was verified that there was an increase in ROTI in the period of the solar flare and in the equatorial region of the Sun-oriented Earth. Detection of an Earth-directed solar flare is of great interest for the GNSS positioning and Space Weather, since, probably after a flare, there will be geomagnetic and ionospheric storms within few days (as occurred on 7 and 8 September), which will deteriorate the positioning accuracy.

KEYWORDS: ROTI Index. GNSS. Ionospheric Irregularities. Solar Flare.

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INTRODUCTION

The error due to the ionosphere in the GNSS (Global Navigation Satellite System) observables (pseudorange and carrier phase) is proportional to the Total Electron Content (TEC) presented in the signal trajectory between the satellite and the terrestrial station, and inversely proportional to the square of the signal frequency (SEEBER, 2003). TEC varies in time and space with respect to the variation of the solar radiation and of the terrestrial geomagnetic field.

In addition, the TEC is subject to significant changes due to the occurrence of solar events, such as solar flares and Solar Radio Bursts (SRB). During solar flares, one of the earliest phenomena that occur is the increase in the electromagnetic solar radiation in the length range of X-ray and EUV (Extreme Ultraviolet). In the scenario of the solar flare being directed to the Earth, a series of phenomena can occur in the ionospheric layer, which are called Sudden Ionospheric Disturbances (SID) (DAVIES, 1990). Among the existing SID there is the Sudden Increases in TEC (SITEC). Examples of effects of SITEC on GNSS positioning can be found, for example, in: Pereira and Camargo (2017), Carrano, Bridgwood and Groves (2009), Matsuoka, Camargo and Batista (2006), and Afraimovich et al. (2001).

TEC sudden increasing generates a process of irregularities in the density of electrons, which can be quantified through the Rate of Change of TEC (ROT). Among the several indexes that can be estimated from the ROT, the ROTI (PI et al., 1997) stands out because it presents a temporal resolution of 5 minutes. Since electromagnetic solar radiation propagates at the speed of light in a vacuum, the first ionospheric disturbances occur approximately eight minutes after the flare. In this sense, ROTI stands out as a prominent detector of solar flares.

Since ROTI is estimated from GNSS observables of dual/triple frequency receivers, it is assumed that active GNSS network stations distributed over the Earth surface can be used as true solar monitoring sensors, as is carried out by the STEREO (Solar Terrestrial Relations Observatory) and SOHO (Solar and Heliospheric Observatory). The differential of the use of the active networks for solar monitoring is in the fact that it is possible to identify the real location of incidence of the electromagnetic radiation in the terrestrial atmosphere, and so, to be a system that has a high number of stations, which guarantees the requirements of integrity, continuity and availability.

Therefore, the objective of this paper is to show the viability of using IGS network as sensor for detecting solar flare, specifically through the ROTI ionospheric index and focusing on the equatorial region, where Brazil is mostly located and ionospheric irregularities are more active. For this, a solar flare (classified as X9.3) occurred on September 6, 2017 was used as study case. It is noteworthy that the influence of the September 6, 2017 flare on ROTI index has been previously explored, however, such studies were focused on mid-latitude regions, such as Europe (BERDERMANN et al., 2018), or considering the whole Earth in general (ZHOU et al., 2018).

As justification, the detection of solar flare directed to the Earth is of great interest for the positioning and navigation by GNSS, for example, in the precision agriculture, take-off and landing of aircrafts, monitoring of oil rigs and structures, and RTK (Real Time Kinematic). After a flare, the probability of geomagnetic

storms and, consequently, ionospheric storms occur within few days is high, as recorded on September 7 and 8, 2017 (DE PAULA et al., 2019), which in turn may deteriorate the accuracy of the positioning.

TOTAL ELECTRON CONTENT AND SOLAR FLARES

TEC represents the number of electrons contained in the path traveled by the signal, from the satellite to the receiver, being represented in TECU (TEC Unit), where 1 TECU is equivalent to 1×10^{16} electrons/m². It can be obtained using the pseudoranges derived from the codes in GPS L1 and L2 (PD_{rL1}^s , PD_{rL2}^s), from the linear combination presented by Equation 1 (MATSUOKA; CAMARGO, 2004). The TEC can also be estimated using the carriers GPS L1 and L5; in this case must replace the subscript (L2) to (L5) in Equation 1.

$$TEC_r^s = \frac{f_{L1}^2 f_{L2}^2}{40.3(f_{L1}^2 - f_{L2}^2)} [(PD_{rL2}^s - PD_{rL1}^s) - v_{PD}] \quad (1)$$

where f_{L1} and f_{L2} are the frequencies of the carriers GPS L1 and L2, respectively, and v_{PD} contains the systematic errors not eliminated in the linear combination and random errors.

The estimation of the TEC can also be determined from the linear combination between the phase measurements of the GPS L1 and L2 carriers (Φ_{rL1}^s , Φ_{rL2}^s), given by Equation 2 (MATSUOKA; CAMARGO, 2004), or between the phase measurements of the L1 and L5 carriers.

$$TEC_r^s = \frac{f_{L1}^2 f_{L2}^2}{40.3(f_{L1}^2 - f_{L2}^2)} [(\lambda_{L2} \Phi_{rL2}^s - \lambda_{L1} \Phi_{rL1}^s) - (\lambda_{L1} N_{rL1}^s - \lambda_{L2} N_{rL2}^s) - v_{\Phi}] \quad (2)$$

where λ_{L1} , λ_{L2} , N_{rL1}^s and N_{rL2}^s are the wavelengths and ambiguities of the carriers GPS L1 and L2, respectively, and v_{Φ} contains the systematic errors not eliminated in the linear combination and random errors.

In relation to the state of the ionosphere, several variables influence its behavior, such as: regular temporal variations (daily, seasonal and solar cycles), variations with geomagnetic activity, influences of geographic location, solar flares, among others (LEICK, 1995).

In relation to solar flares, it is characterized by a rapid increase in the level of energy on the surface of the Sun, with emission of radiation at all wavelengths of the electromagnetic spectrum (especially in the bands of the EUV and X-ray). The duration of a flare can range from three minutes to a few hours, with a mean time of 30 minutes (DAVIES, 1990). If the electromagnetic radiation coming from a solar flare is directed to the Earth, a series of phenomena can be triggered in the ionosphere, generally called SID. During the events of SID, rapid variations in phase and/or amplitude and loss of GNSS signal power may occur (RUVIARO; MATSUOKA; CAMARGO, 2013).

The solar flares can also be accompanied by SRB. The frequency of a solar radio burst is associated with the altitude within the solar atmosphere where the explosive release of energy takes place. This relationship is due to the variation of the plasma parameters such as magnetic field strength and electron density, both of which increase as the altitude within the solar atmosphere decreases. SRB releasing large levels of microwave radiation are typically associated with solar flares, which involve both the solar corona and chromosphere. During the occurrences of SRB, a reduction in the carrier-to-noise ratio (C/No) of the GNSS signals can be observed by receivers on the sunlit hemisphere of Earth (CARRANO; BRIDGWOOD; GROVES, 2009).

Using high-rate GNSS receivers throughout the Earth, Carrano, Bridgwood and Groves (2009) investigated the impacts of SRB on the performance of GPS and quantify the SITEC caused by the solar flares. The C/No reduction experienced by a GNSS receiver during a SRB depends on the solar incidence angle in relation to the antenna, and the results were intermittent loss of lock, and complete loss of GNSS positioning information lasting for several minutes.

IONOSPHERIC IRREGULARITIES AND ROTI INDEX

The ionospheric irregularities are perturbations in ionospheric plasma density, which arise through Rayleigh-Taylor (R-T) plasma instability processes occurring in the equatorial ionosphere. This instability gives rise to irregularities in the ionospheric F layer with a broad spectrum of size scales ranging from a few centimeters to hundreds of kilometers.

Electron density irregularities can produce short-period variations in the trans-ionospheric signals, caused by rapid phase and amplitude fluctuations, thus causing a weakening and variations of the signal received by the GNSS receivers (WEBSTER, 1993). These rapid fluctuations in phase and amplitude of the signal are called ionospheric scintillations.

Several studies on ionospheric irregularities have been carried out, such as: De Paula et al. (2019), Moraes et al. (2018), Sousasantos et al. (2018), Muella et al. (2017), Pereira and Camargo (2017), Pereira and Camargo (2016), Pereira and Camargo (2013), Matsuoka et al. (2013), Oladipo and Schüler (2013), Chu et al. (2008), Li, Ning and Yuan (2007), Shan et al. (2002), Sobral et al. (2002), Skone, Knudsen and De Jong (2001), Mendillo, Lin and Aarons (2000), Abdu et al. (1998), Pi et al. (1997), and Wanninger (1993). From these studies it was observed that the effects of ionospheric irregularities are more present after sunset, from September to April in the Southern Hemisphere, during periods of high solar activity and with great longitudinal dependence. In addition, it was also verified that the ionospheric scintillation is related to the Equatorial Ionization Anomaly (EIA), being detected greater intensity in the places closest to the crests of the anomaly.

In order to evaluate the ionospheric activities, several indexes can be used, which can be obtained from (a) ionosonde data: AI index (BREMER et al., 2006) and AI modified index (MIELICH; BREMER, 2010); (b) IONEX files: Wp and W-index (GULYAEVA; STANISLAWASKA, 2008; GULYAEVA et al., 2013); and (c) GNSS observables: I_{ROT} (WANNINGER, 1993), σ_{ϕ} (VAN DIERENDONCK; KLOBUCHAR; HUA, 1993), ROTI (PI et al., 1997), f_p and F_p (MENDILLO; LIN; AARONS, 2000), S4

(CONKER et al., 2003), S_ϕ (FORTE, 2005), σ_{CHAIN} (MUSHINI et al., 2012) and DIX (JAKOWSKI; BORRIES; WILKEN, 2012).

The ROTI estimate is based on the Rate of Change of TEC (ROT). The ROT is calculated through the ratio of the difference of the TEC obtained consecutively between two epochs, and the time interval elapsed between the respective determinations (PEREIRA; CAMARGO, 2017):

$$ROT = \frac{TEC_{t_2} - TEC_{t_1}}{t_2 - t_1} = \frac{\Delta TEC}{\Delta t} \quad (3)$$

where the TEC can be obtained using either the pseudorange coming from the codes on the carriers GPS L1 and L2 (Equation 1) or L1 and L5, or from the combination between the phase measurements of carriers L1 and L2 (Equation 2) or L1 and L5.

Substituting Equation 2 into Equation 3 gives an estimate of the ROT having only phase measurements of the GPS L1 and L2 carriers at the t_1 and t_2 epochs as parameters (PEREIRA; CAMARGO, 2017):

$$ROT = \frac{9.52 \cdot 10^{16} [\lambda_{L2} (\Phi_{rL2t_2}^s - \Phi_{rL2t_1}^s) - \lambda_{L1} (\Phi_{rL1t_2}^s - \Phi_{rL1t_1}^s)]}{t_2 - t_1} \quad (4)$$

However, for GLONASS, which uses multiple divisions of frequencies to distinguish each satellite (FDMA), one should use (PEREIRA; CAMARGO, 2017):

$$ROT = \frac{\frac{f_{L1}^2 f_{L2}^2}{40.3(f_{L1}^2 - f_{L2}^2)} [\lambda_{L2} (\Phi_{rL2t_2}^s - \Phi_{rL2t_1}^s) - \lambda_{L1} (\Phi_{rL1t_2}^s - \Phi_{rL1t_1}^s)]}{t_2 - t_1} \quad (5)$$

where f_{L1} , f_{L2} , λ_{L1} and λ_{L2} are the frequencies and wavelengths of the carriers L1 and L2 of each GLONASS satellite observed.

The ROTI index, given by Equation 6, is the standard deviation of the ROT estimated for all satellites over a five-minute interval (PI et al., 1997):

$$ROTI = \sqrt{\langle ROT^2 \rangle - \langle ROT \rangle^2} \quad (6)$$

where $\langle \rangle$ represents the average.

According to Pereira and Camargo (2014), $ROTI \leq 0.05$ represents low levels of irregularities, $0.05 < ROTI \leq 0.2$ indicates moderate irregularities, and when

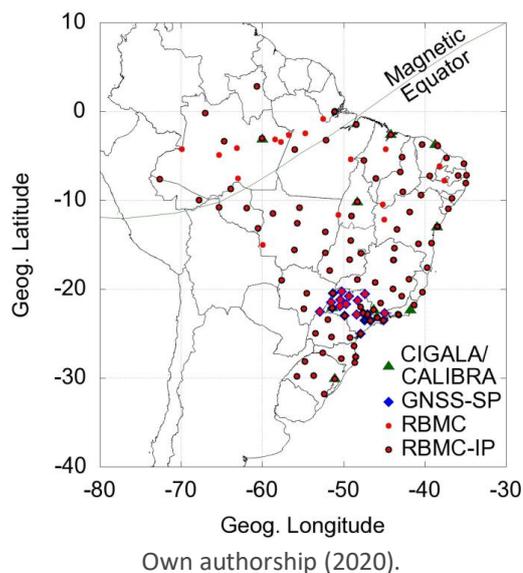
ROTI > 0.2 the occurrence of strong levels of ionospheric irregularities is represented.

DETECTION OF THE SOLAR FLARE OF SEPTEMBER 6, 2017 USING IGS NETWORK

In Brazil, users and researchers who aim to estimate indexes of ionospheric irregularities, as well as indexes of ionospheric scintillation, in real time and post-processed, can use the scientific program Ion_Index (PEREIRA; CAMARGO 2016), available at <https://www.fct.unesp.br/#!/pesquisa/grupos-de-estudo-e-pesquisa/gege/software/>.

Ion_Index indexes are estimated from the GNSS receiver data infrastructure of Brazilian active networks, such as RBMC (Brazilian Network for Continuous Monitoring of the GNSS Systems), GNSS-SP (GNSS Active Network of Sao Paulo State) and CIGALA (Concept for Ionospheric Scintillation Mitigation for Professional GNSS in Latin America) / CALIBRA (Countering GNSS High Accuracy Applications Limitations Due to Ionospheric Disturbances in Brazil) (Figure 1). The program also allows estimating indexes based on the availability of any RINEX (Receiver Independent Exchange Format) file by the user, such as IGS stations.

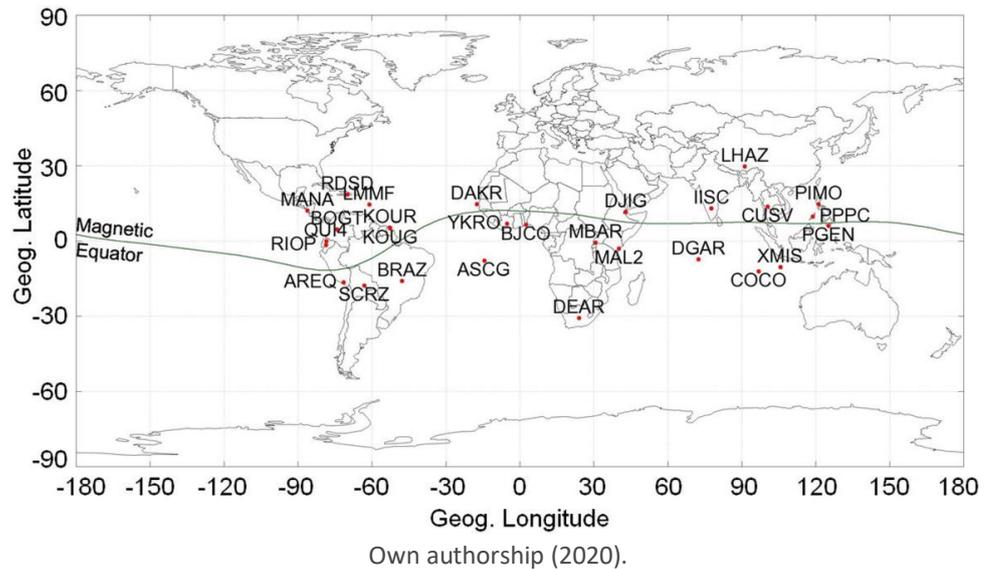
Figure 1 – Map of active GNSS networks in Brazil used by Ion_Index



Since the Space Weather Prediction Center (SWPC) from National Oceanic and Atmospheric Administration (NOAA) reported on its website (<http://www.swpc.noaa.gov/>) the occurrence of the solar flare on September 6, 2017 at 11:53 UT (Universal Time), instant in which there was an increase in X-ray emission (class X9.3), it was estimated the ROTI for several stations of the IGS network. For the estimation of the index, the GPS L1/L2 phase measurements were used, with a 35° elevation mask and 350 km height for the ionospheric layer.

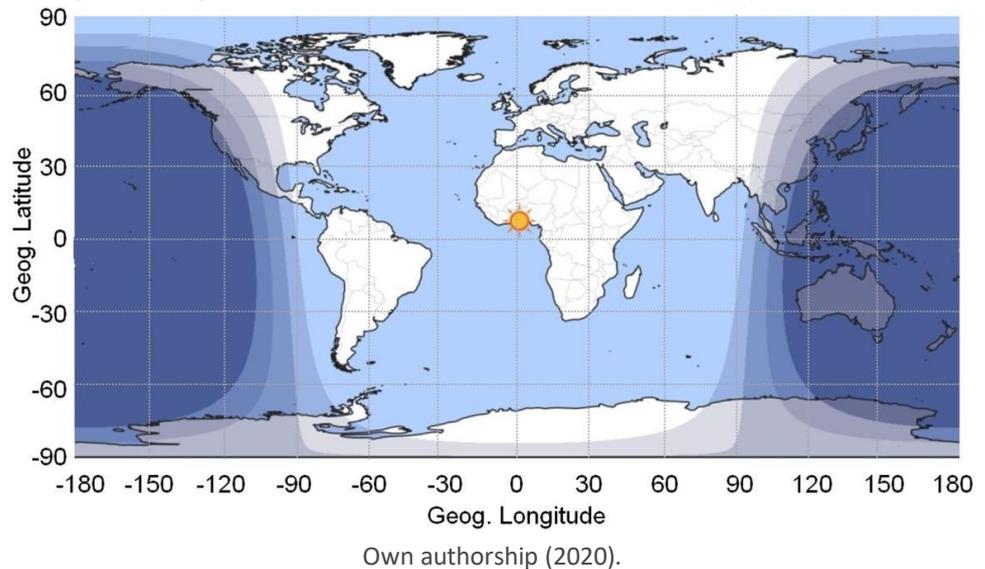
Figure 2 shows the locations of the 28 IGS stations selected. The criterion for choosing the stations was to contemplate, in an approximate way, the entire low latitude region of the Earth surrounding the Magnetic Equator, which is under the effect of the main ionospheric phenomena, like the EIA.

Figure 2 – IGS stations selected for the detection of the solar flare on September 6, 2017 through the ROTI index



To verify the region of incidence of electromagnetic solar radiation on Earth due to flare, the region of solar illumination was determined for the 12:00 UT on September 6, 2017, as shown in Figure 3.

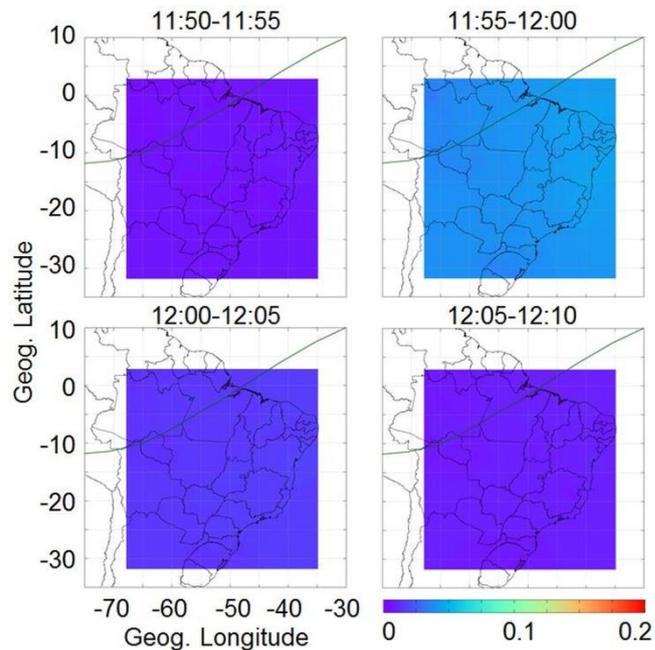
Figure 3 – Region of solar illumination on Earth at 12:00 UT on September 6, 2017



As shown in Figure 3, the SID and consequently the ionospheric irregularities are expected to occur in the equatorial region of the Earth facing the Sun after the flare, i.e., in areas of South America, Central America, Atlantic Ocean, Africa, Indian Ocean and South India.

Concerning it, Figure 4 shows, for example, maps of ionospheric irregularities by ROTI index for Brazilian region for the period before the arrival of radiation (11:50-11:55 UT), during the incidence occurrence (11:55-12:05 UT) and post-incidence period (12:05-12:10 UT).

Figure 4 – ROTI maps over Brazil for 11:50-12:10 UT on September 6, 2017. Time interval of each map is 5 minutes. The color scale of ROTI index is between 0 (purple) to 0.2 (red)

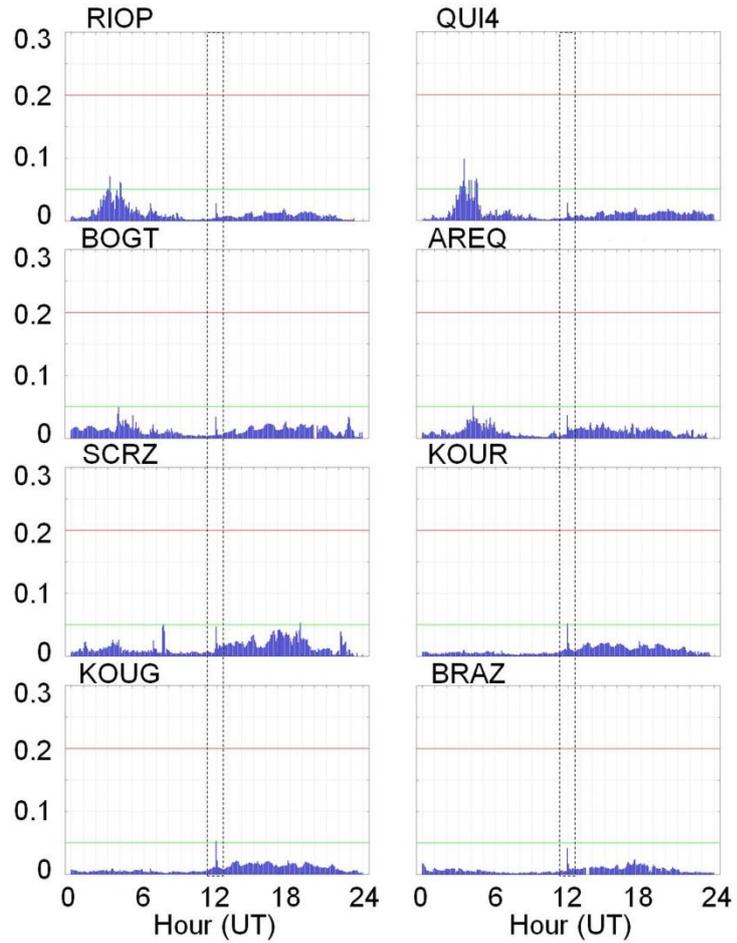


Own authorship (2020).

Figure 4 shows that, even though it was a period of low solar activity, before the spring equinox and close to 12:00 UT (9:00 local time), there was a slight alteration of the electron density in the ionospheric layer in the region, which indicates that sudden ionospheric disturbances occurred due to the solar flare.

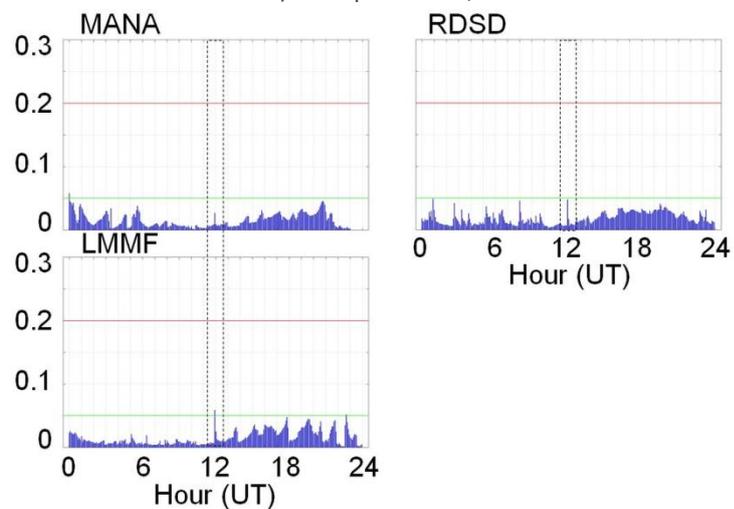
The variability of the electronic density can be observed spatially and temporally when analyzing the ROTI graphs for the IGS stations selected in the regions of South America (Figure 5), Central America (Figure 6), Africa and the Atlantic Ocean (Figure 7), as well as for the DGAR station in the Indian Ocean and for the IISC station in India (Figure 8). In the Figures 5 to 8 the green line indicates the threshold between low and moderate levels of irregularities, the red line indicates the boundary between moderate and strong levels, while the dotted black rectangle represents the instant of the solar flare and the moment of incidence of the electromagnetic radiation on Earth. The presentation sequence of graphs is from left to right, top to bottom, so that the stations are arranged according to the longitude, from west to east.

Figure 5 – ROTI index of IGS stations selected in South America (RIOP, QUI4, BOGT, AREQ, SCRZ, KOUR and BRAZ) on September 6, 2017



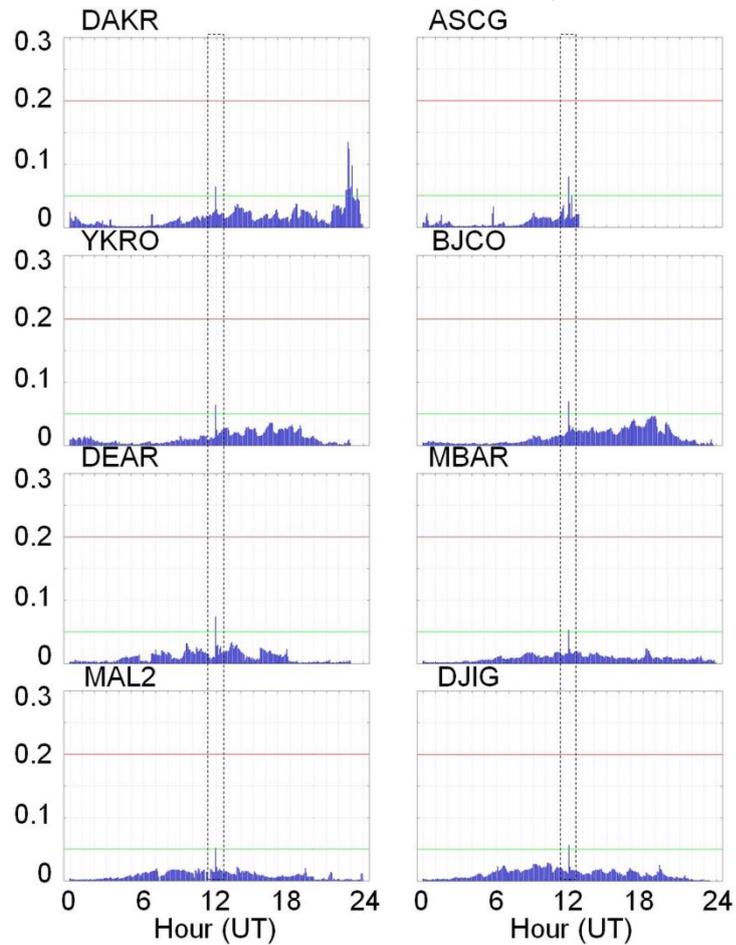
Own authorship (2020).

Figure 6 – ROTI index of IGS stations selected in Central America (MANA, RDSD and LMMF) on September 6, 2017



Own authorship (2020).

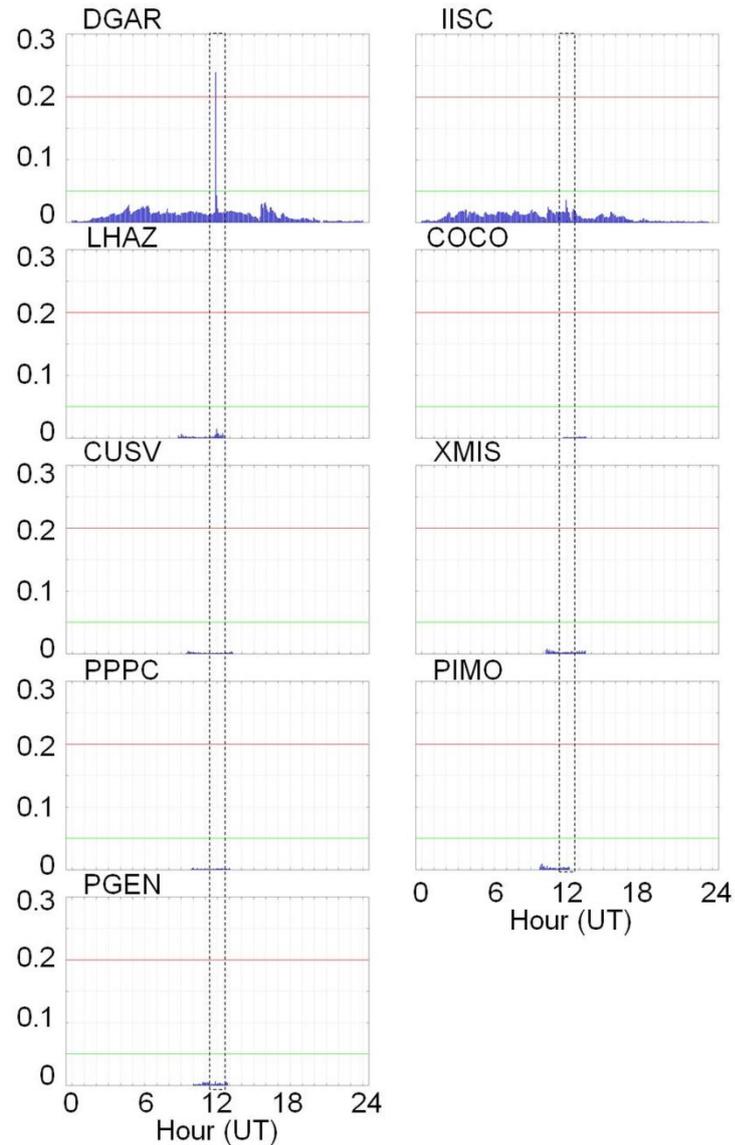
Figure 7 – ROTI index of IGS stations selected in Africa and Atlantic Ocean (DAKR, ASCG, YKRO, BJCO, DEAR, MBAR, MAL2 and DJIG) on September 6, 2017



Own authorship (2020).

From Figures 5 to 7 it is observed that all the stations presented a moderate short-lived increase of ROTI at the moment of the solar flare, regardless of geographic location. In Figure 8 one notes that only the DGAR and IISC stations showed an increase of ROTI close to 12:00 UT, which corroborates with the solar illumination region at the time (Figure 3), unlike the other Asian stations, which did not detect irregularities in the density of electrons because they were in the nocturnal face of the Earth. It is important to note that the occurrences of high ROTI values at other times of the day, such as from 0:00 to 6:00 UT in South America (Figure 5) and from 21:00 to 24:00 UT in DAKR (Africa, Figure 7), are due to the dynamics and behavior of ionospheric bubbles, which cause ionospheric irregularities. Such bubbles occur in the equatorial region and at low latitudes, originating after sunset and moving from west to east, mainly during the equinox period (September) (PEREIRA, 2018).

Figure 8 – ROTI index of IGS stations selected in Asia and Indian Ocean (DGAR, IISC, COCO, CUSV, XMIS, PPPC, PIMO and PGEN) on September 6, 2017



Own authorship (2020).

Since it is feasible to detect the solar flare using active GNSS networks, as well as to determine the region of incidence of the electromagnetic radiation in the Earth's atmosphere, it is possible to adopt mitigation techniques in the GNSS positioning for the effects of the geomagnetic storm and, later, of the ionospheric storm, which will occur after a few days as a result of the solar flare.

For the present case study, two geomagnetic storms were recorded on September 7 and 8, 2017 according to De Paula et al. (2019). S4 and TEC obtained from GPS and VHF receivers, the data from a digisonde, and also from magnetometers and the SWARM-A satellite were used for the analyses of the ionospheric irregularities over the low-latitude region. The authors highlighted that the ionospheric scintillation measured by the GNSS receivers located in latitudinal range from 4.7°S to 20.7°S and longitudinal range of 39°W to 47.4°W had their standard observational data entirely modified during the storms. This modification was in the form of a large scintillation enhancement on the night of

7/8 and a complete scintillation inhibition on the night of 8/9. As the ionospheric scintillation may affect the GNSS signals and the air navigation and positioning systems, as well as some telecommunication systems, it is very important to analyze its behavior during magnetic storms.

CONCLUSIONS

The use of IGS network stations, widely used for positioning purposes, into solar flare detection system translates in an important method for the monitoring of Space Weather.

The rapid detection of Earth-directed solar flare and the actual location of incidence of radiation allow GNSS users to develop and/or to apply mitigation techniques in a timely manner so that positioning accuracy is not so degraded by geomagnetic and ionospheric storms that may occur. Examples of mitigation are the non-use of the signals from the satellites that are in the direction of the solar flare, or not to realize the positioning during the minutes after the flare.

From the experiment it can be seen that, after the solar flare occurred at 11:53 UT on September 6, 2017, the first ionospheric disturbances were recorded by the ROTI index close to 12 UT, time difference referring to distance Sun-Earth.

The study and monitoring of the Sun's activities through special satellites such as the STEREO and SOHO missions are the most appropriate forms currently available. However, the missions to study the Sun-Earth dynamics are few and very expensive. Therefore, the ROTI index estimated from active GNSS network data serves as an alternative for the rapid detection of solar flare because it uses the infrastructure already deployed by the IGS and other national networks. Another contribution of the use of active networks is due to the high number of existing stations, which guarantees the requirements of integrity, continuity and availability.

As a recommendation, IGS has the supply of RINEX files from all stations with data sampling rate higher or equal to 1 Hz, which would allow a more accurate estimation of the ROTI index, as well as obtain it with a time resolution of less than five minutes, which would be interesting for instantaneous detection of flare.

Detecção de explosão solar utilizando estações da rede IGS: estudo de caso para 6 de setembro de 2017

RESUMO

A pesquisa apresenta a viabilidade de se utilizar estações GNSS (*Global Navigation Satellite System*) da rede IGS (*International GNSS Service*) na detecção de explosão solar. Para isso foi considerada como estudo de caso a explosão ocorrida no dia 6 de setembro de 2017, classificada como X9.3. Na situação da explosão estar direcionada a Terra, uma série de eventos pode ocorrer na ionosfera, os quais são denominados de Distúrbios Ionosféricos Súbitos (SID – *Sudden Ionospheric Disturbances*). Entre os tipos de SID há os Aumentos Súbitos no Conteúdo Total de Elétrons (SITEC – *Sudden Increases in the Total Electron Content*). Essa variabilidade imediata no TEC pode ser estimada a partir do índice ROTI. Uma vez que a radiação eletromagnética solar leva aproximadamente oito minutos para atingir a Terra, o índice ROTI apresenta-se como um interessante detector de explosão solar. Nesse sentido, o ROTI foi estimado utilizando dados de várias estações IGS. Foi verificado que houve um aumento nos valores de ROTI no período da explosão solar e na região equatorial orientada na direção do Sol. A detecção de uma explosão solar direcionada à Terra é de grande interesse para o posicionamento GNSS e o Clima Espacial, uma vez que, provavelmente após uma explosão, haverá tempestades geomagnéticas e ionosféricas num curto prazo de dias (conforme verificado nos dias 7 e 8 de setembro), o que deteriorará o posicionamento.

KEYWORDS: Índice ROTI. GNSS. Irregularidades Ionosféricas. Explosão Solar.

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