GNSS Total Electron Content (TEC) variability during geomagnetic storms

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***Abstract*— Global Navigation Satellite Systems (GNSS) operations involve trans-ionospheric radio wave propagation that can be affected by space weather phenomenon like geomagnetic storms. The occurrence of these geomagnetic storms causes significant changes in the ionosphere layer; which is also the biggest source of error in GNSS positioning and timing applications. In absence of high frequency scintillation monitoring receivers, the levels of ionosphere irregularities and their evolution can be studied using common non-scintillation receivers. The study demonstrates the feasibility of using existing network of permanent GNSS stations around the globe to monitor the changes in Total Electron Content (TEC) during a geomagnetic storm. In order to depict the effect of geomagnetic storm on the ionosphere layer TEC, the transient variation of rate of TEC (ROT) and rate of TEC index (ROTI) are estimated in this research using GPS observations. The results in case of moderate and minor storms are presented in this paper and demonstrate the TEC fluctuations during quiet ionosphere as compared to geomagnetic storms. The research presented in this paper indicates the crucial threat that geomagnetic activity has for GNSS and its associated applications.**

Keywords*— *Ionosphere, TEC, geomagnetic storm, GNSS

I. Introduction

The ionosphere ranges from 50km to 1000km above the Earth's atmosphere and is a composition of charged particles, generated by ionization of atmospheric gasses. The ionosphere is particularly difficult to monitor and model because of the variation of the ionization with change in season, day and sun-spot cycle. Other than the cyclic variation ionosphere also suffers from sudden changes due to the ionosphere storms that occur in conjunction with geomagnetic storms. These scintillation have an adverse effect on the radio waves passing through this medium [1].

With recent advancements in the GNSS, it has become a core technology in developing the socio-economic infrastructure. The GNSS applications range over a huge spectrum including provision of emergency services, traffic monitoring, vehicle tracking, livestock monitoring, precision agriculture, aviation, deformation monitoring and much more. However, like any other radio signal, the GNSS signals are prone to errors; natural or artificial. The artificial errors may be due to jamming or spoofing; while natural errors may be caused by atmospheric degradation, troposphere, ionosphere, multipath or cycle slips. The worst of the natural errors is caused by the ionosphere, where it can affect the positioning results by 5-15m on a quiet day and up to 60m on a stormy day [2]. Therefore, the ionosphere must be monitored and characterized. Ionosphere monitoring using GNSS has a two-fold effect: the GNSS PNT may be improved by calculating the amount of degradation caused by the ionosphere and in turn the ionosphere parameters may be derived for modelling the ionosphere itself. Among the various methods used for ionosphere monitoring, deployment of permanent GNSS stations with dual-frequency receiver is the most popular one . More than 700 stations exist world-wide belonging to different GNSS networks e.g. IGS, EPN, UNVACO as indicated in Fig., making it an ideal network for monitoring. These stations log and archive the GNSS data and post-process it to present the GNSS community with products such as precise ephemeris. The major ionopsheric product of these networks is the Total Electron Content or TEC value. The TEC value is measured to approximate the irregularities and fluctuations caused by the ionosphere. A newer IGS product to characterize the ionosphere irregularities is rate of TEC (ROT) and rate of TEC Index (ROTI). This measure has a computational advantage over the TEC root-mean-square (σtec). Various studies, using different sampling rates, have concluded that the fluctuations of ionosphere may be better approximated by ROT and ROTI [3, 4]. Several papers have been published to highlight the effect that solar activity has on TEC [5-7]. This paper focuses on the variation in the electron content of the ionosphere during geomagnetic storms

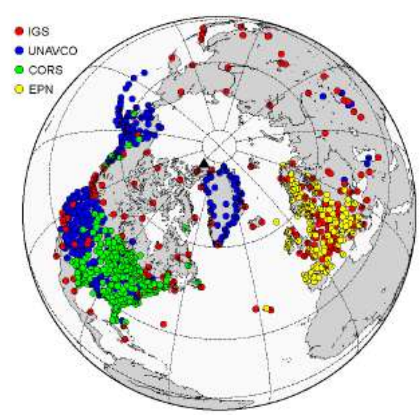

Fig. 1. Worldwide Network of Permanent GNSS Stations

by using the data archived at the permanent stations by IGS. The subsequent sections are arranged as follows: Section 2 explains the methodology by giving an overview of the calculations involved in TEC, ROT and ROTI; Section 3 presents results obtained during a quiet and stormy day and presents a comparative analysis; Finally Section 4 concludes the research conducted.

II. Methodology

A. Data Source

The International GNSS Service (IGS), started in 1994, provides precise and high-quality GNSS products to its users. These products are beneficial to the public in various scientific and commercial applications. The IGS mission states [8]:

"The International GNSS Service provides, on an openly available basis, the highest-quality GNSS data, products and services in support of the terrestrial reference frame, Earth observation and research; positioning, navigation and timing; and other applications that benefit science and society."

Fig. 2. IGS Network

The IGS has GNSS monitoring and tracking stations spread over the globe depicted in Fig..

In order to analyze the variability of ionosphere the data from the IGS station Cordoba, Argentina was used. The details for this GNSS site are presented in **Error! Reference source not found.**. This site is located in the Southern hemisphere near the equator and therefore ideal to analyze the low-latitude effects. To compare the extent of effect of geo-storms two days: one quiet and one stormy. The data has been obtained in Receiver Independent Exchange (RINEX) format and was passed through quality testing first to ensure that the logged data is up to standard.

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B. Total Electron Content (TEC)

The TEC represents the total number of electrons on the path from the satellite to the receiver and is quantified as TECu

where $1\,TECu = 10^{16}\,electrons/m^2$. In simple terms TEC is basically:

TABLE I

CORD STATION SPECIFICATIONS

Site Name	Cordoba
Site ID	CORD
Agency	JPL
Coordinates	2345503.9452, 4910842.9601, 3316365.5474
Receiver	JAVAD TRE_G3TH DELTA
Antenna	TPSCR.G3

$$TEC = \int_{RX}^{Sat} N\,ds \qquad (1)$$

where $'N'$ is electron density.

This TEC value can be directly translated into the errors in meters, expressed as:

$$d_t = \frac{40.3.TEC}{f^2} \qquad (2)$$

d_t is the equivalent GPS ionosphere delay in [m]
f is the radio wave frequency (single frequency receiver: $1.575\ GHz$)

C. Rate Of TEC Index (ROTI)

The ROTI is defined as the standard deviation of the ROT (Rate Of TEC) and is measured in TECu/min. In order to calculate the ROT, the geometry-free phase combination needs to be estimated first:

$$L_{GF}(i) = L_1(i) * \lambda_1 - L_2(i) * \lambda_2 \qquad (3)$$

where L_n is the phase measurement at frequency n
λ_n is the wavelength at frequency n
The ROT is then estimated as:

$$ROT\ (i) = \frac{L_{GF}(i) - L_{GF}(i-1)}{\Delta t * 10^{16} * 40.3 * \left(\frac{1}{f_1^2 - f_2^2}\right)} \qquad (4)$$

where Δt is the difference between two consecutive epochs, in mins.

ROTI is finally obtained by averaging the ROT over N epochs and deriving the standard deviation:

$$ROTI(i) = \sqrt{\frac{1}{N}\sum_{j=i=N}^{i}(ROT(j) - \overline{ROT})^2} \qquad (5)$$

The ROTI identifies the presence of fluctuations but cannot determine their exact size however it is computationally straight-forward and allows the results to be presented in an understandable manner. Generally, an increase in ROTI causes the error in the positioning solution to escalate exponentially [9].

III. Case Studies

A. A Quite Day (5th Sept 2017)

To set a reference, Day 248 of year 2017 i.e 05 Sept 2017 was selected randomly. No ionosphere or geomagnetic activity was observed on this day by any major observatory.

B. A Stormy Day (7-8th Sept 2017)

To analyze the effect of geo-storms on ionosphere, the solar activity on 7-8 Sept 2017 is selected as a test case. This storm started brewing up between the night of 7th and 8th Sept 2017 and reached its maximum impact during the day of 8th Sep 2017. The daily average solar activity was recorded up to an Ap of 106 and maximum Kp of 8+. It is ranked at 20 among the top 50 geomagnetic storms recorded [10].The 7 day summary recorded by DSCOVR is presented in Fig.. Several recently published studies [11-14] have chosen this particular storm to perform the research since it has had a very profound and significant effect on GNSS.

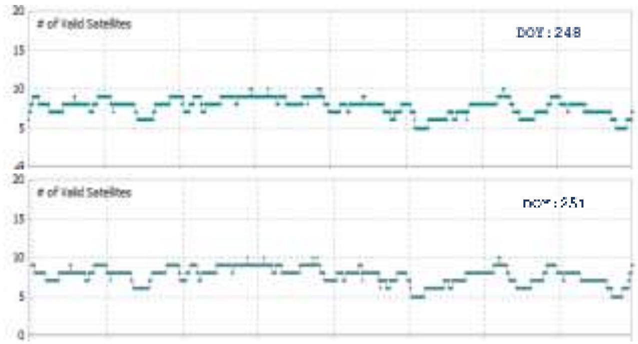

Fig. 3. Number of visible satellites

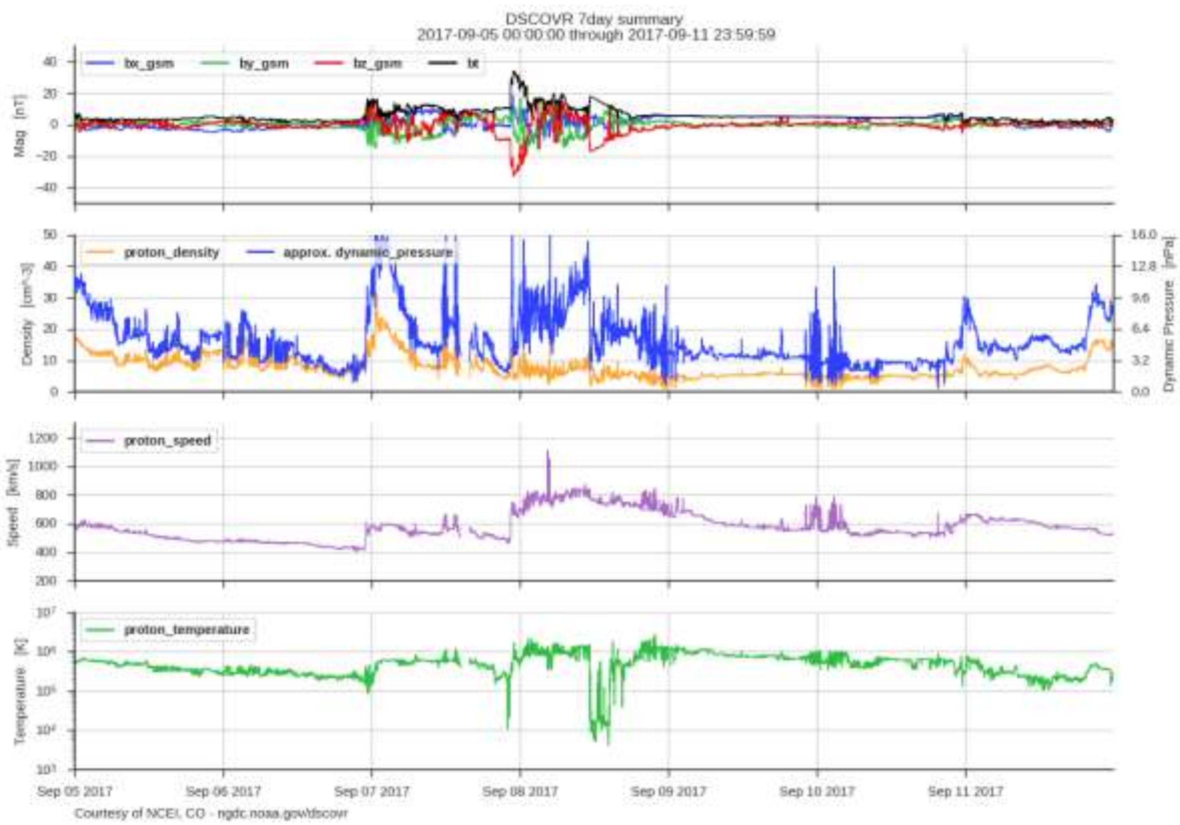

Fig. 4. DISCVR 7-Day Summary

IV. OBSERVATIONS

The basic analysis was carried out by estimating the number of visible satellites at all epochs, a ground track and estimation of position components in x, y and z direction. Furthermore, the elevation angle, slant TEC, ROT and ROTI were estimated for randomly chosen satellites throughout the day.

A. Number of Visible Satellites

Fig. depicts the viable satellites that can be used for positioning at each epoch. It is observed that at least four

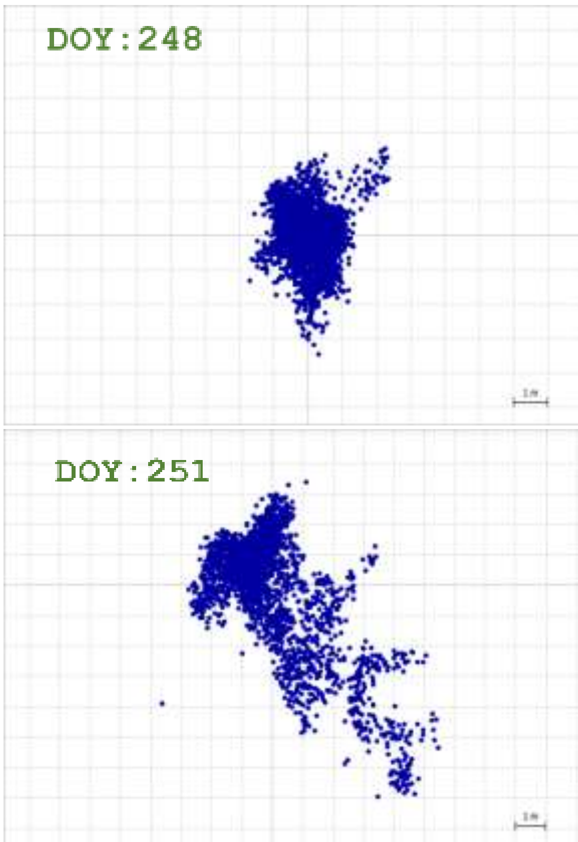

Fig. 5. Ground Track for the receiver

satellites were visible at all epochs for position calculations for both cases. This is because the ionosphere fluctuations does not affect satellite visibility.

B. Position Errors

Fig. shows difference of horizontal and vertical components from actual position in ECEF reference frame. It is observed that the horizontal error varies up to 3 meters and vertical error u to 10 meters for the quiet day. However, the geomagnetic storm of Day 251 has a drastic effect on the position error where the horizontal component of the position varies up to 5 m and the vertical component goes up to 30 m.

C. TEC Analysis

Fig. and Fig. depict the TEC analysis for both cases for three different satellites: Satellite 7, 20 and 29 for Day 248 and Satellite 16, 18 and 21 for Day 251.

The first row of both the graphs depicts the elevation angle of the satellite. The second row illustrates the STEC. It can be observed that TEC fluctuations exist even for a quiet day but they are very minor. Generally, the value of slant TEC remain below 40 TECu/min for a calm day. In case of the ionosphere storm, the TEC fluctuations not only increase in numbers but also in amplitude, taking the maximum variation up to 80-100 TECu/min.

The third row represents the ROT variation over time computed at each minute interval. It can be seen that the ROT values follow the trend of TEC values. The ROT increases in presence of the storm and almost doubles in amplitude.

The last row depicts the ROTI estimated over 5 minute interval. The average ROTI increases from 0.01 for a calm day to 0.082 in the presence of a storm.

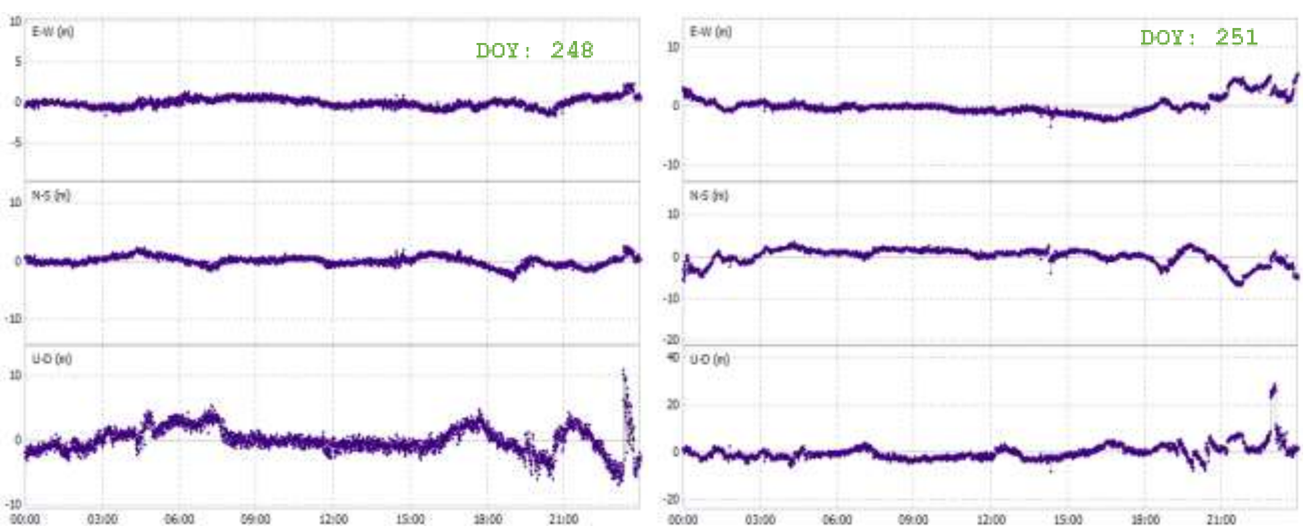

Fig. 6. XYZ component of positional error

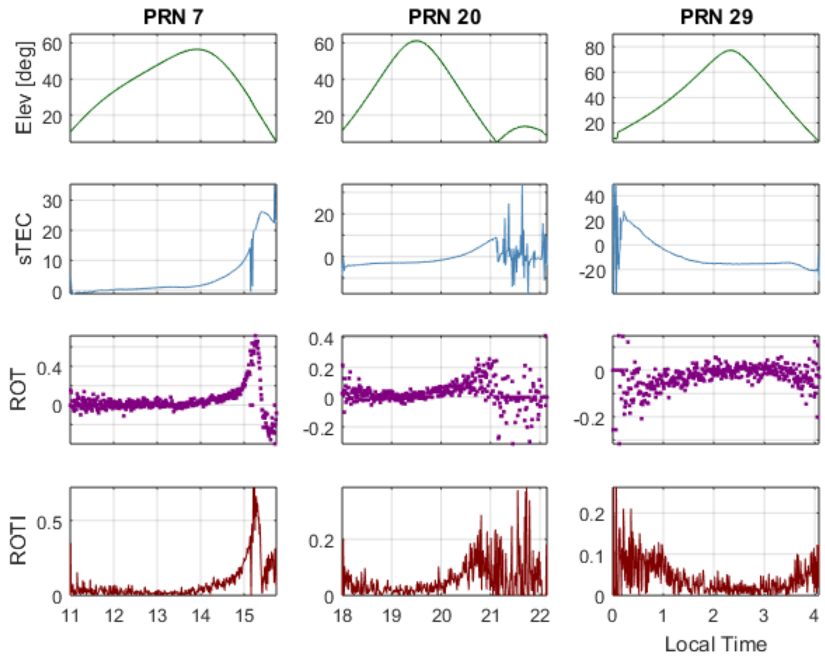

Fig. 7. The Local Time variation of elevation angle, slant TEC (sTEC), ROT, and ROTI on Day 248 for Sat#7. Sat#20 and Sat#29

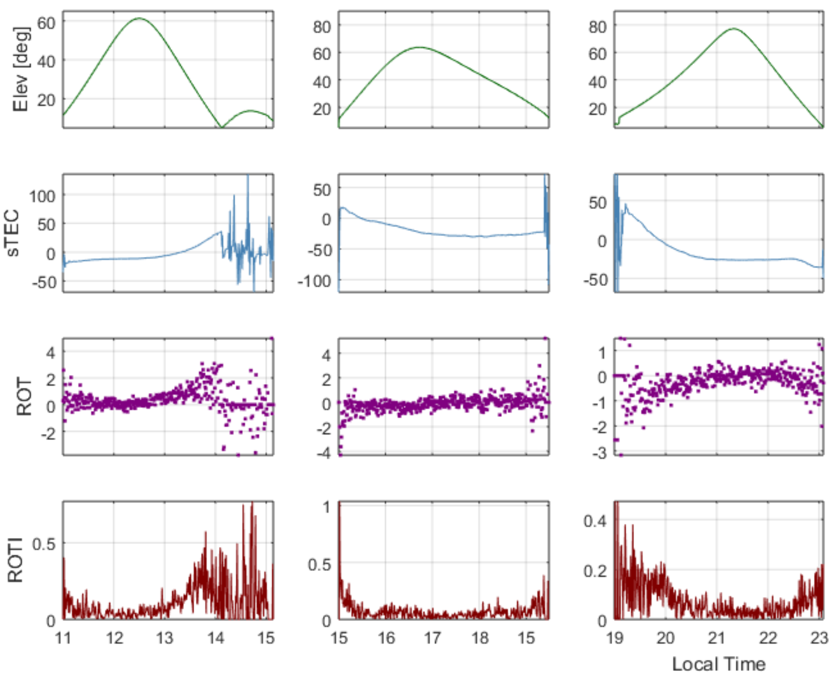

Fig. 8. The Local Time variation of elevation angle, slant TEC (sTEC), ROT, and ROTI on Day 251 for Sat#16. Sat#18 and Sat#21

The third row represents the ROT variation over time computed at each minute interval. It can be seen that the ROT values follow the trend of TEC values. The ROT increases in presence of the storm and almost doubles in amplitude.

The last row depicts the ROTI estimated over 5 minute interval. The average ROTI increases from 0.01 for a calm day to 0.082 in the presence of a storm.

fluctuate drastically in presence of an ionosphere storm casing positional errors up to 5m.

For further work it is encouraged that the magnitude of effect of geomagnetic storms may be measured by evaluating the relation between Kp index and TEC units. The spatial and temporal validation of the results may be demonstrated using data sets from other storms and other GNSS stations.

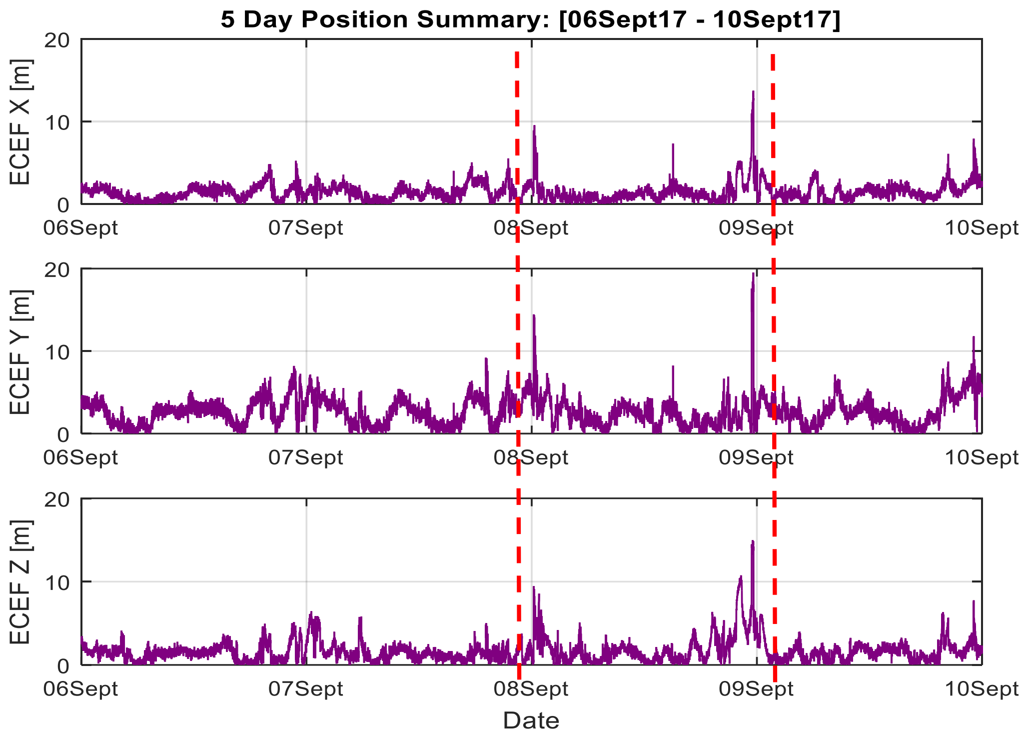

Fig. 9. 5 Day summary of positional errors

V. Conclusion and Future Work

The study analyzed the impact of ionosphere storms on the variability of TEC by using the geo storm of 7-8 Sept 2017 as a test case. It was observed that the PVT (position velocity time) solution degrades severely in presence of a geo storm, causing positional errors up to 5m in the horizontal component and up to 30m in vertical component. The ionosphere fluctuations directly impact TEC and ROTI, where both of them increase almost two-fold.

Fig. presents the positional errors summary for five continuous days from 6 Sept 2017 to 10 Sept 2017, where the sudden effect of the geo storm is clearly visible. It can be seen that the storm hit in two bursts: In the morning and towards the end of the day; the same was confirmed by another multi-instrument study in [15].

To conclude, the research study demonstrated the effect of a geo magnetic or ionosphere storm on the positioning solution, TEC and rate of TEC calculated by a GNSS receiver. It was demonstrated that the statistical features of the electron content

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