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TEC Response and Subsequent GPS Error Caused by the Most severe Geomagnetic Storm of Solar Cycle 24 at India

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This paper presents the response of low-latitude and mid-latitude ionosphere to a severe geomagnetic storm that occurred on 17 March 2015 at 0445 UT, and the subsequent effect of this storm on GPS error in the East-West (E-W) and North-South (N-S) directions. The Vertical Total Electron Content (VTEC) data has been analysed from three dual frequency GPS receivers, which were installed under the framework of the International GNSS Service (IGS). For each day of the year, the data is downloadable as a single file in the Receiver Independent Exchange Format (RINEX) from the IGS data portal. The VTEC values from the IGS are obtained at one minute intervals. Results show the variations in GPS derived VTEC during the severe geomagnetic storm. Negative ionospheric storms caused by composition changes are observed at mid-latitude region of Lucknow, while positive ionospheric storms caused by magnetospheric convection and Equatorial Ionospheric Anomaly (EIA) are prominent at low-latitude regions of Bangalore and Hyderabad. The maximum depletion in VTEC peak at mid-latitude region of Lucknow when compared to the quiet day mean VTEC was 61 percent during a negative ionospheric storm that occurred on 18 March 2015, and maximum enhancement in VTEC peak at low-latitude region of Bangalore and Hyderabad when compared to the quiet day mean VTEC was 26 percent and 21 percent respectively during an early positive ionospheric storm on 18 March 2015. Positive ionospheric storms caused by enhanced EIA and Prompt Penetration Electric Fields (PPEF) are prominent at low-latitudes. The highest GPS error during storm time was +7.2m and +11.3m in E-W and N-S directions respectively at Lucknow. The average GPS error in E-W and N-S directions during storm time was higher at the mid-latitude station of Lucknow.

Keywords: GNSS, Vertical Total Electron Content (VTEC), IGS, Geomagnetic storms, Storm day, Quiet Day

1Introduction

Ionospheric disturbance caused by the sun's electromagnetic radiation has been an important area of research since the discovery of theory of ionization of an atmospheric layer by Sydney Chapman in 1931. There has been much advancement in ionospheric research and space technology since then. Particularly, the invention of Global Navigation Satellite Systems (GNSS) has increased our dependence on navigation tools. Today, in the 21st century, all forms of navigation use GNSS services for guidance. There are several other GNSS-reliant systems like precision agriculture, surveying, communication, and internet and most importantly power grids. Strong ionospheric storms or disturbances pose a threat of disrupting the functioning of GNSS-reliant systems that are primary for many human activities today. Furthermore, ample research has been done on seismo-ionospheric anomalies, which are disturbances in the ionosphere that appear around the time of natural disasters like earthquakes[1]. It is therefore of utmost importance to understand the regional and global behavior of ionosphere with respect to the sun's electromagnetic radiation on a diurnal, monthly, seasonal and yearly basis. Such spatial and temporal observations will lay the foundation for generating now casting and forecasting models of ionospheric parameters, which can later be used to mitigate errors caused in GNSS-reliant systems[2]. In the last decade, many researchers have studied on the diurnal, monthly, seasonal and annual variations of ionospheric parameters in low-latitude and mid-latitude regions[3-10]. Many others offered comparison results of the measured data obtained from different resources at various geographic locations with various models, such as IRI and NeQuick[11-15].

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In this paper, ionospheric behavior will be discussed in detail with regard to mostly one parameter i.e. Total Electron Content (TEC). TEC is defined as the total number of electrons in a vertical column of one square meter, a parameter that would allow us to assess and visualize ionospheric behavior conveniently[16]. It is mathematically expressed as an integral of the entire ionospheric electron density profile. The unit of measurement for TEC is TEC Units (TECU = 10^{16} m^{-2}) [17]. In the past, TEC was measured using various techniques, but with developments in space technology and radio diagnostics, it is now mostly measured by Global Positioning System (GPS) or other GNSS services. With increasing GNSS networks and faster internet capabilities, the spatial and temporal extent of TEC data today is large. Furthermore, the Very High Frequency (VHF) and Ultra High Frequency (UHF) radio waves that carry such data do not undergo severe degradation during ionospheric storms[2]. These characteristics of present-day TEC data make it an appropriate parameter to analyze and visualize ionospheric behavior. It is also important to note that most communication and navigation errors caused by phase advance and Doppler shift of carrier, time delay of modulation, Faraday rotation of polarization, *etc.* are predominantly related to TEC[17].

The aim of this study is to analyze variations in TEC over the Indian subcontinent in response to the strongest geomagnetic storm of solar cycle 24, and further analyze the subsequent positioning error caused in GPS by such TEC variations. 2015 is the year that witnessed the most geomagnetic activity in solar cycle 24 (2008 to 2020). There were up to three severe ionospheric storms in 2015 with the strongest storm of the solar cycle occurring on 17 March 2015 at 2200 UT. The study is part of a larger research project, which is working on hostingreal-time ionospheric data on an open access Web-platform

2 Literature

2.1. TEC derived from GNSS

GNSS is an effective tool for measuring TEC along the ray path of a satellite and receiver. Moreover, dual-frequency GNSS allows for estimation of TEC more accurately by eliminating ionospheric errors as opposed to single-frequency GNSS stations where the main source of error is ionospheric delay[18]. Dual-frequency GNSS receivers use pseudo-range and carrier phase measurements to compute Slant TEC (STEC)[19]. The formula for STEC as a function of pseudo-range (P), which is the pseudo distance between satellite and receiver at the time of receiving the signal, is given by[16]

$$STEC_P = \frac{2}{k}\left[\frac{{f_1}^2{f_2}^2}{{f_1}^2 - {f_2}^2}\right](P_2 - P_1) + \tau^r + \tau^s + I + T + mpp \quad \text{... (1)}$$

where, k is a constant whose value is 80.62 (m^3/s^2); f_1 and f_2 are frequencies of pseudo-ranges P_1 and P_2; τ^r and τ^s are the differential code bias and inter-frequency bias corresponding to P_1 and P_2; I is ionospheric induced error; T is tropospheric induced error; mpp is multipath error.

Similarly, the formula for STEC as a function of carrier phase, which is the pseudo-range expressed in units of cycles of carrier frequency is given by

$$STEC_C = \frac{2}{k}\left[\frac{{f_1}^2{f_2}^2}{{f_1}^2 - {f_2}^2}\right](L_1\lambda_1 - L_2\lambda_2) + \varepsilon^r + \varepsilon^s - I + T + \lambda N \quad \text{... (2)}$$

where, λ_1 and λ_2 are the wavelengths of carrier phases L_1 and L_2; ε^r and ε^s are the differential code bias and inter-frequency bias corresponding to L_1 and L_2; I is ionospheric induced error; T is tropospheric induced error; N is integer ambiguity.

$STEC_P$ has high noise and low ambiguity whereas $STEC_C$ has low noise and high ambiguity. Therefore, by combining both, accuracy of data can be improved[19]. By further converting STEC to Vertical TEC (VTEC), effects of increased path distance caused due to the oblique path travelled by GNSS signal between receiver and satellite are removed[18]. The relationship between STEC and VTEC is expressed as[16]

$$VTEC = (STEC - b_s - b_r)\cos\chi' \quad \text{... (3)}$$

where, b_s and b_r are satellite bias and receiver bias respectively; χ' is the zenith angle at the Ionospheric Piercing Point (IPP). IPP is expressed as[19]

$$\chi' = \arcsin\left[\frac{R_e}{R_e + h_m}\sin\chi\right] \quad \text{... (4)}$$

where χ is the zenith angle at receiver position, R_e is the mean radius of the earth and h_m is the height of ionospheric layer. By substituting equation 4 in equation 3, we get

$$VTEC = STEC\left\{\cos\left[\arcsin\left(\frac{R_e}{R_e + h_m}\sin\chi\right)\right]\right\} \quad \text{... (5)}$$

IPP refers to the region of ionosphere where the GPS signal passes through maximum electron density. Mean IPP is 350 kilometers[18].

2.2. International GNSS Service (IGS)

IGS is a collaborative effort by more than 200 self-funded organisations across the world (mostly universities, research centers and space agencies). The aim of the service is to provide GNSS products with high accuracy, spatial and temporal coverage. Dual-frequency and more recently triple-frequency GNSS stations are used by IGS to gather data from more than a hundred countries[20-21]. The data is free for public use and therefore can be downloaded from the IGS data portal. However, a few countries exercise restriction in data sharing.

IGS currently distributes data collected and archived from two GNSS services: GPS and GLONASS; each of which are the satellite-based navigation systems of the United States of America (USA) and Russia. IGS initially relied only on data gathered from GPS satellite constellation. But in 2005, data from GLONASS was integrated into the IGS data flow after continuous efforts to do so since 200[20]. The combined use of both satellite navigation systems has increased the overall accuracy.

IGS products fundamentally measure two atmospheric parameters: Tropospheric Zenith Path Delay (ZPD) and Ionospheric TEC. This is done by combining pseudo-range measurements of GNSS with IGS precise clocks and orbits. For this study, ionospheric TEC values are extracted from five IGS stations each of which are listed along with their latitude, longitude and station code in Table 1.

Data in the IGS portal is downloadable in Receiver Independent Exchange Format (RINEX). The RINEX format allows for easy exchange of data and was first presented and accepted in 1989. Since then there have been upgrades and minor changes to the format. For the purpose of this study, RINEX Version 2.11 observation (.o) files are used. The observation files are used to extract TEC values.

IGS products are maintained by a Central Bureau located at NASA's (National Aeronautics and Space Administration) Jet Propulsion Laboratory (JPL). IGS products are a service of the International Association of Geodesy (IAG) and are recognized by the Federation of Astronomical and Geophysical Data Analysis Services (FAGS)[16].

Table 1 — List of IGS stations used for study
(Source :http://www.igs.org/network.html)

IGS Station Code	City	G. Lat	G. Long
IISC	Bangalore	13.02	77.57
HYDE	Hyderabad	17.42	78.55
LCK3	Lucknow	26.91	80.96
SGOC	Colombo	6.89	79.87
LHAZ	Lhasa	29.66	91.10

G. Lat' and 'G. Long' denote 'Geographic Latitude' and 'geographic Longitude' respectively.

2.3. Interplanetary Magnetic Field (IMF)

The sun has a complex magnetic field with distributed magnetic field lines of varying intensities. This magnetic field is not restricted to its immediate vicinity. It is carried through interplanetary space by solar wind. When the path of such solar wind is directed towards earth, geomagnetic storms can be expected as a result of interaction between IMF and earth's dipole-like magnetic field. B_t is a vector that denotes the overall IMF carried by solar wind while B_x, B_y and B_z denote its components in X, Y and Z axes. B_x and B_y are parallel to the ecliptic while B_z is perpendicular to the ecliptic. When B_z is oriented southward, it connects strongly with the earth's magnetic field which is oriented northward. The two opposite charges attract, causing disruption in the magnetosphere. Furthermore, when B_z turns southward and increases in intensity, interplanetary electric field (IEF) penetrates to low-latitude ionosphere leading to abnormal increases in ionospheric TEC[22]. The unit of measurement for IMF is nano-Tesla (nT). B_z values of -10 nT or lower are an indication of geomagnetic disturbances.

2.4. Disturbance storm time (Dst) and Planetary K (K_p) indices

The earth's magnetic field behaves like a dipole with equipotential lines that are closed on the day side and open towards the night side. This phenomenon is caused by electro-magnetic fields of varying magnitudes formed around the earth as a result of ionosphere-atmosphere interaction and magnetospheric convection[23]. Charged particles from the ionosphere or those carried by IMF's are constantly trapped on magnetic field lines. These generate an electric field known as ring current that is oriented towards the west. During geomagnetic storm period, ring current increases due to higher injection of charged particles into the magnetosphere and ionosphere by IMF. The vice-versa is true for quiet periods. Given the direct correlation between ring current and storm behavior, it is widely accepted as a storm-time indicator[24]. Ring current is measured by a parameter called Disturbance Storm Time Index or Dst. The unit of measurement is nano-Tesla (nT).

Another index that is a good measure of magnetospheric convection is the Planetary K or K_p

index. It is derived by measuring horizontal variations in the magnetic field at thirteen sub-auroral locations using a magnetometer. Based on the amplitude of magnetic variation at each location, standardized K values are estimated in the range of 0 to 9 using a quasi-logarithmic function. The standardized values are corrected for daily and annual variations that differ with location of observatory. Finally, all thirteen corrected K values are averaged to obtain the final K_p index[24]. K_p is a dimensionless parameter.

3 Method of Analysis

Solar and geomagnetic indices have been used to identify space weather events caused by the interaction of magnetosphere and solar flares. Hourly averaged values of B_z, Dst and K_p for 2015 are downloaded from NASA's OMNIWeb service (https://omniweb.gsfc.nasa.gov/form/dx1.html). These indices have been used to extract the strongest geomagnetic storm that has occurred in solar cycle 24. The duration of the geomagnetic storm is known as 'storm time', and the days such durations of time have occurred in are known as 'event days'. The indices were further used to extract five consecutive 'quiet days' which experienced least geomagnetic activity in the month of March, 2015. The VTEC measured on 'quiet days' is averaged to provide 'quiet day mean VTEC'. Later, these hourly averaged indices were plotted for 'event days' with respect to 'Universal Time (UT)', and compared with overlaid plots of 'quiet day mean VTEC' and 'event day VTEC' in order to explain fluctuations in ionospheric TEC as a result of increasing or decreasing solar and geomagnetic activity.

In this study, TEC data for 2015 over the Indian subcontinent has been extracted from RINEX observation (.o) files that are downloadable from the IGS data service portal hosted by NASA: ftp://cddis.gsfc.nasa.gov/gnss/data/daily/2015/. RINEX .o files are extracted using an open-source software designed by Dr. Gopi Seemala of the Indian Institute of Geomagnetism (IIG). Once extracted, each observation file provides magnitude of VTEC in the ionospheric region over the respective IGS station for the respective day of year with a temporal resolution of one minute. Apart from plotting these VTEC values for each location with respect to 'UT' to observe variation of ionospheric TEC on 'event days' and 'quiet days', this data was further used to generate a contour plot for mapping 'Mean Annual VTEC' with respect to 'UT' and 'Geographic Latitude' for the year of 2015.

Finally, GPS error during 'event days' and 'quiet days' has been calculated using the RINEX .o files and RINEX navigation (.n) files that are downloadable from the above mentioned IGS data portal. The .n file contains ephemeris data (precise clock and orbit measurements) that is transmitted by the GPS satellite. The RINEX .o and .n files were processed in 'RTKLib' software to obtain solution files (.pos). 'RTKLib' is an open source program package for GNSS positioning. Comparing the positioning obtained from the RTKLib solution files with the actual position of the station (geographic latitude and geographic longitude), GPS error in North-South (N-S) and East-West (E-W) direction was calculated. The GPS error is so calculated and plotted for 'event days', and is overlaid with 'quiet day mean GPS error' that is calculated by averaging GPS error recorded on the five quietest days of March 2015.

4 Results

4.1. Observations of VTEC from three stations across India between 16 March 2015 and 20 March 2015

From Fig. 1 it can be observed that, the first solar event occurred on 17 March 2015, with the Sudden Storm Commencement (SSC) occurring at 0445 UT. After SSC, the initial fast decay lasted till 0700 UT. Subsequently the Main Phase (MP) of the storm started at 0800 UT and ended at 2200 UT, when the Dst value reached its lowest at -223 nT. The Recovery Phase (RP) of the storm started at 2200 UT on 17 March 2015, and the Dst continued to be lower than -50 nT until 1000 UT on 20 March 2015.

An IMF with southward B_z of magnitude -16 nT came into interaction with the magnetosphere at 0800 UT on 17 March 2015. As a result, the Dst decreased to -73 nT and K_p measured 7.7 at 1200 UT, indicating a severe geomagnetic storm. On the same day, an IMF with a southward B_z of -18 nT came into interaction with the magnetosphere at 1400 UT. Immediately after this, the Dst dropped to extreme negative values on 17 March 2015, reaching -223 nT at 2200 UT. The K_p index remained higher than 7 until the midnight (0000 UT) of 18 March 2015, indicating severe storm conditions throughout the afternoon and evening of 17 March 2015. The average Dstand K_p before the storm, on the quiet days of 14, 15 and 16 March 2015 are 11 nT and 1.8 respectively.

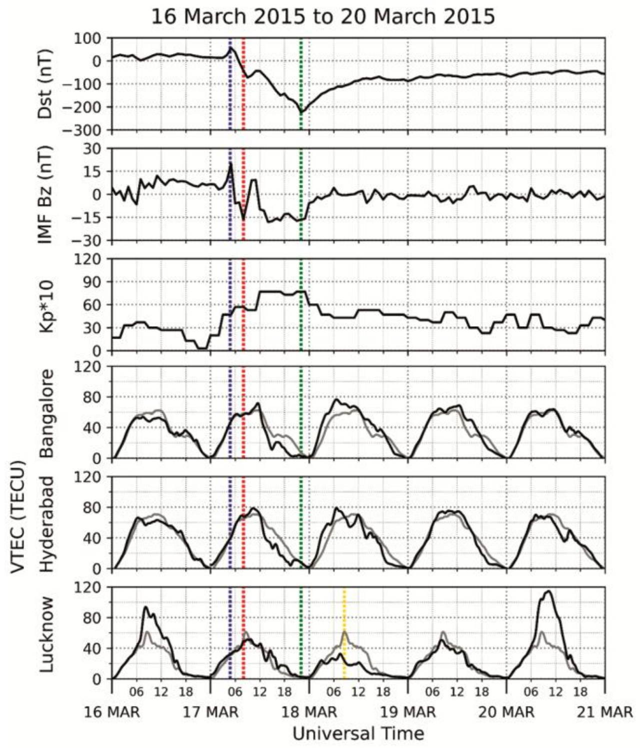

Fig. 1 — A graphical representation of Dst, IMF Bz, K_p index, VTEC and quiet day mean VTEC between 16-20 March 2015 at Bangalore, Hyderabad and Lucknow. The Sudden Storm Commencement time (SSC~0445 UT on 17 March) is shown by the blue dotted line; the Major Phase Commencement time (MPO~0800 UT on 17 March) is shown by the red dotted line; the Recovery Phase Commencement time (RPO~2200 UT on 17 March) is shown by the green dotted line; The peak hours of ionization on 18 march 2015 at Lucknow is shown by the yellow dotted line; VTEC variation is illustrated by the black solid line; Quiet day mean VTEC variation is illustrated by the grey solid line.

The average Dst and K_p after the storm subsided, on the quiet days of 18, 19 and 20 March 2015 are -76 nT and 4.1 respectively.

Figure 1 further illustrates VTEC observations from three stations across India plotted for event days. VTEC at Lucknow on quiet days of March reaches its highest values at approximately 0830 UT, and VTEC starts depleting slowly from the very next hour till it reaches its lowest values at approximately 1600 UT. However, after SSC, electron content depletions trigger an immediate negative ionospheric storm in Lucknow on 17 March 2015. VTEC during the peak hours of ionization (0830 UT) of 17 March 2015 depleted by 19 percent, when compared to the quiet day mean VTEC value at the same time. After the Main Phase (MP) of the storm ended at 2200 UT on 17 March 2015, a delayed and more intense negative ionospheric storm was observed at Lucknow on 18 March 2015. VTEC during the peak hours of ionization of 18 March 2015 depleted by 61 percent, when compared to the quiet day mean VTEC value at the same time. A negative ionospheric storm was observed again on 19 March 2015 at Lucknow, and it was similar to that observed after SSC on 17 March 2015. This meant, the VTEC during peak hours of ionization of 19 March 2015 decreased by 19 percent, when compared to quiet day mean VTEC value at the same time. VTEC at Lucknow recovered exponentially on the final event day, reaching its maximum value of 113 TECU at 1000 UT on 20 March 2015. This is the highest recorded VTEC value at Lucknow in all five days encompassing event 1. This meant a phenomenal 70 percent increase in VTEC during peak hours of ionization of 20 March 2015, when compared to quiet day mean VTEC value at the same time.

At Hyderabad and Bangalore, the quiet days and storm days show very similar TEC patterns and behaviors. VTEC at Hyderabad and Bangalore on quiet days of March reaches its highest values at 1030 and 1130 UT respectively, and continues to be high until 1200 UT. VTEC starts slowly depleting after 1200 UT, till it reaches its lowest values at 2000 UT and 2100 UT respectively. After SSC, enhancements in electron content trigger an immediate positive ionospheric storm in Hyderabad and Bangalore on 17 March 2015. The VTEC during peak hours of ionization (1030 UT and 1130 UT respectively) of 17 March 2015 increased by 10 percent in Hyderabad and 13 percent in Bangalore, when compared to quiet day mean VTEC value at the same time at the respective locations. After the Main Phase (MP) of the storm ended at 2200 UT on 17 March 2015, an early positive ionospheric storm was observed at Hyderabad and Bangalore on 18 March 2015 at 0640 UT. VTEC at 0640 UT on 18 March 2015 increased by 21 percent in Hyderabad and 26.5 percent in Bangalore, when compared to quiet day mean VTEC value at the same time at the respective locations. On 18 March 2015, VTEC reached its highest value at 0640 UT in Hyderabad and Bangalore. This implies that the VTEC peak after storm day shifted to earlier UT at both locations, when compared to VTEC peak on the quiet days at the respective locations. The positive ionospheric storm triggered in Hyderabad and Bangalore on 17 March 2015 subsides on 19 March 2015, when magnitude of VTEC slowly decreases to normal quiet day values and TEC behavior resembled that of the quiet days.

4.2. Effect on GPS measurements at Bangalore between 16 March 2015 and 20 March 2015

Form Fig. 2 it can be observed that, at Bangalore, the highest GPS error on 17 March 2015 in the East-West (E-W) direction is +5 m at 1530 UT. The average GPS error in the E-W direction between 1530 and 1600 UT on 17 March 2015 was +3 m. This can be attributed to the sudden increase and decrease in VTEC between 1500 and 1800 UT on 17 March 2015 at Bangalore, which can be observed as a small secondary peak in Fig. 1 reaching 21 TECU at 1610 UT. An average GPS error of -3 m was recorded between 0730 and 0800 UT on 17 March 2015 in the North-South (N-S) direction at Bangalore, following the Sudden Storm Commencement (SSC) at 0445 UT. An average error of -3 m was recorded again between 1000 and 1100 UT in the N-S direction on 17 March 2015, following the commencement of the Main Phase (MP) of the storm at 0800 UT. Finally, an average GPS error of -4 m was recorded in the N-S direction between 1500 and 1600 UT on 17 March 2015 at Bangalore. The high GPS error in N-S directions between 1500 and 1600 UT can be attributed to the small secondary peak in Bangalore between 1500 and 1800 UT on 17 March 2015. On 18 March 2015, at Bangalore, the highest GPS error in the N-S direction was +6 m at 0520 UT. This can be attributed to the early positive ionospheric storm that occurred in Bangalore on 18 March 2015. On the same day and location, average GPS error in the N-S direction was +4 m between 1800 and 1840 UT.

4.3. Effect on GPS measurements at Hyderabad between 16 March 2015 and 20 March 2015

From Fig. 3 it can be observed that, at Hyderabad, the highest GPS error on 17 March 2015 in the East-West (E-W) direction is +6.8 and +6.3 m at 1500 and 1630 UT respectively. This can be attributed to the sudden increase and decrease in VTEC between 1500 and 1630 UT on 17 March 2015 at Hyderabad, which can be observed as a small secondary peak reaching 32 TECU at approximately 1600 UT in Fig. 1. While the average GPS error in the E-W

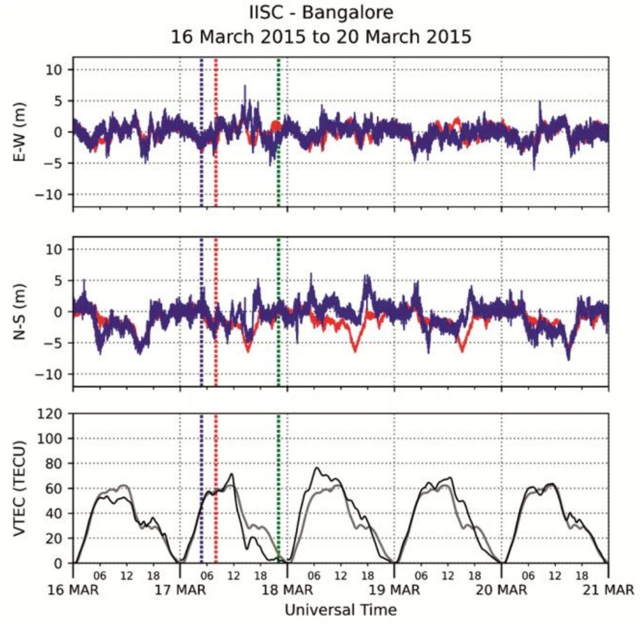

Fig. 2 — GPS error in East-West (E-W) and North-South (N-S) directions along with VTEC and quiet day mean VTEC,between 16 and 21 March 2015 at Bangalore. The solid blue line denotes measured GPS error during storm days; the solid red line denotes quiet day mean GPS error; the Sudden Storm Commencement time (SSC~0445 UT on 17 March) is denoted by the blue dotted line; the MajorPhase Commencement time (MPO~0800 UT on 17 March) is denoted by the red dotted line; the Recovery Phase Commencement time (RPO~2200 UT on 17 March) is denoted by the green dotted line.

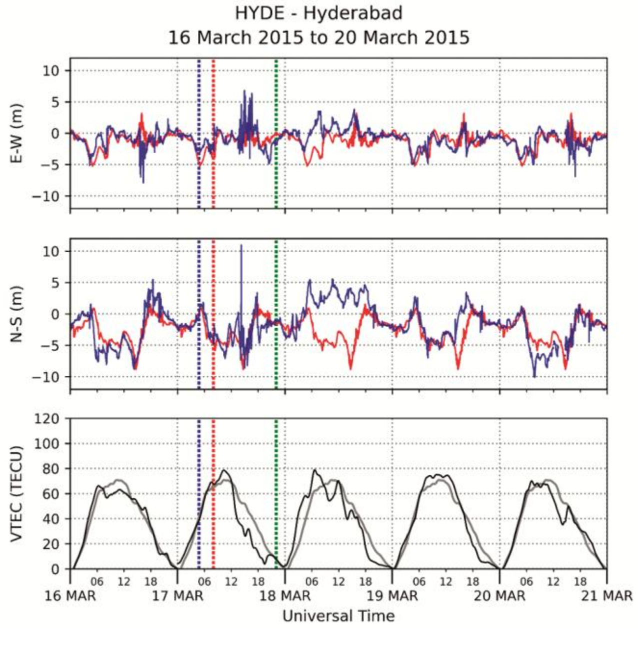

Fig. 3 — GPS error in East-West (E-W) and North-South (N-S) directions along with VTEC and quiet day mean VTEC,between 16 and 21 March 2015 at Hyderabad. The solid blue line denotes measured GPS error during storm days; the solid red line denotes quiet day mean GPS error; the Sudden Storm Commencement time (SSC~0445 UT on 17 March) is denoted by the blue dotted line; the Major Phase Commencement time (MPO~0800 UT on 17 March) is denoted by the red dotted line; the Recovery Phase Commencement time (RPO~2200 UT on 17 March) is denoted by the green dotted line.

direction between 1500 and 1630 UT on 17 March 2015 is +2 m only, the error during this timeframe constantly fluctuates to +4 m and +5 m. An average GPS error of +3.2 m was recorded between 0730 and 0800 UT in the E-W direction on 18 March 2015. This can be attributed to the early positive ionospheric storm that occurred on 18 March 2015 at 0640 UT in Hyderabad. At Hyderabad, on the quiet days of March, mean GPS error in the North-South (N-S) direction between 0700 and 1130 UT is -4.6 m. This can be attributed to the increasing electron content due to ionization in the atmosphere during sunlit hours of the day. The comparison between N-S GPS error during storm days and mean N-S GPS error during quite days that is illustrated in Fig. 2, clearly shows that measured GPS error deviates significantly from quiet day mean GPS error at 0545, 1040 and 1745 UT on 18 March 2015. The GPS error in N-S direction at the aforementioned durations of time is +5 m at Hyderabad. While the GPS error in N-S direction at 0545 UT can be attributed to the early positive ionospheric storm that occurred on 18 March 2015 at 0640 UT in Hyderabad, the GPS-error in N-S direction at 1040 UT can be attributed to the sudden increase in VTEC between 1000 and 1200 UT. In Fig. 1, this can be observed as a secondary peak at 1200 UT on 18 March 2015 at Hyderabad.

4.4. Effect on GPS measurements at Lucknow between 16 March 2015 and 20 March 2015

From Fig. 4 it can be observed that, at Lucknow, the highest GPS error on 17 March 2015 in the East-West (E-W) direction is +7.2 m at 1620 UT. The average GPS error in the E-W direction between 1520 and 1620 UT is +4.4 m. This can be attributed to the sudden increase and decrease in VTEC on 17 March 2015 at Lucknow at two instances: between 1345 and 1545 UT, and between 1615 and 1850 UT. These instances can be observed in Fig. 1 at Lucknow as a small secondary peak reaching 37 TECU at approximately 1430 UT, and another smaller tertiary peak reaching 18 TECU at 1710 UT. An average GPS error of +3.7 mwas recorded between 0210 and 0340 UT in the E-W direction on 18 March 2015 at Lucknow. This can be attributed to the sudden increase and decrease in VTEC between

0220 and 0400 UT on 18 March 2015 at Lucknow, which can be observed as a small peak in Fig. 1 reaching 24 TECU at 0300 UT. Similarly, an average GPS error of +3.5 m was recorded between 0700 and 0740 UT in the E-W direction on 18 March 2015 at Lucknow. This can be attributed to the sudden increase and decrease in VTEC between 0430 and 0900 UT on 18 March 2015 at Lucknow, which can be observed as a sharp secondary peak in Fig. 1 reaching 33 TECU at 0730 UT. The average GPS error in the North-South (N-S) direction between 0600 and 0740 UT on 18 March 2015 at Lucknow is +7.8 m. The highest GPS error of +11.3 m in the N-S direction was recorded at Lucknow during this time at approximately 0615 UT. This can be attributed to the sharp secondary peak between 0430 and 0900 UT at Lucknow on 18 March 2015.

5 Discussions

5.1 VTEC response to geomagnetic storm on 17 March 2015 at Bangalore, Hyderabad and Lucknow

At the low-latitude stations of Bangalore and Hyderabad, VTEC on quiet days generally reaches its peak values between 1100 UT. During the geomagnetic storm on 17 March 2015, positive ionospheric storms are observed at both locations on 17 March 2015 and 18 March 2015. After the commencement of Main

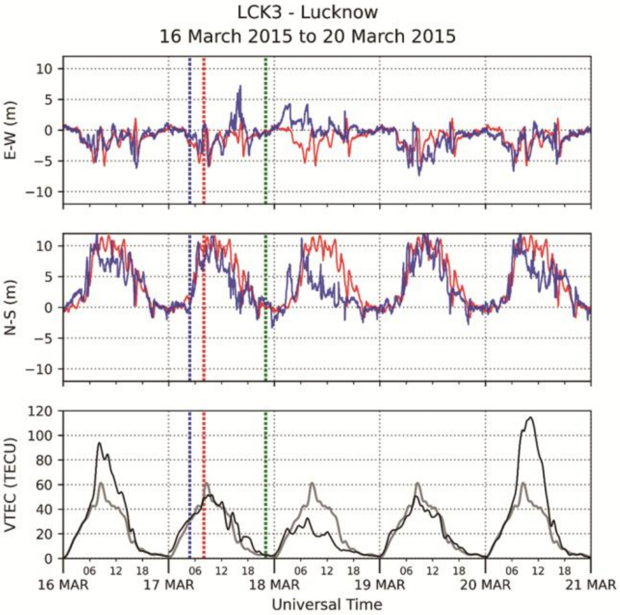

Fig. 4 — GPS error in East-West (E-W) and North-South (N-S) directions along with VTEC and quiet day mean VTEC,between 16 and 21 March 2015 at Lucknow. The solid blue line denotes measured GPS error during storm days; the solid red line denotes quiet day mean GPS error; the Sudden Storm Commencement time (SSC~0445 UT on 17 March) is denoted by the blue dotted line; the Major Phase Commencement time (MPO~0800 UT on 17 March) is denoted by the red dotted line; the Recovery Phase Commencement time (RPO~2200 UT on 17 March) is denoted by the green dotted line.

Phase (MP) on the early hours of 17 March 2015, the VTEC peak on that day shifted to later UT at low-latitudes. An early positive ionospheric storm occurred again on the early hours of 18 March 2015 at both locations. Both positive ionospheric storms can be attributed to enhanced Equatorial Ionospheric Anomaly (EIA) or "Fountain Effect". The thermospheric winds present in the E-region laying over the equator causes the ions to travel across the magnetic field lines. The moving ions create an eastward electric field (E), whose electric field lines are mapped along the northward magnetic field (B) lines. This creates an upward (E x B) plasma drift resulting in the fountain effect, which is responsible for enhanced TEC in the equatorial and low-latitude regions [25]. Furthermore, a twin-peak is observed at Hyderabad on 18 March 2015 where VTEC reaches peak values at 0640 (79 TECU) and 1200 UT (70 TECU). While the enhancement in VTEC on the early hours of 18 March 2015 at Hyderabad can be attributed to storm induced effects on ionosphere, the delayed enhancement at 1200 UT can be attributed to EIA. A possible cause for decrease in VTEC between 0700 and 1200 UT on 18 March 2015 could be an increase in recombination rates due to changing ionospheric chemistry and/or temperature at this time. This temporary E x B plasma drift produces a peak of ionization at 1200 UT on 18 March 2015 at Hyderabad, which subsequently decreasesduring the night. Another possible cause for this second VTEC peak at 1200 UT could be Prompt Penetration Electric Fields (PPEF), which are driven by the leakage of high-latitude convection electric fields to low-latitudes. The intense turbulence of the electric fields resulting from the magnetosphere–ionosphere interactions could be responsible for dramatic changes in VTEC.

At the mid-latitude station of Lucknow, VTEC on quiet days of March generally reaches its peak values between 0800 and 0900 UT. This duration is known as the 'peak hours of ionization'. At Lucknow, ionospheric storm occurred immediately after SSC on 17 March 2015, and following the termination of Main Phase (MP), when geomagnetic disturbance is at its maximum. Since the termination of Main Phase (MP) occurs late at night, an early negative ionospheric storm is witnessed on 18 March 2015, with VTEC reaching its peak values during the day at earlier UT. The negative ionospheric storm conditions at Lucknow can be attributed to enhanced electron content losses due to composition changes in the ionosphere. According to Mendillo[2], composition changes that influence negative storm conditions are a result of storm induced modifications to thermospheric convection. On the quiet days following a geomagnetic storm, the VTEC increases abnormally as observed on 20 March 2015, where VTEC increases after three consecutive days that saw TEC depletions induced by an extremely strong geomagnetic storm. This VTEC enhancement on 20 March 2015 at Lucknow can be attributed to electron content added into the region's ionosphere through convection from higher latitudes.

Furthermore, smaller VTEC peaks illustrating sudden enhancements in VTEC are observed on 17 and 18 March 2015 at all three locations between 1200 UT and 1800 UT. Such delayed electrodynamics can arise from winds generated by auroral heating that reach low latitudes. This is also known as the "Disturbance Dynamo" mechanism. The delayed electric field produced by the disturbance dynamo is driven by joule heating due to storm energy input[4,26-28]. Depending on the polarity and duration of these electric fields, they can either cause large uplifts or downdrafts of the ionospheric plasma leading to enhancement or depletion of VTEC. However, an analysis of the mechanisms leading to TEC enhancement and depletion is beyond the scope of this paper.

5.2 GPS error caused by variations in ionospheric VTEC during storm time at Bangalore, Hyderabad and Lucknow:

At low-latitude regions of Bangalore and Hyderabad, the highest error in E-W direction on 17 March 2015 was observed between 1500 and 1630 UT. In both regions, this can be attributed to the secondary VTEC peak between 1500 and 1600 UT as observed in Fig. 1. The cause of such enhancement in VTEC in the post-afternoon duration of the day could be due to delayed electrodynamics induced by the geomagnetic storm that occurred on the early hours of 17 March 2015. While GPS error in the E-W direction on 18 March 2015 at Bangalore did not deviate much from the respective quiet day mean GPS error, an average GPS error of -3.2 m was recorded in the E-W direction on 18 March 2015 at Hyderabad. This could be attributed to VTEC enhancements caused by magnetospheric and ionospheric convection processes during the early positive ionospheric storm that occurred in Hyderabad at 0645 UT on 18 March 2015. Furthermore, while the GPS error in N-S direction on 17 March 2015 at Hyderabad did not deviate much from the respective quiet day mean GPS error, an average GPS error of -3 m was recorded in the N-S direction on 17 March 2015 in Bangalore between 0700 to 0800UT, and 1000 and 1100 UT. VTEC enhancements triggered after Sudden Storm

Commencement (SSC) and during the Main Phase (MP) of the storm could be the cause of GPS error in the N-S direction at Bangalore on the morning hours of 17 March 2015. At both Bangalore and Hyderabad, the GPS error in the N-S direction on 18 March 2015 was recorded at +5-6 m between 0500 and 0600 UT. This could be attributed to VTEC enhancements caused by the early positive ionospheric storm that occurred between 0600 and 0700 UT on 18 March 2015 at both locations. A GPS error of +5 m was recorded in the N-S direction on 18 March 2015 at Hyderabad at 1040 UT. This could be attributed to VTEC enhancement between 1000 UT and 1200 UT in Hyderabad on 18 March 2015 that can be observed as a clear secondary peak in Fig. 1.

At the mid-latitude region of Lucknow, high GPS error was recorded in both E-W and N-S directions during storm days. While the highest GPS error of +7.2 m was recorded at Lucknow in the E-W direction on the evening (1620 UT) of 17 March 2015, the highest GPS error of +11.3 m was recorded at Lucknow in the N-S direction on the morning (0615 UT) of 18 March 2015. In almost all instances where a GPS error of +3 m was exceeded in the E-W and N-S directions at Lucknow on 17 and 18 March 2015, the cause seems to be sudden depletions in VTEC governed by recombination chemistry that is followed by an immediate enhancement in VTEC due to magnetospheric convection processes at mid-latitudes.

5.3. Contour plot depicting 'Mean Annual VTEC' with respect to 'UT' and 'Geographic Latitude' for the year of 2015

From Fig. 5, it can be observed that, the EIA region lies between 10 N and 20 N latitudinal regions. Further, the Mean Annual VTEC values observed at Lucknow are lower than those at low-latitude regions of Hyderabad and Bangalore. However, on certain quiet days of the year, VTEC at Lucknow reaches values that largely exceed those at the low-latitude stations. This can be observed in Fig. 1 on the quiet days of 16 and 20 March 2015.

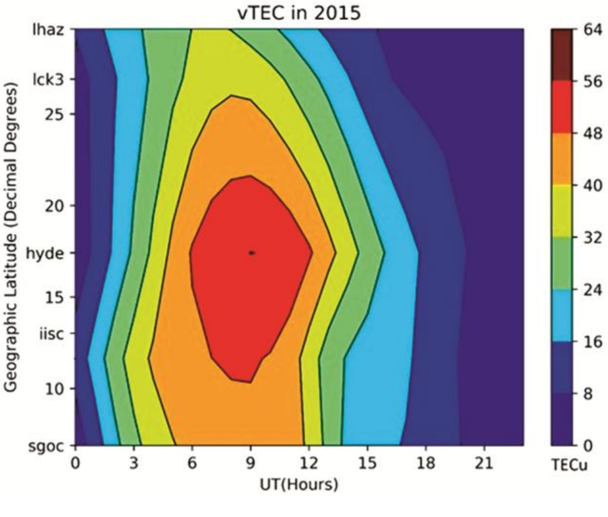

Fig. 5 — Contour plot showing diurnal variation of Mean Annual VTEC with respect to Geographic Latitude for the year 2015.

6 Conclusions

Ionospheric disturbances caused by severe geomagnetic storms at low-latitude and mid-latitudes regions of India accurately coincide with previous observational studies on storm-time VTEC variations at similar latitudinal regions around the globe. For instance, while a negative ionospheric storm was witnessed at the mid-latitude region of Lucknow in response to the geomagnetic storm that occurred on 17 March 2015, positive ionospheric storms occurred in the low-latitude regions of Bangalore and Hyderabad where ionospheric VTEC is governed by electrodynamic mechanisms such as the EIA. Furthermore, storm induced effects on ionosphere are first felt at mid-latitude regions, and these effects last longer for negative ionospheric storms. While enhanced EIA plays a prominent role in positive storm phases, the delayed and prolonged storm effects play an equally important part in determining the duration and magnitude of VTEC enhancements. At low-latitude and mid-latitude regions, if the termination of Main Phase (MP) occurs in the evening, the VTEC peak increases in magnitude and shifts to earlier UT the following day. Further, quiet day mean VTEC values observed at Lucknow are lower than those at low-latitude regions of Hyderabad and Bangalore. This is due to the increased intensity and duration of solar radiation at low-latitude regions. However, on certain quiet days of the year, VTEC at Lucknow reaches values that largely exceed those at the low-latitude stations. This can be observed in figure 1 on the quiet days of 16 and 20 March 2015. This study strongly recommends further inquiry into the thermospheric and magnetospheric convection processes, which govern such VTEC enhancements at mid-latitude region of Lucknow on quiet days.

GPS error in E-W and N-S directions is higher at the mid-latitude region of Lucknow than at the low-latitude regions of Bangalore and Hyderabad. While GPS error at Lucknow during storm time could be attributed to sudden increases and decreases in VTEC that are governed by recombination chemistry and magnetospheric convection processes at mid-latitudes, GPS error at Bangalore and Hyderabad are caused by increased VTEC during positive ionospheric storm durations that are governed by magnetospheric and ionospheric convection processes at low-latitudes. At the low-latitude regions of Bangalore and Hyderabad, fluctuations in VTEC caused by delayed electrodynamics contribute to GPS error in the post afternoon durations of the storm days (17 and 18 March 2015), especially between 1400 and 1800 UT.

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