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# "IMPACTS OF INTENSE GEOMAGNETIC STORM ON NAVIC/IRNSS SYSTEM"

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## ABSTRACT

The Total Electron Content (TEC) of Navigation with the Indian Constellation (NavIC)/ Indian Regional Navigation Satellite System (IRNSS) was examined under the influence of an intense geomagnetic storm occurred on 8 September, 2017, in the low latitudes of the Indian region. One week (3 September, 2017 to 9 September, 2017) data from five stations located in the equatorial region and in the Equatorial Ionization Anomaly (EIA) area in India are collected from Accord NavIC/IRNSS dual-frequency (L5 and S-band) receivers for the investigation. The diurnal TEC comparison between IRI-2007 empirical model and NavIC/IRNSS dual frequency model is done. Through a comparative study, of TEC at the five locations, we clearly observed geomagnetic storms using dual-frequency NavIC/IRNSS receivers, while the diurnal TEC behavior of the IRI-2017 model was the same on all observation days. On the intense stormy day, we observed an increase of about 19 TECU for the area near the equator and decrease of about 20 TECU in the EIA region compared to other observed quiet days. As a result, positive correlation between TEC and storm occurrence were found in the equatorial region, while a negative one in EIA region. In order to support dramatic change in TEC during intense geomagnetic storm, geomagnetic indices and solar wind/IMF parameters maps are added. The results have been further validated using TEC map from IGS data and thermosphere O/N2 ratio map from Global UV Imager (GUVI).

## 1. INTRODUCTION

The regional Navigation with the Indian Constellation (NavIC)/Indian Regional Navigation Satellite System (IRNSS) system developed by the Indian Space Research Organization (ISRO) will use radio wave signals in L5 band (1164.45 to 1188.45 MHz) with a carrier frequency of 1176.45 MHz (F1) and S band (2483.5 to 1188.45 MHz) with a carrier frequency of 2492.08 MHz (F2), in order to provide accurate positioning anytime in India [Desai et al., 2018; 2017; 2016; ICD, 2011]. NavIC/IRNSS signals that propagated through the low latitude ionosphere are affected by the inhomogeneous, anisotropic, and dispersive nature of the ionosphere. This characteristic can introduce additionally unknown delay in the signals, which in turns cause a degradation of the positional accuracy of the NavIC/IRNSS system [Desai et al., 2018; 2015, Ruparelia et al., 2015]. These degradations depend on the Total Electron Content (TEC), signal frequency and elevation angle of NavIC/IRNSS satellites above the horizon. Ionospheric TEC is the total number of electrons that are integrated between two points along a tube of one square meter cross-section; TEC variation depends entirely on geographical locations and geophysical events such as solar flares and geomagnetic storms [Chakraborty et al., 2014]. Geomagnetic storm occurs when the Earth's magnetic field is affected by solar disturbance or solar flare.

The severity of a geomagnetic storm is usually classified on the basis of Disturbance storm time index Dst (i.e., the average value of the horizontal component of the earth's magnetic field measured in nano Tesla (nT)) and a weighted average of K-indices (Kp, Planetary K indices) from a network of geomagnetic observatory. The K index quantifies the perturbation of the horizontal component of the Earth's magnetic field, where the Ap index provides the daily average of geomagnetic activity. According to the Dst and Kp indices geomagnetic storm is classified as super (Dst < -25° NT, Kp=9), intense (-10° NT > Dst > -25° NT, Kp=8), or medium (Dst <-10° NT, Kp=7) [Gonzalez et al., 1994, Chakraborty et al., 2014; 2015]. The geomagnetic storms can be also identified by various other parameters such as Auroral Electrojet (AE), the symmetric disturbance the magnetic field H (SYM-H), the Interplanetary Magnetic Field (IMF), the Interplanetary Electric Field (IEF) and the solar radio flux at a wavelength of 10.7 cm (2800 MHz) called the F10.7 index.

Geomagnetic storm effects on Global Positioning System (GPS) based navigation data were observed by Rao et al., in 2009, Kumar et al., in 2010, Rao et al., in 2013, Astafyeva et al., in 2014, De Siqueira Negreti et al., in 2017. Rao et al., [2009], found that in the Equatorial Ionization Anomaly (EIA) crest region during the geomagnetic storms on November 9 and 10, 2004, the TEC value raised up to 90 TEC units, which is equivalent to a ionospheric delay around 15 meters. Rao et al. 2013, observed a significant increase of the TEC values during the three major geomagnetic storms in 2011; this was obtained from GNSS system by using the International Reference Ionosphere (IRI) 2007 empirical model at a low-latitude Bangalore (77.510E, 13.030N) station in India.. IRI model was also applied by Samed et al., [2016] and Abreu et al., [2017]; they compared GPS TEC over the western Black Sea and Brazilian sector respectively, during the unusual solar minimum activity in 2009. Astafyeva et al., (2014), showed that the density of Loss of Lock (LoL) increased up to a maximum of 3% during super storm and 1% when an intense storm occurred. During the 2013 high intensity, long duration, continuous auroral electrojet activity event, TEC increases from 25 to 80 % compared to quiet time were observed by De Siqueira Negreti et al., (2017). Desai et al., (2018) analyzed the impact of GIVE model for improving the positional accuracy of NavIC/IRNSS system under the quiet and disturbed days. However, the study about the effect of intense geomagnetic storms on NavIC/IRNSS system still remains open.

In this paper, we investigated the impacts of intense (minimum Dst = -124, Kp = 8, Ap = 106) geomagnetic storms beginning from September 08 2017 on newly emerging regional NavIC/ IRNSS systems. The effect of the storm is verified by analyzing the diurnal TEC behavior of one week data collected by dual frequency NavIC/IRNSS receivers at five different locations; one is located near the Indian equator (IIST Trivandrum) and four EIA are (SVNIT Surat, IIT Mumbai, CBIT Hyderabad, IIT Gandhinagar). A TEC map from the online IRI model was also added and the TEC changes for all observational days were found to be identical. The dual-frequency NavIC/IRNSS TEC statistical analysis shows that on a stormy day (8 September, 2017), the TEC increases of the NavIC/IRNSS satellite near the Indian equator is about ~20 TECU (TEC Units) and while the TEC in the EIA region decreased of ~14 TECU compared to what observed in quiet days. Therefore, the impact of the storm occurred as a positive increment in areas close to the equatorial region, while in the EIA area was negative. The geomagnetic indices such as Dst(nT), AE(nT), Sym-H(nT), IMF-Bz(nT) and interplanetary parameters (Kp, Ap) were observed to verify the existence of intense storms on September 8, 2017. The observation is further validated by plotting a world TEC map after collecting the data in IONEX file format from International GNSS Service (IGS) and thermosphere O/N2 ratio map from online Thermosphere Ionosphere Mesosphere Energetic and Dynamics (TIMED) based Global Ultraviolet Imager (GUVI) site.

## 2. GEOMAGNETIC PARAMETER ANALYSES AND DATA COLLECTION

The Dst(nT), AE(nT) and Sym-H(nT) indices from World Data Center (WDC) for geomagnetism, Kyoto (http:// wdc.kugi.kyoto-u.ac.jp), the Kp, Ap and F10.7 indexes from OMNIWeb data explorer (https://omniweb.gsfc.nasa.gov) and IMF Bz (nT) from Advanced Composition Explorer (ACE) level 2 data server (http://www.srl.caltech.edu /ACE /ASC /level2 /lvl2DATA_MAG.html) are obtained and observed for the storm verification. The appearance of the geomagnetic storm that began on 8 September 2017 is verified by plotting Kp (see Figure 1) Dst, Ap, AE, Sym-H, F10.7, IMF Bz, and IEF Ey indexes (see Figure 2) from 3 September to 9 September 2017. From the changes in the indices, it can be seen that the storm began on 7 September, 2017 at approximately 22:00 UTC (16:30 LT) and ended at 04:00 UTC on 9 September, 2017. The minimum values of the Dst index (-128nT) and Sym-H (-146nT) were found at 02:00 UTC on 8 September, 2017. Similarly, the AE and Ap indices are observed with maximum value of 236 and 2677 (nT), respectively. After 8 September, 2017, the AE index in-

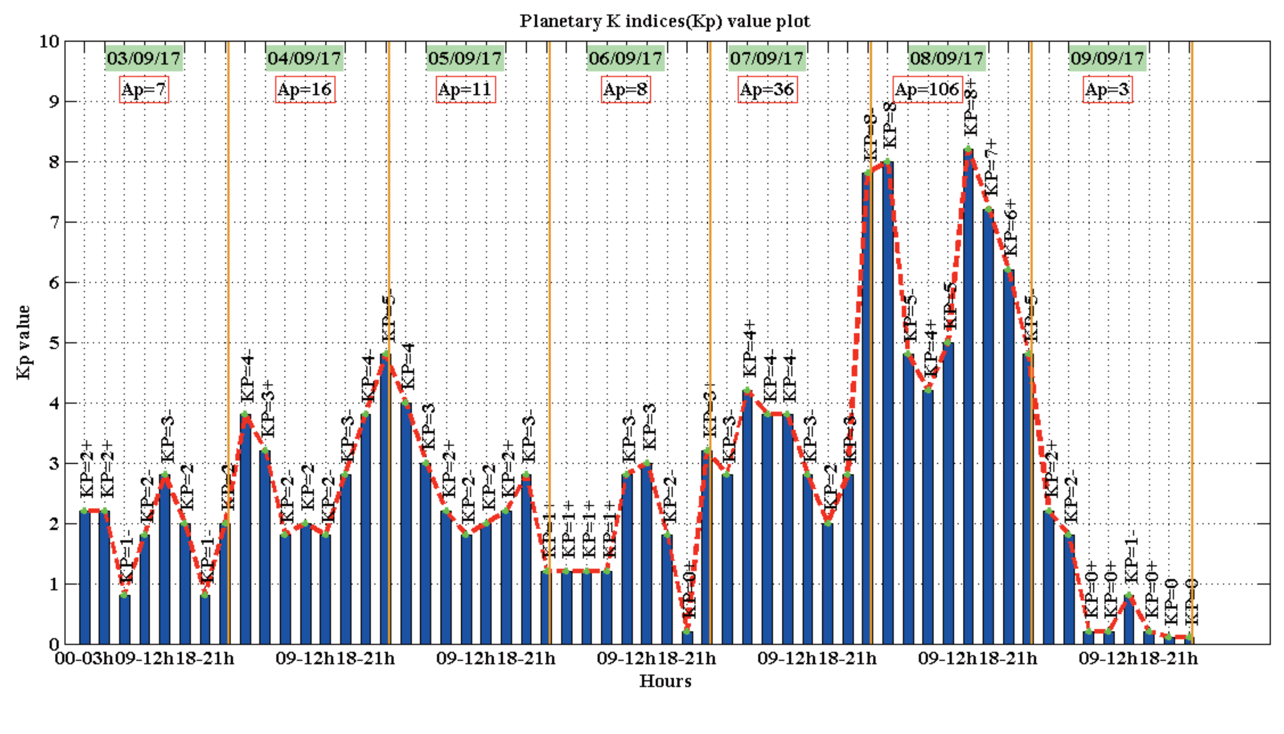


FIGURE 1. Graphical Represenatation of Kp Indices.

creased significantly, indicating that the heat generated during geomagnetic storms in high latitudes may lead to the generation of highly perturbed electric fields. Also, note that when the IMF Bz component downward direction, the IMF Ey upward and vice versa. The Kp value increase to 8 (see Figure 1), reaffirming the intense storm

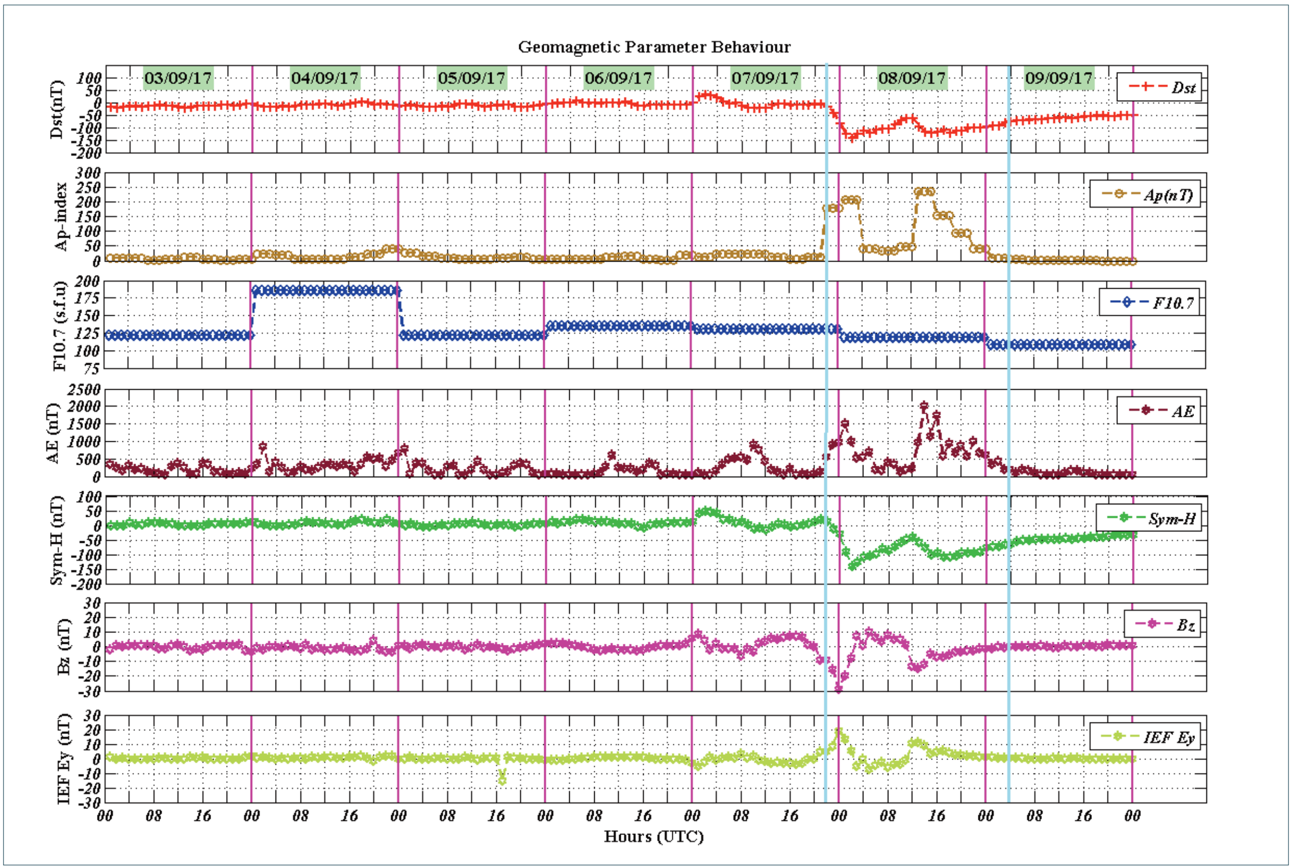


FIGURE 2. Graphical Represenatation of various geomagnetic parameters.

on 8 September, 2017.

The geographical location of data collection NavIC/IRNSS receiver station are as follows; SVNIT Surat (21.16° N, 72.78° E), IIT Mumbai (19.03° N, 72.91° E), CBIT Hyderabad (17.39° N, 78.31° E), IIT Gandhinagar (22.52° N, 72.92° E) and IIST Trivandrum (8.62° N, 77.03° E); their locations are depicted in Figure 3.

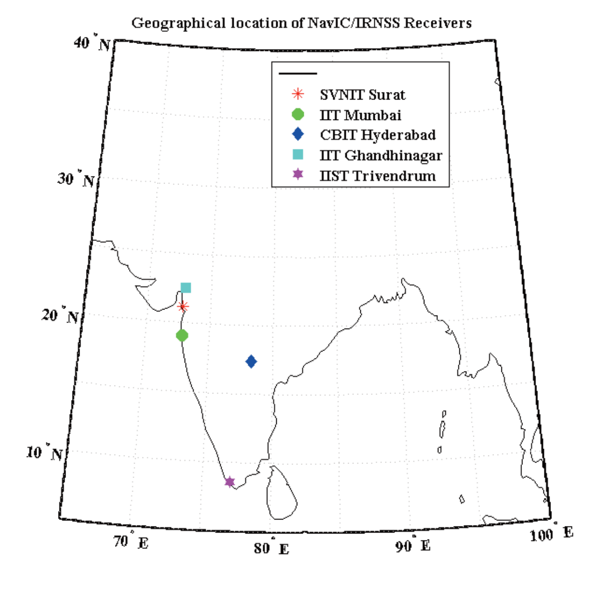


**FIGURE 3.** Geographical Location of NavIC / IRNSS receiver stations.

The IIST Trivandrum is located nearer to extended equatorial region, whereas the other four stations are located in EIA region. The TEC for the NavIC/IRNSS system can be estimated proportional to the rang difference using the dual frequency model given by Equation (1) [ICD, 2011].

$$STEC = \frac{1}{40.3} \times \frac{F_1^2 * F_2^2}{(F_1^2 - F_2^2)} (P1 - P2), (\text{electrons}/\ m^2), \quad (1)$$

$$\text{VTEC} = \text{STEC} * \text{F},$$

where, P1 and P2 are the pseudo-ranges of the NavIC/IRNSS signal at F1 (L5 band) and F2 (S band) frequencies, respectively. After correcting the satellite and receiver deviations, the Slant TEC (STEC) is converted to a Vertical TEC (VTEC) using an elevation (El) based mapping function. Using thin shell model by assuming a height of h=350 km above the earth surface and earth radius Re = 6378.137 km at Ionospheric Pierce Points (IPP), the elevation dependant mapping function is given by

$$F = \sqrt{1 - \left\{ \frac{R_e * \cos(E_l)}{R_e + h} \right\}^2} \quad (2)$$

The NavIC/IRNSS satellites data is collected by Accord NavIC/IRNSS+GPS receiver provided by Space Application Centre (SAC), ISRO Ahmedabad. The data for the Sardar Vallbhbhai National Institute of Technology (SVNIT), Surat (21.16° N, 72.78° E) is acquired by the Accord NavIC/IRNSS+GPS receiver, which is located at the Communication Research Laboratory of Electronics Engineering Department. The NavIC/IRNSS satellites data for the location of IIT Mumbai, CBIT Hyderabad, IIT Gandhinagar, IIST Trivandrum is provided by SAC, ISRO Ahmedabad through ftp link.

From 3 September, 2017 (Time Of Week Count (TOWC) =0) to 9 September, 2017 (TOWC=648000), the raw data files of the dual-frequency NavIC/IRNSS receivers for the above five locations were collected. At present, NavIC/IRNSS 1A is almost unusable due to the failure of the airborne atomic clock, and the NavIC/IRNSS 1I, which was navigated on April 12, 2014, replaced NavIC/IRNSS 1A [ISRO, 2018]. Therefore, the data of NavIC/IRNSS 1A was not considered for result analysis. The received data was distinguished day-wise for each of the NavIC/IRNSS satellites (labeled 1B to 1G). Initially, the distance between the NavIC/IRNSS satellites (1B to 1G) and the user receiver is calculated by extracting the time to travel information from the raw data. After calculating the ranges or distances for the single satellite, L5 and S bands TEC is measured using the dual-frequency approach presented in equation 1. Data analysis has been carried out using the MATLAB 2014 software tool.

For the above five geographic locations, the effects of geomagnetic storms can also be observed by collecting TEC using the online IRI model (https://omniweb.gsfc.nasa.gov). The IRI is the online standard empirical model developed by the Space Research Council (COSPAR) and the International Radio Science Union (URSU). The storm effect has been further verified after collecting and plotting data in IONEX file format from International GNSS Service (IGS) site (ftp://cddis.gsfc.nasa.gov/gnss/products /ionex) and Thermospheric O/N2 data mapped with spatial resolution of 1.75°x1.75° collected and mapped using GUVI (http://guvitimed.jhuapl.edu/guvi-galleryl3on2) during the storm event. Detailed results analysis are provided in the next section.

## 3. DISCUSSION OF DETAIL RESULT ANALYSIS

Figure 4 depicts the diurnal variation of TEC comparison of six NavIC/IRNSS (1B, 1C, 1D, 1E, 1F and 1G) satellites visible at the SVNIT Surat, EIA location. Time scales and dates are Universal Time (UT) or Uni-

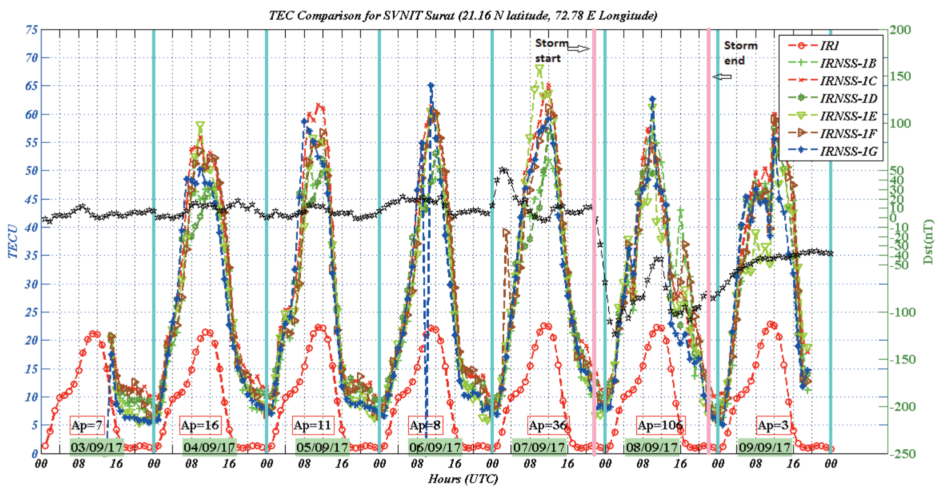


**FIGURE 4.** TEC Comparison between IRI-Model and Dual frequency NavIC/IRNSS Receiver for SVNIT Surat (21.16° N latitude, 72.78° E Longitude).

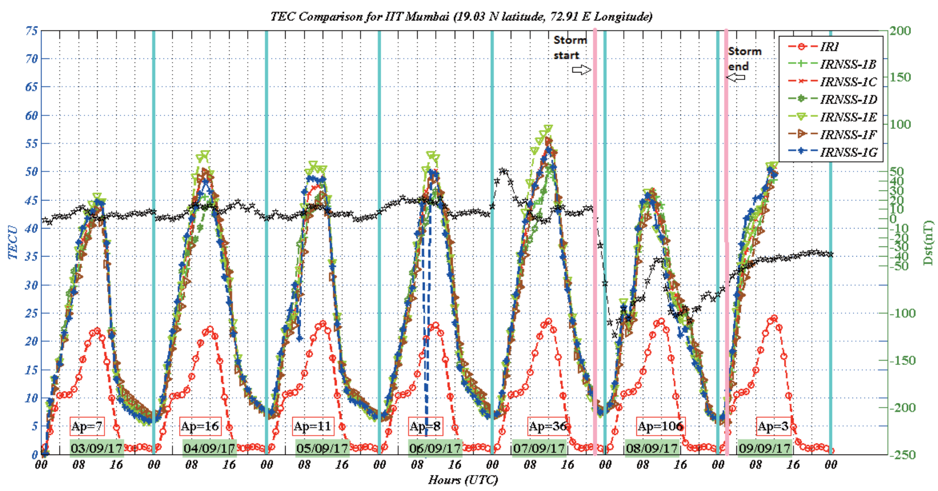


**FIGURE 5.** TEC Comparison between IRI-Model and Dual frequency NavIC/IRNSS Receiver for IIT Mumbai (19.03° N latitude, 72.91° E Longitude).

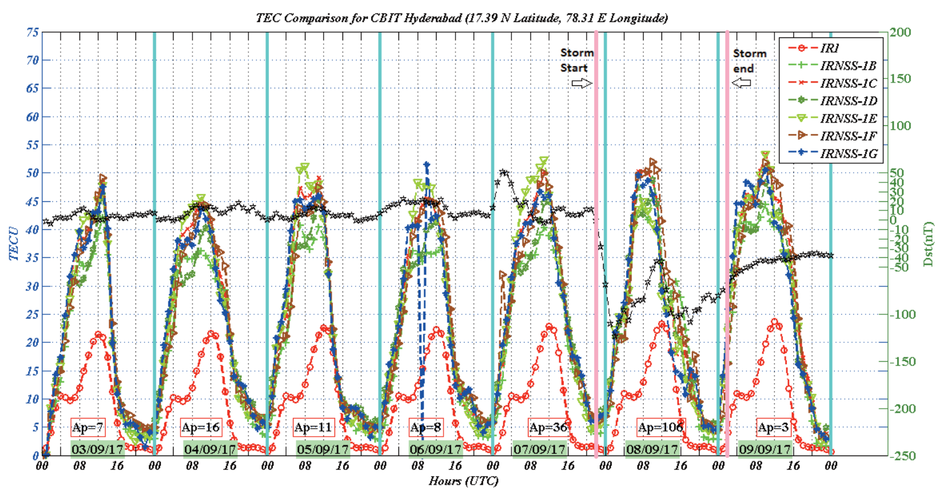


**FIGURE 6.** TEC Comparison between IRI-Model and Dual frequency NavIC/IRNSS Receiver for CBIT Hyderabad (17.39° N latitude, 78.31° E Longitude)

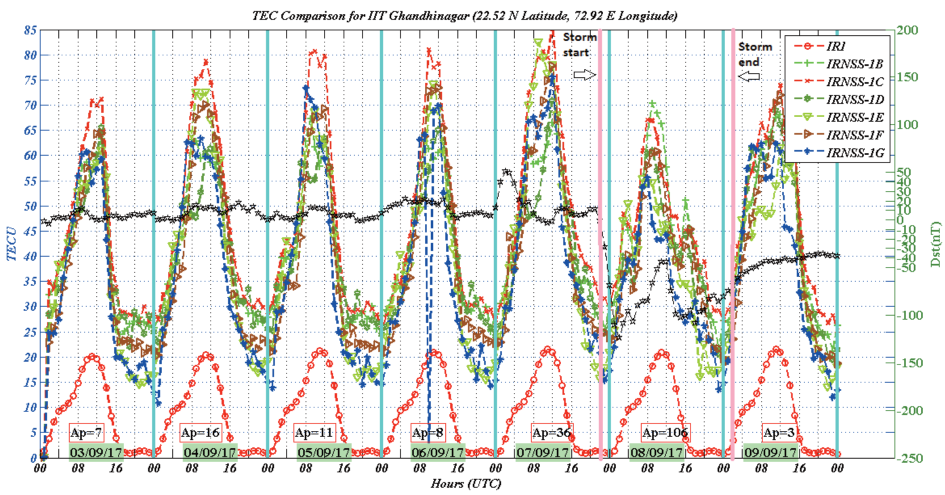


**FIGURE 7.** TEC Comparison between IRI-Model and Dual frequency NavIC/IRNSS Receiver for IIT Gandhinagar (22.52° N latitude, 72.92° E Longitude).

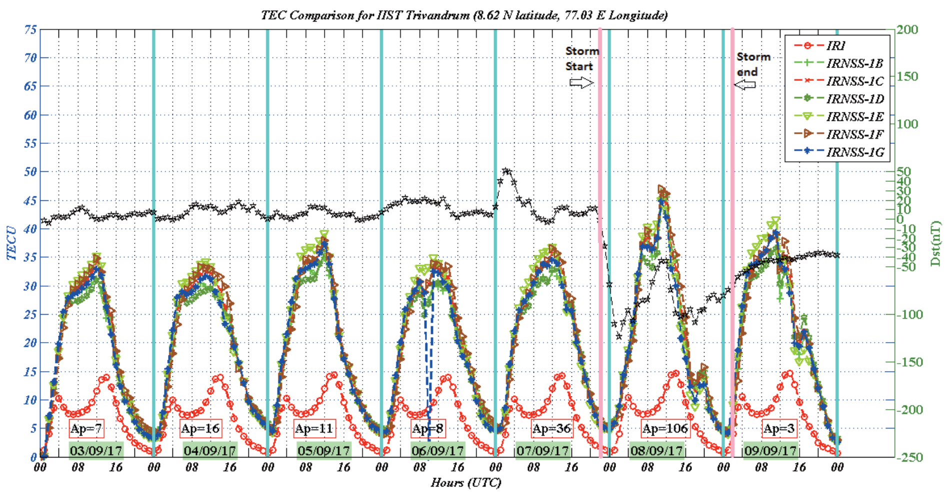


**FIGURE 8.** TEC Comparison between IRI-Model and Dual frequency NavIC/IRNSS Receiver for IIST Trivandrum (8.62° N latitude, 77.03° E Longitude).

versal Time Coordinates (UTC). The corresponding Local Time (LT) or Indian Standard Time (IST) is 5.30 hours ahead to UTC. For the available data starting from TOWC = 47290 (3 September, 2017, UTC= 13:08:10, LT = UTC+ 5:30 = 18:38:10) to TOWC = 584267 (9 September, 2017, UTC = 18:17:47, LT = UTC + 5:30 = 23:47:47) NavIC/ IRNSS satellites TEC is plotted. The TEC values estimated using the online IRI-2012 model at the SVNIT Surat location are also added for comparison. In order to observe TEC changes during geomagnetic storm events, the Dst index is also plotted as a reference. IRI-2012 TEC changes are almost the same for all the quiet days, with only 1 to 2 TECU increasing on storm days (8-9 September, 2017). Drastic changes in the TEC are observed for all NavIC/IRNSS satellite on 8 September, 2017 with respect to Dst index, confirming that the storm effects on this day. For all observation days, the lowest TEC for all NavIC/IRNSS satellites to be around 5 to 8 TECUs and IRI models 0.7 to 0.9 TECUs is found. On all observation days, the TECs of the NavIC/IRNSS 1B satellite is the lowest with respect to the TECs of all other NavIC/ RNSS satellites.

Similarly, Figures 5 to 8 depicts the TEC comparison at the EIA locations IIT Mumbai, CBIT Hyderabad, IIT Gandhinagar and near the equatorial location IIST Trivandrum, respectively for the visible six NavIC/IRNSS (1B, 1C, 1D, 1E, 1F and 1G) satellites. It is also observed that average maximum TEC for lowest latitude station (located nearer to equatorial region) IIST Trivendrum (8.62° N, 77.03° E) is around 35 to 40 TECU, while for the other station we have: CBIT Hyderabad (17.39° N, 78.31° E) is about 45 to 50 TECU, IIT Mumbai (19.03° N, 72.91° E) is around

50 to 60 TECU, SVNIT Surat (21.16° N, 72.78° E) is nearer 60 to 65 TECU and IIT Gandhinagar (22.52° N, 72.92° E) is around 65 to 85 TECU. Similarly, for the average minimum TEC, IIST Trivendrum is around 3 to 4 TECU, CBIT Hyderabad approximately 3 to 5 TECU, IIT Mumbai around 6 to 7 TECU, SVNIT Surat nearer 5 to 8 TECU and IIT Gandhinagar approximately 10 to 15 TECU. Therefore, it is found that TEC also increased from low latitude to high latitude. Similar observations are also found for the TEC estimation using the IRI-2012 model.

Sudden, changes in TEC are also observed at all NavIC/IRNSS receiver locations on 8 September, 2017. However, the changes in the IRI-2017 model are the same for all locations for all days. Hence, the IRI-2012 model fails to detect the event, while the dual-frequency NavIC/IRNSS receiver effectively identifies the existence of a geomagnetic storm. Details on the maximum and median TEC values are presented in Table 1.

According to the statistical analysis of equatorial IIST Trivandrum, it can be inferred that ~20 TECUs increment of maximum value is observed for 1B to 1G NavIC/IRNSS satellites (maximum TECU values 50.83, 48.09, 48.57, 46.05, and 50.55) during the geomagnetic storm event (8 September, 2017) compared to all the others normal days. At the same location, TEC median value is in a range between ~17 TECUs and ~23 TECUs for all NavIC/IRNSS Satellites. Similarly, for CBIT Hyderabad an increase of the maximum values of ~4 TECUs is observed during the geomagnetic storm event. Moreover, at IIT Mumbai the TEC values decrease up to 2 to 6 TECUs, at SVNIT Surat the decrease was ~10 TECUs and IIT Ghandhinagar reduction of maximum values of ~14 TECUs is observed for NavIC/IRNSS satellites during stormy days compared to quiet days.

The difference between the average value of the quiet days TECU (3 September, 2017 to 7 September, 2017, before the storm day) and the average of all satellite TECUs for the equatorial region (IIST Trivandrum), CBIT Hyderabad, IIT Mumbai, SVNIT Surat and IIT Gandhinagar are shown in Figures 9 to 13, respectively. From Figure 9, an ~16 TECUs increase from the average of quiet days is observed for IIST Trivandrum (area near the equator) at 10:00 UTC, on the stormy day (8 September, 2017). Similarly, CBIT Hyderabad and IIT Mumbai reduced of ~16 TECUs at 12:00 UTC, while SVNIT Surat reduced of ~18 TECUs at 13:00 UTC and IIT Gandhinagar of ~20 TECU. As a result, the positive change of the TEC related to the storm was found in areas close to the equator region (IIST Trivandrum and CBIT Hyderabad) and negative one for a EIA region (IIT Mumbai, SVNIT Surat, and IIT Gandhinagar).

To confirm this large diurnal TEC variation, we also examined the thermospheric layer O/N2 ratio and TEC map constructed from IGS station data. In order to verify the neutral component change during intense storm period, the O/N2 ratio retrieved by the GUVI instrument is shown in Figure 14. Based on the O/N2 data, these rates are observed to be higher than other normal days during geomagnetic storm events (8 September, 2017). The higher the O/N2 ratio is related to the increased ionization of the ionosphere, so the TEC increases and vice versa. Therefore, a correlation between the O/N2 ratio and the perturbed TEC was found.

The global TEC map data for the intense stormy day (8 September, 2017, corresponding to day 251) and day after the storm (9 September, 2017, corresponding to day 252) are downloaded from GNSS IGS server (ftp://cddis.gsfc.nasa.gov/ gnss/products/ionex/2017) in global IONEX file format [eg. codg2510.17i]. The global TEC mapping is done using MATLAB. Figure 15 shows the global TEC map for the 8-9 September 2017 with a time resolution of 2 hours. As it can be seen from Figure 15, an increment of about 10 to 20 TECU is observed on the intense stormy day (8 September 2017) compared to the quiet day (9 September, 2017). The TEC map of the IGS stations also shows that TEC values in the low latitude India region are high during the period of 14:00-20:00 UTC are, while in the other hours the TEC map show the normal behavior. Therefore, both the IGS TEC map and the GUVI-derived thermospheric layer O/N2 ratio show the same significant differences, as we observed in the NavIC/IRNSS TEC data at the IIST Trivandrum location. Regarding the different behavior of IIT Mumbai, IIT Gandhinagar, and SVNIT Surat India, it can be noted that on 8 September, 2017, there was a significant west-facing electric field during the recovery phase of the storm, which seems to inhibit the formation of an equatorial anomaly that usually occurs on a quiet day. This may be the reason for the positive trend of TEC response in IIST Trivandrum, while in IIT Mumbai, SVNIT Surat, IIT Gandhinagar is negative. Therefore, our results also confirm the observations of Buonsanto et al., 1990 and Pedatell et al., 2009 that positive and negative storm effects depend on the stage of the storm, the local time and latitude of the location.

## 4. CONCLUSION

The paper shows the impact of intense geomagnetic storm (8 September, 2017) on NavIC/IRNSS system for the low latitudes of Indian region. The investigation is carried out based on TEC, for the location of IIST Trivandrum (Equatorial region), SVNIT Surat, IIT

| | TECU (Maximum) | | | | | | TECU (Median) | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Date (dd/mm/yy) | IRNSS-1B | IRNSS-1C | IRNSS-1D | IRNSS-1E | IRNSS-1F | IRNSS-1G | IRNSS-1B | IRNSS-1C | IRNSS-1D | IRNSS-1E | IRNSS-1F | IRNSS-1G |
| IIST Trivandrum (8.62 N latitude, 77.03 E Longitude) | | | | | | | | | | | | |
| 3/9/17 | 31.28 | 34.22 | 31.36 | 35.53 | 35.04 | 33.17 | 17.78 | 17.36 | 17.47 | 17.57 | 18.16 | 17.71 |
| 4/9/17 | 30.54 | 32.50 | 29.69 | 34.50 | 33.46 | 31.83 | 21.90 | 22.81 | 23.54 | 22.10 | 21.68 | 22.38 |
| 5/9/17 | 35.08 | 37.80 | 36.01 | 39.31 | 37.94 | 37.48 | 18.35 | 18.58 | 18.68 | 18.84 | 18.24 | 19.23 |
| 6/9/17 | 31.03 | 33.27 | 31.75 | 35.03 | 34.64 | 32.92 | 21.12 | 21.20 | 20.88 | 20.26 | 21.62 | 18.41 |
| 7/9/17 | 32.66 | 35.72 | 33.16 | 37.07 | 36.63 | 34.77 | 23.59 | 23.65 | 23.84 | 23.18 | 23.60 | 23.43 |
| 8/9/17 | 50.83 | 48.09 | 48.57 | 46.04 | 50.55 | 46.53 | 17.87 | 17.70 | 17.58 | 18.81 | 18.11 | 18.21 |
| 9/9/17 | 36.67 | 39.48 | 36.75 | 41.96 | 39.24 | 39.38 | 20.71 | 21.41 | 22.92 | 19.26 | 21.30 | 21.49 |
| CBIT Hyderabad (17.39 N latitude, 78.31 E Longitude) | | | | | | | | | | | | |
| 3/9/17 | 42.28 | 48.28 | 46.67 | 47.85 | 49.08 | 47.93 | 12.27 | 14.69 | 14.60 | 13.74 | 14.02 | 15.72 |
| 4/9/17 | 36.75 | 44.58 | 40.62 | 45.66 | 44.28 | 43.58 | 21.60 | 24.60 | 25.43 | 24.21 | 21.53 | 25.26 |
| 5/9/17 | 41.03 | 49.12 | 45.17 | 51.24 | 47.85 | 46.49 | 16.65 | 19.72 | 20.44 | 19.84 | 17.65 | 19.98 |
| 6/9/17 | 37.47 | 45.85 | 42.02 | 48.69 | 45.47 | 51.88 | 16.55 | 17.99 | 19.90 | 18.07 | 18.08 | 17.49 |
| 7/9/17 | 40.39 | 50.17 | 45.37 | 52.58 | 49.96 | 47.20 | 23.16 | 25.54 | 27.22 | 25.64 | 26.71 | 25.44 |
| 8/9/17 | 47.43 | 50.90 | 49.18 | 45.69 | 52.21 | 49.58 | 24.01 | 22.31 | 22.38 | 22.98 | 22.13 | 19.85 |
| 9/9/17 | 44.45 | 53.28 | 49.62 | 53.61 | 51.79 | 52.51 | 33.42 | 36.28 | 36.99 | 35.02 | 35.96 | 35.27 |
| IIT Mumbai (19.03 N latitude, 72.91 E Longitude) | | | | | | | | | | | | |
| 3/9/17 | 45.48 | 46.83 | 46.69 | 47.14 | 45.10 | 46.07 | 16.00 | 15.46 | 15.54 | 15.58 | 16.07 | 13.69 |
| 4/9/17 | 45.85 | 49.97 | 44.56 | 53.39 | 49.93 | 48.27 | 22.58 | 23.01 | 24.14 | 23.84 | 21.70 | 24.34 |
| 5/9/17 | 46.36 | 49.05 | 47.98 | 51.45 | 46.10 | 49.14 | 19.01 | 18.98 | 19.34 | 19.52 | 18.23 | 19.03 |
| 6/9/17 | 46.21 | 50.39 | 46.74 | 53.40 | 48.96 | 50.19 | 19.73 | 19.49 | 19.51 | 19.35 | 19.52 | 17.01 |
| 7/9/17 | 50.15 | 55.83 | 51.63 | 57.80 | 55.71 | 53.95 | 25.24 | 25.48 | 25.98 | 26.03 | 24.62 | 25.79 |
| 8/9/17 | 47.96 | 47.18 | 46.65 | 47.04 | 46.89 | 45.93 | 24.38 | 24.40 | 24.05 | 23.67 | 23.68 | 23.27 |
| 9/9/17 | 48.74 | 51.17 | 50.78 | 52.08 | 50.37 | 50.82 | 36.11 | 38.67 | 41.61 | 39.29 | 33.35 | 43.09 |
| SVNIT Surat (21.16 N latitude, 72.78 E Longitude) | | | | | | | | | | | | |
| 3/9/17 | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| 4/9/17 | 47.73 | 58.45 | 48.83 | 59.03 | 55.61 | 51.59 | 21.62 | 25.27 | 24.55 | 24.86 | 22.38 | 22.81 |
| 5/9/17 | 52.72 | 61.55 | 53.05 | 56.19 | 56.84 | 58.90 | 18.35 | 21.84 | 21.24 | 21.45 | 19.41 | 19.10 |
| 6/9/17 | 54.34 | 65.10 | 57.82 | 69.36 | 64.17 | 60.51 | 18.98 | 20.74 | 20.81 | 21.02 | 21.13 | 18.26 |
| 7/9/17 | 55.09 | 63.82 | 56.31 | 71.55 | 67.75 | 65.41 | 24.48 | 28.13 | 28.07 | 27.36 | 28.28 | 26.25 |
| 8/9/17 | 57.10 | 58.10 | 51.19 | 64.96 | 57.02 | 62.80 | 28.69 | 27.18 | 25.91 | 26.89 | 29.15 | 22.25 |
| 9/9/17 | 55.40 | 61.86 | 59.28 | 53.73 | 59.77 | 56.85 | 43.07 | 42.82 | 42.62 | 34.03 | 40.12 | 39.18 |
| IIT Gandhinagar (22.52 N latitude, 72.92 E Longitude) | | | | | | | | | | | | |
| 3/9/17 | 64.11 | 73.33 | 65.96 | 74.41 | 65.92 | 62.89 | 34.79 | 35.58 | 31.93 | 32.01 | 28.06 | 25.75 |
| 4/9/17 | 63.56 | 79.31 | 62.08 | 75.53 | 71.06 | 64.88 | 38.70 | 41.44 | 37.67 | 39.07 | 35.25 | 30.01 |
| 5/9/17 | 70.84 | 80.93 | 64.45 | 68.82 | 69.51 | 75.58 | 37.40 | 40.83 | 35.40 | 34.47 | 30.85 | 29.33 |
| 6/9/17 | 63.85 | 82.22 | 66.27 | 76.35 | 74.45 | 70.32 | 35.73 | 36.87 | 34.43 | 36.31 | 31.90 | 26.99 |
| 7/9/17 | 67.84 | 86.75 | 71.57 | 83.35 | 77.80 | 77.12 | 41.38 | 45.96 | 42.70 | 42.14 | 39.29 | 36.40 |
| 8/9/17 | 70.50 | 68.30 | 62.81 | 60.24 | 61.53 | 55.97 | 42.10 | 44.92 | 40.22 | 37.57 | 38.61 | 31.50 |
| 9/9/17 | 68.41 | 77.20 | 69.61 | 62.28 | 71.99 | 65.53 | 46.31 | 48.48 | 44.21 | 44.57 | 41.18 | 38.83 |

**TABLE 1.** TEC comparisons for Dual frequency NavIC / IRNSS receiver and IRI-2012 online model.

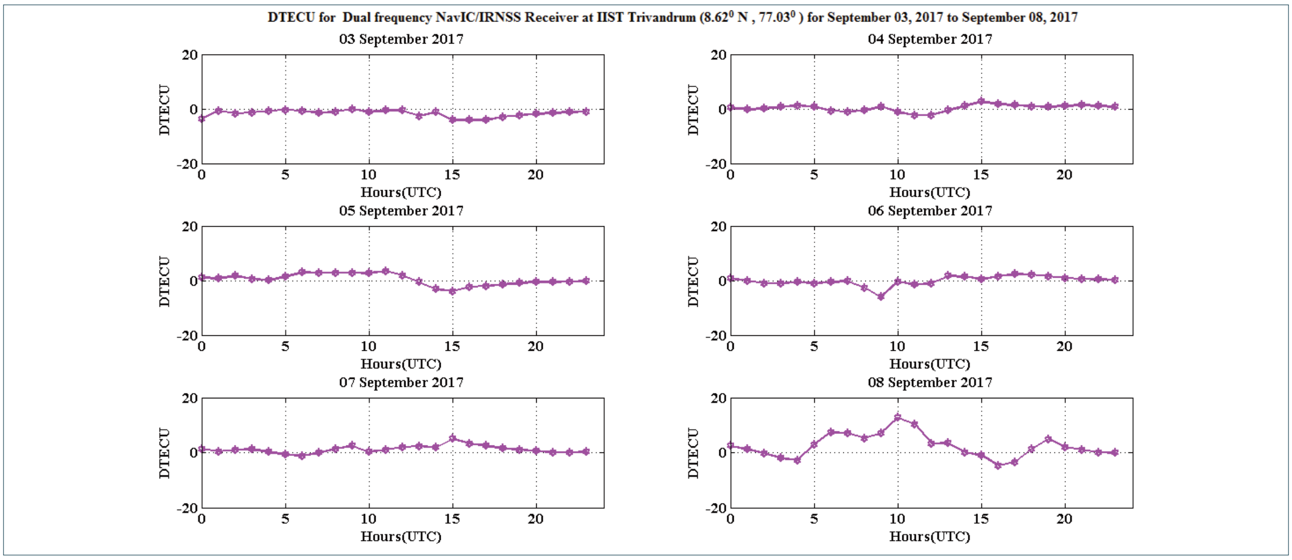


FIGURE 9. DTECU for Dual frequency NavIC/IRNSS Receiver at IIST Trivandrum (8.62° N latitude, 77.03° E Longitude) for September 03, 2017 to September 08, 2017.

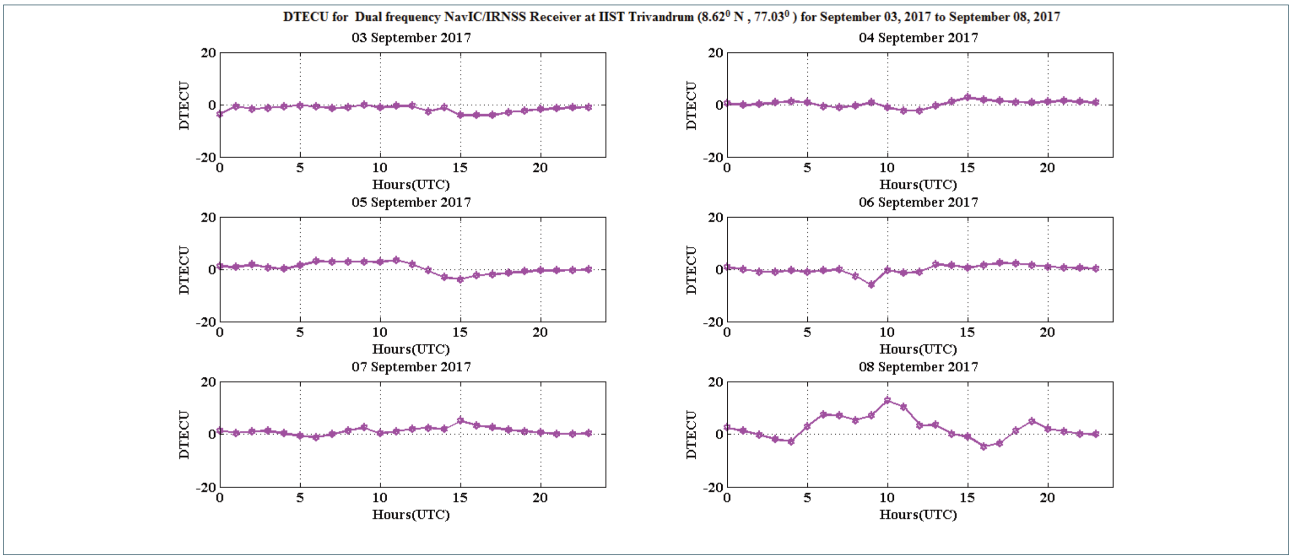


FIGURE 10. DTECU for Dual frequency NavIC/IRNSS Receiver at CBIT Hyderabad (17.39° N latitude, 78.31° E Longitude) for September 03, 2017 to September 08, 2017.

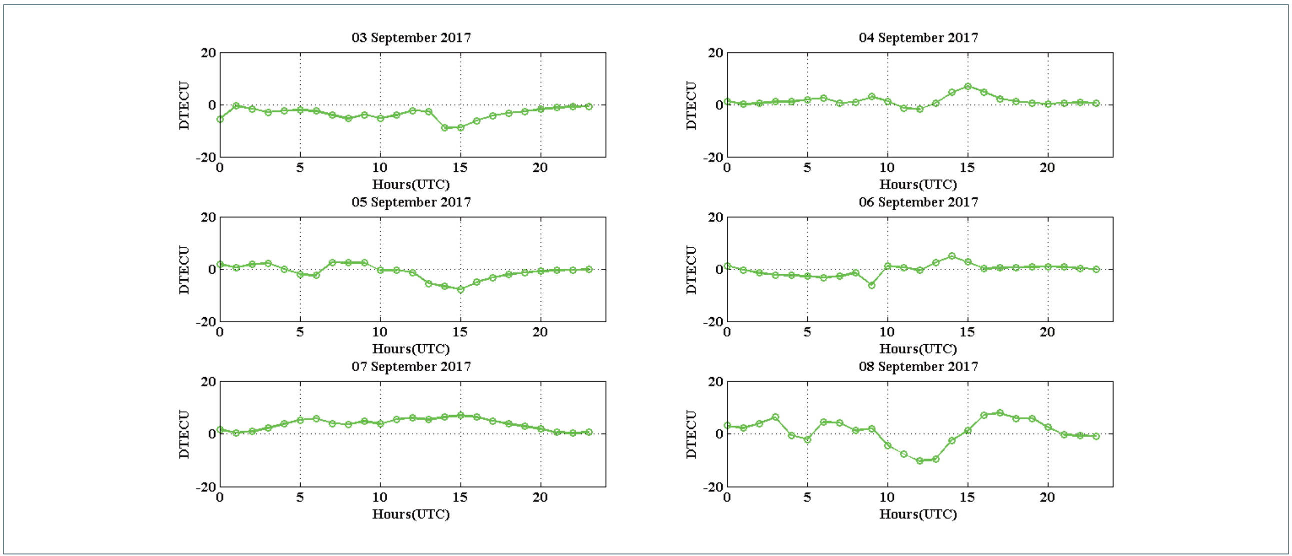


FIGURE 11. DTECU for Dual frequency NavIC/IRNSS Receiver at IIT Mumbai (19.03° N latitude, 72.91° E Longitude) for September 03, 2017 to September 08, 2017.

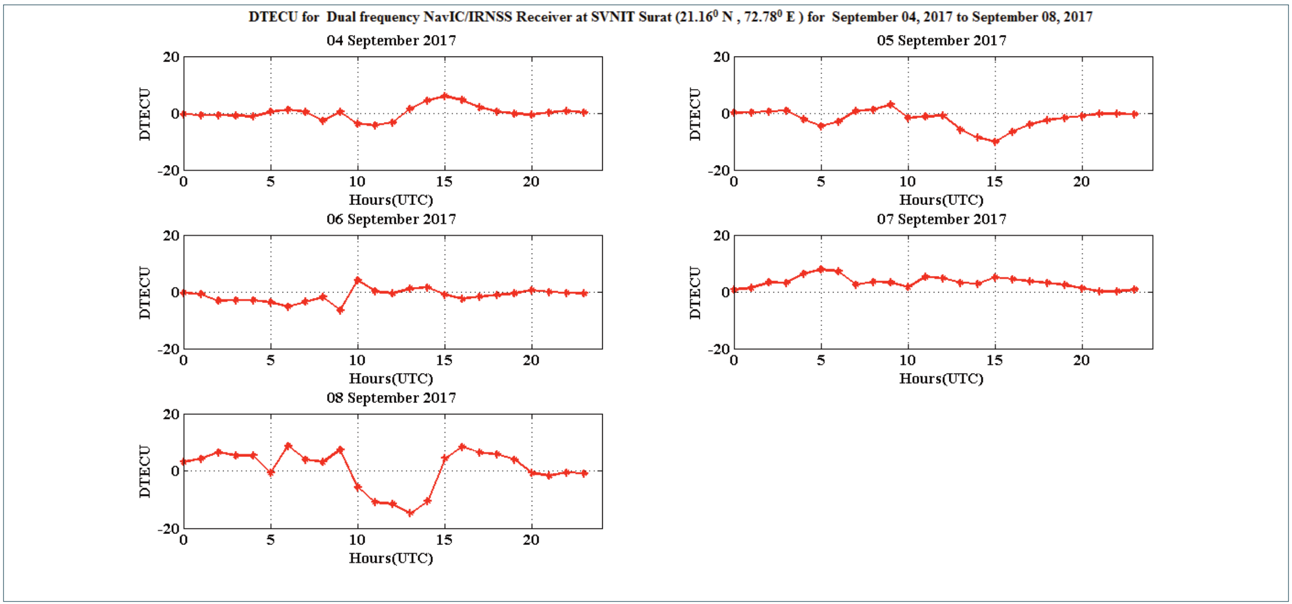


**FIGURE 12.** DTECU for Dual frequency NavIC/IRNSS Receiver at SVNIT Surat (21.16° N latitude, 72.78° E Longitude) for September 04, 2017 to September 08, 2017

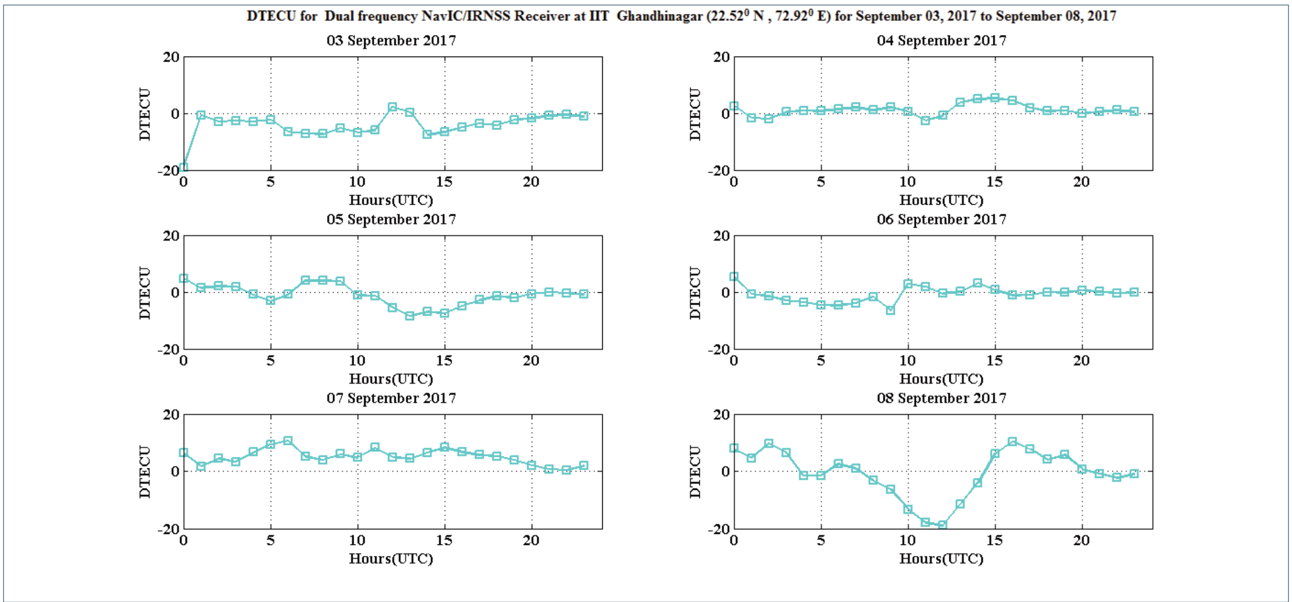


**FIGURE 13.** DTECU for Dual frequency NavIC/IRNSS Receiver at IIT Gandhinagar (22.52° N latitude, 72.92° E Longitude) for September 03, 2017 to September 08, 2017

Mumbai, CBIT Hyderabad and IIT Gandhinagar (EIA region). The one week NavIC / IRNSS dual-frequency (L5 and S-band) receivers data of above five locations are collected for the investigation. The diurnal TEC comparison between IRI-2012 empirical model and NavIC/IRNSS dual frequency model has been done. From the statistical analysis of NavIC/IRNSS dual frequency TEC, on the stormy day, IIST Trivandrum (near the equator) increased of about 10 TECUs at 10:00 UTC, CBIT Hyderabad and IIT Mumbai decreased of about 16 TECUs at 12:00 UTC, SVNIT Surat decreased of about 18 TECUs at 13:00 UTC, and IIT Gandhinagar decreased of about 20 TECU. Therefore, the effect of intense geomagnetic storms is easily identified from the observations of TEC data analysis using NavIC/IRNSS dual-frequency receivers at various location. The diurnal TEC behavior of the IRI-2012 model is to be found the same for all observation days. In order to support drastic change in TEC during intense geomagnetic storm (8 September, 2017), Planetary Kp indices, Dst(nT), Ap index, F10.7, AE(nT) index, Sym-H(nT) index, IMF Bz(nT), and IEF Ey(nT) parameter maps are added. Results are further validated using TEC map from IGS data, thermosphere O/N2 ratio map from GUVI. A positive

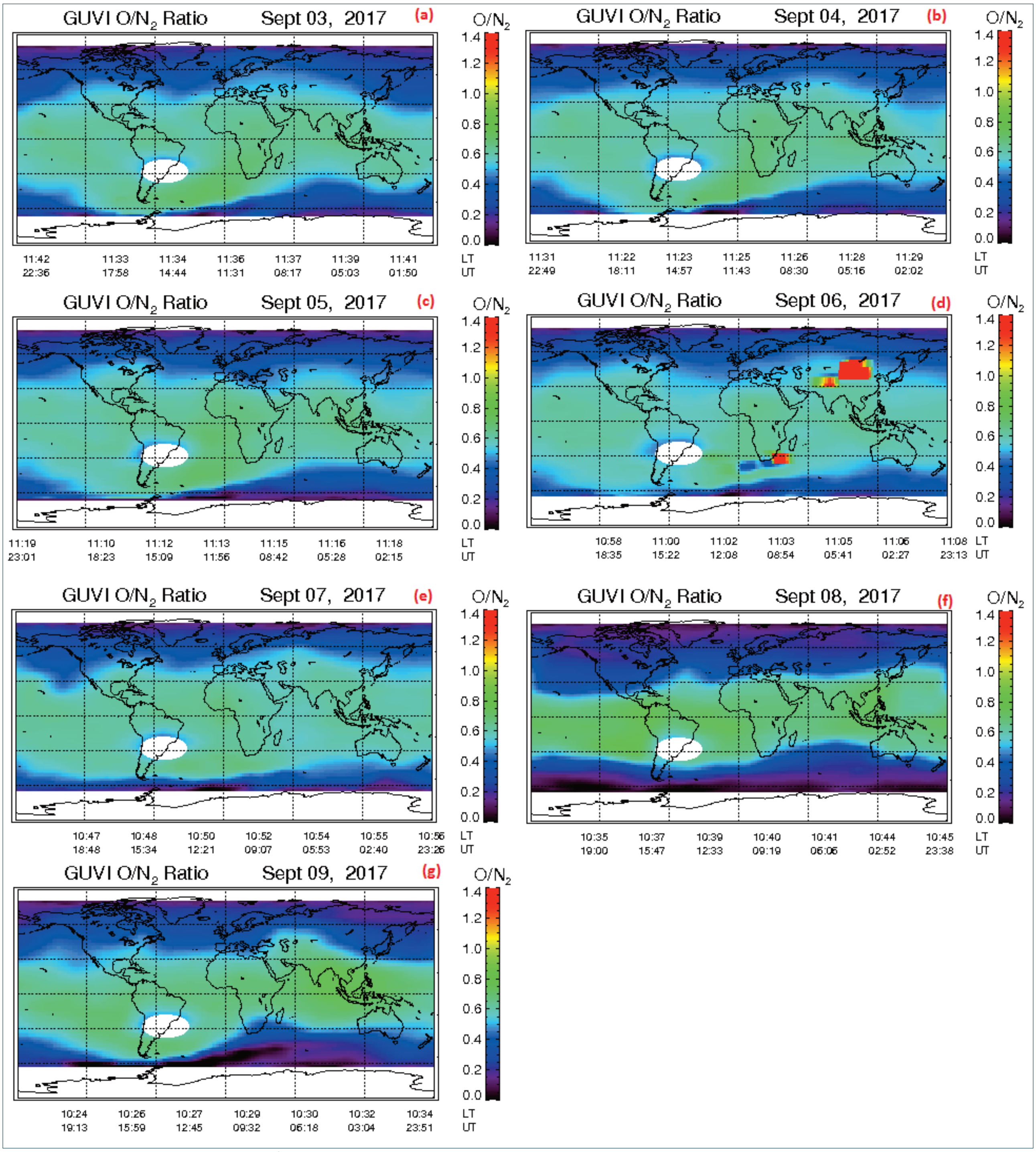


**FIGURE 14.** Global Thermospheric O/N2 Mapping using GUVI data server.

correlation between the storm occurrence and the TEC increment is found in the equatorial region, while a negative one in the EIA. The delay of the NavIC/IRNSS signal caused by the Ionosphere is directly related to the TEC. Therefore, changes in TEC during geomagnetic storm events strongly affect the signal propagating through the Ionosphere, which leads to a decrease in the positional accuracy of the system. Hence, to improve the positional accuracy of the NavIC/IRNSS system the estimation and mitigation of Ionospheric effects is essential.

## Data and Sharing Resources

- http://wdc.kugi.kyoto-u.ac.jp , World, Data Center (WDC) for geomagnetism, Kyoto for the Dst(nT), AE(nT) and Sym-H(nT) indexes.
- https://omniweb.gsfc.nasa.gov , OMNIWeb data explorer for the Kp, Ap and F10.7 indexes.
- http://www.srl.caltech.edu/ACE/ASC/level2/lvl2DATA_MAG.html, Advanced Composition Explorer (ACE) level 2 data server for IMF Bz (nT).
- http://guvitimed.jhuapl.edu/guvi-galleryl3on2,

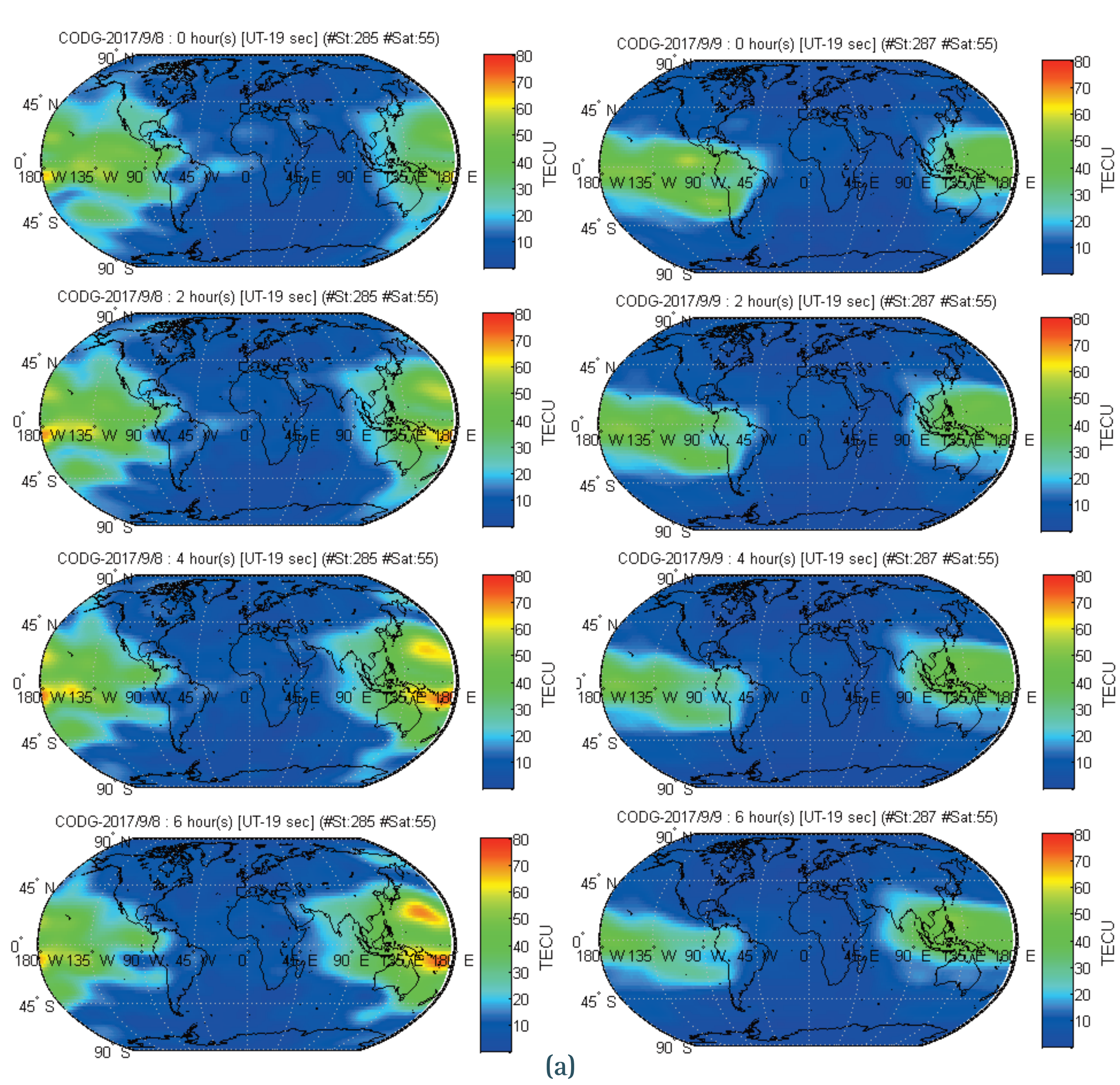


**FIGURE 15.** (a) Global TEC Mapping (Two hours resolution) comparison (8 September 2017 and 9 September 2017) using global IONEX file from GNSS IGS data server ( 00-06 hours).

GUVI for the investigation of Thermospheric O/N2 data.

- ftp://cddis.gsfc.nasa.gov/gnss/products/ionex , International GNSS Service (IGS) server, IONEX file for world TEC data.
- ftp://210.212.130.77, SAC, ISRO ftp link for NavIC/IRNSS Data sharing.

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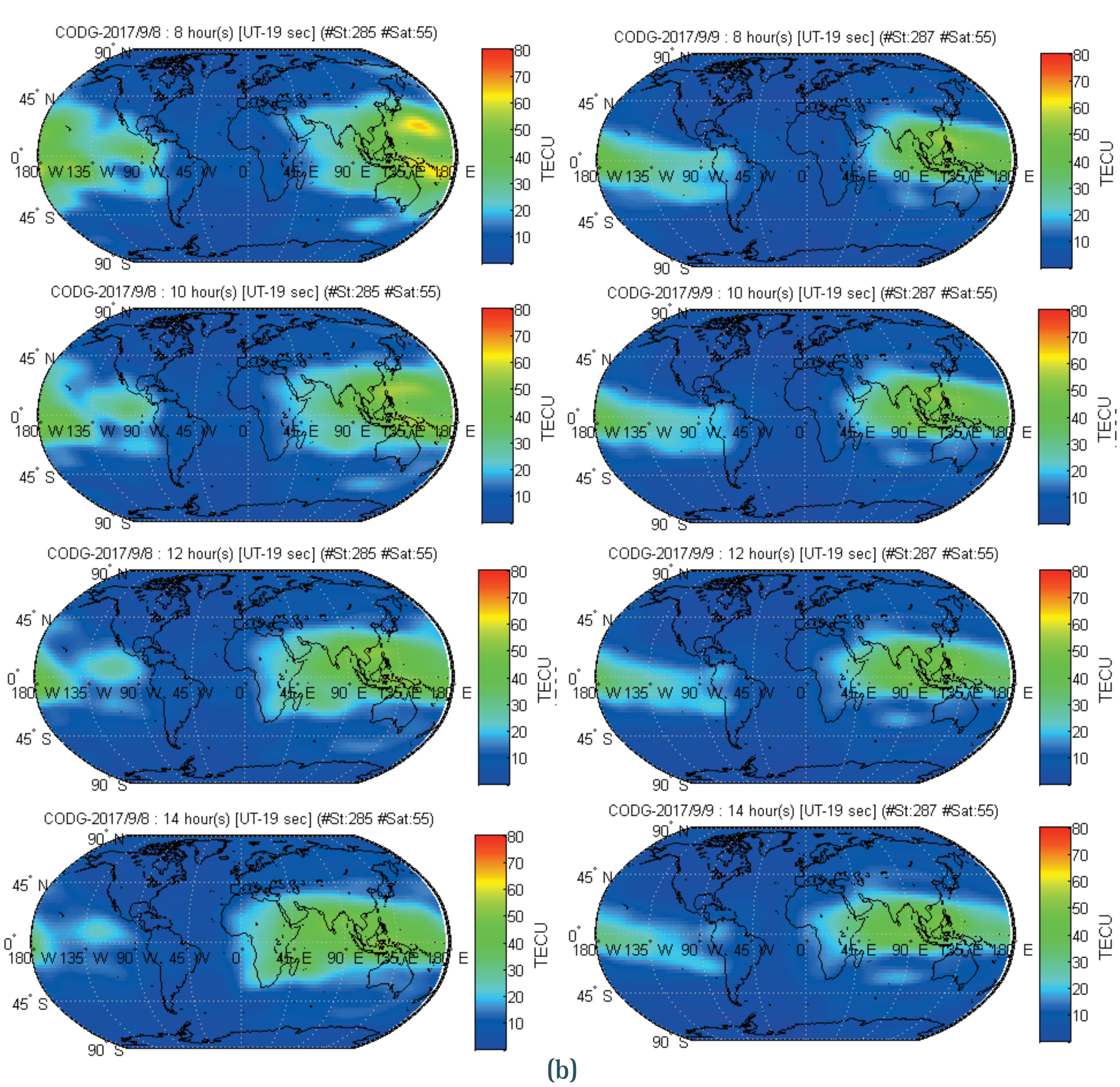


**FIGURE 15.** (b) Global TEC Mapping (Two hours resolution) comparison (8 September 2017 and 9 September 2017) using global IONEX file from GNSS IGS data server ( 08-14 hours).

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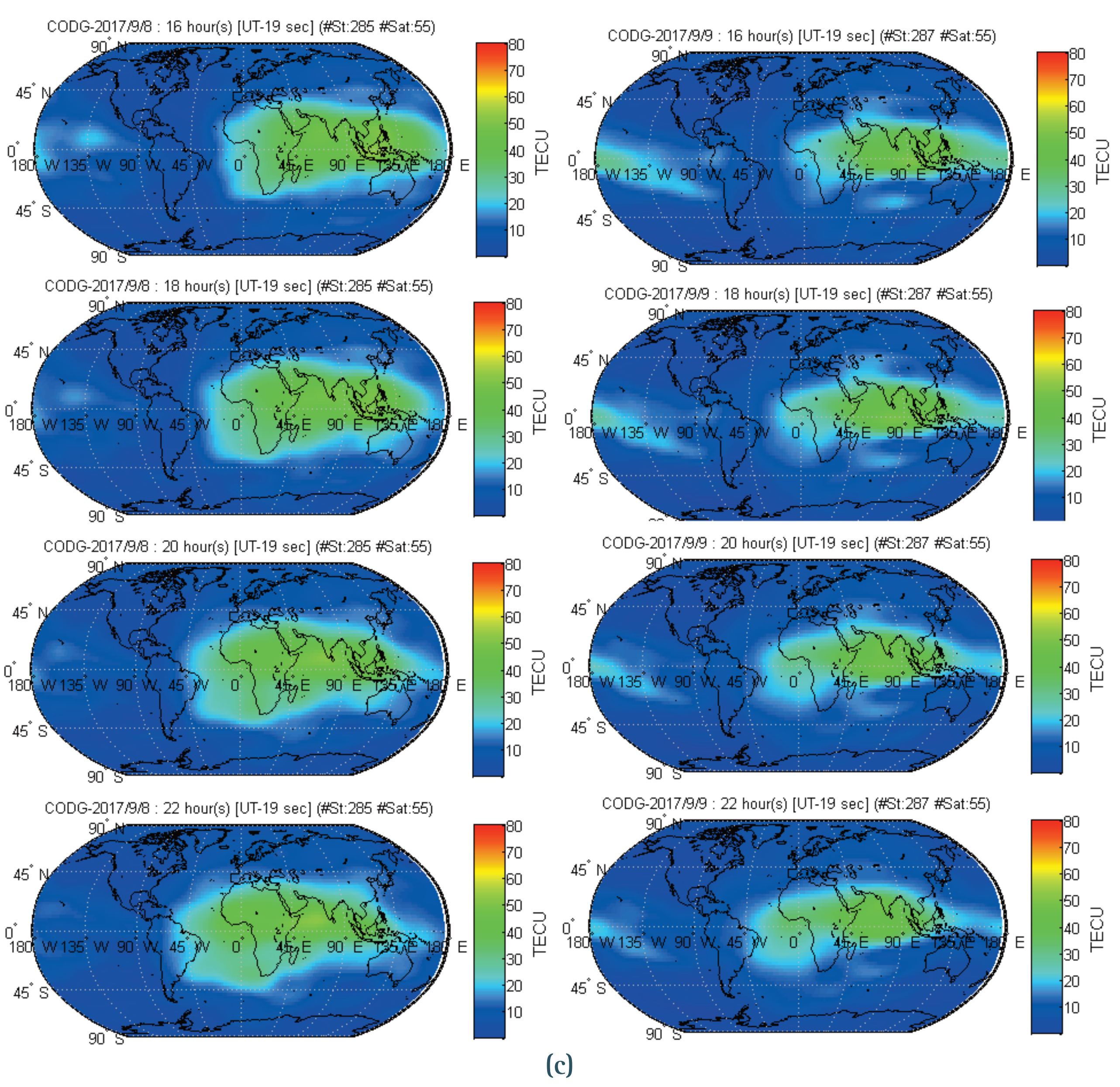


**FIGURE 15.** (c) Global TEC Mapping (Two hours resolution) comparison (8 September 2017 and 9 September 2017) using global IONEX file from GNSS IGS data server ( 16-22hours).

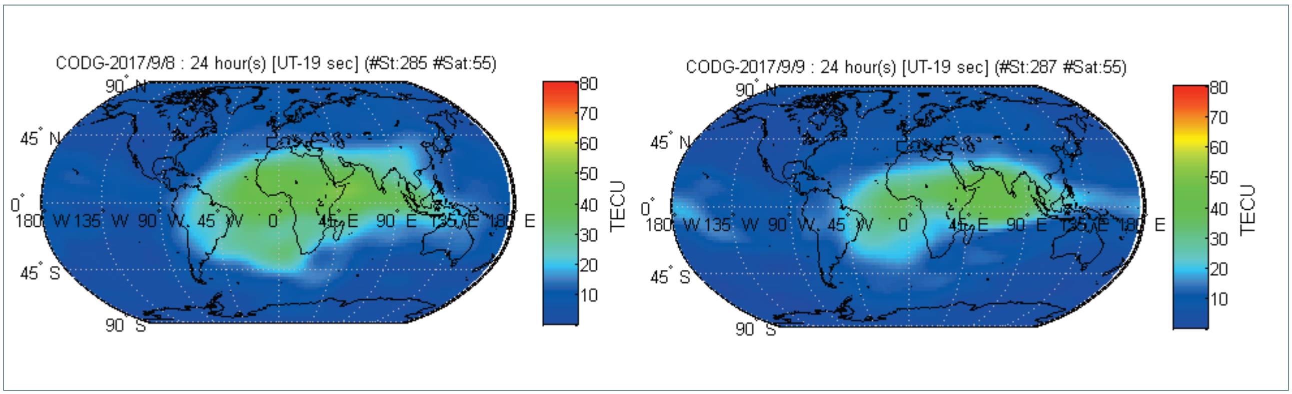


**FIGURE 15.** (d) Global TEC Mapping (Two hours resolution) comparison (8 September 2017 and 9 September 2017) using global IONEX file from GNSS IGS data server ( 24 hours).

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