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Study of Ionospheric TEC Variability over Low, Mid and High Latitudes during Solar Maximum

Roshni Atulkar[1], Azad A. Mansoori[2], Parvaiz A khan[3] and P. K. Purohit[1]

[1]National Institute of Technical Teachers, Training and Research, Bhopal – 462002, MP, India.

[2]Department of Electronics, Space Science Laboratory, Barkatullah University, Bhopal – 462026, MP, India.

[3]Department of Electronics and Communication Engineering, Islamic University of Science and Technology, Pulwama, J & K, India.

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ABSTRACT

Total electron content (TEC) is a key ionospheric parameter that describes the major impact of the ionosphere on the propagate on of radio waves which is crucial for terrestrial and space communication. The present investigation is dedicated to study the latitudinal variability of ionosphere. The study is carried out by taking three stations one each in low, mid and high latitude regions namely IISC, Bangalore, India (13.02^0 N, 77.57^{0}E), GUAO, Urumqi, China (43.82^{0}N, 87.60^{0}E) and NYAL, NY-Alesund, Norway (78.92^{0}N, 11.86^{0}E) respectively. To study the changes in the ionosphere at three selected station we have considered the GPS observations. The GPS derived TEC values have been collected from the SOPAC (Scripps Orbits and Permanent Array Center) data archive of the IGS (International GPS service). The study is carried out during the high solar activity period of 24th solar cycle i.e. during January 2012 to December 2012. We also studied the behaviour of ionospheric Total Electron Content (TEC) during the geomagnetic storms. We have selected 5 intense geomagnetic storms (Dst ≤ -100nT) that were observed during the year 2012. From our analysis we observed that TEC achieves its highest values during the months of October and March at low latitude, during the month of April and May at mid latitude and during the September and March at high latitude while the lowest values of TEC were recorded at all the station in December month. Similarly, the highest values of TEC are recorded during the equinox season while the lowest values are recorded in winter season.

Introduction

The ionosphere is just the one percent of the atmosphere above 100 km, it is very important because of its influence on the passage of radio waves. The propagation of the radio waves throughout the ionosphere is strongly influenced by its regular variations (diurnal, seasonal, solar cycle, latitudinal) as well as by different short and long term changes. . A number of studies conducted in the past have revealed some important similarities and differences between the high, mid and low latitude ionosphere. It is believed that the ionospheric variability at low, mid, and high latitudes is caused by variations in the external forces that originate from the thermosphere, the magnetosphere, and the lower atmosphere [1]. The polar ionosphere is directly connected to the outer space by the geomagnetic field lines configuration and then particularly sensitive to the perturbation events. The variability of the low latitude ionosphere is due to the large scale electrodynamics associated with the equatorial electrojet (EEJ), equatorial ionization anomaly (EIA), Plasma fountain, Equatorial wind and temperature anomaly etc. [2] Studied the latitudinal variations of the day to day TEC variability at five stations in the northern hemisphere during the solar maximum years 1981 and 1989 respectively of the 21 and 22nd solar cycles and also during the common solar minimum year 1985. The effect of solar phase change in the variability is found to be the least for the mid latitude station of Boulder and most during the nighttime for the high latitude station of Goose bay. TEC variability reveals narrowing of the spectrum from low to high latitudes during the solar minimum phase while the reverse seems to be the case during the solar maximum. [3] Studied the diurnal, seasonal and annual behaviour of ionospheric total electron content. They investigated the variation of TEC during high solar active period in Malaysian region and they observed that the amplitude of the seasonal variation of TEC is directly proportional to the solar activity and the pattern of seasonal variation of TEC is solar activity dependent. [4] Studied the diurnal variability of TEC at Waltair (India) and they observed many characteristics typical to low latitude ionosphere such as short lived pre dawn minimum, a steep post sunset fall. [5] also presented the temporal and spatial variability of TEC derived from temporal simultaneous and continuous measurement for the first time using the GPS network of 18 receiver located from the equator to the northern crest of the equatorial ionization anomaly region and beyond, covering a geomagnetic latitude range 1 degree to 24 degree North. [6] Studied the variability in TEC with different solar indices i.e EUV, F10.7, solar flux and smoothed sunspot number (SSN) for summer, winter and equinoxes. They concluded that TEC exhibited nonlinear relationship with smoothed sunspot number (SSN) in general and linear variations with EUV and F10.7 solar flux. [7] studied the long term variability of ionospheric TEC with different solar indices like CME Occurrence, Solar EUV Flux, Solar Radio Flux F10.7cm, Flare Index and Sunspot Number (Rz) and they revealed that the variation of ionospheric TEC has more close agreement with solar radiation fluxes (EUV Flux, Solar Radio Flux F10.7cm and

Tele:

E-mail addresses: purohit_pk2004@yahoo.com

Sunspot Number) than with other indices like Flare Index and CME Occurrence.

The mid-latitude ionosphere is affected less by electron density gradients than both the high and low latitude ionospheres. The changes in the temporal and spatial features of TEC at the mid latitudes are relatively small compared to the equatorial and low-latitude regions [8], where these changes are significant due to the dynamical behaviour of the ionosphere because of the various processes associated with the phenomena of equatorial ionization anomaly (EIA) and equatorial spread-F (ESF) irregularities. These perturbations involve large enhancement and depletions of the electron content at the F2 region during periods termed as positive and negative storm phases, respectively. [9] Found the Ionospheric TEC variability statistically correlates with 11 year cycle of solar activity in the normal range. They also oberseved seasonal dependence of the peak TEC and the nighttime secondary TEC. [10] Studied the mean diurnal, seasonal and annual variations of vertical total electron content (VTEC) from 2004 to 2011 at Brazilian Antarctic Station (62.1°S, 58.4°W). They found the maximum daytime VTEC had an annual variation that decreased from 2004 to 2008, and then starting to increase in 2009, which followed the variation of the solar activity. [11] found that the behavior of high latitude ionosphere is different from the other latitudes. The plasma density of this region increases which is known as plasma patches.

Event Selection

To accomplish this study we have used the GPS observations at three latitude regions low, mid and high namely IISC, Bangalore, India (13.02^0 N, 77.57^0E), GUAO, Urumqi, China (43.82^0N, 87.60^0E) and NYAL, NY-Alesund, Norway (78.92^0N, 11.86^0E) respectively. For this study we have used only the data of year 2012 (January to December). We also selected the five intense geomagnetic storms that occurred during this period to study the behavior of ionosphere during adverse geomagnetic conditions. We checked for all the required data sets of the study. Only those events were considered for which all the data sets were available. The complete catalogue of all the selected geomagnetic storms events is provided in the table 1.

Data Sets and Methodology

To carry out this study we have used mainly two type of data sets: Ionospheric data (GPS derived TEC) and geomagnetic indices (Dst Index, IMF-Bz and AE index).

Total Electron Content (TEC)

A network of GPS receivers is spread over the globe and data is recorded regularly. The data recorded at all the stations which form the part of International GPS Service (IGS) is freely available to users and can be downloaded from the URL http://sopac.ucsd.edu/dataArchive/.

The data downloaded from the web is in RINEX format, which is then processed by using appropriated tools to get the required Total Electron Content (TEC). The temporal resolution of the data is usually 30s. The dual frequency GPS receivers provide the carrier phase and pseudo-range measurements in two L-band frequencies (L1=1575.42MHz and L2=1227.60 MHz). The TEC is computed from the combined L1 and L2 pseudo-ranges and carrier phase.This gives STEC which is then converted to VTEC by using the formula:

$$VTEC = Cos\chi * STEC$$

Where χ is the angle of incidence at 350 km altitude of GPS ray path from satellite to ground receiver.

$$Cos\chi = \sqrt{1 - \left(\frac{RE - Cos(e)}{RE - Hiono}\right)^2}$$

Where *RE* is the radius of Earth, *e* is the elevation angle of satellite and *Hiono* is the height of IPP, assumed to be 350km.

Interplanetary and Geomagnetic Indices

We know Dst is the primary index that is used describe the intensity of a geomagnetic storm by providing the direct measure of ring current intensity. The Dst is a geomagnetic index which monitors the world wide magnetic storm level. It is constructed by averaging the horizontal component of the geomagnetic field from mid-latitude and equatorial magnetograms from all over the world. Negative Dst values indicate a magnetic storm is in progress, the more negative Dst is the more intense the magnetic storm. The negative deflections in the Dst index are caused by the storm time ring current which flows around the Earth from east to west in the equatorial plane. The ring current results from the differential gradient and curvature drifts of electrons and protons in the near Earth region and its strength is coupled to the solar wind conditions. Only when there is an eastward electric field in the solar wind which corresponds to a southward interplanetary magnetic field (IMF), there is significant ring current injection resulting in a negative change to the Dst index. Thus, by knowing the solar wind conditions and the form of the coupling function between solar wind and ring current, an estimate of the Dst index can be made.

The AE index is of particular relevance to the auroral latitudes, where most of the energy from the outer magnetospheric domain is transferred during a magnetic disturbance in the form of intermittent particle precipitation, and field aligned currents. Energy-transfer processes are so frequent and so rapidly fluctuating here that average taken over 3- hour periods becomes meaningless. The time interval selected for scaling magnetograms is therefore one minute. The AE index easily represents the onset and decay of magnetospheric disturbance.

We have downloaded the data of Dst index and AE index from Space Physics Data Facility OMNI website (http://omniweb.gsfc.nasa.gov/). We have used the hourly values of Dst for the investigation. We have also taken the IMF Bz from the measurements of ACE satellite at www.srl.caltech.edu/ACE with 1h resolution to characterize the Interplanetary Magnetic Field conditions.

Result and Discussion

The ionsopheric conditions vary with season, local time, geographic location and magnetic activity. Therefore, we have studied the variability of ionospheric TEC diurnally, monthly as well as seasonally at three latitudes low, mid and high. At the same time we have also selected five intense geomagnetic storms and studied the variability of ionosphere during the disturbed geomagnetic conditions.

The interplanetary and geomagnetic conditions during the year 2012 are shown in Figure 1. The Figure 1 shows the variation of Dst index, Kp index, IMF Bz, AE index, Solar Radio Flux (F10.7) and Sun Spot Number (Rz) for the year 2012. From the Figure we clearly notice that there has been a mixed type of activity during the year 2012. There were a number of geomagnetic storms. Also there was large number of days for which the geomagnetic activity was quite low.

Table 1. Catalogue of all the five selected intense geomagnetic storm events along with various important characteristics

Event Date	Peak Dst (Min.)	IISC (Low Latitude)			GUAO (Mid Latitude)			NYAL (High Latitude)		
		Event Peak	Median Peak	Enhancement Peak	Event Peak	Median Peak	Enhancement Peak	Event Peak	Median Peak	Enhancement Peak
09-Mar-12	-143	72.23	60.86	11.36	45.21	25.95	19.25	20.51	11.43	9.07
24-Apr-12	-104	79.32	61.45	17.86	34.13	27.70	6.42	14.13	10.32	3.80
15-Jul-12	-133	64.49	44.62	19.86	26.82	14.90	11.91	10.98	6.88	4.09
01-Oct-12	-133	75.89	64.89	10.99	37.17	26.75	10.41	19.49	12.19	7.29
14-Nov-12	-109	75.53	55.05	20.47	34.99	21.17	13.81	16.72	6.24	10.47

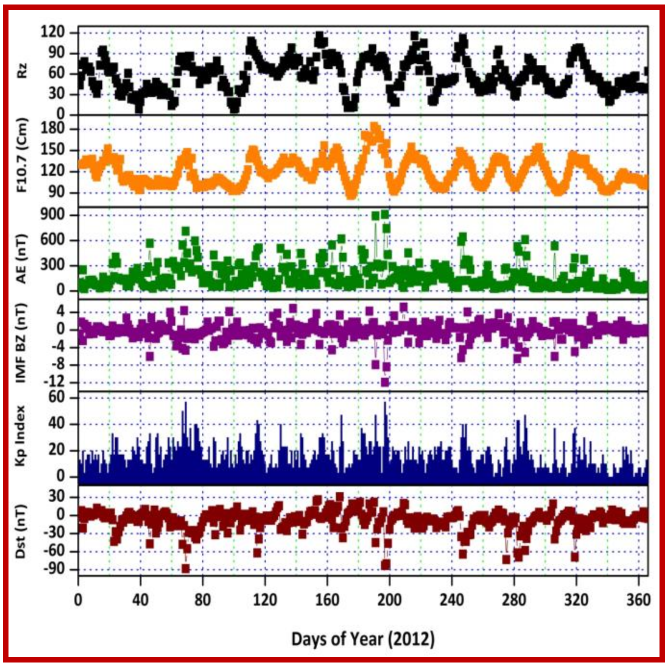

Figure 1. The daily behaviour of various geomagnetic and interplanetary indices during the year 2012

Diurnal variability of TEC

The variability of TEC for all the days of each of the 12 months is presented in Figure 2 for low latitude station IISC, Bangalore, India (13.02^0 N, 77.57^{0}E). Different color lines shows the variation of TEC for all days of the each month and black bold line shows the variation of the median of the month. From the figure we find that the TEC observed highest peaks during the months of April, September and October with peak vallue of about 80 TECU while the shallow peaks were observed during the month of December, January, February, June, July and August with peak value of about 55-60 TECU. The diurnal pattern observed during all the months has same shape with occurrence of diurnal peak between the same times. The peak value during different days of each month varies only within in the range of about 30 TECU. However, the peak value changes from month to month.

The variability of TEC for all the days of each of the 12 months is presented in Figure 3 for mid latitude station GUAO, Urumqi, China (43.82^{0}N, 87.60^{0}E). From the figure we find that the TEC observed highest peak values during the months of March, April, September and October with peak value of about 38-45 TECU while the shallow peaks were observed during the month of December, January, February, June, July and August with peak value of about 18-25 TECU. The diurnal pattern observed during all the months has same shape with occurrence of diurnal peak between the same times. The peak value during different days of each month varies only within in the range of about 25 TECU. However, the peak value changes from month to month.

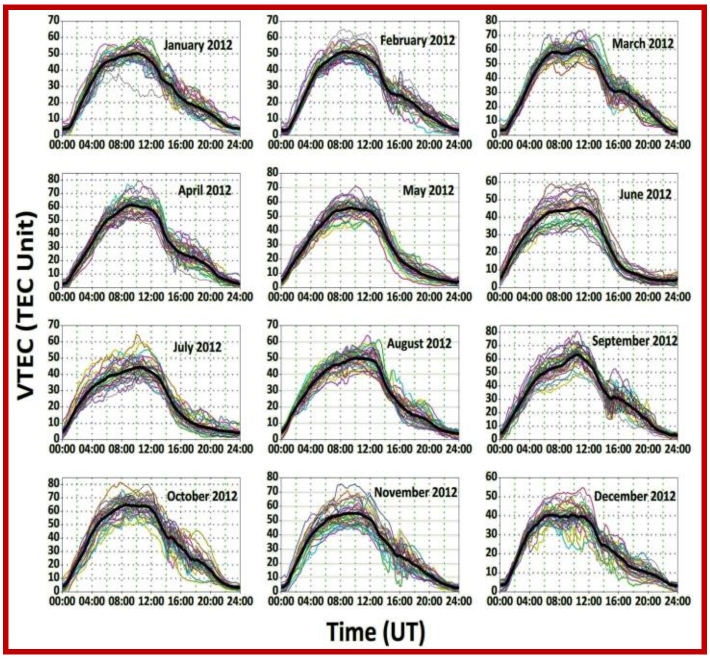

Figure 2. The diurnal variability of the TEC during all the months of the year 2012 at IISC

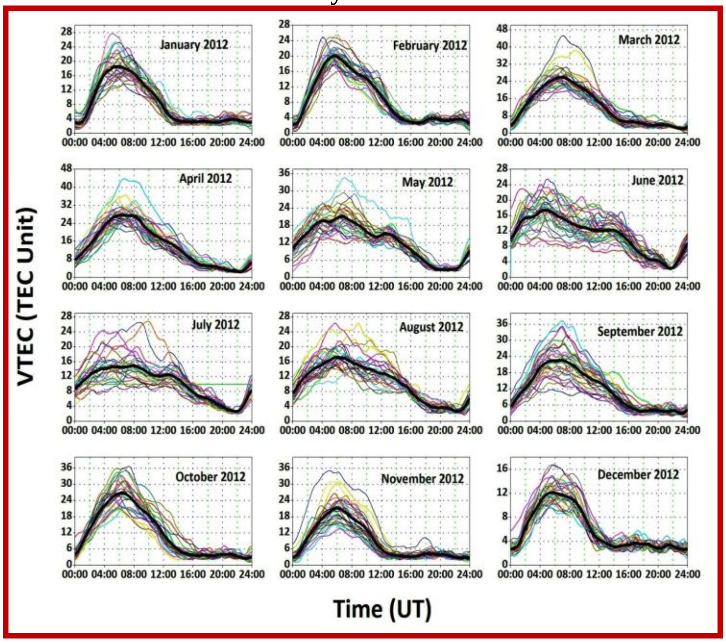

Figure 3. The diurnal variability of the TEC during all the months of the year 2012 at GUAO

The variability of TEC for all the days of each of the 12 months is presented in Figure 4 for high latitude station NYAL, NY-Alesund, Norway (78.92^{0}N, 11.86^{0}E). From the figure we find that the TEC observed highest peaks during the months of

March, April, September and October with peak value of about 18-22 TECU while the shallow peaks were observed during the month of December, January, February, June, July and August with peak TEC of about 9-14 TECU. The diurnal pattern observed during all the months has same shape with occurrence of diurnal peak between the same times. The peak value during different days of each month varies only within in the range of about 14 TECU. However, the peak value changes from month to month.

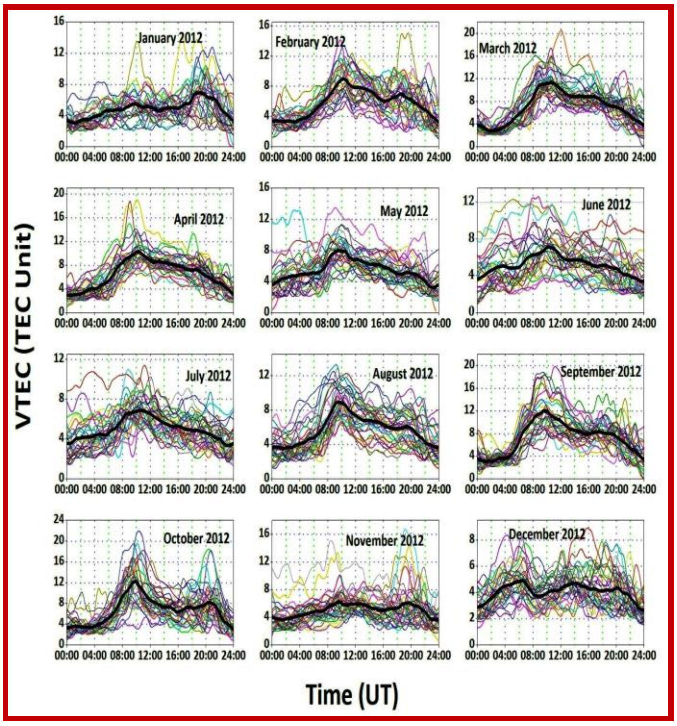

Figure 4. The diurnal variability of the TEC during all the months of the year 2012 at NYAL

From the Figures 2, 3 and 4 we find that the maximum TEC values were observed at low latitude station, IISC, Bangalore, India followed by mid latitude station GUAO, Urumqi, China and high latitude station NYAL, NY-Alesund, Norway. At the same time minimum TEC values were also observed at low latitude station, IISC, Bangalore, India followed by high latitude station NYAL, NY-Alesund, Norway and mid latitude station GUAO, Urumqi, China.

Diurnal variability of TEC have been studied by plotting TEC for each day of year for a period of one year from 01 January 2012 to 31 December 2012 at low, mid and high latitude stations. Figure 5 shows the diurnal variation of TEC during the year 2012 for IISC, Bangalore, India (13.02^0 N, 77.57^0E), GUAO, Urumqi, China (43.82^0N, 87.60^0E) and NYAL, NY-Alesund, Norway (78.92^0N, 11.86^0E) stations.

Monthly Variability of TEC

The month to month variability of the TEC for each month of year 2012 at IISC, Bangalore, India (13.02^0 N, 77.57^0E), GUAO, Urumqi, China (43.82^0N, 87.60^0E) and NYAL, NY-Alesund, Norway (78.92^0N, 11.86^0E) stations is shown in Figure 6. The variability during all the days of each month is averaged to construct the Figure 6. The Figure shows that the monthly variation of TEC is maximum during the month of October at low latitude station, IISC, during the month of April at mid latitude station GUAO and during the month of September at high latitude station NYAL. While the minimum TEC is observed during the month of December at all the three latitude stations. The TEC starts increasing from the month of December and achieves peak in the month of March or April after that it again starts decreasing and reaches minimum in the month June or July.

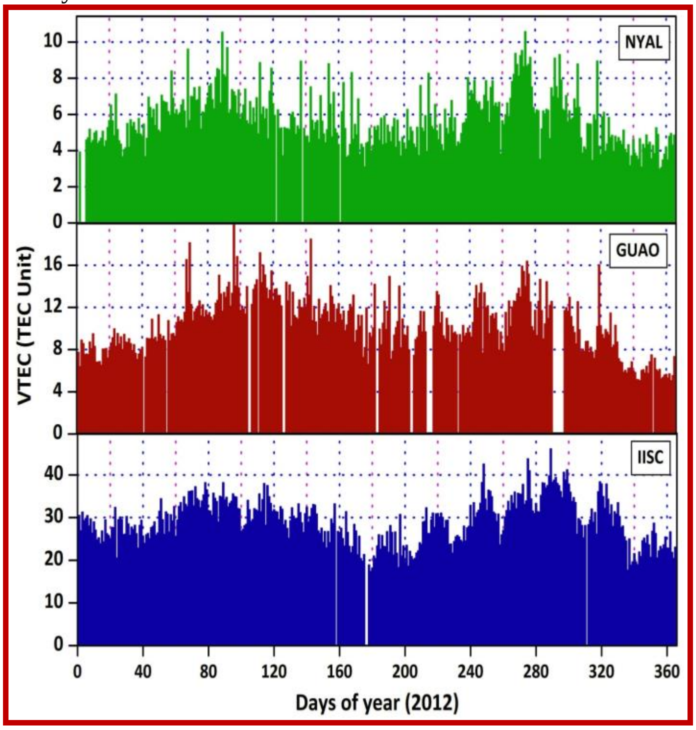

Figure 5. Diurnal variability of TEC during the year 2012 for IISC, GUAO and NYAL stations

Then it starts increasing again and reaches maximum during the month of September or October after which it starts decreasing and by the end of December it reaches to minimum. Therefore, we see that monthly variability of TEC follows semi-annual variability.

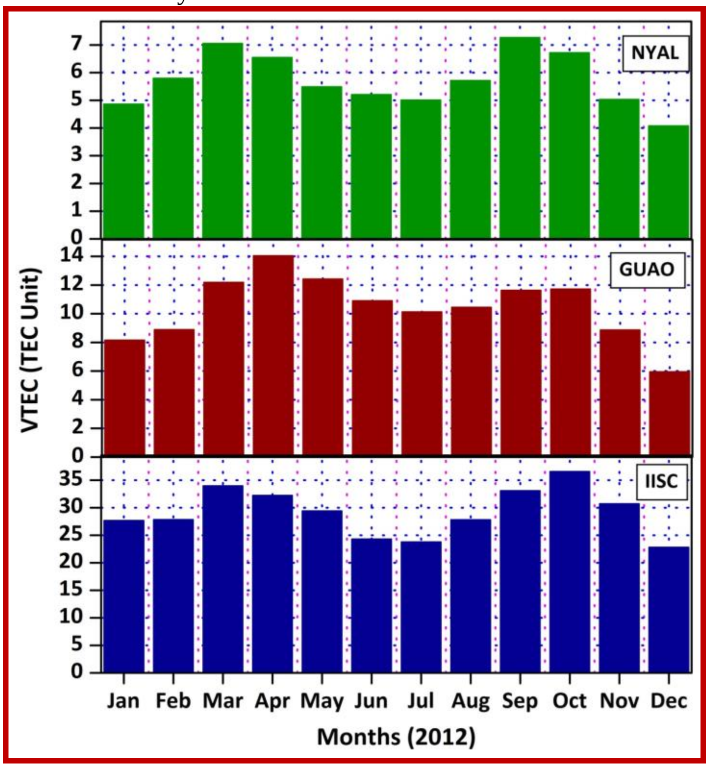

Figure 6. Monthly variability of TEC during the year 2012 for IISC, GUAO and NYAL stations

Seasonal Variability of TEC

Since, the seasonal variations of TEC is due to the tilt and rotation of the earth around the Sun; the relative position of the Sun moves from one hemisphere to the other with seasonal variation of solar zenith angle and intensity of radiation at any geographical location. Usually, the whole year is categorized into three seasons, i.e. summer, winter and equinox. We have also studied the seasonal variability of TEC at all the three latitude (low, mid and high) stations. The seasonal variability of TEC during three different seasons of the year 2012 at IISC, Bangalore, India (13.02^0 N, 77.57^{0}E), GUAO, Urumqi, China (43.82^{0}N, 87.60^{0}E) and NYAL, NY-Alesund, Norway (78.92^{0}N, 11.86^{0}E) stations is shown in Figure 7. The Figure shows that at all the three stations the TEC is maximum during the equinox season followed by summer and winter season.

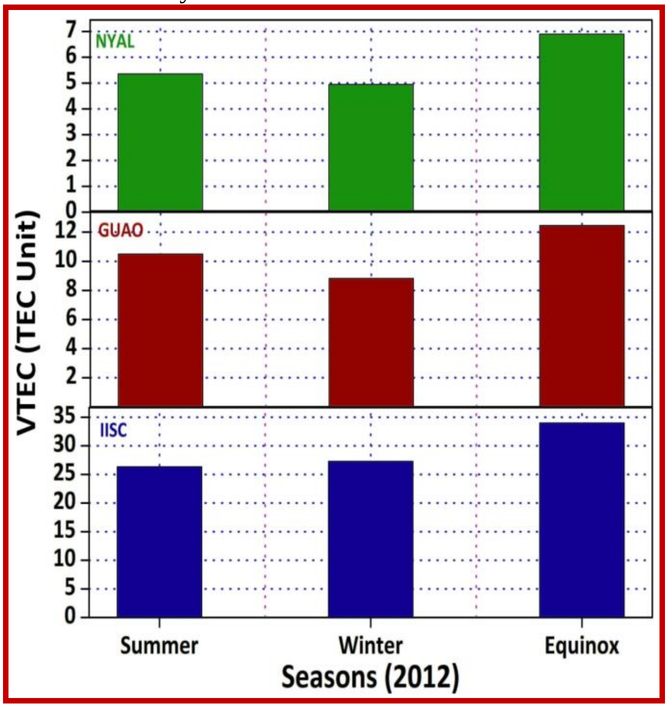

Figure 7. Seasonal variability of TEC during the year 2012 for IISC, GUAO and NYAL stations

Variability of TEC during Intense Geomagnetic Storms

The geomagnetic storm represents the most outstanding example of solar wind- magnetospheric interaction, which causes global disturbances in the geomagnetic field as well as the ionospheric disturbances. We study the behaviour of ionospheric Total Electron Content (TEC) during the geomagnetic storms. For the present investigation we have selected 5 intense geomagnetic storms (Dst ≤ -100nT) that were observed during the peak phase of solar cycle 24 i.e. during 2012. We studied the behaviour of ionospheric TEC at at low, mid and high latitude stations viz IISC, Bangalore, India (13.02^0 N, 77.57^{0}E), GUAO, Urumqi, China (43.82^{0}N, 87.60^{0}E) and NYAL, NY-Alesund, Norway (78.92^{0}N, 11.86^{0}E) respectively during the selected five intense geomagnetic storm events of year 2012. The geomagnetic storms of 09 March 2012, 24 April 2012, 15 July 2012, 01 October 2012 and 14 November 2012 with minimum Dst value of -143nT,-104nT, -133nT,-133nT, and -109nT respectively were selected to study the behaviour of ionospheric TEC during these geomagnetic storm conditions. All the five cases are discussed serially as follows;

Geomagnetic Storm of 09 March 2012

One of the intense geomagnetic storms of year 2012 was observed on 09 March 2012. The storm intensity index Dst had the minimum or peak value of -143nT. The storm had a sudden commencement phase followed by the initial and main phase. The recovery phase of the storm lasted for a couple of days after the main phase. Prior to the onset of this geomagnetic storm the z component of Interplanetary Magnetic Field (IMF) Bz was in southward direction for a substantial period of time and achieved a peak value of -16.4nT. During the main phase of the storm the value of AE-index achieved a peak of 1785nT.

The behaviour of ionospheric TEC before, after and on the storm day along with Dst index, IMF BZ index and AE index are shown in Figure 8. It can be clearly seen from the Figure that the ionospheric TEC increased significantly during the main phase of the storm i.e. 09 March 2012 at low latitude station IISC, India and mid latitude station GUAO, China. However the ionospheric TEC decreases at the high latitude station, Nyal, Norway during the main phase of storm. Thus the impact of geomagnetic storm is clearly seen on the ionsoperhic TEC as a positive enhancement at low and mid latitudes.

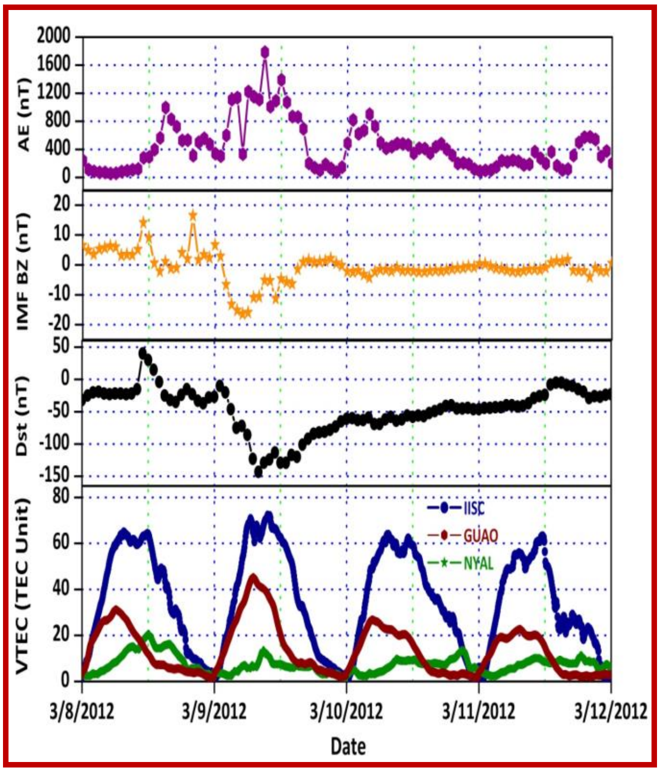

Figure 8. The temporal evolution of Ionospheric TEC along with Dst, IMF Bz and AE during the geomagnetic storm of 09 March 2012

Geomagnetic Storm of 24 April 2012

An intense storm of year was observed on 24 April 2012. The minimum Dst recorded during this storm was -104nT. The most important factor responsible for a geomagnetic storm is the south directed IMF Bz. We also observed a southward turning of IMF Bz prior to the onset of the geomagnetic storm with a peak value -15.4nT. During the main phase of the storm the value of AE-index achieved a peak of 1383nT.

The behaviour of ionospheric TEC during this geomagnetic storm along with Dst index, IMF BZ index and AE index are shown in Figure 9. The main phase of the geomagnetic storm was observed on 24 April 2012. From the Figure we find that the ionospheric TEC decreased during the main phase of geomagnetic storm at all the three latitude stations. But the effect of this storm was observed on the other day i.e. 25 April 2012 and TEC shows a significant enhancement at low latitude station IISC. However the ionospheric TEC did not show any significant change during the entire event at mid and high latitude stations.

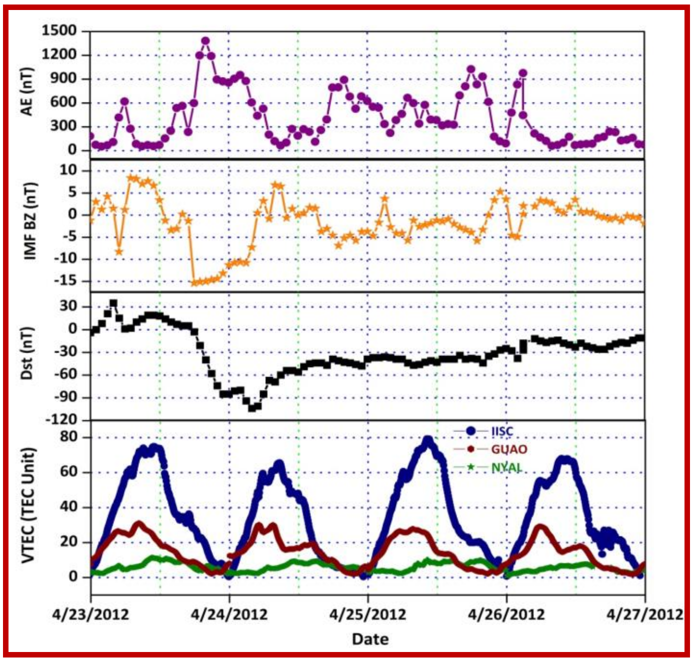

Figure 9. The temporal evolution of Ionospheric TEC along with Dst, IMF Bz and AE during the geomagnetic storm of 24 April 2012

Geomagnetic Storm of 15 July2012

The geomagnetic storm that occurred on 15 July 2012 was an intense geomagnetic storm with peak or minimum Dst -133nT. The peak value of IMF Bz prior to the onset of this geomagnetic was -18.7nT. During the main phase of the storm the value of AE-index achieved a peak of 1368nT. The effect of geomagnetic storm of 15 July 2012 on the ionospheric TEC along with Dst index, IMF BZ index and AE index are shown in Figure 10. From the Figure that there is a decrease in TEC during main phase of storm at high and mid latitude an increase in TEC at low latitude.

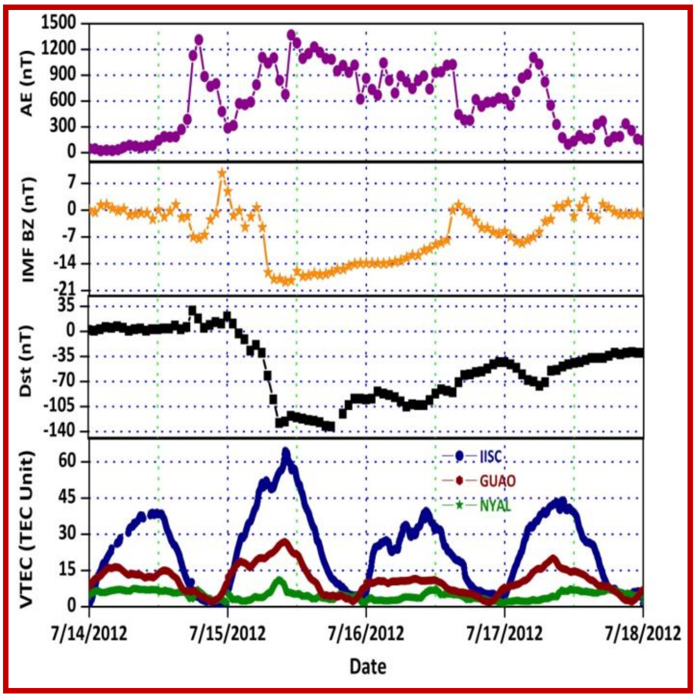

Figure 10. The temporal evolution of Ionospheric TEC along with Dst, IMF Bz and AE during the geomagnetic storm of 15 July 2012

The effect of this storm on the ionospheric TEC was very strong. It can be clearly seen from the Figure that the ionospheric TEC increased significantly during the main phase of the storm at all the three latitude stations. Thus the impact of geomagnetic storm is clearly seen on the ionsoperhic TEC as a positive enhancement at all the three latitude stations

Geomagnetic Storm of 01 October 2012

Another intense storm of year was observed on 01 October 2012. The geomagnetic storm of 01 October 2012 has the same minimum Dst as the storm of 15 July 2012. Both the geomagnetic storms had the minimum or peak Dst of -133nT. However the effect of both the storms on the ionosphere was different.

During the main phase of the storm the value of IMF Bz index and AE-index achieved a peak of -19.1nt and 987nT respectively. The effect of geomagnetic storms of 01 October 2012 on the ionospheric TEC along with Dst index, IMF BZ index and AE index are shown in Figure 11.

From the Figure we find that the ionospheric TEC increased significantly during the main phase of the storm at low latitude station IISC, India and mid latitude station GUAO, China. However at the high latitude station Nyal, Norway the effect of this storm was observed on the other day i.e. 02 October 2012 and TEC shows a significant enhancement. Thus we find that the even the geomagnetic storms of same intensity do not produce the same effect on the ionosphere.

Geomagnetic Storm of 14 November 2012

An intense storm of year was observed on 14 November 2012. The minimum Dst of this geomagnetic storm was observed -109nT. The minimum IMF Bz prior to the onset of this geomagnetic storm was -17.4nT. During the main phase of the storm the value of AE-index achieved a peak of 1009nT. The effect of geomagnetic storm of 14 November 2012 on the ionospheric TEC along with Dst index, IMF BZ index and AE index are shown in Figure 12.

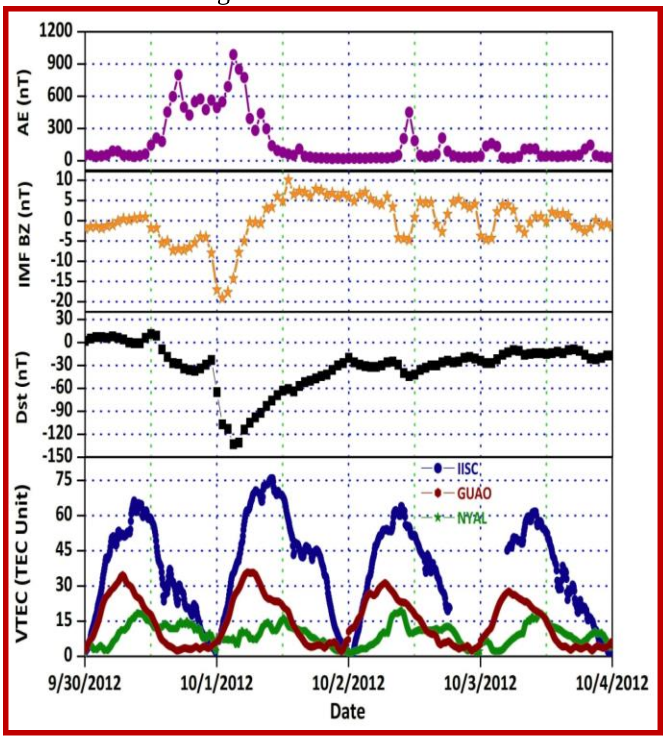

Figure 11. The temporal evolution of Ionospheric TEC along with Dst, IMF Bz and AE during the geomagnetic storm of 01 October 2012

It can be clearly seen from the Figure that the ionospheric TEC shows a strong enhancement during the main phase of the storm i.e. 14 November 2012 at low and mid latitude stations. However the ionospheric TEC decreases at the high latitude station, during the main phase of storm.

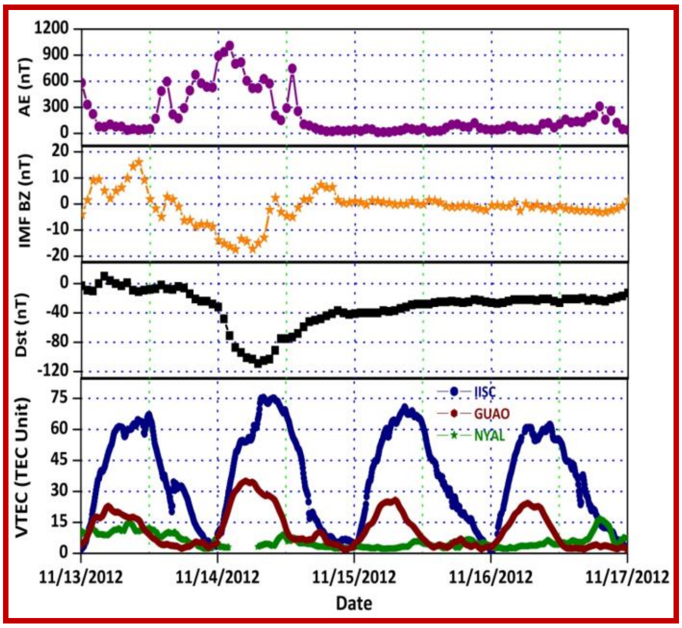

Figure 12. The temporal evolution of Ionospheric TEC along with Dst, IMF Bz and AE during the geomagnetic storm of 14 November 2012

Conclusion

The main conclusions drawn from the present study are as follows:

✓The TEC achieves its highest values during the months of October and March at low latitude, April and May at mid latitude and in September and March at high latitude while the lowest values of TEC were recorded at all the station in December month.

✓Similarly, the highest values of TEC are recorded during the equinox season while the lowest values are recorded in the month of winter at all the three stations.

✓The effect of geomagnetic storms on VTEC is highest at low latitude, moderate at mid latitude and low at high latitude.

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