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Study of ionospheric TEC variability over low, mid and high latitudes during solar maximum and its comparison with IRI-2012 and IRI-2016 model

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Total electron content (TEC) is a key of ionospheric parameters which is defined as the total number of electrons present within a cross-section 1 m^2 along the integrated path from the satellite to the receiver. TEC describes the major impact of the ionosphere on the propagation of radio waves which is crucial for terrestrial and Earth space communication including Global Positioning System (GPS). For this analysis we used dual frequency GPS observations at low, mid and high latitude stations IISC, Bangalore, India (13.02°N, 77.57°E), GUAO, Urumqi, China (43.82°N, 87.60°E) and NYAL, NY-Alesund, Norway (78.92°N, 11.86°E) respectively; we used one year of data for a high solar activity period of 24th solar cycle, i.e. during January 2012 to December 2012. From our analysis we observed that GPS-TEC achieves its highest values during the months of October and March at low latitude, during the months of April and May at mid latitude and during September and March at high latitude while the lowest values of TEC were recorded at all the stations in December. Almost a linear relationship between ionospheric GPS-TEC with IRI-2012 and IRI-2016 was observed at low and mid latitude stations; however, high latitude TEC does not show any significant relation to IRI 2012 and IRI 2016 TEC. This research obtains a practical approach to study the ionospheric variability at low, mid, and high latitude and compares with the latest IRI-2012 and IRI-2016 models during the high solar activity period 2012.

Keywords: Ionosphere, total electron content, GPS

1 Introduction

The ionospheric region is very important because of its influence on the passage of radio waves. The propagation of the radio waves throughout the ionosphere is

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strongly influenced by its regular variations like diurnal, seasonal, solar cycle, latitudinal as well as by different short and long term changes. Short term variability is mainly caused by the impact on the upper atmosphere of charged particles' fluxes, i.e. electrons and protons continuously emitted by the Sun and that constitute the "solar wind". The total electron content is a very important ionospheric parameter, characterized by spatial and temporal variations. The spatial variation generally corresponds to the various ionospheric latitude regions. The temporal variability is characterized by cycle variability on diurnal, seasonal, inter-annual and 27 day solar cycle timescales. The solar EUV radiation controls temporal variability in the ionosphere. Therefore changes in TEC are one of the most serious concerns at low, mid and high latitudes. The GPS TEC is the total number of electrons in a vertical column of 1 m^2 cross-section from the height of the GPS satellite 20,200 km to the receiver on the ground. It is measured in TEC unit (TECU) and 1 TECU is equal to $1 \cdot 10^{16}$ el m^2. Jayachandran et al. (1997) studied the latitudinal variations of the day to day TEC variability at five stations in the northern hemisphere during the high solar activity years 1981 and 1989 respectively of the 21st and 22nd solar cycles and also during the common low solar activity year 1985. The effect of solar phase change in the variability is found to be lowest at the mid latitude station of Boulder and highest during the night time at the high latitude station of Goose Bay. TEC variability reveals narrowing of the spectrum from low to high latitudes during the solar minimum phase whereas the reverse appears to be the case throughout the solar maximum. Rama Rao et al. (1980) studied the diurnal variability of TEC at Waltair (India) and they observed many characteristics typical of low latitude ionosphere such as short lived pre dawn minimum and a steep post sunset fall. Rama Rao et al. (2006) also presented the temporal and spatial variability in TEC derived from temporal simultaneous and continuous measurement for the first time using the Indian GPS network of 18 receivers 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. Dabas et al. (1993) studied the variability of TEC with different solar indices, i.e. EUV, F10.7 solar flux and smoothed sunspot number (SSN) for summer, winter and equinoxes and they concluded that TEC exhibited nonlinear relationship with smoothed sunspot number (SSN) in general and linear variations with EUV and F10.7 solar flux. 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 (Davies, 1980), where these changes are significant due to the dynamical behaviour of the ionosphere because of the various processes associated with the phenomena of equatorial ionisation 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. Correia et al. (2013) analyzed the mean diurnal, seasonal and annual variations of vertical total electron content (VTEC) at Brazilian Antarctic Station (62.1°S, 58.4°W) from 2004 to 2011. They found that the maximum daytime VTEC had an annual variation that decreased from 2004 to 2008, and then started to increase in 2009, which followed the variation of the solar activity. Olwendo et al. (2012a) found the semiannual variation with two maxima in the months of March–April and September–October.

They also reported that seasonal variations in the nighttime TEC reveal semiannual periodicity with high background levels observed in the equinoctial months and low background levels in solstice over the Kenyan regions. In addition, Olwendo et al. (2012b) found out that the highest and the lowest monthly VTEC values are observed in the equinoctial months and in the June solstice months, respectively, during the period of 2009 to 2011 over the same Kenyan regions. Chakraborty et al. (2014) studied the behavior of high latitude ionosphere which is different from the other latitudes, the geomagnetic field lines are almost vertical at high latitude, with penetration of soft high energetic particles. The plasma density of this region increases which is known as plasma patches. Kumar et al. (2014) have noted that the GPS-TEC values get reduced between 0300 and 0430 UT and started to increase between 0430 and 0930 UT during the period of 2011. They have also depicted that the TEC values are found to be highest during the equinoctial months during the period of 2010. The distribution and characteristics of TEC over low, mid, and high latitudes have been investigated by several authors (Yizengaw et al. 2007; Liu et al.2008; Jain et al. 2011; Zou et al. 2011; Sojka et al. 2012; Kumar et al. 2012; Atulkar et al. 2015). Measurements of TEC using GPS and from IGS stations are not possible over all areas, therefore, for the worldwide distribution of TEC, we need some model data. For ionospheric TEC measurements, different empirical models just like the International Reference Ionosphere (IRI) (Bilitza 2001; Bilitza and Reinisch 2008), semi-empirical low-latitude ionospheric model (SLIM) (Anderson et al. 1987), parameterized, real-time ionospheric specification model (PRISM) (Daniell and Brown 1995), NeQuick (Nava et al. 2008), and Utah State University–Global Assimilation of Ionospheric Measurements (USA–GAIM) (Scherliess et al. 2006) are being used in the scientific community. Out of these models, the IRI is widely used and is constantly being improved and updated by various research groups (Limberger et al. 2013). At present time, the most recent version of this model is IRI-2016. Barma et al. (1997) studied predicted TEC and compared it with the measured values at 26 degree N geographic and 21 degree N magnetic latitudes in 1997. They concluded that the predicted TEC values by using IRI differ significantly from the measured values. The aim of the present study is to investigate the ionospheric variations using GPS TEC measurement obtain at the low, mid and high latitude and its comparison with the latest IRI-2012 and IRI-2016 models during high solar activity period 2012.

2 Data sets and methodology

To carry out this study we have used mainly two types of data sets: ionospheric data (GPS derived TEC) from GPS measurements and TEC from the International Reference Ionosphere (IRI-2012 and IRI-2016) models data.

2.1 Ionospheric data (GPS derived TEC) from GPS measurements

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

The data downloaded from the online 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 30 s. The dual frequency GPS receivers give the carrier phase and pseudo-range measurements in two L-band frequencies (L_1 = 1575.42 MHz and L_2 = 1227.60 MHz). The TEC is computed from the combined L_1 and L_2 pseudo-ranges and carrier phase.

This gives STEC which is then converted to VTEC by using the formula:

$$\mathrm{VTEC} = \cos\chi \cdot \mathrm{STEC},$$

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

$$\cos\chi\sqrt{1-\left(\frac{R_\mathrm{E}}{R_\mathrm{E}-H_\mathrm{iono}}\cos e\right)^2},$$

where R_E is the radius of the Earth, e is the elevation angle of satellite and H_iono is the height of IPP assumed to be 350 km.

2.2 GPS derived TEC from the IRI-2012 and IRI-2016 models

The International Reference Ionosphere (IRI) is an international project sponsored by the Committee on Space Research (COSPAR) and the International Union of Radio Science (URSI). These organizations formed a Working Group in the late sixties to produce an empirical standard model of the ionosphere, based on all available data sources. Several steadily improved editions of the model have been released. For given location, time and date, IRI describes the electron density, electron temperature, ion temperature, and ion composition in the altitude range from about 50 km to about 2000 km; and also the electron content. The IRI model obtains TEC by integrating the electron density profile from the lower boundary to a user specified upper boundary (Bilitza 2001). The CCIR is recommended for continental areas, whereas the URSI option is recommended over the ocean areas (Rush et al. 1989; Aggarwal 2011). The IRI-2016, a latest updated empirical standard model of the ionosphere, is improved from the limitations of the previous IRI-2012 model. In the present study, we have investigated the discrepancies between the ground-based GPS observation and the IRI-2012 and IRI-2016 model TEC values by using the IRINeQ, IRI01-corr, and IRI-2001 options for the topside Ne and the ABT-2009 option for the bottomside thickness shape parameter. The TEC data from the IRI-2012 and IRI 2016 models has been downloaded from the website http://omniweb.gsfc.nasa.gov/vitmo/iri2012_vitmo.html.

For our investigation we used the GPS derived TEC and TEC from IRI-2012 and IRI-2016 Models of the IISC, Bangalore, India (13.02°N, 77.57°E), GUAO, Urumqi, China (43.82°N, 87.60°E) and NYAL, NY-Alesund, Norway (78.92°N, 11.86°E) stations.

3 Results and discussion

The ionsopheric conditions vary with the seasons, local time, geographic location and magnetic activity. Therefore, we have studied the variability of ionospheric TEC

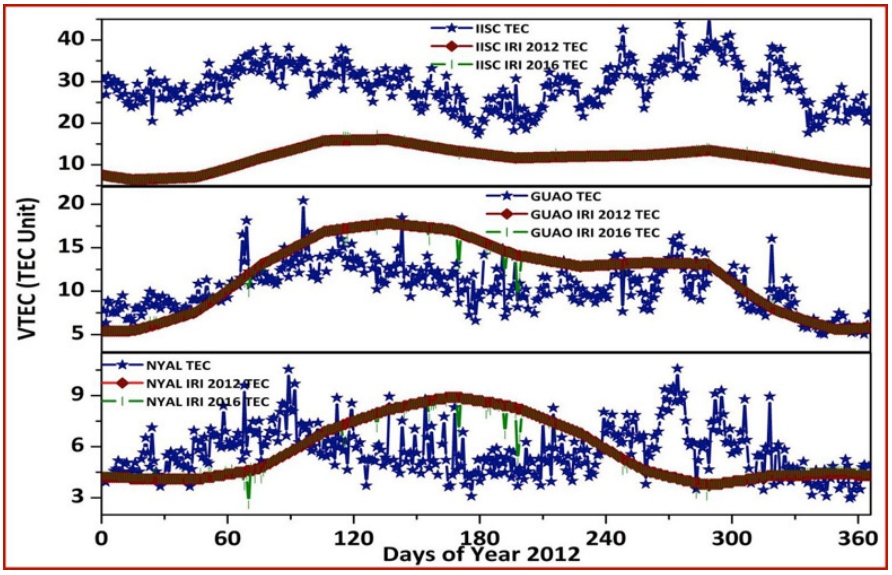


Figure 1 Daily variability of GPS-TEC with IRI-2012 and IRI-2016 TEC during the year 2012 at IISC, GUAO and NYAL stations.

diurnally and monthly at all three latitudes – low, mid and high.

Figure 1 presents the daily variability of GPS-TEC with IRI-2012 and IRI-2016 TEC during the year 2012 for IISC, Bangalore, India (13.02°N, 77.57°E), GUAO, Urumqi, China (43.82°N, 87.60°E) and NYAL, NY-Alesund, Norway (78.92°N, 11.86°E) stations. Different color lines show the variation of GPS TEC and IRI-2012 and IRI-2016 models TEC. From the figure we find that the TEC observed highest peaks during the whole year with peak TEC of about 40 TECU at low latitude while the shallow peaks were observed at mid and high latitudes with peak TEC of about 20–25 at mid latitude and 9–12 TECU at high latitude. From the figure we find that the IRI-2012 and IRI-2016 TEC follows almost synchronous variation with GPS derived TEC at low and mid latitude stations however, at the high latitude station GPS TEC does not show any significant relation with IRI-2012 and IRI-2016 TEC. We also find that the values of IRI-2012 TEC and IRI-2016-TEC are almost the same throughout the year. From the figure we also find that the values of GPS derived TEC are much higher than the IRI-2012 and IRI-2016 TEC at low latitude station and at the mid latitude station the values of GPS derived TEC and IRI-2012 and IRI-2016 TEC are almost the same however the values of IRI-2012 and IRI-2016 TEC are higher than the GPS derived TEC most of the time during the year.

The month to month variability of the GPS TEC with IRI-2012 and IRI-2016 TEC for each month of year 2012 at IISC, Bangalore, India (13.02°N, 77.57°E), GUAO, Urumqi, China (43.82°N, 87.60°E) and NYAL, NY-Alesund, Norway (78.92°N, 11.86°E) stations is shown in Fig. 2. Figure 2 reflects the similar pattern as shown in Fig. 1, however the variation is smooth in Fig. 2. Here we also find that the IRI-2012 and IRI-2016 TEC follows an almost synchronous variation with GPS derived TEC at low and mid latitude stations however at the high latitude station GPS TEC does

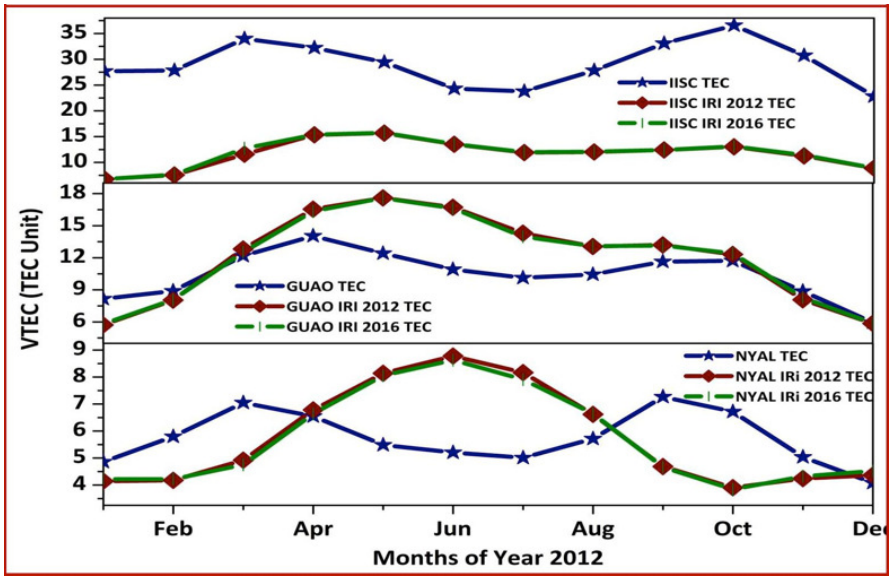


Figure 2 Monthly variability of GPS-TEC with with IRI-2012 and IRI-2016 TEC during the year 2012 at IISC, GUAO and NYAL stations.

not show any significant relation with IRI-2012 and IRI-2016 TEC. Here also we find that the values of GPS derived TEC are much higher than the IRI- 2012 and IRI-2016 TEC at low latitude station and at the mid latitude station the values of GPS derived TEC and IRI-2012 and IRI-2016 TEC are almost the same however the values of IRI-2012 and IRI-2016 TEC are higher than the GPS derived TEC during most of the months of the year 2012. The figure shows that the monthly values of GPS TEC and IRI-2012 and IRI-2016 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 of June or July. 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 a minimum for the start of the next cycle. Therefore, we see that monthly variability of TEC follows a cycle type of variability.

To quantify the association between GPS derived TEC and IRI-2012 and IRI-2016 TEC, we constructed the scatter plots and derived the correlation between the monthly averaged values of GPS derived TEC and IRI-2012 and IRI-2016 TEC. Figure 3 shows the scatter plot and correlation analysis between the monthly averaged values of GPS TEC with IRI-2012 and IRI-2016 TEC during the year 2012 at low, mid and high latitude. From the figure we find that at low latitude station both the IRI-2012 and IRI-2016 TEC exhibits a good correlation with GPS derived TEC, however the correlation between IRI-2016 TEC and GPS TEC is slightly better than the correlation between IRI-2012 TEC with GPS TEC. At mid latitude station both the

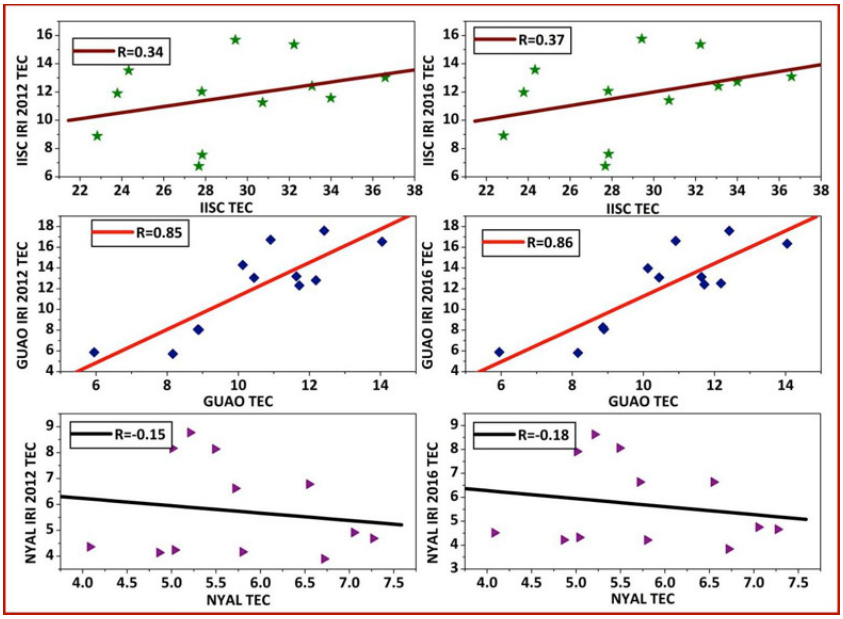


Figure 3 Scatter and correlation of GPS-TEC with IRI-2012 and IRI-2016 TEC during the year 2012 for IISC, GUAO and NYAL stations.

IRI-2012 and IRI-2016 TEC exhibits a strong correlation with GPS derived TEC, however the correlation between IRI-2016 TEC and GPS TEC is slightly better than the correlation between IRI-2012 TEC with GPS TEC. Thus we can say that the performance of IRI-2016 model is better than the IRI-2012 model. At high latitude station both the IRI-2012 and IRI-2016 TEC exhibits a negative correlation with GPS derived TEC. From our results we can say that both the IRI-2012 and IRI-2016 models are the most suitable for mid latitudes followed by low latitudes and the least suitable for high latitudes. Correlation coefficients of IRI-2012 TEC and IRI-2016 TEC with GPS derived TEC at low latitude station are 0.34 and 0.37 respectively. Correlation coefficients of IRI-2012 TEC and IRI-2016 TEC with GPS derived TEC at mid latitude station are 0.85 and 0.86 respectively.

Correlation coefficients of IRI-2012 TEC and IRI-2016 TEC with GPS derived TEC at high latitude station are –0.15 and –0.18 respectively.

4 Conclusion

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

- The diurnal values of GPS derived TEC are much higher than the IRI-2012 and IRI-2016 TEC at low latitude station and almost the same at the mid latitude station however the values of IRI-2012 and IRI-2016 TEC are higher than the GPS derived TEC most of the time during the year 2012.

- The monthly TEC starts increasing from the month of December and achieves a peak in the month of March or April after that it again starts decreasing and reaches a minimum in the month of June or July. Then it starts increasing again and reaches a maximum during the month of September or October after which it starts decreasing and by the end of December it reaches a minimum for the start of the next cycle. Therefore, we see that the monthly variability of TEC follows a cycle type of variability.
- The IRI-2012 and IRI-2016 models are the most suitable for mid latitude followed by low latitude and the least suitable for high latitude. Correlation coefficients of IRI-2012 TEC and IRI-2016 TEC with GPS derived TEC at low latitude station are 0.34 and 0.37 respectively. Correlation coefficients of IRI-2012 TEC and IRI-2016 TEC with GPS derived TEC at mid latitude station are 0.85 and 0.86 respectively. Correlation coefficients of IRI-2012 TEC and IRI-2016 TEC with GPS derived TEC at high latitude station are –0.15 and –0.18 respectively.
- The IRI-2012 and IRI-2016 models are the most suitable for mid latitude followed by low latitude and the least suitable for high latitude.

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