Vertical TEC variations and model during low solar activity at a low latitude station, Xiamen

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Abstract

GPS-derived vertical TEC recorded at Xiamen (24.5°N, 118.1°E, geomagnetic latitude 13.2°N), China, during year 2006 is analyzed for the first time and compared to that predicted by ionosphere model SPIM recommend by ISO. A manifest seasonal anomaly is found with the high value during equinoctial season and low value during summer and winter season. Relative standard deviation for VTEC shows high value at around midnight and before sunrise. The correlation analysis exhibits that the variation of VTEC has a very weak relation with geomagnetic and solar activities (Dst, AP, SSN and F10.7). Comparative results reveal that the SPIM overestimates the observed VTEC at most of the time.

Keywords: Equatorial ionospheric anomaly; Vertical TEC; Seasonal variation; SPIM

1. Introduction

The low latitude and equatorial ionospheres are unique due to the complex dynamic processes associated with the phenomenon of equatorial ionospheric anomaly (EIA) at F layer. The distribution of ionization density at F layer in the vicinity of magnetic dip equator is characterized by a trough at the equator and two crests on either side of the equator (at about ±15° magnetic latitude). A physical mechanism called as fountain effect was used to explain this interesting phenomenon. The mutual perpendicular eastward electric field and northward geomagnetic field at the geomagnetic equator gives rise to an upward \( E \times B \) drift during the daytime. After the rising plasma is lifted to greater altitudes, it diffuses along magnetic field lines due to the combined influence of the gravity and pressure gradient forces. It results in the formation of fountain which produces an enhanced electron concentration (or crest) at F region latitudes on both sides of the equator and a reduced electron concentration (or trough) at the geomagnetic equator (Appleton, 1946; Martyn, 1947, 1955; Duncan, 1960).

The total electron content (TEC) is one of the most important parameters to characterize the variability of ionosphere, which is calculated as an integral of electron number density along the line of sight from satellite to receiver. It is accepted that the magnitude and variation of TEC are related to local time, solar activity, geomagnetic conditions, region of the earth and sudden space weather events. The changes in the temporal and spatial features of TEC in the equatorial and low latitude ionospheres are significant due to the behavior of EIA and other dynamic processes such as the equatorial spread-F (ESF) irregularities. Over the last few years, ionospheric TEC was studied using GPS technique by several authors (Huang and Cheng, 1996; Tsai et al., 2001; Wu et al., 2004, 2008; Rama Rao et al., 2006; Bhuyan and Borah, 2007; Bagiya et al., 2009; Kumar and Singh, 2009; Mukherjee et al., 2010). A remarkable seasonal variation of TEC was found by above researches, which is high value during equinoctial months.
and low value during summer and winter months. Researchers also analyzed the correlation between the variation of TEC and magnetic and solar activity. Through studying the solar cycle variation of EIA in TEC using observed data from a single ground station at Lunping (25.00°N, 121.17°E), Huang and Cheng (1996) found no significant solar cycle effect in the occurrence time of the most developed equatorial ionospheric anomaly and the winter crest appears larger and earlier than the summer crest. Wu et al. (2004) found there is weak correlation between EIA and F10.7, and the seasonal variation of EIA are likely influenced by the seasonal variations of geomagnetic activity (Dst) during the solar minimum by analyzing a short-term data set (September 1996 to August 1997). Wu et al. (2008) studied ten years GPS data and suggested that the geomagnetic effects (Kp) on the crest are short-term and solar effects (F10.7) are long-term. Kumar and Singh (2009) studied magnetic and solar effect on characteristic of EIA by using GPS data from Varanasi. They found that the correlation between solar activities and EIA is poor while the seasonal variation of Kp-index likely influence the seasonal variation of EIA crests. Bagiya et al. (2009) found a good positive correlation between solar activity and TEC value and they suggested that the low latitude TEC magnitude and daily peak time depends on the equatorial Electro jet conditions.

As more and more application of GPS based navigation and positioning in people’s lives and science researches, the electron density is a matter to be concerned due to its over- \[ \text{TEC}_{\text{sl}} = (\text{TEC}_{\text{sl}} - b_s - b_r) \cos \left( \arcsin \left( \frac{R_E \cos \alpha}{R_E + h} \right) \right) \] where the \( \text{TEC}_{\text{sl}} \) is slant path total electron content, \( b_s \) and \( b_r \) are the satellite and receiver biases, respectively, \( R_E = 6378 \text{ km} \), and \( h \) is the height of the ionospheric layer, \( \alpha \) is the elevation angle of satellite. Because pseudo-range with low elevation is apt to be affected by multipath effect and the reliability decrease, and if the chosen elevation is too high, there will be relative few satellites to record at the ground-based GPS receiver which results in decrease of the measured data, thus, in order to minimize the time shift and neglect unwanted errors due to multipath and insure the number of data, we chose 30° as the cut off elevation angle. To achieve Eq. (1), it needs to calculate the \( \text{TEC}_{\text{sl}} \) which is obtained from the pseudo-ranges (\( P_1 \) and \( P_2 \)) and the phases (\( L_1 \) and \( L_2 \)) of the two signals, respectively, given by

\[ \text{TEC}_{\text{sl}} = \left( \frac{f_1 f_2}{40.31 (f_1^2 - f_2^2)} \right) (P_2 - P_1) \] \[ \text{TEC}_{\text{sl}} = \left( \frac{f_1 f_2}{40.31 (f_1^2 - f_2^2)} \right) (L_1 \lambda_1 - L_2 \lambda_2) \] where \( \lambda_1 \) and \( \lambda_2 \) are the wavelengths corresponding to \( f_1 \) and \( f_2 \), respectively. The results of Eqs. (2) and (3) are the absolute and relative value of \( \text{TEC}_{\text{sl}} \). To obtain the high accuracy for \( \text{TEC}_{\text{sl}} \), a parameter \( B_{rs} \) named baseline was introduced, which is computed as the average difference between \( \text{TEC}_{\text{sl}} \) and \( \text{TEC}_{\text{sl}} \) from \( i = 1 \) to \( i = N \), where the \( N \) represents the number of measurement, which are produced by the satellites. The definition of \( B_{rs} \) as follows:

\[ B_{rs} = \frac{\sum_{i=1}^{N} (\text{TEC}_{\text{sl}} - \text{TEC}_{\text{sl}}) \sin^2 x_i}{\sum_{i=1}^{N} \sin^2 x_i} \] where the sine-squared of the satellite’s elevation \( x_i \) is regarded as a weighting factor to reduce the multipath effect. We fitted the \( \text{TEC}_{\text{sl}} \) to \( \text{TEC}_{\text{sl}} \) then got the slant \( \text{TEC}_{\text{sl}} \) by:

\[ \text{TEC}_{\text{sl}} = \text{TEC}_{\text{sl}} + B_{rs} \]
Because the slant TEC is the total number of electrons in a column of the unit cross section along the ray path, it is desirable to calculate an equivalent vertical value of TEC, which is independent of the elevation of the ray path. To convert the slant $T_{EC_{sl}}$ to vertical TEC, we assumed the ionosphere to be a thin screen shell model and its center is assumed to be the same as that of the Earth. It is because the main contribution to TEC variations would occur around the height of the maximum ionization and this allows us to consider the ionosphere as a thin layer located at the height of ionosphere F2 layer. According to Davies (1990), the height of the mean layer of the ionosphere could lie between 300 and 450 km and it is assumed to be 400 km in this paper and, got the calculation technique of VTEC as shown in Eq. (1).

To analyze the correlation between VTEC and geomagnetic and solar activity, the Ap index, and F10.7 data were downloaded from website (http://www.swpc.noaa.gov), sunspot number SSN from the website (ftp://ftp.ngdc.noaa.gov) and Dst data from website (http://wdc.kugi.kyoto-u.ac.jp), respectively.

3. Results and discussion

3.1. Diurnal and seasonal variations of VTEC

To study the diurnal distribution of VTEC for different seasons, the observed data set are divided into three sections with equinox (March, April, September and October), summer (May, June, July and August) and winter (January, February, November and December). An average value of VTEC for each hour in universal time (UT) is calculated over three seasons and all the year and shown in Fig. 1. As expected, the VTEC exhibits obvious seasonal anomaly that large value appears at equinoxial season while small value appears during summer and winter. In detail, the diurnal maximum value occurs at 0600 UT during equinox and winter while it delays 2 h to 0800 UT in summer. For the annual average, the diurnal variation shows the same trend as winter and its peak value is 26 TECU. In addition, the mean peak VTEC displays that the maximum of VTEC reaches 33 TECU in equinox followed by 24 TECU in winter and 23 TECU in summer. It can be seen that the diurnal peak VTEC is earlier and slightly higher in winter than summer, which displays the feature of weak winter anomaly this year.

In order to further examine the variation of VTEC in detail. We calculate the relative standard deviation (RSD) for three seasons and over the year. The $\text{RSD} = \left( \frac{\text{VTEC standard deviation}}{\text{VTEC mean value}} \right) \times 100$. For the diurnal distribution of RSD, one could see from Fig. 2 that it is similar increasing tendency from 00 UT to 14 UT for three seasons, after that the RSD appears maximum with 88% at 15 UT during equinoctial months while about 83% at 21 UT during summer and winter. For the annual average variation the max value of RSD is also at 21 UT. As a whole, RSD shows higher value during 12–17 UT and lower value during 19–23 UT for equinox, while it displays same trends from 15–23 UT during summer and winter. The behaviors of RSD for different seasons indicate that the distribution of VTEC has a large fluctuation, especially at around midnight (~15 UT) and pre-sunrise hour (~21 UT). The minimum of the RSD is larger than 20%, which reveals that the periods of low solar activity may lead to higher levels of relative standard deviation. Lazo et al. (2004) found that the relative variability (relative standard deviation) of TEC is higher during dawn and sunset period, mainly in equinoxial months. Our results have a little difference with Mukherjee et al. (2010). They analyzed the standard deviation and relative variability index for the VTEC data during period 2005–2006 at Bhopal and found that standard deviation of VTEC for the three

![Fig. 1. Seasonal mean diurnal variation of VTEC during 2006 at Xiamen (24.5°N, 118.1°E). LT = UT + 8 h.](image-url)
seasons is relatively smooth during nighttime hours and increases after predawn with a maximum value at afternoon hours, while the relative variability index for summer is higher as compared to other seasons. The smaller anomaly of peak VTEC in winter and summer presented in this work is consistent with other studies (Huang and Cheng, 1996; Wu et al., 2004; Kumar and Singh, 2009). In general, the behaviors of seasonal (winter) variation of VTEC could be interpreted by two possible mechanisms, which are Neutral atmosphere model and neutral wind. Johnson (1963) suggested that the composition change can be a result of asymmetric heating of the two hemispheres resulting in neutral constituents being transported from the summer to the winter hemisphere. Torr and Torr (1973) suggested that the increase of the O/N2 ratio caused by the convection of atomic oxygen from the summer to the winter hemisphere. Therefore, the recombination in winter hemisphere is weaker than that in summer hemisphere, which results in the relative higher electron concentration in winter. Another possible mechanism of this variation is the change of direction of neutral wind. A meridional component of neutral wind blows from the summer to the winter hemisphere which can reduce the crest value during summer solstice as it blows in an opposite direction to the plasma diffusion process originating from the magnetic equator; at the equinoxes, meridional winds blows pole-wards should result in a high ionization crest value. Based on this scenario, a seasonal effect on the crest should be expected with the crest maximum at the equinoxes and minimum at the summer (Bramley and Young, 1968; Stening, 1992; Wu et al., 2004, 2008; Bhuyan and Borah, 2007).

3.2. Effects of solar and magnetic activities

Since the F region density has great weight for total electron content, the strength of the crest and variation of the EIA is reflected in TEC. In this work, the magnitude of daily peak VTEC is used to quantify the strength of northern EIA crest around 118ºE longitudes. Fig. 3 gives the annual variation of daily EIA crest. It is noted that the value of daily peak VTEC also has distinct seasonal and annual anomaly, with relative high magnitude in equinocial months (March, April, September, and October), which means that the daily peak VTEC and hourly VTEC have the similar fluctuation for long variation. To examine the influence of magnetic and solar activity on the daily peak VTEC, the Dst index, Ap index, solar flux index F10.7 and sunspot number SSN were chosen to give correlation analysis with peak VTEC and shown in Fig. 4, respectively. For each plot in Fig. 4 the line fitting and correlation coefficients (represented by the capital R) were determined and the corresponding fitting is shown by the straight line. The results from these plots reveal that the correlation of daily peak VTEC with daily Dst, Ap, F10.7 and sunspot number SSN is very low (R < 0.3) for year 2006. In order to understand the effect solar activity and geomagnetic activity on the monthly variation of peak VTEC, we study the monthly average effects for 12 months. Fig. 5 shows the correlation of peak VTEC with those four indices. Again, the SSN shows a positive correlation with peak VTEC (R = 0.26), and there is no or less relationship between monthly VTEC and monthly Ap (R = 0.05), Dst (R = −0.11), and F10.7 (R = 0.14).

The above correlation analyses indicate that during the low solar activity year, 2006, the effects of geomagnetic and solar activities on northern EIA crest around 118ºE longitudes in both daily peak and seasonal variation of VTEC are very weak. In general, electron populations in the ionosphere are mainly controlled by solar photo-ionization and recombination processes. The photo-ionization caused by solar EUV radiation can produce more electrons and therefore enhances the background electron density. During
the equinoxes, the subsolar point is around the equator, where the eastward electrojet-associated electric field is often largest. Because of the collocation of the peak photoelectron abundance and the most intense eastward electric field region, the fountain effect should be developed the most; during the solstices, photoelectrons at the equator decrease because the subsolar point moves to higher latitudes and the fountain effect is expected to wane (Wu et al., 2004). This EUV effect could be demonstrated in our result (the correlation between peak VTEC and SSN is the best, compared to other three indices). A positive linear relationship between the value of EIA and the sunspot number also has been found by Huang and Cheng (1996). But Kumar and Singh (2009) found that SSN has very little effect ($r = -0.03$) on the variation of EIA crest in TEC and suggested that this may be due to the solar minimum period of May 2007 to April 2008. For the effect of Dst-index on TEC, our finding in the present paper is similar with Kumar and Singh (2009), they also found a bad relationship between the monthly values of the EIA crest in TEC and the monthly Dst-index ($R = -0.03$). However, Wu et al. (2004) found a good correlation of the monthly values of the anomaly crest with the monthly Dst index and suggested that the Dst index is a more suitable parameter for studying long-term
ionospheric dynamics around the EIA regions. **Wu et al. (2008)** found a good correlation of EIA and F10.7 (correlation coefficient = 0.87) through analyzing a long-term data set (1994–2003). **Bagiya et al. (2009)** reported that there is positive correlation between peak TEC and solar radio flux. But in our work, the effect of F10.7 is relative week (R = 0.17 for daily value and R = 0.14 for monthly value).

### 3.3. Comparison with SPIM

Modeling and predicting the value and variation of ionosphere parameter is still a subject for scientist. Researchers may be able to set up early warning procedures by learning how to predict TEC values in advance, which can give enough time to protect valuable communication’s satellites from the space weather impact. Empirical ionosphere model such as IRI, which has been used to research the temporal and spatial change of TEC, provides a good prediction mostly. Some authors through comparing the observed TEC and the modeling result of IRI found that the value predicted by the IRI shows relative higher than measurements. **Obrou et al. (2009)** studied the comparison between the modeled TEC by IRI and ionosonde observation at an equatorial latitude station, Korhogo. They found the IRI overestimates the value of TEC and, the discrepancies are evident in equinox at low solar activity. **Bhuyan et al. (2006)** and **Bhuyan and Borah (2007)** compared the GPS-derived TEC and IRI model in Indian region. They also found that the model output were higher than measurements. The relative large difference between observation and model prediction is not surprising since the IRI model is primarily based on data from mid latitudes with only few additional data from low and equatorial latitudes (Bilitza, 2001).

Advanced modeling and forecasting of the total electron content, defining distribution of density, temperature, and effective collision frequency of electrons through the ionosphere and plasma-sphere is one of the goals of the ISO modeling efforts. The international Standard Plasmasphere Ionosphere Model, SPIM, in the framework of project of the International Standardization Organization, is based on the IRI and merged the Russian Standard Model of Ionosphere, SMI up to 20,000 km for altitude at any longitude, geodetic latitude from 80°N to 80°S, for any time of day, day of year, wide range of the solar and magnetic activity indices (Gulyaeva, 2003; Troitsky et al., 2007). SPIM model driven by input file allows ingestion of routine magnetic indices updated every 3 h via internet. Special subroutine of SPIM code provides forecast of magnetic activity 3 h in advance. This model also could be used to predict F2 layer critical frequency, F2 layer peak height, foF2, electron density at the bottom side and top side, etc. The source code could be downloaded from website (ftp://ftp.izmiran.rssi.ru/pub/izmiran/SPIM).

To test and verify the usability of SPIM in the low latitude, in this work, we use SPIM to model the TEC in Xiamen, and make compare with the GPS derived data. Fig. 6 shows the measured and SPIM predicted TEC for different seasons of year 2006. It is seen from the figure that the SPIM overestimates TEC over year; however, it exhibits similar tendency during the whole day. For the occurrence time of daily peak VTEC, the value SPIM predicted is earlier than observation, which is the predicted VTEC reaches

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**Fig. 5. Correlation coefficients comparing monthly peek VTEC with monthly averaged Dst index, Ap index, F10.7 and SSN.**

**Fig. 6. Comparison of measured TEC and SPIM predicted TEC for different seasons of year 2006.**
maximum at 05 UT during equinox and winter while at 06 UT during summer. In order to understand more about the usability of the SPIM, a relative difference parameter is used to describe the model result for observed data, which is defined as follows:

$$RD_{VTEC} = 1 - \frac{VTEC(Obs)}{VTEC(SPIM)}$$

where $VTEC(Obs)$ represents the GPS-derived $VTEC$ and $VTEC(SPIM)$ is the output of SPIM. Fig. 7 shows the diurnal distribution of $RD_{VTEC}$ regardless the seasons. It is noted that $RD_{VTEC}$ are almost plus, which means the predicted results of SPIM overestimate the $VTEC$ at all seasons and almost all the time. On the whole, the $RD_{VTEC}$ is relative high during 14–19 UT and the highest value could reach to 0.6.
Although the height (20,000 km) that SPIM could model seems more reasonable for calculating the TEC and the model can predict a good variation tendency for TEC and the seasonal anomaly, with the high value during equinox and relative low value during winter and summer, the morphological characteristics of VTEC as shown in this paper indicate that the shortcoming of SPIM can easily be seen when it is applied at Xiamen, a station of the low latitude. The difference between model and observation could be partly caused the shape of profile assumed by the model. Another reason of difference could be related with the second part of SPIM, Russian Standard Model of Ionosphere (SMI), which based on the data more from high latitude, so when the model is used to predict the TEC or other ionospheric parameters, it may not show great agreement with the measurements from the low latitude. Like as the reports sited and analyzed by Bhuyan and Borah (2007), the outputs of IRI may overestimate the GPS TEC at most time during low solar activity both in the Indian and East Asian longitude sectors, thus, the SPIM, which based IRI and merged the Russian Standard Model of Ionosphere overestimates the TEC is to be expected.

4. Conclusion

In the present paper we investigated the diurnal and seasonal variations, solar and magnetic activity effects on the characteristics of the equatorial ionospheric anomaly by using the GPS-derived VTEC at Xiamen (24.5°N, 118.1°E, geomagnetic latitude 13.2°N), which is situated in the region of northern equatorial anomaly. In order to test and verify the usability of SPIM recommend by International Standardization Organization (ISO), the GPS-derived TEC have been compared with the model prediction. The main results from this study are as follows:

1. The magnitude of vertical TEC exhibits remarkable seasonal variation with maximum in equinocial months and minimum in winter and summer months. The small winter anomaly is found in year 2006.
2. The relative standard deviation for VTEC shows high value at around midnight and before sunrise.
3. The correlation analyses between peak VTEC and magnetic and solar index indicate that the effect of magnetic and solar activity is relative weak during year 2006, both in the daily value and monthly value. There is almost no correlation between daily VTEC and daily Dst ($R = -0.09$), monthly VTEC and monthly Ap ($R = 0.05$). The sunspot number SSN have the best correlation with peak VTEC among the chosen magnetic and solar index.
4. The predicted vertical TEC by SPIM is greater than the GPS-derived TEC. Which illustrates that this ionosphere model recommend by International Standardization Organization need to improve its prediction accuracy in the area of low latitude.

It should be pointed out that this work is our first time to analyze one year data of VTEC during low solar activity at low latitude station, which is not enough to reveal all characteristics of ionospheric variation in this region. More studies about ionosphere at the low latitude in China zone for different solar activities and places will be done in the near future.

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