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TOTAL ELECTRON CONTENT VARIATIONS DURING DIFFERENT GEOMAGNETIC ACTIVITIES IN ILE-IFE, NIGERIA

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ABSTRACT

GPS-derived vertical Total Electron content (TEC) recorded at Ile-Ife (Mlat. 7.52°N and Mlong. 4.28°E), Nigeria during the year 2011 for different geomagnetic activities was analyzed to investigate TEC variations. The results showed that TEC exhibit diurnal and seasonal variations, with equinoctial season recording the highest TEC during the daytime maximum. Winter anomaly was absent. Comparative results revealed that IRI-2012 underestimates measured TEC during the different geomagnetic activities in Ile-Ife. An average value of about 40% deviation between the modeled and measured TEC was obtained during moderate and intense geomagnetic activities, while that during low geomagnetic activities was about 11%.

Keywords: Equatorial ionisation anomaly, vertical TEC, global positioning system, international reference ionosphere.

INTRODUCTION

The ionosphere is an important error source for the signal of the Global Positioning System (GPS).GPS satellites are at an altitude of about 20,200km and transmit signals through the ionosphere to the receiver on the earth surface. As the global positioning system signal propagate through the ionosphere, the carrier experiences a phase advance and the code experiences a group delay due to total number of free electrons along the path of the signals from the satellite to the receiver. The ionospheric effects during geomagnetic activities on navigational control application, satellite tracking, positioning and communication and time information depends on the variations in the Total Electron Content (TEC) in the ionosphere. The TEC provides an overall description of the ionization in the ionosphere during different geomagnetic activities and so forms important ionospheric parameters for several practical purposes.

The extensive study of the geomagnetic activities in the ionosphere has revealed the primary physical mechanisms responsible for generating the large disturbances that are observed to occur in the ionosphere. Ariyibi *et al*. (2013b) interpreted the data records in Ile-Ife station (TEC and S4 index) from 4 - 6 April, 2010 and used it to study the effects of geomagnetic storms on TEC in African ionosphere and the scintillation variations during the storms. The ionospheric condition during low geomagnetic activity period and their seasonal dependence was also discussed. The dependence of TEC on level of geomagnetic activity, time and seasons of the year was observed. TEC was enhanced during the daytime and was highest during the equinoctial months. Scintillation occurrence was closely linked to TEC depletion and not necessarily geomagnetic storms in the station. Olatunbosun and Ariyibi (2015) also combined GPS data from three stations of Ile-Ife, Addis Ababa and Bangalore to draw comparative results in TEC variations in the stations. It was found that Ile-Ife station had the least diurnal and seasonal TEC variations. Jimoh *et al.* (2016) also used GPS data obtained from Ile-Ife to study the effect of geomagnetic storm on TEC variations. It was observed significant enhancement in TEC during geomagnetic storms. Fayose *et al*. (2012) studied the diurnal and seasonal variations of vertical TEC at Akure, Nigeria using GPS data. They observed that the mean TEC varies from pre-dawn minimum to a maximum during the afternoon and then decreases. The low values of TEC are observed in winter and high values observed in equinox.

Among the different sources of global positioning system positional errors, ionospheric delay, which is proportional to the TEC, is the highest contributor. Therefore in order to get better accuracy, it is necessary to have a precise knowledge of the accurate value and the variations of the TEC measured at different geomagnetic activities. This research work therefore studies the variations of TEC during different geomagnetic activities in low latitude

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station over Ile-Ife. The measured TEC was compared with modelled TEC for better reproduction of IRI models.

MATERIALS AND METHODS

Methodology

The data obtained from the dual frequency SCINDA NovAtel GSV 4004B GPS receiver installed at Department of Physics and Engineering Physics, Obafemi Awolowo University, Ile- Ife, Nigeria (geographical Latitude 7º 33[1] N and Longitude 4º 33[1] E and geomagnetic dipole coordinate of Latitude 9.84ºN and Longitude 77.25ºE) were processed using GPS-TEC analysis software developed by Gopi (2010). The application gave the slant total electron content (STEC) which is dependent on elevation angle. The geomagnetic indices of Disturbance storm index (Dst) and planetary K index (Kp) obtained from World Data Center (WDC) for geomagnetism was used to identify and classify the storm events. The IMF-Bz and plasma speed (Vp) was used to describe the condition of the ionosphere. The model TEC data from International Reference Ionosphere (IRI) of 2012 version were obtained from OMNI web (omniweb.gsfc.nasa.gov/vitmo/iri_vitmo.html) for different geomagnetic conditions. These were plotted alongside the measured TEC for comparison. The location of the study area in the Nigeria map is shown in the Figure 1. It lies within the equatorial ionisation anomaly (EIA) zone.

The GPS receiver measures the pseudoranges using the coarse acquisition code on L_1 and the precise (P) code on L_2.The slant TEC (STEC) is obtained according to Langley (2000) and Fedrizzi *et al*. (2005). It is related to the calibrated $TEC_{BE}$and the dual frequency code measurements by:

$$STEC = \frac{1}{40.3} \times \left(\frac{1}{L_1^2} - \frac{1}{L_2^2}\right)^{-1} \times (P_1 - P_2) + TEC_{BE} \quad (1)$$

where P_1 = Pseudo range at L_1, P_2 = Pseudo range at L_2 and TEC_{BE} is the bias error correction, which is different for different satellite – receiver pairs (Bagiya *et al*., 2009). The vertical TEC (VTEC) therefore, is obtained by taking the projection from the slant to the vertical using the thin shell model assuming a height of 350km, following the technique given by Klobuchar (1986).

$$VTEC = STEC \times Cos\left[Sin^{-1}\left(\frac{R_E\, Cos\, e}{R_E + h_{max}}\right)\right] \quad (2)$$

where the radius of the Earth, R_e = 6378km, the height to the pierce point, h_{max} = 350km, and z = elevation angle at the ground station, as depicted in Figure 2. VTEC is in TEC units (TECu) and 1TECu = 10^{16} electrons/m^2.

RESULTS AND DISCUSSION

Classification of geomagnetic activities

The geomagnetic activities were classified as low, moderate, intense and quiet conditions. These classifications were informed based on the geomagnetic indices of Dst, Kp and Ap. While Dst index was used to identify the geomagnetic conditions, Kp and Ap indices were used to ascertain the level of severity of the geomagnetic activities. The summary of the classification of the geomagnetic activities considered in this paper is shown in Table 1.

Solar Interplanetary Condition

The condition of the ionosphere during the different geomagnetic conditions were investigated using ionospheric parameters of Interplanetary Magnetic Field of Z-component (IMF-Bz) and plasma speed (Vp), in conjunction with the geomagnetic indices. Figures 1 – 3 show the interplanetary conditions during the different classes of geomagnetic activities. The intense storm on 26 September and the moderate storm on 10 -11 March was marked with storm sudden commencement (SSC) when the IMF-Bz suddenly turned southward. A positive phase of IMF-Bz observed indicates compression in earth’s magnetic field. This is an indication that the factors generating the positive phase have a bearing on the southward turning of the IMF-Bz. The plasma speed abruptly increased during the main phase of the storm. The ionospheric condition was different during the low storm event on 28 July, with IMF-Bz remaining northward and low value of plasma speed.

Rapidly decreasing IMF-Bz during the intense and moderate storms caused a sudden increase in polar cap potential, resulting in the generation of sudden region-1 currents which could not be shielded by the region-2 currents. This caused the high latitude electric potential (normally shielded by the region-2 currents) to reach the lower latitudes (Peymirat *et al*., 2000).

TEC variations

Diurnal variations of TEC

The diurnal variations of vertical TEC during the different geomagnetic activities were investigated using GPS- and IRI- derived TEC. In the day-to-day variations as represented in Figure 4, different geomagnetic conditions were represented. The results showed that TEC varies diurnally, with maximum values attained during the daytime (11:00 – 18:00 LT). The TEC variations were also found to be dependent on geomagnetic conditions, with enhanced TEC maximum corresponding to low Dst values. The results also revealed that IRI model underestimates the measured TEC in Ile-Ife station during all the geomagnetic conditions. The underestimation was more during the high geomagnetic activities, with average deviation of about 40%.

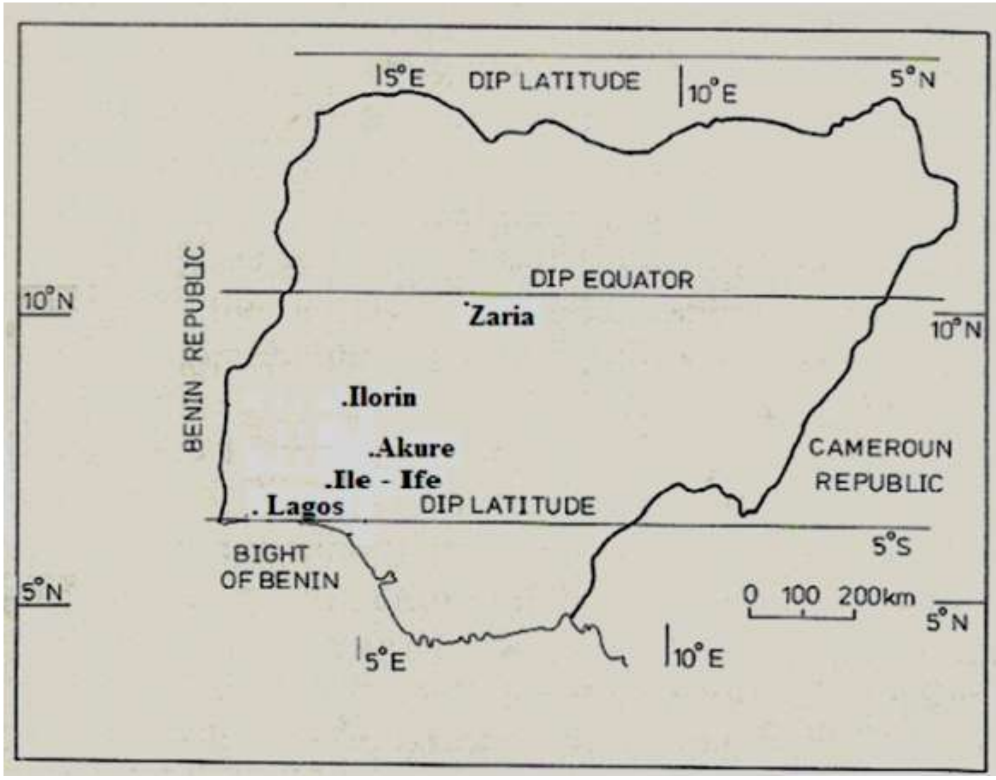

Fig. 1. Map of Nigeria showing the location of Ile-Ife GPS receiver station (After Ogunade, 1987).

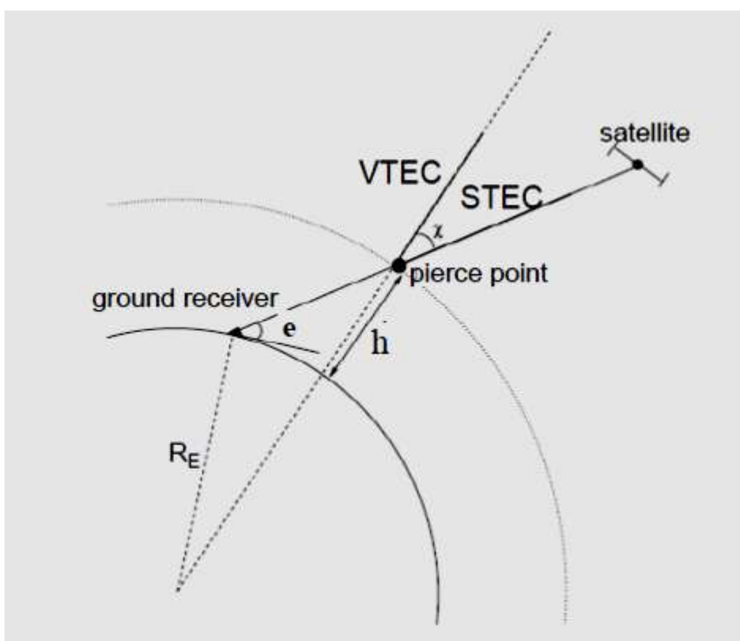

Fig. 2. Geometry for the conversion of slant TEC to vertical TEC.

Seasonal variations of TEC

TEC was further investigated for seasonal dependence. This was done by grouping the monthly mean into three seasons of Equinox (March, April, September and October), Winter (January, February, November and December) and Summer (May, June, July and August). From Figure 5, it was obvious that TEC variations were dependent on seasons of the year. The equinoctial season

Table 1. The classifications of geomagnetic activities in 2011 (From WDC Kyoto, Japan).

Days of the Year	Geomagnetic Indices			
	Maximum Kp	Dst (nT)	Maximum Ap	Class of storms
A. Disturbed days in 2011				
1. May 2nd	3 +4 4 +3 3 3 +3 +3	-49	18 27 32 15 15 1818 15	Low
2. March 10th 11th	2 2 +4 +4 -3 -2 4 5 5 5 +4 +2 2 -4 +5 6	-60 -83	9 32 22 12 7 27 39 56 32 7 6 32 48 67	Moderate
3. August 6th 4. September 26th 5. October 25th	6 +5 4 -4 4 -3 +1 +3 1 +1 -7 +6 -5 -3 3 2 1 +1 1 1 +5 -6 +6 +5	-107 -101 -132	94 48 22 27 22 18 5 15 5 3 4 5 39 94 94 56 154 67 39 15 15 7 5 3	Intense
B. Quiet Day in 2011				
1. July 28th 2. August 4th	1 -1 +0 +0 +0 +0 +1-1	≤-3 ≤-4	3 5 2 2 2 2 3 5	Quiet

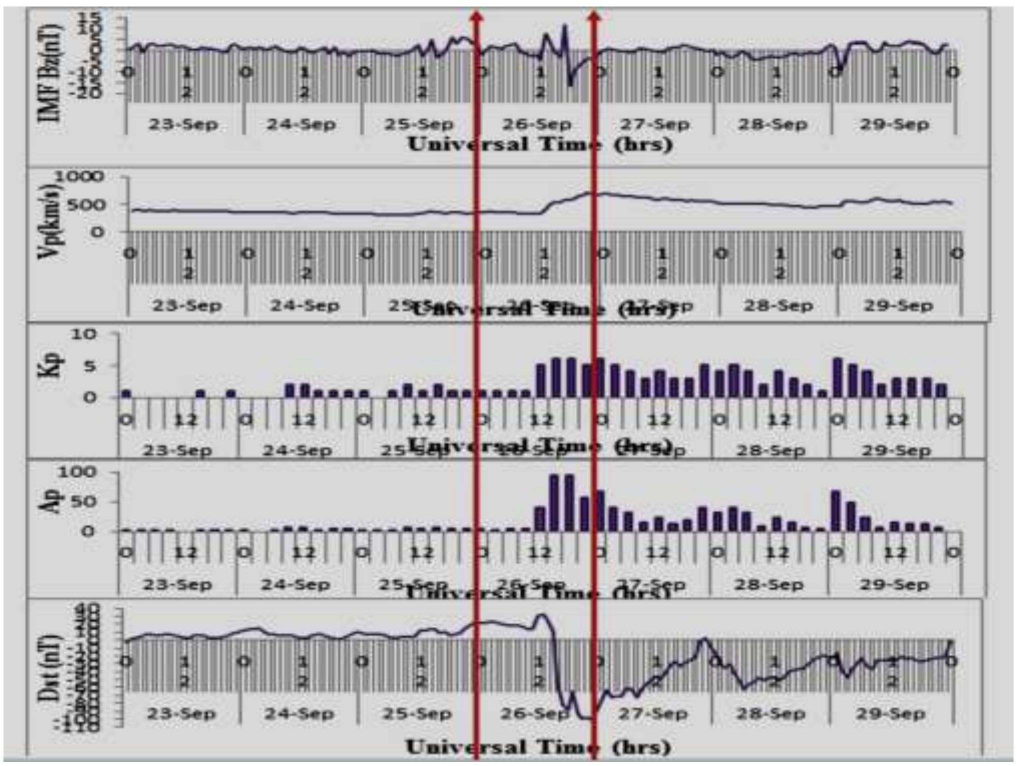

Fig. 1. Solar Interplanetary Condition for intense storm on 26 September 2011.

recorded the highest value of TEC during the daytime plateau, followed by the summer and winter seasons. The seasonal variation of TEC can be explained using thermospheric neutral composition phenomenon. Rishbeth and Setty (1961) suggested that the seasonal changes result from changes in ratio of the concentration of atomic oxygen and molecular nitrogen in the F-region. During the daytime, the equator is hotter than the pole, therefore meridional wind flows towards the pole from the equator. This flow of meridional wind changes the neutral composition and O/N_2 decreases at equatorial and low latitude stations. The decrease is maxima in equinoctial seasons. Also, at 350 km altitude (F2-layer), N_2 dissociation is the major process which removes ambient electrons. Hence, the decrease in O/N_2 ratio will result in higher electron density and comparative results showed that IRI underestimates measured TEC during the daytime in all seasons. The IRI maximum TEC values are about 34, 32 and 24 TECu and GPS maximum TEC values are about 49, 35 and 35 TECu for equinox, summer and winter seasons, respectively. It became obvious that the underestimation was more during high geomagnetic activities, with equinox and winter seasons having the highest deviation of about 31% each, while the summer season recorded the least deviation of about 9%.

Many comparisons of observed F region parameters, such as TEC at low latitudes with IRI predicted values have

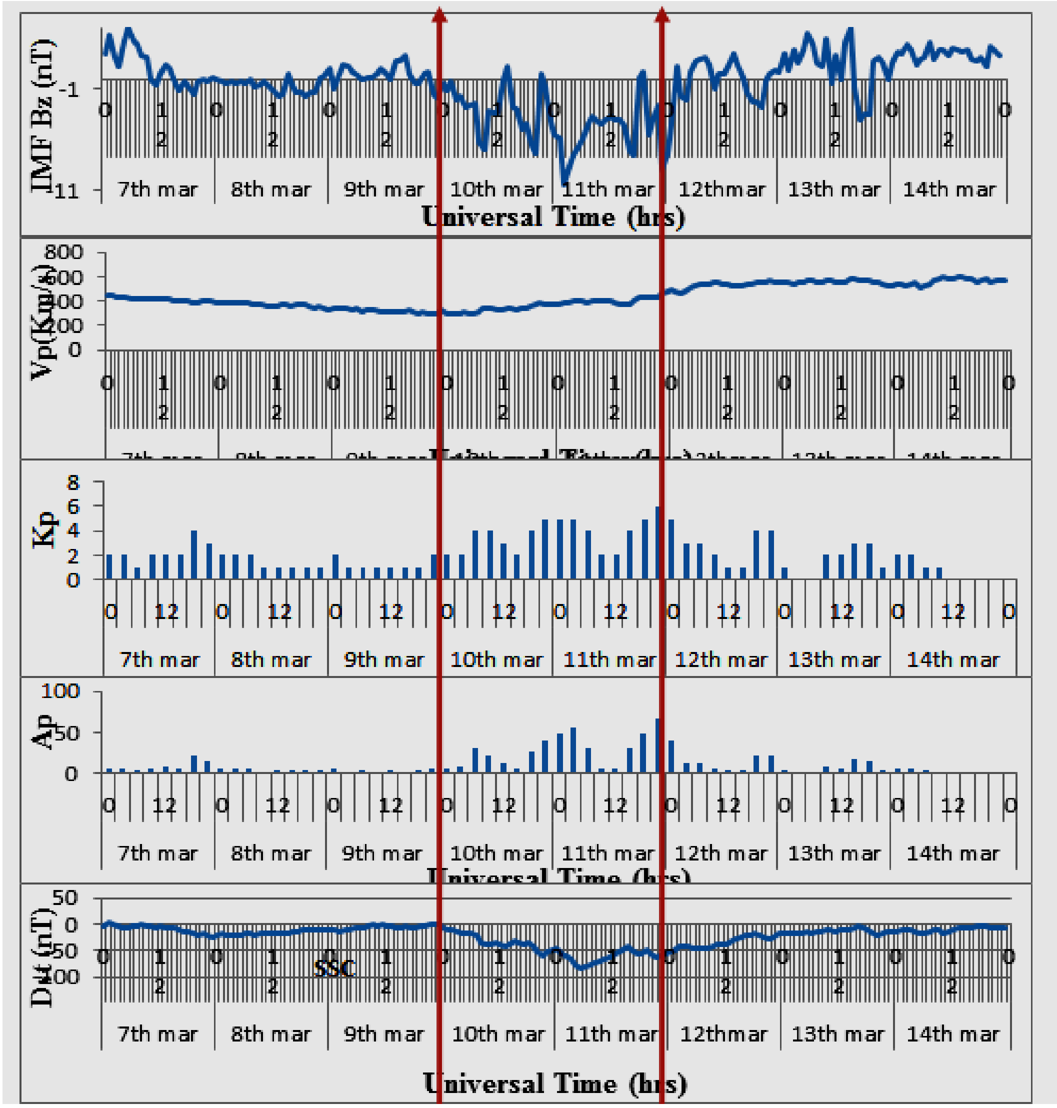

Fig. 2. The Solar Interplanetary Condition for moderate storm periods of 7-14 March, 2011.

been made by many research in different locations. For example, Ezquer *et al*. (1995) used GPS measurement over Tucuman (24.9^{o}S, 294.6^{o}E, geomagnetic latitude 15.45^{o}S) during high solar activity year of 1982. Their results showed that IRI-90 overestimates the TEC measured over the station during hours of minimum TEC (00:00–10:00 LT) and underestimated it during hours of maximum TEC (12:00–18:00 LT). Also, Abdu *et al*. (1996) compared the IRI-90 predictions and observed F-region parameters, e.g., foF2, hmF2, and TEC for the equatorial anomaly region in the Brazilian sector. The results were also compared with those obtained from the Asian and Indian longitude sectors. They found that the TEC predicted by the IRI shows good agreement with observation at intermediate solar activities. IRI overestimates the TEC during solar minimum in the Brazilian and Asian longitude sectors. Contrarily, IRI tends to underestimate the anomaly region TEC during solar maximum in both longitude sectors. Shastri *et al*. (1996) made a study of the performance of the IRI-90 in the Indian sector from a comparison of foF2 observed at four locations and found that the IRI in general overestimates the observed peak density at all solar activity levels. The difference between observation and prediction varies with local time and location. On the other hand, Iyer *et al*. (1996) have shown that the IRI overestimates TEC during low solar activity and under estimates it in high solar activity at the crest of the anomaly both in the Indian and East Asian longitude sectors. However, this is the first comparative result of modelled TEC and measured TEC in Ile-Ife, Nigeria. Our result showed that IRI-2012 underestimates TEC during the different geomagnetic conditions and was more during high solar activities. The underestimation was during the

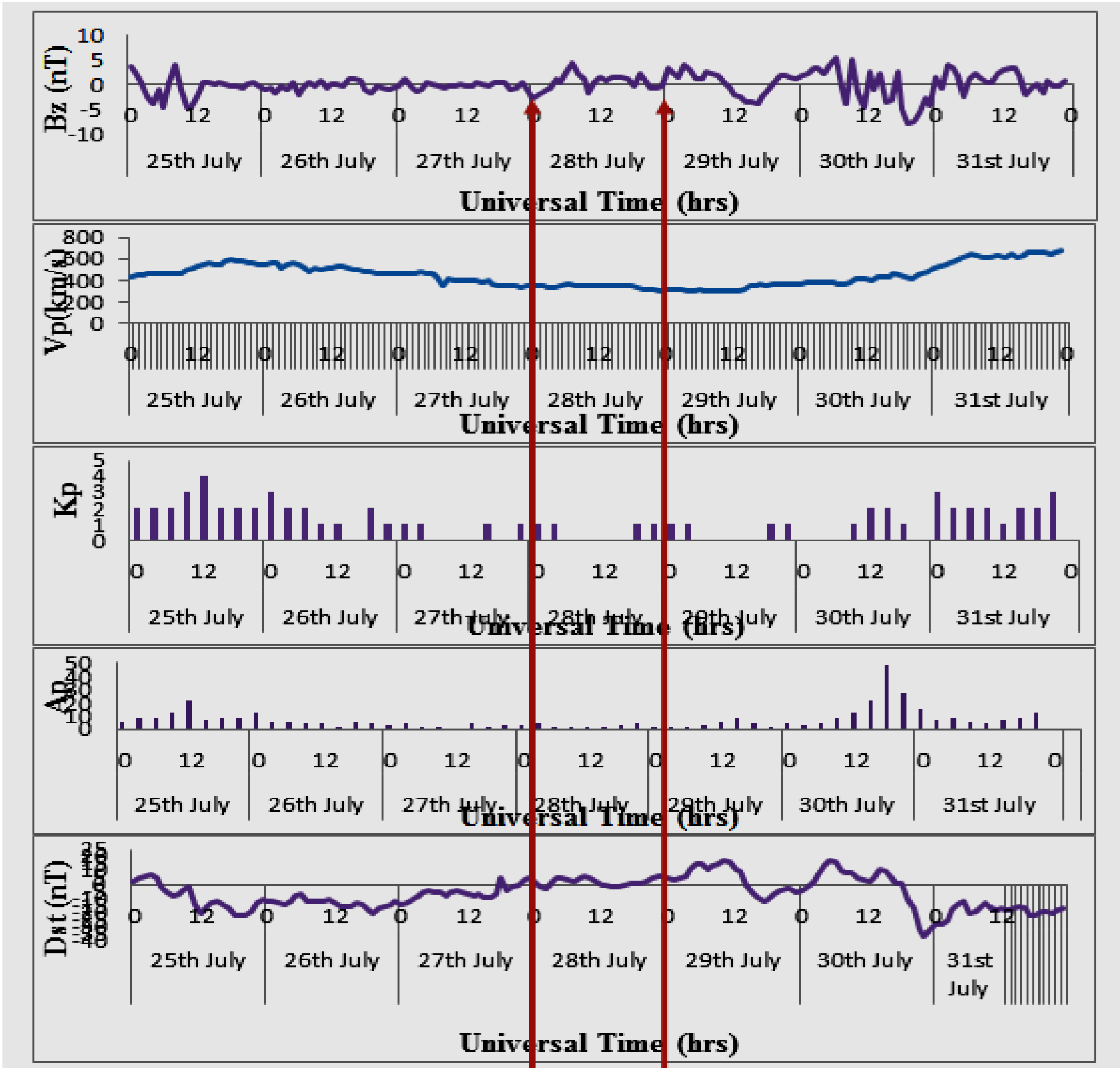

Fig. 3. The Solar Interplanetary Condition for quiet days from 25-31 July, 2011.

daytime plateau and the build-up region. However, it averagely overestimated the measured TEC during the decay region.

Correlation of TEC with geomagnetic activities

The summary of the geomagnetic indices and solar interplanetary parameters during quiet, low, moderate and intense storm days is presented in Table 2. Visible in the table was the dependent of TEC values along the equatorial ionosphere on not only the Dst values, but also on factors such as IMF- Bz and Kp. The 28 July for instance recorded the lowest Dst value of -3 nT and also had IMF-Bz pointing northward with maximum value of 4.3 nT. In terms of TEC variations, it recorded the least value of TEC variation. This was not the same during increased geomagnetic activities where the Dst values were lowest at -107, -101, -83, and -60 nT. The IMF-Bz pointed southward in all the days and also had enhanced TEC variation, which was dependent on season. The Kp values ranged between 1(quiet day) to 6 (intense storm day) and correspondingly have 37 TECu and 60 TECu. The variation of TEC with Kp was similar to its variation with Dst. The behaviour of the Ap values are similar to that of Kp variations and so can be used in place of one another. The variation of Vp values with TEC was such that an abrupt increase in Vp resulted to enhanced TEC, which was also dependent on seasons.

CONCLUSION

TEC variations during different geomagnetic activities revealed day-to-day, monthly and seasonal variations. The amplitude of TEC is dependent on time of the day and the activity of the Sun. Geomagnetic storm enhances the TEC

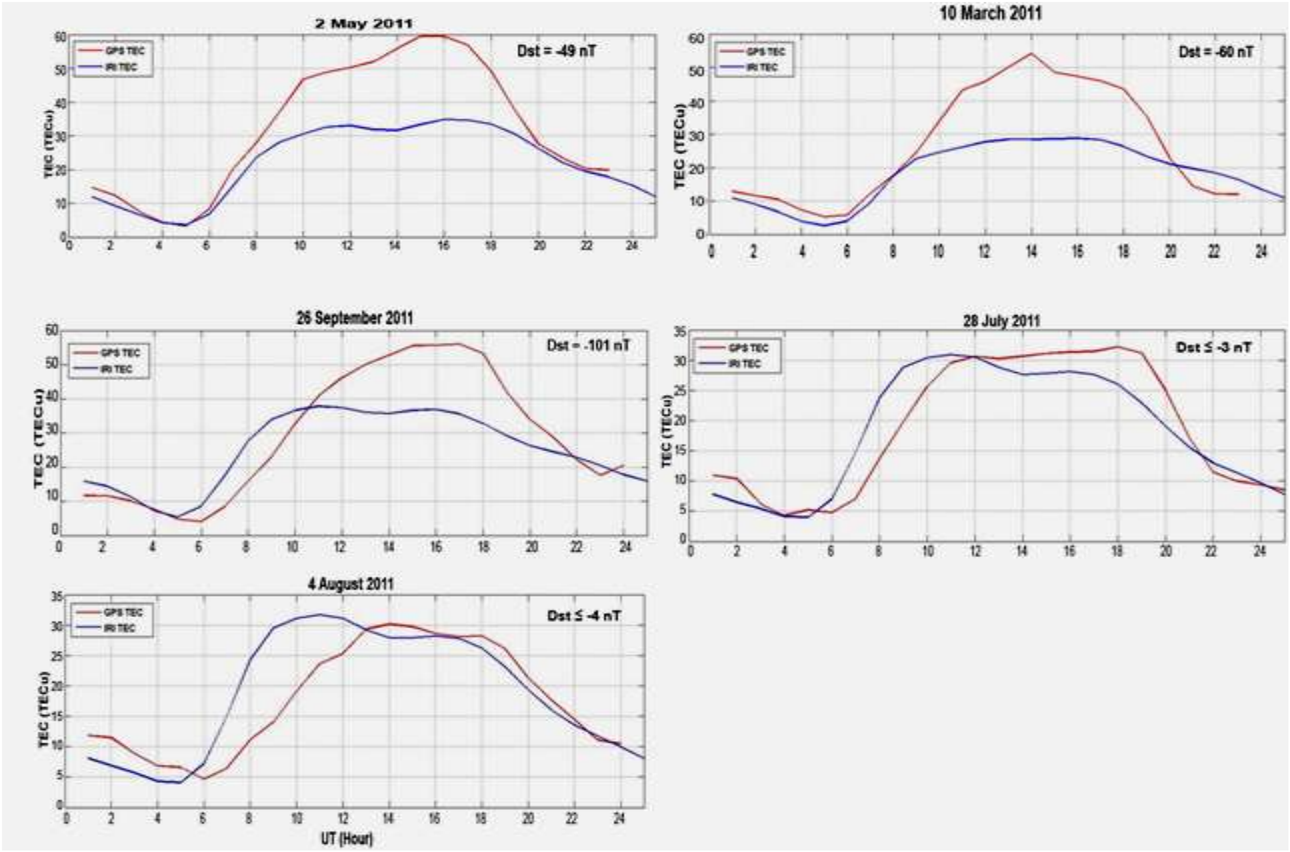

Fig. 4. Diurnal Variation of GPS and IRI TEC during different geomagnetic activities.

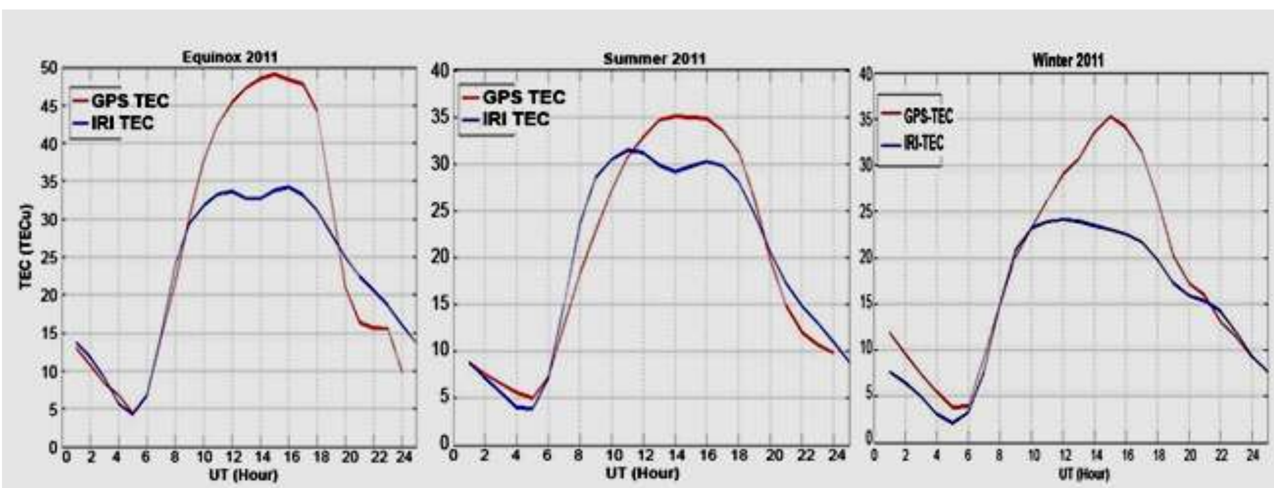

Fig. 5. The Seasonal Variation of GPS-derived and IRI-derived TEC in Ile-Ife.

variations. Comparative results between GPS- and IRI-derived TEC showed similar pattern of diurnal variations. The TEC increases gradually from hours of minimum TEC (06:00 – 07:00 LT) during all seasons, reaching maximum during the day (11:00 – 18:00 LT). At sunset, the TEC values decreased, reaching minimum at about sunrise. The study also revealed that IRI-2012 underestimates the GPS TEC in all seasons during the daytime plateau. The underestimation was highest during the effort by International Geophysical Year (IGY) through coordinated global observations has yielded in increased ionospheric research to primarily help in the design and operation of HF radio wave communication systems. The African region covers a highly variable part

Table 2. The Correlation of geomagnetic indices with TEC variations during different geomagnetic activities.

Storm	Dst (nT)	Max. Kp	Max. Ap	Max. Vp (km/s)	Max. IMF-Bz(nT)	Max. TEC (TECu)
Quiet day (July 28)	-3	1	5	360	+4.3	37
Low Storm (May 2)	-49	4	32	700	-3.2	64
Moderate Storm (a) March 10 (b) March 11	-60 -83	4 6	39 67	300 400	-7.3 -10.5	59 60
Intense storm (a) August 6 (b) September 26	 -107 -101	 6 6	 94 94	 600 700	 -7.0 -16.4	 48 60

of the equatorial electrojet and EIA (Equatorial Ionisation Anomaly) phenomena making its predictability difficult. The need for accurate ionospheric TEC (Total Electron Content) models at global and regional scales has also been stressed. The results of this research have revealed the need for adjustment in the IRI-2012 for better representation of low-latitude ionosphere, more especially Ile-Ife, Nigeria.

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