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Diurnal Variation of TEC and S_4 Index During the Period of Low Geomagnetic Activity at Ile-Ife, Nigeria

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Abstract Ile-Ife lies on the equatorial anomaly region where the ionospheric current is greatly influenced by the existence of the equatorial electrojet. The dual frequency SCINDA NovAtel GSV 4004B GPS receiver recently installed at Ile-Ife [on geographical latitude 7°33′N and longitude 4°33′E and geomagnetic dipole (coordinate) of latitude 9.84°N and longitude 77.25°E] is currently operational and recording data from the available global positioning system satellites. The receiver provides the data on total electron content (TEC) and the scintillation index (S_4). This paper presents the first sets of results from this station. Data records for the month of February 2010 were analyzed using the WinTec-P software program and these were interpreted to discuss the diurnal variation of the TEC and S_4 index during the period considered, as having low geomagnetic activity. The vertical TEC in this study showed that the values vary widely from as low as 0 TECu about sunrise to about 35 TECu during the day. Depletion in TEC was also noticed about sunset and marked by the occurrence of scintillations with a maximum index value of 0.3. Results of the IRI models and the observed TEC differ considerably; hence, there is the need to improve IRI models for its adaptability to the Africa ionospheric conditions.

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Keywords Equatorial ionosphere · Geomagnetic activity · Scintillations

الخلاصة

إن يل - إيفي تقع على منطقة الشذوذ الاستوائي حيث يتأثر التيار الأيوني الدائري إلى حد كبير بوجود الكهربائي الاستوائي. إن مستقبل التردد المزدوج SCINDA نوفاتيل GSV 4004 B في إيل - إيفي المثبت مؤخرا على خط العرض الجغرافي 7^0 33’ N و خط الطول 4^0 33’E والجيومغنطيسية ثنائية القطب (إحداثيات) من خط العرض شمالا 9.84^0 و خط الطول 77.25^0 شرقا هو حاليا في العمل ويسجل بيانات من الاقمار الصناعية لتحديد المواقع المتاحة. ويقدم هذا المستقبل بيانات عن إجمالي المحتوى الإلكتروني (TEC) ومؤشر الومضات (S4). وتعرض هذه الورقة العلمية مجموعة النتائج الأولى من هذه المحطة، حيث تم تحليل سجلات البيانات لشهر فبراير 2010م باستخدام برنامج حاسوبي WinTec-P وتفسيرها لمناقشة الاختلاف النهاري لمؤشر TEC و S4 خلال الفترة التي تم النظر فيها على أنها قليلة النشاط المغنطيسي الأرضي. وقد أظهرت TEC العمودية في هذه الدراسة أن القيم تختلف اختلافا كبيرا من منخفضة لحدود 0 TECu عن شروق الشمس إلى حوالي 35 TECu خلال النهار. ولوحظ أيضا نضوب في TEC حول غروب الشمس التي تمثلت في حدوث التألق مع قيمة مؤشر أقصى قدره 0.3. وتختلف نتائج نماذج IRI و TECالملاحظة اختلافا كبيرا، وبالتالي، فإن هناك حاجة إلى تحسين نماذج IRI لقدرتها على التكيف مع ظروف الغلاف الأيوني لإفريقيا.

1 Introduction

The electromagnetic waves undergo dispersion in the ionosphere. The ionospheric morphology is mainly due to the temporal and diurnal variability of the electron density which is dependent on the solar and geomagnetic activities. The determination of the total electron content (TEC) and the scintillation index (S_4) provides a basis for the description of the ionospheric condition. References [1–3] have actually established that the estimation of TEC using global positioning system (GPS) satellites and receivers is increasingly

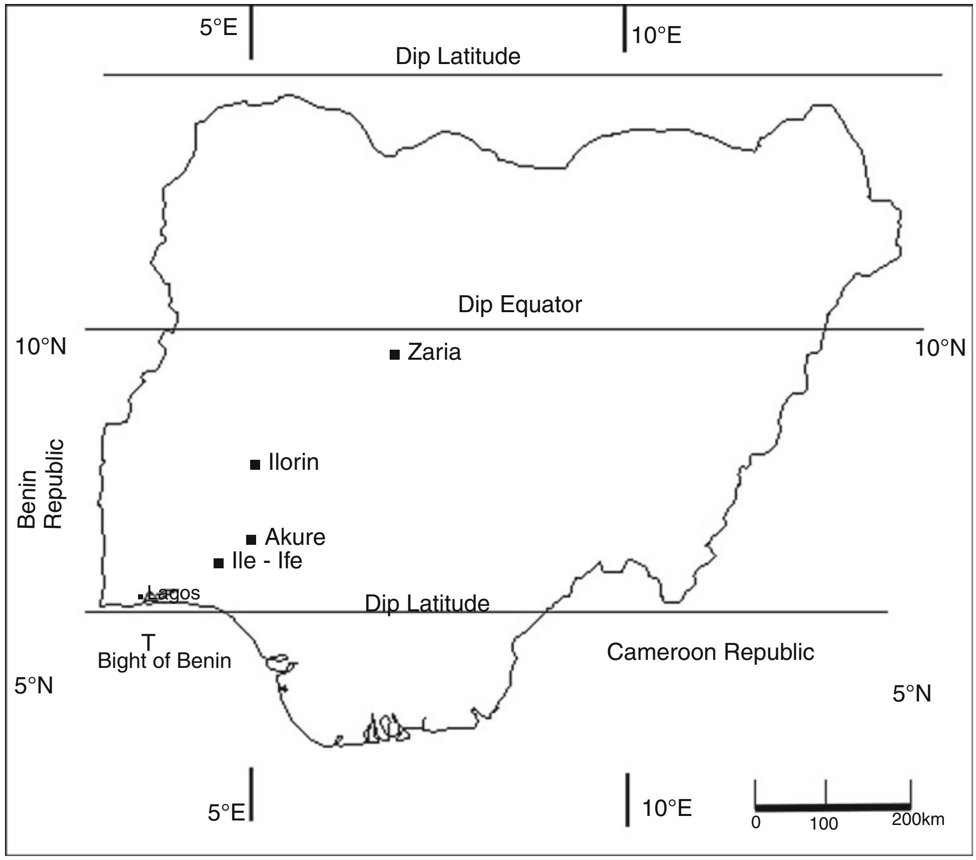

Fig. 1 Map of Nigeria showing the location of the GPS receiver station, Ile-Ife. Adapted from [16]

very useful and valuable for investigating global and local ionospheric structures because of the worldwide coverage provided by a constellation of about 30 satellites and ground receiver networks.

Equatorial ionosphere exhibits large spatial gradients in electron density due to the well-known equatorial ionization anomaly (EIA) with the trough at the magnetic equator and its crest at ±17 north and south of the magnetic dip. However, previous study by Rastogi and Klobuchar [4] shows the variation in the position of the crest of the EIA and this was evidenced in the variability of TEC that was measured by the GPS receiver stations. The variation or the instabilities in the plasma density on the ionosphere are an impediment to radio communication, as they result in the scattering of the incident radio waves, practically at all frequencies of interest. This phenomenon is generally referred to as ionospheric scintillation. It can either be in form of fluctuations in the measured amplitude or the measured phase of the radio frequency (RF) signals as they pass through the ionospheric region.

The study of ionospheric condition using GPS measurements in the equatorial regions of the world, including South America and Asia has been reported widely by [5–9] among others. Not until recently, similar efforts over the African equatorial regions have been scanty or very few if it existed. However, relevant previous works known in the area were by [10,11]. Both were able to utilize the ionosonde measurements to investigate the F-region vertical drift.

The highest TEC in the world is known to occur in the equatorial anomaly region. The ionospheric instabilities are generally due to scintillations and nighttime enhancements, and also have solar cycle dependence, as reported by several authors [12–14]. Frequent scintillations and high rates of change of TEC can cause loss of lock to single or dual frequency receiver which may result in the decrease of positioning accuracy at low latitudes [15].

The recently established dual frequency GPS receiver station in Ile-Ife, Nigeria is located on geographical latitude 7°33′N and longitude 4°33′E and geomagnetic dipole (coordinate) latitude 9.84°N and longitude 77.25°E as shown in Fig. 1 and falls within the equatorial anomaly region. This work presents the first set of results from the station. The calibrated TEC and the computed scintillation index, S_4, were used to discuss the prevailing local diurnal variation of the ionospheric condition over the study area.

2 Method

In April 2009, the Boston College, USA in conjunction with ICTP organized the first workshop on Satellite Navigation

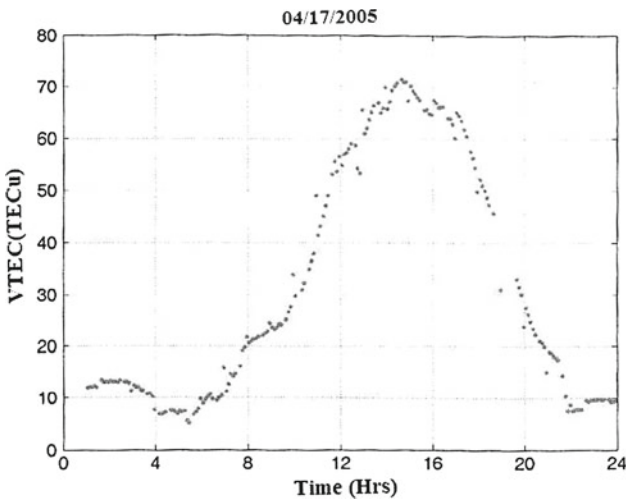

Fig. 2 Diurnal variation of TEC at a low-latitude station, Rajkot, India [6]

Science and Technology for Africa at the ICTP, Trieste, Italy. At the end of the workshop, a SCINDA NovAtel GSV 4004B GPS receiver equipment was donated to the Obafemi Awolowo University, Ile-Ife, to increase the coverage of the GPS network in Nigeria and the entire Africa. The station was set up in June 2009 and actual data gathering commenced before the end of 2009. The NovAtel GSV 4004B GPS receiver model measures the pseudo ranges using the coarse acquisition code on L_1 and the precise (P) code on L_2.

Monthly records of data were routinely retrieved from the system and stored on CDs. In the beginning, it was difficult to get continuous data records for a period of 24 h due to frequent power outages at the station. However, the power situation improved early in 2010 and fairly good monthly data were obtained in February 2010 and were thus analyzed and interpreted to discuss the diurnal variation of TEC and S_4 index. The Dst values obtained from the World Data Centre (WDC, Kyoto, Japan) for the month of February 2010 showed that it ranges between 0 and ±35 nT for the entire month. This indicated low level of geomagnetic activity for this period.

A similar study on the diurnal variation of TEC was carried out by Bagiya et al. [6] for Rajkot (India) GPS receiver station located on geomagnetic latitude 14.21°N and longitude 145.08°E. Figure 2 shows a typical result from the station. The TEC has a daily peak value of 70 TECu occurring around 14:00 hours local time (LT).

2.1 The TEC and Scintillation Measurements

Using the dual frequency GPS observations, one can take advantage of the ionosphere's dispersive character to compute the slant TEC (STEC) [17,18]. The STEC is the measure of the total number of free electrons in a column of the unit cross section along the path of the electromagnetic wave between the satellite and the receiver. The total number of free electrons is proportional to the ionospheric differential delay between L_1 (1,575.42 MHz) and L_2 (1,227.60 MHz) signals.

$$\text{STEC} = \int_{\text{receiver}}^{\text{satellite}} N \, \mathrm{d}s \tag{1}$$

Where N is the electron density, 1 TEC unit = 10^{16} electrons/m^2. Generally, the STEC is obtained from the TEC_{BE} and the dual frequency code measurements, given by

$$\text{STEC} = \frac{1}{40.3} \times \left(\frac{1}{L_1^2} - \frac{1}{L_2^2} \right)^{-1} \times (P_1 - P_2) + \text{TEC}_{\text{BE}} \tag{2}$$

where P_1 is pseudo range at L_1, P_2 pseudo range at L_2, and TEC_{BE} the bias error correction and is different for different satellite–receiver pairs.

The calibrated TEC can be computed from the relative TEC when the receiver bias and correct satellite differential code biases are obtained following from [19]. The vertical TEC (VTEC) is obtained by taking the projection from the slant to the vertical using the thin shell model assuming a height of 350 km, following the technique given by [20]:

$$(\text{VTEC}) = \text{STEC} \times \text{Cos}\left[\arcsin \left(\frac{R_e \cos z}{R_e + h_{\max}} \right) \right] \tag{3}$$

where the radius of the Earth, R_e = 6,378 km, the height to the pierce point, $h_{\max}$ = 350 km, and z = elevation angle at the ground station.

The rapid fluctuations in the amplitude or phase of the signals are referred to as scintillation. This occurs when the GPS or satellite-based augmentation system (SBAS) satellite signal travels through small-scale irregularities in electron density profiles in the ionosphere; this particularly happens in the evening and nighttime in equatorial regions.

The amplitude scintillation monitoring is traditionally accomplished by monitoring S_4 index. The index is the normalized standard deviation of the signal intensity (I) received from satellites and $\langle I \rangle$ is the ensemble average of the intensity. The total amplitude scintillation S_4 is inclusive of the ambient noise and Carrano and Groves [19] defined it as the ratio of the signal intensity standard deviation and signal intensity mean as

$$S_4 = \frac{\sqrt{\langle I^2 \rangle - \langle I \rangle^2}}{\langle I \rangle} \tag{4}$$

For S_4 = 0.0, this indicates no modulation and for S_4 = 1.0, this indicates 100 % modulation. The WinTEC, P software programme of Carrano and Groves [19] was used to process the data to obtain the vertical (or calibrated) TEC and

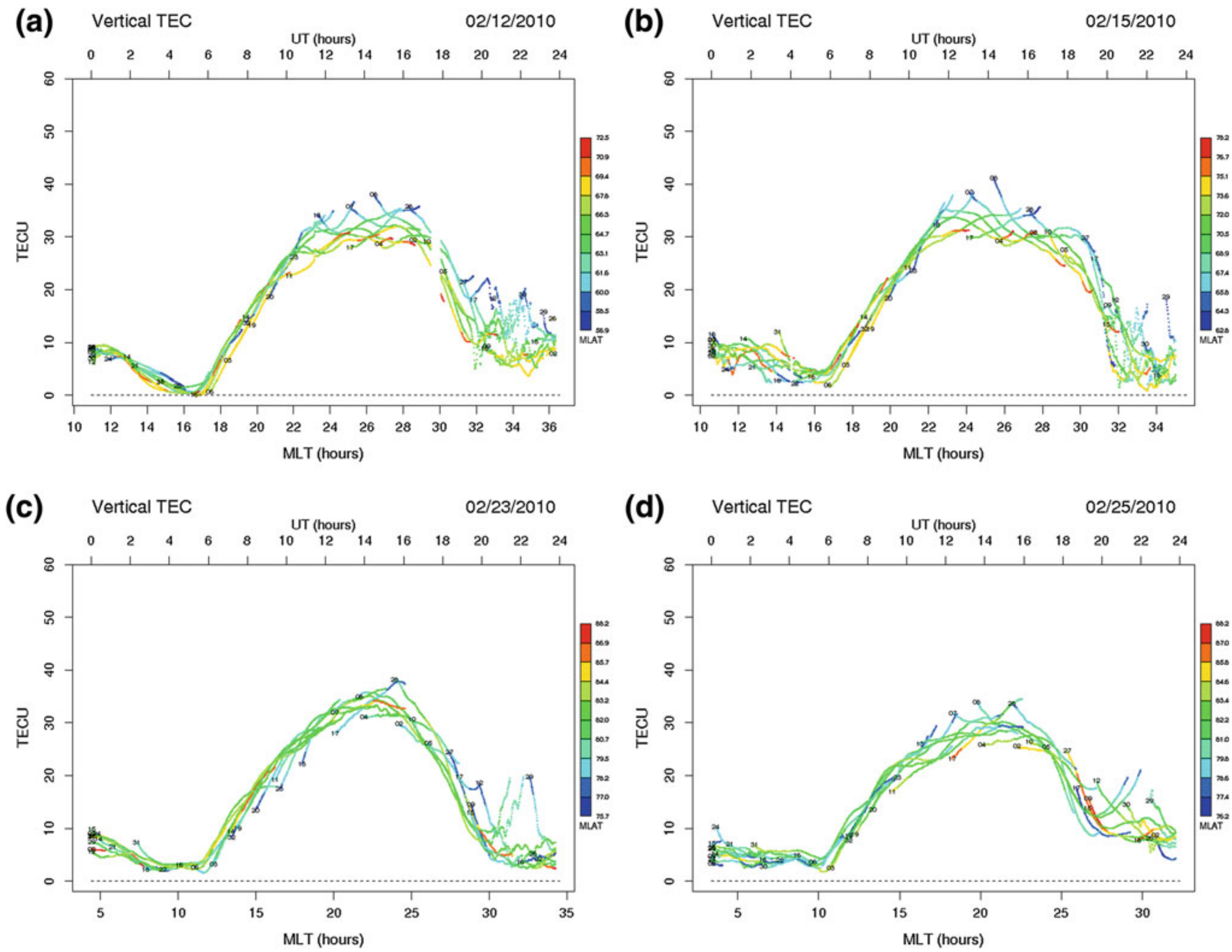

Fig. 3 A plot of the diurnal variation of vertical TEC for the 4 days considered

the scintillation index S_4. For this particular receiver, a frequency of 50 Hz data rate was used to calculate the S_4 index. The calibrated TEC was obtained by levelling the phases to the pseudo ranges to give the relative TEC and followed by the estimation/removal of the instrumental biases to give the vertical (or calibrated) TEC.

3 Results

The results of the computed VTEC and S_4 index are presented in this section. Results of different satellite passes designated by a PRN number on different dates and times are shown in Figs. 3 and 5. Figure 3a–d shows the plots of the VTEC (in TEC units or TECu) over a 24-h period for the days under consideration. The colored legend in the figures shows the graduation of the (geo-) magnetic latitude (MLAT) of the satellite pass, from the lower blue color to the higher red color. From the plotted VTEC, the diurnal pattern can be divided into three different segments, namely the build-up region, the daytime plateau, and the decay region which is similar to the observations made by Bagiya et al. [6].

The observed VTEC for 12th Feb is as shown in Fig. 3a. The VTEC has a value of 10 TECu at about midnight and then shows a steady decrease reaching a minimum of 0 TECu at 06:00 hours. This, however, increases steeply, almost immediately reaching a broader peak of 35 TECu at about 15:00 LT. The VTEC then decreases steadily from this peak value until it reaches a minimum value (0 TECu) at about 21:00 LT. This continues afterwards till about midnight and minor enhancement in TEC values was also noticed. These fluctuations in TEC values are probably due to the precipitating effects of the rising plasma plumes or bubbles in the ionosphere at the equatorial anomaly region as observed by Valladares et al. [9] and Dashora and Pandey [5].

The plots of the VTEC for the other days, namely 15th, 23rd and 25th Feb, are similarly behaved except that the first minima are not zero at 07:00 LT but have a value of about

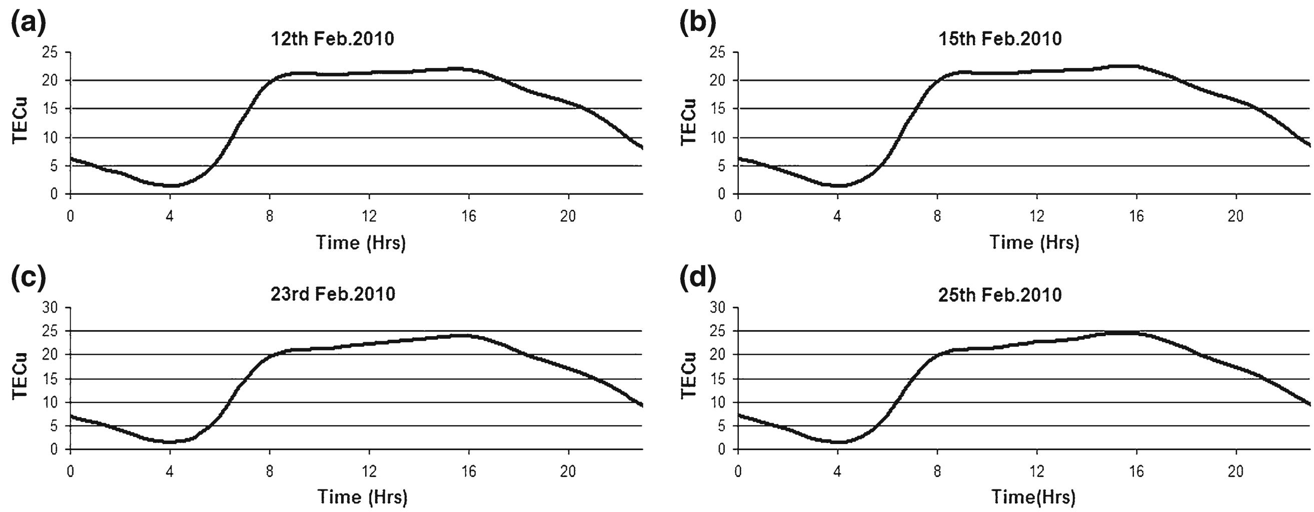

Fig. 4 The IRI 2007 model for the TEC on the days considered

2 TECu. Also the peak of the TEC on 23rd Feb is not as broad as that of the others at 14:00 LT. This is an indication of the complexity in the dynamical nature of the ionospheric condition at the equatorial region due to the effects of the equatorial electroject (EEJ) on the geomagnetic field [6] which enhances the eastward current flow within ±3° of the magnetic equator. In addition, the depletion in TEC due to plasma instabilities after sunset is also noticed to occur consistently around 21:00 LT which is contrast to the observations of Dashora and Pandey [5] in the Asian sector where it occurred around 23:00 LT probably due to longitudinal difference and the drift of the EEJ. Figure 4 is the international reference ionosphere (IRI) model of the TEC on the days considered. When this is compared with the observed results shown in Fig. 3, the results are similar except that the maximum TECu value at the pre-dawn period is 5 TECu instead of 10 TECu in the observed results. In addition, during the day, the observed results range between 30 and 35 TECu, while the modeled results are generally below 25 TECu, and the scintillations phenomena (i.e., amplitude fluctuations) which are seen in the observed results are not shown in the IRI modeled result. It is therefore necessary for TEC values in the modeled results to be adjusted to obtain a better fit with observed results.

Figure 5 shows the observed variations of the scintillation index, S_4, for 12th Feb for all the satellites that were visible to the GPS receiver station. Figure 5 also shows the variations of the satellite elevation angles, as they pass over the station. Following from the earlier discussion, satellites with the PRN's numbers with remarkable scintillations records after sunset were considered for interpretation and others were not used for interpretation due to their little significance when compared to the selected ones. On 12th Feb after sunset (i.e., after 19:00 LT) to midnight, the satellites with PRN's 02, 04, 05, 08, 10, 15 and 28 were considered.

Essentially, the satellites elevation angle ranges from 20° to 90° with the peak elevation angle of 90° attained by the satellites with PRN08 and PRN10 and the least of elevation maxima of 40° was attained by the satellite with PRN02 when compared to the other satellites under consideration. The scintillations were observed at about 21:00 LT corresponding to when there was TEC depletion in agreement with [5]. The scintillation index (S_4) ranges between minimum and maximum values of 0.0 and 0.3, respectively. The scintillation index of 0.3 can be seen particularly on PRN 02, PRN 04, PRN 05 and PRN 28, after neglecting multipath effect (example of this effect is shown by the fluctuating index values at about 22:00 UT on PRN 02).

Generally, the minimum value of the index was observed to coincide when the elevation angle of the satellite is higher and this confirms the angular dependence of the index. This is because at lower elevation angles, there would be the contribution from multipath fluctuations due to ground-based reflectors that obstruct the sky. According to Dashora and Pandey [5], the scintillation index greater than 0.2 is considered to imply a significant level of scintillation. The occurrence of high scintillation index during nighttime period according to [12] and [21] can be ascribed to the rising of plasma bubbles (from the F-layer of the ionosphere) at the magnetic equator to the topside of the ionosphere to produce scintillations in patches.

The IRI model for the equatorial vertical ($E \times B$) drift velocity is as shown in Fig. 6. As expected, the $E \times B$ drifts are upwards in the daytime and downwards during nighttime. The daytime upward drifts are responsible for producing crest in the F-region peak electron density at the magnetic equator corresponding to the period of high TEC values [22]. The noticeable deflection on the downward side of the vertical drift velocity during nighttime can be attributed to the occurrence of scintillations.

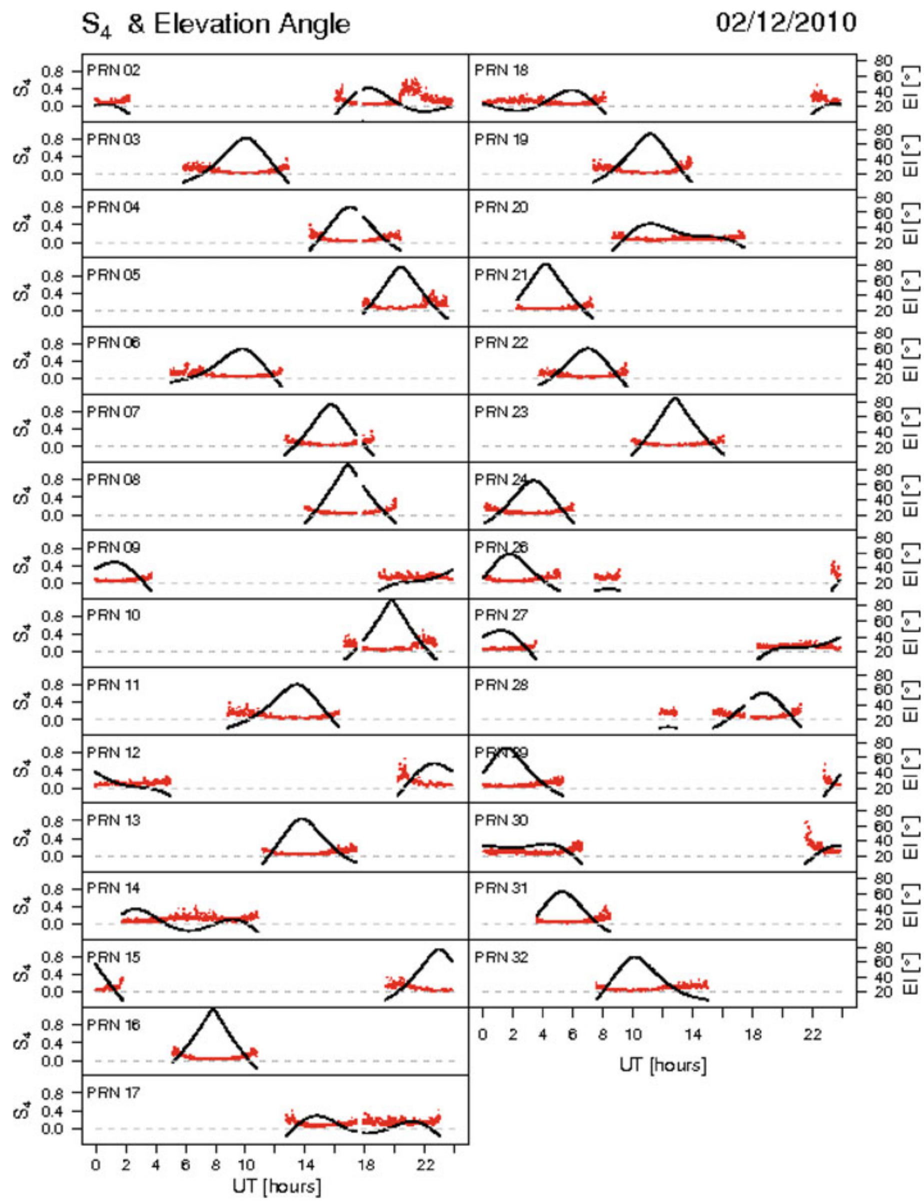

Fig. 5 Scintillation index S_4 observed by the satellites and the satellites elevation angles on 12 Feb 2011

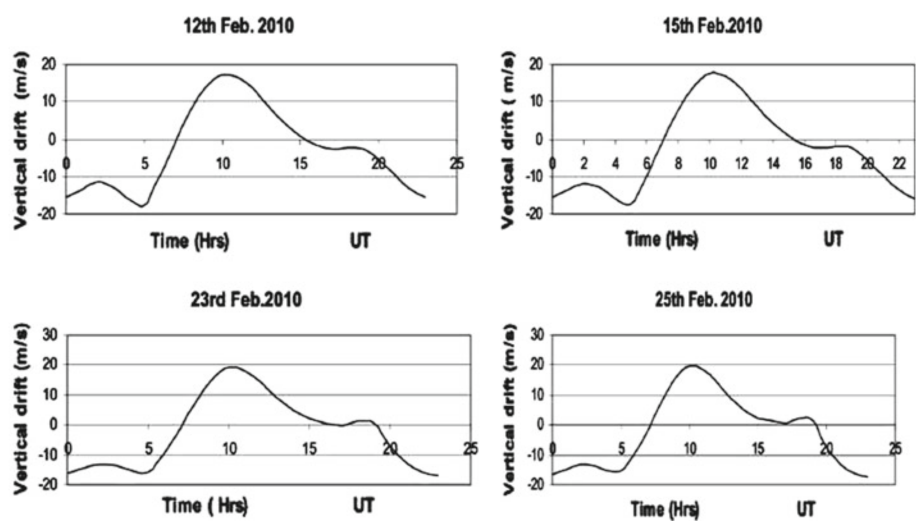

Fig. 6 Vertical drift velocities during the period considered

4 Summary and Conclusions

From the calibrated (vertical) TEC and the computed scintillation index using the GPS receiver station at Ile-Ife, Nigeria, the examples of diurnal variation of the equatorial ionosphere were presented for February 2010. The VTEC in this study showed that the values vary widely from as low as 0 TECu about sunrise to about 35 TECu during the daytime. This observation when compared with the Rajkot's data suggests a trade off between the broadness of the peak and the maximum peak possible. Depletion in TEC was also noticed about sunset and marked by the occurrence of scintillations. The study also shows that the TEC values in the IRI model need some adjustments to obtain a better fit with the observed results.

This is a preliminary result from this station. Future studies will seek to establish the seasonal variability of the TEC, S_4 index and their dependence on solar and geo-magnetic activities. Further work will also examine the latitudinal dependence of these ionospheric parameters over the African ionosphere. It is believed that the results from these studies will be useful in efforts to improve the IRI models and their adaptability to the Africa ionospheric conditions.

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References

1. Mendes da Costa, A.; Boas, J.W.V.; Junior, F.E.: GPS total electron content measurements at low-latitudes in Brazil for low-solar activity. Geofisica Internacional. **43**, 129–137 (2004)
2. Breed, A.M.; Goodwin, G.L.: Total electron content measurements in the Southern Hemisphere using GPS satellites, 1991 to 1995. Radio Sci. **33**(6), 1705–1726 (1998)
3. Hernandez-Pajares, M.; Juan, J.M.; Sanz, J.: New approaches in global ionospheric determination using ground GPS data. J. Atmos. Solar Terrest. Phys. **61**, 1237–1247 (1999)
4. Rastogi, R.G.; Klobuchar, J.A.: Ionospheric electron content within the equatorial anomaly belts. J. Geophys. Res. **88**, 10259 (1990)
5. Dashora, N.; Pandey, R.: Observations in equatorial anomaly region of total electron content enhancements and depletions. Annales Geophysicae. **23**, 2449–2456 (2005)
6. Bagiya, M.S.; Joshi H.P.; Iyer, K.N.; Aggarwal M.; Ravindran, S.; Pathan, B.M.: TEC variations during low solar activity period (2005–2007) near the Equatorial Ionospheric Anomaly Crest region in India. Annales Geophysicae. **27**, 1047–1057 (2009)
7. Biqiang, Z.; Weixing, W.; Libo, L.; Tian, M.: Morphology in the total electron content under geomagnetic disturbed conditions: results from global ionosphere maps. Annales Geophysicae. **25**, 1555–1568 (2007)
8. Mansilla, G.A.; Mosert, M.; and Ezquer, R.G.: Seasonal variation of the total electron content, maximum electron density and equivalent slab thickness at a South-American station. J. Atmos. Solar Terrest. Phys. **67**, 1687–1690 (2005)
9. Valladares, C.E.; Villalobos, J.; Sheehan, R.; Hagan, M.P.: Latitudinal extension of low-latitude scintillations measured with a network of GPS receivers. Ann. Geophys. **22**, 3155–3175 (2004)
10. Oyekola, O.S.; Oluwafemi, C.C.: Morphology of F-region vertical $E \times B$ drifts in the African sector using ionosonde measurements. Ann. Geophys. **50**(5), 615–625 (2007)
11. Obrou, O.K.; Bilitza, D.; Adeniyi, J.O.; Radicella, S.M.: Equatorial F2-layer peak height and correlation with vertical ion drift and M (3000) F2. Adv. Space Res. **31**(3), 513–520 (2003)
12. Kumar, S.; Gwal, A.K.: VHF ionospheric scintillations near the equatorial anomaly crest: solar and magnetic activity effects. J. Atmos. Solar Terrest. Phys. **62**, 157–167 (2000)
13. Balan, N.; Bailey, G.J.; Moffett, R.J.: Modeling studies of ionospheric variations during an intense solar cycle. J. Geophys. Res. **99**, 17467–17475 (1994)
14. Huang, Y.-N.; Cheng, K.: Solar cycle variation of the total electron content around equatorial anomaly crest region in East Asia. J. Atmos. Solar Terrest. Phys. **57**(12), 1503–1512 (1995)
15. Doherty, P.; Coster A.; Murtagh, W.: Space weather effects of October–November 2003. GPS Solutions. **8**, 267–271 (2004). doi:10.1007/s10291-004-0109-3
16. Ogunade, S.O.: Geomagnetic variations in southwestern-Nigeria: preliminary results. Annales Geophysicae. **06**(B), 607–611 (1987)
17. Langley, R.B.: GPS, the Ionosphere, and the Solar Maximum. GPS World, Canada, pp. 44–49 (2000)
18. Fedrizzi, M.; de Paula, E.R.; Langley, R.B.; Komjathy, A.; Batista, I.S.; Kantor, I.J.: Study of March 31, 2001 magnetic storm effects on the ionosphere using GPS data. Adv. Space Res. **36**(3), 534–545 (2005). doi:10.1016/j.asr.2005.07.019
19. Carrano, C.; Groves, K.: Remote sensing the ionosphere, using GPS-SCINDA. IHY Africa/Scinda 2009 workshop, Zambia
20. Klobuchar, J.A.: Design and characteristics of the GPS ionospheric time delay algorithm for single frequency users. In: Institute of Electrical and Electronics Engineers, pp. 280–286 (1986)
21. Abdu, M.A.; Sobral, J.H.A.; Paula, E.R.; Batista, I.S.: Magnetospheric disturbance induced equatorial plasma bubble development and dynamics: a case study in Brazilian sector. J. Geophys. Res. **108**(A12) (2003). doi:10.1029/2002JA009721
22. Hanson, W.B.; Moffet, R.J.: Ionozation transport effects in the equatorial F-region. J. Geophys. Res. **71**(23), 5559–5572 (1966)