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To cite this version:

Christian Zoundi, Frédéric Ouattara, Rolland Fleury, Christine Amory-Mazaudier, Patrick Lassudrie-Duchesne. Seasonal TEC Variability in West Africa Equatorial Anomaly Region. European Journal of Scientific Research, 2012, 77 (3), pp.309-319. hal-00968583

HAL Id: hal-00968583
https://hal.sorbonne-universite.fr/hal-00968583v1

Submitted on 1 Apr 2014

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European Journal of Scientific Research
ISSN 1450-216X Vol.77 No.3 (2012), pp.309-319
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http://www.europeanjournalofscientificresearch.com

Seasonal TEC Variability in West Africa Equatorial Anomaly Region

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Abstract

This paper presented the seasonal variability of TEC/ GPS data recorded at Ouagadougou a West Africa GPS station located near the magnetic equator. Seasonal data TEC time variations are compared to those of TEC derived from IGS GPS network maps. The present study showed that TEC map model predicts well data TEC during equinoctial months and fairly well during solstice months. The best prediction is obtained during spring and the worst during winter. The analysis of seasonal TEC profiles highlighted that model accuracy shows seasonal variations with respect to the complexity of TEC time variations. This work pointed out that model accuracy depends not only on the integration of station data in IGS GPS network data but also on the presence of daytime multi-peaks and/or the presence and the amplitude of night time peak. Solstice and summer data TEC analysis showed that those present F2 layer annual anomaly.

Keywords: Equatorial anomaly, GPS, Total electron content, TEC map, Geomagnetic storms

1. Introduction

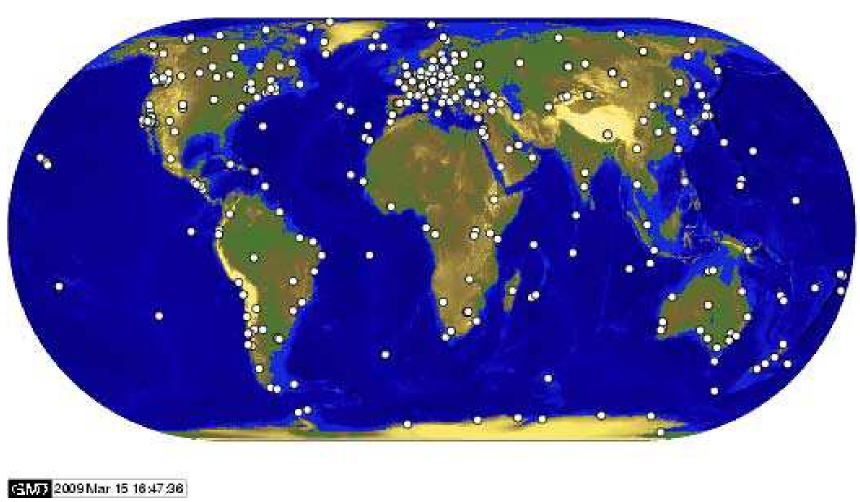
During the last decade Total Electron Content (TEC) provided by Global Positioning System (GPS) receivers in many stations of the world allowed to study ionosphere. Many studies were done, on the comparison between in situ TEC measurement and existing ionospheric models (e.g. Jin and Spark [1]; Chauhan and Singh [2]; Ouattara and Fleury [3]) and on ionospheric pattern and scintillation (e.g. Mannucci et al. [4]; Sardon et al. [5]; Jakowaski [6]; Liu and Gao [7]; Rama Rao et al. [8]; Ray and DasGupa [9]; DasGupta et al. [10]; Spogli et al. [11]; Prikryl et al. [12]). Maruyama et al. [13]; Guarnieri et al. [14]; Jain et al. [15]; Malik et al. [16]; Adewale et al. [17] studied the ionospheric disturbances related to geomagnetic storms. Very few studies of ionosphere using GPS receivers concern African sector (e.g. Moetseki et al. [18]; Adewale et al. [17]; Ouattara and Fleury [3]). Such situation mainly results from the insufficiency of in situ measurements. To overcome this problem, it became a priority in scientific program as AMMA (Analyse Multidisciplinaire de la Mousson Africaine) or International Heliophysical Years (IHY) campaign (2007-2009) to install scientific instruments as GPS or magnetometers in order to help developing countries to participate to the understanding of the global study of the phenomena involved in Solar-Terrestrial relationship (monsoons, climate changes, etc.). It is important to note that the IHY campaign lies on a triptych concept such as instruments, observations and education (Davila et al. [19] and Kitamura et al. [20]).

This study presents first results of TEC measurements made with GPS receivers involved in AMMA and IHY program in West Africa. The second section of this paper concerns data and GPS stations used and the third one the methodologies and procedures for obtaining GPS TEC. Results and discussions constitute the fourth part of the work and the conclusion the last one.

2. Data and GPS Stations Used

We use the GPS TEC data of Ouagadougou station (Geo Lat: 12°21’ N; Geo long: -1°30’ E) in Burkina Faso and CODG TEC or TEC maps carried out at this station. TEC map are made by Centre for Orbit Determination in Europe (CODE). This centre is one of the centres of analysis of International GNSS Service (IGS) where GNSS stands for Global Navigation Satellite Systems. This centre publishes ionosphere maps (Schaer [21]) and gives the correct GPS orbits, Earth orientation parameters and GPS stations coordinates and global ionosphere map namely global ionosphere maps (GIMs). CODG permits the determination of GPS TEC in specific region identified by geographical coordinates determined by the IGS GPS network (Figure 1). CODG is an experimental model based on an ionospheric single layer model (SLM) (Boutiouta et al. [22]; Norsuzila et al. [23]). Single layer model assumes that free electrons are concentrated in a spherical scale with infinitesimal layer. The diameter of each grid is over 2000 km. The elevation angle is less than 20°. All CODG slant TEC values for selected stations (about 200 in the Earth) and for one day are converted to CODG vertical TEC and tabulated in IONosphere Exchange (IONEX) format (Schaer et al. [24]). Therefore, it becomes possible to determine Vertical TEC wherever in the globe.

Figure 1: IGS GPS stations network



Ouagadougou station operated since 2006 and is involved in AMMA project. Since 2011 AMMA stations data contributed to IGS GPS Network data. We also used the Dst to determine the day state.

3. Methodologies and Procedures for Obtaining GPS TEC

The GPS satellites that orbit the Earth, at altitude 20,200 km above the Earth's surface provide the Total Electron Content (TEC): total number of electrons integrated along the path from receiver to each GPS satellite. The TEC is expressed by $TEC = \int_R^S n_e(\Sigma) d\Sigma$ where n_e is electron density, R the receiver and S the satellite. TEC is measured in TEC Unit (TECU), $1\,\text{TECU} = 10^{16}\,\text{electron/m}^2$.

In this paper, we considered two methods: TEC obtained by using dual frequency (as GPS satellites broadcast two L-band signals at two frequencies) and IGS TEC map. TEC obtained by using dual frequency concerned the GPS stations of Ouagadougou and IGS TEC map is used for Niamey station. We also model Ouagadougou station with TEC map in order to determine the accuracy of this method for non IGS stations.

3.1. TEC Carried out by using Receiver Dual Frequency

GPS receivers provide both carrier phase delays L and pseudo ranges P of the dual frequencies. Each satellite of the GPS satellites constellation broadcasts two L-band signal at two frequencies ($f_1 = 1575.42$ MHz and $f_2 = 1227.60$ MHz) which are derived from the fundamental frequency $f_0 = 10.23$ MHz as $f_1 = 154.f_0$ and $f_2 = 120.f_0$. The group delay resulting for that is: $P_1 - P_2 = 40.3\ \text{TEC}\left(\frac{1}{f_1^2} - \frac{1}{f_2^2}\right)$ with P_1 and P_2 are the pseudo ranges for f_1 and f_2 respectively. By rewriting the equation of group delay we obtain: $TEC = \frac{(P_1 - P_2)}{40.3}\frac{f_1^2 f_2^2}{f_2^2 - f_1^2}$. As the TEC between the satellite and the user depends on the satellite elevation angle, this measurement is called Slant TEC (STEC). Therefore the obtained TEC values from GPS receivers are STEC. This parameter is a measure of the total electron content of the ionosphere along the ray path from the satellite to receiver. Thus, it depends on the ray path geometry through the ionosphere. It appears the necessity to convert STEC to vertical TEC (VTEC) which is independent of the elevation of the ray path (Norsuzila et al. [29]). For that ionosphere is considered as single layer or thin shell and a mapping function of this single layer model (SLM) is used to conversion STEC to VTEC. Our mapping function $f(\alpha)$ can be expressed as: $f(\alpha) = \left[1 - \left(\frac{R_E \sin\alpha}{R_E + h_m}\right)^2\right]^{-0.5}$ where R_E is the mean Earth radius, h_m is the height of maximum electron density (Norsuzila et al. [29]) or the altitude of the thin layer above the surface of the Earth (Adewale et al. [17]) and α the zenith angle at the receiver sites. α can be obtained when satellite position and the coordinates of receiver location are known. h_m is the height corresponding to the maximum electron density at the F2 peak. According to Norsuzila et al. [29], h_m ranges from 250 to 350 km at mid latitudes and from 350 to 500 km at equatorial. In this study we take h_m= 350 km as done by several authors in their ionosphere study (e.g. Chauhan and Singh [2]; Malik et al. [16] and Adewale et al. [17]). This value of h_m is seem to be due to the fact that the electron density of ionosphere reaches its peak at about 350 km (Norsuzila et al., 2008 [29]) and in two dimensional point of view ionosphere is assumed to be at 350 km of altitude above the Earth's surface in a concentrated spherical shell of infinitesimal thickness (Gao and Liu [30]). Basically the typical value for R_E and h_m are set to 6371km and 450 km, respectively. For evaluating IGS global TEC map the more precise mapping function is used $f(\alpha)=\left[1-\left(\frac{R_E \sin a\alpha}{R_E+h_m}\right)^2\right]^{-0.5}$ (Schaer et al. [31]). In this equation a is correction factor which is closed to unity.

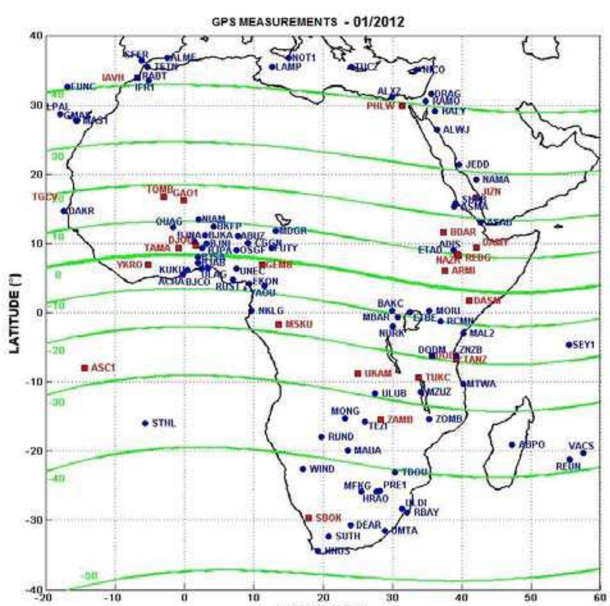
It is important to note that determining TEC by using only pseudo range gives noisily result. So, it is necessary to calculate relative phase delay between the two carrier frequencies to obtain more precise result. We are now face to two cases: the first one which consists to use only pseudo range and gives an absolute scale of TEC with less precision and the second one which consists to use only differential phase. In this later case we increase measurement precision, but as actual number of cycles of phase is unknown, absolute TEC is impossible to obtain. For solving this problem the both parameters are used and the procedure consists to reduce pseudo range noise by smoothing GPS pseudo range data with carrier phase measurements. This technique is called carrier phase smoothing or carrier phase levelling and permits to obtain STEC (Hansen et al. [32]). To accurate TEC estimation, we follow Sardon et al. [5] by removing differential instrument biases because satellites and receivers for the GPS observables are biased on the instrumental delays (Norsuzila et al. [29]). We can pointed out here that the conversion from STEC to VTEC by using mapping function also introduces some error which is obvious at low latitude where exist larger electron density and great gradient (Komjati et al. [33]).

For summarizing to obtain VTEC we firstly use GPS data display by Ouagadougou station. This experimental data are called Receiver Independent Exchange (RINEX) data. Secondly we compute STEC by using carrier phase smoothing the pseudo ranges method. Thirdly, we remove all biases from obtained TEC and fourthly we convert STEC to VTEC by applying mapping function.

3.2. TEC Map Carried out by using IGS GPS Networ

CODG GPS TEC or TEC map is determined by means of IGS stations, through Global Ionosphere Map, shown in figure 1. Generally, this figure let us see few Africa GPS stations are involved in IGS network. We underline here that the insufficiency of stations can act negatively on the precision of the model results in Africa region GPS TEC evaluation. Now following IHY project GPS stations are implemented over the continent. Figure 2 shows the recent Africa GPS stations map.

Figure 2: Africa GPS network. Blue stations are provided their GPS measures during 2011 and the others (red stations) not. We have several GPS Networks: AMMA and NIGNET in West Africa and NIGNET and UNAVCO for the others.



IGS analysis centres deliver in the Ionosphere Exchange (IONEX) format their results of whole global CODG TEC which is a global VTEC. The biases of all satellites involved are putted in Differential Code Biases (DCB) format (Schaer et al. [24]).

For the understanding of the response of CODG model in West Africa region, we compare observed data which are in situ GPS TEC of Ouagadougou station with CODG model TEC estimation at this station.

4. Results and Discussion

For seasonal treatment we only use months and years with all daily data available. The available data concern spring month of year 2007 and winter, summer and autumn for year 2006. Our seasons are: winter (December, January and February); spring (March, April and May); summer (June, July and August) and autumn (September, October and November); equinoctial months are (March and April; September and October) and solstice months concern (June and July; December and January).

In Figures 3-6 are superimposed daily variations of TEC measured by the station of Ouagadougou in red and those established by the model CODG in blue. Figure 3 is devoted to April 2007 and figure 4 to October 2006. Figures 5 and 6 present TEC variations for solstice months with figure 5 for June 2006 and figure 6 for December 2006, respectively. The analysis of these four months TEC profile shows:

Figure 3: Local time variations of in situ GPS TEC and TEC map at Ouagadougou station during spring. Red curve corresponds to in situ TEC and blue curve to TEC map.

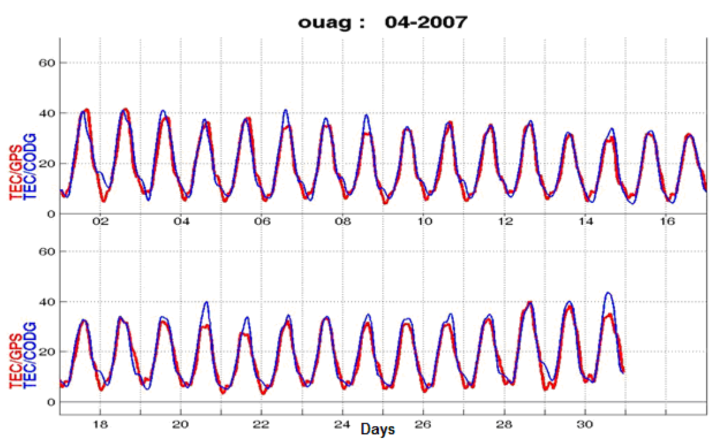


Figure 4: Local time variations of in situ GPS TEC and TEC map at Ouagadougou station during autumn. Red curve corresponds to in situ TEC and blue curve to TEC map.

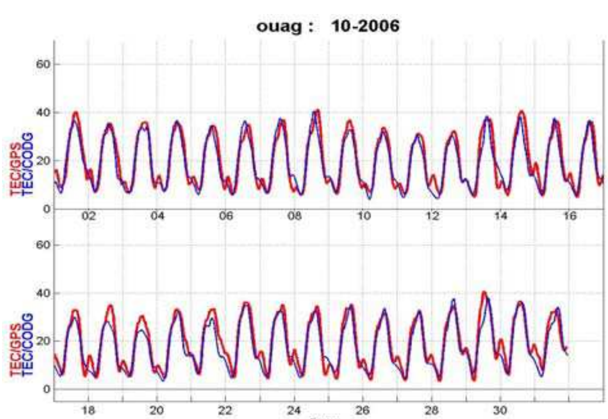


Figure 5: Local time variations of in situ GPS TEC and TEC map at Ouagadougou station during summer. Red curve corresponds to in situ TEC and blue curve to TEC map.

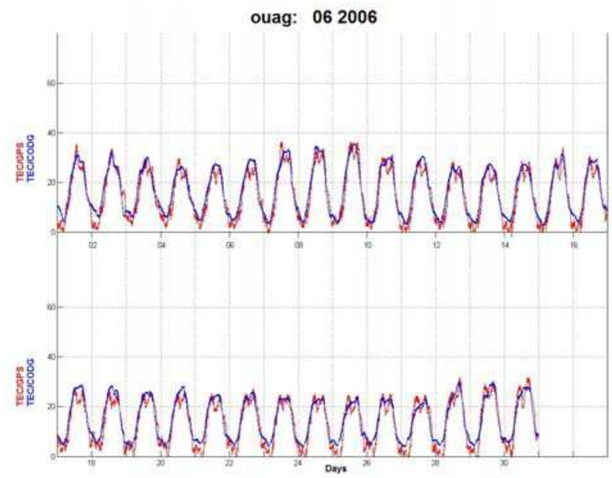
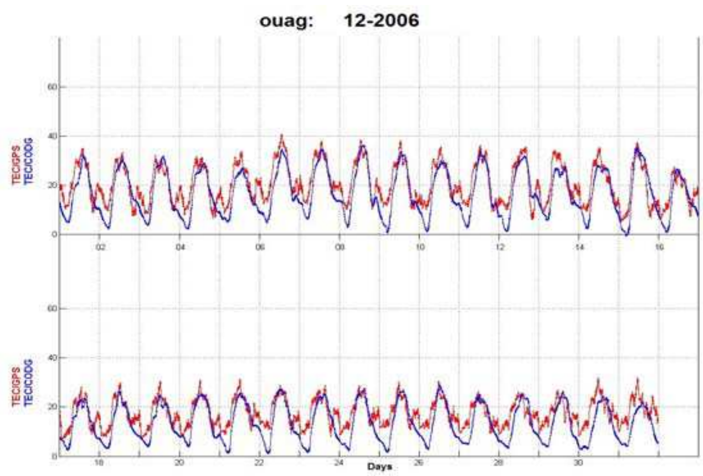


Figure 6: Local time variations of in situ GPS TEC and TEC map at Ouagadougou station during winter. Red curve corresponds to in situ TEC and blue curve to TEC map.



1) A good agreement between the variations of TEC in Ouagadougou and those of CODG model for both equinoxes (figures 3 and 4), and this especially for the month of April 2007 (Figure 3).

Figure 3 shows the day-to-day variability of model accuracy. That depends on daytime amplitude and night time peak presence and/or amplitude. In April, data and model present a dome profile at daytime and show sometime night peak with weak amplitude. This night peak when it exists, is not always observed at the same time in both TEC profiles and may be explained the weak night time model accuracy.

The data TEC of figure 4 is more variable than that of figure 3. In October, at daytime experimental TEC profiles are dome profile while model TEC profiles present not only dome profile but also afternoon predominance peak profile. The latter profile is observed during some days (3, 21, 29 and 31). At night a significant peak of the TEC is observed. This peak is observed on the descending phase of the daily variation of TEC. This peak is not generally reproduced by model and when it does, both TEC amplitudes are different. This night peak amplitude expresses the day-to-day variability and may be explained why model accuracy is better in spring than in autumn.

2) Figures 5 and 6 show more complex day-to-day variability of in situ TEC than that figures 3 and 4. Fairly good agreement is observed during June (figure 5). Model predictions in December (figure 6) are not good.

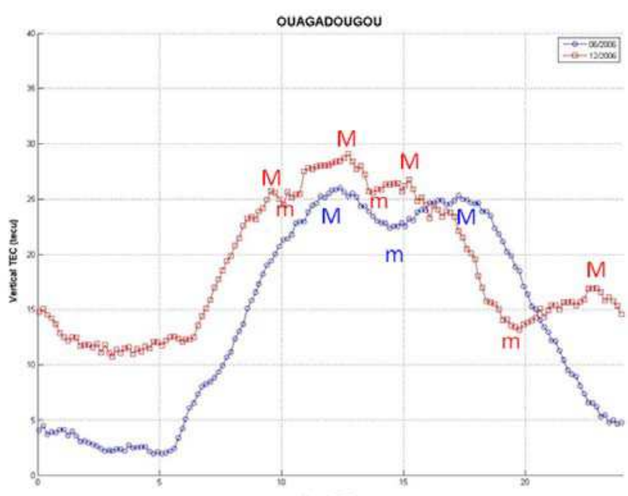
Figure 5 shows in situ TEC profiles with several daytime double peak morphologies (dominance morning peak, dominance afternoon peak and symmetric double peak). At that time CODG TEC profiles present dome, morning predominance and afternoon predominance peak profiles. Regarding the observed variations of TEC in June 2006 (Figure 5), TEC data show a double peak structure during the day which is not reproduced by the model CODG. The amplitude the TEC during night is generally smaller than that modeled by CODG.

With respect to the variations of TEC observed in December 2006 (Figure 6) we observe a peak of TEC every night very much detached from the daily TEC observed. We also observe that the intensity of TEC measured in Ouagadougou is greater than the TEC modeled during all the nights. In December a structure with many peaks of TEC (1, 2 or 3) exists during the day. The complex structure of TEC profile for this season that is often characterized by daytime multi-peaks profile (2 or 3 peaks) and the presence of night time peak with pronounced amplitude may be explained the bad predictions of the model during winter.

It emerges from these figures, that CODG model roughly estimates TEC, but cannot reproduce the daytime double peaks and night time peak. Such differences may be explained by the lack of IGS stations in this sector so that all the ionosphere electrodynamics is not integrated to this TEC estimation. Only solstice profiles present double peaks and night peak which result from the effects of EXB and the pre-reversal enhancement of F region electric field, respectively (Fejer et al. [34]; Fejer [35] and Fairley et al. 36]). The best responses are observed during spring (figure 3) and autumn (figure 4). Therefore, CODG well predicts TEC during equinoctial months and not during solstice months at Ouagadougou station. We can assert that CODG model at Ouagadougou is fairly realistic.

For the well understanding of the fairly good response of the model during solstice months (figures 5 and 6), we plotted in figure 7, the daily variations of December TEC (red curve) and June TEC (blue curve). The curves represent each ten minutes median plot of vertical TEC values. We indicated by m the profile minimum and by M the profile maximum.

Figure 7: Hourly variation of in situ TEC at Ouagadougou station for solstice months. Blue curve corresponds to summer (June month) and red curve to winter (December month).



In June two maxima are observed with roughly the same amplitude around ~12.30 (~26 TECU) and around 17.30 (~25 TECU). Around 15.00 TU a minimum occurs. Its amplitude is around 22.5 TECU.

In December the structure is more complex there are several maxima and minima. In December graph the main peak appears at 1200 UT (~29 TECU). It appears between two secondary peaks, one at 0.900 UT (~26 TECU) and one at 15.00 UT (~27 TECU). Another peak occurs at night around 23.00UT (~17 TECU). This graph shows predominance of a morning peak even though it is seen at midday. In June graph the noon bite out profile shows fairly symmetric peaks in magnitude (~25 TECU) at 1200 UT and 1700 UT.

In Figure 7, it can be seen that the peak of December occurring at 15.00UT is located at the trough of June curve. From 00.00 UT to 16.00 UT and after 20.00 UT December TEC is larger than June TEC. This observation shows that there is more ionosphere in December than in June. The same observation has been pointed out by Rishbeth and Muller Wodarg [37] when they studied the variability of F2 layer peak electron density (NmF2). They noticed that NmF2 in January-December is greater than that of June-July. They named this anomaly F2 layer annual asymmetry and explained it by the dynamical influences of the lower atmosphere (below about 30 km).

A night peak is observed only in the graph of December.

The profile with double peaks and trough around midday, clearly observed in June is a well known noon bite out profile. It is the signature of ExB. Moreover, Faynot and Vila [38] gave the different types of foF2 profiles observed at Ouagadougou station. These types are: (1) noon bite out profile or B profile (two peaks with trough around midday), (2) morning peak profile or M profile, (3) dome profile or D profile, (4) plateau profile or P profile and (5) afternoon peak profile or reversed profile or R profile. As the parameter foF2 is able to describe the distribution of E layer electric current through the study of ground recorded magnetic field variations (Dunford [39] and Vassal [40]), Vassal [41] relied different types of foF2 profiles of West Africa equatorial region on different types of E layer electric current. For that, they attributed to:

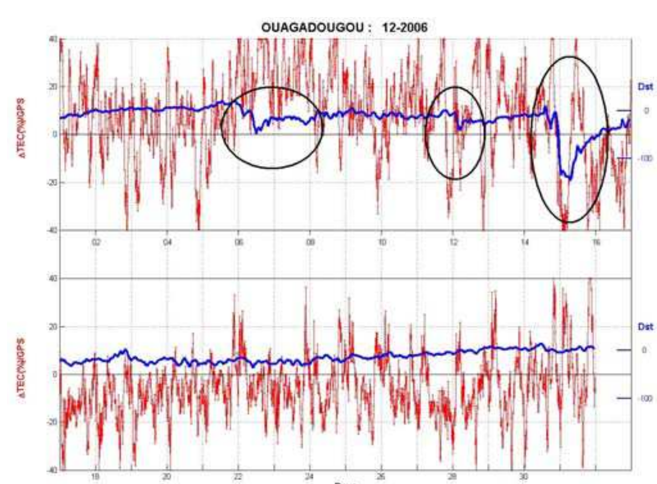
1) D and P profiles to the absence of electrojet;
2) R profile to the presence of intense counter electrojet;
3) M profile to the presence mean intensity electrojet
4) B profile to the presence of strength electrojet.

Basically, the noon bite out profile observed here (figure 7) characterized the presence of strength electrojet current.

The night peak in in situ TEC profile of December is the effect of the pre-reversal electric field in equatorial region (effects of E and F regions dynamo, see Fejer et al. [34]; Fejer [35]; Fairley et al. [36], Rishbeth [42]; Heelis et al.[43]; Matuura [44]; Walton and Bowhill [45], Stening [46]and Fejer et al., [47]).

To understand the bad response of the model during December (figure 6), in figure 8 we give hourly ΔTEC variation during December (red curve) and Dst Variation (blue curve). ΔTEC is expressed as: $\Delta TEC = TEC_{measured} - TEC_{median}$. The horizontal axis is time and expresses in Universal Time (UT) unit. We just underline that in our geographic location UT corresponds to Local Time (LT). Black circles give disturbance periods.

Figure 8: Hourly variation of residual TEC (red graph) and Dst (blue graph) during winter (December month).



It can be seen in figure 8, three storms characterized by a decrease of the Dst and a string variability of ΔTEC. These storm periods correspond to three days for the first period (December 6, 7 and 8), two days for the second period (December 12 and 13) and three days for the third period (December 14, 15 and 16). The biggest storm is the last one with the Dst amplitude 150γ. For the given days, the presence of these storms may be explained the fairly response of CODG model during these days. It can be added to this probably reason the probable presence of night peak. In fact, Ouattara [48] showed that at Ouagadougou station, when night peak in foF2 profile appeared, IRI did not reproduce this peak and explained a fairly good accuracy of IRI-2007 model. With figure 8, it can be possible to detect in TEC variations the state of ionosphere: quiet or disturbed ionosphere (see also the works of Malik et al. [16] and Adewale et al. [17] for TEC using in ionospheric study during storm periods). For the other days, daytime multi-peaks and/or night time peak may be explained the bad response of CODG Model

6. Conclusion

The present study shows seasonal variability and day-to-day variability of CODG model accuracy. During equinoxes data TEC profile shows dome profiles and during solstices the profiles are more complex with dome and multi-peaks profiles. CODG model fairly estimates seasonal data TEC at Ouagadougou station. The fairly good response of the model is not only due to the absence of GPS stations in the IGS GPS network for West Africa. In fact, model accuracy is better in equinoxes than in solstices. On the other hand, (1) in equinox, CODG TEC predicts well spring data TEC and fairly well predicts autumn data TEC, (2) in solstice, the predictions are better in summer than in winter and (3) during spring model good predicts data TEC. The complex structure of diurnal TEC profile may also be responsible to the fairly response of CODG model. In fact, night time peak seems to be responsible to the winter bad response of model and its autumn fairly good prediction. On the other hand, daytime multi-peaks are may be responsible to the winter bad response of model and its summer fairly good prediction.

Acknowledgment

Authors thank Olivier Bock from Service d'Aéronomie, Paris, France for his cooperation by providing Ouagadougou GPS station data before putting them in IGS GPS network data

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