Morphology of GPS and DPS-TEC Over an Equatorial Station: Validation of IRI and NeQuick 2 Models.

Olumide O. Odeyemi[1] , Jacob Adeniyi[2] , Olushola Oladipo[3], Olayinka Olawepo[3], Isaac Adimula[3], Elijah Oyeyemi[1]
[1] Department of Physics, University of Lagos, Nigeria olumidephysics@yahoo.com, oodeyemi@unilag.edu.ng
[2] Department of Physical Sciences, Landmark University, Omu-Aran, Nigeria adeniyi.jacob@lmu.ng.edu
[3] Physics Department, University of Ilorin, Ilorin

Correspondence to: Olumide O. Odeyemi (olumidephysics@yahoo.com; oodeyemi@unilag.edu.ng)

0.0 Abstract

We investigated total electron content (TEC) at Ilorin (8.50^{o}N 4.65E, dip lat. 2.95) during a low solar activity in 2010. The investigation involved the use of GPS derived TEC, estimated from digisonde portable sounder data (DPS), the International Reference Ionosphere (IRI) and NeQuick 2 (NeQ) models. During the sunrise period, we found that the rate of increases in DPS-TEC, IRI-TEC and NeQ-TEC were higher with respect to GPS-TEC. One reason for this can be alluded to an overestimation of plasmaspheric electron content (PEC) contribution in modeled TEC and DPS-TEC. A correction factor around the sunrise, where a significant percentage deviation between the modeled TEC and GPS-TEC was obtained, will correct the differences. Our finding revealed that during the daytime when PEC contribution is known to be absent or insignificant, GPS-TEC and DPS-TEC in April, September and December predict TEC very well. The lowest discrepancies were observed in May, June and July (June solstice) between the observed and all the model values at all hours. There is an overestimation in DPS-TEC that could be due to extrapolation error while integrating from the peak electron density of F2 (NmF2) to around ~ 1000 km in the Ne profile. The underestimation observed in NeQ-TEC must have come from the inadequate representation of contribution from PEC on the topside of NeQ model profile, whereas the exaggeration of PEC contribution in IRI-TEC amount to overestimation in GPS-TEC. The excess bite-out observed in DPS-TEC and NeQ-TEC shows the indication of over prediction of fountain effect in these models. Therefore, the daytime bite-out observed in these two models requires a modifier that could moderate the perceived fountain effect morphology in the models accordingly. The daytime DPS-TEC performs better than the daytime IRI-TEC and NeQ-TEC in all the months. However, the dusk period requires attention due to highest percentage deviation recorded especially for the models in March, November and December. Seasonally, we found that all the TECs maximize and minimize during the March

equinox and June solstice, respectively. Therefore, GPS-TEC and modeled TEC reveal the semi-annual variations in TEC.

Keywords: (Total Electron Content (TEC); International Reference Ionosphere (IRI) and NeQuick 2 Models)

1.0 Introduction

Total electron content (TEC) is the total number of free electrons in a columnar of one square meter along the radio path from the satellite to the receiving station on the Earth. TEC exhibits diurnal, seasonal, solar cycle and geographical variations. Therefore, the physical and dynamical morphology of the TEC over a given location is of great importance in trans-ionospheric communications during undisturbed and disturbed geomagnetic conditions (Jesus et al., 2016; Tariku, 2015; and Akala et al., 2012; Aravindan and Iyer, 1990). GPS-TEC is quantified from the GPS orbiting satellites to the GPS receiver station on the Earth, with an approximate distance of 20200 km (Liu et al., 2006). Thus, a typical GPS-TEC measurement includes the complete plasmaspheric electron content (PEC). The digisonde portable sounder (DPS) measures the bottomside and topside TEC to obtain the total TEC from the electron density (Ne) profile. The topside DPS-TEC is extrapolated from the peak electron density of the F2 region (NmF2) to around ~ 1000 km thus, the major PEC contribution from the greater altitudes is excluded from DPS-TEC measurement (Belehaki et al., 2004; Zhang et al., 2006 and Reinisch and Huang, 2001).

The International Reference Ionosphere (IRI) model is based on worldwide data from various measurements (Bilitza, 2001; Bilitza, 1986; Bilitza and Rawer, 1998). The IRI model provides reliable ionospheric densities, composition, temperatures, and composition in the ionospheric altitude range (Bilitza, 2001; Radicella et al., 1998 and Coisson et al., 2009). The latest version of IRI model can be found at all time on the web (http:nssdc.gsfc.nasa.gov/space/model/ions/iri.html) with improvements on earlier versions of the model. The NeQuick 2 (NeQ) models, the position, time and solar flux or sunspot number over a given location are embedded in the NeQ model code (Coïsson et al., 2006; Andreeva and Lokota, 2013 and Bidaine and Warnant, 2011). The output of the NeQ program and corresponding TEC are by the electron density along any ray-path and numerical integration in space and time respectively.

The availability of ionospheric parameters for global ionospheric models is insufficient over the African sector compared to the consistent input of the parameters from the Asian and American sectors. Therefore, the continuous investigations of the parameters over Africa are required to improve the global ionospheric model. For example, Bagiya et al. (2009) studied TEC around equatorial-low latitude region at Rajkot (22.29° N, 70.74° E, dip 14.03° N) during low solar activity, Olwendo et al. (2012) and Karia and Pathak. (2011) investigated the TEC data at Kenyan and Surat (India), respectively. They all found a semi-annual variation with minimum and maximum TEC June solstice and March equinox, respectively. Using Faraday rotational technique, Olatunji (1967) investigated TEC variation over equatorial station at Ibadan. He found no daytime bite-out and seasonal anomaly over the equatorial region. Rastogi et al. (1975) observed the diurnal variation of TEC using Faraday rotation over the magnetic equator. They found that the TEC at the topside was higher than the TEC at the bottomside during the nighttime, however during the daytime, equal distribution of TEC was found on the topside and the bottomside of electron density (Ne) profile.

Regarding the DPS-TEC measurement, Barbas et al. (2010) examined GPS-TEC and DPS-TEC at Tucuman (26.69◦S, 65.23◦W) during different seasons. They concluded that the DPS-TEC represented the GPS-TEC with minimal discrepancy in all seasons. Reinisch et al. (2004) researched GPS-TEC and DPS-TEC at mid-latitude and equatorial region. They found that the variations of GPS-TEC and DPS-TEC appeared similar but the daytime values of GPS-TEC were higher than daytime DPS-TEC. Zhang et al. (2004) studied the variations of DPS-TEC and GPS-TEC over Hainan and reported that the daytime DPS-TEC and GPS-TEC values were close during the daytime but during dusk period, a significant discrepancy between DPS-TEC and GPS-TEC was observed. Belehaki et al. (2004) extracted the plasmaspheric electron content (PEC) from the GPS-TEC at Athens (38°N, 23.5°E) over a year. They reported a maximum and minimum contribution of PEC in the morning and evening, respectively. Mosert et al (2007), Jodogne et al. (2004) and Mckinnell et al. (2007) concluded that estimated PEC from the GPS-TEC and DPS-TEC is possible in colocated GPS and DPS station. Adewale et al. (2012), Okoh et al. (2015), Jee and Scherliess (2005), Kenpankho et al (2013), Sulungu et al. (2017), and Migoya Orué et al. (2008) validated the IRI-TEC with GPS-TEC in different regions and found high discrepancies between the IRI-TEC and GPS-TEC when compared different IRI-model options.

Concerning the studies on NeQ model, Cherniak and Zakharenkova (2016) validated NeQ model. They established that the topside ionosphere above ~ 500km in the NeQ model is consistently underestimated due to inaccurate representation of topside Ne profile. Rabiu et al. (2014) validated NeQ model using GPS-TEC over equatorial station of Africa. They reported that the upper boundary of NeQ model, up to 20,000 km needed to be adjusted to accommodate the PEC-TEC in NeQ model. Leong et al. (2013) investigated TEC and NeQ models. They found that the observed TEC and NeQ TEC were close in values during dusk periods, but the changed TEC revealed higher discrepancies during the post-sunset. Yu et al. (2012) investigated the monthly average of NeQ-TEC model over three stations in China (Changchun, Beijing, and Chongqing) during the quietest period. They revealed that NeQ accurately predicted GPS-TEC. However, the NeQ-TEC underestimated the GPS-TEC during the dusk period. Rios et al. (2007) investigated the variations of DPS-TEC and IRI-TEC and found that DPS-TEC was smaller compared to IRI TEC. McNamara (1985) observed discrepancies between DPS-TEC and IRI-TEC and found that the IRI underestimated the DPS-TEC during the daytime. Obrou et al. (2008) compared the DPS-TEC and IRI-TEC at Korhogo during high and low solar activity. They found that the variations of DPS-TEC and IRI-TEC were close in values during high solar activity (HSA) and low solar activity (LSA) but the performance of IRI-TEC was better during HSA compared to LSA.

The current contributions of Africa on the improvement of ionospheric models (IRI and NeQuick) are not adequate compared with the continuous support received from Asia and South America. The insufficient instrumentation at the equatorial region of Africa has a considerable effect on the shortcoming. Therefore, the continuous validation of IRI and models with the observed parameter is necessary for improved ionospheric model. Furthermore, the investigation on DPS-TEC has not been reported extensively for comparison purpose over the equatorial region of Africa. Therefore, this study investigates the combined morphologies between the variations of GPS-TEC and DPS-TEC, and validations of IRI-TEC, and NeQ-TEC models with the observed parameters. Our finding will reveal the suitability of modeled TEC in place of GPS-

TEC. The result will also reveal the appropriate model for the equatorial station in Africa. Thus, the changed TEC obtained from the combined relationship between GPS-TEC, DPS-TEC, IRI-TEC and NeQ-TEC could be used to improve the discrepancy in the models.

2.0 Methods of Analysis of GPS and DPS Data

The five quietest days ($Ap \leq 4$) of GPS and DPS-TEC data obtained from the international quiet days (IQD) were presented and analyzed during the year 2010 with the local time (LT).

2.1 GPS-TEC

The slant TEC records from GPS have errors due to satellite differential delay (satellite bias (bs)) and receiver differential delay (receiver bias (br)) and receiver inter-channel bias (b_{SR}). This uncorrected slant GPS-TEC measured at every one-minute interval from the GPS receiver derived from all the visible satellites at the Ilorin station are converted to vertical GPS-TEC using the relation below in equation (1).

$$(GPS - TEC)_V = (GPS - TEC)_S - [b_S + b_R + b_{SR}]/S(E) \qquad 1$$

Where $(GPS - TEC)_S$ is the uncorrected slant GPS-TEC measured by the receiver, S(E) is the obliquity factor with zenith angle (z) at the Ionospheric Pierce Point (IPP), E is the elevation angle of the satellites in degrees and $(GPS - TEC)_V$ is the vertical GPS-TEC at the IPP. The S(E) is given as

$$S(E) = \frac{1}{\cos(z)} = \left[1 - \left(\frac{R_E \times \cos(E)}{R_E + h_s}\right)^2\right]^{-1/2} \qquad 2$$

Where R_E is the mean radius of the Earth measured in kilometer (km), and h_S is the height of the ionosphere from the surface of the Earth, which is approximately equal to 400 km according to Langley et al. (2002) Rama Rao et al., (2006a) and Mannucci et al. (1993) . The five most quietest slant GPS-TEC data for each month in the year 2010 were analyzed using Krishna software (Global Positioning System total electron content analysis application user's manual, 2009, Institute for Scientific Research, Boston College, Chestnut Hill, Massachusetts). This software reads raw data and corrects all source of errors mentioned above from Global Navigation Satellite System service (IGS) code file. A minimum elevation angle of 20 degrees is used to avoid multipath errors. The estimated vertical GPS-TEC data is subjected to a two sigma

(2σ) iteration. This sigma is a measure of GPS point positioning accuracy. The average one-minute VTEC data were converted to hourly averages.

2.2 DPS-TEC

Regarding the total electron content (TEC) from the digisonde portable sounder (DPS), the Standard Archive Output (SAO) files obtained from the DPS at the University of Ilorin were edited to remove magnetically disturbed days. Huang and Reinisch (2001) technique was used to compute the DPS-TEC. The complete vertical DPS-TEC computation is obtained by applying the integration over the vertical electron density (Ne(h)) profile as shown in the equation below.

$$TEC = \int_{0}^{hmF\,2} Ne_B\,(dh) + \int_{hmF\,2}^{1000} Ne_T\,(dh) \qquad 3$$

where Ne_B and Ne_T are the bottomside and topside Ne profiles, respectively. The Ne_B is computed from the recorded ionograms by using the inversion technique developed by Huang and Reinisch (1996). It is known that the information above the peak of the F2 layer is absent from the record of the ionogram. Thus, the Ne_T is computed by approximating the exponential functions with suitable scale height (Bent et al., 1972) with less estimated error of 5%. The ionograms are manually scaled and inverted into electron density profile using the NHPC software and later processed with the SAO explorer software based on the technique described above to obtain the TEC (Reinisch et al., 2005). An average of TEC for each hour is computed over the selected days. The universal time (UT) is the time standard for the record of GPS and DPS data but we converted UT to local time (LT) by adding one hour to corresponding UT. Nigeria is 1 hour in advance of Greenwich Mean Time (GMT) thus, 0100 UT is the same as 0200 LT in Ilorin, Nigeria. In this study, the seasonal variation was arranged into four seasons, as, March equinox or MEQU (March, and April), June solstice or JSOL (June, and July), September equinox or SEQU (September, and October) and December solstice or DSOL (November, December). Due to technical reasons, there were data gaps in all days during January and February in the DPS measurements; therefore, we decided to neglect data in January and February in GPS-, IRI-, and NeQ measurements for comparison purposes thus, two simultaneous representative months were used to infer each season. The average of the median of the five quietest days for the representative months is evaluated to give each parameter a particular season discussed above.

2.3 Validation of IRI - 2016 and NeQuick 2 Models

The observed TEC and NmF2 were compared with the IRI-2016 model. The website http://www.ccmc.gssfc.nasa.gov/modelweb/models/iri_vitmo.php provides the modeled TEC values. The upper boundary height 2000 km was used, and the B0 table option was selected for the bottomside shape parameter. The equations 3a, 3b and 3c represent the difference between GPS-TEC and DPS-TEC, GPS-TEC and IRI-TEC and GPS-TEC and NeQ-TEC while equations 4a, 4b, and 4c below show the percentage change between GPS-TEC and DPS-TEC, GPS-TEC and IRI-TEC, and GPS-TEC and NeQ-TEC.

$$\Delta_{DPS-GPS} = DPS_{TEC} - GPS_{TEC} \quad \text{3a}$$

$$\Delta_{IRI-GPS} = IRI_{TEC} - GPS_{TEC} \quad \text{3b}$$

$$\Delta_{NeQ-GPS} = NeQ_{TEC} - GPS_{TEC} \quad \text{3c}$$

$$\%(\Delta_{DPS-GPS}) = \frac{DPS_{TEC} - GPS_{TEC}}{DPS_{TEC}} \times 100 \quad \text{4a}$$

$$\%(\Delta_{IRI-GPS}) = \frac{IRI_{TEC} - GPS_{TEC}}{IRI_{TEC}} \times 100 \quad \text{4b}$$

$$\%(\Delta_{NeQ-GPS}) = \frac{NeQ_{TEC} - GPS_{TEC}}{NeQ_{TEC}} \times 100 \quad \text{4c}$$

$\Delta_{GPS/DPS}$, $\Delta_{GPS/IRI}$, and $\Delta_{GPS/NeQ}$, represent the difference between GPS-TEC and DPS-TEC, GPS-TEC and IRI-TEC, and GPS-TEC and NeQ-TEC, respectively while $\%(\Delta_{GPS/DPS})$, $\%(\Delta_{GPS/IRI})$, and $\%(\Delta_{GPS/NeQ})$, represent the percentage deviation between GPS-TEC and DPS-TEC, GPS-TEC and IRI-TEC, and GPS-TEC and NeQ-TEC, respectively.

The Abdus Salam International Centre for Theoretical Physics (ICTP) - Trieste, Italy in collaboration with the Institute for Geophysics, Astrophysics and Meteorology (IGAM) of the University of Graz, Austria developed the web front-end of NeQuick. This quick-run ionospheric electron density model developed at the Aeronomy and Radiopropagation Laboratory modeled TEC along any ground-to-satellite straight line ray-path. Therefore, the observed TEC used for the validation of the NeQ was obtained from https://t-ict4d.ictp.it/nequick2/nequick-2-web-model.

3.0 Result

3.1 Monthly Median Variations of GPS and modeled TEC

The TEC inferred from the measured GPS-, DPS- and modeled TEC have been estimated during quiet period in 2010 at the Ilorin station. Figure 1a shows the simultaneous plots of hourly variations of the monthly median of GPS-, DPS-, IRI-, and NeQ- TEC during quiet period. The GPS-TEC is plotted in black line with the star symbol; the DPS-TEC is in green line with the diamond symbol, IRI-TEC is in red line with zero symbols, and finally, the NeQ-TEC is in blue line with multiplication symbol. All TEC plots are regulated by the same local time (LT) on the horizontal axis. The result shows that the morphologies of GPS-, DPS-, modeled-TEC increase gradually from the sunrise period (0700 -0900 LT) and reach the daytime maximum, mostly around (1200 - 1700 LT), and then later decay steadily until minimum value is reached around 0600 LT. Therefore, our result suggest that the diurnal variations of the observed and modeled TEC capture the well known solar zenith angle dependence of TEC since they are all characterized with pre-sunrise minimum, daytime maximum, daytime depression (modeled TEC) and post-sunset decay. The lowest and highest pre-sunrise minimum were ranged from 0.66 TECU (DPS) - 4.49 TECU (DPS) while the lowest and highest daytime maximum were found between 17.75 TECU (NeQ) - 38.0 TECU (DPS). The noontime bite-out was observed in modeled TEC around 1200 LT and 1500 LT except in GPS-TEC where the bite-out was inconspicuous except that the shift in daytime maximum in GPS-TEC between 1500 and 1700 LT in all months. The two moderate peaks (pre-noon peak and post-noon peak) observed in DPS-TEC and modeled TEC were due to the effect of bite-out on the modeled TEC signature. However, the pre-noon and post-noon peaks were absent in the variation of GPS-TEC since the noontime bite-out is not well captured in GPS-TEC morphology. We also found that around the sunrise period, the model TEC rises faster than the GPS-TEC but IRI-TEC rises faster compared to DPS-TEC and IRI-TEC. Between 0600 and 0900 LT, the lowest and highest difference in the rises of IRI-TEC compared to GPS-TEC were ~ 5.0 TECU (March) and 15.3 TECU (November), respectively. The post noontime decay was faster in DPS-TEC compared to GPS-TEC and modeled TEC in all months. Figure 1b reveals the simultaneous seasonal variations of GPS-; DPS-; and modeled-TEC during quiet period of (i) March Equinox, (ii) June solstice, (iii) September equinox and (iv) December solstice. The daytime maximum ranges are between ~ 24.8 TECU (NeQ) - ~ 34 TECU (DPS), ~ 19.2 TECU (NeQ) - ~ 22.6 TECU (DPS), ~ 24.9

TECU (NeQ) - ~ 33.5 TECU (DPS) and ~ 24.55 TECU (NeQ) - ~ 31 TECU (DPS), in March equinox, June solstice, September equinox, and December solstice, respectively. We observed that GPS-TEC and modeled TEC were maximum and minimum TEC at March equinox and June solstice indicating semi-annual variation in TEC.

3.2 Percentage deviation of DPS-TEC; IRI-TEC; and NeQ-TEC

Figures 2a, 3a and 4a and Figures 2b, 3b, and 4b show hourly variations of ΔTEC and mass plot of hourly variations of % ΔTEC, respectively between GPS-TEC and DPS-; IRI-; and NeQ-TEC from March to December during quiet period. In Figure 2a and 2b, the overestimated $\Delta TEC_{DPS\text{-}GPS}$ is found to be within ~ 5.13 TECU (March) - ~ 19.12 TECU (July) around 0700 - 1600 LT while the underestimated $\Delta TEC_{DPS\text{-}GPS}$ is ranged between ~ 3.2 TECU (June) - ~ 16.4 TECU (November) around 1700 - 2400 LT. The overestimation and underestimation of $\%\Delta_{IRI\text{-}GPS}$ are ranged from ~ 2% - ~ 49% and ~ - 1.36% - ~ - 306%, respectively. From Figures 3a and 3b, the overestimated $\Delta TEC_{IRI\text{-}GPS}$ occurred regularly around 0400 - 1200 LT in all months. The overestimated and underestimated $\Delta TEC_{IRI\text{-}GPS}$ ranges between ~ 9.13 TECU (July) - ~ 15.3 TECU (November) and ~ 0.15 TECU (October) - ~ 0.95 TECU (July), respectively. However, a few underestimation and overestimation of $\Delta TEC_{IRI\text{-}GPS}$ occur irregularly around 1300 - 0300 LT in all months. We also found that IRI-TEC completely overestimated GPS-TEC in May and June between 0100 and 2400 LT. The overestimation of $\%\Delta TEC_{IRI\text{-}GPS}$ ranges between ~ 0.1% to ~ 86% in all months. In Figures 4a and 4b, NeQ-TEC overestimated GPS-TEC within 0100 - 1100 LT and 2000 - 2400 LT with $\Delta TEC_{NeQ\text{-}GPS}$ ranges from ~ 9.72 (September) and ~ 0.01 (April). We also found that NeQ-TEC underestimated $\Delta TEC_{NeQ\text{-}GPS}$ is between ~ 9.72 (Nov) - ~ 0.11(May). The overestimation and underestimation of $\%\Delta TEC_{NeQ\text{-}GPS}$ are within ~ 0.02% - ~ 81% and ~ - 0.3% - ~ - 75% respectively.

3.3 Comparisons of the percentage deviations from GPS-TEC

From Figure 2b, 3b, and 4b, The percentage deviation between GPS- and DPS-TEC are greater than 100% in March August, September, November and December between 0400 - 0500 LT and around 2200 - 2400 LT in June and July. The percentage deviation between GPS- and IRI-TEC are also lower than 100% except in March around 0400 LT whereas the deviation between GPS- and IRI-TEC is greater than 100%. The percentage deviations in DPS and modeled-TEC during dusk periods are always higher than their corresponding deviations during the daytime. During the daytime, the values of deviation are small in DPS and NeQ-TEC compared to IRI-TEC.

4.0 Discussion of Result

An investigation into the variations of GPS-TEC, DPS-TEC, IRI-TEC, and NeQ-TEC at an equatorial station (8.5^{0}N 4.65^0 E) in Africa during low solar activity in the year 2010 has been carried out. The TEC increases gradually from the sunrise period, then slowly reaches the daytime maximum, and later decays till the pre-sunrise minimum. This result indicates that the TEC is a solar zenith angle dependence indicating maximum and minimum TEC during the noontime and dusk time, respectively (Wu et al.2008; Aravindan and Iyer 1990; and Kumar and Singh 2009). Interestingly, our result that reveal the faster rise in the DPS-TEC compared to GPS-TEC during sunrise is not consistent with the findings of Ezquer et al. (1992) at Tucumán (26.9° S; 65.4° W), Belehaki et al. (2004) at Athens, McNamara (1985) at low latitude and Obrou et al. (2008) at Korhogo (9.33°N, 5.43°W, Dip = 0.67°S). They all found that the variation of GPS-TEC rises faster than the DPS-TEC during the sunrise. The evidence of PEC on GPS-TEC was recently reported by Belehaki et al. (2004). They extracted the plasmaspheric electron content (PEC) from the GPS-TEC and found a significant PEC in the morning and evening. Also, Jodogne et al. (2004), Mosert et al. (2007), and Mckinnell et al. (2007) obtained a rough estimation of PEC from the GPS and DPS-TEC. They concluded that the combined GPS-TEC and DPS-TEC could give the PEC of a given location. Therefore, the higher rise in DPS-TEC compared to GPS-TEC during the sunrise could be attributed to inaccurate representation of PEC in the topside DPS-TEC profile during the extrapolation from the peak of NmF2 to around ~ 1000 km of Ne profile. Since, a typical TEC measurement naturally includes the PEC contributions (Belehaki et al. 2003; Balan and Iyer, 1983; Carlson, 1996; and Breed et al, 1997).

The higher values in DPS-TEC compared with IRI-TEC around sunrise is not consistent with Rios et al. (2007) who investigated the comparison of DPS-TEC and IRI-TEC. They found that DPS-TEC is smaller than IRI TEC at all hours. They concluded that the prediction of IRI-TEC included the high topside Ne profile. Thus, our observation suggests that the IRI-TEC has incorporated low topside Ne profile in the IRI model or the excessive exaggeration of PEC contribution in the topside Ne profile in the DPS-TEC.

Our finding that reveals equal daytime GPS-TEC and DPS-TEC in April, August and December may suggests that the topside Ne profile in GPS-TEC and is well captured in the DPS-TEC topside profile the absence of or negligible PEC in DPS-TEC values. The insignificance of daytime PEC has been reported by Rastogi et al. (1971) and Belehaki et al. (2004). Our higher daytime DPS-TEC compared with daytime IRI-TEC is consistent with McNamara (1985). However, Obrou et al. (2008) at the equatorial station, found higher the IRI-TEC than the DPS-TEC at the low solar activity. Therefore, the reduced daytime IRI-TEC compared with GPS-TEC indicates the excessive PEC removal from the model values that its PEC contribution had been initially exaggerated during the sunrise. Furthermore, the reduced NeQ-TEC values compared to GPS-TEC in all months is consistent with the report of Migoya-Orue et al. (2017), Zakharenkova (2016), Rabiu et al., (2014) and Nava and Radicella (2009). They concluded that the PEC contribution on topside NeQ profile is required for the accurate prediction of the model.

The daytime bite-out in TEC is linked to the occurrence of the most active fountain effect during the noontime at the magnetic equator. The bite-out results from the vertical drift which is the combined effect of mutually perpendicular electric and magnetic fields on the plasma. The drift lifts the plasma at the magnetic equator and diffused along geomagnetic field lines into the high latitudes, therefore, leaving the reduced TEC at the magnetic equator (Bandyopadhyay, 1970; Olwendo et al., 2013; Skinner, 1966; Bolaji et al., 2012). However, the absence of daytime bite-out (Olatunji, 1967) in GPS-TEC in our finding may be due to the greater productions of the bottomside and topside electron content that are enhanced quickly to replenish the loss of the ionization that occurs through the fountain effect during the noontime.

The hourly variations of percentage difference between GPS-TEC and all models TEC reveal that the pre-sunrise values in DPS-TEC, IRI-TEC and NeQ-TEC require attention due to high percentage difference recorded in all variations especially in March for DPS-TEC and the models, and November and December for DPS-TEC only. The daytime DPS-TEC value is closer to the GPS-TEC value compared to the daytime IRI-TEC and NeQ-TEC values. The nighttime NeQ-TEC and IRI-TEC perform better with GPS-TEC compared with DPS-TEC in all months. However, more improvement is also required to minimize the effect of the discrepancies observed during the dusk periods. More work need to be done during the pre-sunrise in all models especially in March for all models, and November and December for DPS-TEC.

Seasonally, we found that TEC is maximum and minimum during the equinoxes and the solstices, respectively. Our report is consistent with Mala et al. (2009), Wu et al. (2008), Kumar and Singh (2009), and Balan and Rao, (1984) who investigated TEC in various regions. They concluded that the seasonal variation in TEC is attributed to the seasonal differences in thermospheric composition. Moreover, the sub-solar point is around the equator during the equinox. Consequently, the sun shines directly over the equatorial region, and in addition to the high ratio of O/N2 around the region, this translates to stronger ionization, thus, semi-annual pattern is formed. Our finding is supported by Ross Skinner, (1966), Bolaji et al. (2012), and Scherliess and Fejer (1999) who obtained semi-annual variation in TEC. Scherliess and Fejer (1999) also concluded that daytime E × B drift velocity could result to semi-annual variation because the drift is more and less significant in the equinoctial months and June solstice, respectively.

5.0 Conclusion

(i)We have investigated and compared the variations of observed and modeled TEC over an equatorial station of Africa during just ascending phase cycle of low solar activity in the year 2010. Our findings show that both the observed and modeled TEC are solar zenith angle dependent. (ii)Our observation revealed faster sunrise increase in the modeled TEC relative to GPS-TEC which suggest the misinterpretation of the topside Ne profile of the modeled TEC in order to incorporate the plasmaspheric electron content (PEC). (iii)We also found equal daytime TEC between observed TEC and modeled TEC suggesting that the model TEC could represent GPS-TEC in the absence of plasmaspheric TEC contribution. (iv)We attributed the inconspicuous bite-out in the GPS-TEC during the daytime to the quick refill of fountain effect by higher rate of plasma production at the magnetic equator around the noontime. (v)The discrepancy between GPS-TEC and modeled TEC during the dusk period requires attention in particular around 0400 - 0500 LT that shows the highest percentage deviations. (vi) We also found that the overestimation of % $\Delta TEC_{IRI\text{-}GPS}$ in May and June at all hours of the day.(vii)Furthermore, the percentage deviations in DPS and modeled-TEC during dusk periods is always higher than their corresponding deviations during the daytime and the values of daytime deviation in DPS and NeQ-TEC are smaller compared to daytime deviation in IRI-TEC. This study was carried out during the quietest period of the year 2010; it will be of advantage to investigate and compare studies on the most disturbed days with our results. Moreover, additional stations around the equatorial region will be required to validate the latitudinal effect of the model TEC; this could improve the model parameters for better ionospheric modeling over African sector.

6.0 Acknowledgments

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7.0 References

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7.0 Figures

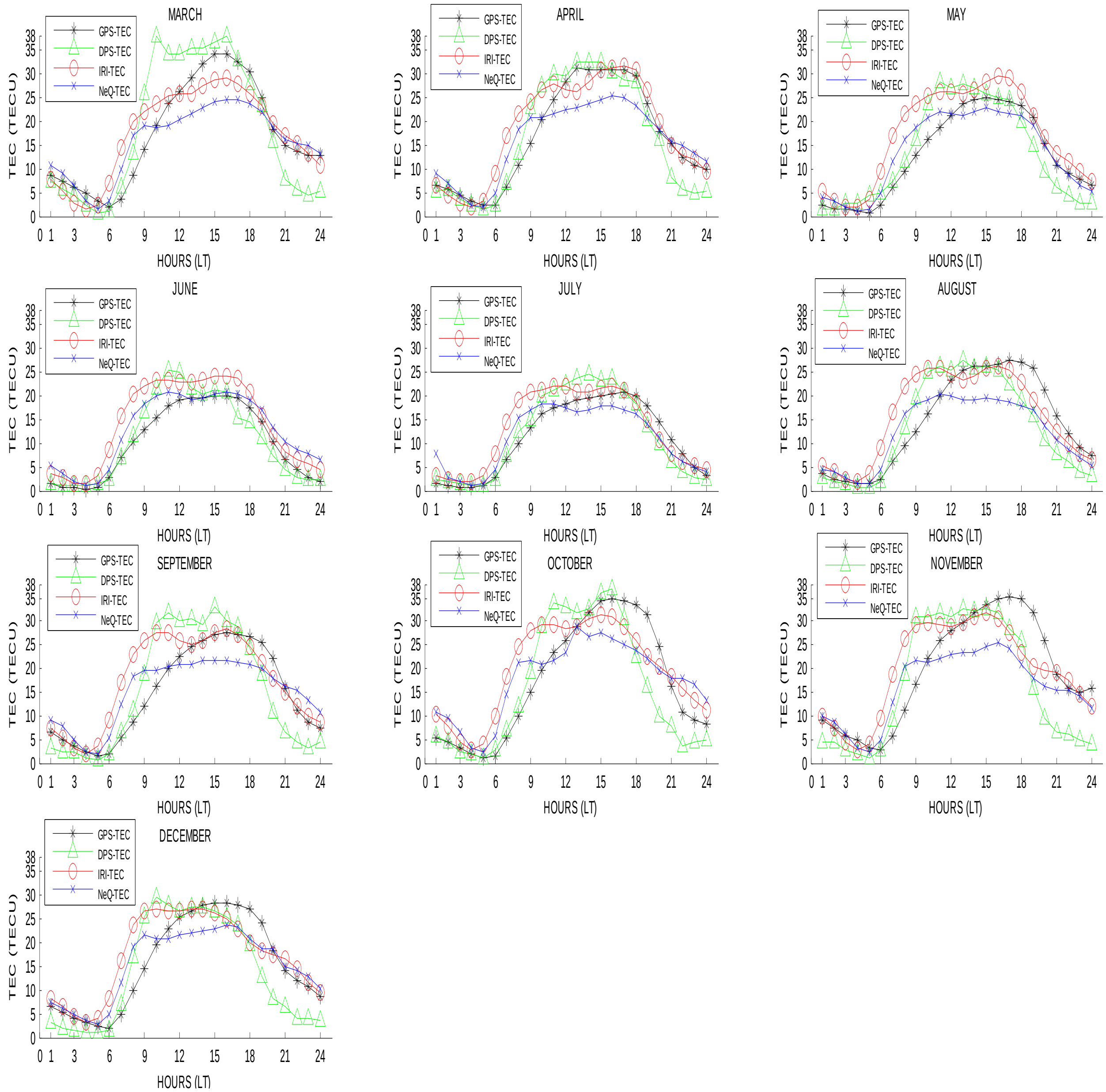

Figure1a. The hourly variations of the monthly median of GPS, DPS, IRI, and NeQuick TEC in March-December during quiet period.

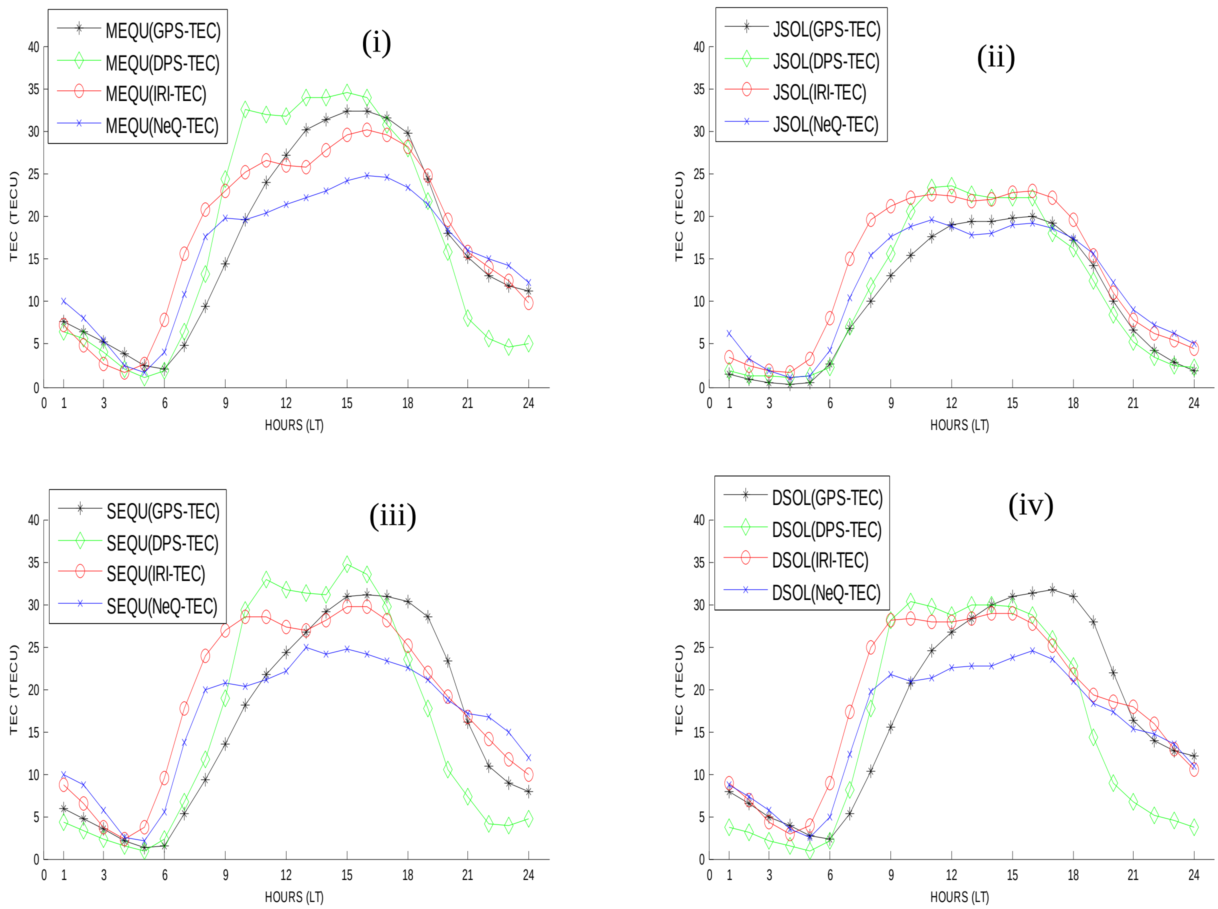

Fig 1b Seasonal variations of GPS-TEC, DPS-TEC, IRI-TEC and NeQ-TEC in (i)March Equinox, (ii)June Solstice, (iii)September Equinox, and (iv)December Solstice over Ilorin during quiet periods in 2010.

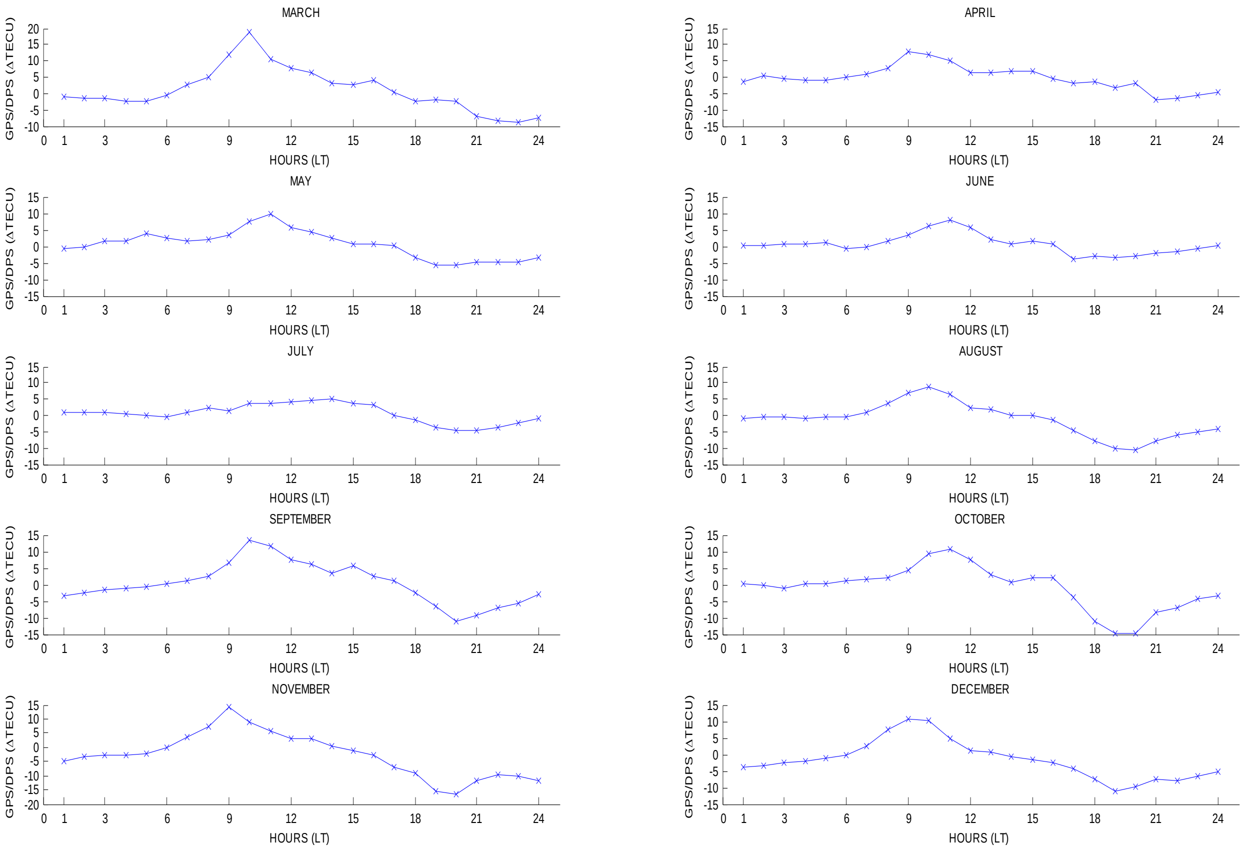

Figure 2a. The hourly ΔTEC variations between the GPS-TEC and DPS-TEC from March - December during quiet period.

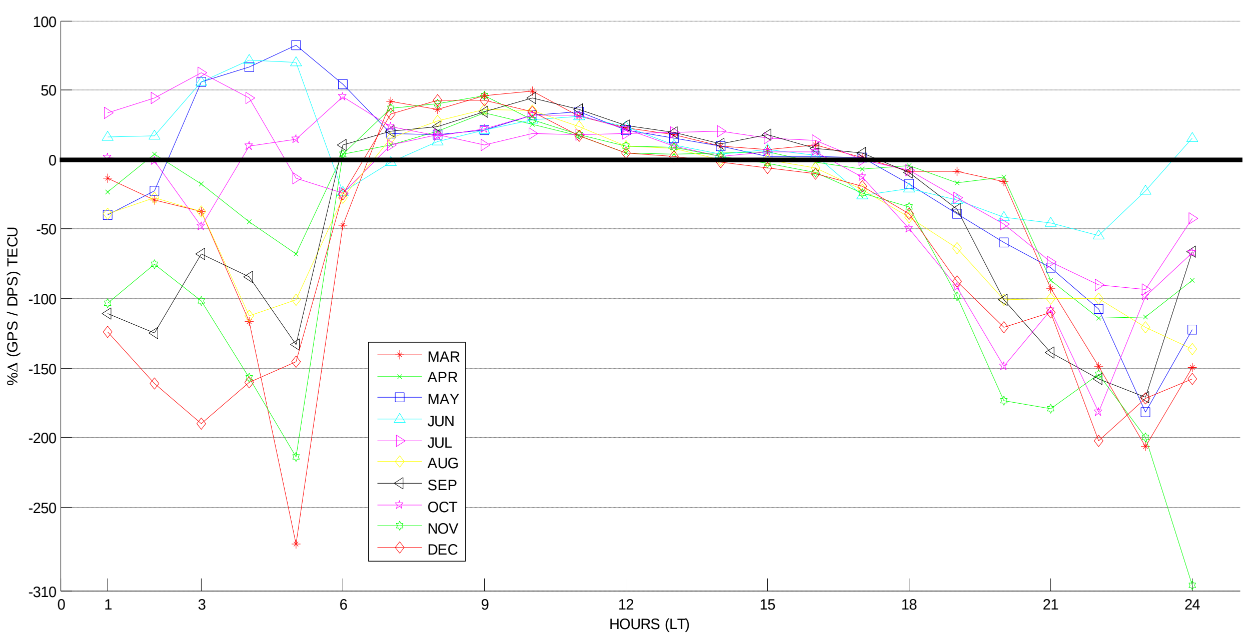

Figure 2b. The mass plot of the hourly %Δ TEC variations between the GPS-TEC and DPS-TEC from March - December during quiet period.

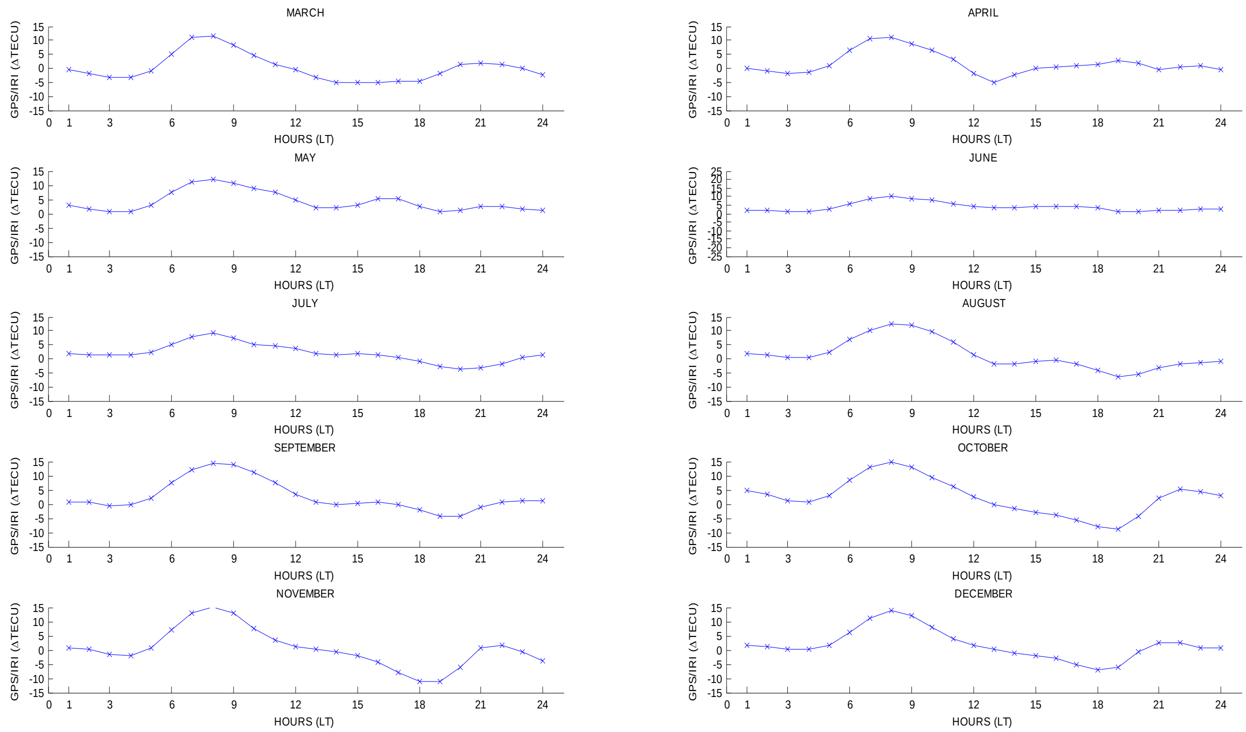

Figure 3a. The hourly ΔTEC variations between the GPS-TEC and IRI-TEC from March - December during quiet period.

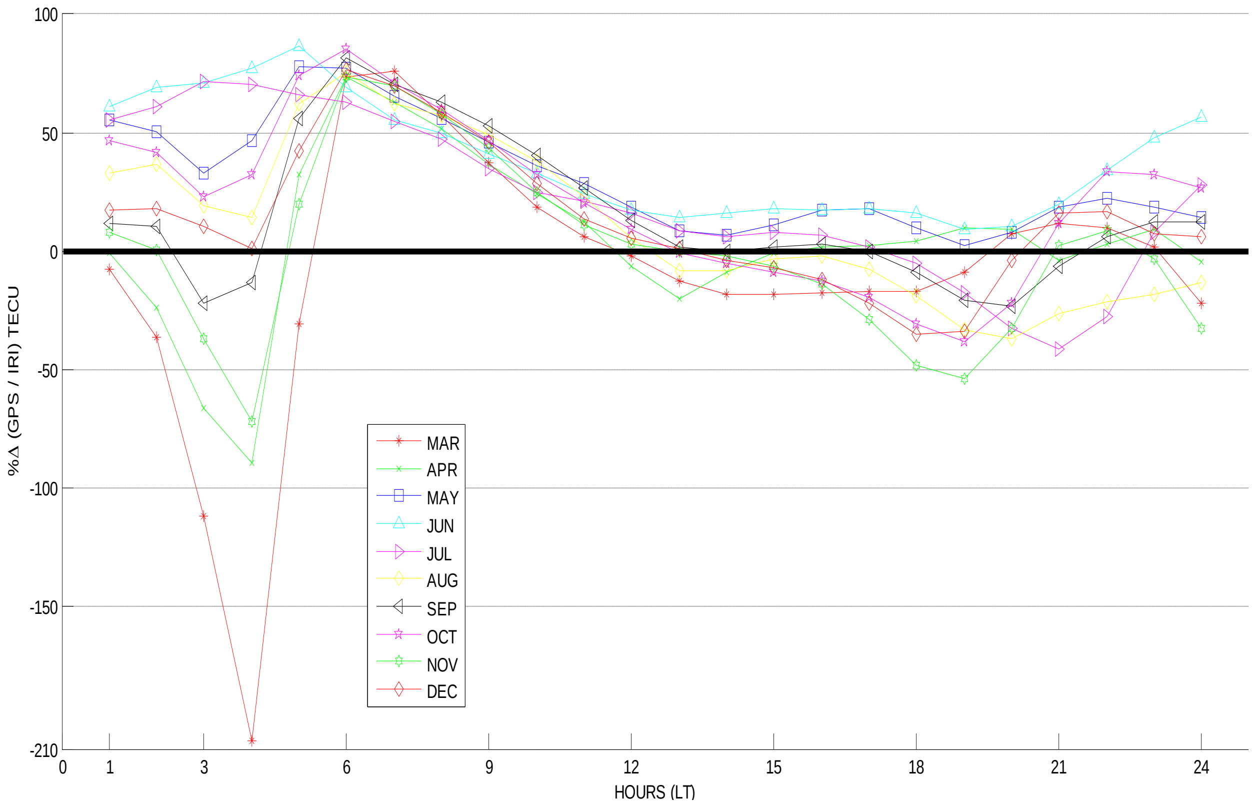

Figure 3b. The mass plot of the hourly %Δ TEC variations between the GPS-TEC and IRI-TEC from March to December during quiet period.

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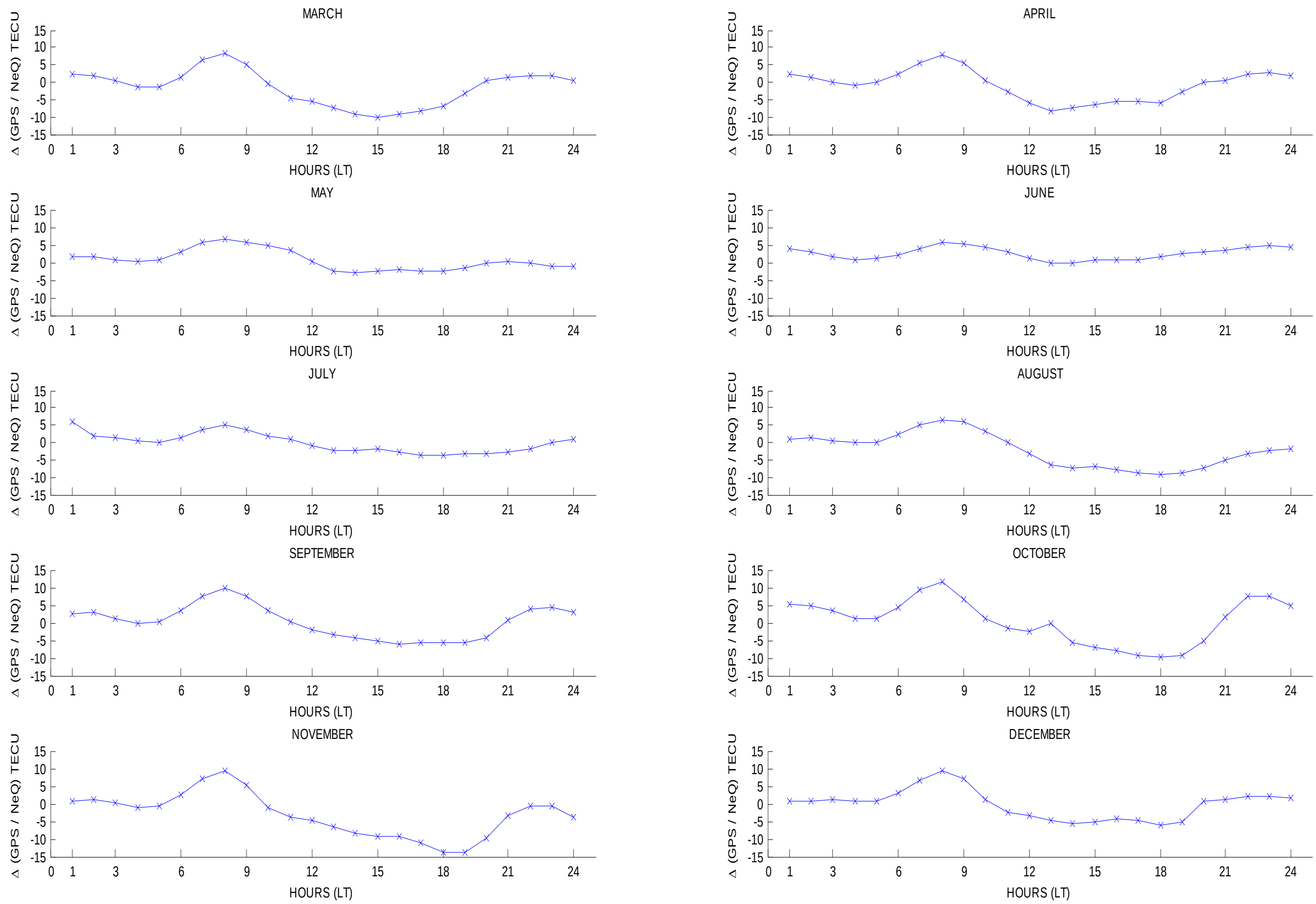

Figure 4a The hourly ΔTEC variations between the GPS-TEC and NeQ-TEC from March - December during quiet period.

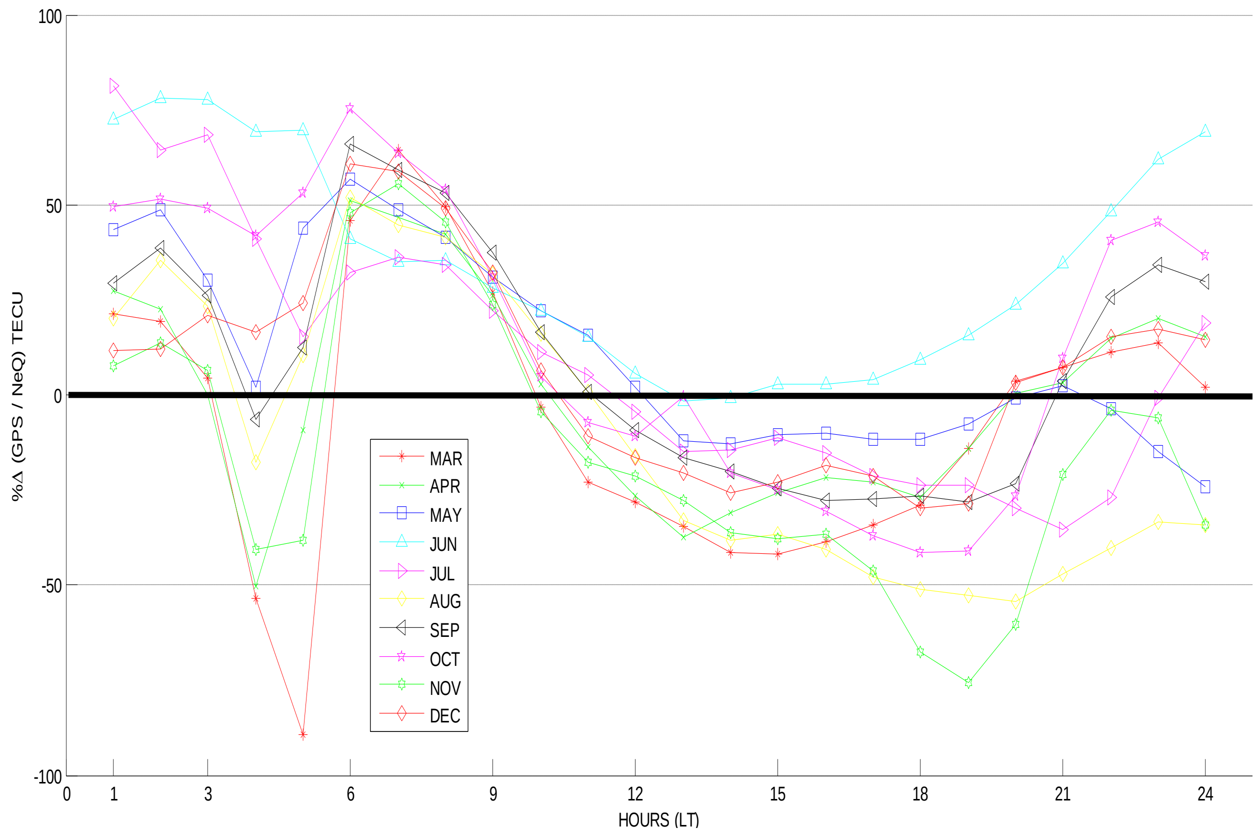

Figure 4b. The mass plot of the hourly % Δ TEC variations between the GPS-TEC and NeQ-TEC from March - December during quiet period