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Observed Discrepancies in International Reference Ionosphere Model Predictions at a Nigerian Low - Latitude Station

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***Abstract* - IRI–2016 and GPS derived Total Electron Content (TEC) has been analyzed for comparative results. Day–to–day, monthly, seasonal and annual variations of TEC were observed, with IRI prediction values consistently higher than the GPS measured TEC values at all segments, especially during the day time plateau and decay region. The relative deviation of measured TEC from the modeled TEC showed appreciable difference, about 70% in most cases. IRI–2016 therefore, over–estimates GPS–derived TEC in Lagos low–latitude station. Investigation of TEC variation with geomagnetic storms revealed that IRI predicted GPS measurement better during storms.**

Keywords: IRI Model, GPS, Ionosphere, Total Electron Content, Low–Latitude.

I. INTRODUCTION

The ionosphere of the Earth has negative influence on space borne and ground based technological systems. It is such that the satellite signals that traverse it, has its frequency carriers experiencing phase advance, while the frequency codes experience group path delay as a result of free electron density between the transmitter and the receiver. These effects on carriers and codes result in range errors in positioning and navigation [3].

Proper analyses of these free electrons, usually measured as Total Electron Content (TEC) accounts for the range errors. TEC of the ionosphere is an important parameter to characterize the ionosphere. It is the total number of electrons present along a path between a radio transmitter and a receiver. The true value of TEC enables the appropriate range corrections, as well as accounting for errors introduced in the range delays owing to the effects of space weather related events. Sudden variations in TEC degrade the phase and amplitude of the received signals, hence are impediment to the trans–ionospheric communication and navigation.

The effects of the Earth's ionosphere on communication and navigation are more at the Equatorial Ionization Anomaly (EIA) zone of the low–latitude. This is because a large fraction of solar energy absorbed within ±30° latitude zone centered on the equator [1], resulting in higher ionization. The zone has been found to be characterized with complexities in the variations of free electrons, e.g. [8].

The Global Positioning System (GPS) technique of measuring TEC has become an effective and powerful tool in the investigation of the ionosphere. This is due to its continuous operation in all weather conditions, signal reception with high time resolution and simultaneous measurements of TEC from different geographic locations. The results of this have been used in most cases to set up new models for TEC and to verify existing models. In the verifications of existing models for instance, it has usually been an over estimation or under estimation during the different times of the day. For example, [2] reported an over estimation of measured TEC by IRI–2012, especially during high geomagnetic activity in an Ile–Ife low–latitude station.

In this work, the IRI–2016 and GPS–derived TEC recorded at Lagos, Nigeria for the year 2014 are analyzed. Comparative results were derived using measured and modeled data by analyzing day–to–day, monthly, seasonal and annual variations of TEC. We also verified the effects of geomagnetic activity on the TEC variations. The results from this work will contribute to adjusting existing TEC models, as well as setting up new models.

II. DATA AND METHODS

GPS Receiver INdependent EXchange (RINEX) data files have been obtained from the Nigerian Global Navigation Satellite Systems Reference Network (NIGNET) for a Lagos station (6.35°N, 3.45°E, dip latitude 7.5°). TEC is computed from the combined L1 (1575 MHz) and L2 (1228 MHz) pseudo ranges and carrier phase, which is the slant TEC (STEC). It is obtained from the difference between the pseudo

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ranges (P1and P2)and the difference between the phases (L1 and L2of the two GPS signals as represented in Equation 1. [10] Noted that if accurate estimates of the ionospheric TEC are to be made, the differential instrumental biases must be removed.

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

Where P1is pseudo range at L1, P2 is pseudo range at L2 and TEC_{BE} is the user–defined TEC offset.

As STEC is dependent on the ray path geometry through the ionosphere, it is desirable to calculate an equivalent vertical value of TEC, which is independent of the elevation of the ray path, as represented in Equation 2. The vertical TEC is obtained by taking the projection from the slant to vertical using a thin shell model, assuming a height of 350 km following the techniques given by [5]. This is depicted in Figure 1.

$$VTEC = STEC \times \cos\left[\sin^{-1}\left(\frac{R_E \cos\theta}{R_E + h_{max}}\right)\right] \quad (2)$$

R_E = 6378 km, θ = elevation angle of GPS satellite at the ground station and h_{max} is the height of ionospheric penetration point (IPP) usually assumed to be 350 – 400 km.

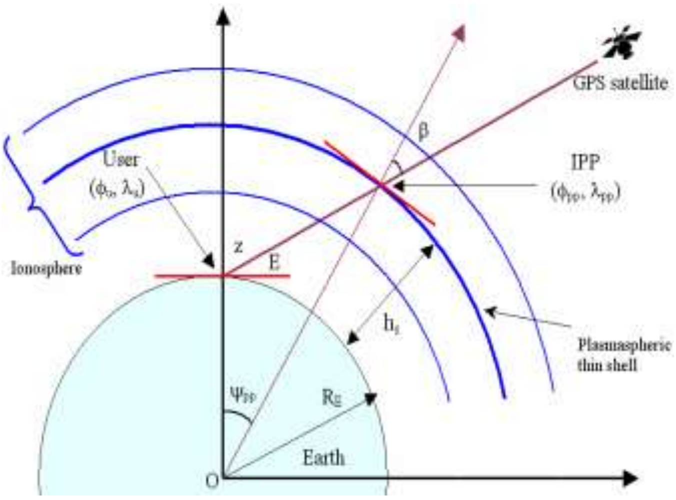

Figure 1: Geometry for the Conversion of Slant TEC to Vertical TEC (After [4])

The GPS data was processed using GPS–TEC analysis software. The software reads satellite biases from DCM IGS code files, calculates the receiver bias and the inter–channel biases from different satellites in the receiver. It plots the vertical TEC values on the screen and writes ASCII output files (CMN and STD) in the same directory of data file.

The International Reference Ionosphere (IRI–2016) model TEC data was assessed and this was used to obtain comparative results between measured and modelled TEC. The disturbance storm time (Dst) index was obtained from World Data Center (WDC) for geomagnetism, Kyoto, Japan, which was used to identify storm events.

III. RESULTS AND DISCUSSION

a) Day–to–Day Variation of TEC

The day–to–day variations of TEC for the months of the year, 2014 are shown in Figures 2a-b. For each day, the three segments of build–up region, daytime plateau and decay region expected of low latitude was observed. A significant day–to–day variation in TEC was observed, with appreciable difference in the magnitude of the measured and modelled TEC, especially during the daytime plateau and decay period. The month of April recorded the highest TEC variation for both measured– (GPS) and modelled– (IRI) TEC. Days 2 – 5 witnessed under estimation of GPS–TEC by IRI–TEC values, while the other days of the same month experienced over estimation of the measured values. The month of July and August recorded the least variation in IRI–TEC (about 40 TECu).

In explanation to the three segment in low latitude plots, the total magnetic field tube is very small at equatorial and low latitudes. This results in the electron contents in the field tubes collapsing rapidly after sunset in response to the low temperature in the thermosphere in the nighttime. Following the sunrise, the magnetic field tubes again get filled up rapidly because of their low volume resulting in steep increase in ionization [6]. This is the large variability imposed on the low latitude ionosphere during sunrise and sunset transition.

The day–to–day variability in TEC, which has also been observed by some authors (e.g. [8];[9]; [11]), may be due to the changes in the activity of the sun itself and to the associated changes in the intensity of the incoming radiations and the zenith angle at which they are incident on the Earth's atmosphere. Other factors that may be responsible for this variation are: EEJ strength, Earth’s magnetic field and the dynamics of the neutral wind [9].

b) Monthly Mean Variation of TEC

The comparative plots of monthly mean TEC variation for GPS– and IRI–TEC are shown in Figure 3. For the GPS measured TEC, the minimum mean TEC was registered from about 18:00 – 09:00 UT, while that for IRI TEC was at about 20:00 – 07:00 UT. This implies that the build–up and decay time for GPS took longer time than that for the IRI. The afternoon maximum took shorter time of about 8 hours for GPS measurement, while the IRI prediction took longer time

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of about 13 hours. In terms of TEC magnitude, the months of March to June and October to November recorded high TEC values ranging from 44 – 52 TECu for IRI prediction, while values ranging from 34 – 44 TECu were recorded during the afternoon maximum in the months of March, April and October for GPS measurement. This shows that the IRI prediction over estimates GPS measurement in all the months, except in March.

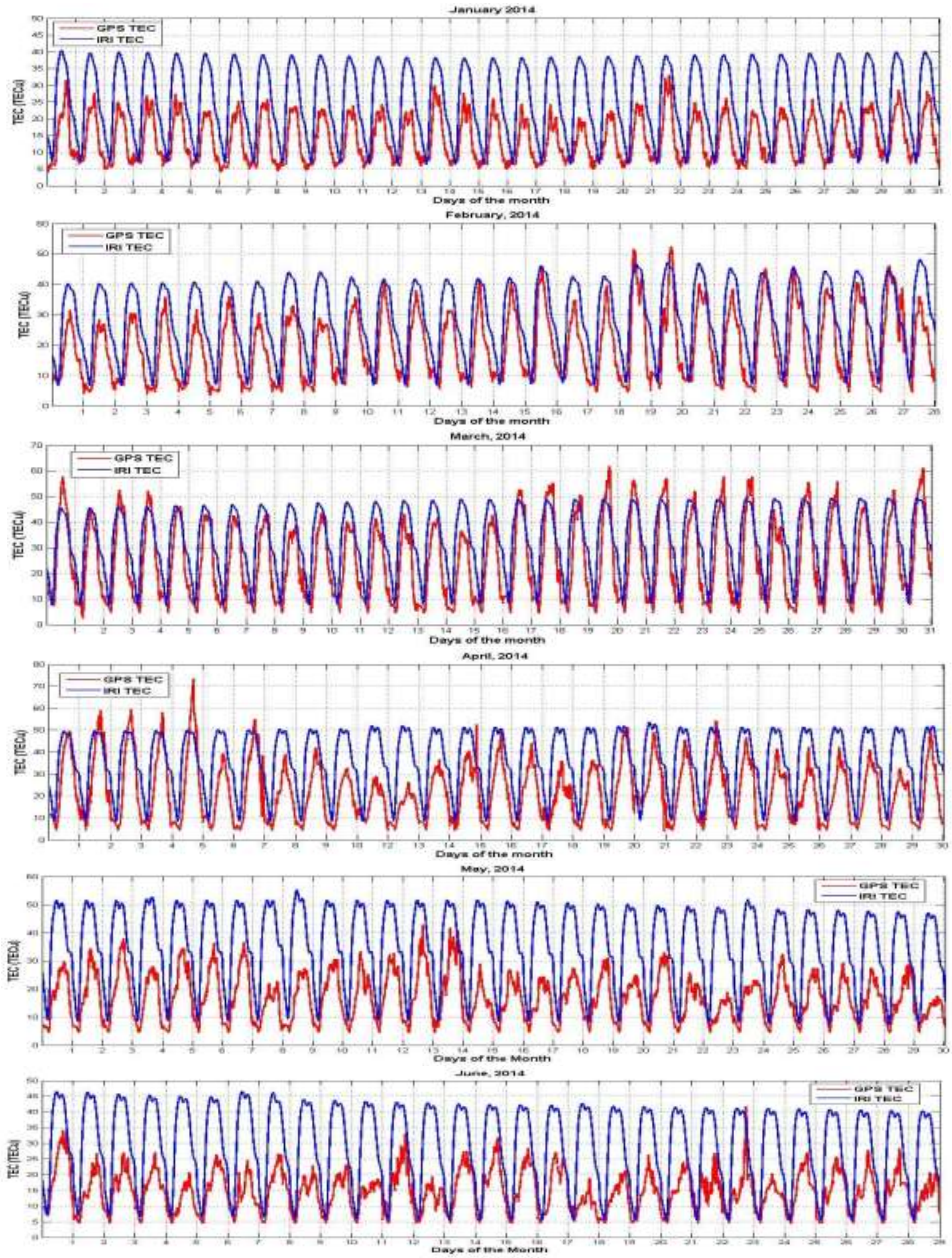

Figure 2a: Day-to-Day Variation of TEC from January to June 2014

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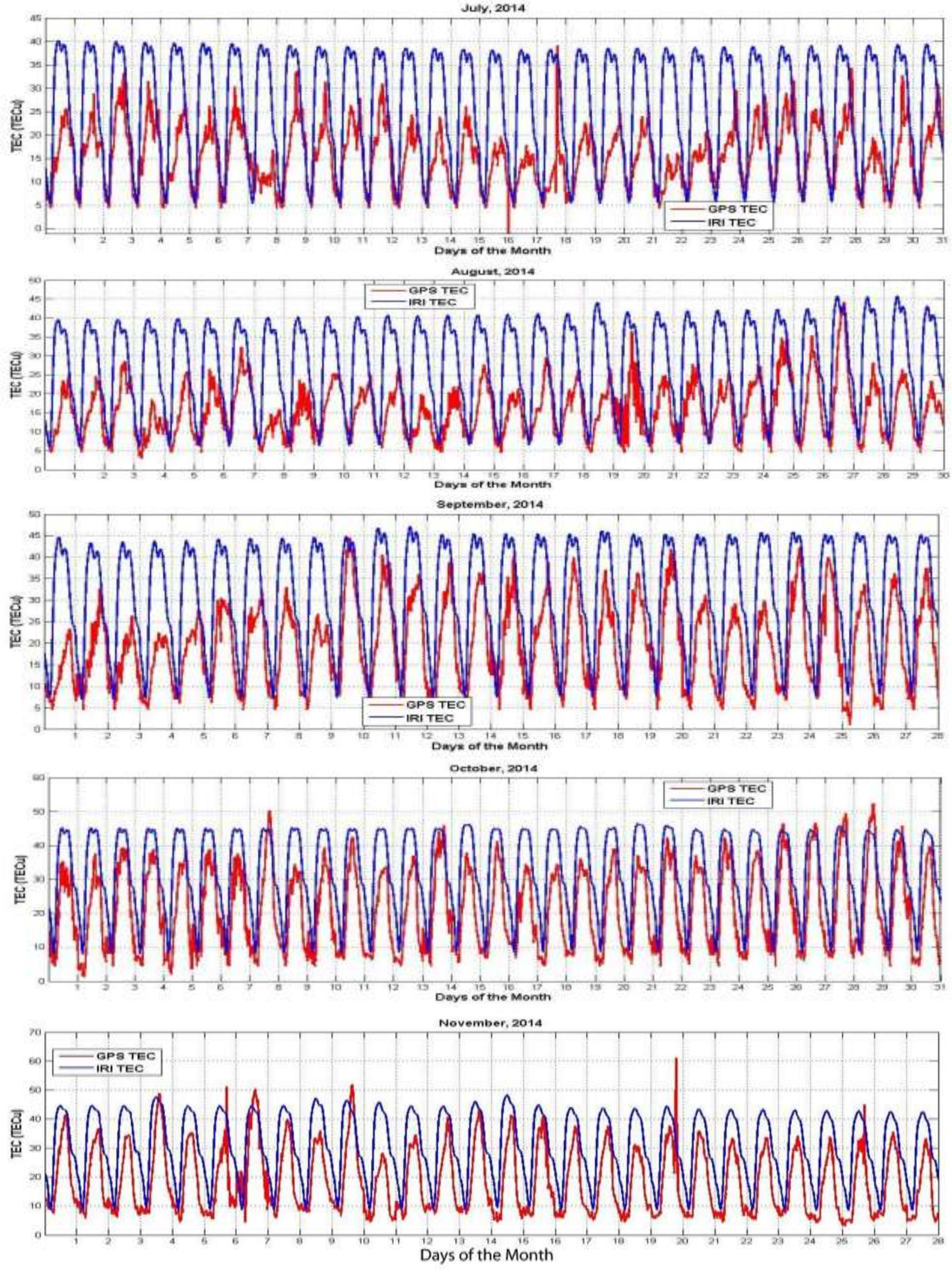

Figure 2b: Day-to-Day Variation of TEC from June to November 2014

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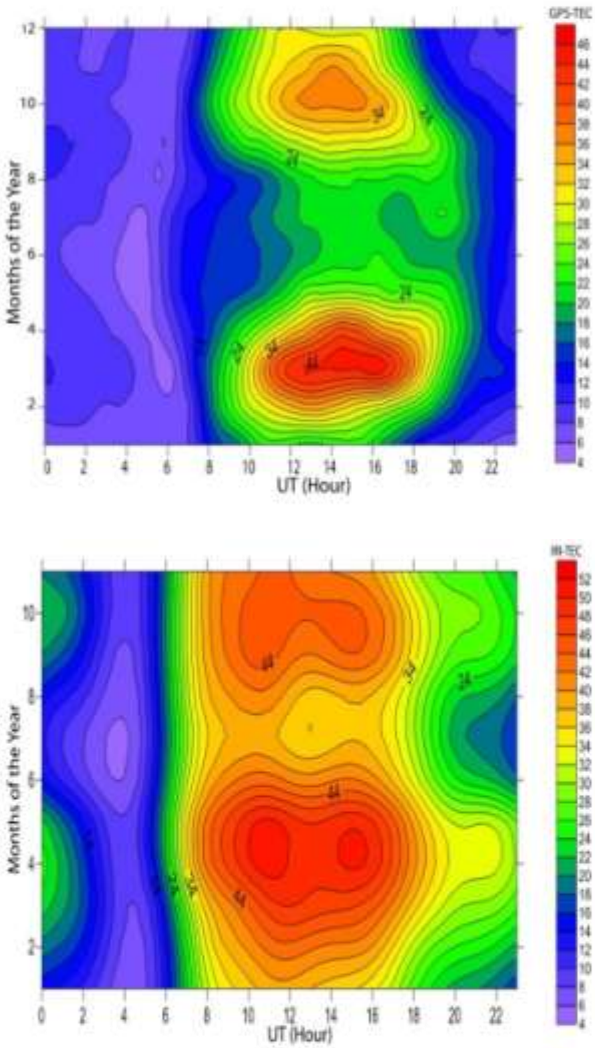

Figure 3: Monthly Mean Variation of TEC: (a) GPS-measured TEC and (b) IRI-predicted TEC

c) Seasonal and Annual Variation of TEC

Seasonal variation in TEC is due to the tilt and rotation of the Earth around the Sun. In this study, seasons of the year were classified into four: Winter (December, January and February), Spring (March, April and May), Summer (June, July and August) and Autumn (September, October and November). Figure 4 shows the seasonal variation of GPS– and IRI–TEC. From the figure, it was obvious that TEC varies from season to season, with the Spring season recording the highest peak TEC of 50 TECu and 37 TECu for IRI and GPS respectively. Summer season recorded the lowest peak TEC of 41 TECu and 22 TECu for IRI and GPS respectively. The variations are more during the daytime, suggesting the effect of solar activity on TEC variation. A remarkable over estimation of GPS–TEC by IRI–2016 modelled TEC was observed in all the seasons. In winter, the IRI peak TEC was about 42 TECu while the GPS peak TEC was about 28 TECu, representing about 33% over estimation. This was also true for the spring, summer and autumn season, where the over estimation was about 26%, 46% and 24% respectively. The over estimation was mostly during the daytime plateau and decay period. It was also observed that the build–up region for GPS–TEC took longer time (about 2 hours difference) than the IRI–TEC in all seasons, suggesting a harmonization between the universal time and the local time of the station (UT = LT+1).The annual variation of TEC in Figure 5 also revealed an over estimation of measured TEC by the modelled TEC by about 39% during the daytime plateau and averagely about 52% during the decay period.

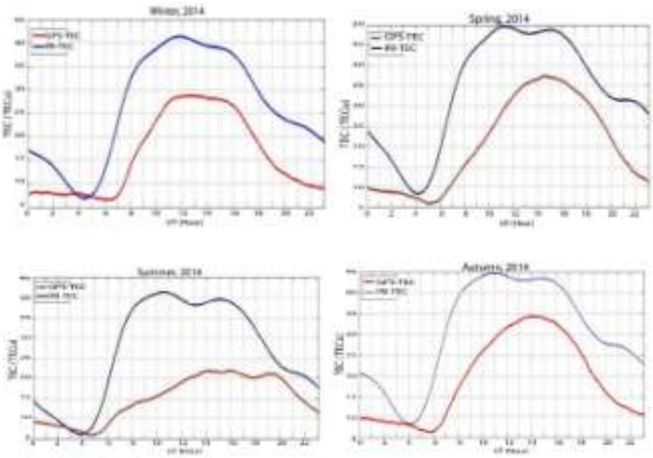

Figure 4: Seasonal Variation of TEC. GPS-TEC measurement and IRI-TEC Model are in blue and red profiles respectively

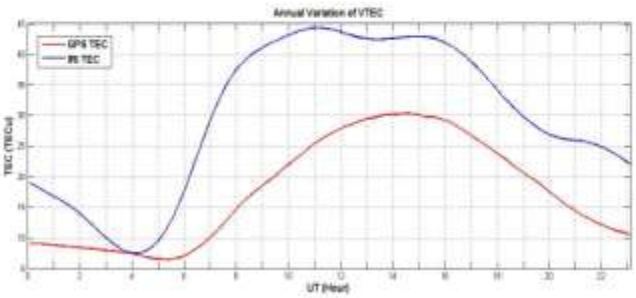

Figure 5: Annual Variation of TEC. GPS-TEC measurement and IRI-TEC Model are in blue and red profiles respectively

d) Relative Deviation of TEC

To ascertain the level of deviation in TEC between the measured and modelled values during the three segments, the relative deviation was evaluated from the expression:

$$1 = \frac{GPS-TEC}{IRI-TEC} \quad (3)$$

Figure 6 shows the selected months of the year used to investigate the level of deviation in the day–to–day variation between the measured and modelled TEC. Values below zero

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indicates under estimation, while that above zero represent over estimation. From the plots, it is obvious that over estimation of GPS–TEC by IRI–2016 TEC dominates. The magnitude of the over estimation in this station is such that serious and urgent attention be given to the model to be able to reproduce the true picture of TEC variation. In January 2014, for instance, the over estimation ranges between 10 – 75% and took dominancy throughout the month. Under estimation was sparingly seen in very few days.

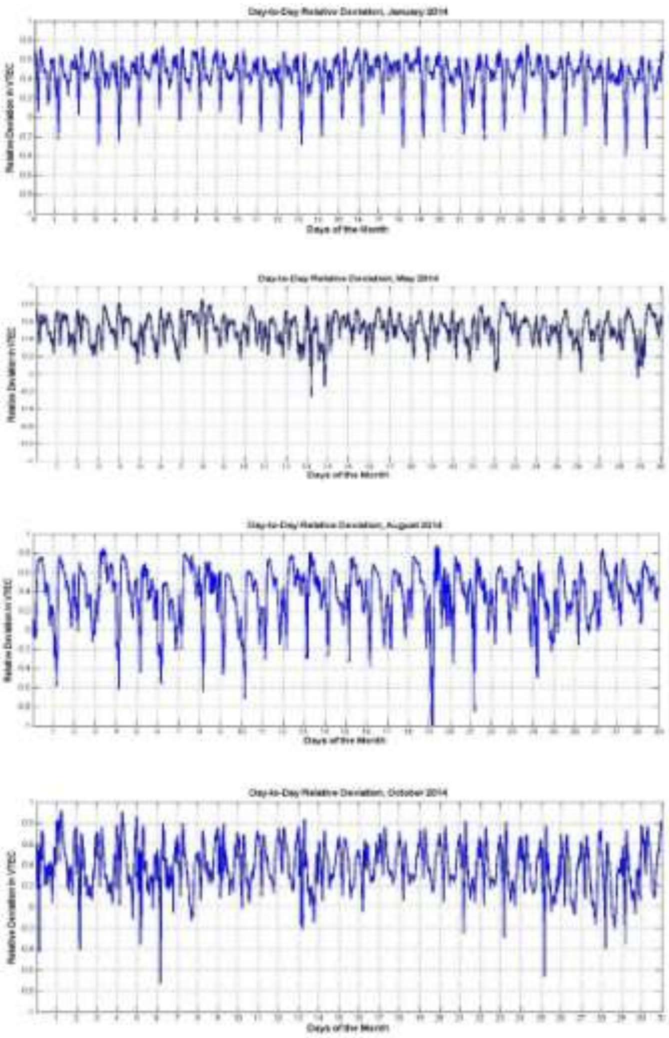


Figure 6: Day-to-Day Relative Deviation in TEC

This observation was true for the other months as shown in the figure. Figure 7 shows the deviation during the seasonal variation of TEC. It reveals that the under estimation of measured by modelled TEC was recorded only during 04:00 – 05:00 UT in winter and summer, with values of about –0.1 respectively. The rest of the day witnessed appreciable over estimation. The spring and autumn seasons witnessed over estimation throughout the day. A major contributor to these differences can be the shape of the topside IRI profile [7] and the effects of plamasphere.

e) Effects of Geomagnetic Storm on TEC

Figure 8 represents TEC variations for some geomagnetically disturbed days. The IRI–TEC plots (in blue colour) showed relatively smooth curve, with peak variations during the daytime. In the other hand, the GPS–TEC variations exhibited some levels of irregularities, especially during the daytime. Comparing Figure 7 with Figures 4 and 5 (seasonal and annual variations of TEC), one can conclude that the high level of irregularities could be as a result of penetration of eastward electric field, causing geomagnetic storm. The IRI–TEC prediction was also better during the geomagnetic storm main phase.

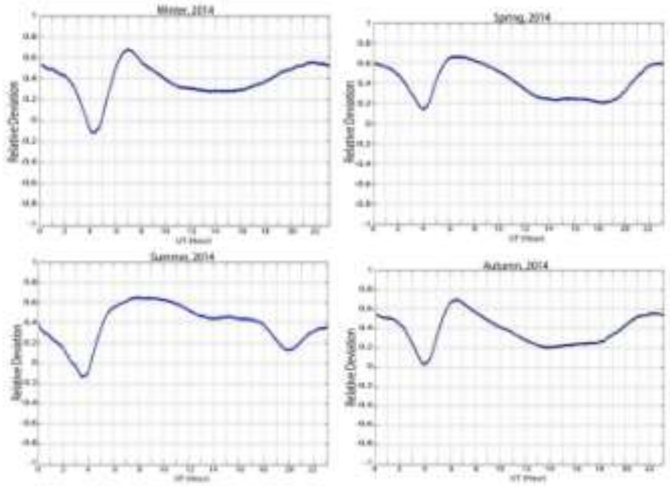
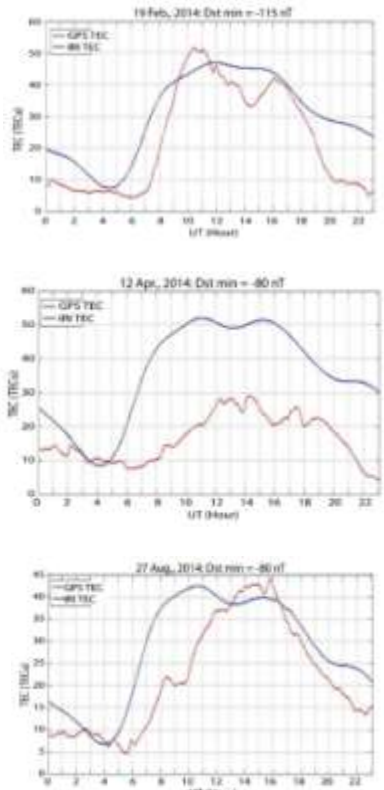


Figure 7: Seasonal Relative Deviation in TEC



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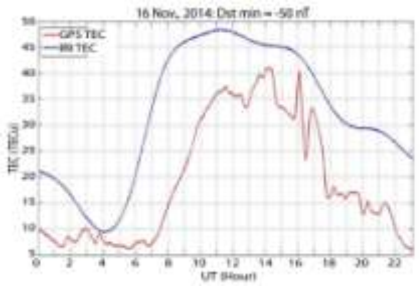

Figure 8: TEC Variation during Geomagnetic Disturbances

Cases of 19thFebruary and 27th August were only over–estimated during the decay periods. In terms of TEC magnitude, it was obvious that TEC was enhanced as a result of the storms. Comparative results from the seasonal and annual variation of TEC revealed maximum GPS measured TEC to be about 37 TECu in spring equinox and about 30 TECu for annual variation. The value however increased to about 51 TECu on 19 February when the minimum Dst value was –115 nT.

IV. CONCLUSION

With the goal of establishing an international standard for the specification of ionospheric parameters based on all worldwide available data from both ground–based and satellite observations, the International Reference Ionosphere (IRI) project was initiated by the Committee on Space Research (COSPAR) and by the International Union of Radio Science (URSI) in the late 1960s. The IRI model is continually upgraded as new data and new modelling approaches become available, and this process has resulted in several major milestone editions of IRI. The IRI–2016 is the latest edition of IRI project. In this work, the GPS–derived TEC from Lagos, Nigeria low–latitude station was compared with the IRI–derived TEC (IRI–2016 TEC). The IRI–2016 consistently over estimated GPS–derived TEC during daytime plateau and decay period. The level of deviation of measured TEC values from IRI–2016 TEC values was enormous (up to 70%). The discrepancy recorded cannot be attributed to the effect of plasmasphere alone, since it was so large. Also, IRI representing the monthly average behavior of the ionosphere at a given place and time predicts changes from month to another, but not from day to day. This may have resulted in poor day–to–day prediction, with highest percentages of over estimation of GPS–TEC.

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