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A comparative study of Nigerian GNSS Reference Network's – Global Positioning System (NIGNET's-GPS) vertical Total Electron Content (vTEC) measurements with the International Reference Ionosphere - Total Electron Content (IRI-TEC) predictions over Calabar, Nigeria

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A study of the vertical Total Electron Content (vTEC) values as measured by the Nigerian GNSS Reference Network's (NIGNET's) GPS receiver in Calabar with geographic coordinates: 4.95°N, 8.32°E and geomagnetic coordinates: 6.46°N, 81.59°E has been carried out for some selected days in the year 2013. The results obtained are compared with the corresponding predictions of the three topside options for the TEC predictions (NeQuick, IRI01-cor, and the IRI 2001) of the International Reference Ionosphere (IRI) model (version 2012) over Calabar region. Despite some gaps in the measured vTEC values by the GPS receiver in Calabar, the results of this research shows high hourly and diurnal correlation of about 0.9 with the IRI-vTEC predictions for the days examined; thus supporting the viability of the receiver as a vTEC measuring device. The NeQuick option gives the best topside representation for the region.

Key words: Nigerian GNSS Reference Network's – Global Positioning System (NIGNET's-GPS) Receiver, vertical Total Electron Content (vTEC), International Reference Ionosphere (IRI)-Model.

INTRODUCTION

Total electron content (or TEC), an important descriptive quantity in space weather studies, is the total number of electrons in the ionosphere integrated between two points, along a tube of cross-sectional area of one meter

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squared. Its unit is often given in multiples of the TEC unit (TECU), defined as 1 TECU = $10^{16}.m^{-2}$ (Hofmann-Wellenhof et al., 2001). Because of its dispersive nature, the total electron content in the ionosphere is significant in determining the scintillation and frequency-dependent group and phase delays of radio waves through the medium. These observed carrier phase delays of received radio signals transmitted from satellites are manifested in the ionosphere above the equatorial ionization anomaly (EIA) regions, due to the high background electron density coupled with its rapid and complex variation (Guoqi et al., 2013). The magnitude and variation of TEC is related to the local time, solar activity, geomagnetic conditions, region of the earth and other sudden space weather events. Some researchers have estimated vertical Total Electron Content parameters using a single-frequency approach of Global Navigation Satellite System data and thereafter compared their results with those obtained from dual frequency measurements (e.g. Zhang et al*.,* 2017; Win et al., 2016; Rao, 2017; Torben and Olushola, 2013).

Consequently, some other authors have carried out comparative studies on GPS TEC variations and International Reference Ionosphere (IRI) predictions for other regions in Nigeria. These include studies by Adewale et al. (2011), *Okoh* et al*.* (2011), Rabiu et al. (2011) and Okoh et al. (2012, 2015). As a follow-up to some of their recommendations, we have carried out a study of the vertical total electron content (vTEC) values as measured by the NIGNET's (Nigerian GNSS Reference Network) GPS receiver in Calabar, Nigeria (Geographic coordinates: 4.95°N, 8.32°E; Geomagnetic coordinates: 6.46°N, 81.59°E) for the year 2013. The results obtained were compared with the corresponding prediction of the three topside options for TEC predictions (NeQuick, IRI01-cor, and the IRI2001) of the International Reference Ionosphere (IRI) model (version 2012) over Calabar region.

The International Reference Ionosphere (IRI) is an empirical model developed (globally) to predict parameters in respect to radio propagation through the ionosphere. Some of these parameters include vertical profiles of electron density, electron and ion temperatures and the relative share of the different positive ions, vertical electron content, and F1 and spread-F probability. IRI is a working group, jointly sponsored by the Committee on Space Research (COSPAR) and the International Union of Radio Science (URSI). It is generally regarded as the international standard for specifying ionospheric parameters (Bilitza, 2001; Bilitza and Reinisch, 2008; Bilitza and McKinnell, 2011; Okoh et al*.*, 2012). In addition, as posited by Adewale et al*.* (2011), the accuracy of the IRI model on the specific region and/or time high since it is a data based model.

IRI has several applications in areas such as aerospace-based engineering endeavours, space weather (through the provision of real-time atmospheric parameters), and visualization tools for educational purposes (Oyeyemi, 2014).

Our motivation for this work stems from the fact that, since the installation of NIGNET's GPS receiver in Calabar in 2011, no study has been carried out to evaluate its viability for the measurement of the vertical Total Electron Content (vTEC) over the Calabar region. In addition, we believe that the work will help fill the knowledge gap in modelling and predicting TEC values in the equatorial region using the IRI model. Again, this increase in knowledge of the ionosphere, especially for the African equatorial region, will enhance global efforts aimed at correcting ionospheric influences on the radio signals propagating through the region.

DATA SOURCES AND METHOD OF ANALYSIS

vTec from the IRI model

The three topside options for TEC predictions, namely; NeQuick, IRI01-corr, and the IRI2001 of the International Reference Ionosphere IRI (2012) model were used to obtain the predicted values of TEC over the Calabar region. In the modelling, the following optional parameters; sunspot numbers (Rz12), F10.7 radio flux (daily and 81-day), and the ionospheric index (IGI2) were not specified, while the foF2 storm model was switched on. The upper limit for electron content was set at 1500 km.

vTec from GPS receivers

The GPS data used for this work were obtained from the Nigerian GNSS Reference Network (NIGNET) project, established in 2008 by the Office of the Surveyor General of Nigeria (Jatau et al., 2010). The network consists of the state-of-the-art CORS (Continuously Operating Reference Station) GNSS (Global Navigation Satellite Systems) equipment, and is intended to implement the new fiducial geodetic network of Nigeria. In other words, NIGNET is expected to directly contribute for the AFREF (African Reference France) project.

Apart from the above stated objectives, the NIGNET system also has the capability to acquire real-time ionospheric GPS data such as vTEC amongst others, in RINEX (Receiver Independent Exchange) format, which allows the user to post-process and get results that are more accurate.

The post-processing and analysis of the RINEX data was carried out using GPS_Gopi_v2.9.3, a GPS_TEC analysis application developed by Dr. Gopi Seemala of the Indian Institute of Geomagnetism (IIG), Navi Mumbai, India (Seemala, 2014).

The NIGNET GPS receivers measure pseudoranges and carrier phases at L1 (1575.42 MHz) and L2 (1227.60 MHz) and operates on two different carrier frequencies, namely, f1 and f2. These frequencies are derived from the fundamental frequency fo = 10.23 MHz, that is, f1 = 154fo and f2 = 154fo. The GPS receivers being a dual-frequency receiver measures the difference in ionospheric delay between the L1 and L2 signal. The group delay for a dual-frequency receiver is given by Ya'acob and Idris (2012).

$$\Delta P = P_2 - P_1 = 40.3TEC\left[\frac{1}{f_2^2} - \frac{1}{f_1^2}\right] \quad (1)$$

Where P_1 and P_2 are the group path lengths, and f_1 and f_2 are the corresponding high and low frequencies respectively. The total electron content (TEC) is thus obtained from Equation 1 as follows:

$$TEC = \frac{1}{40}\left[\frac{f_1^2 f_2^2}{f_1^2 - f_2^2}\right](P_2 - P_1) \quad (2)$$

The TEC value obtained from Equation 2 is called the slant TEC (sTEC), and it is a measure of the total electron content of the ionosphere along the geometrical path taken by the signal from the satellite to the receiver. Its measurement is based on the model that the ionosphere is a spherical shell at fixed height given by the centre of mass of the ionospheric profile at 600 km above the earth's surface.

The vertical total electron content (vTEC) is obtained from the sTEC values by using an appropriate mapping function given by Ya'acob and Idris (2012):

$$vTEC = sTEC(\cos\chi') \quad (3)$$

where χ' is the zenith angle at the ionospheric piece point (IPP), which is the user line of sight to the tracked satellite.

RESULTS AND DISCUSSION

Half-hourly variation

The plots of the half-hourly variation of the three different topside options of the IRI model and the corresponding GPS-TEC values for the selected days: 31st January, 28th February, 30th March, 30th April,31st May, 30th June, 15th July, 30th September, 31st October, 30th November, and 31st December, 2013 were generated. Apart from July 15th, these dates were selected on the basis of their being the last of each month for the year under study. July 15th was selected because it was the only date having a complete data for that month, while no data was recorded by the receiver in August. The results obtained are as shown in Figures 1(a – k).

As can be seen from Figures (1a – k), the trend of both the GPS and the three IRI models are quite similar, albeit with some slight disparities. Consequently, for all the eleven days considered, the TEC values were higher during daytime compared to night-time with the TEC values increasing abruptly from dawn (0600 h), reaching peak values during the period 1400 - 1700 h (UT) before falling abruptly at dusk (1800 h). These maxima coincide with the time suggested for high solar ionization activity in the ionosphere, and agrees with similar studies carried out for other regions in Nigeria by Adewale et al. (2011), Okoh et al. (2011), Rabiu et al. (2011) and Okoh et al. (2012).

In order to further elucidate the comparative variations of vTEC from GPS and IRI models (through similarities in trends and profiles, and how close the values are), we calculated the correlation coefficients (Table 1), the root-mean square deviations (RMSD), and also the percentage root-mean-square deviations (%RMSD) (Table 2) of the IRI-TEC values from the GPS-TEC values for the eleven days using the standard algebraic expressions for evaluating these quantities. The results as shown in Table 1 inferred that there is a very high correlation coefficient (in most cases, of about 0.9) between the GPS TEC values and all the three topside options. In addition, the root-mean-square deviations were relatively low, ranging from 19 to 31% for the nequick option, 16 to 36% for the IRI 2001 option, and 17 to 58% for the IRI 01-cor option. These high correlation coefficients and relatively low RMSDs between the GPS and IRI TEC values thus support the use of IRI model to predict the GPS TEC measurements over Calabar region.

Year-round day-to-day variations

The plots illustrating the year-round day-to-day variations of the GPS TEC and IRI model-predicted TEC values at dawn (0006 UT), mid-day (0011 UT), dusk (1700 UT), and mid-night (2300 UT) are given in Figures 2a to 2d. The hourly correlation coefficients and the corresponding RMSD and %RMDS for all the days of the year are presented in Tables 3a and 3b respectively.

Conclusion

We have carried out a comparative study of NIGNET'S GPS vTEC measurements with the three topside IRI - vTEC predictions over Calabar, Nigeria for the year 2013. The results obtained show that despite some gaps in the measured vTEC values by the GPS receiver in Calabar, there is a high hourly, and diurnal correlation (about 0.9) between it and the IRI-vTEC predictions for the days examined. This strongly supports the viability and use of the receiver as a vTEC measuring device. Furthermore, of the three topside options, the NeQuick option gave the best topside representation for the region.

In other to validate the predictive value of the IRI model over Calabar region, similar work should be carried out in the same area. This will help to determine an agreeable upper integration height for the IRI models for which the RMSDs from the GPS-TEC values are minimal. In addition, studies should be carried out in the region during years of high solar activity.

CONFLICT OF INTERESTS

The authors have not declared any conflict of interests.

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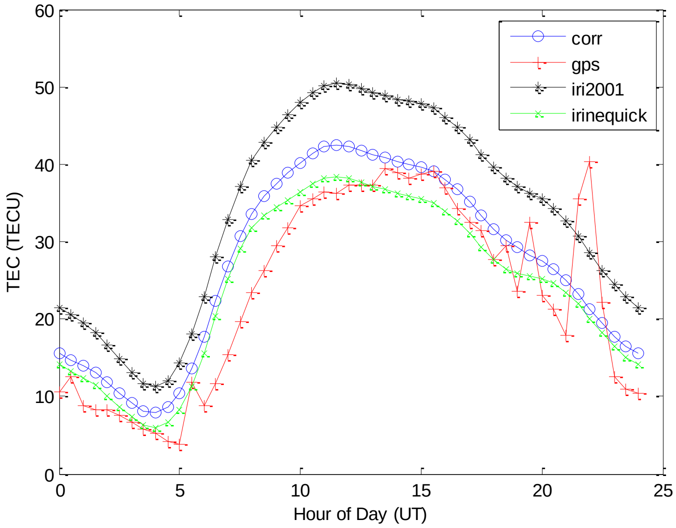
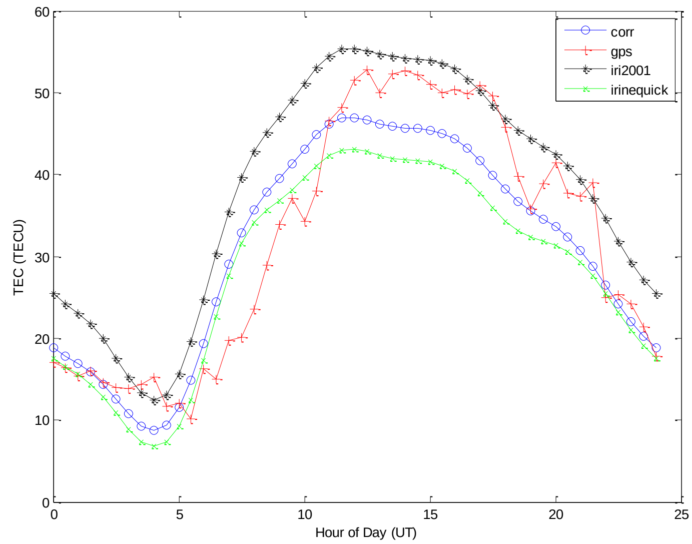
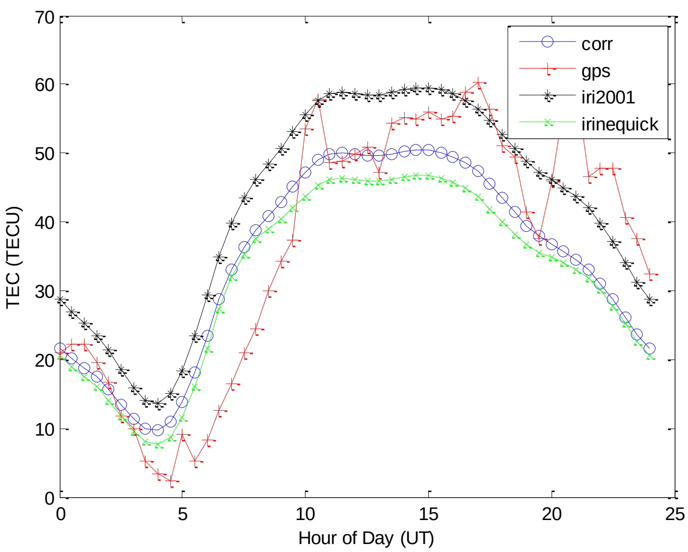

corr
gps
iri2001
irinequick
TEC (TECU)
Hour of Day (UT)

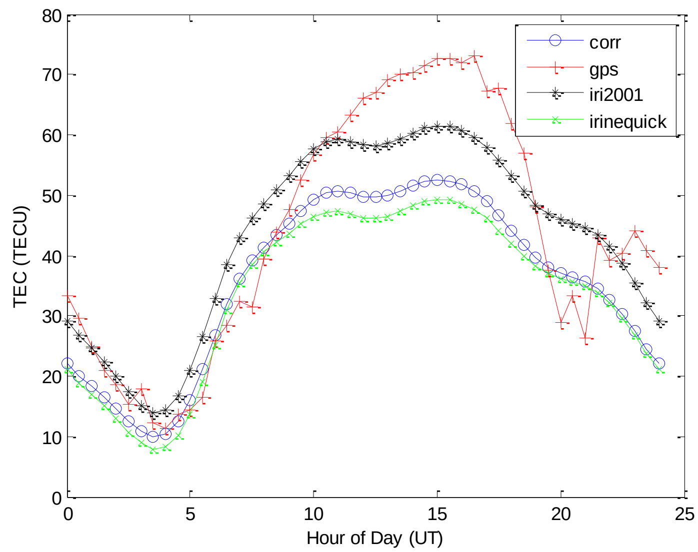
(a)


corr
gps
iri2001
irinequick
TEC (TECU)
Hour of Day (UT)

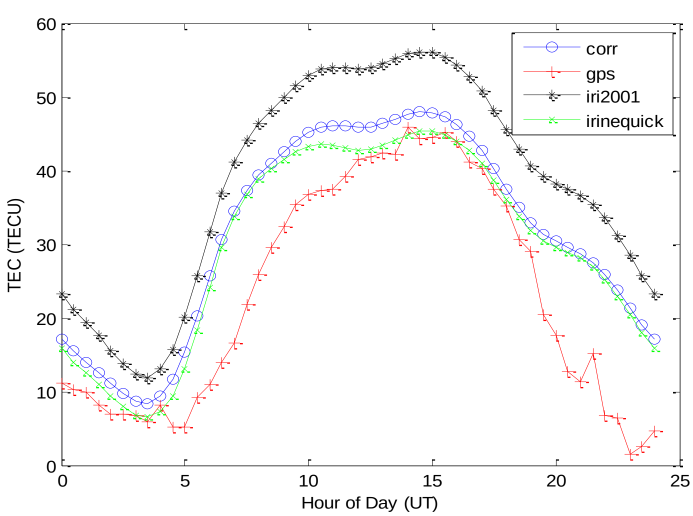
(b)


corr
gps
iri2001
irinequick
TEC (TECU)
Hour of Day (UT)

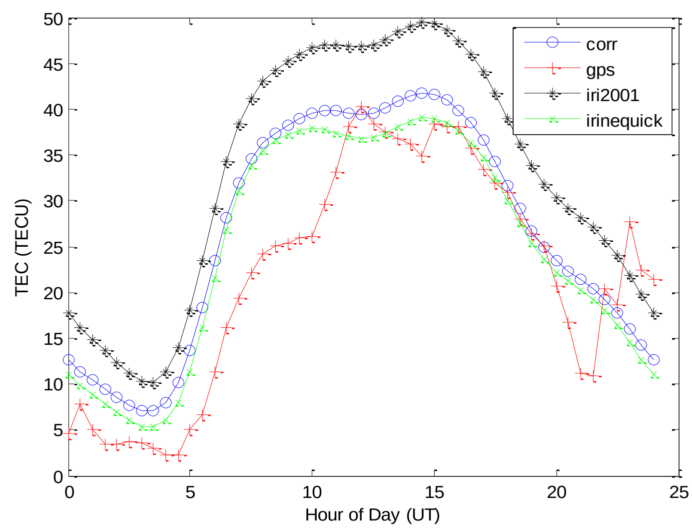
(c)


corr
gps
iri2001
irinequick
TEC (TECU)
Hour of Day (UT)

(d)


corr
gps
iri2001
irinequick
TEC (TECU)
Hour of Day (UT)

(e)


corr
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iri2001
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TEC (TECU)
Hour of Day (UT)

(f)

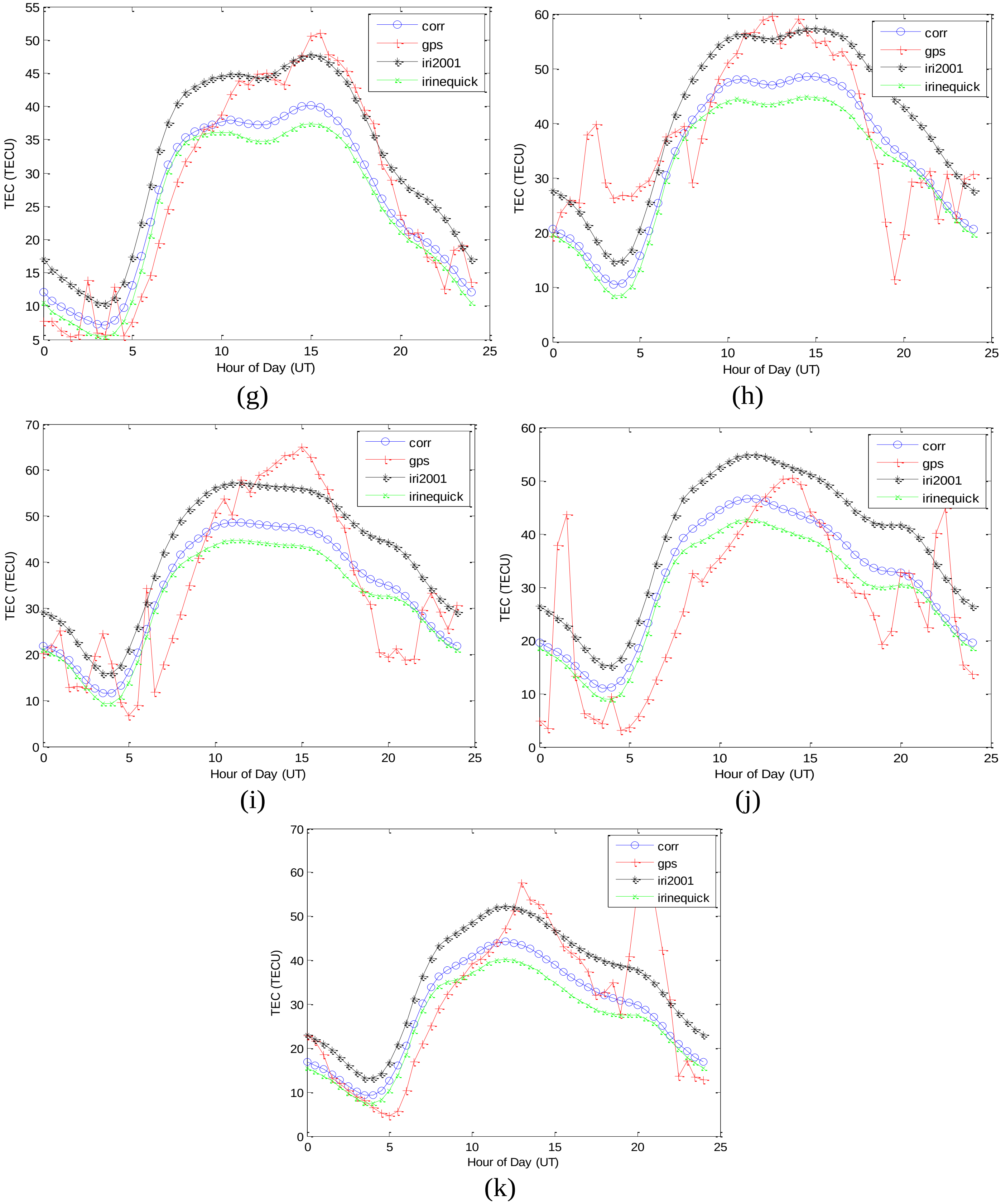

Figure 1. Half-hourly variations for the selected days: (a) 31st January (b) 28th February (c) 30th March (d) 30th April (e) 31st May (f) 30th June (g) 15th July (h) 30th September (i) 31st October (j) 30th November, and (k) 31st December, 2013 respectively.

Table 1. Correlation coefficient between IRI-TEC and GPS-TEC values for the selected days.

DATE	NEQUICK	IRIR-CORR	IRI2001
31-01-2013	0.9064	0.9093	0.9182
28-02-2013	0.9090	0.9201	0.9262
30-03-2013	0.8492	0.8464	0.8681
30-04-2013	0.9027	0.9167	0.9185
31-05-2013	0.9153	0.9298	0.9209
30-06-2013	0.8876	0.8941	0.9022
15-07-2013	0.9433	0.9507	0.9527
30-09-2013	0.7259	0.7556	0.7314
31-10-2013	0.8164	0.8344	0.8267
30-11-2013	0.7721	0.7701	0.7804
31-12-2013	0.8301	0.8276	0.8449

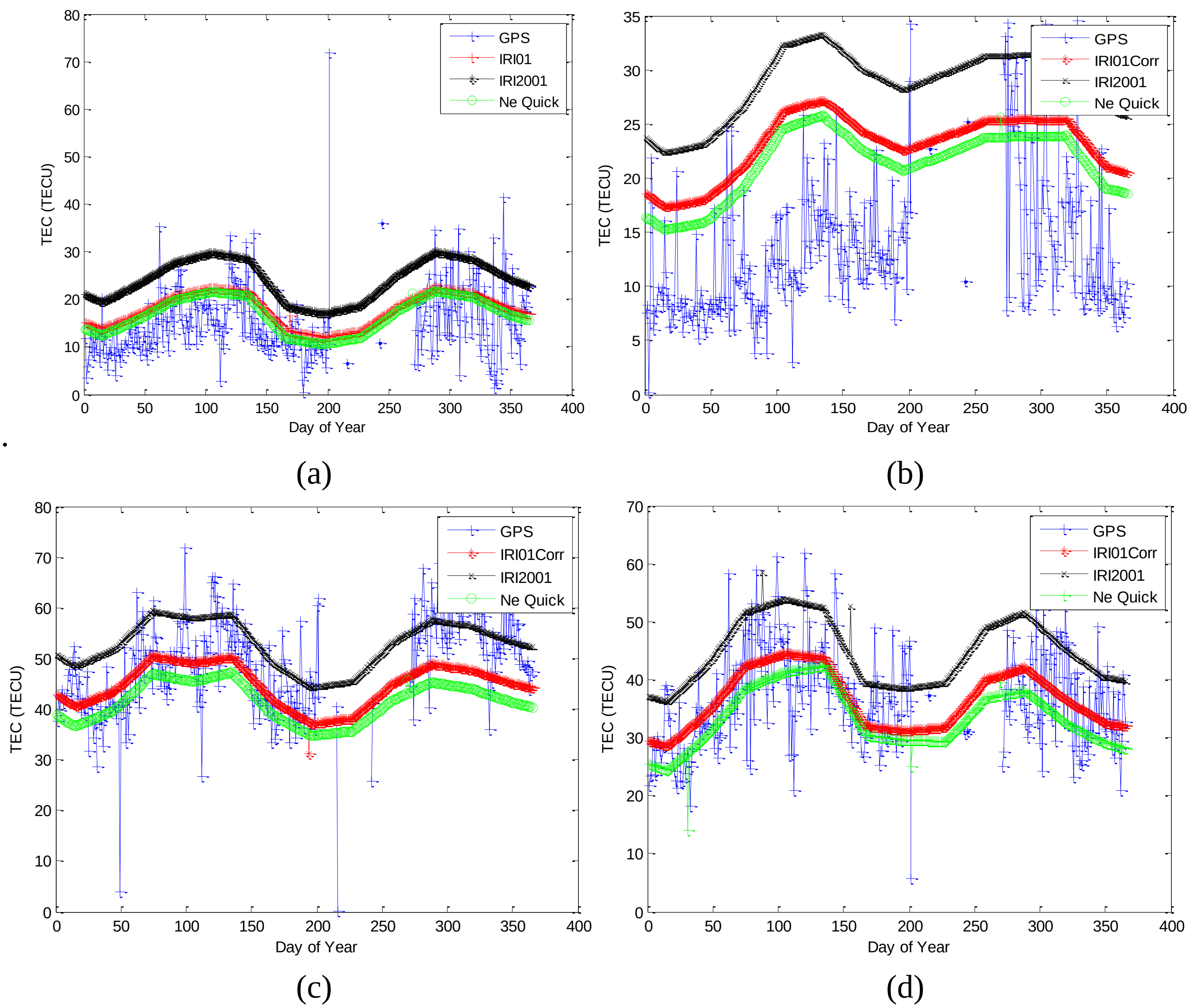

Figure 2. Plots of annual GPS TEC and IRI model-predicted TEC values at (a) dawn (0006 UT), (b) mid-day (0011 UT), (c) dusk (1700 UT), and (d) mid-night (230 UT).

Table 2. Root-mean-square deviations (RMSD) and the percent root-mean-square deviations (%RMSD) of the IRI-TEC values from the GPS-TEC values for the selected days.

DATE	NEQUICK		IRIR-CORR		IRI2001	
	RMSD	%RMSD	RMSD	%RMSD	RMSD	%RMSD
31-01-2013	5.2999	19.9851	6.2789	23.6765	11.5565	43.5775
28-02-2013	7.3087	20.6698	5.9431	16.8077	8.3159	23.5185
30-03-2013	11.0681	27.0243	10.2400	25.0024	10.8203	26.4194
30-04-2013	13.9794	29.0312	12.1752	25.2845	8.4172	17.4801
31-05-2013	9.0299	32.6372	10.0105	36.1815	16.3050	58.9320
30-06-2013	6.6095	26.3548	7.5029	29.9172	12.5642	50.0987
15-07-2013	6.7959	21.6342	5.7754	18.3857	6.5918	20.9846
30-09-2013	11.6912	28.9990	10.2469	25.4165	10.5464	26.1594
31-10-2013	11.1859	28.7743	10.1419	26.0888	12.2925	31.6210
30-11-2013	9.5605	30.8683	10.2936	33.2353	14.7048	47.4779
31-12-2013	10.8569	31.2400	9.7409	28.0288	9.9601	28.6596

Table 3a. Hourly correlation coefficients between the three topside IRI models and the GPS TEC values for all days of the year.

Hour of Day (h) (UT)	NeQuick	IRI-Corr	IRI2001
0000	0.4752	0.4669	0.3654
0001	0.5745	0.4451	0.5124
0002	0.4871	0.3652	0.4432
0003	0.4118	0.4121	0.5423
0004	0.3184	0.3322	0.3141
0005	0.3451	0.3114	0.3031
0006	0.4472	0.4031	0.4004
0007	0.4443	0.4231	0.4021
0008	0.3619	0.3442	0.3002
0009	0.3536	0.3033	0.3422
0010	0.4316	0.3561	0.3432
0011	0.4761	0.4031	0.3566
0012	0.5449	0.4643	0.4052
0013	0.5514	0.4231	0.4112
0014	0.5205	0.5001	0.4811
0015	0.5028	0.4821	0.4636
0016	0.5433	0.5134	0.4734
0017	0.5768	0.5233	0.4831
0018	0.5380	0.4922	0.4634
0019	0.3516	0.4641	0.4421
0020	0.2793	0.3221	0.2111
0021	0.2875	0.2331	0.2112
0022	0.4939	0.3521	0.3212
0023	0.6038	0.4331	0.3421

GNSS Reference NETwork (NIGNET) project, in the Office of the Surveyor General of Nigeria for providing the GPS data used in this work. In addition, many thanks to Dr. Gopi K. Seemala of the Indian Institute of Geomagnetism (IIG), Navi Mumbai, India for granting access to the GPS TEC analysis software, and to Dieter Bilitza and the IRI group for making the IRI models available.

Table 3b. Hourly root-mean-square and percent root-mean-square deviations of the three topside IRI models from the GPS TEC values.

Hour of Day (h) (UT)	RMSD (TECU)			%RMSD		
	NeQuick	IRI-Corr	IRI2001	NeQuick	IRI-Corr	IRI2001
0000	5.0319	4.8657	11.0087	32.1584	32.7684	66.8520
0001	5.3351	4.9928	10.6251	35.2033	41.0155	62.2942
0002	4.4911	5.0341	10.3066	39.3356	30.0192	60.3066
0003	4.9887	5.6233	9.4713	48.6620	37.9702	54.3419
0004	3.8250	4.4552	9.9588	49.3649	85.2613	46.1253
0005	3.9894	7.4513	10.5655	51.6724	250.5456	261.5541
0006	10.3365	12.0562	16.3274	67.03020	145.3765	166.5432
0007	12.0146	13.1743	9.4133	52.5505	14.7605	34.8791
0008	9.9077	11.6663	10.9099	32.2139	66.2947	81.2625
0009	8.0719	9.3127	14.7795	21.2570	35.3078	38.9446
0010	7.6371	8.1547	13.1394	17.5131	12.9752	30.0404
0011	8.9553	8.2341	11.6982	18.6940	13.7043	24.5801
0012	11.1803	10.4351	10.1019	21.9548	15.8754	19.9325
0013	13.0539	13.5522	11.4356	24.7725	14.4346	22.1344
0014	13.5847	12.8713	14.2133	25.5500	15.0739	34.5412
0015	13.2616	13.2655	12.3244	25.3512	15.2567	34.8972
0016	11.5831	10.8831	9.8723	23.6539	17.2121	24.5666
0017	9.4125	9.2167	11.4471	21.5588	22.7922	32.6678
0018	6.9231	6.0771	10.4372	19.3595	36.0679	30.5521
0019	7.1642	6.3361	9.0244	25.0521	44.1609	23.4324
0020	8.8882	9.2723	13.6733	33.3567	43.8653	36.8961
0021	8.3262	6.0231	11.3833	31.2783	39.6856	22.0133
0022	7.1092	7.9951	15.7726	27.9865	36.2154	38.6783
0023	6.6456	7.2133	12.45621	28.3545	36.2311	25.6581

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