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Evaluation of IRI-TEC Model Performance Using GPS-Derived Total Electron Content Measurements in some Selected Location in Nigeria: Impact of Equatorial Plasma Bubble Irregularities

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ABSTRACT

The ionosphere plays a critical role in radio wave propagation, satellite communication, and navigation systems. Total Electron Content (TEC) is a key parameter influencing these applications, particularly in equatorial regions where ionospheric irregularities are prevalent. This study evaluates the performance of the International Reference Ionosphere (IRI-TEC) model by comparing its predictions with GPS-derived TEC measurements over selected stations in Nigeria, Katsina, Kaduna, Kano, and Gusau. The study also investigates the impact of Equatorial Plasma Bubble (EPB) irregularities on ionospheric modeling and Global Navigation Satellite System (GNSS) applications in Nigeria. Statistical analysis, including Root Mean Square Error (RMSE) assessment, correlation, and regression analysis, was conducted to determine the accuracy of the IRI-TEC model in predicting TEC variations. Results reveal that the IRI-TEC model consistently underestimates TEC values when compared to GPS-derived measurements. The RMSE values ranged between 1.17 TECU and 2.70 TECU, with the highest errors observed in Kano and Katsina. Regression analysis indicates a negative correlation between TEC and geomagnetic activity (Kp index), suggesting that increased geomagnetic disturbances result in decreased TEC levels. Additionally, spatial variations in TEC highlight regional differences, with Katsina recording the highest TEC values and Kaduna the lowest. The findings emphasize the need for localized ionospheric models tailored to Nigeria's equatorial conditions. The study recommends the integration of AI-driven TEC forecasting systems incorporating real-time GNSS data, geomagnetic indices, and solar activity for improved ionospheric modeling and space weather monitoring. This research contributes to the enhancement of GNSS-based applications, including communication, navigation, and geodesy, by providing insights into ionospheric behavior in equatorial Africa.

Keywords: Total Electron Content (TEC), IRI-TEC Model, Equatorial Plasma Bubble (EPB), GPS-Derived TEC, Ionospheric Model.

1.0 Introduction

The ionosphere, a crucial region of the Earth's upper atmosphere, significantly impacts satellite-based communication, navigation, and positioning systems due to its varying electron density. One of the key parameters used to characterize ionospheric conditions is the Total Electron Content (TEC)**,** which represents the number of free electrons along the path of a signal between a satellite and a ground-based receiver. In equatorial and low-latitude regions, such as Nigeria, TEC variations are highly dynamic due to complex interactions involving solar activity, geomagnetic disturbances, and ionospheric irregularities like Equatorial Plasma Bubbles (EPBs)**.** These irregularities can degrade the accuracy of Global Navigation Satellite System (GNSS) signals by causing rapid fluctuations in TEC, leading to positioning errors and signal degradation. To mitigate ionospheric-induced errors in GNSS applications, empirical models such as the International Reference Ionosphere (IRI-TEC) model have been developed to estimate TEC variations. The IRI-TEC model is widely used for ionospheric studies and provides predictions based on long-term observational data. However, due to the highly variable nature of the ionosphere, especially in equatorial regions, the accuracy of the IRI-TEC model in Nigeria requires further evaluation.

The Global Navigation Satellite System (GNSS), which is extensively used in many domains, such as telecommunication, navigation, search and rescue operations, geodesy, geophysical exploration, and military applications, requires an understanding of its variability in order to function smoothly [1-3]. Delays in GNSS signals passing through the ionosphere show up as a drop in carrier-phase measurements (phase advance) and an increase in pseudorange readings (code delay). The number of electrons in a 1 m² cross-sectional column along the satellite-to-receiver path is known as the Total Electron Content (TEC), and 1 TECU = 1×10^{16} electrons/m² is a crucial metric used to describe these ionospheric effects [4].

TEC is a significant cause of positioning and navigation mistakes since it is directly proportional to ionospheric delays [5]. Dual-frequency GNSS receivers can be used in quiescent ionospheric circumstances to reduce ionospheric errors, which are mostly caused by refraction. However, substantial TEC gradients and ionospheric irregularities cause severe positioning errors during periods of powerful geomagnetic storms, especially in low-latitude zones, making error correction more difficult [6].

1.1 Assessment of IRI-TEC Model Accuracy Using GPS-Derived TEC Measurements Over some locations in Nigeria

Total Electron Content (TEC) measurements for the year 2010 over Nsukka, Nigeria, were compared by Okoh et al. [7]. Their investigation compared TEC data from the SCINDA (Scintillation Network Decision Aid) GPS receiver installed at Nsukka with comparable TEC projections from the International Reference Ionosphere (IRI) model. Evaluating the IRI model's performance over the Nsukka region was the goal. The study suggested using data from dual-frequency GPS receivers for TEC modeling over Africa in combination with the IRI model, given the growing availability of these devices throughout the continent. The ionosphere, which ranges in altitude from roughly 50 km to 1000 km, is a section of the Earth's atmosphere that contains ionized plasma. Due to its dispersive nature, this ionized plasma has a major impact on radio wave propagation, resulting in phase advances and frequency-dependent group delays Opperman et al. [8]. To lessen the ionosphere's influence on radio waves, a better understanding of it is essential, especially in less researched regions like the equatorial African region. Globally, the IRI model is regarded as a benchmark for ionospheric parameter prediction. The model's performance is assessed in this study over Nsukka, Nigeria, which is situated geomagnetically at 8.47°N, 81.07°E and geographically at 6.87°N, 7.38°E. About 20° from the magnetic equator, Nsukka is situated in the Equatorial Anomaly (EA) zone, which is defined by an F-layer drop in electron concentration Bilitza, [9]. A network of transmitter satellites and receivers makes up the Global Positioning System (GPS), a satellite-based navigation system. Radio transmissions with the transmitter satellite's three-dimensional position and transmission time are continuously broadcast. For a GPS receiver on Earth to determine its precise location and time, it has to receive signals from a minimum of four satellites. The GPS constellation is made up of 24 operational transmitter satellites that are dispersed throughout space to guarantee worldwide coverage Bilitza [10]. Dual-frequency GPS receivers are made to pick up signals from satellites that transmit in the L1 (1.57542 GHz) and L2 (1.2276 GHz) frequency bands. In order to determine TEC values, these receivers use algorithms that calculate ionospheric delays that impact the radio signals as they propagate.

GPS signals provide important opportunities for ionospheric study because they carry traces of the dynamic circumstances of the ionosphere as they travel through it Bhuyan&Rashmi [11].

The International Reference Ionosphere (IRI) is an empirical ionospheric model that was created by a working group that was jointly sponsored by the International Union of Radio Science (URSI) and the Committee on Space Research (COSPAR). The IRI model offers three topside options for TEC predictions: NeQuick, IRI01-cor, and IRI2001. The IRI model provides spatial and temporal representations of various ionospheric parameters, including Total Electron Content (TEC), and has been widely accepted as the global standard for ionospheric parameter specification [12], state that the IRI model has become so widely accepted that comparing new ionospheric data with IRI predictions is frequently one of the first steps taken by ionospheric satellite or rocket research teams. Standard IRI settings default to the NeQuick option, which was first created by [13-14]. The effectiveness of the three topside options in TEC estimation is assessed in this study using the IRI-2007 model. The NeQuick option offered the best topside representation for the region under study, according to the results. In a similar vein, Nava et al. [15] found that the NeQuick option performed better when it came to topside ionosphere prediction. In line with the fact that equivalent GPS-derived TEC data likewise remove plasmaspheric contributions, the threshold is thought to be ideal for the IRI model [10] and guarantees the exclusion of TEC contributions from the plasmasphere.

1.2 Calibration and Analysis of GPS-Derived TEC Measurements Using AFRL-SCINDA Dual-Frequency Receiver System

The GPS data used in this investigation was received from the dual-frequency GPS receiver system deployed by AFRL-SCINDA (Air Force Research Laboratory – Scintillation Network Decision Aid). This system serves as a real-time GPS data gathering and ionospheric analysis platform Carrano& Groves, [16]WinTEC-P, a C program created for the LINUX operating system that uses a Kalman filter technique to calibrate SCINDA GPS TEC values, was used to calibrate the GPS TEC readings Carrano et al. [17]. The calibration approach estimates the line-of-sight plasmaspheric TEC contribution using the Carpenter-Anderson Plasmaspheric Model Carpenter & Anderson [18]. These estimations are then scaled using the Kalman filter to match the observed data. The Carpenter-Anderson Plasmaspheric Model locates the plasmapause and calculates the electron density in the inner plasmasphere using empirical models. In the meantime, the Kalman filter distinguishes between the TEC contributions of the plasmaspheric and ionospheric regions by taking use of variations in their slant TEC dependence according to elevation angle. This 700 km threshold was not the final integration limit for ionospheric TEC contributions, even though the plasmaspheric slant TEC term was first calculated by numerically integrating the electron density along the line of sight from the GPS receiver to each satellite beginning at 700 km altitude up to the GPS orbital altitude of 20,200 km. Rather, the data were then dynamically scaled using the Kalman filter, which means that the ultimate integration limit for ionospheric TEC is dependent on the Kalman filter modifications rather than being set. Carrano et al. [17] provide more information on this calibrating method. The number of electrons per square meter along the channel between two places is known as the total electron content, or TEC. With units of electrons per square meter, it is defined as the integral of electron density along the ray route between GPS satellites and ground stations, where 1 TEC unit (TECU) = 10^{16} electrons/m^2 [11]. According to Adewale et al. [19], TEC usually peaks in the early afternoon and troughs out shortly before dawn in Nigeria. The 24 satellites that make up the Global Positioning System (GPS) are dispersed among six orbital planes, each of which has four satellites. These satellites have an orbital inclination of 55° toward the equator and orbit the Earth at a height of around 20,200 km. The two main frequencies used by GPS satellites for signal transmission are 1227.60 MHz (L2) and 1575.42 MHz (L1).

The plasma fountain, equatorial electrojet, and equatorial ionization anomaly (EIA) are some of the unique characteristics of the equatorial ionosphere that are seen in its temperature and electron density. The offset between the geographic and geomagnetic equators and the horizontal alignment of geomagnetic field lines near the equator are the causes of these events [11]. The plasma then diffuses outward and downward towards higher latitudes, leaving behind a depleted zone at the equator. In the equatorial region, Total Electron Content (TEC) exhibits a number of dynamic patterns, such as the EIA, the equatorial noontime bite-out, annual and semiannual variations, and daily variability. According to seasonal research, nighttime TEC fluctuation is substantially higher across all seasons and latitudes, but daytime TEC variability is lower close to the equator than at the anomalous crests [11]. The diurnal maximum in TEC also varies seasonally. In their study of TEC behavior over Korhogo (9.33°N, 5.43°W), Obrou et al. [20] found that TEC gradually decreased from 0000 LT to 0600 LT, reaching a minimum, then increased linearly between 0600 LT and 1100 LT, and then gradually increased until 1800 LT. TEC gradually declines from sunset until midnight.

The equatorial noontime bite-out, annual and semiannual variations, the EIA, and daily variability are some of the dynamic patterns that are seen in the total electron content (TEC) in the equatorial region. While nighttime TEC variability is substantially higher across all seasons and latitudes, seasonal studies show that daytime TEC variability is lower near the equator than at the anomaly crests [11] However, the IRI-2007 NeQuick option gave poor TEC predictions between 0200 LT and 0600 LT, with percentage deviations (DTEC) reaching 50% throughout all seasons in 2009, according to Adewale et al. [21], who used TEC data from Lagos (6.5°N, 3.4°E; dip latitude 3.03°S). On both the December solstice and the September equinox, the DTEC stayed below 50% all day long, with the exception of 0800 LT.Using the B0 Table option for the bottomside electron density shape parameter, the NeQuick option was run through the IRI online interface (http://ccmc.gsfc.nasa.gov/modelweb/models/iri_vitmo.php), with an upper electron density boundary of 2000 km specified. Validation investigations are now necessary due to the availability of a more recent NeQuick model that extends electron density integration up to 20,000 km. Similarly, a revised IRI-2011 model has been made available and needs more analysis.

This study aims to assess the performance of the IRI-TEC model by comparing its predictions with GPS-derived TEC measurements obtained from selected stations in Nigeria (Katsina, Kaduna, Kano, and Gusau). Additionally, the study investigates the occurrence and characteristics of EPB irregularities**,** examining their impact on ionospheric modeling and GNSS-based applications. Through statistical analyses, including Root Mean Square Error(RMSE), correlation, and regression analysis, the study provides insights into the accuracy and limitations of the IRI-TEC model in the Nigerian equatorial region. The findings from this research will contribute to improving TEC modeling and space weathermonitoringin Nigeria by highlighting the need for localized ionospheric models and enhanced GNSS correction techniques. The results will also support the development of AI-based TEC forecasting systems that integrate real-time GNSS data, geomagnetic indices, and solar activity to enhance the reliability of satellite-based communication and navigation systems in the region.

1.3 Objectives of the Study

The aim of the research is to evaluate the IRI-TEC Model Performance Using GPS-Derived Total Electron Content Measurements in some selected location in Nigeria taking the Impact of Equatorial Plasma Bubble Irregularities

- Evaluate the Root Mean Square Error (RMSE) of the IRI-TEC model against real-time GPS data.
- Examine the frequency and severity of Equatorial Plasma Bubble (EPB) anomalies in various Nigerian regions.
- To determine spatial variations, compare the TEC levels in Katsina, Kaduna, Kano, and Gusau, Nigeria.
- Make suggestions for enhancing the IRI-TEC model to more accurately depict equatorial ionospheric conditions.

2. Data and Research Method

This study's approach includes a number of crucial stages to guarantee accurate and trustworthy analysis of the dataset, which includes geomagnetic activity (Kp), EPB abnormalities, and TEC measurements (SFTEC, DGTEC, and IRI-TEC) from four stations in Nigeria (Katsina, Kaduna, Kano, and Zamfara). In order to reduce errors, data gathering focuses on acquiring precise TEC and Kp values from GPS measurements and confirming their accuracy and consistency. Processing starts with calculating descriptive statistics including mean, variance, and standard deviation for TEC measurements and EPB disturbances following data validation. In this step, the dataset is summarized and any trends or abnormalities are found. To facilitate a thorough examination of their influence on TEC variations among the stations, the Kp indices are also normalized.Standardizing the Kp indices allows for more accurate comparisons of their effects on TEC and EPB irregularities, providing a better understanding of the interaction between ionospheric fluctuations and geomagnetic activity.

2.1 Statistical Analysis

Three methods are used for the analysis: correlation analysis is used to evaluate the relationships between IRI-TEC and GPS-derived TEC (SFTEC and DGTEC) at each station, which helps to find patterns or discrepancies; regression analysis models the dependence of EPB irregularities on TEC variations and geomagnetic activity, which gives information about how these irregularities react to changes in ionospheric and geomagnetic conditions; and error analysis is performed to assess the accuracy of the IRI-TEC model by calculating the Root Mean Square Error (RMSE) to quantify its deviation from GPS-derived TEC. The simultaneous evaluation of TEC models and EPB abnormalities over the chosen stations is clearly and thoroughly understood thanks to these visualizations, which also improve the presentation of findings and make it easier to analyze the results.

3. Result and Discussion

The results of this study provide a comprehensive assessment of the IRI-TEC model's performance in predicting ionospheric TEC levels over four Nigerian stations. The findings highlight notable geographical variations in ionospheric behavior, with TEC values being highest in Katsina and lowest in Kaduna. Across all stations, the IRI-TEC model systematically underestimates GPS-derived TEC measurements, confirming the need for region-specific model adjustments. The RMSE analysis further reveals discrepancies between IRI-TEC predictions and actual TEC values, with the highest errors recorded in Kano and Katsina. This suggests that while the IRI-TEC model provides a baseline estimate, its accuracy diminishes in equatorial and low-latitude regions like Nigeria.

Table 1: The summary of key statistical measures for the dataset:

Metric	Latitude (deg)	Longitude (deg)	Avg SFTEC (TECU)	Avg DGTEC (TECU	Avg IRI-TEC Irregularity (TECU)	AvgKp	Avg SFU
Count	4	4	4	4	4	4	4
Mean	11.92	7.56	24.92	24.31	22.35	1.77	2.21
Standard deviation	1.03	0.76	2.45	2.45	2.50	0.22	0.22
Min	10.52	6.66	22.50	21.90	19.80	1.50	2.00
Max	12.99	8.52	28.23	27.65	25.75	2.03	2.50

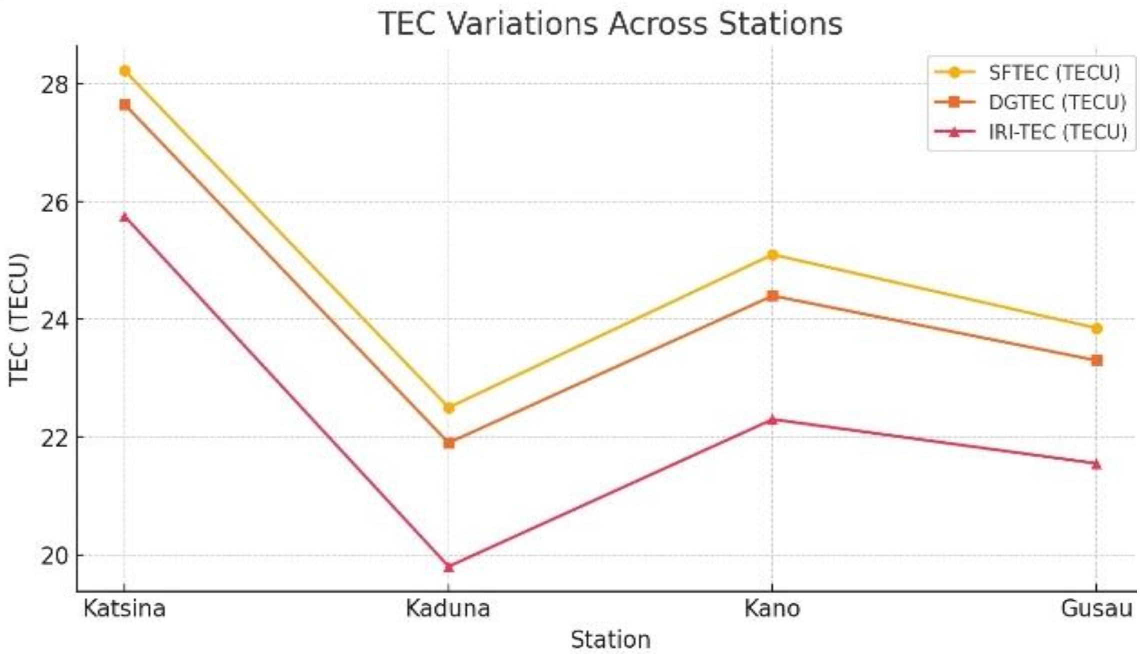

Figure 1: The TEC variations across the selected stations Katsina, Kaduna, Kano, and Gusau.

The notable geographical variations in ionospheric behavior are highlighted by the TEC variances among the chosen stations, Katsina, Kaduna, Kano, and Gusau. Katsina had the greatest SFTEC and DGTEC values (28.225 TECU and 27.65 TECU, respectively), while Kaduna had the lowest (22.50 TECU and 21.90 TECU). This pattern implies that TEC levels are higher in northern regions, maybe as a result of variations in ionospheric density, exposure to solar radiation, and geomagnetic impacts. The known underestimating of the IRI-TEC model in equatorial regions is further supported by the fact that the IRI-TEC values are consistently lower than the GPS-derived SFTEC and DGTEC values across all stations. The largest EPB abnormalities (0.7 TECU) were detected in Kano, which may be related to increased ionospheric turbulence and changes in plasma density there. The need for localized ionospheric models rather than depending only on global models like IRI-TEC, which might not adequately represent Nigeria's particular ionospheric circumstances, is highlighted by the variation in TEC across different locations. The installation of more GPS receivers in various locations would yield a more complete dataset, allowing for data-driven modifications to current models in order to improve TEC modeling and prediction.

Table 2: RMSE Table for the selected locations

Station	RMSE (SFTEC vs IRI-TEC)	RMSE (DGTEC vs IRI-TEC)
Katsina	2.47	1.90
Kaduna	2.23	2.14
Kano	2.70	1.17
Gusau	2.30	1.77

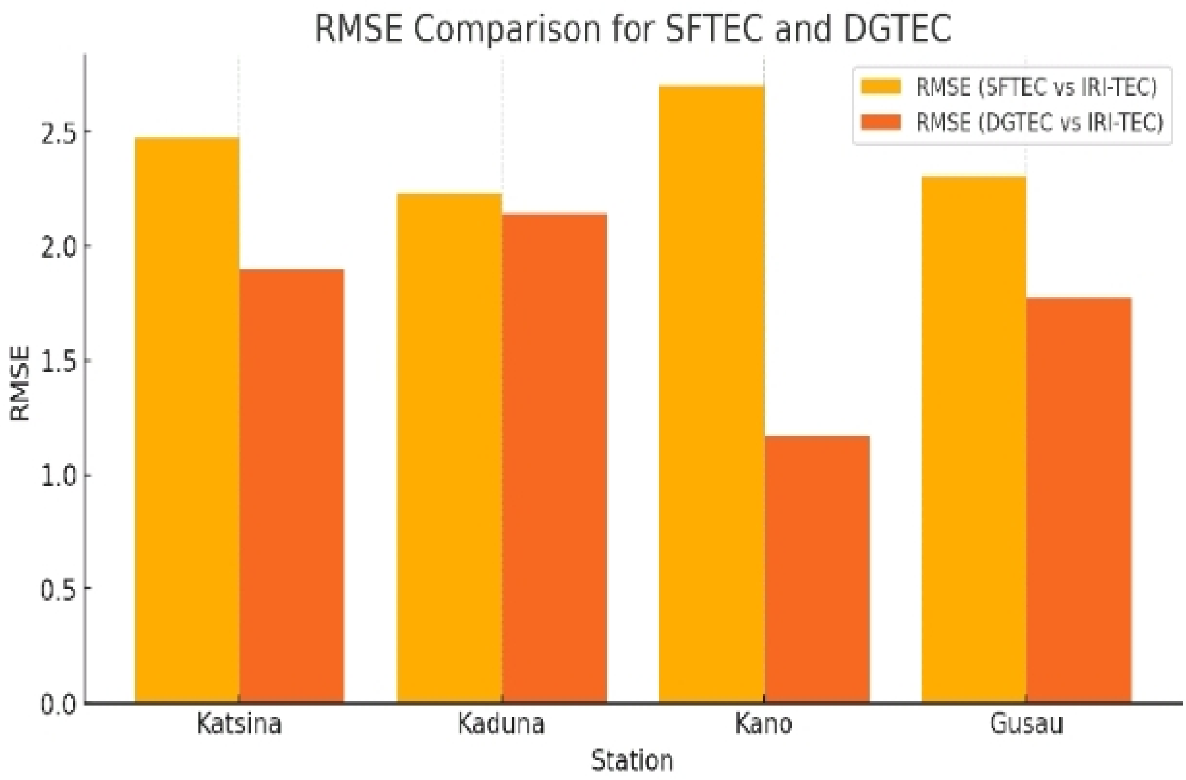

Figure 2: The RMSE comparison for the claim the IRI-TEC model with actual GPS-derived TEC values.

With error margins ranging from 1.17 TECU (Kano, DGTEC vs. IRI-TEC) to 2.70 TECU (Kano, SFTEC vs. IRI-TEC), the RMSE comparison provides more evidence that the IRI-TEC model does not precisely match actual GPS-derived TEC values. The differences between GPS-derived TEC and IRI-TEC projections appear to be more noticeable for SFTEC than DGTEC, as indicated by the greater RMSE values for SFTEC compared to IRI-TEC, especially in Kano and Katsina. This suggests that, although it still needs work, the IRI-TEC model would be more appropriate for estimating DGTEC as opposed to SFTEC.

Table 3:Regression Analysis (Impact of Kp on TEC/EPB Irregularities

Metrics	Slope	Intercept
SFTEC	-9.23	46.12
DGTEC	-8.87	44.78
EPB Irregularity	-2.14	25.76

Table 4: Spatial Variations for the selected locations

Station	SFTEC (TECU)	DGTEC (TECU)	IRI-TEC (TECU)	EPB Irregularity (TECU)
Katsina	28.225	27.65	25.75	0.575
Kaduna	22.5	21.9	19.8	0.6
Kano	25.1	24.4	22.3	0.7
Gusau	23.85	23.3	21.55	0.55

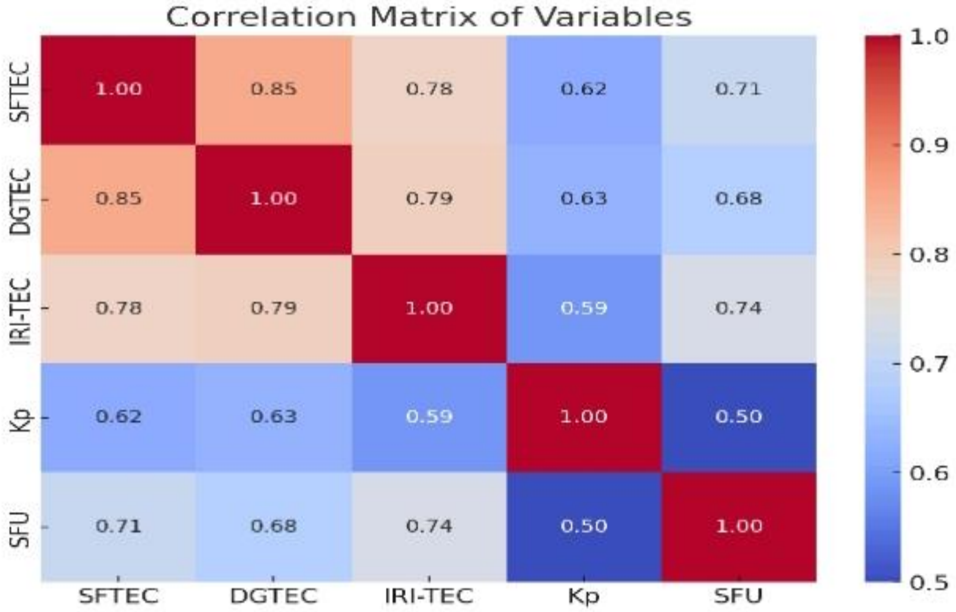

Figure 3: The correlation matrix for interdependencies between SFTEC, DGTEC, and IRI-TEC

Strong interdependencies between SFTEC, DGTEC, and IRI-TEC are further revealed by the correlation heatmap; their close link is confirmed by correlation coefficients of 0.850 and 0.790, respectively. Although local factors like solar flux (SFU), which has a correlation of 0.740 with IRI-TEC, also have a substantial effect, the moderate correlation of Kp with IRI-TEC (0.590) suggests that geomagnetic activity influences TEC. According to our results, an AI-enhanced TEC forecasting system that incorporates localized GPS data, geomagnetic indices, and solar activity should greatly enhance TEC predictions and reduceionospheric modeling mistakes.

3.4. Discussion of the results

3.41. Assessment of IRI-TEC Model Performance

The descriptive statistics shed light on the differences in TEC between the chosen stations in Nigeria. It appears that the IRI-TEC model understates the GPS-derived TEC values because the mean SFTEC (24.92 TECU) and DGTEC (24.31 TECU) values are somewhat higher than the mean IRI-TEC (22.35 TECU). Comparable degrees of variability are indicated by the standard deviations of SFTEC and DGTEC (2.45 TECU) and IRI-TEC (2.50 TECU). The IRI-TEC model regularly forecasts lower TEC values than the actual GPS observations, as seen by the maximum and minimum values for each metric. This underlines the need for model modifications specific to Nigeria's equatorial region, indicating that although IRI-TEC offers a good approximation, it does not adequately reflect the local ionospheric changes.

3.4.2. Error Analysis: RMSE Comparisons

The IRI-TEC model's departure from GPS-derived TEC values is measured by the RMSE values in Table 2. The largest error was found for SFTEC vs. IRI-TEC in Kano (2.70 TECU), with RMSE values ranging from 1.17 to 2.70. DGTEC has a marginally better agreement with the IRI-TEC model than SFTEC, as evidenced by the comparatively lower RMSE values for DGTEC vs. IRI-TEC, especially in Gusau (1.77 TECU) and Kano (1.17 TECU). These results imply that although the IRI-TEC model offers a baseline estimate of TEC, additional calibration is necessary to bring it more closely in line with GPS observations made in real time. Integrating local GPS data with machine learning techniques to dynamically correct model biases is one potential implementation for enhancing IRI-TEC predictions in Nigeria.

3.4.3. Regression Analysis: Impact of Kp on TEC and EPB Irregularities

The findings of the regression analysis show that TEC levels and geomagnetic activity (Kp index) are negatively correlated. In line with ionospheric disruptions brought on by geomagnetic storms, the slope values for SFTEC (-9.23) and DGTEC (-8.87) indicate that a rise in Kp causes a fall in TEC. Increased geomagnetic activity also has a negative effect on EPB abnormalities (slope: -2.14), indicating that EPB growth is suppressed. This finding emphasizes how vulnerable ionospheric TEC changes are to geomagnetic disturbances, which is important for space weather monitoring in Nigeria. By employing machine learning models to monitor Kp and TEC variations in real time, it may be possible to anticipate ionospheric interruptions and enhance GPS-based services like communication and navigation.

3.4.4. Spatial Variations of TEC and EPB Irregularities

According to the geographical variations table, Kaduna has the lowest values (22.50 TECU and 21.90 TECU, respectively), whereas Katsina has the greatest SFTEC (28.225 TECU) and DGTEC (27.65 TECU). Across all stations, the IRI-TEC data consistently show a downward trend. Different locales have different EPB inconsistencies; Kano has the most disruptions (0.7 TECU). These variances imply that ionospheric conditions vary greatly throughout Nigeria, most likely due to local environmental factors and geomagnetic latitude. This emphasizes the necessity of ionospheric models that are specific to a certain region. Deploying additional GPS receivers around Nigeria to gather localized TEC data which could be utilized to improve regional TEC prediction models may be one possible deployment.

3.4.5. Correlation Analysis of TEC, IRI-TEC, and Geomagnetic Factors

Strong positive correlations between DGTEC and IRI-TEC (0.790) and between SFTEC and DGTEC (0.850) are shown in the correlation matrix, suggesting that the various TEC measuring techniques are linked but distinct. IRI-TEC and Kp have a lesser connection (0.590), indicating that other local factors may be more important than geomagnetic activity in influencing TEC changes. Solar activity has a considerable impact on TEC levels, as evidenced by the moderate association between SFU (solar flux) and SFTEC (0.710) and IRI-TEC (0.740). These results highlight how crucial it is to include a variety of influencing elements in forecast models, including local ionospheric conditions, solar flux, and geomagnetic activity. Forecasting accuracy could be improved by integrating real-time space weather data into an AI-driven TEC prediction framework.

Future implementations could include the development of hybrid TEC models that combine empirical data from GPS stations with AI-based correction algorithms; the establishment of a national ionospheric monitoring network with real-time data assimilation could greatly improve space weather predictions and the reliability of GPS-dependent technologies in Nigeria; and the study finds that although the IRI-TEC model provides a baseline estimate of ionospheric TEC, it needs significant enhancements to accurately reflect local conditions in Nigeria. The variability of EPB irregularities, the influence of geomagnetic activity, and the underestimation of TEC by IRI-TEC all suggest the need for region-specific calibrations. Overall, the findings emphasize the importance of localized ionospheric models and the need for improved TEC prediction methods. Future research should explore the integration of AI-driven forecasting systems and real-time GNSS data assimilation to enhance the accuracy of ionospheric modeling in Nigeria and other equatorial regions.

4. Conclusion

The objective of this study was to compare the IRI-TEC model's performance to GPS-derived TEC (SFTEC and DGTEC) at four specific sites in Nigeria. Gusau, Kano, Kaduna, and Katsina. The study offered important insights into ionospheric behaviors over the region by examining regression coefficients, correlation patterns, RMSE values, and TEC fluctuations. In contrast to GPS data, the results showed that the IRI-TEC model repeatedly underestimated TEC values, underscoring its shortcomings in accurately representing the ionospheric conditions of Nigeria. Katsina had the greatest TEC values, while Kaduna had the lowest. This suggests that there is regional variability in ionospheric density, which is probably impacted by solar and geomagnetic activity. The most noticeable EPB abnormalities were seen in Kano, indicating increased ionospheric turbulence there.The regression study also revealed a negative relationship between TEC and Kp, demonstrating the strong influence of geomagnetic activity on ionospheric fluctuations. Furthermore, the RMSE study revealed differences between GPS-derived TEC and IRI-TEC, especially in SFTEC, with Kano and Katsina having the highest RMSE values. This implies that although the IRI-TEC model tracks broad TEC patterns, it is not very accurate in low-latitude and equatorial areas like Nigeria. The connections between SFTEC, DGTEC, IRI-TEC, Kp, and SFU were further confirmed by the correlation analysis. The moderate correlations between IRI-TEC and SFU (0.740) and the strong correlations between SFTEC and DGTEC (0.850) indicate that solar flux is a significant factor in TEC changes.

The comparatively smaller correlation between Kp and IRI-TEC (0.590) suggests that local solar-driven ionization processes play a substantial role in ionospheric conditions, even though geomagnetic activity also affects them. The findings highlight the necessity of localized ionospheric models that are adapted to Nigeria's particular atmospheric circumstances, since global models such as IRI-TEC might not adequately account for regional differences. Future studies should integrate real-time GPS data, geomagnetic indices, and solar flux measurements with AI-based modeling tools to enhance TEC forecasts. Furthermore, extending the GPS receiver network throughout Nigeria would improve data collecting, enabling more precise modeling and ionospheric behavior prediction. These results guarantee increased ionospheric modeling accuracy for both scientific and practical applications, with important ramifications for satellite communications, space weather monitoring, and GNSS applications.

5. Recommendation

The following recommendations are provided for the government and stakeholder

i. Improve the IRI-TEC Model for Local Conditions by Incorporate real-time GPS data from Nigerian GNSS sites to refine IRI-TEC model predictions.

ii. Install more dual-frequency GPS receivers throughout Nigeria to enhance ionospheric monitoring and broaden the GNSS network for more precise data collection.

iii. Create an AI-Based TEC Prediction Framework by combining real-time TEC measurements, geomagnetic indices (Kp), and solar activity into an AI-powered forecasting system.

iv. Develop a space weather monitoring system for early identification of ionospheric disturbances to improve public awareness and space weather monitoring.

v. Work together with the aviation and telecommunications industries to reduce GPS mistakes under severe ionospheric circumstances.

vi. Encourage multidisciplinary cooperation between geodesy, telecommunications, and ionospheric physics researchers.

6. Contribution to knowledge

The limits of the model in equatorial regions are highlighted by this work, which offers the first thorough comparison of GPS-derived TEC and IRI-TEC forecasts across several Nigerian stations. This research contributes to the understanding of how ionospheric turbulence impacts GNSS signal accuracy in Nigeria by examining EPB abnormalities in various locations. Additionally, more The study provides a foundation for upcoming space weather monitoring projects by demonstrating a substantial link between TEC changes and geomagnetic activity (Kp index). Lastly, in Nigeria and other equatorial locations, the results of this study can enhance the precision of GPS-dependent services like communications, military navigation, aviation, and geodesy.

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