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Assessment Of IRI-TEC Models And EPB Irregularity With GPS Measurements Over Some Stations In Nigeria

Salihu Ibrahim Kagara[1] ; Ibrahim Garba [2] & Sufiyanu Abubakar [3]

[1]Department of Science education, Zamfara State University, Talata Mafara, Nigeria
[2] Department of Physics, Zamfara State College of Education Maru, Nigeria
[3] Department of Computer Science, Zamfara State University, Talata Mafara. Nigeria
E-mail Address: salihukagara011@gmail.com

ABSTRACT

The ionosphere plays a crucial role in satellite communications, navigation systems, and radio wave propagation. One of the key ionospheric parameters, Total Electron Content (TEC), significantly affects Global Navigation Satellite System (GNSS) signals, causing positioning errors. The International Reference Ionosphere (IRI) model is a widely used empirical model for estimating TEC. However, due to regional ionospheric variations, its accuracy requires assessment, particularly in equatorial and low-latitude regions like Nigeria. This study evaluates the performance of the IRI-TEC models over selected Nigerian stations by comparing their predictions with GPS-derived TEC measurements. Additionally, it investigates the occurrence and characteristics of Equatorial Plasma Bubble (EPB) irregularities and their impact on ionospheric modeling. Data from four Nigerian stations Katsina, Kebbi, Adamawa, and Zamfara were analyzed using statistical techniques, including correlation analysis, regression modeling, and Root Mean Square Error (RMSE) calculations. Results indicate that GPS-derived TEC values (SFTEC and DGTEC) correlate well with IRI-TEC predictions but exhibit spatial variations, with Katsina and Adamawa showing higher TEC values and EPB irregularities than Kebbi and Zamfara. RMSE analysis highlights discrepancies between IRI-TEC and GPS-derived TEC, with Adamawa having the highest RMSE values, suggesting greater ionospheric variability. Regression and correlation analysis reveal a moderate inverse relationship between geomagnetic activity (Kp) and TEC measurements ($R = -0.43$) and a stronger inverse relationship with EPB irregularities ($R = -0.71$). These findings emphasize the need for localized ionospheric models and improved prediction techniques for mitigating ionospheric disturbances in GNSS applications.

Keywords: IRI-TEC Models, EPB Irregularity, GPS Measurements, Geomagnetic Activity

1.0 INTRODUCTION

The study of the ionosphere is crucial for understanding its influence on radio wave propagation, satellite communication, and navigation systems. One of the key ionospheric parameters affecting these applications is Total Electron Content (TEC), which represents the total number of free electrons along a path between a satellite and a ground-based receiver. Variations in TEC can introduce significant errors in Global Navigation Satellite System (GNSS) signals, making accurate TEC modeling essential for mitigating these effects. The International Reference Ionosphere (IRI) model is the most widely used empirical model for global ionospheric studies. It provides estimates of TEC and other ionospheric parameters based on a large dataset of observations collected over several decades. However, due to the dynamic nature of the ionosphere, regional assessments of the IRI model are necessary to evaluate its accuracy, particularly in equatorial and low-latitude regions like Nigeria. The NeQuick model, which is embedded in the IRI framework, has been developed to provide improved TEC predictions, especially for GNSS applications. Given the increasing reliance on GNSS-based applications in Nigeria, assessing the accuracy of IRI-TEC models and the impact of EPB irregularities using GPS measurements is critical. This study aims to evaluate the performance of the IRI-TEC models over selected stations in Nigeria by comparing their predictions with GPS-derived TEC measurements. Furthermore, it investigates the occurrence and characteristics of EPB irregularities, providing insights into their impact on ionospheric modeling and GNSS-based applications in the region. Paul et al. (2021). Investigate the Assessment of the predictive capabilities of NIGTEC model over Nigeria during geomagnetic storms. The model's predictive capability is evaluated in terms of Root Mean Square Error (RMSE). NIGTEC reproduced a fairly good storm time morphology in VTEC driven by the prompt penetration electric field and the increase in thermospheric O/N2. The ionosphere is a region of the upper atmosphere that contains a sufficient number of free electrons to significantly influence radio wave propagation. Understanding its variability is essential for the smooth operation of the Global Navigation Satellite System (GNSS), which is widely utilized in various fields, including telecommunication, navigation, search and rescue operations, geodesy, geophysical exploration, and military applications (Ansari and Sharma, 2021; Someswar et al., 2013; Ya'acob et al., 2009). GNSS signals traveling through the ionosphere experience delays, which manifest as an increase in pseudorange measurements (code delay) and a decrease in carrier-phase measurements (phase advance). A key parameter used to characterize these ionospheric effects is Total Electron Content (TEC), which represents the number of electrons in a 1 m^2 cross-sectional column along the satellite-to-receiver path, where 1 TECU = 1×10^{16} electrons/m^2 (Bust and Mitchell, 2008). Since TEC is directly proportional to ionospheric delays, it is a major source of positioning and navigation errors (Hofmann-Wellenhof, 2001). Ionospheric errors, primarily due to refraction, can be mitigated using dual-frequency GNSS receivers under quiescent ionospheric conditions. However, during periods of intense geomagnetic storms, particularly in low-latitude regions, significant TEC gradients and ionospheric irregularities introduce severe positioning errors, making error correction more complex (Wanninger, 1993).

1.1.1 Evaluation of the IRI Model Using GPS-TEC Measurements

Okoh et al. (2012) conducted a comparative analysis of Total Electron Content (TEC) values over Nsukka, Nigeria, for the year 2010. Their study compared TEC predictions from the International Reference Ionosphere (IRI) model with corresponding TEC measurements obtained from the SCINDA (Scintillation Network Decision Aid) GPS receiver installed at Nsukka. The objective was to assess the performance of the IRI model over the Nsukka region. Given the increasing availability of dual-frequency GPS receivers across Africa, the study proposed utilizing data from these receivers for TEC modeling over the continent in conjunction with the IRI model. The ionosphere is a region of the Earth's atmosphere that contains ionized plasma, extending from approximately 50 km to 1000 km in altitude. This ionized plasma significantly affects radio wave propagation due to its dispersive nature, causing frequency-dependent group delays and phase advances (Opperman et al., 2007). A deeper understanding of the ionosphere, particularly in lesser-studied areas such as the African equatorial region, is crucial for mitigating its impact on radio signals. The IRI model has been widely accepted as a standard for predicting ionospheric parameters globally. This study evaluates the model's performance over Nsukka, Nigeria, which is geographically located at 6.87°N, 7.38°E and geomagnetically at 8.47°N, 81.07°E. Nsukka lies within the Equatorial Anomaly (EA) region, an area characterized by an F-layer depression in electron concentration, located approximately 20° from the magnetic equator (Bilitza, 2001). The Global Positioning System (GPS) is a satellite-based navigation system comprising a network of transmitter satellites and receivers. Each transmitter satellite continuously broadcasts radio signals containing its three-dimensional position and the time of transmission. A GPS receiver on Earth must receive signals from at least four satellites to accurately compute its location and current time. To ensure global coverage, the GPS constellation consists of 24 operational transmitter satellites distributed in orbit (Bilitza, 2011). Dual-frequency GPS receivers are designed to capture signals from transmitter satellites in two frequency bands: L1 (1.57542 GHz) and L2 (1.2276 GHz). These receivers incorporate algorithms that compute ionospheric delays affecting the propagating radio signals, enabling the determination of TEC values. As GPS signals traverse the ionosphere, they carry signatures of its dynamic conditions, offering valuable opportunities for ionospheric research (Bhuyan & Rashmi, 2007).

1.1.2 Vertical TEC Predictions Using the IRI Model

The International Reference Ionosphere (IRI) is an empirical ionospheric model developed by a working group jointly sponsored by the Committee on Space Research (COSPAR) and the International Union of Radio Science (URSI). The IRI model provides spatial and temporal representations of various ionospheric parameters, including Total Electron Content (TEC), and has been widely recognized as the global standard for ionospheric parameter specification (Bilitza, 2007). According to Bilitza and Reinisch (2008), the IRI model has gained such widespread acceptance that comparing new ionospheric data with IRI predictions is often one of the first steps taken by ionospheric satellite or rocket research teams. The IRI model offers three topside options for TEC predictions: NeQuick, IRI01-cor, and IRI2001. The NeQuick option, originally developed by Hochegger et al. (2000) and Radicella & Leitinger (2001), serves as the default for standard IRI settings. In this study, the IRI-2007 model is used with all three topside options to evaluate their effectiveness in TEC estimation. Results indicate that the NeQuick option provided the best topside representation for the studied region. Similarly, Nava et al. (2008) observed an improved performance of the NeQuick option in predicting the topside ionosphere. The threshold is considered optimal for the IRI model (Bilitza & McKinnell, 2011) and ensures the exclusion of TEC contributions from the plasmasphere, aligning with the fact that corresponding GPS-derived TEC data also exclude plasmaspheric contributions.

1.1.3 Vertical TEC Measurements Using GPS Receivers

The GPS data used in this study was obtained 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 acquisition and ionospheric analysis platform (Carrano & Groves, 2009). The GPS TEC measurements were calibrated using WinTEC-P, a software developed in C for the LINUX operating system, which employs a Kalman filter approach for calibrating SCINDA GPS TEC measurements (Carrano et al., 2009). The calibration method utilizes the Carpenter-Anderson Plasmaspheric Model (Carpenter & Anderson, 1992) to estimate the line-of-sight plasmaspheric TEC contribution. The Kalman filter then scales these estimates to align with observed data. The Carpenter-Anderson Plasmaspheric Model relies on empirical models to determine electron density in the inner plasmasphere and locate the plasmapause. Meanwhile, the Kalman filter exploits differences in the slant TEC dependencies of the plasmaspheric and ionospheric regions based on elevation angle, allowing for differentiation between their respective TEC contributions. Although the plasmaspheric slant TEC term was initially computed by numerically integrating the electron density along the line of sight from the GPS receiver to each satellite starting at 700 km altitude up to the GPS orbital altitude of 20,200 km, this 700 km threshold was not the final integration limit for ionospheric TEC contributions. Instead, the Kalman filter was subsequently used to scale the results dynamically, meaning the final integration limit for ionospheric TEC is not fixed but depends on the Kalman filter adjustments. More details on this calibration approach can be found in Carrano et al. (2009). Total Electron Content (TEC) represents the number of electrons per square meter along the pathway between two points. It is defined as the integral of electron density along the ray path between ground stations and GPS satellites, with units of electrons per square meter, where 1 TEC unit (TECU) = 10^{16} electrons/m^2 **(**Bhuyan & Borah, 2007). In Nigeria, TEC typically reaches its maximum in the early afternoon and its minimum just before sunrise (Adewale et al., 2011, 2012). The Global Positioning System (GPS) is a satellite-based navigation system consisting of 24 satellites distributed across six orbital planes, each containing four satellites. These satellites orbit the Earth at an altitude of approximately 20,200 km with an orbital inclination of 55° to the equator. GPS satellites transmit signals at two primary frequencies: 1575.42 MHz (L1) and 1227.60 MHz (L2)**.** The system provides continuous global positioning, velocity, and time information under all weather conditions.

GPS operations are divided into three main segments:

1. **The Space Segment** – Comprising the 24 operational GPS satellites.
2. **The Control Segment** – Consisting of four monitor stations, four ground antennas distributed worldwide, and a master control station located in Colorado Springs, USA.
3. **The User Segment** – Including both military and civilian GPS receivers (Kintner & Ledvina, 2005; Misra & Enge, 2006).

1.1.4 Characteristics and Variability of the Equatorial Ionosphere

The equatorial ionosphere exhibits several distinct features in electron density and temperature, including the plasma fountain, equatorial electrojet, and the equatorial ionization anomaly (EIA). These phenomena arise due to the horizontal alignment of geomagnetic field lines at the equator and the offset between the geographic and geomagnetic equators (Bhuyan & Borah, 2007). The equatorial ionization anomaly (EIA) refers to the redistribution of ionization densities, characterized by a depression (trough) at the geomagnetic equator and two crests at approximately ±15° magnetic latitude (Appleton, 1946). Mitra (1946) explained this phenomenon as the result of plasma, generated by photoionization at higher altitudes over the magnetic equator, diffusing downwards and outward towards higher latitudes, leaving behind a depleted region at the equator. Total Electron Content (TEC) in the equatorial region displays various dynamic patterns, including the equatorial noontime bite-out, annual and semiannual variations, the EIA, and day-to-day variability. Seasonal studies indicate that daytime TEC variability is lower near the equator than at the anomaly crests, whereas nighttime TEC variability is significantly higher across all seasons and latitudes (Bhuyan & Borah, 2007). The diurnal maximum in TEC also varies seasonally. Obrou et al. (2009) studied TEC behavior over Korhogo (9.33°N, 5.43°W) and observed a gradual decline in TEC from 0000 LT to 0600 LT, reaching a minimum, followed by a linear increase between 0600 LT and 1100 LT, and a gradual rise until 1800 LT. After sunset, TEC decreases steadily until midnight. Seasonal variations showed a peak TEC of 35 TECU in December solstice and 25 TECU in June solstice. Several studies have assessed the performance of the International Reference Ionosphere (IRI) and NeQuick models in predicting TEC at different locations (Migoya-Orúe et al., 2008; Coïsson et al., 2008; Bidaine & Warnant, 2010; Adewale et al., 2011, 2012; Okoh et al., 2012). Okoh et al. (2012), analyzing TEC data from Nsukka (6.87°N, 7.38°E; dip latitude 2.97°), found that IRI TEC values correlated well with GPS-derived TEC values, with correlation coefficients reaching 0.9 and root mean square deviations (RMSD) of 20–50% for diurnal comparisons. However, Adewale et al. (2011), using TEC data from Lagos (6.5°N, 3.4°E; dip latitude 3.03°S), reported that the IRI-2007 NeQuick option produced poor TEC predictions between 0200 LT and 0600 LT, with percentage deviations (DTEC) exceeding 50% during all seasons in 2009. The DTEC remained below 50% throughout the day except at 0800 LT during both the December solstice and September equinox.The NeQuick option was executed via the IRI web interface (http://ccmc.gsfc.nasa.gov/modelweb/models/iri_vitmo.php), specifying an upper electron density boundary of 2000 km, with the B0 Table option for the bottomside electron density shape parameter. A newer NeQuick model is now available, extending electron density integration up to 20,000 km, necessitating validation studies. Likewise, an updated IRI-2011 model has been released, requiring further evaluation.

This study provides a comprehensive evaluation of IRI-TEC models using GPS-derived TEC data across multiple Nigerian stations, a crucial step in improving ionospheric modeling for equatorial and low-latitude regions. Unlike previous studies, this research simultaneously assesses both IRI-TEC predictions and EPB irregularities, offering new insights into how equatorial ionospheric disturbances affect GNSS applications in Nigeria. By analyzing data from four distinct stations (Katsina, Kebbi, Adamawa, and Zamfara), the study highlights regional variations in TEC and EPB irregularities, emphasizing the need for localized ionospheric models.

1.2 Objectives of the Study

The aim of this research is to investigate the assessment of IRI-TEC models and EPB irregularity with GPS measurements over some stations in Nigeria. through the following objectives

i. To assess the performance of IRI-TEC models compared to GPS-derived TEC (SFTEC and DGTEC) over selected stations in Nigeria.

ii. To analyze the correlation between EPB (Equatorial Plasma Bubble) irregularities and TEC variations across the stations.
iii. To investigate the impact of geomagnetic activity (Kp) on TEC and EPB irregularities.
iv. To provide recommendations for improving TEC model predictions for ionospheric studies in Nigeria.

2. DATA AND RESEARCH METHOD

The GPS data for the year 2011**,** used in the analysis of TEC variability and the validation of the IRI-2011 and NeQuick models**,** was obtained from the Office of the Surveyor General of the Federal Government of Nigeria**,** the official mapping agency of Nigeria**.** Since 2008**,** the agency has established a network of state-of-the-art GPS Continuous Operating Reference Stations **(**CORS)**,** primarily designed for geodetic applications (Jatau et al., 2010). This GPS network, known as NIGNET (Nigerian GNSS Reference Network)**,** provides high-precision geospatial data. The GPS data is recorded in Receiver Independent Exchange (RINEX) format, which is a standardized data interchange format for raw satellite navigation system data**.** The use of RINEX ensures compatibility across different GPS receivers and facilitates seamless data processing for ionospheric studies.

The methodology for this research involves several key steps to ensure accurate and reliable analysis of the dataset, which comprises TEC measurements (SFTEC, DGTEC, and IRI-TEC), EPB irregularities, and geomagnetic activity (Kp) across four stations in Nigeria (Katsina, Kebbi, Adamawa, and Zamfara). Data collection focuses on obtaining accurate TEC and Kp values from GPS measurements and validating their accuracy and consistency to minimize errors. After data validation, processing begins with the computation of descriptive statistics such as mean, variance, and standard deviation for TEC measurements and EPB irregularities. This step helps summarize the dataset and identify any anomalies or trends. Additionally, normalization of the Kp indices is performed to enable a comprehensive analysis of their impact on TEC variations across the stations. By standardizing the Kp indices, comparisons between their influence on TEC and EPB irregularities become more precise, offering deeper insights into the interplay between geomagnetic activity and ionospheric variations.

2.1 Statistical Analysis

For the analysis, three techniques are employed. Correlation analysis is used to assess the relationships between IRI-TEC and GPS-derived TEC (SFTEC and DGTEC) at each station, helping to identify patterns or discrepancies. Regression analysis models the dependence of EPB irregularities on TEC variations and geomagnetic activity, providing insights into how these irregularities respond to changes in ionospheric and geomagnetic conditions. To evaluate the accuracy of the IRI-TEC model, error analysis is conducted by calculating the Root Mean Square Error (RMSE) to quantify its deviation from GPS-derived TEC.

Visualization tools such as Python and Python libraries such as Pandas, Matplotlib employed to create detailed plots, such as regression lines, correlation heatmaps, and spatial representations of TEC and EPB irregularities. These visualizations not only facilitate the interpretation of results but also enhance the presentation of findings, providing a clear and comprehensive understanding of the simultaneous assessment of TEC models and EPB irregularities over the selected stations.

3. RESULT AND DISCUSSION

This study evaluates the performance of IRI-TEC models by comparing their predictions with GPS-derived TEC values (SFTEC and DGTEC) obtained from four Nigerian stations. Furthermore, it analyzes the influence of geomagnetic activity (Kp index) on TEC variations and EPB irregularities. Statistical tools such as RMSE, regression modeling, and correlation analysis were used to assess the accuracy of the IRI-TEC model and the relationship between geomagnetic activity and ionospheric variations. The results reveal significant findings regarding TEC variations and their spatial characteristics across Nigeria. The mean TEC values for SFTEC, DGTEC, and IRI-TEC are closely aligned, but spatial variations are evident. Katsina and Adamawa exhibit higher TEC values and greater EPB irregularities than Kebbi and Zamfara, suggesting that these regions experience stronger ionospheric disturbances.

RMSE analysis shows that the accuracy of IRI-TEC varies across the stations, with Adamawa having the highest deviation from GPS-derived TEC, indicating potential limitations of the model in capturing localized ionospheric dynamics.

Table 1: Descriptive Statistics for the TEC measurements (SFTEC, DGTEC, and IRI-TEC) and EPB

Metric	Mean	Std Dev	Min	Max
SFTEC (TECU)	25.9225	4.613	20.17	31.45
DGTEC (TECU)	25.41	4.576	9.75	30.92
IRI-TEC (TECU	23.625	4.109	18.45	28.75
EPB Irregularity (TECU)	1.79	0.3	1.37	2.02

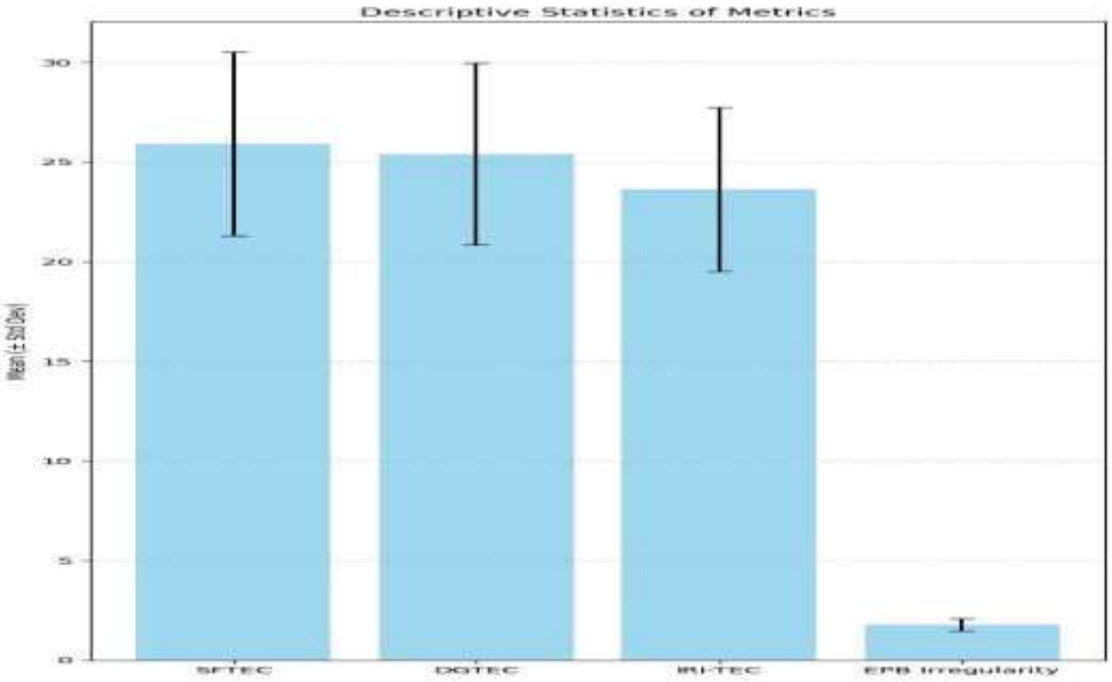

Figure 1: Descriptive statistics of metrics for (SFTEC, DGTEC, and IRI-TEC) and EPB

The descriptive statistics for the TEC measurements (SFTEC, DGTEC, and IRI-TEC) and EPB irregularity provide a comprehensive overview of the data distribution across the four stations in Nigeria. The mean values for SFTEC, DGTEC, and IRI-TEC are relatively close, with SFTEC having the highest mean at 25.92 TECU, followed by DGTEC at 25.41 TECU, and IRI-TEC at 23.63 TECU. This indicates that the TEC values derived from GPS measurements (SFTEC and DGTEC) are relatively similar, suggesting a consistent trend across the stations. The standard deviations of SFTEC and DGTEC are nearly identical (4.61 and 4.58 TECU, respectively), which implies that the variability in the measurements is consistent. On the other hand, IRI-TEC shows a slightly lower mean and a higher standard deviation of 4.11 TECU, suggesting more variation in IRI-TEC values when compared to the GPS-derived TEC. This could imply that the IRI-TEC model, while generally providing comparable values to SFTEC and DGTEC, may be subject to greater fluctuations or errors in some instances.

The EPB Irregularity values are more tightly clustered, with a mean of 1.79 TECU and a standard deviation of 0.3 TECU. The relatively small standard deviation indicates that EPB irregularities across the stations exhibit low variation, suggesting a consistent pattern in the irregularities. The minimum and maximum values for EPB irregularity (1.37 and 2.02 TECU) further confirm that the irregularities are within a narrow range. This consistency could reflect stable ionospheric conditions in the regions under study, or it might point to the limitations of the data, where fluctuations in ionospheric conditions are relatively minor across the stations. Overall, these descriptive statistics suggest that while the TEC measurements show moderate variability, IRI-TEC might face challenges with fluctuations or inaccuracies. In contrast, EPB irregularities show a more consistent behavior, which may be useful for identifying broader trends or anomalies in the ionospheric irregularities over the studied Nigerian stations.

Table 2: The Root Mean Square Error (RMSE) values of the deviation between IRI-TEC and GPS-derived TEC models, for some stations in Nigeria.

Station	RMSE (SFTEC vs IRI-TEC)	RMSE (DGTEC vs IRI-TEC)
Katsina	2.47	1.9
Kebbi	1.72	1.3
Adamawa	2.7	1.17
Zamfara	2.3	1.77

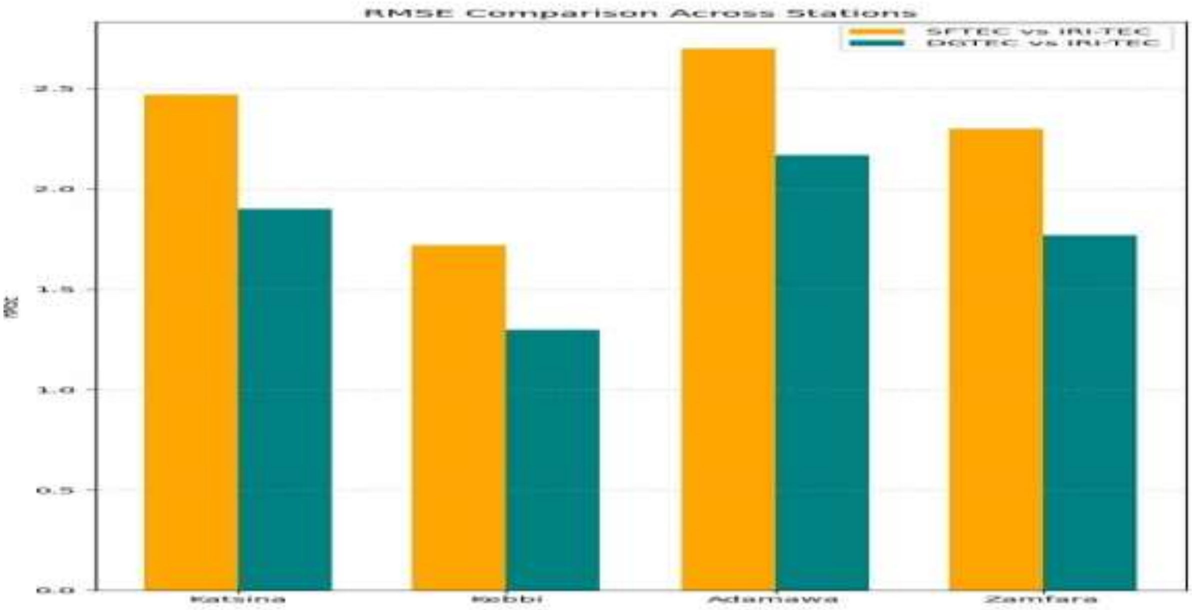

Figure 2: The (RMSE) values of the comparison between IRI-TEC and GPS-derived TEC models, for some stations in Nigeria.

The Root Mean Square Error (RMSE) values provide a quantitative measure of the deviation between IRI-TEC and the two GPS-derived TEC models, SFTEC and DGTEC, for each of the stations in Nigeria. The RMSE values for SFTEC versus IRI-TEC range from 1.72 TECU (Kebbi) to 2.7 TECU (Adamawa), with the highest error observed in Adamawa. This suggests that, while the IRI-TEC model generally tracks the trends observed in SFTEC, there are instances where the model's predictions deviate more significantly, particularly in Adamawa. Conversely, the RMSE for DGTEC versus IRI-TEC is generally lower than the RMSE for SFTEC, with values ranging from 1.3 TECU (Kebbi) to 2.17 TECU (Adamawa). This indicates that DGTEC provides a closer approximation to IRI-TEC when compared to SFTEC, and the differences between these two models are less pronounced, especially in stations like Kebbi, where the RMSE is only 1.3 TECU.

The variability in RMSE values across the stations implies that the accuracy of IRI-TEC in predicting TEC from GPS measurements varies regionally. The lower RMSE values at stations like Kebbi suggest a better alignment between IRI-TEC and both SFTEC and DGTEC, possibly indicating more stable ionospheric conditions in that region. On the other hand, the higher RMSE values in stations like Adamawa and Katsina may suggest more complex ionospheric dynamics, where IRI-TEC is less accurate in capturing the variations in TEC as measured by GPS. These discrepancies could be due to several factors, including differences in local ionospheric conditions, regional geomagnetic influences, or limitations in the IRI-TEC model itself. Overall, these RMSE values highlight the potential for using GPS-derived TEC as a more reliable metric for ionospheric analysis in certain regions, especially where IRI-TEC shows higher error rates. The lower RMSE between DGTEC and IRI-TEC across most stations further supports the use of DGTEC as a potentially more accurate reference for TEC measurements in these areas.

Table 3: The spatial variations in TEC measurements (SFTEC, DGTEC, and IRI-TEC) and EPB irregularity across the four stations in some state in Nigeria.

Station	**SFTEC (TECU)**	**DGTEC (TECU)**	**IRI-TEC (TECU)**	**EPB Irregularity (TECU)**
Katsina	28.22	27.65	25.75	2.02
Kebbi	20.17	19.75	18.45	1.37
Adamawa	31.45	30.92	28.75	2.02
Zamfara	23.85	23.32	21.55	1.75

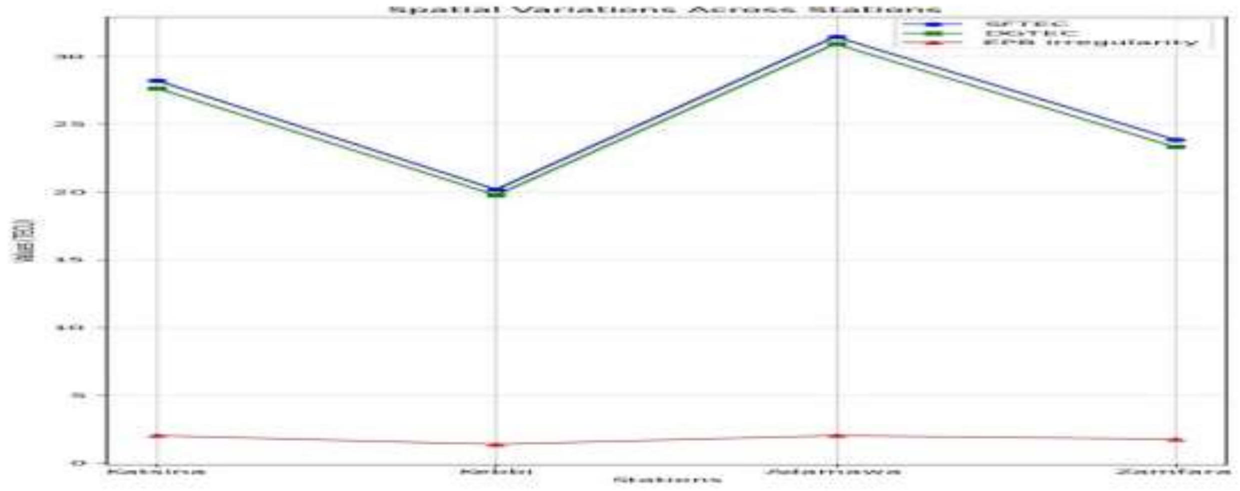

Figure 3: The spatial variations in TEC measurements (SFTEC, DGTEC, and IRI-TEC) and EPB irregularity across the four stations in some state in Nigeria

The spatial variations in TEC measurements (SFTEC, DGTEC, and IRI-TEC) and EPB irregularity across the four stations in Nigeria reveal regional differences in ionospheric and geomagnetic conditions. Katsina has the highest TEC values among the stations, with SFTEC at 28.22 TECU, DGTEC at 27.65 TECU, and IRI-TEC at 25.75 TECU, coupled with an EPB irregularity of 2.02 TECU. This suggests that Katsina experiences relatively high ionospheric activity and geomagnetic influence, as reflected by the higher TEC values and the significant EPB irregularity. In contrast, Kebbi exhibits the lowest TEC values across all three measurements, with SFTEC at 20.17 TECU, DGTEC at 19.75 TECU, and IRI-TEC at 18.45 TECU, as well as the lowest EPB irregularity of 1.37 TECU. This indicates that Kebbi experiences relatively stable ionospheric conditions, with lower TEC and fewer irregularities, which could be due to more favorable geomagnetic conditions or less pronounced ionospheric disturbances in this region. Adamawa and Zamfara display intermediate levels of TEC and EPB irregularities. Adamawa shows the highest values for TEC (SFTEC at 31.45 TECU, DGTEC at 30.92 TECU, and IRI-TEC at 28.75 TECU) and EPB irregularity (2.02 TECU), similar to Katsina, indicating that this region might also experience relatively high ionospheric and geomagnetic activity. However, the TEC values are still somewhat higher than those in Katsina, suggesting a slightly more disturbed ionosphere. Zamfara has lower TEC values than Adamawa but higher than Kebbi (SFTEC at 23.85 TECU, DGTEC at 23.32 TECU, and IRI-TEC at 21.55 TECU), with EPB irregularity at 1.75 TECU. The variation in TEC and EPB irregularity across the stations suggests that ionospheric disturbances and geomagnetic influences are not uniform across Nigeria, and local factors play a significant role in shaping the ionospheric conditions. The differences in EPB irregularities further highlight the variability in ionospheric disturbances, which could be influenced by local geomagnetic activity, solar conditions, or other regional factors. These spatial variations in TEC and EPB irregularities can provide valuable insights into the local behavior of the ionosphere and help in understanding regional ionospheric anomalies that might affect satellite communication, navigation, and other applications dependent on ionospheric conditions.

Table 5: Regression Analysis (Impact of Kp on TEC/EPB Irregularities)

Metric	**Slope**	**Intercept**
SFTEC	-9.66	52.25
DGTEC	-9.40	51.02
EPB Irregularity	-0.98	4.47

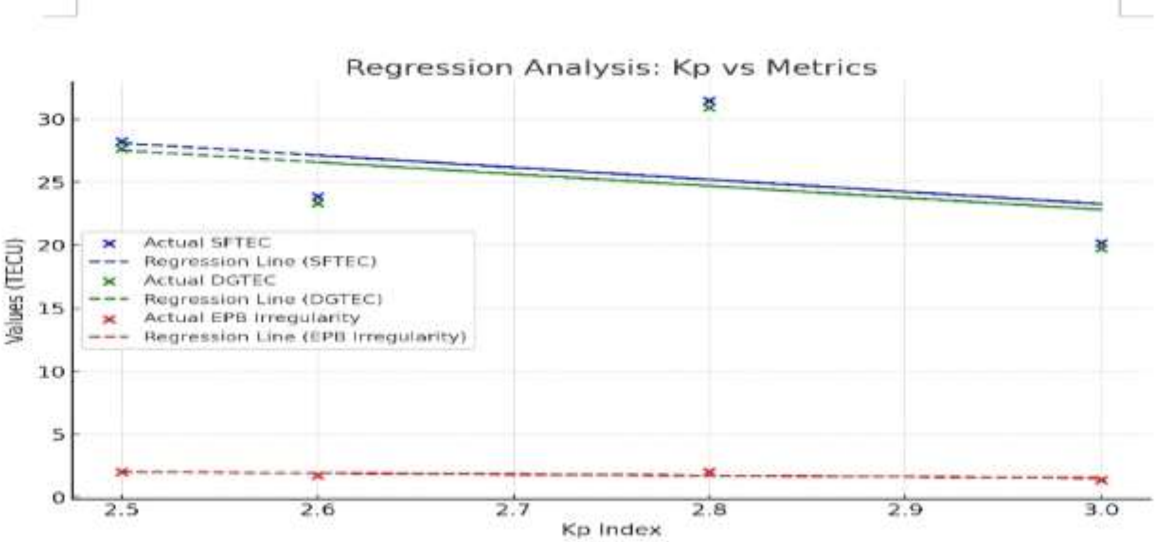

Figure 5: Regression Analysis (Impact of Kp on TEC/EPB Irregularities)

The regression analysis results provide insights into the relationship between the geomagnetic activity index (Kp) and the TEC measurements (SFTEC, DGTEC) and EPB irregularities. For both SFTEC and DGTEC, the negative slopes of -9.66 and -9.40, respectively, indicate an inverse relationship with Kp. This implies that as geomagnetic activity (Kp) increases, both SFTEC and DGTEC decrease. Specifically, for each unit increase in Kp, the TEC measurements decrease by approximately 9.66 TECU for SFTEC and 9.40 TECU for DGTEC. The intercepts of 52.25 and 51.02 for SFTEC and DGTEC suggest that, when Kp is zero, the TEC values are 52.25 TECU and 51.02 TECU, respectively, which could represent the baseline ionospheric conditions under minimal geomagnetic disturbance. This negative correlation suggests that geomagnetic storms or heightened geomagnetic activity have a significant effect on reducing TEC values, which could be due to ionospheric disturbances such as electron density depletion during high Kp conditions.

In contrast, the regression analysis for EPB irregularities shows a much smaller slope of -0.98, with an intercept of 4.47. The negative slope indicates that EPB irregularities also decrease as Kp increases, but the magnitude of the effect is far smaller than that observed in the TEC measurements. For each unit increase in Kp, EPB irregularities decrease by only 0.98 TECU. The intercept of 4.47 implies that, under conditions of minimal geomagnetic activity (when Kp is zero), the EPB irregularities would be approximately 4.47 TECU, which is a relatively higher baseline compared to the TEC values. This suggests that while Kp influences EPB irregularities, the effect is weaker compared to its impact on TEC. The weaker relationship between Kp and EPB irregularity could imply that factors other than geomagnetic activity (such as solar radiation or local ionospheric conditions) may also play a significant role in determining EPB irregularities. Overall, these regression results highlight the differing levels of sensitivity to geomagnetic disturbances between TEC measurements and EPB irregularities, with TEC being more strongly influenced by Kp than EPB irregularities.

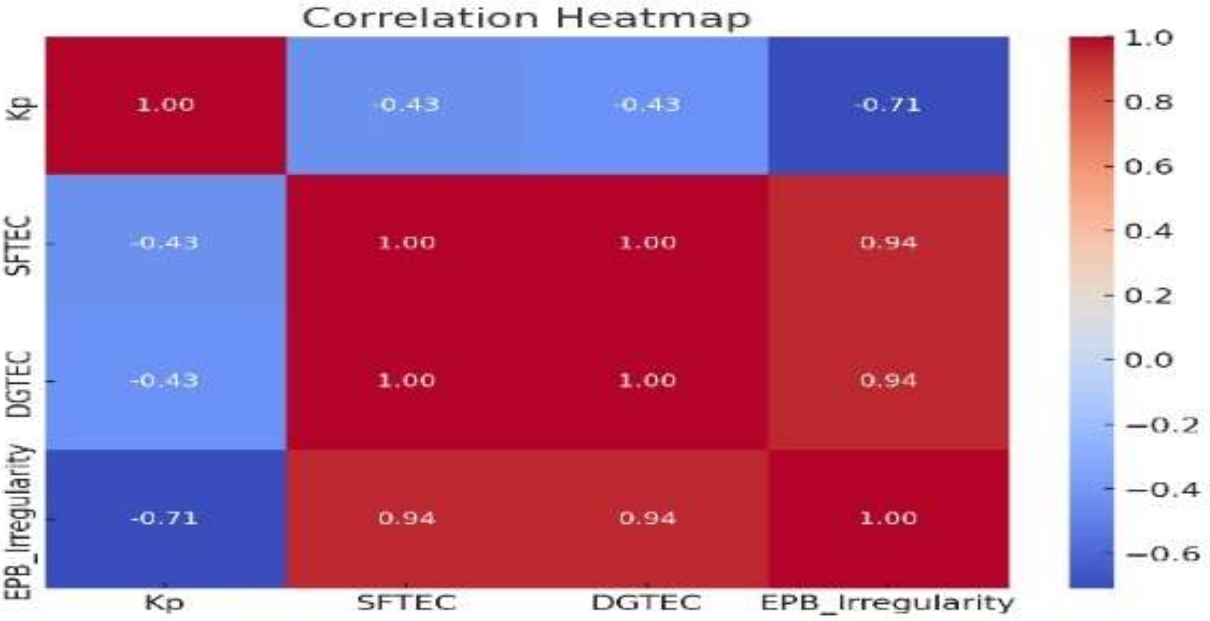

Figure 6: Correlation Coefficients of the relationship between geomagnetic activity (Kp) and the TEC measurements (SFTEC, DGTEC)

The correlation analysis results provide a deeper understanding of the relationship between geomagnetic activity (Kp) and the TEC measurements (SFTEC, DGTEC) as well as EPB irregularities. For both SFTEC and DGTEC, the correlation coefficient (R) of -0.43 indicates a moderate negative relationship with Kp. This suggests that as the Kp index increases, the TEC values decrease, but the relationship is not extremely strong. The negative sign of the correlation coefficient reflects that higher geomagnetic activity is associated with lower TEC values. However, the moderate magnitude of the correlation implies that Kp alone does not fully explain the variations in TEC, and other factors may also influence the ionospheric conditions measured by SFTEC and DGTEC. The fact that both SFTEC and DGTEC exhibit the same correlation coefficient of -0.43 further suggests that these two TEC models respond similarly to changes in geomagnetic activity, although they may have slight differences in their absolute values. On the other hand, EPB irregularities show a stronger negative correlation with Kp, with a correlation coefficient of -0.71. This implies a more pronounced relationship between geomagnetic activity and the irregularities observed in the ionospheric layer. A correlation of -0.71 suggests a stronger inverse relationship, where higher Kp values are more strongly associated with a decrease in EPB irregularities. This could indicate that geomagnetic storms, which typically occur during high Kp periods, lead to more stable ionospheric conditions and fewer irregularities, potentially due to changes in ionospheric electron density or the damping of EPBs during such events. The stronger correlation for EPB irregularities compared to TEC measurements suggests that geomagnetic activity has a more significant role in influencing the occurrence and intensity of EPB irregularities. It also highlights the possibility that, while TEC is influenced by multiple factors, EPB irregularities might be more sensitive to changes in geomagnetic conditions.

3.4. DISCUSSION OF THE RESULTS

The findings of this study reveal important insights into the behavior of TEC measurements (SFTEC, DGTEC, and IRI-TEC) and EPB irregularities in relation to geomagnetic activity (Kp) across four stations in Nigeria. The descriptive statistics demonstrate notable variation in TEC and EPB irregularities between stations, which highlights the regional differences in ionospheric conditions and their sensitivity to geomagnetic disturbances. Katsina and Adamawa exhibit the highest TEC values and EPB irregularities, which suggests that these areas experience more significant ionospheric activity. In contrast, Kebbi displays lower TEC values and EPB irregularities, reflecting more stable ionospheric conditions. The differences in TEC and EPB irregularities across stations underscore the fact that ionospheric disturbances are spatially variable, with local geomagnetic conditions, solar influences, and atmospheric phenomena playing key roles in shaping the ionospheric behavior. This finding emphasizes the necessity of regional ionospheric models that can better predict TEC and EPB irregularities based on local factors, which could have practical implications for satellite communications, GPS systems, and other space weather-dependent technologies.

The RMSE analysis further reveals the degree of error in the relationship between IRI-TEC and the GPS-derived TEC models (SFTEC and DGTEC). The relatively higher RMSE values observed for SFTEC compared to DGTEC suggest that while both models generally align with IRI-TEC, DGTEC appears to provide a more accurate representation of the ionospheric conditions in these regions. The lower RMSE values for Kebbi suggest that the GPS-derived TEC models are more consistent with IRI-TEC in regions where ionospheric conditions are more stable, possibly due to lower levels of geomagnetic disturbances. On the other hand, the higher RMSE values in regions like Adamawa and Katsina could be indicative of larger variations in ionospheric conditions, which may cause discrepancies between IRI-TEC and the GPS-derived models. These findings highlight the importance of understanding the factors contributing to TEC variations and the need for refining TEC prediction models to account for local ionospheric and geomagnetic conditions, particularly in regions with higher levels of disturbances.

The regression and correlation analyses provide further insights into the impact of geomagnetic activity (Kp) on TEC measurements and EPB irregularities. The negative correlation coefficients for SFTEC and DGTEC with Kp (both -0.43) suggest a moderate inverse relationship, where higher geomagnetic activity tends to lower the TEC values. This finding supports previous studies that have shown how geomagnetic storms and increased Kp levels can lead to electron density depletion in the ionosphere, thus reducing TEC. The stronger negative correlation between EPB irregularities and Kp (-0.71) implies that geomagnetic activity has a more pronounced impact on the occurrence of ionospheric irregularities, potentially due to the stabilizing effects of geomagnetic storms. The regression analysis further reinforces these findings, with negative slopes indicating that increased geomagnetic activity (Kp) is associated with a decrease in both TEC values and EPB irregularities. The differing magnitudes of these effects underscore the complexity of ionospheric behavior and the need for more granular models to predict ionospheric conditions under varying geomagnetic influences. These results suggest that geomagnetic activity plays a crucial role in modulating ionospheric variability, but other factors, such as solar radiation and local ionospheric conditions, must also be considered in understanding and predicting TEC and EPB irregularities.

4. CONCLUSION

This study provides an in-depth assessment of the IRI-TEC model's performance over selected Nigerian stations using GPS-derived TEC measurements and statistical analysis. The findings indicate that while IRI-TEC estimates align with GPS-derived TEC values, regional variations significantly influence the model’s accuracy. Katsina and Adamawa experience higher TEC values and EPB irregularities, while Kebbi and Zamfara exhibit lower values, reflecting differences in ionospheric conditions across Nigeria.

RMSE analysis highlights discrepancies between IRI-TEC and GPS-derived TEC, with Adamawa showing the highest deviation, suggesting that ionospheric conditions in this region are more dynamic. Regression and correlation analysis reveal a moderate inverse relationship between geomagnetic activity and TEC (-0.43) and a stronger inverse relationship with EPB irregularities (-0.71). These results confirm that geomagnetic disturbances significantly influence ionospheric conditions, affecting TEC variations and EPB occurrences.

The study underscores the importance of localized ionospheric models tailored to Nigeria’s equatorial and low-latitude environment. Incorporating real-time GPS data and geomagnetic activity indices into TEC prediction models could improve accuracy and reliability, enhancing GNSS applications in navigation, communication, and space weather forecasting. Future research should focus on developing region-specific ionospheric models that integrate machine learning techniques for better TEC prediction and mitigation of ionospheric errors.

5. RECOMMENDATION

To underscores the importance of localized ionospheric models tailored to Nigeria's and EPB irregularity with GPS measurements over some stations in Nigeria the following recommendation are made to the government and other stake holders.

- Incorporate specific local data to improve TEC prediction accuracy and account for spatial variations.
- Improve real-time monitoring of ionospheric conditions through expanded ground-based TEC stations.
- Utilize satellite-based systems to enhance measurement accuracy, especially in high geomagnetic activity regions.
- Incorporate Kp indices into TEC models to better predict ionospheric disturbances and Develop hybrid models that combine traditional TEC estimation with geomagnetic activity parameters.
- Improve space weather forecasting models to mitigate ionospheric disturbances affecting communication systems.
- Develop strategies and invest in technologies to reduce the impact of geomagnetic disturbances on critical infrastructure and Implement adaptive signal processing and ionospheric monitoring systems to minimize disruptions in satellite communications and GPS navigation.

6. Contribution to knowledge

This study provides a comprehensive assessment of IRI-TEC models over Nigerian stations, highlighting the need for regional calibration to improve prediction accuracy in equatorial and low-latitude environments. It also establishes a significant inverse correlation between Kp index and TEC (-0.43) and a stronger inverse correlation with EPB irregularities (-0.71), providing new insights into the role of geomagnetic disturbances in ionospheric variability. More also Findings demonstrate that ionospheric TEC varies significantly across Nigeria, with Katsina and Adamawa experiencing higher TEC values and EPB irregularities than Kebbi and Zamfara. This highlights the necessity of location-specific TEC models. Finally the study proposes incorporating geomagnetic activity indices into TEC models to improve prediction accuracy, particularly during geomagnetic disturbances. This contributes to advancements in space weather forecasting and GNSS-based applications.

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