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RESEARCH ARTICLE

Evaluating the Impact of Ocean Tide Loading Models on GNSS-Derived Coordinates along the West African Coastline

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Abstract

The use of High-precision Global Navigation Satellite System (GNSS) is strongly influenced by Ocean Tide Loading (OTL), which results from the redistribution of ocean mass under the gravitational forces of the Moon and Sun. These deformations introduce systematic errors that can significantly degrade positioning accuracy, particularly for coastal reference stations. This study investigates the performance of five global Ocean Tide Models (OTMs), such as FES2004, FES2014b, TOPEX7.2, GOT4.7, and HAMTIDE, in GNSS data processing along the West African coastline. GNSS observations from February 2022 were processed using the Bernese GNSS Software (v5.2) under a consistent parameter setting, with OTL corrections applied separately for each model. Positional accuracy was assessed through Root Mean Square Error (RMSE) analysis of the estimated coordinates relative to a priori values. The results reveal distinct variability in OTM performance. FES2004, the model adopted by the International Earth Rotation Service (IERS), achieved the most reliable accuracy (27.1–42.4 mm), with GOT4.7 and HAMTIDE showing comparable results (27.4–42.6 mm). By contrast, FES2014b produced larger discrepancies, with RMSE values reaching 98.2 mm, while TOPEX7.2 exhibited systematic weaknesses across several stations. The Z-component of position was consistently the most affected, and spatial variability was evident, with CBCR showing the highest OTL sensitivity and LGLA the least.The findings highlight the critical role of accurate Ocean Tide Loading (OTL) corrections in ensuring reliable GNSS coordinate estimation along coastal West Africa. FES2004 continues to demonstrate superior performance, yet GOT4.7 and HAMTIDE also exhibit promising consistency and can serve as viable alternatives. Further research using extended temporal datasets and denser GNSS network coverage is essential to improve OTL model validation and regional applicability

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1.0 INTRODUCTION

1.1 Background to the study

The Global Navigation Satellite System (GNSS) consists of satellite constellations that provide Positioning, Navigation, and Timing (PNT) services on both regional and global scales. The Earth, however, is a dynamic body that undergoes deformation across a wide range of spatial and temporal scales, which can be observed using space geodetic techniques such as Very Long Baseline Interferometry (VLBI), Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS), Satellite and Lunar Laser Ranging (SLR/LLR), and GNSS (Altamimi *et al*., 2016; Rizos *et al*., 2017). Among these techniques, GNSS has emerged as a powerful tool for monitoring real-time Earth deformation, largely due to the proliferation of GNSS stations worldwide, alongside relatively low installation and maintenance costs (Blewitt &Lavallée, 2002; Dach *et al*., 2015).

However, the effective application of GNSS for geophysical and geodetic monitoring requires rigorous modeling of all systematic errors that degrade precision at the millimeter level (Blewitt, 2015; Montenbruck& Gill, 2023). One significant source of such error is the deformation of the Earth's crust due to the redistribution of ocean mass under the gravitational forces of celestial bodies, particularly the Moon and the Sun, a phenomenon known as Ocean Tide Loading (OTL) (Farrell, 1972; Petrov & Boy, 2004).
The loading of the Earth caused by ocean mass redistribution is difficult to model precisely because of the highly complex nature of coastlines, seafloor topography, uncertainties in geophysical models, and limitations associated with Green's functions (Anderson, 2020; King *et al*., 2021). To address these challenges, several Ocean Tide Models (OTMs) have been developed to predict the deformation and provide correction terms for GNSS data processing (Penna *et al*., 2007; Lyard *et al*., 2021). Following the advent of satellite altimetry missions such as TOPEX/Poseidon, Jason-1, Jason-2, and the GOCE (Gravity Field and Ocean Circulation Explorer), combined with advances in mathematical and statistical modeling, a new generation of OTL models has emerged, including the Finite Element Solution (FES), Topex/Poseidon series(TPXO), and Goddard Ocean Tide (GOT) series (Ray, 2013; Carrère *et al*., 2016; Lyard *et al*., 2021).

2.0 THE STUDY AREA

The West African Coastline forms a major segment of the Atlantic seaboard of Africa, extending for approximately 6,000 km from Mauritania (about 20°N) through Senegal, The Gambia, Guinea-Bissau, Guinea, Sierra Leone, Liberia, Côte d'Ivoire, Ghana, Togo, Benin, and Nigeria, to Cameroon in the Gulf of Guinea. This vast coastal belt constitutes a dynamic geodetic and geophysical environment where oceanic, atmospheric, and terrestrial processes interact continuously. Climatically, the region is strongly influenced by the West African Monsoon System, characterized by alternating wet and dry seasons. Rainfall distribution varies from less than 300 mm/year in the arid coastal Sahel (Mauritania–Senegal) to over 3,000 mm/year in the humid equatorial sectors (southern Nigeria and Cameroon). Mean annual temperatures range between 24°C and 32°C, with marked maritime modulation. These variations directly affect tropospheric conditions, soil moisture, and crustal responses that influence GNSS signal propagation and station stability (Almar *et al*, 2023). Geologically and geomorphologically, the coastline exhibits diverse settings, including deltaic plains (e.g., Niger and Volta Deltas), estuarine and mangrove wetlands, sandy barrier systems, and rocky headlands. These features are shaped by tectonic stability, sediment supply, tidal amplitude, and oceanic loading. The Atlantic Ocean's semi-diurnal and diurnal tidal systems induce significant Ocean Tide Loading (OTL) effects, vertical and horizontal crustal deformations that can reach several centimeters, posing challenges for achieving centimeter-level GNSS positioning accuracy along the coastal network. Within this region, a growing network of Continuously Operating Reference Stations (CORS) supports geodetic infrastructure, navigation, and environmental monitoring. However, the accuracy of CORS-derived coordinates is influenced by local geophysical corrections, particularly the OTL model used during data processing. Variations in coastline morphology, bathymetry, and proximity to tidal basins mean that a single OTL model may not accurately represent loading responses across all stations. Consequently, the West African Coastline provides an ideal natural laboratory for assessing the spatial variability and effectiveness of OTL models (e.g., FES2014b, TPXO, GOT) in CORS data processing. Understanding these effects enhances the reliability of GNSS-based geodetic solutions, improves vertical datum consistency, and supports coastal monitoring, subsidence studies, and infrastructure resilience across the region. Figure 1 shows the COR station location assessed along the West African coastline.

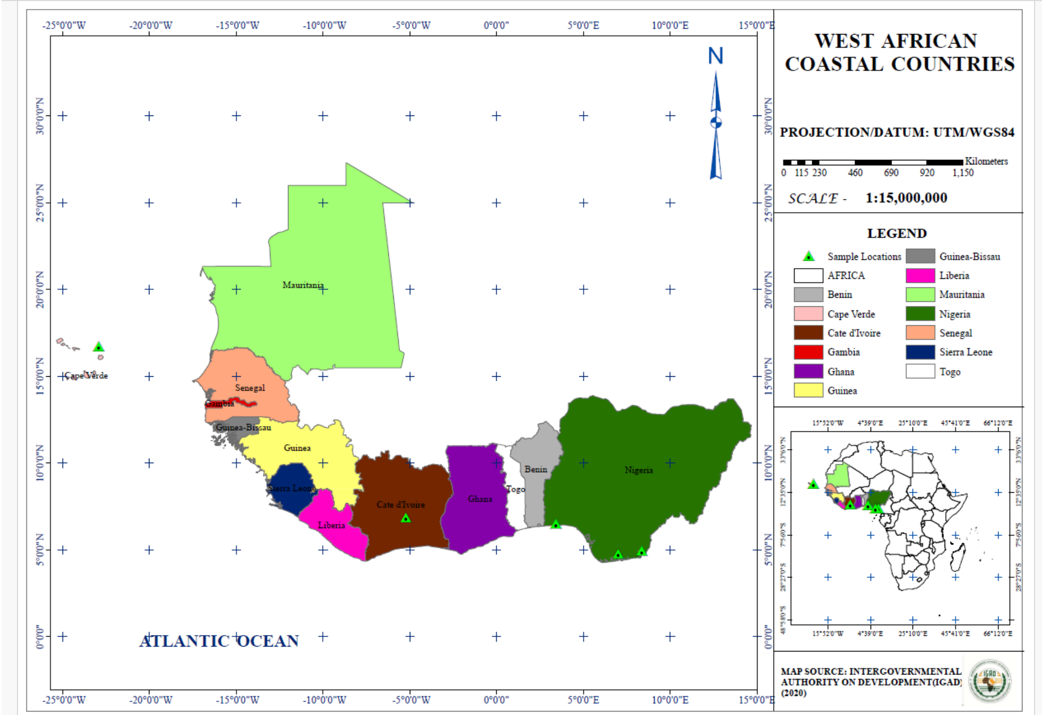

Figure 1: Map of West Africa Coastline Showing the Location of the CORS used. (Source: Author 2025)

2.1 Station Description

The station used in this study, as shown in Figure 1, is five (5) in number. Out of these five, three are part of the Nigeria COR station Network, usually known as NIGNET, managed by the Office of the Surveyor General of the Federation (OSGoF), while the remaining are part of the International GNSS Network (IGS). The spatial location and station ID are described in Table 1.

Table 1: Continuously Operating Reference Station Description

Station ID	Station Description
LGLA	This station is located on the rooftop of a building named Erastus Akimbola Hostel for post graduate students in the University of Lagos campus. Its approximate position is **06º 31' 2.38''**, **003º 23' 51.44 '', corresponding to** latitude and longitude respectively. The station is 14km away from the Atlantic Ocean.
PHRI	This station is located in Port Harcourt, particularly situated in the Niger Delta region, an area influenced by large river discharge into the Atlantic Ocean. The station is located on the rooftop of the faculty of Environmental Science Building in Rivers State University. Also, this station is part of the NIGNET Station. The spatial location of the station is given thus **04º 47' 57.73''** as latitude, **006º 58' 43.81''** as longitude. The distance from the station to the Atlantic Ocean is approximately 46km.
CBCR	This station is in Cross River State, located in Southeastern Nigeria. Calabar lies along the Gulf of Guinea Coast and is characterized by a tropical climate and an estuarine system. Its proximity to the Atlantic makes it highly sensitive to ocean loading effect, particularly due to the irregular coastline and dynamic hydrological processes (Okeke *et al.*, 2020). This station is part of the NIGNET station owned by the Nigerian Government. The approximate coordinate of this station is expressed in the World Geodetic System

Station ID	Station Description
	(WGS) as **04º 57' 1''.10** as latitude, **008º 21' 5''.65** as longitude. The station is approximately 18km away from the Atlantic Ocean.
CPVG	This station is in Cape Verde, an island along the Atlantic Ocean that provides a unique offshore setting away from continental influences. The station belongs to research centers, space agencies, and mapping organizations under the auspices of the International Association of Geodesy (IAG). Its approximate location of the station is given thus: **16º 43' 55.37'',-22º 56' 5.64''** as latitude, longitude respectively. The station is approximately 4km away from the Atlantic Ocean.
YKRO	This station is in Yamoussoukro in Côted'Ivoire, which serves as a reference for geodetic work. This station is part of the IGS. Its spatial location is given as **6º 52' 14.017013'',-5º 14' 24.334689'',** and 270.1832m as latitude, longitude, and ellipsoidal height, respectively. The station is 193km away from the Atlantic Ocean.

Source (Author 2025).

3.0 MATERIALS AND METHODS

The data from Calabar, Lagos, and Port Harcourt were obtained from the NIGNET website, while data from Côte d'Ivoire and Cape Verde were obtained from the IGS website. The Station was processed using Bernese GPS processing software version 5.2. Thus, the RINEX observation files were renamed in accordance with the Bernese format, where necessary satellite orbit files, Earth rotation parameter, ionospheric files, the differential code biases, and models were downloaded from the Bernese website. The parameter settings for the processing strategy are shown in Table 3. The CORS data used over the West African Coastline were processed using the Precise Point Positioning (PPP) technique implemented in Bernese 5.2. The Center of Mass Corrections (CMC) for each OTL model were obtained from the Onsala Space Observatory, while GNSS orbit and clock products were sourced from the International GNSS Service (IGS) through the Crustal Dynamics Data Information System (CDDIS). The data used for this study is GPS data for February 2022. The geocentric Cartesian coordinate is provided from the raw data for the station assessed in this study. However, for network adjustment and baseline formulation, IGS CORS data for the corresponding period were used. The selected CORS are listed in Table 2

Table 2: List of 3 selected IGS CORS

S/NO.	IGS COR ID	Geographical Location
1	MBAR	Uganda
2	MELI	Spain
3	ZAMB	Zambia

Table 3: Parameter Setting and Models for Data Processing Strategy

Parameters	Processing Strategy
Network design	OBS-MAX.
Elevation cut-off angle	15°.
Weighting of GPS observations	Cos2 (z); z = zenith angle.
Sampling rate	30-180s.
Orbits/EOP	IGS final Orbit and Earth Orientation parameters (EOP).
Station coordinates	Tightly constrained to the ITRF2014 reference frame.
Absolute antenna phase centre corrections	PHAS COD.I08, SATELLIT.I08.

Parameters	Processing Strategy
Ocean loading model	Varying: FES2004, FES2014, TOPEX7.2, GOT4.7 band HAMTIDE.
Ionosphere	Double-difference ionospheric-free (IF) linear combination.
Ionosphere model for ambiguity fixing	Global ionosphere model from CODE.
Gradient estimation	Horizontal gradient parameters: tilting at a 24-hour interval.
A priori model	A priori Saastamoinen hydrostatic model with a dry Neill mapping function.
Mapping function	Wet-Neill mapping function (1hr interval).
Relative troposphere constraints	Loose.
ZPD estimates	Hourly (1hr).

The OTMs were used in the processing of the CORS data by varying them while other factors and inputs remained constant. Thus, using the continuous values for the a priori coordinates, the yielding station coordinates were estimated. The data was reprocessed five times with the five models examined in this study. The effect of varying the ocean tide model on the position domain was assessed using the root mean square error (RMSE).

4.0 RESULTS

To determine the effect of each model on the estimated station coordinates, the root mean square error and the mean difference in coordinate using the a priori coordinate as a reference were derived in Tables 4 to 6. The mean error difference and the RMS error were derived for FES2004 in Table 4.

Table 4: Mean Errors and RMSE from FES 2004 Ocean Tide Model

Station ID	Type	Diff. in Coordinate Estimated Coord.-A-priori Coord. (m)	RMS Error(m)
CBCR	X	-0.1070	0.0413
	Y	0.0858	0.0399
	Z	-0.3172	0.0324
YKRO	X	1.2211	0.0377
	Y	0.4050	00347
	Z	0.1287	00274
CPVG	X	1.0754	0.0388
	Y	0.3576	0.0361
	Z	0.3277	0.0293
LGLA	X	-0.0421	0.0421
	Y	0.0419	0.0419
	Z	0.0407	0.0407

The minimum and maximum RMS errors are 0.0274m and 0.0421m, respectively. Hence, the model error falls within the 27.4mm to 42.1mm limit of accuracy. As regards FES2014b, the Mean Error and the RMS error for FES2014b are derived in Table 5

Table 5: Mean Errors and RMSE from FES 2014b Ocean Tide Model

Station ID	Type	Diff. in Coordinate Estimated Coord.-A priori Coord. (m)	RMS Error(m)
CBCR	X	-0.1234	0.0415
	Y	-0.0399	0.0989
	Z	-0.3418	0.0318
YKRO	X	1.2528	0.0378
	Y	0.4219	0.0344
	Z	0.1450	0.0272
CPVG	X	-1.0884	0.0390
	Y	-0.3634	0.0360
	Z	0.3241	0.0291

LGLA	X	-0.0023	0.0424
	Y	0.0185	0.0420
	Z	0.0087	0.0407

The minimum and maximum RMS errors are 0.0272m and 0.09821m, respectively. Hence, the model error falls within the 27.2mm to 98.2mm limit of accuracy. As regards TOPEX7.2, the Mean Error and the RMS error for TOPEX7.2 are derived in Table 6

Table 6: Mean Errors and RMSE from TOPEX7.2 Ocean Tide Model

Station ID	Type	Diff. in Coordinate Estimated Coord. -A priori Coord. (m)	RMS Error(m)
CBCR	X	-0.1651	0.0450
	Y	-0.1459	0.0435
	Z	-0.0235	0.0601
YKRO	X	1.4478	0.0405
	Y	0.2771	0.0371
	Z	0.1551	0.0067
CPVG	X	-0.7437	0.0404
	Y	-0.4469	0.0391
	Z	-0.1272	0.0126
LGLA	X	-0.0031	0.0459
	Y	0.0211	0.0458
	Z	-0.0001	0.0701

The minimum and maximum RMS errors are 0.0371m and 0.0459m, respectively. Hence, the model error falls within the 6mm to 45.9mm limit of accuracy. As regard GOT4.7, the Mean Error and the RMS error for GOT4.7 are derived in Table 7

Table 7: Errors and RMSE from GOT4.7 Ocean Tide Model

Station ID	Type	Diff. in Coordinate Estimated Coord. -A priori Coord. (m)	RMS Error(m)
CBCR	X	-0.1222	0.0417
	Y	-0.0991	0.0402
	Z	-0.3367	0.0321
YKRO	X	1.2634	0.0380
	Y	0.4245	0.0346
	Z	0.1443	0.0274
CPVG	X	-1.1011	0.0392
	Y	-0.3657	0.0362
	Z	0.3218	0.0293
LGLA	X	-0.0024	0.0426
	Y	0.0179	0.0422
	Z	0.0079	0.0409

The minimum and maximum RMS errors are 0.027m and 0.0426m, respectively. Hence, the model error falls within the 27.4mm to 42.6mm limit of accuracy. As regards HAMTIDE, the Mean Error and the RMS error for HAMTIDE are derived in Table 8

Table 8: Errors and RMSE from HAMTIDE Ocean Tide Model

Station ID	Type	Diff. in Coordinate Estimated Coord.-A priori Coord. (m)	RMS Error(m)
CBCR	X	-0.1227	0.0417
	Y	-0.0995	0.0401
	Z	-0.3366	0.0321
YKRO	X	1.2638	0.0380
	Y	0.4248	0.0346

Station ID	Type	Diff. in Coordinate Estimated Coord.-A priori Coord. (m)	RMS Error(m)
	Z	0.1443	0.0274
CPVG	X	-1.1011	0.0392
	Y	-0.3655	0.0362
	Z	0.3218	0.0293
LGLA	X	-0.0024	0.0426
	Y	0.0179	0.0422
	Z	0.0079	0.0408

The minimum and maximum RMS errors are 0.0274m and 0.0426m, respectively. Hence, the model error falls within the 27.4mm to 42.6mm limit of accuracy. As regard HAMTIDE, the Mean Error and the RMS error for HAMTIDE are derived in Table 7.

4.1 Discussion of Results

For analysis, Table 9, which is the summary of the range of the RMSE for the five (5) global models selected for the study area

Table 9: Summary of the RMSE range of the five OTL

TYPE	OCEAN TIDE MODEL	RMSE RANGE
	FES2004	27.1mm to 42.4mm
GLOBAL OTMs	FES2014B	27.6mm to 98.2mm
	TOPEX7.2	37.1mm to 45.9mm
	GOT4.7	27.4mm to 42.6mm
	HAMTIDE	27.4mm to 42.6mm

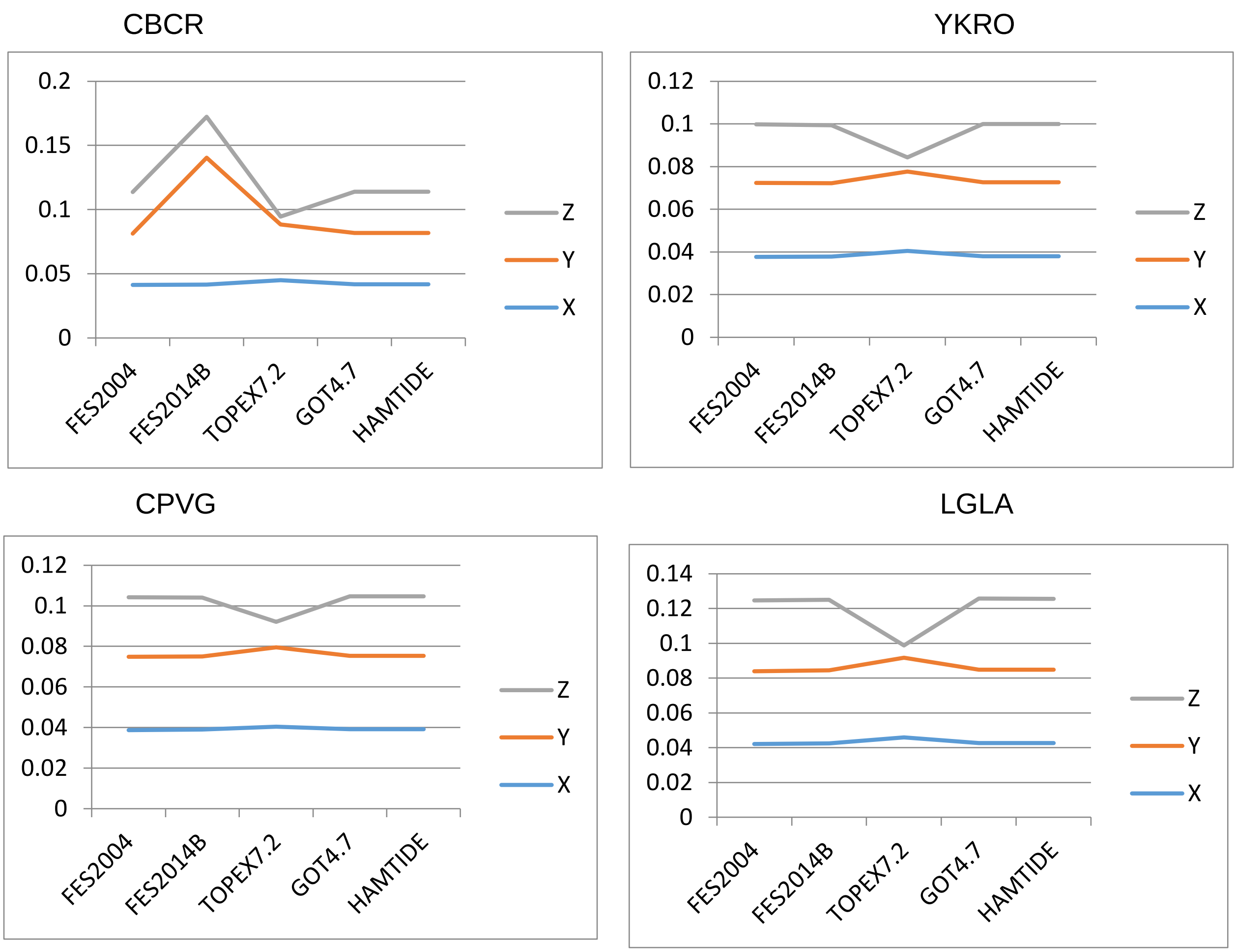

Figure 2: The magnitude of the position RMSE from the five OTMs

It can be seen from Figure 2, TOPEX7.2 has the highest positional error at the three stations, namely YKRO, CPVG, and LGLA, while FES2014B has the highest positional error at CBCR. However, the effect of the Ocean Tide loading is seen to impact the Z-component. The positional impact of the OTL decreases progressively from CBCR (highest) to lower (LGLA), suggesting the spatial variability of ocean tide effects across stations with regard to their locations. The impact on the COR stations closer to the coastline is higher compared to the stations located away from the coastline. This is a consequence of the propagation of the tidal wave force on the coastline, which travels inland with a lesser magnitude. In any case, it underscores the importance of applying OTL corrections for coastal and near-coastal stations; ignoring OTL can lead to significant positioning errors, while inland stations may experience relatively minor but still measurable effects.

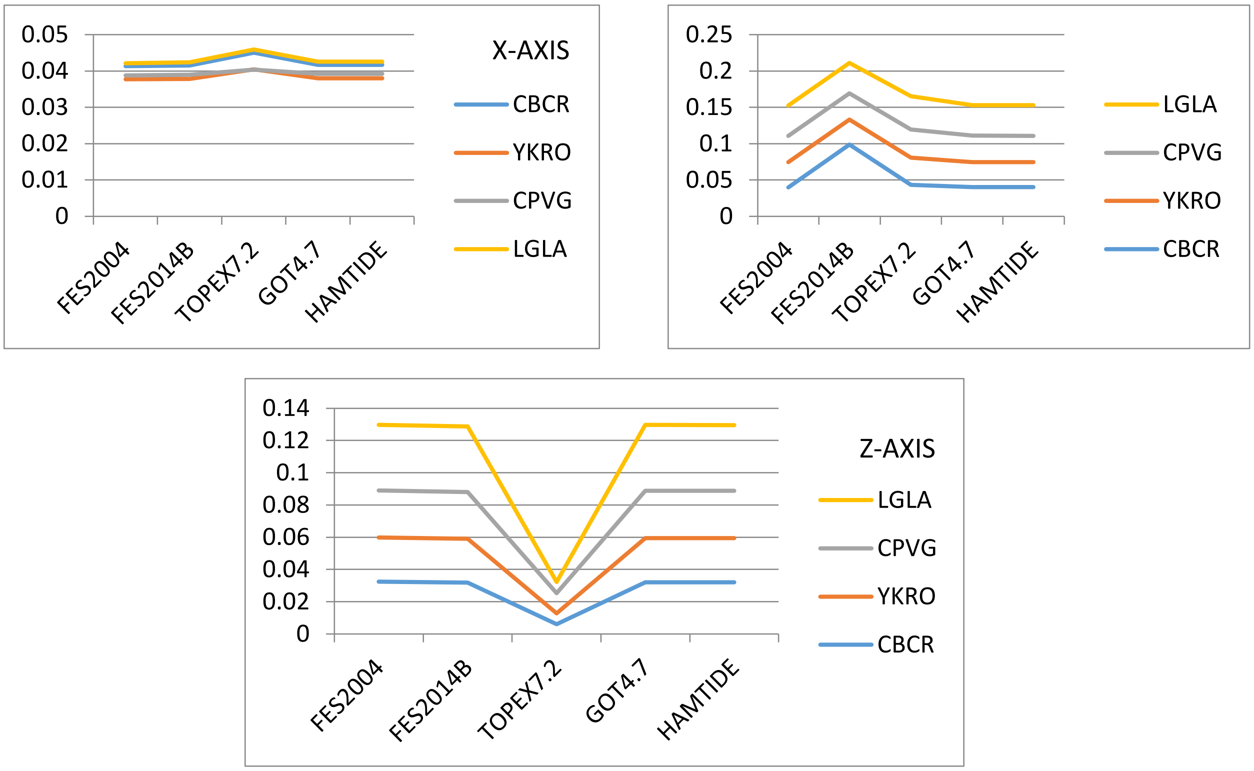

Figure 3: The trend of the five OTMs in the XYZ-axis at the Stations along the Coastline

Figure 3 shows the trend of error for each of the OTMs in the position coordinate domain. TOPEX7.2 shows some level of weakness by performing poorly, which may be attributed to non-compatibility with the coastline configuration of the model. The result suggests that FES2004 which is the global model adopted by the International Earth Rotation Service (IERS) has RMSE rangeof 27.1mm to 42.4mm followed by GOT4.7 and HAMTIDE having the same RMSE range of 27.4mm to 42.6mm respectively are preferred in the processing of GNSS data along the West African coastline if FES2004 can't be assessed followed closely by FES2014B and TOPEX7.2 respectively.

5.0 CONCLUSION

This study examines the effect of various ocean loading models on the accuracy of data processing over CORS for selected sites along the West African Coastline. The OTL parameter was obtained from the Onsala space observatory through the website (http: holt.oso.chalmers.se/loading). These OTL models were used in the processing using the Bernese software version 5.2 by changing the model after estimating the position, while other parameters, such as the tropospheric and other input options, remain unchanged, see Table 2. This is done to see the variation in the given a-priori coordinate and the estimated coordinate. The results, evaluated using Root Mean Square Error (RMSE), indicate that in addition to the globally adopted Finite Element Solution (FES2004), the models GOT4.7 and HAMTIDE demonstrated comparable and reliable performance. By contrast, FES2014b and TOPEX7.2 yielded larger positional discrepancies. These findings suggest that GOT4.7 and HAMTIDE are the most suitable alternatives for GNSS data processing along the West African coastline when FES2004 is not available. Since this study was based on a one-month dataset, it is strongly recommended that future investigations employ longer observation periods and incorporate additional coastal CORS stations to better evaluate and optimize the performance of OTL models in the region.

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