Performance Evaluation of the Recent GOCE-Based Global Geopotential Models using Terrestrial Gravity Data in Nigeria

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Abstract: In this study, twelve (12) GOCE-based and other four (4) high degree and order (d/o) combined Global Geopotential Models (GGMs) were assessed in Nigeria. The high d/o combined GGMs SGG-UGM-2, GECO, EIGEN_6C4, and EGM2008 were evaluated up to their maximum d/o (i.e., 2190) to select one to be used for Spectral Enhancement Method (SEM). The models were compared to terrestrial FA gravity anomaly data before and after applying SEM by Residual Terrain Model (RTM) for combined models and by RTM and the coefficients of EGM2008 for satellite-only models. The agreements of combined models with terrestrial FA gravity anomaly data in terms of root mean square (RMS) were approximately 7.91 to 8.29 mGal, respectively. Among the satellite-only models, GO_CONS_GCF_2_SPW_R5 showed the best results before and after the SEM application. All GOCE-based models exhibited good performance at long and medium wavelengths, confirming the good recovery of the gravity field by the spatial gravity mission in these spectral bands. From these findings, it can be said that EGM2008 and SGG-UGM-2 on the high d/o combined models' side and GO_CONS_GCF_2_SPW_R5 on the low d/o satellite-only models' side best fit the study area and hence encourage its use in geosciences.

Keywords: Free-Air gravity anomaly, Global Geopotential Models, GOCE, Residual Terrain Model, Spectral Enhancement Method.

INTRODUCTION

Low Earth Orbiting (LEO) satellites, such as the Challenging Minisatellite Payload (CHAMP), Gravity Recovery and Climate Explorer (GRACE), and Gravity Field and Steady-state Ocean Circulation Explorer (GOCE), pioneered a new phase in the study of Earth's gravity field and contributed to new advances in the determination of Global Geopotential Models (GGMs) and related parameters (Erol *et al.*, 2020; Guimarães *et al.*, 2012). These LEO satellites have recently made significant contributions to the improvement of GGMs in terms of their precision and spatial resolution. Consequently, this can be assumed to be a fruitful insight that has greatly influenced geodesy and other geosciences (Erol *et al.*, 2020).

The GOCE mission was a European Space Agency (ESA) project launched by Plesetsk Cosmodrome in Russia on March 17, 2009 (El-Ashquer *et al.*, 2016; Erol *et al.*, 2020; Odera & Fukuda, 2017). This satellite uses a satellite gravity gradiometer (SGG) in conjunction with the high-to-low (hl) satellite-to-satellite-tracking (SST) technique (Erol *et al.*, 2020). In addition to the new SGG technique, the GOCE mission was launched at a low orbit altitude to create a near-global map of Earth's gravity field with high resolution and accuracy. The SGG data alone are insufficient to determine the low-degree harmonic coefficient of the gravity field with high accuracy. This was due to the noise characteristics of the gradiometer (Erol *et al.*, 2020). As a result, GPS SST data are required to determine the precise orbit, thus geolocating the tensor observables and long-wavelength component of the gravity field (Erol *et al.*, 2020).

The primary goal of the GOCE mission is to provide geoid undulation and gravity anomalies of 1-2 cm and 1-2 mGal, respectively. The GOCE satellite mission will also contribute to the creation of a new gravity field map with a spatial resolution of 100 km (equivalent to 200 ° spherical harmonic expansion) (Alothman *et al.*, 2016; Elsaka *et al.*, 2015; Erol *et al.*, 2020; Guimarães *et al.*, 2012; Hirt *et al.*, 2011; Odera & Fukuda, 2017; Yahaya & El Azzab, 2019). The ESA project created three types of models for GOCE High-level Processing Facility (HPF) (El-Ashquer *et al.*, 2016; Elsaka *et al.*, 2015; Erol *et*

al., 2020; Godah *et al.*, 2015; Lu *et al.*, 2017; Odera & Fukuda, 2017). The space-wise (SPW), time-wise (TIM), and direct (DIR) approaches are three options. The SPW method is based on least-squares collocation and takes advantage of the spatial correlation of the gravitational field signal. Both TIM and DIR approaches are based on the least-squares method. The recently released GOCE-based models have a spatial resolution of 83.5 km for the SPW, 71.5 km for the TIM, and 66.8 km for the DIR models, respectively (El-Ashquer *et al.*, 2016; Alothman *et al.*, 2016). This is calculated as:

$$N_{max} \approx \frac{2\pi R_E}{\lambda} \approx \frac{\pi R_E}{D} \quad (1)$$

Where Nmax is the maximum spherical harmonic (SH) degree, RE is the mean radius of Earth at the reference ellipsoid (6378.137 km), and D is the spatial resolution (i.e., half of the wavelength) in km.

In addition to the three ESA solutions, models have been developed based on a combination of other data sources such as terrestrial gravity, satellite altimetry, CHAMP, and GRACE (Alothman *et al.*, 2016; El-Ashquer *et al.*, 2016). The Gravity Observation Combination (GOCO) models, the European Improved Gravity Models of the Earth by New Techniques (EIGEN) model series, the Delft Gravity Model (DGM) solution, and the Bonn ITG-GOCE02 (Institute of Geodesy and Geoinformation, University of Bonn) solution are all included.

Numerous studies have been conducted on the accuracy assessment of GOCE-based GGMs in different regions of the world and by different researchers. Apeh and Tenzer (2022) conducted a study to determine the optimum GGM for geological mapping of the Afikpo and Anambra Basins in Nigeria. Other research includes (Hirt *et al.*, 2011) on a worldwide scale (Guimarães *et al.*, 2012) in Brazil, (Alothman *et al.*, 2016; Elsaka *et al.*, 2015) in Saudi Arabia (El-Ashquer *et al.*, 2016) in Egypt, (Godah *et al.*, 2015) in Poland, (Lu *et al.*, 2017) and (Odera & Fukuda, 2017) in Japan, (Odera, 2019) in South Africa, (Yahaya & El Azzab, 2019) in the Niger Republic, and (Erol *et al.*, 2020) in Turkey.

To assess the accuracy of these GOCE-based models, terrestrial datasets (gravity data, GNSS/leveling data, or a combination of both) must be used. Therefore, the current study aims to evaluate these models and choose the best model for geoid modelling and other geodetic applications in Nigeria.

Datasets and Source

The datasets used in this study and their sources are summarized in Table 1.

Table 1: Datasets and sources

S/No	Datasets	Sources
1.	Terrestrial gravity data	Bureau Gravimétrique International (BGI) website (bgi.omp.obs-mip.fr)
2.	GGMs	ICGEM website (http://icgem.gfz-potsdam.de/ICGEM)
3.	SRTM2gravity datasets	http://ddfe.curtin.edu.au/models/SRTM2gravity2018

Global Geopotential Models

Four (4) high degree and order (d/o) GGMs (SGG-UGM-2, GECO, EIGEN-6C4, and EGM2008) were evaluated up to their maximum d/o (2190) to select one to be used for gravity database densification. Twelve (12) GOCE-based GGMs developed between 2010 and 2019 were used in this study. Table 2 shows these models with their names, years developed, degree, and order (d/o) and the data used to develop them.

Table 2: GGMs used in the study

Model	Year	Degree	Data
SGG-UGM-2	2020	**2190**	EGM2008, S(GRACE) S(GOCE)
GO_CONS_GCF_2_TIM_R6	2019	**300**	S(GOCE)
GO_CONS_GCF_2_SPW_R5	2017	**330**	S(GOCE)
GECO	2015	**2190**	EGM2008, S(GOCE)
GO_CONS_GCF_2_SPW_R4	2014	**280**	S(GOCE)
GO_CONS_GCF_2_TIM_R5	2014	**280**	S(GOCE)
EIGEN-6C4	2014	**2190**	A, G, S(GOCE), S(GRACE), S(LAGEOS)
GO_CONS_GCF_2_TIM_R4	2013	**250**	S(GOCE)
GO_CONS_GCF_2_TIM_R3	2011	**250**	S(GOCE)
GO_CONS_GCF_2_DIR_R2	2011	**240**	S(GOCE)
GO_CONS_GCF_2_TIM_R2	2011	**250**	S(GOCE)
GO_CONS_GCF_2_SPW_R2	2011	**240**	S(GOCE)
GO_CONS_GCF_2_DIR_R1	2010	**240**	S(GOCE)
GO_CONS_GCF_2_TIM_R1	2010	**224**	S(GOCE)
GO_CONS_GCF_2_SPW_R1	2010	**210**	S(GOCE)
EGM2008	2008	**2190**	A, G, S(GRACE)

The datasets used in the development of the models are summarized in the data column, where **S** is for satellites (e.g., GRACE, GOCE, LAGEOS), **A** is for altimetry, and **G** is for ground data (e.g., terrestrial, ship-borne, and airborne measurements).

Study Area and Terrestrial Free-Air Anomaly Gravity Data

The terrestrial FA anomaly gravity data used in this study were obtained from the BGI (bgi.omp.obs-mip.fr). These data contain 2857 points obtained from different sources, as mentioned in the BGI database. Figure 1 shows the geographic location of the data.

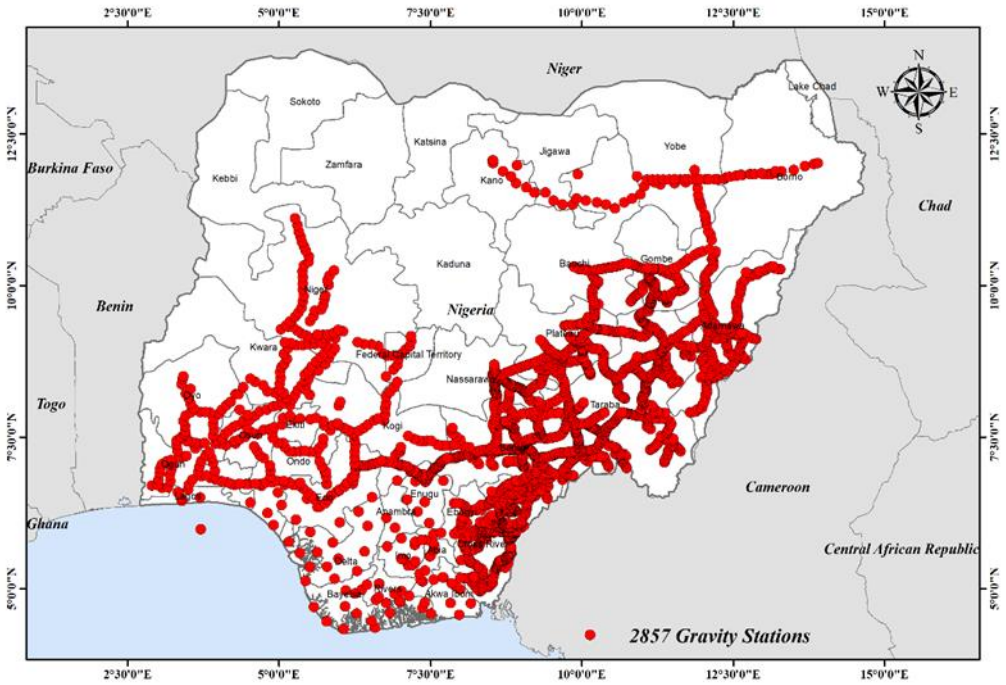

Figure 1. Geographic locations of FA anomaly terrestrial gravity data (Scale 1:2000 kM)

METHODOLOGY

Determining the optimum GGM for a study area was best achieved by assessing it using terrestrial datasets. This can be achieved using GNSS/leveling datasets, FA gravity anomalies, or a combination of both (El-Ashquer *et al.*, 2019). There is no basis for comparing GGMs and terrestrial datasets because the former has limited spherical harmonic (SH) d/o and the latter has full spectra (El-Ashquer *et al.*, 2019; Hirt *et al.*, 2011; Yahaya & El Azzab, 2019). To achieve an acceptable level of comparison, two (2) methods are available (El-Ashquer *et al.*, 2019; Hirt *et al.*, 2011): low-pass filtering, which requires the data to be in a gridded format, and Spectral

Enhancement Method, which is independent of the spatial arrangement of the datasets.

SEM is used to recover Earth's gravitational field quantities, such as height anomalies, geoid undulations, deflections of the vertical, and gravity disturbances (Hirt *et al.*, 2011; Šprlák *et al.*, 2012; Yahaya & El Azzab, 2019).

To fill the spectral gap between these two datasets, the high-degree spectral bands of EGM2008 or any high d/o GGM with NMax = 2190 and have performed optimally in the study area (Yahaya & El Azzab, 2019) and the estimated omission error from the Residual Terrain Model (RTM) (El-Ashquer *et al.*, 2019), which provides an insight into the short-wavelength gravity field constituents.

The GGMs under evaluation were expanded from their maximum d/o to 2190 using EGM2008 or the selected high d/o GGM. This recovers the missing spectral bands between the model and EGM2008. In contrast, the RTM omission error estimates fill the spectral content of the model above 2190 (El-Ashquer *et al.*, 2019).

The resolution of the Digital Elevation Model (DEM) used to compute the RTM corresponds to approximately 216000 for a 3-arc-second resolution (Hirt *et al.*, 2011; Yahaya & El Azzab, 2019). Figure 3 shows the application of the SEM.

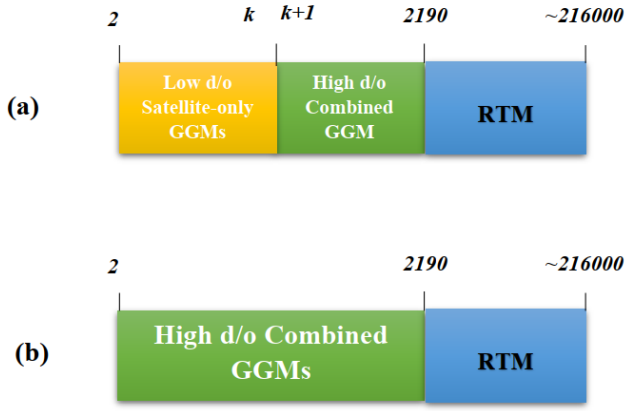

Figure 2- SEM for GGM evaluation; (a) for low d/o satellite-only models, & (b) for high d/o combined models.

Gravity anomalies Δg_{GGM} from the GGMs, residual FA gravity anomalies Δg_{res}, and RTM gravity signals Δg_{RTM} were computed using Eq. (2) - (4) (Hofmann-wellenhof & Moritz, 2006).

$$\Delta g_{GGM} = \frac{GM}{r^2}\sum_{n=2}^{\infty}(n-1)\left(\frac{a}{r}\right)^2 \times \sum_{m=0}^{n}(\bar{C}_{nm}\cos m\lambda + \bar{S}_{nm}\sin m\lambda)\bar{P}_{nm}(\cos\theta) \quad (2)$$

$$\Delta g_{res} = \Delta g - \Delta g_{GGM_2^n} - \Delta g_{EGM2008_{n+1}^{2190}} - \Delta g_{RTM} \quad (3)$$

$$\Delta g_{RTM} = G\iint_E \int_{h_{ref}}^{h} \frac{\rho(x,y,z)(h_p - z)}{\left[(x_p-x)^2+(y_p-y)^2+(h_p-z)^2\right]^{\frac{3}{2}}} dxdydz \quad (4)$$

where *GM* is the geocentric gravitational constant, *r* is the geocentric radius, *a* is the semi-major ellipsoid axis that represents the equatorial radius of the mean Earth's ellipsoid, $\bar{C}_{nm}$ and $\bar{S}_{nm}$ are the fully normalized potential cosine and sine coefficients, λ is the geodetic longitude, $\bar{P}_{nm}$ denotes the associated fully normalized Legendre functions, and θ is the polar distance. where Δg is the terrestrial FA gravity anomaly, $\Delta g_{GGM_2^n}$ is the FA gravity anomaly from the GGM with d/o 2 to n, $\Delta g_{EGM2008_{n+1}^{2190}}$ is the FA gravity anomaly synthesized from EGM2008 from d/o n+1 to its maximum d/o of 2190, and Δg_{RTM} is the RTM gravity signal. *G* denotes the Newtonian gravitational constant, *E* is the planar projection of the integration area, h_{ref} represents the height of the smoothed DEM, *h* is the height of the detailed DEM, *x*, *y*, and *z* are the Cartesian coordinates of the integrated topography, $\rho(x,y,z)$ is the mean reference crustal density of the Earth, i.e., 2.67g.cm^{-3}, and x_P, y_P, and h_P are the coordinates

and height of the computational point in the Cartesian coordinate system, in which the RTM is evaluated.

RESULTS AND DISCUSSION

Computing Gravity Anomaly from GGMs and comparing it with Terrestrial Gravity

Free-Air (FA) gravity anomaly derived from the GGMs was computed using the ICGEM (http://icgem.gfz-potsdam.de/ICGEM) calculation service. This was performed in two phases based on the types of GGMs used in the study (i.e., satellite-only and combined models) (see Tables 3 and 4). Table 3 shows that EGM2008 fits the terrestrial FA gravity data better than the other three models (SGG-UGM-2, GECO, and EIGEN-6C4), with RMS value of 7.91 mGal. This result was closely followed by that of SGG-UGM-2, with an RMS value of 7.92 mGal. This result is in tandem with the work of Yahaya and El Azzab (2019), who also employed three (EGM2008, GECO, and EIGEN-6C4) of the four models used in this study.

Table 3- Statistics of the performance of high d/o GGMs against Terrestrial FA Gravity datasets

Model	Degree	Min	Max	STD	Mean	RMS
SGG-UGM-2	2190	-50.96	87.62	7.89	0.40	7.92
GECO	2190	-54.09	92.63	8.28	0.26	8.29
EIGEN-6C4	2190	-56.75	91.32	8.19	0.35	8.22
EGM2008	2190	-49.68	86.70	7.90	0.41	7.91

Comparing the FA gravity anomaly derived from the GGMs to the satellite-only models, Table 4 shows that GO_CONS_GCF_2_SPW_R5 had the best result, with an RMS value of 11.12 mGal. This was followed by GO_CONS_GCF_2_TIM_R5 and GO_CONS_GCF_2_TIM_R6 with RMS values of 12.11 and 12.12 mGal respectively.

Table 4- Statistics of the performance of low d/o GGMs against Terrestrial FA Gravity datasets

Model	Degree	Min	Max	STD	Mean	RMS
GO_CONS_GCF_2_TIM_R6	300	-62.17	99.51	12.10	0.87	12.12
GO_CONS_GCF_2_SPW_R5	330	-60.16	95.83	11.12	0.61	11.12
GO_CONS_GCF_2_SPW_R4	280	-63.33	99.55	12.13	0.74	12.13
GO_CONS_GCF_2_TIM_R5	280	-63.34	99.53	12.12	0.76	12.11
GO_CONS_GCF_2_TIM_R4	250	-63.56	89.19	12.36	0.93	12.38
GO_CONS_GCF_2_TIM_R3	250	-63.55	88.67	12.38	0.74	12.38
GO_CONS_GCF_2_DIR_R2	240	-64.10	87.98	12.47	0.84	12.46
GO_CONS_GCF_2_TIM_R2	250	-63.50	98.75	12.34	0.94	12.34
GO_CONS_GCF_2_SPW_R2	240	-64.09	98.58	12.48	0.85	12.47
GO_CONS_GCF_2_DIR_R1	240	-64.12	97.54	12.46	0.85	12.47
GO_CONS_GCF_2_TIM_R1	224	-64.50	95.65	12.50	0.72	12.51
GO_CONS_GCF_2_SPW_R1	210	-64.56	97.58	12.65	0.83	12.64

However, it can be said that the high d/o combined GGMs fit the terrestrial FA gravity anomaly better than satellite-only models. This finding corroborates the results of (El-Ashquer *et al.* (2019), Goyal *et al.* (2018), Hirt *et al.* (2011), and Yahaya and El Azzab (2019). These models were further assessed using the RMS values of the differences in gravity anomalies as a function of the truncation of d/o. The truncation started from d/o 100 to 200 for both the combined and satellite-only models. The results are presented in Tables 5 and 6, respectively.

The combined models showed similar results throughout the truncation, as the RMS values gradually decreased with increasing d/o (see Table 5). It can be deduced that EGM2008 and SGG-UGM-2 exhibited the best performance, with very close results throughout the truncations. This confirms the findings of (Yahaya & El Azzab, 2019).

Table 5- RMS of gravity anomaly differences as a function of d/o of spherical harmonics in high d/o GGMs

Model	RMS					
	100	***120***	***140***	***160***	***180***	***200***
SGG-UGM-2	17.63	17.11	16.74	16.19	15.55	15.01
GECO	17.64	17.15	16.95	16.26	15.68	15.21
EIGEN-6C4	17.64	17.14	16.88	16.23	15.62	15.12
EGM2008	17.63	17.12	16.73	16.19	15.57	15.00

Table 5 can be seen graphically in Figure 3, where the trend pattern of the decrease in RMS values is observed with an increase in d/o.

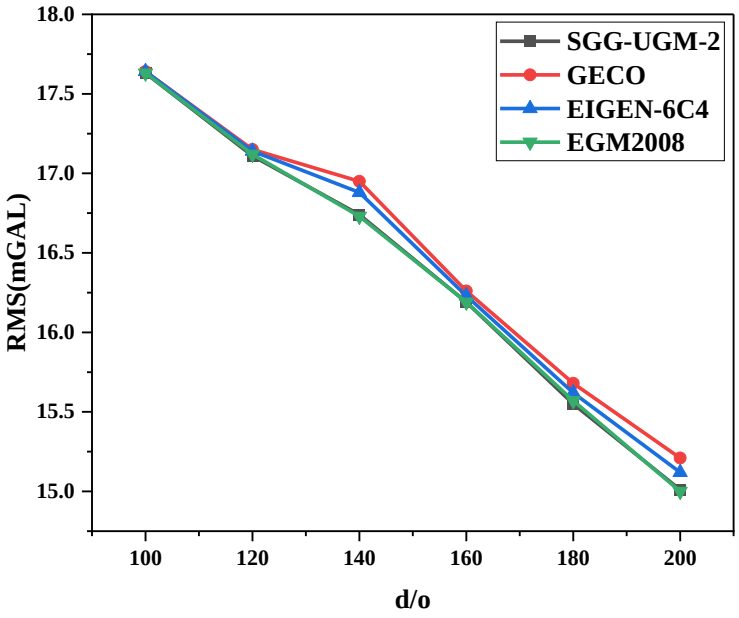

Figure 3: Performance of high d/o GGMs against Terrestrial FA gravity data from d/o 100 to 200

The low d/o models also showed similar results throughout the truncation, as the RMS values gradually decreased with increasing d/o (Table 6). Model GO_CONS_GCF_2_SPW_R5 turns out with the best performance against FA Terrestrial gravity data. This was followed by GO_CONS_GCF_2_TIM_R6, and the remaining ten (10) models followed closely similar results.

Table 6: RMS of gravity anomaly differences as a function of d/o of spherical harmonics in low d/o GGMs

Model	RMS					
	100	***120***	***140***	***160***	***180***	***200***
GO_CONS_GCF_2_TIM_R6	17.66	17.21	16.82	16.31	15.76	15.32
GO_CONS_GCF_2_SPW_R5	17.66	17.23	16.75	16.29	15.72	15.30
GO_CONS_GCF_2_SPW_R4	17.84	17.23	16.87	16.35	15.76	15.33
GO_CONS_GCF_2_TIM_R5	17.83	17.25	16.78	16.34	15.76	15.35
GO_CONS_GCF_2_TIM_R4	17.87	17.23	16.84	16.34	15.80	15.36
GO_CONS_GCF_2_TIM_R3	17.87	17.23	16.85	16.36	15.76	15.32
GO_CONS_GCF_2_DIR_R2	17.87	17.30	16.85	16.34	15.74	15.35
GO_CONS_GCF_2_TIM_R2	17.87	17.23	16.84	16.36	15.78	15.34
GO_CONS_GCF_2_SPW_R2	17.87	17.32	16.84	16.34	15.75	15.36
GO_CONS_GCF_2_DIR_R1	17.87	17.23	16.87	16.35	15.80	15.51
GO_CONS_GCF_2_TIM_R1	17.91	17.32	16.89	16.34	15.83	15.53
GO_CONS_GCF_2_SPW_R1	17.93	17.34	16.98	16.46	15.84	15.68

Table 6 is also presented graphically in Figure 4, where the trend pattern of the decrease in RMS values is observed with an increase in d/o.

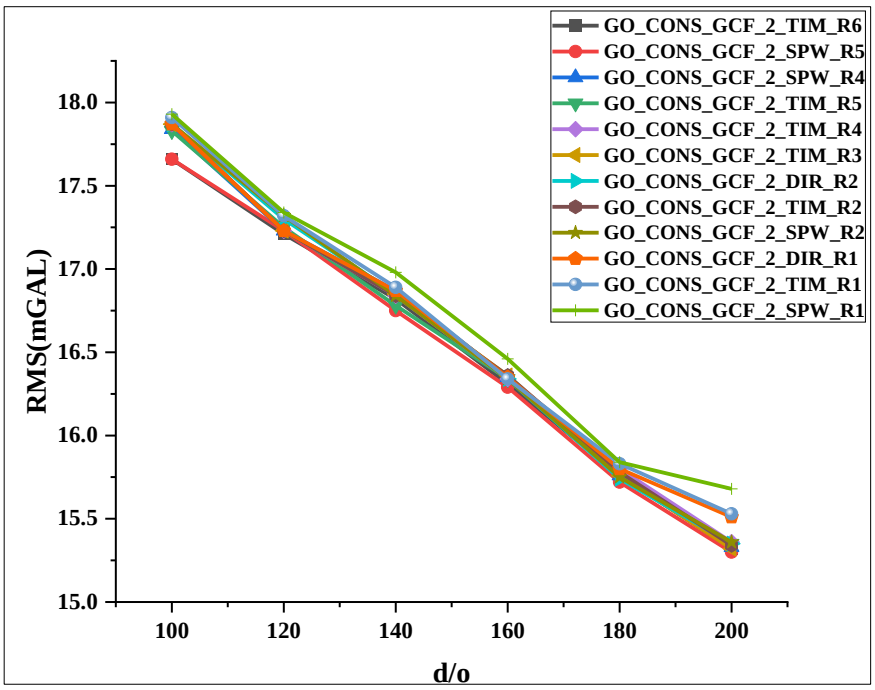

Figure 4: Performance of low d/o GGMs against Terrestrial FA gravity data from d/o 100 to 200

To compare the terrestrial gravity and gravity functionals derived from GGMs after applying SEM

SEM was applied to the GGMs to fill the spectral gap between them and the terrestrial gravity datasets. This also provides a basis for comparing the two datasets. The results obtained after applying SEM showed no improvement in the combined high d/o GGMs. EGM2008 remained the same with no change in the RMS value of 7.91 mGal, while the remaining three models deteriorated after the application of SEM with an increase in RMS values. This corroborates the findings of Yahaya and El Azzab (2019), and Šprlák *et al.* (2015). The results are presented in Table 7.

Table 7: Statistics of the performance of high d/o GGMs against Terrestrial FA Gravity datasets after applying SEM

Model	Degree	Min	Max	STD	Mean	RMS
SGG-UGM-2	2190+RTM	-50.45	87.72	8.01	0.55	7.93
GECO	2190 +RTM	-54.54	92.71	8.37	0.39	8.31
EIGEN-6C4	2190 + RTM	-57.20	90.70	8.28	0.48	8.23
EGM2008	2190 + RTM	-49.66	86.08	7.98	0.53	7.91

However, the satellite-only (GOCE-Based) models all showed significant improvement after the application of SEM, which is in agreement with many studies (El-Ashquer *et al.*, 2016, 2019; Hirt *et al.*, 2011). The result follows a sequence similar to that before the application of SEM, with GO_CONS_GCF_2_SPW_R5 having the best result, with an RMS value of 11.09 mGAL. The results are presented in Table 8.

Table 8: Statistics of the performance of low d/o GGMs against Terrestrial FA Gravity datasets after applying SEM

Model	Degree	Min	Max	STD	Mean	RMS
GO_CONS_GCF_2_TIM_R6	300 + $\Delta g_{EGM2008_{301}^{2190}} + RTM$	-62.24	99.55	12.09	0.98	12.10
GO_CONS_GCF_2_SPW_R5	330 + $\Delta g_{EGM2008_{331}^{2190}} + RTM$	-61.17	99.30	11.11	0.76	11.09
GO_CONS_GCF_2_SPW_R4	280 + $\Delta g_{EGM2008_{281}^{2190}} + RTM$	-63.87	99.78	12.11	0.93	12.11
GO_CONS_GCF_2_TIM_R5	280 + $\Delta g_{EGM2008_{281}^{2190}} + RTM$	-63.97	101.31	12.10	0.79	12.12
GO_CONS_GCF_2_TIM_R4	250 + $\Delta g_{EGM2008_{251}^{2190}} + RTM$	-63.78	98.91	12.23	0.68	12.25
GO_CONS_GCF_2_TIM_R3	250 + $\Delta g_{EGM2008_{251}^{2190}} + RTM$	-63.55	88.88	12.23	0.87	12.23
GO_CONS_GCF_2_DIR_R2	240 + $\Delta g_{EGM2008_{241}^{2190}} + RTM$	-64.78	89.88	12.30	0.99	12.30
GO_CONS_GCF_2_TIM_R2	250 + $\Delta g_{EGM2008_{251}^{2190}} + RTM$	-63.96	98.92	12.25	0.97	12.26
GO_CONS_GCF_2_SPW_R2	240 + $\Delta g_{EGM2008_{241}^{2190}} + RTM$	-64.69	99.98	12.29	0.88	12.29
GO_CONS_GCF_2_DIR_R1	240 + $\Delta g_{EGM2008_{241}^{2190}} + RTM$	-64.43	105.50	12.30	0.98	12.30
GO_CONS_GCF_2_TIM_R1	224 + $\Delta g_{EGM2008_{225}^{2190}} + RTM$	-64.54	102.55	12.44	0.98	12.45
GO_CONS_GCF_2_SPW_R1	210 + $\Delta g_{EGM2008_{211}^{2190}} + RTM$	-64.76	97.98	12.48	0.87	12.47

The models were further assessed as a function of the truncation of d/o using the RMS values of the differences in gravity anomalies. As stated earlier, the truncation began at d/o 100 and ended at 200 for the two categories of GGMs used (satellite-only and high-degree combined models). Tables 9 and 10 present these results. The obtained results showed that the high d/o GGMs at lower d/o showed significant improvement in RMS values and followed a somewhat similar pattern as it was before the application of SEM. EGM2008 also came out as the optimum model, this was followed by SGG-UGM-2 and the remaining two models followed closely with very identical results (see Table 9).

Table 9- RMS of gravity anomaly differences as a function of d/o of spherical harmonics in high d/o GGMs after applying SEM

Model	RMS					
	100	***120***	***140***	***160***	***180***	***200***
SGG-UGM-2	17.47	16.95	16.59	16.03	15.40	14.64
GECO	17.48	16.99	16.79	16.10	15.52	15.05
EIGEN-6C4	17.48	16.98	16.72	16.07	15.46	14.96
EGM2008	17.14	16.63	16.24	15.70	15.08	14.51

The trend pattern of the performance of high-d/o GGMs is shown graphically in Figure 5. EGM2008 showed a better result across all truncations, and the result was closely followed by that of SGG-UGM-2, whereas the remaining two models showed very similar results. All four models showed good improvements when processed at lower d/o ratios and were in good agreement with the terrestrial gravity dataset after

the application of SEM. This also corroborates the findings of Yahaya and El Azzab (2019).

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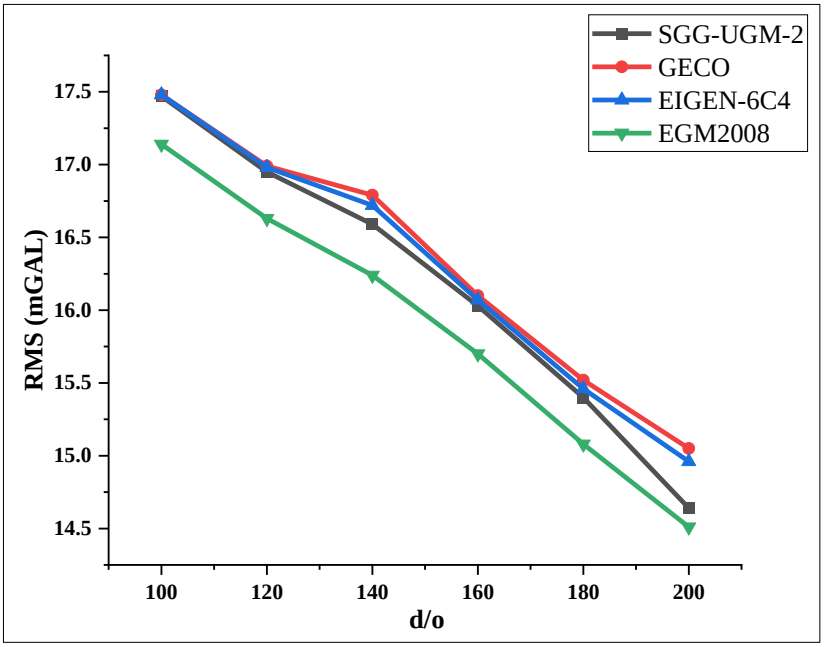

Figure 5: Performance of high d/o GGMs against Terrestrial FA gravity data from d/o 100 to 200 after applying SEM

However, the low d/o models also showed similar results throughout the truncation as the RMS values gradually decreased with an increase in d/o (see Table 10). GO_CONS_GCF_2_SPW_R5 was found to be the best model and showed optimal results against the FA terrestrial gravity data. This was followed by GO_CONS_GCF_2_TIM_R6 and the remaining ten (10) models followed closely with similar results.

Table 10- RMS of gravity anomaly differences as a function of d/o of spherical harmonics in low d/o GGMs after applying SEM

Model	**RMS**					
	100	***120***	***140***	***160***	***180***	***200***
GO_CONS_GCF_2_TIM_R6	17.62	17.17	16.79	16.28	15.73	15.29
GO_CONS_GCF_2_SPW_R5	17.62	17.19	16.71	16.25	15.68	15.26
GO_CONS_GCF_2_SPW_R4	17.82	17.21	16.85	16.33	15.74	15.31
GO_CONS_GCF_2_TIM_R5	17.80	17.22	16.75	16.31	15.73	15.32
GO_CONS_GCF_2_TIM_R4	17.84	17.20	16.81	16.31	15.77	15.33
GO_CONS_GCF_2_TIM_R3	17.84	17.20	16.82	16.33	15.73	15.29
GO_CONS_GCF_2_DIR_R2	17.84	17.27	16.82	16.31	15.73	15.32
GO_CONS_GCF_2_TIM_R2	17.84	17.20	16.81	16.33	15.80	15.31
GO_CONS_GCF_2_SPW_R2	17.84	17.29	16.81	16.31	15.72	15.33
GO_CONS_GCF_2_DIR_R1	17.84	17.20	16.84	16.32	15.77	15.48
GO_CONS_GCF_2_TIM_R1	17.87	17.28	16.85	16.30	15.79	15.49
GO_CONS_GCF_2_SPW_R1	17.90	17.31	16.95	16.43	15.81	15.65

The trend pattern of the performance of the low-d/o models after the application of SEM is also shown in Figure 6. The performance of the models against terrestrial FA gravity anomalies is very close, and it can also be said that the accuracy continues to improve with an increase in d/o.

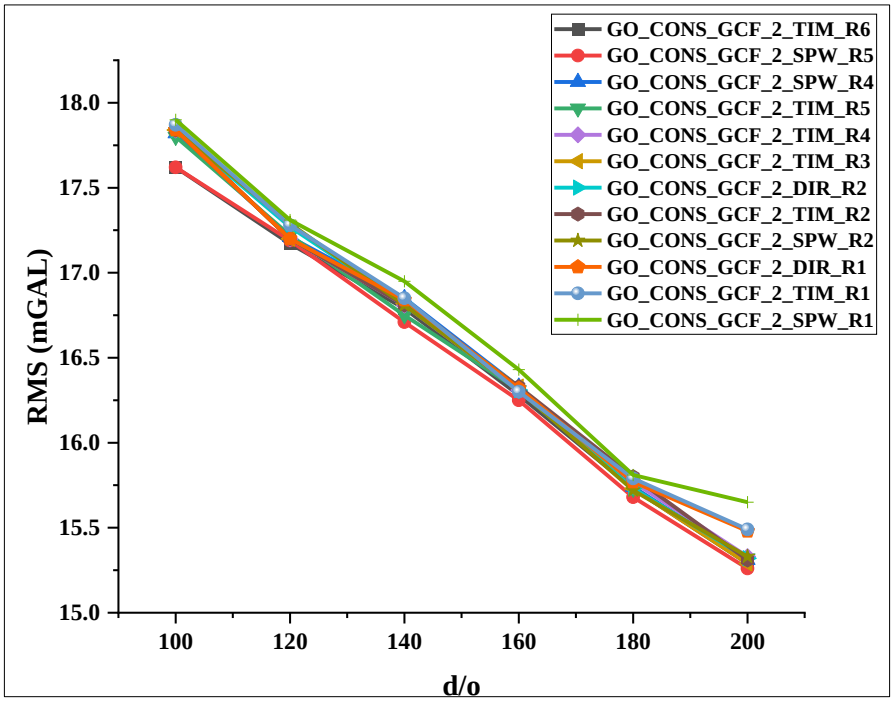

Figure 6- Performance of low d/o GGMs against Terrestrial FA gravity data from d/o 100 to 200 after applying SEM.

CONCLUSION

In this study, a total of sixteen (16) Global Geopotential Models (GGMs) were assessed in Nigeria. Four (4) are high degree and order (d/o) combined models, and the remaining twelve (12) are low d/o satellite-only (GOCE-based) models. These models were evaluated up to their maximum d/o and compared to terrestrial free-air gravity anomaly data before and after applying SEM.

The high d/o models were evaluated separately to select the appropriate model for use in the application of SEM. EGM2008 manifested the best result and was hence used to compensate for the low d/o models from their maximum d/o up to the maximum d/o of EGM2008 (2190).

EGM2008 showed better agreement with the terrestrial FA gravity data before the application of SEM, with an RMS value of 7.91 mGal and the value remained unchanged after applying SEM. Processing the high d/o models as a function of the truncation of d/o from 100 to 200, EGM2008 also provided the best results before and after applying the SEM.

GO_CONS_GCF_2_SPW_R5 on the other hand showed better agreement with the terrestrial FA gravity anomaly data before and after the application SEM with RMS values of 11.12 mGal and 11.09 mGal respectively. Unlike the high d/o models, the low d/o models showed significant improvement after the application of SEM.

The two different types of GGMs used in the present study showed improvements when processed as a function of the truncation of d/o from 100 to 200. The accuracy of GGMs increases with an increase in d/o.

Generally, the study evaluated the performance of GOCE-based GGMs with four (4) other high d/o GGMs over Nigeria, which is the first of its kind in the study area. The study provides insight into the expected accuracy of the use of GGMs in obtaining FA anomalies in the area of interest. However, the collection and densification of more gravity data, particularly in the northern part of the study area, is encouraged.

RECOMMENDATIONS

In this study, the accuracy of twelve (12) GOCE-based GGMs and other four (4) high d/o combined GGMs was tested. SEM was later applied to these models and tested again. Hence, the following recommendations are made:

1. To obtain terrestrial FA gravity anomaly data over Nigeria, models such as EGM2008 and SGG-UGM-2 should be adopted because of their accuracy;
2. High-d/o combined models should be used ahead of those with lower d/o; and
3. Densification of gravity points is also encouraged, especially in the Northern part of the study area.

ACKNOWLEDGEMENT

The authors wish to thank the Tertiary Education Trust Fund (TETFund) for providing the necessary funding for the research as well as the Directorate of Research and Innovation, Nuhu Bamalli Polytechnic Zaria, for seeing this research worthy of being funded. We also thank the Bureau Gravimétrique International (BGI) for providing the terrestrial Free-Air Gravity anomaly data used in carrying out this research.

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