

Research Article



Comparative Study on the Accuracy of Terrestrial and Global Gravitational Models (GGMs) Gravity Anomalies for Akure Environs, Ondo State, Nigeria

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Abstract: Spherical harmonic expansion is a mathematical method used to describe Earth's gravity field, derived from potential coefficients observed both on Earth's surface and from space. The International Centre for Gravity Earth Models (ICGEM) publishes Global Gravitational Models (GGMs), which require validation using terrestrial data to assess their suitability in specific regions. This study evaluates and compares gravity anomalies derived from five GGMs (EGM 2008, GECO, XGM2019e-2159, SGG-UGM-2, and EIGEN-6C4) with terrestrial gravity data over the Akure area of Ondo State, Nigeria. Gravity values and geodetic coordinates from 23 stations were analyzed. Terrestrial gravity data were sourced from previous field surveys, while GGM data were obtained from the International Centre for Global Earth Gravity Model (ICGEM). The study computed and compared free-air and Bouguer anomalies with mean differences ranging from -1.725 to 6.800 mGal (with standard errors between 1.058 to 1.965 mGal) for free-air anomalies, and -2.107 to 4.546 mGal (with standard errors between 0.773 to 1.041 mGal) for Bouguer anomalies. Statistical analyses revealed that the EGM 2008, GECO, and XGM 2019e-2159 models provided the best-fit with terrestrial measurements. These models can thus serve as reliable alternatives or complements to terrestrial gravity data for geoid determination in the Akure region. The study identifies EGM2008, GECO, and XGM2019e_2159 as the most suitable GGMs for geophysical applications in this area.

Keywords: Gravity Anomalies, Global Gravitational Model, Terrestrial, Accuracy

INTRODUCTION

The historical scarcity of gravity observations on Earth's surface can be attributed to the laborious and time-consuming techniques traditionally involved, which limited our understanding of global gravity variations, especially for applications such as geoid determination (Apeh et al., 2018). The geoid, defined as an equipotential surface of the Earth's gravity field, is determined through precise gravity measurements, with adjustments made to account for topographic and oceanic influences. Gravity measured at any point on Earth's surface is affected by multiple sources, including Earth's rotation, distance from the geocenter, topographic relief, tidal variations, and fluctuations in gravimeters (Yilmaz et al., 2018). Accurate modelling requires isolating and subtracting these influences using reliable Earth models.

Recent advancements in geodesy have been driven by satellite missions such as the Gravity Recovery and Climate Experiment (GRACE), which enable the observation of gravity variations from space. Despite these advances, there remains a critical need for ground-based gravity measurements to validate and enhance satellite-derived solutions, especially in regions where satellite coverage is limited or data quality is compromised (Šprlák et al., 2012).

Gravity anomalies which are the departures of the observed gravity from a reference value serve as key indicators of subsurface structure and are widely used in geophysical investigations (Yilmaz & Kozlu, 2018). While terrestrial gravity measurements have long been the standard for accurate anomaly determination, Global Gravitational Models (GGMs) are increasingly used as a more accessible and cost-effective alternative (Abd-Elmotaal et al., 2018; Tugi et al., 2016). GGMs offer extensive spatial coverage, making them especially useful for large-scale applications and geoid modelling. However, concerns persist about their reliability and accuracy when compared to locally acquired terrestrial gravity data. This uncertainty arises due to varying data quality, calibration techniques, and modelling assumptions employed by different data providers (Tugi et al., 2016).

Therefore, it becomes imperative to thoroughly evaluate the accuracy of GGM-derived gravity anomalies by comparing them with terrestrial measurements. Such evaluations help ensure the reliability of geophysical interpretations and inform the selection of the most appropriate geoid model for a specific region. Although GGMs provide continuous spatial data, especially in remote or data-sparse regions, their limitations such as reduced resolution, model truncation errors, and reliance on assumptions about topographic mass distribution can lead to significant discrepancies at local scales. These inaccuracies are particularly critical in regions with complex geology, such as Akure, where localized local variations may significantly influence gravity signals.

Several studies such as [Yilmaz \(2023\)](#), [Yilmaz et al. \(2016\)](#), and [Tata et al. \(2019\)](#) underscore the importance of such evaluations. [Yilmaz et al. \(2018\)](#) emphasized the necessity of validating GGM-derived anomalies with terrestrial data. [Jekeli et al. \(2013\)](#) evaluated the effectiveness of combining terrestrial and airborne gravity anomaly measurements for geoid determination in South Korea. The study's findings indicate that geoid undulation can be determined with a standard deviation of 6 cm, in comparison to geoid undulations obtained from GPS/levelling data. However, the study emphasizes that failure to appropriately consider the gravitational impact of the topographic masses above the geoid can result in a significant bias of approximately 8 mgal in gravity anomalies, potentially causing errors in geoid height biases of up to 10 cm. In another study conducted by [Saari & Bilker-Koivula \(2015\)](#), height anomaly discrepancies of about 15 cm and gravity anomaly differences of about 10 mgal were found in Finland as a result of an analysis of satellite-based GGMs using terrestrial data. [Huang & Véronneau \(2009\)](#) found that the RMS difference between gravity anomalies generated from GGM and terrestrial gravity data was 5 mgal on sea and lake surfaces in Canada, but 14 mgal on land, indicating that the RMS shows a height-dependent trend. [Moka & Apeh \(2017\)](#) conducted research on the fit of GGMs over terrestrial gravity data in part of South East Nigeria. Terrestrial absolute gravity data collected from the Nigerian Geological Survey Agency were used to analyze six models, revealing RMSE ranging from 1.286 to 3.708 mGal when compared to terrestrial gravity data. The study also found a strong inverse (negative) correlation between estimated absolute gravity values and ellipsoidal height. In a similar investigation, [Apeh et al. \(2018\)](#) explored the assessment of gravity data derived from GGMs using terrestrial gravity data in Enugu state, Nigeria. The results revealed RMS differences ranging from 9.530 mgal to 37.113 mgal between the estimated bouguer anomalies from the ICGEM website and their positionally corresponding terrestrial bouguer anomalies. [Apeh & Tenzer \(2022\)](#) also developed a tailored gravity model (TGM) utilizing GGMs, terrestrial gravity data, and Digital Elevation Models (DEMs). The TGM was constructed by computing gravity values from the XGM2019e_2159 global model on a topographic surface generated using the Multi-Error-Removed Improved-Terrain (MERIT) DEM. Residual gravity effects from the SRTM2gravity global model were algebraically incorporated, with the removal of a detected systematic bias. Independent statistical evaluation revealed discrepancies within ± 10 mgal, an improved RMS from 16.7 to 6.4 mgal, and successful bias elimination. [Yilmaz & Kozlu \(2018\)](#) also compared the precision of three recent high-degree GGMs (WGM2012 model, GECO model and EIGEN6C4 model). Gravity anomalies (free-air and bouguer) were computed using these models over a predetermined study area in Turkey. Evaluation of the models shows that, WGM2012 exhibited the least standard deviation (13.45 mGal) and RMSE (15.42 mGal) for free-air gravity anomaly residuals, while EIGEN6C4 demonstrated the least standard (8.05 mGal) and RMSE (8.12 mGal) for bouguer gravity anomaly residuals when compared with corresponding terrestrial gravity data.

Despite these global efforts, there remains a notable gap in research evaluating the performance of GGMs relative to terrestrial gravity data specifically in the Akure environs, Ondo State, Nigeria. This study aims to address this gap and identify the GGM(s) most suitable for gravity anomaly applications in the region. Akure was chosen as the study area due to its diverse geological formations and significant topographic variability, which make it an ideal setting for assessing the performance and limitations of GGMs.

Given the importance of accurate gravity data for applications such as orbit determination, inertial navigation, and geophysical exploration, this study evaluates the accuracy of Bouguer and free-air gravity anomalies derived from five (5) recent GGMs i.e. EGM2008 ([Pavlis et al., 2012](#)), GECO ([Gilardoni et al., 2016](#)), XGM2019e_2159 ([Zingerle et al., 2020](#)), SGG-UGM-2 ([Liang et al., 2020](#)), and EIGEN-6C4 ([Foerste et al., 2014](#)) against terrestrial measurements. The findings will determine the extent to which GGMs can serve as substitutes or complements to direct observations in the Akure area.

To achieve the aim of this research, the specific objectives are to:

- i. Compare the accuracy of terrestrial and GGM-derived gravity anomalies in the Akure environs
- ii. Determine the level of correlation between the terrestrial and GGM-derived datasets

- iii. Assess the reliability and suitability of GGMs data for geoid model determination in the study area.

Overview of Gravity Anomalies under Investigation

The difference between an observed gravity value (g) reduced to the geoid and a normal, or theoretical, computed gravity value (γ), at the mean Earth ellipsoid, at the projection of the same terrain point on the geoid and the ellipsoid, respectively, is termed the gravity anomaly (Δg) (Barthelmes, 2013) as expressed in Eq. (1):

$$\Delta g = g_p - \gamma \quad (1)$$

A series of gravity corrections is applied to the measured gravity to classify gravity anomalies into free air and Bouguer anomalies. The computation of gravity anomalies is commonly referred to in geodetic literature as a reduction technique, wherein observable gravity is reduced to the geoid (Barthelmes, 2013). Here, Δg represents the gravity anomaly, g_p is the gravity reduced to the geoid and γ is the normal gravity reduced to the ellipsoid.

Gravity anomalies can be obtained through both terrestrial observations and satellite measurements. Terrestrial gravity anomalies denote variations in the Earth's gravitational field measured directly on the ground using specialized instruments known as gravimeters. These measurements are conducted at specific locations within a study area to determine gravitational acceleration, offering valuable insights into subsurface density distribution and geological structures.

Alternatively, gravity anomalies can be derived from satellite measurements and accessed through online databases or software tools. These measurements are collected by dedicated satellite missions, such as the Gravity Recovery and Climate Experiment (GRACE) or the Gravity Field and Steady-State Ocean Circulation Explorer (GOCE). These missions are specifically designed to measure the Earth's gravity field from space, providing a broader perspective on gravity anomalies.

Free Air Gravity Anomaly

The free air gravity anomaly is calculated by applying the free air correction to the difference between the measured gravity reduced to the geoid and the theoretical gravity derived on a specific ellipsoid. The model presented by Hackney & Featherstone (2003) for computing the free air anomaly is expressed as:

$$\Delta g_{FA} = (g_{obs} - \gamma_o + 0.3086H)mGal \quad (2)$$

Where Δg_{FA} is the free air anomaly, g_{obs} is the observed gravity, γ_o is the theoretical / normal gravity and H is the orthometric height.

Bouguer Gravity Anomaly

There are two forms of Bouguer anomalies: simple and complete. The simple Bouguer gravity anomaly does not account for topographic/terrain influences in its calculations. It is derived by applying the Bouguer correction solely to the gravity anomaly in free air. The model for computing the simple Bouguer gravity anomaly, according to Hackney & Featherstone (2003), is expressed as:

$$\Delta g_{SB} = (\Delta g_{FA} - 0.0419\rho H)mGal \quad (3)$$

Here Δg_{SB} represents the simple Bouguer Gravity Anomaly and ρ is the density.

When a terrain adjustment is applied to the basic Bouguer gravity anomaly, the result is the computation of the full (complete) Bouguer gravity anomaly. The model for calculating the complete Bouguer gravity anomaly, as described by Barthelmes (2013), is given by:

$$\Delta g_{CB} = (\Delta g_{SB} + TC)mGal \quad (4)$$

Here Δg_{CB} is the complete Bouguer Gravity Anomaly, and TC represents the Terrain Correction.

Global Geopotential Models

A Global Geopotential Model (GGM) is a series of spherical harmonic coefficients, as represented by Equation 5, capturing Earth's gravitational field in various wavelengths (Barthelmes, 2013). Users of GGMs can leverage the position of a point of interest and account for propagated errors in the

parameters defining the GGM to compute values related to gravity functionals, including gravity anomalies, geoid heights, and height anomalies. Additionally, they can estimate the expected errors associated with these functionals (Apeh et al., 2018).

Typically, the gravitational potential of the Earth outside its masses is represented by a set of fully normalized spherical harmonic coefficients, denoted as $C_{l,m}^-$, $S_{l,m}^-$, constituting a global gravity field model. The gravitational potential, VE , can be expressed as a series of fully normalized solid spherical harmonics outside the Earth as in Eq. (5) (Apeh et al., 2018; Wenzel, 2005).

$$VE(r, \theta, \lambda) = \frac{GM_E}{r} \sum_{l=0}^{L_{max}} \left(\frac{a}{r}\right)^l \sum_{m=0}^l (\bar{C}_{l,m} \cos m\lambda + \bar{S}_{l,m} \sin m\lambda) \bar{P}_{l,m}(\cos\theta) \quad (5)$$

Where GM_E is the Earth's gravitational constant, a is the semi-major axis of the reference ellipsoid, $\bar{C}_{l,m}$, $\bar{S}_{l,m}$ are the fully normalized spherical harmonic coefficients, $\bar{P}_{l,m}$ is the fully normalized associated Legendre functions of the first kind, l is the degree, m is the order, r is the radius (geocentric distance), λ is the spherical longitude, θ is the polar distance (spherical colatitude) l_{max} is the maximum degree of expansion.

The formula for the expansion of gravity anomaly in a series of spherical coordinates is given in Eq. (6) (Apeh et al., 2018; Wenzel, 2005).

$$\Delta g_{sa} = \frac{GM_E}{r^2} \sum_{l=2}^{L_{max}} \left(\frac{a}{r}\right)^l (l-1) \sum_{m=0}^l (\Delta \bar{C}_{l,m} \cos m\lambda + \Delta \bar{S}_{l,m} \sin m\lambda) \bar{P}_{l,m}(\cos\theta) \quad (6)$$

Where Δg_{sa} is the Gravity anomaly in spherical approximation.

Study Area

The research area is in Akure Township, Ondo State, Nigeria's south-western region. It was located within Akure South Local Government Area of Ondo State, between Latitude 07° 15' N and 07° 30' N of the Equator, and Longitude 05° 15'E and 05° 25'E of the Greenwich Meridian. Akure's topography is generally undulating, with a rugged terrain consisting of hills and valleys, with elevations ranging from 330m above Mean Sea Level (MSL) in the southwest border (Nigerian Army Barracks) to 399m in the north eastern border (Shagari estate), as shown in Figure 1 (Tata & Ono, 2018).

Geologically, Akure lies within the Precambrian Basement Complex of southwestern Nigeria, composed mainly of granitic gneisses, migmatites, and older granites (Owoyemi et al., 2000). These rock formations are known to cause heterogeneous mass distributions that influence local gravity fields. The presence of rugged terrain and variable lithology makes Akure a compelling location for evaluating how well GGMs replicate terrestrial gravity anomalies, particularly in regions with complex subsurface structures.

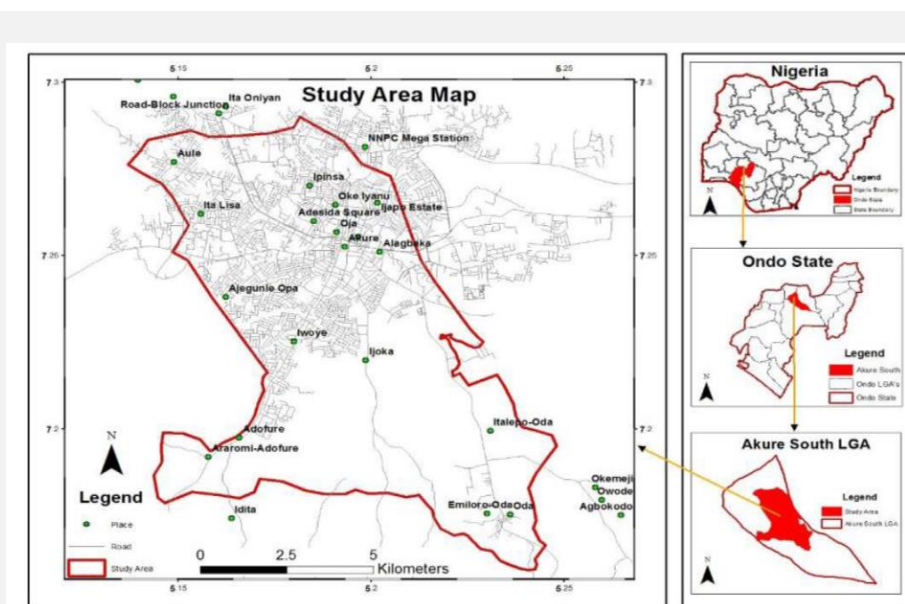


Figure 1. Map of the study area.

MATERIALS & METHODS

Methodology

In this study, data collection involved the gathering of terrestrial gravity values and geodetic coordinates from twenty-three (23) control points. The terrestrial gravity measurements were conducted by professionals affiliated with the National Geological Survey Agency (NGSA) in Nigeria. Both the gravity base station at Akure Post Office and the base station at Saint Peter’s College Akure served as control points. Gravity values at all control stations were determined using a Lacoste and Romberg (G-512 series) gravimeter with an accuracy of ±0.01 mgal. South differential Global Positioning System (DGPS) was employed in static mode to determine the positions and ellipsoidal heights of each point. Corrective measures such as latitude, drift, tide, free air, and Bouguer corrections were applied to ensure accuracy. By utilizing the international gravity formula of geodetic system 1930 for normal gravity computation (Eq.7), the gravity anomaly for each observed point within the study area was derived.

$$\gamma_0 = 9.78049(1+0.0052884\sin^2\varphi - 0.0000059\sin^2 2\varphi) \text{ m.s}^{-2} \tag{7}$$

Additionally, gravity anomalies were acquired from five recent Global Geopotential Models (GGMs): SGG-UGM-2, GECO, EIGEN-6C4, XGM2019e2159, and EGM2008. The GGM characteristics are detailed in Table 1.

Table 1. GGM models with properties

| S/N | Model | Maximum degree | Year | Data |
|-----|--------------|----------------|------|----------------------------------|
| 01 | SGG-UGM-2 | 2190 | 2020 | EGM2008, S(GOCE) |
| 02 | GECO | 2190 | 2015 | EGM2008, S(GOCE) |
| 03 | EIGEN-6C4 | 2190 | 2014 | A,G,S(GOCE), S(GRACE), S(LAGEOS) |
| 04 | XGM2019e2159 | 2190 | 2020 | A,G,S(GOCE), S(GRACE), |
| 05 | EGM2008 | 2190 | 2008 | A, G, S (GRACE) |

Where S is for satellite (e.g., GRACE, GOCE, LAGEOS), A is for altimetry, and G is for ground data (e.g., terrestrial, shipborne and airborne measurements). T for Topography.

The terrestrial gravity data underwent reduction through the application of free-air and Bouguer corrections, computed using equations 2 and 3, respectively. The calculation of Bouguer and free-air anomalies for the chosen models was executed through the ICGEM Calculation Services, illustrated in Figure 2. The process involved uploading the (control) points to be determined in Excel (CSV) format on the site. Subsequently, each Global Geoid model was selected in the model selection section, and Bouguer and free-air anomalies were computed by clicking the calculation button.

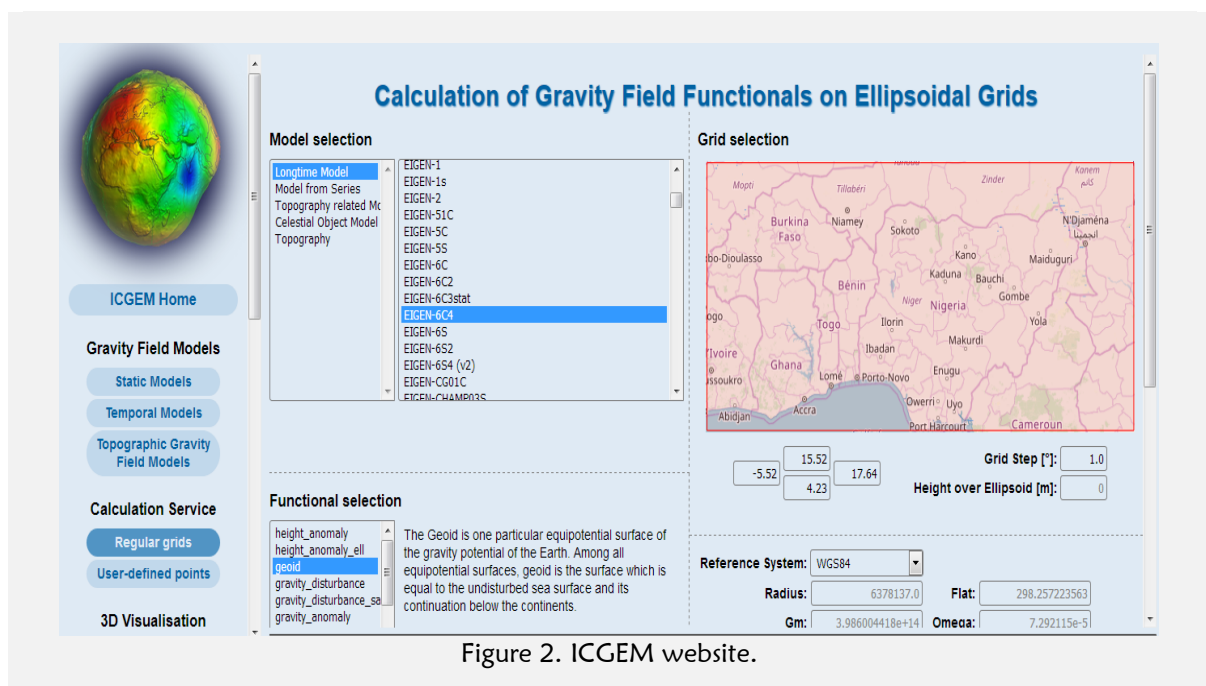


Figure 2. ICGEM website.

Although the terrestrial gravity measurements were conducted using a high-precision Lacoste and Romberg gravimeter (G-512 series) with an accuracy of ± 0.01 mGal and under professional supervision, several potential sources of bias could affect the data quality. The gravimeter was carefully calibrated prior to data collection to ensure accurate readings. Environmental factors such as temporal gravity variations caused by tides, atmospheric pressure changes, and local vibrations may introduce noise or small deviations. However, these factors were addressed by applying standard corrections for latitude, drift, tide, and other relevant influences, minimizing biases and enhancing data reliability.

Additionally, potential errors from the Bouguer correction mainly due to assumptions about subsurface density and terrain effects were minimized through the use of carefully selected terrain correction value. These steps helped to reduce inaccuracies arising from complex local geology in the Akure region. While residual errors from instrument calibration and operational factors may still exist, the comprehensive correction procedures provide a balanced and robust terrestrial dataset for comparison with GGM-derived gravity anomalies.

The gravity anomalies derived from the GGMs were compared with terrestrial gravity anomalies using statistical metrics, including mean, root mean square error (RMSE) and standard deviation (SE), to assess the differences between the two datasets. Additionally, correlation analysis was conducted to reveal the relationship between terrestrial and GGMs' free-air and Bouguer gravity anomalies for each of the five models. The objective was to determine the best-fit model for the study area, as illustrated in Figure 3.

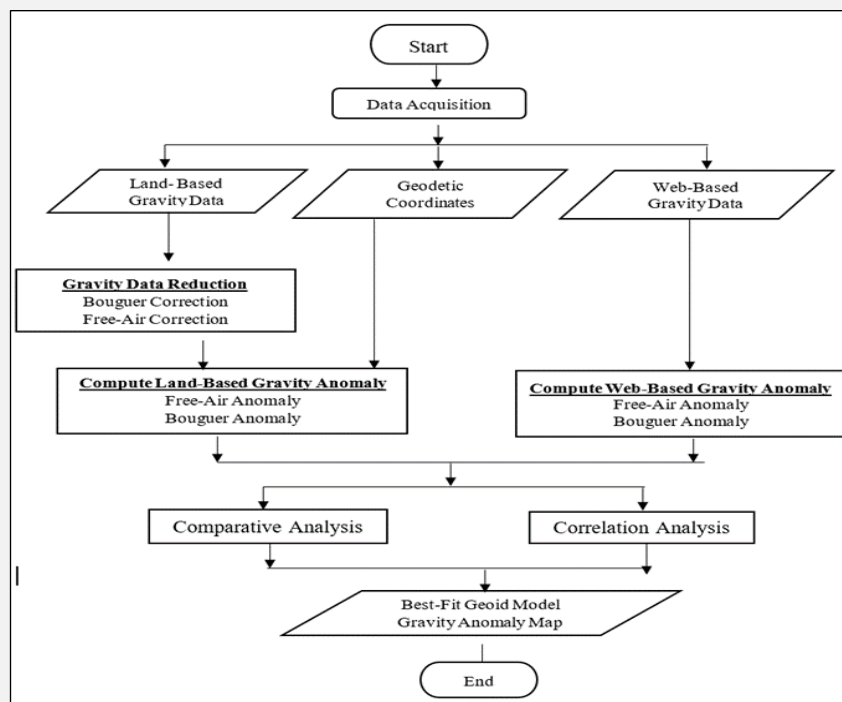


Figure 3. Flow chart of the research methodology.

Hypothesis Testing

In this study, t-distribution statistics was used to test whether there is any significant difference in the variances obtained from the two methods (terrestrial and GGM). The hypothesis testing is stated below;

Null Hypothesis (H_0): The variances obtained are not significantly different (Null hypothesis = $H_0: \delta_1^2 = \delta_2^2$).

Alternative Hypothesis (H_1): There is a significant difference in the variances obtained (Alternative hypothesis = $H_1: \delta_1^2 \neq \delta_2^2$).

The decision rule is as follows: If the calculated t-statistic exceeds the critical t-value at a 0.05 significance level, then the null hypothesis (H_0) is rejected in favor of the alternative hypothesis (H_1).

RESULTS & DISCUSSION

The study results include statistics detailing the differences between terrestrial and GGMs Bouguer anomalies (Table 2), as well as differences in free-air anomalies (Table 3). T-test comparisons for both free-air and Bouguer anomalies are presented in Tables 4 and 5, respectively. Additionally, Tables 6 and 7 outline the relationships between terrestrial and GGMs' free-air and Bouguer anomalies.

The terrestrial Bouguer anomaly was compared with the computed Bouguer anomalies from each GGM. Table 2 presents the statistical differences, including minimum value, maximum value, root mean square error (RMSE), and standard error (SE). Notably, the difference between the terrestrial and EGM 2008 showed the least root mean square error of 4.228 mGal, with a standard error of 0.882 mGal, outperforming other GGMs. This result suggests that EGM 2008 is the most suitable global geoid model among the five considered for computing Bouguer anomalies in the Akure area.

Table 2. Statistics of differences between the terrestrial and GGMs Bouguer anomalies

| Model names | Min. (mGal) | Max. (mGal) | RMSE (mGal) | SE (mGal) |
|-----------------------------|-------------|-------------|-------------|-----------|
| Terrestrial - EGM 2008 | -6.385 | 5.202 | 4.228 | 0.882 |
| Terrestrial – GECO | -2.3 | 9.427 | 4.529 | 0.944 |
| Terrestrial - XGM2019e-2159 | -2.161 | 10.498 | 4.890 | 1.020 |
| Terrestrial - SGG-UGM-2 | 0.604 | 12.156 | 6.416 | 1.338 |
| Terrestrial - EIGEN-6C4 | 0.967 | 12.636 | 6.783 | 1.414 |

Table 3 presents the statistical differences between terrestrial and Global Geoid Models (GGMs) in terms of free-air anomalies, including minimum and maximum values, RMSE, and SE. The difference between terrestrial and GECO exhibits the least RMSE of 3.342 mGal, with a standard error of 0.697 mGal, surpassing differences with other GGMs. This result suggests that GECO is the most suitable model among the five GGMs considered when computing free-air anomalies in the study area.

Table 3. Statistics of differences between the terrestrial and GGMs free-air anomalies

| Model names | Min. (mGal) | Max. (mGal) | RMSE (mGal) | SE (mGal) |
|-----------------------------|-------------|-------------|-------------|-----------|
| Terrestrial - EGM 2008 | -7.514 | 7.154 | 4.049 | 0.844 |
| Terrestrial – GECO | -3.312 | 11.376 | 3.342 | 0.697 |
| Terrestrial - XGM2019e-2159 | -2.72 | 12.448 | 3.757 | 0.783 |
| Terrestrial - SGG-UGM-2 | -0.527 | 14.106 | 5.112 | 1.066 |
| Terrestrial - EIGEN-6C4 | -0.066 | 14.585 | 5.487 | 1.144 |

Figure 4 illustrates the variation of Bouguer anomalies for five GGMs across the study stations, comparing them with terrestrial Bouguer anomalies. Each colored line represents the Bouguer anomaly for a specific GGM, while the dotted blue line represents the terrestrial Bouguer anomaly. The close alignment of the colored lines with the terrestrial anomaly indicates their relative accuracy. Notably, the red line, representing EGM2008, closely aligns with the terrestrial Bouguer anomaly, suggesting it as the best-fit model for the Bouguer anomaly in the study area.

Figure 5 displays the variation of free-air anomalies for the same five GGMs, comparing them with terrestrial free-air anomalies. The blue line represents the terrestrial free-air anomaly, and each colored line represents the free-air anomaly for a specific GGM. The close alignment of the colored lines with the terrestrial anomaly indicates their relative accuracy. Specifically, the grey line, representing GECO, closely aligns with the terrestrial free-air anomaly, further supporting its suitability as the best-fit model for this parameter.

Table 4 displays the results of a t-test comparing terrestrial and GGMs' free air anomalies for the five models. For the EGM 2008 model, the mean difference between terrestrial and GGM measurements is negative (-1.725), indicating that terrestrial measurements are larger on average. However, this difference is not statistically significant ($p=0.125$), suggesting comparable accuracy for both measurement methods. For the GECO and XGM2019e-2159 models, the mean differences are positive (2.286 and 2.792, respectively), with the differences statistically significant at the 5% level (p -values 0.043 and 0.013). This indicates that GGM measurements tend to be larger, suggesting slight biases or regional variations captured differently by these models. The SGG-UGM-2 and EIGEN-6C4 models show notably larger mean differences (6.80 and 5.544, respectively), significant at the 1% level indicating substantial

discrepancies with terrestrial data. This implies these models may be less suitable for local gravity anomaly estimation in the study area.

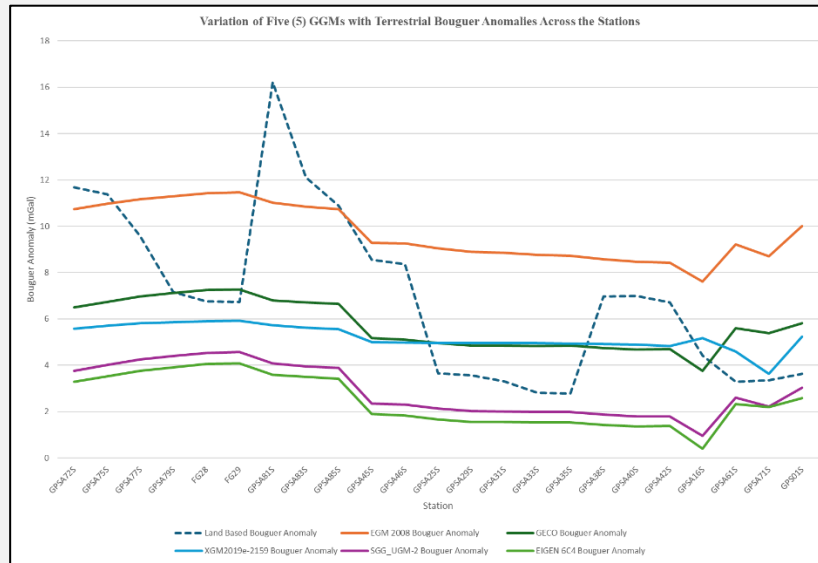


Figure 4. Plot of variation of five GGMs with terrestrial (land-based) Bouguer anomalies.

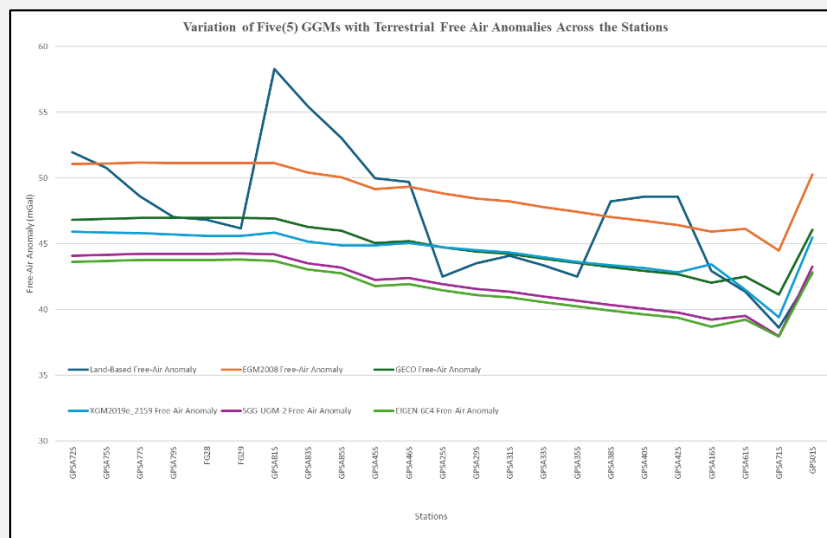


Figure 5. Plot of variation of five GGMs with terrestrial (land-based) free air anomalies.

Table 4. T-test comparison for the free air anomaly for the five models

| Models | Mean difference (mGal) | Standard error (mGal) | T-statistic | 95% confidence interval | P-value |
|---------------|------------------------|-----------------------|-------------|-------------------------|-----------|
| EGM 2008 | -1.725 | 1.094 | -1.576 | -3.96 ± 0.51 | 0.125** |
| GECO | 2.286 | 1.077 | 2.122 | 0.081 ± 4.91 | 0.043** |
| XGM2019e-2159 | 2.792 | 1.058 | 2.638 | 0.619 ± 4.964 | 0.013** |
| SGG-UGM-2 | 6.80 | 1.965 | 3.462 | 2.815 ± 10.784 | 0.0014*** |
| EIGEN-6C4 | 5.544 | 1.08 | 5.134 | 3.335 ± 7.755 | 0.000*** |

***Significant at 1% level, ** Significant at 5% level

Table 5 presents the t-test results comparing terrestrial and GGM Bouguer anomalies. For EGM 2008, the mean difference is negative and statistically significant (-2.107, $p < 0.001$), indicating terrestrial

measurements tend to be larger. While statistically significant, the moderate magnitude of this difference suggests both methods can be used with caution, depending on the precision required. For GECO and XGM2019e-2159 models, mean difference are positive (1.287 and 1.793), with statistical significance observed only in XGM2019e-2159 at the 5% level. The SGG-UGM-2 and EIGEN-6C4 models again exhibit large, statistically significant differences, reinforcing their limited applicability for Bouguer anomaly estimations in Akure.

Table 5. T-test Comparison for the Bouguer anomaly for the five models

| Models | Mean difference (mGal) | Standard error (mGal) | T-statistic | 95% Confidence interval | P-value |
|---------------|------------------------|-----------------------|-------------|-------------------------|----------|
| EGM 2008 | -2.107 | 1.041 | -2.024 | -4.205 ± -0.009 | 0.049** |
| GECO | 1.287 | 0.795 | 1.619 | -0.348 ± 2.923 | 0.117** |
| XGM2019e-2159 | 1.793 | 0.773 | 2.319 | 0.194 ± 3.391 | 0.029** |
| SGG-UGM-2 | 4.109 | 0.799 | 5.141 | 2.466 ± 5.752 | 0.000*** |
| EIGEN-6C4 | 4.546 | 0.798 | 5.696 | 2.905 ± 6.187 | 0.000*** |

***Significant at 1% level, ** Significant at 5% level

Tables 6 and 7 summarize the correlation between terrestrial gravity anomaly values and those derived from five Global Gravity Models (GGMs) for both free-air and Bouguer anomalies. For free-air anomalies (Table 6), the EGM2008, GECO, and XGM2019e_2159 models exhibit strong positive correlations with terrestrial data, with correlation coefficients of 0.597, 0.597, and 0.581, respectively. The EIGEN-6C4 model also shows a strong positive correlation (0.594), while the SGG-UGM-2 model demonstrates a weak and statistically insignificant negative correlation (-0.121, p=0.582), highlighting its poor agreement with terrestrial measurements in the study area.

Table 6. Relationship between the terrestrial and GGMs free air anomaly

| Models | Free-air anomaly | | | | |
|--------------------------|---------------------|---------------------|---------------------|---------------------|---------------------|
| | (1) | (2) | (3) | (4) | (5) |
| Terrestrial (1) EGM 2008 | 0.597 (0.003)*** | | | | |
| (2) GECO | | 0.596 (0.003)*** | | | |
| (3)XGM2019e-2159 | | | 0.581 (0.004)*** | | |
| (4) SGG-UGM-2 | | | | -0.121 (0.582)** | |
| (5) EIGEN-6C4 | | | | | 0.595 (0.003)*** |

***Significant at 1% level, ** Significant at 5% level

Table 7. Relationship between the terrestrial and GGMs Bouguer anomaly

| Models | Bouguer anomaly | | | | |
|--------------------------|-------------------|---------------------|---------------------|---------------------|---------------------|
| | (1) | (2) | (3) | (4) | (5) |
| Terrestrial (1) EGM 2008 | 0.44 (0.036)** | | | | |
| (2) GECO | | 0.598 (0.003)*** | | | |
| (3)XGM2019e-2159 | | | 0.596 (0.003)*** | | |
| (4) SGG-UGM-2 | | | | 0.614 (0.002)*** | |
| (5) EIGEN-6C4 | | | | | 0.595 (0.003)*** |

***Significant at 1% level, ** Significant at 5% level

For Bouguer anomalies (Table 7), all five models exhibit positive correlations with terrestrial data. The GECO, XGM2019e_2159, SGG-UGM-2, and EIGEN-6C4 models show strong positive correlations, with coefficients of 0.598, 0.596, 0.614, and 0.595, respectively. The EGM2008 model shows a moderate positive correlation of 0.44. These results suggest that, overall, the GECO, XGM2019e_2159, and EIGEN-6C4 models consistently align well with terrestrial observations for both anomaly types.

Discussion of Result

This study statistically evaluated the accuracy of GGMs gravity anomalies computed from five recent models, considering both free air and Bouguer anomaly components. The accuracy of GGM-derived Bouguer and free air anomalies with respect to terrestrial Bouguer and free air anomalies is assessed by the proximity of the RMSE value to zero. A smaller RMSE value indicates better accuracy, while a larger RMSE value suggests low accuracy. The comparison revealed that the difference between the terrestrial Bouguer anomaly and the EGM 2008 Bouguer anomaly had the least RMSE of 4.228 mGal (Table 2), suggesting that EGM 2008 is the best-fit GGM among the models for computing the Bouguer anomaly. Similarly, the comparison of free-air anomalies showed that the difference between the terrestrial and GECO anomalies had the least RMSE of 3.342 mGal (Table 3), indicating that GECO is the best-fit GGM for free-air anomaly computations among the models used. Similarly, the reliability of the structure of the signal in GGM-derived Bouguer and free air anomalies to terrestrial Bouguer and free air anomalies is determined by the correlation coefficient's proximity to ± 1 . A correlation coefficient nearing ± 1 signifies a more accurate representation of the signal structure, whereas a coefficient deviating further from ± 1 indicates a less accurate representation of the signal structure at each control station. For free air anomalies, the first three models (EGM 2008, GECO, and XGM2019e-2159) exhibited strong positive correlations, while the SGG-UGM-2 model showed a weak negative correlation. Similarly, for Bouguer anomalies, the EGM 2008 model indicated a moderate positive correlation, while the other models demonstrated strong positive correlations.

The superior performance of the EGM 2008 model for Bouguer anomalies in the Akure region can be attributed to its higher spatial resolution and incorporation of extensive terrestrial gravity data during its development. These characteristics enable EGM 2008 to better capture localized gravity variations caused by the region's complex geology and diverse topography. In contrast, the GECO model's strength in modeling free-air anomalies stems from its integration of recent satellite gravity measurements and updated geopotential coefficients, which more accurately reflect the surface and near-surface mass distribution of the area. This makes GECO particularly suitable for free-air anomaly applications in Akure's geophysical context.

These results align with findings from other regional studies worldwide. For instance, a study by Kamto et al. (2020) assessed the accuracy of the EGM2008 model in the mountainous regions of Cameroon, finding that the model effectively captured localized gravity variations, similar to our findings in the Akure region. Additionally, research by Narayan et al. (2023) evaluated the GECO model's performance in the Bay of Bengal, reporting strong correlations between GECO-derived, XGM2019e-2159-derived and terrestrial free-air anomalies, aligning with our results in Akure. These comparisons underscore the applicability of EGM2008, GECO, and XGM2019e-2159 models in diverse geological settings.

The results underscore important implications for the practical use of GGMs as alternatives to terrestrial gravity measurements in applied geosciences. In regions where terrestrial data acquisition is hindered by logistical, financial, or environmental constraints, high-performing models such as EGM 2008 and GECO can offer viable, cost-effective substitutes for geodetic and geophysical applications. For instance, in local geoid modeling, these models can support preliminary height system development, especially in regions lacking dense gravity data. Additionally, the relatively low RMSE values and strong correlations observed for some models suggest that they may be suitable for broad-scale geological mapping and initial stages of mineral/resource exploration, where rapid gravity anomaly estimates are required to delineate large-scale subsurface features. However, the statistically significant differences in Bouguer anomalies between GGM-derived and terrestrial values indicate that GGMs may fail to account for localized geological variations, such as density heterogeneities or terrain-induced gravitational effects, which are critical in high-resolution geophysical surveys. Therefore, while GGMs provide a strong foundation for gravity-based investigations, their integration with high-resolution terrestrial gravity data remains essential for improving accuracy in detailed applications such as subsurface modeling, infrastructure planning, or environmental geophysics. Regional validation of GGMs should also be prioritized to identify the most suitable models for specific geological environments.

CONCLUSION

This research has statistically evaluated the accuracy of five (5) GGMs using terrestrial (land-based) free-air and Bouguer gravity anomalies measured across twenty-three (23) control stations in Akure, Ondo State, Nigeria. The results revealed that the EGM 2008 model has the least RMSE when compared to terrestrial Bouguer anomalies, making it the most suitable for Bouguer gravity computations in the study area. Similarly, the GECO model exhibited the lowest RMSE when compared to terrestrial free-air anomalies, indicating its superiority for free-air applications. These findings demonstrate that models like EGM 2008, GECO, and XGM2019e_2159 can be used either independently or in conjunction with terrestrial data to improve gravity-based geophysical investigations in Akure and similar regions. To enhance the accuracy of geophysical modeling, future applications should consider hybrid approaches that integrate high-resolution terrestrial gravity data with satellite-derived GGMs. Such integration can help mitigate the limitations of individual datasets, particularly in areas with complex terrain or heterogeneous geology. Further research should also explore the incorporation of detailed topographic data to improve local gravity field estimates. Additionally, conducting comparative analyses across diverse geological settings is recommended to better understand the limitations of GGMs and enhance their global applicability.

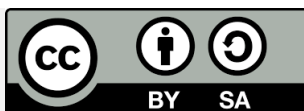
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