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Research Article

Validation of GOCE Gravity Data, Using Terrestrial Observed Gravity Anomalies Over Enugu State, Nigeria

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ABSTRACT

Gravity Recovery and Ocean Circulation Explorer (GOCE) is one of the gravity data that can be used for the determination of gravity field parameters such as the deflection of the vertical component, geoid height etc. GOCE mission was aimed at measurement of gravity field anomalies with accuracy of 10-2ms-2 and to determine the geoid with an accuracy of 1-2cm.The use of this GOCE data in an area, just like any other global geo-potential model (GGM) will depend on its fit to the terrestrial observed values. The main thrust of this paper is to validate GOCE data over terrestrial observed gravity anomalies for one hundred and fifteen points where bouguer gravity anomaly has been computed over Enugu State in Nigeria. The computed gravity anomaly obtained using the GOCE data was compared to the one obtained terrestrially for the entire points. The maximum and minimum difference was 0.064768m/gal and 29.62059m/gal. The root mean square error is 13.79396, 14.42247 and 13.09670 for the different epochs R3, R4, R5 respectively. It was found that GOCE derived gravity values cannot be used in Nigeria to represent point values because it has a long wavelength of measurement. It may however be considered for a reference for geoid computation where it takes care of the long wavelength as part of the gravity field.

Key words: Gravity Anomalies, Geopotential Model, GOCE, Geoid, Gravity

INTRODUCTION

The earth gravity field and its time variation are essential in the study of fundamental earth processes such as mantle convection, plate tectonic, fluid mass transport both on the surface (e.g., ocean and atmospheric circulation, and hydrology, ice sheet) and in the core (Fubara, Fajimirokun, & Ezigbo). The gravity field of the earth is critical in such areas as positioning and navigation, metrology, geophysics, geodynamics, oceanography, cryospheric sciences and other disciplines related to the earth's climate and environment (Torge and Muller). The accurate determination of the gravity field and its temporal variations is one of the three fundamental pillars of modern geodesy (besides of geometry and earth rotation) (Torge & Muller, Fubara; Agajelu) [1-3].

Terrestrial gravity observation is a very tedious process but precise in meeting the geodynamic and geopotential need of the local area. However, Satellite method such as Gravity Recovery and Climate Experiment (GRACE), Challenging Mini-Satellite Payload (CHAMP), and Gravity Recovery and Ocean Circulation Explorer (GOCE) has come to the rescue by providing global data of long-wavelength with varying accuracies at different parts of the globe (Flechtner, Gruber, Guntner, Mandea). The usefulness of any satellite global gravity model in any region depends on its fitness in the region as well as the required accuracy. Hence, there is need to investigate the fitness of the global satellite gravity mission within the local gravity field. This research therefore seeks to determine the fitness of GOCE data acquired over an area by comparing it with directly observed data. In order words comparing the gravity anomalies obtained based on bouguer reduction method by the GOCE satellite and the gravity anomalies obtained by terrestrial observation using the time-wise approach. It is based on the following objectives; acquiring terrestrial gravity anomaly observation from the Nigeria Geological Surveys at selected points in Enugu State (115 station-validation point); extracting an up-to-date GOCE satellite gravity anomaly data for the same

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points; fitting the reference system used in deriving the two sets of gravity anomalies as well as pre-process the terrestrial gravity anomalies as checks against errors; computing the difference between the two sets of gravity anomalies at the validation points and determining the fitness of the GOCE and terrestrial gravity data over Enugu State. Hart & Orupabo, 2016 asserts that gravity anomaly fields must be derived from the observed gravity field for oil and gas exploration, mineral ore exploitations and allied geological activities [4].

Several related scientific studies have been carried out for which findings provided a framework for this study. This is further explained as literatures reveals that some countries have already tried to validate the GOCE gravity values over the terrestrially observed gravity values. In Norway, it was shown, that the combination of EGM2008 and the Residual Terrain model allows reproducing the terrestrial data to 4.3 mgal (standard deviation over the whole of Norway). This is also in good agreement with the study of (Hirt) who applied the same method in Switzerland. (Sprlak) in Brazil, used 262 GPS-levelling sites, Earth Gravitational Model 2008 (EGM08) and Residual Terrain Model (RTM) are to assess the current performance of geopotential models derived from GOCE observations. The validation is based on the differences between GPS-levelling and GOCE-derived models. For the former, the spectral content beyond the GOCE-derived models' maximum degree is removed by using EGM08 and RTM. The results indicate that the GOCE-based models: DGM-1S, SPW (Releases 1 and 2), TIM (Releases 1, 2, 3 and 4), and DIR (Releases 2, 3 and 4), at their maximum degrees have a worse performance than EGM08 while DIR-R1 shows an improvement of 11%. Furthermore, from the steepness of the slopes of the root mean square error (RMSE), it is observed that the optimal combination between DIR-R1 and EGM08 occurs at degree 230 (RMSE of 0.201 m). For the satellite-only models, DIR-R3 reduces the RMSE by ~1.4% compared to TIM-R4 at degree 190. These results are important for Brazil where the accuracy of the current geoid model is approximately 0.28 m. (Toth) in Germany, the focus is on the regional validation of the GOCE products by independent terrestrial data sets, including terrestrial gravity anomalies, height anomalies from the high-resolution gravimetric quasi-geoid models EGG2008 and GCG05, and astrogeodetic vertical deflections. Differences between the terrestrial data sets and the available GOCE geopotential models, with envisaged accuracies of 1 mgal for gravity and 1-8 2 cm for geoid heights, both at a solution of 100 km, are computed and analysed in Germany (Roland) [5].

The result of this research will help the geodesist, geologist and geophysicists to verify if gravity anomalies obtained directly from GOCE satellite could be adopted as an alternative to terrestrially observed gravity anomalies for geophysical, geological, and geodynamic modelling [6].

Study Area

The area covered by this work is the Southern Eastern part (Enugu precisely) of Nigeria where sufficient gravity observation has been carried out by the Nigeria Geological Survey as shown in figure 1. A total of 115 points was selected to serve as validation points for this work. The South East is predominantly hilly and undulating terrain with underlying deposit of coal and allied crustal materials [7].

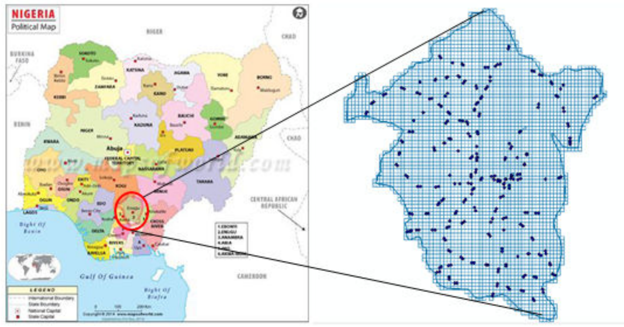
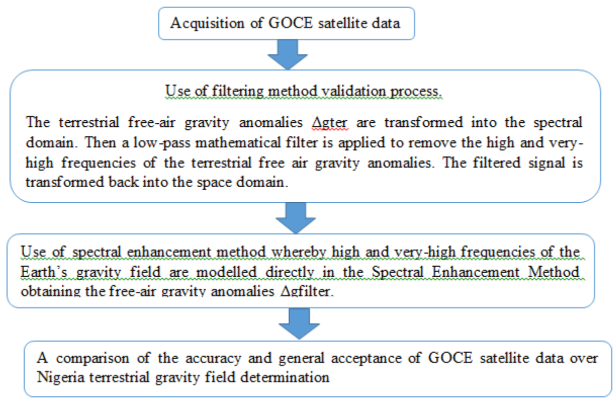


Figure1: Area of Study, showing the 115 points of the terrestrially observed points.

Materials and Methods

The Method used in the evaluation of the GOCE gravity anomaly values is as shown in the flow chart below;



In theory, GOCE satellites provide within the required accuracies the gravity anomaly of places around the earth surface. But to be adopted locally as the gravity anomaly, a lot of considerations has to be put in place. These include the ellipsoid used, the normal height of the observed point, the correction technique adopted and the accuracy and measurement procedure used for the observation of the terrestrially observed gravity anomalies values as shown in equation [8].

$$\Delta g = g - \gamma_o \qquad (1.0)$$

Where, is the gravity Anomaly

g is the observed gravity value reduced to the geoid

Computed gravity value at the mean earth ellipsoid

The mathematical model for the estimation of the free air and simple bouguer anomalies as given by Murray and Tracey (2001) as shown in equation 2.0 and 3.0

$$\Delta g_{FA} = (g_{OBS} - \gamma_e + 0.3086H)mgal \qquad (2.0)$$

Where, Δg_{FA} = Free Air Anomaly, g_{OBS} = Observed Gravity, γ_e = Computed gravity value at the mean earth ellipsoid and H = Orthometric Height

$$\Delta g_{SB} = (\Delta g_{FA} - 0.0419\ell H)mgal \qquad (3.0)$$

Where, Δg_{SB} = Simple Bouguer Gravity Anomaly, ℓ = Density

The WGS 84 ellipsoid was used as the default ellipsoid by GOCE mission but the terrestrially observed gravity anomaly values used the 1967 Geodetic Reference system Gravity formula. The height reduction both systems used was the bouguer method of height reduction. In another vein, the aggregate corrections applied in this gravity survey include latitude, tidal, altitude, free air, Bouguer, terrain and drift corrections. The refined Bouguer Anomaly is obtained thus (Hofmann-Wellenhof and Moritz, 2005) as shown in equation 4.0:

$$BA = G_{obs} - G^{th} + F - Bc + Tc \qquad (4.0)$$

Where:

Gobs= Observed Gravity,

Gth= latitude correction,

BA = Bouguer Anomaly,

Bc= 0.1119H = Attraction of Bouguer plate,

F =0.3086H = Free air reduction,

Tc= Terrain correction.

For this survey, 1967 Geodetic Reference System Gravity formula was used as shown in equation 5.0.

$$Gth = 978031.85(1.0 + 0.005278895\sin 2\varphi + 0.000023462\sin 4\varphi)\ (mgal) \qquad (5.0)$$

Where: φ= Latitude.

As published by NGSA, the following instruments were used for the terrestrial observation of Bouguer gravity data in Enugu State.

Lacoste and Romberg (G-512) gravimeter (±0.01 mgal)

FA-181 Wallace, Tiernan and Brunton Barometric altimeters (±1 m)

American Paulin System MDM-5 (±0.5 m)

Sling Psychrometer

Garmin CSx 76 GPS (±3 m)

The Gravimeter was calibrated using the line designated as the Central Calibration Line (CCL) and situated in the northern part of Nigeria. It covers the longest gravity range observed in the country. Its extreme absolute gravity values are 977844.608 mgal at Jos and 978221.324 mgal at Illela which yield a maximum interval gravity value of 376.716 mgal. The absolute gravity values along the calibration line are referred to the IGSN 71 datum, (Osazuwa). The scale was calibrated to the Smithsonian meteorological table. The results will be statistically analysed using the linear regression model, this is to ascertain the degree of correlation as a basis of validation. Regression is a statistical technique for estimating the relationship among variables. The type of regression we are interested in is the linear regression as there are several of types of regression techniques. Linear regression is a linear approach to modelling the relationship between a scalar response (and dependent variable) and one or more explanatory variables (or 47 independent variables). The root mean squares for the different observations are as shown in equation 6.0. This is a statistical indicator to ascertain the degree of correlation between variables [9].

$$X_{RMS} = \sqrt{\frac{1}{n}\left(x_1^2 + x_2^2 + x_3^2 + \ldots + x_n^2\right)} \qquad (6.0)$$

Result and Analysis

A Specimen of the results obtained from both systems: The GOCE data values and the terrestrial obtained values are shown in table 1.

Table1: Results obtained from the Online Computation of GOCE Gravity Anomalies

Longitude	Latitude	Earth_Gravity_Bouger mgal	GOCE_Bouger_m/gal_R3_TIM	GOCE_Bouger_m/gal R4_TIM	GOCE_Bouger_m/gal R5_TIM
7.6062	6.556	24.1563	7.018928	7.383531	7.169934
7.6512	6.7442	17.4218	2.777866	4.911119	0.335978
7.5826	6.6422	17.2356	4.501046	5.318342	3.798989
7.5423	6.5746	15.6651	5.653763	5.728662	6.017494
7.521	6.5328	17.4962	6.380236	6.045408	7.314453
7.1073	6.5135	23.3471	4.782268	0.625607	7.018731
7.1191	6.5571	29.345	4.02803	0.035343	6.394568
7.1305	6.5993	24.5393	3.085519	-0.65886	5.625011
7.1563	6.6386	21.7172	1.997847	-1.32001	4.793144
7.1719	6.6815	18.2159	0.703103	-2.19256	3.718013
7.2096	6.7113	13.413	-0.28241	-2.58718	2.796467
7.4137	6.5286	14.0194	5.483807	4.215432	7.299286
7.4152	6.5424	8.78055	5.180781	3.982183	6.913944
7.4159	6.6381	3.51179	2.568119	1.966412	3.748377
7.4254	6.7088	0.939944	0.426485	0.472569	1.121452
7.4116	6.8139	-0.49954	-3.12794	-2.32698	-2.5886
7.4561	6.8846	2.14265	-4.96795	-3.10795	-5.54936

7.3894	6.5365	12.7356	5.129757	3.659061	7.100142
7.388	6.6225	7.3215	2.822259	1.826801	4.389012
7.3758	6.6782	5.32676	1.07406	0.347693	2.567089
7.4048	6.7205	-0.39385	-0.12059	-0.18776	0.820232
7.4171	6.7499	-1.44184	-0.9771	-0.6703	-0.33565
7.4277	6.7655	-2.07418	-1.40901	-0.84715	-1.01639
7.4552	6.8103	-2.808	-2.58434	-1.35887	-2.87277
7.4645	6.8475	-0.49199	-3.69978	-2.0267	-4.35137
7.4917	6.8963	0.655071	-4.86464	-2.55679	-6.30435
7.5347	6.9648	5.70935	-6.26909	-3.07236	-9.00097
7.6329	6.87	12.8611	-1.565	1.596551	-5.32709
7.6628	6.8543	13.8745	-0.38151	2.779412	-4.28585
7.7024	6.823	15.8019	1.545936	4.557579	-2.24595
7.7353	6.8034	20.0606	3.024075	5.910458	-0.60727
7.717	6.7784	19.8135	3.319944	5.960903	0.077232
7.7476	6.7177	26.6198	5.877833	8.015743	3.443226

The table1 shows clearly the values obtained by the terrestrial observations and the values obtained by the different epochs and time intervals. Similarly, figure 2 shows the graphical representation of the values in relation to different epochs and between time intervals. The uniqueness and the correlation of the values underpins the precision of the values irrespective of the variation of the epochs. The magnitude of the values from the terrestrial observed and that of the satellite-based is critically obvious [10].

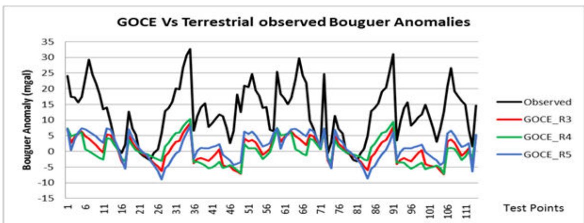


Figure2: A Graphic Representation of the Terrestrial Observed Versus GOCE Values

In order to do a proper critique on whether the gravity anomalies obtained from GOCE could be used over Nigeria, a regression analysis was carried to determine the coefficient of correlation.

Correlation is a measure of relationship between two mathematical variables or measured data values (Ayeni). Linear correlation refers to straight line relationships between two variables. A correlation can range between -1 (perfect negative relationship) and +1 (perfect positive relationship), with 0 indicating no straight-line relationship. The result of the correlation analysis gotten from Earth gravity anomaly by bouguer method with the Time wise gravity anomaly obtained from the GOCE satellites was compared as shown in Figure3 [11].

Correlations

		Earth_Gravity_Bouger	GOCE_Bouger_R3_TIM to R5_TIM
Earth_ Gravity_ Bouger	Pearson Correlation	1	.567**
	Sig. (2-tailed)		.000
	N	342	342
GOCE_Bouger_R3 _TIM toR5_TIM	Pearson Correlation	.567**	1
	Sig. (2-tailed)	.000	
	N	342	342

**. Correlation is significant at the 0.01 level (2-tailed). Which defines a very weak relationship since it is NOT close to +1 (strongest significant value), but close to 0 which indicates the strongest possible disagreement.

Figure3: Specimen of Correlation Analysis

The correlation value between the terrestrially observed gravity anomaly values as compared with the GOCE gravity anomaly values for the different time epoch as given as follows: GOCE_Bouguer_R3_Timewise approach against Terrestrial observation = 0.632201; GOCE_Bouguer_R4_Timewise approach against Terrestrial observation = 0.492238; GOCE_Bouguer_R5_Timewise approach against Terrestrial observation = 0.592949.

The correlation values show a weak relationship as it is not close to +1 values which signifies a perfect possible agreement in the values obtained. While for the regression analysis, we compared the results gotten from Earth gravity anomaly by bouguer method with the Time wise gravity anomaly obtained from the GOCE satellites.

We chose the earth gravity anomaly by bouguer method as dependent variable and GOCE Bouguer R3_TIM to R5_TIM (time wise approach) as the constant predictors, this is because the Earth gravity anomaly values by bouguer method serves as the basis for comparison. The one-way ANOVA is used to determine whether there are any statistically significant differences between the means of three or more independent (unrelated) groups with a dependent variable in this case (terrestrial derived gravity data). Tables 4-7 display the outcome of the statistical analysis for correlation validation.

There was significant relationship between Earth_ Gravity_ Bouger and GOCE_ Bouger_R3_TIM to R5_TIM at 0.5 significant levels. ($F = 160.909$, $p<0.05$) where p is the calculated value. This shows there is enough evidence to reject the null hypothesis; therefore, there is a non-zero correlation. There is a relationship between the two variables, at a confidence level of 95%.

Table2: Analysis of Terrestrial versus GOCE obtained gravity anomalies values using Bouguer

Model	Sum of Squares	df	Mean Square	F	Sig.
Regression	8303.4	1	8303.4	160.909	.000b
Residual	17545.1	340	51.603		
Total	25848.5	341			
a. Dependent Variable: Earth_ Gravity_ Bouger					
b. Predictors: (Constant), GOCE_ Bouger_R3_TIM to R5_TIM					

Table3: Model Summary of Terrestrial versus GOCE obtained Gravity Anomalies Values using Bouguer

Model Summary									
Model	R	R Square	Adjusted R Square	Std. Error of the Estimate	Change Statistics				
					R Square Change	F Change	df1	df2	Sig. F Change
1	.567a	0.321	0.319	7.18353	0.321	160.909	1	340	0
a. Predictors: (Constant), GOCE_ Bouger_R3_TIM to R5_TIM									

ANOVA[a]						
Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	8303.396	1	8303.396	160.909	.000[b]
	Residual	17545.066	340	51.603		
	Total	25848.462	341			
a. Dependent Variable: Earth_ Gravity_ Bouger						
b. Predictors: (Constant), GOCE_ Bouger_R3_TIM to R5_TIM						

Figure4: ANOVA Analysis of Terrestrial versus GOCE obtained Gravity Anomalies values using Bouguer

COEFFICIENTS[a]							
Model	Unstandardized Coefficients		Standardized Coefficients	t	Sig.	95.0% Confidence Interval for B	
	B	Std. Error	Beta			Lower Bound	Upper Bound
(Constant)	11.606	.394		29.465	.000	10.831	12.380
GOCE_ Bouger_R3_ TIM to R5_TIM	1.198	.094	.567	12.685	.000	1.012	1.384
a. Dependent Variable: Earth_ Gravity_ Bouger							

Figure5: Regression Analysis of Terrestrial versus GOCE obtained Gravity Anomalies values using Bouguer

GOCE mission provides appreciable quantum of gravity data for the earth gravity field modelling. However, the duration of the observation period, the positional attribute of the satellite and the high accuracy of the gravity gradiometer can be contributary to GOCE's ability to see gravity variations with time. Table 4, shows the discrepancies between the terrestrial gravity derived data and satellite (GOCE) derived with respect to the epoch. Figure 3 describe the graphical representation of the residuals.

Table4: Difference in the terrestrially observed gravity against the GOCE observed values in m/gal.

Earth_ Gravity _ Bouger mgal	GOCE_ Bouger _ R3_TIM mgal	GOCE_ Bouger _ R4_TIM mgal	GOCE_ Bouger _ R5_TIM mgal	Difference Earth and GOCE R3 mgal	Difference Earth and GOCE R4 mgal	Difference Earth and GOCE R5 mgal
24.1563	7.018928	7.383531	7.169934	17.13737	16.77277	16.98637
17.4218	2.777866	4.911119	0.335978	14.64393	12.51068	17.08582
17.2356	4.501046	5.318342	3.798989	12.73455	11.91726	13.43661
15.6651	5.653763	5.728662	6.017494	10.01134	9.936438	9.647606
17.4962	6.380236	6.045408	7.314453	11.11596	11.45079	10.18175
23.3471	4.782268	0.625607	7.018731	18.56483	22.72149	16.32837
29.345	4.02803	0.035343	6.394568	25.31697	29.30966	22.95043
24.5393	3.085519	-0.65886	5.625011	21.45378	25.19816	18.91429
21.7172	1.997847	-1.32001	4.793144	19.71935	23.03721	16.92406
18.2159	0.703103	-2.19256	3.718013	17.5128	20.40846	14.49789
13.413	-0.28241	-2.58718	2.796467	13.69541	16.00018	10.61653
14.0194	5.483807	4.215432	7.299286	8.535593	9.803968	6.720114
8.78055	5.180781	3.982183	6.913944	3.599769	4.798367	1.866606
3.51179	2.568119	1.966412	3.748377	0.943671	1.545378	-0.23659
0.939944	0.426485	0.472569	1.121452	0.513459	0.467375	-0.18151
-0.499538	-3.12794	-2.32698	-2.5886	2.6284	1.827439	2.089062

2.14265	-4.96795	-3.10795	-5.54936	7.110605	5.250603	7.692011
12.7356	5.129757	3.659061	7.100142	7.605843	9.076539	5.635458
7.3215	2.822259	1.826801	4.389012	4.499241	5.494699	2.932488
5.32676	1.07406	0.347693	2.567089	4.2527	4.979067	2.759671
-0.393852	-0.12059	-0.18776	0.820232	-0.27326	-0.20609	-1.21408
-1.44184	-0.9771	-0.6703	-0.33565	-0.46474	-0.77154	-1.10619
-2.07418	-1.40901	-0.84715	-1.01639	-0.66517	-1.22703	-1.05779
-2.808	-2.58434	-1.35887	-2.87277	-0.22366	-1.44913	0.064768
-0.491989	-3.69978	-2.0267	-4.35137	3.207794	1.534711	3.859383
0.655071	-4.86464	-2.55679	-6.30435	5.519713	3.211862	6.959423
5.70935	-6.26909	-3.07236	-9.00097	11.97844	8.781705	14.71032
12.8611	-1.565	1.596551	-5.32709	14.4261	11.26455	18.18819
13.8745	-0.38151	2.779412	-4.28585	14.25601	11.09509	18.16035
15.8019	1.545936	4.557579	-2.24595	14.25596	11.24432	18.04785
20.0606	3.024075	5.910458	-0.60727	17.03652	14.15014	20.66787
19.8135	3.319944	5.960903	0.077232	16.49356	13.8526	19.73627
26.6198	5.877833	8.015743	3.443226	20.74197	18.60406	23.17657
30.697	7.545775	9.262479	5.821862	23.15122	21.43452	24.87514
32.7006	9.027828	10.31165	8.055738	23.67277	22.38895	24.64486
6.58173	-3.77047	-3.46767	-2.23946	10.3522	10.0494	8.821189
11.1467	-2.37703	-3.27714	0.2073	13.52373	14.42384	10.9394
14.0599	-2.05585	-3.70863	1.15581	16.11575	17.76853	12.90409
15.3	-2.62586	-4.50565	0.978112	17.92586	19.80565	14.32189
7.82904	-3.01198	-5.33542	0.96168	10.84102	13.16446	6.86736
8.9484	-1.98992	-5.05558	1.424229	10.93832	14.00398	7.524171
10.438	-0.77773	-4.38073	1.68485	11.21573	14.81873	8.75315
11.8706	0.688689	-3.37421	2.281068	11.18191	15.24481	9.589532
11.1855	-4.53127	-5.29578	-1.15725	15.71677	16.48128	12.34275

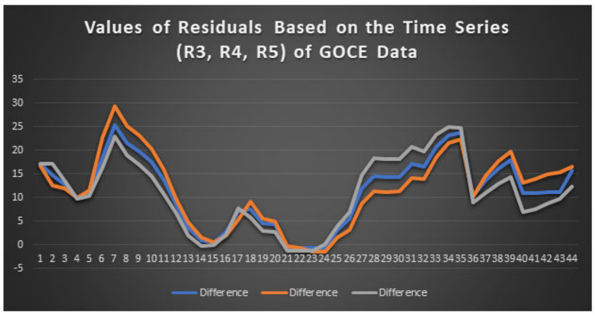


Figure6: A Graphical Representation of the Residuals of GOCE Values in Time Series

In view of the uniqueness of the dataset, the root mean square error showed these values as indicator of correlation, Xrms of GOCE time wise approach R3 = 13.79396 mgal; Xrms of GOCE time wise approach R4 = 14.42247 mgal and Xrms of GOCE time wise approach R5 = 13.09670 mgal. This shows a clear difference in the terrestrially observed gravity values and the GOCE acquired values.

CONCLUSION

The main purpose of this study is to validate the GOCE gravity anomaly values over Enugu State, South Eastern part of Nigeria. In carrying out this we did statistical analysis to compare the values gotten from GOCE versus terrestrially observed values using regression and correlation methods. The correlation value between the terrestrially observed gravity anomaly values as compared with the GOCE gravity anomaly values for the different time epoch as given as follows: GOCE_Bouguer_R3_Timewise approach against Terrestrial observation=0.632201; GOCE_Bouguer_R4_Timewise approach against Terrestrial observation=0.492238; and GOCE_Bouguer_R5_Timewise approach against Terrestrial observation = 0.592949. The correlation values show a weak relationship as it is not close to +1 values which signifies a perfect possible agreement in the values obtained. The conclusion from the analysis done shows that the values obtained by GOCE cannot be used over Nigeria. Since there are no relationships between the gravity anomaly values obtained by terrestrial means and the other values obtained from GOCE satellites through regression and correlation analyses. The differences are quite significant; this underpins our findings as statistically GOCE derived values do not fit over the study area of this research [12].

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