Transformation of Global to Local Geoid for Regional Geoid Modelling: Results from Enugu State, Nigeria

Victor NNAM, Francis OKEKE and Joseph ODUMOSU, Nigeria

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SUMMARY

ThiRegional geoid modelling is an age-long problem in geodesy. Over the years the gravimetric and geometric methods of geoid modeling stand out as the most preferred and utilized methods. However, due to several factors ranging from lack of sufficient gravity data, poor integrity of available gravity data, parametric inconsistencies in adopted national Vertical Reference Systems, improper definition of national height datum e.t.c, the use of both methods especially in developing countries is equivocal. Recently, the spatial resolution and accuracy of global geoid models (GGM) are improving for all parts of the world thus addressing the problems of availability, consistency and resolution of data. Therefore, this study proposes a low-cost method of geoid modelling, wherein the regional geoid model is obtained by transforming the global geoid to local geoid. The Transformation of Global to Local (TGL)geoid method is based on the concept of transforming ellipsoidal heights and geoidal undulations between various datums. The method was tested in Enugu state of Nigeria and the results obtained were compared with the Geometric and Gravimetric Geoid models. A total of 25 control points with known Ortometric heights and evenly distributed across the study area were used for comparing the results obtained from the three methods.Statistical analysis of the results obtained shows high level of consistency between the three (3) methods. Furthermore, Root Mean Square Errors of ±0.123 m and ± 0.389 m were obtained between the Geometric method and the TGL then gravimetric methods respectively when compared with known orthometric heights at control points.The TGL method is recommended as a reliable alternative for regional geoid modeling in areas where funds are unavailable for rigorous gravity observations.

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1.0 INTRODUCTION

Most of the reasons that have deterred the realization of a reliable national geoid for Nigeria have been due to funding, reliability and resolution of available gravity data (Ezeigbo et al, 2007, Nwilo, 2013, Odumosu and Nnam, 2020).However, with the continuous rise in MSL the need for reliable geoid models for quick conversion of ellipsoidal to Orthometric heights cannot be overemphasized. Orthometric heights are natural heights that are conventionally accepted for prediction of fluid flows and mitigation of natural hazards. Despite their suitability for engineering works, the practical realization of Orthometric heights through the process of spirit leveling is physically tedious and computationally error prone (Vanícek et al, 1980). Ellipsoidal heights on the other hand are referenced to the ellipsoid of revolution and have a much more mathematical than physical meaning (Amos, 2010). Although, ellipsoidal heights are purely geometrical, the observational and computational convenience offered by this system to the geodetic community ignites a need for proper determination of the relationship between the duo height systems (Featherstone & Kuhn, 2006).

The gravimetric method of geoid modelling has been the most accept able method of geoid modelling and adopted by several countries (Sengendo, 2015). Attempts have been made towards developing a national geoid for Nigeria using based on the gravimetric method (Ezeigbo et al, 2006; Moka et al, 2017; Odumosu and Nnam, 2020), and consequently, the obtained result subjected to the limitations earlier identified. Next to the gravimetric method in terms of usage is the geometric method (Amos, 2007). This method is relatively easy, fast and efficient provided both the ellipsoidal and Orthometric heights of several control points well distributed across the area is available, and that both height systems are referred to the correct datum. The Orthometric heights of the control stations to be used for the GNSS/Levelling geoid (geometric geoid) must be properly corrected for the effect of gravity after a rigorous adjustment (Isioye et al, 2010), while the ellipsoidal heights must be referenced to the local ellipsoid. This is necessary in order to eliminate possible parametric bias between the reference datum for both systems in the evaluation of the geometric geoid. Furthermore, there should be a good distribution of control points across the area upon which the geometric geoid is to be computed.Unfortunately, due to paucity of funds, developing countries especially those with vast spatial extent find it difficult to meet up the data requirements for achieving the geometric geoid as well.

This study presents an alternative and low-cost geoid modeling technique which depends on the transformation of global to local (TGL) geoid. The proposed method called the TGL method depends on the fact that long wavelength geoid can easily be obtained by the mathematical manipulation of the normalized coefficients of Global Geoid Models (GGM's). This global geoid is then converted to the local geoid by mathematical manipulations. The gravimetric and geometric methods of geoid modeling have been well discussed in several geodetic literatures, as such; theoretical discussion in this paper will focus on the TGL method only.

2.0 THE TGL METHOD

The TGL method is based on the concept of transforming ellipsoidal heights and geoidal undulations between different geodetic datum(Kotsakis, 2008). The method relies on the availability of accurate transformation parameters for transforming curvilinear coordinates between both datum.

Recall the non-rigorous Euclidean similarity transformation model (equation 1) which is used to convert Cartesian coordinates between two geodetic reference frames transformation model given in equation (1a)

$$\begin{bmatrix} x' - x \\ y' - y \\ z' - z \end{bmatrix} = \begin{bmatrix} t_x \\ t_y \\ t_z \end{bmatrix} + \begin{bmatrix} \delta_s & \varepsilon_z & -\varepsilon_y \\ -\varepsilon_z & \delta_s & \varepsilon_x \\ \varepsilon_y & -\varepsilon_x & \delta_s \end{bmatrix} \begin{bmatrix} x \\ y \\ z \end{bmatrix} \qquad (1a)$$

Equation 1a can be re-written as (1b)

$$x'_{GRF2} = t + (1 + \delta_s)\mathbf{R}_{(\varepsilon_x,\varepsilon_y,\varepsilon_z)} x_{GRF1} \qquad (1b)$$

Where

R = orthogonal matrix that performs three successive rotations around the axes of GRF1 to bring them parallel to the axes of GRF2.

t = Cartesian coordinate origin vector of GRF1with respect to GRF2

δ_s = unit less factor expressing scale difference between the two frames

x'_{GRF2} = Cartesian coordinates vector of same points with respect to GRF2

GRF1 = Geodetic Reference Frame 1

GRF2 = Geodetic Reference Frame 2

Consider the relationship between Cartesian coordinates and curvilinear coordinates as given by equation (2)

$$\begin{bmatrix} x \\ y \\ z \end{bmatrix} = \begin{bmatrix} (N + h)cos\varphi \cos\lambda \\ (N + h)cos\varphi \sin\lambda \\ (N(1 - e^2) + h)\sin\varphi \end{bmatrix} \qquad (2)$$

Where

$N = \frac{a}{W}$ (Prime vertical radius of curvature)

a = semi major axis

φ, λ, h = geodetic coordinates

W = latitude dependent unit less quantity = $\sqrt{1 - e^2 sin^2\varphi}$

Differentiating equation 2 with respect to variation in curvilinear geodetic coordinates, we get to equation (3)

$$\begin{bmatrix} d_x \\ d_y \\ d_z \end{bmatrix} = \mathbf{J} \begin{bmatrix} d_\varphi \\ d_\lambda \\ d_h \end{bmatrix} \qquad (3)$$

Where

$$\mathbf{J}(\text{Jacobian}) = \begin{bmatrix} -(M + h)\sin\varphi\cos\lambda & -(N + h)\cos\varphi\sin\lambda & \cos\varphi\cos\lambda \\ -(M + h)\sin\varphi\sin\lambda & (N + h)\cos\varphi\cos\lambda & \cos\varphi\sin\lambda \\ (M + h)\cos\varphi & 0 & \sin\varphi \end{bmatrix} \qquad (4)$$

$M = \frac{a(1-e^2)}{W^3}$ (Meridian radius of curvature)

Substituting the left hand side of equation (3) with the Cartesian coordinate transformation in equation (1a) and solving for dh, yields (5)

$$h^{'} - h = \delta h(t_x) + \delta h(t_y) + \delta h(t_z) + \delta h(\varepsilon_x) + \delta h(\varepsilon_y) + \delta h(\varepsilon_z) + \delta h(\delta s) \quad (5)$$

Where

$\delta h(t_x) = t_x \cos\varphi \cos\lambda$

$\delta h(t_y) = t_y \cos\varphi \sin\lambda$

$\delta h(t_z) = t_z \sin\varphi$

$\delta h(\varepsilon_x) = -\varepsilon_x \mathrm{N}e^2 \sin\varphi \cos\varphi \sin\lambda$

$\delta h(\varepsilon_y) = \varepsilon_y \mathrm{N}e^2 \sin\varphi \cos\varphi \cos\lambda$

$\delta h(\delta s) = (aW + h)\delta s$

Equation (5) presents a one step similarity transformation procedure for transforming ellipsoidal heights in one reference frame (h with respect to GRF1) to another geodetic reference frame ($h^{'}$with respect to another geodetic reference frame GRF2) at any point in space with known curvilinear coordinates φ, $\lambda$and h.

Taking an assumption that the points whose ellipsoidal height is being transformed is located on the geoid, then equation (5) becomes equation (6) which is a direct similarity transformation model for geoid heights

$$N^{'} - N = \delta N(t_x) + \delta N(t_y) + \delta N(t_z) + \delta N(\varepsilon_x) + \delta N(\varepsilon_y) + \delta N(\varepsilon_z) + \delta N(\delta s) \quad (6)$$

Where

N = Geoid height with respect to GRF1

$N^{'}$ = Geoid height with respect to GRF2

$\delta N(t_x) = t_x \cos\varphi \cos\lambda$

$\delta N(t_y) = t_y \cos\varphi \sin\lambda$

$\delta N(t_z) = t_z \sin\varphi$

$\delta N(\varepsilon_x) = -\varepsilon_x \mathrm{N}e^2 \sin\varphi \cos\varphi \sin\lambda$

$\delta N(\varepsilon_y) = \varepsilon_y \mathrm{N}e^2 \sin\varphi \cos\varphi \cos\lambda$

Since the evaluation point is located on the geoid surface, its ellipsoidal height woud be identical to the geoid undulation with respect to the same geodetic reference frame ($h = N$). Therefore, the scale dependent term becomes

$$\delta N(\delta s) = (aW + N)\delta s \quad (7)$$

By evaluation, the curvilinear geodetic coordinates (φ, λ) used in the trnsformation of equation (6) refer to the horizontal positions of the evaluation point specified with respect to geodetic reference frame 1 (GRF1). The points refer to earth surface points whose geoidal undualtion are available in GRF1 and needs to be transformed to geodetic reference frame 2 (GRF2).

Assuming that the evaluation points are located on the geoid, the corresponding direct (linearized) extended similarity transformation (which is given as the TGL transformation model) is given by equation (8)

$$N^{'} - N = \delta N(t_x) + \delta N(t_y) + \delta N(t_z) + \delta N(\varepsilon_x) + \delta N(\varepsilon_y) + \delta N(\delta s) + \delta N(\delta_a) + \delta N(\delta_f) \quad (8)$$

Where

$\delta N(\delta_a) = -W\delta_a$

$$\delta N(\delta_f) = \frac{a(1-f)}{W} sin^2\varphi\delta_f$$
$$\delta_a = a^{'} - a$$
$$\delta_f = f^{'} - f$$

Equation (8) can be further simplified into equation (9)

$$\Delta N_i = \Delta a + \Delta X_0 \cos\varphi_i \cos\lambda_i + \Delta Y_0 \cos\varphi_i \sin\lambda_i + \Delta Z_0 \cos\varphi_i\, sin\lambda_i + a\Delta f\, sin^2\varphi_i (9)$$

Where:

ΔN = Difference in geoidal undulation between both ellipsoids (WGS84 and Clarke 1880)
Δa = difference in semi-major axis
ΔX_0 = Translation parameter in the X-direction from datum 1 to datum 2
ΔY_0 = Translation parameter in the Y-direction from datum 1 to datum 2
a = semi major axis
Δf = difference in flattening
φ_i = Latitude in datum 2
λ_i = Latitude in datum 2

By direct evaluation of equation (9), the TGL geoid is computed.

3.0 STUDY AREA

The proposed method was implemented in Enugu state. Enugu state is located in the South Eastern geopolitical zone of Nigeria and has a land mass area of about 7,161 sq km. It is bounded by Ebonyi state to the East, Anambra state to the west, Abia state in the south and Kogi/Benue states in the North. Figure 1 shows an administrative map of Enugu state. The state has generally variable topography ranging from 57.18m in the flat areas to 598.67m in the hilly areas

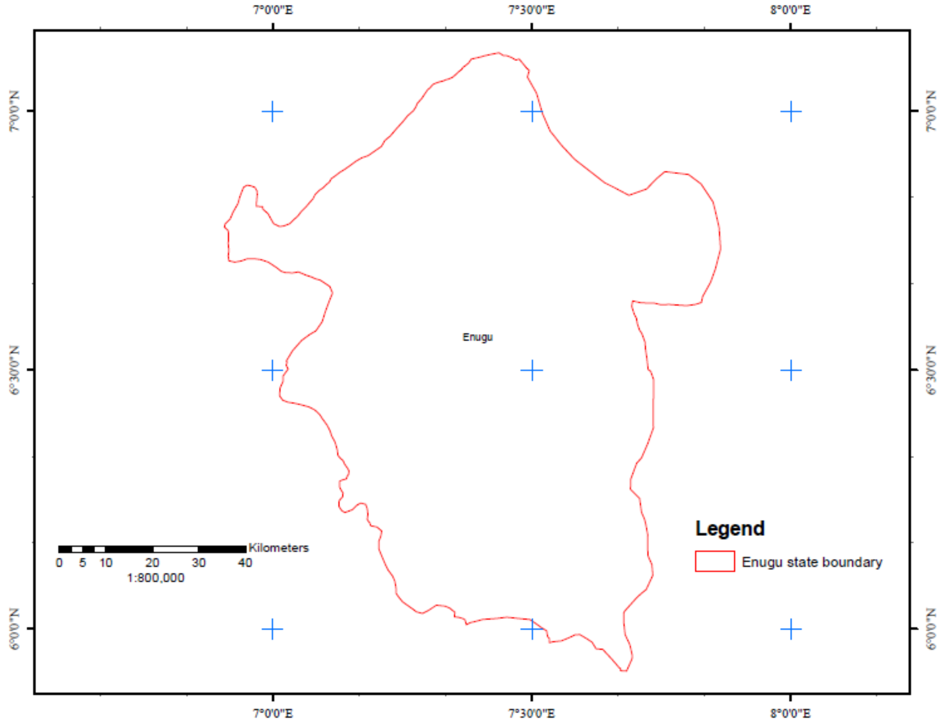


Figure 1: Administrative boundary of Enugu state

4.0 MATERIALS AND METHODS

Several types of data were utilized in this study in order to achieve the aim of the study. Since each geoid modelling method required different data type, the data types used for this study are presented in sub-sections below:

4.1 Data used for gravimetric geoid modelling:

For this study, terrestrial gravity data for 289 gravity points observed by the Nigerian Geological Survey Agency (NGSA) was used for the computation of the gravimetric geoid. The 289 gravity points were observed by NGSA during a 45days observation campaign. A summary of the gravity data acquisition and quality of data after post processing analysis is as presented in Table 1

Table 1 Summary of meta-data for gravity data used for gravimetric geoid computation

S/N	Parameter	Data quality
1	Number of points	289 points
2	Drift rate	0.000017mgals/sec
3	Observational method	profile method
4	Minimum value gravity anomaly	-7.356mgals
5	Maximum value of gravity anomaly	115.652mgals
6	Mean of gravity anomaly	15.023mgals
7	Post adjustment standard deviation	Not available

4.2 Data used for TGL geoid modeling

The curvilinear coordinates of the twenty five (25) OSGOF points located across Enugu state were used for the implementation of the TGL geoid model. The curvilinear coordinates were obtained alongside with the height information. It was discovered that the station horizontal coordinates were obtained via GNSS static observation. The station curvilinear coordinates were obtained in Clarke 1880 and WGS84 reference ellipsoids respectively. Long wavelength geoid information used for the TGL method was obtained using the EGM2008 model. Summary of some properties of the EGM2008 derived geoid undulation are presented in Table 2

Table 2 Properties of the EGM 2008 geoid heights

S.N	Description	Value
1	Max spherical harmonic degree	2190
2	Max spherical harmonic order	2156
3	Coefficients	Fully normalized
4	Tide system	Tide free
5	Geoid undulation commission error	0.150 m

4.3 Data used for geometric geoid modeling of selected points used for check

The two basic height systems (ellipsoidal heights and orthometric heights) were the major data sets used in development/determination of geometric geoid. The twenty five (25) OSGOF (Office of the Surveyor General of the Federation) secondary control stations located across Enugu state were used to calculate the geometric geoid of selected station which was used to check the performance / accuracy of the computed gravimetric and TGL geoids of the study area. Information from the OSGOF observation team reveal that the ellipsoidal heights were obtained by the use of GNSS receiver units with observations made in static mode. Orthometric heights of same stations were similarly obtained from OSGOF. Observation for orthometric height was made by spirit leveling and loop closures made to ensure; although the elevation differences has not been adjusted. The meta-data for the heights obtained at the OSGOF stations is as presented in table 3.

Table 3 Meta-data for OSGOF control points

S/N	Parameter	Ellipsoidal Height	Orthometric Height
1	Observational Technique	Static GNSS positioning	Spirit Leveling
2	Positional Accuracy	First order	First order
3	Misclosure	>0.1m	Not specified
4	Corrections for gravity	Not applicable	No
5	Network adjustment	Not applicable	Yes

4.4Methodology

A diagrammatic overview of the methods employed in this study and the segregation of methods into various stages is as presented in Figure 2(a) and (b).

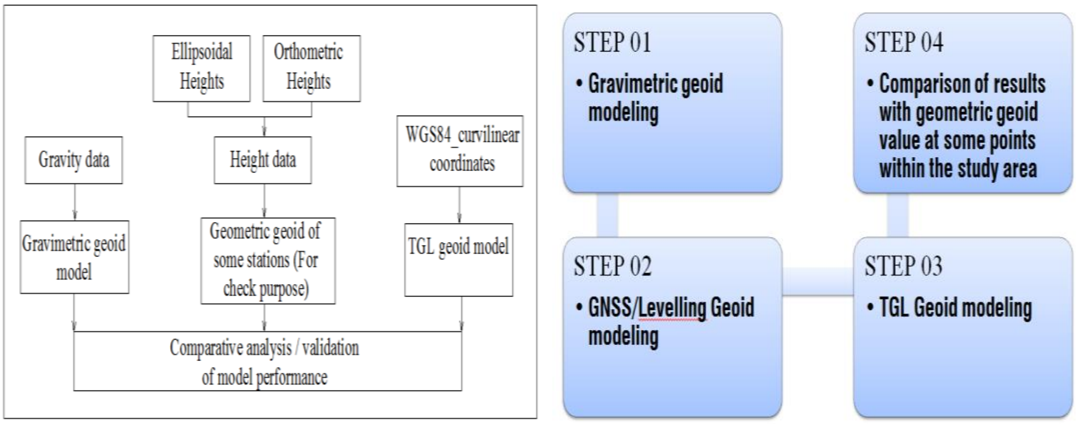


Figure 2(a): Research methodology (b) steps involved in the study

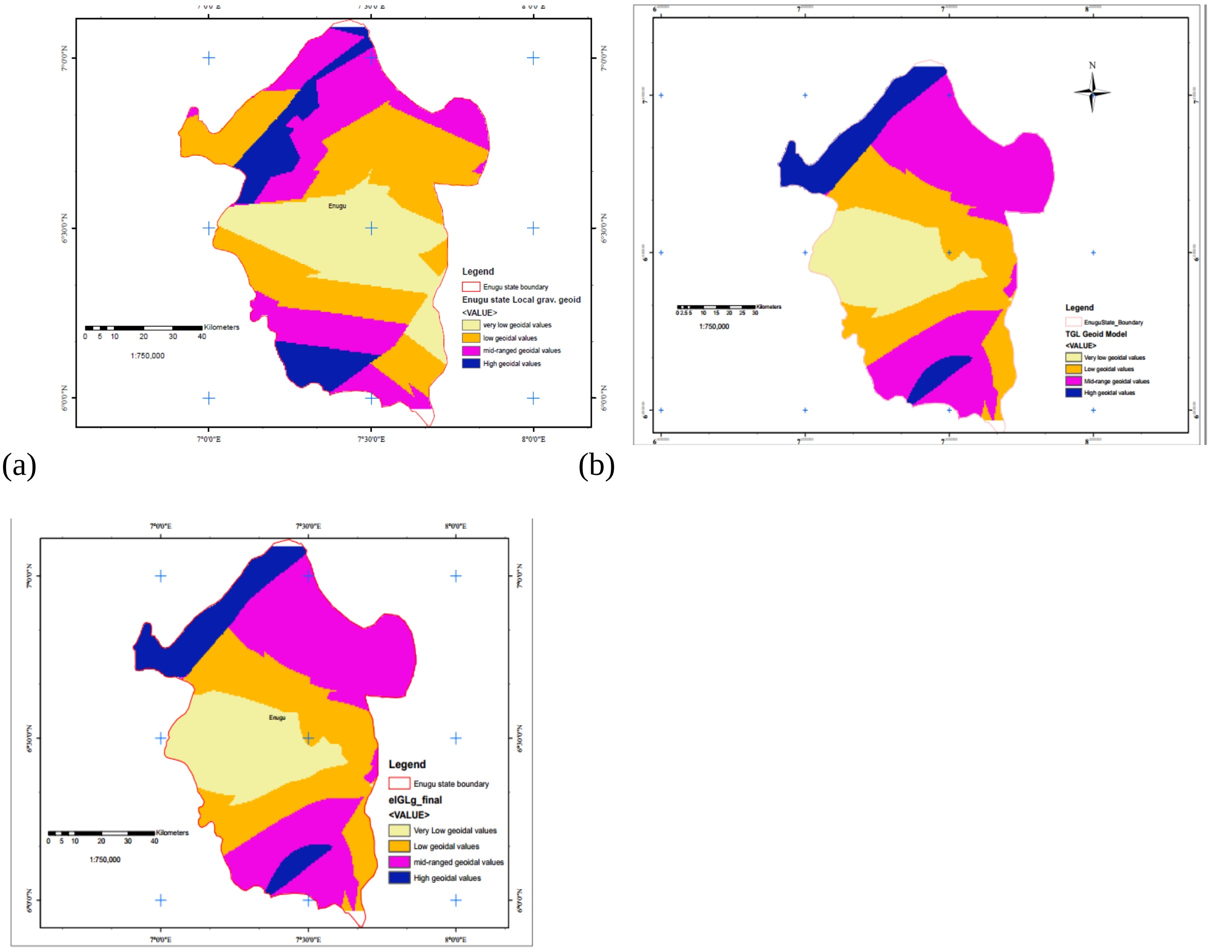
As seen in Figure 2(a) the various data requirements that lead to the development of each of the geoid models is shown. The gravimetric geoid was first developed using the conventional RCR technique by the application of the Stokes integral. Detailed description of the gravimetric geoid RCR technique can be found in Odumosu and Nnam (2020). Also, the conventional algebraic addition was adopted for developing the GNSS/levelling geoid. Again, detailed description of the GNSS/levelling can be found in Fotopulous (2003). Thereafter, given the curvilinear coordinates of the 25 OSGOF stations, equation (9) was used to compute the TGL geoid for the 25 OSGOF stations. The national transformation parameters as given in Okeke et al (2017), was utilized in the implementation of equation (9).

5.0 RESULTS AND DISCUSSION OF RESULTS

After computation of the geoid model using the three methods, the results obtained were analyzed comparatively as seen in table 4. In order to determine the most suitable result, the geometric geoid values obtained from the 25 OSGOF stations due to its simplicity of computation was adopted as standard values that were used to check the reliability of the gravimetric and TGL geoid methods. Table 4, shows the obtained values of the geoid undulation from all the three methods at the 25 OSGOF stations. It is seen that the gravimetric geoid model had the greatest deviation of its values from the geoid model obtained from other methods (Geometric and TGL methods). While very close values of geoid undulation is observed in the three methods at some locations, significantly wide differences is noticed at some other locations. This difference between the geoid values obtained from both methods can be further appreciated from the comparative graphical plot shown in Figure 3 (a - c).

Table 4 Comparative an
alysis of the Local geoid computed at some of the OSGOF stations

STA_ ID	Grav Geoid (m)	TGL Geoid (m)	GNSS/Level Geoid (m)
XSV 650	5.1400	5.0691	5.0361
XSV 652	6.6881	4.9402	5.7284
U12	3.5684	5.0634	5.0018
U13	4.9323	5.1032	5.3050
XSV 653	5.3794	4.6289	4.6765
XSV 796	7.0620	5.1683	5.1064
XSV 653AZ	5.3958	4.6369	4.6824
XSV 795AZ	5.5795	4.5391	4.7353
XSV 649	2.0727	5.2236	5.2297
XSV 658	5.7737	5.3278	5.2419
XSV 655	6.6097	5.1707	5.1531
XSV 655AZ	6.6290	5.1721	5.1534
XSV 654	6.8990	5.0100	5.0411
XSV 984	2.8255	5.2288	5.5568
XSV 996	4.4326	5.2699	4.0851



(a) (b)

(c)

Figure 3: Geoid model of Enugu state by (a) Gravimetric (b) TGL model (c) GNSS/Levelling method

Figures3(a) – (c) all appear visually similar with slight differences between them. A very strong positive correlation is observed between the geometric geoid and TGL geoid while the gravimetric geoid deviates slightly in pattern from both. This pattern is probably associated to the following reasons:

- The TGL and geometric geoid models were developed using exactly the same points (25 OSGOF control stations). The points are however scantily located across the study area and as such the graphical model would rely much on interpolative estimations at other points.
- Also, since the TGL geoid model utilizes a direct transformation based approach from WGS84 to Clarke 1880 datum, there would be a high level of correlation between the resulting geoid obtained from it and the geoid from the geometric method. This is because, the local orthometric heights and local ellipsoidal heights are relatively free of the local gravity component as the national VRF upon which they are based/derived has not been corrected for the effects of gravity (Isioye et al, 2010).

Based on the gravimetric and TGL geoid models, ellipsoidal heights of all the 25 other state-wide vertical control points across Enugu state were converted to Orthometric heights and the obtained values compared with the known Orthometric height of the stations. The 25 state controls used were not used in the development of the TGL geoid model but left out strictly for the purpose of Leave Out (LO) validation. Descriptive statistics of results obtained from both the gravimetric and TGL derived orthometric heights are given in Table 5.

As seen from Table 5, the gravimetric geoid model has overall RMSE of 0.389m across the study area. This RMSE is good and suggests a centimetre accuracy gravimetric geoid, but a look at the range obtained reveal very high difference with a maximum residual of 3.157m. This large discrepancy could be as a result of poor accuracy of the gravity data as the data was collected by the NGSA. Besides, according to the meta-data for the gravity data as obtain from NGSA (Table 1), the post adjustment standard deviation is uncertain. As such, the observed orthometric height deviation could be attributed to possible mishandling during the gravity observations bearing in mind that gravity surveys for geophysical exploration do not necessarily require most of the refinements done when gravity campaign is conducted for geodetic purposes.

Table 5 Descriptive statistics of residuals between known station Orthometric heights and Orthometric height of stations computed using gravimetric and TGL geoid models**.**

Parameter	*Gravimetric model*	*TGL model*
Mean	-0.3892m	-0.1228
Standard Error	0.3721m	0.12952
Standard Deviation	1.5342m	0.53401
Sample Variance	2.3538m	0.28517
Kurtosis	1.0587	1.04306
Skewness	1.2949	-1.1034
Range	5.2499m	2.00226
Minimum	-2.0929m	-1.2141
Maximum	3.1570m	0.78816
Confidence Level (95.0%)	0.7888	0.27456
RMSE	0.389m	0.123m

On the other hand, the TGL derived Orthometric heights were more consistent with the known orthometric heights of the stations used for validation. The derived Orthometric heights obtained from the TGL model indicated more consistency with the known local orthometric heights of the stations having a RMSE of 0.123m. Further look at the descriptive statistics show that the range of the residuals is acceptable (about 2m). This range corresponds to maximum and minimum residual values of 0.78m and -1.2m respectively.

6.0 CONCLUSION AND RECOMMENDATION

The TGL method as presented in this study has proven to be a suitable method having produced results that are consistent with both the gravimetric method and the geometric methods. In fact, taking the geometric method as standard procedure, the TGL method with a

RMSE of 0.123m produced better results in conversion of ellipsoidal to orthometric heights than the gravimetric method which gave a RMSE of 0.389m. Based on the statistics of the differences obtained by comparing the orthometric height obtained via the TGL and gravimetric method with the known values (Table 5), it can be inferred that the TGL method is suitable for geoid modeling especially where the accuracy and spatial resolution of the gravity data is in doubt.

The study recommends that the method should be tested in areas with larger spatial extent with larger topographic variability. This will enable study on the performance of the model in hilly and mountainous terrain and also to identify the effects of topography on the model, Further, since the TGL method relies primarily on the accuracy of the transformation parameters, further studies are required to identify the rate of propagation of errors in transformation parameter estimation on the resulting TGL geoid model.

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CONTACTS

Dr Victor C.Nnam
Geosquaremeter Innovative Limited, Enugu State, Nigeria.
Tel. +2348032760910
Email: victor.nnam@gmail.com

Prof. Francis I. Okeke
Department of Geoinformatics and Surveying,
University of Nigeria, Enugu Campus, Enugu State, Nigeria.
Tel. +2348035627286
Email: francis.okeke@unn.edu.ng

Dr. Joseph O. Odumosu
Department of Surveying and Geoinformatics,
Federal University Oye Ekiti, Ekiti State, Nigeria.
Tel.+2348065916462
Email: joseph.odumosu@futminna.edu.ng