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Development of a MATLAB-Based Graphic User Interface (GUI) for 3D Datum Transformation using Molodensky-Badekas Model

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Abstract

Datum transformation is fundamental in geospatial data analysis, enabling the integration of datasets referenced to different geodetic datums. Given the mathematical complexity of datum transformations, this study presents a MATLAB-based graphical user interface (GUI), designed to perform three-dimensional datum transformations between the WGS 84 and Clarke 1880 ellipsoids using the Molodensky-Badekas (MB) model. The transformation parameters were determined employing least squares estimation techniques using 30 common points, and independently validated using five stations. These geodetic controls were obtained from the office of the Surveyor General of the Federation (OSGOF), Nigeria. The estimated transformation parameters are $T_x = -111.797 \pm 0.099$ *m,* $T_y = -95.604 \pm 0.099$ *m,* $T_z = +118.576 \pm 0.099$ *m,* $R_x = 0.00000203$ *rad,* $R_y = 0.00000052$ *rad,* $R_z = -0.00001198$ *rad, and scale = 0.9999968 ± 0.00000038. Validation results yielded* $RMSE_x = 1.41$ *m,* $RMSE_y = 0.16$ *m,* $RMSE_Z = 0.32$ *m, and an overall RMSE of 1.52 m, demonstrating the robustness and reliability of the implemented MB transformation. The developed GUI supports both single-point and batch processing, includes comprehensive input validation and error handling, and enables users to export results in comma-separated values (CSV) format. These capabilities make the tool a practical, efficient, and accessible solution for geodetic mapping applications in Nigeria.*

Keywords: Datum Transformation, Molodensky-Badekas, MATLAB, GNSS

1.0 Introduction

Geodetic datum transformation is a fundamental process in geospatial data analysis, enabling the transformation of coordinates between different reference systems to ensure accuracy and consistency across spatial datasets (Vaníček & Steeves, 1996; Deakin, 2006; Iliffe & Lott, 2008). A geodetic datum defines the reference framework for positioning, including an ellipsoid, its orientation, and its relationship to the Earth's surface (Vaníček & Steeves, 1996; Jekeli, 2006). With the increasing reliance on satellite-based positioning systems such as the Global Positioning System (GPS) and the need to integrate legacy data, mostly in the local geodetic datum, with modern geocentric datum, e.g., World Geodetic System 1984 (WGS 84), datum transformations have become increasingly important (Iliffe & Lott, 2008; Ogaja, 2024). For instance, the integration of complex data sources from different sensors in hydrographic and navigation systems requires the transformation of data acquired in the individual sensor frameworks to a common datum for effective integration (Basil, 2024). The importance of datum transformation is widely recognized across fields such as surveying and mapping, urban planning, GIS, environmental monitoring, and navigation (Featherstone, 1996; Iliffe & Lott, 2008; Urquizo et al., 2021; Ogaja, 2024). This need is consistent with ongoing efforts to establish a unified geocentric datum for Africa (African Geodetic Reference Frame) (Wonnacott, 2005), including Nigeria, aimed at modernizing national geospatial infrastructure. In particular, it supports the updating of historical spatial datasets, primarily referenced to local datum (e.g., Minna Datum), into globally consistent reference frames such as WGS84 and the International Terrestrial Reference Frame (ITRF) (Adebomehin & Akinyede, 2019).

Datum transformation techniques first emerged in the early twentieth century, when geodetic surveys relied primarily on local ellipsoids (Molodensky, 1942). In the 1940s, Mikhail Molodensky introduced the standard Molodensky method, which transforms geodetic coordinates directly using three linear shift parameters (ΔX, ΔY, ΔZ) together with changes in ellipsoid parameters (Δa, Δf) (Molodensky, 1942). Although straightforward, this method provides only moderate accuracy, typically on the order of 5-10 meters, and does not allow exact recovery of the original coordinates through forward and backward transformation (Ruffhead, 2021). To overcome these limitations, conformal transformation approaches were developed, including the three-parameter model, which converts geodetic data to Cartesian coordinates, applies shifts, and then reconverts them to geodetic coordinates (Phang and Setan, 2007). While more accurate, these methods are computationally intensive due to iterative processes (Vaníček & Steeves, 1996). The Molodensky-Badekas (MB) model, developed in the late 1960s (Molodensky et al., 1962; Badekas, 1969), emerged as a hybrid technique, combining the conceptual simplicity of the standard Molodensky approach with the precision of linearized conformal transformations (Badekas, 1969; Deakin, 2006). By employing either a 7- or 10-parameter formulation, the MB model achieves a sub-meter accuracy, making it appropriate for current applications (Phang & Setan, 2007; Annan et al., 2016).

Datum transformation techniques vary in complexity, precision and accuracy. While some transformation models apply simplified mathematical models for simplicity of usage, others include rotational parameters, translations, and scale to better mimic real-world geophysical phenomena. Among these, the MB model has gained popularity because of its capacity to produce geophysically and mathematically sound local transformation solutions (e.g., Urquizo & Mugnier, 2021). Unlike global models, e.g., the Bursa-Wolf (BW) transformation model (Bursa, 1962), the MB model employs a centroid-based method to reduce distortions in local transformations (Deakin, 2006), making it ideal for countries with non-uniform geodetic control networks or localized surveying systems (Iliffe & Lott, 2008). A comparison of MB and BW transformation models is provided in (e.g., Abbey et al., 2020; Kalu et al., 2021). While the two methods are theoretically and mathematically equivalent (Al Marzooqi et al., 2005; Phang & Setan, 2007; Ruffhead, 2021), MB avoids the large numbers that occur in the derivation of Bursa-Wolf parameters. MB compatibility with both geocentric and topocentric coordinate systems increases its appeal for practical applications (Deakin, 2006).

The robustness of the MB model, further strengthened through least squares adjustment for parameter estimation, makes it highly suitable for advanced geospatial applications (Phang & Setan, 2007; Alsadik, 2019). However, its implementation in developing countries faces notable challenges. Many existing transformation tools are integrated into costly commercial software or require substantial expertise in advanced geodetic computations and programming, placing them beyond the reach of non-specialists. Additionally, the absence of dedicated graphical user interfaces (GUIs) makes the model challenging to use for field surveyors, students, and professionals in related disciplines, such as urban planning and environmental studies (Igbokwe et al., 2016). These limitations underscore the urgent need for a localized, user-friendly MATLAB–based GUI for MB model transformation.

Developing a MATLAB-based GUI for the MB model will significantly enhance its usability for both geospatial and non-geospatial professionals, including researchers. The motivation for this project stems from the need to simplify the use of the MB model by providing an intuitive and user-friendly computational tool. Although the method is sufficiently rigorous for rotations smaller than 2″ (Ruffhead, 2021), applying it in practice can involve awkward computations, notably in the conversion of Cartesian coordinates to geodetic coordinates without appropriate software support. This project, therefore, aims to develop a MATLAB-based GUI that enables users to perform MB transformations easily, offering a clear interface for entering coordinates, estimating parameters and visualizing the results. The objectives include designing a MATLAB GUI capable of handling MB datum transformations, accepting user inputs for both coordinates and transformation parameters and validating its accuracy by comparing the outputs with established benchmarks. Additionally, the project aims to assess the usability and practical applicability of the GUI in a geospatial context, identifying its strengths and limitations.

This project bridges the gap between theoretical rigour and practical application, providing a tool that simplifies complex transformations for users with varying levels of expertise. In summary, this project seeks to create a MATLAB-based GUI that enhances the accessibility and usability of the MB model for datum transformations. By combining a robust mathematical framework with a user-friendly interface, the GUI aims to support geospatial professionals in achieving high-accuracy coordinate transformations, contributing to advancements in geodetic practice.

2.0 Methodology

2.1 Data Collection and Description

The dataset used in this study consists of 35 geodetic control points with known coordinate values in both Clarke 1880 (local) and WGS 84 (global) geodetic datum. Thirty points were used for parameter estimation, and five for validation of the estimated geodetic transformation parameters. These control points were obtained from the Office of the Surveyor General of the Federation (OSGOF), Nigeria. The dataset was part of the first-order geodetic control point established by OSGOF across Nigeria. The geoid undulation for the common points was obtained from the International Centre for Earth and Gravity Model (ICGEM). Each control point includes latitude, longitude, and height values (orthometric height) for Clarke 1880 and ellipsoidal height for WGS 84.

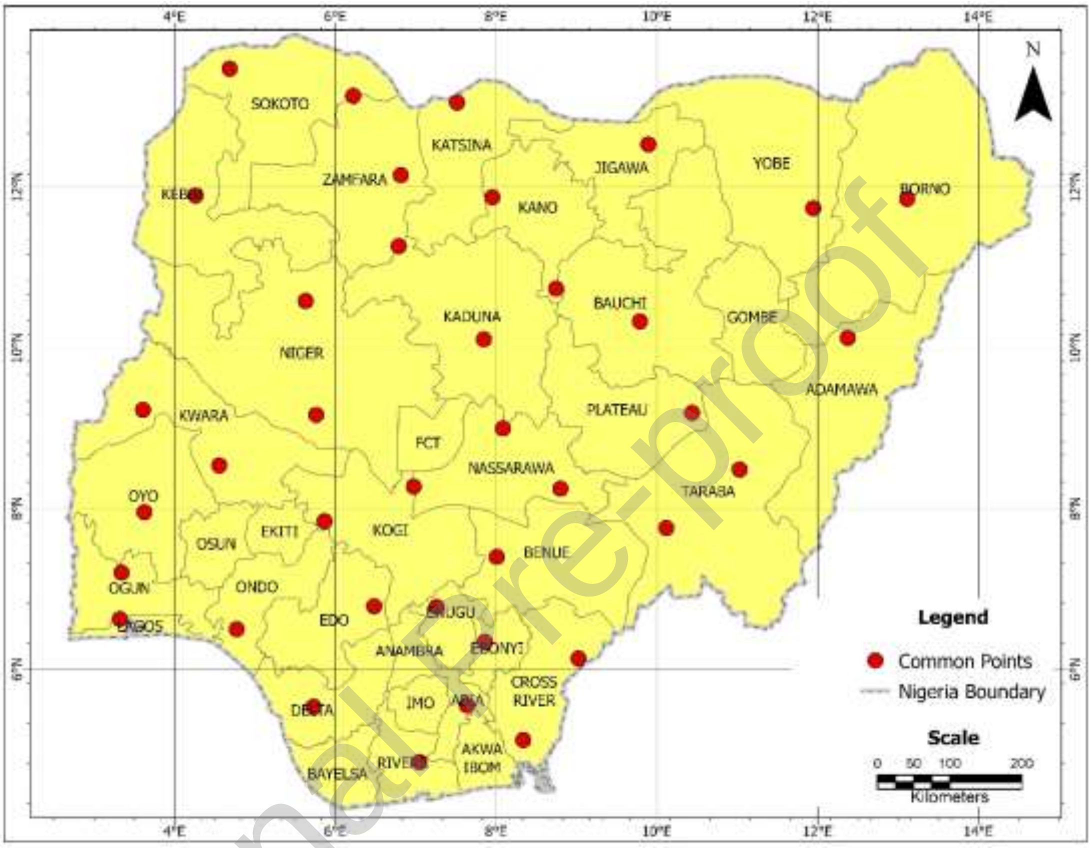

Figure 1: The distribution of the geodetic control network used for the estimation of datum transformation parameters and validation

2.2 Data Processing and Preparation

Data preparation involved data cleaning, formatting, and transforming the datasets into forms suitable for numerical computation. Using the Earth Gravity Model (EGM) 2008 geoid model, the orthometric heights were converted into ellipsoidal heights; also, the geodetic (φ, λ, h) coordinates were converted into Cartesian (X, Y, Z) coordinates using equations 1-4 (Jekeli, 2006):

$$X = (N + h)\cos\phi\cos\lambda \tag{1}$$

$$Y = (N + h)\cos\phi\sin\lambda \tag{2}$$

$$Z = ((1 - e^2)\,N + h)\sin\phi \tag{3}$$

$$N = \frac{a}{\sqrt{(1 - e^2 \sin^2\phi)}} \tag{4}$$

Where N is the radius of curvature, h is the ellipsoidal height, ϕ is the geodetic latitude, λ is the longitude, a is the semi-major axis, and e is the first eccentricity of the ellipsoid. The Cartesian coordinates provided the numerical foundation for implementing the MB model, which operates in 3D space. All processed datasets were stored in MATLAB-readable text files and verified through random sampling to ensure accuracy.

2.3 Datum Transformation Model

The choice of MB offers a simpler implementation than the Helmert transformation and its localised equivalent. MB also avoids the large numbers that occur in the derivation of Bursa-Wolf parameters. This makes the MB transformation model suitable for precise and accurate regional or local transformations. The model applies three translations($T_x, T_{y,} T_z$); three rotations($R_x, R_{y,} R_z$); one scale factor; a fixed reference point or Centroid (X_o, Y_o, Z_o) as expressed in equation 5 (Deakin, 2006; Ruffhead, 2021):

$$\begin{bmatrix} X_2 \\ Y_2 \\ Z_2 \end{bmatrix} = \begin{bmatrix} X_0 \\ Y_0 \\ Z_0 \end{bmatrix} + (1+s) \times \begin{bmatrix} 1 & -R_z & -R_y \\ R_z & 1 & -R_x \\ -R_y & -R_x & 1 \end{bmatrix} \times \begin{bmatrix} X_1 - X_0 \\ Y_1 - Y_0 \\ Z_1 - Z_0 \end{bmatrix} + \begin{bmatrix} T_x \\ T_y \\ T_z \end{bmatrix} \quad (5)$$

where (X_1, Y_1, Z_1) is the original geocentric coordinates in the source datum; ($T_x, T_{y,} T_z$) is the translation parameter; R is the rotation vector, s is the scale parameter, and $X_0, Y_{0,} Z_0$ is the centroid parameter. Equation 5 can be written in a more simplified form as given in equations (6-8) (Deakin, 2006):

$$X_2 = X_1 + T_x + s \cdot (X_1 - X_0) - R_z \cdot (Y_1 - Y_0) + R_y \cdot (Z_1 - Z_0) \quad (6)$$

$$Y_2 = Y_1 + Ty + s \cdot (Y_1 - Y_0) + R_z \cdot (X_1 - X_0) + R_x \cdot (Z_1 - Z_0) \quad (7)$$

$$Z_2 = Z_1 + T_z + s \cdot (Z_1 - Z_0) - R_y \cdot (X_1 - X_0) + R_x \cdot (Y_1 - Y_0) \quad (8)$$

2.4 The Method of Least Squares for Transformation Parameter Estimation

The datum transformation parameters were estimated using the least squares method employing the observation equation model. The method of least squares yields the most probable values by minimizing the sum of the squares of weighted residuals (Ogundere, 2019). For each of the thirty control points, three observation equations were formed, resulting in a system of linearized equations represented in matrix form as given in equation 9 (Alsadik, 2019; Ogundere, 2019):

$$\hat{V} = A\hat{X} - L \quad (9)$$

where V is the vector of residuals, A is the design (Jacobian) matrix, X is the vector of unknown parameters, and L is the vector of observed differences between data points. Applying the least-squares criterion, the normal equation is as given in equation 10 (Ogundere, 2019):

$$\hat{X} = (A^T PA)^{-1} A^T PL \quad (10)$$

where P is the weight matrix for each of the observations, which was set to an identity matrix, i.e., all observations were assumed to be of equal weight. The solution of equation 10 yields the most probable values of the transformation parameters.

The variance-covariance matrix of the unknown parameter is given in equation (11),

$$C_{\hat{X}} = \sigma_o^2 \left(A^T PA \right)^{-1} \quad (11)$$

where σ_o^2 is the a-posterior variance of unit weight given as:

$$\sigma_o^2 = \frac{V^T PV}{n-m} \tag{12}$$

where n denotes the number of observations, and m the number of unknown parameters. The leading diagonal is the variance of the unknown parameter. The standard deviation (square root of the variance) and Root Mean Square Error (RMSE) were also computed to quantify the internal precision of the estimated datum transformation parameters.

2.5 GUI Design and Implementation

The GUI was developed using MATLAB App Designer, which offers a visual platform for combining scripts with interactive components. The main aim was to create an intuitive application that enables users without programming experience to perform 3D datum transformations. The implementation workflow for the GUI is illustrated in Figure 2. The interface of the GUI includes (1) a datum parameter tab, (2) a tab for single transformation, and batch transformation, as shown in Figures 3 and 4.

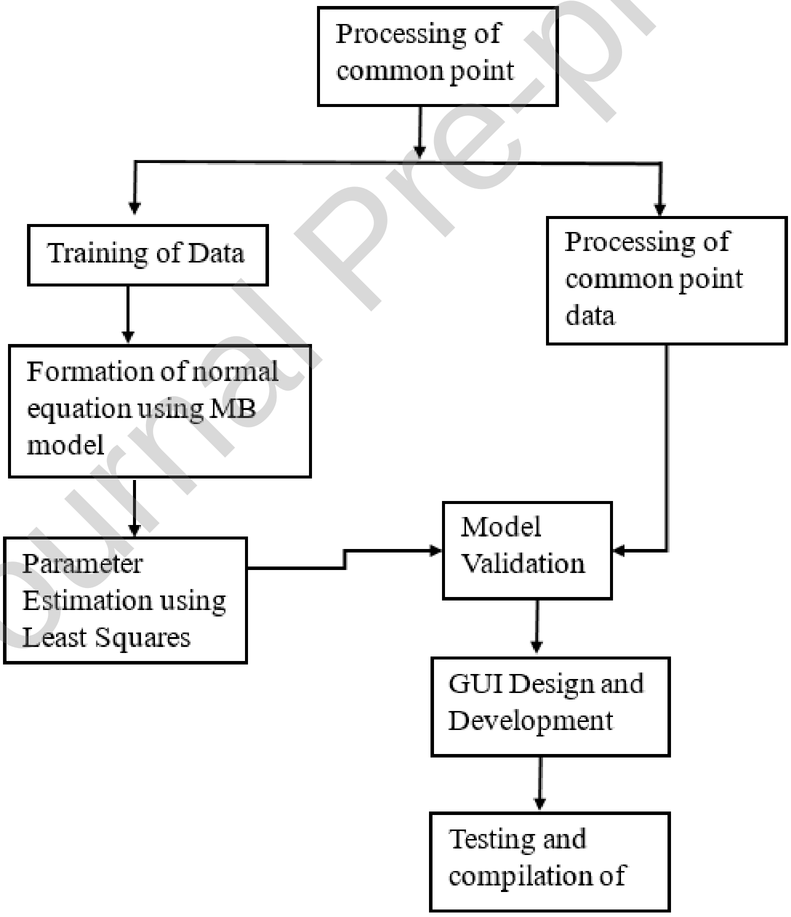

Figure 2: Flowchart of the datum transformation software

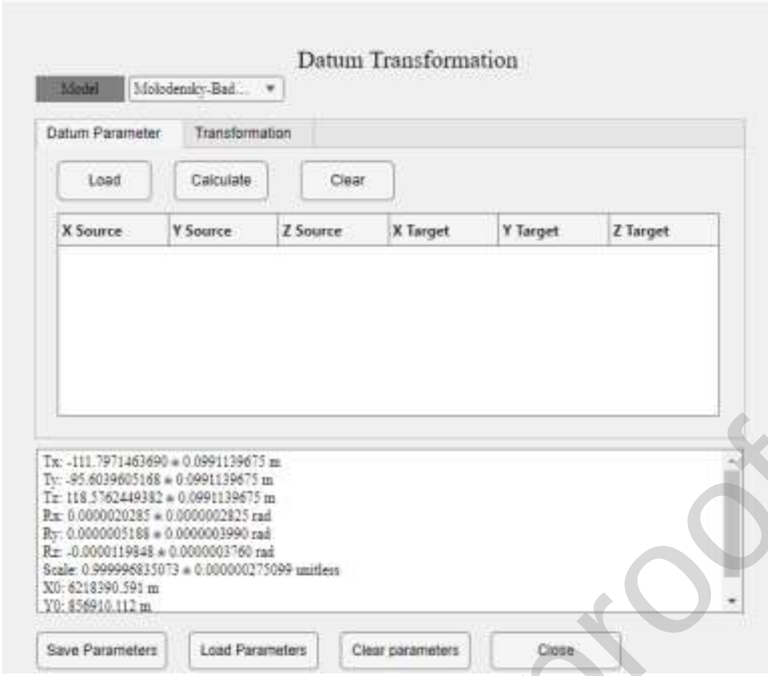

Figure 3: screenshot of the datum parameter tab.

The "Load Parameters" icon in Figure 3 enables users to select the dataset required for computing the datum transformation parameters. Once loaded, the data are displayed in a table beneath the icon. The "Calculate" icon processes the selected data and presents the resulting transformation parameters in a second display window. The "Clear" icon removes the contents of the table shown in the user interface window.

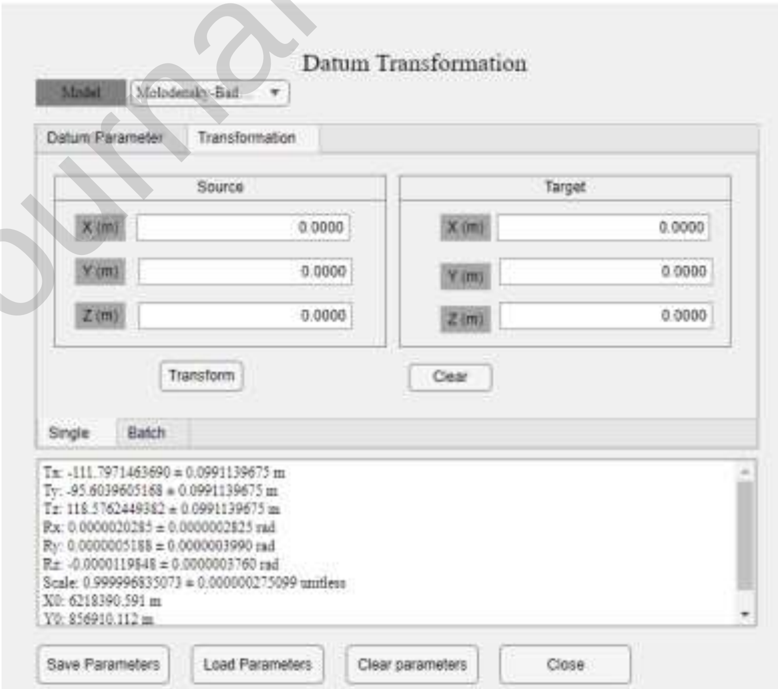

Figure 4: screenshot of the datum transformation tab

The "Transform" button in Figure 4 applies the datum transformation to the selected points based on the model chosen from the drop-down menu, while a dedicated text box displays the three translation parameters, three rotation parameters, the scale factor, their corresponding standard deviations, and the centroid values. The Load Parameter button allows users to import datum parameters from a notepad or .txt file and automatically populate the text box, whereas the "Save Parameter" button enables users to store the computed parameters shown in the text box back into a notepad or .txt file. Finally, the "Close" button is used to exit the UI figure.

3.0 Results and Discussion

3.1 Parameter Estimation and Comparison

Table 1 presents the geodetic datum transformation parameters estimated using the MB model, derived from 30 geodetic control points distributed across Nigeria. To evaluate the reliability of the estimated parameters, the estimated transformation parameters were compared with the published transformation values reported by Uzodinma (2005), who obtained translation components of –93.81 m, –89.24 m, and +118.14 m for T_X, T_Y and $T_{Z,}$ respectively. The results from this study exhibit a strong agreement with the results of Uzodinma (2005), indicating a high level of consistency between both solutions. The small discrepancies can be attributed to differences in the number of stations used and their spatial distribution. This close agreement between both results validates the reliability of the implemented MB model using the method of least squares and supports the use of the developed GUI tool for regional transformations in Nigeria.

Table 1: Estimated datum transformation parameters using the method of least squares from 30 geodetic network points in Nigeria.

Parameters	Estimated values	Standard deviation	Unit
T_X	-111.797146	± 0.0991139675	M
T_Y	-95.6039605	± 0.0991139675	M
T_Z	118.5762449	± 0.0991139675	M
R_X	2.0285E-06	± 0.0000002825	Rad
R_Y	5.188E-07	± 0.000000399	Rad
R_Z	-1.1985E-05	± 0.000000376	Rad
s	0.999996835	± 0.000000275099	
X_o	6218390.591		M
Y_o	856910.112		M
Z_o	1070980.308		M

3.2 Model Validation

Model validation was performed using five independent control points that were not included in the parameter estimation stage. These points served to evaluate the accuracy of the implemented MB-model. The validation involved comparing the coordinates transformed through the MATLAB-based Graphical User Interface (GUI) with their corresponding known WGS 84 reference coordinates. The resulting residuals for the selected validation points, presented in Table 2, were computed using equations (13-15):

$$V_x = X_{observed} - X_{Transformed} \quad (13)$$

$$V_y = Y_{observed} - Y_{Transformed} \quad (14)$$

$$V_z = Z_{observed} - Z_{Transformed} \quad (15)$$

Table 2: Validation of the estimated datum transformation parameter. The table shows the difference between the model (estimated values) and the known values of the validation control (test) points.

Point ID	V_x	V_y	V_z
1	1.491	0.079	0.067
2	0.165	-0.074	0.119
3	1.684	-0.085	0.25
4	1.55	0.212	0.525
5	1.551	0.267	0.405

We also computed the residual at the 30 control stations used in the estimation of the datum parameter, presented in Figure 5

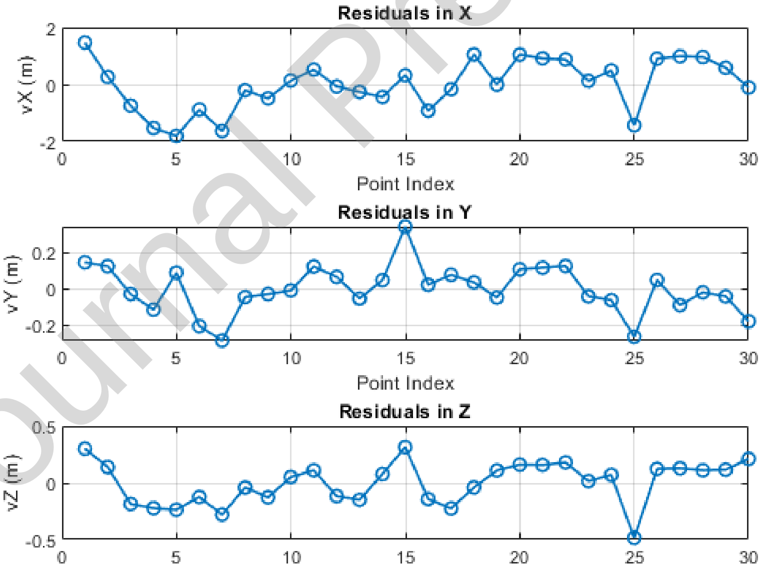

Figure 5: Distribution of the residual at the 30 control points used in the estimation of the datum parameters

The residuals show strong agreement between the transformed and reference coordinates, with positional deviations below ±2 m horizontally and ±0.6 m vertically. The spatial distribution of these residuals indicates a consistent and unbiased performance of the MB transformation model implemented in MATLAB.

The RMSE quantifies the average positional deviation of transformed coordinates from the true (observed) WGS-84 coordinates and is given as:

$$RMSE = \sqrt{\frac{\Sigma V^2}{n}} \quad \text{where n = 5} \tag{16}$$

Table 3: Square of Residuals

Point ID	$V_x{}^2$	$V_y{}^2$	$V_z{}^2$	ΣV^2
1	2.222	0.006	0.004	2.232
2	0.027	0.005	0.014	0.046
3	2.835	0.007	0.063	2.905
4	2.403	0.045	0.276	2.724
5	2.406	0.071	0.164	2.641
Σ	9.893	0.134	0.521	10.548

The computed RMSE values at the validation (test) points are 1.41, 0.16, and 0.32 m for the X, Y, and Z axes, respectively, with an overall RMSE of 1.52 m. These results show that the transformation attains its highest accuracy in the Y (north–south) and Z (vertical) directions, whereas the X (east–west) component exhibits comparatively greater variability. The computed RMSE values of the residual at the control points 0.874515, 0.128577, and 0.184521 m for the X, Y, and Z axes, respectively.

4.0 Conclusions and Recommendations

This study presented the transformation, validation, and analysis results obtained using the developed MATLAB-based GUI for implementing the MB model. Validation using independent control points yielded RMSE values of 1.41, 0.16, and 0.32 m in the X, Y, and Z axes, respectively, with an overall accuracy better than 1.5 m. The small and randomly distributed residuals indicate the absence of systematic bias, while the agreement between the estimated parameters and values reported in previous studies confirms the robustness of the implemented model.

The developed GUI demonstrated efficiency in processing multiple datasets and provides a practical interface that supports both coordinate transformation and datum parameter estimation through least squares, including the display of associated parameter uncertainties. This enhances user understanding of transformation reliability and promotes wider applicability in regional geodetic tasks.

Based on the findings, the following recommendations are proposed for future development:

1. Integration of dynamic geoid models: Incorporating APIs or databases for real-time access to contemporary geoid models (e.g., EGM2020, XGM2019e) would improve vertical transformation capability.
2. GIS interoperability**:** Linking the application with GIS platforms such as QGIS or ArcGIS would enhance spatial data visualization and streamline workflow integration.

3. Machine learning optimization: Data-driven approaches could be explored to refine residual patterns and enhance transformation accuracy.

4. Web-based implementation: Developing an online version of the application would improve accessibility and facilitate broader user engagement.

Further improvements and feedback from users are encouraged to support continued refinement of the software.

You can contact the authors via the email provided to get the compiled version of the app. Comments and suggestions are welcome from readers and users.

Data Availability: The data used in this study were sourced from the office of the Surveyor General of the Federation of Nigeria, and it is available on request.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.