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GEOMETRIC GEOID MODEL DETERMINATION FOR CAMP DAVID ESTATE, CENTENARY CITY, ABAKALIKI, EBONYI STATE

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ABSTRACT

The precision of height determination is essential for engineering and surveying applications. However, in many urbanizing areas in Nigeria, such as Camp David Estate, Abakaliki, there is no localized geoid model, which leads to vertical datum discrepancies and poor integration of GNSS-derived elevations. This study employs the GPS/levelling method to develop a geometric local geoid model tailored for Camp David Estate. Ellipsoidal heights were obtained via static GNSS observations, while orthometric heights were derived through precise spirit levelling. Geoid undulations were computed by subtracting orthometric heights from ellipsoidal heights, followed by polynomial surface modelling to construct the geoid model. The ellipsoidal heights ranged from 45.921 m to 59.150 m (mean = 53.76 m), and orthometric heights ranged from 24.49 m to 37.72 m (mean = 31.87 m). Geoid undulations were relatively uniform (mean = 21.4310 m, SD = 0.0028 m), indicating the reliability of the simple geoid model. Validation against EGM2008 revealed a consistent bias of -0.1898 m. These results confirm the suitability of the geometric method for localized geoid modelling in urban Nigerian settings. The derived model should be adopted for surveying and geospatial operations in the study area to enhance vertical accuracy.

Keywords: Geoid model, GNSS/levelling, Camp David Estate, orthometric height, EGM2008

1. Introduction

Accurate height determination remains a fundamental component of geodesy, surveying, civil engineering, and environmental monitoring. It plays a pivotal role in theinfrastructural design, terrain evaluation, flood vulnerability assessments, and sustainable urban development [1], [2]. A precise vertical reference system is essential to ensure consistency in elevation data across geospatial applications. One of the most critical reference surfaces used in vertical positioning is the geoid an equipotential surface of Earth's gravity field that closely approximates mean sea level. In geodetic practice, vertical measurements are typically expressed as orthometric heights, which are referenced to the geoid. However, modern satellite-based positioning systems, such as the Global Navigation Satellite System (GNSS), provide ellipsoidal heights referenced to a mathematical figure the reference ellipsoid rather than the geoid [3], [4].

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To integrate GNSS-derived heights into traditional surveying and engineering workflows, it is necessary to convert ellipsoidal heights into orthometric heights. This requires knowledge of the geoidal undulation which is the vertical separation between the ellipsoid and the geoid at all points [5], [6]. There are two types of Geoid Models, produced from different methods of geoid determination, and they are the Global Geoid Models and the Local Geoid Models. Global Geoid Models, such as the Earth Gravitational Model 2008 (EGM2008) and Ohio State University 1991 (OSU 91), provide estimates of geoid undulations at a global scale. These models are developed from satellite altimetry, terrestrial gravity measurements, and spherical harmonic expansions [7]. While they are valuable for large-scale applications, global models such as EGM2008) often lack the spatial resolution and accuracy required for localized engineering or cadastral works, especially in regions with sparse terrestrial gravity data like Nigeria [8], [9], [10].

To address these deficiencies, local geoid models are developed using astrogeodetic methods, gravimetric methods or the geometric method. The geometric approach is also referred to as the GNSS/levelling Method. This method involves observing ellipsoidal heights using GNSS and orthometric heights through precise spirit levelling, then computing geoid undulations by subtracting the two [11], [12]. The technique is widely regarded as a cost-effective and accurate means of determining local geoid surfaces, especially in regions where gravimetric data is limited [13], [14].

Numerous studies have validated the applicability of the GNSS/levelling method in different parts of the world. For example, [15] employed fuzzy logic theory to enhance local geoid accuracy, while [16] implemented a particle swarm optimization technique to refine geometric geoid surfaces. In the Nigerian context, [17] successfully applied this method at Nnamdi Azikiwe University, and similar models have been developed in Enugu [8], Abuja [6], Benin City [11] and Akure [18], yielding centimetre-level accuracy suitable for practical geodetic use.

Moreover, hybrid approaches combining gravimetric and geometric observations have emerged to improve model reliability. [12],[19] outlined procedures for deriving gravimetric-geometric geoid models, emphasizing the importance of integrating local gravity anomalies for refined accuracy. Their work on theoretical gravity modelling using the Clarke 1880 ellipsoid [14] further supports the development of highly tailored geoid solutions for specific geodetic regions. In addition to vertical referencing, geoid models support several critical applications such as height system unification, digital terrain modelling, water resource management, and construction control. Their importance is amplified in rapidly urbanizing zones, where infrastructure layouts and drainage networks depend heavily on accurate and consistent elevation data [2], [1].

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Camp David Estate in Centenary City, Abakaliki, Ebonyi State, Nigeria, is a contemporary example of such an urban area experiencing rapid transformation. As a government-backed residential and administrative hub, it hosts various infrastructure projects, including road construction, housing development, and utility networks. However, the absence of a localized geoid model for this estate presents a major limitation to precision surveying and construction planning. Relying solely on EGM2008 or legacy benchmarks introduces elevation inconsistencies that can compromise structural design, drainage flow, and urban layout [20], [6].

Therefore, this study aims to develop a precise local geometric geoid model for Camp David Estate using GNSS/levelling techniques. The model will serve as a vertical datum for transforming GNSS-observed ellipsoidal heights into orthometric heights with centimeter-level precision. By bridging the vertical referencing gap, the proposed model will enhance spatial data accuracy, support engineering design, and contribute to the geodetic infrastructure needed for sustainable urban development in Abakaliki and its environs.

2. Materials and Methods

2.1 Study Area

This research was conducted within Camp David Estate, a rapidly developing residential and administrative zone located in Centenary City, Abakaliki, the capital of Ebonyi State, Nigeria. The estate spans an approximate area of 100 hectares and is strategically situated near significant landmarks such as the Ebonyi State Government House and several ministerial and infrastructural complexes. The topography of the area is characterized by gently undulating terrain with elevation values ranging between 24.49 m and 37.72 m above mean sea level. The region experiences tropical climatic conditions with distinct wet and dry seasons, and the underlying geology consists primarily of sedimentary formations typical of southeastern Nigeria. Due to ongoing urban development projects and the need for precise engineering design, the area was deemed suitable for developing a localized geoid model using geodetic methods, see figure 2.1.

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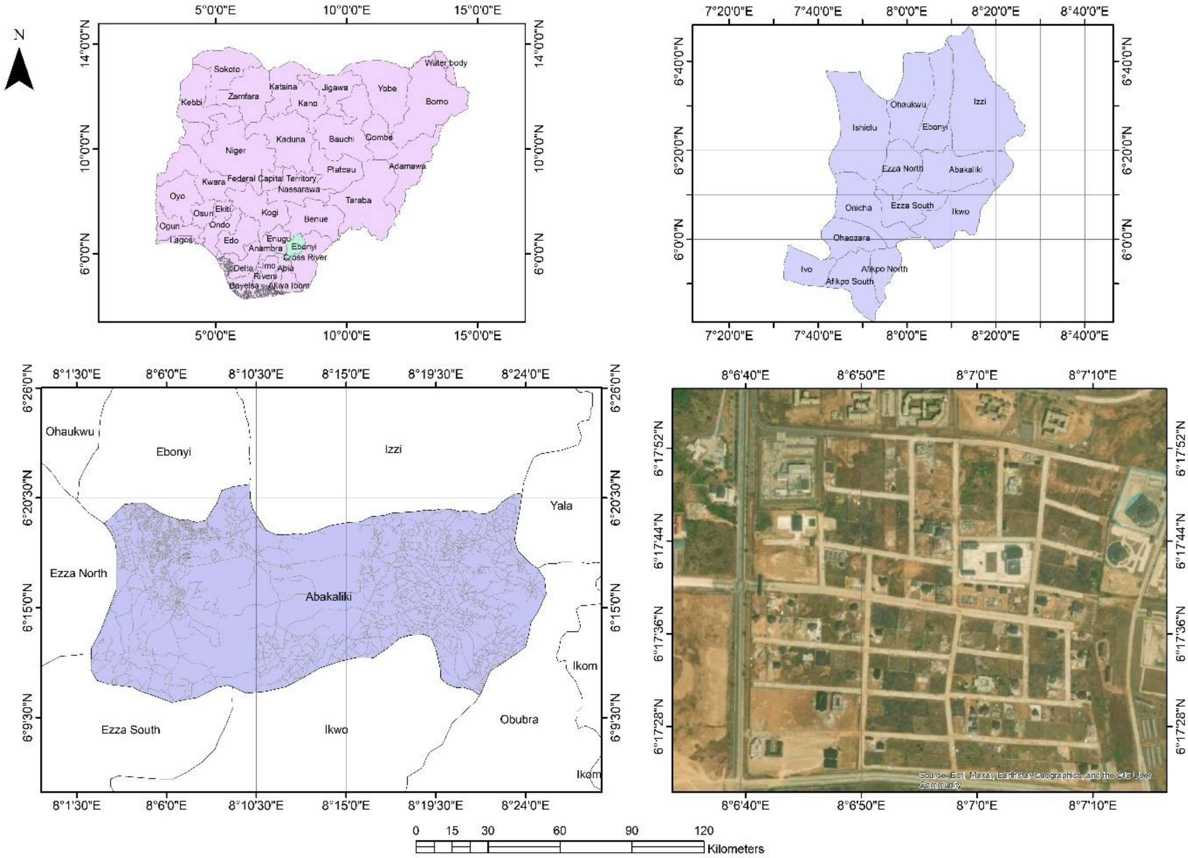

Figure 2.1: Map of the Study Area

2.2 Materials and Equipment

This study utilized a combination of field observation tools and analytical software to obtain and process both ellipsoidal and orthometric height data.

For GNSS observations, dual-frequency GNSS receiver was employed, specifically the Leica GS15 receivers. This high-precision geodetic receiver was designed for static positioning tasks and is capable of tracking multiple satellite constellations, including GPS, GLONASS, and GALILEO. The equipment setup included geodetic-grade antennas that were mounted securely on tripods to maintain vertical alignment. A known base station was established on a geodetically referenced control point within the estate, while rover receivers were used to observe the remaining control stations.

Precise levelling was carried out using a Leica NA2 automatic level along with thermally stable invar staffs to ensure high-precision measurement. Invar staffs were selected due to their resistance to thermal expansion, thus guaranteeing consistent readings regardless of field temperature variations.

The software tools used in data processing included Leica Geo Office (LGO) for GNSS data post-processing and coordinate computation. Microsoft Excel was utilized for data tabulation, computation of height differences, and statistical analysis. MATLAB software was used for the polynomial surface fitting of geoid undulations and the development of the geoid model. ArcGIS 10.8 was employed for geospatial visualization, contour generation, and map creation. Additionally, root mean square error (RMSE) and bias analysis were computed to assess model performance.

2.3 Data Collection Procedure

The field data collection involved two distinct geodetic activities: static GNSS observation and precise differential levelling. These two methods were combined to derive the ellipsoidal and orthometric heights of selected control points within the estate.

GNSS observations were performed in static mode. A total of 58 well-distributed control points were selected across the study area to ensure spatial coverage and uniform representation of the terrain. Each GNSS receiver was left to occupy the control point for a minimum observation session of four hours, the observations lasted 20 days. This duration ensured sufficient satellite geometry, positional dilution of precision (PDOP), and redundancy for post-processing. The base station was set up on a control point with known ellipsoidal coordinates.

Precise spirit levelling was carried out concurrently using a known bench mark to obtain orthometric heights of the same control points. The levelling survey followed a closed-loop design to allow for error adjustment and quality control. For each observation, backsight and foresight readings were taken and averaged to minimize instrument and reading errors. The levelling lines were measured along the estate's access roads and clear pathways, ensuring stable footing for the level and staff. Measurement precision was carefully maintained by regularly checking and calibrating the instrument using the two-peg test.

All observed heights from GNSS and levelling were checked for internal consistency and recorded in data sheets before being transferred for computation.

2.4 Computation of Geoid Undulations

Geoid undulations, which represent the vertical separation between the ellipsoid and the geoid, were computed by subtracting the orthometric height obtained from levelling from the ellipsoidal height obtained via GNSS observations. The relationship is expressed mathematically as:

$$N = h - H$$

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Where N is the geoid undulation, h is the ellipsoidal height from GNSS, and H is the orthometric height from levelling. This computation was carried out for each of the 58 control points. The resulting undulation values were analyzed using basic descriptive statistics to evaluate their distribution across the estate. The mean, minimum, maximum, and standard deviation of geoid undulations were computed and tabulated to assess the terrain uniformity and suitability for simple surface modelling.

2.5 Geoid Model Development

The computed geoid undulations were used to develop a mathematical model representing the local geoid surface across Camp David Estate. A second-order polynomial surface fitting technique was employed for this purpose. This technique was chosen because of its balance between model simplicity and fitting accuracy, especially in moderately undulating terrain.

The general form of the polynomial surface model is given as:

$$N(x, y) = a0 + a1x + a2y + a3x2 + a4xy + a5y2 \qquad \dots (1)$$

Where:

$N(x, y)$ is the geoid undulation at location (x, y),

$x \ and \ y$ are the Easting and Northing coordinates of the control points,

$a0$ through $a5$ are the coefficients of the polynomial determined using the least squares method.

MATLAB software was used to compute the best-fitting coefficients by minimizing the residuals between the observed and predicted geoid undulations. The accuracy of the fitted surface was assessed by calculating the residuals (errors) at each point and then computing the Root Mean Square Error (RMSE) using the formula:

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(N_{observed,i} - N_{predicted,i}\right)^2}$$

A lower RMSE value indicated better model accuracy and stronger predictive capability of the fitted polynomial.

2.6 Validation of the Local Geoid Model Against EGM2008

To assess the reliability and accuracy of the locally derived geoid model, a comparison was made with the Earth Gravitational Model 2008 (EGM2008), which is one of the most commonly used global geoid models. The EGM2008 model provides geoid undulation values globally based on satellite altimetry, terrestrial gravity observations, and spherical harmonic expansions up to degree 2159.

Geoid heights corresponding to the 58 control points were extracted from EGM2008 using the GeographicLib geoid evaluation tool and cross-referenced with the locally computed values. The difference between the local and global geoid undulations was computed at each point, and the mean difference (bias) was calculated to quantify the deviation:

$$\text{Bias} = \frac{1}{n}\sum_{i=1}^{n}\left(N_{local,i} - N_{EGM2008,i}\right)$$

This analysis helped to validate the performance of the local geoid model and to highlight the inadequacies of using EGM2008 alone for high-precision surveying in the study area.

2.7 Spatial Interpolation and Visualization

To enable a continuous geospatial representation of geoid undulations across the entire estate, the computed point-based geoid values were interpolated using the Inverse Distance Weighting (IDW) technique in ArcGIS 10.8. IDW was selected because it is suitable for small-area interpolation where the influence of known points diminishes with distance.

Contour maps of ellipsoidal heights, orthometric heights, and geoid undulations were subsequently generated. These maps allowed for visual interpretation of the vertical characteristics of the terrain and served as a vital tool for spatial decision-making, infrastructure planning, and engineering design. The contour intervals were adjusted to reflect the terrain's subtle undulations, ensuring clarity and usability for stakeholders.

3. Results

This section presents the key results obtained from GNSS static observations, precise levelling, geoid undulation computation, polynomial surface fitting for geoid modelling, and a comparative assessment

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with the global Earth Gravitational Model 2008 (EGM2008). The results are interpreted to assess the quality, consistency, and spatial characteristics of the height data and the derived geoid model.

3.1 Ellipsoidal Height Determination from GNSS Observations

The ellipsoidal heights for the 58 selected control points across Camp David Estate were obtained from static GNSS observations conducted over a period of 4 hours per station. The data was processed using Leica Geo Office software with corrections applied from a nearby Continuously Operating Reference Station (CORS) to enhance positional accuracy.

The results show that ellipsoidal heights across the estate ranged from 45.921 meters (lowest point) to 59.150 meters (highest point), with a calculated mean of 53.76 meters. The standard deviation was 3.14 meters, indicating moderate topographic variation. The results confirm that the estate terrain is neither flat nor extremely rugged, but gently undulating—a characteristic typical of the Abakaliki region.

Figure 3.1 displays a contour map generated from the GNSS ellipsoidal heights, revealing elevation gradients sloping from northeast to southwest. These variations correspond with the estate's natural drainage patterns and are relevant for planning infrastructure such as road layouts and stormwater management.

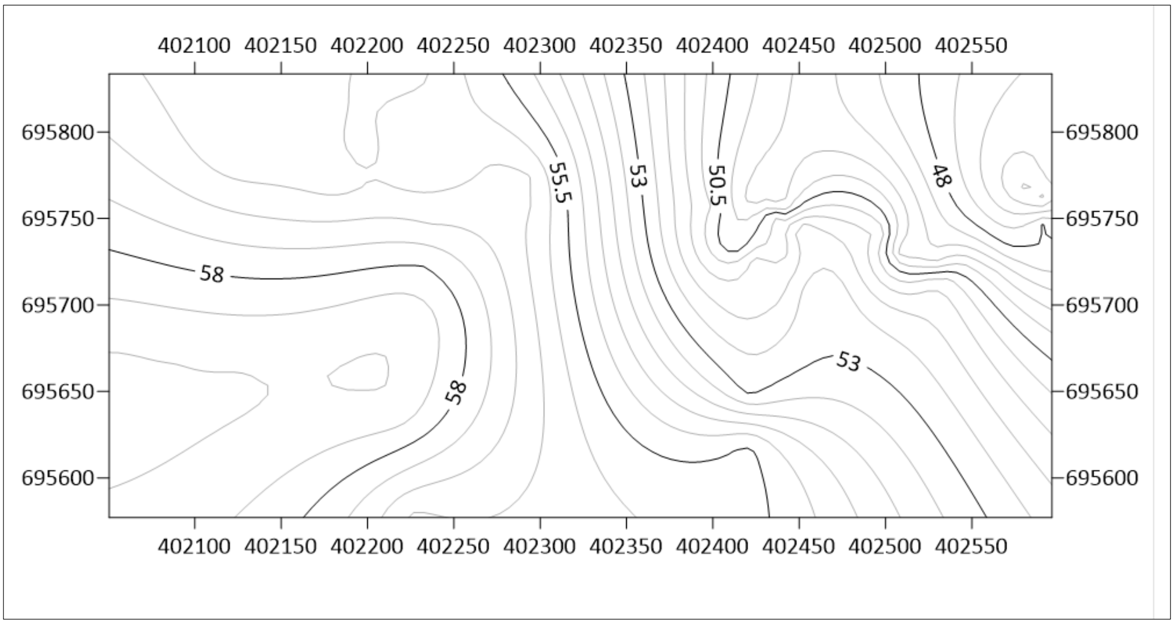

Figure 3.1: Contour of the Ellipsoidal Heights

3.2 Orthometric Height Results from Precise Spirit Levelling

Precise spirit levelling was performed across all control points to determine orthometric heights, using a Leica NA2 level and invar staffs. Levelling loops were carefully closed and adjusted using the least squares method, with misclosures well within the manufacturer's tolerance limits.

The resulting orthometric heights ranged from 24.49 meters to 37.72 meters, with a mean of 31.87 meters and a standard deviation of 3.08 meters. The near-identical variability compared to ellipsoidal heights reflects the consistent nature of the topographic surface in the area.

Figure 3.2 presents an orthometric height map generated using Inverse Distance Weighting (IDW) interpolation. This visualization supports the finding that the terrain is well-suited for engineering works and simplifies the modelling of the geoid surface due to low variation in topography.

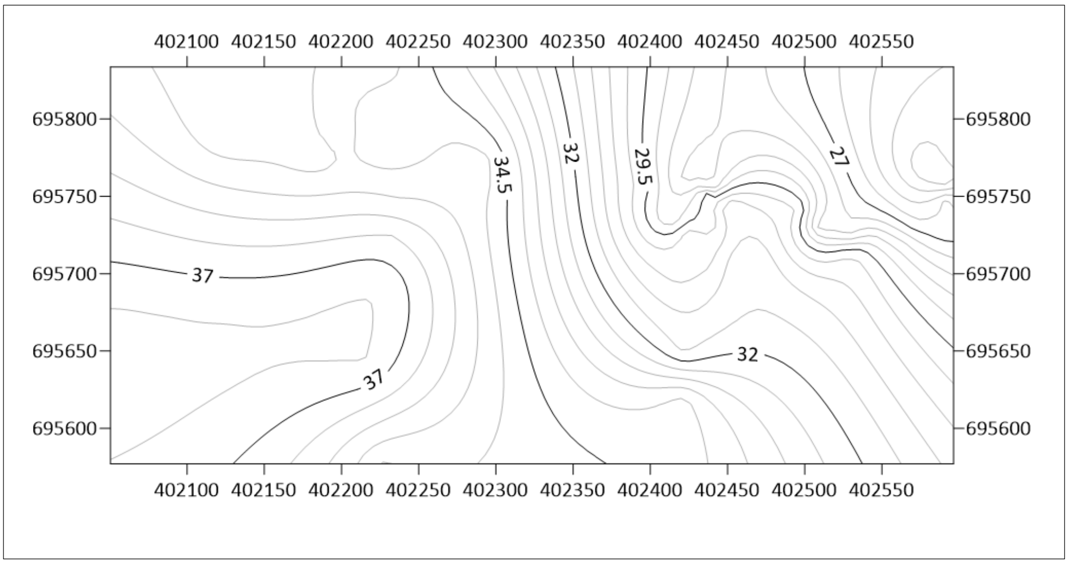

Figure 4.2: Contour of the Orthometric Heights

3.3 Computation of Geoid Undulations

The computed undulation values ranged narrowly from 21.4295 meters to 21.4341 meters, with a mean value of 21.4310 meters and a standard deviation of only ±0.0028 meters. The range of undulation values was 0.0046 meters, indicating high uniformity.

The tight clustering of values indicates the gravitational field within the estate is smooth and homogeneous, free from significant subsurface density anomalies. This level of consistency is ideal for low-order surface modelling. Figure 3.3 (geoid undulation distribution map) confirms the minimal spatial variation, with most areas falling within ±0.002 meters of the mean.

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Table 3.1: Descriptive statistics of the geoid undulations.

Statistic	Value (m)
Minimum	21.4295
Maximum	21.4341
Mean	21.4310
Standard Deviation	0.0028
Range	0.0046

These values indicate that in areas like Camp David Estate, where terrain and gravity conditions are consistent, low-complexity geoid modelling is both feasible and reliable.

3.4 Polynomial Surface Fitting and Local Geoid Model Development

A second-order polynomial regression surface was fitted to the geoid undulation data using MATLAB's least squares optimization technique. The regression model took the general form $equation$ 1in section 2.5

This polynomial structure allowed the model to account for both linear and mild nonlinear variations in the spatial distribution of the geoid surface across the estate. While higher-order polynomials can model more complex surfaces, they often introduce unwanted oscillations (overfitting) and are not suitable for relatively flat or gently undulating terrains such as those of the study area.

The input dataset for model development consisted of 58 control points, each with UTM Easting and Northing coordinates and geoid undulation values computed as the difference between ellipsoidal and orthometric heights.

The data were processed using in matlab, where the independent variables (Easting and Northing) were expanded into polynomial features, and an inbuilt least squares linear regression was applied to determine the model coefficients.

The resulting fitted equation obtained from the regression analysis is expressed as:

$$N(x,y) = 103031.60 - 0.1057x - 0.2351y - 3.668 \times 10 - 8\,x2 + 1.943 \times 10 - 7xy$$

This equation constitutes the geometric geoid model for the study area and provides a deterministic method for predicting geoid undulations at any location within Camp David Estate, provided the UTM Easting and Northing are known.

The fitted model showed excellent agreement with the observed values. The residuals between observed and predicted undulations were all within ±0.002 meters. The Root Mean Square Error (RMSE) for the fitted surface was ±0.0013 meters, demonstrating a high degree of model accuracy.

This result is particularly significant because it confirms that in areas with subtle topographic variation and uniform gravitational behavior, low-order polynomial surfaces can adequately capture the geoid shape. Table 3.2 presents the statistical performance of the polynomial fitting.

Table 3.2: Polynomial Fitting Performance Metrics

Metric	Value (meters)
Root Mean Square Error (RMSE)	±0.0013
Maximum Residual	±0.0020
Minimum Residual	±0.0004

This highly accurate model can now be applied to any GNSS-derived ellipsoidal height within the estate to instantly compute orthometric heights, improving surveying efficiency.

3.5 Comparison with EGM2008

To validate the derived local geoid model, it was compared with the EGM2008 global geoid model. Geoid heights were extracted for each of the 58 control points using the GeographicLib online geoid calculator. The differences between the local model and EGM2008 were computed as:

$$\text{Difference} = N_{\text{local}} - N_{\text{EGM2008}}$$

The comparison revealed a systematic negative bias of -0.1898 meters, with EGM2008 underestimating the geoid height for all points in the study area. The standard deviation of the differences was 0.0026 meters, indicating that while EGM2008 is consistent, it is offset from the true geoid surface for the study area.

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This outcome highlights the limitation of global models in resolving local gravity features and justifies the need for high-resolution local geoid models. A summary of the comparison is provided in Table 3.3.

Table 3.3: Local Geoid Model vs EGM2008 Summary

Statistic	Value (m)
Mean Difference (Bias)	-0.1898
Minimum Difference	-0.1923
Maximum Difference	-0.1865
Standard Deviation of Bias	0.0026

This systematic bias further confirms that reliance on EGM2008 alone for precise vertical referencing in the study area would result in errors exceeding 18 cm—an unacceptable margin in most engineering and geodetic applications.

4. Discussion of Results

The results obtained from this study offer robust empirical support for the effectiveness of GNSS/levelling techniques in developing a local geometric geoid model in urban settings such as Camp David Estate, Centenary City, Abakaliki. The findings revealed a spatially stable geoid surface with minimal undulation variation, underscoring the viability of low-order polynomial surface fitting for local geoid modelling.

4.1 Interpretation of Height Data

The ellipsoidal heights, derived from static GNSS observations, and the orthometric heights, obtained through precise spirit levelling, displayed strong spatial consistency. Ellipsoidal heights ranged from 45.921 m to 59.150 m, while orthometric heights varied between 24.49 m and 37.72 m. The low standard deviations (3.14 m for ellipsoidal heights and 3.08 m for orthometric heights) indicate terrain homogeneity across the estate. These results are comparable to those reported by [11], [17], where gently undulating terrain facilitated accurate surface model fitting.

The internal consistency and precision of the GNSS and levelling observations enhanced the reliability of the computed geoid undulations. The closed-loop levelling methodology, combined with differential GNSS corrections, further minimized systematic error, aligning with recommendations by [12], who emphasized the importance of observational control in local geoid modelling.

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4.2 Uniformity of Geoid Undulations

A key result of this study is the exceptionally uniform geoid undulation values, which ranged narrowly from 21.4295 m to 21.4341 m, with a standard deviation of ±0.0028 m. This finding reflects a stable local gravitational field, which is ideal for polynomial modelling. Similar undulation uniformity was reported by [1] and [10] in their GNSS/levelling studies in Australia and Nigeria, respectively.

The spatial uniformity of the geoid indicates the absence of significant geological anomalies or abrupt topographical discontinuities. This supports the use of a second-order polynomial surface, avoiding the overfitting risk associated with more complex models. According to [13], uniformity in geoid heights often correlates with higher model stability and accuracy.

4.3 Accuracy of Polynomial Surface Fitting

The second-order polynomial model applied in this study achieved a high predictive accuracy, with an RMSE of ±0.0013 m. Residuals were uniformly distributed within ±0.002 m, confirming the suitability of least squares surface fitting techniques for geoid modelling in compact, homogeneous urban settings. These results are validated by local studies such as[14], who applied polynomial regression in Minna and Abuja with similar levels of accuracy.

The model's effectiveness demonstrates that simple, well-calibrated geometric models can replace more data-intensive gravimetric techniques in small areas, especially when time and resources are limited. This echoes the conclusions of [5], who found that geometric methods were sufficient for certain regional applications.

4.4 Comparison with EGM2008 and the Case for Local Models

When the locally derived geoid undulations were compared with those from the global EGM2008 model, a consistent underestimation of -0.1898 m was observed. This bias confirms the limitations of global geoid models in high-precision, local-scale applications. This result corroborates findings from [8], [9], [10] all of whom demonstrated that EGM2008 fails to account for local gravitational anomalies in Nigerian terrain.

The observed bias highlights the necessity for local geoid modelling efforts tailored to specific geodetic conditions. GNSS receivers defaulted to global models such as EGM2008 risk propagating elevation errors into engineering and surveying outputs. The need for locally adjusted models is further supported by [7], who emphasized that global models are approximations and should be complemented by local calibration for regional use.

The local geoid model developed in this study has immediate and practical implications. It enables surveyors to convert GNSS-derived ellipsoidal heights to orthometric heights accurately, streamlining workflows and eliminating the need for repetitive levelling. Engineers and urban planners can use the model for drainage design, road gradient assessments, and volumetric earthworks with confidence in height precision.

As demonstrated by [2] , [14], a consistent and accurate local vertical reference system enhances interoperability across projects, reduces vertical datum discrepancies, and improves the quality of cadastral and civil infrastructure datasets. The geoid model serves not only as a height transformation tool but also as a geospatial decision-support framework.

The results reaffirm the findings of [15], [16], who emphasized the utility of computational intelligence and optimization techniques in achieving similar levels of geoid model accuracy. These methodologies, coupled with field-tested geometric principles, confirm the reliability of GNSS/levelling for localized geoid realization.

5 Conclusion

This research successfully demonstrated the feasibility and accuracy of developing a localized geometric geoid model for Camp David Estate using GNSS/levelling techniques. The study was initiated to address the need for an accurate vertical datum to support infrastructure development in the estate, given the limitations of relying on global geoid models such as EGM2008.

Ellipsoidal and orthometric heights derived from field observations exhibited strong spatial coherence, allowing for the accurate calculation of geoid undulations. The minimal variability in undulation values confirmed that the study area lies within a stable gravitational zone, making it suitable for low-order polynomial modelling. The second-order polynomial surface used to fit the undulations yielded a residual error of ±0.0013 m—demonstrating exceptional model precision and alignment with similar studies.).

The comparison with EGM2008 revealed a systematic bias of -0.1898 m, further underscoring the inadequacy of global models for local-scale engineering or surveying applications in Nigeria. This finding aligns with the conclusions of [7], [9], who advocate for regional model customization using local data.

From a practical standpoint, the derived model supports efficient and accurate height transformation, eliminating the need for labour-intensive levelling campaigns and enhancing the operational efficiency of

GNSS-based surveys. It provides a stable and consistent vertical reference that can be adopted across construction, cadastral, and environmental management projects in the estate.

In broader terms, this study contributes to the body of geodetic knowledge advocating for decentralized geoid modelling in developing countries. It provides a replicable framework for urban centers across Nigeria and similar contexts, promoting geospatial infrastructure modernization. Future studies need to integrate gravity anomaly datasets or use hybrid models (gravimetric-geometric) for further refinement, as indicated by [4], [3].

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