International Journal of Geosciences, 2024, 15, 927-939
https://www.scirp.org/journal/ijg
ISSN Online: 2156-8367
ISSN Print: 2156-8359

Establishment of a Geometric Geoid Model and Evaluation of the EGM2008 and EIGEN-6CA Models over the Dakar-Thies-Mbour Triangle in Senegal

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How to cite this paper: Diouf, D., Tine, M.G., Gueye, S.M.M. and Fall, S.S. (2024) Establishment of a Geometric Geoid Model and Evaluation of the EGM2008 and EIGEN-6CA Models over the Dakar-Thies-Mbour Triangle in Senegal. *International Journal of Geosciences*, **15**, 927-939.
https://doi.org/10.4236/ijg.2024.1511050

Received: October 19, 2024
Accepted: November 24, 2024
Published: November 27, 2024

Abstract

High-accuracy geoid determination is an essential goal that many groups of scientists and countries are striving to achieve. Techniques for determining geoid models have evolved over time. Unfortunately, this all-important determination requires relatively substantial technical and financial resources, depending on the type of geoid to be determined. This situation justifies the inadequacy, and sometimes absence, of accurate geoid models in many countries, despite the new challenges of altimetric positioning using space or satellite positioning techniques. This study focuses on the establishment of a geometric geoid model using simplistic techniques that are accessible and applicable in restricted or wide areas, with or without gravimetric data. The study was applied to the Dakar-Thiès-Mbour triangle, the two regions in the extreme west of Senegal that are home to the most infrastructure projects with the highest socio-economic stakes, as well as mines currently being exploited, and therefore the highest stakes in terms of positioning. This study also enabled us to assess the accuracy of a number of global field models in Senegal, which are used by some professionals for altimetric positioning using Global Positioning Satellite Systems (GNSS) in the absence of a local geoid model. The estimated geoid model is based on the determination of undulation at various sample points in the study area. To this end, a campaign of GNSS observations and direct levelling was carried out on the various points spread across the study area. These measurements were then used to determine the undulation at each point. Bilinear interpolation was used to deduce the undulations throughout the study area, based on the altimeter conversion grid. This grid was evaluated using GPS/level control points.

Keywords

Model, Geoid, Geometric Levelling, GNSS, Undulation, EGM2008, EIGEN-6CA

1. Introduction

Precise positioning has seen many advances in recent decades, with the use of new instruments, satellite constellations and positioning techniques [1]-[3]. However, this performance is more accentuated and more accessible in planimetry than in altimetry. On the one hand, this is due to the principle and nature of operation of some of the instruments and methods used, such as GNSS, and on the other, to the need, in most cases, to use a precise physical reference surface, which is not always accessible for altimetry determinations.

To better support this third component, many countries have redefined their vertical datum according to the resources available.

Senegal, like other countries such as France with the Nivellement Général de la France (NGF) and Canada, with the Canadian Geodetic Vertical Datum of 2013 (CGVD2013) for example, took initiatives in 2004 and 2012 to set up a new vertical datum (vertical conversion grid) based on data from the Senegalese vertical frame, commonly known as Nivellement Général de l'Afrique de l'Ouest de 1953 (NGAO53), and global field models [4]-[7].

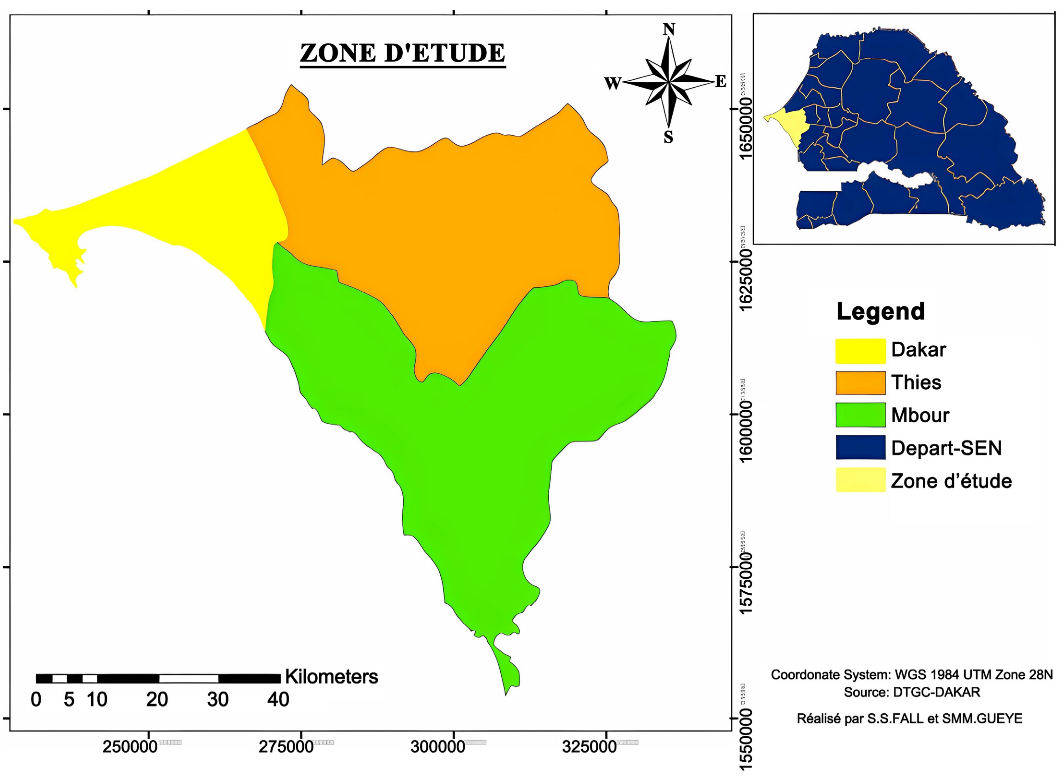

Figure 1. Study area.

But this grid, known as GGS12v1 (Geoid Geometric Senegal 2012) version 1, has been found to have limitations or inaccuracies that could be linked to the insufficient number of points used in the observation and levelling campaigns (particularly between target localities) and their unbalanced, non-homogeneous distribution. Despite these efforts to develop a local model, global field models, particularly the EGM2008 model, remain the best known and most widely used by professionals for GNSS measurements and processing requiring orthometric height determinations. Many of these professionals use these models without any knowledge of their quality or level of accuracy in their study area. It is in this context that this study was carried out to assess the quality of some of these global gravity models and to establish a local geometric geoid model. This geometric geoid model was developed as an alternative to the global models, while at the same time attempting to reduce the effects of the limitations of the GGS12v1 model in a smaller study area with much more at stake in terms of positioning in Senegal (**Figure 1**).

2. Geoid Determination Methods

Geoid determination methods have evolved over the years. Older geoid calculation methods were based on astro-geodetic observations [8]. On a set of points with known geographical coordinates, the astronomical coordinates are deduced from observations made on stars. Having these two values, the components of the deviation from the vertical (ξ; η) are calculated for each point. Geodetic coordinates are used to set the geoid in the system.

Today, the methods used are either based exclusively on gravity measurements (satellite, airborne or terrestrial) for gravity geoids, or on gravity measurements combined with GNSS and levelling measurements for hybrid geoid models, or based exclusively on GNSS and levelling measurements for geometric geoid models [9]-[12]. In the absence of sufficient gravity data, some countries have resorted to gravitational field models, the one chosen being adapted locally from GNSS measurements and direct levelling. In Africa, the adaptation of a global geoid represents a solution for obtaining more accurate local geoids. In Morocco, for example, the GHM16 Hybrid Geoid of Morocco was calculated in 2016 by adapting the EIGEN-6C4 global geoid to 1230 levelled GNSS points, based on the principle of linear trend removal and interpolation of residuals by Kriging [13].

In Senegal, the GGS12v1 model is the latest geoid model produced in 2012 by adjusting EGM2008. It follows on from the GGS04 grid produced in 2004 by adaptation of EGM96. GGS12v1 was calculated from GPS points (for height measurements) and level points (for altitude measurements) distributed over five zones (cities, namely Dakar, Thiès, Mbour, Kaolack and Louga). These points are concentrated on these few cities and are defined independently. This situation means that the model has certain limitations: there are not enough calculation points for such a zone, and the points are poorly distributed throughout the territory. This situation also explains the rather limited accuracy of the model, which is estimated at between 1 and 5 cm around these points and 1 to 2 m over the rest of the territory (Figure 2).

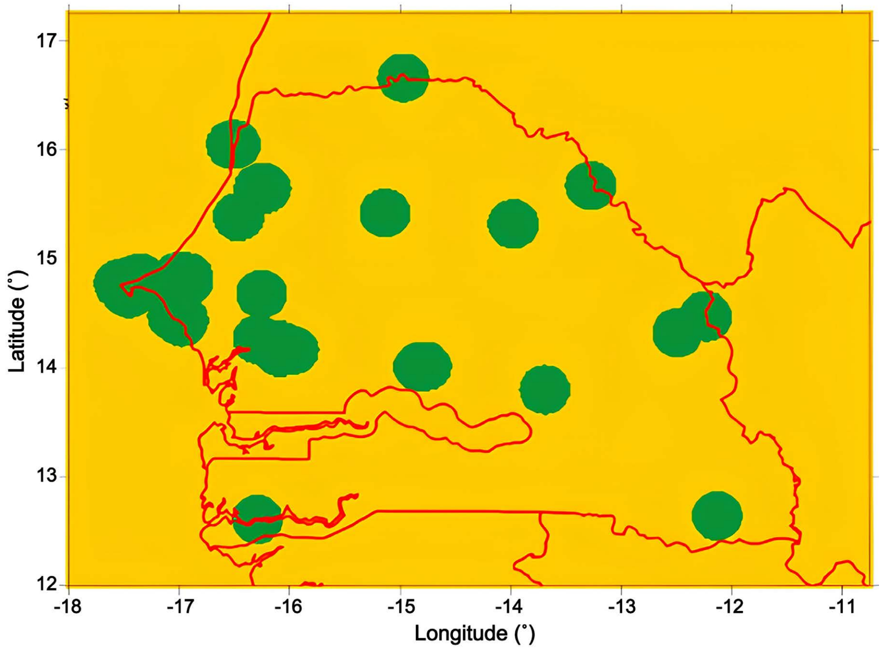

Figure 2. Distribution of precision codes in the GGS12v1 grid integrated into the new Circé Sénégal v 2.0.0 (in green the precision is centimetric (1 to 5 cm) and in yellow the precision is 1 to 2 m) [3].

For this study, the method used is the adaptation of a global geoid adjusted by GNSS/level points. The accuracy of the model calculated will depend on the suitability of the model chosen for the area and the accuracy of the levelled points. Comparison data are taken from the National Geospatial Agency (NGA) and International Centre for Global Earth Models (ICGEM) calculators. Existing global field models are characterized by different calculation data and degrees. Field models based solely on satellite data (CHAMP01S, GRACE01S, EIGEN-2, etc.) are characterized by lower degrees (70 to 250), which limit their resolution or accuracy, although they generally have global coverage [14]. This global coverage means they can be used for global applications and studies that may require less precision, and in areas where ground, airborne or marine data are lacking. As for models based on combined data, they offer better resolution (larger degrees) with greater accuracy. These combined data are satellite data, ground data (terrestrial, shipboard and airborne gravity data) and altimetry data (Table 1). This combination of data makes it possible to establish field models with higher resolutions (degrees from 300 to 2190) and therefore greater accuracy. However, this accuracy depends on the availability, quantity and quality of the data used to calculate the model in each region of the world. This means that, even if these field models remain the most accurate, their precision can vary from a few centimeters to a few decimeters from one region to another. As ground data is generally supplied by research centers and national structures, subsoil resource exploration companies, etc., not all countries have the same level of input into the calculation of these models. The problem or inadequacy of data availability being one of the characteristics of developing countries, these models are generally less accurate in these countries, which may therefore limit their use.

Table 1. Characteristics of models determined by combined methods.

Models	Date	Data	Degree
EGM2008	2008	A, G, S (GRACE)	2190
EIGEN-5C	2008	A, G, S (GRACE), S (LAGEOS)	360
EIGEN-6C	2011	A, G, S (GOCE), S (GRACE), S (LAGEOS)	1420
EIGEN-6C2	2012	A, G, S (GOCE), S (GRACE), S (LAGEOS)	1949
EIGEN-6C3stat	2014	A, G, S (GOCE), S (GRACE), S (LAGEOS)	1949
EIGEN-6C4	2014	A, G, S (GOCE), S (GRACE), S (LAGEOS)	2190
EIGEN-51C	2010	A, G, S (CHAMP), S (GRACE)	359

A: altimetry data; **G**: ground data (e.g. ground, onboard and airborne measurements); **S**: satellite data.

After analyzing these different models, we chose the five (05) with the greatest degrees, given that the greater the degree, the more the terms of the spherical harmonic development will represent local variations of the field. The models selected are: EIGEN-6C4, EGM2008, EIGEN-6C, EIGEN-6C3stat, EIGEN-6C2.

We compared the deviation of the undulations obtained from the two calculators with the reference undulations obtained from the information (ellipsoidal heights and orthometric altitudes) presented on the point sheets (**Table 2**).

Table 2. Comparison of gaps between NGA and ICGEM corrugations.

Points	Longitude	Latitude	$N_{icgem} - N_{ref}$ (m)	$N_{nga} - N_{ref}$ (m)
DK03	−17.441894	14.673994	0.383	−0.053
DK04	−17.428746	14.672739	0.389	−0.031
DK05	−17.437805	14.679993	0.403	−0.032
TH02	−16.942231	14.780714	0.445	0.034
MB02	−16.983476	14.420640	0.376	−0.0293
DK06	−17.451935	14.680540	0.400	−0.046
TH04	−16.916371	14.780231	0.442	0.036
TH05	−16.941383	14.786108	0.494	0.08
B137	−17.123818	14.779229	0.471	0.057

Comparison of the results in **Table 2** showed a fairly large phase shift at ICGEM. We were able to illustrate these discrepancies with the EGM2008 model, and the discrepancies found at NGA level are most closely related to the reference values (by levelling). These deviations are due to the management of zero degrees, which is different for the two ECUs.

Indeed, the philosophy of ICGEM's services is not to change any of the model coefficients, including the model's geocentric gravitational constant (GM), and therefore not to modify the parameters defining the reference system relative to which the geoid is to be calculated. This differs from other calculators which add a correction term. The same observation was made by comparing, for 66 points spread across the study area, the undulations (with ICGEM) derived from direct levelling and GNSS (Nmes) measurements and the undulations calculated from the EGM2008 and EIGEN-6C4 models (with higher degrees) with decimetric deviations (**Figure 3** and **Table 3**).

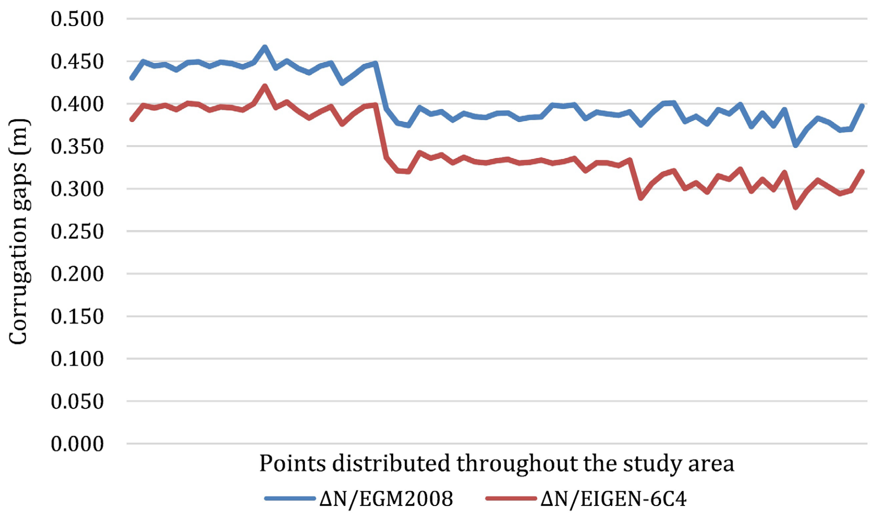

Figure 3. Variation in undulation deviations measured using the EGM2008 and EIGEN-6C4 models.

Despite the decimetric deviations of the undulations provided by the two models from the geometric undulations ($N_{\text{measured}} = h - H_{\text{GPSNIV}}$), the EIGEN-6CA field model nevertheless provides corrugations slightly closer to those measured (average deviations of 35 cm), compared with the EGM2008 model (average deviations of 41 cm). However, the dispersion of the EIGEN-6CA deviations remains relatively greater (RMS = 39 mm) than that of the EGM2008 deviations (RMS = 30 mm), as shown in **Table 3**.

Table 3. Mean and RMS undulation deviations measured and calculated with EGM2008 and EIGEN-6C4.

Variations	$N_{\text{measured}} - N_{\text{EGM2008}}$	Measured $- N_{\text{EIGEN-6CA}}$
Averages	0.405	0.345
RMS	0.030	0.039

We concluded that for practical use, with waveforms more in line with those obtainable in the field by professionals, the NGA calculator remains more appropriate and will be used for the rest of the study. However, this calculator only offers EGM models, which led us to the final choice of the EGM2008, which remains the most recent model in its category.

The EGM2008 model is the result of the final reiteration of a modeling and estimation approach carried out over several years. It was developed at degree 2159, and follows on from several preliminary gravitational models with increasingly improved performance. EGM2008 is a spherical harmonic model of the Earth's gravitational potential, combined with gravitational information obtained from a global set of free-air mean gravity anomalies. It is defined on a 5 arc-minute equi-angular grid that was formed by merging terrestrial, altimetric and airborne gravity data. This gravity model is complete up to spherical harmonic degree and order 2159, and contains additional coefficients extending up to degree 2190 and order 2159. Compared with EGM96, EGM2008 represents an improvement of a factor of six in resolution and a factor of three to six in accuracy [15], depending on the gravity quantity and geographical area.

In areas covered by high-quality gravity data, the discrepancies between EGM2008 geoid undulations and independent GPS/levelling values are of the order of ±5 to ±10 cm [15]. EGM2008 represents an important phase in global gravity field modelling, demonstrating for the first time that, with accurate and detailed gravity data, it is possible to produce a single global model capable of meeting the requirements of a very wide range of applications.

3. Instruments and Methods

The data used in this study are those used in the field model calculations presented in **Table 1** and those derived from our field measurements. For this on-site data collection, we carried out two levelling campaigns. The first measurement campaign concerned direct levelling, which was carried out on a double track at two stations, using a Leica NAK2 automatic level with a standard deviation of 0.7 mm/km of double track. This campaign enabled us to obtain the orthometric heights of the points on the various tracks covering our study area.

The second measurement campaign involved GNSS observations made in static mode with Leica GS14 and CHC I50 receivers. These post-processed GNSS measurements in 3D positioning were used to calculate the ellipsoidal height at each point.

The undulations obtained from the orthometric and ellipsoidal heights on the points observed in the field ($N_{\text{measured}} = h - H_{\text{GPSNIV}}$) were compared with the undulations obtained from EGM2008 using the formula:

$$\Delta N_i = N_{i\text{mesured}} - N_{i\text{EGM}} \quad (i \text{ levelled GPS points}) \tag{1}$$

The differences ΔN_i obtained were considered as the biases of the EGM2008 model in the area. To correct these biases, these values were interpolated for each grid node from the Δn calculation.

$$\Delta n = \Delta N_n + N_{n\text{EGM}} \quad (n \text{ grid nodes}) \tag{2}$$

Grid modeling using the kriging method was carried out on these bias values in order to correct the undulations of the field model (EGM2008). Kriging is one of the most widely used and accurate interpolation methods, considering the spatial dependency structure of the data. It is a stochastic method of linear, unbiased estimation, minimizing the estimation variance as calculated using the variogram, and thus uses a geostatistical approach. This interpolation has enabled us to construct a 30" × 30" grid whose node values are represented by bias-corrected EGM2008 undulation values.

4. Results and Discussion

By processing the data from the various measurement campaigns, we were able to calculate the undulation for the various densified points according to the formula:

$$N_{\text{measured}} = h - H_{\text{GPSNIV}} \tag{3}$$

with,

N_{measured} = undulation

h_{GPS} = ellipsoidal height derived from GNSS measurements

H_{NIV} = orthometric altitude derived from direct levelling measurements

From the established grid, an application was developed in python to represent our local geoid model with the altimetric conversion grid called Geometric Geoid Dakar-Thiès-Mbour 2021 (GGDTM21). This grid has been modeled in the form of level lines representing undulation variations in our study area (**Figure 4**).

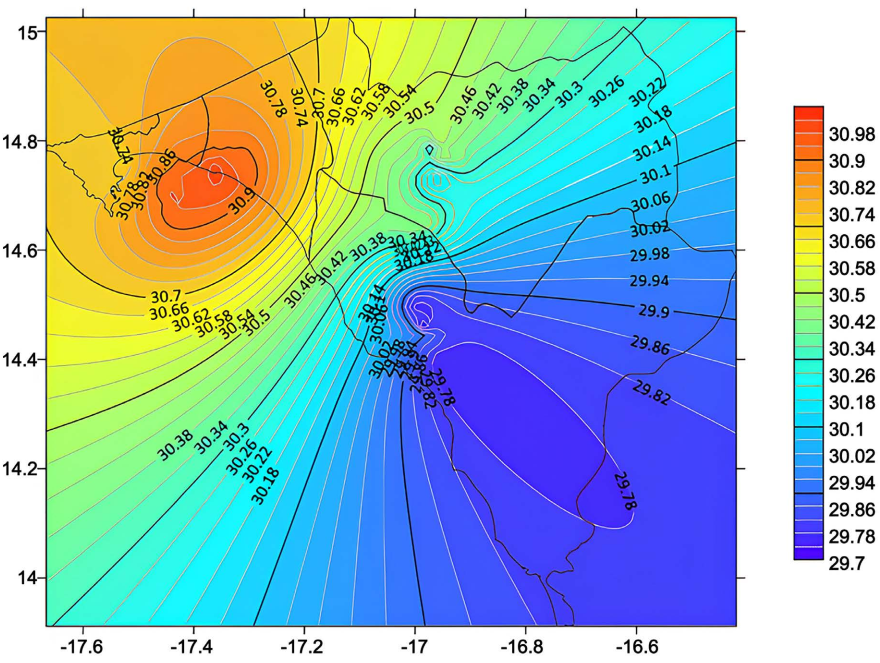

Figure 4. GGDTM21 grid.

We can note variations in undulation from 29.7 m to 30.98 m. This shows a relatively homogeneous local geoid shape in the study area, which can be justified by the limited extent of the study area, which nevertheless has a relatively rugged relief. This grid uses bilinear interpolation to calculate the undulation of a given point (**Figure 5**). It provides the user with the undulation and elevation of a point based on its geographic coordinates, enabling us to define its position within our study area.

Considering an elementary mesh of our grid containing the point M whose undulation is unknown and made up of the four nodes (whose undulations are noted N_1, N_2, N_3 and N_4), delimited by:

- longitudes λ_1, λ_2, λ_3 and λ_4
- latitudes ϕ_1, ϕ_2, ϕ_3 and ϕ_4

To find the undulation of the point M (N_M) belonging to this mesh and of longitude λ_M and latitude ϕ_M, we proceed as follows:

N_M as a function of the values at the nodes (N_1, N_2, N_3, N_4) by bilinear interpolation as follows:

$$N_M = (1-x)(1-y)N_1 + (1-x)yN_2 + x(1-y)N_3 + xyN_4 \tag{4}$$

With

$$x = \frac{\lambda_M - \lambda_1}{\lambda_3 - \lambda_1} \tag{5}$$

$$y = \frac{\varphi_M - \varphi_1}{\varphi_2 - \varphi_1} \tag{6}$$

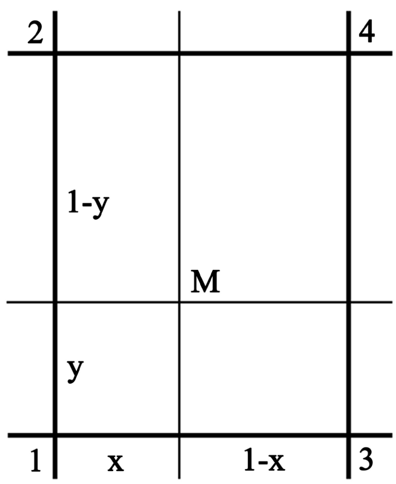

Figure 5. Bilinear interpolation applied.

When calculating the geoid, we discarded nine (9) so-called control points distributed across the three localities forming the study triangle. After interpolation and modeling of the geoid, the values of the undulations of these points on the new geoid are calculated using the GGDTM21 grid (N_{cal}). We then calculated the difference between the calculated undulations and those obtained from measurements ($N_{cal} - N_{mes}$) (**Table 4**).

Table 4. Comparison of measured and calculated undulation deviations.

Points	Longitude	Latitude	h-ellip	N_{mes}	N_{cal}	$N_{cal} - N_{mes}$ (m)
DK03	−17.44189	14.673994	39.78	30.933	30.931	0.002
DK04	−17.42875	14.672739	33.604	30.941	30.9525	−0.012
DK05	−17.43781	14.679993	35.498	30.922	30.9333	−0.011
TH02	−16.94223	14.780714	120.553	30.436	30.4284	0.008
MB02	−16.98348	14.42064	40.9817	29.8593	29.8507	0.009
DK06	−17.45194	14.68054	36.198	30.906	30.9091	−0.003
TH04	−16.91637	14.780231	103.369	30.394	30.3957	−0.002
TH05	−16.94138	14.786108	94.658	30.39	30.4148	−0.025
B137	−17.12382	14.779229	66.525	30.623	30.6236	−0.001
		Average deviation				**0.008**

The difference between point undulations obtained from measurements (N_{mes}) and those interpolated or calculated (N_{cal}) with the GGDTM21 model ranges from a maximum value of 25 mm at point TH05 to a minimum value of 1 mm at point B137, with an average variation of 8 mm. These results give an average subcentrimetric accuracy for our model in the study area. The model's performance of this kind makes it suitable for use in virtually any altimeter positioning work that professionals may need to carry out.

Although direct or geometric levelling has long been the only way to provide orthometric heights with millimeter or centimeter accuracy, the long distances generally required, together with the accumulation of systematic and accidental errors, could rapidly diminish this expected accuracy. With the short to medium-length baselines defined in GNSS positioning, whether in real-time kinematic (RTK) or static mode, such paths can be avoided. As a result, the adoption and integration of a precise geoid model in GNSS calculations makes it possible to define an alternative to direct levelling, particularly in the case of paths.

It should be stressed, however, that the accuracy of the model may logically deteriorate as the points calculated move further away from our study area, due to the extrapolation that the model will make to perform the calculations, hence the importance of extending it to other areas or regions at a later date (**Figure 6**).

The nine (9) control points were used to compare the GGDTM21 and GGS12v1 models presented above. To this end, the differences between the undulations derived from direct levelling and GNSS measurements taken as references, and the undulations derived from the GGDTM21 and GGS12v1 models were calculated (**Table 5**).

Undulation deviations between models GGDTM21 and GGS12v1 remain relatively low for most points. Higher deviations were obtained on points TH04 and TH05 of 56 mm and 72 mm respectively with model GGS12v1, reflecting the average deviations of 8 mm and 19 mm noted respectively on the two models mentioned. Of the nine (9) control points tested, the deviation from our GGDTM21

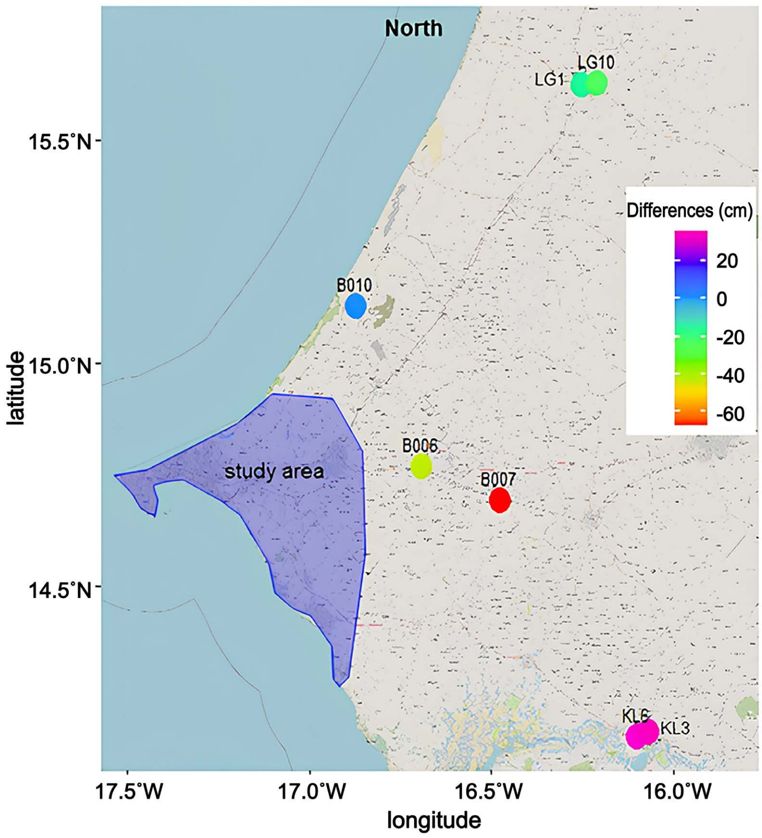

Figure 6. Differences between measured and calculated undulations at points outside the GGDTM21 model coverage area.

Table 5. Gap comparison between GGDTM21 and GGS12v1.

Points	N_{mes} (m)	$N_{GGDTM21}$ (m)	$N_{GGS12v1}$ (m)	$N_{mes} - N_{GGDTM21}$ (m)	$N_{mes} - N_{GGS12v1}$ (m)
DK03	30.933	30.931	30.929	0.002	0.004
DK04	30.941	30.953	30.946	−0.012	−0.005
DK05	30.922	30.933	30.938	−0.011	−0.016
TH02	30.436	30.428	30.441	0.008	−0.005
MB02	29.859	29.851	29.855	0.008	0.004
DK06	30.906	30.909	30.912	−0.003	−0.006
TH04	30.394	30.396	30.397	−0.002	−0.003
TH05	30.390	30.415	30.446	−0.025	−0.056
B137	30.623	30.624	30.695	−0.001	−0.072
	Average deviations			**0.008**	**0.019**

grid is less than the deviation from GGS12v1 for six (6) points, namely DK03, DK05, DK06, TH04, TH5 and B137. The gap is greater for the remaining three (3) points TH02, DK01 and MB02. It should be noted that these last three points were used for the GGS12v1 calculation, hence the low deviation on this model. We can therefore deduce that the GGDTM21 model provides results more in line with field measurements in the study area. The level of consistency noted between the two models could be greatly reduced over much wider areas if our GGDTM21 model is extended along the same lines. This would be justified by the limited distribution of GGS12v1 calculation points that characterizes this model. Nevertheless, the GGS12v1 model remains for the time being broader with a greater geographical coverage, but could be improved by following the principle of elaboration of the GGDTM21 model.

5. Conclusion

A better knowledge of the geoid enables us to determine the altitude of a point, which remains essential in various fields with different levels of precision. Nevertheless, it is not always accessible, or is obtained with an accuracy that does not meet certain requirements or specifications. In this respect, the substantial resources required to establish and adopt an accurate national geoid model are a stumbling block for many countries. As a result, these countries or stakeholders resort to global field models with limited local accuracies, or to geometric geoid models with variable accuracies and geographic coverage. This was the case with the gravity field models studied, particularly EGM2008 and EIGEN-6CA, despite the fact that the EGM2008 model is still used by many professionals in Senegal. We were thus able to determine a local geoid over the Dakar-Thiès-Mbour triangle by combining direct levelling and GNSS techniques. Interpolation of the various data obtained enabled us to establish a GGDTM21 geometric geoid model, which was compared with the main models currently available to users in the study area. The results of this comparison are more in line with field measurements, for the GGDTM21 model established. Such models offer an alternative to the lack of more accurate and consistent gravimetric or hybrid models. But today, the availability of gravity or gravimetric data in developing countries remains the main challenge for the establishment of accurate local geoid models in line with international and scientific standards. Such an outcome would facilitate the establishment of a regional, or even global, geoid model.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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