Scientific Research Publishing

International Journal of Geosciences, 2026, 17(9), 703-721
https://www.scirp.org/journal/ijg
ISSN Online: 2156-8367
ISSN Print: 2156-8359

Comprehensive Numerical Approach to Assessment of Terrain Corrections and Residual Terrain Model over Cameroon

Essama Lionel Fernand Eloundou[1*], Houetchak Ludovic Kandé[1*], Petou Rokis Malquaire Kue[1], Robert Nouayou[2]

[1]Research Laboratory in Geodesy, National Institute of Cartography, Yaoundé, Cameroon
[2]Department of Physics, Faculty of Sciences, University of Yaoundé I, Yaoundé, Cameroon
Email: *lkande2001@yahoo.fr, *lionel.eloundou7@outlook.com

How to cite this paper: Eloundou, E.L.F., Kandé, H.L., Kue, P.R.M. and Nouayou, R. (2026) Comprehensive Numerical Approach to Assessment of Terrain Corrections and Residual Terrain Model over Cameroon. *International Journal of Geosciences*, **17**, 703-721.
https://doi.org/10.4236/ijg.2026.179033

Received: July 7, 2026
Accepted: September 21, 2026
Published: September 24, 2026

Abstract

Gravity reduction schemes, particularly residual terrain model and terrain corrections, constitute one of the main shortcomings of gravity databases in African countries. The calculation of these quantities often requires the evaluation of several parameters for selecting the height database, the digital terrain model and the integration radii. The article aims to develop high-resolution spatial grids of gravity terrain corrections (TC) and the residual terrain model (RTM) for Cameroon based on a global numerical approach. The digital elevation/bathymetry (DEM/DBM) created with a global resolution of 1 arc-second (~30 m) was obtained by merging the SRTM1 model for the mainland zone and the SRTM15+ model for the marine zone, and constitutes the main data for modeling terrain effects. Computations were based on terrestrial gravity stations and a grid of points regularly spaced 1.5 arc-minutes apart, with integration radii of 20 and 200 km for inner and outer zones respectively, and a standard density of 2670 kg/m^{-3}. In addition, low-pass filtered mean elevation surfaces, with spatial scales of ~100 km and ~9 km respectively, were used to calculate RTM effects. Local data of terrain corrections published for the first time in Cameroon show 91.25% of terrain corrections below 1 mGal, with only 38.43% of values below 0.10 mGal for terrestrial gravity stations, and 8.31% of values between 1 and 10 mGal. Data on RTM effects with a spatial scale of ~9 km show 87.03% of direct effects below 5 mGal, while RTM effects with a spatial scale of ~100 km show 74.89% of direct effects below 5 mGal. The data of this study have a number of applications in geophysics and geodesy, which require accurate spatial resolutions for calculating terrain effects in order to properly reduce gravimetric observations.

Keywords

Digital Elevation Model, SRTM, Terrain Correction, Residual Terrain Model, Cameroon

1. Introduction

Gravity reduction schemes are needed in geophysics to characterize geological features using the gravity investigation method and in geodesy to determine the geoid. Several independent gravity reduction methods are then used, including terrain corrections, simple and refined Bouguer effects, residual terrain models and isostatic reduction schemes [1]. These methods are applied to the study area depending on how the topographic masses are considered [2]. Terrain corrections correspond to the sum of the gravitational attraction of topographic masses around a measurement point. These surrounding masses can be assimilated to features that can be calculated using an integration [3]. Terrain corrections are used to compensate for the gravitational effects of residual topography at the Bouguer plate and must therefore be consistent with the Bouguer model [4]. In addition, terrain corrections are used when meshing and predicting gravity data to reduce aliasing prior to geoid calculation. In the past, terrain corrections were calculated manually using topographic maps and graticules of segmented annuli [5] [6]. The problem with this old method is that it is prone to many errors, requires long hours of work and is less accurate. Several methods, both analytical and numerical, can be used to calculate terrain corrections. The first, in the spatial domain, decomposes the surrounding terrain into finite bodies of known structural geometry, such as prisms [7] [8] or tesseroids [9] [10]. It may also adaptively combine several geometric representations, including polyhedrons, prisms, tesseroids, and point masses [11]. The second, in the spectral domain, computes the complete spectrum of the gravitational field generated by the topographic masses. The application of these methods was made possible with the advent of computer tools. Thus, the first programs for calculating terrain corrections using DEM digital terrain models emerged. Gridded elevation data and formulas for the gravitational effect of regular solids were first used by [12] [13] to calculate computer-aided terrain corrections, but only for remote areas, while [14] [15] included nearby areas. [16] developed terrain corrections based on the conical prism model, while [17] adopted the formula of a square vertical prism with an inclined surface to better capture the actual topography. Terrain effects have also been assessed using a set of Gaussian functions [18] or Fourier methods [19]. Other authors propose techniques based on the spherical harmonic of the surface elevation [20] or suggest approaching the terrain using an algorithm based on Gaussian quadrature [21]. All research into the resolution and optimization of numerical computations of terrain corrections tends towards precise mathematical modeling of surface features [21]-[25]. Nowadays, it is recommended to calculate terrain corrections using digital terrain models, which replace topographic maps and enable easy and extensive calculation of terrain effects. Planar, spherical or ellipsoidal approximation of the topography around a calculation point enables the most appropriate modeling method to be chosen for reducing the residual effects of topography. The first geophysical surveys in Cameroon were reconnaissance surveys, which led to the mapping of reconnaissance gravity anomalies in Cameroon, aiming to understand the surface and deep geological features [26]-[32]. It should be noted that all these studies are based on simple Bouguer anomaly maps, given that to obtain a complete Bouguer anomaly, it is necessary to apply a terrain correction. There is no doubt that terrain correction is the main source of deficiency in gravity survey databases. On the other hand, short-wavelength modeling of the gravity field, using the residual field model approach, has been used in geophysics to fill in the missing spectral bands (very high frequencies) of high-resolution combined gravity earth models [33] [34], and in geodesy for the calculation of the gravity Geoid centered on Cameroon [35] [36]. Apart from the above references and a few unpublished descriptive studies, local terrain correction (TC) and residual terrain model (RTM) have not been sufficiently researched in Cameroon. Gravity reduction schemes are therefore an urgent requirement for local, regional and even cross-border studies. In this paper, the focus is placed on the production of TC and RTM grids over the whole of Cameroon and its surroundings for geodetic and geophysical exploration applications. These gravity reduction schemes are calculated at gravity stations and at points on a grid with regularly spaced positions. The method refers to the use of a high-resolution digital elevation/bathymetry model DEM/DBM as the main input data, obtained by merging SRTM topography and SRTM15+ bathymetry data. We analyze the spatial extent over which TC and RTM effects can be assessed, based on a judicious choice of integration radii that allow global consideration of terrain effects, beyond which the influence of topographic masses becomes negligible. We also analyze the influence of altitude differences on terrain effects, using stations from gravity databases and those extracted from DEM/DBM. The differences obtained from this comparison are then analyzed using a number of statistical measures (maximum, minimum, mean, standard deviation, root mean square). Finally, recommendations are given for implementing the results.

2. Study Area

The study area is located in Central Africa, with a land surface covering the whole of Cameroon and bordered to the south by Equatorial Guinea, Gabon and Congo, to the east by the Central African Republic, to the north by Chad and to the west by Nigeria. The marine part of the study area covers a small part of the Inner Gulf of Guinea in the Atlantic Ocean. The study area is marked with the geographical limits—$1^\circ < \varphi < 17^\circ$ in latitude and $5^\circ < \lambda < 19^\circ$ in longitude (**Figure 1**). Altitudes vary widely in Cameroon, from 30 meters in the littoral near the coastal region to around 3000 meters in the South-West, West, and Adamaoua regions with the highest peak peaking at 4037.7 m [37]. Cameroon's geology can be summed up both by the age, variety and extent of its crystalline and metamorphic rocks, and by the intensity of the deformations and fractures of the ancient basement. All of these factors influence the current landforms. The territory is made up of a Precambrian basement comprising magmatic and metamorphic rocks, mainly granites and migmatics, rejuvenated during the Pan-African episode [38] [39].

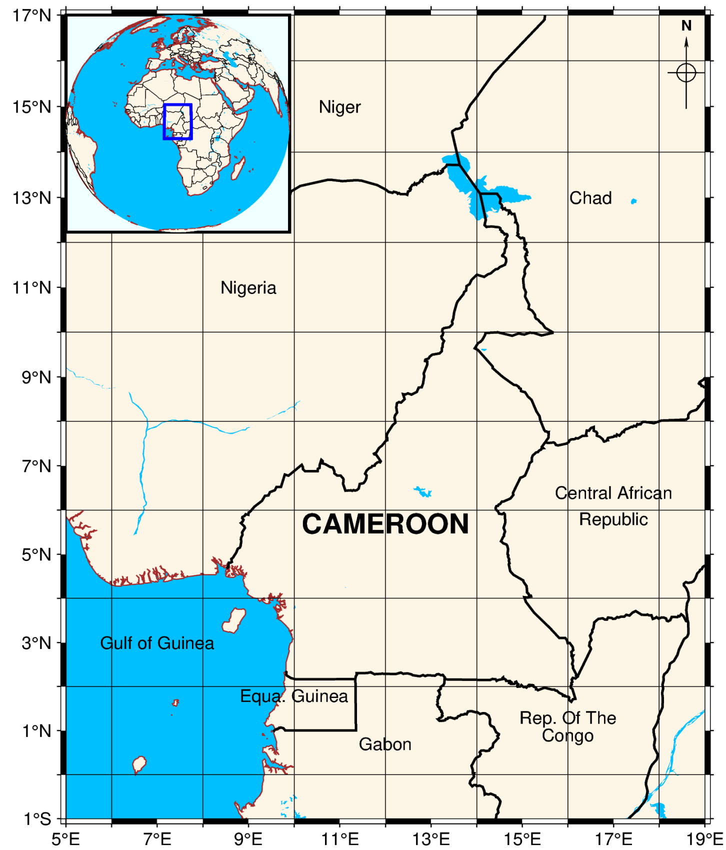

Figure 1. Map of the target area centred on Cameroon. The marine part represents the inland area of the Gulf of Guinea in the Atlantic Ocean.

3. Data and Methods

3.1. Elevation Data

Digital terrain models (DTMs) are the basic input data for calculating terrain effects, particularly TC and RTM effects. The quality of a DTM is described by its vertical accuracy, *i.e.*, how well the elevations describe the underlying topographic surface. In order to calculate the gravitational effect of frequencies due to the earth's topography, two initial models of topography and bathymetry were used to create a high-resolution global model. The land surface is derived from the Shuttle Radar Topography Mission (SRTM1) model, which is a global DTM with a spatial resolution of 1" (01 arc-second) in geographic coordinate, corresponding to a distance of around 30 m in the cartographic projection plane [40]. The global SRTM was generated from C-band interferometric data from the "Space-borne Imaging Radar" collected during the SRTM mission in 2000. The vertical accuracy of this model in mainland Cameroon is ±7.10 m root mean square [41]. SRTM1 data were downloaded using the USGS Earth Explorer interface in GeoTiff format as a $1^\circ \times 1^\circ$ tile from http://earthexplorer.usgs.gov/.

As the SRTM DTM does not incorporate marine bathymetry values, the initial model was filled with values (depths) from the SRTM15+ global bathymetric model, which is an updated version of the SRTM+ series [42] [43]. SRTM15+ is a freely distributed global dataset of terrestrial topography and marine bathymetry at a spatial resolution of 15" (15 arc-seconds, ~450 m). The version (V2.1) of the model used is published by [44] and available through the web page https://portal.opentopography.org/.

The SRTM15+ model, originally provided at a spatial resolution of 15", was resampled to 1" to match the SRTM1 grid, using the same spatial extent and cubic interpolation. The values (depths) extracted from the SRTM15+ bathymetric model are considered less accurate in terms of resolution than the values (heights) extracted from the SRTM1 DTM. The SRTM1 grid, which provides the highest spatial resolution, was therefore used as the reference grid for spatial alignment. In coastal areas, SRTM1 was retained for land surfaces, whereas SRTM15+ was used for submerged areas to ensure a consistent transition between topography and bathymetry. The resulting model therefore provides a continuous land-sea surface at a spatial resolution of 1". The high-resolution global DEM/DBM model obtained after fusion covers the range—$2^\circ < \varphi < 18^\circ$ in latitude and $4^\circ < \lambda < 20^\circ$ in longitude (**Figure 2**). The choice of a larger geographical coverage beyond the target area is necessary to avoid edge effects when calculating TC and RTM effects.

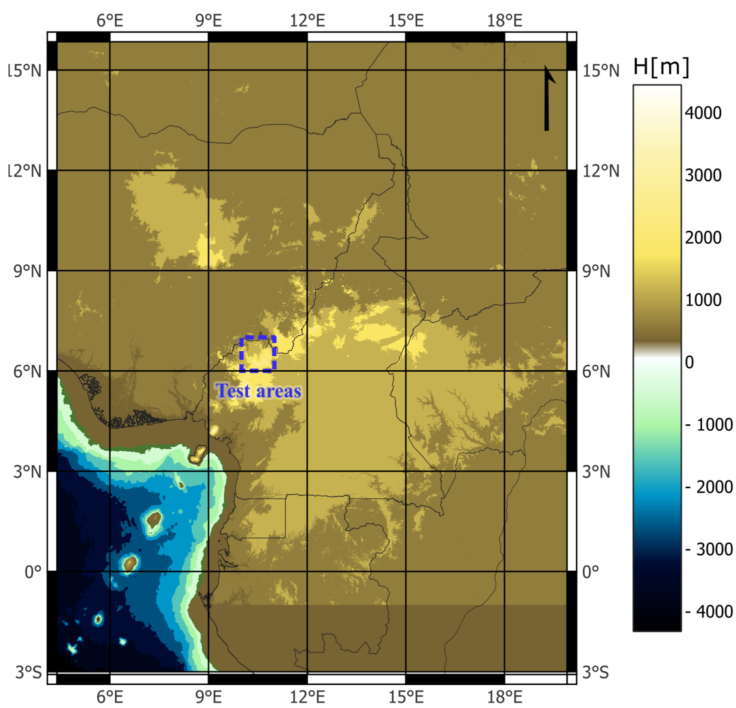

Figure 2. Global Digital Elevation Model/Digital Bathymetry Model (DEM/DBM) obtained after merging the SRTM1 and SRTM15+ models.

3.2. Gravity Data and Computation Points

Earth gravity data cover a vast area from parallel −1˚ to 17˚ North latitude to meridian 3˚ to 19˚ East longitude. Part of the data was supplied by the Bureau Gravimétrique International (BGI) and another part by the National Institute of Cartography in Cameroon (NIC). The NIC dataset is the result of various dedicated gravity collection campaigns carried out between 2014 and 2021. They consist of 1193 earth gravity base stations, with station coordinates determined by GPS positioning using single-frequency receivers in WGS84 (World Geodetic System 1984). The BGI dataset is the result of campaigns carried out between 1960 and 1967 by various organizations, including the Office de la Recherche Scientifique et Technique d'Outre-Mer (ORSTROM). It consists of 36 427 terrestrial gravity reference stations. Elevation values were obtained by barometric levelling using Wallace and Tiernan or Thommen type 3B4 barometers [45].

A preprocessing procedure was applied to remove outliers from the gravimetric databases (BGI/NIC). The data-cleaning process consisted of: converting the points from the different databases into a common reference system, taking into account the WGS84 geodetic reference system [46]; comparing the distance between closely spaced gravity stations using a distance threshold of 20 m to account for errors associated with coordinate accuracy; and finally, comparing the elevation differences between neighboring gravity stations. After removing gross errors from the gravity data originating from the different sources, a final dataset of 29 653 gravity values was retained for the calculation of TC and RTM effects (**Figure 3**).

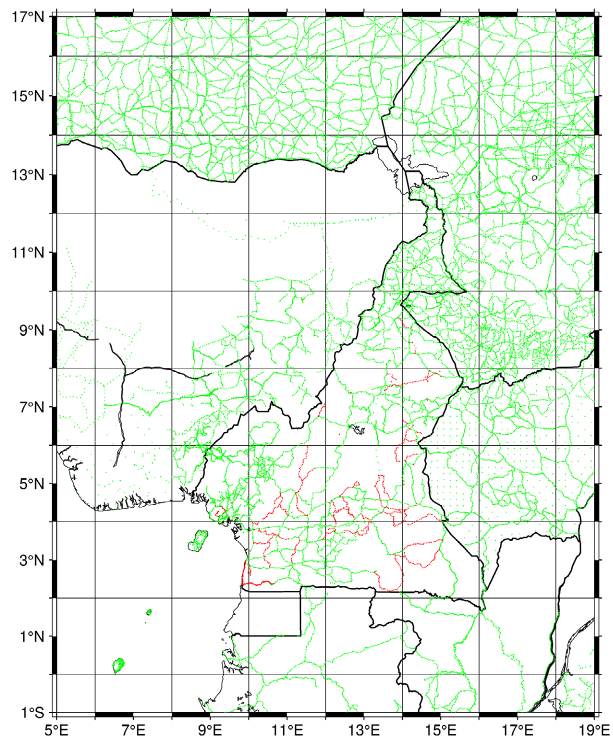

Figure 3. Onshore distributions of gravity data: Bureau Gravimétrique International BGI (green), National Institute of Cartography in Cameroon NIC (red).

In addition, we generated a grid of points spaced 1.5 arc minutes apart (0.025˚), and the heights were extracted from the global DEM/DBM at the grid nodes. This operation produces an evenly spaced grid of stations, guaranteeing homogeneity in map production. The NIC/BGI database, whose altitudes were observed by operators located at gravity stations, is the original database cited in the text, while the alternative database constructed from the altitudes obtained from the global DEM/DBM represents the new database.

3.3. Gravimetric Terrain Correction

The gravimetric terrain correction refers to the geophysical notion of a quantity that filters out the gravitational effect of topographic masses around a gravimetric measuring station. This correction takes into account variations in the terrain in order to isolate gravimetric anomalies linked to geological features. Terrain correction is not the attraction of topography, but rather the random signal from the terrain above the Bouguer plate (**Figure 4**).

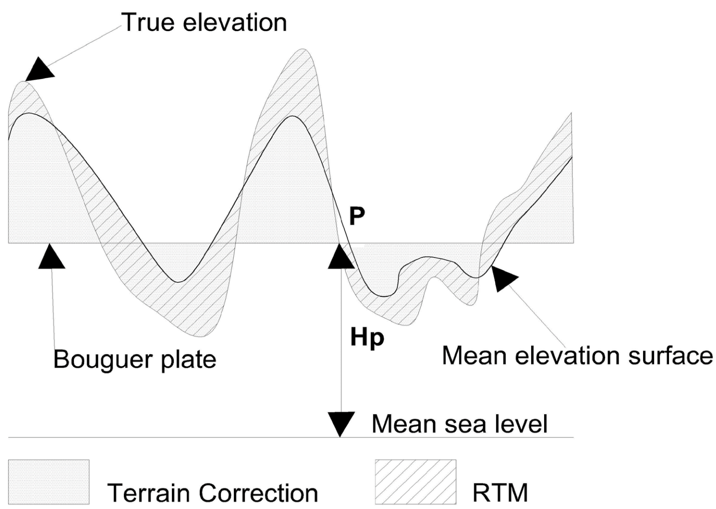

Figure 4. Terrain correction and residual terrain model.

In surface approximation, the calculation of classical TC at a point $P(x_P, y_P, H_P)$ is given by the following relationship [47]:

$$T_c\left(x_p, y_p, H_p\right) = G\iint\int_{H}^{H_p} \frac{\rho(x,y,z)\left(H_p - z\right)}{\left(\left(x_p - x\right)^2 + \left(y_p - y\right)^2 + \left(z_p - z\right)^2\right)^{\frac{3}{2}}} \mathrm{d}x\mathrm{d}y\mathrm{d}z \quad (1)$$

where P is the point above the gravity station, (x_P, y_P, H_P) the plane coordinates and orthometric altitude of point P, (x, y, z) the cartesian coordinates of the integration point, G the universal constant of gravity and $\rho(x, y, z)$ the density of topographic masses in the vicinity of point P.

Due to the complexity of the topography of Cameroon, the main area of investigation in this study, classical terrain corrections were calculated for all gravity station measurements using the TC program from the GRAVSOFT software suite

[48]. This algorithm is based on the integration of rectangular prisms and the use of the global DEM/DBM obtained by merging the SRTM1 and SRTM15+ models. The analytical expression of the terrain corrections for the rectangular prism is evaluated according to two integration radii. Radius R1, for areas close to the point of calculation, corresponds to the detailed DEM/DBM (high resolution) where the contribution of the gravitational effect of topographic masses is most important, is given by the following relationship [7] [49] [50]:

$$T_c = G\rho \left\| \left| \left| x\ln\left(x+r\right) + y\ln\left(x+r\right) - z\tan^{-1}\left(\frac{xy}{zr}\right) \right|_{x_1}^{x_2} \right|_{y_1}^{y_2} \right|_{z_1}^{z_2} \tag{2}$$

where: $r = \sqrt{x^2 + y^2 + z^2}$ with (x, y, z) the coordinates of the prism's vertices in the plane.

The radius R2, for areas further away from the gravity station, which allows the calculation of terrain corrections to be extended to the coarse DEM/DBM (low resolution) where the contribution of the gravitational effect of topographic masses is least significant, is evaluated by the following approximate expression [47] [51]:

$$\begin{aligned} T_c = {} & xy\log\left(z+r\right) + xz\log\left(y+r\right) + yz\log\left(x+r\right) \\ & -\frac{x^2}{2}\tan^{-1}\frac{yz}{xr} - \frac{y^2}{2}\tan^{-1}\frac{xz}{yr} - \frac{z^2}{2}\tan^{-1}\frac{xy}{zr} \end{aligned} \tag{3}$$

According to the computation methodology implemented in GRAVSOFT, terrain corrections are evaluated based on both fine and coarse digital elevation models (DEMs). The fine, high-resolution DEM captures strong relief variations caused by local topography, while the coarse DEM represents the average contribution of distant terrain. Thus, near zones around each computation point were evaluated using the high-resolution global DEM/DBM grid at 1", since TC must be performed using the most precise and highest-resolution elevation model available even in low-altitude areas [52]. The choice of a coarse DEM represents a compromise between computational accuracy and efficiency. As shown by [53], using DEMs with a resolution of 1" for the inner zone and 15" for the outer zone can achieve sub-mGal accuracy with significantly reduced computation time. The far zone was evaluated using a DEM/DBM with a spatial resolution of 10" (ten arc-seconds). The coarse DEM/DBM was generated by simple averaging of the high-resolution 1" grid using the SELECT program from the GRAVSOFT software suite.

3.4. Residual Terrain Model

The residual terrain model represents all local high-frequency topographic irregularities, which are taken into account by simulating a smooth mean elevation surface (**Figure 4**). The RTM effect or direct effect can be evaluated by the Bouguer plane anomaly taken between the actual elevation surface and the mean elevation surface, from which the classic terrain correction is subtracted [47]:

$$\Delta g_{\mathrm{RTM}} \approx 2\pi G\rho\left(h - h_{\mathrm{ref}}\right) - T_c \tag{4}$$

where h and h_{ref} represent the actual altitude and mean elevation surface of the calculation point respectively, G is the gravitational constant and ρ the density of the crust. RTM effects can be evaluated by the approximate (equation 4) when a short wavelength reference elevation surface is chosen and especially for a topographic reference surface $N = 180$ [47]. The reference elevation surface that incorporates global geopotential models (GGMs) capable of representing the mean elevation of a target area can be defined using two main approaches:

1) a low-pass filtering method applied to digital elevation models (using direct or moving averages), and 2) a spherical harmonic expansion of the topographic surface. [54] investigated the magnitude of differences between RTM effects computed using various types of reference elevation surfaces obtained from these approaches, with reference topographies of resolutions ranging from 5' to 30' or finer. In gravimetric geoid determination based on the Remove-Compute-Restore (RCR) procedure, high-resolution GGMs truncated at short, medium, and long wavelengths are often employed. Consequently, in this study, RTM effects were calculated at different spatial scale resolutions. [55] demonstrated that a reference elevation surface determined by low-pass filtering is more suitable for capturing local terrain features.

Following the procedure presented in the Gravsoft Tutorial, three (03) surfaces are required to calculate RTM effects. The first surface is a detailed DEM/DBM, the second is a coarse DEM/DBM obtained from the SELECT program and the third surface is the average elevation surface obtained by low-pass filtering the coarse DEM/DBM using the TCGRID program. For short wavelengths, the global DEM/DBM was resampled to a resolution of 01 arc minute (0.0167˚). Then a moving average of a 5 × 5 window (~9.3 km) was applied, while for medium and long wavelengths the global DEM/DBM was resampled to a resolution of 6 arc minutes (0.10˚) and a moving average of a 9 × 9 window (~100 km) was applied.

3.5. Integration Radius

To calculate the terrain effects at a gravity station, the topographic surface around the station is subdivided into two parts, and the gravitational effects are evaluated up to a certain distance, called the integration radius. The first part, with radius R1, concerns corrections close to the station and the second part, with radius R2, concerns corrections further away from the station. As the near zone generates the greatest contribution to terrain effects, the choice of the R1 value is a compromise between computation time and accuracy of corrections, while the R2 value has to be made a priori with the need to take into account the effect of the Earth's curvature [56]. To determine the optimum values for the integration radii, the methodology proposed by [21] was adopted. It consists in setting the value of one of the radii such that the effects of relief beyond it are negligible. Terrain corrections are then calculated at gravity stations by varying the second radius and setting a reference value. Finally, the comparison of each correction with the reference value gives the optimum value of this second radius for a given quality criterion. For example, to evaluate the R1 proximal radius, field corrections are calculated for several R1 values ranging from 5 to 22.50 km, with R2 set at 220 km and R1ref = 22.50 km taken as the reference for comparison. Similarly, to evaluate R2, the R1 radius was set at 22.5 km, with R2 varying between 166.70 and 300 km, with R2ref = 300 km taken as the reference for comparison. The tests were carried out in a high-altitude zone, in the South-West Cameroon region (**Figure 2**), and the quality criterion selected was the maximum value.

3.6. Altitude Differences and Terrain Effects

There are definite differences between the altitudes derived from the gravimetric databases collected by GPS or barometer and those derived from the global DEM/DBM model. These differences in altitude were analyzed to verify their impact on terrain corrections and RTM effects, the aim being to select the database that best represents the topography around the stations. Thus, the calculation of terrain effects (TC and RTM) from the new DEM/DBM database and for a mean surface elevation spatial scale of ~100 km is compared with the terrain effects from the original database by a simple difference.

$$\Delta X = X\left(\text{original}\right) - X\left(\text{new}\right) \tag{5}$$

where X represents the altitude of stations H, terrain corrections and the residual terrain effect. The effect of differences was analyzed using descriptive statistics and the Pearson correlation test with 5% confidence level.

3.7. Calculating Terrain Effects

Terrain effects (TC, RTM) were calculated for the area defined by the geographical limits—$1^\circ < \varphi < 17^\circ$ and $5^\circ < \lambda < 19^\circ$ at a spatial resolution of 1" (~30 m). This zone includes the Republic of Cameroon and part of the surrounding countries, including Niger, Equatorial Guinea, Gabon, Congo, Central African Republic, Chad and Nigeria. Terrain effects were calculated only for the land surface, as terrestrial gravity data are generally available at a higher spatial resolution than marine gravity data, which would make the results difficult to compare. All the input parameters for calculating terrain effects must be carefully chosen. The most important parameter is the altitude of the calculation points; if wrongly chosen, it can lead to incorrect values in the future database. Another important parameter is the density of the crust in the study area, which is generally approximated to a constant value. There are no reliable and realistic density models in the study area, so the average density of the crust ρ = 2670 kg/m^3 was chosen. Apart from the parameters mentioned above, other parameters can also limit the accuracy of the calculation, such as the mathematical expressions used, the planar approximation of the terrain and the inaccuracy of the geometry of the bodies approximating the topography.

4. Results and Discussion

4.1. Integration Radius

The contribution of near (R1) and far (R2) integration radii to the calculation of TC for the test area in the South-West Cameroon region is shown in Figure 5. The maximum absolute values of the differences in TC with respect to the reference radii R1ref = 22.50 km and R2ref = 300 km decrease as the radii R1 and R2 respectively increase. With R1ref = 22.50 km as reference, the R1 proximal radius influences the TC and RTM effects. Indeed, for an R1 radius of 5 km, the maximum value of the differences is 0.0260 mGal, which leads to the conclusion that an R1 = 10 km radius is sufficient to obtain an accuracy of 0.01 mGal for this case study. For an R2 radius of 220 km, the maximum difference is 0.156 mGal, which indicates that an R2 = 220 km radius is sufficient to obtain a TC contribution within 0.1 mGal. However, the study area also includes low-altitude regions and relatively flat topography, where the contribution of the near (R1) and far (R2) integration zones may decrease because of the low elevations of the gravity stations. Taking these conditions into account, an R1 radius of 20 km for the near zone and an R2 radius of 200 km for the far zone are considered sufficient to assess terrain effects while accounting for the Earth's curvature. Taking these conditions into account, an R1 radius of 20 km for the near zone and an R2 radius of 200 km for the far zone will be sufficient to assess terrain effects and take into account the effect of the Earth's curvature.

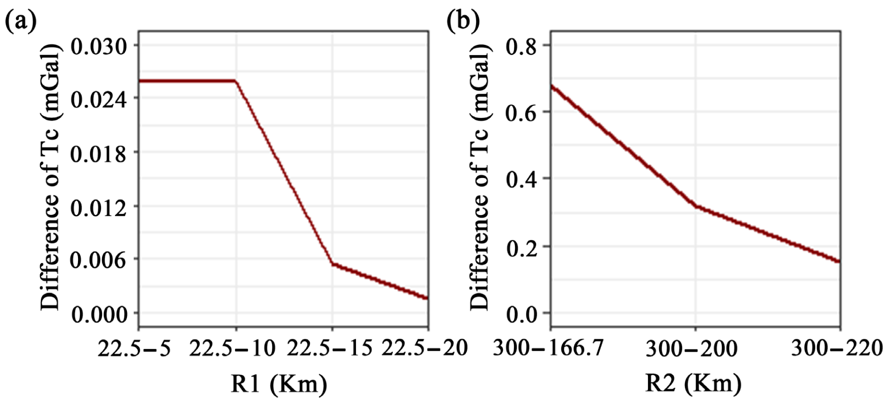

Figure 5. Maximum absolute values of terrain correction differences as a function of integration radius (R) (a) R1 varying from 5 to 22.50 km with R2 = 220 km and (b) R2 varying from 166.70 to 300 km with R1 = 22.50 km. Notation used: TC—Terrain Correction, R—Radius.

4.2. Altitude Differences and Terrain Effects

Table 1 shows the descriptive statistics of the ground effects calculated from the new database derived from the global DEM/DBM model, and their differences from the original database. The RTM effects correspond to a surface of average elevation with a spatial scale of ~100 km.

According to the mean values of the differences (Table 1), the TC in the original database are higher than those computed from the new DEM/DBM-based database, whereas RTM effects are overestimated in the latter. The observed bias is significant for both quantities and reflects the influence of altitude differences on terrain-effect computations.

Table 1. Descriptive statistics of terrain effects for new database derived from DEM/DBM model and their differences with the original database. The RTM effects correspond to a surface of average elevation with a spatial scale of ~100 km.

	Min	Max	Mean	STD
	New database			
H DEM/DBM (m)	0.00	4023.56	413.31	241.96
T_c (mGal)	0.00	91.71	0.50	2.20
Δg_{rtm} (mGal)	−73.91	137.36	−1.04	16.50
	Differences (Original − new)			
H (m)	−959.75	836.00	−4.96	66.84
T_c (mGal)	−30.18	79.72	1.31	5.66
Δg_{rtm} (mGal)	−154.47	60.05	−2.07	10.30

To assess the influence of elevation discrepancies (ΔH) on the gravimetric calculations between the DEM/DBM-derived database and the terrestrial gravity stations, a correlation analysis was performed between the elevation differences (ΔH), the TC differences (ΔT_c), and the residual gravity anomalies (Δg_{rtm}). The results (Figure 6(a) and Figure 6(b)) reveal a near-linear relationship, showing that even small elevation mismatches can produce significant variations in TC and Δg_{rtm} values. Overall, the absolute differences in terrain effects increase with elevation, and the regression curves are well approximated by second-degree polynomials.

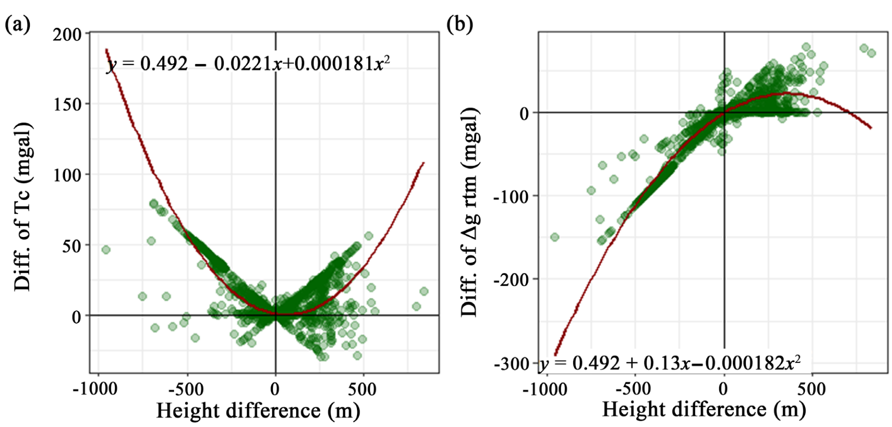

Figure 6. Differences in terrain effects as a function of altitude differences between the original (gravity stations) and new (Global Digital Elevation Model/Digital Bathymetry Model) databases: a) Terrain correction; b) Residual Terrain effects.

The correlation analysis shows that the difference in terrain effects is moderately correlated with elevation differences for terrain corrections, with a correlation coefficient of 0.472, whereas a strong correlation is observed for RTM effects, with a correlation coefficient of 0.87. The large discrepancies in altitude between the original and new databases result from erroneous height values at certain gravity stations. These altitude errors affect the calculated terrain effects, whose magnitudes are strongly correlated with the station elevations. To minimize these impacts, the new database, with altitudes derived from the global DEM/DBM, was adopted, as it better represents the coherence and continuity of topography around the gravity stations.

4.3. Grid of Terrain Corrections and RTM Effects

Table 2 shows the overall statistics (gravity station and interpolated grid points) for the calculation of TC and RTM effects at spatial scales of ~9 km and ~100 km for the entire study area. The gravity stations combined with the interpolated grid points form a total dataset of 1,895,505 points distributed across the study area. In this study, we employed the bicubic interpolation method, which provides a smooth representation of topographic gradients. TC fluctuates around an average value of 0.48 mGal, with the exception of mountainous areas. In line with similar studies, the highest values are found in areas of rough topography, with maximum values around Mount Cameroon estimated at around 109 mGal. In fact, 91.25% of terrain corrections are less than 1 mGal, with only 38.43% of values less than 0.10 mGal, and 8.31% of values between 1 and 10 mGal.

Table 2. Descriptive statistics for terrain corrections and RTM effects calculated for the gravity stations and grid points in the study area.

Spatial scale (km)	Min	Max	Mean	STD
		T_c (mGal)		
	0	109.87	0.48	1.41
		Δg_{rtm} (mGal)		
~100	−75.03	184.99	0.66	15.86
		Δg_{rtm} (mGal)		
~9	−116.65	84.99	−0.05	9.03

The RTM effects vary from −116.65 to 84.99 mGal, and from −75.03 to 184.99 mGal, respectively, for spatial scales of ~9 km and ~100 km. These results show that the range of values of the RTM effects is greater for a reference elevation surface with a spatial scale of ~100 km. RTM effects with a spatial scale of ~9 km (d/o 2190) have 87.03% of values below 5 mGal compared with 74.89% for RTM effects with a spatial scale of ~100 km (d/o 200). The figures (**Figures 7(a)-(c)**) show the TC and RTM calculated at spatial scales of ~9 km and ~100 km.

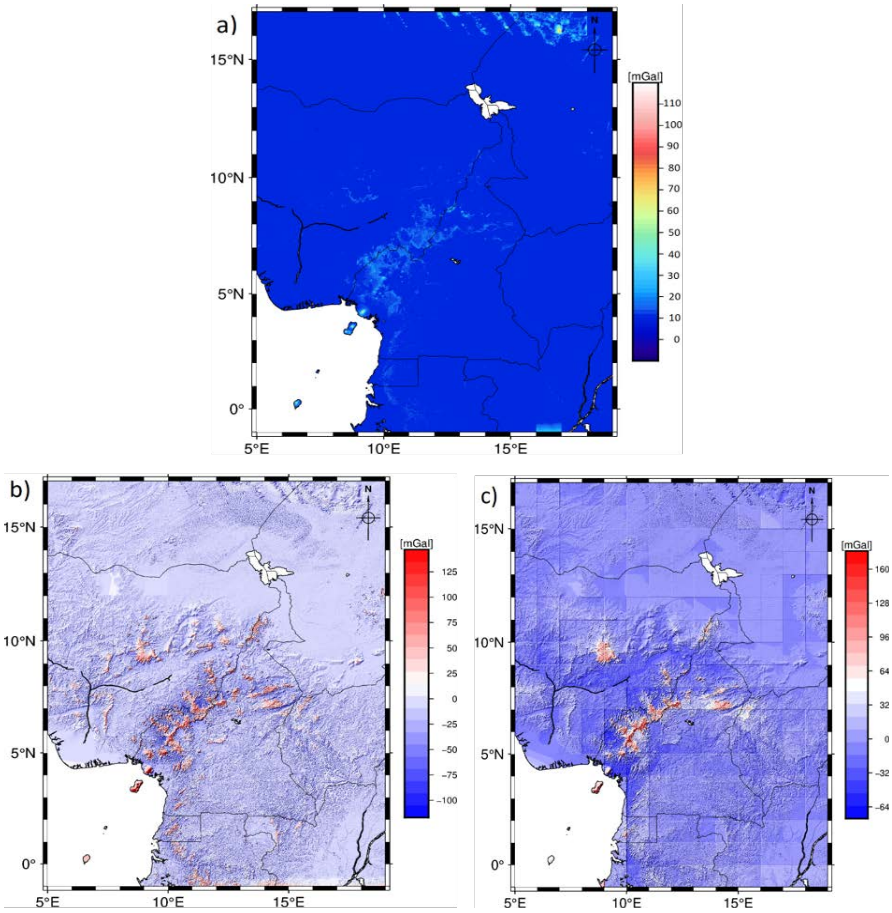

Figure 7. Differences in terrain effects as a function Grid of gravity effects: a) Terrain correction; b) Residual Terrain effect (~9.3 km); c) Residual Terrain effect (~100 km).

It is acknowledged that artefacts present in the input topographic datasets, such as voids, as well as altimetric and planimetric inaccuracies, combined with the inherent simplifications of the numerical prismatic method, may introduce limitations in the modeled terrain effects. These approximation errors can locally reach a few milligals, particularly in areas characterized by complex and rugged topography. The adopted modelling approach assumes a constant reference density of 2670 kg/m^3, thereby neglecting potential lateral density variations and density anomalies associated with contrasting geological formations. Developing a more detailed and physically consistent modelling framework that integrates local density models together with lake bathymetry data would provide a more realistic representation of terrain effects and constitutes a valuable direction for future research.

5. Conclusions and Recommendations

In this study, a global DEM/DBM with a resolution of 01 arc-second (~30 m) centered on Cameroon is obtained by merging the SRTM1 model for the land surface and the SRTM15+ model for the marine zone. The global DEM/DBM model created served as the main input data for calculating and plotting terrain correction and residual terrain effects maps for the land surface of Cameroon. These gravity reduction schemes (TC and RTM) were constructed at the spatial resolution of 01 arc-second of the initial DEM/DBM for corrections close to the gravity station, and 10 arc-seconds of the degraded DEM/DBM for corrections further away, with integration radii R1 = 20 km and R2 = 200 km, respectively. These integration radii have been shown to be sufficient to achieve good accuracy for terrain corrections and RTM effects. In addition, low-pass filtered mean elevation surfaces, with spatial scales of ~100 km and ~9 km respectively, were used to assess RTM effects.

Elevation differences derived from gravity databases and global DEM/DBM were compared. Elevation differences were shown to be correlated with differences in terrain effects. These differences in altitude lead to an overestimation of the terrain corrections and therefore influence the contribution of the Bouguer plate to the direct effect. In addition, terrain corrections are very sensitive to variations in topography, so terrain effect values for gravity stations close to the coast in the land-sea transition zone are also overestimated. We suggest using terrain effects calculated mainly with the DEM/DBM global database, as it best describes the coherence and continuity of the topography around these stations.

The published terrain correction map shows 91.25% of terrain corrections below 1 mGal, with only 38.43% of values below 0.1 mGal for terrestrial gravity stations, and 8.31% of values between 1 and 10 mGal. The South-West Cameroon region, with its complex topography, has the highest values of terrain corrections, up to 109 mGal. These values fall within the range of signals likely to be significant in a mining exploration context, and confirm the importance of evaluating terrain corrections (TC) in Cameroon. Terrain corrections can be used for geophysical applications such as the complete Bouguer reduction at gravity stations in Cameroon.

RTM effects on a spatial scale of ~9 km (d/o 2190) have 87.03% of values below 5 mGal compared with 74.89% for RTM effects on a spatial scale of ~100 km (d/o 200), with extreme values that are not very representative of the study area, ranging from −116.65 to 84.99 mGal, and from −75.03 to 184.99 mGal for the ~9 km and ~100 km spatial scales respectively. RTM effects can be used for many geodetic applications, including the meshing of gravity data, the calculation of the gravity geoid (RCR method) to smooth gravity anomalies prior to interpolation, and the spectral enhancement of GGMs beyond the nominal model resolution.

It is important to note that calculation point errors or DEM/DBM errors can easily lead to anomalies of a few mGal in the calculation of terrain effects in Cameroon. It will therefore be necessary to give preference to the values of terrain effects derived from known gravity stations to the detriment of interpolated values derived from the calculation grid, which appear to underestimate the magnitude of terrain effects at certain points.

Acknowledgements

The authors would like to thank the Bureau Gravimétrique International (BGI) for providing the terrestrial gravity data for the study area and all the institutions and web servers that have made the Global Digital Elevation Models available to the public (NASA, USGS, Open Topography website and portal). The first author is grateful to Professor René Forsberg, who kindly provided us with the GRAVSOFT software suite for calculating terrain effects. We would also like to thank the entire team of the Research Laboratory in Geodesy (LAREG) of the National Institute of Cartography for their comments, which helped to improve this work. We thank the anonymous reviewer for their constructive comments that helped to significantly improve the quality of this manuscript.

Author Contributions

Conceptualization: E.L.F. Eloundou, H.L. Kande; methodology: E.L.F. Eloundou, H.L. Kande, P.R.M. Kue; validation: E.L.F. Eloundou, H.L. Kande, P.R.M. Kue; analysis: E.L.F. Eloundou, H.L. Kande, P.R.M. Kue; Field investigation: E.L.F. Eloundou, H.L. Kande, P.R.M. Kue; supervision: R. Nouayou. All authors have read and agreed to the published version of the manuscript.

Conflicts of Interest

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

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