Refinement of Bouguer anomalies derived from the EGM2008 model, impact on gravimetric signatures in mountainous region: Case of Cameroon Volcanic Line, Central Africa

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Key Points:
- RTM values on the study area are ranging from −53.59 to 34.79 mGal
- The impact of the omission error is more felt on the shallow part of the crust including the Cameroon Volcanic Line and around Takamanda, Essu, Dumbo, and Ngambe localities
- A high resolution DTM must be used to decrease the omission error while preparing a global geopotential model

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Abstract: Global geopotential models have not included the very high frequencies of the Earth’s external gravity field. This is called omission error. This omission error becomes more important in mountainous areas (areas with highly variable topography). The work reported here consists in reducing the omission error in measurements of Bouguer gravity anomalies, by refining the global geopotential model EGM2008 using the spectral enhancement method. This method consists in computing the residual terrain effects and then coupling them to the gravimetric signal of the global geopotential model. To compute the residual terrain effects, we used the Residual Terrain Model (RTM) technique. To refine it required a reference surface (ETOPO1) developed up to degree 2190 (the maximum degree of the EGM2008 model) and a detailed elevation model (AW3D30). Computation was performed with the TC program of the GRAVSOFT package. The topography of the study area was assumed to have a constant density of 2670 kg/m³. For the inner and outer zones, the respective integration radii of 10 km and 200 km have been chosen. We obtained very important RTM values ranging from −53.59 to 34.79 mGal. These values were added to the gravity anomalies grid of the EGM2008 model to improve accuracy at high frequencies. On a part of the Cameroon Volcanic Line and its surroundings (mountainous area), we made a comparison between the residual Bouguer anomalies before and after refinement. We report differences ranging from −37.40 to 26.40 mGal. We conclude that the impact of omission error on gravimetric signatures is observed especially in areas with high variable topography, such as on the Cameroon Volcanic Line and around the localities of Takamanda, Essu, Dumbo, and Ngambe. This finding illustrates the great influence that topography has on accurate measurement of these gravity anomalies, and thus why topography must be taken into account. We can conclude that in preparing a global geopotential model, a high resolution DTM must be used to decrease the omission error: the degree of expansion has to increase in order to take the higher frequencies into account. The refined Bouguer anomalies grid presented here can be used in addition to terrestrial gravity anomalies in the study area, especially in mountainous areas where gravimetric data are very sparse or non-existent.

Keywords: residual Terrain Model; EGM2008; Omission error; refined Bouguer anomalies; mountainous area

1. Introduction
The EGM2008 model is a representation of the external gravity field of the Earth. This high-resolution Global Geopotential Model (GGM) was published in 2008 by the United States National Geospatial-Intelligence Agency (Pavlis et al., 2008; http://earthinfo.nga.mil/GandG/wgs84/gravitymod/egm2008/index.html). It contains spherical harmonics coefficients up to degree and order 2160 with some additional coefficients up to 2190. This corresponds to a spatial resolution of 5 arc-minutes (9 km at the equator) depending on the latitude. Nowadays, GGMs serve as good alternatives to create a synthesis of the Earth’s gravity field, espe-
cally in areas with no terrestrial gravimetric data or for which the data provide insufficient coverage, an observation made by Abd-Elmotaal et al. (2018). Geodetic and geophysical studies of Cameroon have increasingly used terrestrial gravity field parameters calculated from the EGM2008 model (Ngatchou et al., 2014; Lordon et al., 2017, 2018; Kuisseu et al., 2018; Shandini et al., 2018).

However, gravimetric (free-air and Bouguer) anomalies derived from this global geopotential model are subject to signal omission error (Gruber, 2009). The omission error includes especially the short wavelengths of the Earth’s gravity field that are not represented in the GGMs (Torge, 2001). Characteristics of the real gravity field that are at a smaller scale than those captured by standard geopotential models are thus omitted. The long wavelengths contribution of the Earth’s gravity field signal is evaluated with GGMs while the short wavelengths are calculated using digital terrain models. The omission error increases in mountainous or rough areas (Jekeli et al., 2009). This is because terrestrial topography is the main source of high frequencies in the Earth’s gravimetric signal (Forsberg, 1984). It is therefore better to use a digital terrain model of high resolution in order to have a gravimetric signal of good accuracy over a study area, especially when the area includes complex topography. Apeh et al. (2019) evaluated considerable omission errors on some high-resolution global geopotential models in a state of Nigeria. They obtained significant error values, ranging from −24.6 to 37.5 mGal. They concluded that refined Bouguer gravity anomalies (gravity anomalies to which the residual terrain effects have been added) derived from GGMs are more accurate than unrefined Bouguer gravimetric anomalies derived from GGMs. In fact, the refinement percentage for the RMS difference of the computed and refined Bouguer anomalies (respect to terrestrial Bouguer anomalies) ranges from 7.8% to 44.7%. The importance of residual terrain correction have been highlighted also by other investigators (Tong LT et al., 2007; Wang JH and Geng Y, 2015; Sampietro et al., 2007; Huang, 2012; Leaman, 1998).

On the other hand, the terrestrial gravimetric data available on the study area are very sparse and have a poor distribution. A densification of these gravimetric data is necessary for a better exploitation. Unfortunately, gravity measurements are quite expensive and take a long time, especially in areas with rough topography. It is therefore very difficult to build a sufficiently dense gravity network for good applications in geophysics and geodesy. Improving the accuracy of the gravimetric signal from the global geopotential model EGM2008 is a very good alternative.

The main objective of this work is to refine and quantify topography effects on Bouguer gravity anomalies derived from the EGM2008 model. The frequency gap that exits between GGMs and the Earth’s actual gravity field can be partially resolved by applying the Spectral Enhancement Method (SEM) (Hirt et al., 2011). In this method, the residual terrain method (Forsberg and Tscherning, 1981; Forsberg, 1984, 1985) is applied to highlight the high frequencies of the gravimetric signal (residual terrain effects). A high resolution Digital Terrain Model (DTM) representing surface topography is used for this purpose. To compute the residual topographic effects, we use two available data sources: The ALOS World-3D digital terrain model 30 m (Tadono et al., 2016; Takaku et al., 2016) and the spherical harmonic model ETOPO1 (Drewes et al., 2016), which represents the long wavelengths of the Earth’s topography. Then we combine these residual field effects to refine the Bouguer anomalies grid derived from the EGM2008 model. Finally, we evaluate the impact of the omission error on gravimetric signatures in mountainous areas.

2. Study Area and Major Geological Structures

Our study area (target area) is located between 8° to 17° East longitude and 1° to 14° North latitude. It completely covers Cameroon in Central Africa (Figure 1). The target area includes seven countries surrounding Cameroon, including: Niger, Nigeria, Chad, Central African Republic, Congo, Gabon, and Equatorial Guinea. The marine part of this study area is the Gulf of Guinea located in the Atlantic Ocean.

The main structural units of Cameroon are: The Cameroon Volcanic Line (CVL), the Adamawa Plateau, the Central African Shear Zone (CASZ), the northern edge of the Congo Craton, and the Benue trough with associated sedimentary basins (Figure 2). Several volcanic zones and major faults are also represented. The Cameroon Volcanic Line is an alignment of continental and oceanic volcanic centers in an approximate direction of N30°E. This major tectonic structure of West Africa goes from the Pagalu Island in the Atlantic Ocean to Lake Chad and extends up to 1600 km long (Gèze, 1941). In this work, we consider only the continental

Figure 1. Map of the target area in Central Africa. This map presents Cameroon surrounded by seven countries. The marine part of this area is located in the Atlantic Ocean.
part, which includes a series of high volcanic reliefs: Mount Oku (3011 m), Mount Bamboutos (2670 m), Mount Manengouba (2420 m), and Mount Cameroon (4095 m). The Adamawa Plateau is a large uplift basement block dating from Cretaceous (Nnange et al., 2001). It is located in the northeastern part of Cameroon (Figure 2). Organized in tiers from 900 to 1500 meters above sea level, the Adamawa plateau steeply dominates the Benue Trough but gradually goes down to the south towards the South Cameroon Plateau. The Benue trough is a large basin of about 100 km wide. Its major axis is approximately NE-SW from the Niger Delta basin to Lake Chad. It contains mainly sediments of marine sandstone. A sedimentary part of this trough is found in the North and consists of a series of small synclines (Maurin and Guiraud, 1990). The boundary between the Pan–African Belt and the Congo Craton crosses the Cameroon southern part and progresses toward the north of Central African Republic (Boukeke, 1994; Mbom-Abane, 1997). The Congo Craton (south of the boundary) is thrust under the Panafican block in the north, along an intracrustal discontinuity. The Central African Shear Zone is a major tectonic structure extending from Dafour (Sudan) to the Adamawa Plateau (Dorbath et al., 1986). In the Adamawa region, the CASZ extends in the south–west direction and constitutes the Foumban Shear Zone (ZCF).

3. Data and Methods

3.1 Elevation Data

Elevation data cover a larger area (5° to 20° East longitude and 0° to 15° North latitude) to take into account the effects of sufficient topographic masses around the computation point. They must have a high accuracy and a good resolution to be as close as possible to the Earth’s topography. These elevation models are provided by the ALOS World-3D Digital Terrain Model 30 m (Tadono et al., 2016; Takaku et al., 2016). Yap et al. (2019) have made a recent study on the vertical accuracy of some high resolution digital terrain models (30 m) available in Cameroon. Their statistical analyses of the digital terrain models relative to ground control points revealed that the AW3D30 DTM (with a mean of −0.10 m and a STD of 13.07 m) gave the best representation of the Earth’s surface topography of Cameroon and its surroundings. In addition, it can be seen that the altitudes of the Earth’s surface topography in this model vary up to a maximum of 4030 m. This altitude is very close to the height of Mount Cameroon (4037 m) evaluated by Kamguia et al. (2015) and which happens to be the highest mountain peak in Central Africa. It is therefore wise to use the AW3D30 Digital Terrain Model because of its good accuracy and high resolution in our study area. On Figure 3, we note that the Earth’s surface topography of Cameroon is highly variable. It is quite complex and rough in some areas including those around the Cameroon Volcanic Line and on the Adamawa plateau.

3.2 Gravity Data (EGM 2008)

The gravity data used in this work are derived from the global geopotential model EGM2008 (Pavlis et al., 2008). This model is an improved version of the Earth Gravitational Model EGM96, developed by the National Geospatial-Intelligence Agency (NGA). It includes surface gravimetric measurements (terrestrial, marine, and airborne), satellite altimetry, and satellite gravimetric measurements (GRACE mission). The EGM2008 model is a spherical har-
monic expansion of the external gravimetric field of the Earth up to the degree and order 2159, with some additional spherical harmonics coefficients extending to degree 2190 and order 2159 (Pavlis et al., 2012).

The spherical harmonic coefficients of the EGM2008 model are used to calculate free air anomalies. The WGS 84 Geodetic Reference System (GRS) was used to define the geometry and the normal gravitational potential of the reference ellipsoid. The computed values refer to the surface of this reference ellipsoid. The Bouguer anomalies of the EGM2008 model are obtained after applying the topographic correction computed from the ETOPO1 topographic model (Amante and Eakins, 2008). These topographic corrections are evaluated using a spherical harmonic approach to improve the accuracy of results on a global scale (Balmino et al., 2012). Bouguer corrections have been computed using a density of 2670 kg/m³. The Bouguer anomaly map derived from the EGM2008 model is available in our study area and it is presented in Figure 4 as a 10 mGal contour map.

### 3.3 Spherical Harmonic Reference Surface

To achieve the objectives of this study, it was necessary to incorporate a smoother reference surface. This surface represents long wavelengths of the real topography and must be subtracted from the precise digital terrain model. According to Forsberg (1984), the reference surface can be obtained by either of two approaches: (a) by transforming the detailed digital terrain model into a coarse DTM, or (b) by using a spherical harmonic expansion of the terrestrial topography up to a certain order. We have chosen the second approach. Hirt (2010) has shown that in order to solve the omission error problem generally contained in global geopotential models, the spherical harmonic reference surfaces are better, compared to the averaged surfaces. The ETOPO1 spherical harmonic model of the Earth’s topography is chosen as the reference surface. It is publicly available on the website of the International Center for Global Earth Models (ICGEM) (Drewes et al., 2016). The orthometric heights of this reference area were calculated up to 2190 through the ICGEM calculation service (Barthelmes, 2013).

\[
H(\lambda, \phi) = R \sum_{l=0}^{l_{\text{max}}} \sum_{m=0}^{l} P_{lm} \sin \phi \left( C_{lm}^{\text{topo}} \cos \lambda + S_{lm}^{\text{topo}} \sin \lambda \right),
\]

where: \(H(\lambda, \phi)\) is topographic height of reference surface from mean sea level, \(R\) is reference radius, \(C_{lm}^{\text{topo}}\) and \(S_{lm}^{\text{topo}}\) are spherical harmonic expansion coefficients, \(P_{lm}(\sin \phi)\) is legende function of degree \(j\) and order \(m\).

### 3.4 Spectral Enhancement Method

The spectral enhancement method (Hirt et al., 2011) consists in reducing the frequency gap between the global geopotential models and the external gravity field of the Earth. In this work, we have to combine the gravimetric spectrum of the EGM2008 model taken up to its maximum degree with the components of higher frequencies. These components are actually the terrain effects of the so-called residual terrain model (RTM) (Forsberg, 1984). This method has been successfully applied by many authors (Forsberg, 1985; Hirt et al., 2010; Sampietro et al., 2017; Zaki et al., 2018) to improve the performance of GGM on areas with a very rough topography.

The effects of the Residual Terrain Model (RTM) correspond to the topographic effects with respect to a reference surface. These effects can be likened to a Bouguer plate taken between the real topographic surface and the reference surface from which classical terrain corrections are subtracted (Forsberg, 1984):

\[
\Delta g_{\text{RTM}} \approx 2\pi G \rho (H - H_{\text{ref}}) - C,
\]

where: \(H\) and \(H_{\text{ref}}\) are respectively the orthometric heights of the points of the real topography and the reference surface. \(G\) is the gravitational constant and \(\rho\) is the density of topographic masses. \(C\) corresponds to the classical terrain correction; at a point \((x_M, y_M, H_M)\), it is given by the following equation (Forsberg, 1984):

\[
C = G \rho \iiint \frac{z - H_M}{(x - x_M)^2 + (y - y_M)^2 + (z - H_M)^2}^{3/2}.
\]

Earlier, RTM effects and terrain corrections were calculated using charts and models (Hayford and Bowie, 1912; Hammer, 1939). RTM effects and terrain corrections can also be calculated using Digital Terrain Models. To perform this, a high resolution digital terrain model is used for a topography close to the computation point out to a limited radius, and a coarse DTM (smoother than the first) is used to represent the remote topographic masses up.
to a specified radius. Surface topography contains density anomalies that deviate from the standard rock density ($\rho = 2670 \text{ kg/m}^3$). A better knowledge of the distribution of these densities in the topography would make it possible to improve the modeling of the residual terrain effects (Hirt, 2010). So, for futures studies of RTM effects on the study area, we should integrate a topographical density model in our computations (Sheng et al., 2019).

The GRAVSOFT programs (SELECT and TC) were used to compute the effects of the residual terrain model (Forsberg and Tscherning, 2008). Because of computer limitations, the SELECT program is first used to convert the AW3D30 DTM into a 10 arc-second resolution grid. This grid is used to represent the topography close to the computation point. For the remote topography, we used a 3 arc-minutes resolution grid obtained by smoothing the 10 arc-second resolution grid with SELECT. The reference surface is obtained by expanding the ETOPO1 spherical harmonic model up to 2190, which corresponds to the maximum degree of the global geopotential model EGM2008. This reference surface is used because it makes it possible to subtract the frequencies of the Earth topography already contained in the EGM2008 model. The TC program (computation of topographic gravity effects by considering a homogeneous rectangular prism) is used to compute RTM effects. Some authors (Ismail, 2016; Yahaya and El Azzab, 2018) have tested the optimal choice of integration radius, the influence it could have on the different quantities calculated, and the computation time induced. Their results show that if we choose 10 km and 200 km as limits of the inner and outer zones respectively, we should expect very small errors and a reasonable computation time during the terrain effects evaluation, whether we are in a flat or mountainous area. These integration radius values were thus chosen in this work. The computed residual terrain effect values were then added to the Bouguer anomaly values of the EGM2008 model to obtain more refined values.

4. Results and Discussion

4.1 Residual Terrain Effects Map and Refined Bouguer Anomalies Map

Figures 5 and 6 below show respectively the distribution of RTM effects on the gravity anomalies grid derived from the EGM2008 model and on the new grid of refined Bouguer anomalies. Associated with these two figures is Table 1, which presents statistics of the Bouguer anomaly grids derived from the EGM2008 model before and after refinement, as well as those of RTM effects.

Figure 5 shows that RTM effects vary laterally within the study area. We can also notice, from Table 1, that the RTM effects are well-centered and that these terrain effects change with the intensity of the external topography’s undulations. In mountainous and rough areas (in particular, the western highlands that cover much of the Cameroon Volcanic Line, the Plateau of Adamawa that is punctuated by small volcanoes, and the Mandara Mountains that contain a relief with steep slopes) RTM-effect values are not negligible. They range from $-49.79$ to $37.76$ mGal. These topographic effects are not taken into account in the gravimetric signal derived from the EGM2008 model, whereas they are quite important. Their omission could undoubtedly reduce precise in-

![Figure 5](image_url) RTM effects map on the Bouguer anomaly grid derived from the EGM2008 model. The regions affected by RTM effects are mostly found in the North of Adamawua Plateau, on the Cameroun Volcanic Line and its surroundings. The RTM effects in the rest of the map are negligible.

![Figure 6](image_url) Refined Bouguer anomaly map derived from the developed EGM2008-R model. (Intervals: 5 mGal; color-scale unit: mGal). The map is interpolated onto a regular 2 km grid. At this scale, the differences between this map and Bouguer anomaly map derived from the EGM2008 model (Figure 4) are not visible.
terpretations in geophysics and geodesy, especially in studies made at a local scale. To overcome this problem of omission error in areas with a highly variable topography, the effects of residual terrain are added to the Bouguer anomalies grid derived from the EGM2008 model. A new, more refined, Bouguer anomaly grid is thus obtained (see Figure 6). Table 1 shows that the standard deviation increases slightly (from 44.12 mGal to 44.24 mGal), confirming that the very high frequencies missing in the EGM2008 grid have been taken into account in the new grid, refined by the topographic effects.

The iso-value map of the refined Bouguer anomalies presented in Figure 6 shows information that correlates perfectly with the position of some major geological structures (Figure 2). The refined Bouguer anomaly map is dominated by the long wavelength components, which makes it difficult to see the influence of residual terrain effects on gravimetric signatures. On this map, the maximum anomalies are found mostly in the south–west of the study area. We also observe two large regions with negative anomalies in the Center and South of the considered region. A gradient zone around the 4°N parallel separates the two previous anomalies. We can also note the existence of positive anomalies in the west in a N45°E direction. The two local maxima of quasi-circular shape are located in the south–west of the zone. These maxima are aligned in the LVC direction. According to Adighije (1981) and Fairhead and Okereke (1987), the positive signatures in the direction of the Benue Trough are due to an uprising of the Moho. The positive anomaly peaks observed in the trough direction may be due to the presence of igneous rocks within the basement or Cretaceous sediments (Cratchley et al., 1984; Benkhelil, 1989; Ofoegbu and Mohan, 1990). However, these positive signatures are surrounded by some negative anomalies attributed to the presence of Cretaceous sediments (Elf-Serepca, 1981, Cratchley et al., 1984). The negative beach barge of Bouguer anomalies oriented E–W observed at the center of the study area characterizes the Adamawa Plateau (Djomani et al., 1992; Nouotchogwe Tatchum et al., 2006). Based on the work of Fairhead and Okereke (1987), Djomani et al. (1992), these negative anomalies are attributed to a low density mass present in the upper mantle near the uplift and located at a depth ranging from 80 to 140 km. The gravimetric anomaly gradient zone observed around the 4° parallel increases slightly (from 44.12 mGal to 44.24 mGal), thus obtaining a map of the very high frequencies missing in the EGM2008 grid have been taken into account in the new grid, refined by the topographic effects.

Table 1. Bouguer anomaly statistics before and after refinement and RTM effects.

|            | Min (mGal) | Max (mGal) | Mean (mGal) | STD (mGal) |
|------------|------------|------------|-------------|------------|
| EGM2008    | −258.01    | 238.57     | −40.25      | 44.12      |
| RTM effects| −149.79    | 37.76      | −0.25       | 2.71       |
| EGM2008-R  | −253.61    | 238.59     | −40.32      | 44.24      |

When we look at the new refined Bouguer anomaly map, we do not observe differences from the Bouguer anomaly map before refinement (Figure 2) because we are on a regional scale. The observation of these differences could be more appreciable with a regional/residual separation of the gravimetric anomalies. Although the gravimetric anomaly signal is highly variable in the upper crust, some residual details would be masked by lower frequencies located deeper. A more local scale, based on the removal of long wavelength components of these gravity anomalies, could allow a better appreciation of the impact of residual terrain effects on gravity anomalies signatures.

4.2 Impact on Gravimetric Signatures in Mountainous Area (Cameroon Volcanic Line and Its Surroundings)

Bouguer gravity anomalies contain the combined effects of large, deep, and superficial structures with a limited lateral extension. The impact of the refinement of Bouguer anomalies is more noticeable at local scales and in the superficial part of the lithosphere. This is why we have computed the residual anomalies at a smaller scale and in a mountainous region (localities on and around the Cameroon Volcanic Line). For this, the polynomial fitting method (Radhakrishna and Krishnamacharyulu, 1990) is used because it makes possible a separation of Bouguer anomalies into residual and regional components. As the degree of the polynomial n increases, the regional anomalies are more close to the Bouguer anomaly, thus revealing more geological structures close to the upper crust. So we have applied a third order polynomial on the EGM2008-grid because we wanted to avoid elimination of shallow structures represented in the residual anomalies. We have also applied the same polynomial (computed from EGM2008-grid) to reduce the same effect from the refined model EGM2008-R. Residual anomaly maps before and after refinement are presented in Figures 5a and 5b. Figure 5c highlights the influence of omission error on the gravity anomalies by presenting a map of the differences between the Bouguer residual anomalies before and after refinement.

By carefully observing the two residual maps of Bouguer anomalies (Figure 5a and 5b), we already notice many differences that appear after refinement. At several places on the refined map the contours of Bouguer anomalies have a new shape, position, and direction. Table 2 below presents the statistics of Bouguer anomalies before and after refinement, as well as their differences.

Table 2. Residual Bouguer Anomaly (RBA) statistics before and after refinement in mountainous areas and their differences.

|            | Min (mGal) | Max (mGal) | Mean (mGal) | STD (mGal) |
|------------|------------|------------|-------------|------------|
| RBA before refinement | −153.34    | 187.48     | −0.72       | 22.84      |
| RBA after refinement    | −149.37    | 174.69     | −1.64       | 22.87      |
| Differences            | −37.97     | 26.40      | −0.92       | 4.45       |

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which, ranging from −37.40 to 26.40 mGal, are considerable. We also note that the minimum and maximum gravimetric anomaly values change respectively from −153.34 to −149.37 mGal and from 187.48 to 174.64 mGal, demonstrating the large influence that topography has on these gravity anomalies and thus emphasizing the importance of taking topography precisely into account.

The residual anomaly maps show the heterogeneity or density variation of the different geological formations within the Earth’s crust. The residual map of Bouguer anomalies before refinement (Figure 7a) shows alternatively negative and positive anomalies. The zones of negative anomalies are most often related to the presence of sedimentary basins or an intrusion of low density materials. Negative NW-SE anomalies are located around Douala. They are due to the presence of a sedimentary basin dating from the early Cretaceous (Regnoult, 1986; Nguene et al., 1992). Along the localities of Monatele, Bafia, and Yassem, there are small anomalies with a N-S direction translating low density geological formations in the superficial part of the Earth’s crust. Indeed, large parts of these localities are drained by the Sanaga River and its tributaries, hence the negative signature due to the presence of alluvium or low density geological outcrops. The zones of very negative amplitude with a NE-SW direction and located around Manyemen and Fontem are caused by the southern part of the Benue Trough filled with Cretaceous sedimentary deposits of low density (Benkhellil, 1986). The signatures of negative anomalies located in Nigeria (north of Takamanda) are surely caused by the Benue Trough. Negative anomalies around the locality of Banya are probably due to the influence of the large, low-density masses found beneath the Adamawa plateau (Djomani et al., 1992; Noutchogwe et al., 2006). Negative gravity anomalies in the Efo-lofo locality may be associated with a low density geological formation.

The residual anomaly map from the EGM2008 model also shows several areas of positive anomalies. Around the locality of Takamanda, we can observe positive anomalies with high amplitude. These positive signatures are probably caused by granitic intrusions in this area (Toteu et al., 1987, 2004). Mount Cameroon is also based on an area of positive anomalies. Indeed, Mount Cameroon covers volcanic formations of high density dating from the Cenozoic until the present era (Déruelle et al., 1991, 2007). These volcanic massifs extend along the volcanic line of Cameroon, from which local positive anomalies are observed along the NE-SW direction. The contact zone between the Congo craton and the Pan–African Belt is marked by positive anomalies, particularly in the Nyambe and Nguila localities. These anomalies are probably due to the presence of very dense bodies in the crustal part and in the upper mantle following tectonic compression (Boukeke, 1994).

Gravity interpretations made from the residual anomaly map of the EGM2008 model coincide in general with the results of several previous geological and geophysical investigations. Nevertheless, after refinement of this residual map, we notice some differences that affect the gravimetric signature of the target area. In fact, the positive and local signatures around the locality of Essu did completely change their directions on the new map (from

Figure 7. Residual Bouguer anomalies map in mountainous areas (Cameroon Volcanic Line) before refinement (a) and after refinement (b); (c) differences between the residual Bouguer anomalies maps before and after refinement.
N45°W to N30°W). The new map (Figure 7b) gives a better estimate of the impact of RTM effects on the EGM2008 grid. At the East of Nwa locality, we observe some anomalies with negative amplitude. The area located at the West of Bafia has a new shape; the negative anomalies contours have been modified. Above the locality of Ngambe, we note the appearance of three local and negative anomalies in the N30°W direction that were almost non-existent in the previous map. Moreover, the map of differences between Bouguer residual anomalies before and after refinement (Figure 7c) allows a better assessment of the influence of the residual terrain effect on gravity signatures. The most affected areas are marked in blue and pink on this map. We note that the areas highly affected by the residual land effect are located on the Cameroon Volcanic Line and around Takamanda, Essu, Dumbo, and Ngambe localities. Mount Cameroon is an inaccessible area to measure gravity data because of its rugged terrain. Many geophysical investigations with new gravity data are being carried out around this area to improve knowledge of the nature of shallow and deep structures, the orthometric height of Mount Cameroon, and the depth of various geological features (Kenfack et al., 2011; Kamguia et al., 2015; Nguiya et al., 2019). Despite better results, improvements are still to be made in our knowledge of this mountainous area. Marcel et al. (2016) highlighted the absence of terrestrial gravity data in Ngambe, Takamanda, and Fontem localities and used the EGM2008 model, which provides more homogeneous data. Nevertheless, these localities are highly affected by the omission error that skews an accurate reading of the gravimetric signatures due to Earth’s topography (see Figure 7c). The use of the new refined Bouguer anomaly map improves the reading of gravimetric signatures in these areas.

However, a comparison with terrestrial gravity data available for Cameroon and its surroundings needs to be performed in order to evaluate the quality and accuracy of the gravimetric anomalies of the EGM2008 model after correction of omission error.

### 4.3 Results Validation

Validating our results goes through two stages. First, we have compared the new EGM-R grid with local terrestrial gravity data. The second step consists in making a comparison of the RTM effects obtained with those computed by Hirt et al. (2014) on a global scale. All these comparisons have been performed on a mountainous area where RTM effects have greater amplitudes.

#### 4.3.1 Comparison with terrestrial Bouguer anomalies

The gravity dataset used for this comparison was collected at 60 irregularly spaced gravity stations located on a mountainous area. These gravity data were collected during 2008 by the National Institute of Cartography (NIC) to acquire more data and fill the gaps around Mount Cameroon. Lacoste–Romberg gravimeters were used to collect the data at these stations. The measurements were taken from the base station used by the previous institutions and located at Buea (Up Station). The acquired data were corrected for instrumental drift. Using the Geodetic Reference System GRS80, the Bouguer anomaly was computed for all survey stations. Nguiya et al. (2019) have recently used these gravity data to study the crustal structure beneath the Mount Cameroon region.

The structure of the signal between the terrestrial, EGM2008, and EGM2008-R Bouguer anomalies is illustrated in Figure 8. The differences between EGM2008, EGM2008-R, and terrestrial Bouguer anomalies at each of the 60 stations are presented in Table 3.

Figure 8 shows the differences between the terrestrial gravity signal and the EGM2008 and refined-EGM2008 grids. Table 3 highlights the approximation between the new EGM2008-R grid and the terrestrial gravity anomalies with the Root-Mean-Square (RMS) which goes from 11.71 to 6.41 mGal. In fact, the closer the value of the Root-Mean-Square (RMS) to zero, the more accurate is the EGM2008-R derived Bouguer anomaly to the terrestrially-measured Bouguer anomaly. Large RMS values between the terrestrial gravity data and the EGM2008 model would be undoubtedly caused by: omission and commission errors present in this model, possible errors in the observed gravity data, and/or topographical biases between the Digital Terrain Models (DTM) such as ETOP01 and terrestrial elevation data. The decrease in RMS after refine-
Table 3. Statistical result of the differences between EGM2008, EGM2008-R and terrestrial Bouguer anomalies at each of the 60 stations.

|          | Min (mGal) | Max (mGal) | Mean (mGal) | STD (mGal) | RMS (mGal) |
|----------|------------|------------|-------------|------------|------------|
| EGM2008  | −12.31     | 70.55      | 2.26        | 11.59      | 11.71      |
| EGM2008 refined | −7.94     | 40.21      | 1.18        | 6.35       | 6.41       |

The ERTM2160 model shows that the gravimetric signal has been enriched in short wavelengths (correction of omission error). In addition, the mean and the standard deviation go respectively from 2.26 mGal to 1.18 mGal and from 11.56 mGal to 6.35 mGal. These statistical parameters are considered to be an improvement of the EGM2008 Bouguer anomaly grid after refinement by the RTM, especially in mountainous areas. We conclude that signal omission errors can greatly deteriorate the accuracy of parameters computed from the EGM2008 model. The EGM2008-refined Bouguer gravity anomalies are better in accuracy than the EGM2008-computed Bouguer gravity anomalies.

4.3.2 Comparison with the ERTM2160 model
The ERTM2160 model has been developed by Hirt et al. (2014). It provides computerised maps of Earth’s short-scale gravity field at 0.002 degree (7.2 arc-seconds, or ~220 m in latitude direction) resolution for all land areas of Earth within 60 geographic latitude, and an adjoining ~10 km marine zone along the coast lines, with the exception of Greenland. The spectral band-width of ERTM2160 is ~10 km (harmonic degree 2160) to ~250 m. The ERTM2160 gravity field model is freely available via http://ddfe.curtin.edu.au/gravitymodels/ERTM2160.

Figures 9a and 9b show respectively the RTM effects of the ERTM2160 model and those calculated in this work in a mountainous region of the study area. We observe several features of similarity between the two figures. The RTM effects are significant (signatures in blue and red color) on areas with highly variable topography.

Table 4 presents the statistics of the RTM effects obtained in this study and those calculated by Hirt et al. (2014), as well as their differences. The field effects obtained in this work are very close to those provided by the ERTM2160 model. We get differences with a maximum of 6.53 mGal and a minimum of −7.40 mGal. The small differences observed would be caused by the difference in resolution of the two residual data grids.

From these last results, the global geopotential model EGM2008 proves to be more efficient in relatively flat terrain. In fact, residual terrain effects are approximately null when we are in these areas. But in rugged terrain or in areas with a highly variable topography, the accuracy of anomalies derived from the geopotential model is reduced. This work has allowed us to show that the use of more detailed digital terrain models is very important in the development of this type of geopotential model. The use of refined Bouguer anomalies from the EGM2008 model is a good alternative for areas without terrestrial gravity data, especially areas that are difficult to access because of rough terrain. A combination of this new refined EGM2008 grid with available terrestrial gravity data would be a good initiative to model a new gravimetric database, more accurate and consistent, over the study area.

5. Conclusion and Recommendations
The main objective of this work was to use the spectral enhance-

Table 4. Statistical result of the RTM effects computed in this study; by Hirt et al. (2014) and released in the ERTM2160 model; and their differences.

| RTM effects   | Min (mGal) | Max (mGal) | Mean (mGal) | STD (mGal) |
|---------------|------------|------------|-------------|------------|
| By this study | −49.79     | 37.76      | −0.25       | 2.71       |
| By Hirt et al. (2014) | −55.20     | 43.19      | −0.64       | 2.87       |
| Differences   | −7.40      | 6.53       | −0.22       | 0.45       |

Figure 9. RTM effects map on a mountainous portion of the study area. (a) Computed in this study. (b) Computed by Hirt et al. (2014) and released in the ERTM2160 model.
ment method to reduce omission errors in Bouguer anomalies data derived from the EGM2008 global geopotential model. The gravimetric signal from mountainous regions where the topography is highly variable has wavelengths shorter than the maximum degree of spherical harmonic coefficients in the global geopotential model EGM2008. In Cameroon and its surroundings, terrain effects were computed using the Residual Terrain Model method, taking care to avoid frequencies already contained in the EGM2008 model. We noted significant values ranging from −53.59 to 34.79 mGal. These values are higher when we are in mountainous areas (Highlands of West Cameroon, Adamaua Plateau, and Mandara Mountains of North Cameroon). To refine the Bouguer anomalies from the EGM2008 model, we coupled them to the residual terrain effects. A comparison of the old grid and the new grid of gravity anomalies shows some differences: the contours shape change, the color details present in the old grid disappear in the new grid and others appear, the minimum value of the Bouguer anomalies made a significant gap from −14.63 to −35.39 mGal. After reducing omission error in the EGM2008 model, we evaluated impact of these errors on gravimetric signatures in a mountainous region of our study area. The differences between the residual maps of Bouguer anomalies before and after refinement still give important values ranging from −37.40 to +26.40 mGal. The impact is therefore more felt on the shallow part of the crust including the Cameroon Volcanic Line and around Takamanda, Essu, Dumbo, and Ngambe localities. All these results show that the omission error present in the GGM cannot be neglected. This new Bouguer anomaly grid is a good alternative for areas with rugged terrain where gravity data are very scattered or absent. But this grid cannot replace terrestrial gravity data in a flat terrain. A constant density (2.67 g/cm$^3$) is assumed in the computation of RTM effects whereas topography on the surface is not completely homogeneous. However, one perspective obtainable from this work is perhaps that it might be advisable to use a current geopotential model from the GOCE mission instead of the EGM2008 model. The long to medium wavelength components are more accurate than those contained in the EGM2008 model (commission error). Moreover, due to computer limitations, it was not possible for us to have a resolution higher than 10 arc-seconds over all of the study area. The resolution of the RTM effects computed needs to be improved in a future study. The new anomaly grid from this work is perhaps that it might be advisable to use a current geological model to reduce omission errors in Bouguer anomalies data. The omission error present in the GGM cannot be neglected.

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