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THE MOUNT CAMEROON HEIGHT DETERMINED FROM GROUND GRAVITY DATA, GLOBAL NAVIGATION SATELLITE SYSTEM OBSERVATIONS AND GLOBAL GEOPOTENTIAL MODELS

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Abstract

This paper deals with the accurate determination of mount Cameroon orthometric height, by combining ground gravity data, global navigation satellite system (GNSS) observations and global geopotential models. The elevation of the highest point (Fako) is computed above the WGS84 reference ellipsoid. The geoid undulation and the height of Fako above mean sea level were also determined. Ground data consist of a sparse gravity net recorded around 1950, densified with recent data collected on and around the mountain. GNSS data consist of ellipsoidal elevations and precise horizontal point coordinates computed from GPS satellites observations, and those of other systems orbiting around the Earth. Global geopotential models involved are a hybrid model EGM-GGM and the recent Earth Gravity Model EGM2008. The method used appears more flexible than spirit leveling, which is too expensive, time consuming, difficult and of very low accuracy in mountainous areas, where the topography is very rough. Mount Cameroon, which is the highest summit in central and western Africa, is now known to culminate at 4037.7 ± 0.7 m above sea level. This height is nearly 60 m less than the approximate value of 4095 m published by the National Institute of Cartography.

Introduction

Mount Cameroon, an active volcano standing majestically at the bottom of the Gulf of Guinea, is the highest summit of West and Central Africa. Its precise orthometric height is unknown. Many studies carried out in the area used heights ranging from 4000 to 4100 m (Deruelle, Ngounouno & Demaiffe, 2007; Fitton & Dunlop, 1985; Kamdem *et al.*, 2002; Kenfack *et al.*, 2011; Ngounouno, 1998; Nnange *et al.*, 2001; Reusch *et al.*, 2010; Suh *et al.*, 2005; Tokam *et al.*, 2010). The official height obtained from trigonometric leveling and barometric measurements, and published by the National Institute of Cartography, is 4095 m (Carme, 2012). Due to a rough topography and weather conditions, only the barometric method was conducted up to the summit. Compared to the technical standards used presently, the above result obtained during the colonial period do not reflect the real height, which may be less or greater. In addition, the mountain is situated in a very dynamic environment and has erupted five times since 1940. Therefore, its height may have changed significantly. Hence, a precise orthometric height determination is needed for scientific, strategic, military navigation, political and environmental reasons.

Classical spirit leveling (direct and trigonometric leveling) is indicated for accurate height determinations (Cheinway *et al.*, 2007). This method is applied mainly in areas with less pronounced topography. However, mount Cameroon is situated in a topographically very rough region, hence, the use of GPS/leveling approach (Cheinway *et al.*, 2007). The accuracy of this method, widely used for mountain height determination and detection of vertical land motion (Banerjee, Foulger & Dabral, 1999; Fujii & Satomura, 1998; Gueguen, 2001), is based on the quality of the geoid model considered. The latest should be compatible in accuracy and resolution with GPS-derived ellipsoidal heights. The geoid is the equipotential surface of the earth's gravity field that corresponds most closely with mean sea level in the open oceans, thus, ignoring oceanographic effects such as salinity, pressure and temperature variations. One needs a dense gravity net, along with additional elevation data, for a precise geoid determination.

Presently, Cameroon is carrying out a reserch programme to determine a precise local geoid model. The applications of this reference surface became interesting as the advent of precise positioning by satellite to realize GPS/leveling, where purely geometrical ellipsoid elevations are transformed into orthometric heights based on a geoid model. This paper presents the application of this approach to the determination of the height of mount Cameroon. The data used were ground gravity anomalies, GNSS satellite observations and global geopotential models. The status of gravity and elevation data over the mount Cameroon area were significantly increased, during some GPS and gravity expeditions organised by the mapping Institute of Cameroon. The local geoid model of Cameroon (Kamguia *et al.*, 2007) was recomputed, accounting for the newly collected gravity data, in order to increase its accuracy in the area.

Height determination and height system in Cameroon

The relationship between barometric pressure and height was used in the past to calculate height, when a direct connection to sea level was impossible. This approach was used to estimate the first value of the height of mount Cameroon at 4095 m (Carme, 2012; Geze, 1943). However, the method delivers a poorly defined height above the atmospheric pressure at sea level, with uncertainty of more than 10 m. Using a local gravimetric geoid model combined with GPS measurements, precise orthometric heights can be computed, based on a reference height system and a geodetic network. For this purpose, the geodetic network of mount Cameroon was established in 2011, with 25 reference points and 510 intermediates (Carme, 2012). The orthometric heights in this network were determined using a reference surface (CGM11) obtained after adjusting the global geoid model EGM2008 (Palvis, 2008) to a network of 130 precisely leveled points in the country, with accuracy estimates between 10 and 20 cm (Carme, 2012). This network is part of the benchmarks called General Leveling of Central Africa (NGAC), established during the colonial period, using a tide gauge at Pointe Noire in Congo.

Another modern approach for height determination is Radar interferometry (Hastings & Dunbar, 1998). The method measures the difference in range between two observations of a given ground point, with sufficient accuracy to allow accurate topographic reconstruction. The shuttle radar topographic mission (SRTM) is an example which produced elevations with respect to the WGS84 reference ellipsoid (NASA, 2003), further converted into orthometric heights using the EGM96 (Lemoine *et al.*, 1998) geoid model. The highest point of mount Cameroon, derived from SRTM digital terrain model, is 4031 m.

Geoid of Cameroon in the study area

The global navigation satellite system (GNSS) gives point coordinates very accurately in a three-dimensional terrestrial frame relatively to WGS84 reference ellipsoid. A conversion of GNSS geometrical heights into physical heights above the geoid is possible, if the geoid-ellipsoid undulation is known. This undulation can be obtained from global gravity models (GGM), or from local geoids. Orthometric heights are deduced from geoid undulations, and elevations above the reference ellipsoid (neglecting the curvature of the plumb line) using the equation:

$$H = h - N \text{ (Heiskanen \& Moritz, 1967)} \quad (1)$$

The elevations are generally very accurate, depending on the type of positioning, the environment of the station and the quality of the receivers. Therefore, the accuracy of the heights computed from equation (1) depends mainly on the accuracy of the geoid model used. Moreover, the geoid model used should be more representative of gravity data and geoid undulations in the area. To achieve this, one needs to select this model among many others, after a series of tests comparing global and local geoid available in the study area. This method is used to determine the mount Cameroon height, combining many data sources namely:

- The GNSS observations from field campaigns, for ellipsoidal height computations.
- Gravity data, also from field expeditions, used to recompute the geoid model of Cameroon.
- Global geopotential models used to recompute the geoid model of Cameroon (CGM05-R).

The local geoid model of Cameroon (Fig. 1) was recalculated following the strategy summarised by (Kamguia *et al*., 2007). Sixty-two thousand gravity data points on land and ocean areas, including data derived from satellite altimetry were involved. A hybrid global geopotential model (EGM-GGM) supplied the longer wavelength components of this geoid model (CGM05-R). EGM-GGM is obtained by adjusting the GRACE model GGM02C to degree, and order 360 using the harmonic coefficients of the model EGM96 beyond the maximal degree 200 of GGM02C. The medium wavelength components were computed using the best gridded residual gravity anomalies by integration in Stokes's formula (Heiskanen & Moritz, 1967). The digital terrain model SRTM (NASA, 2003)contributed to its short wavelength components. A quasi-geoid model was first determined and further converted to the geoid, using a grid of simple Bouguer gravity anomalies (Kamguia *et al*., 2007).

Experimental

Ground gravity observations

Ground data are scalar gravity measure-

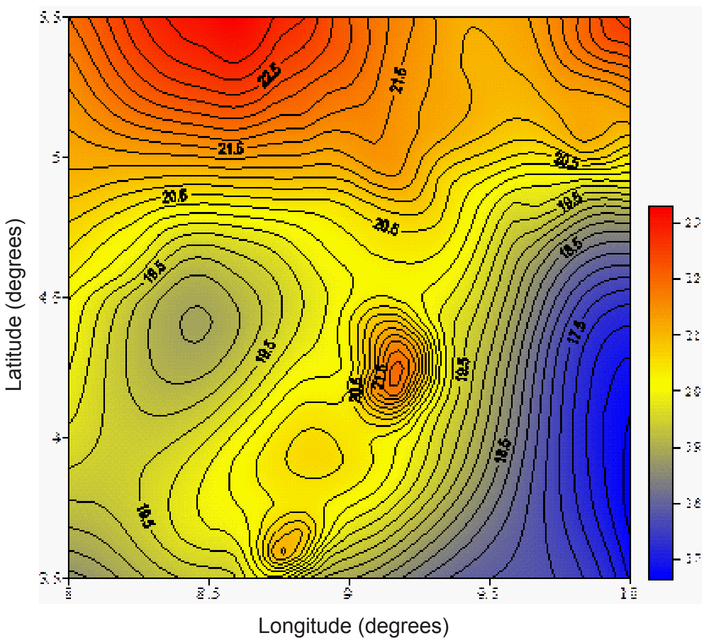

Fig. 1. The local geoid model CGM05-R recomputed in the study area. Mercator projection; interval: 0.2 m

ments obtained from two sources: Data computed by Collignon (1968) and Poudjom-Djomani (1993) in the area (with many gaps, Fig. 2), obtained from the Bureau de Gravimetrie Inertnational (BGI), and those from field campaigns organised by the National Institute of Cartography of Cameroon, from 2007 to 2011, in a small part of the area. Using the gravity database released by the BGI, the gravity anomalies were recomputed (Kamguia *et al.*, 2007). For the newly established stations (Fig. 2), a Lacoste & Romberg (Model G, n° 471) gravitymeter was used for the measurements along many loops. Each survey loop lasted 1day. These loops were short due to terrain difficulties (rough topography). The data recorded were tied to the Martin Network of ORSTOM (Duclaux *et al.*, 1954), using the nearest base station situated in Douala. The accuracy of the gravity measurements is about 0.5 mGal. These data were recently introduced into a geophysical interpretation over the mount Cameroon area (Kenfack *et al.*, 2011).

At each of the above new stations, the scalar gravity reading were corrected and reduced to calculate as follows:

$$\Delta g = g - g_0 \quad (2)$$

where g (mGal) is the scalar gravity and g_0 (mGal), the theoretical gravity attraction on the reference ellipsoid. The latest is the normal gravity defined on the WGS84 reference ellipsoid by the Somigliana formula (Moritz, 1992; Somiglian, 1929):

$$g_0 = \frac{a\gamma_e \cos^2\varphi + b\gamma_p \sin^2\varphi}{\sqrt{a^2\cos^2\varphi + b^2\sin^2\varphi}} \quad (3)$$

where a and b are the semi major and the semi minor axis, respectively, of the reference ellipsoid; γ_c and γ_p the normal gravity for $\phi = 0$ (at the equator) and $\phi = 90^o$ (at the pole) and ϕ the latitude of the station, respectively. Table 1 shows the statistics of old and new data computed using equations (2) and (3). The free-air anomalies were further computed from measured data after accounting for the free-air correction approximated using:

$$\delta g = 0.3086H \quad (4)$$

where H is the measured height. Free-air anomalies from EGM2008 at the new grav-

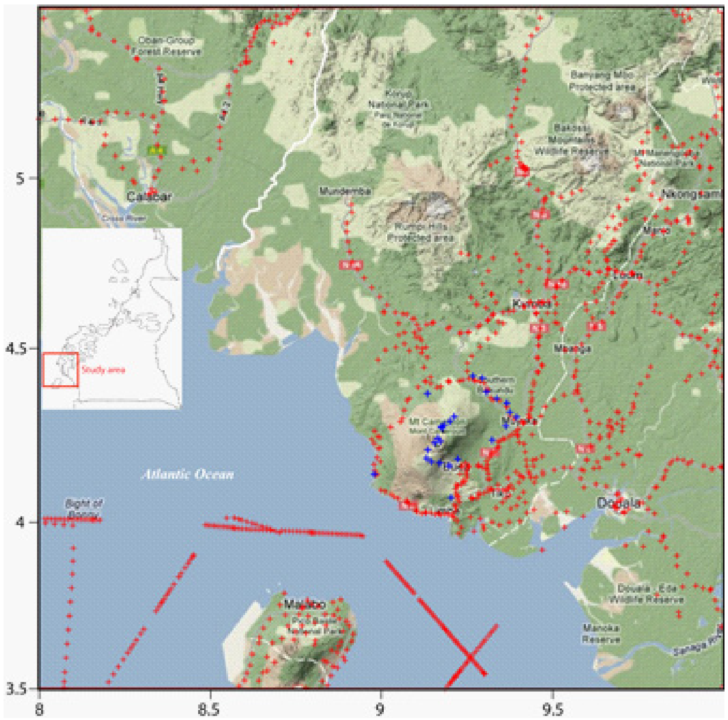

Fig. 2. Geographical distribution of old and newly installed gravity stations in the study area. + : Old data ; + : New data

TABLE 1

Statistics of measured free-air anomalies and the corresponding ones calculated from the global model EGM2008

Data	*Number of points*	*Max.*	*Min.*	*Mean*	*STD*
Old gravity anomaly (mGal)	1078	104.767	- 84.205	- 0.598	36.65
New gravity anomaly (mGal)	39	422.521	- 41.804	155.434	165.523
EGM2008 gravity anomaly (mGal)	39	455.168	- 23.513	181.655	175.552
Difference between new and EGM2008					
Free-air anomalies (mGal)	39	28.677	- 65.301	-18.212	17.912
Combined gravity anomaly (mGal)	1117	422.521	- 84.205	4.851	55.206

ity stations are also indicated in Table 1 for statistical analysis.

The combined gravity database, represented on the gravity anomaly map (Fig. 3) was used to recompute the geoid model of Cameroon (CGM05-R) in the study area, following the stages and strategy by Kamguia (2007). New gravity anomalies seem accurate as they closely fit data from EGM2008 in the mount Cameroon area (Table 1). These data from EGM2008 are represented on Fig. 4, with contour lines nearly similar to those of Fig. 3.

Global navigation satellite system (GNSS) data

Spatial GNSS data are information recorded by receivers from GNSS satellites orbiting the Earth. These observations are used to compute geocentric coordinates of the new gravity stations in the WGS84 reference system, and to calculate their ellipsoidal coordinates (latitudes, longitudes, elevations). The field observations were conducted in a differential GPS mode, using two-frequency GPS receivers. For the first campaign in 2010, a network of six points (each point observed during at least 2 h) were created, including the point at the

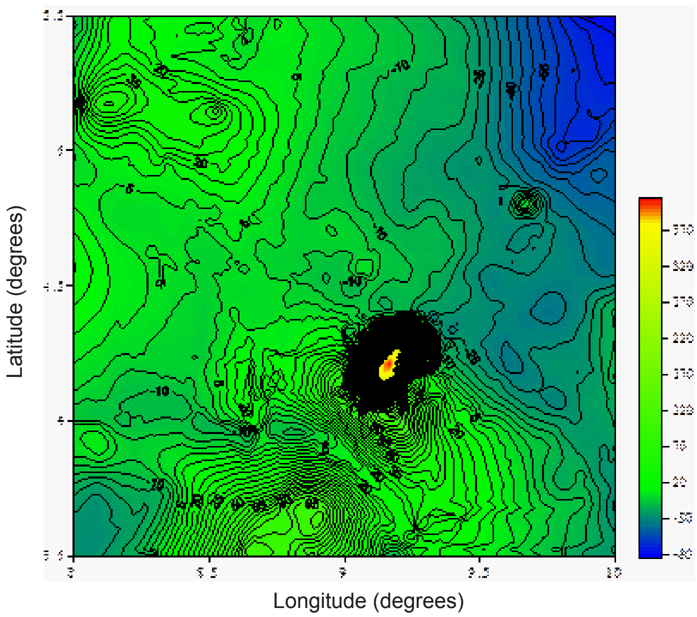

Fig. 3: Combined free-air gravity anomaly contour map of the area from new and existing data. Mercator Projection ; units: mGal

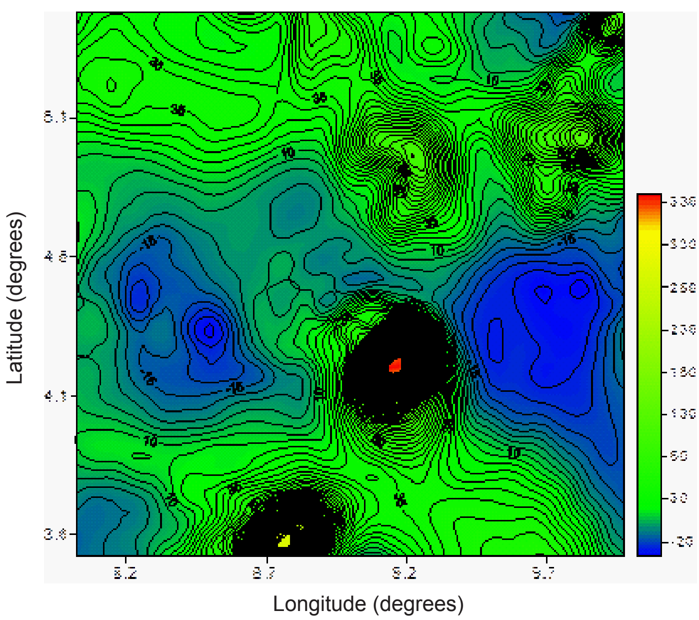

Fig. 4: Free-air gravity anomaly contour map of the area from EGM08. Mercator Projection ; units: mGal.

summit of mount Cameroon called "SOMMET". One of them (GPS011) was tied to a point "COTCO" situated in Douala. This point served as a reference during the construction of a GPS network along the Chad-Cameroon pipeline. The coordinates of COTCO were determined from long observations pointed on precise ephemerides, using four base stations of the International Terrestrial Reference Frame (Gueguen, 2001), realisation 2000 (ITRF2000). During the second campaign in 2011, another network of 11 points was established, and tied to the national geodetic network of Cameroon (RGC) by measuring 3 references (B 183; B 472 and B 476). One of the points (INC 0016) was in the first network. It was also used as a control point during the determination of the mount Cameroon elevation.

The computations were done in one single adjustment (Fig. 5), using the Leica Geo-office software, based on the powerful MOVE3 kernel with rigorous algorithms *(http://www.leica-geosystems.com/4621.htm)*. Four geodetic points (INC 0016; B 183; B 472 and B 476) were considered as control points. The

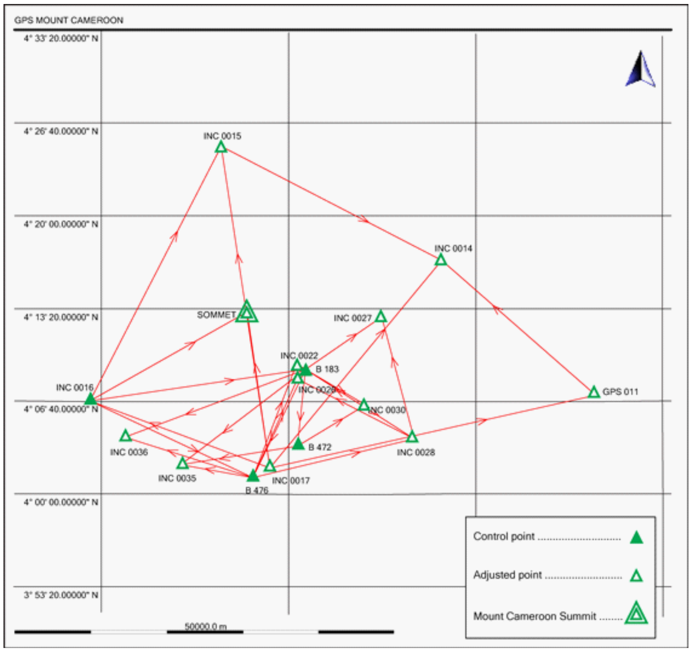

Fig. 5. Baselines between points of the GPS network in the mount Cameroon area

obtained for mount Cameroon was 4059.97 m.

Global geopotential models

Spherical harmonic coefficients of global geopotential models (GGM) served for gravimetric geoid computations. They are also used to calculate geoid undulations of points directly. In both cases, the GGM used best represent geoid undulations and gravity anomalies in the area of interest. GRACE models (Tapley *et al.*, 2005) seem more appropriate for local geoid computation in Africa (Mercy, 2003). Whilst computing the first local geoid model of Cameroon (Kamguia, 2007), it was shown that the GGM (EGM-GGM) obtained by adjusting the GRACE model GGM02C (Tapley *et al.*, 2005) to degree and order 360 using the harmonic coefficients of the model EGM96 [12] beyond the maximal degree

TABLE 2

Point coordinates of the GPS network in the mount Cameroon area

Point Id	Point Class	Latitude	Longitude	Ellip. Hgt.	Sd. Latit...	Sd. Lon...	Sd. Hei...
INC 0016	Control	4° 06' 42.45370" N	8° 59' 12.26583" E	28.2616	0.0000	0.0000	0.0000
B 476	Control	4° 01' 12.48910" N	9° 10' 49.41290" E	94.7920	0.0000	0.0000	0.0000
B 472	Control	4° 03' 25.83770" N	9° 13' 58.73300" E	242.9040	0.0000	0.0000	0.0000
B 183	Control	4° 08' 57.01250" N	9° 14' 34.41670" E	866.3910	0.0000	0.0000	0.0000
SOMMET	Adjusted	4° 13' 04.75535" N	9° 10' 24.33492" E	4059.9718	0.0089	0.0094	0.0274
INC 0027	Adjusted	4° 12' 45.24624" N	9° 19' 57.86731" E	412.7074	0.0073	0.0139	0.0256
INC 0026	Adjusted	4° 08' 17.44504" N	9° 13' 58.29086" E	992.1090	0.0096	0.0127	0.0287
INC 0022	Adjusted	4° 09' 23.00013" N	9° 13' 53.99319" E	985.3087	0.0102	0.0129	0.0364
INC 0017	Adjusted	4° 01' 54.62370" N	9° 12' 02.38250" E	84.8511	0.0027	0.0032	0.0080
INC 0015	Adjusted	4° 24' 56.83076" N	9° 08' 34.28679" E	390.4973	0.0033	0.0042	0.0097
INC 0014	Adjusted	4° 16' 48.08392" N	9° 24' 17.15978" E	56.9368	0.0039	0.0049	0.0115
INC 0028	Adjusted	4° 04' 00.04220" N	9° 22' 18.98591" E	33.2454	0.0044	0.0061	0.0148
INC 0035	Adjusted	4° 02' 06.34930" N	9° 05' 41.22827" E	62.9439	0.0052	0.0059	0.0137
INC 0030	Adjusted	4° 06' 23.25575" N	9° 18' 49.37183" E	367.4097	0.0094	0.0126	0.0226
INC 0036	Adjusted	4° 04' 06.78745" N	9° 01' 41.39993" E	31.7996	0.0172	0.0210	0.0588
GPS 011	Adjusted	4° 07' 05.86015" N	9° 35' 13.31204" E	26.4419	0.0041	0.0049	0.0121

coordinates of the point of interest "SOMMET" were then determined, after adjustment. Table 2 shows the horizontal coordinates and heights computed as above, for the network adjustment. The ellipsoidal height

200 of GGM02C, best represents geoid undulations and gravity data in Cameroon. In the mount Cameroon area:

- New gravity data are available to fill gaps in the existing sparse gravity net.
- EGM2008 seems more representative of gravity data and geoid anomalies in the world (Kostakis, 2008).

In order to select the appropriate geoid model for the determination of the height of mount Cameroon, only the EGM2008 model was compared to the local geoid model of Cameroon CGM05-R recomputed after adding the new gravity data, and using the strategy indicated by Kamguia (2007). The digital terrain model SRTM (NASA, 2003) contributed for shortest wavelength components of CGM05-R. EGM-GGM supplies both the longer wavelength components of gravity data and the intermediate quasi-geoid. The long wavelength of gravity anomalies, and quasi-geoid undulations are computed using equations (5) and (6), respectively:

In the two equations, GM is the geocentric gravitational constant, r,λ,ϕ are the spherical coordinates of the computation point, γ is the normal gravity on the reference ellipsoid, a is the equatorial radius of the earth, P_{nm} (Sinϕ) is the fully normalised associated legendre functions for degree n and order m, ΔC_{nm} and ΔS_{nm} are the normalised spherical harmonic coefficients reduced for even zonal harmonic for the ellipsoid and complete to degree and order N_{max} of the model.

$$\Delta g_{reg} = \frac{GM}{r^2} \sum_{n=2}^{N_{\max}} \left(\frac{a}{r}\right)^n (n-1) \sum_{m=0}^{n} \left(\Delta\overline{C}_{nm} \cos m\lambda + \Delta\overline{S}_{nm} \sin m\lambda\right) \overline{P}_{nm}(\sin\varphi) \quad (5)$$

$$N = \frac{GM}{\gamma r} \sum_{n=2}^{N_{\max}} \left(\frac{a}{r}\right)^n \sum_{m=0}^{n} \left(\Delta\overline{C}_{nm} \cos m\lambda + \Delta\overline{S}_{nm} \sin m\lambda\right) \overline{P}_{nm}(\sin\varphi) \quad (6)$$

The first stage of the statistical comparison between EGM2008 and CGM05-R is made here. The standard deviation (STD) of their undulations is chosen as the quantity containing the information. Therefore, a geoid model is considered more representative of the data in the study area if the STD of the undulations obtained is the smaller.

Table 3 shows the results of comparisons of undulations from EGM2008 and CGM05-R in the area. From these results, it can be concluded that data obtained from EGM2008 were smoother than those from the recomputed geoid model of Cameroon. The STD from EGM2008 is 0.02 m smaller than that from CGM05-R.

The geometric geoid obtained from GPS/leveling is an independent data source to evaluate global and local geoid models. A set of GPS/leveling points, part of the national geodetic network of Cameroon (NGC), are used to compute a geometric geoid (using equation 1). This network consists of 57 stations, precisely levelled and with height above the reference ellipsoid, determined in the study area between latitudes and lon-

TABLE 3

Statistics of global and local geoid undulations in the target area (625 points), in meters

Models	*Max.*	*Min.*	*Mean*	*STD*
CGM05-R	23.29	16.62	20.02	1.44
EGM2008	22.38	15.54	19.35	1.42

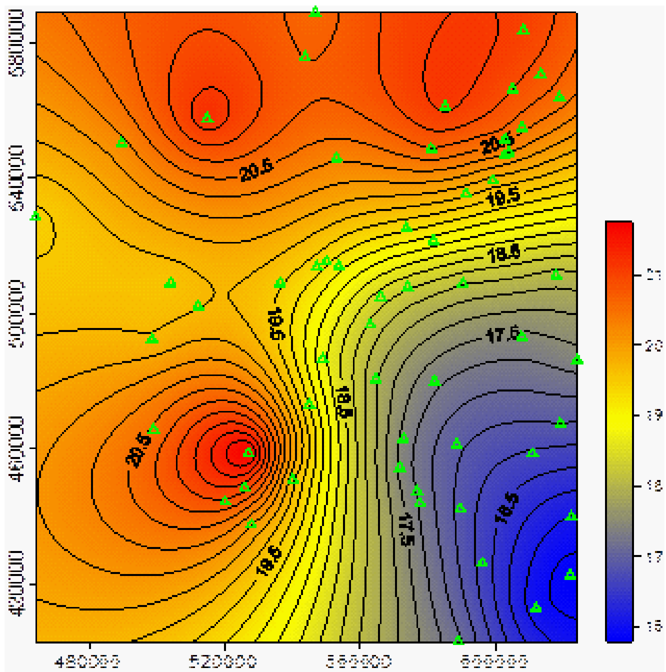

Fig. 6. GPS geometric geoid of the mount Cameroon area (contour interval : 0.2 ; unit = metre ; Δ = GPS/leveling points)

TABLE 4

Values of undulation of the geometric geoid (GPS/Leveling) and EGM2008 in the mount Cameroon area (unit: meter)

Geoid model	*Number of stations*	*Max.*	*Min.*	*Mean*	*STD*
Geometric geoid (GPS/ leveling)	57	21.81	15.79	19.04	1.60
EGM2008	57	21.02	15.73	19.23	1.74

TABLE 5

Statistical difference between the geometric geoid, EGM2008 and CGM05-R (unit: meter)

Differences in undulations	*Number of points*	*Max.*	*Min.*	*Mean*	*STD*
$N_{GPS/lev} - N_{CGM05-R}$	57	0.98	0.07	0.23	0.21
$N_{GPS/lev} - N_{EGM08}$	57	0.79	0.06	0.19	0.26

gitudes (Fig. 6). The statistics of the geometric geoid are indicated in Table 4. Geoid undulations computed at these 57 levelled points, using EGM2008 harmonic coefficients, were also indicated for statistical analysis.

The geoid obtained from GPS/ leveling points seems accurate as its undulations fit data from EGM2008 in the mount Cameroon area. The statistic analysis of the differences between these undulations is presented in Table 5. From the table, CGM05-R probably represents more precisely the data (geoid undulations) in the mount Cameroon area. The smallest STD of the difference of undulations (0.21 m) was obtained for the recomputed local geoid model. For this reason and the other previous analyses, CGM05-R is chosen to produce the geoid undulation *N* of the summit of mount Cameroon, that will be introduced in equation (1) in order to calculate its orthometric height.

Result

Computation of the height of mount Cameroon

The height of mount Cameroon was computed using equation (1), where h is determined from GPS measurements, and N from the geoid model. CGM05-R is shown to best represent geoid data in the area. It was chosen to produce the geoid undulation N of the summit of the volcano that will be introduced in equation (1) in order to compute the height.

From computations, the geoid undulation of the summit of mount Cameroon (geodetic coordinates φ = 4º 13` 04.7553`` and λ = 9º 10` 24.3349``) is N = 22.862``. This value was interpolated in the 5` × 5` grid of CGM05-R using the bilinear method (Deruelle *et al*., 2007; Madjahed & Zeggai, 2012). The absolute accuracy to be applied to the computed value of N is the difference obtained between undulations from CGM05-R and the geometric geoid from GPS/leveling, that is ΔN = 0.21m. Therefore, the mount Cameroon geoid undulation is N_{summit} = 22.8 ± 0.2 m.

The geometric height h above the reference ellipsoid to be introduced in equation (1) is indicated in Table 2, obtained after GNSS computations. This height h = 4059.9718 m. Its absolute accuracy also obtained from the GNSS computations is Δh = 0.03 m . Therefore, the ellipsoidal height of mount Cameroon is 4059.97 ± 0.03 m.

The height above the geoid of the summit of mount Cameroon obtained from equation (1) is, therefore, H = 4037.17 m. For the absolute accuracy computed from both the accuracies of h and N: one has

$$\Delta H = \sqrt{(\Delta h)^2 + (\Delta N)^2} \quad (7)$$

From equation (7), $\Delta H = 0.2\ m$. Therefore, the mount Cameroon orthometric height was $H = 4037.2 \pm 0.2\ m$.

Discussion and conclusion

The precise value of the mount Cameroon has been determined from spatial data received from GNSS satellites, ground gravity data and data from global geopotential models. Mount Cameroon culminates at a height of 4037.2 ± 0.2 m. The value can still be refined. To achieve this, the gravity data of the area should be more densified. Other stations should be added on the side where the study was unable to access. This is possible only by air borne gravity measurements, since no access is possible by foot. New global geopotential models are still being computed and released. These new models should also be tested along with EGM2008, to decide the best model, and thereby access a more accurate height of the mountain.

Two error sources affected the computed ellipsoidal height of the summit; the weather conditions as stated earlier and the quality of the reference point GPS 011. Since this point is not part of the geodetic network of Cameroon, one needs to brave the difficult conditions of climbing the volcano to repeat the GNSS observations and tying the summit directly to the national geodetic network installed around the mountain.

The height obtained was less than that computed from barometric method in 1900. The difference of nearly 60 m is enough to interest scientific, strategic, navigation, military, political and environmental actors in Cameroon. This gap can be attributed either to the poor accuracy of the barometric method or the dynamic activity of the mountain. Mount Cameroon is in a geodynamic environment, and it is possible that due to crustal and upper mantle movements such as subsidence, lateral movement, rotation and distortion that can affect elevation and horizontal position, there was compaction of materials below the summit. One needs to understand clearly the origin of the Cameroon volcanic line, and the mount Cameroon's, in order to decide the meaning of this height difference. This origin is still unknown, as many theories coexist, each of them proposing a model of the formation/evolution of the line (Moreau *et al*., 1987) and the mount Cameroon.

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