Evaluation of the Earth Gravity Model EGM2008 in Algeria

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Abstract

The present work focuses on the comparison between the (EGM2008) that was recently released by the NGA (*National Geospatial-Intelligence Agency*, *U.S*)/EGM-development team and supplied to a new Joint Working Group established between IGFS and the IAG commission 2 for validation, with land gravity anomalies supplied by the B.G.I. and a pre-processed 5'x 5' grid of the free air anomalies covering the area bounded by the limits $16° \leq \varphi \leq 40°$ and $-10° \leq \lambda \leq 14°$ provided us by GETECH, some of the precise GPS data collected from the international TYRGEONET (*TYRhenian GEOdynamical NETwork*), ALGEONET (*ALGerian GEOdynamical NETwork*) projects with baseline length ranging from about 1 to 1000 km and Algerian gravimeric geoid model based on OSU91A geopotential model in order to assess its quality in Algeria region. Additional comparisons of the terrestrial point data (such as the gravity data and the GPS-based geoid heights used in this study) with the corresponding values obtained from other geopotential models were made. Six global geopotential models were used in this comparison: The new GRACE satellite-only and combined models EIGEN-GRACE02S and GGM02C, the combined CHAMP and GRACE model EIGEN-CG01C, combined CHAMP and LAGEOS model EIGEN-GL04C, OSU91A and EGM96. The comparisons were made at all gravity and GPS levelled data by computation of the residual data (i. e. observed data minus model). The geopotential model that provides the closest statistical fit to these data can be assumed to be the most suitable model to adopt for the determination of the new Algerian gravimetric geoid.

The study shows that all tested models are an improvement over OSU91A geopotential model used in all previous Algerian geoid computations and that new released combined model (EGM2008) is relatively superior to other models in the Algerian region. According to our numerical results, the EGM2008 model fits best the observed values used in this investigation. Its standard deviation fit with GPS/levelling data is 21.2cm and 19.6cm before and after the bias and tilts fitting using four parametric transformation model.

Key words: Geopotential model, TYRGEONET and ALGEONET projects, GPS/Levelling.

1. Introduction

The choice of the best geopotential model to reduce geodetic data is one of the critical steps in computing the geoid. Several studies have shown that the geopotential models tailored to regional or local gravity data are best suited for many applications in solid Earth sciences, as e.g. to study the structure of the Earth, to compute the orbit of a satellite, and for high precision geoid computations.

Over the last 40 years, continuous improvements and refinements to the basic theory have been paralleled by the availability of more accurate and complete data and by improvements in the computational resources available for numerical modelling studies. These advances have led to the development of a sequence of global geopotential models of increasing spherical harmonic degree and order, and hence resolution. The most recent models are released from satellite gravity missions CHAMP and GRACE and will be mapping the Earth's gravity field with significantly increasing accuracy and spatial resolution. The data obtained from these missions are being and will be used to develop a series of new static satellite-only gravity models down to 150 – 200 km wavelength, as well as combined Earth Gravity Models (EGM's) down to about 20 km wavelength. In 2008, the official Earth Gravitational Model EGM2008 has been publicly released by the U.S. National Geospatial-Intelligence Agency (NGA) EGM Development Team. This model is complete to degree and order 2159, and contains additional spherical harmonic coefficients (SHCs) extending to degree 2190 and order 2159. It represents a spatial resolution of 5 minutes of arc (about 9 km).The purpose of this work is to give a brief summary of the evaluation results for the Earth gravity model (EGM2008) in Algeria region. In addition, the Geopotential Models (GGMs) derived from the new satellite missions LAGEOS, CHAMP and GRACE (EIGEN-GRACE02S, GGM02C EIGEN-CG01C and EIGEN-GL04C), OSU91A and the most accurate high degree geopotential model EGM96 are also compared with land gravity anomalies and GPS/Levelling geoid heights in Algeria in order to find the GGM that best fits the local gravity field feautures over this region. The first one (EIGEN-GRACE02S) is developed to degree and order 150 while the GGM02C solution was created to degree and order 200. All remaining geopotential models are completed to degree and order 360. These comparisons are performed with and without filtering. Several techniques are possible to do that filtering. A sample for the filtering using a very simple approach is shown in the next paragraph. This is done in order to tune the validation data within the same spectral bandwidth provided by the EGM.

In the next sections the data used for the comparison will be described and the results of the comparison will be shown. The statistical parameters considered in this work are the mean and the standard deviation of the differences between the geopotential models and tested data. The most informative of these statistics is the standard deviation because the mean of the differences is distorted by the exclusion of the zero-order term. Therefore, the best fitting GGM will have the lowest standard deviation between itself and the tested gravity.

2. Data used

2.1. Gravity data

Two data sets of free gravity anomalies were used for the comparison as control data:

- A set of 12472 terrestrial gravity anomalies covering the territory of Algeria, was supplied by the B.G.I. No information concerning the accuracy of the data is available. The data set is referred to the IGSN71 gravity datum and processed using the GRS80 gravity formula. All data have been checked and duplicate points removed in a consistent manner. Figure 1 shows the geographical distribution of the BGI gravity data.

- A pre-processed 5'x 5' grid of the free air anomalies covering the area and bounded by the limits $16° \leq \varphi \leq 40°$ and $-10° \leq \lambda \leq 14°$. This grid containing 289 x 289 points has been provided us by GETECH through the agreement between the National Centre of Space Techniques/Geodetic Laboratory and University of Leeds/GETECH without any information on the accuracy of the different values. Figure 2 gives a graphical representation of the gravity data coverage in the computation area. From this figure, it becomes clear that the coverage with gravity observations is not sufficient for some land areas particularly in the south of the Algeria and new measurements are needed to accomplish a homogeneous coverage.

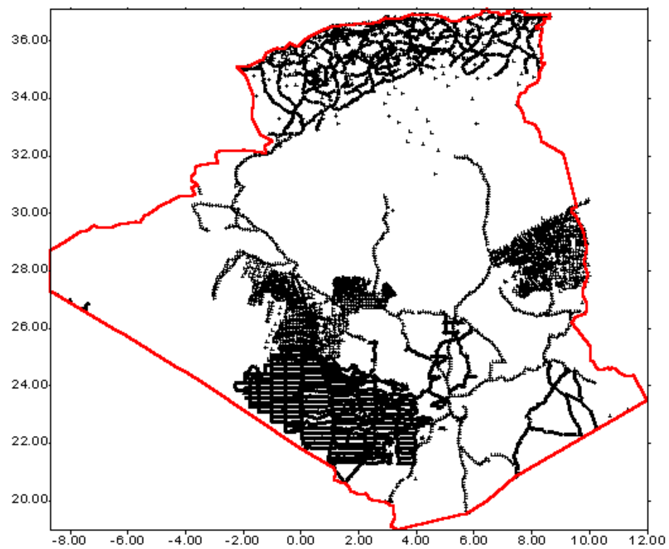

Figure 1. Geographical distribution of BGI gravity measurements

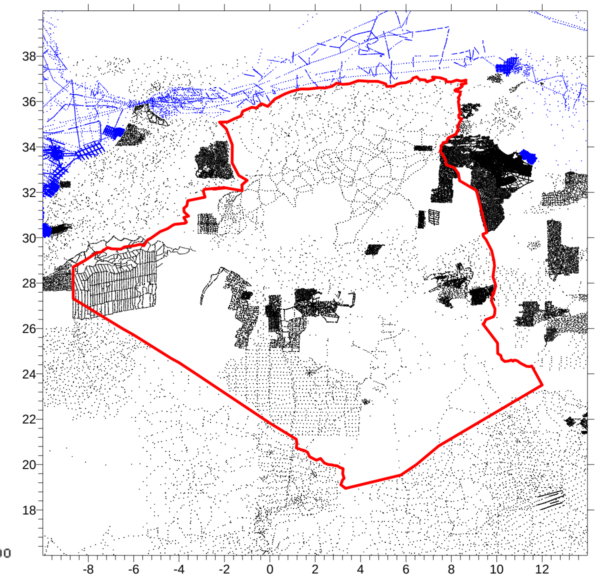

Figure 2. Geographical distribution of GETECH gravity data

2.2. GPS/Levelling data

There are several GPS/levelling points distributed over some regions of Algeria, principally in the northern part of the country. The distribution is fairly good but the total number of the GPS stations is too small in relation to the area of the northern part of Algeria. For this investigation, 71 precise GPS levelled points have been used for the evaluation and validation of the new gravimetric geoid of which 45 are benchmarks of the first order levelling network, and the others belong to the second order levelling network. All of these points are located in the north of Algerian territory between the limits $31° \leq \varphi \leq 37°$ and $-2° \leq \lambda \leq 9°$. The geographical distribution of the available GPS/levelling data is shown in Figure 3. The GPS observations were performed using ASHTECH Z-12 dual frequency receivers with an observation period between 3 and 12 hours and were processed with the Bernese GPS software version 4.2 developed at the Astronomical Institute of the University of Bern (Beutler et al., 2001) using the precise ephemerides supplied by IGS. The computed ellipsoidal heights were referred to WGS84 system and their standard deviations do not exceed 3 cm. All GPS stations have been connected by traditional levelling to the national levelling network, which gives orthometric heights. The accuracy of the levelling heights may be estimated at about 6 cm depending on the type of connection measurements because some GPS points used in this work as benchmarks are located in mountainous regions in which the spirit levelling would be impractical. Unfortunately, the non-availability of GPS levelling data in the whole of the country with a homogeneous distribution and sufficient density does not allow a more reliable assessment, at the national scale, of the quality of the global geopotential model EGM2008.

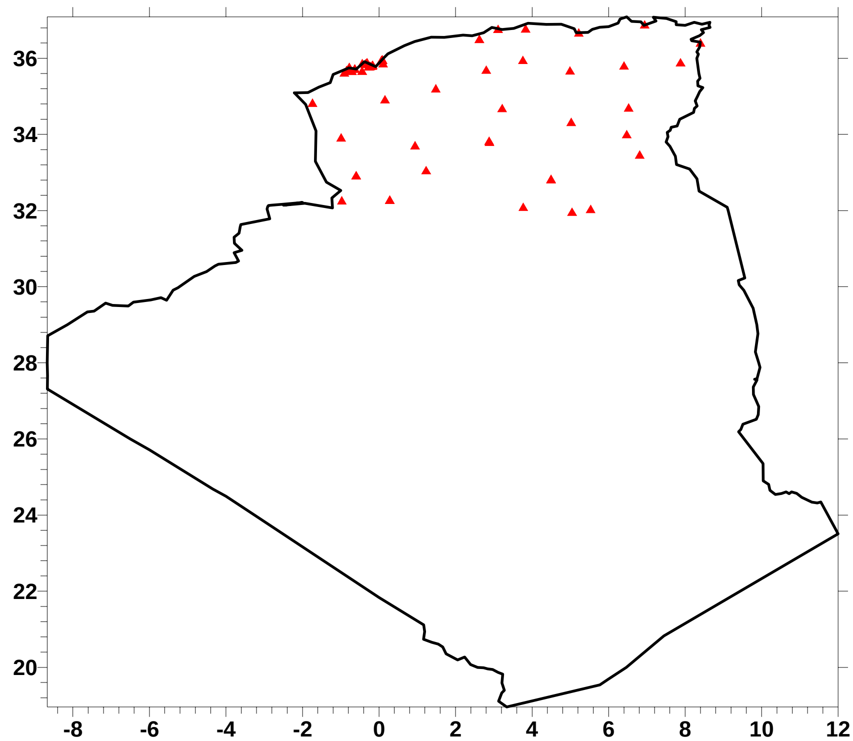

Figure 3. Geographical distribution of GPS/Levelling stations in the northern of Algeria

2.3. Algerian gravimetric geoid model

In view of the use of the GPS for the orthometric height computation, the National Centre of Space Techniques through the national projects of research, has recently focused a part of the current research on the precise geoid determination using different methods. The most recent solution of a preliminary geoid over the Algerian territory was done in 2002 using the spectral combination technique in connection with the remove-restore procedure (Forsberg and Sideris, 1993). For this computation, the pre-processed 5'x 5' grid of the free air anomalies covering the area bounded by the limits $16° \leq \varphi \leq 40°$ and $-10° \leq \lambda \leq 14°$, derived by merging terrestrial gravity data and satellite altimetry data, have been used. This grid contains 289 x 289 points and has been provided us by GETECH. The computation of the effects of the topography according to the RTM reduction modelling method (Forsberg, 1985) is based on the global topographic model GLOBE of 30" x 30". However, for the long wavelength gravity field information the spherical harmonic model OSU91A completed to degree and order 360 (Rapp et al., 1991) was employed. The final quasi-geoid was obtained by adding the geopotential model contribution and the residual terrain effect on the 5' x 5' residual quasi-geoid grid. The major contributions to the final quasi-geoid are coming from the OSU91A geopotential model. The standard deviations of the contributions from gravity data and DEM are ± 1.4 m and ± 0.007 m respectively. So, we will note that in the Algerian territory, the indirect quasi-geoid effect is significant only in mountainous areas where it reaches values from one to a few decimeters. On the remaining territory it is on the level of a few millimeters. However, the Algerian height system is based on orthometric heights, so the gravimetrically determined quasi-geoid has been transformed to a geoid model and then compared to geoid undulations provided by GPS and levelling (Benahmed Daho and Fairhead, 2004).

3. Evaluation results

3.1. Comparison with free gravity anomalies

The free air gravity anomalies from BGI and GETECH are compared with corresponding values computed from the tested geopotential models, and the smallest residuals imply the best Earth Geopotential Model. These comparisons are performed in both cases with and without filtering. In first case (with filtering), before comparing them and in order to make a fair comparison and taking into account the EGM's omission error, all tested geopotential models were truncated to degree and order 150 that represents the current limit for the new GRACE satellite-only EIGEN-GRACE02S. BGI and GETECH free air gravity anomalies are low-pass filtered using the high degree geopotential model EGM2008 from degree 151 to degree 2190, i.e. free air gravity information in this spectral range is subtracted from the BGI and GETECH free-gravity anomalies data sets before they are compared to the corresponding quantities obtained from the tested EGM (Gruber, 2004). The results for these comparisons in both cases are summarised for BGI free air gravity anomalies in Table 3, and for GETECH gravity data in Table 4 (the statistics given in bold within the parentheses refer to the values obtained with filtering). All the original data are referred to GRS80. The computations were carried out using the FORTRAN program harmonic_synth_v02 developed by NGA and supplied to a new Joint Working Group established between IGFS and the IAG Commission 2 for validation and quality assessment of GRACE, CHAMP and GOCE-based satellite-only and combined solutions for the Earth's static gravity field. Figure 4 shows the histograms of the differences between BGI free air anomalies and those obtained from all tested geopotential models without filtering.

Geopotential models	Minimum	Maximum	Mean	σ
OSU91A	-97.035 **(-106.680)**	125.561 **(68.215)**	0.300 **(1.308)**	13.164 **(6.534)**
EGM96	-100.959 **(-101.977)**	112.026 **(56.941)**	-2.170 **(-0.942)**	13.542 **(6.683)**
EIGEN-CG01C	-98.959 **(-103.739)**	110.187 **(58.515)**	-2.103 **(-0.704)**	14.056 **(6.649)**
EIGEN-GL04C	-99.362 **(-104.522)**	112.031 **(58.750)**	-1.924 **(-0.531)**	14.029 **(6.659)**
GGM02C	-93.885 **(-104.938)**	123.040 **(57.294)**	-1.123 **(-0.566)**	14.910 **(6.345)**
EIGEN-GRACE02S	-90.684 **(-106.680)**	144.810 **(68.215)**	-1.136 **(1.308)**	17.196 **(8.413)**
EGM2008	-104.094 **(-104.094)**	55.925 **(55.925)**	-0.610 **(-0.610)**	6.119 **(6.119)**

Table 3. Statistics of the reduced data between the BGI gravity data and the geopotential models (mgal).

From the Table 3 and in both cases (with and without filtering), we can see that the free air gravity anomalies computed from EGM2008 model have been significantly improved as compared to other tested geopotential models.

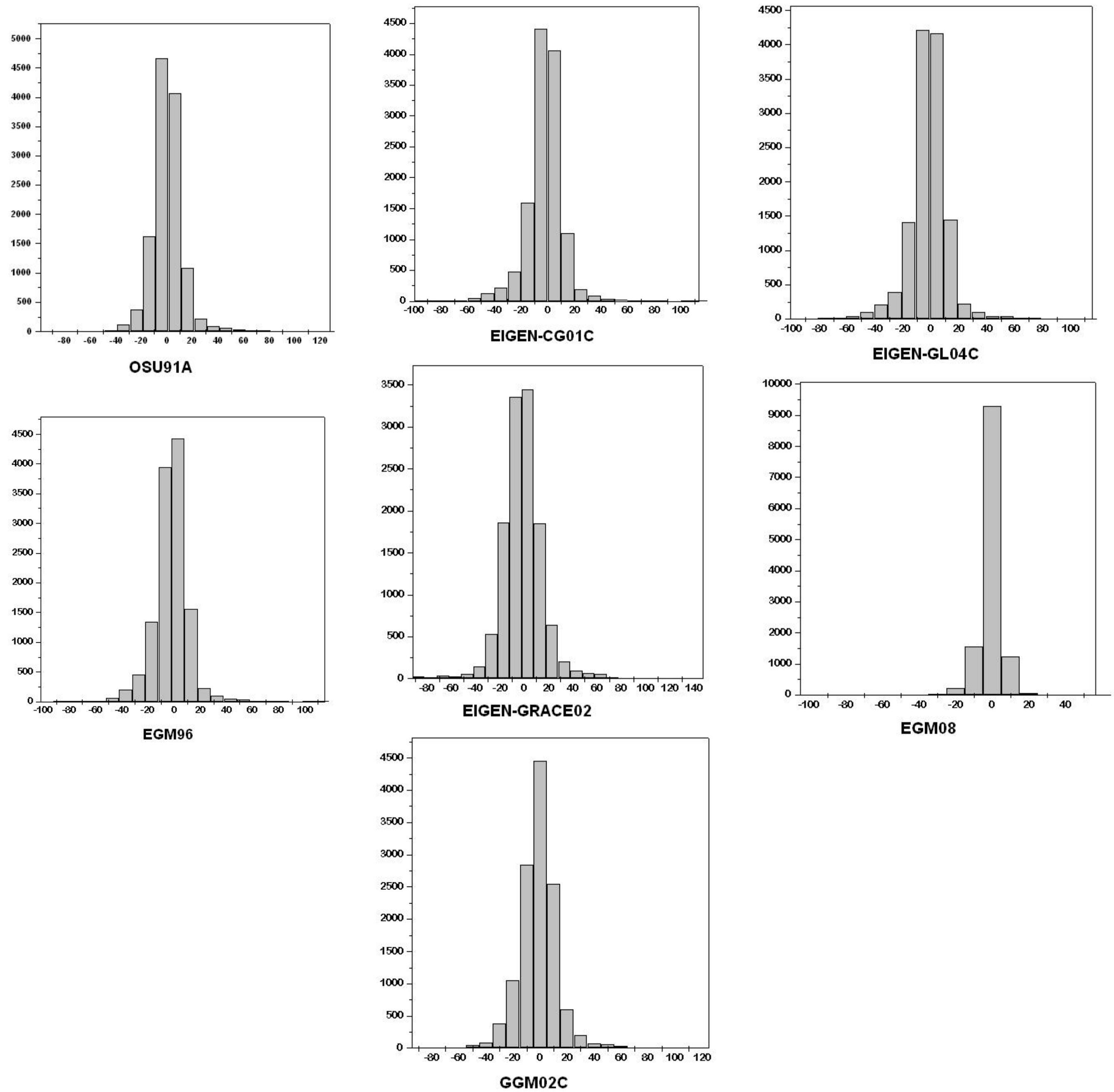

Figure 4. Histograms of difference between BGI free air anomalies and those computed from tested geopotential models. The full spectral range for all tested geopotential models has been used.

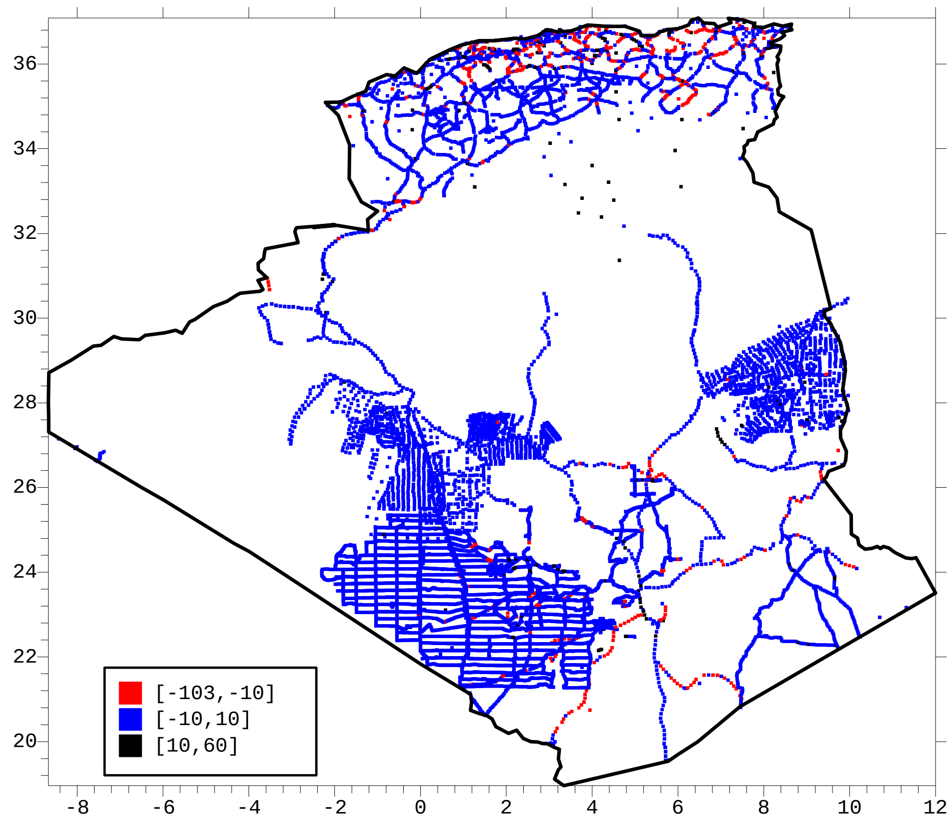

Figure 5. Free air gravity anomalies differences between the BGI gravity data and EGM2008 model (mgal).

The figure 5 represents the classed post map of the differences between the BGI free air anomalies and corresponding ones from EGM2008 model. According to the used BGI land gravity data, the EGM2008 geopotential model is able to recover gravity anomalies over 92.4% of the Algerian territory to within 10 mgal (see figure 5). The majority of the free-air gravity anomalies computed from EGM2008 over land show a good correspondence with the land free-air gravity anomalies, even in areas where there are large gravity anomaly gradients such as central Algeria (see figure 5). The largest differences are in the mountainous regions and along Algerian coastline.

Geopotential models	Minimum	Maximum	Mean	σ
OSU91A	-122.11 **(-261.27)**	190.57 **(108.86)**	-2.25 **(-2.24)**	14.82 **(15.27)**
EGM96	-143.06 **(-269.45)**	167.09 **(113.80)**	-2.57 **(-2.56)**	15.51 **(15.50)**
EIGEN-CG01C	-133.90 **(-270.82)**	170.06 **(111.68)**	-2.62 **(-2.60)**	15.66 **(15.50)**
EIGEN-GL04C	-133.85 **(-269.63)**	170.78 **(114.37)**	-2.60 **(-2.58)**	15.66 **(15.50)**
GGM02C	-139.58 **(-271.64)**	183.38 **(113.27)**	-2.57 **(-2.58)**	17.65 **(15.42)**
EIGEN-GRACE02S	-142.36 **(-283.99)**	215.04 **(121.03)**	-2.60 **(-2.62)**	19.69 **(16.75)**
EGM2008	-271.94 **(-271.94)**	110.91 **(110.91)**	-2.60 **(-2.58)**	15.35 **(15.35)**

Table 4. Statistical comparisons between geopotential models and GETECH free-air gravity anomalies (mgal).

From the statistics of Table 4, it is unclear which model consistently gives the best agreement with GETECH free-air anomalies. We can see that all geopotential models excepting GRACE satellite-only gravity model give almost the same results in terms of the standard deviation. This is because no new gravity data have been used in this region for the determination of the tested GGM models compared to OSU91A model.

4.2. Comparison with GPS/Levelling data

The global geopotential models discussed above were also compared with a number of GPS/Levelling data set available only in the northern of Algeria. The comparisons were performed with and without filtering using the same procedure described above. At these 71 points, both h (ellipsoidal height) and H (orthometric height) are known. The GPS/levelling height N^{GPS} is the result of the difference between the ellipsoidal height obtained by GPS and the orthometric one obtained by spirit levelling and gravity information. However, the geoid undulation derived from GPS/Levelling refers to the GRS80 ellipsoid and their corresponding values computed from GGM refer to a mean Earth ellipsoid that does not have the same dimensions as the WGS84 ellipsoid and hereby, it is necessary to take into account the effect of the different equatorial radius in the computation of the geoid undulation using the spherical harmonic expansion for each model. The statistics of the differences in benchmarks before and after fitting the systematic biases and tilts using a four-parameter model for both cases (without and with filtering) are summarised in Table 5 and Table 6 respectively. In all cases, the statistics shown refer to the values without fitting, whereas the statistics given within the parentheses refer to the values of the residuals obtained after the fitting of the following four-parameter transformation model (Heiskanen and Moritz , 1967):

$$\mathbf{N_i^{EGM} - N_i^{GPS} = \cos\Phi_i \cos\lambda_i . x_1 + \cos\Phi_i \sin\lambda_i . x_2 + \sin\Phi_i . x_3 + x_4 + v_i} \quad \textbf{(1)}$$

where ($\mathbf{N^{EGM}}$) is interpolated geoid undulation at a network of GPS benchmarks from geopotential models, ($\mathbf{N^{GPS}}$) is the corresponding GPS/levelling-derived geoid height, $\mathbf{x_4}$ is the shift parameter between the vertical datum implied by the GPS/levelling data and the gravimetric datum, $\mathbf{x_1}$, $\mathbf{x_2}$ and $\mathbf{x_3}$ are the shift parameters between two 'parallel' datums and v_i denotes a residual random noise term. The vector of unknown parameters is solved by minimizing the quantity $\mathbf{v^T v}$. The adjusted values for the residuals $\mathbf{v_i}$ give a realistic picture of the level of absolute agreement between the tested geopotential models based geoid and the GPS/levelling data.

Geopotential models	Minimum	Maximum	Mean	σ
OSU91A	-3.006	1.747	0.202	1.194
	(-1.500)	**(1.400)**	**(0.000)**	**(0.491)**
EGM96	-0.896	0.779	-0.028	0.340
	(-0.750)	**(0.520)**	**(0.000)**	**(0.294)**
EIGEN-CG01C	-0.740	0.681	-0.009	0.357
	(-0.687)	**(0.532)**	**(0.000)**	**(0.302)**
EIGEN-GL04C	-0.633	0.637	-0.016	0.333
	(-0.530)	**(0.676)**	**(0.000)**	**(0.295)**
GGM02C	-0.987	0.924	0.258	0.480
	(-1.195)	**(0.805)**	**(0.000)**	**(0.381)**
EIGEN-GRACE02S	-1.817	1.437	0.468	0.834
	(-1.908)	**(1.140)**	**(0.000)**	**(0.582)**
EGM2008	-0.666	0.610	-0.077	0.212
	(-0.558)	**(0.517)**	**(0.000)**	**(0.196)**

Table 5. Comparison of all geoid undulations from geopotential models with GPS/Levelling heights before and after the bias and tilt fitting (m). The full spectral range for all tested geopotential models has been used.

When filtering was not applied (see Table 5), we can see that the Earth Gravity Model EGM2008 fits better than the other models the GPS/Levelling heights. The geoid undulations computed from this model have been significantly improved as compared to other tested models.

Geopotential models	Minimum	Maximum	Mean	σ
OSU91A	-2.804 **(-1.271)**	1.635 **(1.293)**	-0.152 **(0.000)**	0.997 **(0.565)**
EGM96	-1.008 **(-0.566)**	0.693 **(0.377)**	-0.252 **(0.000)**	0.317 **(0.191)**
EIGEN-CG01C	-0.787 **(-0.574)**	0.529 **(0.543)**	-0.207 **(0.000)**	0.222 **(0.214)**
EIGEN-GL04C	-0.777 **(-0.516)**	0.301 **(0.469)**	-0.220 **(0.000)**	0.207 **(0.197)**
GGM02C	-0.679 **(-0.571)**	0.527 **(0.495)**	-0.071 **(0.000)**	0.212 **(0.199)**
EIGEN-GRACE02S	-0.990 **(-1.213)**	1.725 **(0.600)**	-0.078 **(0.000)**	0.447 **(0.396)**
EGM2008	-0.666 **(-0.558)**	0.610 **(0.517)**	-0.077 **(0.000)**	0.212 **(0.196)**

Table 6. Comparison of all geoid undulations from geopotential models with GPS/Levelling heights before and after the bias and tilt fitting (m). The filtering has been applied to the GPS based geoid heights.

From the statistics of Table 6 (with filtering), the standard deviations values of the differences show significant improvements with respect to OSU91A. All other models excepting GRACE satellite-only gravity model present very similar results. The best agreement (EIGEN-GL04C) is at the ± 20.7cm level in terms of the standard deviation of the differences, before the bias and tilt fit. For the OSU91A, EGM96, EIGEN-CG01C, GGM02C, EIGEN-GRACE02S and EGM2008 models, it is at the ± 99.7cm, ± 31.7cm, ± 22.2cm, ± 21.2cm, ± 44.7cm and ± 21.2cm respectively. After the bias and tilt fit, the improvement is almost at the 43.2cm level for OSU91A, the 12.6cm for EGM96, and the 8mm for EIGEN-CG01C, the 1cm for EIGEN-GL04C, the 1.3cm for GGM02C model, the 5.1cm for GRACE02S model, and 1.6cm for the new released model EGM2008. In addition, we can see that the results from EGM96 after fitting remain very close to those given by the EGM2008 model in terms of the standard deviation. The two curves present the same behaviour (see Figure 6). No significant differences between these curves are shown. Based on the data sets used in the present work, the new released Earth Gravity Model EGM2008 is consistently superior to other tested geopotential models.

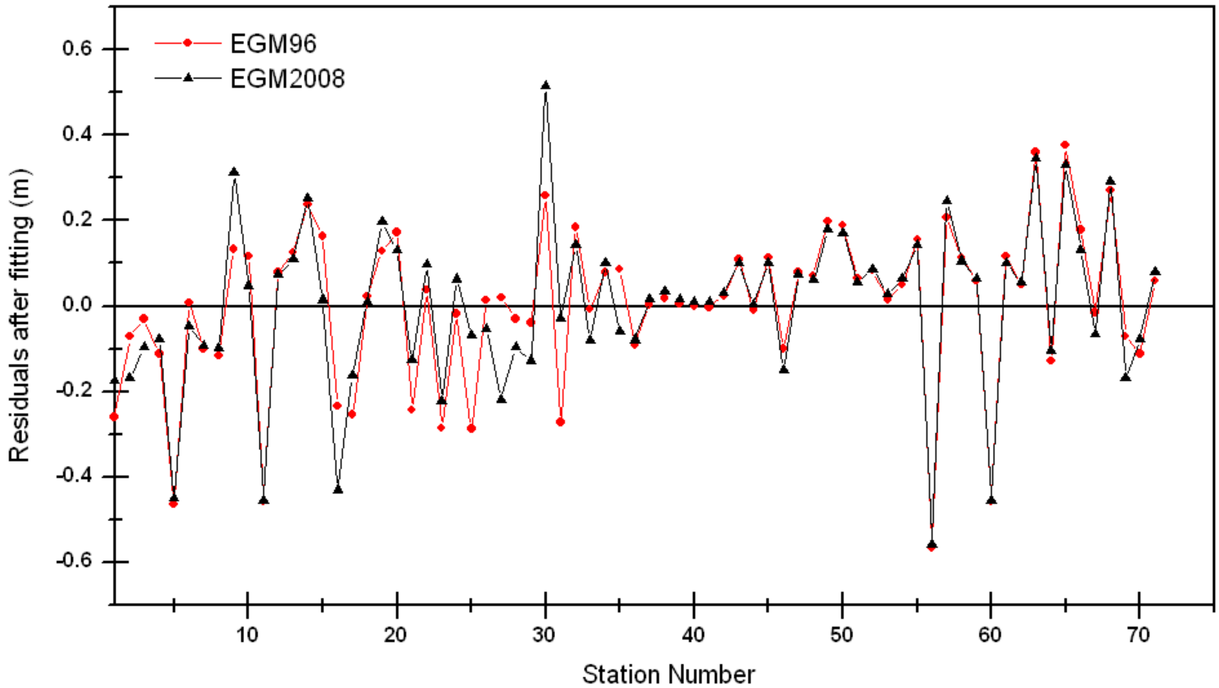

Figure 6. Residuals in benchmarks, after fitting and with filtering, from EGM96 and their corresponding from EGM2008 (m).

3.3. Comparison of the EGM2008 with gravimetric geoid model

The difference between gravimetric geoid model for Algeria and geoid undulations computed using EGM2008 model complete to degree and order 2190 range between -6.63m and 6.11m with an average of 0.54m and a standard deviation of about ±1.29m. The large discrepancies in Algeria, with the maximum (+6m) occurring in the South and South-Western regions. No terrestrial data were available for these areas. The maximum negative difference occurs in Mediterranean Sea, outside the area of interest (see figure 7). These large discrepancies are attributed, principally, to GETECH gridded gravity data quality used in the computation of the gravimetric geoid solution for Algeria (Benahmed Daho and Fairhead, 2004).

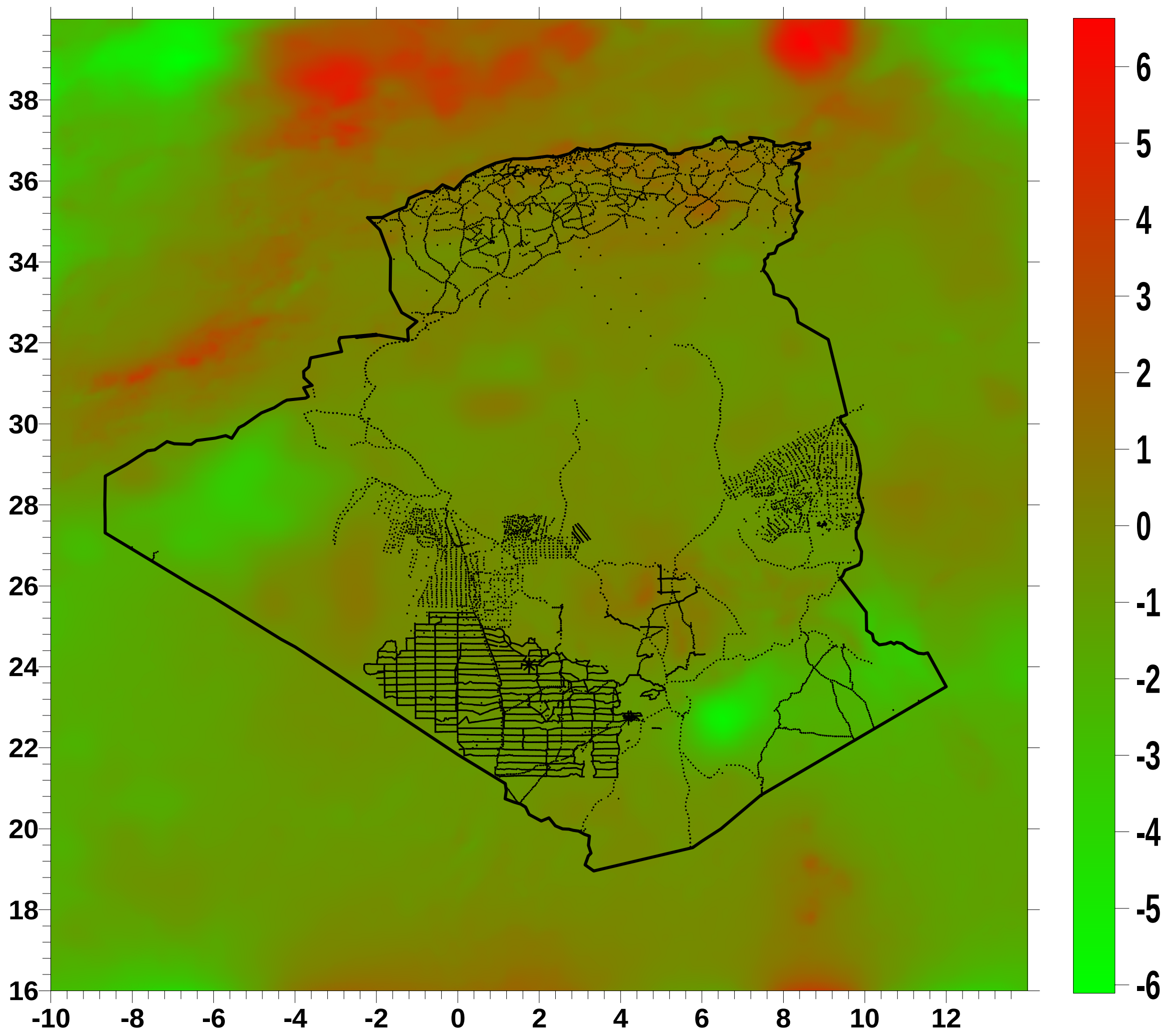

Figure 7. Map of differences between gravimetric geoid model for Algeria and geoid undulations computed by using EGM2008 model complete to degree and order 2190 (mgal).

4. Conclusion

This paper has described the comparisons of the GPS/Levelling geoid undulations and gravity anomalies in Algeria with those computed from the new released Earth global model EGM2008. Additional comparisons of the terrestrial point data with the corresponding values obtained from the geopotential models OSU91A, EGM96, the new Global Gravity Models from the recent satellite gravimetric missions CHAMP and GRACE were made. Based on the data sets used in the present work to evaluate the performances the new realised geopotential model EGM2008 within Algeria one has to note that in general the new model is an improvement over OSU91A geopotential model used in all previous Algerian geoid computations. According to our numerical results, the EGM2008 model fits better the observed values. The geoid undulations computed from this model have been significantly improved as compared to other tested models. The overall best agreement (±21.2cm) in the experimental area before fitting is achieved when the global geopotential model EGM2008 was used.

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