Fetching the Most Appropriate Global Geopotential Model for Egypt

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ملخص البحث

يوجد الان مجموعه كبيره من النماذج التوافقيه العالمية الحديثة لمجال الجاذبيه الارضيه, تعتمد هذه النماذج اساسا علي البيانات المنتجه من الاقمار الاصطناعيه الجديده الخاصه بالجاذبيه (CHAMP, GREACE, GOCE), و من المهم تقييم اداء هذه النماذج محليا لتحديد انسب نموذج في اداءه بالنسبه لمصر. فى هذا البحث تم تقييم اداء بعض تلك النماذج المنتجة في الفتره ما بين 1996 حتي الان محليا, عن طريق حساب قيم الشواذ التثاقليه لكل منهم عند شبكة من النقاط موزعة كل [1'x1'] تغطى مجمل مساحة مصر, ثم مقارنة قيم الشواذ المحسوبة من كل نموذج بالقيم الحقيقيه المرصودة لتلك الشواذ عند بعض النقاط الموزعه عشوائيا علي مجمل المساحه لاستبيان ايهم اكثر تمثيلا لمجال الجاذبيه الارضيه في مصر.وقد اظهرت النتائج ان النموذج التوافقى EGM2008 يعد افضلهم علي الاطلاق فقد تفوق في اداءه علي النموذجين EGM96 و EIGEN-6C 2011 بمقدار 1.23 و 2.54 مره علي التوالي بدلالة قيم الخطأ التربيعى المتوسط المحسوبة لكل منهم. مما سبق وبناءعلي النتائج التي تحصلنا عليها ينصح باستخدام نموذج EGM2008 في حسابات الجيود في مصر.

ABSTRACT

New additional Global Geopotential Models [GGMs] have now been released into the public domain, those including data from the CHAMP, GREACE and GOCE dedicated satellite gravimetric mission. Those satellite tracking data have resolved the long wave length component of the global gravity field with rather very high accuracy **[10]**.

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Therefore, it is important to evaluate those new models over Egypt to determine which; of them is the most appropriate GGM there. In this study a comparison of the performance of three of the GGMs released between 1996 tell now (EGM96, EGM2008 and EIGEN-6C 2011) over Egypt is made. The gravity anomalies computed from the models are compared with point free air gravity anomalies on land. The results have indicated the outstanding performance of EGM2008 to the other examined GGMs undoubtedly. EGM2008 has1.23 times better statistics than the EGM96 and 2.54 times than EIGEN-6C 2011, in terms of root mean square error [r.m.s.e].

1. Introduction

Any element of the gravity field in local or regional areas are usually determined by combining the spherical expansion of the earth's potential [geopotential model] and a set of observed points or mean anomalies. The computation can be performed using e.g. Least squares collocation procedures, FFT, Stock's integral function …etc.

The determination of any element of gravity field is a repetitive task which, should be updated with time, as far as new gravity field data are collected and/or refined computational approaches are applied or new GGMs are released into the public domain **[3] and [4].**

The higher accuracy of geoid computation required nowadays necessitates the need for an accurate GGM, which in turn necessitates the need for examining the performance of such newly released models in any local area to choose the best of them. Many of such studies have been done before in Egypt such as; **[1], [2], [5], [6], [7], [8] , [9], [11], [13], [14]**.This study aims also to evaluate the behavior of those new models over Egypt to determine which; of them is the most appropriate GGM there.

This thesis includes six sections arranged as follows:

The first one includes an introduction, to demonestrate the need for the evaluation process of the different GGMs over any local area.

Section two includes the basic relations that conect some of the gravity field elements with the harmonic coeffients of any GGM.

The thrid section gives some details about three of the released GGMs. Since the previous studies on the GGMs and their behavior over Egypt during the last two decades had proven that EGM96 was the best model which fits that territory, this model thus is used in the comparison with other two of the newly released models, which are EGM2008 and EIGEN-6C 2011.

Section four includes the available data, its validation and distribution over Egypt.

In section five the used methodology and software are presented.

In section six, analysis of the results of the comparison of free air gravity anomalies at discrete points, give an indication of GGMs accuracy and pointed out the one of best behavior in the Egyptian region.

In section seven the final conclusion and recommendations are drawn.

2.Elements of the Earth's Gravity Field, Background and Relations

The spherical harmonic representation of the Earth’s gravitational potential, could be

$$V(r,\theta,\lambda)=\frac{GM}{r}\left[1+\sum_{n=2}^{\infty}\left[\frac{a}{r}\right]^{n}\sum_{m=-n}^{n}\overline{C}_{nm}^{s}\overline{Y}_{nm}(\theta,\lambda)\right] \quad [1]$$

Where

r is the geocentric distance;

θ is the geocentric co-latitude; and

λ is the longitude;

GM is the geocentric gravitational constant and "a" usually the equatorial radius of adopted mean earth ellipsoid is scaling factor associated with the fully normalized spherical "s" geopotential coefficients, $\overline{C}_{nm}$,

$$\overline{Y}_{nm}(\theta,\lambda)=\overline{P}_{n|m|}(\cos\theta)\cdot\begin{Bmatrix}\cos m\lambda\\ \sin|m|\lambda\end{Bmatrix}\begin{matrix}\text{if } m\geq 0\\ \text{if } m<0\end{matrix} \quad [2]$$

Where,

$\overline{P}_{nm}$ [cosθ] are the fully normalized associated Legendre functions of the first kind **[15]**.

The disturbing potential T at a point P [r , θ , λ] is the differences between the actual gravity potential of the Earth and the normal potential of equipotential ellipsoid at P. Based on equation [1] the spherical harmonic representation of T is :

$$T(r,\theta,\lambda) = \frac{GM}{r}\sum_{n-2}^{\infty}\left[\frac{a}{r}\right]^{n}\sum_{m=-n}^{n}\overline{C}_{nm}^{s}\,\overline{Y}_{nm}(\theta,\lambda) \qquad [3]$$

The above formula have been expanded in several processes to get any element of the earth's gravity field. The relationship between the coefficient of any spherical harmonic model and gravity anomalies [Δg_{GM}] is given **[16]** as follows:

$$\Delta g_{GM} = \frac{GM}{r^2}\left[\sum_{n-2}^{n_{\max}}(n-1)\left[\frac{a}{r}\right]^{n}\sum_{m=0}^{n}\overline{C}_{nm}^{*}\cos m\lambda + \overline{S}_{nm}\sin m\lambda\right]\overline{P}_{nm}(\sin\varphi) \qquad [4]$$

Where

n_{max} is the maximum degree;

n , m is the degree and order respectively;

$\overline{C}^{*}_{nm}$ the relevant fully normalized spherical harmonic C-coefficients of degree n and order m, reduced for the even zonal harmonics of the WGS-84 reference ellipsoid,

$\overline{S}_{nm}$ the relevant fully normalized spherical harmonic S-coefficients of degree n and order m,

ϕ, λ is the geocentric latitude and longitude;

a is the scaling factor and r is the geocentric distance.

3. Global Geopotential Models

3-1 Earth Gravitational Model 1996 [**EGM96**]

EGM96 is a spherical harmonic model of the earth's gravitational potential in degree and order (n, m) of 360, which corresponds to the spatial resolution (π/n), of 55 km, where 1° is represented by 110 km on Earth's surface. EGM96 was produced by the US National Imagery and Mapping Authority [NIMA]**.** EGM96 was developed by combining surface gravity data, ERS-1/GEOSAT altimeter-derived anomalies, extensive satellite tracking data including new data from satellite laser ranging [SLR], the global positioning system [GPS], NASA's tracking and data relay satellite system [TDRSS] **[17].**

3-2 Earth Gravitational Model 2008 [**EGM2008**]

EGM2008 is a spherical harmonic model of the earth's external gravitational potential in degree and order of 2160, with additional spherical harmonic coefficients extending up to degree and order of 2190 that offers a spatial resolution of 9 km. EGM2008 incorporates improved 5x5 min gravity anomalies, altimetry-derived gravity anomalies and has benefited from the latest GRACE based satellite solutions **[18]**.

3-3 EIGEN-6c 2011

European Improved Gravity model of the Earth by New techniques [EIGEN-6c], high-resolution global gravity field model, published in 2011, was the first global combined gravity field model including GOCE data. It had been computed from a combination of LAGEOS, GRACE and GOCE data, it was completed to degree and order 1420. It consists of:

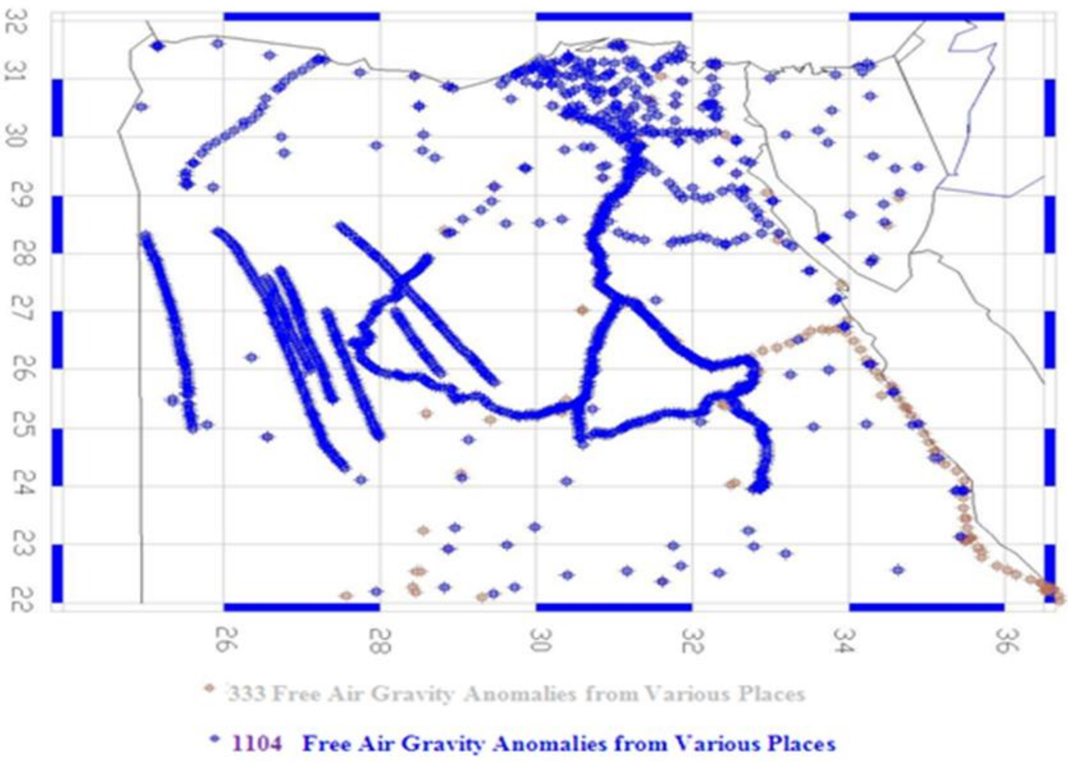
- 6.5 years of LAGEOS [SLR] and GRACE [GPS-SST and K-band range rate] data from the time span 1 Jan 2003 till 30 June 2009
- 6.7 months of GOCE data [Satellite gradiometry only] from the time span 1 Nov 2009 till 30 June 2010.
- The DTU2010 global gravity anomaly data set obtained from altimetry **[12]**.

4. The Available Used Data

The local gravity data used in this study were grouped in two sets as shown in [Figure1]. Firstly, all old available free-air gravity anomalies at[1440] points, where [the sources of these data their number and distributed are well documented in many previous works as shown in **[5]**, **[6]**, **[7]**, **[8]** and **[14]** secondly free-air gravity anomaly values at [333] points were obtained from BGI [Bureau Gravimetric International], where their observational mean stander deviation is [0.24mgal], while the stander deviation estimated for older gravity anomaly data distributed all over the whole territory of Egypt is [0.73mgal] on average. As can be seen from [Figure1], free air gravity data distribution is not homogeneous over Egypt, with significant gaps, particularly in the eastern and western deserts. The validation of the finally used data here were based on comparing the gravity value of each point to values at the nearest four surrounding stations, to identify any large discrepancies (more than 3 segma), which were subsequently removed. After validation the remaining used data were [1104 old data +333 BGI] with observational stander deviation as shown in table [1].

Table [1]: The raw and filtered data numbers

Item	Data No. before filtration	Number of filtered data	Average standard deviation (mgal)
Gravity anomalies[old]	1440	1104	0.73 -0.67
Gravity anomalies[BGI]	333	333	0.24
Gravity anomalies[old+ BGI]	-	1437	0.63



[Figure 1]: The Local Geodetic Data used in this Study

5. Evaluation, methodology and used software

According to the available data and its distribution over Egypt, the evaluation process had been done for the whole area of Egypt and then for two elect regions of highly intensive data with 333 data points in each, where region one lies between 29.5° to 31.5°N and 29.5° to 32.5° E, while region two lies between 25° to 28°N and 26° to 29°E], plus a third region having [333] data points obtained from BGI as shown in figure [2], where the mean stander deviation of the terrestrial 333 data points used in the three regions were found equal to [0.45mgal], [0.35mgal] and [0.24mgal] respectively.

The precision of the behavior of each model in the case studies here is represented in terms of stander deviation [STA.DEV.] of the residual computed from each model as follows:

$$\sigma_{\Delta g_r} = \sqrt{\frac{\sum_{i=1}^{n}\left(\Delta g_{r_i} - \overline{\Delta g_r}\right)^2}{n-1}} \qquad [5]$$

Where,

$$\Delta g_{r_i} = \left(\Delta g_i - \widehat{\Delta g_i}\right)$$

$$\overline{\Delta g_r} = \frac{1}{n}\sum_{i=1}^{n} \Delta g_{r_i} \qquad [6]$$

The accuracyof the behavior of each model is represented in terms of root mean square error [r.m.s.e] as follows:

$$\text{RMS} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(model_i - obseved_i)^2}$$

$$\text{RMS} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(\Delta g_i - \widehat{\Delta g_i}\right)^2} \qquad [7]$$

Used software

The software used in our computation was the well known gravsoft292 package supplied by Prof.. Tscherning, which have been a valuable and reliable programs for calculations. It was particularly kind of him to allow us to use this software.

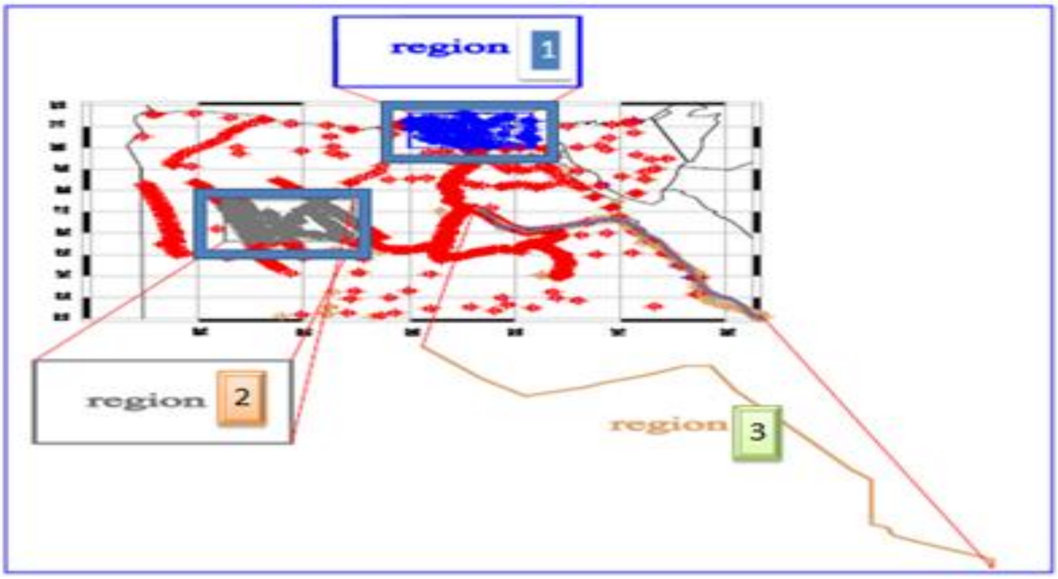


Figure [2]: Highly Intensive Regions of data in Egypt

6. Results and Analysis

Table [2] represents the results of the evaluation process at grid points [1'x1'] of the three models over the whole territory of Egypt .

Free air gravity anomaly	**Min** mgal	**Max** mgal	**Mean** mgal	**Std. Dev.** mgal
EGM1996	-179.430	182.96	6.618	27.990
EGM2008	-131.750	158.157	6.257	25.073
EGM2011-EIGEN6C	-345.150	10.967	-204.325	72.600

Table [3] represents the results of the comparison among the three harmonic models at grid points [1'x1'] over the whole territory of Egypt .

Free air gravity anomaly	**Min** mgal	**Max** mgal	**Mean** mgal	**Std. Dev.** mgal
EGM2008- EGM2011-EIGEN6C	-372.381	5.826	-210.582	67.748
EGM2008-EGM1996	-192.691	133.081	-0.361	19.770
EGM2011 -EGM1996	-193.030	300.911	118.523	93.662

Table [4] shows the statistical comparison among the terrestrial gravity anomalies and those computed from the different harmonic models at scattering points of the first chosen region **Figure [2]**

Free air gravity anomaly[region 1]	**Min** mgal	**Max** mgal	**Mean** mgal	**Rms** mgal	**S. D. Of the residual** mgal
$G.A_{terrs}$-EGM96	-94.351	76.434	-2.451	24.812	18.369
$G.A_{terrs}$-EGM2008	-127.390	44.765	0.411	18.870	18.369
$G.A_{terrs}$- EGM2011-EIGEN6C	-29.034	203.773	105.619	57.499	57.787

[Table 5] Shows the statistical comparison among the terrestrial gravity anomalies and those computed from the different harmonic models at scattering points of the second chosen region **Figure [2]**

Free air gravity anomaly[region2]	**Min** mgal	**Max** mgal	**Mean** mgal	**R.m.s** mgal	**S. D. Of the residual** mgal
$G.A_{terrs}$-EGM96	-45.475	64.395	-9.766	16.030	15.857
$G.A_{terrs}$-EGM2008	-44.281	67.209	-11.933	14.953	14.358
$G.A_{terrs}$- EGM2011	125.059	302.591	184.821	29.240	31.309

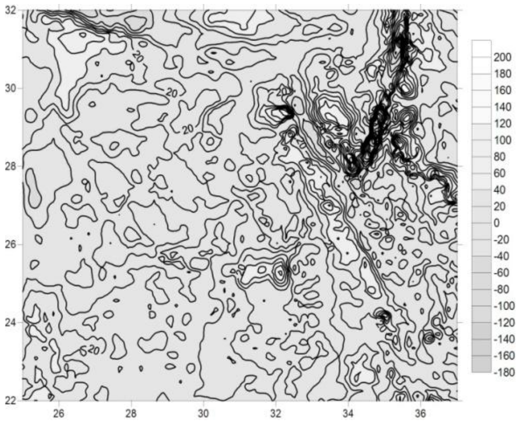
Table [6] represents the statistical comparison among the terrestrial gravity anomalies and those computed from the different harmonic models at scattering points of the third data set from BGI **Figure [2]**

Free air gravity anomalies[BGI]	**Min** mgal	**Max** mgal	**Mean** mgal	**Rms** mgal	**S. D. Of the residual** mgal
$G.A_{terrs}$-EGM96	-44.969	43.809	4.833	12.422	12.443
$G.A_{terrs}$-EGM2008	-51.494	41.809	-1.030	11.383	11.399
$G.A_{terrs}$- EGM2011	125.059	302.591	184.821	27.810	28.144

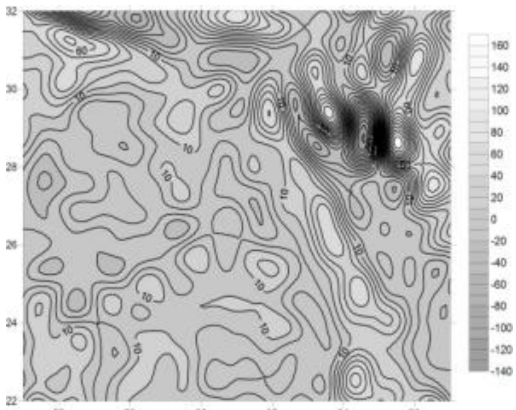
Table [7] Shows the statistical comparison between the terrestrial gravity anomaly data at scattering points over the whole territory of Egypt and those computed from the different harmonic models at the same scattering points.

Free air gravity anomalies	**Min** mgal	**Max** mgal	**Mean** mgal	**Rms** mgal	**S. D. Of the residual** mgal
G.A$_{terrs}$-EGM96	-144.228	153.364	0.278	26.576	27.674
G.A$_{terrs}$-EGM2008	-98.474	131.428	1.901	19.943	19.710
G.A$_{terrs}$- EGM2011	67.535	390.737	214.911	61.200	50.039

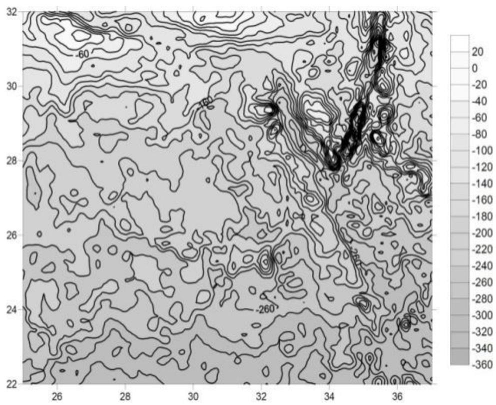
Figure [3] represents a free air gravity anomaly map obtained from 1'x1' grid of Δg_f computed from EGM2008 Model for the whole area of Egypt, and Figure [4] represents the same obtained from EGM96 while figure [5] represents also the same from EGM2011,where [latitude, longitude are in degree and gravity anomaly in mgal].



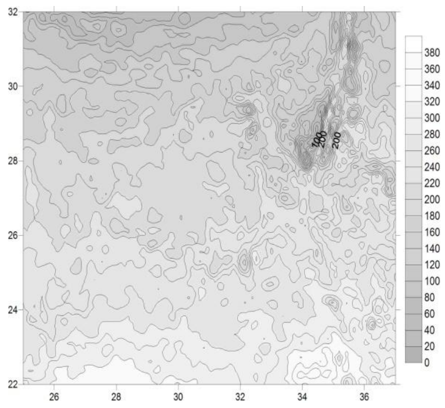
[Figure 3]



[Figure 4]



[Figure 5]



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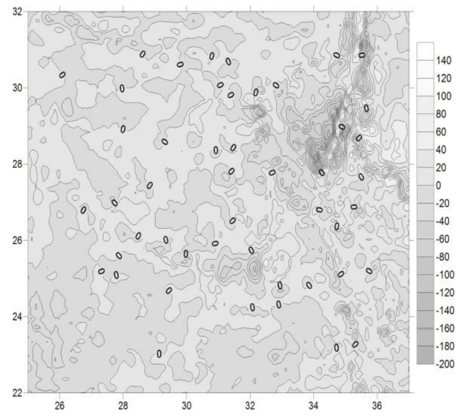
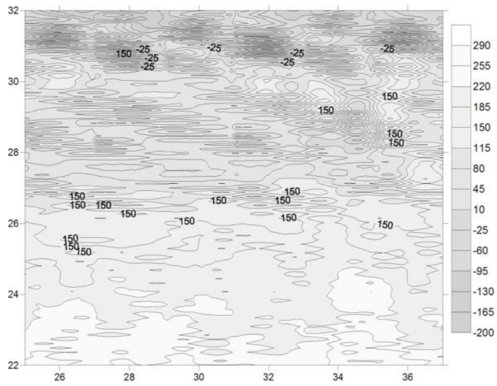
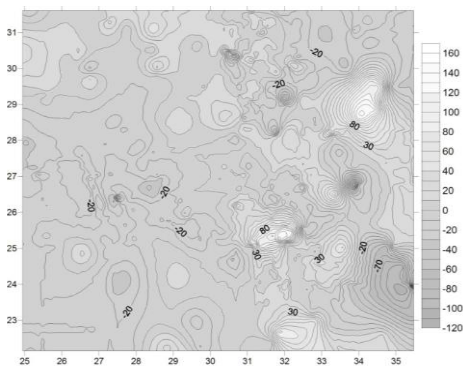


[Figure 7]

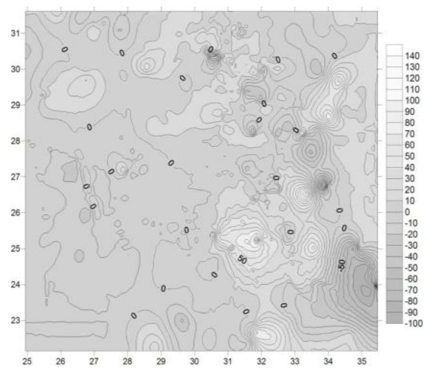


[Figure 8]

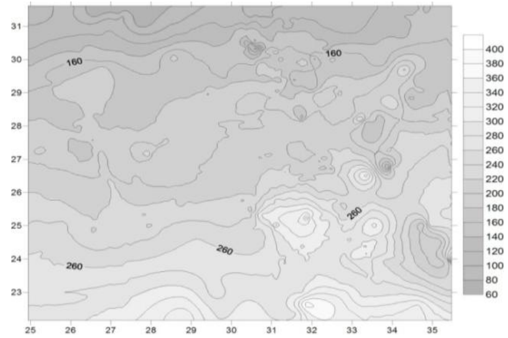
Figure [6] shows the difference of gravity anomalies obtained from EGM2008 and EGM2011-EIGEN6Cfor the whole area of Egypt. Figure [7], Shows the difference of gravity anomalies obtained fromEGM2008 and EGM96, while Figure [8] represents the difference of gravity anomalies obtained fromEGM96 and EGM2011-EIGEN6C, where [latitude, longitude are in degree and gravity anomaly in mgal].



[Figure 9]

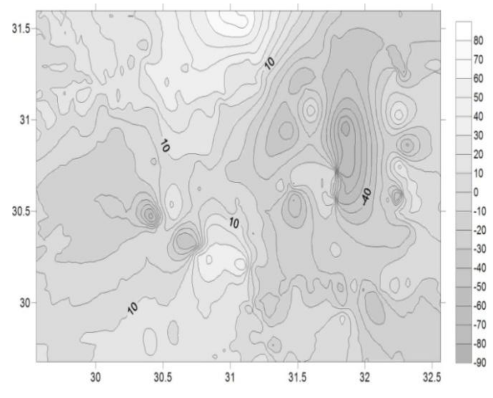


[Figure 10]

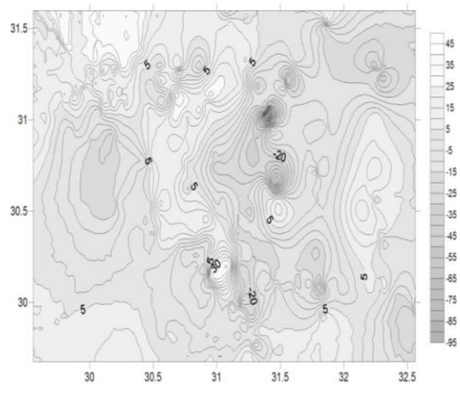


[Figure 11]

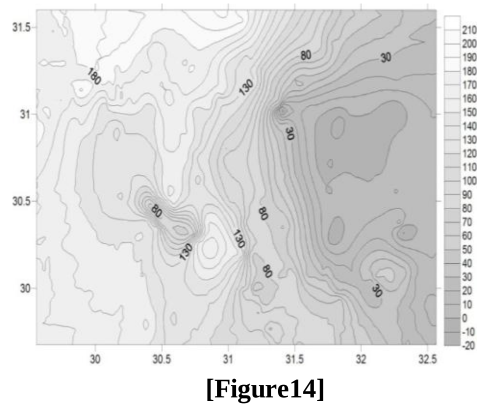
Figure [9] represents Δg_f difference between Terrestrial gravity anomaly data and EGM96 for the whole area of Egypt. Figure [10] shows Δg_f difference between Terrestrial gravity anomaly data and those obtained from EGM2008 , while figure [11] demonstrates Δg_f difference between terrestrial gravity anomaly data and those obtained from EGM2011, where [latitude and longitude are in degree while gravity anomalies are in mgal].



[Figure12]

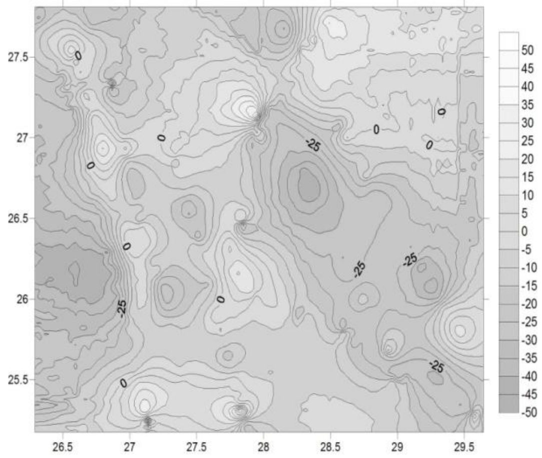


[Figure13]

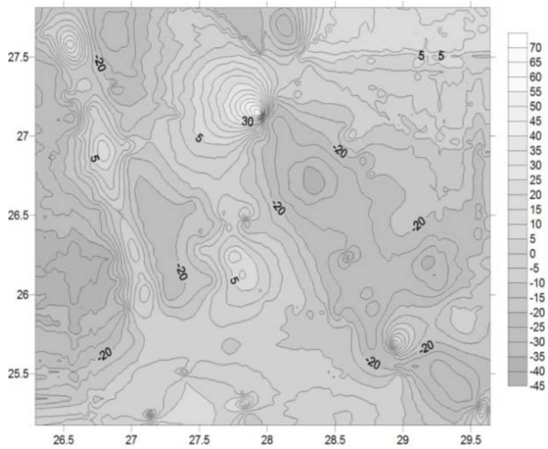


[Figure14]

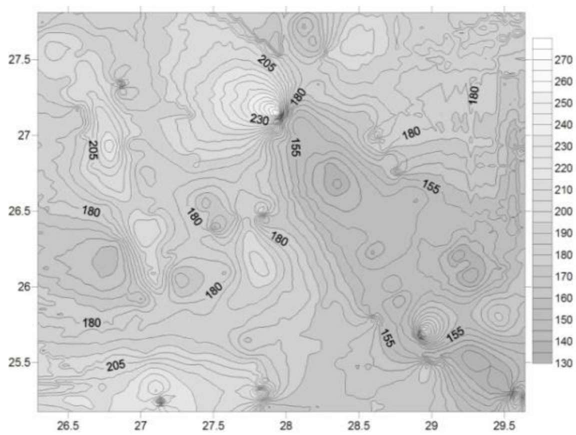
Figure [12] represents the difference between terrestrial gravity anomalies in the first elected dense data area, [first region] and the corresponding gravity anomalies obtained from EGM96. Figure [13] shows the difference between terrestrial gravity anomalies and those computed from EGM2008 in the second region, while in Figure [14] the difference between terrestrial gravity anomalies and the corresponding anomalies computed from EGM2011-EIGEN6C referred to the same area, where [latitude, longitude are in degree, gravity anomaly in mgal].



[Figure 15]



[Figure16]



[Figure17]

Figure [15] represents the difference between terrestrial gravity anomalies in the second elected dense data area, [second region] and the corresponding gravity anomalies obtained from EGM96. Figure [16] shows the difference between terrestrial gravity anomalies and those computed from EGM2008 in the second region, while in Figure [17] the difference between terrestrial gravity anomalies and the corresponding anomalies computed from EGM2011-EIGEN6C referred to the same area, where [latitude, longitude are in degree, gravity anomaly in mgal].

7. Conclusion and Recommendations

From the results shown in tables [4] to [6] we can notice that the best model of the three is EGM2008, since it gives the least [r.m.s.e] compared with the other two models when applied over the three regions. The graduation in the values of the obtained [r.m.s.e], i.e. [18.870 mgal], [14.953 mgal] and .[11.38 mgal] respectively, seems to be reasonable and was logically expected since the mean stander deviation of the used data in the three regions were; [0.45mgal], [0.35mgal] and [0.24mgal] respectively .

The results shown in tables [7] of GGMs evaluation over the whole area of Egypt have indicated that the smallest [r.m.s.e] is [19.94 mgal], referred to EGM2008, which confirms the conclusion drawn on the above paragraph, explicitly this model is the best of the three. The value of the [r.m.s.e], to be precise [19.94 mgal] referred to EGM2008 shown in table [7] is larger than those referred to EGM2008 given in tables from [4 to 6] when applied over the three elected regions is also logic, due to existence of several gap areas; empty of terrestrial data in the whole territory of Egypt, in addition to the higher value of the average standard deviation of the data over the whole area compared to the average at the three regions.

It also indicated from the values shown in the last column in tables [4 to 7] the values of the S. D. of the residual of each model over the specific area, we can confirm the previous conclusion, i.e. EGM2008 is the best of the three models.

From the values of [r.m.s.e] shown in tables [4 to 7] we can conclude that EGM2008 has thus 1.23 times better statistics than the EGM96 and 2.54 than EGM2011-EIGEN6C therefore; this model makes a significant improvement over all other models, and thus is advised to be used in computation for the geoid in Egypt.

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Links to some International Geoid Organizations:

Bureau Gravimétrique International [BGI]http://bgi.cnes.fr:8110/

http://cddis.nasa.gov/926/egm96/[EGM96The NASA GSFC and NIMA Joint Geopotential Model]

http://earth-info.nga.mil/GandG/wgs84/gravitymod/egm2008/index.html[Earth Gravitational Model 2008 [EGM2008]

http://www.esa.int/Our_Activities/Observing_the_Earth/The_Living_Planet_Programme/Earth_Explorers/GOCE

International Center for Global Earth Models [ICGEM]
http://icgem.gfz-potsdam.de/ICGEM/Main.html
International Gravity Field Service [IGFS]http://www.igfs.net/