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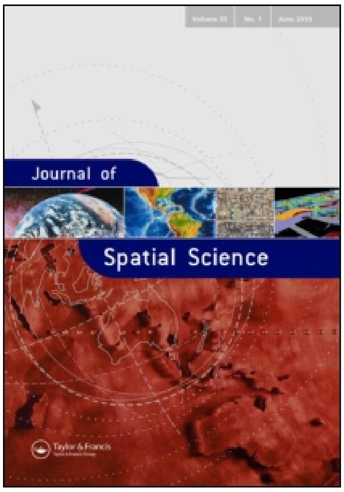

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Towards the redefinition of the Egyptian geoid: Performance analysis of recent global geoid and digital terrain models

G. M. Dawod[a][b]
[a] Survey Research Institute, Egypt [b] Umm Al-Quraa University, Makkah, Saudi Arabia

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Towards the Redefinition of the Egyptian Geoid: Performance Analysis of Recent Global Geoid and Digital Terrain Models

G. M. Dawod

Launches of the CHAMP (CHAllenging Mini-satellite Payload) and GRACE (Gravity Recovery And Climate Experiment) satellite missions have produced a new generation of global geopotential models (GGMs). The performance of seven recent GGMs has been analyzed using a local geodetic dataset (terrestrial gravity and GPS/levelling points) in Egypt. The results show that the EIGEN-CG01C model is best at representing the long and medium wavelengths of the gravity field in Egypt. Its average accuracy, in terms of geoid undulations, when compared to known points, is estimated to be 0.36 m. Additionally, four digital terrain models (GTOPO30, SRTM, DTM2002, LDTM) have been investigated, leading to the conclusion that DTM2002 should be utilized in computing the terrain corrections for gravimetric geoid development in Egypt. When combined with local geodetic data, these two global models (EIGEN-CG01C and DTM2002) will support the production of a precise local geoid model, to be used in conjunction with Global Positioning System-based surveying and mapping projects in Egypt.

KeyWords: Global Geopotential Models, Geodesy, Regional Gravimetric Geoid, Digital Terrain Models, GPS/levelling, Egypt.

G. M. Dawod
Survey Research Institute
Egypt; currently at
Umm Al-Quraa University
Makkah
Saudi Arabia
dawod_gomaa@yahoo.com

INTRODUCTION

The rapid growth of Global Positioning System (GPS) utilisation in Egypt in recent decades necessitates having a nation-wide precise geoid model in order to transform the GPS-derived ellipsoidal heights to orthometric heights used in surveying and mapping. Global Geopotential Models (GGMs) produce a quasi-geoid, not the geoid itself. Since the height system used in Egypt is orthometric, GGM-based quasi-geoid heights have to be converted to true geoid undulations by adding a correction term, before GPS ellipsoidal heights can be converted to orthometric heights (Heiskanen and Moritz, 1967, p.326; Rapp, 1997). Neglecting such a correction may be misleading in fitting gravimetric quasi-geoids to GPS/Levelling data (Featherstone, 2006). Nevertheless, in order to improve local geoid modeling, the choice of an optimum GGM for a particular region is crucial (Kiamehr and Sjöberg, 2005a), which is one of the main objectives of this investigation.

Geoid development in Egypt has been addressed by a variety of researchers (e.g. Alnaggar, 1986; Abdelmotaal, 2002; Saad and Dawod, 2002). The geoid solution of Alnaggar (1986) is considered the pioneering nation-wide (22^{o}N<latitude<32^{0}N, 25^{o}E<longitude< 37^{o}E) geoid, developed using a least-squares collocation technique and heterogeneous geodetic data including terrestrial gravity, astronomic deflections of the vertical and Doppler/levelling undulations. Abdelmotaal (2002) has developed an Egyptian gravimetric geoid model, based on available free-air gravity anomalies and a local DTM, fitted to local GPS/levelling data. Another geoid solution, called EGGG2003, has been developed by Abdelmotaal (2003) using a technique (called the *Window* technique) to create an adapted version of the EGM96 global model to get a better fit to the Egyptian gravity field in a Fast Fourier Transform (FFT) process. Abdelmotaal (2006) developed and applied a high-degree tailored reference model by merging the available gravity anomalies with EGM96. Such a process gave better residual gravity anomalies than the original EGM96, and the variance was reduced by one third (*ibid*). A recent generation of geoid models for Egypt on a five-minute grid has been developed by Saad and Dawod (2002): SRI2001A is a gravimetric geoid computed using local gravity, a local Digital Terrain Model (DTM) and the EGM96 GGM, using a remove-compute-restore FFT processing methodology. SRI2001B is a geoid based on surface-fitting of the SRI2001A model to GPS/levelling (*ibid*). Moreover, there are other studies that have developed geoid models for particular areas of interest in Egypt (e.g. Tscherning *et al.,* 2001).

Practical studies have proved that, when comparing the GGM-based undulations to local geodetic datasets, none of the GGMs fit well to the Egyptian gravity field (e.g. Abdelmotaal, 2006; Saad and Dawod, 2002). In the last few years, several factors have given rise to the need for a new precise geoid model for Egypt, particularly the release of new GGMs and the compilation of more local geodetic datasets. This paper aims to provide guidelines for processing a new geoid for Egypt through analyzing the performance and accuracy of recent GGMs and DTMs.

RECENT GLOBAL GEOPOTENTIAL MODELS

The launch of the CHAMP (CHAllenging Mini-satellite Payload) in 2000 and the twin satellites GRACE (Gravity Recovery and Climate Experiment) in 2002, and the probable launch of GOCE (Gravity field and steady-state Ocean Circulation Explorer) in 2008 have introduced a new era in global gravity field determination (e.g. Featherstone, 2003). The CHAMP and GRACE satellite missions improve knowledge of the long and medium wavelength features of the gravity field. The future GOCE satellite will improve knowledge of the short-wavelength components up to degree 300. These new satellite missions allow the computation of a new generation of GGMs, which will significantly improve upon, and thus supersede, existing GGMs (e.g. Reigber *et al.,* 2006; Bilker, 2005; Featherstone, 2003). The International Center for Global Gravity Field Models (ICGEM, Potsdam, Germany) makes available a number of GGMs in the form of fully-normalized spherical harmonic coefficients that can be used to compute geodetic and gravitational quantities (http://icgem.gfz-potsdam.de/ICGEM/ICGEM.html).

It should be noted that GGMs, when used in a spherical harmonic expansion, produce quasigeoid not geoid solutions since the processing yields height anomalies not geoid undulations. Several researchers have considered this issue and have presented solutions to convert height anomalies to geoid heights (e.g. Heiskanen and Moritz, 1967, p.326, Eq. 8-100). Rapp (1997) suggested that potential coefficient models be used first to calculate a height anomaly, and then a correction term, represented by a high degree spherical harmonic expansion, be applied to give the geoid undulation. The geoid/quasigeoid separation is not the main focus of the current study, but such a conversion is an important step in the development of a precise geoid model for Egypt (particularly to convert GPS ellipsoidal heights to orthometric heights), and should be taken into consideration in due course.

In the last five years, several GGMs have been developed and released for world-wide use. Out of the most-recently released GGMs, a group of seven have been selected for this study and are briefly described in Table 1. The choice of these GGMs was made to cover a variety of models that have various degree and order (e.g. 140, 200, and 360), and various combinations of input data (satellite tracking data, terrestrial gravity data and altimetry data). The EGM96 model has been included in this study, even though it is older than the other GGMs, since it is broadly utilised worldwide and in Egypt (e.g. Saad and Dawod, 2002; Abdelmotaal, 2006).

Model	Year	Degree	Data	Reference
EIGEN-GL04C	2006	360	S,G,A	Förste *et al.* (2006)
EIGEN-CG03C	2005	360	S,G,A	Förste *et al.* (2005)
GGM02C	2004	200	S,G,A	Tapley *et al.* (2005)
EIGEN-CG01C	2004	360	S,G,A	Reigber *et al.* (2006)
EIGEN-3P	2003	140	S	Reigber *et al.* (2005)
EIGEN-2	2003	140	S	Reigber *et al.* (2003)
EGM96	1996	360	S,G,A	Lemoine *et al.* (1998)

Table 1. *GGMs to be evaluated in this study*

Data: S=Satellite Tracking Data, G = Terrestrial Gravity Data, A = Altimetry Data

The EIGEN-CG01C global geoid model has an overall accuracy of 20 cm and 5 mgal, in terms of geoid heights and gravity anomalies respectively (Reigber *et al.*, 2006). The model benefits significantly from recently released gravity anomaly compilations over polar regions. In general, the accuracy of EIGEN-CG01C over the oceans is better than over the continents, reflecting the higher quality of the available satellite altimetry data (*ibid*).

The EIGEN-CG03C global mean gravity field model is a combination of data from the GRACE mission (376 days in the periods: February-May 2004; July-December 2003 and February-July 2004) and the CHAMP mission (860 days in the period October 2000-June 2003), plus altimetric and gravimetric surface data (Förste *et al.*, 2005). This model has an overall accuracy in terms of geoid heights and gravity anomalies of 30 cm and 8 mgal, respectively (*ibid*).

The EIGEN-GL04C gravity field model is an upgrade of EIGEN-CG03C. This model combines data from GRACE and LAser GEOdynamics Satellite (LAGEOS) missions plus 0.5 x 0.5 degree gravimetry and altimetry surface data (Förste *et al.*, 2006). The satellite data have been analyzed by two organizations: GFZ Potsdam and Groupe de Recherche de Geodesie Spaciale (GRGS) Toulouse. The processing standards used by both analysis centres were identical, with the exception of the ocean model used for correcting short-term mass variations. The surface data used were identical to the EIGEN-CG03C solution except for the geoid undulations over the oceans, which have been derived from a new GFZ mean sea surface height (MSSH) model (e.g. Förste *et al.,* 2006; and ICGEM page http://www.gfz-potsdam.de/pb1/op/grace/results/grav/g005_eigen-gl04c.html#t0).

The GGM02S satellite-only GGM was derived using approximately 14 months of GRACE data from April 2002 to December 2003 (Tapley *et al.* 2005). The satellite-only GGM02S solution (complete to degree/order 160) has been combined with the terrestrial gravity information used in EGM96, to obtain GGM02C (complete to degree/order 200) preserving the strength of the GRACE information at longer wavelengths and the surface information contained in EGM96 at shorter wavelengths. Calibrated error estimates for the GGM02 generation of models (either GGM02S or GGM02C) indicate a global geoid height RMS error of approximately 7 mm to degree/order 70, with no discrimination between land and ocean (Tapley *et al., 2*005). At low and mid degrees (approximately degree 5-70), this improvement is nearly two orders of magnitude better than pre-GRACE models, and more than a factor of two improvement over the earlier GGM01 generation (e.g. http://www.csr.utexas.edu/grace/gravity/ggm02/GGM02_Notes.pdf).

EIGEN-2 is a CHAMP-only gravity field model derived from CHAMP GPS satellite-to-satellite and accelerometer data for the period July to December 2000, and September to December 2001 (Reigber *et al. 2*003). Although higher-degree/order terms exist in EIGEN-2, the solution has full power only up to about degree/order 40 due to signal attenuation because of the satellite's altitude. The accuracy of EIGEN-2 is 10 cm and 0.5 mgal in terms of geoid heights and gravity anomalies, respectively, at a half wavelength resolution of 550 km. This is an improvement by almost one order of magnitude compared to any multi-satellite pre-CHAMP satellite-only gravity field model (*ibid*).

EIGEN-3P (EIGEN-3 preliminary) is a CHAMP-only gravity field model derived from CHAMP GPS satellite-to-satellite and accelerometer data for the period July 2000 through June 2003 (Reigber *et al.,* 2005). At the time of its release, this GGM was considered a preliminary model since its final processing had not been completed. EIGEN-3P differs from EIGEN-2 not only by the six times larger amount of CHAMP data but also by a different parameterisation

Gravity Model	USA 6169 points	Canada 1930 points	Europe 186 points	Australia 201 point	Weighted Mean 8486 points
EIGEN-GL04C	0.363	0.261	0.332	0.262	0.337
EIGEN-CG01C	0.374	0.277	0.412	0.281	0.351
EIGEN-CG03C	0.367	0.311	0.397	0.277	0.353
EGM96	0.402	0.366	0.487	0.314	0.394
GGM02C	0.491	0.381	0.492	0.390	0.464
EIGEN-3P	0.830	0.862	1.333	0.856	0.849
EIGEN-2	0.971	1.082	1.620	1.072	1.013

Table 2. *Root mean square (RMS) differences of GPS-levelling minus GGM derived quasi-geoid heights (m) (after ICGEM)*

of the accelerometer calibration. Although higher-degree/order terms exist in EIGEN-3P, the solution has full power only up to about degree/order 65, once again due to signal attenuation (for more details, see: http://www.gfz-potsdam.de/champ/results/index_RESULTS.html).

To evaluate the performance of the GGMs described above, their estimated height anomalies have been compared against geoid undulations at known GPS/levelling stations in USA, Canada, Europe, and Australia (for more details on this comparison and its results, see http://icgem.gfz-potsdam.de/ICGEM/evaluation/evaluation.html). The results of this comparison are presented in Table 2. The final column of Table 2 shows the weighted mean difference, computed using the number of points in each region as the relevant weighting factor.

It can be seen from Table 2, that despite the incorporation of recent satellite and terrestrial gravity data in the development of the newer GGMs, only three, namely EIGEN-GL04, EIGEN-CG01C, and EIGEN-CG03C, perform better – and that only marginally – than the older EGM96 model.

In this context, it is worth mentioning that a new GGM (the Earth Geopotential Model 2007/8 or EGM07/8) is under development by the US National Geospatial Intelligence Agency (NGA) (NGA, 2007) and will take advantage of updated satellite, surface gravity, elevation and altimetry data. EGM07/8 will be complete to degree and order 2160, with 5′ x 5′ resolution and 15 cm RMS expected accuracy (Forsberg, 2007). EGM07/8 is expected to be released to the public in early 2008 (NGA, 2007).

RECENT DIGITAL TERRAIN MODELS

Digital Terrain Models (DTM) are essential for gravity data processing and geoid model development, particularly for the computation of terrain corrections to observed terrestrial gravity data, and for downward continuation computations. Topographic height, bathymetry, and ice thickness data support the computation of analytical continuation terms, and the development of models to convert height anomalies to geoid undulations (e.g. Heiskanen and Moritz, 1967, p. 326). The effect of the topography (represented by a DTM) is accounted for in the calculation of reduced gravity anomalies as (*ibid*):

$$\Delta g = \Delta g_F - \Delta g_h - \Delta g_{Ref} \qquad (1)$$

where Δg_F is the free-air anomaly, Δg_h is the effect of the topography, and Δg_{Ref} is the effect of reference gravity field represented by a GGM. The full geoid undulation N is then computed as:

$$N = N_{\Delta g} + N_h + N_{Ref} \qquad (2)$$

where $N_{\Delta g}$ is the contribution of the reduced gravity anomalies computed by Stokes's integral, N_h is the contribution of the topography or the terrain effect, and N_{Ref} is the contribution of the reference gravity field computed by the spherical harmonic expansion (For more information on the FFT technique, see Sideris and Footopoulus, 2005).

Recently, global topographic and bathymetric databases have been compiled and released, leading to the development of a new, more detailed global model called DTM2002. DTM2002 combines (Saleh and Pavlis, 2002):

(1) The GTOPO30 and GLOBE global 30Ð DEMs (Hastings and Dunbar, 1999);
(2) The ACE 30Ð DEM (Johnson et al., 2001);
(3) Near ocean-wide bathymetric information predicted from altimetry data and constrained by ship-borne depth soundings (Smith and Sandwell, 1997);
(4) The Generic Mapping Tools (GMT) high-resolution global shoreline and land type database (Wessel and Smith, 1996);
(5) New 5 km grids of ice surface elevations from altimetry data and the JGP95E geoid model over Antarctica and Greenland;
(6) Revised ice thickness data over Antarctica (on a 50 km grid) and Greenland (5Ðx10Ð);
(7) Depth data (30Ð) for the Great Lakes (Ekholm, 1996).

DTM2002 was compiled in a 30Ð version that provides surface elevations and ocean depths only, and in 2Ð and 5Ð versions that include depth data for certain large lakes and ice thickness information (*ibid*). A part of DTM2002 (the 30″ version) corresponding to the Egyptian territories has been obtained (Saleh, 2004) and utilized in this research.

GTOPO30 is a global DTM, completed in late 1996, with a horizontal grid spacing of 30″ (approximately 1 km). GTOPO30, developed over a three-year period through a collaborative effort led by the US Geological Survey's EROS Data Center (EDC), was derived from several raster and vector sources of topographic information. The vertical accuracy of GTOPO30 is quoted to be ± 30 m at the 90 percent confidence level (for more details, see http://edcdaac.usgs.gov/gtopo30/README.html#h31). GTOPO30 can be downloaded from http://edcdaac.usgs.gov/. The window of GTOPO30 that corresponds to the Egyptian territories has been extracted and utilized in this research.

The Shuttle Radar Topography Mission (SRTM) global DTM is a joint project between the US National Imagery and Mapping Agency (NIMA) and the National Aeronautics and Space Administration (NASA) (see http://www2.jpl.nasa.gov/strm/). A 90 m SRTM DTM for many parts of the world has been compiled and released (*ibid*). SRTM has been used in geoid modelling for several regions, particularly for topographic and downward continuation corrections (e.g Kiamehr and Sjöberg, 2005b). The window of the SRTM DTM corresponding to the Egyptian territories has been downloaded and has been considered in this study.

Even though DTM2002, GTOPO30 and SRTM are the only global DTMs that have been presented and evaluated in the current study, other DTMs (e.g. the Global Land One-km Base Elevation, GLOBE DTM) should also be evaluated in any future attempt to develop a precise Egyptian geoid model.

AVAILABLE EGYPTIAN GEODETIC DATABASES

The local geodetic data used in this study was held in two databases (Table 3). Firstly, terrestrial gravity values have been measured at 1138 points (Figure 1). The date of these observations and their accuracy vary greatly between the most recent Egyptian National Gravity Standardisation Network of 1997 (ENGSN97) (Dawod, 1998) and older gravity surveys carried out several decades ago. The accuracy of ENGSN97 gravity values is 0.022 mgal, while the accuracy estimate for older gravity data is 0.5 mgal on average (Dawod and Alnaggar, 2000). As can be seen from Figure 1, gravimetric data distribution is not homogeneous over Egypt, with significant gaps, particularly in the Eastern and Western deserts (*ibid*). An evaluation of the existing gravity data, based on comparing the gravity value of each point to values at the nearest four stations, was carried out to identify any large discrepancies. This process identified 58 points (about 5 percent) as suspected outliers and these were subsequently removed.

The second compiled geodetic data base consists of 202 GPS/levelling points (Figure 2), where geoid undulations have been directly computed. The majority of this data set comes from GPS campaigns carried out by the Nile Research Institute (NRI) for updating the hydro-topographic maps of the Nile (Dawod and Abdel-Aziz, 2003). The accuracy of the derived geoid undulations has been estimated to be ± 5 centimetres (*ibid*). Once again, an examination of the data was carried out by comparing the geoid undulation at each point to corresponding values at the nearest four stations. This examination revealed that 18 points (about 9 percent) were possible outliers and these data points were removed from the dataset.

Data Type	No. of points	Precision
Terrestrial Gravity:		
1- ENGSN97 Network	150	± 0.022 mgal
2- Older gravity points	988	± 0.500 mgal
GPS/levelling	202	± 0.05 m

Table 3: *Available local geodetic data*

Additionally, a local 5′ x 5′ DTM has been utilized for comparison of the global DTMs over Egypt (El Sagheer, 1995). This nationwide Egyptian LDTM has been developed using digitized hard copy topographic maps as well as scattered height data points (*ibid*).

It should be noted at this point that the number and the distribution of the available terrestrial gravity data over Egypt is not ideal for reliable geoid computation using the traditional FFT process. It may be necessary, therefore, to apply either an isostatic compensation model, or independent knowledge on the density distribution, e.g. from seismic data, to take into account the influence of the crust-mantle interface on the geoid. Abdelmotaal and Kühtreiber (2003) proposed the use of seismic Moho depths, representing the actual compensating masses, with variable density anomalies. The results showed that such a strategy gives better geoid accuracy compared to the GPS/levelling geoid (*ibid*). This work should be investigated in any future development of a precise geoid model for Egypt, but has not been considered further in the current study.

PERFORMANCE OF GGMS OVER EGYPT

Amos and Featherstone (2003) have argued that terrestrial gravity anomalies do not form a very good test of GGMs, because these terrestrial data are highly susceptible to medium- and

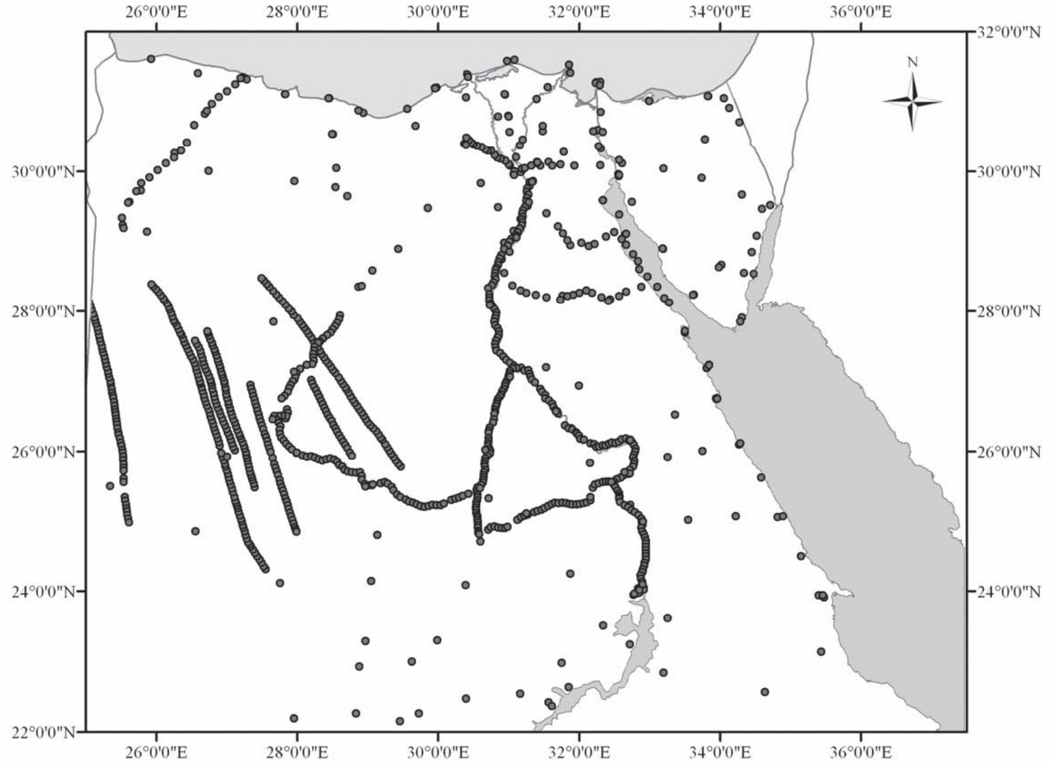

Figure 1. *Available local gravity stations*

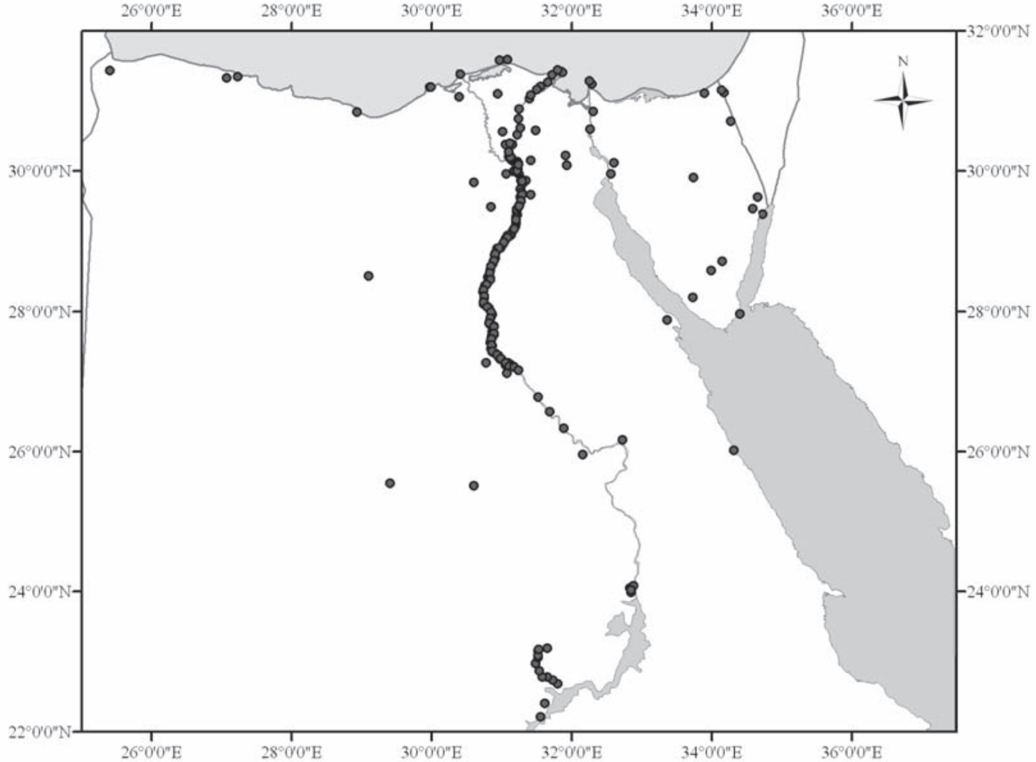

Figure 2. *Available stations with known geoid undulations*

long-wavelength errors due to factors such as distortions in the vertical geodetic datum and gravimeter drift. Additionally, they have pointed out that GPS/levelling data are also ambiguous not only because of potential datum errors, but also due to the fact that such datasets are usually collected over a long period of time, while processing algorithms and data availability (particularly precise GPS orbits) have matured.

However, a comparative analysis between GGMs and terrestrial data will reveal valuable information in the context of developing a local geoid for Egypt, particularly in terms of choosing a GGM that optimally maps the long- and medium-wavelength gravitational field in the area. It is a matter of fact that the local terrestrial gravity data, when combined with a GGM will enhance its performance, so that this addition should be the rational approach for developing a precise local geoid for Egypt.

The process of determining the *best* GGM for Egypt, consisted of two steps. Firstly, the spherical harmonic expansion coefficients of the GGMs (Table 1) were downloaded from the ICGEM website. Also, a new GGM has been created in this current study (named GGM02C/EGM96) by extending the GGM02C model to degree 360 through adding the EGM96 coefficients >200 to GGM02C. This step aims to see if such an extension has a significant effect on the final results (e.g. Tapley *et al.*, 2005; Featherstone, 2005).

Secondly, the program SHS360 (Spherical Harmonic Solution to degree and order 360) (Tscherning, 1976) has been used to compute gravity anomalies and quasi-geoid undulations at all points shown in Figures 1 and 2, respectively. The results have been compared with the measured values, and are presented in Tables 4 and 5 in order of increasing mean.

Table 4 reveals several important points about the performance of GGMs in terms of gravity field representation in Egypt. Concerning the RMS values, the EIGEN-CG01C and the EGM96 models give the same RMS, and the EIGEN-GL04C is also very close to this value.

GGM (degree)	Min	Max	Mean	RMS
EIGEN-CG01C (360)	-146.4	102.6	-20.85	25.9
EIGEN-GL04C (360)	-143.6	103.3	-20.94	26.0
GGM02C/EGM96 (360)	-160.3	113.1	-21.97	28.2
EGM96 (360)	-135.4	98.7	-22.08	25.9
GGM02C (200)	-179.8	114.1	-23.01	27.4
EIGEN-3P (140)	-214.6	109.5	-25.74	30.1
EIGEN-CG03C (360)	-212.3	111.9	-26.92	30.0
EIGEN-2 (140)	-226.6	131.7	-27.71	32.8

Table 4. *Gravity anomaly differences (observed - model) at 1080 check points (mgal)*

GGM (degree)	Min	Max	Mean	RMS
EIGEN-CG01C (360)	-0.98	2.05	-0.07	0.36
GGM02C (200)	-1.24	1.87	-0.25	0.44
GGM02C/EGM96 (360)	-1.61	2.32	-0.28	0.54
EIGEN-CG03C (360)	-1.38	1.79	-0.43	0.36
EIGEN-GL04C (360)	-1.62	1.73	-0.57	0.38
EGM96 (360)	-1.60	1.41	-0.74	0.39
EIGEN-3P (140)	-3.63	3.10	-0.92	1.04
EIGEN-2 (140)	-4.12	4.79	-2.71	1.30

Table 5. *Geoid undulation differences (observed - model) at 184 check points (m)*

The new generated model GGM02C/EGM96 does not offer an improvement over the original GGM02C solution, which may be attributed to the long and medium wavelength features being dominant in this case. Also, it can be seen that the EGM96 is better than CGM02C and CGM02C/EGM96 which identifies EGM96 as the marginally superior GGM and shows that supplementing CGM02C with the higher order coefficients does not improve its resolution. Moreover, it can be concluded that the lower the degree and order of the GGM, the lower the expected accuracy and precision (e.g. Bilker, 2005). This can be seen from Table 4, where the satellite-only GGMs EIGEN-3P and EIGEN-2 (degree and order equal 140) gave larger RMS values than the GGMs of degree and order 360, which is expected due to the omission errors. The only exception is EIGEN-CG03C, with degree and order 360, which produced a slightly worse RMS than GGM02C (degree and order 200).

Furthermore, several remarks can be made, based on the results presented in Table 5, concerning the performance of GGMs in terms of computing geoid undulations in Egypt. The most important point is that the EIGEN-CG01C produced the smallest mean undulation difference. Along with EIGEN-CG01C, GGM02C, EIGEN-CG03C, EIGEN-CLO4C and EGM96, all produced mean undulation differences less than half a metre. As expected, the satellite-only GGMs, EIGEN-3P and EIGEN-2, produced the largest mean undulation differences, which again can be attributed to their relatively low degree and order and, hence, their limited capacity to model the short wavelength variations of the gravity field (i.e. the omission errors). In terms of the RMS values, EIGEN-CG01C and EIGEN-CG03C performed the best, followed by EIGEN-GL04C, EGM96, and GGM02C. However the mean undulation differences were larger in the latter four cases.

It follows from the models tested and in terms of modeling known gravity anomalies and geoid undulations over Egypt, EIGEN-CG01C is the GGM that most accurately represents the gravity field. It is worth mentioning that the EIGEN-CG01C has been used to develop local gravimetric geoid models for Bolivia (Corchete *et al.*, 2006) and Iberia (Corchete *et al.*, 2005). Although it is one of the older models, EIGEN-CG01C was the second best of the GGMs compared against GPS/levelling data worldwide (see Table 2). Furthermore, it is likely that the performance of different GGMs varies from one region to another, particularly in areas where local gravimetric data have not been incorporated in the development of those GGMs. For example, Kiamehr (2006) used 260 GPS/levelling points to test the performance of several GGMs (CGM02S, CGM02C, EIGEN-02S, EIGEN-CG01, GPM98C, EGM96, and a tailored CGM02/EGM96) over Iran, and found that the satellite-only CGM02S fitted the GPS/levelling data best in both relative and absolute terms.

PERFORMANCE OF DTMS OVER EGYPT

Table 6 presents the statistics of the height differences for the four DTMs when compared to the local geodetic datasets. From the mean and RMS values it is clear that DTM2002 was superior to both the global DTMs (GTOPO30 and SRTM) and the local DTM (LDTM). It can be concluded therefore that DTM2002 will improve the development of a new gravimetric geoid for Egypt, particularly in the computation of the terrain corrections.

CONCLUSIONS

A significant step in the development of a precise geoid model for Egypt is the utilisation of a global geoid model that accurately maps the gravity field variations in this area, along with a DTM that represents the topographic variations with a considerable level of reliability.

The performance of eight recent GGMs has been compared against the local geodetic data over parts of Egypt. The results show that the EIGEN-CG01C is the best GGM in terms representing the gravity anomalies (with a mean difference of -20.9 mgal and an RMS of 25.9 mgal), and also in representing the geoid undulations (with a mean difference of -0.07 m and an RMS of 0.36 m). From these findings it is anticipated that the EIGEN-GC01C GGM will yield considerable enhancements within the FFT process for developing a local precise geoid model for Egypt.

Additionally, the DTM2002 has shown to be the more accurate terrain model, than either the global DTMs (GTOPO30 and SRTM) or the local DTM, in representing the topography variations in Egypt, with a mean height difference (as compared against known orthometric heights) of 0.6 m and an RMS of 20.7 m.

Therefore, it can be concluded that EIGEN-CG01C is the optimum global geoid model, and the DTM2002 is the optimum digital terrain model for use in Egypt. It is recommended that these two models should be utilised in the development of a new precise geoid for Egypt.

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DTM	Min	Max	Mean	RMS
GTOPO30	-332.0	214.2	-80.7	93.3
LDTM	-97.3	97.5	-3.0	25.9
SRTM	-132.5	94.0	-0.9	25.1
DTM2002	-80.8	73.9	0.6	20.7

Table 6. *Statistics of the height differences (observed - DTM) at 1264 check points (m)*

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