Evaluation and Adaptation of the EGM2008 Geopotential Model along the Northern Nile Valley, Egypt: Case Study

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Abstract: The performance of the new EGM2008 global geopotential model (GGM), over the northern Nile valley and delta in Egypt, has been evaluated. Over 305 global positioning system (GPS)/levelling stations, the standard deviation of the undulation differences has been estimated to be 0.23 m. Thus, it can be concluded that the EGM2008 is superior to earlier GGMs over the northern area of Egypt by a factor of 1.6. Moreover, four mathematical models have been investigated in order to incorporate local data sets with the EGM2008, leading to the conclusion that the first-order polynomial is the optimum one. An improvement of about 26% has been obtained after applying that regression model, and the standard deviation has been decreased to 0.17 m. As a result, the EGM2008 produces a crucial influence on integrated GPS surveys where the orthometric heights can be obtained without any additional costs. Such a practice presents a suitable alternative, from an economical point of view, to substitute the expensive traditional levelling technique particularly for topographic mapping.

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Introduction

Geoid models are used in GPS surveys in order to convert the GPS-based geodetic heights to orthometric heights usually used in surveying and mapping applications. A large number of global geopotential models (GGMs) have been released and used in geoid modeling all over the world. A basic utilization of GGMs is to represent the long wavelength component of the Earth gravitational field in modeling geoidal undulations [e.g., Daho et al. (2008) and Krynski and Lyszkowicz (2006)]. Combining GGMs and local geodetic data sets has been investigated extensively in order to increase the performance precision in local regions through minimizing the long-wavelength geoid errors and the datum inconsistencies between local height data and GPS data [e.g., Benahmeddaho and Fairhead (2007) and Reguzzoni et al. (2005)]. Such a procedure offers an appropriate alternative, from an economical point of view, to substitute the expensive traditional levelling technique.

Regarding Egypt, several researchers have investigated the utilization of GGMs in developing geoid models. For example, Ghanem (2001) has developed a 2.5×2.5 in. grid gravimetric national geoid for Egypt, based on the EGM96 GGM. When compared against (only) 10 GPS/levelling points, that geoid produced a standard deviation of 0.47 m and the standard deviation after fitting that gravimetric geoid to the GPS/leveling points was better than 0.13 m. Additionally, Amin et al. (2005) has used a tailored GGM model, denoted as EGM96EGCT, that was estimated up to degree and order 599, based on the coefficients of the EGM96 and all the available terrestrial geodetic data in Egypt. Then, that model was used to develop a gravimetric geoid model for Toshka area (about 1000 km south of Cairo) and, when compared against (only) 29 GPS/levelling points, produced a standard deviation of 0.16 m. Moreover, a recent study by Dawod (2008) has analyzed the performance of eight recent GGMs using local geodetic data sets (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. The objectives of this paper are to evaluate the performance of the most-recent released GGM (EGM2008) and to investigate the incorporation of local geodetic data sets in order to increase its precision in integrated GPS surveys in the Nile valley and delta area, Egypt. Moreover, the utilization of this new GGM in the African continent, in general, is also discussed.

EGM2008 Geopotential Model

The Earth Gravitational Model EGM2008 has been publicly released by the U.S. National Geospatial-Intelligence Agency (NGA) in mid-2008 (http://earth-info.nima.mil/GandG/wgs84/gravitymod/egm2008). This model is complete to degree and order 2,160, and contains additional spherical harmonic coefficients extending to degree 2,190 and order 2,159. Full access to the model's coefficients and other processing programs is available from the NGA site at http://earth-info.nima.mil/GandG/

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Table 1. RMS Differences of GPS-Levelling Minus GGM Derived Quasigeoid Heights (m) (after ICGEM)

Region	United States	Canada	Europe	Australia	All
Number of points	6,169	1,930	186	201	8,486
Gravity model (Year, degree)	RMS differences between GPS/leveling and GGM derived geoid undulations (in meters)				
EGM2008 (2008, 2,190)	0.25	0.13	0.19	0.22	0.22
EIGEN-05C (2008, 360)	0.34	0.25	0.29	0.24	0.32
EIGEN-GL04C (2006, 360)	0.34	0.25	0.34	0.25	0.32
EIGEN-CG03C (2005, 360)	0.35	0.31	0.39	0.26	0.34
EIGEN-CG01C (2004, 360)	0.35	0.27	0.41	0.26	0.33
EGM96 (1996, 360)	0.38	0.36	0.48	0.30	0.37

wgs84/gravitymod/index.html. Even before its official release, a primarily version of this model was distributed and being used in various researches [e.g., Felus et al. (2008) and Merry 2003: http://www.eepublishers.co.za/view.php?sid=13532]. EGM2008 model is a unique GGM representing the Earth gravitational field by spherical harmonic coefficients, since it precedes any earlier GGM by reaching degree and order equals 2,160.

The EGM2008 is based on the satellite-only gravity ITG-GRACE03S GGM combined with a recent global 5×5 in. terrestrial gravity anomaly data set. The EGM2008 does not include any GPS/levelling or astronomic deflection of the vertical data. Remarkable improvements have been obtained when EGM2008 has been compared against GPS/levelling in United States, where the weighted standard deviation has been decreased from 18.2 cm (for the EGM96) to 4.8 cm in case of removing a linear trend (Pavlis et al. 2008: http://earth-info.nima.mil/GandG/wgs84/gravitymod/egm2008/NPavlis&al_EGU2008.ppt).

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). To evaluate the performance of GGMs, their estimated height anomalies have been compared against geoid undulations at known GPS/levelling stations in United States, Canada, Europe, and Australia (for more details on this comparison and its results, see http://icgem.gfz-potsdam.de/ICGEM/evaluation/evaluation.html). Considering the number of GPS/levelling stations as the weights, a weighted mean of RMS, for all stations, has been computed for each GGM. The results are presented in Table 1, where the computed weighted RMS mean values are given in the last column. Obviously, the EGM2008 shows better precision than all other GGMs by a factor of at least 1.5, which indicates that it the most precise available GGM in this moment.

Additionally, the EGM2008 has produced significant improvements when compared to 1,542 GPS/levelling points in Greece, where the standard deviation decreased to about 0.14 m after a least square bias fit (Kotsakis et al. 2008). Another test of the EGM2008 GGM in Croatia has shown that its overall precision estimate is 0.088 m after removing a shift of 0.899 m (Liker et al. 2008).

Data Used

In order to assess the performance of the EGM2008 GGM over Egypt, a local geodetic data has been used. This recent database consists of 305 GPS/levelling points (Fig. 1), where geoid undulations have been directly computed. The majority of this data set comes from GPS campaigns carried out by the Nile Research Institute for updating the hydrotopographic maps of the Nile. It is a matter of fact that about 90% of the population of Egypt live in the Nile valley and delta region, and thus most of the surveying and geodetic activities, and thus data, exit in this area. Regarding this geodetic data set, both the GPS and the spirit levelling networks have been observed, through subsections, applying the first-order standards and specifications, and have adjusted using the least-square adjustment techniques. The orthometric heights of the stations have been obtained through tying the first-order levelling loops to the national vertical datum of Egypt that is based on the mean sea level at Alexandria tide gauge of 1906. The accuracy of the derived geoid undulations has been estimated to be ±5 cm (Dawod and Ismail 2005). The entire network has been used, in this study, in order to get reliable results about the performance of the EGM2008 using all available recent precise data.

Processing and Results

The first step in the processing strategy was to compute the EGM2008-based geoid undulations over the known points. The hsynth_WGS84.exe program, along with the two data files: EGM2008_to2190_TideFree.gz and Zeta-to-N_to2160_egm2008.gz have been downloaded from the NGA website. Then, the observed geoid undulations have been compared against the EGM2008 corresponding values at known points. The attained results are tabulated in Table 2, from which it can be noticed that the standard deviation of the undulation differences is 0.23 m. This precision measure of the EGM2008 GGM over Egypt is almost identical to its global precision value presented in Table 1.

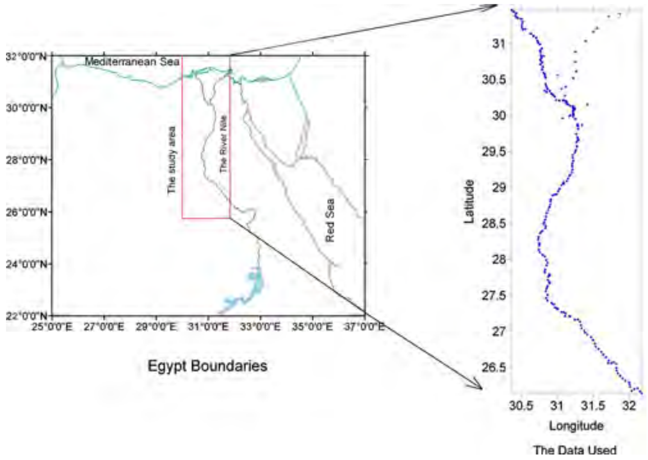

Fig. 1. GPS/levelling known stations

Table 2. Known and EGM2008 Geoid Undulations over Check Points (m)

	Minimum	Maximum	Mean	Standard deviation
Known undulations	12.00	16.84	14.33	1.15
EGM2008 undulations	11.91	17.40	14.55	1.26
Undulation differences	−0.76	0.41	−0.23	0.23

Table 3. Results of Models Relating the EGM2008 Undulations to Known Undulations over Check Points (m)

	Minimum	Maximum	Mean	Standard deviation
$\Delta N^1 = N_{\mathrm{obs}} - N^1_{\mathrm{EGM2008}}$	−0.53	0.44	−0.0004	0.19
$\Delta N^2 = N_{\mathrm{obs}} - N^2_{\mathrm{EGM2008}}$	−0.53	0.57	−0.0002	0.17
$\Delta N^3 = N_{\mathrm{obs}} - N^3_{\mathrm{EGM2008}}$	−0.50	0.57	−0.0003m	0.18
Kriging corrector surface	−0.53	0.57	−0.0003	0.17

Dawod (2008) has found out that the best GGM that represent the gravitational field over Egypt is the EIGEN-CG01C, which produced a standard deviation of the undulation differences that equals 0.36 m. Consequently, it can be concluded that the EGM2008 GGM is superior to earlier GGMs over Egypt by a factor of 1.6.

The second stage of processing was to modify the EGM2008 GGM to the local geodetic data in order to increases its precision performance. Several mathematical models have been proposed in such integration step [e.g., Tranes et al. (2007) and You (2006)]. In the current study, four models have been tested: a bias and a tilt, a first-order regression, a second-order regression, and the Kriging model. The attained bias and tilt's model has been found to be

$$N^1_{\mathrm{EGM2008}} - N_{\mathrm{EGM2008}} = 1.271413252 - 0.102945895 \times N_{\mathrm{EGM2008}} \tag{1}$$

where N_{EGM2008}=original geoid undulation of the EGM2008 GGM and N^1_{EGM2008}=modified corresponding value (both in meters).

The first-order regression model was computed as

$$N^2_{\mathrm{EGM2008}} - N_{\mathrm{EGM2008}} = -5.529490551 - 0.05161249\varphi + 0.219581806\lambda \tag{2}$$

where N^2_{EGM2008}=modified geoid undulation of the EGM2008 GGM (in meters); φ=geodetic latitude in decimal degrees; and λ=geodetic longitude in decimal degrees.

The coefficients of both latitude and longitude (φ and λ) in Eq. (2) represent slopes of the undulation differences between the observed and the EGM2008 undulations. It is suggested that these slopes are due to the errors associated with the GPS/levelling data and the inconsistence between the associated geodetic datums.

The second-order regression model was computed as

$$N^3_{\mathrm{EGM2008}} - N_{\mathrm{EGM2008}} = 72.70656003 - 0.585861292\varphi - 4.214098131\lambda + 0.009003071\varphi^2 + 0.069825898\lambda^2 \tag{3}$$

The fourth tested model was using the Kriging technique to develop a correction surface that spatially distributes the EGM2008 undulation difference in the study area. The Surfer software was used where the linear semivariogram method (Barnes 1991) was applied. Fig. 2 depicts the attained undulation difference residuals due to the above four methods. It can be seen, from this figure, that there is no specific spatial pattern in the distribution of the residuals. That is due to the existing inconsistencies between the datums implied by both the GPS and levelling data sets. For example, one of the major defects of the Egyptian national control networks (1906–1945) is that they have been adjusted section-by-section not in a unique rigorous least-square adjustment (Mohamed 2005). Additionally, the vertical datum of Egypt has been defined, in 1906, based on a single tide gauge station located at Alexandria harbor on the Mediterranean sea (ibid).

The achieved results, presented in Table 3, show that significant improvements have been obtained. The standard deviation of the EGM2008-based GGM has been decreased by about 0.26%. Also, the similarities exist between those models' residuals (Fig. 2) show that no large differences between the four tested math-

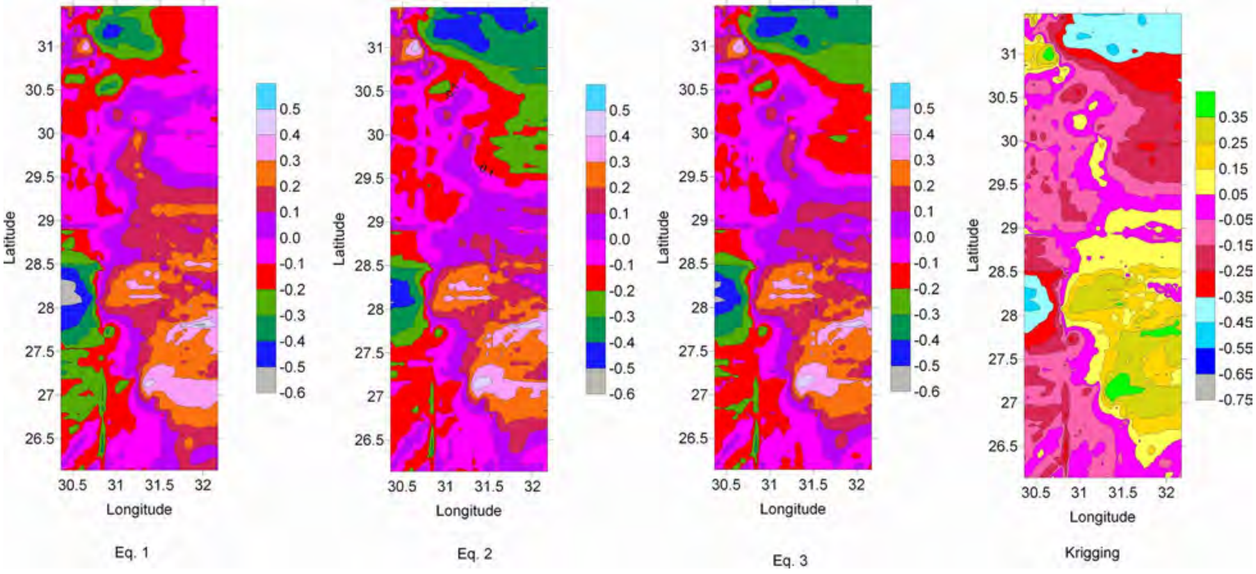

Fig. 2. Undulation difference residuals clue to the four used methods

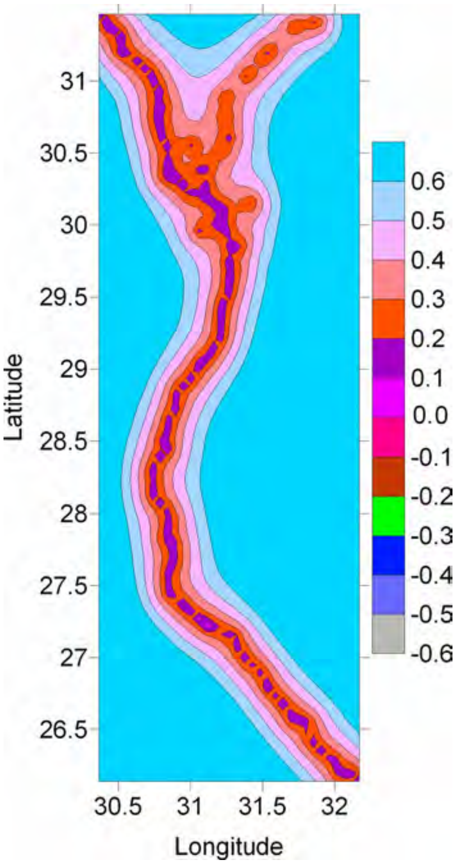

Fig. 3. Standard deviations of the Kriging method

ematical models. Moreover, it is clearly seen that the large residuals exist outside the area of the available data, where the extrapolation takes place. However, the first-order regression and the Kriging models produce relatively smaller standard deviation of the undulation differences (0.17 m). Hence, these two models are the suitable candidates in adapting the original EGM2008 undulations to local geodetic data in the study area. Fig. 3 presents the standard deviations of the Kriging output. It worth mentioning that such a surface is significantly applicable within the area where available data exist, since the extrapolation outside this area may introduce large errors. This can be clearly seen from Fig. 3 where the standard deviations within the data area is almost less than 0.2 m while it is increased to about 0.5 m in the outer area.

For integrated GPS surveys, the orthometric heights of the surveyed stations can be computed with a “reasonable” level of precision with no additional costs. This can be achieved by computing the EGM2008 geoid undulation values, using the NGA programs, and then compute the corresponding undulation corrections either by using Eq. (2) or by interpolating the corrector surface. The precision of this strategy in obtaining orthometric heights can be estimated to be 0.17 m. Even though this precision may not be suitable for high-precision surveying applications such as the augmentation of the national Egyptian vertical datum, it is acceptable in various surveying and mapping applications such as topographic mapping. Consequently, a considerable cost reduction is accomplished in GPS surveying projects in Egypt.

Additionally and on a continental basis, the precision of the EGM2008 suggests that it would be an appropriate GGM to be used in the on-going project for developing a geoid of Africa. This continental geoid is being developed as a component of the African Reference Frame project to define a continental reference system for Africa to be fully consistent and homogeneous with the global reference frame of the ITRF (Wonnacott 2006). A gravimetric geoid model called the African Geoid Project was developed based on the EGM96 GGM, and when compared against 8 GPS/levelling data in Egypt produced a standard deviation of 0.80 m (Merry 2003).

Conclusions

The release of the EGM2008 GGM, early this year, is a millstone step in enhancing gravitational and geoidal modeling on a global scale. Based on several comparisons against GPS/levelling data sets, the precision level of the EGM2008 is estimated to 0.22 m. In Egypt, it has been found that the best GGM that represent the gravitational field is the EIGEN-CG01C, which produced a standard deviation of the undulation differences that equals 0.36 m. This study has evaluated the performance of EGM2008 over 305 GPS/levelling points in the northern Nile valley and delta, Egypt, and has found that its precision is 0.23 m. Consequently, it can be concluded that the EGM2008 GGM is superior to earlier GGMs over this part of Egypt by a factor of 1.6. Furthermore, incorporating local geodetic data sets, in the study area, decrease this standard deviation figure to 0.17 m. Additionally, it has been found that the first-order regression model is the best mathematical relationship in modeling the undulation differences in the study area. Although this precision may not be appropriate for high-precision surveying applications such as the augmentation of the national Egyptian vertical datum, it is adequate in various surveying and mapping applications such as topographic mapping. Hence, it can be concluded that EGM2008 can play an essential role in integrated GPS surveys where the orthometric heights can be obtained without any additional costs. The presented methodology may be re-applied in the future having new GGMs released, or new local Egyptian geodetic data sets being collected in other regions. On a continental basis, the precision of the EGM2008 suggests that it would be the appropriate GGM, for the time being, to be used in the on-going effort for developing a geoid of Africa.

Notation

The following symbols are used in this paper:

N_{EGM2008} = original geoid undulation of the EGM2008 GGM (meter);

N^{1}_{EGM2008}, N^{2}_{EGM2008}, and N^{3}_{EGM2008} = modified geoid undulation of the EGM2008 GGM due to several regression models (meter);

λ = geodetic longitude (decimal degrees); and

φ = the geodetic latitude (decimal degrees).

References

Amin, M., El-Fatairy, S., and Hassouna, R. (2005). “A precise geoidal map of the southern part of Egypt by collocation: Toshka geoid.” *FIG Working Week 2005 and GSDI-8 Conf.*, International Federation of Surveyors, Cairo, Egypt.

Barnes, R. (1991). “The variogram sill and the sample variance.” *Math.*

Geol., 23(4), 673–678.

Benahmeddaho, S., and Fairhead, J. (2007). "Accuracy assessment of the available geoid models in Algeria." *Comput. Geosci.*, 33, 76–82.

Daho, S., et al. (2008). "New investigation on the choice of the tailored geopotential model for Algeria." *J. Geodyn.*, 45, 154–162.

Dawod, G. (2008). "Towards the redefinition of the Egyptian geoid: Performance analysis of recent global geoid models and digital terrain models." *Journal of Spatial Science*, 53(1), 31–42.

Dawod, G., and Ismail, S. (2005). "Enhancing the integrity of the national geodetic data base in Egypt." *Proc., FIG Working Week and GSDI-8 Int. Conf.*, International Federation of Surveyors, Cairo, Egypt.

Felus, Y., Steinberg, G., and Tuchin, Y. (2008). "On the augmentation of Isreaeli GPS-BM data with a global earth geoid model." *Proc., FIG Working Week 2008*, International Federation of Surveyors, Stockholm, Sweden.

Ghanem, E. (2001). "GPS-gravimetric geoid determination in Egypt." *Geo-spatial Information Science*, 4(1), 19–23.

Kotsakis, C., Katsambalos, K., and Ampatzidis, D. (2008). "Evaluation of EGM2008 using GPS and leveling heights in Greece." ⟨http://users.auth.gr/~kvek/Crete_Paper_2008.pdf⟩.

Krynski, J., and Lyszkowicz, A. (2006). "Regional quasi-geoid determination in the area of Poland." *Proc., 5th FIG Regional Conf.*, International Federation of Surveyors, Accra, Ghana.

Liker, M., Lucic, M., Barisic, B., Repanic, M., and Grgic, I. (2008). "How most recent global geopotential models fit the Croation territory." ⟨http://www.cgi.hr/radovi/how%20most%20recent%20global%20geopotential%20models%20fit%20the%20croatian%20territory.pdf⟩.

Merry, C. (2003). "The African geoid project and its relevance to the unification of African vertical reference frames." *Proc., 2nd FIG Regional Conf.*, International Federation of Surveyors, Marrakech, Morocco.

Mohamed, H. (2005). "Realization and redefinition of the Egyptian vertical datum based on recent heterogeneous observations." Ph.D. dissertation, Shoubra Faculty of Engineering, Benha Univ., Cairo, Egypt.

Pavlis, N., Holmes, S., Kenyon, S., and Factor, J. (2008). "An earth gravitational model to degree 2160." EGM2008, Proc., European Geosciences Union general assembly, Vienna.

Reguzzoni, M., Sanso, F., and Venuti, G. (2005). "The theory of general kriging, with applications to the determination of a local geoid." *Geophys. J. Int.*, 162(2), 303–314.

Tranes, M., Meyer, T., and Massalski, D. (2007). "Comparisons of GPS-derived orthometric heights using local geometric geoid models." *J. Surv. Eng.*, 133(1), 6–13.

Wonnacott, R. (2006). "The AFREF Project: Background, rationale and progress." *Proc., 5th FIG Regional Conf.*, International Federation of Surveyors, Accra, Ghana.

You, R. (2006). "Local geoid improvement using GPS and leveling data: Case study." *J. Surv. Eng.*, 132(3), 101–107.