*Geophysica* (2023), 58 (1), 33–45

# Recent High-Order Global Geopotential Models for Geoid Modelling in Egypt

*Gomaa Dawod*[1,*] *and Essam Al-Krargy*[1]

[1]Survey Research Institute, National Water Research Center, Giza, Egypt
[*]Corresponding mail address: `gomaa_dawod@nwrc.gov.eg`

(Submitted: 2023-03-07; Accepted: 2023-07-05)

## *Abstract*

*An optimum Global Geopotential Model (GGM) is required either to represent the long wavelength of the Earth's gravitational field in gravimetric geoid modelling or to act as a stand-alone national geoid in some developing countries. Thus, the current research aims to investigate the performance of seven recent high-order GGMs over Egypt utilizing the most recent precise Global Navigation Satellite Systems(GNSS)/Levelling datasets. Attained results showed that the investigated GGMs perform differently over Egypt with an accuracy level varying between* $\pm 0.249\,\mathrm{m}$ *for the SGG-UGM-1 model and* $\pm 0.300\,\mathrm{m}$ *for the GECO model. Removing outliers in the terrestrial dataset reveal significant improvements, in terms of standard deviations. Consequently, the performance of the investigated GGMs has been modified where the EIGEN-6C4 model became the best model with a standard deviation equals* $\pm 0.172\,\mathrm{m}$. *Furthermore, a 3D spatial correction surface has been constructed and has been added to the original EIGEN-6C4 model to get an enhanced version of the global EIGEN-6C4. Over checkpoints, the average error of the enhanced model equals* $-0.018\,\mathrm{m}$ *with a standard deviation equal* $\pm 0.011\,\mathrm{m}$. *That means that incorporating terrestrial geodetic data into the global EIGEN-6C4 model has increased its accuracy in Egypt by almost 36 %. Accordingly, such developed enhanced GGM represent the optimum stand-alone geoid model in Egypt. Nevertheless, such accuracy levels of GGMs do not fulfill the requirements of high-accuracy surveying and civil engineering applications. That concludes that a precise national geoid model is still crucial. It is recommended that all available geodetic datasets should be collected from all governmental and private organizations to construct a national geodetic database that would be implemented in modelling an Egyptian local geoid.*

*Keywords: Global Geopotential Models (GGMs); geoid modelling; GNSS/levelling; gravity field; corrector surface*

## *1 Introduction*

A geoid model is required in a wide range of geodetic, mapping, civil engineering, and environmental applications as a height conversion tool to transform the Global Navigation Satellite Systems (GNSS)-based ellipsoidal heights to the Mean Sea Level (MSL)-based orthometric heights. A geoid model can be developed from large enough and well-distributed gravity and/or GNSS/Levelling datasets over a particular spatial region. Geoid modelling is still an essential task for geodesists worldwide in different countries and continents such as Indonesia (*Lestari et al.*, 2022), Iraq (*Jassim and Yousef*, 2021), Thailand (*Phinyo et al.*, 2021), Africa (*Abd-Elmotaal et al.*, 2020), Saudi Arabia (*Borghi et al.*, 2020), India (*Singh and Srivastava*, 2018), and Egypt (*Dawod and Mohamed*, 2022).

Global Geopotential Models (GGM) have been developed during the last few decades to describe the long wavelength of the Earth's gravitational field. GGM can also be utilized as a local geoid model in a regional scale acknowledging their precision limits and their validation in different geodetic and geophysical activities. Analysis of the properties of the available GGMs for selecting the optimum model in a region or a country is necessary as their accuracies are varying spatially. Such an analysis has been performed recently in several countries. For example, *Tocho et al.* (2022) investigated the accuracy of five high-resolution GGMs over GNSS/Levelling points in Argentina. Similarly, *Isik et al.* (2022) analyzed the performance of GGMs for gravimetric geoid modelling in Turkey. Also, high-order GGMs were evaluated over Sudan based on GNSS/Levelling datasets (*Osman et al.*, 2021). *Liang et al.* (2022) proposed a new method for improving GGMs using GNSS/Levelling data and applying this approach in China.

GGM analysis has been done extensively in Egypt, in the last couple of decades, either nationally or regionally. For an instant, *Hamdy and Elshewy* (2022) tested the GGMs performance in Northern Egypt over GNSS/Levelling stations. In addition, *Elsaka and El-Ashquer* (2022) combined GGMs-based gravity anomalies and terrestrial gravity observations to determine a local geoid model in the Western desert of Egypt. *Elwan et al.* (2021) developed a local geoid model also for the western desert of Egypt combining terrestrial gravity and GGMs. Also, GGMs were investigated for geoscience and archaeology activities in Egypt (*Klokočníka et al.*, 2020). In addition, (*Dawod et al.*, 2019) examined the accuracy of a particular GGM over Egypt and Northeast Africa using gravity and GNSS/Levelling datasets.

An optimum GGM is required either as a tool to derive geoid undulation or to be utilized in gravimetric geoid modelling over an area. The current study aims to assess the local accuracy of some recent high-resolution GGMs using local geodetic datasets to determine the most accurate one which has geoid undulations best fit the observed GNSS/Levelling values over the Egyptian territories.

## 2 *Available data*

Since 1966, the International Center for Global Earth Model (ICGEM) has collected and published GGMs with variable data characteristics and maximum orders or maximum degree of spherical harmonics (*ICGEM*, 2023). Out of the available 178 GGMs, seven models were selected for this study. All of them are high order with order ranges between 1949 and 2190 released between 2011 and 2020. Table 1 summarized the characteristics of the selected models. The ICGEM organization evaluates the accuracy of each GGM, i.e., the Root Mean Square (RMS) about the mean of GNSS/levelling minus gravity field model derived geoid heights, over 24 014 GNSS/Levelling points in several countries and publishes the RMS of those discrepancies (Table 2.1). It can be noticed that the accuracy (indicated by the RMS) of the selected GGMs ranges between $\pm 0.173$ m and $\pm 0.187$ m.

Egypt lies in the Northeast region of Africa from 24.7°E to 37°E and from 22°N to 31.6°N (Fig. 2.1). Its topography is nearly smooth, MSL heights vary between $-137$ m in the Katarra depression and in some northern lakes to 2600 m in mountainous regions in

Table 2.1: Characteristics of the Utilized High-Order GGMs (after *ICGEM*, 2023).

| No | GGM | Year | Degree | Data* | Accuracy: RMS (m) | Reference |
|---|---|---|---|---|---|---|
| 1 | `SGG-UGM-2` | 2020 | 2190 | A, EGM2008, S(GOCE), S(Grace) | ± 0.177 | *Liang et al.*, 2020 |
| 2 | `XGM2019e_2159` | 2019 | 2190 | A, G, S(GOCO6s), T | ± 0.173 | *Zingerle et al.*, 2020 |
| 3 | `GECO` | 2015 | 2190 | EGM2008, S(GOCE) | ± 0.176 | *Gilardoni et al.*, 2016 |
| 4 | `EIGEN-6C4` | 2014 | 2190 | A, G, S(GOCE), S(Grace), S(Lageos) | ± 0.178 | *Förste et al.*, 2014 |
| 5 | `EGM2008` | 2008 | 2190 | A, G, S(Grace) | ± 0.187 | *Pavlis et al.*, 2012 |
| 6 | `SGG-UGM-1` | 2018 | 2159 | EGM2008, S(GOCE) | ± 0.176 | *Liang et al.*, 2018 |
| 7 | `EIGEN-6C3stat` | 2014 | 1949 | A, G, S(GOCE), S(Grace), S(Lageos) | ± 0.179 | *Förste et al.*, 2012 |

* where A denotes altimetry, S is for satellite gravity missions (e.g., GRACE, GOCE, LAGEOS), G for ground data (e.g., terrestrial, shiborne and airborne measurements) and T is for topography.

the Sinai, Red Sea coasts, and in southwest regions. The average MSL height of Egypt is 302 m.

In total 736 national GNSS/Levelling points were utilized to investigate the accuracy of the selected GGMs over Egypt (*SRI*, 2022). These points were measured by the Survey Research Institute (SRI) of the National Water Research Center (NWRC) in several national projects over the last few years. Their accuracies, in terms of both ellipsoidal and orthometric heights, have been estimated to be less than ±0.05 m (ibid). Thus, they might be considered the most accurate geodetic datasets in Egypt. Figure 2.1 depicts the spatial distribution of the available geodetic dataset.

## *3 Methodology*

Overall, the processing methodology of the current research (Fig. 3.1) comprises few steps: estimating the GGMs-based geoid undulations, comparing them to the corresponding values over the known GNSS/Levelling checkpoints, to determine the best GGM that describes the Earth's gravitational field over Egypt accurately.

Global geopotential models express the gravitational potential of the Earth ($V$) into a series of spherical harmonics as (*Hofmann-Wellenhof and Moritz*, 2005)

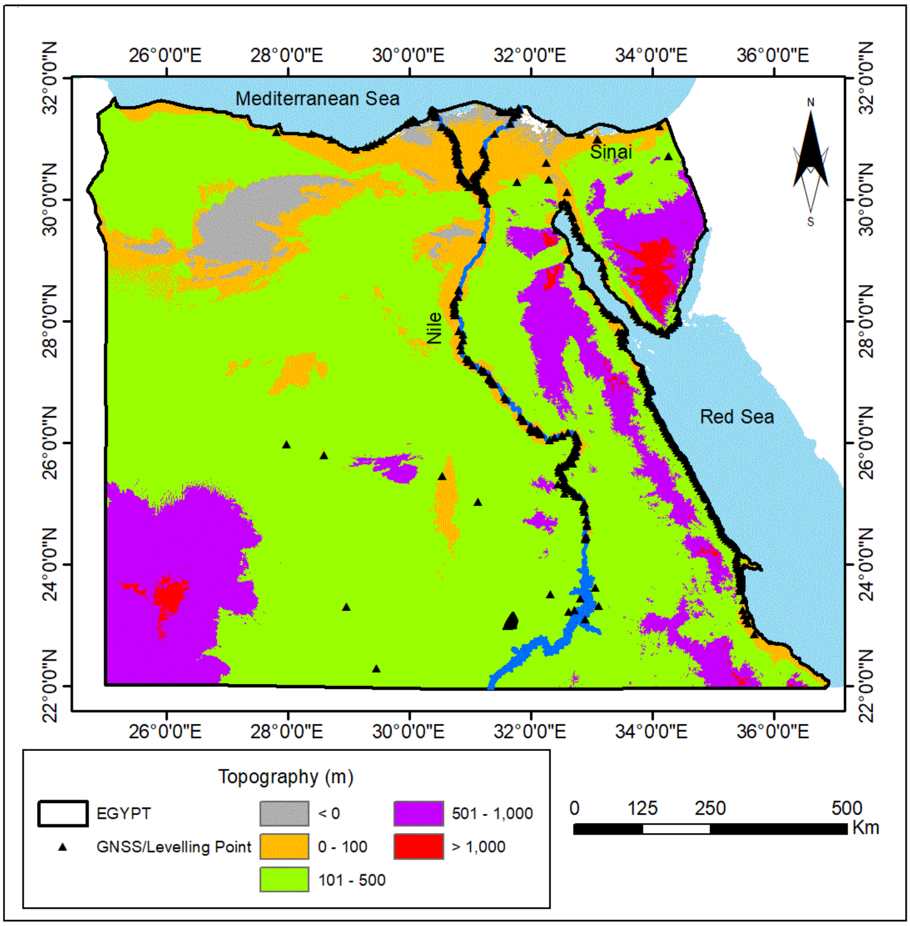


Fig. 2.1: The Study Area and Available Data.

$$V = \frac{GM}{r}\left(1-\sum_{\mathrm{n}=2}^{\infty}\left(\frac{a}{r}\right)^{n} J_{\mathrm{n}}P_{\mathrm{n}}(\cos\vartheta) + \sum_{\mathrm{n}=2}^{\infty}\sum_{\mathrm{m}=1}^{\mathrm{n}}\left(\frac{a}{r}\right)^{n}\left[C_{\mathrm{nm}}\cos m\lambda + S_{\mathrm{nm}}\sin m\lambda\right]P_{\mathrm{nm}}(\cos\vartheta)\right), \tag{3.1}$$

where $GM$ is the gravitational constant, $r$ is the radial distance, $a$ is the equatorial radius of the Earth, $\theta$ and $\lambda$ are the geodetic latitude and longitude respectively, $J_{\mathrm{n}}$ are the zonal harmonics, those contain the $S_{\mathrm{nm}}$ and $C_{\mathrm{nm}}$ are the tesseral harmonics, $P_{\mathrm{nm}}$ are the associated Legendre coefficients, $n$ and $m$ are the degree and order of the geopotential model.

Then, the geoid undulations of each investigated GGM, $N_{\mathrm{GGM}}$, could be evaluated as (*Dawod et al.*, 2019):

$$N_{\mathrm{GGM}} = \frac{GM}{r\gamma}\sum_{\mathrm{n}=2}^{\mathrm{n_{max}}}\left(\frac{a}{r}\right)^{n} - \sum_{\mathrm{m}=0}^{\mathrm{n}}\left[(C_{\mathrm{nm}}\cos m\lambda)+(S_{\mathrm{nm}}\sin m\lambda)\right]P_{\mathrm{nm}}(\sin\vartheta)\ , \tag{3.2}$$

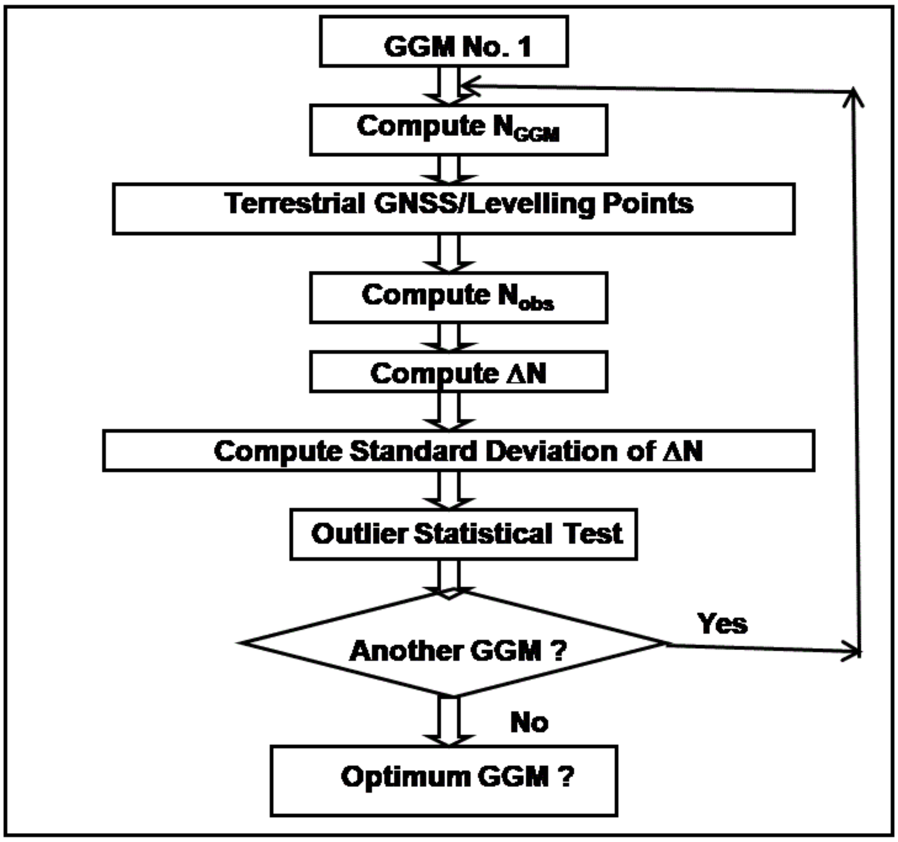


Fig. 3.1: The processing flow.

where $n_{\max}$ is the maximum degree of the GGM, and $\gamma$ is the normal gravity.

On the other hand, the observed geoid undulations, $N_{\text{obs}}$, is the difference between GNSS ellipsoidal heights, $h$, and the MSL orthometric heights, $H$, at each observed terrestrial station:

$$N_{\text{obs}} = h - H \tag{3.3}$$

Thus, the GGM's errors, $\Delta N$, can be defined at each observed point as

$$\Delta N = N_{\text{GGM}} - N_{\text{obs}} \; . \tag{3.4}$$

The standard deviation of the GGM discrepancies, $\sigma_{\Delta N}$, can be estimated as

$$\sigma_{\Delta N} = \sqrt{\sum_{\text{i=1}}^{\text{P}} (\Delta N_i - \Delta N_{\text{mean}})^2} \; , \tag{3.5}$$

where P denotes the total number of available GNSS/Levelling points, and $\Delta N_{\text{mean}}$ is the average of GGM's errors [Eq. (3.4)] at all stations.

Furthermore, an outlier detection statistical test was used to detect and remove erroneous levelling measurements. The utilized criteria for an outlier in the observation is

$$\frac{[\Delta N_{\mathrm{i}}]}{\sigma_{\Delta N}} > 3\ . \tag{3.6}$$

## *4 Processing and results*

The harmonic coefficients of the each selected GGM were downloaded from the ICGEM website (*ICGEM*, 2023). The Gravsoft package (*Forsberg and Tscherning*, 2008) was used for generating a grid presenting geoid undulation in Egypt for each selected GGM. The grid values are initiated with label of latitude ($\varphi$) and longitude ($\lambda$) and spacing. The grid label defines the exact latitude and longitude of the grid points, irrespectively whether the grids point values or average values over grid cells. The gridding procedure could be also applied using the UTM projected coordinates (ibid). Table 4.1 summarizes the characteristics of the attained results. Together with spatial analysis it can be concluded that there are no significant differences between the selected GGMs in Egypt. Geoid undulation and spatial distribution of the selected GGMs are almost identical expect some minor differences in the Sinai Peninsula and the western desert.

Table 4.1: Statistics of the GGM-Based Geoid Undulations in Egypt

| **No.** | **GGM** | **Minimum (m)** | **Maximum (m)** | **Average (m)** |
|---|---|---|---|---|
| 1 | `SGG-UGM-2` | 5.1 | 23.6 | 14.8 |
| 2 | `XGM2019e_2159` | 5.1 | 23.6 | 14.8 |
| 3 | `GECO` | 5.0 | 23.6 | 14.8 |
| 4 | `EIGEN-6C4` | 5.1 | 23.6 | 14.8 |
| 5 | `EGM2008` | 5.2 | 23.7 | 14.8 |
| 6 | `SGG-UGM-1` | 5.1 | 23.6 | 14.8 |
| 7 | `EIGEN-6C3stat` | 5.1 | 23.6 | 14.8 |

Next, each selected GGM was compared with the SRI 2021 national gridded geoid model developed by *Al-Karargy and Dawod* (2021). This model has an accuracy of ±0.13 m (ibid) and it was developed using 247 first-order terrestrial gravity observations and fitted to 900 GNSS/Levelling stations. It can be considered as the most recent and accurate national geoid model of Egypt, and thus the comparison of the selected GGMs with this model is useful in determining the optimum GGM. The differences between the geoid undulations are shown in Table 4.2.

Furthermore, a comparison between the GNSS/Levelling points and the GGMs was done. The GGMs perform roughly similarly with a minimum standard deviation of ±0.249 m for the `SGG-UGM-1` model and a maximum ±0.300 m for the `GECO` model (Table 4.3). However, such levels of accuracy are greater than the ones presented in Table 2.1 for the GGMs. That might indicate that the terrestrial dataset may include some erroneous measurements or outliers. Thus, the statistical test [Eq. (3.6)] was performed and as a result, almost 10 % of the available points were removed from the dataset. After removing outliers significant improvements, in terms of standard deviations, were

Table 4.2: Differences between the GGMs and the SRL2021 Local Geoid Model (SDs = Standard Deviations).

| No. | GGM | Minimum (m) | Maximum (m) | Average (m) | SDs (m) |
|---|---|---|---|---|---|
| 1 | `SGG-UGM-2` | −1.7 | 2.6 | 0.8 | ± 0.37 |
| 2 | `XGM2019e_2159` | −0.5 | 3.2 | 0.8 | ± 0.33 |
| 3 | `GECO` | −1.7 | 2.2 | 0.7 | ± 0.36 |
| 4 | `EIGEN-6C4` | −1.9 | 2.4 | 0.7 | ± 0.36 |
| 5 | `EGM2008` | −2.9 | 2.7 | 0.7 | ± 0.51 |
| 6 | `SGG-UGM-1` | −1.7 | 2.2 | 0.7 | ± 0.36 |
| 7 | `EIGEN-6C3stat` | −1.9 | 2.4 | 0.7 | ± 0.36 |

obtained (Table 4.4). Fig. 4.2 depicts the histogram distribution of GGMs errors over the entire spatial study area. It shows that some GGMs depict closely the normal distribution curve while others do not. From this figure and table, it can be recognized that the `EIGEN-6C4` model became the best model with a standard deviation of ±0.172 m and the `SGG-UGM-1` model the worst one with a standard deviation of ±0.194 m.

Table 4.3: Discrepancies of the GGM-Based Geoid Undulations over GNSS/Levelling Stations Before Removing Outliers (SDs = Standard Deviations).

| No. | GGM | Minimum (m) | Maximum (m) | Average (m) | SDs (m) |
|---|---|---|---|---|---|
| 1 | SGG-UGM-2 | −0.712 | 0.703 | −0.371 | ± 0.286 |
| 2 | XGM2019e_2159 | −0.700 | 0.703 | −0.347 | ± 0.287 |
| 3 | GECO | −0.719 | 0.717 | −0.332 | ± 0.300 |
| 4 | EIGEN-6C4 | −0.710 | 0.688 | −0.342 | ± 0.275 |
| 5 | EGM2008 | −0.666 | 0.638 | −0.298 | ± 0.252 |
| 6 | SGG-UGM-1 | −0.660 | 0.649 | −0.362 | ± 0.249 |
| 7 | EIGEN-6C3stat | −0.709 | 0.707 | −0.340 | ± 0.284 |

Table 4.4: Discrepancies of the GGM-Based Geoid Undulations over GNSS/Levelling Stations After Removing Outliers (Min = Minimum, Max = Maximum, Avg = Average).

| No. | GGM | Min (m) | Max (m) | Avg (m) | Standard Deviations (m) | |
|---|---|---|---|---|---|---|
| | | | | | Value | Improvements |
| 1 | SGG-UGM-2 | −0.499 | 0.478 | −0.258 | ± 0.190 | 51% |
| 2 | XGM2019e_2159 | −0.500 | 0.506 | −0.250 | ± 0.205 | 40% |
| 3 | GECO | −0.501 | 0.494 | −0.223 | ± 0.190 | 58% |
| 4 | EIGEN-6C4 | −0.504 | 0.484 | −0.216 | ± 0.172 | 60% |
| 5 | EGM2008 | −0.493 | 0.505 | −0.208 | ± 0.191 | 32% |
| 6 | SGG-UGM-1 | −0.501 | 0.498 | −0.250 | ± 0.194 | 28% |
| 7 | EIGEN-6C3stat | −0.499 | 0.496 | −0.216 | ± 0.179 | 59% |

The discrepancies of the `EIGEN-6C4` model over the 666 GNSS/Levelling stations (remain after outlier detection over the available 736 points) were spatially modeled to construct a spatial correction surface over Egypt. Furthermore, 66 points were reserved for the final quality check. The obtained correction surface was added to the original

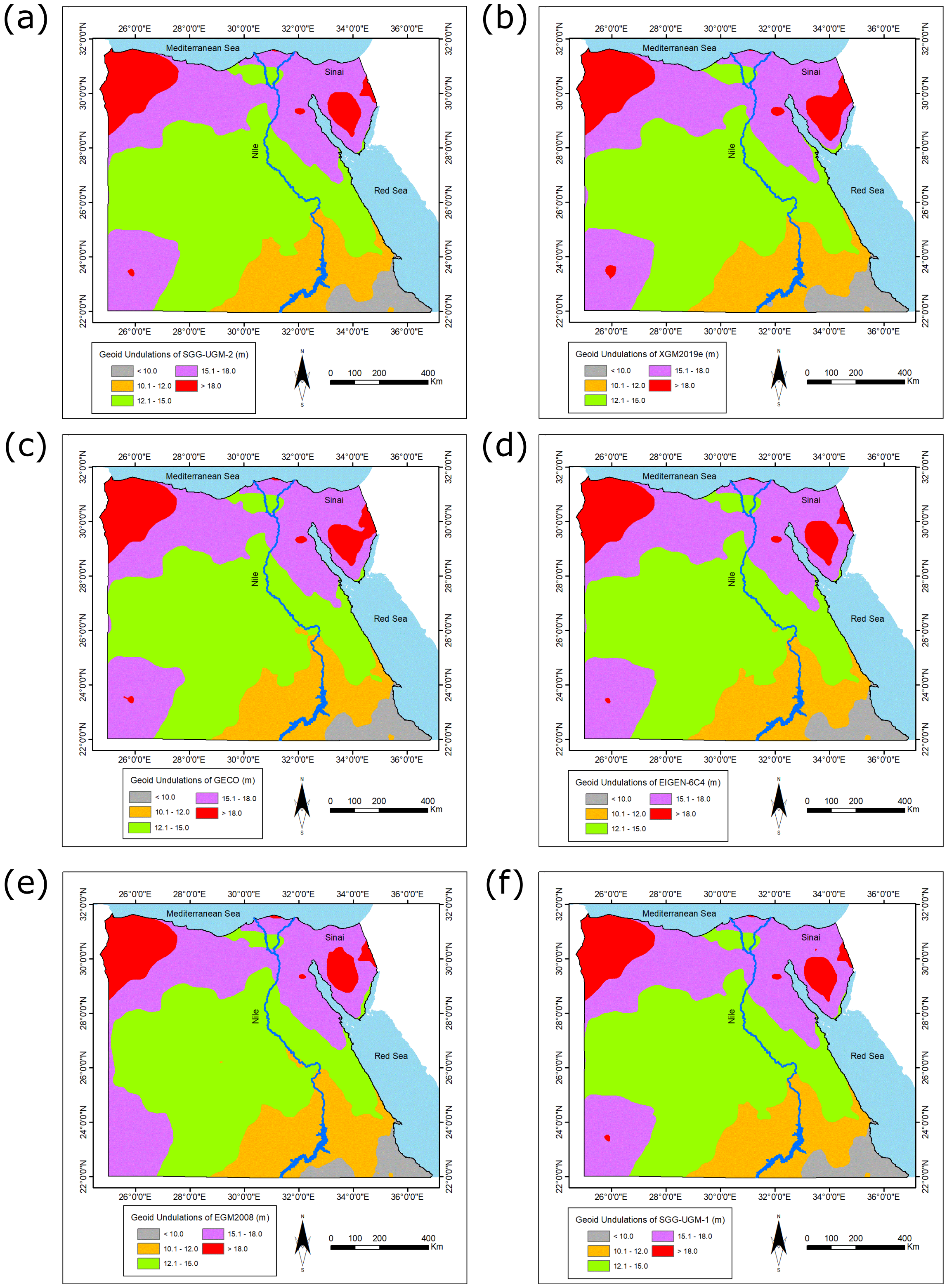
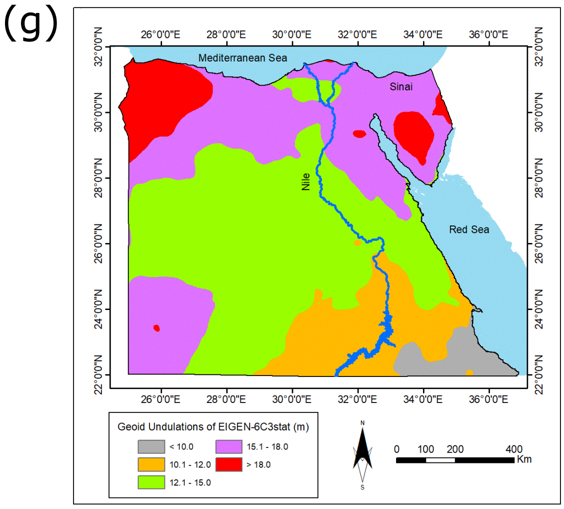


Fig. 4.1: GGM-Based Geoid Undulations over Egypt, (a) SGG-UGM-2, (b) XGM2019e_2159, (c) GECO, (d) EIGEN-6C4, (e) EGM2008, (f) SGG-UGM-1, (g) EIGEN-6C3stat (see next page).

`EIGEN-6C4` model and an updated version of the global model was generated (Fig. 4.3). Over the 66 checkpoints, the errors of the updated model vary between −0.180 m and



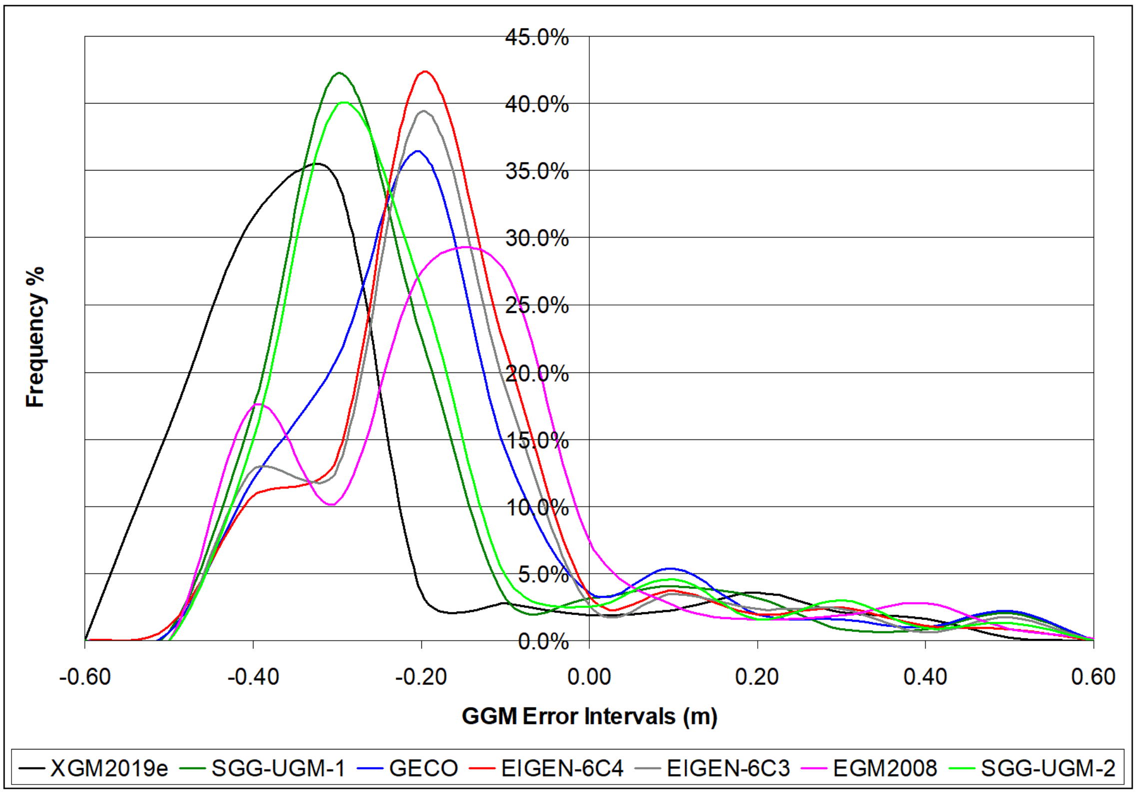


Fig. 4.2: Histograms of GGM Errors.

0.143 m with a mean of −0.018 m and a standard deviation equals ±0.011 m. Incorporating terrestrial geodetic data into the global `EIGEN-6C4` model has increased its accuracy in Egypt by almost 36 % as the overall standard deviation has been decreased from ±0.172 m to ±0.110 m. Even though some previous studies (e.g., *Hamdy and Elshewy*, 2022) estimated smaller errors of other GGMs over certain small spatial regions within Egypt, the attained findings in the current research might be superior since the processing has been performed over the entire Egyptian territories. Thus, the accomplished updated GGM (Fig. 4.3) provides the optimum stand-alone geoid model in Egypt.

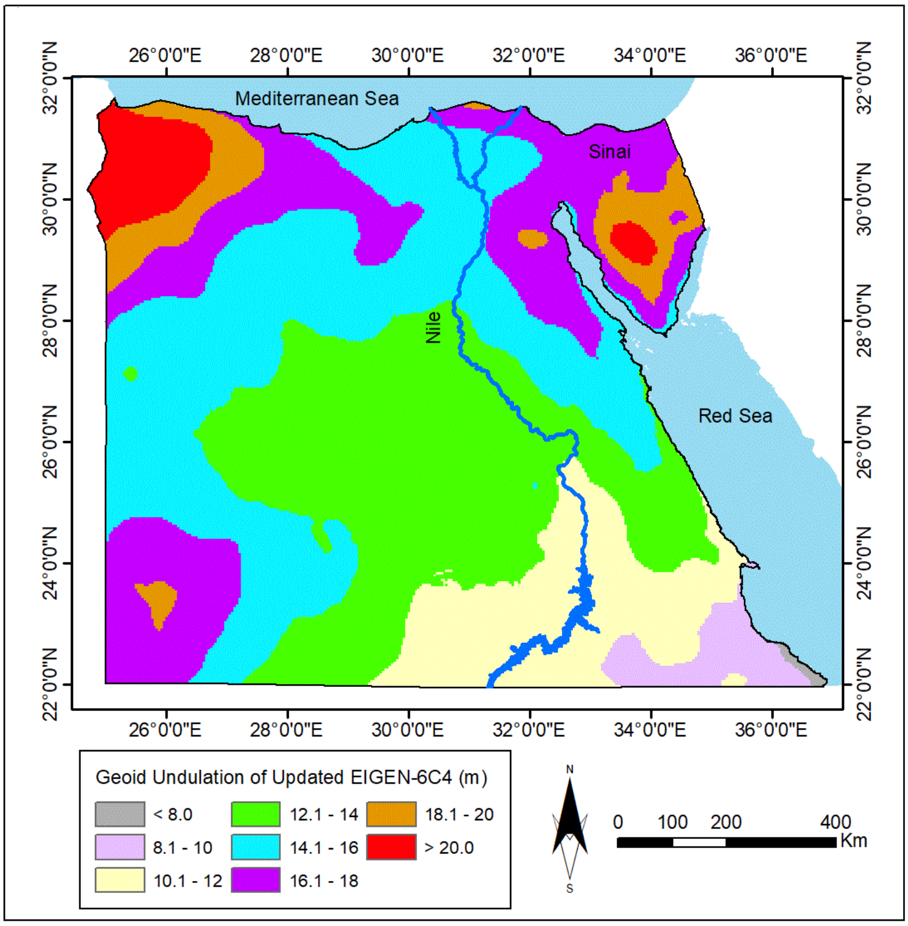


Fig. 4.3: Updated EIGEN-6C4 GGM Geoid Undulations in Egypt.

## *5 Discussion and conclusions*

An optimum Global Geopotential Model (GGM) is necessary either to represent the long wavelength of the Earth's gravitational field in gravimetric geoid modelling or to act as a stand-alone national geoid in some developing countries. In several developing countries, there are no published accurate geoid models to be utilized as a height conversion tool in GNSS surveying and mapping projects. Thus, selecting the optimum GGM and updating it with local geodetic datasets in a country could be a cost-effective alternative. The current research aims to investigate the performance of seven recent high-order GGMs in Egypt. The investigated models consist of `SGG-UGM-2`, `XGM2019e_2159`, `GECO`, `EIGEN-6C4`, `EGM2008`, `SGG-UGM-1`, and `EIGEN-6C3stat` models. The assessment has been performed utilizing the most recent precise Global Navigation Satellite Systems(GNSS)/Levelling datasets in Egypt.

Over the available GNSS/Levelling stations, the investigated GGMs perform roughly comparable with a standard deviation varies between ±0.249 m and ±0.300 m. Since those levels of accuracy are different from the published worldwide ones, it might indicate that the terrestrial dataset may include some erroneous measurements or outliers. Performing a statistical test for outlier detection resulted in removing almost 10 % of the available stations After outliers are flagged and removed, a 3D spatial correction surface over the Egyptian territories has been constructed and it has been added to the original `EIGEN-6C4` model to get an updated version of the global `EIGEN-6C4`. The comparison over checkpoints revealed that the errors of the updated model have a mean of $-0.018\,\mathrm{m}$ and a standard deviation equals $\pm 0.011\,\mathrm{m}$. That concludes that incorporating terrestrial geodetic data into the global `EIGEN-6C4` model has increased its accuracy in Egypt by almost 36 % as the overall standard deviation has been decreased from $\pm 0.172\,\mathrm{m}$ to $\pm 0.110\,\mathrm{m}$.

It should be noticed that some previous studies reported small errors of GGMs over small particular regions within Egypt, the current research has the advantage of performing the GGMs analysis over the entire country to select the most accurate model from a national perspective. Thus, such an accomplished updated GGM represents the optimum stand-alone geoid model in Egypt.

However, such accuracy levels of GGMs do not meet the requirements of high-accuracy surveying and civil engineering applications. That concludes that a precise national geoid model is still a must. It is recommended that all available geodetic datasets should be collected from all governmental and private organizations to construct a national geodetic database that will be implemented in modelling an Egyptian local geoid.

## *References*

Abd-Elmotaal, H. A., N. Kühtreiber, K. Seitz and B. Heck, 2020. "A Precise Geoid Model for Africa: AFRgeo2019". In: *Beyond 100: The Next Century in Geodesy*. Ed. by J. T. Freymueller and L. Sánchez. Cham: Springer International Publishing, 77–87. ISBN: 978-3-031-09857-4.

Borghi, A., R. Barzaghi, O. Al-Bayari and S. Al Madani, 2020. Centimeter precision geoid model for Jeddah region, Saudi Arabia. *Remote Sensing*, **12**, 2066. DOI: `10.3390/rs12122066`.

Dawod, G. and H. Mohamed, 2022. GIS-based geoid refinement by GNSS/levelling data: A case study of Egypt. *International Journal of Engineering Inventions*, **11** (2), 25–32.

Dawod, G., H. Mohamed and E. Al-Krargy, 2019. Accuracy assessment of the PGM17 global geopotential model: a case study of Egypt and Northeast Africa. *Arabian Journal of Geosciences*, **12**, 246. DOI: `10.1007/s12517-019-4418-9`.

Elsaka, B. and M. El-Ashquer, 2022. Determination of local quasi-geoid models using FFT estimation technique based on combined gravity anomalies from CHAMP, GRACE, GOCE, future satellite missions and in-situ gravity observations in western desert of Egypt. *IOSR Journal of Applied Geology and Geophysics*, **10** (1), 15–24.

Elwan, M., A. Helaly, K. Zharan, E. Issawy and A. Abd El-Gawad, 2021. Local geoid model of the western desert in Egypt using terrestrial gravity data and global geopotential models. *Arabian Journal of Geosciences*, **14**, 1436. DOI: `10.1007/s12517-021-07817-6`.

Forsberg, R. and C. Tscherning, 2008. *Gravsoft geodetic gravity field modelling programs*. National Space Institute, Denmark.

Förste, C., S.L. Bruinsma, F. Flechtner, J.C. Marty, J.M. Lemoine, C. Dahle, O. Abrikosov, K. Neumayer, R. Biancale, F. Barthelmes and G. Balmino, 2012. “A preliminary update of the Direct approach GOCE Processing and a new release of EIGEN-6C”. Presented at AGU Fall Meeting, San Francisco, USA.

Förste, C., L. Sean, O. Abrikosov, J. Lemoine, J. Marty, F. Flechtner, G. Balmino, F. Barthelmes and R. Biancale, 2014. *EIGEN-6C4 The latest combined global gravity field model including GOCE data up to degree and order 2190 of GFZ Potsdam and GRGS Toulouse*. DOI: `10.5880/ICGEM.2015.1`.

Gilardoni, M., M. Reguzzoni and D. Sampietro, 2016. GECO: a global gravity model by locally combining GOCE data and EGM2008. *Studia Geophysica et Geodaetica*, **60**, 228–247. DOI: `10.1007/s11200-015-1114-4`.

Hamdy, A. and M. Elshewy, 2022. Assessing the accuracy of the geoid heights calculated by interpolation and extrapolation from global geoid models in northern Egypt. *Journal of Al-Azhar University Engineering Sector*, **17** (63), 502–511.

Hofmann-Wellenhof, B. and H. Moritz, 2005. *Physical geodesy*. New York: SpringerWien.

ICGEM, 2023. *International Center for Global Earth Model*. Accessed Jan 10. URL: `http://icgem.gfz-potsdam.de/home`.

Isik, M., M. Çevikalp, B. Erol and S. Erol, 2022. Improvement of GOCE-based global geopotential models for gravimetric geoid modeling in Turkey. *Geosciences* (12). DOI: `10.3390/geosciences12120432`.

Jassim, M. and M. Yousef, 2021. Local geoid model generation using the geometrical approach. *Journal of Civil Engineering and Architecture* (15), 437–445. DOI: `10.17265/1934-7359/2021.08.005`.

Al-Karargy, E and G. Dawod, 2021. “Optimum combinations of GGM and GDEM models for precise national geoid modelling”. In: *Proceedings of Engineering and Technology Innovation*. Vol. 18, 15–24.

Klokočníka, J., V. Cílekb, J. Kosteleckýc and A. Bezděk, 2020. Gravity aspects from recent Earth gravity model EIGEN 6C4 for geoscience and archaeology in Sahara, Egypt. *Journal of African Earth Sciences*, **168**. DOI: `10.1016/j.jafrearsci.2020.103867`.

Lestari, R., B. Bramanto, K. Prijatna, A. Pahlevi, W. Putra, R. Muntaha and F. Ladivanov, 2022. Local geoid modeling in the central part of java, Indonesia, using Q1 terrestrial-based gravity observations. *Geodesy and Geodynamics*. DOI: `10.1016/j.geog.2022.11.007`.

Liang, W., J. Li, X Xu, S. Zhang and Y. Zhao, 2020. A High-Resolution Earth’s Gravity Field Model SGG-UGM-2 from GOCE, GRACE, Satellite Altimetry, and EGM2008. *Engineering*, 860–878. DOI: `10.1016/j.eng.2020.05.008`.

Liang, W., R. Pail, X. Xu and J. Li, 2022. A new method of improving global geopotential models regionally using GNSS/levelling data. *Geophysical Journal International*, **221**, 542–549. DOI: `10.1093/gji/ggaa047`.

Liang, W., X. Xu, J. Li and G. Zhu, 2018. The determination of an ultra high gravity field model SGG-UGM-1 by combining EGM2008 gravity anomaly and GOCE observation data. *Acta Geodaeticaet Cartographica Sinica*, **47** (4), 425–434. DOI: `10.11947/j.AGCS.2018.20170269`.

Osman, A., M. Anjasmara1, A. Ruby and Z. Udama, 2021. "Assessment of high-degree reference models and Recent Goce/Grace Global Geopotential Models over Sudan based on the GPS/Leveling data". In: *IOP Conf. Series: Earth and Environmental Science*. Vol. 936. DOI: `10.1088/1755-1315/936/1/012035`.

Pavlis, N.K, S.A Holmes, S.C Kenyon and J.K. Factor, 2012. The development and evaluation of the Earth Gravitational Model 2008 (EGM2008). *Journal of Geophysical Research: Solid Earth*, **117**, B04406. DOI: `10.1029/2011JB008916`.

Phinyo, K., P. Dumrongchai, C. Srimanee and B. Witchayangkoon, 2021. Methodology of Local Geoid Improvement Using Least-Squares Collocation with Parameters and an Optimal Covariance Function. *International Transaction Journal of Engineering, Management, & Applied Sciences & Technologies*, **12** (5). DOI: `10.14456/ITJEMAST.2021.105`.

Singh, D. and R. Srivastava, May 6–11, 2018. "Development of geoid model – a case study on western India". In: *Proceedings of the FIG Congress*. Istanbul, Turkey.

SRI, 2022. A geodatabase of GNSS/Levelling data over Egypt. Tech. rep. 2. Giza, Egypt: Survey Research Institute.

Tocho, C., E. Antokoletz, A. Gómez, H. Guagni and D. Piñon, 2022. Analysis of high-resolution global gravity field models for the estimation of International Height Reference System (IHRS) coordinates in Argentina. *Journal of Geodetic Science*, (12), 131–140.

Zingerle, P., R. Pail, T. Gruber and X. Oikonomidou, 2020. The combined global gravity field model XGM2019e. *Journal of Geodesy*, **94**, 66. DOI: `10.1007/s00190-020-01398-0`.