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Assessment of the most recent satellite based digital elevation models of Egypt

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ABSTRACT

Digital Elevation Model (DEM) is crucial to a wide range of surveying and civil engineering applications worldwide. Some of the DEMs such as ASTER, SRTM1 and SRTM3 are freely available open source products. In order to evaluate the three DEMs, the contribution of EGM96 are removed and all DEMs heights are becoming ellipsoidal height. This step was done to avoid the errors occurred due to EGM96. 601 points of observed ellipsoidal heights compared with the three DEMs, the results show that the SRTM1 is the most accurate one, that produces mean height difference and standard deviations equal 2.89 and ±8.65 m respectively. In order to increase the accuracy of SRTM1 in EGYPT, a precise Global Geopotential Model (GGM) is needed to convert the SRTM1 ellipsoidal height to orthometric height, so that, we quantify the precision of most-recent released GGM (five models). The results show that, the GECO model is the best fit global models over Egypt, which produces a standard deviation of geoid undulation differences equals ±0.42 m over observed 17 HARN GPS/leveling stations. To confirm an enhanced DEM in EGYPT, the two orthometric height models (SRTM1 ellipsoidal height + EGM96) and (SRTM1 ellipsoidal height + GECO) are assessment with 17 GPS/leveling stations and 112 orthometric height stations, the results show that the estimated height differences between the SRTM1 before improvements and the enhanced model are at rate of 0.44 m and 0.06 m respectively.

1. Introduction

DEM is one of the most popular data models used for the purpose of terrain modeling. Each DEM contains intrinsic errors due to primary data acquisition technology and processing methodology in relation to a particular terrain and land cover type. The accuracy of these datasets is often unknown and is non-uniform within each dataset. DEMs are useful for many purposes, and are an important precondition for many applications (Kim and Kang, 2001; Vadon, 2003). DEMs have been found useful in many fields of study such as Cut and fill analysis in Civil Engineering (Brown and Arbogast, 1999; Aruga et al., 2005), Cartographic purposes, such as contour maps and relief shadings (Jenny, 2001; Oksanen and Sarjakoski, 2005), Hydrological and hydraulic applications (Maidment, 1993; Moore, 1996; Tucker et al., 2001; Alho et al., 2005), Agricultural applications (Pilesjö et al., 2006) and Geological applications (Borga et al., 1998; Chorowicz et al., 1999; Van Dijk et al., 2000).

DEM is generated using different techniques such as Photogrammetry, Light Detection and Ranging (LIDAR) and Radar (Garcia, 2005). Acquisition of quality DEM data over a large area is a challenging task because of the complicated generation process. The available open source DEMs such as SRTM 1 arc second, SRTM 3 arc second, ASTER GDEM (30 m) and many other resolutions. Small scale DEM representation is required for global and regional scale simulation studies, but the feasibility of application depends on vertical accuracy (Brasington and Richards, 1998; Dragut and Eisank, 2011).

In Egypt, (El-Sagheer, 2004) has developed a local Digital Terrain Model (DTM) model for EGYPT (called DTM-2003) through digitizing 1:250,000 and 1:100,000 hard copy topographic maps. (Dawod, 2008) investigated the following four digital terrain mod-

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els: GTOPO30, SRTM 3, DTM2002 and LDTM (3 global and one local); and he concluded that the DTM2002 model should be utilized in computing the terrain corrections for the gravimetric geoid development in Egypt. In additional, he also analyzed the performance of seven recent GGMs by using a local geodetic dataset (terrestrial gravity and GPS/leveling points) in Egypt. The results show that the EIGEN-CG01C GGM model is best at representing of the gravity field in Egypt. Its average accuracy, in terms of the geoid undulations when compared to known nine points, is estimated to be 0.36 m. In addition, (Al-Krargy et al., 2015) evaluated three (DEM) models such as (ASTER, SRTM 3 arc-second, and GTOPO30) and evaluated seven GGM such as (EIGEN-6C4, GO_CONS_GCF_2_DIR_R5, GO_CONS_GCF_2_TIM_R5, DGM-1S, EGM2008, EIGEN-5C and EGM96) by using precise local geodetic dataset (gravity and GPS/Levelling data) covers the Egyptian territories. The attained results show that, the SRTM 3 DEM produces a mean standard deviation of ±4.3 m, when compared over 1227 points of the observed orthometric heights. Furthermore, it has been shown that the EGM2008 is the most precise global model over Egypt, as it produces a mean standard deviation of geoid undulation differences which equals ±0.23 m over the observed 1074 GPS/Leveling stations.

The present study is to assess the accuracy of DEM and GGM available in Egypt. This was done to configure an enhanced model of the available Digital Elevation Models (DEMs) and evaluate this model using GPS/leveling stations checkpoints.

1.1. Digital elevation model

Several global DEMs have been developed and released in the last two decades. Nevertheless, the spatial resolution and the precision of global DEM models vary significantly. In this research, three global DEM models have been tested in order to evaluate their accuracy in depicting the topography of Egypt. Those models are:

- **The Advanced Space-borne Thermal Emission and Reflection Radiometer**
  (ASTER) sensor was originally launched in December 1999 as part of NASA's Earth Observing System on the Terra Spacecraft. On June 29, 2009, NASA and the Ministry of Economy, Trade, and Industry (METI) of Japan released a Global Digital Elevation Model (GDEM) to users worldwide at no charge as a contribution to the Global Earth Observing System of Systems. ASTER GDEM data covers 99% of the Earth's surface. This "Version 1" ASTER GDEM (GDEM 1.0) was compiled from over 1.2 million scene-based DEMs covering land surface between 83° degrees north (N) and 83° south (S) latitudes. NASA and METI released a second version of the ASTER GDEM (GDEM 2) in mid-October 2011. ASTER creates its DEM by using two camera sensors, one pointed directly down, and one-off nadir (at an angle). For this study, ASTER GDEM version-2 was downloaded from (https://earthexplorer.usgs.gov/).
- **Shuttle Radar Topography Mission (SRTM) Digital Elevation Model**
  The mission was launched on 11 February 2000 aboard the Space Shuttle Endeavour. Using radar interferometry, a 3-arc second (SRTM-3) DEM was produced covering almost 80% globe excluding polar regions. Initially a 1-arc second data product was also produced, but was not available for all countries. However since January 2015 NASA is providing the 1-arc second data freely for many countries and in August 2016 the SRTM1-arc second data became freely available for Egypt. The SRTM elevation data for the study area was downloaded from (http://earthexplorer.usgs.gov) website.
  The data currently is being distributed by NASA/USGS (finished product) contains 'no-data' termed as voids where water or heavy shadow prevented the quantification of elevation. These are generally small holes, which nevertheless render the 'no data' especially in fields of hydrological modeling. Later, through further processing the original DEMs were filled in these no-data voids. Data were collected using two

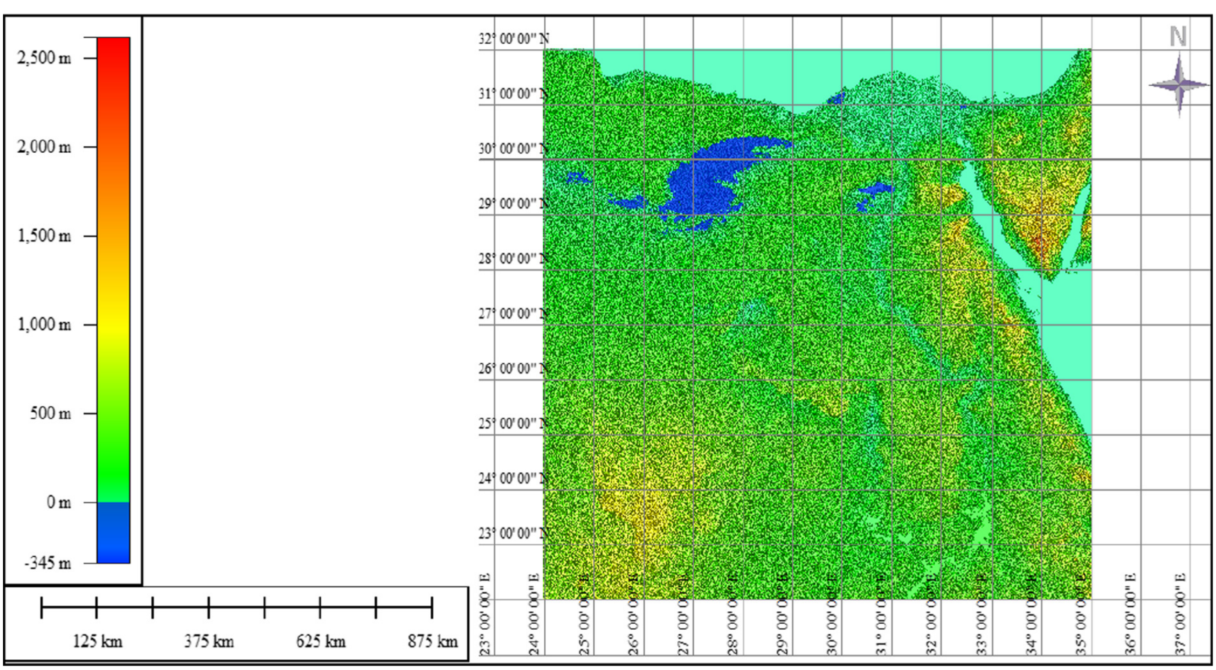
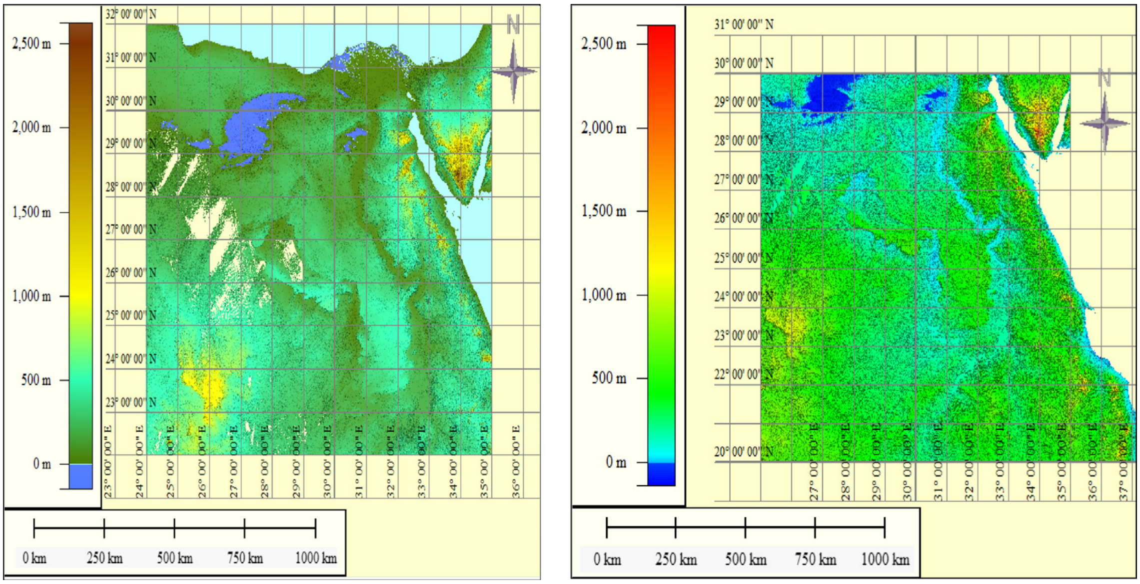


Fig. 1. Digital Elevation Model of ASTER GDEMs (Resolution one arc second) for Egypt.



SRTM DEM resolution 30 m data   SRTM DEM resolution 90 m data

Fig. 2. SRTM 1 arc-second compared to SRTM 3 arc-second.

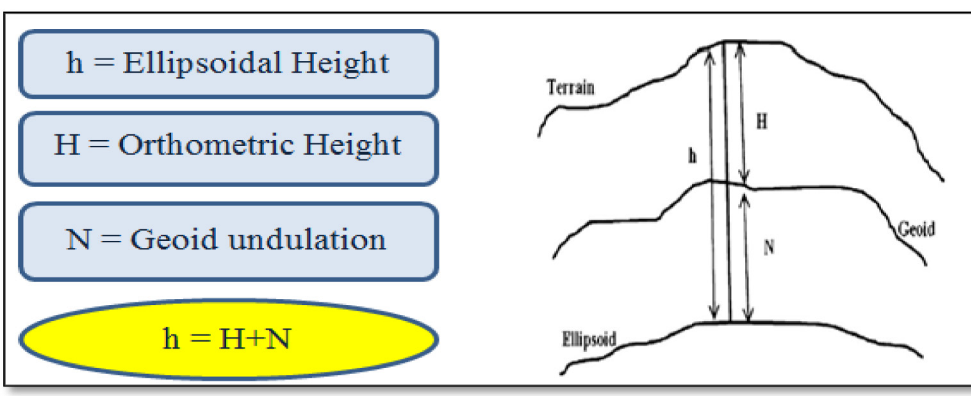


Fig. 3. Relation between ellipsoid height, orthometric height and geoid undulation.

Table 1
Characteristics of utilized GGM models.

No.	GGM Model	Year	Degree	Data Type
1	GECO	2015	2190	S(GOCE), EGM2008
2	EIGEN-6C4	2014	2190	S (GOCE, GRACE, LAGEOS), G, A
3	EIGEN-6C2	2012	1949	S (GOCE, GRACE, LAGEOS), G, A
4	EGM2008	2008	2190	S (GRACE), G, A
5	EGM96	1996	360	EGM96S, G, A

where: S = Satellite tracking data, G = Terrestrial gravity data, A = Altimetry data, GOCE, GRACE, and LAGEOS are gravity satellite missions.

interferometers, C-band (American) and X-band (German) systems, at 1-arc second (30 m) (Jenson et al., 1998; Sharma et al., 2010).

The window of each DEM that corresponds to the Egyptian territories has been downloaded and utilized in this research. For example, the ASTER DEM of Egypt (Fig. 1) shows that the elevations range from −345 m to 2500 m. (Fig. 2) show the differences between SRTM 1 and SRTM 3.

2. Reference datum of various DEMs

The Horizontal datum of ASTER and SRTM is World Geodetic System 1984 (WGS84). Horizontal resolution of ASTER and SRTM datasets is measured in arc seconds. An arc second is equivalent to roughly 30 m. For further explanation of arc seconds, see (Gesch, 2007). The vertical datum of ASTER DEM and SRTM is EGM96. Vertical resolution is measured in meters with ASTER and SRTM measured in whole meter increments. The global posi-

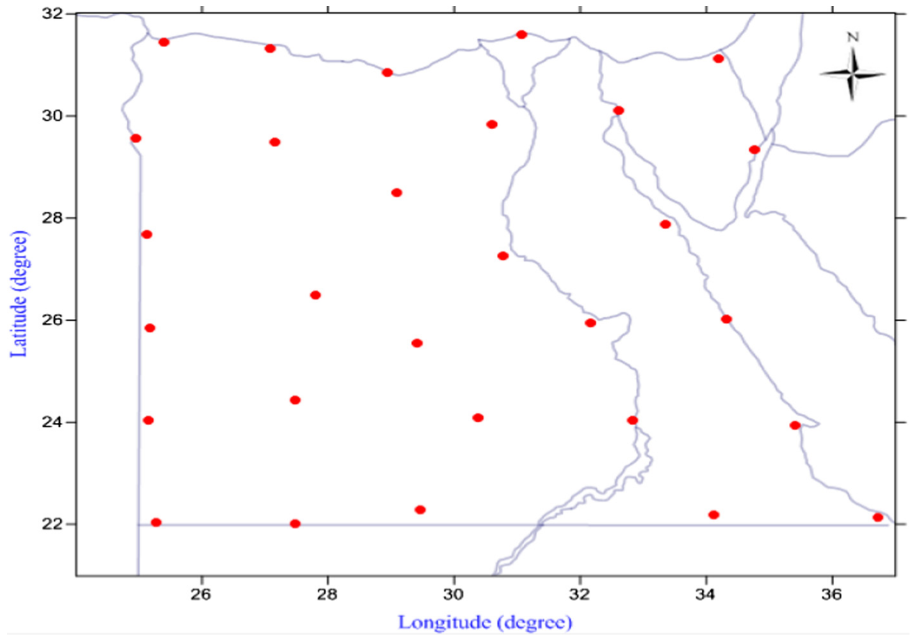


Fig. 4. The HARN network in Egypt.

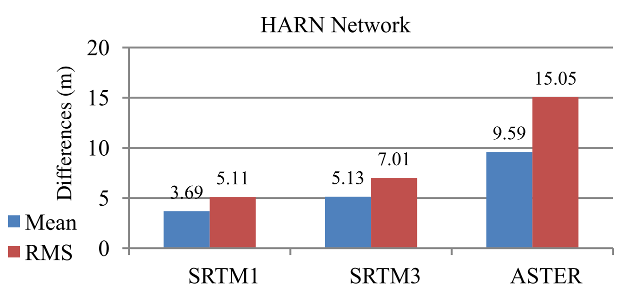


Fig. 5. Height differences between stations of HARN network and the selected GDEMs.

tioning system (GPS) uses WGS84 vertical datum as default and computes the height relative to this (Ward et al., 2006). The elevation of a point on Earth surface computed from Mean Sea Level (MSL) can vary from GPS derived elevation because of the variation between WGS84 ellipsoid and Geoid (local MSL). The Geoid surface is an equipotential or constant geopotential surface which corresponds to MSL. The geoid height/geoid undulation (N) is the difference in height between geoid and ellipsoid at a point. Fig. 3 represents ellipsoid height (h) and height above geoid surface (H) which is orthometric height. However, it can be derived that:

$$h = H + N \tag{1}$$

3. Global geopotential models (GGM)

In the current research, five GGM models have been chosen to evaluate their accuracy with GPS/leveling points to select the accurate one to develop the precise DEM in EGYPT. These GGM models available at the website of the International Center for Global Earth

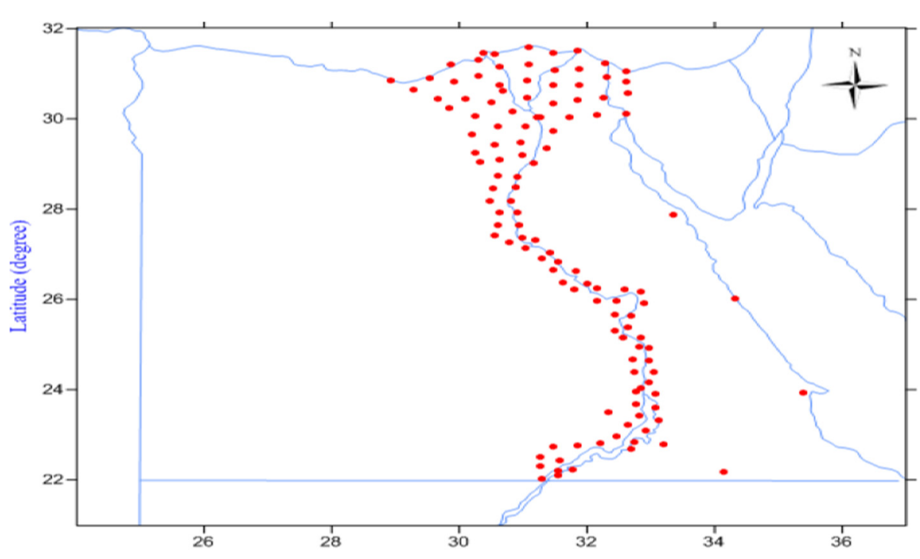


Fig. 6. The NACN network in Egypt.

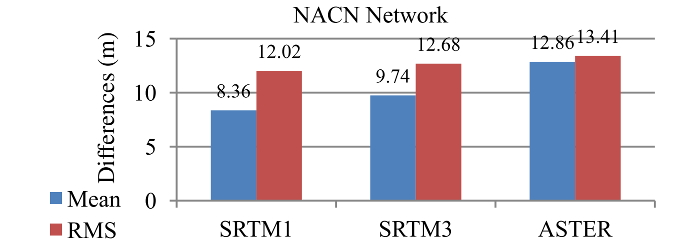


Fig. 7. Height differences between stations of NACN network and the selected GDEMs.

Models (http://icgem.gfz-potsdam.de/ICGEM/ICGEM.html). The selection is basically depending upon the maximum degree and order of each GGM and the most-recent GGMs in the last twenty years. Those models are:

- **EIGEN-6C2**: The European Improved Gravity Model of the Earth by New Techniques model has been inferred from the combination of LAGEOS, GRACE, GOCE and surface gravity data and the model released in 2012. It is maximum degree/order 1949 (Forste et al., 2012).
- **EIGEN-6C4**: A model released in 2014. The combined gravity field model EIGEN-6C4 is the latest combined global gravity field model of GFZ Potsdam and GRGS Toulouse (Foerste et al., 2014). EIGEN-6C4 has been generated including the satellite gravity gradiometry data of the entire GOCE mission (November 2009 till October 2013); and it is of maximum spherical degree and order 2190.
- **EGM2008**: Earth Gravitational Model has been publicly released by the USA National Geospatial-Intelligence Agency (NGA) EGM Development Team. This gravitational model is complete to the spherical harmonic degree and order 2159 (Pavlis et al., 2008); and it contains additional coefficients extending to degree 2190 and order 2159.
- **EGM96**: Earth Gravitational Model 1996 is one of the global geoid models that can be used to calculate the orthometric elevation, when the values of ellipsoid heights are given by the GPS positioning tool. The EGM96 is a combined geopotential model consisting of the spherical harmonic coefficients, complete to degree and order 360.
- **GECO**: GECO is a global gravity model, computed by combining the GOCE-only TIM R5 (time-wise approach) solution into EGM2008 (Gilardoni et al., 2016). From degree 360 to degree 2190 the GECO coefficients are the same of EGM2008.

Table 1 summarizes the main characteristics of those GGM models. As it is demonstrated in Table 1, it can be realized that the selection of such models depicts a variety in their nature in terms of development year, maximum model degree, and the types of data utilized in the development of each model.

4. Available data

The three Digital Elevation Models (DEMs) are assessed by using 601 GPS/Levelling stations as shown in (Fig. 12). The stations were divided into four sections High Accuracy Reference Network

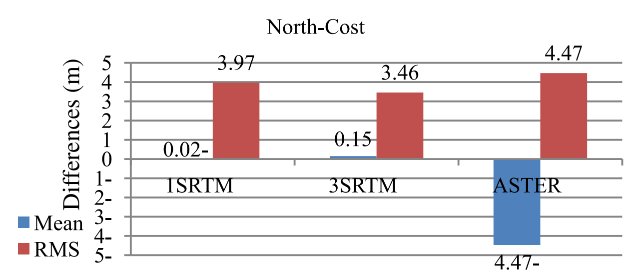


Fig. 9. Height differences between stations of the North-cost data and the selected GDEMs.

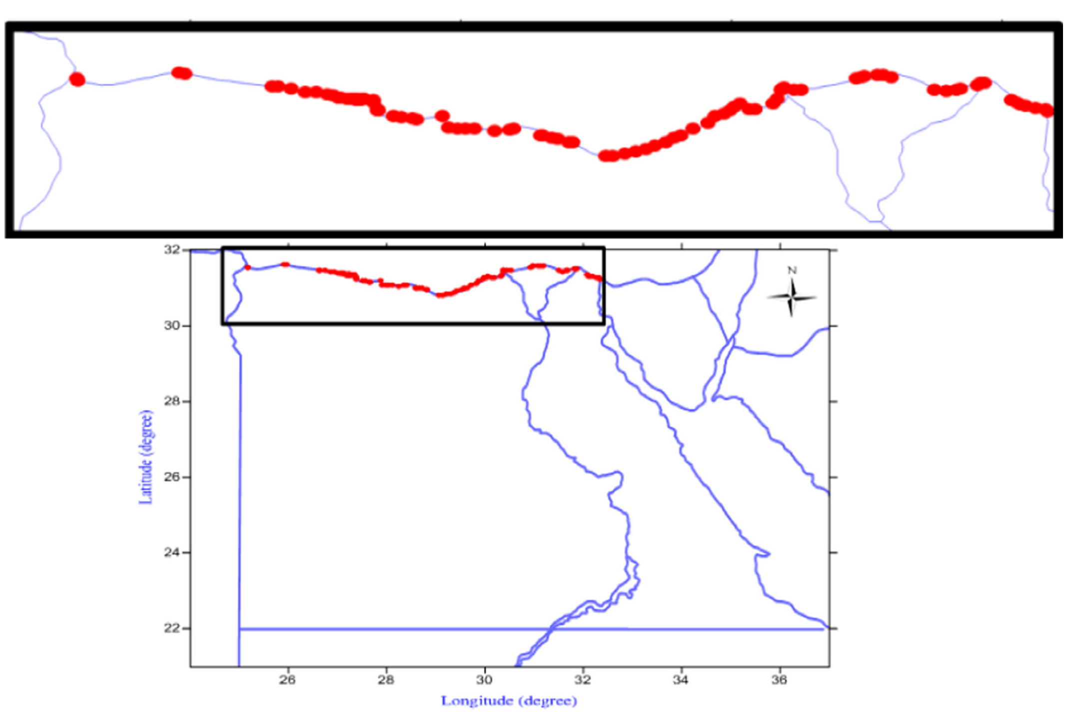


Fig. 8. North-cost data in EGYPT.

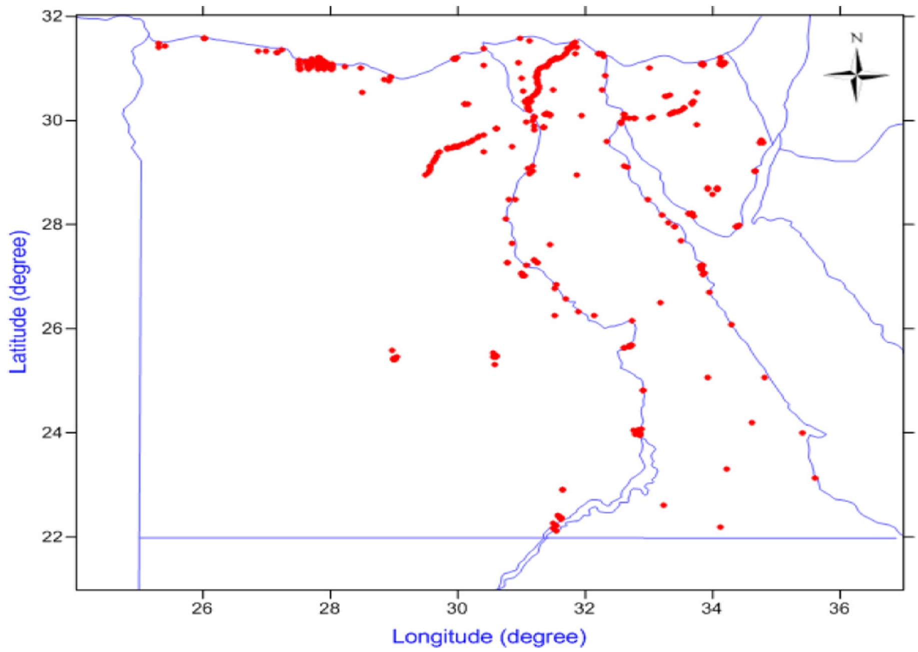


Fig. 10. Distribution of the 365 points covering some areas in Egypt.

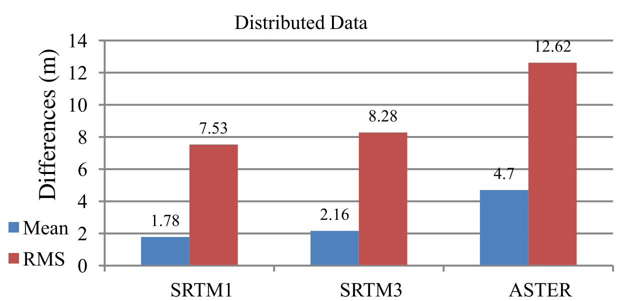


Fig. 11. Height differences between stations of the distributed and selected GDEMs.

(HARN) that contain 30 stations, National Agricultural Cadastral Network (NACN) that contain 123 stations (including 12 stations from HARN Network) (Scott, 1997), North-Cost data (95 stations) and the distributed data (365 stations). The number and distribution of the stations was poor, concentrated mainly along the Nile valley and the North-Cost; thus, a lot of areas were empty. The used data to evaluate the Global Geopotential Models (GGMs) and the developed DEM can be divided into (17) GPS/leveling stations of HARN Network and (112) GPS/leveling stations (17 points of HARN and 95 points of North-cost data) with Known geoid undulation.

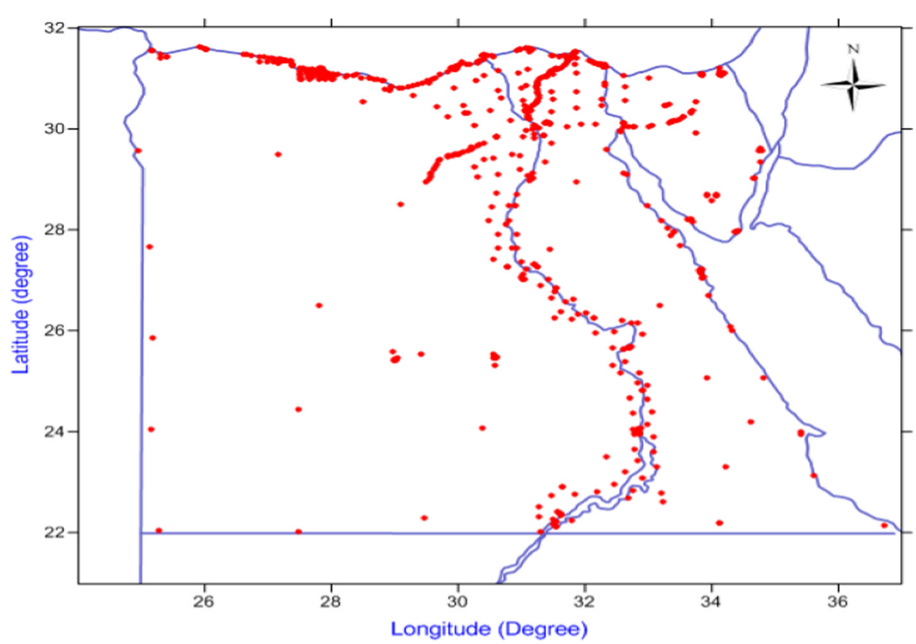


Fig. 12. All study data of the 601 available points in Egypt.

Fig. 13. Height differences between stations of all used data and selected GDEMs.

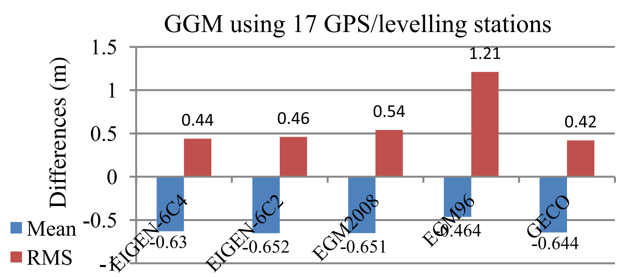


Fig. 14. Height differences between 17 check points and SRTM1.

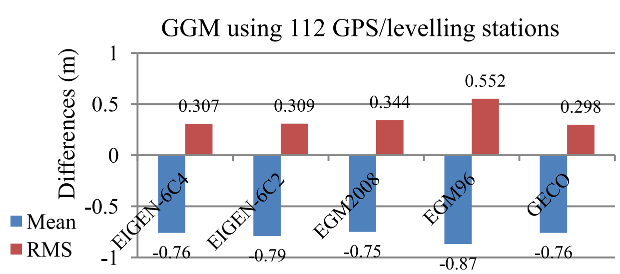


Fig. 15. Height differences between 112 check points and SRTM1.

5. Results

To configure a develop DEM for Egypt, three steps should be considered:

(a) Evaluation of DEM models,
(b) Evaluation of GGM models, and
(c) Check the developed DEM. The attained results are discussed in the three following sub-sections.

5.1. DEM evaluation results

To evaluate the three digital elevation models and to avoid the errors resulted from using EGM96, we used it to convert the used DEMs heights to ellipsoidal heights. However, because the distribution of the available test points is irregular, the data used to evaluate three DEMs was divided into four parts, described in the following:

5.1.1. HARN network

The Egyptian National High Accuracy Reference Network (HARN), observed by the Egyptian Survey Authority. In this regard, it should be mentioned that the HARN network consists of 30 stations at approximately 200 km interval at known ellipsoidal heights; however, 13 stations (located in remote areas) have no observed orthometric heights, consequently, no geoid undulation could be obtained for these stations. The precision of the HARN network is 0.1 ppm (PPM). The distribution of HARN stations is shown in (Fig. 4). An analysis was carried out using the 30 HARN stations, based on their geodetic coordinates. The statistics of the estimated height differences are presented in (Fig. 5). The SRTM1 DEM yields height differences ranging from −3.97 m to 23.59 m, with an average of 3.69 m and standard deviations equaling ±5.11 m. On the other hand, the SRTM3 DEM produces height differences which vary from −2.89 m to 35.23 m, with an average of 5.13 m and standard deviations equaling ±7.01 m. Furthermore, the ASTER DEM produces height differences varying from −23.81 m to 69.76 m, with an average 9.59 m and standard deviations equaling ± 15.05 m. Therefore, it can be realized that the SRTM1 DEM produces the smallest differences (both in average and RMS values), while the ASTER gave the biggest differences.

5.1.2. NACN network

Egypt Survey Authority (ESA) established the National Agricultural Cadastral Network (NACN) that mainly covers the Nile valley and the Delta. NACN consists of 123 stations, with a station separation of 50 km approximately, whose relative precision is 1: 1,000,000. An analysis was carried out using 123 stations (including 12 stations from HARN networks). NACN covers the green area of Egypt (the Nile Valley and the Delta) as shown in (Fig. 6). The

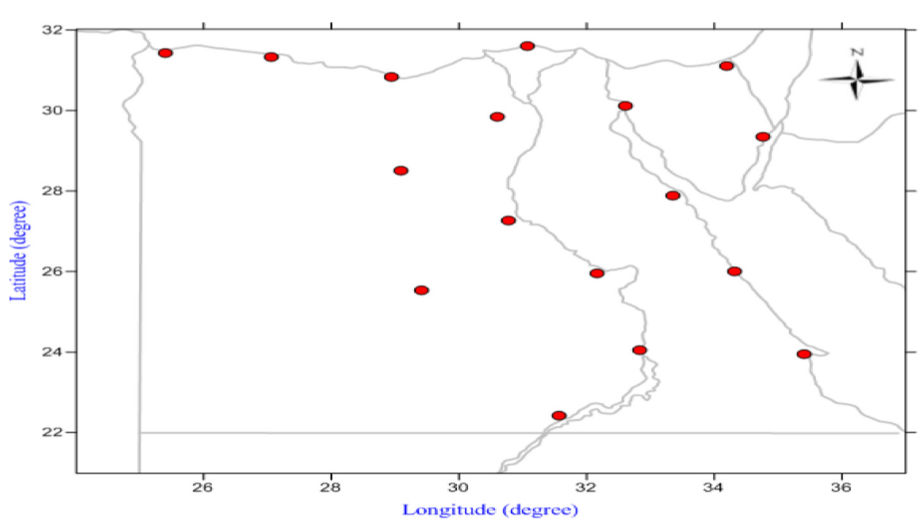


Fig. 16. The distribution of 17 GPS/leveling stations check points in Egypt.

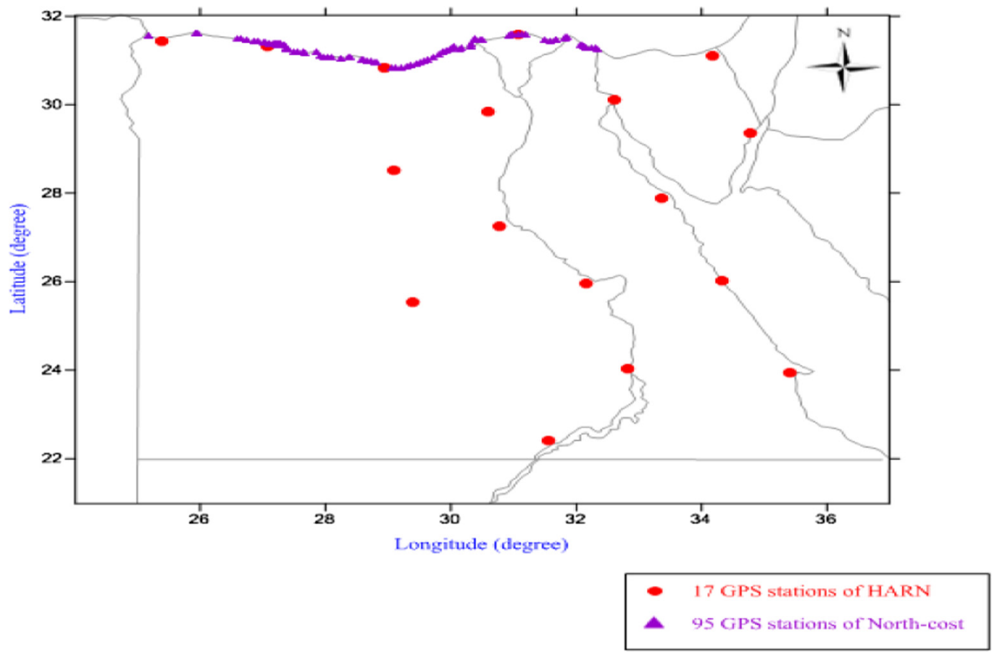


Fig. 17. The distribution of 112 GPS/leveling stations checkpoints.

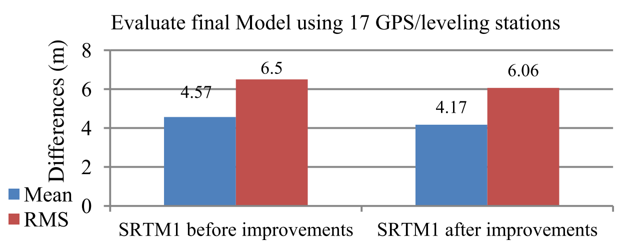


Fig. 18. Height differences between 17 check points and SRTM1before and after improvements.

statistics of the estimated height differences are presented in (Fig. 7). It can be seen that the SRTM1 DEM created height differences ranging from −5.057 m to 64.34 m, with an average of 8.36 m and standard deviations equaling ± 12.02 m. Furthermore, the SRTM3 generated height differences ranging from −4.98 m to 66.00 m, with an average of 9.74 m and standard deviations equaling ± 12.68 m. On the other hand, the ASTER DEM produced height differences varying from −13.92 m to 69.77 m, with an average of 12.86 m and standard deviations equaling ± 13.41 m. Therefore, it can be realized that the SRTM1 DEM produces the smallest differences (both in average and RMS values), while the ASTER gave the biggest differences.

5.1.3. North-cost data

An analysis was carried out using 95 available points, covering the North-Cost area of Egypt. The distribution of data is shown in (Fig. 8). The statistics of the estimated height differences are presented in (Fig. 9). The SRTM1 DEM yields height differences ranging from −27.03 m to 7.9 m, with an average of −0.02 m and standard deviations equaling ± 3.97 m. On the other hand, the SRTM3 DEM produces height differences varying from −22.13 m to 7.9 m, with an average of 0.15 m and standard deviations equaling ± 3.46 m. Moreover, the ASTER DEM produces height differences varying from −17.45 m to 5.98 m, with an average of 9.59 m and standard deviations equaling ± 4.47 m. Therefore, it can be realized that the SRTM3 DEM produces the smallest differences (in RMS values); however, the SRTM1 DEM produces the smallest mean, while the ASTER gave the biggest differences.

5.1.4. Distributed data

An analysis was carried out using 365 available points, covering some areas in Egypt as shown in (Fig. 10). The statistics of the estimated height differences are presented in (Fig. 11). The SRTM1 DEM creates height differences ranging from −28.39 m to 26.38 m, with an average of 1.78 m and standard deviations equaling ± 7.53 m. On the other hand, the SRTM 3 generates height differences ranging from −28.68 m to 40.73 m, with an average of 2.16 m and standard deviations equaling ± 8.28 m. Furthermore, the ASTER DEM produces height differences varying from −32.16 m to 69.30 m, with an average of 4.70 m and standard deviations equaling ± 12.62 m. Therefore, it can be realized that the SRTM1 DEM produces the smallest differences (both in average and RMS values), while the ASTER gave the biggest differences.

5.1.5. All available data

By evaluating using 601 points as shown in (Fig. 12), The statistics of the estimated height differences are presented in (Fig. 13). Clearly, it can be realized that the SRTM 1 arc second DEM produces the smallest differences (both in mean and RMS values), while the ASTER gave the biggest differences. Hence, it can be concluded that SRTM 1 arc second is the most precise global DEM model in representing the topography of Egypt.

5.2. GGM evaluation results

The performance analysis of the GGM five models by comparing the observed N values against the estimated GGM-based N for each GGM model. The attained results are presented in Figs. 14 and 15. From Fig. 14, the GECO GGM produces the smallest RMS for the differences with a value of ± 0.42 m; while the EIGEN-6C4 comes in the second place with an RMS of ± 0.44 m; and in the last place, the EGM96 GGM came with a value of ± 1.21 m. As it is depicted in Fig. 15, the GECO GGM produces the smallest RMS for the differences with a value of ± 0.298 m. Then, the EIGEN-6C4 comes in the second place with an RMS of ± 0.307 m. Finally, the EGM96 GGM

Table 2
Comparison between SRTM1 before and after improvements by using 17 GPS/leveling stations.

DEM Models	Differences between observed and SRTM1 Orthometric Heights (m)			
	Minimum	Maximum	Mean	RMS
SRTM1 before Improvements	−5.05	21.79	4.57	6.50
SRTM1 after improvements	−3.97	21.59	4.17	6.06

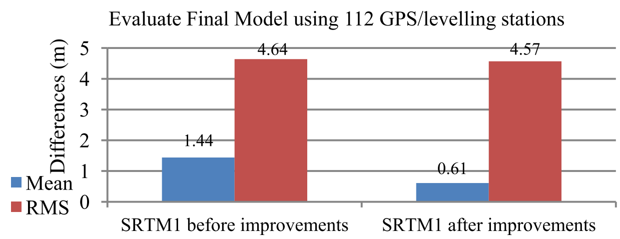


Fig. 19. Height differences between 112 check points and SRTM1before and after improvements.

came in the last place with a value of ± 0.552 m. It can be realized, from two figures, that the GECO GGM produces the smallest differences (in term of RMS values) compared to the observed geoid undulation values. The EIGEN-6C4 GGM came in the second place with a close RMS value, while the EGM96 GGM gives the largest differences. As seen in Table 1, both GECO and EIGEN-6C4 have maximum degree of 2190, while EGM96 has maximum degree of only 360. That might explain the attained results, since the higher degree of a model, the smaller spatial resolution in representing the gravity field. Hence, it can be concluded that GECO model is the most precise GGM model of Egypt. For more improvement, the GECO geoid has been fitted to GPS using kriging trend function by using 17 HARN GPS/leveling stations. The distribution of the most reliable/available GPS/leveling stations used in the GGMs evaluation are shown in Figs. 16and 17.

5.3. Local DEM evaluation results

To confirm an enhanced DEM in EGYPT, the two orthometric height models (SRTM 1 ellipsoidal height + EGM96) and (SRTM 1 ellipsoidal height + Fitted GECO) are assessment with 17 GPS/leveling stations (HARN network) and 112 GPS/leveling stations of HARN network and 95 stations of North-Cost of Egypt. The distribution of the most available GPS/leveling stations used in the enhanced DEM evaluation are shown in Figs. 16 and 17.

Firstly, by using 17 GPS/leveling stations the statistics of the estimated height differences are presented in Fig. 18 and Table 2, it can be seen, that the enhanced model creates height differences range from −3.97 m to 21.59 m, with an average of 4.17 m and standard deviations equals ± 6.06 m compared to the model before making improvements, generate height differences range from −5.05 m to 21.79 m, with average 4.57 m and standard deviations ± 6.50 m. According to the results, the estimated height differences between the enhanced model and the SRTM1 DEM before and after improvements at rate of 0.44 m.

Secondly: by using 112 GPS/leveling stations, the statistics of the estimated height differences are presented in Fig. 19 and Table 3, it can be seen, that the enhanced model create height differences range from −27.02 m to 21.59 m, with an average of 0.61 m and standard deviations equals ± 4.57 m compared to the model before making improvements, generate height differences range from −26.74 m to 21.79 m, with average 1.44 m and standard deviations ± 4.64 m. According to the results, the estimated height differences between the enhanced model and the SRTM1 DEM before and after improvements at rate of 0.06 m.

6. Conclusion

A national Digital Elevation Model (DEM) is crucial to a wide range of surveying and civil engineering applications worldwide so that to develop a national DEM for EGYPT, the limitations of available geodetic data sized the precision of such models. In order to increase the accuracy of a DEM in EGYPT, a precise Global Geopotential Model (GGM) along with a precise Digital Elevation Model (DEM) is needed. Apart of this study aims to quantify the precision of most-recent released GGM and global DEM models based on a precise local geodetic dataset (GPS/Leveling data) covers the Egyptian territories to develop a national digital elevation model. Thus, this research study has compared three GDEM (SRTM 1 arc second, SRTM 3 arc second and ASTER) over precise GPS/leveling points. On the other hand, five GGM (namely GECO, EIGEN-6C4, EIGEN-6C2, EGM2008 and EGM96) over most-recent precise GPS/leveling points, in order to increase the accuracy of the precise digital elevation model in Egypt.

The accomplished results show that the SRTM1 arc second produces the smallest differences (both in mean and RMS values), while the ASTER gave the largest differences. Concerning the GGM evaluation, the attained findings show that the GECO GGM produces the smallest differences (in term of RMS values) compared to the observed terrestrial values. The EIGEN-6C4 GGM came in the second place with a close RMS value, while the EGM96 give the largest differences. Consequently, it can be concluded that the GECO is the most precise GGM model in representing the gravity field of Egypt in term geoidal undulations. To increase the accuracy of the SRTM1 DEM, Subtraction the SRTM1 DEM with GECO GGM to configure the enhanced model (orthometric height) by using GLOBAL MAPPER program and Checking the enhanced model, by comparing its results against known GPS/leveling check points, it can be concluded that: firstly, by using 17 GPS/leveling stations of HARN network. secondly, by using 112 GPS/leveling stations. The enhancement of a local DEM is important for a variety of surveying and mapping applications in Egypt, so, it is strongly recommended utilizing the enhanced digital elevation model in future

Table 3
Comparison between SRTM1 before and after improvements by using 112 check points.

DEM Models	Differences between observed and SRTM1 Orthometric Heights (m)			
	Minimum	Maximum	Mean	RMS
SRTM1 before improvements	−26.74	21.79	1.44	4.64
SRTM1 after improvements	−27.02	21.59	0.61	4.57

surveying and mapping projects in Egypt and GECO GGM and the SRTM1 arc second DEM should be considered in the undergoing developing of a precise national Egyptian geoid model.

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