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Toward a Centimeter-Geoid Model for Engineering Surveying in Egypt: Status and Projected Activities

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Abstract With the broad spread of Global Navigation Satellite Systems (GNSS) utilization in geomatics and engineering surveying in Egypt in the last two decades, a precise geoid model becomes an essential demand. This paper investigates the possibilities of using global or local geoid models for height conversion in engineering activities. It has been found that most Global Geopotential Models (GGMs) could not depict the gravitational field over Egypt with a precision level less than 0.20 meter. On the other hand, recent available local geoid models still suffer from several factors and their accuracy still in the range of 0.10-0.15 meters. Precise surveying projects necessitate a more-accurate geoid model. As a result, the Survey Research Institute (SRI) has initiated a national collaborative effort to develop a centimeter-level hybrid geoid model for Egypt. So, three new geodetic networks; namely GNSS, levelling, and gravity, will be established on a national basis with first-order geodetic specifications and a reasonable grid spacing. The project aims to develop a national geoid model with a few-centimeter accuracy in the first phase, which can be modified later to achieve the one-centimeter accuracy level. Status of geodetic infrastructures and geoid modelling in Egypt, along with the projected geospatial activities are presented in details in this paper.

Keywords GNSS Surveying, Gravity, Levelling, Geoid, Egypt

1. Introduction

Geoid modelling is looking for the precise determination of geoid undulations between the geodetic heights obtained from the Global Navigation Satellite Systems (GNSS) techniques and the orthometric heights, or levels, relative to the Mean Sea Level (MSL). Consequently, geoid models are essential for the utilization of gnss (particularly the Global Positioning System: GPS) in civil engineering projects. geoid models could be developed globally, regionally, nationally, or on a local scale. in the last few years, many countries all over the world have developed their national geoid models for a variety of engineering applications, e.g. Japan [1], Argentina [2], Latvia [3], Nigeria [4], and Tanzania [5].

In Egypt, since the development of the first pioneer national-scale geoid [6], several geoid researches have been carried out. For example, Dawod [7] has developed a national geoid model based on the data of the Egyptian National Standardization Network of 1997 (ENGSN97) along with GPS/levelling data. Saad and Dawod [8] have developed a national geoid model based on the EGM96 global geopotential model along with GPS/levelling datasets. In addition, Abd-Elmotaal [9] has developed a gravimetric geoid model utilizing high-degree tailored reference geopotential models. Recently, Al-Karargy [10] has developed a national geoid model for Egypt based on recent accurate geodetic databases. Additionally, Al-Ashqar [11] has investigated the integration of Global Geopotential Models (GGMs) with local databases for the development of a hybrid geoid model for Egypt.

The major complications affecting the development of a precise geoid model for Egypt could be: (1) the availability of geodetic data, (2) the accuracy and datum conflict of available data, and (3) the non-homogeneous spatial distribution of available data over the Egyptian territories. This paper aims to investigate the geodetic infrastructures in Egypt, and to analyze the current geoid modeling activities. Furthermore, a new strategy of precise geoid development is proposed and discussed in details.

2. Geoid Modelling

The geoid undulation (N) can be computed from gravity data by the well-known Stokes' formula (e.g. Heiskanen and Moritz [12]):

$$N = {}^{R}\!/_{4\pi\gamma} \iint_{\sigma} S(\psi)\Delta g d\sigma \qquad (1)$$

where: R is the mean Earth radius, γ is the normal gravity on the reference ellipsoid, Δg is the gravity anomaly, $d\sigma$ is an infinitesimal surface element on the unit sphere σ, and $S(\psi)$ is the Stokes' function which can be expressed as a series of Legendre polynomial $Pn(\cos\psi)$ over the sphere:

$$S(\psi) = \sum_{n=2}^{\infty} ({}^{2n+1}\!/_{n-1}) P_n(\cos\psi) \qquad (2)$$

Stokes' formula (Eq. 1) needs to be applied over the whole Earth; however in practice gravity datasets of the whole Earth are not available. Thus the gravimetric geoid modelling methods break up the gravity anomalies (Δg) into three components:

$$\Delta g = +\Delta g_{REF} + \Delta g_{F} + \Delta g_{h} \qquad (3)$$

where: ΔgF represents the free-air gravity anomalies, Δgh is the effect of topography, and Δg_{REF} represents the gravity anomalies of a reference gravity field represented by a GGM.

Therefore, the full geoid undulation (N) is decomposed into three components too:

$$N = N_{REF} + N_{\Delta g} + N_{h} \qquad (4)$$

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, and N_{REF} is the contribution of the reference gravity field.

Globally, the geoid undulations (N) may be computed using the following spherical harmonic expansion:

$$N = ({}^{GM}\!/_{r\gamma}) \sum_{n=2}^{n\max} (a/r)^{n} - \sum_{m=0}^{n} ((\bar{C}_{nm}\cos m\lambda) + (\bar{S}_{nm}\sin m\lambda)) P_{nm}\sin\varphi) \qquad (5)$$

where: n is the degree of the GGM model, n max is the maximum degree of the GGM model, m is the maximum order of the model, γ is the normal gravity of the reference ellipsoid, r is the geocentric radial distance of the computation point projected on the ellipsoid, G is the Newtonian gravitational constant, M is the mass of the Earth, a is the semi-major axis, ϕ is the geocentric latitude, λ is the geocentric longitude, C-nm and S-nm are the fully normalized harmonic coefficients, and Pnm is the fully normalized associated Legendre polynomial.

GGM models have been developed since the 1960s as an important tool for geoid modelling on a regional or local scales. So far, there are more than 150 GGM available at the website of the International Center for Global Earth Models (*http://icgem.gfz-potsdam.de/ICGEM/ICGEM.html*). In developing GGM models, datasets from several sources might be utilized such as: satellite-based gravity data, terrestrial gravity data, satellite altimetry data, and terrestrial geodetic data. Therefore, the maximum degree and the precision of GGM models vary significantly.

3. Geoid Status in Egypt

Geoid modelling is a scientific task by nature, and the governmental surveying organizations, in many developing countries, are interested in utilizing a geoid model not developing one. So, the availability of required datasets might be a major problem facing researchers in such countries. The traditional geodetic data infrastructures in Egypt have major drawbacks in terms of precision, availability, datum conflict, and spatial distribution, as will be discussed herein.

Gravity observations have been carried out in Egypt since 1908, primarily for oil and mineral exploration [13]. The earliest absolute gravity observations in Egypt have been carried out in 1908 at Helwan observatory, south of Cairo. Between 1922 and 1950, some foreign geophysical exploration companies have carried out second-order gravimetric survey mainly in the western desert. Within an international gravity program, 21 stations have been established in Egypt in 1950-1951 and tied to the Potsdam gravity reference system. Moreover, as a part of the International Gravity Standardization Network 1971 (IGSN-71), 11 gravity stations have been measured in Egypt. A ten-year project (1974 - 1984) for compilation of gravity maps of Egypt has resulted in the National Gravity Standard Base Net (NGSBN-77). The project was executed and supervised by the General Petroleum Company (GPC) under the auspices of the Egyptian Academy of Sciences and Technology. The NGSBN-77 consists of 66 stations (Figure 1) and has tied to IGSN-71. More recently, the Survey Research Institute (SRI) has established the most-recent most-accurate Egyptian National Gravity Standardization Network (ENGSN97) between 1994 and 1997. It consists of 5 absolute gravity stations and 145 relative gravity stations (Fig. 1). Several recent studies (e.g. Al-Ashqar, [11] and Al-Karargy, [10]) have concluded that the second-order gravity measurements, in the western desert, are not precise enough for geoid modelling in Egypt, and emphasized that only NGSBN-77 and ENGSN-97 should be utilized to represent precisely the gravitational field of Egypt. Thus, the precise gravity stations in Egypt are not quit enough, in terms of number and distribution, for accurate gravimetric geoid modelling.

Regarding the geodetic vertical datum and reference networks in Egypt, it is a matter of reality that the national MSL has been determined in 1906. It was based on collecting and averaging daily sea level data at the Alexandria tide gauge between 1898 and 1906. However, it is evident that MSL has been significantly changed due to global warming on a global basis. Mohamed [14] has concluded that the relative rising rate of MSL at Alexandria equals 1.7 mm/year. Additionally, it has been found that the linear velocity estimate of the tide gauge GPS station height equals -0.47 mm/year. Therefore, it is concluded that the absolute sea level rise at Alexandria has been computed as 2.17 mm/year (ibid). On the other hand, the Egyptian first-order levelling network (Fig. 2) had been carried out from 1906 to 1936, in order to establish fundamental benchmarks over the cultivated lands of Egypt to control the levelling works that was performed by the irrigation departments and to unify a precise vertical datum for the irrigation system in Egypt. Concerning the systematic error sources in the Egyptian precise levelling network, the effect of refraction has been treated by field observational procedures in order to reduce it as much as possible. However, the correction for other sources of systematic errors, namely orthometric and tidal corrections, have not been considered in the computation of the network [15]. Another defect of that network is that no integrated least-square adjustment has been carried out, but it was adjusted loop by loop, which decreased its overall precision (ibid).

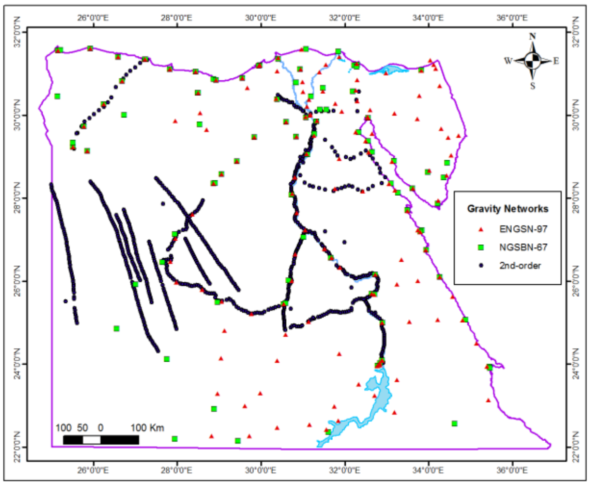

Figure 1: Traditional Gravity Stations in Egypt

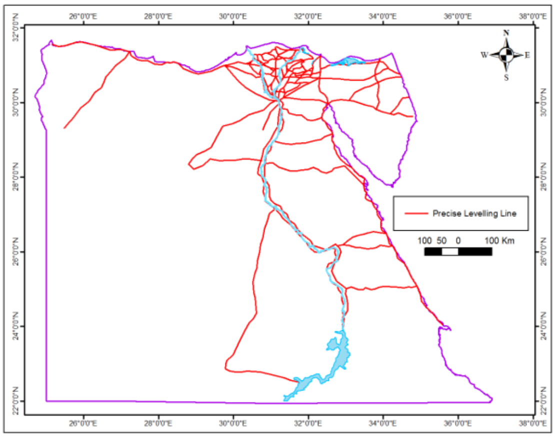

Figure 2: The Precise Levelling Network in Egypt

The Egyptian Survey Authority (ESA) has established the GPS-based High Accuracy Reference Network (HARN) in 1995. It consists of 30 stations with an almost 200 kilometer spacing covering Egypt. Next, ESA has established the National Agriculture Control Network (NACN) consisting of 112 stations along the Nile valley and Delta (Fig. 3). Both networks have been referenced to the International Terrestrial Reference Frame of 1994 (ITRF94). It worth mentioning that only 16 stations of the HARN and NACN have measured orthometric heights, and thus could be utilized in geoid modelling. Moreover, in 2010 ESA has established 40 Continuous Operating Reference Stations (CORS) to provide corrections to GNSS users in Egypt. Those stations, referenced to ITRF2008, have been established on the top of ESA buildings, and thus have no orthometric heights.

On the other hand, the utilization of GGMs only does not meet the accuracy limits required for GNSS surveying for engineering projects in Egypt. Many research studies have been performed to investigate the accuracy of GGMs in representing the gravitational field over Egypt. For example, Dawod et al. [13] have tested the Earth Geopotential Model 2008 (EGM2008) over known 305 GPS/levelling stations and found that the undulation differences range from -0.76 m to 0.41 m, with a mean of -0.23 m and a standard deviation equals ± 0.23 m. Al-Karargy et al. [16] showed that EGM2008 gave a mean standard deviation of gravity differences equals ± 25.1 mGal when examined over 941 observed gravity points in Egypt. Even when integrating GGMs with the available geodetic datasets, the developed hybrid geoid models produce accuracy levels in the order of ± 0.10 to 0.15 m approximately on a national scale (e.g. Al-Ashqar, [11] and Al-Karargy, [10]). Again, such a precision limit is not appropriate for GNSS engineering surveying applications.

Analyzing the status of geodetic data infrastructures in Egypt reveals critical challenges regarding precise geoid modelling. First, the vertical geodetic datum determined in 1906 has been changed significantly due to the global warming evidence in the twentieth century. Secondly, the available precise gravity stations are quite little and do not homogeneously cover the country. Additionally, it is a matter of fact that a large percentage of the first-order Bench Mark (BM) stations has been destroyed due to the urban growth in Egypt in the last few decades [17]. Also, field reconnaissance has revealed that some GPS and ENGSN97 gravity stations have been lost in several places due to urban development. Furthermore, the spatial separation and distribution of GPS and gravity networks, as depicted in the last figures, do not support the requirements of precise geoid modelling over Egypt. Hence, a new strategy is needed to cope with those serious problems of the national geodetic infrastructures.

4. Undergoing National Geoid Activities

Recently, SRI has completed a prototype research study for densification of geodetic networks and development of a precise geoid model in the Minufiya governorate, north of Cairo. A network of 47 new BM has been established with an average spacing of 4 kilometers apart. That entire network has been positioning by GPS applying the international geodetic standards and specifications, and tied to the national geodetic datum of Egypt. The least-squares adjustment method has been carried out for both networks. The geoidal undulations have been achieved with a few centimeters level of precision (Fig. 4), and a precise geoid model has been developed for the study area [18-19]. This case study has motivated SRI to propose the development of a precise geoid model for entire Egypt.

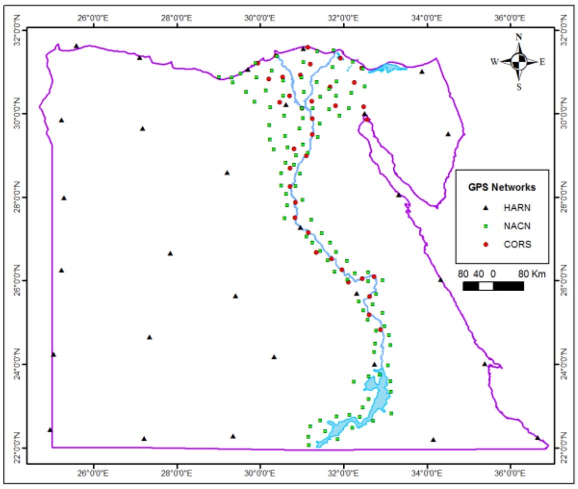

Figure 3: The GPS Networks in Egypt

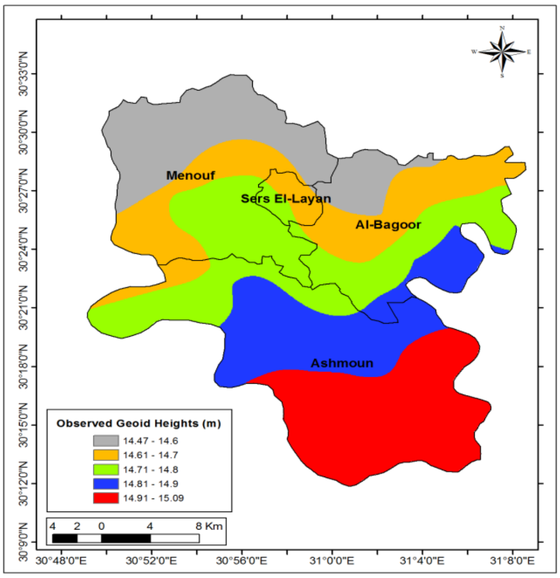

Figure 4: The Local Geoid of Minufiya Governorate

During the second half of 2016, SRI has organized many workshops, attended by professional from many governmental organizations, in order to discuss the geoid modelling future activity. Those organizations include: the Egyptian Surveying Authority (ESA), the Egyptian Commission of Surveying and Mapping (ECSM), the National Research Institute for Astronomy and Geophysics (NRIAG), the Egyptian Mineral Resources Authority (EMRA), the Nuclear Materials Authority (NMA), the Egyptian General Petroleum Corporation (EGPC), the National Authority for Remote Sensing and Space Sciences (NARSS), and many university professionals. The workshops reveal essential facts about the national resources, in terms of existing data and capabilities, that could be participated in a national effort to develop a precise geoid model for Egypt. For example, it has been recognized that NMA acquires an aircraft equipped with an airborne gravity meter, among other sensors. Also, EMRA has recent gravity databases in different regions of Egypt, while NRIAG has collected gravity and GPS measurements in the southern region, particularly around lake Nasser. Moreover, SRI has acquired a recent precise GPS/levelling database of more than 500 stations mainly along the coastlines (Fig. 5). Hence, it is a matter of reality that the unification and integration of all available resources and efforts will be supportive in national geoid modelling.

Based on the comprehensive deliberations in the organized workshops, a proposal of national geoid modelling has been accomplished. The objectives and strategy of that proposal, in the first phase, could be summarized as (Fig. 6):

- Collecting, analyzing, and validating all available measurements in a unique information system.
- Redefining the MSL datum based on recent heterogeneous data at available tide gauge stations.
- Establishing three high-accuracy geodetic reference networks (terrestrial gravity, GPS, and precise levelling) on a national base with homogenous spatial distribution using 10x10 kilometer interval.
- Measuring airborne gravity in remote areas of Egypt, where terrestrial gravity can not accomplished.
- Developing a national gravimetric geoid model, then fitting it to GPS/levelling data.
- Capacity building and professional training of junior engineers in geoid modelling.

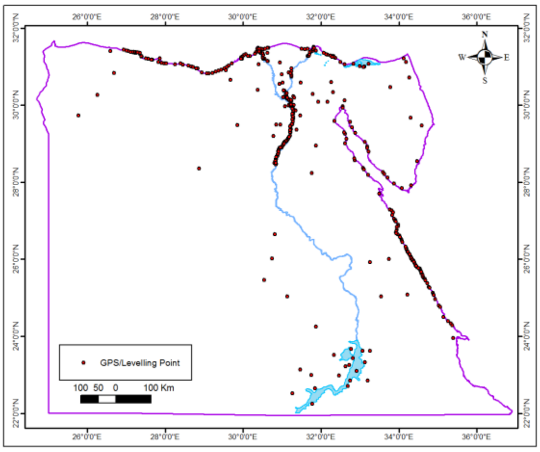

Figure 5: The Available SRI GPS/Levelling Stations

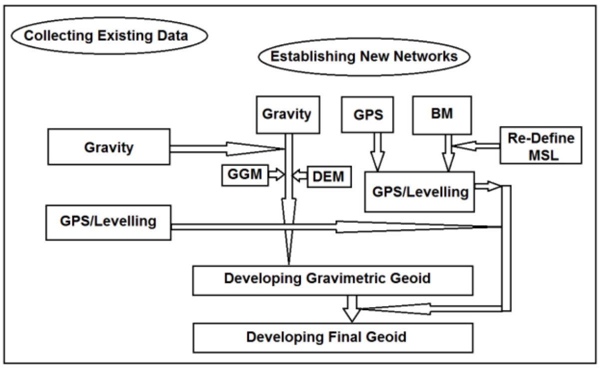

Figure 6: The Main Steps for Developing a Geoid Model For Egypt

The proposed geoid modelling task could be divided into two phases: (a) a two-year first phase that could result in a national geoid model with an approximate accuracy of 3-4 cm; and (b) the second phase that deals with densification of geodetic measurement permitting the development of a centimeter level of accuracy geoid for Egypt. The budget of that proposal could be financed through the current undergoing national project for establishing the Spatial Data Infrastructure (SDI) for Egypt. Economically speaking, such a geoid model will broaden the utilization of GNSS positioning techniques in engineering applications, which in turn will considerably decrease their costs comparing with the usage of terrestrial surveying methods.

5. Conclusions

In engineering surveying, the transformation of GNSS-based geodetic heights to the MSL-based orthometric heights requires a precise geoid model. On a national basis over Egypt, the most available geoid models produce an accuracy levels of 0.10-0.15 m. On the other hand, the utilization of GGM models gives errors in the order of more than 0.20 m. That accuracy is, by default, not appropriate for engineering activities. The main reason behind this situation is the lack of precise and homogeneously-distributed geodetic database over the country. Based on several workshops organized by SRI, it has been found that the optimum strategy is the unification and integration of all available resources and capabilities in carrying out a national project for developing a geoid model for Egypt. In this paper, the proposal is discussed in details including the strategy and technical procedures for conducting that effort. The anticipated project intends to develop a national geoid model with a few-centimeter accuracy in the first phase, which can be modified later to achieve the one-centimeter accuracy level. From an economic perspective, a national geoid model will broaden the utilization of GNSS positioning techniques in engineering applications in Egypt, and significantly decrease their costs compared with the time-consuming and expensive terrestrial surveying methods.

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