

Comparison of Geoid Undulation Values Using Different Global Geopotential Models over Egypt

Tarek M. Awwad
Department of Civil Engineering, College of Engineering,
Al-Azhar University, Cairo, Egypt

Abstract: While the most challenge research scopes of geodesy/surveying science are to identify the highly accurate three-Dimensional (3D) coordinates (ϕ , λ , h/H), the vertical positioning (h/H) are the most crucial for many applications in civil engineering projects. These projects require to convert the Ellipsoidal height (h) [observed by the Global Positioning System (GPS)] to orthometric Height (H) [observed by traditional field survey techniques such as spirit levelling]. The difference between the ellipsoidal height (h) and orthometric Height (H) called the geoid undulation or geoidal height (N). The Global Geopotential Model (GGM) is a model that is being represented by the spherical harmonic coefficient that defines the potential of gravitational in the spectral domain. Lately several GGM have been developed based on the accurate data collected by the different satellite missions. Due to the importance of Egypt location, there are many efforts for applying (as international projects) and/or modifying (as researches studies) several of these GGMs. Also, since, Egypt has area up to one million km² and due to the limited input data for different GGMs, therefore, the accuracy of the GGMs are low. So, it's expected that the undulation values (N) will be different when using different GGMs. This paper aim to study the relation between the undulation values (N) using most common eight GGMs. The study will be on regular points distribution (346 point) between latitudes ϕ [22°N, 31°N] and between longitudes λ [26°E, 36°E] which cover whole Egypt territories. Generally, the maximum (N) value reach 21.47 m at [29.5°N, 33.5°E], the minimum value reach 7.23 m at [22.5°N, 36°E], the maximum difference of N calculated using deferent GGM reach 6.08 m at [28.5° N, 34°E] and the minimum difference reach 0.36 m at [26°N, 27°E].

Key words: Geoid, undulation, GGM, ellipsoidal heights, orthometric heights, Egypt

INTRODUCTION

One of the most challenge research scopes of geodesy were to identify the highly accurate three-Dimensional (3D) reference frame for the Earth system. Many researchers carried on their shoulders identifying (3D) locations of any point (ϕ , λ , h/H) on the Earth by choosing the utmost precision mathematical form which expresses the Earth's size and its geometric shape. The researchers divided the (3D) position to two components; horizontal and vertical. The vertical component is the main concern of this paper.

The vertical positioning has two main factors the height and the datum (based on the used reference surface). According to Davis *et al.* (2011), there are two reference surfaces to compute the vertical positioning; the ellipsoid and the equipotential surface. Ellipsoidal datum is based on a geometric model, an ellipsoid that approximates the Earth's surface without the topography. These ellipsoid heights are typically realized through observations from space based systems such as the Global Positioning System (GPS). Equipotential

surface (the geoid) is the surface of constant gravity potential. The gravitational potential of the Earth depends on the distribution of mass density throughout the Earth. This surface includes topography and therefore, differs from a geocentric ellipsoid, up to 100 m, because of the Earth's irregular mass distribution, being higher than the ellipsoid when there is a greater mass.

So, there are two heights values for any point; ellipsoidal heights/Geodetic heights (related to the geodetic reference ellipsoid surface) and orthometric heights (related to the equipotential surfaces/The geoid). The difference between the ellipsoidal height (h) and orthometric Height (H) called the geoid undulation or geoidal height (N) which can be calculated using Eq. 1 and is shown in Fig. 1:

$$N = h - H \quad (1)$$

The ellipsoidal heights are measured by the GPS techniques and the orthometric heights are measured by traditional field survey techniques such as spirit levelling or Total station. Lately the advantages of space-based

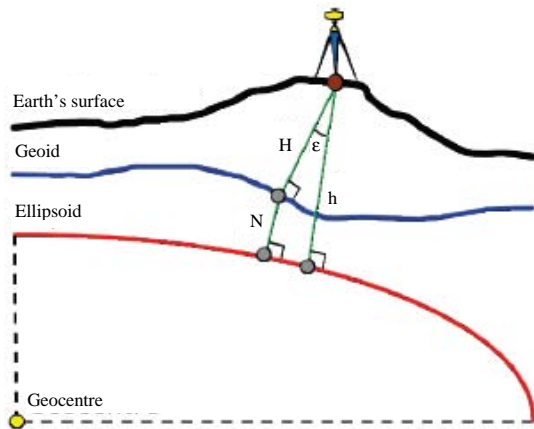


Fig. 1: The relations between ellipsoid height (h), orthometric Height (H) and geoid undulation (N) (Yilmaz *et al.*, 2017)

technique, lead to wide spread of using the GPS observations which refer to the World Geodetic System 1984 (WGS84) ellipsoid. On other hand, most of projects require orthometric heights to be used in engineering applications and mapping processes. According to Eq. 1 geoid undulation/geoidal height (N) is required for every observed point to get its orthometric Height (H) from the ellipsoid height (h).

The Global Geopotential Model (GGM) is a model that is being represented by the spherical harmonic coefficient that defines the potential of gravitational in the spectral domain (Tugi *et al.*, 2016). Over the last two decades, several GGM have been developed based on the accurate data collected by the satellite missions CHALLENGING Minisatellite Payload (CHAMP), Gravity Recovery And Climate Experiment (GRACE), Global Ocean Circulation Experiment (GOCE) and LASER GEODYNAMIC Satellite (LAGEOS). The GGM data which published in public domain (<http://icgem.gfz-potsdam.de/ICGEM/>) by the International Centre of Global Earth Models (ICGEM), can be classified to satellite-only model (consists of only artificial satellite-based gravity observation such as from CHAMP, GRACE and GOCE) and combined model (combined together with other gravimetry data from terrestrial and/or the airborne, satellite altimetry and topography or bathymetry data such as from LAGEOS) (Tugi *et al.*, 2016).

Lately, in Egypt the researchers are interested to find the best GGM which fit Egypt such as Mahmoud (2012), quantify the GGM precision in Egypt such as Al-Krargy *et al.* (2015), developed a national geoid model for Egypt such as Dawod (1998, 2008), Abd-Elmotaal (2008), Rabah and Kaloop (2013), Al-Krargy *et al.* (2014) and evaluation the GGM performance generally such as Krynski and Kloch (2009), Foerste *et al.* (2009) and

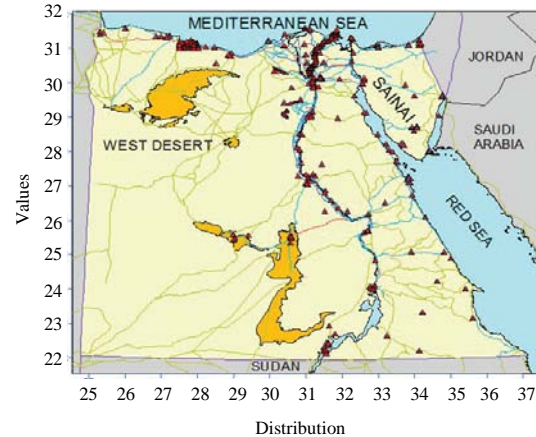


Fig. 2: Distribution of the 394 available points with observed geoid undulation (Mahmoud, 2012)

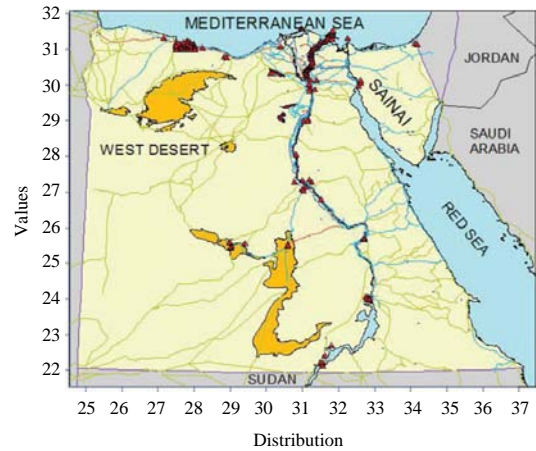


Fig. 3: Distribution of the 158 points only were accepted of the 394 available points (Mahmoud, 2012)

Yilmaz *et al.* (2016). There is no research to study the relationship of undulation values (N) obtained using different GGMs. So, this paper aim is to study the relation between the collected undulation values (N) using eight most common GGMs. The study will be on points distributed evenly across Egypt.

Literature review: In this section, some important studies related to this work will be highlighted. According to Mahmoud (2012), twenty five GGMs were evaluated with consideration variability of data input type which varied from terrestrial gravity data, satellite tracking data and altimetry data. The research used 394 ground stations distributed over Egypt as shown in Fig. 2 with known geoid shift values (N) coming from observed GPS and levelling surveys. Only 158 stations were accepted and 236 stations were rejected as shown in Fig. 3 (Mahmoud, 2012). Undulation value (N) was calculated

Table 1: Most recent GGMs used by Al-Krargy *et al.* (2015)

| Models | Years | Degree | Data type |
|----------------------|-------|--------|-------------------------------|
| EGM2008 | 2008 | 2190 | S (GRACE), G, A |
| EIGEN-5C | 2008 | 360 | S (GRACE, CHAMP), G, A |
| EGM96 | 1996 | 360 | S, G, A |
| EIGEN-6C4 | 2014 | 2190 | S (GOCO, GRACE, LAGEOS), G, A |
| GO_CONS_GCF_2_DIR_R5 | 2014 | 300 | S (GOCO, GRACE, LAGEOS) |
| GO_CONS_GCF_2_TIM_R5 | 2014 | 280 | S (GOCO) |
| DGM-1S | 2012 | 250 | S (GOCO, GRACE) |

S = Satellite tracking data, G = Terrestrial gravity data, A = Altimetry data and CHAMP, GRACE and LAGEOS are gravity satellite missions

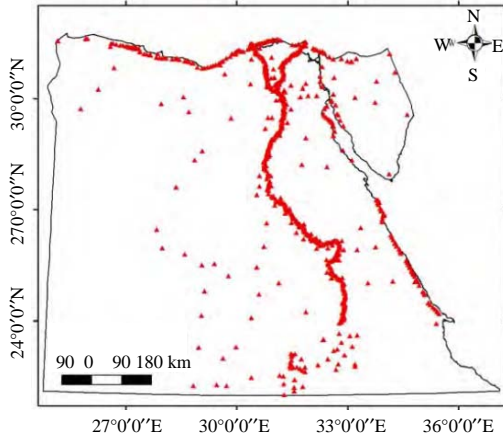


Fig. 4: GPS/levelling points used by Al-Krargy *et al.* (2015)

for each ground station once using GGM and another from GPS/leveling. Then, the difference (ΔN) was calculated as GGM error at each ground station and the standard deviations (σ) of (ΔN) for each data set were calculated. By analyzing the results, the author recommended ten GGMs as best models fit Egypt window and classified them to three accuracy levels as follows (Mahmoud, 2012); EGM 2008 (up to 2190 degree) and EIGEN-CG01C (360) as a first level. EIGEN-CG03C (360), EIGEN-05C (360), EIGEN-GL04C (360), EGM2008 (360) and GGM03C (360) are classified as a second level. The third level are GGM02C (200), EIGEN GRACE-02S (150) and EGM96 (360).

Also, Al-Krargy *et al.* (2015) compared most-recent seven GGMs as shown in Table 1 and evaluate their accuracy when using precise local geodetic datasets in Egypt. They used 1074 GPS/Levelling stations as shown in Fig. 4, also 941 observed terrestrial gravity points. He arranged the GGMs according to the accuracy of geoid undulations as shown respectively in Table 1.

MATERIALS AND METHODS

Data over Egypt and GGM methodology: According to the previous analysis of related research for using different

GGMs over Egypt, this study will be exposed to the relationships for several recommended GGMs by other researchers. Eight from most common GGMs used in Egypt were selected and are as shown in Table 2. Also, this study will use 346 equally distributed points located between latitudes (ϕ) [22°N, 31°N] and between longitudes (λ) [26°E, 36°E] to cover whole Egypt as shown in Fig. 5.

Since, the study of relationships in this paper will be based on the geoid undulation values (N) which can be calculated by several GGMs, then the basic method which uses by GGMs to calculate the geoid undulation values (N) will be briefly described. According to Al-Krargy *et al.* (2015), the geoid undulation (N) can be computed from gravity data by the well-known Stoke's formula as shown in Eq. 2. Practically the gravity datasets of the whole Earth are not available, therefore the gravity anomalies (Δg) are divided to components as shown in Eq. 3. Finally, the final geoid undulation (N) can be calculated using three components as shown in Eq. 4:

$$N = \frac{R}{4\pi\gamma} \iint_{\sigma} S(\Psi) \Delta g d\sigma \quad (2)$$

Where:

- R = The mean Earth radius
- γ = The normal gravity on the reference ellipsoid
- $d\sigma$ = An infinitesimal surface element on the unit sphere σ
- $S(\Psi) = \sum_{n=2}^{\infty} (2n+1/n-1)$ = The Stoke's function which can be expressed as a series of Legendre polynomial $P_n(\cos \Psi)$
- $P_n(\cos \Psi)$
- Δg = The gravity anomaly and can be written as:

$$\Delta g = \Delta g_{REF} + \Delta g_F + \Delta g_h \quad (3)$$

Where:

- Δg_{REF} = The gravity anomalies of a reference gravity field represented by a GGM
- Δg_F = The free-air gravity anomalies
- Δg_h = The effect of topography

$$N = N_{REF} + N_{\Delta g} + N_h \quad (4)$$

Table 2: Eight selected GGMs in this study

| Model | Years | Degree | Data type |
|-------------|-------|--------|------------------------|
| EGM96 | 1996 | 360 | S, G, A |
| EIGEN-CG01C | 2004 | 360 | S(CHAMP, GRACE), G, A |
| GGM03C | 2009 | 360 | S(GRACE), G, A |
| EIGEN-CG03C | 2005 | 360 | S(CHAMP, GRACE), G, A |
| EIGEN-GL04C | 2006 | 360 | S(GRACE, LAGEOS), G, A |
| EIGEN-5C | 2008 | 360 | S(GRACE, LAGEOS), G, A |
| EGM 2008 | 2008 | 360 | S(GRACE), G, A |
| EGM2008 | 2008 | 2190 | S(GRACE), G, A |

S = Satellite tracking data, G = Terrestrial gravity data, A = Altimetry data and CHAMP, GRACE and LAGEOS are gravity satellite missions

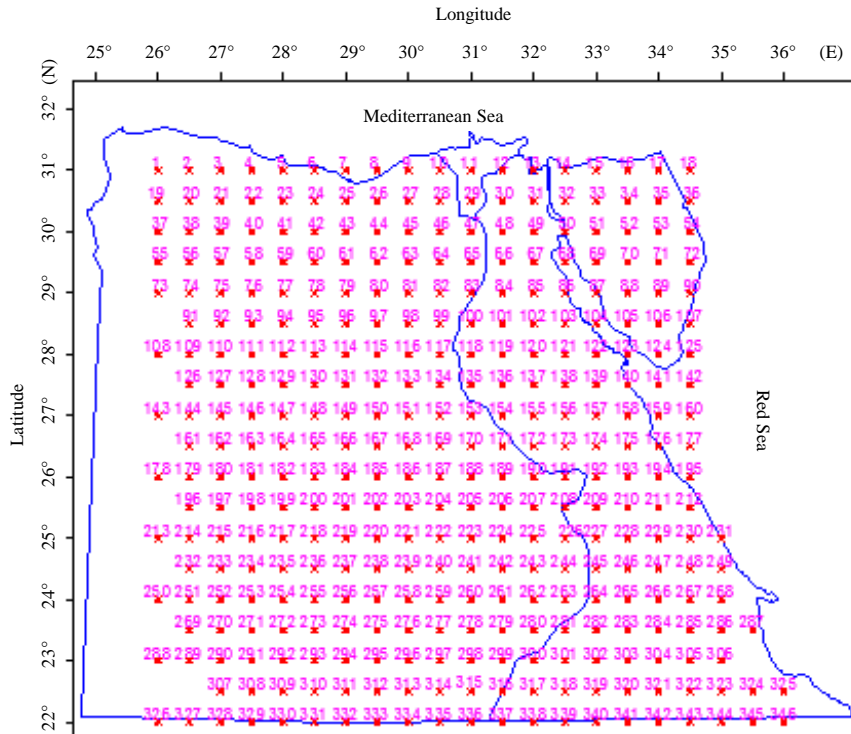


Fig. 5: The 346 equally distributed points over Egypt

Where:

N_{REF} = The contribution of reference gravity field

$N_{\Delta g}$ = The contribution of reduced gravity anomalies

N_h = The contribution of topography

Also, another researcher (Mahmoud, 2012) mentioned the main concept to calculate the geoid undulation values (N) by GGMs as following; “the geo-potential models are available with coefficients (C_{nm}) and (S_{nm}) complete up to degree and order (n, m). So, the geoid undulations above the reference (normal) ellipsoid are computed from the fully normalized spherical harmonic coefficients to degree (n) using the truncated formula” as shown in Eq. 5 (Mahmoud, 2012):

$$N = (GM/r\gamma) \sum_{n=2}^{n=m_{max}} \left(\frac{a}{r}\right)^n - \sum_{m=0}^n \left[\left(\bar{C}_{nm} \cos m\lambda \right) + \left(\bar{S}_{nm} \sin m\lambda \right) \right] \bar{P}_{nm} \sin \phi \quad (5)$$

Where:

- G = The Newtonian gravitational constant
- M = The Mass of the Earth
- $\bar{C}_{nm}, \bar{S}_{nm}$ = The fully normalized geo-potential coefficients of degree and order (n, m)
- $\bar{P}_{n,m}$ = The fully normalized associated legendre function of degree and order (n, m)
- α = The semi-major axis
- n = The degree of the geo-potential model
- γ = The normal gravity on the reference ellipsoid
- r = The radial distance from Earth’s mass center
- ϕ, λ = The geocentric latitude and longitude

RESULTS AND DISCUSSION

The test in this study has been carried out as follows; The 346 points are distributed equally as an array to cover whole Egypt with 0.5° interval of both latitudes (ϕ) and longitudes (λ). The distance between points is 50 Km, approximately. The latitudes (ϕ) of the points start from 22°N to 31°N and longitudes (λ) starts from 26°E to 36°E (Fig. 5).

Eight GGMs, as shown in Table 2 have been chosen in this research to calculate eight undulation values (N) of

each point for the 346 points. All these data are available from the author but due to the limited space only the results with interval of one degree are shown in Table 3. The point number (ID) in Table 3 shows the point number as original data shown in Fig. 5.

To avoid the prolongation in the narrative Fig. 6-15 show the eight undulation values calculated for every one degree latitude and 0.5° longitude. While the conclusion of this research will be based on the analysis of that data for all 346 points which used in this study with interval 0.5° in both latitude and longitude.

Table 3: Calculated undulation values using eight GGMs for 186 points only as an example

| Point (ID) | Latitude (Deg.) | Longitude (Deg.) | Calculated (N) values (m) | | | | | | | | Max. diff. (m) |
|------------|-----------------|------------------|---------------------------|-----------------|------------|-----------------|-----------------|--------------|--------------------|---------------------|----------------|
| | | | EGM96 (1) | EIGEN-CG01C (2) | GGM03C (3) | EIGEN-CG03C (4) | EIGEN-GL04C (5) | EIGEN-5C (6) | EGM 2008 (360) (7) | EGM 2008 (2190) (8) | |
| 1 | 31 | 26.0 | 21.39 | 20.84 | 21.25 | 21.31 | 21.29 | 21.34 | 21.23 | 20.85 | 0.55 |
| 2 | 31 | 26.5 | 20.93 | 20.38 | 20.79 | 20.84 | 20.89 | 21.06 | 20.95 | 20.61 | 0.68 |
| 3 | 31 | 27.0 | 19.84 | 19.25 | 19.77 | 19.64 | 19.78 | 19.99 | 19.66 | 19.25 | 0.75 |
| 4 | 31 | 27.5 | 18.50 | 17.77 | 18.30 | 18.07 | 18.29 | 18.36 | 18.21 | 17.96 | 0.73 |
| 5 | 31 | 28.0 | 17.08 | 16.30 | 16.89 | 16.53 | 16.78 | 16.74 | 16.89 | 16.58 | 0.78 |
| 6 | 31 | 28.5 | 16.01 | 15.38 | 15.87 | 15.59 | 15.76 | 15.72 | 15.77 | 15.50 | 0.63 |
| 7 | 31 | 29.0 | 15.29 | 14.65 | 15.07 | 14.91 | 14.92 | 14.96 | 14.86 | 14.72 | 0.64 |
| 8 | 31 | 29.5 | 15.43 | 14.81 | 15.18 | 15.14 | 15.05 | 15.20 | 15.02 | 14.62 | 0.81 |
| 9 | 31 | 30.0 | 15.74 | 15.23 | 15.44 | 15.61 | 15.47 | 15.52 | 15.44 | 15.01 | 0.73 |
| 10 | 31 | 30.5 | 15.79 | 15.23 | 15.36 | 15.61 | 15.44 | 15.45 | 15.55 | 15.01 | 0.77 |
| 11 | 31 | 31.0 | 16.02 | 15.36 | 15.59 | 15.71 | 15.58 | 15.59 | 15.80 | 15.34 | 0.67 |
| 12 | 31 | 31.5 | 16.36 | 15.49 | 15.96 | 15.77 | 15.76 | 15.70 | 16.03 | 15.64 | 0.86 |
| 13 | 31 | 32.0 | 16.81 | 15.74 | 16.34 | 15.97 | 16.11 | 16.16 | 16.37 | 15.94 | 1.07 |
| 14 | 31 | 32.5 | 17.07 | 16.14 | 16.62 | 16.34 | 16.55 | 16.54 | 16.55 | 16.31 | 0.94 |
| 15 | 31 | 33.0 | 17.79 | 17.22 | 17.25 | 17.41 | 17.58 | 17.47 | 17.20 | 16.80 | 0.98 |
| 16 | 31 | 33.5 | 17.79 | 17.41 | 17.27 | 17.58 | 17.64 | 17.55 | 17.30 | 17.01 | 0.78 |
| 17 | 31 | 34.0 | 17.54 | 17.25 | 17.30 | 17.38 | 17.23 | 17.66 | 17.20 | 17.02 | 0.64 |
| 18 | 31 | 34.5 | 18.44 | 18.34 | 18.19 | 18.44 | 18.15 | 18.87 | 18.17 | 17.62 | 1.24 |
| 37 | 30 | 26.0 | 21.06 | 20.64 | 20.87 | 21.02 | 20.81 | 20.94 | 21.05 | 20.56 | 0.50 |
| 38 | 30 | 26.5 | 20.02 | 19.57 | 19.86 | 19.97 | 19.80 | 19.85 | 20.01 | 19.59 | 0.45 |
| 39 | 30 | 27.0 | 18.64 | 18.13 | 18.41 | 18.47 | 18.43 | 18.42 | 18.38 | 17.95 | 0.69 |
| 40 | 30 | 27.5 | 17.78 | 17.16 | 17.40 | 17.41 | 17.52 | 17.51 | 17.47 | 17.02 | 0.76 |
| 41 | 30 | 28.0 | 17.31 | 16.64 | 16.91 | 16.83 | 16.99 | 16.95 | 17.00 | 16.57 | 0.73 |
| 42 | 30 | 28.5 | 17.24 | 16.52 | 16.86 | 16.74 | 16.83 | 16.88 | 16.85 | 16.37 | 0.88 |
| 43 | 30 | 29.0 | 17.13 | 16.36 | 16.72 | 16.68 | 16.67 | 16.58 | 16.65 | 16.50 | 0.77 |
| 44 | 30 | 29.5 | 16.90 | 16.15 | 16.51 | 16.59 | 16.52 | 16.36 | 16.58 | 16.30 | 0.75 |
| 45 | 30 | 30.0 | 16.69 | 15.92 | 16.28 | 16.44 | 16.38 | 16.11 | 16.47 | 16.08 | 0.77 |
| 46 | 30 | 30.5 | 16.59 | 15.90 | 16.20 | 16.41 | 16.40 | 15.98 | 16.29 | 15.79 | 0.80 |
| 47 | 30 | 31.0 | 15.97 | 15.23 | 15.68 | 15.64 | 15.74 | 15.76 | 15.74 | 15.49 | 0.74 |
| 48 | 30 | 31.5 | 16.25 | 15.54 | 15.98 | 15.82 | 15.99 | 16.39 | 16.16 | 15.96 | 0.85 |
| 49 | 30 | 32.0 | 16.79 | 16.44 | 16.75 | 16.62 | 16.77 | 17.17 | 16.70 | 16.45 | 0.74 |
| 50 | 30 | 32.5 | 16.13 | 16.20 | 16.50 | 16.36 | 16.40 | 16.53 | 16.30 | 15.99 | 0.53 |
| 51 | 30 | 33.0 | 17.38 | 18.16 | 18.08 | 18.36 | 18.24 | 18.17 | 18.08 | 17.73 | 0.97 |
| 52 | 30 | 33.5 | 18.21 | 19.57 | 19.41 | 19.81 | 19.58 | 19.56 | 19.06 | 18.64 | 1.60 |
| 53 | 30 | 34.0 | 17.02 | 18.52 | 18.59 | 18.77 | 18.52 | 18.50 | 18.34 | 18.14 | 1.76 |
| 54 | 30 | 34.5 | 17.04 | 18.38 | 18.29 | 18.61 | 18.45 | 18.20 | 18.58 | 18.20 | 1.57 |
| 73 | 29 | 26.0 | 18.17 | 17.69 | 18.01 | 18.11 | 17.94 | 17.96 | 17.82 | 17.33 | 0.85 |
| 74 | 29 | 26.5 | 17.21 | 16.69 | 17.05 | 17.15 | 17.03 | 16.97 | 17.11 | 16.66 | 0.55 |
| 75 | 29 | 27.0 | 16.30 | 15.72 | 16.01 | 16.12 | 16.16 | 15.96 | 15.96 | 15.64 | 0.66 |
| 76 | 29 | 27.5 | 15.73 | 15.07 | 15.40 | 15.37 | 15.51 | 15.24 | 15.31 | 14.97 | 0.76 |
| 77 | 29 | 28.0 | 15.76 | 14.97 | 15.30 | 15.20 | 15.31 | 15.13 | 15.35 | 14.97 | 0.79 |
| 78 | 29 | 28.5 | 16.23 | 15.37 | 15.76 | 15.61 | 15.57 | 15.62 | 15.59 | 15.18 | 1.05 |
| 79 | 29 | 29.0 | 16.69 | 15.75 | 16.17 | 16.08 | 15.89 | 16.05 | 15.98 | 15.53 | 1.16 |
| 80 | 29 | 29.5 | 16.87 | 15.91 | 16.28 | 16.35 | 16.07 | 16.23 | 16.31 | 15.95 | 0.96 |
| 81 | 29 | 30.0 | 16.24 | 15.29 | 15.73 | 15.78 | 15.57 | 15.73 | 15.55 | 15.17 | 1.07 |
| 82 | 29 | 30.5 | 15.64 | 14.77 | 15.21 | 15.22 | 15.22 | 15.29 | 14.91 | 14.43 | 1.21 |
| 83 | 29 | 31.0 | 15.59 | 14.97 | 15.45 | 15.33 | 15.55 | 15.44 | 15.19 | 14.75 | 0.83 |
| 84 | 29 | 31.5 | 16.16 | 15.99 | 16.53 | 16.28 | 16.57 | 16.52 | 16.18 | 15.70 | 0.87 |
| 85 | 29 | 32.0 | 16.55 | 17.11 | 17.60 | 17.42 | 17.57 | 17.36 | 17.51 | 16.72 | 1.05 |
| 86 | 29 | 32.5 | 15.10 | 16.77 | 16.94 | 17.20 | 17.11 | 16.45 | 16.99 | 16.98 | 2.10 |
| 87 | 29 | 33.0 | 14.03 | 16.78 | 17.12 | 17.40 | 17.11 | 17.17 | 16.73 | 15.95 | 3.37 |
| 88 | 29 | 33.5 | 15.35 | 18.75 | 19.63 | 19.54 | 19.25 | 19.48 | 19.40 | 18.95 | 4.28 |

Table 3: Continue

| Point (ID) | Latitude (Deg.) | Longitude (Deg.) | Calculated (N) values (m) | | | | | | | EGM 2008 (360) (7) | EGM 2008 (2190) (8) | Max. diff. (m) |
|------------|-----------------|------------------|---------------------------|-----------------|------------|-----------------|-----------------|--------------|-------|--------------------|---------------------|----------------|
| | | | EGM96 (1) | EIGEN-CG01C (2) | GGM03C (3) | EIGEN-CG03C (4) | EIGEN-GL04C (5) | EIGEN-5C (6) | | | | |
| 89 | 29 | 34.0 | 14.09 | 17.57 | 18.65 | 18.43 | 18.35 | 17.88 | 19.20 | 18.60 | 5.11 | |
| 90 | 29 | 34.5 | 11.15 | 13.88 | 14.87 | 14.68 | 14.91 | 14.82 | 15.53 | 15.76 | 4.61 | |
| 108 | 28 | 26.0 | 15.81 | 14.84 | 15.53 | 15.49 | 15.40 | 15.39 | 15.25 | 14.83 | 0.98 | |
| 109 | 28 | 26.5 | 15.70 | 14.79 | 15.42 | 15.42 | 15.48 | 15.45 | 15.31 | 14.94 | 0.91 | |
| 110 | 28 | 27.0 | 15.46 | 14.54 | 15.12 | 15.08 | 15.34 | 15.26 | 15.31 | 14.96 | 0.92 | |
| 111 | 28 | 27.5 | 15.26 | 14.31 | 14.84 | 14.75 | 15.13 | 15.03 | 14.95 | 14.66 | 0.96 | |
| 112 | 28 | 28.0 | 14.97 | 13.89 | 14.49 | 14.28 | 14.62 | 14.59 | 14.32 | 13.97 | 1.08 | |
| 113 | 28 | 28.5 | 15.16 | 14.01 | 14.59 | 14.42 | 14.53 | 14.64 | 14.55 | 14.22 | 1.15 | |
| 114 | 28 | 29.0 | 15.51 | 14.38 | 14.87 | 14.85 | 14.66 | 14.81 | 14.88 | 14.47 | 1.13 | |
| 115 | 28 | 29.5 | 15.39 | 14.30 | 14.76 | 14.83 | 14.41 | 14.53 | 14.71 | 14.42 | 1.09 | |
| 116 | 28 | 30.0 | 15.02 | 14.05 | 14.25 | 14.57 | 14.16 | 14.16 | 14.54 | 14.14 | 0.97 | |
| 117 | 28 | 30.5 | 14.35 | 13.53 | 13.79 | 13.96 | 13.82 | 13.72 | 14.15 | 13.82 | 0.82 | |
| 118 | 28 | 31.0 | 14.31 | 13.78 | 14.23 | 14.10 | 14.31 | 14.33 | 14.47 | 14.03 | 0.68 | |
| 119 | 28 | 31.5 | 14.72 | 14.73 | 15.08 | 14.99 | 15.38 | 15.62 | 15.25 | 14.64 | 0.98 | |
| 120 | 28 | 32.0 | 14.58 | 15.29 | 15.87 | 15.57 | 15.86 | 16.20 | 15.88 | 15.51 | 1.61 | |
| 121 | 28 | 32.5 | 14.77 | 16.47 | 16.95 | 16.85 | 16.86 | 16.84 | 17.14 | 16.43 | 2.37 | |
| 122 | 28 | 33.0 | 13.95 | 16.77 | 16.84 | 17.29 | 17.02 | 16.47 | 16.84 | 16.86 | 3.34 | |
| 123 | 28 | 33.5 | 12.23 | 15.67 | 15.69 | 16.28 | 15.97 | 15.77 | 15.90 | 15.36 | 4.04 | |
| 124 | 28 | 34.0 | 11.25 | 14.60 | 15.24 | 15.19 | 15.10 | 16.03 | 15.91 | 16.05 | 4.80 | |
| 125 | 28 | 34.5 | 11.04 | 13.71 | 14.55 | 14.20 | 14.39 | 14.96 | 14.47 | 13.86 | 3.92 | |
| 143 | 27 | 26.0 | 14.97 | 14.05 | 14.56 | 14.58 | 14.35 | 14.51 | 14.77 | 14.47 | 0.92 | |
| 144 | 27 | 26.5 | 15.08 | 14.30 | 14.75 | 14.78 | 14.60 | 14.72 | 14.77 | 14.34 | 0.77 | |
| 145 | 27 | 27.0 | 14.92 | 14.15 | 14.56 | 14.56 | 14.52 | 14.64 | 14.53 | 14.16 | 0.77 | |
| 146 | 27 | 27.5 | 14.80 | 13.90 | 14.25 | 14.27 | 14.39 | 14.38 | 14.40 | 14.21 | 0.89 | |
| 147 | 27 | 28.0 | 14.59 | 13.54 | 14.00 | 13.94 | 14.19 | 13.93 | 13.70 | 13.21 | 1.38 | |
| 148 | 27 | 28.5 | 14.21 | 13.07 | 13.72 | 13.57 | 13.80 | 13.55 | 13.09 | 12.79 | 1.42 | |
| 149 | 27 | 29.0 | 14.08 | 13.02 | 13.69 | 13.62 | 13.65 | 13.58 | 13.53 | 13.13 | 1.06 | |
| 150 | 27 | 29.5 | 14.08 | 13.25 | 13.73 | 13.90 | 13.68 | 13.69 | 13.91 | 13.44 | 0.83 | |
| 151 | 27 | 30.0 | 13.78 | 13.11 | 13.49 | 13.73 | 13.41 | 13.45 | 13.71 | 13.39 | 0.67 | |
| 152 | 27 | 30.5 | 13.55 | 12.99 | 13.34 | 13.53 | 13.35 | 13.37 | 13.68 | 13.29 | 0.69 | |
| 153 | 27 | 31.0 | 13.26 | 12.78 | 13.28 | 13.23 | 13.35 | 13.27 | 13.21 | 13.07 | 0.57 | |
| 154 | 27 | 31.5 | 12.87 | 12.42 | 13.19 | 12.82 | 13.18 | 13.06 | 12.84 | 12.54 | 0.77 | |
| 155 | 27 | 32.0 | 13.45 | 13.19 | 14.00 | 13.60 | 13.94 | 13.78 | 13.58 | 13.07 | 0.93 | |
| 156 | 27 | 32.5 | 14.15 | 14.17 | 14.96 | 14.62 | 14.68 | 14.66 | 14.19 | 13.92 | 1.04 | |
| 157 | 27 | 33.0 | 14.69 | 15.05 | 15.62 | 15.49 | 15.24 | 15.58 | 15.43 | 14.81 | 0.93 | |
| 158 | 27 | 33.5 | 14.75 | 15.44 | 15.38 | 15.80 | 15.44 | 15.79 | 16.06 | 16.03 | 1.30 | |
| 159 | 27 | 34.0 | 13.11 | 13.96 | 13.77 | 14.20 | 14.01 | 13.90 | 13.96 | 13.56 | 1.09 | |
| 160 | 27 | 34.5 | 12.27 | 12.70 | 12.61 | 12.85 | 12.94 | 12.43 | 12.41 | 12.31 | 0.67 | |
| 178 | 26 | 26.0 | 14.26 | 14.16 | 14.48 | 14.59 | 14.77 | 14.39 | 14.75 | 14.47 | 0.61 | |
| 179 | 26 | 26.5 | 13.81 | 13.85 | 14.15 | 14.25 | 14.22 | 14.09 | 14.40 | 14.09 | 0.59 | |
| 180 | 26 | 27.0 | 13.38 | 13.36 | 13.66 | 13.71 | 13.50 | 13.72 | 13.47 | 13.37 | 0.36 | |
| 181 | 26 | 27.5 | 13.25 | 12.99 | 13.33 | 13.33 | 13.10 | 13.33 | 13.06 | 12.54 | 0.79 | |
| 182 | 26 | 28.0 | 13.14 | 12.47 | 13.00 | 12.87 | 12.82 | 12.86 | 12.93 | 12.67 | 0.67 | |
| 183 | 26 | 28.5 | 12.98 | 12.11 | 12.91 | 12.63 | 12.78 | 12.69 | 12.78 | 12.41 | 0.87 | |
| 184 | 26 | 29.0 | 12.91 | 12.09 | 12.95 | 12.72 | 12.93 | 12.87 | 12.67 | 12.40 | 0.86 | |
| 185 | 26 | 29.5 | 13.20 | 12.61 | 13.31 | 13.27 | 13.36 | 13.39 | 13.15 | 12.81 | 0.78 | |
| 186 | 26 | 30.0 | 13.53 | 13.18 | 13.68 | 13.78 | 13.70 | 13.65 | 13.61 | 13.24 | 0.60 | |
| 187 | 26 | 30.5 | 13.21 | 12.94 | 13.35 | 13.44 | 13.30 | 13.17 | 13.21 | 12.90 | 0.54 | |
| 188 | 26 | 31.0 | 13.13 | 12.73 | 13.24 | 13.19 | 13.14 | 12.95 | 13.14 | 12.71 | 0.53 | |
| 189 | 26 | 31.5 | 13.15 | 12.50 | 13.12 | 13.03 | 13.14 | 12.98 | 12.82 | 12.60 | 0.65 | |
| 190 | 26 | 32.0 | 13.04 | 12.08 | 12.95 | 12.75 | 12.88 | 12.88 | 12.59 | 12.13 | 0.95 | |
| 191 | 26 | 32.5 | 13.17 | 12.01 | 12.92 | 12.80 | 12.80 | 12.77 | 12.49 | 12.20 | 1.17 | |
| 192 | 26 | 33.0 | 13.74 | 12.52 | 13.43 | 13.35 | 13.16 | 13.26 | 12.68 | 12.25 | 1.49 | |
| 193 | 26 | 33.5 | 14.70 | 13.37 | 14.30 | 14.13 | 13.93 | 14.23 | 14.16 | 13.56 | 1.33 | |
| 194 | 26 | 34.0 | 14.39 | 13.09 | 13.79 | 13.72 | 13.71 | 14.12 | 14.31 | 14.10 | 1.31 | |
| 195 | 26 | 34.5 | 12.89 | 11.56 | 12.22 | 12.11 | 12.35 | 12.57 | 12.61 | 12.00 | 1.33 | |
| 213 | 25 | 26.0 | 14.09 | 14.68 | 15.46 | 15.53 | 15.86 | 15.51 | 15.48 | 15.16 | 1.77 | |
| 214 | 25 | 26.5 | 13.49 | 14.36 | 15.14 | 15.12 | 15.29 | 15.19 | 15.00 | 14.74 | 1.80 | |
| 215 | 25 | 27.0 | 13.41 | 14.26 | 14.74 | 14.86 | 14.78 | 14.93 | 14.44 | 14.16 | 1.52 | |
| 216 | 25 | 27.5 | 13.41 | 13.91 | 14.41 | 14.40 | 14.17 | 14.45 | 14.17 | 13.89 | 1.04 | |
| 217 | 25 | 28.0 | 13.61 | 13.64 | 14.24 | 14.14 | 13.99 | 14.22 | 14.39 | 13.94 | 0.79 | |
| 218 | 25 | 28.5 | 13.96 | 13.63 | 14.33 | 14.25 | 14.24 | 14.39 | 14.56 | 14.27 | 0.94 | |
| 219 | 25 | 29.0 | 13.56 | 13.00 | 13.86 | 13.75 | 13.86 | 13.82 | 14.04 | 13.80 | 1.04 | |
| 220 | 25 | 29.5 | 13.21 | 12.66 | 13.44 | 13.41 | 13.47 | 13.39 | 13.49 | 13.18 | 0.83 | |

Table 3: Continue

| Point (ID) | Latitude (Deg.) | Longitude (Deg.) | Calculated (N) values (m) | | | | | | | | Max. diff. (m) |
|------------|-----------------|------------------|---------------------------|-----------------|------------|-----------------|-----------------|--------------|--------------------|---------------------|----------------|
| | | | EGM96 (1) | EIGEN-CG01C (2) | GGM03C (3) | EIGEN-CG03C (4) | EIGEN-GL04C (5) | EIGEN-5C (6) | EGM 2008 (360) (7) | EGM 2008 (2190) (8) | |
| 221 | 25 | 30.0 | 13.29 | 12.92 | 13.41 | 13.52 | 13.45 | 13.41 | 13.29 | 13.16 | 0.60 |
| 222 | 25 | 30.5 | 13.16 | 12.88 | 13.19 | 13.28 | 13.15 | 13.19 | 12.93 | 12.40 | 0.88 |
| 223 | 25 | 31.0 | 13.01 | 12.67 | 12.98 | 12.94 | 12.87 | 13.06 | 13.29 | 13.04 | 0.62 |
| 224 | 25 | 31.5 | 13.03 | 12.49 | 12.92 | 12.82 | 12.87 | 13.07 | 14.05 | 13.38 | 1.56 |
| 225 | 25 | 32.0 | 12.98 | 12.32 | 12.81 | 12.85 | 12.92 | 12.99 | 14.03 | 13.62 | 1.70 |
| 226 | 25 | 32.5 | 12.41 | 11.70 | 12.27 | 12.45 | 12.42 | 12.29 | 12.60 | 12.15 | 0.90 |
| 227 | 25 | 33.0 | 12.14 | 11.37 | 12.08 | 12.24 | 12.09 | 11.89 | 11.63 | 11.21 | 1.04 |
| 228 | 25 | 33.5 | 12.62 | 11.83 | 12.56 | 12.66 | 12.54 | 12.32 | 12.00 | 11.60 | 1.06 |
| 229 | 25 | 34.0 | 13.46 | 12.54 | 13.32 | 13.24 | 13.29 | 13.08 | 12.92 | 12.52 | 0.95 |
| 230 | 25 | 34.5 | 13.59 | 12.53 | 13.24 | 13.11 | 13.35 | 13.24 | 13.23 | 12.88 | 1.06 |
| 231 | 25 | 35.0 | 12.03 | 10.90 | 11.33 | 11.48 | 11.75 | 11.66 | 11.60 | 11.30 | 1.13 |
| 250 | 24 | 26.0 | 14.92 | 16.27 | 17.55 | 17.28 | 17.44 | 17.13 | 17.02 | 16.74 | 2.63 |
| 251 | 24 | 26.5 | 14.49 | 16.30 | 17.43 | 17.11 | 17.18 | 17.18 | 16.38 | 15.97 | 2.95 |
| 252 | 24 | 27.0 | 14.16 | 15.75 | 16.64 | 16.29 | 16.33 | 16.37 | 15.75 | 15.58 | 2.49 |
| 253 | 24 | 27.5 | 13.98 | 15.07 | 15.60 | 15.44 | 15.55 | 15.43 | 15.26 | 14.85 | 1.63 |
| 254 | 24 | 28.0 | 13.81 | 14.43 | 14.89 | 14.84 | 14.93 | 14.84 | 14.96 | 14.74 | 1.14 |
| 255 | 24 | 28.5 | 13.65 | 13.70 | 14.34 | 14.34 | 14.44 | 14.28 | 14.64 | 14.24 | 0.99 |
| 256 | 24 | 29.0 | 13.51 | 13.19 | 13.98 | 14.09 | 14.08 | 14.03 | 14.32 | 14.09 | 1.13 |
| 257 | 24 | 29.5 | 13.17 | 12.65 | 13.55 | 13.66 | 13.50 | 13.56 | 13.67 | 13.25 | 1.02 |
| 258 | 24 | 30.0 | 12.68 | 12.20 | 12.95 | 13.07 | 12.84 | 12.89 | 13.03 | 12.68 | 0.87 |
| 259 | 24 | 30.5 | 12.30 | 11.89 | 12.56 | 12.47 | 12.34 | 12.48 | 12.23 | 11.86 | 0.70 |
| 260 | 24 | 31.0 | 12.11 | 11.77 | 12.46 | 12.11 | 12.25 | 12.46 | 11.98 | 11.64 | 0.82 |
| 261 | 24 | 31.5 | 12.00 | 11.72 | 12.44 | 12.00 | 12.34 | 12.59 | 12.12 | 11.75 | 0.87 |
| 262 | 24 | 32.0 | 11.94 | 11.77 | 12.39 | 12.19 | 12.48 | 12.60 | 12.19 | 11.79 | 0.83 |
| 263 | 24 | 32.5 | 11.45 | 11.44 | 12.00 | 12.09 | 12.11 | 12.10 | 11.71 | 11.38 | 0.74 |
| 264 | 24 | 33.0 | 10.77 | 10.79 | 11.32 | 11.53 | 11.30 | 11.24 | 11.14 | 11.02 | 0.76 |
| 265 | 24 | 33.5 | 10.85 | 10.84 | 11.35 | 11.50 | 11.19 | 11.15 | 11.41 | 10.97 | 0.66 |
| 266 | 24 | 34.0 | 11.72 | 11.50 | 12.02 | 11.95 | 11.80 | 11.82 | 11.89 | 11.64 | 0.52 |
| 267 | 24 | 34.5 | 12.12 | 11.57 | 12.13 | 11.85 | 11.90 | 11.95 | 12.01 | 11.51 | 0.62 |
| 268 | 24 | 35.0 | 11.86 | 10.96 | 11.43 | 11.22 | 11.28 | 11.43 | 11.81 | 11.57 | 0.91 |
| 288 | 23 | 26.0 | 15.41 | 17.26 | 18.16 | 17.95 | 18.40 | 18.26 | 17.60 | 17.32 | 2.99 |
| 289 | 23 | 26.5 | 15.10 | 17.06 | 17.52 | 17.65 | 17.51 | 17.82 | 16.78 | 16.49 | 2.72 |
| 290 | 23 | 27.0 | 14.42 | 15.77 | 15.97 | 16.15 | 15.93 | 16.10 | 15.96 | 15.60 | 1.74 |
| 291 | 23 | 27.5 | 13.63 | 14.23 | 14.51 | 14.47 | 14.60 | 14.56 | 14.95 | 14.65 | 1.32 |
| 292 | 23 | 28.0 | 13.64 | 13.87 | 14.14 | 14.16 | 14.41 | 14.38 | 14.55 | 14.26 | 0.91 |
| 293 | 23 | 28.5 | 13.63 | 13.39 | 13.97 | 13.94 | 14.23 | 13.96 | 14.27 | 13.92 | 0.89 |
| 294 | 23 | 29.0 | 13.13 | 12.55 | 13.46 | 13.43 | 13.51 | 13.34 | 13.63 | 13.27 | 1.08 |
| 295 | 23 | 29.5 | 12.63 | 12.02 | 12.94 | 13.09 | 12.88 | 12.85 | 12.98 | 12.66 | 1.07 |
| 296 | 23 | 30.0 | 11.64 | 11.12 | 12.06 | 12.13 | 11.77 | 11.84 | 11.92 | 11.58 | 1.01 |
| 297 | 23 | 30.5 | 10.85 | 10.60 | 11.42 | 11.37 | 11.16 | 11.20 | 11.22 | 10.91 | 0.82 |
| 298 | 23 | 31.0 | 10.48 | 10.46 | 11.20 | 10.99 | 11.13 | 10.95 | 11.21 | 10.84 | 0.75 |
| 299 | 23 | 31.5 | 10.24 | 10.39 | 11.15 | 10.88 | 11.25 | 10.94 | 11.30 | 10.93 | 1.06 |
| 300 | 23 | 32.0 | 10.12 | 10.31 | 11.09 | 10.99 | 11.30 | 10.95 | 11.29 | 11.02 | 1.19 |
| 301 | 23 | 32.5 | 9.82 | 9.93 | 10.79 | 10.86 | 10.85 | 10.74 | 11.05 | 10.71 | 1.24 |
| 302 | 23 | 33.0 | 9.91 | 9.87 | 10.65 | 10.94 | 10.66 | 10.76 | 11.25 | 10.97 | 1.38 |
| 303 | 23 | 33.5 | 10.17 | 9.69 | 10.53 | 10.64 | 10.37 | 10.51 | 10.85 | 10.53 | 1.16 |
| 304 | 23 | 34.0 | 11.36 | 10.44 | 11.13 | 11.13 | 11.15 | 11.05 | 11.33 | 11.05 | 0.92 |
| 305 | 23 | 34.5 | 11.97 | 10.74 | 11.40 | 11.20 | 11.52 | 11.28 | 11.61 | 11.21 | 1.23 |
| 306 | 23 | 35.0 | 10.96 | 9.51 | 10.31 | 9.96 | 10.31 | 10.29 | 10.05 | 9.78 | 1.45 |
| 326 | 22 | 26.0 | 15.85 | 15.67 | 16.69 | 16.50 | 16.86 | 16.61 | 16.95 | 16.58 | 1.28 |
| 327 | 22 | 26.5 | 15.33 | 15.09 | 15.86 | 16.03 | 15.52 | 15.73 | 16.07 | 15.80 | 0.99 |
| 328 | 22 | 27.0 | 14.22 | 13.74 | 14.34 | 14.58 | 13.84 | 14.22 | 14.70 | 14.39 | 0.97 |
| 329 | 22 | 27.5 | 13.78 | 12.97 | 13.57 | 13.62 | 13.34 | 13.67 | 13.96 | 13.62 | 0.99 |
| 330 | 22 | 28.0 | 13.45 | 12.46 | 13.16 | 13.00 | 13.09 | 13.06 | 13.34 | 13.09 | 0.99 |
| 331 | 22 | 28.5 | 12.81 | 11.67 | 12.63 | 12.27 | 12.63 | 12.44 | 12.59 | 12.35 | 1.14 |
| 332 | 22 | 29.0 | 12.40 | 11.17 | 12.23 | 11.96 | 12.17 | 12.13 | 12.22 | 11.83 | 1.23 |
| 333 | 22 | 29.5 | 11.89 | 10.87 | 11.79 | 11.79 | 11.68 | 11.81 | 11.79 | 11.47 | 1.02 |
| 334 | 22 | 30.0 | 11.36 | 10.60 | 11.33 | 11.46 | 11.17 | 11.50 | 11.31 | 11.08 | 0.90 |
| 335 | 22 | 30.5 | 10.78 | 10.47 | 10.96 | 11.11 | 10.92 | 11.05 | 11.00 | 10.67 | 0.64 |
| 336 | 22 | 31.0 | 10.35 | 10.46 | 10.83 | 10.90 | 10.96 | 10.83 | 10.82 | 10.52 | 0.61 |
| 337 | 22 | 31.5 | 10.12 | 10.43 | 10.87 | 10.87 | 11.07 | 10.96 | 10.72 | 10.44 | 0.96 |
| 338 | 22 | 32.0 | 9.66 | 9.93 | 10.69 | 10.60 | 10.68 | 10.81 | 10.38 | 10.07 | 1.16 |
| 339 | 22 | 32.5 | 9.56 | 9.51 | 10.60 | 10.50 | 10.29 | 10.68 | 10.18 | 9.86 | 1.17 |
| 340 | 22 | 33.0 | 9.62 | 9.26 | 10.14 | 10.44 | 10.01 | 10.22 | 10.03 | 9.59 | 1.18 |

Table 3: Continue

| Point (ID) | Latitude (Deg.) | Longitude (Deg.) | Calculated (N) values (m) | | | | | | | | EGM 2008 (2190) (8) | Max. diff. (m) |
|------------|-----------------|------------------|---------------------------|-----------------|------------|-----------------|-----------------|--------------|--------------------|-------|---------------------|----------------|
| | | | EGM96 (1) | EIGEN-CG01C (2) | GGM03C (3) | EIGEN-CG03C (4) | EIGEN-GL04C (5) | EIGEN-5C (6) | EGM 2008 (360) (7) | | | |
| 341 | 22 | 33.5 | 9.75 | 8.85 | 9.66 | 9.96 | 9.78 | 9.55 | 9.80 | 9.59 | 1.11 | |
| 342 | 22 | 34.0 | 10.73 | 9.47 | 10.26 | 10.31 | 10.53 | 10.23 | 10.22 | 9.91 | 1.26 | |
| 343 | 22 | 34.5 | 11.24 | 9.71 | 10.54 | 10.30 | 10.72 | 10.72 | 10.37 | 10.21 | 1.54 | |
| 344 | 22 | 35.0 | 10.98 | 9.36 | 10.14 | 9.89 | 10.41 | 10.58 | 10.42 | 9.93 | 1.63 | |
| 345 | 22 | 35.5 | 9.94 | 8.53 | 9.37 | 9.24 | 9.47 | 9.51 | 9.63 | 9.85 | 1.42 | |
| 346 | 22 | 36.0 | 8.87 | 7.61 | 8.56 | 8.57 | 8.43 | 8.25 | 8.46 | 7.87 | 1.27 | |

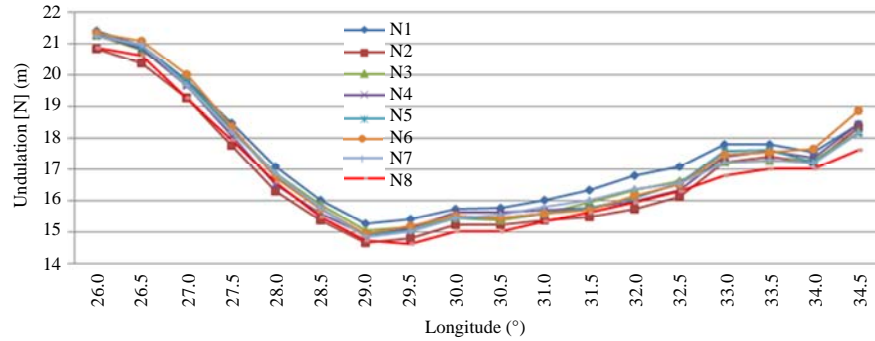


Fig. 6: (N) Values for latitude (ϕ) = 31°N

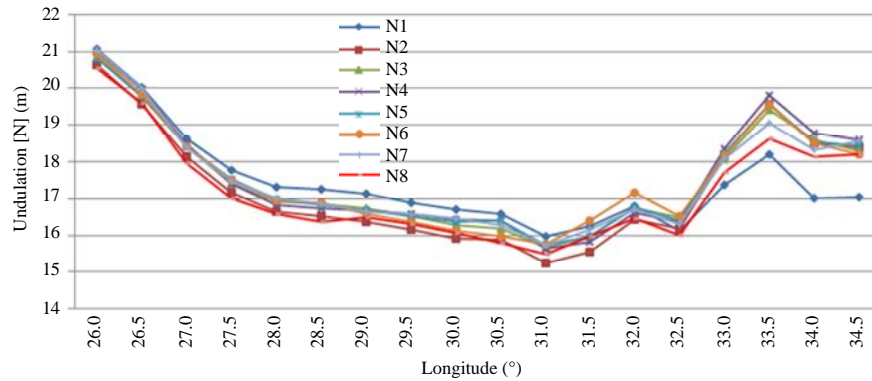


Fig. 7: (N) Values for latitude (ϕ) = 30°N

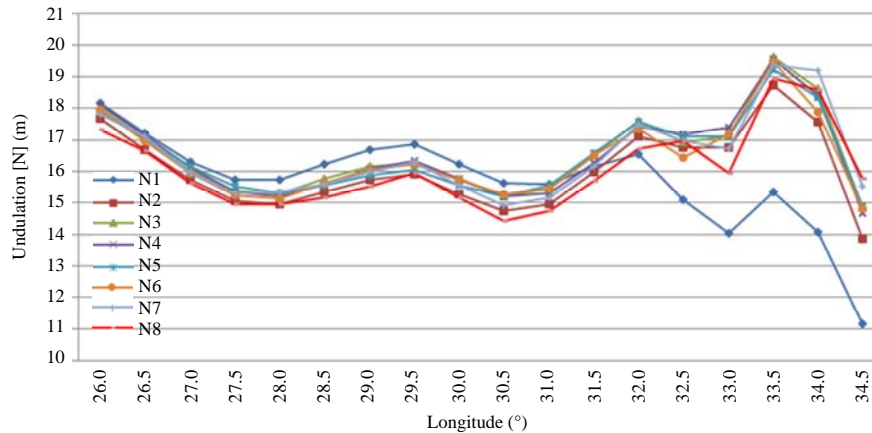


Fig. 8: (N) Values for latitude (ϕ) = 29°N

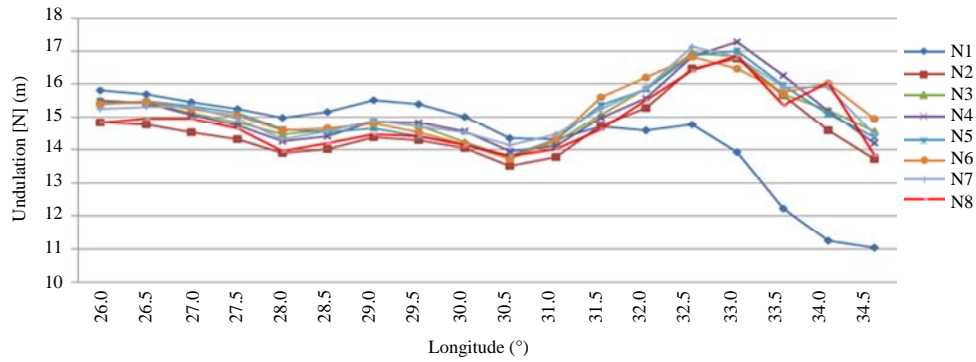


Fig. 9: (N) Values for latitude (ϕ) = 28°N

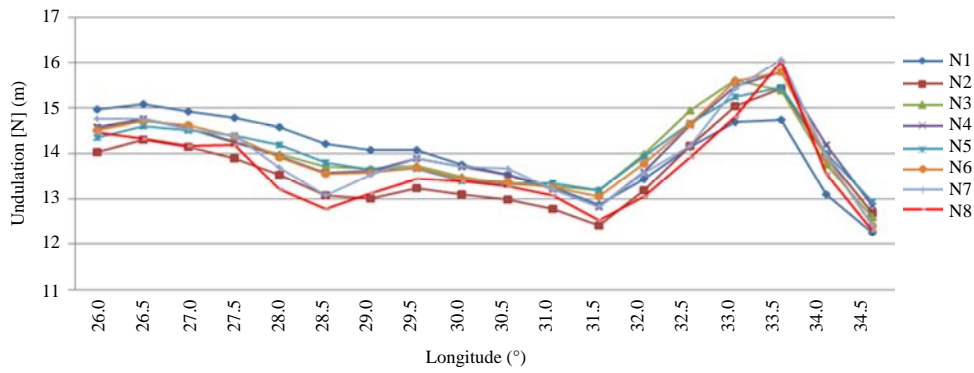


Fig. 10: (N) Values for latitude (ϕ) = 27°N

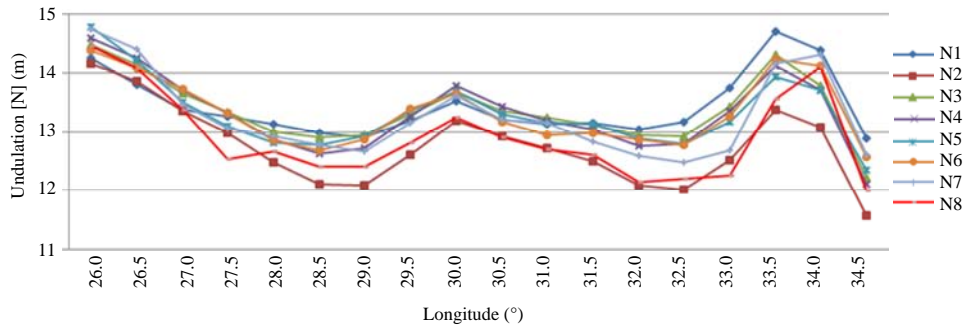


Fig. 11: (N) Values for latitude (ϕ) = 26°N

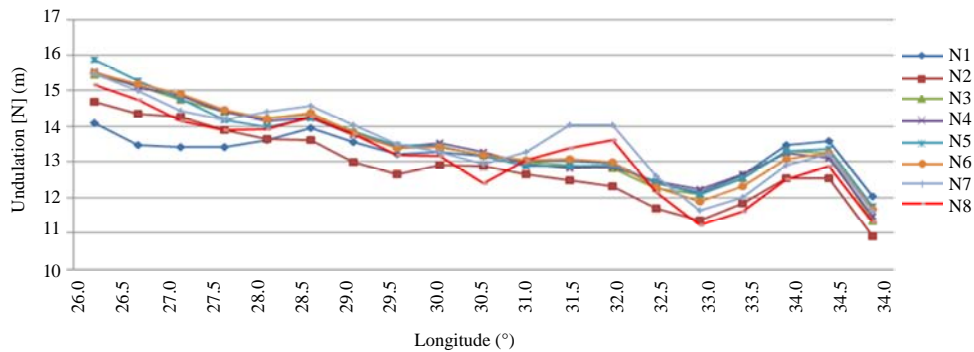


Fig. 12: (N) Values for latitude (ϕ) = 25°N

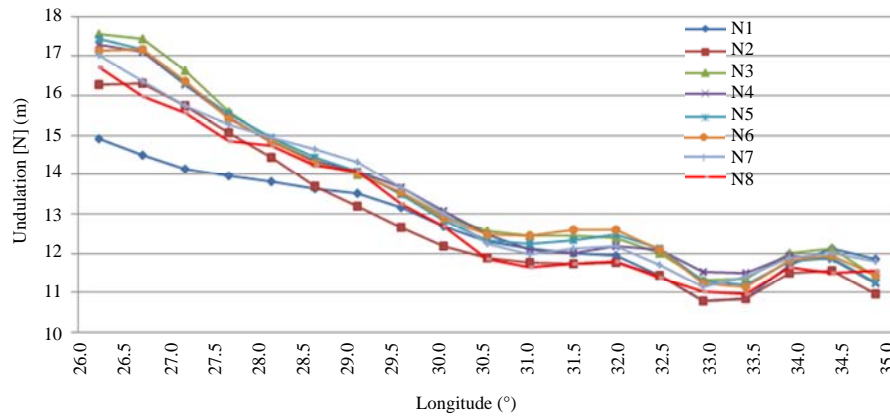


Fig. 13: (N) Values for latitude (ϕ) = 24°N

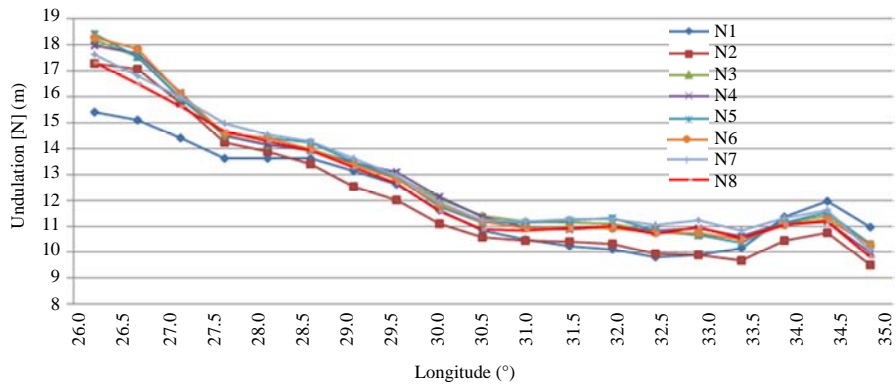


Fig. 14: (N) Values for latitude (ϕ) = 23°N

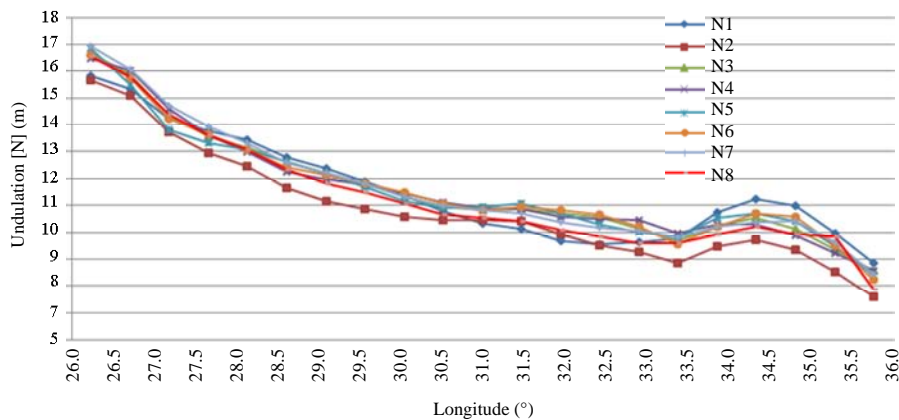


Fig. 15: (N) Values for latitude (ϕ) = 22°N

CONCLUSION

From the tables and figures it can be seen the following; the values of the undulation (N) as expected changes in Egypt from East to West and also from North to South. They have the maximum value = 21.47 m at point

number 70 [29.5°N, 33.5°E] by using GGM03C and its minimum value = 7.23 m at point number 325 [22.5°N, 36°E] using EIGEN-CG01C.

Calculating (N) using the eight suggested GGM gave different values of (N). The differences ranges from 0.36-6.08 m. The maximum difference at point number 106

[28.5°N, 34°E]. This point located in the mountain chain beside Catherins Monastery in Sinai. On the other hand, the minimum difference at point number 180 [26°N, 27°E] which is located in semi-flat area named the Dune Corridor Camp in Western Desert.

The values of (N) and differences between these values calculated in North Delta of Egypt is relatively small, (N) ranges from 14.69 m (at point number 29) to 16.59 m (at point number 46) and the differences range from 0.67 (at point number 11) to 0.86 m (at point number 12).

The values of (N) in South of Egypt decrease by about 7 m going from West to east of Egypt for example at latitude 22°N [N≈15.9 and 8.9 m East at points number 326 (longitude 26°E) and 346 (longitude 36°E), respectively] as shown in Table 3. The differences between (N) calculated using different GGM are relatively small [about 0.61 m at point number 336 and 1.63 at point number 344] with maximum value of about 3 m and the large differences between EGM 96 and EGM 2008.

The most popular two models in Egypt and around the world are using EGM 96 and EGM 2008 (2190). Generally, the differences between the maximum and minimum (N) values which calculated by different eight GGM for every point of 346 points over Egypt proved that; 197 points <1 m, 1 m<118 points <2 m and 31 points>2 m (up to the maximum difference = 6.08 m).

The larger differences are located at two zones; first zone between latitudes (27°N, 30°N) and longitudes (32°E, 34.5°E) with maximum difference equal 6.08 m at point number 106 (28.5°N, 34°E). Second zone is between latitudes (23°N and 25°N) and longitudes (26°E and 28°E).

RECOMMENDATIONS

The future recommendation of this paper is to study more deeply the main reasons of significant differences values between these eight GGM based on the location of different points and also study a relationship to convert the (N) values from one model to another in Egypt.

ACKNOWLEDGEMENTS

My special thanks and deep gratitude should be expressed to Prof. Dr. Mahmoud El Nokrashy O. Ali (Prof. of surveying, Civil Engineering Department, College of Engineering, Al-Azhar University, Cairo, Egypt) for his advices, discussions and valuable remarks.

REFERENCES

- Abd-Elmotaal, H., 2008. Gravimetric geoid for Egypt using high-degree tailored reference geopotential model. *NRIAG. J. Geophys. Spec. Issue*, 1: 507-531.
- Al-Krargy, E.M., M.I. Doma and G.M. Dawod, 2014. Towards an accurate definition of the local geoid model in Egypt using GPS/leveling data: A case study at Rosetta zone. *Intl. J. Innov. Sci. Mod. Eng.*, 2: 10-15.
- Al-Krargy, E.M., M.M. Hosny and G.M. Dawod, 2015. Investigating the precision of recent global geoid models and global digital elevation models for geoid modelling in Egypt. *Proceedings of the Regional Conference on Surveying & Development, October 3-6, 2015, Minia University, Minya, Egypt*, pp: 1-12.
- Davis, D., C. Nanlal and M. Sutherland, 2011. Towards the development of a methodology for vertical separation models in the Caribbean. *Proceedings of the International Conference on Federation of Surveyors Working Week, May 18-22, 2011, CD-ROM, Marrakech, Morocco*, pp: 1-10.
- Dawod, G.M., 1998. A national gravity standardization network for Egypt. *Ph.D Thesis, Zagazig University, Zagazig, Egypt*.
- Dawod, G.M., 2008. Towards the redefinition of the Egyptian geoid: Performance analysis of recent global geoid and digital terrain models. *J. Spatial Sci.*, 53: 31-42.
- Foerste, C., R. Stubenvoll, R. König, J.C. Raimondo and F. Flechtner *et al.*, 2009. Evaluation of EGM2008 by comparison with other recent global gravity field models. *Newtons Bull.*, 4: 26-37.
- Krynski, J. and G. Kloch, 2009. Evaluation of the performance of the new EGM08 global geopotential model over Poland. *Geoinf. Issues*, 1: 7-17.
- Mahmoud, S.S.S., 2012. Assessment of the gravitational global models in Egypt. *Master Thesis, Al-Azhar University, Cairo, Egypt*.
- Rabah, M. and M. Kaloop, 2013. The use of minimum curvature surface technique in geoid computation processing of Egypt. *Arabian J. Geosci.*, 6: 1263-1272.
- Tugi, A., A.H.M. Din, K.M. Omar, A.S. Mardi and Z.A.M. Som *et al.*, 2016. Gravity anomaly assessment using GGMS and airborne gravity data towards bathymetry estimation. *Intl. Arch. Photogramm. Remote Sens. Spatial Inf. Sci.*, 42: 287-297.
- Yilmaz, M., B. Turgut, M. Gullu and I. Yilmaz, 2016. Evaluation of recent global geopotential models by gnss/levelling data: Internal Aegean region. *Intl. J. Eng. Geosci.*, 1: 15-19.
- Yilmaz, M., B. Turgut, M. Gullu and I. Yilmaz, 2017. Application of artificial neural networks to height transformation. *Tehnicki Vjesnik*, 24: 443-448.