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Evaluation of EGM96 and EGM08 based on GPS/Levelling Heights in Egypt

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Abstract

The heights determined by Global Positioning System (GPS) refer to the ellipsoid called the World Geodetic System 1984 (WGS84). Global Geopotential Models (GGMs) that are available on GNSS commercial software are generally used to transform ellipsoidal heights to orthometric heights. In this study, the geoid heights of GPS/Levelling were computed to evaluate the accuracy of the geoid heights obtained from two GGMs, namely, the Earth Gravitational Model 96 (EGM96) and the Earth Gravitational Model 08 (EGM08). Seventeen (17) GPS/Levelling stations of the High Accuracy Reference Network (HARN) over Egypt were used for this purpose. The standard deviations for the differences between the geoid heights obtained through GPS/Levelling and those obtained from EGM96 and EGM08 were determined as ± 1.212 m and ± 0.543 m, respectively. This research confirms that the geoid heights obtained from EGM08 are closer to the geoid heights determined using GPS/Levelling over Egypt.

Keywords: EGM96, EGM08, ME, HARN, RMSE, SD

1. Introduction

Levelling is a conventional geodetic method for detecting elevation differences between places on the Earth's surface. Levelling is a precise measuring method, but it is known to be time-consuming, labour-intensive, and inconvenient because it requires that the distance between each pair of endpoints be covered. (Tzur & Steinberg, 2009). Ellipsoidal heights (h) are ineffectual when it comes to actual surveying, engineering, or geophysical applications,. For them to be effective, they must be translated into orthometric heights (H). Orthometric heights are used in geodetic and surveying applications. The geoid height (N) from the ellipsoid must be known if this translation between the ellipsoidal and orthometric heights is to be made. A WGS84 ellipsoidal height (h) is transformed into an orthometric height (H) by subtracting the geoid height (N) from the ellipsoidal height (h) (see figure 1).

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

(Okiemute et al., 2018)

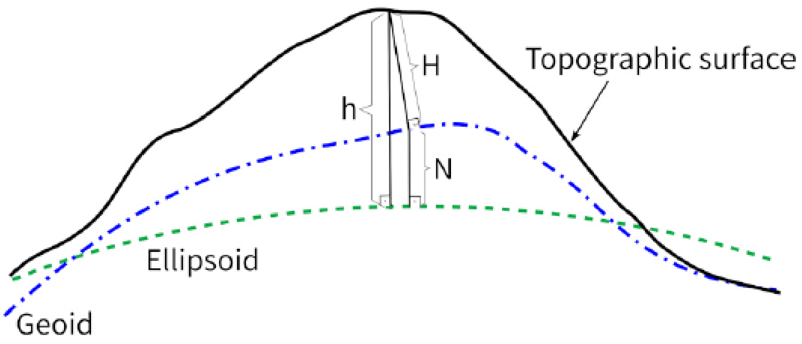

Figure 1: The Relations between Topographic Surface, Geoid and Ellipsoid (Guth et al., 2021).

For obtaining orthometric heights (H), GNSS processing software uses a variety of global geopotential models. The EGM96 and EGM08 are two such models for determining the geoid height (N) which, as mentioned previously, are used to derive the orthometric height (H) from the GPS ellipsoidal height (h) (Peprah et al., 2017). The High Accuracy Reference Network (HARN) is made up of 30 stations, spaced approximately 200 kilometres apart across Egypt, and with a typical accuracy of 1: 10,000,000. (Powell, 1997). This research used 17 stations constituting a HARN over Egypt to determine the geoid heights. These stations were chosen because the heights of HARN stations are the first-order levelling measures that are computed from mean sea level. In addition, the heights of the HARN stations are known on WGS84. Since the EGM96 and EGM08 are common global geopotential models used for obtaining the orthometric height from the ellipsoidal height in the GNSS processing software, this research aimed to evaluate these two models.

Ahmed et al. (2021) evaluated the EGM08 with GNSS/Levelling at 70 reference stations in Egypt. The results they obtained determined a range between − 0.277 m and 1.546 m, with a mean of 0.342 m and RMSE equals ± 0.466 m. Al-Krargy et al. (2014) evaluated some Global Geopotential Models, OUS-91A, EGM96 and EGM2008, in the study area, namely, the Rosetta zone in northern Egypt. The results clearly showed that EGM08 represents the most precise GGM to be used for determining geoid heights in Egypt. Sikder et al. (2020) obtained the RMSE, the mean and the standard deviation of EGM2008 in Bangladesh, are , 0.1757 m, 0.1718 m and 0.0376 m, respectively, for fifteen GNSS/levelling stations. In India, Rao et al. (2012), the use of the GPS/levelling stations to assess the EGM96 and EGM08 in two study areas, established that the RMSE of the EGM96 for the two study areas (1) and (2) was 1.41m and that the RMSE of the EGM08 was 0.5 m for study area (1) and 0.6 m for study area (2).

2. Study Area and Data Collection

In this investigation, the 17 stations of the High Accuracy Reference Network (HARN) were used over Egypt (see figure 2), which has an area of approximately one million square kilometres. The heights of the HARN stations are at the first-order levelling and computed from mean sea level. In addition, the heights of the HARN stations are known on WGS84. The online geoid height calculator, based on the GeoidEval utility, was used to compute the geoid heights of the HARN stations on EGM96 and EGM08.

Figure (2): The distribution of the 17 HARN stations over Egypt.

3. Geoid, Ellipsoid and Orthometric Heights

3.1. Geoid Height

Geoid height is the distance between the reference ellipsoid and the geoid surface measured along the ellipsoidal normal. The geoid is defined by Gauss Listing as an equipotential surface of the Earth's gravity field that coincides with mean sea level. Mean sea level deviates by up to two metres from the equipotential surface (geoid). This is due to a variety of oceanographic phenomena such as, amongst others, fluctuating temperatures, salinity levels, and instantaneous sea surface topographies. (Erol & Çelik, 2004).

3.2. Ellipsoidal Height

The mathematical surface of a rotational ellipsoid is defined by a semi-major axis (a) and its flattening (f) can resemble the physical form of the Earth's surface. All the defining characteristics of the additional ellipsoidal shapes and sizes (semi-minor axis (b), eccentricity (e), and curvature in the prime vertical (V)) can be obtained from these values. (Fotopoulos, 2003). The distance between the earth's topographic surface and the mathematical model of the reference ellipsoid surface is known as the ellipsoidal height (h). GPS are used to determine it (Kasenda, 2009). Mathematically, the ellipsoid surface can be determined as a regular surface, and since it is a reference surface, it is extensively used for horizontal coordinate computations (Gwaleba, 2018).

3.3. Orthometric Height

Orthometric heights (H) are preferred because they are the most closely linked geophysically to mean sea level. The orthometric height is referred to as a vertical datum that is commonly assumed to be the most accurate representation of mean sea level. Orthometric heights are measured along the direction of the plumb line, while ellipsoidal heights are measured along the normal to the ellipsoid.

Owing to the influences of the direction of the gravitational force, also known as the deflection of the vertical, the actual gravity plumb line along which H is calculated is a curved line. The mistake created by this approximation may usually be tolerated in technical applications. The links between the geoid, ellipsoid and orthometric heights are depicted in figure (1) (Gwaleba, 2018).

4. Global Geopotential Models, EGM96 and EGM08

The mathematical function that specifies the Earth’s gravitational field in three-dimensional space is called the Global Geopotential Model (GGM). Several institutions, such as the ESA (European Space Agency), the NGA (National Geospatial-Intelligence Agency) and the GFZ (GeoForschungsZentrum Potsdam), collect gravitational signals from satellites and through altimetry and local surveying, and model the gravitational field through spherical harmonic analysis. Thus, GGMs are ordinarily divided into satellite-only and combined models (Jisun & Hyoun, 2020).

4.1. Earth Gravitational Model 1996 (EGM96)

The EGM96 is a spherical harmonic model of the earth's gravitational potential with a spatial resolution of 55 km and a degree and order of 360. Surface gravitational data, ERS-1/GEOSAT altimeter anomalies, extensive satellite tracking data, including new data from Satellite Laser Ranging (SLR), the Global Positioning System (GPS), NASA's Tracking and Data Relay Satellite System (TDRSS), the French DORIS system, the US Navy TRANET Doppler tracking system, and direct altimeter ranges from TOPEX/POSEIDON (T/P), ERS-1, and GEOSAT, are all used to create the EGM96 (Yilmaz et al., 2010).

4.2. Earth Gravitational Model 2008 (EGM08)

The Earth Gravitational Model 2008, with degree and order of 2160, was created by the National Geospatial Intelligence Agency (NGA) of the United States. It uses the most up-to-date modelling for land and sea areas worldwide. GRACE satellite solutions and a 5'x5' gravity anomaly database were employed in the model. The EGM08 employed a topographic model that was 30"x30" in size. The satellite-only gravitational model, satellite altimetry, and terrestrial gravity measurements were the data sources (Manandhar & K.C, 2018).

5. Evaluating the Performance of Earth Gravitational Models (EGMs)

Several statistical indicators are used to assess the adequacy of the Earth Gravitational Models (EGMs) and the polynomial model. The Mean Error (ME), the Root Mean Square Error (RMSE), and the Standard Deviation (SD) are examples of these indicators (Peprah et al., 2017). The Root Mean Square Error (RMSE) is used to check the accuracy of the variations between a computed or measured value and an estimated value (Abdulrahman, 2021).

The geoidal height difference, ΔN, between (N) GPS/Levelling geoidal heights and computed geoidal heights, referred to as Earth Gravitational Models (N) EGM, is expressed as follows:

$$\Delta \mathrm{N} = \mathrm{N\ GPS/\ Levelling} - \mathrm{N\ EGM} \tag{2}$$

Where

ΔN is the geoidal height difference between the geoidal heights acquired using GPS/Levelling and the geoidal heights obtained using EGM. The average of the geoidal height differences (ΔNmean) is the mean error calculated for each model. The ΔNmean is calculated from the following equation:

$$\Delta N\mathrm{mean} = \frac{1}{n}\sum_{i=1}^{n} \Delta \mathrm{N}i \tag{3}$$

Where

i =1, 2, 3, ..., n, and n is the number of points.

The Root Mean Square Error (RMSE) is used to calculate the geoidal height discrepancies from the following equation:

$$\mathrm{RMSE}=\sqrt{\frac{\sum_{i=1}^{n} \Delta \mathrm{N}i^2}{n}} \tag{4}$$

Equation (5) was used to calculate the Standard Deviation (SD) from the mean of the differences in the geoidal heights:

$$SD=\sqrt{\frac{\sum_{i=1}^{n}(\Delta Ni-\Delta N\ mean)^2}{n-1}} \qquad (5)$$

(Peprah et al., 2017)

6. Procedure

Seventeen (17) HARN stations were used, their heights being representative of the first-order levelling computed from the mean sea level. In addition, the heights of the HARN stations are known on WGS84. The HARN stations were used to assess the accuracy of the EGM96 and EGM08. The following items present the steps:

- Compute the geoid heights from the first-order levels and the geodetic coordinates on WGS1984 for these stations by using equation (1).
- Use the GeoidEval online geoid utility of the EGM96 and EGM08 to compute the geoid heights of the 17 HARN stations by using the geodetic coordinates. (https://geographiclib.sourceforge.io/cgi-bin/GeoidEval).
- Use surfer software to establish the contour maps over Egypt that are based on the 17 HARN stations by using the geoidal heights obtained from GPS/Levelling, EGM96 and EGM08.
- Apply equation (2) to calculate the geoidal height differences between the geoidal heights obtained from GPS/levelling and the geoidal heights determined through the two Earth Gravitational Models, respectively.
- Use equation (3) to compute the mean error for the two Earth Gravitational Models, respectively.
- Use equation (4) to compute the RMSE values for EGM96 and EGM08, respectively.
- Finally, use Equation (5) to assess the two Earth Gravitational Models.

7. Results and Discussion

The results of the comparison made between the geoid heights obtained from GPS/Levelling and those obtained from EGM96 are shown in table (1), where the minimum difference is -0.003 m, the maximum difference is 3.727 m, and the mean difference is 0.072 m. The Root Mean Square Error (RMSE) value is ± 1.178 m, and the Standard Deviation (SD) is ± 1.212 m. On the other hand, according to table (2), the minimum geoid height difference for EGM08 is 0.007 m, the maximum difference is -1.306 m, and the mean difference is -0.236 m. The

Root Mean Square Error (RMSE) and the Standard Deviation (SD) values from EGM08 are ± 0.577 m and ± 0.543 m, respectively. Figure (3) demonstrates the difference between the geoid heights obtained from GPS/Levelling, EGM96 and EGM08, respectively. The difference between the GPS/Levelling and EGM08 results is smaller than the difference between GPS/Levelling and EGM96, (see figure 3).

Table 1: Analysis of the results of the GPS/Levelling geoid heights for the 17 HARN stations and the geoid heights of the same stations on the EGM96.

Stations	N(m)= h (Ellipsoidal) - H (Orthometric)	N(m) (EGM96)	ΔN	ΔN^2	ΔN- ΔNmean	$(\Delta N - \Delta N \text{ mean})^2$
0Z02	9.778	9.43	0.348	0.121104	0.275647059	0.075981301
0Z07	11.049	10.56	0.489	0.239121	0.416647059	0.173594772
0Z08	10.667	10.67	-0.003	9E-06	-0.075352941	0.005678066
0Z09	12.713	12.981	-0.268	0.071824	-0.340352941	0.115840125
0Z10	12.158	12.645	-0.487	0.237169	-0.559352941	0.312875713
0Z11	13.172	12.973	0.199	0.039601	0.126647059	0.016039478
0Z12	14.218	15.504	-1.286	1.653796	-1.358352941	1.845122713
0Z13	12.751	12.945	-0.194	0.037636	-0.266352941	0.070943889
0Z14	14.645	12.533	2.112	4.460544	2.039647059	4.160160125
0Z15	17	13.273	3.727	13.890529	3.654647059	13.35644512
0Z16	17.025	17.3	-0.275	0.075625	-0.347352941	0.120654066
0Z17	16.207	15.984	0.223	0.049729	0.150647059	0.022694536
0Z18	17.826	18.556	-0.73	0.5329	-0.802352941	0.643770242
0Z19	14.945	15.963	-1.018	1.036324	-1.090352941	1.188869536
0Z20	15.067	15.49	-0.423	0.178929	-0.495352941	0.245374536
0Z21	17.242	17.471	-0.229	0.052441	-0.301352941	0.090813595
0Z22	19.331	20.286	-0.955	0.912025	-1.027352941	1.055454066
			0.072352941	23.589306		23.50031188
			ΔN_{mean}= 0.072 m	1.387606235		1.468769493
				1.177966992		1.211928006
				RMSE		SD
				± 1.178 m		± 1.212 m

Table (2): Analysis of the results for the geoid heights of the 17 HARN stations obtained through GPS/Levelling and the geoid heights of the same stations on the EGM08.

Stations	N (m)= h (Ellipsoidal) - H(Orthometric)	N (m) (EGM08)	ΔN	ΔN^2	ΔN - ΔNmean	(ΔN -ΔN mean)^2
0Z02	9.778	10.265	-0.487	0.237169	-0.250882353	0.062941955
0Z07	11.049	11.085	-0.036	0.001296	0.200117647	0.040047073
0Z08	10.667	10.376	0.291	0.084681	0.527117647	0.277853014
0Z09	12.713	12.706	0.007	4.9E-05	0.243117647	0.05910619
0Z10	12.158	12.209	-0.051	0.002601	0.185117647	0.034268543
0Z11	13.172	12.911	0.261	0.068121	0.497117647	0.247125955
0Z12	14.218	15.058	-0.84	0.7056	-0.603882353	0.364673896
0Z13	12.751	13.15	-0.399	0.159201	-0.162882353	0.026530661
0Z14	14.645	15.951	-1.306	1.705636	-1.069882353	1.144648249
0Z15	17	15.94	1.06	1.1236	1.296117647	1.679920955
0Z16	17.025	16.996	0.029	0.000841	0.265117647	0.070287367
0Z17	16.207	16.121	0.086	0.007396	0.322117647	0.103759779
0Z18	17.826	18.442	-0.616	0.379456	-0.379882353	0.144310602
0Z19	14.945	15.58	-0.635	0.403225	-0.398882353	0.159107131
0Z20	15.067	15.217	-0.15	0.0225	0.086117647	0.007416249
0Z21	17.242	17.819	-0.577	0.332929	-0.340882353	0.116200779
0Z22	19.331	19.982	-0.651	0.423801	-0.414882353	0.172127367
			-0.236117647	5.658102		4.710325765
			ΔN_{mean}= - 0.236 m	0.332829529		0.29439536
				0.576913797		0.542582123
				RMSE		SD
				± 0.577 m		± 0.543 m

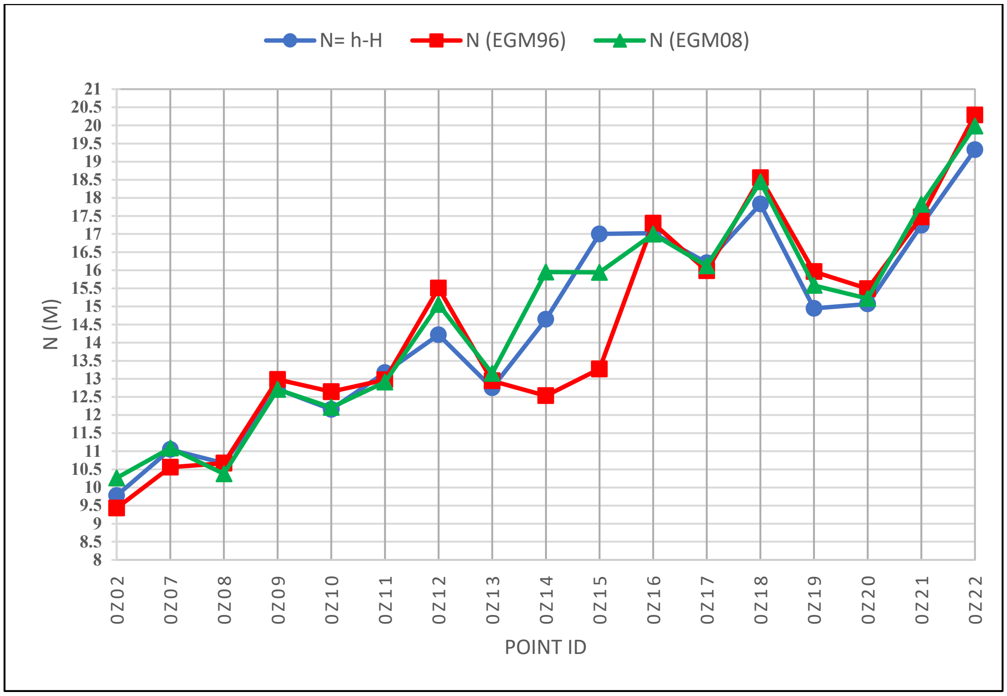

Figure 3: The relationships between the geoidal heights which were obtained through GPS/Levelling, EGM96 and EGM08.

Figures 4–6 show contour maps representing the geoid heights of the 17 HARN stations over Egypt by using GPS/Levelling, EGM96 and EGM08 data, respectively. The contour interval is 0.5 metres.

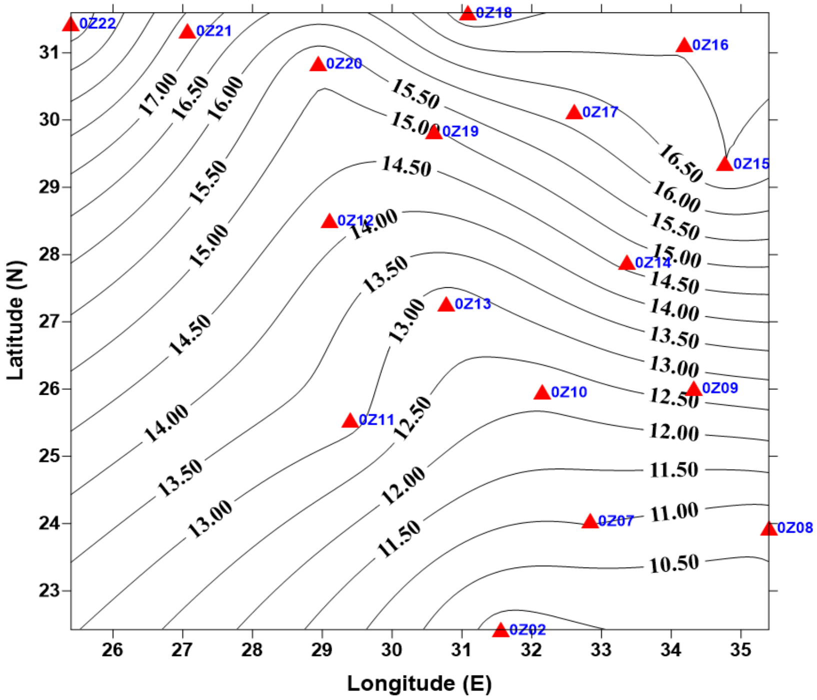

Figure 4: Contour map of geoid heights from GPS/Levelling.

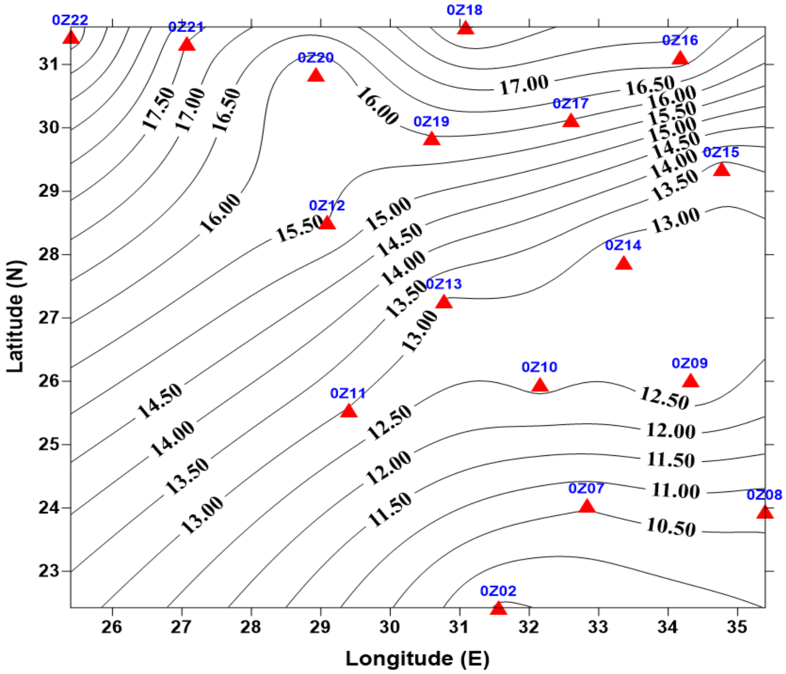

Figure 5: Contour map of geoid heights from EGM96.

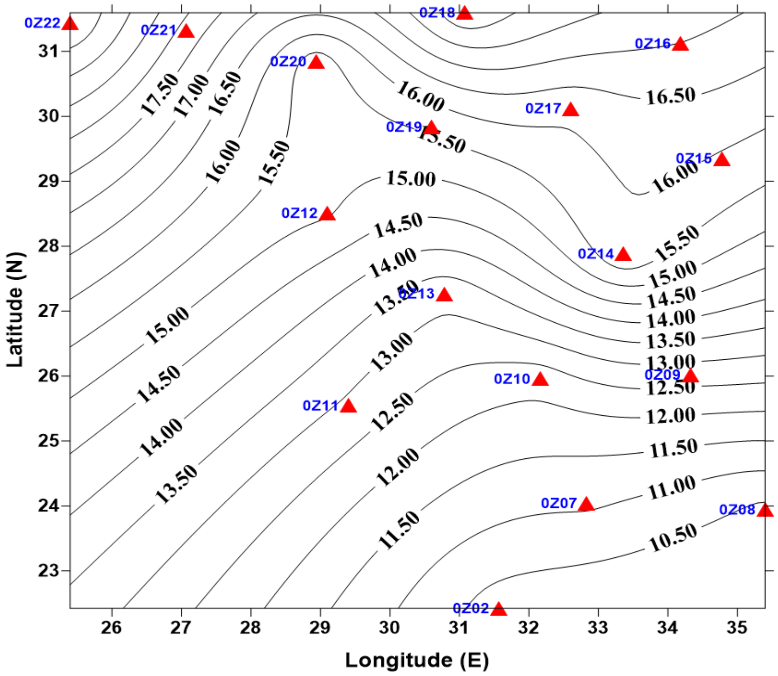

Figure 6: Contour map of geoid heights from EGM08.

8. Conclusions

Earth Gravitational Models are important as they are used for converting ellipsoidal heights obtained by processing GNSS observations to orthometric heights, that can in turn be used in several applications. The assessment of the two EGMs used in several GNSS processing software is summarized in the following items:

- The contour maps show that the geoid heights for Egypt are increased in a northerly direction.
- The results in this study obtained from EGM96 and EGM08 indicate that the preferred Earth Gravitational Model over Egypt is EGM08.
- From the results of the studies that were reviewed in the introduction and the results obtained from this study, it is clear that the RMSE, reflecting the difference of the geoidal heights between the EGM08 and the GPS/levelling data, is within the decimetre range. The results show that EGM08 is superior to EGM96. This is due to the high spherical harmonic degree and order and the variety of data sources used in EGM08.
- We recommend EGM08 as the preferred model for determining orthometric heights from ellipsoidal heights when GNSS measurements are processed.
- It is highly recommended that the number of stations with both ellipsoidal and orthometric heights in Egypt ,be increased in order to obtain a more accurate model for transformation.

9. References

Abdulrahman, F.H. (2021). Determination of the local geoid model in Duhok Region, University of Duhok Campus as a Case study. Ain Shams Engineering Journal, Volume 12, Issue 2, June 2021, (PP. 1293-1304). https://doi.org/10.1016/j.asej.2020.10.004.

Al-Krargy, E.M., Doma, M.I., & Dawod, G.M. (2014). Towards an Accurate Definition of the Local Geoid Model in Egypt using GPS/Levelling Data: a Case Study at Rosetta Zone. International Journal of Innovative Science and Modern Engineering (IJISME), ISSN: 2319-6386, Vol. 2 Issue 11, October 2014.

Ahmed, H.M., Mohamed, E.A., & Bahaa, S.A. (2021). Evaluating two numerical methods for developing a local geoid model and a local digital elevation model for the Red Sea Coast, Egypt. Journal of King Saud University – Engineering Sciences, 2021, https://doi.org/10.1016/j.jksues.2021.04.004.

Erol, B., & Çelik, R.N. (2004). Modelling local GPS/levelling geoid with the assessment of inverse distance weighting and geostatistical kriging methods. Proceedings of 20th ISPRS congress, Technical Commission IV, Volume 35, Istanbul, Turkey, 2004.

Fotopoulos, G. (2003). An Analysis on the Optimal Combination of Geoid, Orthometric and Ellipsoidal Height Data. PhD thesis, Department of Geomatics Engineering, University of Calgary, December, 2003. http://www.geomatics.ucalgary.ca/links/GradTheses.html.

Guth, P.L.; Van Niekerk, A.; Grohmann, C.H.; Muller, J.-P.; Hawker, L.; Florinsky, I.V.; Gesch, D.; Reuter, H.I.; Herrera-Cruz, V.; Riazanoff, S.; López-Vázquez, C.; Carabajal, C.C.; Albinet, C.; Strobl, P. (2021). Digital Elevation Models: Terminology and Definitions. Remote Sensing. 2021, 13, 3581. https://doi.org/10.3390/rs13183581.

Gwaleba, M.J. (2018). Comparison of Global Geoid Models Against the GPS/Levelling-Derived Geoid Heights in Tanzania. Journal of Geomatics, Vol 12, No. 2, October 2018. https://geographiclib.sourceforge.io/cgi-bin/GeoidEval.

Jisun, L., & Hyoun, K.J. (2020). Precision Evaluation of Recent Global Geopotential Models based on GNSS/Leveling Data on Unified Control Points. Journal of the Korean Society of Surveying, Geodesy, Photogrammetry and Cartography, Vol. 38, No. 2, (PP. 153-163), 2020. https://doi.org/10.7848/ksgpc.2020.38.2.153.

Kasenda, A. (2009). High Precision Geoid for Modernization of Height Systems in Indonesia. PhD thesis, School of Surveying and Spatial Information Systems, The University of New South Wales, Sydney NSW, 2052, Australia, July 2009.

Manandhar, N., & K.C, S. (2018). Geoid Determination and Gravity Works in Nepal. Journal on Geoinformatics, Nepal, Vol. 17 No. 1 (2018). https://doi.org/10.3126/njg.v17i1.23003.

Okiemute, E.S., Ono, M.N., & Oduyebo, O.F. (2018). Practical Local Geoid Model Determination for Mean Sea Level Heights of Surveys and Stable Building Projects. IOSR Journal of Environmental Science, Toxicology and Food Technology (IOSR-JESTFT), e-ISSN: 2319-2402, p- ISSN: 2319-2399.Vol. 12, Issue 6. Ver. I (June. 2018), (PP. 30-37), www.iosrjournals.org. https:// DOI: 10.9790/2402-1206013037.

Peprah, M.S., Ziggah, Y.Y., & Yakubu, I. (2017). Performance Evaluation of the Earth Gravitational Model 2008 (EGM2008) – A Case Study. South African Journal of Geomatics, Vol. 6. No. 1, April 2017.
http://dx.doi.org/10.4314/sajg.v6i1.4.

Powell, S. (1997). Results of the Final Adjustment of the New National Geodetic Network. Prepared by Scott M Powell, Geodetic Advisor for the Egyptian Survey Authority, 23-10-1997.

Rao, B.S., Kumar, G.A., Krishna, P.V.S.S.N.G., Srinivasulu, P, & Venkataraman, V.R. (2012). Evaluation of EGM 2008 with EGM96 and its Utilization in Topographical Mapping Projects. Journal of the Indian Society of Remote Sensing, June 2012, DOI: 10.1007/s12524-011-0131-1.

Sikder, M.A.A., Wu, F., Ahmed, W.A., Thodsan, T., & Zhao, Y. (2020). Assessment of Orthometric Height Derived from Levelling, GNSS and EGM2008 Geoid Model in Bangladesh. 2020 15th IEEE International Conference on Signal Processing (ICSP), 06-09 December 2020, Beijing, China.

Tzur, G.E., & Steinberg, G. (2009). Using an Official Undulation Model for Orthometric Height Acquisition by GNSS. Survey Review, Volume 41, Issue 313, (PP. 292-300) (July 2009).
https:// DOI 10.1179/003962609X451546.

Yilmaz, I., Yilmaz, M., Güllü, M., & Turgut, B. (2010). Evaluation of recent global geopotential models based on GPS/levelling data over Afyonkarahisar (Turkey). Scientific Research and Essays. Vol. 5(5), (PP. 484-493), 4 March, 2010.
Available online at http://www.academicjournals.org/SRE.