
Accuracy Assessment of Global Geopotential Models for GIS and Geomatics Applications in Makkah Metropolitan Area

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Abstract

The Global Positioning System (GPS) satellite-based technology has been utilized extensively, in the last few years, for a wide range of Geomatics and Geographic Information Systems (GIS) applications within Makkah metropolitan area. One of the chief concerns dealing with GPS-based heights is their conversion to the Mean Sea Level (MSL) heights that normally used in surveying and mapping through a geoid model. Currently, there is no local geoid model covers Makkah administrative area. Global Geopotential Models (GGM) provide appropriate cost-effective transformation alternatives in such case. A number of the most-recent GGM have been obtained and utilized for representing the Earth's gravity field and converting GPS heights into MSL heights in Makkah city. Terrestrial first-order control points have been used to assess the external quality of GGM's results in order to choose the optimum GGM for geomatics application within the study area. The attained results showed that the EGM2008 model is the most precise GGM within Makkah metropolitan area, with an overall accuracy level about ± 0.16 meter. Moreover, a new modified geoid model was developed for Makkah city, that is based on integrating the original EGM2008 with precise local geodetic datasets. Accordingly, it is recommended to apply the modified version of EGM2008 geoid model in GPS, GIS, surveying, and geomatics projects in Makkah until a complete national Saudi geoid model is developed.

Keywords: GIS, GPS, Geomatics, Heights, Geoid, Makkah.

الملخص العربي:

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Introduction:

Geomatics, Geographic Information Systems (GIS), Remote Sensing (RS), Surveying and mapping applications depend on elevations with respect to the Mean Sea Level (MSL) as the third, or vertical, coordinate. On the other hand, the Global Positioning System (GPS) depends on measuring heights related to a specific ellipsoid that mathematically represents the figure of the Earth. The differences between the MSL-based heights (orthometric heights) and the GPS-based heights (ellipsoidal heights) are known as the Geoidal heights or Geoidal undulations. Hence, it is a must to have a geoid model that depicts the geoidal heights' variations over a specific area of interest. A geoid model enables the transformation of the GPS measured heights into the MSL orthometric heights needed for geomatics applications. Equation 1 and Figure 1 relate those three components:

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

where,

N is the geoidal heights or geoidal undulations
h is the ellipsoidal or GPS-based heights
H is the orthometric or MSL-based heights.

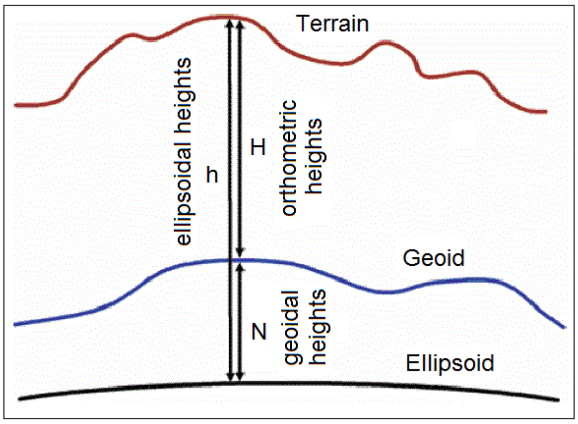


Figure 1: Heights' Types

The geoid can be determined on global, regional, or local scales utilizing a combination of gravity, satellites, astronomical, altimetry, or GPS/levelling datasets. The determination of a national geoid has been a fundamental task for the surveying communities all over the world several decades ago (e.g. Corchete 2011, Kiamehr 2011, Lee and Kim 2012, Kilicoglu et al 2011, and Abdalla and Fairhead, 2011).

In the Kingdom of Saudi Arabia (KSA), geoid modelling has been investigated extensively in the last two decades (e.g. Algarni 1997, Abou Beieh and Algarni 1997). Currently, the development of a national geoid model is undergoing. This project requires a first order network of absolute gravity measurements and GPS network, with suitable distribution of points, on the levelling network, and associated modern gravity base station network in KSA. First step is to reprocess all existing gravity and GPS data (Figure 2). Densification of this network with secondary GPS and gravity measurements tied to a main precise network would result in the determination of an accurate geoid (Mogren 2010). An undergoing project for establishing Continuous Operation Global Navigation Satellite System Network (COGNET) would facilitate geodetic and GIS activities on a national scale in KSA (Al-Sahhaf, 2011). Another gravimetric geoid has been recently developed, based on a total of 504000 land and air-born gravity points that covers almost 70% of KSA (Alothman 2011). That geoid is rather smooth in general except in the southwestern region where mountains occur. In the northwest region, geoid heights reach +18 meters, while in the southeast region it is -36 meters. The accuracy of the geoid is varying in range from 0.01 m in the eastern province to 0.50 m in the northwest of the kingdom (ibid). It is quit important to notice that the gravity data do not cover Makkah city, and hence the developed gravimetric geoid will be quit general over the holly town. The current research study aims to evaluate the performance of most-recent global geoid models in order to choose the optimum one to be utilized in Makkah metropolitan area.

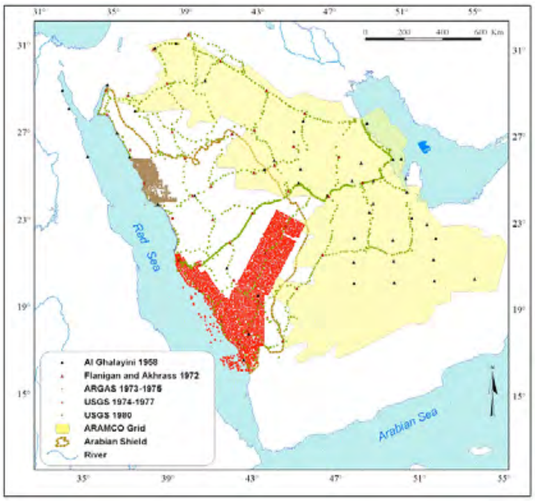


Figure 2: Gravity Networks in KSA
(after Mogren 2010)

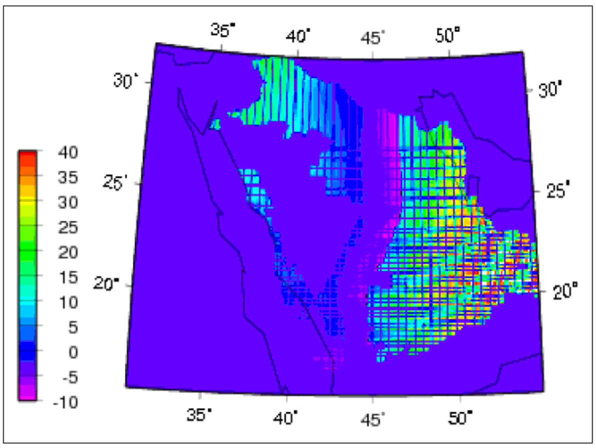


Figure 3: A Gravimetric Geoid over KSA
(after Alothman 2011)

Geoid Modelling:

The geoid is the equipotential surface of the Earth's gravity field approximating mean sea level in an optimum way, and extended under the continents. The geoid is determined using several techniques based on a wide variety of using one or more of the different data sources such as: the gravimetric method using surface gravity data, satellite positioning based on measuring both ellipsoidal heights for stations with known orthometric heights (equation 1), geopotential models using spherical harmonics coefficients determined from the analysis of satellite orbits, satellite altimetry using satellite-borne altimetric measurements over the oceans, astro-geodetic method using stations with measured astronomical and geodetic coordinates; and oceanographic levelling methods used mainly by the oceanographers to map the geopotential elevation of the mean surface of the ocean relative to a standard level surface. Stockes' boundary value problem (BVP) is the gravimetric determination of the geoid. BVP deals with the determination of a potential field, harmonic outside the masses, from gravity anomalies given everywhere on the geoidal surface. The final formula of the geoid undulations, N, is given as [Sideris, 1994]:

$$N = (R/4\pi\gamma)\iint_{\sigma} (\Delta g + \delta\Delta g + \delta A) S(\Psi) d\sigma + (1/\gamma)\delta T \quad (2)$$

where R is the mean radius of the Earth, Δg is the free-air gravity anomaly, γ is the normal gravity, $\delta\Delta$g is the indirect effect on gravity, δA is the attraction change, δT is the indirect effect on the potential, σ denotes the Earth's surface, dσ is the infinitesimal surface element; and S(Ψ) is the Stokes' function. There are several processing techniques for geoid determination, such as the Fast Fourier Transformation (FFT) and the Least-Squares Collocation (LSC). Additionally, the geoid undulations may be computed using the following spherical harmonic expansion:

$$N = (GM/r\gamma)\sum_{n=2}^{n\max}(a/r)^n - \sum_{m=0}^{n}((C^{-}_{nm}\cos m\lambda) + (S^{-}_{nm}\sin m\lambda))P_{nm}\sin\phi) \quad (3)$$

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 P_{nm} is the fully normalized associated Legendre polynomial.

In geoid modelling, usually the geoidal height N is decomposed into three components:

$$N = N_{\Delta g} + N_{GGM} + N_T \quad (4)$$

where: N_{GGM} is the global or long wavelength component determined by a GGM model, $N_{\Delta g}$ is the medium wavelength or local contribution of gravitational variations, and N_T denotes the short wavelength of topography effects. Hence, the precision of a specific GGM would influence the precision of the developed geoid, and this is the main objective of the current research study.

Global Geopotential Models:

Seven Global Geopotential Models (GGM) have been utilized and evaluated in the current research study. Sex of these GGM have been obtained from the International Center for Global Earth Models (IGCEM) website at: http://icgem.gfz-potsdam.de/ICGEM/ICGEM.html. The seventh GGM, the EGM2008, has been obtained from the U.S. National Geospatial-Intelligence Agency (NGA) website at: http://earth-info.nima.mil/GandG/wgs84/gravitymod/egm2008/egm08_wgs84.html. The choice of GGM to be included in this study was basically depend upon several criteria: (a) a variety of the maximum degree and order of GGM (n_{max} in equation 3), (b) a variety of data sources included in each GGM development, and (3) a variety of most-recent GGM in the last five years. Table 1 presents the main characteristics of the utilized GGM models.

Table 1: Characteristics of Utilized GGM

Model	Year	Source	Maximum Degree
DGM-1S	2012	S (GOCO, GRACE)	250
GOCO03S	2012	S (GOCO, GRACE)	250
EIGEN-6C	2011	S (GOCO, GRACE, LAGEOS), G, A	1420
GIF48	2011	S (GRACE), G, A	360
EIGEN-6S	2011	S (GOCO, GRACE , LAGEOS)	240
GGM03C	2009	S (GRACE), G, A	360
EGM2008	2008	S (GRACE), G, A	2190
Where: S means Satellite data, G means Gravity data, A means Altimetry data, GRACE is the Gravity Recovery And Climate Experiment satellite, GOCO is the Gravity and Ocean Circulation Explorer satellite, and LAGEOS is the Laser Geodynamics Satellites.			

The Delft Gravity Model Satellite-only (DGM-1S) GGM has been compiled at the Delft University of Technology in collaboration with the GNSS research center of Wuhan University. DGM-1S represents the static part of the Earth's gravity field in terms of spherical harmonic coefficients up to degree 250. It has been produced on the basis of an optimal combination of data acquired by GRACE and GOCE satellite missions (Hashemi Farahani et al, 2012). GOCO03S model has been produced by the Gravity Observation Combination (GOCO) initiative of the European Space Agency (ESA) in 2012. GOCO3S GGM is a satellite-only model uses GOCE and GRACE satellite data up to degree 250 (Mayer-Gürr T. et al. 2012). EIGEN-6C is a combined GGM that utilized satellite data from GRACE, GOCE, and LAGEOS satellite missions in combination with terrestrial global gravity and altimetry datasets. It has been produced to represent the gravitational field up to degree 1420 (Förste et al., 2011). GIF48 is a combined GGM processed up to spherical harmonics degree

360 (Ries et al., 2011). EIGEN-6S is a satellite-only GGM that utilized satellite data from GRACE, GOCE, and LAGEOS satellite missions, that has been produced to represent the gravitational field up to degree 240 (Förste et al., 2011). GGM03 is another combined GGM up to degree 360, uses an optimal combination of altimetry-derived sea surface data over water, gravity and other types of data over land, with very precise GRACE data (Tapley et al., 2007). The Earth Gravitational Model (EGM2008) is a precise GGM produced up to degree 2160, by the U.S National Geospatial-Intelligence Agency (NGA) in 2008. EGM2008 utilized a 5'x5' area-mean gravity (space, terrestrial, and altimetry) datasets on a global basis (Pavlis et al., 2008).

The International Center for Global Earth Models (IGCEM) has compared all available GGM over GPS/levelling networks in USA, Europe, Canada, and Australia. Table 2 presents results of such evaluations for the selected seven GGM utilized in the current study. The last column of this table has been computed, by the authors, as a weighted mean of the other four columns (where the weights equal the number of check points), that can be considered as an overall precision indicator of the GGM on a global basis. From this table, it can be noticed that the EGM2008 is considered as the most-precise available GGM so far. Additionally, it can be seen the satellite-only GGM (such as DGM-1S and GOCO3S) produced a relatively large RMS due to their low degree of spherical harmonic expansions. It worth mentioning that GGM are used not only for the geodetic and geomatics applications, but generally for a wide range of scientific applications such as solid earth, oceanography, and earth gravity definition. Due to its high precision level and its high degree of spherical harmonics, the EGM2008 has been utilized for geoid modelling in several countries in the last few years, such as in USA (Roman et al., 2010), France (Bonnefond et al., 2012), Sweden (Eshagh 2012), India (Rao et al., 2012), Korea (Lee and Kim, 2012), Turkey (Yilmaz et al., 2010), and Egypt (e.g. Dawod et al., 2010, Rabah and Kaloop, 2011). In KSA, the EGM2008 model has been also utilized to furnishe the long wavelength of the gravitational field in developing a gravimetric national geoid model (Alothman 2011).

Table 2: Root Mean Square (RMS) of Undulation Differences of GGM over Global GPS/Levelling Points
(in meters)

Model	USA	Canada	Europe	Australia	Overall Weighted Mean
	6169 points	1930 points	1235 points	201 points	
DGM-1S	0.441	0.353	0.43	0.366	0.420
GOCO-03S	0.428	0.34	0.418	0.355	0.407
EIGEN-6C	0.247	0.136	0.214	0.219	0.220
GIF48	0.319	0.23	0.275	0.236	0.294
EIGEN-6S	0.446	0.373	0.449	0.397	0.431
GGM-03C	0.347	0.279	0.334	0.259	0.330
EGM 2008	0.248	0.126	0.208	0.217	0.217

(after IGCEM)

The Study Area and Available Data:

Makkah city is located in the south-west part of KSA, about 80 km east of the Red Sea (Fig.4). It extends from longitudes 39° 35' E to 40° 02' E, and from latitudes 21° 09' N to 21° 37' N. The current area of the metropolitan region (the study area) equals 1593 square kilometers. A dataset of first-order GPS stations over Benchmarks has been obtained. Each station has an accurate ellipsoidal height with respect to the WGS84 datum, and a precise orthometric height relative to the Saudi vertical geodetic datum. Thus, a precise geoidal height (N) is determined for this geodetic network (Eq. 1).

Figure 4: Study Area

The topography of the Makkah metropolitan area is complex, where several mountainous regions exist within the urban boundaries of the city. Terrain elevations in Makkah (Figure 5) range from 82 to 982 meters above sea level.

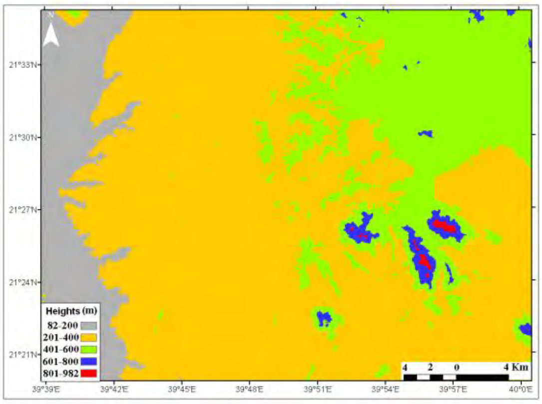


Figure 5: Topography of Makkah city

Processing, Results, and Discussions:

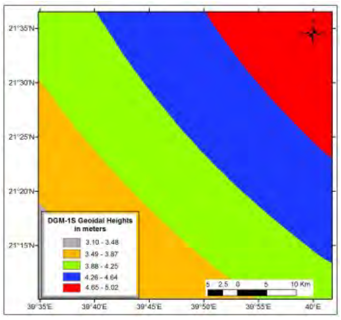
The main objectives of the processing stage of the study are: (1) determine the GGM-based geoid undulations from the selected models, and (2) compare those values with the observed precise undulations at the check points in order to choose the optimum GGM to be utilized in Makkah metropolitan area. Similar studies have been carried out in other countries recently (e.g. Dawod 2008, and Erol et al., 2009).

Two software packages have been utilized in the computation herein: Gravsoft v. 2.66 and hsynth_WGS84. Additionally, the Arc GIS 10 package is also used for presenting final results. Gravsoft is a scientific geodetic gravity field modelling program designed by professor Rene Forsberg of the Danish National Space Institute and professor C. Tscherning of the University of Copenhagen (Gravsoft 2008). The Gravsoft component utilized in this study is the GEOEGM that computes gravitational parameters, particularly the geoidal heights, out of a spherical harmonics expansion GGM. In the first step, the 6 utilized GGM models have been used to represent detailed grids of the geoid over Makkah city (Table 3 and Fig. 6 from a to f). The hsynth_WGS84program is developed by the US NGA that computes the EGM2008-based geoidal undulations for a specific geographic area. It worth mentioning that the hsynth_WGS84 program add a correction term of – 0.53 meter to the EGM2008 geoid undulations to obtain the undulation relative to the WGS84 ellipsoid. This is an important remark if a comparison is made between Gravsoft and hsynth_WGS84 regarding the EGM2008 undulations. The hsynth_WGS84 has been used to compute the EGM2008 geoid over Makkah city (Fig. 6g). Generally, it can be noticed that the GGM outputs over Makkah have significance differences in terms of values and spatial variations.

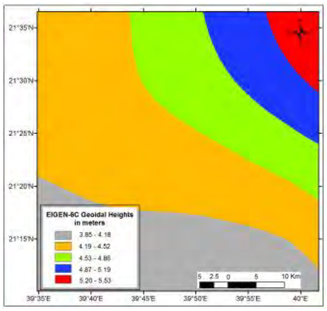
Table 3: Statistics of GGM's Grids over Makkah Metropolitan Area
(in meters)

Model	Minimum	Maximum	Mean	Standard Deviation
DGM-1S	3.101	5.029	4.149	± 0.410
GOCO-03S	2.996	5.086	4.123	± 0.445
EIGEN-6C	3.851	5.533	4.426	± 0.356
GIF48	3.139	4.884	3.850	± 0.375
EIGEN-6S	3.144	5.312	4.337	± 0.463
GGM-03C	3.360	4.920	4.104	± 0.336
EGM 2008	4.531	6.203	5.101	± 0.350

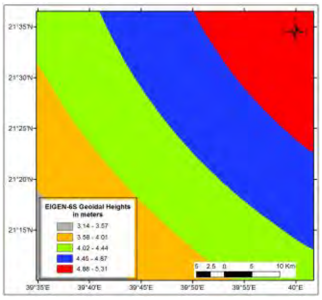
In the second step of the processing stage of the current study, the geoid undulations have been computed over the available GPS/levelling local dataset. The attained results are tabulated in Table 4. Comparing the si b d e l idi o s iesabGGG against the observed accurate ones reveals significant points. First, the general trend of satellite-only GGMs, as expressed by the mean undulation values, is far from the actual or observed one in Makkah. That is expected due to the low order of those GGM models that only represent the long wavelength of the Earth's gravitational field. On the other hand, the combined GGM models produce generally a better representation of the gravitational field due to the incorporation of gravity and altimetry datasets in developing such models. Moreover, it can be noticed that the EGM 2008 is the most closer GGM to the observed local geodetic dataset, in terms of its general or average geoid undulation value (5.22 meter and 5.73 meter respectively).



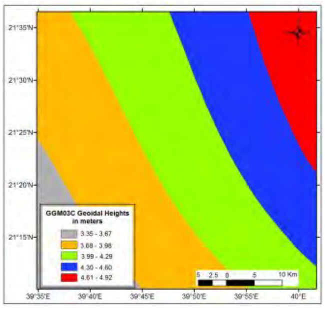
Geoid of DGM-1S
(a)



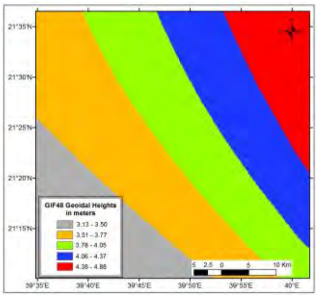
Geoid of EIGEN-6C
(b)



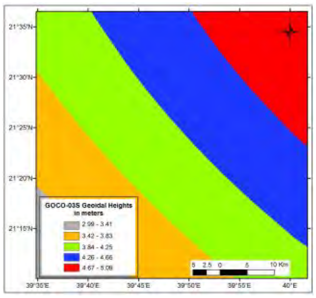
Geoid of EIGEN-6S
(c)



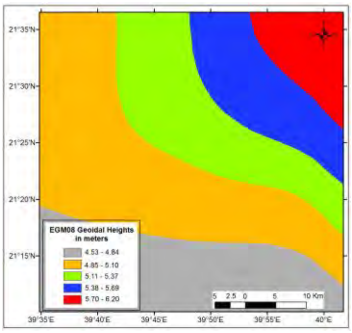
Geoid of GGM-03C
(d)



Geoid of GIF-48
(e)



Geoid of GOCO-03S
(f)



Geoid ofEGM2008
(g)

Figure 6: GGM Geoids over Makkah City

Table 4: Statistics of GGM's Geoidal Heights over Check Points in Makkah
(in meters)

Model	Minimum	Maximum	Mean	Standard Deviation
DGM-1S	4.001	4.704	4.34	± 0.23
GOCO-03S	3.955	4.727	4.33	± 0.25
EIGEN-6C	4.286	4.984	4.55	± 0.22
GIF48	3.663	4.456	4.00	± 0.26
EIGEN-6S	4.185	4.971	4.56	± 0.25
GGM-03C	4.448	5.105	4.70	± 0.21
EGM 2008	4.976	5.622	5.22	± 0.21
Observed Undulations	5.358	6.092	5.73	± 0.23

The next processing step of the current research study focuses on analyzing the undulation differences between the GGM-based values and the observed ones. The accomplished findings are presented in Table 5. Clearly, it can be concluded that the EGM2008 is the most precise GGM in Makkah city since its mean shift is only less than half meter compared to the local geodetic database. It can be noticed that EGM2008 is almost more precise than all other GGM by a factor of two approximately. Consequently, it is concluded that the EGM2008 is the optimum global geopotential model in representing the geoid surface in Makkah metropolitan area.

Table 5: Statistics of Undulation Differences between GGM's Geoidal Heights and Known Undulations over Check Points in Makkah
(in meters)

Model	Minimum	Maximum	Mean	Standard Deviation
DGM-1S	1.077	1.558	1.35	± 0.16
GOCO-03S	1.069	1.604	1.36	± 0.16
EIGEN-6C	0.931	1.298	1.14	± 0.16
GIF48	1.348	1.896	1.69	± 0.19
EIGEN-6S	0.825	1.374	1.13	± 0.17
GGM-03C	1.118	1.667	1.43	± 0.18
EGM 2008	0.224	0.674	0.47	± 0.16

Based on these findings, the current research study continues toward developing a modified geoid model for Makkah city. The Arc GIS software, particularly its spatial analysis component, has been utilized in this stage. A similar application has been performed by Dawod and Mohamed (2009). Such development consists of two steps: (1) developing a grid that spatially represents the deviations of the EGM2008

GGM over Makkah area, and (2) adding these variations to the original EGM2008 grid in order to obtain a modified more-precise geoid model. The attained modified geoid, called MEGM2008, was later compared against the known GPS/levelling check points. The results (Table 6) shows that the mean deviation is almost zero (since the original datum shift was removed), and the standard deviation equals 0.15 meter. The MEGM2008, depicted in Fig.7, may be considered the optimum geoid model so far for Makkah city until an accurate KSA geoid model is developed.

Table 6: Statistics of the Developed Geoid Model for Makkah
(in meters)

	Minimum	Maximum	Mean	Standard Deviation
Undulations of MEGM2008	5.429	6.122	5.69	± 0.20
Differences of MEGM2008 on Check Points	-0.228	0.147	-0.001	± 0.15

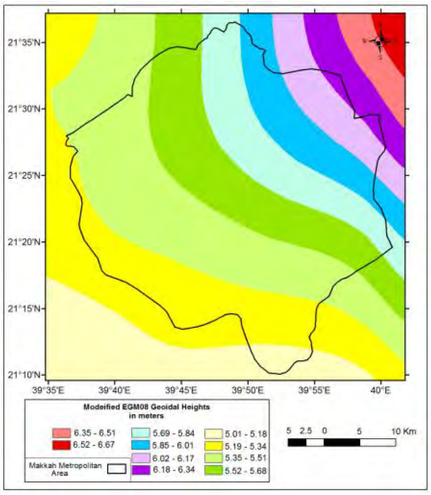


Figure 7: The Developed Geoid Model of Makkah City

Conclusion and Recommendation:

A geoid model is crucial for converting the GPS-based ellipsoidal heights into MSL-based orthometric heights usually used in geomatics, GIS, surveying, and mapping applications. So far, there is no available precise national geoid model that covers the entire territories of Saudi Arabia. The current research study has compared the most-recent released global geopotential models over precise GPS/levelling points, in order to decide the most precise one that precisely represent the Earth's gravitational field over Makkah metropolitan area. It has been found that the EGM2008 produces geoid undulation differences, over check points, that range from 0.224 meter to 0.674 meter, with an average of 0.47 meter and a standard deviation equals ± 0.16 meter. Based on the attained results, it is concluded that the EGM2008 is the most-precise GGM model to be utilized in Makkah city. Furthermore, the EGM2008-based geoidal undulation differences was spatially girded, and then added to the original EGM2008 undulation. By this approach, a new modified geoid model was obtained, that is based on integrating the original EGM2008 with precise local geodetic datasets. That modified geoid, called MEGM2008, has a mean undulation difference of almost zero and standard deviations of ± 0.15 meter. Also, it can be realized that this modified geoid has an increasing trend from the south-west to direction the north-east direction, which is compatible with the topography trend shown in Fig. 5. Consequently, that geoid model may be considered the optimal geoid so far for Makkah city until an accurate national KSA geoid model is developed. It is recommended to apply this geoid in all geomatics applications within Makkah city for converting GPS heights into MSL heights. Moreover, the presented processing strategy is also recommended to be applied in other regions within Saudi Arabia.

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