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LOCAL EVALUATION OF EARTH GRAVITATIONAL MODELS, CASE STUDY: IRAN

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Abstract. Global gravity models are being developed according to new data sets available from satellite gravity missions and terrestrial/marine gravity data which are provided by different countries. Some countries do not provide all their available data and the global gravity models have many vague computational methods. Therefore, the models need to be evaluated locally before using. It is generally understood that the accuracy of global gravity models is enough for local (civil, mining, construction, etc.) projects, however, our results in Iran show that the differences between synthesized values and observation data reach up to ~300 mGal for gravity anomalies and ~2 m for geoid heights. Even by applying the residual topographical correction to synthetized gravity anomalies, the differences are still notable. The accuracy of global gravity models for predicting marine gravity anomalies is also investigated in Persian Gulf and the results show differences of ~140 mGal in coastal areas. The results of evaluating selected global gravity models in Iran indicate that the EIGEN-6C4 achieves the lowest RMS for estimating the geoid heights. EGM08 predicts the closest results to terrestrial gravity anomalies. DIR-R5 GOCE satellite-only model estimates the low-frequency part of gravity field more accurately. The best prediction of marine gravity anomalies is also achieved by EGM08.

Keywords: Global gravity models, GNSS/Leveling, geoid, EGM08.

Introduction

Typically, Earth Gravitational Models (EGMs) are divided into two different types: satellite-only models and satellite-combined models. Satellite-only models are computed using the satellite missions such as GRACE, GOCE, CHAMP and Lageos and provide only the low frequency (maximum degree/order 300) part of gravity field and they are homogenous everywhere as they are independent from any terrestrial data. Besides data from satellite missions, satellite-combined models include the terrestrial gravity information of areas where they have available data and can represent the higher frequency of gravity field (maximum degree/order 2160). Therefore, it is not guaranteed that these models perform the same universally, and they need to be locally investigated if they are the only source to be used for practical purposes.

Mostly in civil projects, the estimation of geoid (or quasigeoid) heights is needed for local determination of the height system. The height datums are often defined by synthesizing values from EGMs. Moreover, many researchers within the frame of projects like: mining, geological and extraction etc. need an estimation of gravity anomalies over study area and synthesized values from EGMs are the only source of data instead of terrestrial gravity anomalies. This is done usually without any error estimation of these models.

On the other hand, in order to compute the local geoid models; typically, the reference field is removed by EGMs and is restored after computing the residual geoid heights. This technique is somewhat being used in many geoid determination techniques (Tscherning *et al.* 1992), Least-Square Modified Stokes' (LSMS) method (Sjoberg 2003) and Stokes-Helmert (SH) method (Vanicek, Martinec 1994), and the same scenario can be done if quasigeoid heights are desired, for instance (Krynski, Lyszkowicz 2005; Klees *et al.* 2008; Cunderlik *et al.* 2010; Foroughi, Tenzer 2014).

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Although many studies have already been published to show how a global model is developed, (Lemoine *et al.* 1998; Pavlis *et al.* 2012; Brockmann *et al.* 2014; Tapley *et al.* 2013; Gilardoni *et al.* 2016; Bruinsma *et al.* 2013; Gatti *et al.* 2014), all of them have many vague computation methods and approximations in order to come up with a, more or less, globally accepted model.

Investigation of the performance of EGMs can be done by analyzing the differences between synthesized values and observation data. Krynski, Lyszkowicz (2005) studied the choice of the EGM in Poland area and found that GGM02S fits the best in their area. Janak, Pitonak (2011) used the GOCE global gravity models and evaluated them using EGM08 and GOCO-02S model. An independent test was also done in their study using terrestrial information. Ferreira *et al.* (2013) did the same test in Brazil using the local GNSS/Leveling points for geoid evaluation and EGM08 as the reference model for gravity anomalies. The both studies resulted that DIR-R1 performs the best for the region. Godah *et al.* (2015) tried to find the best performing GOCE solution in Poland and showed that fifth release of the GOCE global models is the best choice for their study area. Kostelecky *et al.* (2015) compared the EIGEN-6C4 model with EGM08. Their aim was only to evaluate the EIGEN-6C4 model. They also compared the resulting geoid heights with GNSS/Leveling in many areas for instance: USA, Canada, Brazil, Japan, Czech Republic and Slovakia. Karpik *et al.* (2016) evaluated some commonly used global models to predict the local data in West Siberia and Kazakhstan. They showed that the residuals between synthesized values and the terrestrial information are not consistent everywhere in mentioned regions and only 2/3 of their data is compatible with global models.

Similar study has never been done for territory of Iran. Kiamehr (2009) only evaluated the EGM08 using available GNSS/Leveling points in Iran. Later Amjadparvar *et al.* (2011) used the same data points and compared with GOCE global gravity model releases and EGM08. They resulted that the performance of global gravity models in this area is not compatible with GNSS/Leveling height information. However, these studies only evaluated the results of EGM08 and neither of these studies evaluated the prediction of gravity anomalies in Iran.

Sec. 1 of this paper presents the theory of equations needed to evaluate the global models. The statistics of the well-known global models are summarized in Sec. 2. Sec. 3 introduces the study area and the terrestrial data and it is followed by evaluation process in Sec. 3.1 and 3.3. The discussion over the results is given in Sec. 4; and the conclusion and remarks of final evaluation is mentioned in the last Sec.

1. Theory

The Earth's gravitational field (W) can split into normal field (U) and disturbing potential (T) as follows:

$$W(r,\lambda,\phi)=U(\lambda,\phi)+T(r,\lambda,\phi), \qquad (1)$$

where, λ,ϕ are the ellipsoidal longitude and latitude coordinate of the computation point and $r \cong R+h_t$ (R is the mean radius of the Earth) and h_t is the normal height of the point where the potential field is computed. $U(\lambda,\phi)$ is the normal potential of the ellipsoid of revolution where it approximates geoid i.e. $U=W_0$ and W_0 is the potential of the geoid.

The disturbing potential field of the Earth (T) satisfies the Laplace equation, if there are no masses above the geoid (Hofmann Wellenhof, Moritz 2005 Eq. (1–20)):

$$\Delta T=0\,. \qquad (2)$$

Spherical Harmonics (SH) are orthogonal set of solutions to Laplace equation of disturbing field (Eq. (2)), therefore, T in terms of SH reads (*ibid*):

$$T(r,\lambda,\phi)=\frac{GM}{r}\sum_{l=0}^{l_{\max}}\left(\frac{R}{r}\right)^{l}\sum_{m=0}^{l}\bar{R}_{lm}\bar{Y}_{lm}(\lambda,\phi), \qquad (3)$$

where

$$\bar{R}_{lm}=\begin{cases}C_{lm}^{T} & m\geq 0\\ S_{lm}^{T} & m<0\end{cases} \qquad (4)$$

and

$$\bar{Y}_{lm}=\begin{cases}\bar{P}_{lm}(\cos\phi)\cos m\lambda & m\geq 0\\ \bar{P}_{lm}(\cos\phi)\sin|m|\lambda & m<0\end{cases}, \qquad (5)$$

where, GM is the product of Newtonian gravitational constant G and the Erath's mass M . $\bar{P}_{lm}$ is the fully normalized associated Legendre polynomial function of degree l and order m. $l_{\max}$ is the maximum degree of the SH expansion. C_{lm}^{T} and S_{lm}^{T} are the spherical harmonic coefficients of the disturbing potential:

$$C_{lm}^{T}=C_{lm}^{W}-C_{lm}^{U};$$
$$S_{lm}^{T}=S_{lm}^{W}-S_{lm}^{U}, \qquad (6)$$

where C_{lm}^{U} and S_{lm}^{U} are the ellipsoidal normal potential coefficients, where they only exist for zero-orders $(m=0)$ because it is a rotationally symmetric body and also for even-degrees $(l=even)$ as it is equatorially symmetric. (cf. (Barthelmes 2013)).

According to fundamental equation of physical geodesy, the Free-Air (FA) gravity anomalies can be derived as:

$$\Delta g^{fa} = -\frac{\partial T}{\partial r} - \frac{2}{R}T. \tag{7}$$

By substituting Eq. (7) into Eq. (3) we get:

$$\Delta g\left(r,\lambda,\phi\right) = \frac{GM}{r^2}\sum_{l=0}^{l_{\max}}\left(\frac{R}{r}\right)^l \left(l-1\right)\sum_{m=0}^{l}\bar{R}_{lm}\bar{Y}_{lm}\left(\lambda,\phi\right). \tag{8}$$

By using Bruns formula, the height anomaly on the surface of the Erath can be written as:

$$\zeta\left(r,\lambda,\phi\right) = \frac{T\left(r,\lambda,\phi\right)}{\gamma\left(r,\phi\right)}, \tag{9}$$

where, γ is the normal gravity of the ellipsoid of revolution and is denoted by (Hofmann Wellenhof, Moritz 2005):

$$\gamma\left(r,\phi\right) = \gamma_0 - \left(0.30877 - 0.00045\sin^2\phi\right)h + 0.000072h^2, \tag{10}$$

where, h is the height of the point with respect to ellipsoid and γ_0 is the normal gravity on the ellipsoid (GRS80, cf. (Hofmann Wellenhof, Moritz 2005)):

$$\gamma_0 = 978.0490\left(1 + 0.0052884\sin^2\phi - 0.0000059\sin^2 2\phi\right). \tag{11}$$

The height anomaly also can be expressed by substituting the Eq. (9) to Eq. (3), so we get:

$$\zeta\left(\lambda,\phi\right) = \frac{GM}{r\gamma\left(r,\phi\right)}\sum_{l=0}^{l_{\max}}\left(\frac{R}{r}\right)^l \sum_{m=0}^{l}\bar{R}_{lm}\bar{Y}_{lm}\left(\lambda,\phi\right). \tag{12}$$

EGMs express globally the potential field of the Earth in terms of SH coefficients (C_{lm}^{W}, S_{lm}^{W}). By removing the coefficients of the normal ellipsoid, the disturbing potential field is derived which can be used to compute gravity anomalies and height anomalies. Gravity anomalies can also be observed at the surface of the Earth (Vaníček, Krakiwsky 1987):

$$\Delta g_{obs} = g_{obs} - \left(\gamma_0 + 0.3086h\right), \tag{13}$$

where the term $0.3086h$ is called Free-Air correction. In addition, the height anomalies (quasigeoid heights) (ζ) can be derived using the information provided by GNSS/Leveling points:

$$\zeta_{obs} = h - H^N, \tag{14}$$

where, H^N is the normal height of the GNSS/Leveling points.

The observed gravity anomalies and height anomalies should be the same as corresponding synthesized values from EGMs if $l_{\max} = \infty$. However, due to limitations in satellite gravity missions and limit terrestrial gravity observation, current satellite-only EGMs have the maximum degree/order of 300 and satellite-combined models go up to 2160. If the EGMs were the only source to compute gravity function quantities for practical purposes, the omission error of limited degree/order of EGMs would make differences between synthesized and observation values, especially for gravity anomalies. Typically, the higher frequency of gravity field is topographic signal. EGMs already have the effect of global topography in them; therefore, subtraction of a further topographic effect may introduce long-wavelength effects into the synthesized values (Forsberg, Tscherning 2005). The effect of "*residual*" topography, with respect to the reference topography which is already imbedded in EGMs, is called Residual Terrain Model (RTM). The RTM is defined on the basis of introducing a reference topographic model (h_{ref}), which can be either computed by spherical expansion of global topographic coefficients up to same degree/order of used EGM, or by low-pass filtering of the local Digital Terrain Models (DTMs). (cf. (Forsberg 1984)).

The reference height using global topographic models reads:

$$h_{ref}\left(\lambda,\phi\right) = R\sum_{l=0}^{l_{\max}}\sum_{m=0}^{l}\bar{R}_{lm}^{topo}\bar{Y}_{lm}\left(\lambda,\phi\right), \tag{15}$$

where

$$\bar{R}_{lm}^{topo} = \begin{cases} C_{lm}^{topo} & m \geq 0 \\ S_{lm}^{topo} & m < 0 \end{cases} \tag{16}$$

and $C_{lm}^{topo}, S_{lm}^{topo}$ are the cos and sin coefficients of global topography. $l_{\max}$ is usually set the maximum degree of EGMs.

The RTM gravity terrain effect, in the form of planar approximation can be computed by (*ibid*):

$$\delta g_{RTM} = G\rho\iint_E \int_{h_{ref}}^{h} \frac{h_{p-z}}{S^3\left(x_p - x, y_p - y, h - z\right)}dxdydz, \tag{17}$$

where E, is the area of integration, and S is the distance function between two points. x, y, z are the Coordinates of the point in integration area, and x_p, y_p, h are the coordinates of the point, which RTM is evaluated on, and ρ is the mean reference density of topography inside the Earth (2670 kg/m^3). RTM gravity terrain effect can be also expressed in following closed form:

$$\delta g_{RTM} = G\rho\left|\left|\left| x\ln\left(y + r\right) + y\ln\left(x + r\right) - z\arctan\frac{xy}{zr}\right|_x^{x_p}\right|_y^{y_p}\right|_{h_{ref}}^{h}. \tag{18}$$

The observation gravity anomalies should be subtracted by RTM terrain effect to be compatible with the corresponding synthesized values computed by

EGMs. The RTM effect can also be added to synthesized values.

2. Earth gravitational models

GOCE gravity mission improved the information of the low frequency part of the gravity field. By launching this satellite, the satellite-only EGMs were released by using different data period and by using different methods. GO_CONS_GCF_2_SPW_R4, GO_CONS_GCF_2_TIM_R5, and GO_CONS_GCF_2_DIR_R5 are the latest releases of Space-wised, Time-wised, and Direct solution of the GOCE respectively. First model that in this work is short named to SPW_R4 and obtained from the data of 4th version of ESA project, has some additional processing procedures than previous versions, including data preprocessing and orbital filtering and it is developed after space-wise gridding by Least Squares Collocation. Second and third models are the products of 5th version of ESA project that are named here TIM_R5 and DIR_R5.

The three satellite-combined models used in present work are EGM08, EIGEN-6C4 and GECO. EGM08 was the first combined global gravity field model with so high resolution and it was computed from a global set of area-mean free-air gravity anomalies integrated with the information of the GRACE gravity mission (for more details see Pavlis *et al.* 2012). Beside the GRACE data that was already used in EGM08, the GOCE and Lageos data along with more terrestrial gravity data were combined to develop the EIGEN-6C4 model. In GECO model the information from a GOCE satellite-only global model (GO_CONS_GCF_2_TIM_R5), was used to improve the accuracy of EGM08 model in the low to medium frequencies, especially in areas where no data were available at the time of EGM08 computation. The main properties of the satellite-only and combined models used in this study are summarized in Table 1.

3. Evaluation of global gravity models with gravimetric data

The territory of Iran, limited to 44° < λ < 64°, 25° < ϕ < 40° was chosen to validate the global gravity models. This area includes 14479 terrestrial gravity and 8692 marine gravity points in Persian Gulf and Oman sea. Iran has rough topography regions, where the maximum height reaches up to around 4000 m in north, as well as flat areas in the middle and eastern part, which make the region a challenging place to validate Earth gravity models. Figure 1 shows the topography of Iran computed by the Shuttle Radar Topography Mission (SRTM) version 4.

The distribution of FA gravity anomalies over the land areas and their variation are shown in Figure 2 and corresponding plots for marine gravity data set are pictured in the Figure 3. Table 2 presents the statistics of FA anomalies over the land and sea area.

3.1. Evaluation with terrestrial data

Satellite-combined/only models, mentioned in Table 1, were used to synthesize FA (Eq. (8)) over the terrestrial gravity points. The full degree/order of models were employed, which is 2160 for combined models and it varies between 280 and 300 for selected satellite-only models in this paper.

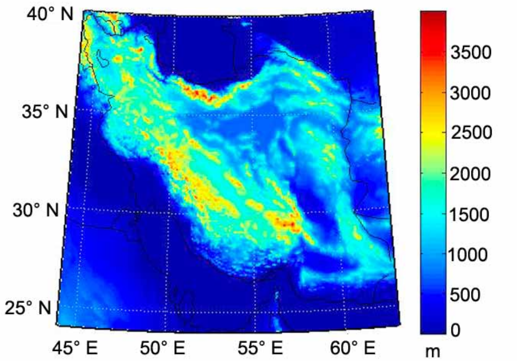


Fig. 1. Topography over Iran

Table 1. Main characteristics of Earth global gravity field models used in this research

	Model	d/o	Semi-major axis a [m]	GOCE data	GRACE data	LAGEOS–1/2 SLR data	Time of releasing	Reference
Satellite-combined	EGM08	2160	6378136.3	–	57 months	–	2008	Pavlis *et al.* 2012
	EIGEN-6C4	2160	6378136.46	~42 months	10 years	25 years	2015	Förste *et al.* 2015
	GECO	2160	6378136.46	~42 months	–	–	2015	Gilardoni *et al.* 2016
Satellite-only	DIR_R5	300	6378136.46	~42 months	10 years	25 years	2014	Bruinsma *et al.* 2013
	SPW_R4	280	6378136.46	~26.5 months	–	–	2014	Gatti *et al.* 2014
	TIM_R5	280	6378136.46	~42 months	–	–	2014	Brockmann *et al.* 2014

The variation of differences between synthesized values and available terrestrial FA over Iran is listed in the Figure 4 and Table 3 and the histogram of differences is shown in Figure 5. Figure 6 shows the scatter plot of residuals with respect to their heights.

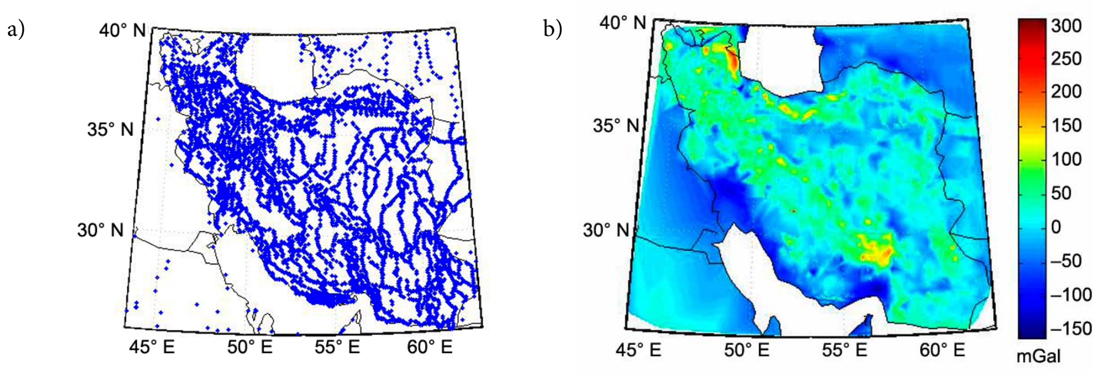


Fig. 2. Distribution of scattered terrestrial gravity points in land area (a), FA gravity anomaly variation (b)

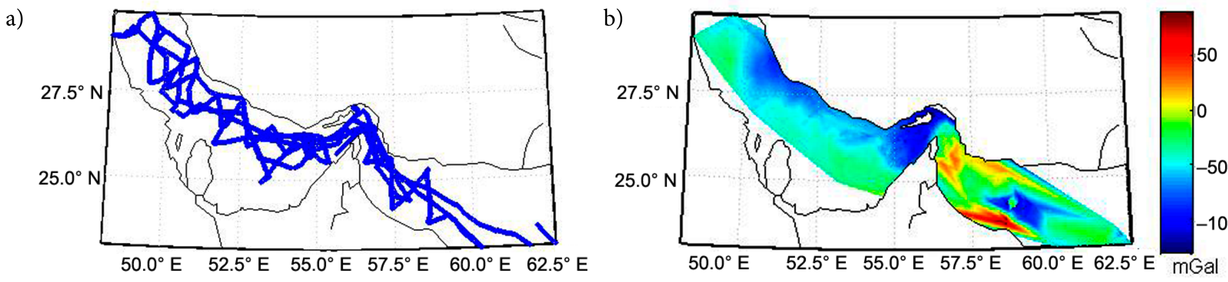
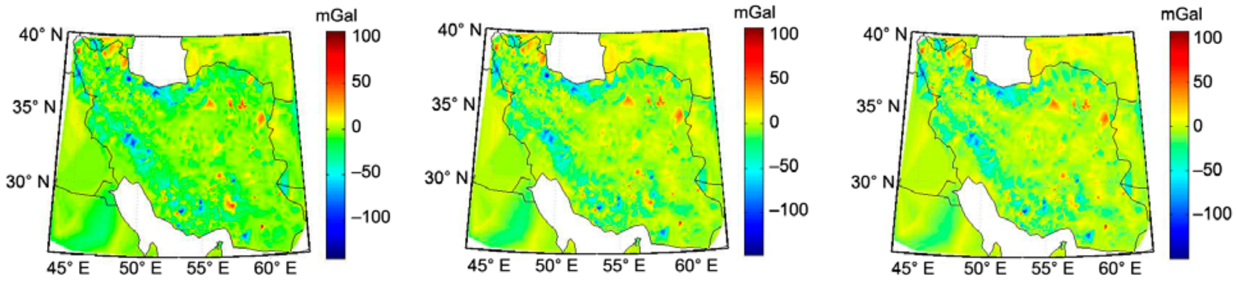


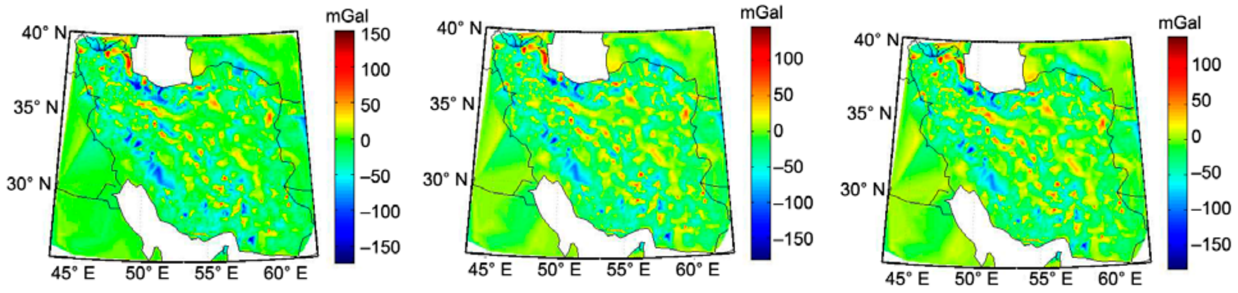
Fig. 3. Distribution of scattered marine gravity points in Persian Gulf (a), FA gravity anomaly variation (b)

Table 2. Statistics of available FA anomalies over Iran

Data	Min (mGal)	Max (mGal)	Mean (mGal)	STD (mGal)
Terrestrial FA anomalies	–163.2	351.5	–6.8	49.7
Marine FA anomalies	–131.5	89.7	–52.5	32.7

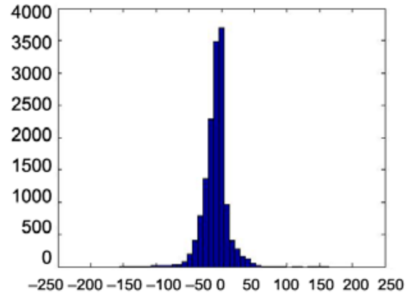


EGM08 EIGEN-6C4 GECO

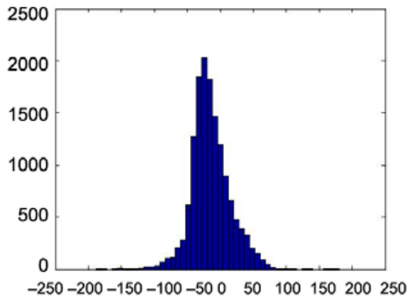


SPW_R4 TIM_R5 DIR_R5

Fig. 4. Differences between synthetic FA anomalies and terrestrial data

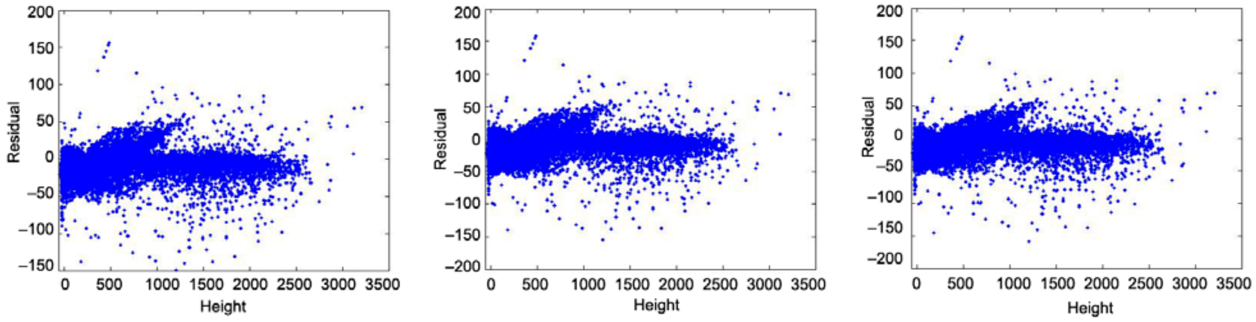


EGM08 EIGEN-6C4 GECO

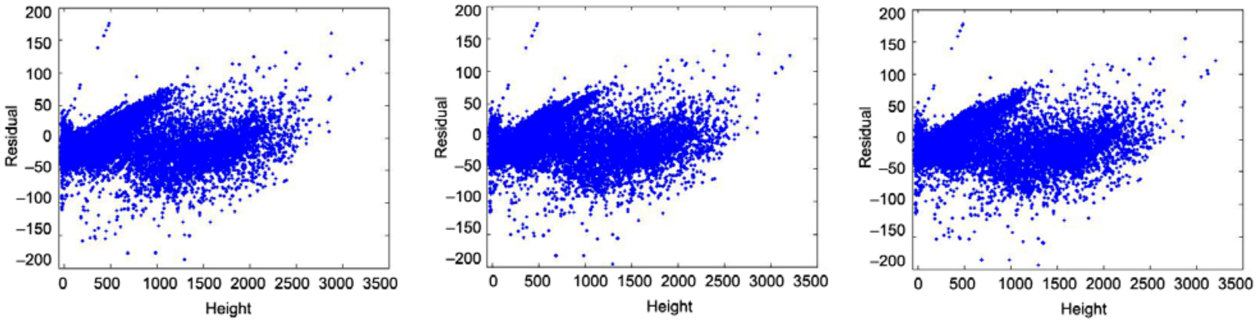


SPW_R4 TIM_R5 DIR_R5

Fig. 5. Histogram of differences between synthetic FA anomalies and terrestrial data



EGM08 EIGEN-6C4 GECO



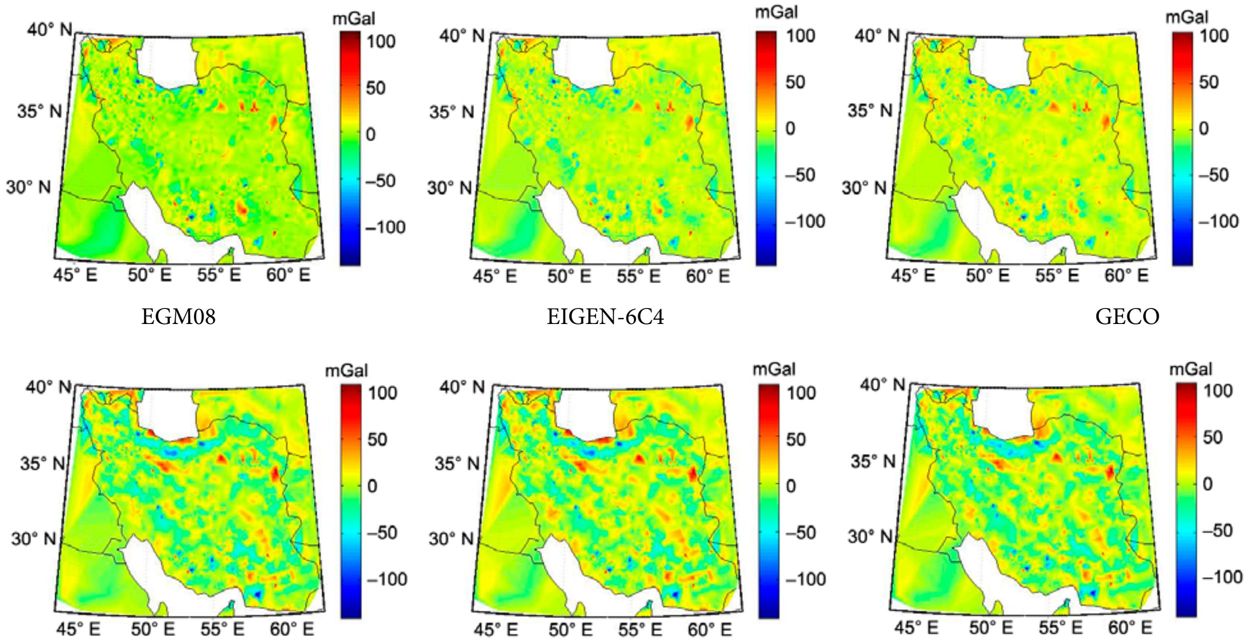
SPW_R4 TIM_R5 DIR_R5

Fig. 6. Scattered plot of differences between synthetic FA anomalies and terrestrial data with respect to height of the points

Table 3. Statistics of differences between synthetic FA and available terrestrial FA

	Model	d/o	Min (mGal)	Max (mGal)	Mean (mGal)	STD (mGal)
Satellite-combined	EGM08	2160	−149.7	156.1	−8.8	18.0
	EIGEN-6C4		−154.9	158.0	−9.4	18.1
	GECO		−157.9	156.2	−9.3	18.3
Satellite-only	DIR_R5	300	−193.7	177.5	−13.4	29.7
	SPW_R4	280	−187.1	175.6	−14.4	30.0
	TIM_R5	280	−195.7	173.3	−15.0	29.8

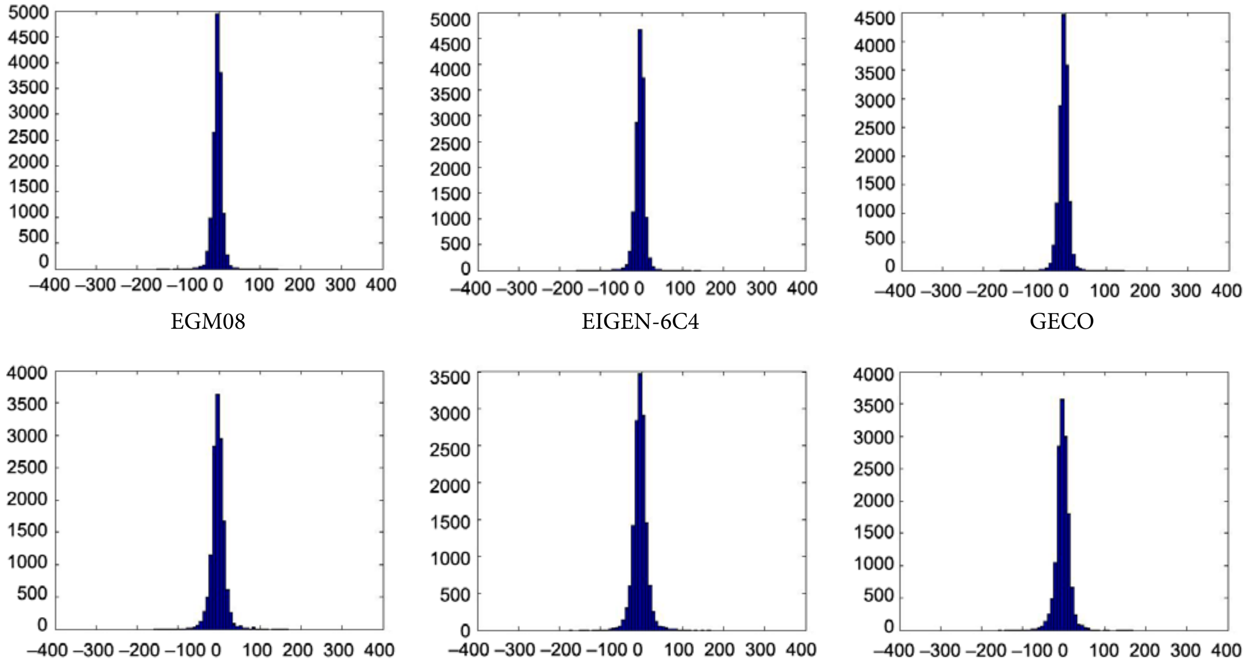
The effect of RTM on FA anomalies was computed using “TC.for” module from GRAVSOFT package (Forsberg, Tscherning 2008). The h_{ref} was computed using Eq. (15) by considering the $l_{\max}$ corresponding to the maximum d/o of each EGM, and the 3×3 arcsec SRTM ver.4 were used as detailed DTM for terrestrial gravity points. The effect of RTM on each point were removed from terrestrial data and again were compared with synthesized values. The intention of removing RTM was improve the fitting between synthesized and observation data. Figure 7 and Table 4 show that STD and mean values of new residuals are smaller, but the range of residuals is bigger. This can be because of errors in few points in the area. The corresponding histograms and scatter plots of the refined residuals are shown in Figure 8 and Figure 9.



EGM08 EIGEN-6C4 GECO

SPW_R4 TIM_R5 DIR_R5

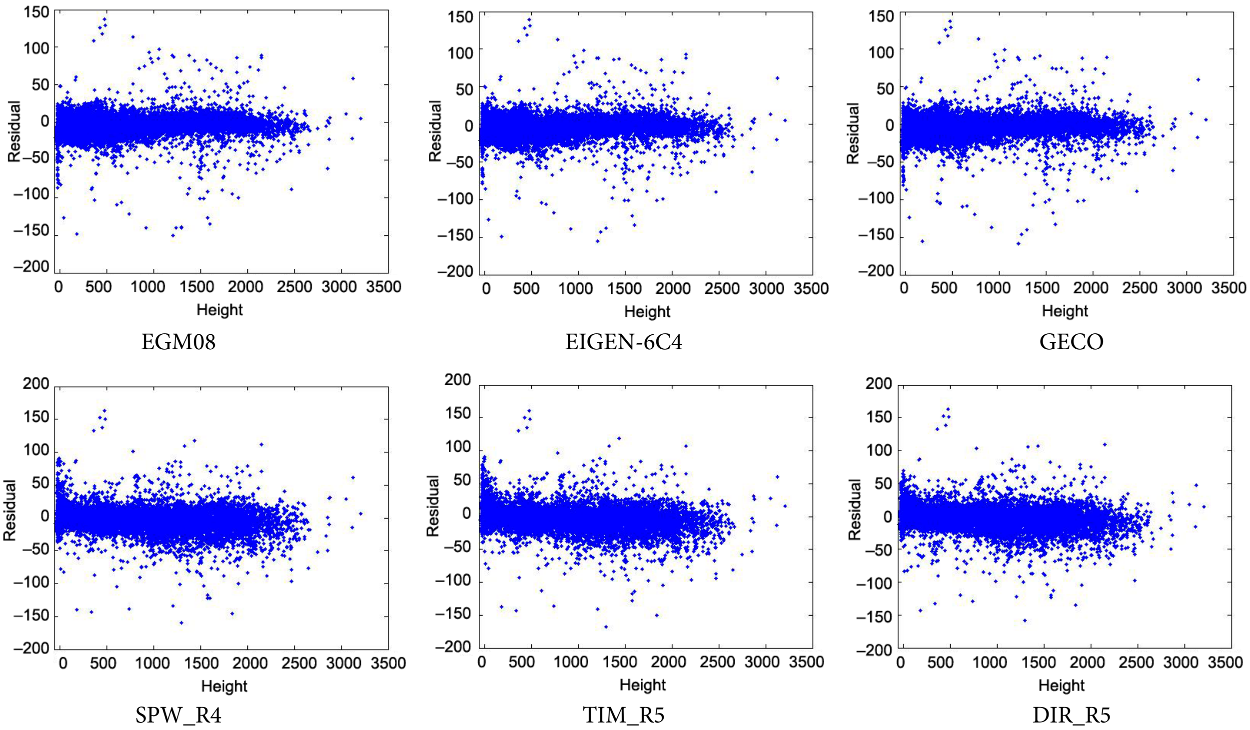
Fig. 7. Variation of residuals between synthetic FA and terrestrial FA, after removing the RTM



EGM08 EIGEN-6C4 GECO

SPW_R4 TIM_R5 DIR_R5

Fig. 8. Histogram of residuals between synthetic FA and terrestrial FA, after removing the RTM



EGM08 EIGEN-6C4 GECO

SPW_R4 TIM_R5 DIR_R5

Fig. 9. Scattered plots of refined residuals (after removing RTM) with respect to height

Table 4. Statistics of residuals of synthetic FA and terrestrial gravimetric anomalies after removing the RTM

	Model	d/o	Min (mGal)	Max (mGal)	Mean (mGal)	STD (mGal)
Satellite-combined	EGM08	2160	−150.8	137.7	−3.6	12.9
	EIGEN-6C4		−156.0	139.7	−4.2	13.0
	GECO		−159.0	137.6	−4.1	13.4
Satellite-only	DIR_R5	300	−158.7	163.5	−2.9	16.7
	SPW_R4	280	−159.7	162.8	−3.2	17.0
	TIM_R5	280	−168.2	160.7	−3.8	17.3

3.2. Evaluation with marine data

To evaluate the performance of global gravity models in southern part of Iran, where the Persian Gulf is located, the same procedure in 3.1 was done using satellite-combined and satellite-only global gravity models. The variation of residuals between FA anomalies derived from global models and FA derived from marine observation is depicted in Figure 10 and the statistics are presented in Table 5.

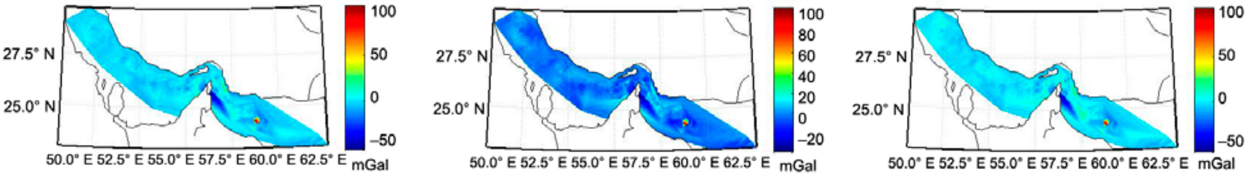
3.3. Evaluation with geometric data

Global gravity models can be used directly to compute the quasigeoid height and they can be converted to geoid by computing topographical correction of geoid-to-quasigeoid separation. Therefore, they need to be evaluated using independent information of geoid or quasigeoid such as GNSS/Leveling points. There are 436 available GNSS/Leveling points, distributed irregularly, across the area of Iran (Fig. 11b). Information of these points are ellipsoidal and normal heights which the normal heights were converted to (Helmert) orthometric heights using Poincare-Prey correction. The orthometric height information of points are derived from the leveling network of first order, available in National Cartographic Center (NCC) of Iran, and ellipsoidal height are processed using GNSS observations. We have then:

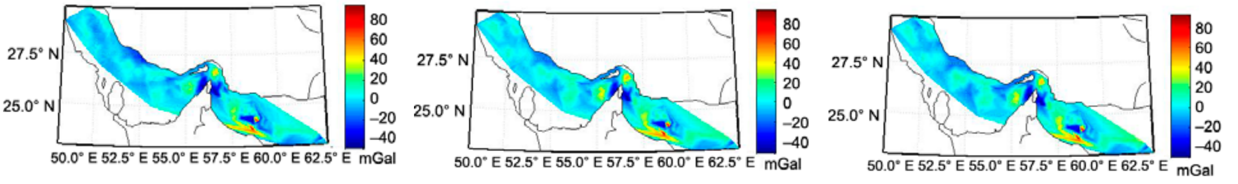
$$N_{GNSS/Leveling} = h - H^{Orth}, \tag{19}$$

where $N_{GNSS/Leveling}$ is compatible with its corresponding computed in Eq. (14). Figure 11a and Table 6 shows the variation of $N_{GNSS/Leveling}$.

Quasigeoid heights (height anomalies) were computed by Eq. (12) and were converted to geoid heights using Poincare-Prey correction. The results were compared with the corresponding ones from GNSS/Leveling points, the variation of differences is shown in Figure 12 and Table 7. Histogram of differences is also plotted in Figure 13.



EGM08 EIGEN-6C4 GECO



SPW_R4 TIM_R5 DIR_R5

Fig. 10. Differences between synthetic FA anomalies and marine FA anomalies

Table 5. Statistics of differences between marine gravity anomalies from global models and marine gravimetric observations

	Model	d/o	Min (mGal)	Max (mGal)	Mean (mGal)	STD (mGal)
Satellite-combined	EGM08	2160	–56.1	137.9	–0.06	11.0
	EIGEN-6C4		–44.9	140.8	–0.06	11.4
	GECO		–57.3	136.8	0.73	11.2
Satellite-only	DIR_R5	300	–52.1	93.5	0.82	16.5
	SPW_R4	280	–48.6	96.0	0.40	15.4
	TIM_R5	280	–54.4	95.1	0.83	16.3

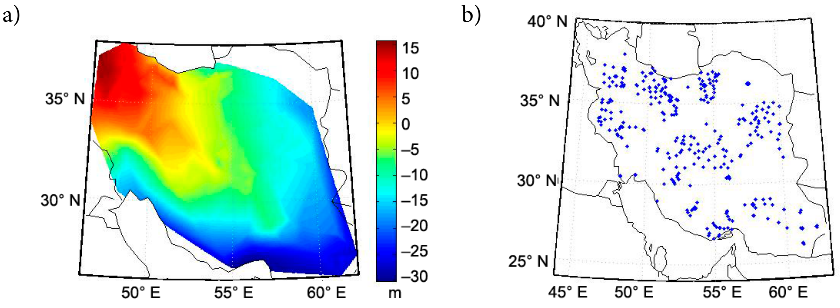
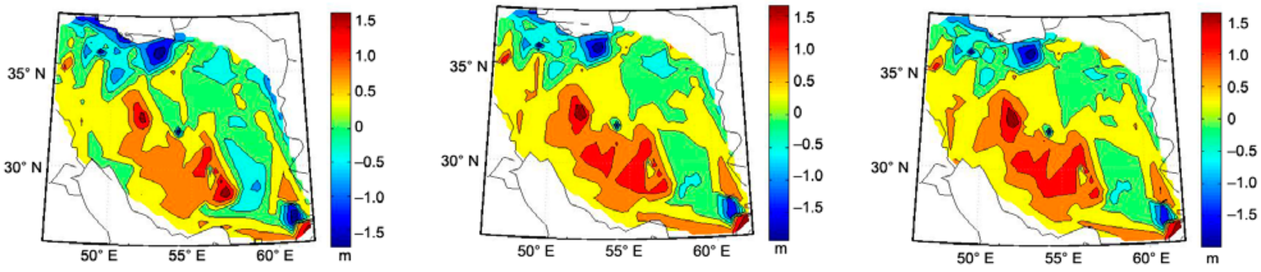


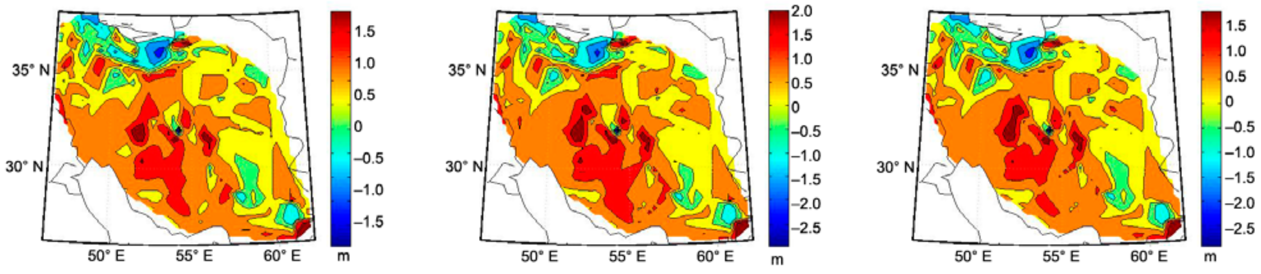
Fig. 11. Variation of geoid heights, derived from GNSS/Leveling points (a), distribution of GNSS/Leveling points across the country (b)

Table 6. Statistics of geoid heights derived from GNSS/Leveling points

Data	Min (m)	Max (m)	Mean (m)	STD (m)
Geoid heights from GNSS/Lev points	–30.1	15.8	–6.2	10.2

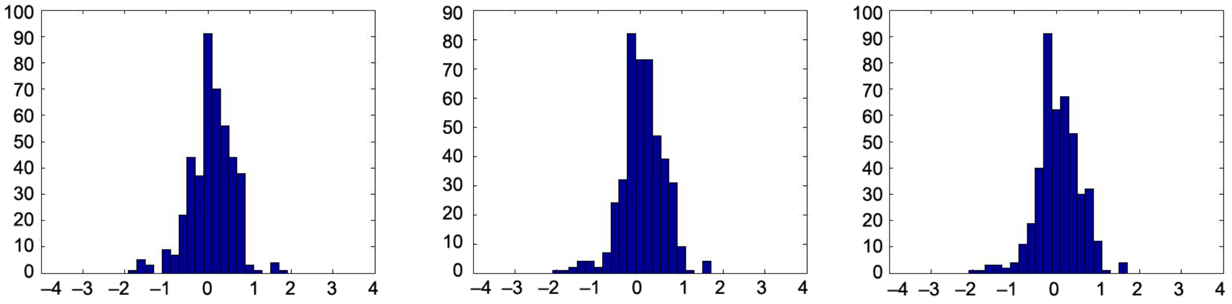


EGM08 EIGEN-6C4 GECO

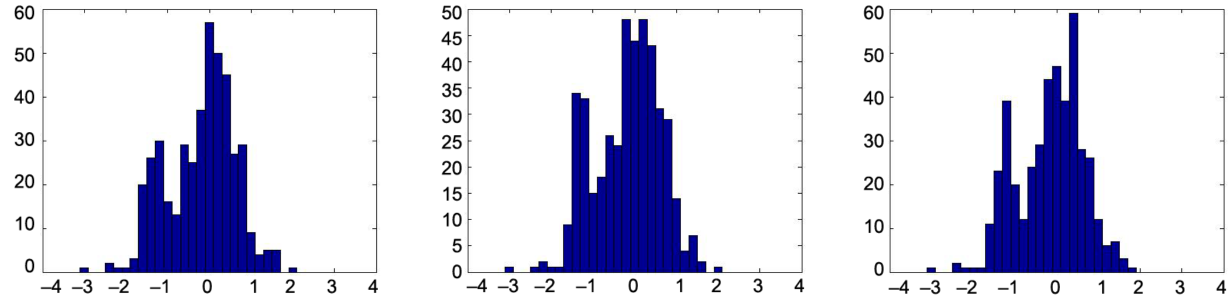


SPW_R4 TIM_R5 DIR_R5

Fig. 12. Variation of differences between synthesized geoid heights, derived from global models and geometric geoid heights, derived from GNSS/Leveling points



EGM08 EIGEN-6C4 GECO

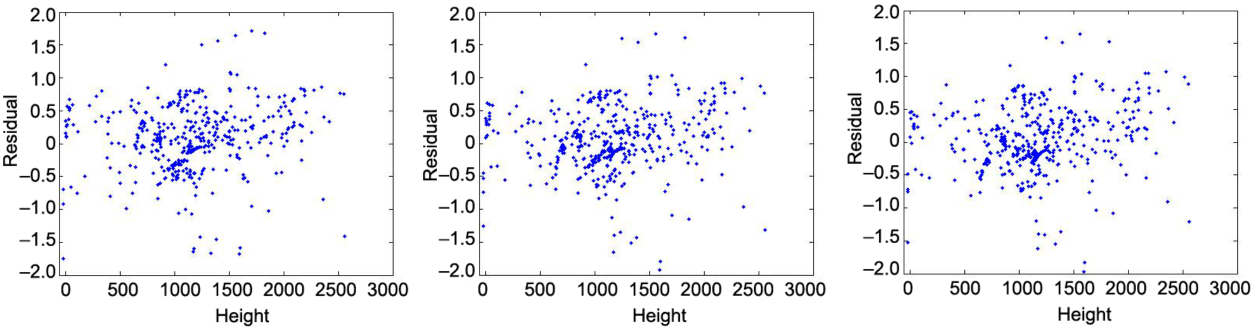


SPW_R4 TIM_R5 DIR_R5

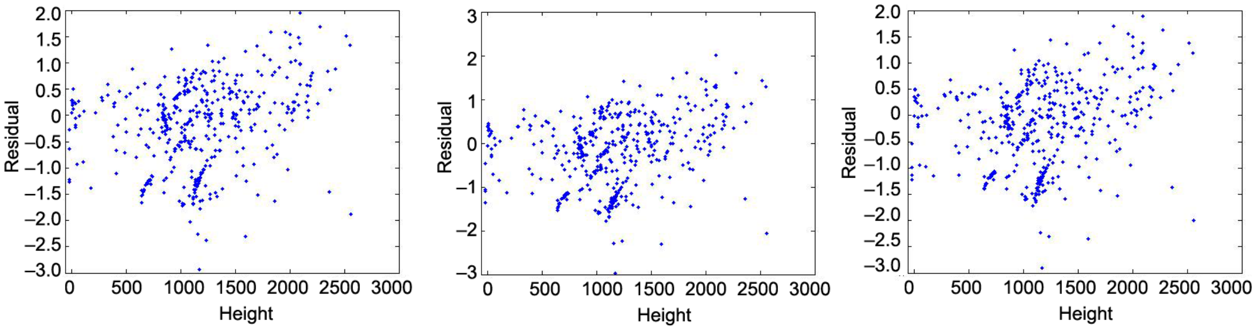
Fig. 13. Histogram of residuals of height anomalies

Table 7. Statistics of differences between geoid heights, from global models and GNSS/Leveling points

	Model	d/o	Min (m)	Max (m)	Mean (m)	STD (m)
Satellite-combined	EGM08	2160	−1.75	1.71	0.09	0.52
	EIGEN-6C4		−1.92	1.66	0.07	0.50
	GECO		−1.97	1.64	0.05	0.51
Satellite-only	DIR_R5	300	−2.91	1.89	−0.16	0.79
	SPW_R4	280	−2.93	1.95	−0.19	0.81
	TIM_R5	280	−2.98	2.00	−0.17	0.80



EGM08 EIGEN-6C4 GECO



SPW_R4 TIM_R5 DIR_R5

Fig. 14. Differences between synthesized geoid heights, derived from global models and geometric geoid heights, derived from GNSS/Leveling points

4. Discussion

Iran is considered as high mountain region with the maximum elevation of ~ 4000 m (Fig. 1) along the northern Alborz Mountains. The range of FA gravity anomalies in this area is ~ 500 mGal (Fig. 2b) which makes it a complex region for global gravity modeling. The scattered gravity observations of Iran were not (fully) provided to be included in the process of developing EMGs. This is well-seen in Figure 4 where the range of differences between synthesized gravity anomalies and observations reach up to ~ 300 mGal for satellite-combined models and ~ 370 mGal for satellite-only models. One can expect bigger differences for satellite-only models because of the larger omission error. Despite the big differences, the histograms of residuals show a random distribution of errors in Figure 5. The EIGEN-6C4 model has narrower histogram and the SPW-R4 histogram looks more randomly distributed rather other satellite-only models. The residuals are correlated with the heights of observations which are depicted in Figure 6 by the relation between residual values and height information. This shows that EGMs perform worse in high mountain areas; this can be either because of neglected high frequency topographic signals or the accuracy of observations in higher elevations. It can be seen that the largest residuals are not only happening at points with high elevation. The dispersion of residuals with respect to the height is less in satellite-combined models as some part of topographic signals were considered in these models. The bias between residuals for satellite-combined models and satellite-only models is ~ 9 mGal and ~ 14 mGal respectively (Table 3). This also can be result of accumulated topographic effects which is typically ignored in EGMs. The range of differences between synthesized gravity anomalies and RTM-removed observations did not change a lot: ~ 280 mGal for satellite-combined and ~ 320 mGal for satellite-only models; but the bias of residuals dropped down to ~ 3 mGal for all tested EGMs (Table 4). The effect of high frequency topographic signals was removed by considering the RTM; this is shown in the color-map of residuals in (Fig. 7) which has smoother trend rather than (Fig. 4); it also can be seen by narrower histograms in (Fig. 8). There is no correlation in the scattered point plots in (Fig. 9) which shows the remaining residuals can only be accounted for the omission errors of EGMs or errors associated with developing procedure. The histograms of residuals for GECO model and DIR-R5 look more random than others in their group. There are still some large residual values in low elevation points (Fig. 9) which were not removed because RTM effect is small in these points.

The Persian Gulf has always been an important study area for the neighbor countries. The EGMs are typically used in this area for predicting gravity anomalies or satellite altimetry-derived height systems. The evaluation of available EGMs in this area showed the range of ~ 200 mGal and ~ 140 mGal differences between marine gravity anomalies and synthesized values from satellite-combined and satellite-only models respectively (Table 5). The satellite-combined models, typically use satellite-altimetry information in developing EGMs, which can be the results of large residuals in coastal areas (Fig. 10) as satellite-altimetry techniques have larger errors in such areas. A bias of 0.7 mGals is seen in GECO model which is not visible in other models.

EGMs are also used to predict the height anomaly in Eq. (14). The omission errors of height anomalies synthesized by EGMs need to be taken into account for practical purposes as it can reach up to ~ 2 m in Table 7. The GNSS/Leveling points are well distributed across the study area (Fig. 11b) and large residuals are mostly in points with high elevation (Fig. 12). Height anomaly is a smooth field (Fig. 11a), so these differences are due to the omission error of EGMs and not neglected topographic signals. This also can be proved by the random pattern of residuals in residual histograms (Fig. 13). Satellite-combined models show more randomly distributed residuals rather than satellite-only models. The EIGEN-6C4 model provides the best random shape histogram of residuals. The scattered plots of relation between residuals of height anomalies and the elevation of each point are shown in (Fig. 14) which do not show any feature but the range of residuals are broadened with respect to different elevation. There is also a bias of ~ 20 cm in the residuals derived from satellite-only models, which is disappeared with satellite-combined models.

Conclusions and remarks

Well-known EGMs were evaluated in a topographic complex area, territory of Iran. The color-map of residuals showed the synthesized values of EGMs should be used more carefully in regions with high elevation. Due to neglected topographic signals, the RTM effect needs to be computed and applied to synthesized values to get closer residual statistics with respect to terrestrial information. The EGM08 performs the best among other tested models for predicting the FA anomalies in land areas; however, EIGEN-6C4 is only 0.1 mGal worse in terms of STD. The fifth release of GOCE satellite mission, DIR-R5, among other satellite-only models, shows the best performance with the STD of 17.4 mGal. This model is suggested for computing the reference field in regional geoid modelling. The forth release of space-wise GOCE satellite mission, SPW-R4, is most suitable satellite-only model in Persian Gulf, and again EGM08 has the best performance among satellite-combined models. The largest differences between synthesized geoidal heights, and the ones derived from GNSS/leveling points are located in the middle and northern part of Iran, where they reach up to 1.7 m. DIR-R5 and EIGEN-6C4 model are best performing satellite-only and satellite-combined model for predicting geoidal heights with the STD metric. GECO model shows the smallest bias as it has the minimum mean among other satellite-combined models. Our investigation shows that, global gravity models do not perform the same in regional cases and they need to be evaluated using local terrestrial/marine gravity information before being used in practice. The STD should not be considered as the only metric for measuring the goodness of EGMs in one area, as it is not useful for practical purposes when the range of residuals is much larger than STD in some points. The summary of these comparison is presented in Table 8.

Table 8. Summary of Comparison of EGMs in Iran

Regions	Anomaly	Measurement tool	Satellite-only	Satellite-Combined
Land areas	Gravity	STD	DIR-R5	EGM08
		Bias	DIR-R5	EGM08
	Height	STD	DIR-R5	EIGEN-6c4
		Bias	DIR-R5	GECO
Persian Gulf	Gravity	STD	SPW-R4	EGM08
		Bias	SPW-R4	EGM08

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