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Assessments of recently released global geopotential models along the Red Sea with shipborne gravity data ☆

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ABSTRACT

The goal of this research is to assess the accuracy of the global geopotential models (GGMs) from 2018 until the present in the Red Sea. The assessment was done by using the gravitational spectral analysis of models with each other and with the comparison with the shipborne gravity anomalies gathered along the Red Sea. In this study, combined models such as (XGM2019e 2159, SGG-UGM 2 and SGG-UGM 1) and satellite-only models such as (GOSG01S, IGGT R1C, Grace02k, DIR R6, GOCO06s, TIM R6 and Grace2018s) are studied. Firstly, all studied GGMs were subjected to gravitational spectral analysis. The statistical results indicate that the combined models outperform the satellite-only models before overcoming the spectral gap. The DIR R6 model is the most reliable of the satellite-only GGMs investigated in this study, exhibiting superior behaviour in all aspects when compared to the other satellite-only GGMs. In addition, the SGG-UGM 2 model is the best of the combined model of this research. Nonetheless, The DIR R6 model showed the best results in band gravitational analysis with spectral enhancement technique.

1. Introduction

The global geopotential model (GGM) is a mathematical model of the Earth's external gravity field based on spherical harmonic (SH) coefficients. The GGM data can be used to study coastal ecosystem processes, as well as heat and energy cycles and water transfers across bodies of water. Furthermore, GGM simplifies height datum unification applications (e.g., (Filmer et al., 2018), as well as oil/gas explorations and other offshore activities. The GGMs are classified into two groups: models derived only from satellite missions, as well as models derived from satellite data integrated with terrestrial, satellite altimetry, airborne gravimetry, and topography/bathymetry data. The GGMs have been significantly improved in terms of resolution and accuracy during the last many years. Gravity observations that are obtained from these models can be used to compute gravimetric geoids or to conduct geophysical and geodynamic investigations such as crustal movements, and a variety of other geodesy applications (Kumar et al., 2020). Oceanographers, geodesists, and other geoscientists are particularly interested in accurately determining the marine geoid since it serves as a natural reference for heights in their research (Kotzev et al., 2009). Diverse gravity data sets from various data sources, such as GGMs, altimetric data, and shipborne gravity, are necessary for the derivation of such a high-resolution and accurate geoid for marine regions.

(Zaki et al., 2018) used shipborne gravity data from the BGI to assess the performance of eight satellite-only GGMs based on GOCE (from 2014 to 2017), in the Red Sea. They revealed that the DIR-R5 model had the best performance satellite-only model in the spectral analysis and the comparison shipborne data. In addition, the EGM2008 was found to be the most effective, with a standard deviation (STD) of 11.11 mGal. However, the EGM2008 suffers from several biases, mostly due to discrepancies in the datum and fluctuation in the accuracy and density of the input observations (Pavlis et al., 2012). Furthermore, medium frequencies in satellite-only GGMs are more accurate, whereas the effects of biases in the EGM2008 are bigger. Furthermore, because the satellite-only GGMs were generated using globally homogeneous data (a unique geocentric ellipsoid), they are unaffected by local biases: the effects of many data sources and inconsistent height data are thus absent.

So, the purpose is to study the acceptability of improving the EGM2008 model by satellite-only GGMs that were released from 2018 until now and assess the accuracy of the new combined

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models. To achieve the study purposes, gravitational spectral analysis and comparison with shipborne gravity data were done for all GGMs.

2. Data

2.1. Shipborne gravity data

The shipborne data in (Zaki et al., 2018) are used. The BGI provided (Zaki et al., 2018) with a total of 95,649 shipborne gravity stations, as well as their spatial distribution, as shown in Fig. 1. The filtering of the shipborne data set was carried out using the leave-one-out cross-validation approach. The mean and STD of shipborne gravity anomalies are −20.17 and 34.05 mGal, respectively.

2.2. Global geopotential models (GGM)

We assess two types of GGMs that have been issued since 2018, seven satellite-only models and three combined models, in this study. The assessment of studied GGMs in this work is accomplished by using shipborne gravity data to perform gravitational spectral analysis across the research area.

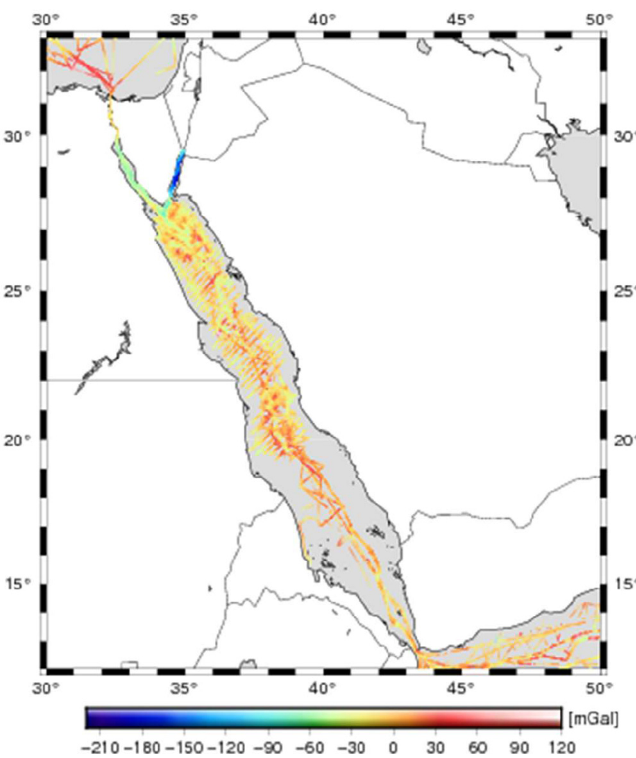


Fig. 1. The Shipborne gravity data along the Red sea.

In summary, a total of recently GGMs have been used as listed in Table 1.

3. Method

3.1. Spectral gravitational validation

The assessment is done by comparing the behaviour of the model's spherical harmonic (SH) coefficients over the full spectral band.

Firstly, degree variances, which are used to represent the signal's strength at multiple spectral wavelengths, are used to do the comparison., as reported in (Rapp and Sünkel, 1986). They can be determined by the following formula, as shown in Eq.1, which can be directly derived using both the fully normalized potential cosine and sine coefficients C_{nm} and S_{nm} :

$$\sigma_n^2 = \sum_{m=0}^{n} \left(C_{nm}^2 + S_{nm}^2 \right) \tag{1}$$

On the other hand, the degree variances error show the overall power of their error power at various spectral bands. They can be computed using the equation presented in Eq.2, which can be derived directly using both the error variances. $\sigma_{C_{nm}}^2$ and $\sigma_{S_{nm}}^2$:

$$\hat{\sigma}_n^2 = \sum_{m=0}^{n} \left(\sigma_{C_{nm}}^2 + \sigma_{S_{nm}}^2 \right) \tag{2}$$

By multiplying with the right eigenvalue, the degree variances error and degree variances of GGMs may be estimated for any geopotential functional, such as geoid height and gravity anomalies (see Table 2. In addition, Eq.3 may be used to calculate the signal-to-noise ratio (SNR), which provides more information about the relative signal intensity given the signal error at a specified degree.

$$SNR = \frac{\sigma_n}{\hat{\sigma}_n} \tag{3}$$

In this context, gravitational spectral validation is frequently achieved by comparing the gravitational spectral behaviour of the studied GGMs with a reference model, such as the EGM2008, in terms of degree variances and Gain differences. The comparison can be directly achieved by evaluating the differences between the C_{nm} and S_{nm} coefficients of the studied models and the EGM2008 model as:

$$\Delta C_{nm} = C_{nm}^{GGM\_Model} - C_{nm}^{EGM2008} \text{ and } \Delta S_{nm} = S_{nm}^{GGM_{Model}} - S_{nm}^{EGM2008} \tag{4}$$

By adding ΔC_{nm}, ΔS_{nm} in Eq. (1),

Table 1
GGMs employed in this study.

Model	Max degree	Year of release	Data source	Reference
EGM2008	2190	2008	Altimetry, Gravity, Satellite (Grace)	(Pavlis et al., 2012)
SGG-UGM 1	2159	2018	EGM2008, Satellite (Goce)	(Wei et al., 2018)
XGM2019e_2159	2190	2019	Altimetry, Gravity, Satellite (GOCO06s), Topography	(Zingerle et al., 2020)
SGG-UGM 2	2190	2020	Altimetry, EGM2008, Grace), Satellite (Goce)	(Liang et al., 2020)
GOSG01S	220	2018	Satellite (Goce)	(Xu et al., 2017)
Grace02k	180	2018	Satellite (Grace)	(Chen et al., 2018)
IGGT_R1C	240	2018	Gravity, Satellite (Goce), Satellite (Grace)	(Lu et al., 2018)
DIR_R6	300	2019	Satellite	(Förste et al., 2019)
TIM_R6	300	2019	Satellite (Goce)	(Brockmann et al., 2019)
GOCO06s	300	2019	Satellite	(Kvas et al., 2021)
Grace2018s	200	2019	Satellite (Grace)	(Mayer-Gürr et al., 2018)

Table 2
The eigenvalues for some potential functionals according to Meissl's scheme (Rummel and van Gelderen, 1995).

Potential function	Eigenvalues	Unit
Signal	1	Dimensionless
Geoid height (N)	R	M
Disturbing potential (T)	$\frac{GM}{R}$	$m^2\ s^{-2}$
Gravity anomaly (Δg)	$\frac{GM}{R^2}(n-1)10^5$	mGal
Gravity disturbance (Δg)	$\frac{GM}{R^2}(n+1)10^5$	mGal

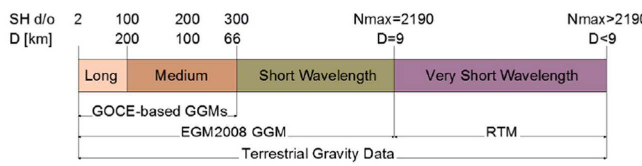


Fig. 2. The spectral enhancement method (SEM) principle (Zaki et al., 2018).

$$\Delta\sigma_n^2 = \sum_{m=0}^{n}\left(\Delta C_{nm}^2 + \Delta S_{nm}^2\right) \tag{5}$$

Additionally, the Gain (Sneeuw, 2000), which provides an approximate measure of the improvement achieved by the GGMs over the reference model (EGM2008), can be used to compare the error magnitudes.

$$\text{Gain} = \frac{\widehat{\sigma}_n^{EGM2008}}{\widehat{\sigma}_n^{GGM\_Model}} \tag{6}$$

3.2. External validation

The external validation aims to assess GGMs using shipborne data. The main issue in comparing satellite-only GGMs to terrestrial data is the spectral content differences. In addition, GGMs have a spectral content limited by their maximum SH degree and order (d/o), do not contain all possible wavelengths. Omission error occurs when the short wavelengths frequencies of the Earth's gravity field are not captured in GGM models. To make an adequate evaluation of GGMs, the spectral enhancement method (SEM) (Hirt et al., 2011) is a good method to fill the spectral gap that exists between GGMs and the real Earth's gravity field (See Fig. 2). This method has already been successfully used on land and at sea by many researchers around the world (Zaki et al., 2018); (Gautier et al., 2021).

By combining the EGM2008′s high-degree spectral bands, (Pavlis et al., 2012) with omission error estimates derived from a Residual Terrain Model (RTM) (Forsberg, 1984), which provides more information on gravity field constituents with extremely small wavelengths, the SEM (Forsberg, 1984) partially bridges the gaps between satellite-only GGMs and terrestrial data.

The satellite-only GGMs are evaluated up to their maximum degree n_1, and the spectral bands from the degree $n_1 + 1$ are filled by a high-resolution GGM (e.g. EGM2008), starting from $n_1 + 1$ to n_{max} (e.g. 2,190) and the RTM effects. Beyond n_{max}, the RTM omission error estimates are used to fill in the gaps in each model's spectral content as much as allowed. The RTM effects, on the other hand, correspond to the effects of topography/bathymetry undulations (SRTM15 + used in this study) taken reference surface such as DTM2006 generated up to its maximum d/o 2190 to reduce the effect of the EGM2008′s topographic signals. The RTM gravity signal can be calculated using the following formula:

$$\delta g = G\rho \int\int\int_{H_{ref}}^{H(x,y)} \frac{(H_p - Z)}{\left[(x-x_p)^2 + (y-y_p)^2 + (z-H_p)^2\right]^{\frac{3}{2}}} d_x d_y d_z \tag{7}$$

where H and H_{ref} are respectively the topography/bathymetric and the reference surface elevations. G is the constant of gravitational, x_p, y_p, and H_p are planar coordinates and ρ is the terrain density of the Earth.

The evaluation of GGMs from marine gravity data is done by calculating the following residual differences:

$$\Delta g_{res} = \Delta g_{Shipborne} - \left(\Delta g_{GGM_2^n} + \Delta g_{EGM2008_{n+1}^{2190}} + \Delta g_{RTM}\right) \tag{8}$$

Where $\Delta g_{Shipborne}$ represents the shipborne gravity anomaly. $\Delta g_{GGM_2^n}$ is the free-air gravity anomaly of the GGM evaluated and developed up to d/o (n). $\Delta g_{EGM2008_{n+1}^{2190}}$ is the gravity anomaly of

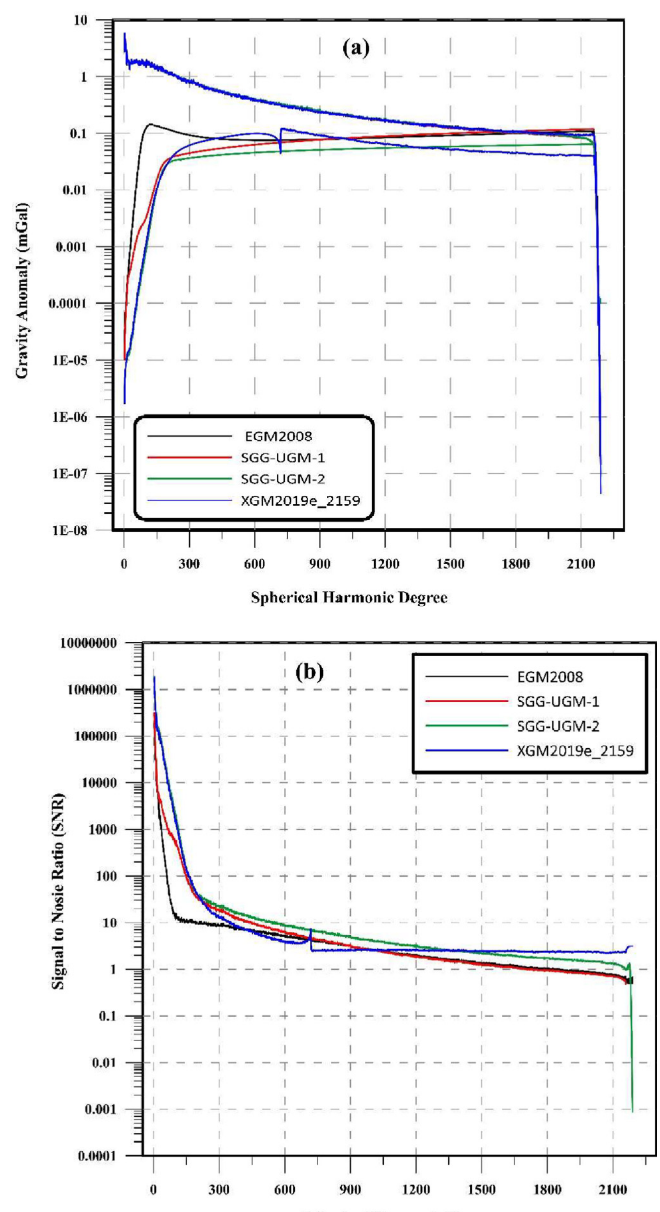


Fig. 3. The square root of degree variances and the error degree variances related to the gravity anomalies of combined GGMs (a) and the SNR for combined GGM models (b).

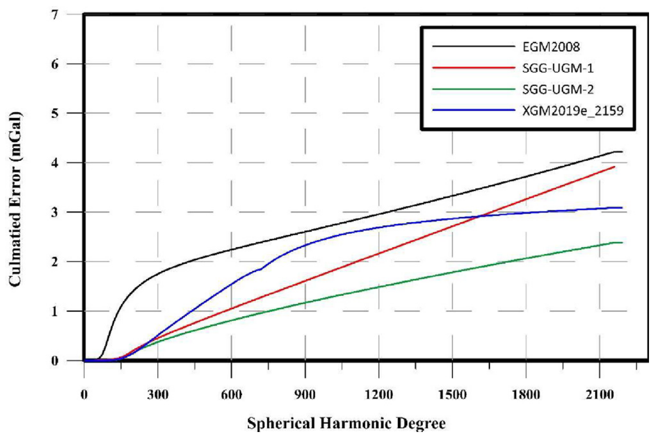


Fig. 4. The cumulative errors of combined models and the EGM2008 with regard to gravity anomalies.

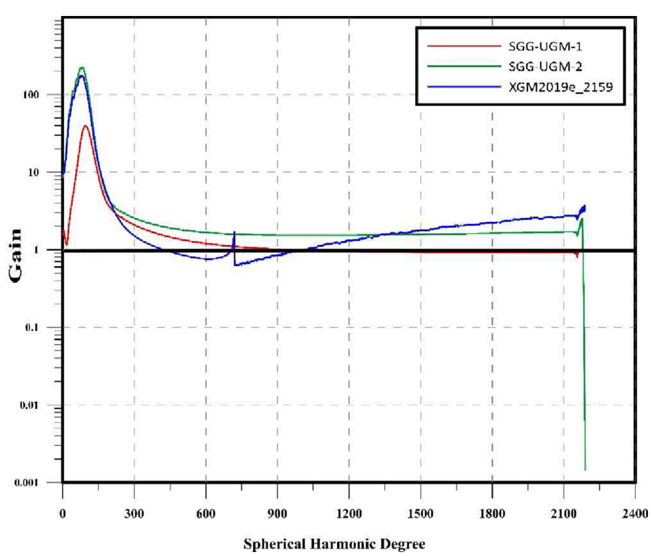


Fig. 5. The Gain of combined models in relation to the EGM2008.

the EGM2008 model evaluated and developed from d/o (n) up to maximum d/o 2190. Δg_{RTM} corresponds to the gravimetric signal of short wavelength calculated by the RTM method.

4. Results

4.1. Spectral gravitational validation of combined models

The gravitational spectral analysis of the error degree variances and the square root of degree variances related to the gravity anomalies for all studied combined GGMs are plotted in Fig. 3a. Up to d/o 2000, there were no visible differences in the degree variance of the various investigated models. The SGG-UGM 2 model displays a superior behaviour in terms of formal errors for other models, the error spectrum offered is lower than that of the EGM2008 up to degree and order 1350. The SGG-UGM 2 model shows smaller errors for the long-wavelengths as a result of the GRACE data's contribution and the addition of marine gravity anomalies. Fig. 3b shows the SNR for the evaluated combined models. As seen, the SGG-UGM 2 retains a better performance compared to the EGM2008 over the entire spectrum up to d/o 1350.

The SGG-UGM 2 exhibited the best overall error spectrum with the fewest cumulative gravity errors up to its maximum degree 2190, according to the cumulative gravity anomalies displayed in Fig. 4. At d/o 750, the SGG-UGM 2 approaches the 1.0 mGal error, while the XGM2019e 2159 does so at d/o 400.

Fig. 5 shows the Gain of the combined models using EGM2008 as a reference for this investigation. When the researched combined models are compared to the EGM2008, the beneficial spectral band provided by the analysed combined models becomes apparent in terms of significant digits of the model Gain. For the SGG-UGM 2, this band extends up to a maximum d/o 2190.

4.2. Spectral gravitational validation of Satellite-only models

The gravitational spectral analysis of the error degree variances and the square root of degree variances related to the gravity anomalies for all studied satellite-only models are plotted in Fig. 6a. The GOCO06s shows a smaller degree variance compared to other models, while the various evaluated models did not show any visible differences in the degree variance up to d/o 185. The

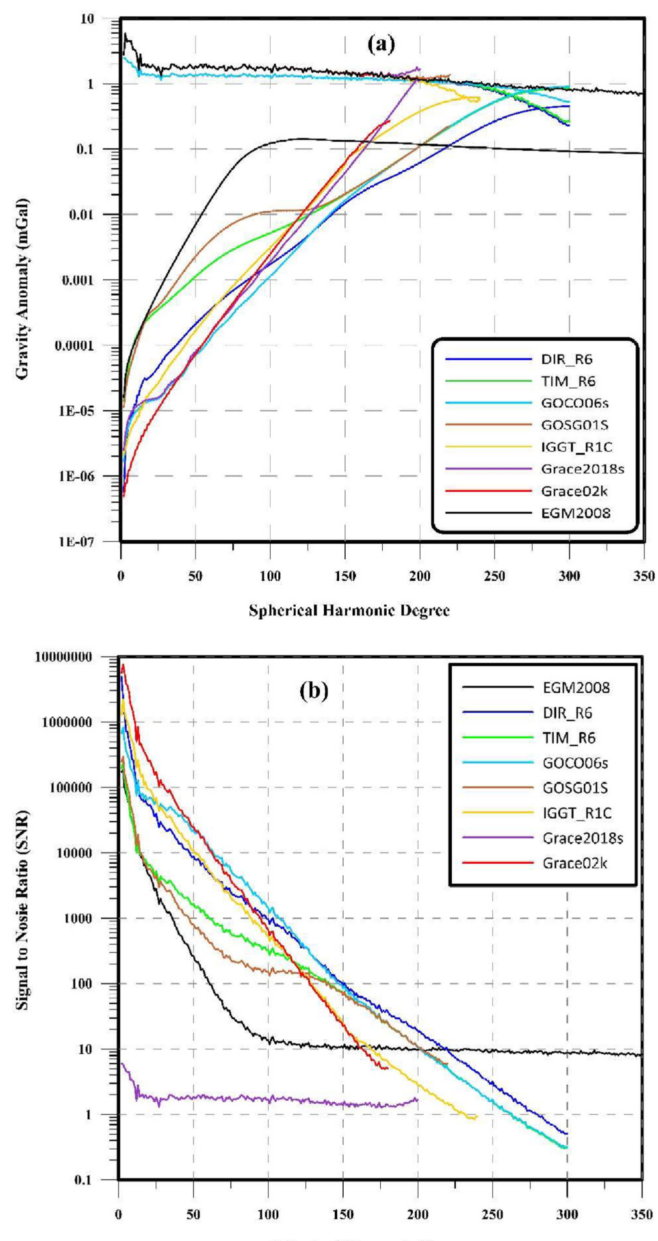


Fig. 6. The error degree variances and the square root of degree variances related to the gravity anomalies of satellite-only models (a) and the SNR for Satellite-only models (b).

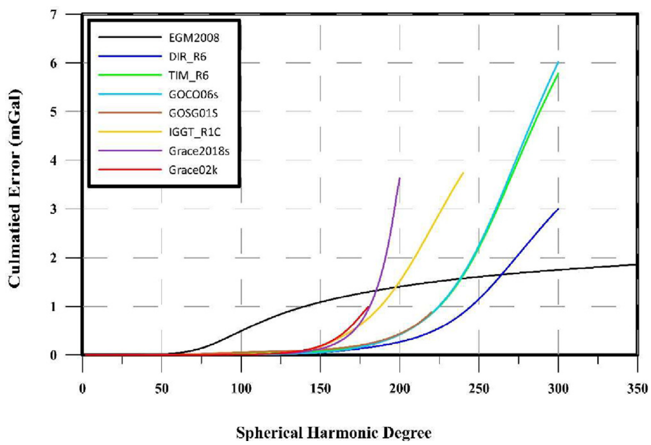


Fig. 7. In terms of gravity anomalies, the cumulative errors of satellite-only models and the EGM2008.

Grace02k model provided error spectrum is lower than that of the EGM2008 up to d/o 40, while the GOCO06s is below that of the EGM2008 from d/o 40 to d/o 125, moreover, the DIR_R6 better results from d/o 125 to d/o 220. Fig. 6b shows the SNR for the evaluated satellite-only models. As seen, the Grace02k is a better performance compared to the EGM2008 over the entire spectrum up to d/o 55, while the GOCO06s has a better performance compared to the EGM2008 from d/o 55 up to d/o 75, moreover, the DIR_R6 better results from d/o 75 to d/o 220. The SNR of the Grace2018s is worse than the EGM2008 compared to other models.

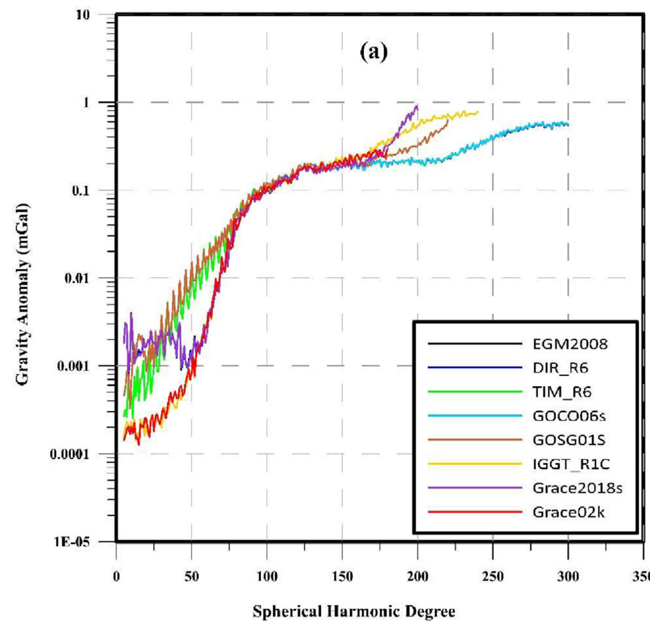
In terms of cumulative gravity anomalies errors, the DIR R6 model had the best overall error spectrum with the fewest cumulative gravity errors of all the satellite-only models studied (see Fig. 7. At d/o 246, the DIR R6 encounters the 1.0 mGal error.

Fig. 8a compares the degree variances of satellite-only models with the EGM2008 in terms of gravity anomalies. On one hand, the IGGT_R1C and Grace02k models showed the lowest differences up to d/o 80, while the various evaluated models did not show any visible differences from d/o 80 to d/o 155.

Fig. 8b, on the other hand, shows the Gain of all satellite-only models taking EGM2008 as a reference. The spectral band ranges up to d/o 165 for the Grace02k and from 165 d/o to 223 d/o for the DIR_R6.

4.3. External validation with shipborne gravity data before SEM principle

Table 3 shows the comparison of the examined GGMs and the EGM2008 with shipborne gravity data at their maximum d/o before applying the SEM. With 9.58 mGal, SGG-UGM 2 had the best STD among the GGMs.



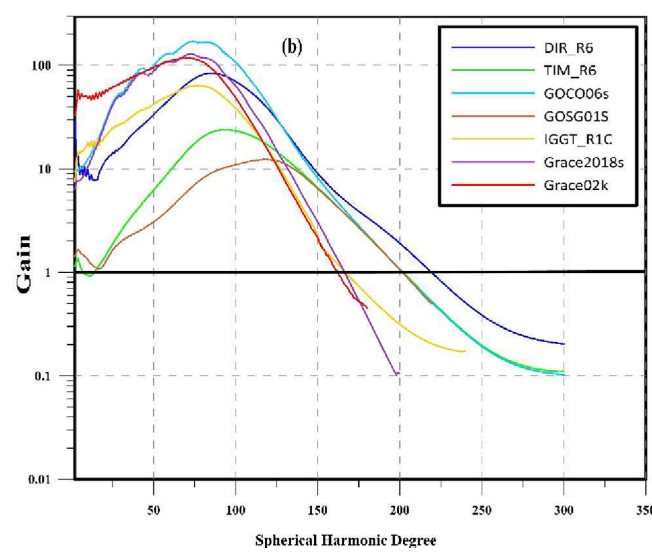


Fig. 8. A representation for the obtained results. a) the difference of the degree variances in terms of gravity anomalies between the satellite-only models and the EGM2008. Unit = mGal; b) the Gain of satellite-only models in relation to the EGM2008.

4.4. Band evaluation of satellite-only models before applying the SEM principle

The statistics of the variations between the studied satellite-only models, from (d/o) ranging from 100 to their maximum d/o

Table 3
The characteristics of the differences between all the evaluated GGMs at their maximum d/o and the shipborne gravity data before applying the SEM [mGal]

Model	Degree	Minimum	Maximum	Mean	STD
EGM2008	2190	−55.57	136.22	−0.50	**11.27**
SGG-UGM 1	2159	−59.16	66.68	−2.29	9.62
XGM2019e_2159	2190	−63.01	66.42	−3.91	10.14
SGG-UGM 2	2190	−56.32	65.94	−2.93	**9.58**
GOSG01S	220	−221.22	120.73	−13.22	38.40
Grace02k	180	−239.66	127.34	−14.39	40.67
IGGT_R1C	240	−208.31	121.67	−12.60	37.00
DIR_R6	300	−194.26	119.92	−12.57	33.47
TIM_R6	300	−192.60	119.61	−12.63	33.29
GOCO06s	300	−191.96	118.81	−12.64	**33.21**
Grace2018s	200	−236.12	120.17	−14.26	40.15

Table 4
The characteristics of the variations between the studied satellite-only models (from d/o 100 to their max. degree) and the shipborne gravity data before using the SEM. Unit = mGal.

Model	Degree	Mean	STD
Grace2018s	100	−22.14	39.53
	120	−17.08	40.71
	140	−16.94	39.20
	160	−15.09	40.39
	180	−14.63	40.71
	200	−14.26	40.15
GOCO06s	100	−22.13	39.54
	120	−17.07	40.71
	140	−16.90	39.20
	160	−15.08	40.37
	180	−14.38	40.76
	200	−12.91	40.02
	220	−13.19	37.97
	240	−13.64	35.43
	260	−12.79	34.14
	280	−12.72	33.57
	300	−12.64	**33.21**
TIM_R6	100	−22.15	39.52
	120	−17.06	40.72
	140	−16.90	39.20
	160	−15.06	40.39
	180	−14.38	40.76
	200	−12.86	40.03
	220	−13.15	37.98
	240	−13.60	35.44
	260	−12.77	34.18
	280	−12.71	33.62
	300	−12.63	**33.29**
DIR_R6	100	−22.13	39.54
	120	−17.07	40.71
	140	−16.89	39.20
	160	−15.04	40.40
	180	−14.36	40.77
	200	−12.82	40.06
	220	−13.09	38.03
	240	−13.47	35.56
	260	−12.78	34.43
	280	−12.69	33.83
	300	−12.57	33.47
IGGT_R1C	100	−22.13	39.53
	120	−17.06	40.72
	140	−16.93	39.18
	160	−15.20	40.21
	180	−13.48	40.73
	200	−11.78	39.47
	220	−12.29	37.72
	240	−12.60	37.00
Grace02k	100	−22.12	39.53
	120	−17.04	40.71
	140	−16.87	39.15
	160	−15.04	40.31
	180	−14.39	40.67
GOSG01S	100	−22.12	39.54
	120	−17.07	40.71
	140	−16.85	39.25
	160	−15.13	40.35
	180	−14.41	40.93
	200	−12.89	39.92
	220	−13.22	38.40

with the external data (shipborne gravity data) are presented in Table 4. The statistical results of the GOCO06s model are better in the study area with an STD of 33.21 mGal at its maximum d/o 300. The GOCO06s model is followed by the TIM_R6 and DIR_R6 models according to the best statistical performances. From Table 4, GOCO06s, TIM_R6 and DIR_R6 are the satellite-only models that best describe the gravity field over the study area (at higher d/o). However, its spectral bands need to be enhanced by high and extremely high frequencies of the Earth's gravity field to improve performance.

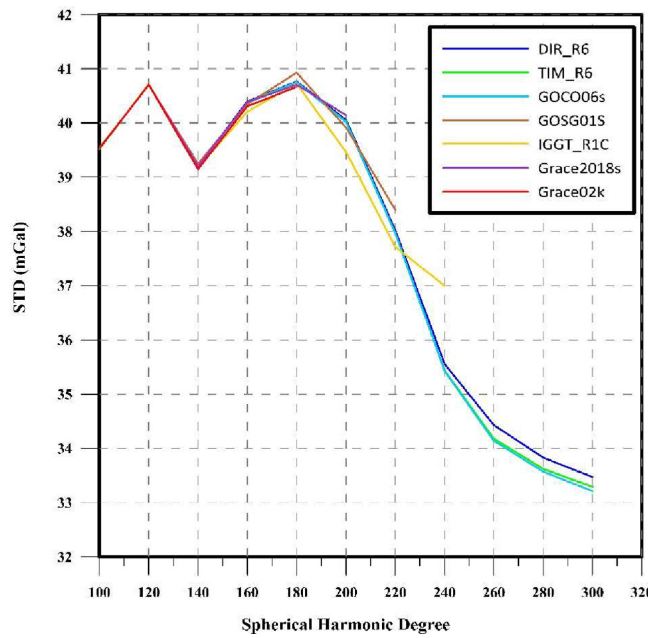


Fig. 9. A representation of the STD of the variations between the satellite-only models and the shipborne gravity data before using the SEM. The unit is mGal.

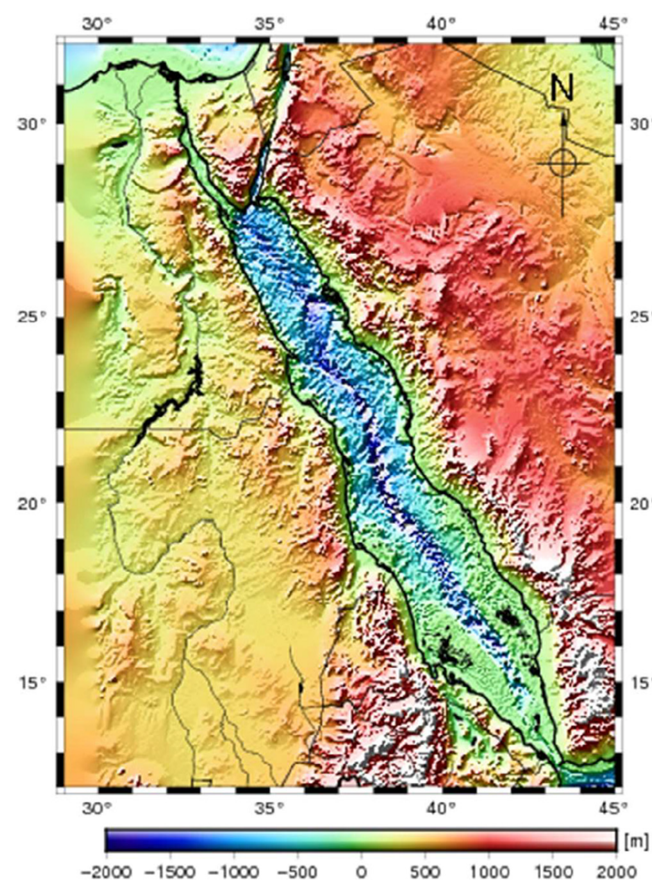


Fig. 10. The SRTM 15 + model for the Red Sea region. Unit = m.

Fig. 9 shows the variation of the STD values from the differences between satellite-only models and shipborne gravity anomalies as a function of spherical harmonics d/o. We notice that all models behave almost the same in d/o 100. Moreover, the STD curves of

Table 5
The characteristics of the differences between the studied satellite-only models and the shipborne gravity data after using the SEM. Unit = mGal.

Model	Degree	Mean	STD
Grace2018s	100	−2.80	10.37
	120	−1.91	10.85
	140	−1.91	11.20
	160	−2.85	11.16
	180	−3.79	11.51
	200	−5.35	12.45
GOCO06s	100	−2.81	10.37
	120	−1.91	10.86
	140	−1.88	11.22
	160	−2.85	11.15
	180	−3.55	11.60
	200	−4.01	11.79
	220	−4.64	12.18
	240	−5.24	13.06
	260	−4.62	13.14
	280	−4.82	13.75
	300	−5.08	14.32
TIM_R6	100	−2.82	10.36
	120	−1.90	10.87
	140	−1.88	11.22
	160	−2.82	11.17
	180	−3.55	11.60
	200	−3.95	11.79
	220	−4.59	12.17
	240	−5.20	13.05
	260	−4.60	13.15
	280	−4.81	13.75
	300	−5.08	14.35
DIR_R6	100	−1.19	**8.74**
	120	−0.29	8.98
	140	−0.25	9.07
	160	−1.20	8.85
	180	−1.91	9.31
	200	−2.30	9.37
	220	−2.93	9.74
	240	−3.46	10.68
	260	−3.01	10.65
	280	−3.18	11.11
	300	−3.41	11.75
IGGT_R1C	100	−2.80	10.37
	120	−1.90	10.86
	140	−1.90	11.22
	160	−2.96	11.24
	180	−2.64	11.82
	200	2.87	11.96
	220	−3.74	12.31
	240	−4.19	13.58
Grace02k	100	−2.79	10.37
	120	−1.88	10.86
	140	−1.84	11.18
	160	−2.81	11.10
	180	−3.55	11.44
GOSG01S	100	−2.80	10.38
	120	−1.91	10.86
	140	−1.82	11.28
	160	−2.90	11.15
	180	−3.58	11.76
	200	−3.98	11.69
	220	−4.66	12.83

each model decrease when spherical harmonics d/o increase; this is normal because the higher the spherical harmonics d/o, the better the model describes the gravity field with a good resolution.

4.5. Evaluation of satellite-only models after using the SEM principle

The main idea of SEM is to fill the spectral gap between GGMs and terrestrial data (i.e. shipborne gravity data) (Hirt et al., 2011). It is combining the EGM2008′s high-degree bands with the RTM's very high-frequency signal (Forsberg, 1984). The 15 arc-second SRTM model (http://earthexplorer.usgs.gov/) as Fig. 10 and the reference surface as DTM2006 produced the RTM signal, which is computed as the differences between the terrain effects.

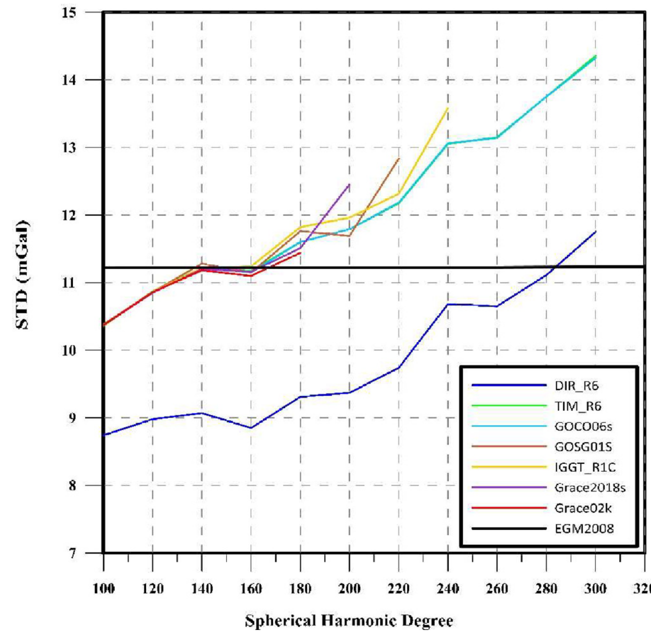


Fig. 11. A representation of the STD of the differences between the satellite-only models and the shipborne gravity data after using the SEM. Unit = mGal.

The RTM effects in this study were calculated using the GRAVSOFT TC, with an integration radius of 100 km. The evaluation of satellite-only models from marine gravity data is done by using Eq.8.

Table 5 and Fig. 11 report the statistics of the differences of the studied satellite-only models and the shipborne gravity data after using the SEM from d/o 100 to the maximum d/o of the evaluated models with a gradual step of 20 d/o.

As depicted in Table 5 and Fig. 11, the DIR_R6 offers the best performance at d/o 100 with a mean of −1.19 mGal, an STD of 8.74 mGal. The TIM_R6 showed the worst behaviour with a mean of −5.08 and an STD of 14.35 mGal.

The histograms of the differences were presented to illustrate the discrepancies between the evaluated GGMs and shipborne data at the maximum d/o of each model after applying the SEM as shown in Fig. 12.

5. Conclusion

The primary goal of this research is to assess various recently released (from 2018 up to the present) satellite-only and combined GGMs in the Red sea. Firstly, the gravitational spectral analysis of the models was performed. The SGG-UGM 2 combined model showed a superior behaviour for all the investigated combined models. furthermore, the DIR R6 satellite-only models outperformed all other satellite-only models. In conclusion, due to the superior behaviour obtained, in all senses, the DIR_R6 satellite-only model, which had a good performance when validated with shipborne data. The DIR_R6 model up to d/o 100 with EGM2008 from 101 to 2190 is recommended to use in the computation of the marine geoid in the Red Sea.

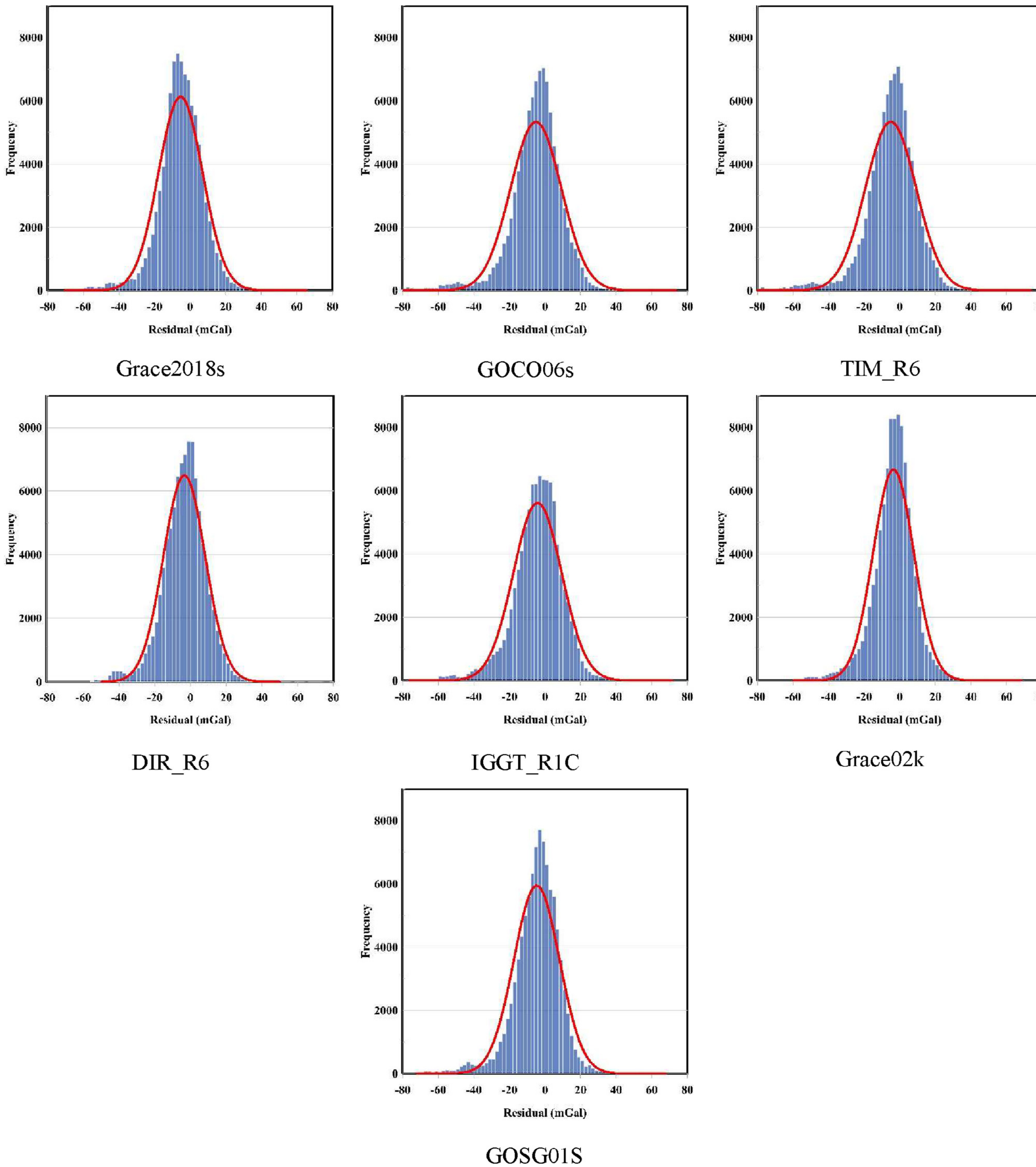


Fig. 12. The histogram of the differences between satellite-only models and the shipborne data after using the SEM at the maximum degree of each model. Unit = mGal.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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