Vietnam Journal of Marine Science and Technology 2023, 23(3) 265–277

Vietnam Academy of Science and Technology

Vietnam Journal of Marine Science and Technology

journal homepage: vjs.ac.vn/index.php/jmst

Evaluation of the precision of some new global Earth Gravitational Models in the East Vietnam Sea

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Received: 23 Febuary 2023; Accepted: 15 May 2023

ABSTRACT

This study is to evaluate the precision of some new global Earth Gravitational Models in the East Vietnam Sea, selecting the best model. The method and the program for calculating Free air gravity anomaly from the global earth gravitational model have been researched and developed. Evaluation of the precision of the models is done by comparing the models with ship-derived gravity anomalies. Data with anomalous signs are detected and removed when the deviation exceeds three times the root mean square deviation. The six global earth gravitational models were evaluated in the experimental section: EGM2008, EIGEN6-C4, GECO, SGG-UGM-1, XGM2019E, and SGG-UGM-2. The evaluation results show that: in the East Vietnam Sea, when compared with 35855 points of shipborne data, the above models respectively have standard deviations of: ±6.046 mGal, ±7.559 mGal, ±5.781 mGal, ±5.832 mGal, ±5.448 mGal, and ±5.236 mGal; all models have mean deviations from shipborne gravity anomalies of about +5 mGal; The correlation between the models and the shipborne data is quite good; The model SGG-UGM-2 has the highest precision. The Free air gravity anomalies from this model have also been calculated over the territorial waters of Vietnam in the form of a grid with a mesh size of 1' × 1'.

Keyword: Earth Gravitational Model, gravity anomaly, East Vietnam Sea.

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https://doi.org/10.15625/1859-3097/18635

ISSN 1859-3097; e-ISSN 2815-5904/

INTRODUCTION

Gravity has a vital role in life and in science. Gravitational potential is the potential of gravity. A formula for calculating gravitational potential has been built from the theory of the universal law of gravitation and centrifugal force [1]. However, since the density of matter in the ground has yet to be discovered, this formula makes only theoretical sense. To overcome this, scientists have developed the formula for calculating gravitational potential into the series of harmonic demand functions and based on the measurement results, determining the coefficients of this function to a specific order and rank and building Earth Gravitational Models (EGMs). Since 1966, world surveyors have identified the first EGM models [2].

In 2003, from the need to access information about the global gravity pattern with the support of the GFZ German Research Centre for Geosciences (GFZ), the International Center for Global Earth Models (ICGEM) was established. ICGEM was initially established to collect static global gravity field models and provide users with easy access to these models. ICGEM has become a single center with the largest and most complete static and dynamic gravity field model collection [2]. To date, this Center has stored and provided 178 EGM models of different degrees, classes, and accuracy, in the form of spherical harmonic coefficients. From these coefficients, it is possible to calculate the factors of gravity potential such as gravity anomaly, height anomaly, plumb line deviation, and noise potential.

Vietnam is a country with an immense sea area. Exploiting the East Vietnam Sea for marine economic development, ensuring national security, preserving sovereignty over seas and islands is a significant policy of the Party and the State of Vietnam [3]. The primary investigation is essential first. Potential factors such as gravity anomalies are important baseline survey data at sea. Gravity anomaly data can be obtained using shipborne gravity or airborne gravity methods. However, these methods are very time-consuming, costly and cannot be performed in sensitive, inaccessible sea areas. Many places have yet to be surveyed regularly or briefly in the East Vietnam Sea [3]. Another method is the determination of the gravity anomaly from satellite altimeter data. Typical global gravity anomaly models are identified from satellite altimeter such as DTU10GRAV, DTU13GRAV, DTU15GRAV, and David Sandwell’s 2016 model. Compared with shipborne gravity data, the accuracy of these models in the East Vietnam Sea is 5.80 mGal, 5.73 mGal, 5.63 mGal, and 5.87 mGal [5, 6], respectively. In work [7], the authors have identified the gravity anomaly from the Cryosat-2 and Saral/AltiKa satellite altimeters with an accuracy of 2.63 mGal. However, the calculation area in this study is limited to the Gulf of Tonkin.

Moreover, the determination of other factors of the gravitational potential (geoid height, plumb line deviation, noise potential) from gravity anomaly data is a rather complicated matter. In that context, we can exploit the global Earth Gravity potential Models (EGM) for use in areas that have yet to be shipborne data or determine of the factors of the gravitational potential from parameters of the EGM. Before exploiting and using, it is necessary to evaluate the accuracy of the global Earth Gravitational Models in the East Vietnam Sea and choose the most suitable model. This study focuses on calculating gravity anomalies from the global Earth Gravitational Models, evaluating the accuracy of some new models over the East Vietnam Sea, and then, selecting the most suitable Earth Gravitational Models in the East Vietnam Sea.

RESEARCH AREA AND DATA

Research area

The research area is located in the East Vietnam Sea with limits from 6^o to 24^o North latitude and 102^o to 118^o East longitude (Fig. 1).

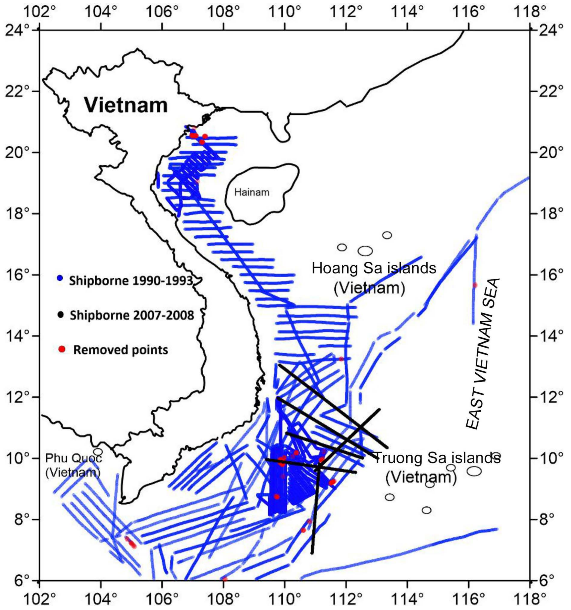


Figure 1. Study area and distribution diagram of direct gravity measurement points

Research data

The global Earth Gravitational Models

The global gravity potential models developed by different organizations from 1966 to the present are 178. These data are provided under ICGEM [2].

These models were evaluated for accuracy by comparing with GNSS-Levelling at 24014 points and calculating the standard deviations, in which Australia includes 7,224 points, Brazil 1,154 points, Canada 2,702 points, Europe 1,047 points, Japan 816 points, Mexico 4,898 points and USA 6,169 points. Fig. 2 depicts the accuracy of the models [8].

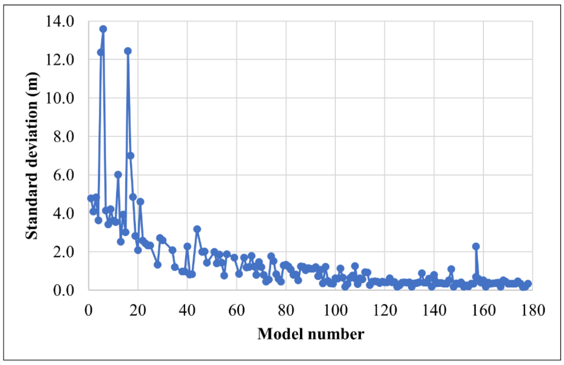


Figure 2. The standard deviation of the global gravity potential models when compared with GNSS-levelling data

From these comparison results, six new models have been selected that best fit the GNSS-levelling data: EGM2008, EIGEN-6C4, GECO, SGG-UGM-1, XGM2019e, and SGG-UGM-2 (Table 1) for assessment on the East Vietnam Sea.

EGM2008 is a global gravity potential model built in 2008 by combining the ITG-GRACE03S gravity potential model and the global free air gravity anomaly data in a 5' × 5' grid. This grid is built from the satellite altimeter and the airborne gravity data. The EGM2008 model is built up to degree and order 2190. Over areas covered with high-quality gravity data, the discrepancies between EGM2008 geoid undulations and independent GPS-Levelling values are 5 cm to 10 cm [9].

Table 1. The selected global gravity models for assessment in the East Vietnam Sea

No.	Model	N_{max}	Standard Deviation (m)							
			Australia (7,224 points)	Brazil (1,154 points)	Canada (2,706 points)	Europe (1,047 points)	Japan (816 points)	Mexico (4,898 points)	USA (6,169 points)	Total (24,014 points)
1	EGM2008	2190	0.095	0.302	0.140	0.125	0.083	0.212	0.248	0.188
2	EIGEN-6C4	2190	0.091	0.234	0.137	0.121	0.079	0.197	0.247	0.178
3	GECO	2190	0.095	0.233	0.142	0.123	0.080	0.186	0.246	0.176
4	SGG-UGM-1	2159	0.092	0.241	0.141	0.121	0.076	0.189	0.245	0.176
5	XGM2019E	2190	0.097	0.208	0.139	0.127	0.090	0.173	0.248	0.173
6	SGG-UGM-2	2190	0.091	0.234	0.139	0.121	0.074	0.190	0.249	0.178

EIGEN-6C4 is a global gravity potential model built and published in 2014 by combining the EGM2008 model with many different types of satellite data, such as the LAGEOS satellite data, the GRACE satellite gravity data, and the GOCE satellite gravity gradient data. The EIGEN-6C4 model was built up to degree and order 2190. This model achieves an accuracy of 4.8 cm compared with the GPS-Levelling data on 675 points in Germany [10].

GECO is a global gravity potential model built and published in 2015 by combining the EGM2008 model with the GOCE satellite gravity gradient data according to the method that uses the error covariance matrix in the calculation. This model was built up to degree and order 2190. Compared to the previous model, like EIGEN-6C4, the GECO model has better quality, especially in Antarctica [11].

SGG-UGM-1 was built and published in 2018 by combining the gravity anomaly calculated from the EGM2008 model with the GOCE gravity gradient data, using the diagonal block least squares method and the OpenMP technique. This model was built up to degree and order 2159. Compared with the GNSS-Levelling data in China and the US, the accuracy level of SGG-UGM-1 derived geoid is between EIGEN-6C2 and EIGEN-6C4, and better than GOSG-EGM and EGM2008 models [12].

XGM2019e is a global gravity potential model built and published in 2019 by combining many data sources, such as the GOCO06s satellite model, the gravity data on land and at sea, and the satellite altimetry-derived gravity data. This model was built up to degree and order 2190. Compared with the GNSS-Levelling data, the accuracy of the XGM2019e model is better than the EGM2008 and EIGEN-6C4 models by a few millimeters [13].

SGG-UGM-2 was built and published in 2020 by combining many types of satellite and ground data, such as the data from the EGM2008 model, the gravity data on land and sea, the gravity data from the GRACE satellite, the GOCE satellite gravity gradient data, and the satellite altimeter data. This model was built up to degree and order 2190. Compared to the GNSS-Levelling data in China and the US, the accuracy of the SGG-UGM-2 is better than the previous models [14].

Shipborne gravity data

In this study, the shipborne data, carried out by a marine geophysical survey ship named Gagarinsky (Russian Federation) in 1990 and 1992, were used. The density of this data on the route is quite large, reaching the ratio from 1:100,000 to 1: 200,000. The measurement networks in the study area are carried out in the direction of latitude, Northeast - Southwest. The coordinates of the measuring points are located according to the global positioning system (GPS) in the WGS84 coordinate system. The shipborne data includes coordinates (longitude-latitude), depth, Free air and Bouger gravity anomalies, measurement time, and distance of measurement points on the route. Detailed information about this data is presented in documents [15, 16].

The shipborne data in the project on marine research cooperation between Vietnam and the French Republic was carried out by the marine survey ship Atalante in 1993, also used. The survey scope is concentrated in the Southeast Sea of Vietnam. The surveyor has carried out thousands of kilometers of geophysical measurements, depth measurements, and geological sampling. The coordinates of the measuring points are located according to the global positioning system (GPS) in the WGS84 coordinate system. All shipborne data is stored in digital form (latitude, longitude, depth, Free air, Bouguer gravity anomaly, magnetic anomaly, time of measurement point, and distance of measurement points on the route) at the Hanoi Institute of Oceanography. More details about this data can be found in the document [15].

Professor Polshkov measured the Gravity Anomaly Dataset (CSL07) in 2007 and 2008. ARK Geophysics Ltd. processed these data in Ho Chi Minh City. Coordinates of points in the

WGS-84 coordinate system. These data include depth, Free air, Bouguer gravity anomalies, and magnetic fields. More details about this data can be found in [17].

Summarizing these data, we selected 35855 points, measured in 1990 - 1993, and 86162 points, measured in 2007–2008, for research purposes. The diagram of the distribution of shipborne data points is presented in Fig. 1.

RESEARCH METHODS

Earth's gravity potential

The gravity potential of a point with coordinates (*x*, *y*, *z*), which denoted *W*(*x*, *y*, *z*), is the sum of the gravitational potential and the centrifugal potential, illustrated by the formula [1]:

$$W(x,y,z)=V(x,y,z)+Q(x,y,z)=G\iiint_V \frac{\delta(a,b,c)}{r}dV+\frac{\omega^2}{2}\left(x^2+y^2\right) \quad (1)$$

where: G is the gravitational constant; $\delta(a, b, c)$ is the material density at the point with coordinates (*a*, *b*, *c*); ω is an angular velocity of the Earth.

Because the material density cannot bedetermined, formula (1) has only theoretical meaning, it cannot be calculated in practice. To overcome this, gravity potential has been expanded into a series of spherical harmonic functions [1]:

$$W(r,\theta,\lambda)=\sum_{n=0}^{\infty}\frac{1}{r^{n+1}}\left[\sum_{m=0}^{n}\left(C_{n,m}\cos m\lambda+S_{n,m}\sin m\lambda\right)P_{n,m}(\theta)\right]+\frac{\omega^2}{2}\left(x^2+y^2\right) \quad (2)$$

where: m, n are degree and order, respectively; $C_{n,m}$, $S_{n,m}$ are conventional gravitational coefficients; $P_{n,m}(\theta)$ is a Legendre polynomial of order *n*, degree *m*.

Based on this formula, scientists determine the coefficients *C*, *S* up to a certain order and degree *n*, *m*. The higher the order and degree, the closer the model is to the real gravity potential. For example, the model EGM96 has order and degree, up to 360; EGM2008 model has order and degree, up to 2190.

Calculate gravity anomaly from the Global Earth Gravitational Model

The gravity anomaly function is defined as [18–20]:

$$\Delta g_{EGM}=\frac{GM}{r^2}\left[\sum_{n=2}^{N_{\max}}\left(\frac{a}{r}\right)^2(n-1)\sum\left(\bar{C}_{n,m}\cos(m\lambda)+\bar{S}_{n,m}\sin(m\lambda)\right)\bar{P}_{n,m}(\sin\varphi')\right] \quad (3)$$

where: GM- Earth's gravitational constant; *r*- distance from the Earth's center of mass; γ- normal gravity above ellipsoid; *a*- semi-major axis of the ellipsoid; φ', λ- geocentric latitude and geocentric longitude; $\bar{C}_{n,m}, \bar{S}_{n,m}$ - normalized gravitation coefficients; $\bar{P}_{n,m}(\sin\varphi')$ - normalized associated Legendre Function; $N_{\max}$- maximum of order and degree.

Distance from the Earth's center of mass at the point (*x*, *y*, *z*) function is defined as:

$$r(\varphi)=\sqrt{x^2+y^2+z^2} =a\sqrt{1-\frac{e^2\left(1-e^2\right)\sin^2\varphi}{1-e^2\sin^2\varphi}} \quad (4)$$

$$x=\frac{a\cos\varphi\cos\lambda}{\sqrt{1-e^2\sin^2\varphi}};\ y=\frac{a\cos\varphi\sin\lambda}{\sqrt{1-e^2\sin^2\varphi}};\ z=\frac{a\left(1-e^2\right)\sin\varphi}{\sqrt{1-e^2\sin^2\varphi}} \quad (5)$$

The Geocentric latitude function is defined as:

$$\varphi' = \arctan\frac{z}{\sqrt{x^2+y^2}} = \arctan\left[\left(\frac{b}{a}\right)^2 \tan\varphi\right] \quad (6)$$

where: b- semi-minor axis of the ellipsoid; φ, λ- latitude and longitude at the point (x, y); $e^2 = \frac{a^2-b^2}{a^2}$ eccentricity first.

The normal gravity above ellipsoid function is defined as:

$$\gamma(\varphi) = \gamma_e \frac{1+k\sin^2\varphi}{\sqrt{1-e^2\sin^2\varphi}} \quad (7)$$

where: $k = \frac{b\gamma_p - a\gamma_e}{a\gamma_e}$; γ_e- normal Gravity at the Equator (on the Ellipsoid); γ_p- normal Gravity at the Pole (on the Ellipsoid).

Legendre Function is defined as:

Set $t = \sin\varphi'$; $u = \cos\varphi'$:

If $n > m$:

$$\bar{P}_{n,m}(t) = a_{n,m} t \bar{P}_{n-1,m}(t) - b_{n,m}\bar{P}_{n-2,m}(t) \quad (8)$$

$$a_{n,m} = \sqrt{\frac{(2n-1)(2n+1)}{(n-m)(n+m)}}; \quad b_{n,m} = \sqrt{\frac{(2n+1)(n+m-1)(n-m-1)}{(n-m)(n+m)(2n-3)}} \quad (9)$$

If $n = m$:

When $m < 1$:

$$\bar{P}_{0,0}(t) = 1 \text{ or } \bar{P}_{1,1}(t) = \sqrt{3}u \quad (10)$$

When $m > 1$:

$$\bar{P}_{m,m}(t) = u\sqrt{\frac{2m+1}{2m}} P_{m-1,m-1}(t) \text{ or } P_{m,m}(t) = u^m\sqrt{3}\prod_{i=2}^{m}\sqrt{\frac{2i+1}{2i}} \quad (11)$$

cos($m\lambda$) and sin($m\lambda$) can calculation by:

$$\sin(m\lambda) = 2\cos\lambda\sin((m-1)\lambda) - \sin((m-2)\lambda) \quad (12)$$

$$\cos(m\lambda) = 2\cos\lambda\cos((m-1)\lambda) - \cos((m-2)\lambda) \quad (13)$$

If $m = 0$:

$$\sin(m\lambda) = 0; \cos(m\lambda) = 1$$

If $m = 1$:

$$\sin(m\lambda) = \sin(\lambda); \cos(m\lambda) = \cos(\lambda)$$

Building a program to calculate gravity anomalies from the global gravity potential model

From the theoretical basis and the above formulas, we build a program to calculate the gravity anomaly from the harmonic coefficients of the global gravity potential model. The interface of the program is shown in Figure 3.

Method to evaluate the precision of the global Earth Gravitational Model

To evaluate the precision of the global Earth Gravitational Model in the East Vietnam Sea, we compared the *EGM*-derived gravity anomaly (Δg^{EGM}) with the shipborne-derived gravity anomaly (Δg^{ship}) at the direct measurement points. The deviation of the gravity anomaly is calculated by the formula:

$$\delta g_i = \Delta_i^{EGM} - \Delta g_i^{ship}, \; i = 1, 2, \ldots n; \; n \text{ is the number of measurement points} \quad (14)$$

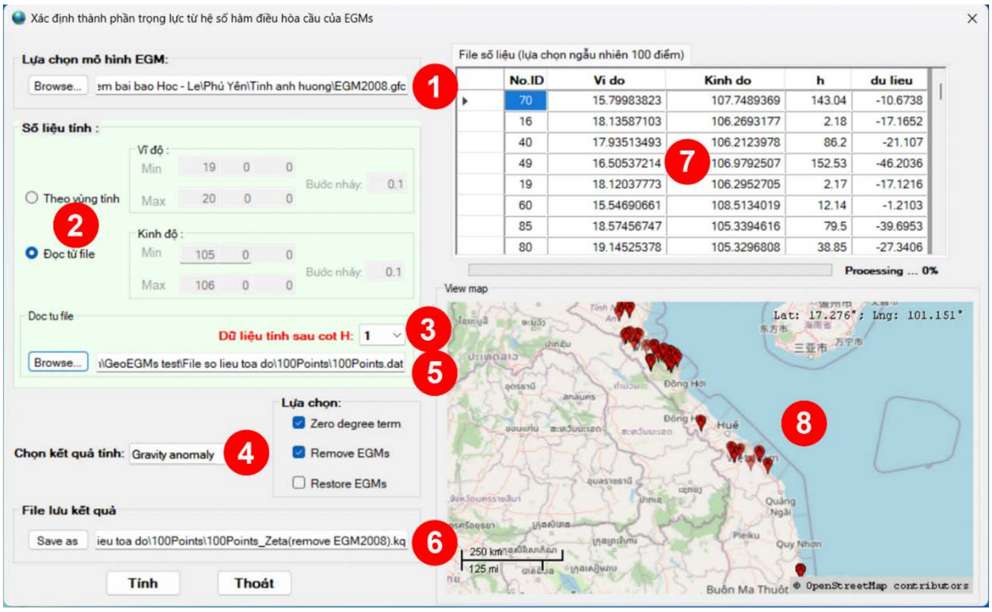


Figure 3. Interface of the program for calculating gravity anomalies from the global gravity potential model. (1): File of harmonic coefficients of global gravity potential model; (2): Choose to calculate by area or calculate for points; (3): Select the data column, for example, gravity usually after the height column; (4): Select calculation results; (5): File of points to be calculated; (6): File containing calculation results; (7): Display calculation results; (8): Display the location of the calculated points on the map

The average deviation is calculated:

$$\delta g_{av} = \frac{1}{n}\sum_{i=1}^{n} \delta g_i \qquad (15)$$

If the mean deviation is approximately zero, then the deviations between the shipborne-derived gravity anomaly and the *EGM*-derived gravity anomaly is not systematic, but random. Then, the Root Mean Square deviation is calculated by the formula:

$$RMS_{\Delta g} = \sqrt{\frac{\sum_{i=1}^{n} (\delta g_i)^2}{n}} \qquad (16)$$

If the mean deviation is not zero, then the deviation between the shipborne-derived gravity anomaly and the *EGM*-derived gravity anomaly is systematic. Then, the standard deviation is calculated using the formula [21]:

$$STD_{\Delta g} = \sqrt{\frac{\sum_{i=1}^{n} (\delta g_i - \delta g_{TB})^2}{n-1}} \qquad (17)$$

The *EGM*-derived gravity anomaly can also be evaluated by the correlation coefficient *R* with the shipborne-derived gravity anomaly. The correlation coefficient *R* measures the correlation between two sets of data. *R* can vary from -1 to +1. If *R* = 1, the two datasets are perfectly linearly correlated. If *R* = -1, the two datasets are negatively correlated. If *R* = 0, the two datasets are not linearly correlated. Thus, if the *EGM* model fits the shipborne-derived gravity anomaly, the their correlation coefficient will equal approximately 1. The correlation coefficient *R* is calculated by the formula [22]:

$$R = \frac{\sum_{i=1}^{n} \left(\Delta g_i^{ship} - \Delta g_{TB}^{ship}\right)\left(\Delta g_i^{EGM} - \Delta g_{TB}^{EGM}\right)}{\sqrt{\sum_{i=1}^{m} \left(\Delta g_i^{ship} - \Delta g_{TB}^{ship}\right)^2 \sum_{i=1}^{m} \left(\Delta g_i^{EGM} - \Delta g_{TB}^{EGM}\right)^2}} \qquad (18)$$

RESEARCH RESULTS

Accuracy assessment results

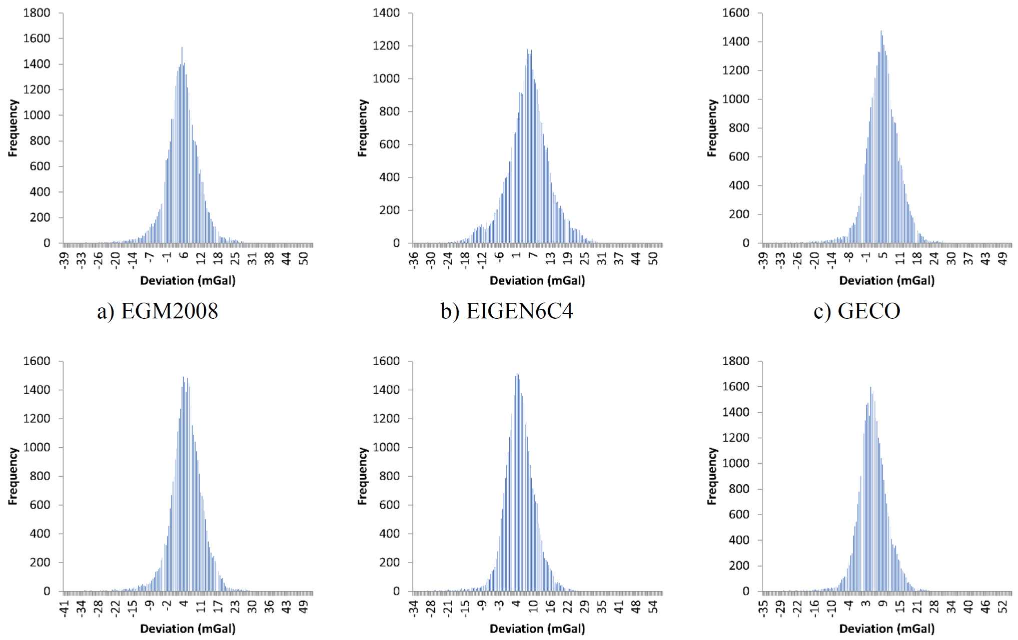
With the above theoretical basis, we evaluated 6 EGM models: EGM2008, EIGEN6-C4, GECO, SGG-UGM-1, XGM2019E, and SGG-UGM-2. The evaluation results are summarized in Table 2.

The results in Table 2 show that The six models have an average deviation from the shipborne-derived gravity anomaly of about +5 mGal. The most accurate is the model SGG-UGM-2. The standard deviations of the models varied from ±5.92 mGal to ±8.02 mGal. The absolute values of the maximum and minimum deviations are quite large, greater than three times the *RMS*, indicating that there are outliers in the data. These values need to be removed from the dataset.

The frequency chart of deviations is shown in Figure 4. This figure shows that deviations with large values occur less frequently. Deviations with small values occur more frequently, it shows that the histogram of the deviation follows the normal distribution, but the peak deviates from the vertical axis to the right, corresponding to the mean deviation. The number of deviations, which exceeds three times *RMS*, is small. The model SGG-UGM-2, with the best deviation distribution, has the best accuracy.

Table 2. The results of accuracy assessment of 6 EGM models in the East Vietnam Sea

No.	Assessment points	Model	Year	N_{max}	δg_{max} (mGal)	δg_{min} (mGal)	δg_{TB} (mGal)	*RMS* (mGal)	*STD* (mGal)	*R*
1	35855	EGM2008	2008	2190	53.74	-39.04	4.98	8.42	6.78	0.937
2	35855	EIGEN6-C4	2014	2190	53.08	-36.22	4.75	9.33	8.02	0.916
3	35855	GECO	2015	2190	52.79	-39.15	4.46	8.13	6.81	0.940
4	35855	SGG-UGM-1	2018	2159	52.41	-40.73	4.97	8.25	6.59	0.939
5	35855	XGM2019E	2019	2190	57.17	-33.86	4.87	7.84	6.14	0.945
6	35855	SGG-UGM-2	2020	2190	55.78	-34.75	5.02	7.76	5.92	0.946



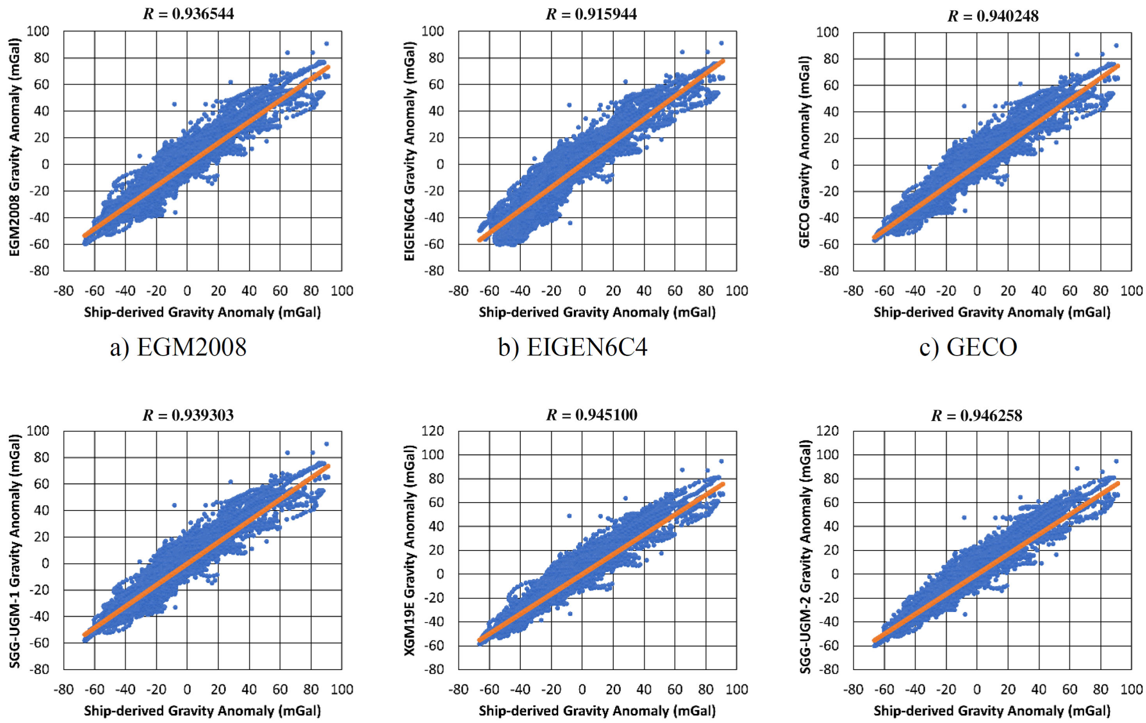
a) EGM2008 b) EIGEN6C4 c) GECO

d) SGG-UGM-1 e) XGM2019E f) SGG-UGM-2

Figure 4. Frequency chart of deviations between the global gravity potential models compared with the shipborne data in the East Vietnam Sea

The correlation of the *EGM*-derived gravity anomaly with the shipborne-derived gravity anomaly is presented in Fig. 5. From this figure, the correlation between these two quantities is quite good; the correlation coefficient is close to 1; SGG-UGM-2 model has the best correlation, consistent with the results in Table 2. However, some points that are scattered away from the main axis, showing poor correlation. These are also the points with large deviations.

According to statistical probability theory, we calculated the number and % of deviations in terms of 1, 2, and 3 times the RMS to get more information about the points with large deviation absolute values. The statistical results are presented in Table 3.



a) EGM2008 b) EIGEN6C4 c) GECO

d) SGG-UGM-1 e) XGM2019E f) SGG-UGM-2

Figure 5. Correlation of the EGM-derived gravity anomaly with the shipborne-derived gravity anomaly

Table 3. The statistical results by quantity statistics and % of the deviations

Model	$-RMS < \delta g < RMS$		$-2RMS < \delta g < 2RMS$		$-3RMS < \delta g < 3RMS$		$\delta g < -3RMS$ and $\delta g > 3RMS$	
	Points	%	Points	%	Points	%	Points	%
EGM2008	25667	71.59%	34584	96.46%	35664	99.47%	191	0.53%
EIGEN6-C4	25446	70.97%	34279	95.60%	35768	99.76%	87	0.24%
GECO	25496	71.11%	34641	96.61%	35674	99.50%	181	0.50%
SGG-UGM-1	25454	70.99%	34659	96.66%	35672	99.49%	183	0.51%
XGM2019E	25631	71.49%	34505	96.23%	35699	99.56%	156	0.44%
SGG-UGM-2	25514	71.16%	34632	96.59%	35715	99.61%	140	0.39%

From the results of Table 3, it can be seen that: Most of the deviations follow the normal distribution of statistical probability for random deviations. The number of deviations exceeds three times the *RMS* is small, accounting for less than 0.53%. These points have unusual signs and do not obey the random law. They are distributed in several places in the East Vietnam Sea (red points in Fig. 1). We checked these points manually and decided to remove them from the calculation results.

After removing the anomalous points, the comparison and evaluation were re-calculated. These results are presented in Table 4. The results in Table 4 and Table 2 show that after removing the outliers, the maximum and minimum deviations are significantly reduced in absolute value; The mean deviation decreased insignificantly; The standard deviation decreases in range from 0.5 mGal to 1.0 mGal. The SGG-UGM-2 is still the most accurate model; its standard deviation reaches 5.24 mGal.

Table 4. Results of accuracy assessment of 6 EGM models in the East Vietnam Sea after removing anomalous points

No.	Model	$\delta g_{\max}$ (mGal)	$\delta g_{\min}$ (mGal)	δg_{TB} (mGal)	*RMS* (mGal)	*STD* (mGal)	*R*
1	EGM2008	25.14	-25.17	4.97	7.83	6.05	0.952
2	EIGEN6-C4	27.97	-27.95	4.76	8.93	7.56	0.930
3	GECO	24.36	-24.40	4.89	7.57	5.78	0.956
4	SGG-UGM-1	24.75	-24.67	5.01	7.69	5.83	0.955
5	XGM2019E	23.46	-23.49	4.89	7.32	5.45	0.961
6	SGG-UGM-2	23.24	-23.18	5.03	7.26	5.24	0.965

The above 6 models were also compared with 86162 shipborne data points measured in 2007–2008 (CSL07) to increase persuasiveness, see Fig. 1. The comparison results are presented in Table 5. The results in Table 5 show that the accuracy of the 6 models when compared with the CSL07 dataset is better than when compared with the 1990-1993 dataset; the SGG-UGM-2 model is still the best model of the 6 models; the accuracy of the SGG-UGM-2 model is 3.17 mGal; the mean deviation is minimal (-0.74 mGal), the correlation between the SGG-UGM-2 model and the shipborne data is very good (0.976).

Table 5. Results of comparing the six EGM models with the CSL07 dataset

No.	Assessment points	Model	$\delta g_{\max}$ (mGal)	$\delta g_{\min}$ (mGal)	δg_{TB} (mGal)	*RMS* (mGal)	*STD* (mGal)	*R*
1	86162	EGM2008	22.05	-33.11	-0.45	3.70	3.68	0.968
2	86162	EIGEN6-C4	23.69	-27.30	-0.50	4.06	4.03	0.963
3	86162	GECO	21.83	-33.24	-0.61	3.75	3.70	0.975
4	86162	SGG-UGM-1	21.72	-33.83	-0.63	3.70	3.65	0.975
5	86162	XGM2019E	19.45	-27.44	-0.67	3.33	3.26	0.980
6	86162	SGG-UGM-2	21.22	-23.40	-0.74	3.25	3.17	0.976

Thus, from the comparison results, the model SGG-UGM-2 is the most accurate in the East Vietnam Sea and is consistent with the fact that the SGG-UGM-2 model was built last among the six surveyed models and used a combination of available data types. Moreover, compared to other models, the SGG-UGM-2 used shipborne data in the China Sea, which is close to the East Vietnam Sea of Vietnam, so this model is more suitable with shipborne data in the East Vietnam Sea. From this model, it is possible to calculate the factors of the potential gravitational field, such as gravity anomaly, geoid height, disturbing potential, and deflections of the vertical in the East Sea, especially in places where direct measurement has yet to be available.

The research results show that Shipborne data on the East Vietnam Sea has yet to be used in building global earth gravity models. Therefore, it is necessary to study and combine the global earth gravity model with shipborne data in the East Vietnam Sea and in coastal areas to build a more accurate gravity model in the East Vietnam Sea.

Results of gravity anomalies in the East Vietnam Sea from the model SGG-UGM-2

The Free air gravity anomalies from the global gravity potential model SGG-UGM-2 over Vietnam's territorial waters are presented in Figure 6. The largest gravity anomaly value is 233.08 mGal, the smallest one is -152.41 mGal, the average one is -1.69 mGal.

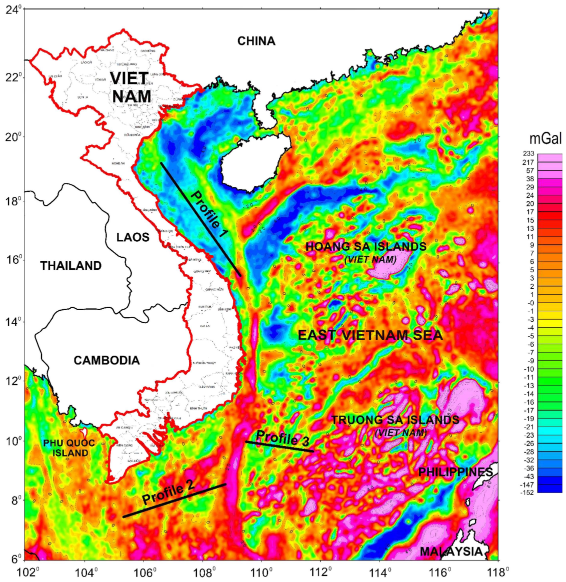


Figure 6. Free air gravity anomaly calculated from the SGG-UGM-2 model over Vietnam's territorial waters

To better understand the deviation between the SGG-UGM-2 model and the shipborne data, three profiles (see Fig. 6) of the deviation are presented in Fig. 7.

Figure 7 shows a large and systematic deviation between the SGG-UGM-2 model and the shipborne data measured in 1990–1993. The deviation appears consistent with the large mean and standard deviation (5.24 mGal and 5.03 mGal) in Table 4; there is a small deviation and no systematic deviation between the SGG-UGM-2 model and the 2007-2008 shipborne data, which agrees with the statistical results in Table 5 (mean deviation is -0.74 mGal and standard deviation is 3.17 mGal).

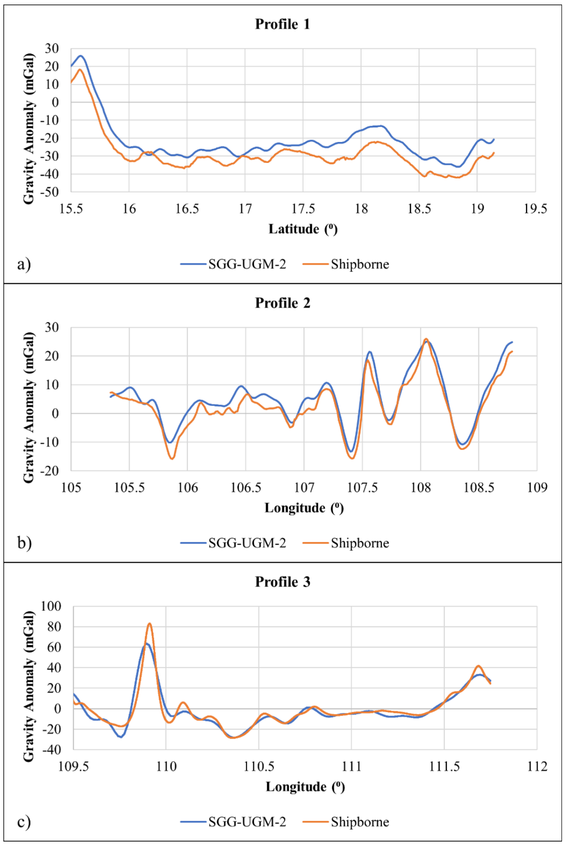


Figure 7. Graph comparing the SGG-UGM-2 model with the shipborne data along profiles in Figure 6: a) and b) data measured in 1990–1993; c) data measured in 2007–2008

CONCLUSION

The accuracy of global earth gravity models was assessed by comparing these models with shipborne data in the East Vietnam Sea. If there is a systematic deviation, the accuracy is evaluated by the standard deviation. If there is no systematic deviation, the root means square deviation evaluates the accuracy.

In the Vietnam East Sea, the accuracy of global earth gravity potential models: EGM2008, EIGEN6-C4, GECO, SGG-UGM-1, XGM2019E, and SGG-UGM-2 when were compared with shipborne data (assessed by standard deviation), were ±6.05 mGal,

±7.56 mGal, ±5.78 mGal, ±5.83 mGal, ±5.45 mGal, and ±5.24 mGal, respectively, in which, the SGG-UGM-2 model has the highest accuracy. From this model, it is possible to calculate the factors of the global earth gravity, such as gravity anomaly, geoid height, disturbing potential, and deflections of the vertical in the East Vietnam Sea, especially in places that have not been shipborne data yet.

The above models have systematic deviations from the shipborne gravity data, expressed as an average deviation of about +5 mGal. Therefore, further research is needed to correct this systematic deviation.

Shipborne data in the East Vietnam Sea have yet to be used to build global earth gravity models. Therefore, studying and combining the global earth gravity model with shipborne data is necessary to build a more accurate gravity model in the East Vietnam Sea and the coastal areas.

Acknowledgments: The authors wish to thank the Scientific Contract 07/2021/D6-DATS (belong to the Project of General investigation of meteorology, oceanographic, geological, environmental factors in the Spratly area at scale 1:200.000) and the Vietnam National Project DTDLCN.07/23 for funding this research.

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