Journal of Sustainability Science and Management
Volume 18 Number 12, December 2023: 111-122
eISSN: 2672-7226

IMPROVING THE ACCURACY OF MARINE GRAVITY ANOMALY DATA FROM COMBINATION OF SHIPBORNE GRAVITY AND GLOBAL MARINE GRAVITY DERIVED FROM SATELLITE ALTIMETRY

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Submitted final draft: 6 August 2023 *Accepted: 23 September 2023* http://doi.org/10.46754/jssm.2023.12.010

Abstract: Currently, utilising satellite altimetry data to derive marine gravity anomalies is the preferred method due to its low cost and ability to cover large areas efficiently. However, accurately obtaining altimeter-derived gravity anomalies in coastal regions remains challenging. This paper aims to improve the accuracy of global marine gravity data in Peninsular Malaysia's marine areas by incorporating both altimetry-derived and ship-track gravity data. After filtering 39,756 marine ship-borne gravity observations with a 95% confidence level and using cross-validation to identify errors, 24,142 gravity points were eliminated, resulting in a decrease in the standard deviation (STD) from 40.600 mGal to 15.663 mGal. Four (4) existing global marine gravity models were evaluated using the filtered ship-borne datasets, and the DTU model version 17 was deemed the optimal model with an RMSE of 10.762 mGal. The least-squares collocation method was used to integrate the gravity data from the ship-borne datasets with the DTU17 model. Validation of the new marine gravity model, which included 50 ship gravity data points, showed a significant improvement with an RMSE of 2.192 mGal.

Keywords: Marine gravity, DTU17, geoid, Peninsular Malaysia.

Introduction

Gravity data have become indispensable for a wide range of applications, particularly in the fields of geodesy and geophysics. In the context of oil and gas exploration in marine regions, marine gravity data plays a crucial role in probing deep crustal structures. They are also valuable for qualitatively interpreting the regional geology and structural characteristics within offshore sedimentary basins (Madon, 2017). In geodetic applications, free air anomalies, hold significant importance for the computation of geoid models, a process central to understanding the Earth's gravitational field. This computation is achieved using Stokes' formula, as outlined by Heiskanen and Moritz (1967):

$$N = \frac{R}{4\pi\gamma} \iint_{\sigma} \Delta g S(\psi) d\sigma$$

where *R* mean Earth's sphere of radius, ψ is the geocentric angle and is an infinitesimal surface element of the unit sphere.

Currently, the computation of geoid models can be approached using various methods, among which the well-established Remove-Compute-Restore (RCR) method (Forsberg, 1984; Schwarz *et al.,* 1990), Stokes-Helmert method (Vaníček & Martinec, 1994), and Least Square Modification of Stokes (LSMSA) with additive correction (Sjöberg, 2003; Sjöberg *et al.,* 2015) are notable examples. When computing a geoid model, the accuracy and quality of gravity data play a vital role in generating precise and high-resolution results.

The computation process necessitates gravity data from diverse sources, encompassing but not limited to Global Geopotential Models

(GGMs), marine gravity, and land gravity. In the case of geoid modelling, data from various origins are integrated into a grid-based framework. In this context, marine gravity data holds particular significance for geoid computation over Peninsular Malaysia, which is encircled by the ocean (Figure 1). This data type furnishes crucial insights into the Earth's gravitational field within aquatic regions, thereby contributing to the accurate determination of geoid models for the area.

Typically, marine gravity data is acquired through direct ship-borne and airborne surveys or derived from satellite altimetric datasets. Over the past 80 years, multiple agencies have conducted measurements of marine gravity data in the South China Sea and the Strait of Malacca for various research purposes. However, gravity anomalies derived from ship observations are often subject to instrumental errors, navigational discrepancies, and variations in reference systems (Denker & Roland, 2005), leading to considerable inconsistencies in the marine gravity data. Moreover, the interpolation of marine ship-track gravity data within sparsely covered regions presents challenges, primarily stemming from the inconsistent horizontal reference datum used for gravity data across individual survey cruises. As a result, meticulous verification of all marine ship-track gravity data is imperative. This verification process serves two critical objectives: Ensuring data consistency with other datasets and preserving data quality by identifying and eliminating gross errors.

In dealing with the problem of the sparse gravity anomaly data from marine ship-tracks, satellite altimetry measurements are an alternative method in providing gravity anomalies for marine regions and become the mainstream approach for obtaining marine gravity. Moreover, collecting gravity data over an extensive marine area is expensive and inefficient (Fan *et al.,* 2021). A number of new satellite altimetry missions, such as SARAL and Cryosat-2, have been launched to improve global high-resolution gravity measurements for marine regions (Christensen & Andersen, 2015). Nowadays, there are several global grid marine gravity models generated from altimetric

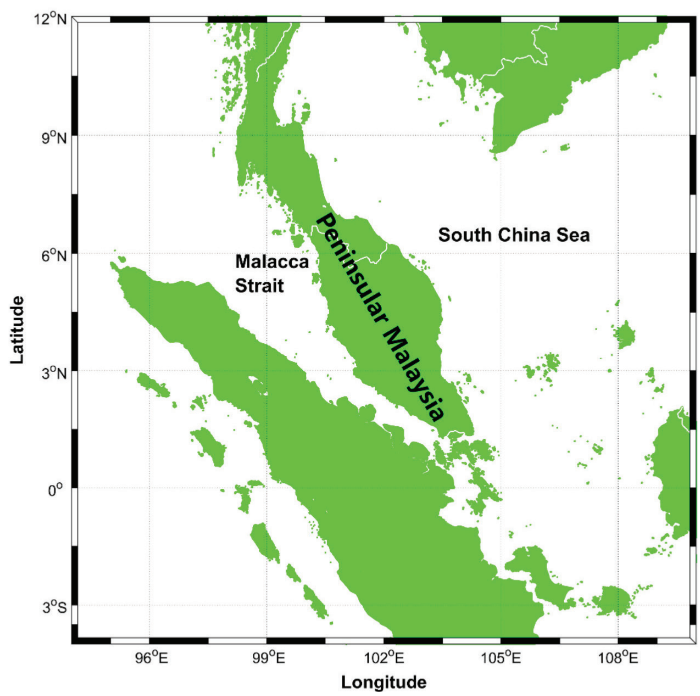

Figure 1: Location of Peninsular Malaysia

datasets, such as KMS02 model (Andersen *et al*., 1999), DTU model (Andersen *et al.,* 2015; Andersen *et al.,* 2017; Anderson & Knudsen, 2019), Sandwell model (Sandwell *et al*., 2014), GMGA02 (Hwang *et al*., 2002), and GSFC00 (Wang *et al.* 2004). Each model is computed based on different mathematical formulations and reference models (EGM96 and EGM2008). Recently, two models have been computed by the Danish Technical University (DTU) and Scripps Institute of Oceanography: the "DTU model" and "Sandwell model", respectively. Figure 2 shows the Sandwell model (a) from Sandwell *et al.* (2014) and the DTU17 model (b) from Anderson and Knudsen (2019).

Unfortunately, the accuracy of gravity anomalies derived from satellite altimetric data in coastal regions is low due to poorly tracked altimetry at coastal areas (Deng *et al.,* 2002), poor shallow-water tidal models, and poor wet delay corrections (Andersen & Knudsen, 2000).

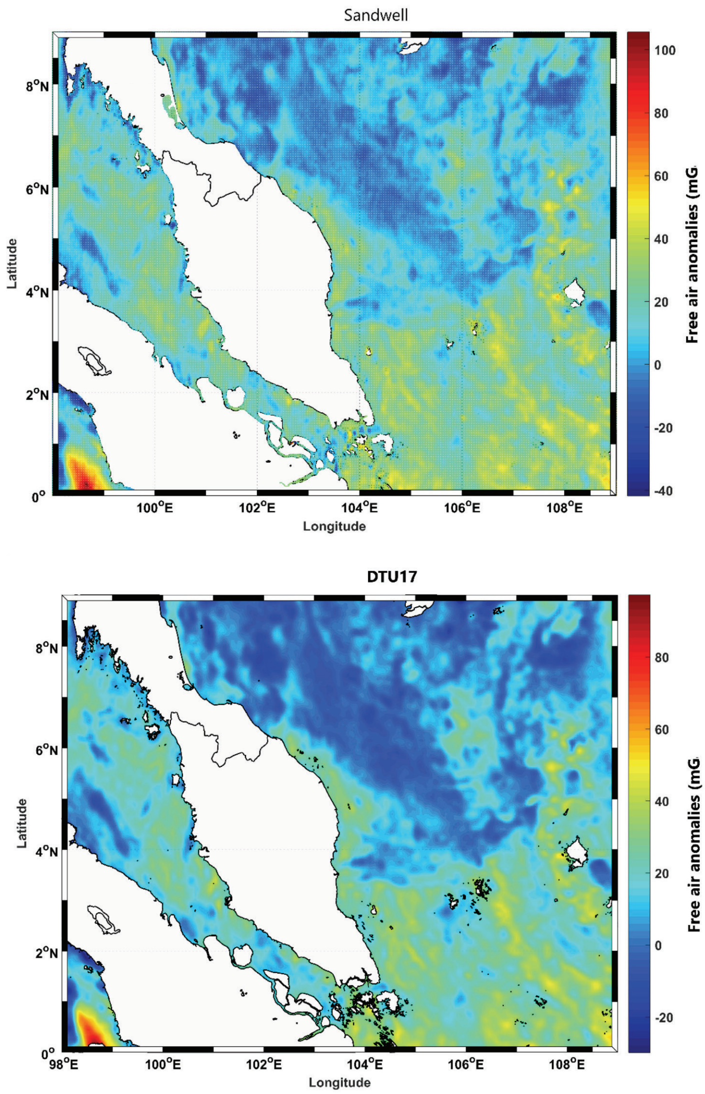

Figure 2: Satellite-altimetry-derived free-air gravity in the Sandwell model (upper) and DTU17 model (lower)

Therefore, satellite altimetric datasets only cover offshore areas and for onshore regions, satellite altimetric data are usually excluded in the geoid model computation (Christensen & Andersen, 2016) or filled in by the gravity data from EGM2008 (Pavlis *et al.,* 2012). Literature records show that there have been a number of studies have conducted comprehensive research to assess the accuracy of gravity anomalies derived from satellite altimetric data with gravity anomalies from ship-borne measurements (e.g., Amos & Featherstone, 2005; Christensen & Andersen, 2016; Zaki *et al.*,2018). Based on a comprehensive comparison by Zaki *et al.* (2018), the accuracy of the DTU model is better than the Sandwell model. This finding is consistent with the earlier study by Christensen and Andersen (2016). However, the accuracy difference between both models is not significant.

In Malaysia, marine gravity from the DTU model is commonly used in geoid computation (Jamil *et al.,* 2017). Although there is a lot of marine gravity data measured by shipborne over Malaysia's offshore region, the data is usually not included in the geoid computation due to the many problematic errors as aforementioned and needs rigorous filtering or analysis before being used in the geoid computation. According to studies by Zaki *et al.* (2018) and Amos and Featherstone (2005), the combination of gravity anomalies from ship-borne and satellite altimetric datasets has been proven to enhance the accuracy of marine gravity anomalies. Therefore, the main objective of this study is to merge marine ship track gravity data with various global gravity models derived from altimetric datasets. First, gravity anomalies from ship-borne data are filtered to detect and eliminate gross errors. Second, marine ship track gravity data without gross errors are used to validate marine gravity data from the Sandwell and DTU models. From the validation process, the best model is fitted to marine ship track gravity data to improve the accuracy of gravity anomalies derived from the altimetric dataset.

Methodology

Filtering the Ship-borne Gravity Data

About 39756 ship-borne gravity points bound between 94°E ≤ λ ≥ 110°E and 4°S ≤ ϕ ≥ 12°N have been downloaded from the International Gravimetric Bureau (http://bgi.obs-mip.fr/data-products/Gravity Databases/Marine-Gravity-data). The distribution of 39756 ship-track gravity data points is shown in Figure 3. The details of the data are listed in Table 1. In the filtering process, two approaches have been implemented to detect the gross errors in 39756 points, as proposed by Zaki *et al*. (2018). First, 39756 ship-track gravity anomalies are filtered using a 95% confidence level or 1.96 sigma rule. Here, any residual greater than 1.96σ is deemed to contain gross errors and eliminated from the database. The mean gravity anomalies is computed and the gravity anomalies error, is determined by subtracting the gravity anomalies, from the mean value.

$$\bar{g}_{ship} = \frac{1}{n}\sum_{i=1}^{n} g_{ship} \tag{1}$$

$$\Delta g_{ship} = g_{ship} - \bar{g}_{ship} \tag{2}$$

Subsequently, the sigma value is computed as follows:

$$\sigma = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(\Delta g_{ship}\right)^2} \tag{3}$$

where *n* is the number of gravity points sampled.

The second step is filtering the ship-borne gravity anomalies using a cross-validation process. This method was first created by Geisser and Eddy (1979) to identify outliers in databases and is more accurate and faster than visual inspection (Kiamehr, 2007). It has been successfully applied by several studies, such as Tscherning (1991), Zaki *et al.* (2018), Featherstone and Sproule (2006), Kiamehr (2007), and Sulaiman *et al.* (2013).

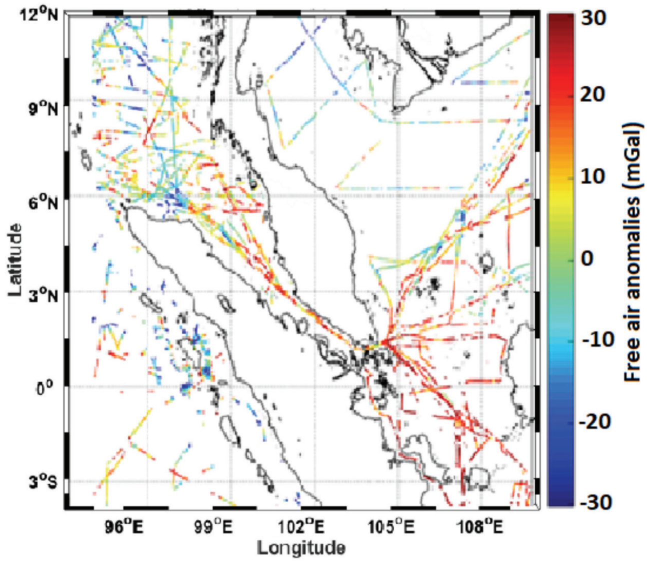

Figure 3: Distribution of gravity anomaly in the study area. Courtesy by Pa'suya (2020)

The procedures of the cross-validation process are as follows:

1. Selection of the most appropriate interpolation method. Various interpolation methods can be used in the cross-validation process, such as Kriging (Krige, 1951), Least Squares Collocation (Moritz, 1972), and Inverse Distance (Babak & Deutsch, 2008). However, the Kriging method has been selected for interpolation because it is the best linear unbiased estimator (Matheron, 1963).
2. Applying the Kriging interpolation method. The interpolation value of gravity anomalies for each validation point is determined using neighbouring data. The observation itself has been excluded.
3. Computation of interpolation errors, $g_{interpolate}$. The results of interpolation errors have been computed by comparing the values of gravity anomalies at the existing validation point, with the values of the interpolated point, $g_{interpolate}$.

$$\Delta g_{interpolate} = g_{interpolate} - g \qquad (4)$$

4. Evaluation of the database quality. Database quality has been evaluated using the standard deviation of residuals between the existing and interpolated values.

Through the analysis of a histogram representing the absolute value differences between existing and interpolated values, a distinct slope change has been identified and utilised as a reference value for outlier detection within the database. This tolerance value has been effectively utilised to differentiate true residual values from outliers. Values that fall below the identified tolerance are considered valid, while those above it are identified as outliers. This process has been conducted repeatedly until the standard deviation of residuals between the existing and interpolated values is less than 1.5 mGal, as suggested by Zaki *et al.* (2018).

Integration of Gravity Anomaly Derived from Altimeter Satellite and Ship-borne

Before the merging process, the filtered gravity anomaly data derived from ship-borne (after the first and second filtering steps) are once again compared with the best-performing satellite altimetric gravity model and analysed using a 99% confidence level. Here, any residual of more than 3σ is deemed to be a gross error and eliminated from the database. The summary of these models is shown in Table 2. Subsequently, satellite altimetric gravity data are fitted to the final ship-borne gravity anomaly data using Least-Squares Collocation (LSC) interpolation. This procedure is performed to improve the accuracy of satellite altimetric gravity data and yield a dataset that is consistent with ship-borne data.

The first step of the fitting procedure is to determine the residual between ship-borne gravity anomaly data, FA_{alt} and altimeter data FA_{alt}:

$$\varepsilon = FA_{alt} - FA_{ship} \quad (5)$$

The altimeter-derived gravity anomaly is bi-cubically interpolated from the best-performing satellite altimetric gravity model. Here, the common fitting model is the 4-parameter Helmert model:

$$\varepsilon' = Cos\,\varphi\, Cos\lambda\, a_1 + Cos\,\varphi\, Sin\lambda\, a_2 + Sin\varphi\, a_3 + Ra_4 \quad (6)$$

where a_1 to a_4 are unknown empirical parameters, R is the residual geoid error as described in Heiskanen and Moritz (1967), φ and λ are the latitude and longitude of each point, respectively. In the LSC, the second-order Markov covariance, $C(s)$ model is used (Forsberg & Tscherning, 2008).

$$C(s) = C_0\,(1+\alpha s)e^{-\alpha s} \quad (7)$$

where s is distance, α is a parameter which determines the correlation length and the C_0 is automatically adapted by the data. Here, the user

Table 1: Details about the ship-track gravity points provided by BGI

Source	Abbreviations	No. of data
Hawaii Institute of Geophysics	HIG	67
Ifz An Sssr	IAS	954
French Research Institute for Exploitation of The Sea	IFREMER	5546
Institute of Geophysics and Planetary Physics	IGP	1374
Inst. Physics Earth Acad	IPEA	140
Lamont Doherty Geological Observatory	LDGO	6314
Navoceano	NAVOCEANO	1326
Netherlands Geodetic Commission	NGC	30
National Oceanic and Atmospheric Administration	NOAA	3726
Noaa/ Us Coast and Geodetic Survey	NOAA/UCGS	2737
Ocean Research Institute, Univ of Tokyo	ORI	2605
Scripps Institution of Oceanography	SIO	8869
Ussr Academy of Sciences, Institute of Earth Physics	USSR/IEP	164
Vniigeophizics An Ussr	VAU	197
Woods Hole Oceanographic Institution	WHOI	4915

Table 2: Summary of satellite altimeter-derived marine gravity anomalies.

Data / Model	Resolution	Reference
DTU 17	1'	Anderson & Knudsen *(2019)*
DTU 15	1'	Andersen *et al. (2016)*
DTU 13	1'	Andersen *et al. (2014)*
Sandwell	1'	Sandwell *et al. (2014)*

must specify the optimum correlation length and the Root Mean Square (RMS) noise for error values (Forsberg and Tscherning, 2008). The optimum correlation length is dependent on the spacing of the data points. On the other hand, the RMS noise for error values is typically a few milligals (mgal), which depends on the assumed gravity anomaly errors. Extensive testing has been conducted to determine the ideal correlation length and RMS noise for error values in the second-order Markov covariance model. The parameters were evaluated within the range of 10-100 km and 1-3 mGal, respectively. Finally, the correction grid, $Corr_{gridded}$ was added to the gridded altimetry data, G_{Alt} to produce new marine gravity anomalies which fit with ship-tracked data, G_{fit}:

$$G_{fit} = Corr_{gridded} + G_{Alt} \tag{8}$$

To evaluate the accuracy of new marine gravity anomalies, 50 ship-borne gravity stations that are not involved in the merging step are randomly selected for the validation process. Here, the gravity anomalies error is calculated by subtracting the reference gravity anomalies from the newly merged gravity anomalies, G_{ship}.

$$\Delta g = G_{fit} - G_{ship} \tag{9}$$

Subsequently, the root means square error (RMSE) is calculated to assess the accuracy of merged gravity anomalies.

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(\Delta g)^2} \tag{10}$$

where n is the number of gravity points.

Results and Discussion

After the first filtering, a total of 16052 data points have been flagged as potential outliers and have been eliminated from the 38965 ship-borne gravity data points. The remaining data after the first filtering have been cross-validated and the process is repeated until the standard deviation of the residuals between the observed and estimated values are less than 1.5 mGal. The results of gravity data analysis after both filtering steps (95% confidence level and cross-validation) are summarised in Table 3. The distribution of the 23,351 shipborne station points suspected as outliers and the 15,614 trusted ship-borne gravity anomaly data points are shown in Figure 4. Almost 61% of the Standard Deviation (STD) is dropping from 40.6 mGal to 15.663 mGal, with minimum, maximum, and mean of -30.268 mGal, 30.271 mGal, and 6.601 mGal, respectively.

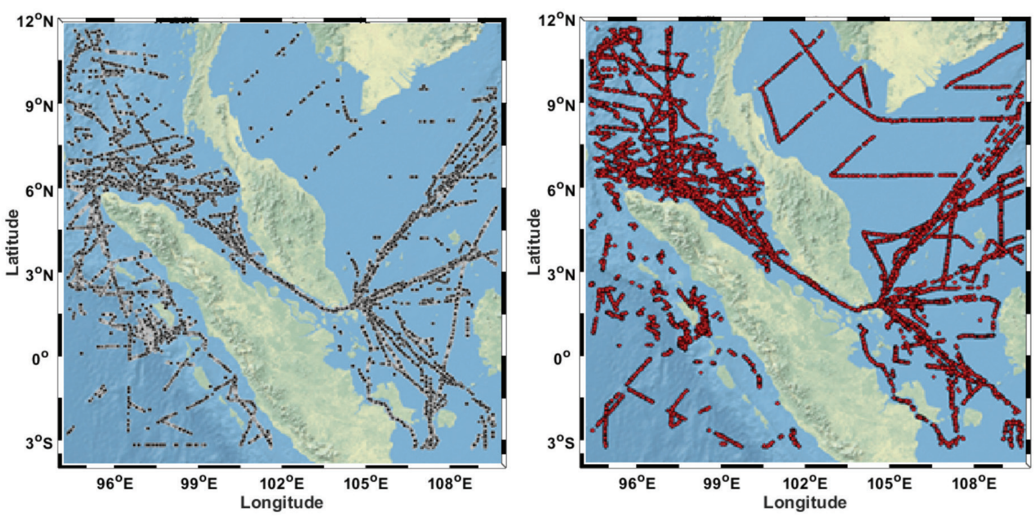

Figure 4: The distribution of the 23351 outliers in shipborne free-air gravity anomalies (left) and 15614 ship-borne stations free from outliers (right)

Table 3: Statistics of the shipborne gravity data before and after first filtering; unit [mGal]

Anomaly Type	No. of Data	Min	Max	Mean
Original	38,965	-220.470	911.000	14.258
After Filtering	15,614	-30.268	30.271	6.601

By using 15614 ship-borne station data points filtered of gross errors, four marine gravity models have been validated to identify the best model for the study region, as shown in Table 4. Based on the results, the DTU model is better than the Sandwell model. In addition, of all DTU models, DTU17 has the best fit with the ship marine data with the minimum, maximum, mean, and Root Mean Square Error (RMSE) of 0.001 mGal, 86.599 mGal, 7.329 mGal, and 10.762 mGal, respectively. Interestingly, the DTU models show an increase in accuracy from DTU13 to DTU17, as shown in Table 4. Comparison between DTU13 and DTU15 shows significant improvement in terms of accuracy and this major improvement is that the computation of DTU15 contained retracted altimetry data. However, the accuracy between DTU15 and DTU17 is not significant, although DTU17 have a major improvement in that the computation of DTU17 contained more CryoSat-2 and SARAL/AltiKa data (Abdallah *et al*., 2022). Besides computation, this model uses FES2012 tide model which provides better accuracy in coastal regions compared to the GOT 4.7 used in DTU15. Probably, the DTU17 is better than DTU15 in the coastal region but needs further studies to confirm this. It is because similar results were also reported by Anderson *et al.* (2018) when compared with the shipborne gravity data over the Arctic Ocean. Since the DTU17 outperformed the global gravity model, the ship-borne gravity data have been combined with the DTU17. However, the consolidation of these two data sources must be performed with caution as both datasets have different accuracies. Table 5 shows the absolute minimum, maximum, mean of error, standard deviation, and RMSE after the comparison and filtering using a 99% confidence level. Based on the results, the standard deviation and RMSE for free air anomalies decrease from 15.663 mGal to 15.558 mGal and from 10.762 mGal to 8.433 mGal, respectively. The mean error value decreases from 7.329 mGal to 6.446 mGal. A total of 410 points have been identified as gross errors and have been eliminated from the dataset.

The final marine gravity anomaly grid combining 15155 filtered ship-track observations and DTU17 gravity anomalies is illustrated in Figure 5 (a). During the LSC process, to grid

Table 4: Statistical analysis of four marine gravity models using 15614 ship-borne station data points [mGal]

Model	Min	Max	Mean	RMSE
DTU 13	0.003	87.012	7.387	10.818
DTU 15	0.000	86.761	7.339	10.767
DTU 17	0.001	86.599	7.329	10.762
Sandwell	0.000	92.220	8.719	12.113

Table 5: Shipborne gravity data before and after comparison with DTU17 model: Unit [mGal]

	No. of Data	Min	Max	Mean	STD	RMSE
Original	15615	0.001	86.599	7.329	15.663	10.762
After Filtering	15205	0.001	25.250	6.446	15.558	8.433

the corrections between ship-borne data and the DTU17 model, a correlation length of 20 km and 1.0 mGal white noise is used in the second-order Markov covariance model after it has been tested using 10 km to 100 km and 1 mGal to 3 mGal. The 50 ship-borne gravity stations that were randomly selected for the validation process are illustrated in Figure 5 (b).

Table 6 shows the statistical analysis of the comparison between 50 points and the DTU17 model after the fitting process and the results reveal a significant improvement. The absolute mean and RMSE after fitting decrease from 6.957 mGal to 1.391 mGal and from 9.546 mGal to 2.192 mGal, respectively, which reflects a significant improvement of DTU17 anomalies after they are fitted to ship-borne anomalies.

Conclusion

This paper explores the combination of ship-borne anomalies with altimeter-derived anomalies to prepare for geoid modelling in Peninsular Malaysia. Initially, a cross-validation technique and 95% confidence level are used to analyse 39756 points of gravity data from ship measurements and identify gross errors. 24,551 ship-borne gravity points are eliminated from the database as a result. Four gravity anomaly models derived from altimetric datasets are evaluated, with the DTU model proving superior to the Sandwell model. Among the DTU models, DTU 17 achieves the best results with an RMSE of 10.762 mGal. Finally, the gravity anomalies from the DTU 17 model are fitted to those from ship-borne datasets using a 4-parameter LSC method with second-order Markov covariance.

Acknowledgements

This research was financially supported by the Universiti Teknologi MARA through the MyRA Research Grant [600-RMC 5/3/GPM (069/2022)]. The authors would also like to thank Universiti Teknologi MARA (UiTM), Perlis Branch for their support during the research and the Bureau Gravimétrique International (BGI) (http://bgi.obs-mip.fr) for providing ship-borne gravity data around the study region.

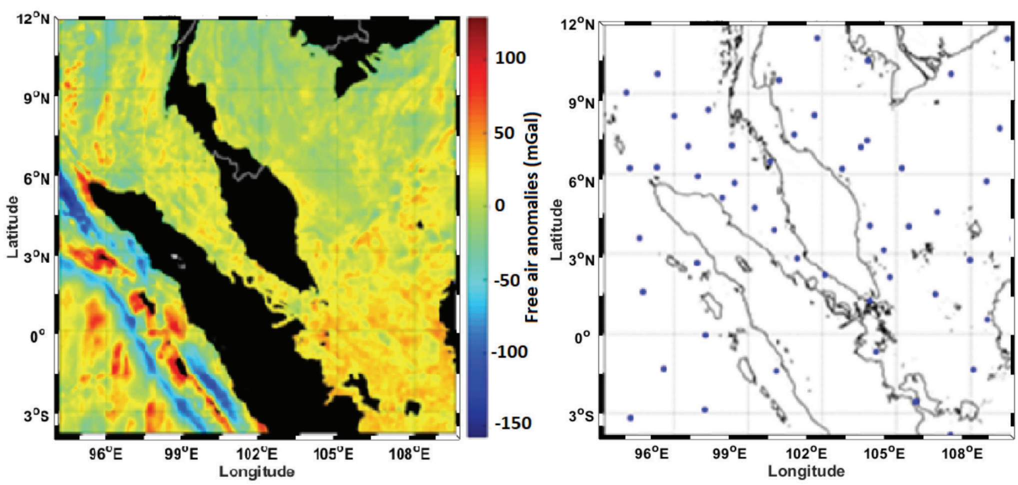

Figure 5: (a) The final marine gravity anomaly grid and (b) Distribution of the 50 ship-borne gravity stations used in the validation process

Table 6: Statistics of the differences between 50 ship-track observations and DTU17 anomalies (mGal)

	Min	Max	Mean	RMSE
Before	0.447	24.356	6.957	9.546
After	0.011	8.100	1.391	2.192

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