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The Verification of Sea Level Anomaly (SLA) Versus Tide Gauge for Geoid Modelling

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ABSTRACT

The increasing long-term sea level rise is particularly interesting and needs a significant investment in coastal protection procedures. The coastal sea level has been verified with tide gauges and well maintained with reliable data accuracy since a few centuries ago. Satellite altimeter has been used for sea level study and increasingly for operational purposes. However, the precision of altimetry data in coastal areas is frequently eliminated by the geographically correlated orbit errors, which induce a regional inhomogeneous mission bias. This study presents an effort to verify sea level anomaly based on altimetry data with tide gauge stations as an early procedure to provide good sea level anomaly data for mean sea surface, gravity anomaly, and geoid determination over Malaysian seas. The altimetry data is validated by comparing the sea level anomaly with ground truth data (tidal data) near the coastal area. Nine selected areas were chosen to represent the ground truth data. The findings found that the altimetry data over the South China Sea (Pulau Tioman, Geting, Cendering, Bintulu, and Kota Kinabalu) provided a good pattern, high correlation, and a minimum root mean square error (RMSE) value after the verification with tidal sea level anomaly data. However, it clearly shows that Tawau station over the Celebes Sea provides a poor pattern, correlation, and a high RMSE value with tidal sea level anomaly data. In conclusion, further enhancements are expected from the refined processing and filtering of altimetry data for the sea level study in the coastal zone.

Keywords:
Sea Level Anomaly, geoid, gravity anomaly, altimetry

1. Introduction

Many scholars have interpreted Geodesy in accordance with their respective interests. For instance, in the case of classical geodesy, Helmert [1] described geodesy as the discipline for measuring and mapping the Earth's surface. In referring to this definition, geodesy plays a leading

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role in determining the position of survey points and their variations over time on the Earth's surface. Lu *et al.,* [2] described geodesy as studies about the shape and size of the Earth as well as its geodynamic phenomena. While Torge and Müller [3] described the tasks of geodesy with respect to the Earth's surface to determine the figure and external gravity field of the Earth, as well as its orientation in space, as a function of time, from measurements on and exterior to the Earth's surface." Geodesy is defined as the science of the measurement and illustration of the Earth (geometry, physics, temporal variations) and other celestial bodies [4].

Geoid determination is one of the main tasks of geodesy and becomes more critical when survey works are done with Global Navigation Satellite System (GNSS) instruments, the use entrusted to geodesists and areas of responsibility of geodesy. After the ellipsoid, the geoid is the subsequent paramount estimation of the figure of the Earth. In Jekeli [5], the geoid is interpreted as an equipotential surface of the Earth's gravity field that closely approximates the mean sea level. The equipotential surface is described as a constant value of the gravity potential on the surface. While in Sjoberg and Bagherbandi [6], the geoid is defined as the equipotential surface of the Earth's gravity field that best fits the mean sea level (MSL). However, MSL can be interpreted as the mean sea surface (MSS) heights in marine areas. The increasing sea levels and long-term sea rise are of particular interest, as are significant investments in coastal protection procedures [7, 8]. The coastal sea level has been measured with tide gauges from more than a century ago, which are well maintained and provide good data accuracy. Tide gauges provide regional high-resolution sea level data that is significant for operational purposes and for monitoring surges, extremes, or tsunamis [9].

Hence, the monthly tidal data from tide gauges used in this study is taken from Permanent Service for Mean Sea Level (PSMSL). Nine (9) tide gauge stations were involved, enveloping the east and west coasts of Peninsular Malaysia and East Malaysia. Altimetry data derived from Radar Altimeter Database System (RADS) must be verified before performing the trend analysis. The comparison of sea level from altimetry and tidal data has been carried out by extracting the monthly sea level anomaly average at the tide gauge locations and the altimeter track near the tide gauge stations. However, the accuracy of coastal altimetry data is still affected by the coexistence of the targeted water and the neighbouring terrain within a footprint [10]. Hence, this study attempts to verify sea level anomaly (SLA) based on altimetry data with ground truth data (tidal data) as an early procedure to provide good SLA data for the following study related to the mean sea surface, gravity anomaly and geoid determination over Malaysian seas.

2. Methodology

This section describes the procedure of altimetry data processing and sea level anomaly verification with tide gauge stations. Figure 1 represents the flowchart of the research methodology involved in this study.

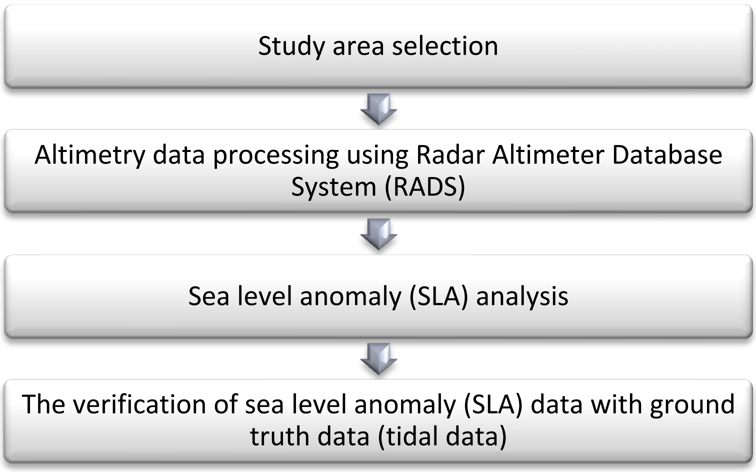


Fig. 1. Flowchart of the research methodology

2.1 Altimetry Data Processing

Satellite altimetry data obtained in this study are presented by the Technical University of Delft (Netherlands). The data can be assessed through the Radar Altimeter Database System (RADS) server at Universiti Teknologi Malaysia (UTM), which provides the latest orbital information and geophysical corrections. Satellite altimetry data implemented in the computation have been preprocessed based on the optimal range and geophysical corrections for the Malaysian region [11]. Most of the ranges and geophysical corrections implemented in this study are based on user manuals and gradual experiences from prior studies [12-15]. The multi-mission satellite altimetry data in this study are processed using the Radar Altimeter Database System (RADS). The altimetry data process began in 2005 with the consideration that in the year 2004, there was a tsunami phenomenon occurring in Sumatra. Based on the previous research by Einarsson *et al.,* [16], there are gravity changes due to the Sumatra-Andaman earthquake (26th December 2004) and Nias earthquake (28th March 2005) by applying data from the gravity recovery and climate changes (GRACE) satellites. The outcomes denote that the GRACE data inversion for the Sumatra-Andaman consequence will comprise a dramatic signal from the Nias earthquake and will support eliminating the modelled Nias consequence from the data.

The altimetry data extracted in this study ranges bordered between 0˚ N ≤ Latitude ≥ 14˚N and 95˚E ≤ Longitude ≥ 126˚ E. Besides, the selected spherical cap is reliant on the presented gravity data in the defined area [17]. Thus, satellite altimetry can be very advantageous regarding data information since altimetry data coverage is provided around the surface of the Earth. This study uses six satellite altimeter missions: ERS-2, Jason-1, Envisat, Jason-2, Cryosat and Saral. Each of these satellite missions has its strengths and weaknesses. Thus, the effort of combining several satellite altimeter mission data is adopted to capitalise the collective strength of each satellite altimeter used. The usefulness of this approach was shown, for instance, by Din [18]. In his study, Din [18] demonstrated the advantages of combining Jason-2 and EnviSat altimetry data, representing an excellent example of capitalising on the operation strength used by the respective satellite altimeter. Eleven years of altimetry data from the six missions mentioned above and used in this study were extracted from 1st January 2005 to 31st December 2015. The extracted data are processed to derive the required SSH and SLA data. The SSH and SLA were specifically processed and used for these reasons. The SSH data are the primary source of mean sea surface derivation, gravity anomaly estimation and geoid height computation. In comparison, the SLA data is utilised to verify the altimetry SLA vs. tidal SLA.

Another vital step in using altimetry data is the correction and the removal of biases, which RADS can handle these processes. The altimeter corrections and biases removal step in RADS data processing requires a region-suitable model. Most of the corrections/model in RADS are suited mainly for the global case and is not meaningful for a regional case. Sea level anomaly and sea surface height data must be corrected for orbital altitude and altimeter range. These are subjected to a long list of corrections in terms of instrument bias, sea state bias, ionospheric delay, dry and wet tropospheric corrections, solid Earth and ocean tides, ocean tide loading, pole tide, electromagnetic bias, and inverse barometer correction. The corrections are applied by utilising models for satellite altimeter missions in RADS. The final corrections/models needed for multi-mission altimeter processing in RADS are displayed in Table 1.

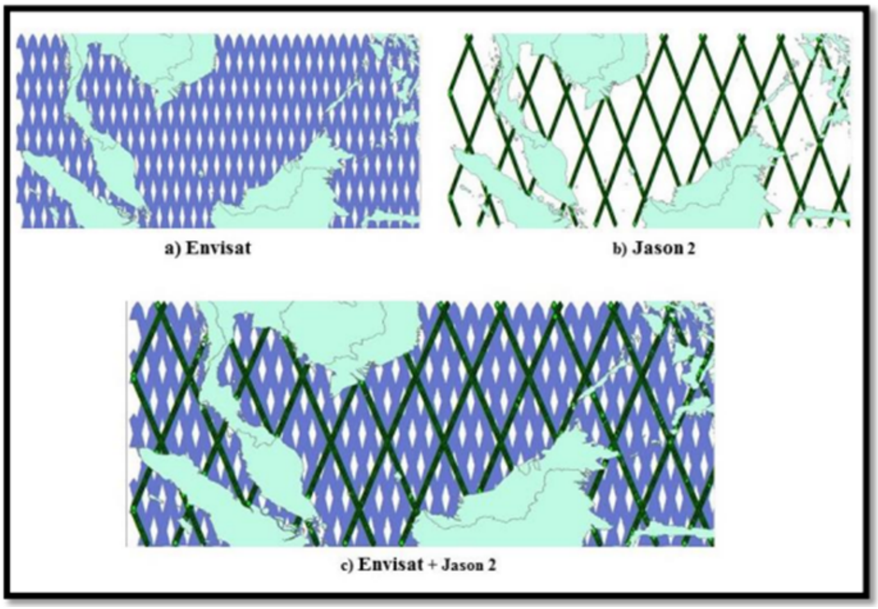
Table 1
Corrections and model adopted for RADS altimeter processing

Correction/Model	Editing (m)		Descriptions
	Min	Max	
Orbit/Gravity field			CNES GDR-C orbital altitude NASA JGM-3
Dry troposphere	-2.4	-2.1	ECMWF
Wet troposphere	-0.6	0	All satellites: Radiometer measurement
Ionosphere	-0.4	0.04	All satellites: Smoothed dual-frequency
Dynamic atmosphere	-1	1	All satellites: MOG2D
Ocean tides	-5	5	All satellites: GOT4.10
Load tides	-0.5	0.5	All satellites: GOT4.10
Solid earth tides	-1	1	Applied (Elastic response to tidal potential)
Pole tides	-0.1	0.1	Applied (Tide produced by Polar Wobble)
Sea state bias	-1	1	All satellites: CLS non-parametric ERS: BM2/BM4 param
Reference	-1	1	DTU13 mean sea surface height
Engineering flag			Applied
Reference frame (cm)			Jason-1 Jason-2

2.2 Crossover Adjustment

The crossover adjustments are performed after the altimetry data are corrected with the altimeter corrections and the bias is removed. However, the sea surface heights (SSH) from different satellite missions are corrected to a "standard" surface due to orbital errors and satellite orbit frame inconsistency [18]. The crossover adjustment is accomplished to confine track correlated residuals and other long wavelength residuals by minimising height differences in crossover points between rising and downward tracks [19]. The crossover adjustments are essential for assuming the geoid signal is static at any point. The area for the crossover minimisation has been enlarged, extending outside the study area. The extension of the crossover area is to avoid inadequacy of crossover information to approximate the consistency (one cycle per orbital revolution) of orbit residual function fitting [12][18]. Hence, the individual crossovers for the time frame are restricted to ±9 days to decrease the possibility of removing actual oceanic signals and sea level trends.

The general procedure of crossover adjustments is to locate sea surface height differences at crossover points and eliminate the radial orbit error. Hence, the local altimetry sea surface map is demonstrated by utilising the mean sea surface heights at the crossover points [18][20]. The details regarding the crossover adjustment procedure are demonstrated in Gysen and Coleman *et al.,* [20]. Figure 2 illustrates the example of the crossover adjustments process from satellite altimeter data (Envisat and Jason-2).



a) Envisat

b) Jason 2

c) Envisat + Jason 2

Fig. 2. Crossover adjustments process from satellite altimeter data (Envisat and Jason-2)

2.3 Filtering and Gridding

Distance-weighted gridding is employed during RADS processing to evaluate points near the centre as vital and far away as moderately inconsequential [18]. The weighting function applied in this study relies on Gaussian distribution, Fw (r). Based on Eq. (1), the sigma, σ denotes the weight allocated to a value at a normal point located at a distance r from the grid point [21].

$$Fw\ (r) = e^{-\frac{r^2}{a^2}} \tag{1}$$

The daily altimetry data from TOPEX-class (Jason-1 and Jason-2) and ERS-class (ERS-2, EnviSat, Cryosat and Saral) are filtered and gridded to sea surface height and sea level anomaly bins (0.25˚ by 0.25˚) utilising Gaussian weighting function with sigma 2.0. Hence, the temporal and spatial weighting on sea surface height and sea level anomaly must be cogitated with the selected block size 0.25˚ (spatial) and cut off at 9 days (temporal). The processing ends with analysing sea surface height and sea level anomaly data.

Eq. (1) is used to analyse sea surface height data with all corrections associated with sea surface height correction. Hence, dry troposphere, wet troposphere, ionosphere, sea state bias, geoid correction, tides and atmospheric corrections are applied to obtain sea surface height data. The geoid corrections provide the largest contribution in measuring sea surface height [18]. Besides, the DTU13 MSS model is used as the mean sea surface (MSS) reference model in order to analyse sea surface height data. However, sea level anomaly is measured by subtracting expediently, eliminating the mean dynamic sea surface height temporal and zero mean. The mean sea surface is usually performed by averaging sea surface height data over a specific period of time, then combined with data from numerous particular repeat missions. Thus, corrections temporal mean is removed, and the time variable is only considered [12]. However, if there are some queries with the processing results, the altimeter corrections and bias removal step are repeated. Figure 3 expresses the RADS processing strategy of altimetry data.

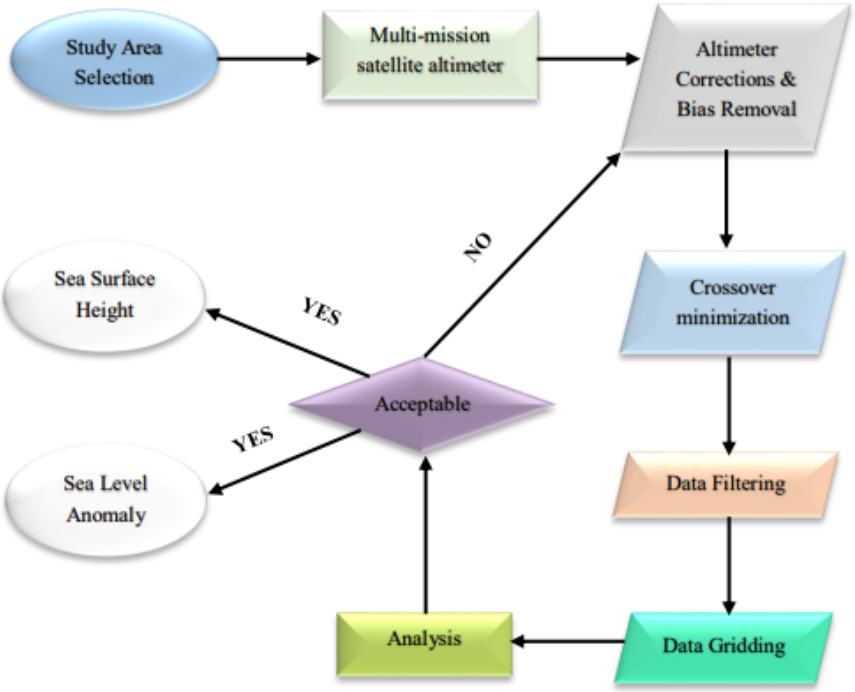


Fig. 3. RADS processing strategy

2.4 The Verification of Sea Level Anomaly (SLA) Data

The verification process includes comparing the sea level anomaly data with ground truth data. In this study, the ground truth data employed are the tidal data. A total of nine selected areas were chosen to represent the ground truth data. The selected areas are shown in Figure 4, which cover both the east and the west coast of Peninsular Malaysia as well as East Malaysia. The sea level anomaly data used for this comparison is based on extracting altimetry data by averaging the monthly sea level anomaly data at the respective tide gauges station. For this purpose, the chosen altimeter track is near the nine selected tide gauge stations. The pattern of altimeter and tide gauge observations is appraised over an equal period in every region sequentially to provide comparable results from 1st January 2005 to 31st December 2015.

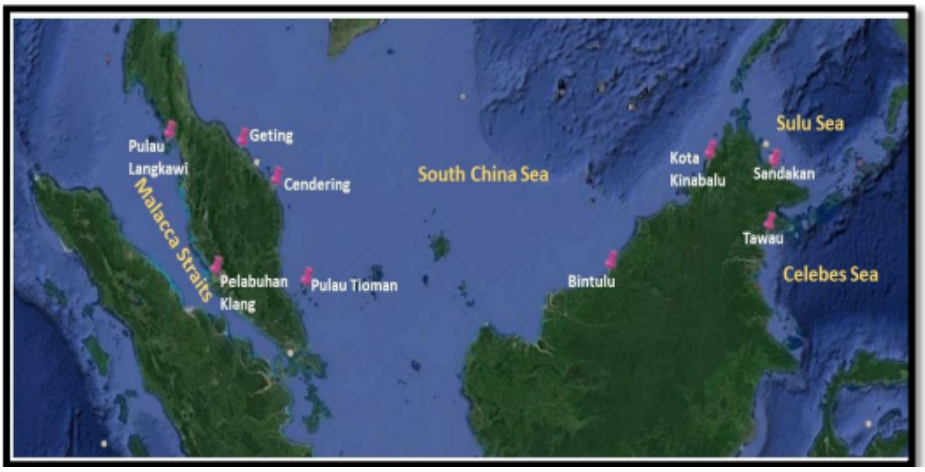


Fig. 4. Nine chosen areas of ground truth for comparison of altimetry and tidal data

Consequently, sea level anomaly daily interpretations are combined into monthly mean interpretations. This method is carried out to sort off more or less align the final monthly altimeter interpretation with the monthly tide gauge interpretation. In fact, the satellite altimeter flies over the tide gauge station in three repeated instants over a period of one month (for TOPEX-class) for the best situation and once a month (for ERS-class) for the worst situation. Hence, the volume of data provided by multi-mission altimetry increases the variations in the altimeter technique more when compared with tidal data.

3. Results

3.1 Data Verification: Altimeter versus Tide Gauge

The verification of the derived altimetry data is required before performing mean sea surface height derivation. This section represents the results of comparing sea level anomaly data from satellite altimeter and ground truth data (tidal data). Nine (9) selected tide gauges stations are used for the data verification covering east and west coast Peninsular Malaysia (Pulau Langkawi, Geting, Pelabuhan Kelang, Cendering and Pulau Tioman) and East Malaysia (Bintulu, Kota Kinabalu, Sandakan and Tawau). The verification results described the pattern, correlation analysis and RMSE value between altimetry and tidal sea level anomaly (SLA) data. Figure 5 illustrates the results of the sea level verification on the west coast of Peninsular Malaysia from the evaluation of the sea level pattern at Pulau Langkawi and Pelabuhan Klang. The correlation in the pattern of sea level from the altimeter and tide gauge designates good conformity at Pulau Langkawi and Pelabuhan Klang, respectively.

As illustrated in Figure 5, the normal sea level anomaly value for the Peninsular Malaysia west coast is from -0.15m to 0.15 m. The correlation analysis of Pulau Langkawi station represents good conformity with the correlation coefficient, R2 value higher than 0.7 (Figure 6). However, the Pelabuhan Klang station indicates a moderate correlation with altimetry data with a 0.6879 R2 value. According to Dancey and Reidy [22], the correlation coefficient value, R2, is categorised as follows: 1 represents perfect correlation, 0.7 to 0.9 depicts the strong correlation, 0.4 to 0.6 denotes moderate correlation and R2 value of less than 0.3 signifies weak correlation.

Then, the sea level pattern over the South China Sea is demonstrated in Figure 7 and Figure 9 by analysing Geting, Pulau Tioman, Cendering, Bintulu and Kota Kinabalu. Both figures demonstrate an equivalent sea level variations pattern with a more or less regular annual cycle, signifying the appropriate range selection and geophysical corrections for these areas. The correlation analysis for these locations provides convincing results with the R2 value at 0.9677, 0.9548, 0.9239, 0.8507 and 0.911 for Geting, Pulau Tioman, Cendering, Bintulu and Kota Kinabalu, correspondingly, as depicted in Figures 8 and Figure 10.

The sea level pattern for the Sulu Sea (signified by Sandakan station) and Celebes Sea (depicted by Tawau station) are illustrated in Figure 11. The variations of the sea level pattern between altimetry SLA and tidal SLA at Tawau station complement well but represent the moderate R2 value at 0.6234. In contrast, Sandakan station represents a good R2 value at 0.893 compared to Tawau (Figure 12). Besides, the correlation between monthly values of altimetry and tidal SLA in all selected areas is greater than 0.6. These results verify that the altimetry processing was performed efficiently in this study; hence, the altimetry data has great capability for sea level anomaly and sea surface height determination using RADS.

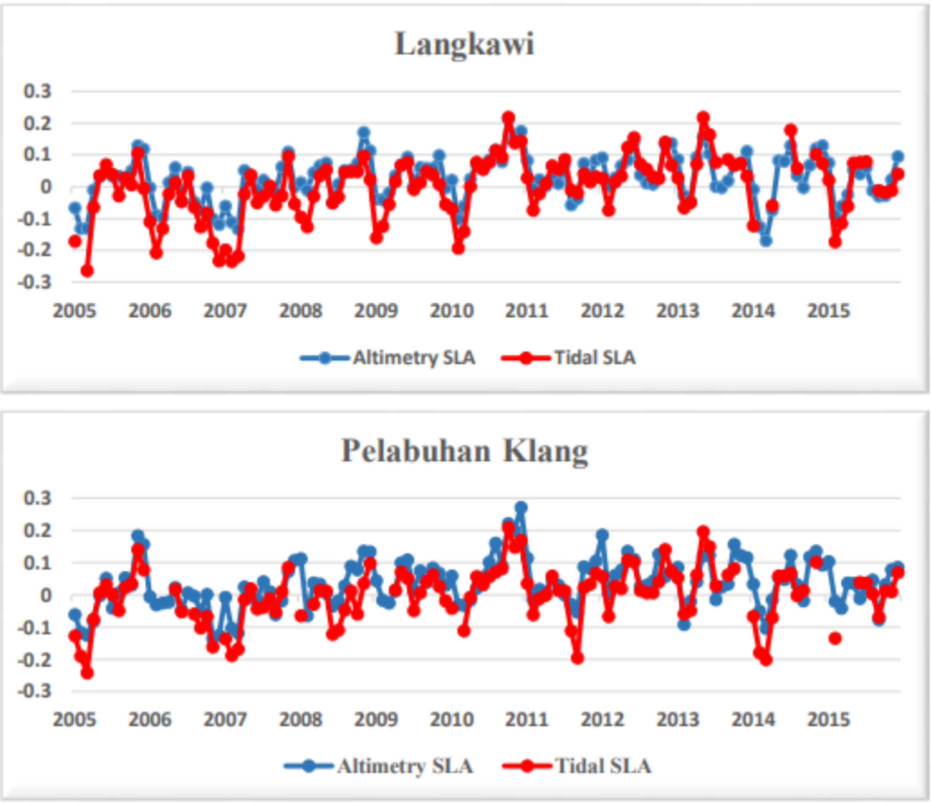


Fig. 5. Sea level comparison altimetry and tidal data at the west coast of Peninsular Malaysia : Pulau Langkawi and Pelabuhan Klang

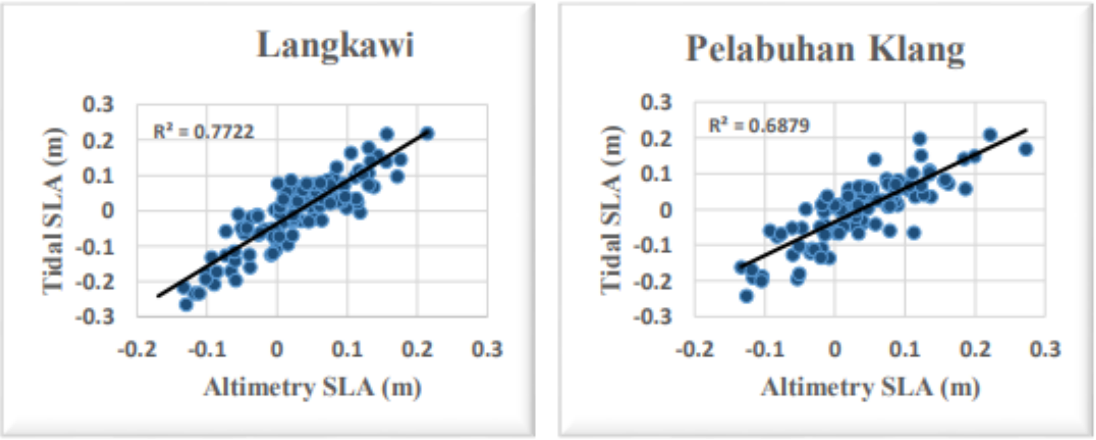


Fig. 6. The altimetry and tidal sea level correlation analysis at the west coast of Peninsular Malaysia: Pulau Langkawi and Pelabuhan Klang

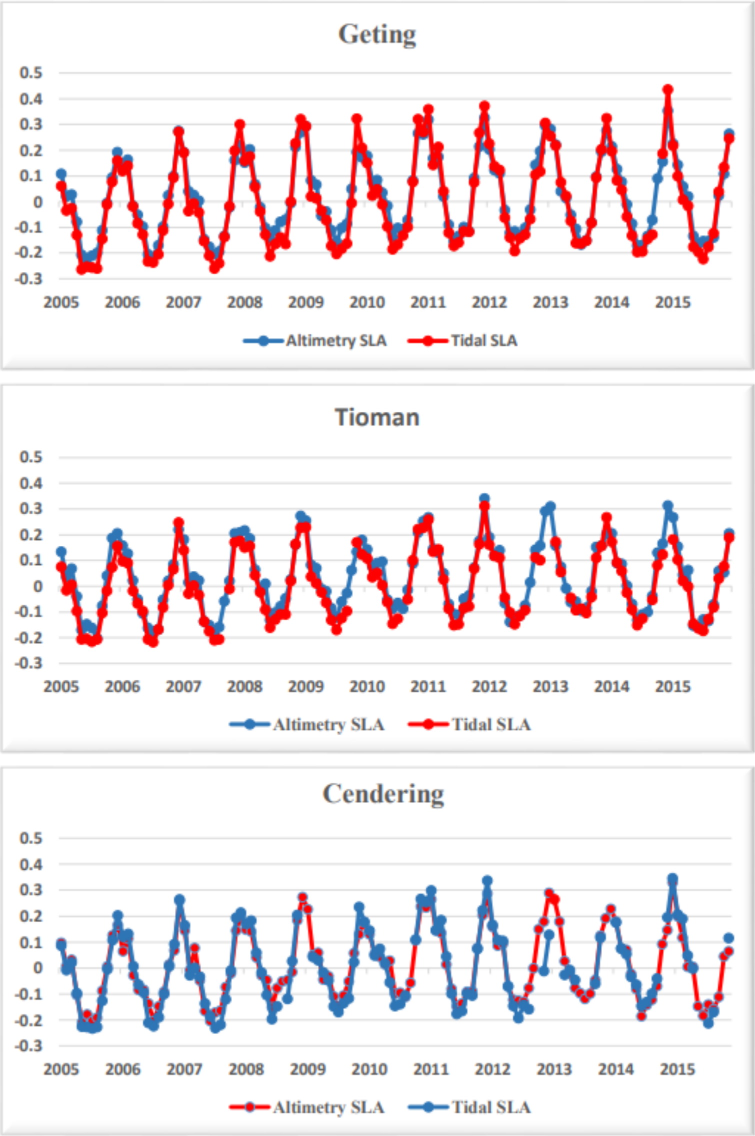


Fig. 7. Sea level comparison between altimetry and tidal data at the east coast of Peninsular Malaysia: Geting, Pulau Tioman and Cendering

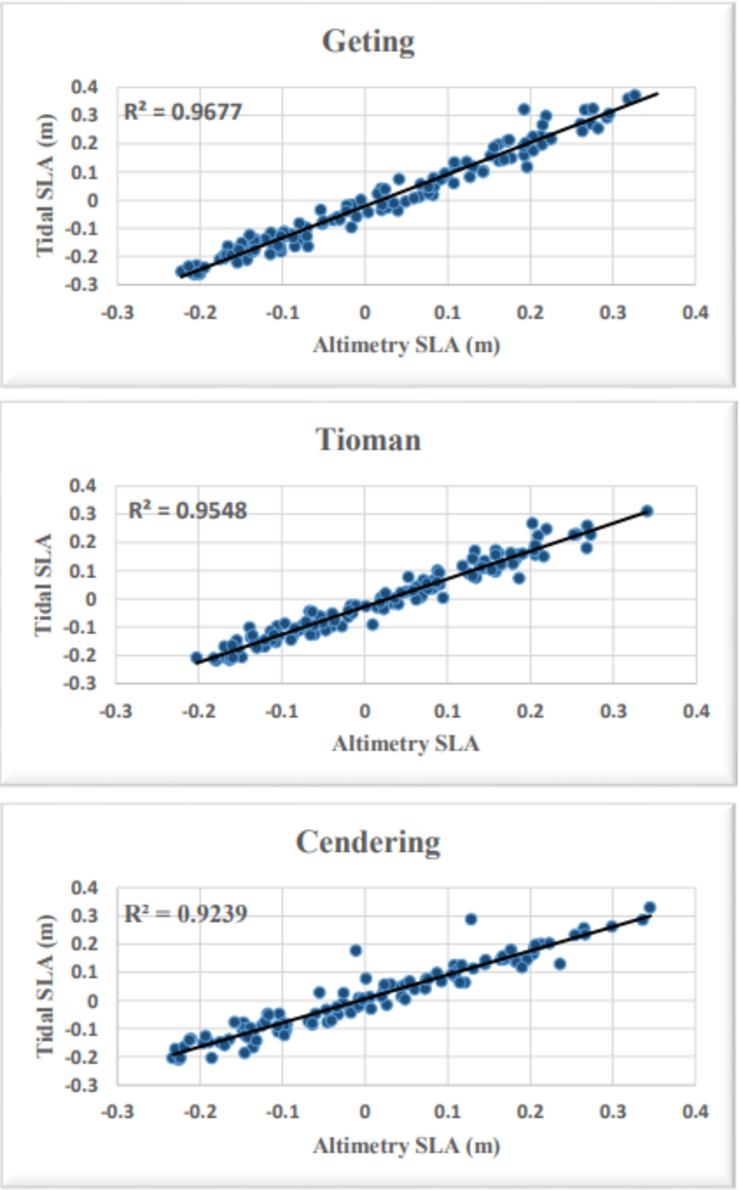


Fig. 8. Sea level comparison between altimetry and tidal data at the east coast of Peninsular Malaysia: Geting, Pulau Tioman and Cendering

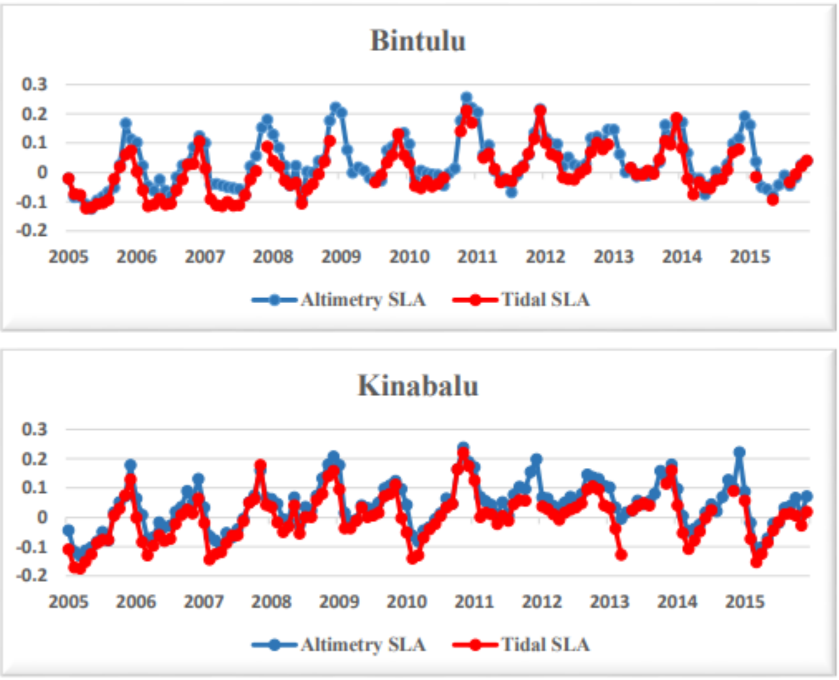


Fig. 9. Sea level comparison between altimetry and tidal data at East Malaysia: Bintulu and Kota Kinabalu

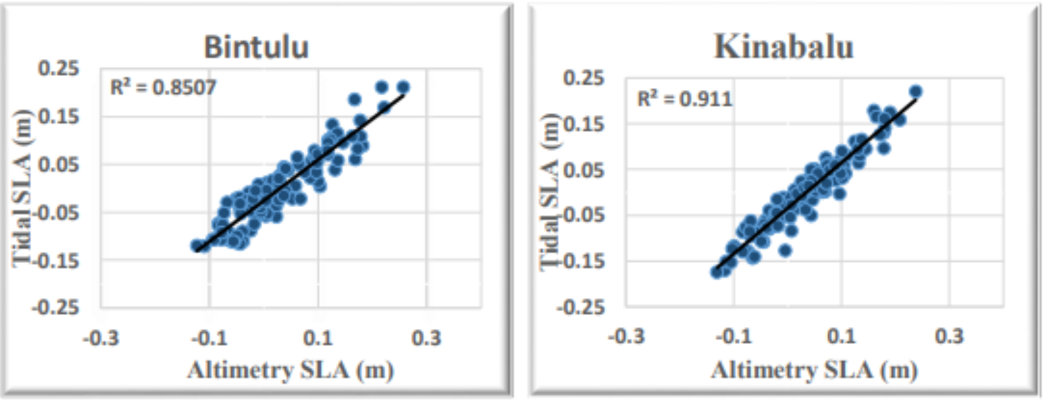


Fig. 10. The altimetry and tidal sea level comparison analysis at East Malaysia; Bintulu and Kinabalu

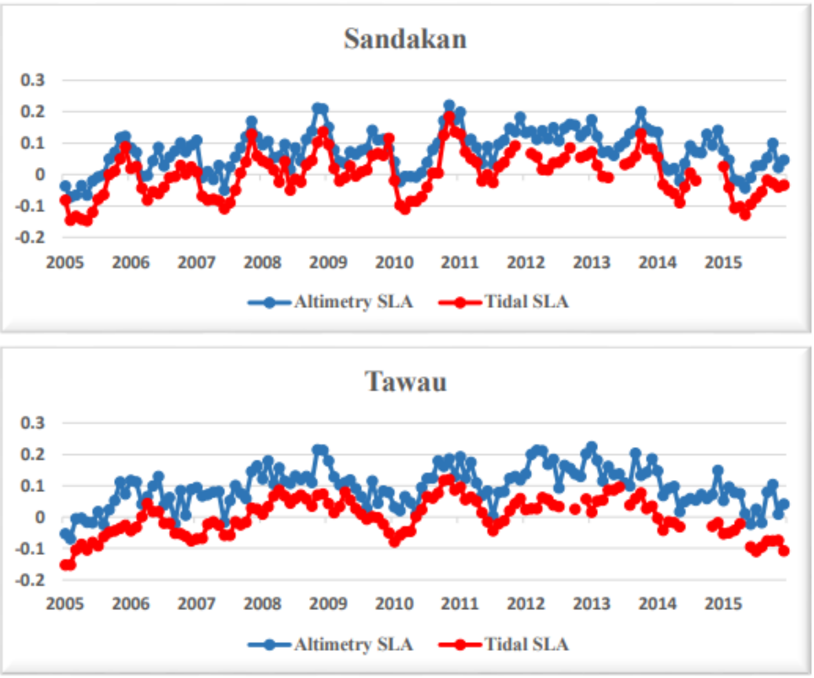


Fig. 11. Sea level comparison between altimetry and tidal data at Sandakan- Sulu Sea and Tawau-Celebes Sea

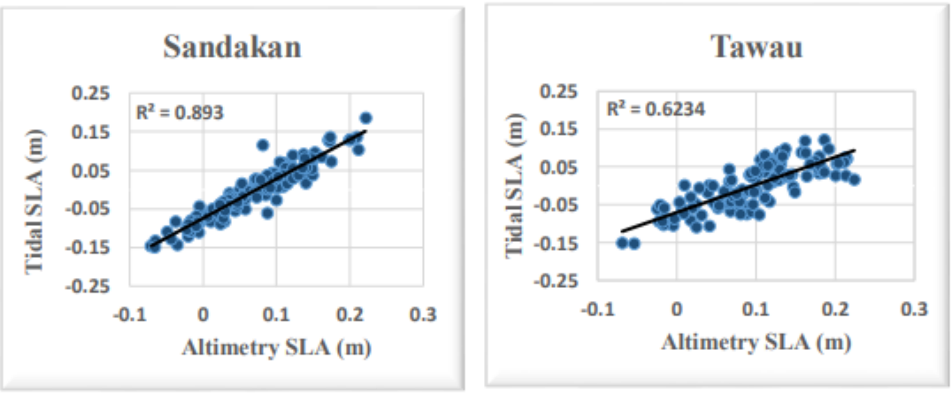


Fig. 12. The altimetry and tidal sea level correlation analysis at Sandakan-Sulu Sea and Tawau-Celebes Sea

In addition, the numerical statistics of altimetry SLA and tidal SLA for all stations are determined, as shown in Table 2. The results show that the tide gauge stations located over the South China Sea indicated the lowest RMSE value at 0.0397 m, 0.0412m, 0.0420m, 0.0427m and 0.0434m for Pulau Tioman, Geting, Kota Kinabalu, Cendering and Bintulu, respectively. However, the RMSE value for Malacca Straits (covered by Pulau Langkawi and Pelabuhan Kelang) represents the second lowest RMSE value with RMSE value at 0.0569 m and 0.0611m. The Tawau station covering the Celebes Sea represents the highest RMSE value over the other stations with 0.1039m, and the Sandakan station covering Tawau station depicts a 0.0762m RMSE value.

Table 2
Numerical statistics of altimetry data with tidal (SLA)

(Unit:m)	Min Difference	Max Difference	Average Difference	RMSE	Rank
P. Tioman	-0.0651	0.1128	0.0282	0.0397	1
Geting	-0.1289	0.0953	0.0191	0.0412	2
K. Kinabalu	-0.0178	0.1236	0.0345	0.0420	3
Cendering	-0.1890	0.1061	-0.0069	0.0427	4
Bintulu	-0.0390	0.1074	0.0298	0.0434	5
P. Langkawi	-0.0771	0.1374	0.0306	0.0569	6
P. Kelang	-0.0836	0.1773	0.0371	0.0611	7
Sandakan	-0.0346	0.1482	0.0727	0.0762	8
Tawau	0.0086	0.2082	0.0959	0.1039	9

Based on this verification, it can be summarised that the altimetry data over the South China Sea (Pulau Tioman, Geting, Cendering, Bintulu and Kota Kinabalu) provide a good pattern, high correlation and minimum RMSE value after verification with tidal SLA data. However, it shows that Tawau station over Celebes Sea provides poor pattern, correlation and high RMSE value with tidal SLA data. This is due to the tide gauge stations' locations and the altimetry data track, where the tide gauge station in Tawau is closer to the coastal area than the open sea area. Hence, it definitely affects the altimetry track on the tide gauge stations. Figure 13 represents the altimetry track in Tawau station. As illustrated in Figure 13, the locations of tide gauge stations are close to the coastal area; hence, it becomes an obstacle for the satellite altimeter to fly on the tide gauge station.

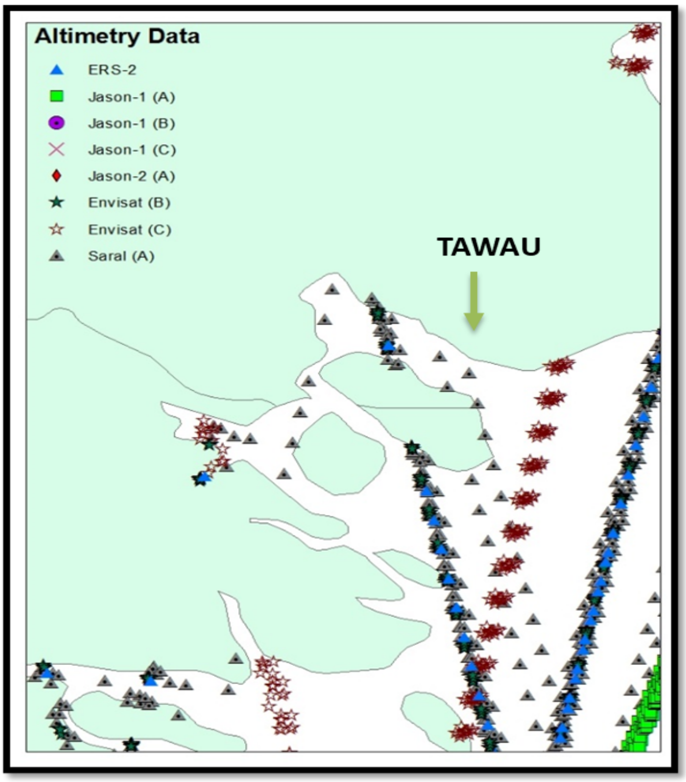


Fig. 13. The relationship between the Tawau tide gauge station and altimetry data

4. Conclusions

The SLA and SSH data are processed in RADS, where geophysical and atmospheric corrections are employed. The altimetry data has been verified with the localised tidal data before performing any derivation and computation. Nine (9) tide gauge stations covering the Malaysian seas: South China Sea, Malacca Straits, Sulu Sea and Celebes Sea are used for altimetry data verification. The results show that the altimetry data over the South China Sea depicts a strong correlation and minimum RMSE value compared to Malacca Straits, Celebes Sea, and Sulu Sea. Hence, the mean sea surface (MSS) will be determined after the sea level anomaly is verified with a tide gauge for the following research: gravity anomaly and geoid determination. Gravity field approximation and marine geoid determination play a crucial role for many professionals and scientific research.

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