



A COMPARISON BETWEEN TIDAL CONSTITUENTS DERIVED FROM SATELLITE ALTIMETRY AND IN-SITU DATA AROUND PENINSULAR MALAYSIA

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Abstract:

Satellite altimetry technology has been widely used in exploring Earth's Ocean activities. Achieving a remarkable accuracy in measuring sea level for ocean tide analysis has led the local researchers to investigate more details on tidal behaviour in the regional area. This study is an attempt to assess the reliability of derived tidal constituents between satellite radar altimetry and in-situ data which is referred to as coastal tide gauges. Three satellite missions denoted as TOPEX class missions namely TOPEX, Jason-1, and Jason-2 were used to derive along-track sea surface height (SSH) time series over 23 years. Besides, four selected coastal tide gauges were used for tidal analysis and validation where the tidal data have at least 19 years of hourly observation. Derivation of tidal constituents from both satellite altimetry and tide gauges were executed by adopting the harmonic analysis method. The comparisons were made by calculating the Root Mean Square Misfit (RMSmisfit) of each tidal constituent between the nearest altimetry point to the tide gauges. After RMSmisfit, Root Sum Square (RSS) values of tidal constituents at each tide gauge were also calculated. The results displayed the RMSmisfit of tidal constituents agreed well with the selected tide gauges which are within 10 cm except for M2 constituents which recorded 10.2 cm. Pelabuhan Kelang tide gauge station showed the highest RSS value followed by Pulau Langkawi which recorded 21.2 cm and 9.8 cm, respectively. In conclusion, overall results can be inferred that the satellite-derived tidal constituents are likely to have good agreement

with the selected tide gauge stations. Nevertheless, further analysis should be executed in determining high precision satellite-derived tidal constituents, especially in the complex regional area.

Keywords:

Satellite Altimetry, Tide Gauge, Tidal Constituents, Harmonic Analysis, Comparison

Introduction

Tide is defined as the rise and fall of sea level which influence by the gravitational attraction between the moon, the earth and the sun. Generally, tides can be modelled by using three methods namely, hydrodynamic modelling, empirical modelling and integration between hydrodynamic model and empirical model (Fok, 2012; Pirooznia et al., 2016; Soltanpour et al., 2017). Before the revolution of satellite radar altimetry technique, tides were analysed and modelled using *in-situ* measurements which normally referred to tide gauge data. Based on the authors' knowledge, some constraints occurred when tidal analysis is only relied on tide gauges. This is due to the installation of tide gauges usually focussed on the coastal area. Thus, the tide models beyond the coastal area are still undetermined and the values commonly based on the assumption with the nearest *in-situ* data. Not only that, if the distributions of coastal tide gauges are not dense enough, the determination of tidal behaviour in the particular area would also be less accurate.

A wide range of ocean activities have been expanded with the advent of satellite altimetry technology. Satellite altimetry has become an essential platform for investigating the Earth's ocean. According to Cazenave (2019), the data measured from satellite altimetry have supported valuable information in Earth sciences domains as well as it revolutionised the knowledge of marine gravity field, ocean tides dynamics, ocean circulation and climate change in respect to sea level rise. Moreover, satellite altimetry also has been used by several researchers to study the ocean activities in a particular region. Hamid et al. (2018), for instance, utilised altimetry data to analyse sea level rates in Malaysia. Subsequently, Din et al. (2019) performed further investigation to measure sea level and vertical land motion (VLM) in Malaysia using multi-mission sensors, including satellite altimetry. Since 1993, satellite altimetry missions have achieved remarkable accuracy in the measurement sea level for ocean tide analysis. This is due to its high precision of orbit and improvement of most recent geophysical corrections.

It is undeniable that the long-term sea level observation from tide gauges can enhance the knowledge of tides. However, these measurements are limited as they measured only near the coast (Gomis et al., 2012). As a result, ocean tide analysis based on tide gauges in the open ocean is limited, leaving tidal characteristics beyond the shore uncertain. Furthermore, advances in altimetry measurement have demonstrated that this platform is routinely used to record global sea level variations with great precision and high spatial-temporal resolution (Feng and Jin, 2015; Salameh et al., 2018). This led to the acquisition of the SSH data from altimetry can be served as tide gauge measurements at each location globally (Fok, 2012).

To this end, the ocean tide can be explored over Malaysian seas since this study is focused on the regional area around the Peninsular Malaysia. Peninsular Malaysia also known as West Malaysia is enclosed by Malacca Straits and South China Sea (SCS). According to Gunathilaka

and Mahmud (2014), the Malacca Straits is a tidally complex area with varies of tidal range patterns and values. Daryabor et al. (2016), on the other hand, claims that the SCS has complex bathymetry and tidal dynamics. As the geography of Peninsular Malaysia is surrounded by many small islands as well as located at intricaded area for tidal system, it would give a great challenge towards satellite altimetry application in estimating the tidal characteristics within the study area.

Henceforth, this study aims to compare the reliability of satellite radar altimetry derived tidal constituents (SDTC) with the coastal tide gauges derived tidal constituents. Derivation of tidal constituents were performed by adopting harmonic analysis method on both altimetry and tide gauge data. The harmonic constants of four major tidal constituents namely M2, S2, K1 and O1 were utilised for the purpose of assessment. The comparison is based on the selected coastal tide gauge stations and the nearest along track satellite derived tidal constituents to the tide gauges. Further details regarding to the data and method used in this study are explained in the next section.

Methodology

Area of Study

As aforementioned, the geographical boundary in this study is limited between 0°N - 9°N latitude and 98°E - 106°E longitude as illustrated in Figure 1. From Figure 1, it can be clearly seen that Peninsular Malaysia is enclosed with Malacca Straits at the west and South China Sea at the east. Strait of Tebrau is situated at the southern of Peninsular Malaysia while Gulf of Thailand is located at the northeast of Peninsular Malaysia. No altimetry track can be observed within the Strait of Tebrau due to the narrow channel between southern of Malaysia and Singapore. Gulf of Thailand is likely to be not obviously to be seen as the study area is limited within the stated geographical coordinate. Thus, the study area is only focus in estimating the tidal constituents around Malacca Straits and South China Sea. Triangle points along the coast of Peninsular Malaysia indicates the distribution of Department of Surveying and Mapping Malaysia (DSMM) tide gauges. The circles indicate the selected tide gauges used in the assessment with SDTC.

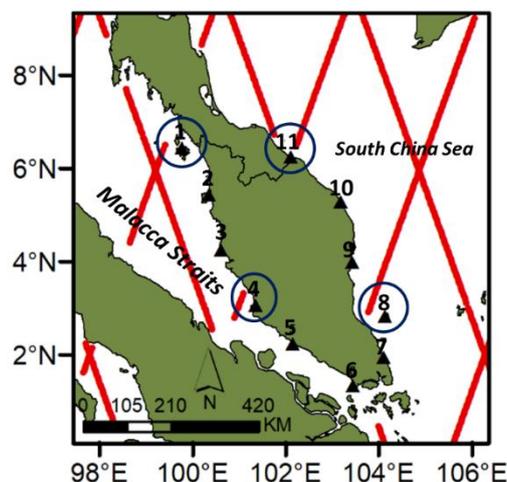


Figure 1: Along Track TOPEX Class Mission (Red) Within The Study Area. Black Triangles Represent The Distribution of DSMM Coastal Tide Gauges Along Peninsular Malaysia

Satellite Altimetry and In-Situ Datasets

To obtain the along track harmonic constants of four major tidal constituents, the sea surface height (SSH) time series were derived and analysed at the corresponding study area. Derivation of SSH from satellite altimetry can be obtained using equation (1) (Ainee, 2016; Hamid et al., 2018; Din et al., 2019).

$$h_{SSH} = H_{alt} - R_{obs} - (h_{dry} + h_{wet} + h_{ion} + h_{DAC} + h_{ocean} + h_{sol} + h_{pole} + h_{ssb}) \quad (1)$$

where, h_{SSH} is the corrected sea surface height, H_{alt} is the satellite altitude, R_{obs} is the altimeter range measurement, h_{dry} is the dry tropospheric correction, h_{wet} is the wet tropospheric correction, h_{ion} is the ionospheric correction, h_{DAC} is the dynamic atmospheric correction, h_{ocean} is the ocean tide correction, h_{sol} is the solid earth tide correction, h_{pole} is the pole tide correction, and h_{ssb} is the sea state bias correction. The SSH time series were computed by applying the best range and geophysical corrections within the study area. The range and geophysical were adopted from Din et al. (2014) as shown in Table 1. However, h_{ocean} must not be applied into the equation as ocean tide is the signal of interest in this study.

Table 1: List of Corrections Applied to SSH Measurements

Correction / Model		Status
Orbit/Gravity field	EIGEN GL04C	Applied
Dry Troposphere	ECMWF	Applied
Wet Troposphere	Radiometer	Applied
Ionosphere	Smooth dual-frequency	Applied
Dynamic Atmosphere	MOG2D	Applied
Ocean Tide	-	Not Applied
Solid Earth Tide	Elastic response to tidal potential	Applied
Pole Tide	Tide produced by Polar Wobble	Applied
Sea State Bias	CLS non-parametric	Applied

Three satellite missions were utilised to estimate tidal constituents such as TOPEX, Jason-1 and Jason-2. All of these missions expressed as TOPEX class missions move along within the same orbit but measure the data at different time. Thus, the estimation of the tidal constituents in this study are carried out by combining all the temporal data which supplementing relatively 23 years of joint TOPEX class missions. Satellite altimetry data were obtained from Radar Altimeter Database System (RADS) as shown in Table 2. Cycle number in the table refers to satellite repetitively or repeat orbit.

Table 2: Satellite Altimetry Missions Involved

Satellite	Phase	Cycle	Mission	Period Time
TOPEX	A	001-364	ERM	January 1993 – August 2002
Jason-1	A	001-260	ERM	January 2002 – January 2009
Jason-2	A	001-303	ERM	July 2008 – October 2016

Notes:

ERM indicates Exact Repeat Mission

According to Kamaruddin et al. (2016), the DSMM had established 21 tide gauge stations since 1984 where 12 tide gauges were located along Peninsular Malaysia and 9 tide gauges were located along East Malaysia. In present, a total of eleven tide gauge stations were installed along the Peninsular Malaysia. However, only four selected tide gauges were used for the comparison with the SDTC because the selected tide gauges were located to the nearest altimetry track in this study. All tidal observations network installed by DSMM observe tide continuously for at least 19 years since 1984. The selected tide gauges for comparison with the nearest altimetry track are highlighted in blue circle in Figure 1.

Harmonic Analysis Method

Before performing harmonic analysis, the SSH times series from TOPEX class missions must be derived by applying the best range and geophysical corrections within the study area. The range and geophysical corrections were adopted from Din et al. (2014). Nevertheless, only ocean tide correction was not applied to the SSH time series as the tidal signal is the interest of this study. Later, the four major tidal constituents at each along track satellite altimetry points were estimated by using harmonic analysis formula as displayed in equation (2) (Ainee, 2016; Alihan, 2018).

$$H(t) = Z_0 + \sum_n Amp \cos(\omega t - \varphi) \quad (2)$$

where, $H(t)$ is the SSH observation data; Z_0 is the mean sea level (MSL); Amp is the amplitude of each tidal constituents; ω is the angular speed of each tidal constituents and φ is the phase delay of each tidal constituents. Based on equation (2), the coefficient of Z_0 , Amp and φ of tidal constituents must be estimated. Thus, this equation is linearised using trigonometric identities as expressed in equation (3) (Katznelson, 2004; Wijaya, 2012; Alihan, 2018).

$$H(t) = Z_0 + \sum_n Amp [\cos \omega t \cdot \cos \varphi + \sin \omega t \cdot \sin \varphi] \quad (3)$$

Assuming a and b as the coefficients of series as follows:

$$a = Amp \cos \varphi \quad , \quad b = Amp \sin \varphi \quad (4)$$

Then, substitute equation (4) into equation (3) to express the periodic functions as shown in equation (5).

$$H(t) = Z_0 + \sum_n a \cos \omega t + b \sin \omega t \quad (5)$$

The coefficient of Z_0 , a and b can be estimated using least square estimation as expressed in equation (6) by harmonic analysis (Wijaya, 2012; Thomson and Emery, 2014; Ainee, 2016; Alihan, 2018).

$$\begin{aligned} AX &= l \\ (A^T A)X &= A^T l \\ X &= (A^T A)^{-1} A^T l \end{aligned} \quad (6)$$

Thus, the *Amp* and φ of tidal constituents can be obtained using trigonometric functions as expressed in equation (7).

$$Amp = \sqrt{a^2 + b^2} \text{ and } \varphi = \tan^{-1} \frac{b}{a} \quad (7)$$

Data Verification

Comparison between SDTC with coastal tide gauges were performed in term of Root Mean Square Misfit (RMS_{misfit}). As mentioned above, only four major tidal constituents (M2, S2, K1 and O1) were used to compared with coastal tide gauge stations. RMS_{misfit} was implemented to measure the difference between amplitude and phase of tidal constituents from satellite altimetry and tide gauges. RMS_{misfit} was calculated based on the equation (8) (Daher et al., 2015; Fu et al., 2020). After RMS_{misfit} computation, Root Sum Square (RSS) was calculated for the overall tide models generated from this study. The formula of RSS is described as in equation (9).

$$RMS_{\text{misfit}} = \left\{ \frac{1}{2N} \sum_{k=1}^N [(A_o \cos G_o - A_m \cos G_m)^2 + (A_o \sin G_o - A_m \sin G_m)^2] \right\}^{\frac{1}{2}} \quad (8)$$

$$RSS = (\sum_{l=1}^M RMS_l^2)^{\frac{1}{2}} \quad (9)$$

where, A_o and G_o are the amplitude and phase estimated from satellite altimetry. Meanwhile, A_m and G_m are the amplitude and phase produced by tide gauges. N indicates the number of assessment samples. M represents the total tidal constituents used in this study.

Results and Discussion

Along Track TOPEX Class Derived Tidal Constituents

Harmonic analysis method has been adopted in this study to analyse the SSH time series from 23 years of TOPEX class mission. The tidal analysis is done to estimate the selected four major tidal constituents (M2, S2, K1 and O1). Only four tidal constituents are estimated in this study because these tidal constituents can be used to determine the tidal types such as semi-diurnal, diurnal and mixed tides based on the ratio of amplitudes, $(K1+O1)/(M2+S2)-1$, as introduced by Courtier (1983). Besides, as referred to DSMM Tide Observation Record, these four constituents are the most dominant component of tide at most of the Malaysian seas. Figure 2 illustrates the along track at each point of TOPEX class derived tidal constituents. It can be clearly seen that the amplitudes of M2 and S2 are greater in Malacca Straits compared to South China Sea. However, the K1 and O1 are vice versa from the M2 and S2 characteristics. This can be inferred that the classification of tide at Malacca Straits is most likely semi-diurnal tide while at South China Sea is either mixed diurnal tide or diurnal tide. The assumptions of classification tides are aligned with the statement from Hoe (1996) where Peninsular Malaysia is dominated by semi-diurnal tide and mixed dominant semi-diurnal except for the Cendering station which has mixed dominant diurnal tide. Cendering station is located at the east of Peninsular Malaysia facing the South China Sea. The classification of tides can be further proven by calculating the form factor or Courtier coefficient (CC) suggested by Courtier (1983). Semidiurnal, semidiurnal with diurnal inequality, mixed, and diurnal tides are

classified by the CC ratio when $0 < CC \leq 0.25$, $0.25 < CC \leq 1.5$, $1.5 < CC \leq 3.0$, and $CC > 3.0$, respectively.

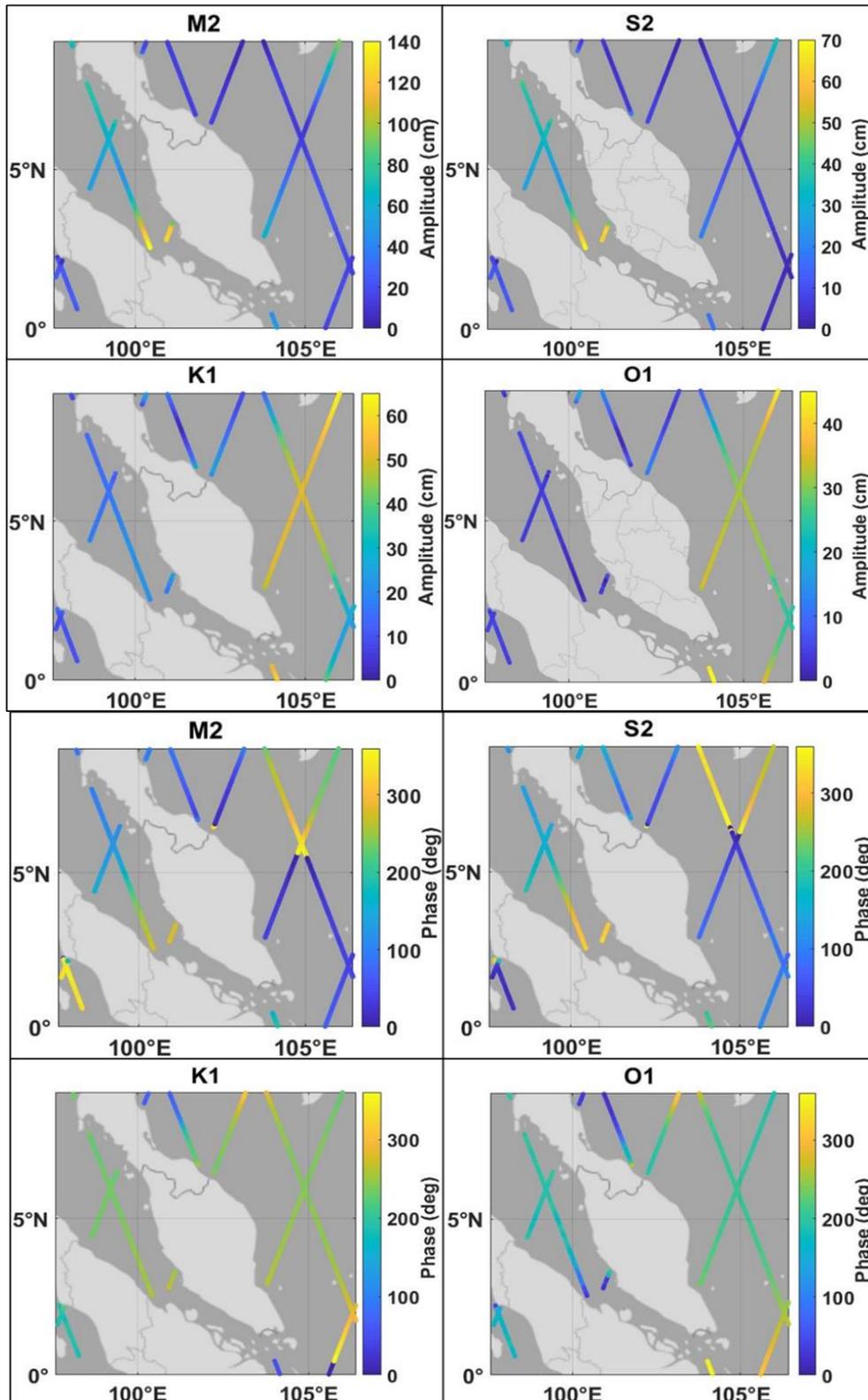


Figure 2: Along Track Satellite (TOPEX class) Derived Amplitude (Top) and Phase (Bottom) of Four Major Tidal Constituents

Comparison with Coastal Tide Gauge Stations

Tidal data from four selected tide gauge stations were used for comparison with the nearest altimetry track. Table 3 shows the locations and distances between tide gauge stations and the nearest altimetry track. Geting station showed the longest distance between tide gauge and altimetry point which is 42.56 km while the shortest distance was at Pelabuhan Kelang which is 36.02 km. Notably that the linear distance is calculated based on two coordinate points.

Table 3: Location and Distance Between Tide Gauges and The Nearest Altimetry Track

Satellite	SDTC		Tide Gauge		Nearest Distance (km)
	Latitude	Longitude	Latitude	Longitude	
P. Tioman	2.904	103.794	2.807	104.138	39.70
Geting	6.568	102.278	6.226	102.105	42.56
Pel. Klang	3.150	101.048	3.051	101.356	36.02
P. Langkawi	6.497	99.417	6.425	99.765	39.26

RMS_{misfit} of tidal constituents between the nearest altimetry track and tide gauges are shown in Figure 3. M2 constituent depicted the highest RMS_{misfit} at all tide gauges involved which is 10.2 cm followed by S2, K1 and O1 constituents which showed 5.7 cm, 1.7 cm, and 1.5 cm, respectively. Large value of RMS_{misfit} from M2 and S2 constituents are probably due to the complexity of the area in which the tide gauges were installed especially at Malacca Straits. According to Oreiro et al. (2014), the predicted RMS_{misfit} grows in proportion to the tidal range. As Gunathilaka and Mahmud (2014) pointed out, the tidal range patterns in the Malacca Straits varies, hence the RMS_{misfit} may be greatly influenced by the tidal range of the location under consideration. Furthermore, tide models used to de-tide SSH are usually more accurate in deep water than near the coast or in the location where there are limited altimetry data. As in this case, it is due to the existence of small islands and a narrow channel.

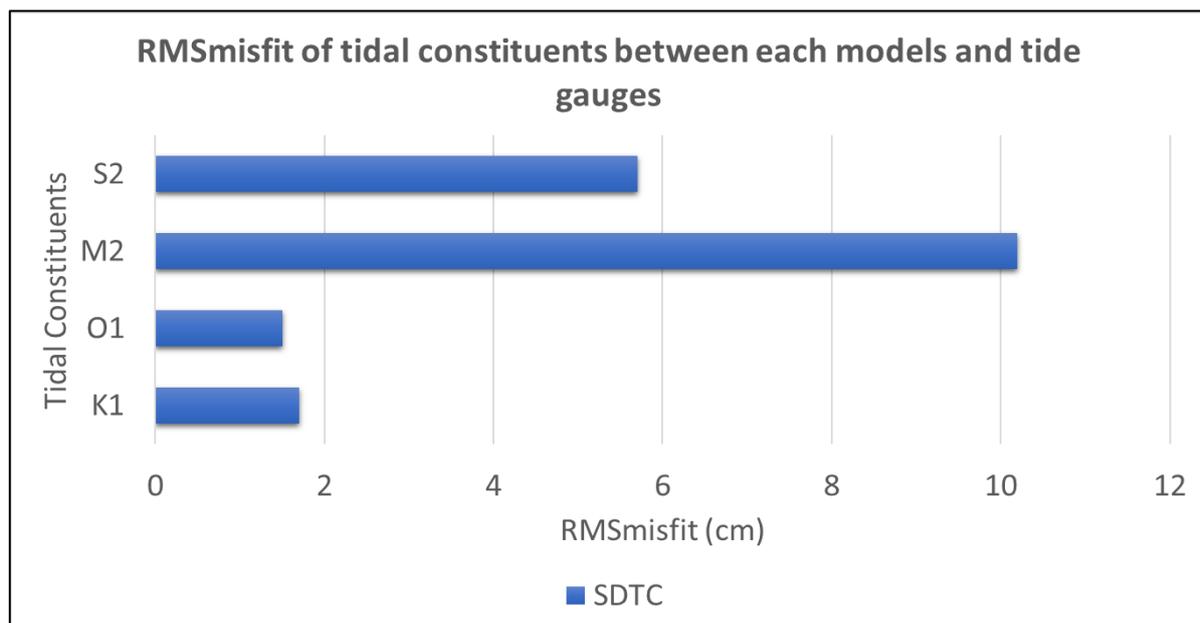


Figure 3: RMS_{misfit} of Four Tidal Constituents Between SDTC and Tide Gauge Stations

RSS value of four major tidal constituents were computed as shown in Figure 4. The number on the top of the bar chart indicates the distance of the nearest altimetry point to the tide gauges. RSS values at Geting and Pulau Tioman showed high precision, which is within 5.0 cm and 5.3 cm, respectively, followed by Pulau Langkawi which recorded RSS value of 9.8 cm. Based on previous study by Fu et al. (2020), the computed RSS value at Pulau Langkawi is within 10-15cm in which the nearest distance of altimetry track with tide gauge station is 39.37km. This can be inferred that the RSS value obtained from this study showed a significant improvement compared to previous study despite of having the approximately similar distance of nearest altimetry track with tide gauge. This might be due to the different corrections applied to the SSH altimetry measurement before the tidal analysis was performed. An appropriate RSS limit value should be specified. Based on Daher et al. (2015), it is assumed that the model results in the shallow-water zone are classified as satisfactory (or acceptable) if the RSS value is less than 12cm. Pelabuhan Kelang displayed the lowest precision where the RSS value is 21.2 cm. Both tide gauges at Malacca Straits exhibited higher values of RSS values than South China Sea because this area is a closed and narrow sea channel and has shallow depth. This can be seen that Pelabuhan Kelang station which was located at the narrow channel of Malacca Straits and obstructed by few small islands as shown in Figure 5. These reasons are most likely caused the tidal constituents having a large gradient.

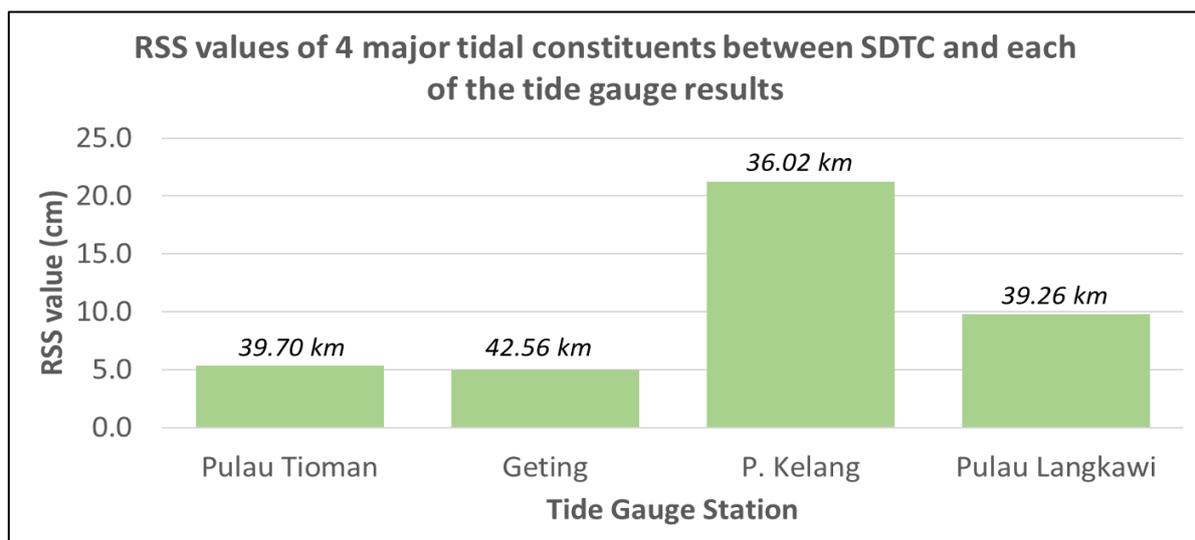


Figure 4: RSS Values of Four Major Tidal Constituents at Each Selected Tide Gauges



Figure 5: Obstruction of Few Small Islands Near Pelabuhan Klang Tide Gauge Station

Consistency of Tidal Constituents at Ascending and Descending Pass

Harmonic analysis is performed at the crossover of satellite altimetry track. This is to assess the consistency of satellite derived tidal constituents at the crossover of ascending and descending pass. It is essential to evaluate this consistency because satellite altimetry is usually moving along its orbit in ascending and descending track. The intersection between ascending and descending track called crossover point should obtained almost similar value of estimated tidal constituents. As observed in Figure 1, there are two crossover points identified where one point is at South China Sea and the other is at Malacca Straits. The statistical result of the crossover difference for each tidal constituent is tabulated in Table 4. The RMS amplitudes difference of four tidal constituents (M2, S2, K1 and O1) between ascending and descending track at both crossover points showed good agreement which is within the range of 0.16 cm to 0.52 cm. In term of phases, the RMS difference values showed consistent results which is within 0.37° to 1.32° . Therefore, it can be inferred that the satellite derived consistent tidal constituents along ascending and descending track as the RMS recorded small difference values. The outcomes showed promising result compared to the previous study by Ainee (2016). As the previous study only focused within the SCS area, the RMS amplitudes difference of four tidal constituents recorded 0.68 cm to 5.50 cm at four selected crossover points. Meanwhile, the RMS phases difference recorded 3.44° to 155.71° .

Table 4: Statistical Result of Crossover Difference for Each Tidal Constituent

Region	Amplitude (cm)				Phase (deg)			
	M2	S2	K1	O1	M2	S2	K1	O1
Malacca Straits	0.31	0.45	0.31	0.39	-1.91	-0.32	-0.34	0.53
South China Sea	0.27	0.12	-0.09	0.98	-1.83	-0.97	1.42	-0.53
<i>Average</i>	<i>0.29</i>	<i>0.28</i>	<i>0.11</i>	<i>0.68</i>	<i>-1.87</i>	<i>-0.64</i>	<i>0.54</i>	<i>0.00</i>
<i>RMS</i>	<i>0.29</i>	<i>0.23</i>	<i>0.16</i>	<i>0.52</i>	<i>1.32</i>	<i>0.51</i>	<i>0.73</i>	<i>0.37</i>

Conclusion

This paper studied an analogy between the satellite radar altimetry and tide gauges derived from four major tidal constituents which are M2, S2, K1 and O1. Before comparison was made, both satellite altimetry and tide gauge data were analysed to estimate the tidal constituents at the particular locations. SSH time series from TOPEX class consist of TOPEX, Jason-1 and

Jason-2 missions were used in this study for tidal analysis. Harmonic analysis method was adopted for both data sources to estimate the tidal constituents. Four tide gauges were used for the purpose of comparison with the nearest altimetry points from tide gauges.

The comparison results showed that the RMS_{misfit} of each tidal constituent agreed well between each other where the values are less than 10 cm except for M2 constituents which recorded slightly more than 10 cm. This might be due to the complexity area within the Malacca Straits, thus, contributing the RMS_{misfit} to be larger. In term of RSS values at each tide gauge, Pulau Tioman and Geting have high precision of tidal constituents which exhibited within the range of 5 cm. Tide gauge at Pelabuhan Kelang showed the highest RSS values followed by Pulau Langkawi which are 21.2 cm and 9.8 cm respectively. Both of these tide gauges located at Malacca Straits where its geography is a narrow channel that most likely contributed large gradient of tidal constituents. Apart from that, the satellite radar altimetry displayed good consistency in estimating the tidal constituents where the RMS crossover differences of amplitude and phase recorded the values of 0.16 cm – 0.52 cm and $0.37^\circ - 1.32^\circ$, respectively.

In conclusion, satellite altimetry is one of the important tools for exploring the ocean activities as well as it could assist in investigating the tidal behaviour in the open sea. This study proved that the satellite derived tidal constituents are agreed well to the coastal tide gauges. However, further studies need to be done to produce high precision tide models, for instance, by increasing the used of tide gauges as well as merging more satellite missions with different types of orbit track to increase the spatial resolution. Furthermore, it is also recommended to investigate the shallow-water tidal constituents in future studies especially in the shallow water where the dynamics become nonlinear and tidal spectra apparently seems to be more complicated.

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