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Deriving offshore tidal datums using satellite altimetry around Malaysian seas

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Abstract. Tidal datums are important for calculating spatial coordinates especially the elevation relative to mean sea level and also crucial for defining the state sovereignty boundaries over maritime areas. Normally, sea level was measured by tide gauges along the coastal for tidal datums computation. However, knowledge of tides is still restricted in coastal areas. Furthermore, tidal range at offshore was simply assumed to be similar as coastal due to the difficulties installing offshore tide gauges. The launching of satellite altimeter technologies with precise orbit determination since 1993 had provided significant accuracy of sea surface height (SSH) measurements. The observed SSH from satellite altimetry can be offered as tide gauge measurements at each location globally. This study aims to derive offshore tidal datums using satellite altimetry around Malaysian seas. SSH time series from TOPEX, Jason-1, Jason-2 and Geosat Follow On (GFO) were analysed using harmonic analysis approach to estimate harmonic constants. A minimum of 19 years tidal predictions were then performed using UTide software to determine Lowest Astronomical Tide (LAT) and Highest Astronomical Tide (HAT). These tidal datums were interpolated into regular 0.125° grids and were assessed with ten selected coastal tide gauges. The findings showed the Root Mean Square Error (RMSE) of spline interpolation yielded better accuracy, 25.5 cm (LAT_{MSL}) and 17.4 cm (HAT_{MSL}) as compared to the RMSE of Kriging interpolation, 31.8 cm (LAT_{MSL}) and 33.8 cm (HAT_{MSL}). In conclusion, deriving offshore tidal datums can serve as input data to unify marine database with coastal areas and also can support many marine applications.

Keywords: Tidal datums, Offshore, satellite altimetry, Lowest Astronomical Tide, Highest Astronomical Tide

Track Name: Coastal Management and Marine Ecosystem

1. Introduction

Tides are usually defined as the vertical periodic rise and fall of water on the surface of the earth that occurs twice in a little more than a day. According to [1], tides are also described as the periodic variation in the level surface of the ocean, inlets, bays, gulfs and estuaries resulting from the gravitational forces of the moon and the sun. Scientists have worked for the past two centuries to headway scientific knowledge of ocean tides [2]. The process of measuring tides is known as tidal observation by using an equipment called tide gauge station. Statistically averaging sea level measurements is the process of stabilising a fluctuating surface to serve as tidal datum [3]. There are many ways to average sea level which giving rise to a variety of tidal datums. Tidal datums are defined as a standard reference elevation used from which to reckon heights or depths in terms of a certain phase of the tide [4, 5, 6]. They are predominantly used to measure depth or water level as well as critical in defining spatial coordinates such as latitude, longitude and elevation with respect to Mean Sea Level (MSL). Not only that, they are also important as legal bodies for establishing the state sovereignty over maritime boundaries.

In determining the tidal datums, tides generally measured by tide gauges along the continental coastline which refer to coastal tide gauges. Although the long-term sea level observations can enhance the understanding of tides, the knowledge is still constrained in the vicinity of coastal areas. [2] stated that the tide measurements further away from coastal made by bottom pressure gauges is slow and less effective. In Malaysia, Department of Survey and Mapping Malaysia (DSMM) is the authority responsible for acquiring, processing, archiving and disseminating the long-term tidal data [7]. At present, there are eleven tide gauge stations along the Peninsular Malaysia coast (West Malaysia) and eight tide gauge stations along the coast of Sabah and Sarawak (East Coast). However, less discoverable on offshore tidal datums in this region is due to the difficulties installing the offshore tide gauges. There might be few offshore tide gauges being installed which could only restricted with the used by the offshore companies. In the past, the tidal range at the coastal was simply inferred to be similar to offshore and the tide phase was computed using shallow water wave theory [8].

Credit goes to an active remote sensing technique so called satellite altimetry, launched in 1970s that provided a comprehensive technique in measuring the global ocean. Satellite altimetry has been used by certain researchers to investigate ocean activities in the specific regions. For instance, [9] analyze the SSH from TOPEX series satellites of 19-year time series to extract the tidal harmonic constants in the Brazilian coast. It shows the Root Sum Square misfit (RSSmisfit) values are less than 12 cm in deep ocean. Besides, [2] has developed an empirical ocean tide models namely OSU12 models by utilizing an enhanced multi-mission satellite altimetry data from TOPEX, Jason-1/-2, Envisat and GFO based on a novel method via spatio-temporal combination, together with a robust estimation technique. The study shows substantial improvement which apparently in regions with high hydrodynamic variability. In Malaysia, [10] has studied on the derivation of tidal constituents from satellite altimetry for coastal vulnerability assessment. It used Mean Tidal Range parameter derived from tidal models where the tidal models were generated from TOPEX and Jason-1 data. The used of tidal models are projected to supplement the existing coastal management system in order to scrutinize the severity of coastal damages caused by sea level rise impacts, particularly in Malaysian coastal areas. Furthermore, Yahaya et al. [11] and Zulkifle et al. [12] have developed regional mean sea surface (MSS) models for Malaysian seas using multi-mission satellite altimetry data. This study generated MSS model by merging 11 years of repeated SSH observations from several satellite altimeter missions.

The improvement of precise orbit determination technique, instrumental and geophysical corrections have provided better accuracy of sea surface height (SSH) measurements since the launch of TOPEX/Poseidon mission [13]. The obtained SSH from satellite altimetry revisits at the similar point for each orbit cycle can be offered as tide gauge measurements at each location globally. Therefore, this study is an attempt to derive offshore tidal datums using satellite altimetry around Malaysian seas. SSH time series of TOPEX class (TOPEX, Jason-1 and Jason-2) and GFO missions were analysed using harmonic analysis approach to estimate the amplitude and phase of eight selected

harmonic constants namely M2, S2, K1, O1, N2, K2, P1, Q1, MF, MM, SA and SSA. These harmonic constants were then used for tidal prediction of at least 19 years to determine the tidal datums. The tidal datums referred in this study are Lowest Astronomical Tide (LAT) and Highest Astronomical Tide (HAT) relative to MSL. Section 2 describes the materials and method, followed by results and discussion in section 3. Lastly, section 4 concludes the overall study.

2.   Materials and method

2.1 Study Area and Datasets

Along track SSH from TOPEX class and GFO missions were extracted using Radar Altimeter Database System (RADS). The extracted SSH data spanning over 23 years for joint TOPEX class and 8 years for GFO mission as listed in table 1. TOPEX, Jason-1 and Jason-2 missions are denoted as TOPEX class because these missions are moving on the same orbit track. The study area was bounded within the geographical coordinates of 0° N - 9° N in latitude and 98° E - 121° E in longitude. Figure 1 illustrates the study area limited to the specified coordinates as well as the along track TOPEX class mission (blue) and GFO mission (green). The black triangles indicate the coastal DSMM tide gauge stations used to assess the estimated offshore tidal datum. Meanwhile, the red points are randomly selected for visualization of SSH time series.

Table 1. List of satellite altimetry data used.

Satellite Mission	Phase	Cycle	Period Time
TOPEX	A	001-364	January 1993 – August 2002
Jason-1	A	001-260	January 2002 – January 2009
Jason-2	A	001-303	July 2008 – October 2016
GFO	A	037-223	January 2000 – September 2008
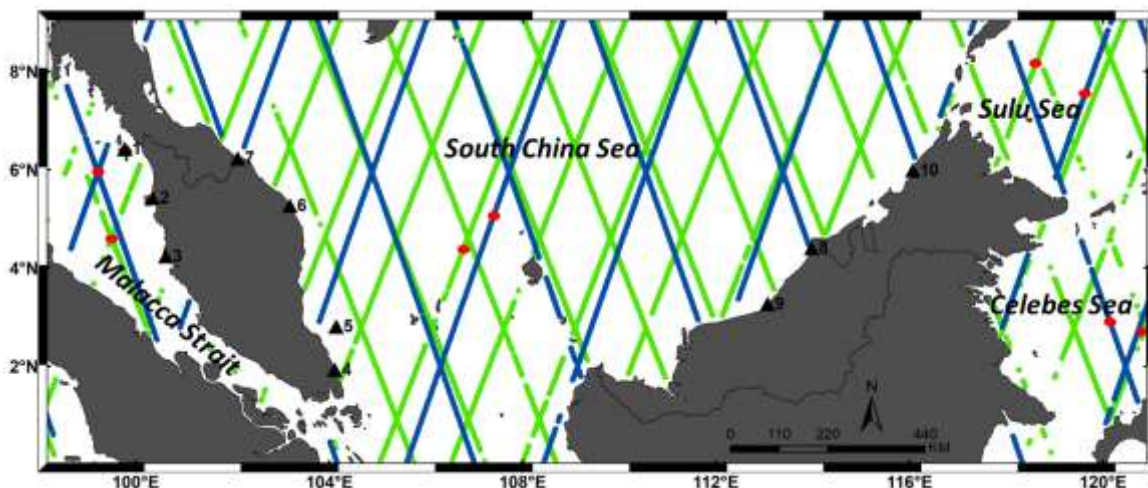
Figure 1. Along-track altimetry missions of TOPEX class (blue) and GFO (green) within the study area as well as the distribution of selected coastal DSMM tide gauge (black triangle).

### 2.2 Satellite Altimetry Processing and Formation of SSH Time Series

As aforementioned, all satellite altimetry used in this study were extracted using RADS server in Universiti Teknologi Malaysia (UTM), providing the latest information on orbits and geophysical corrections. The computation of SSH were processed by applying the preferred range and geophysical correction in the Malaysian region, removing the invalid data and also generating the corresponding refined corrections. SSH altimetry can be derived by using the equation (1) [10,14,15].

$$h_{ssh}^{obs} = H_{alt} - R_{obs} - (h_{dry} + h_{wet} + h_{ion} + h_{ssb} + h_{sol} + h_{pole} + h_{ocean} + h_{DAC} + \varepsilon) \qquad (1)$$

Where, h_{ssh}^{obs} 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_{ssb} is the sea state bias correction, h_{sol} is the solid earth tide correction, h_{pole} is the pole tide correction, h_{ocean} is the ocean tide correction, h_{DAC} is the dynamic atmospheric correction and ε is the other errors induced in altimetry measurement. However, it is noted that h_{ocean} was excluded from being applied into the equation. This is to prevent the ocean tide signal to be eliminated as this signal is crucial in estimating harmonic constants.

2.2.1 Formation of SSH Time Series
This is done by extraction of SSH at each cycle of discrete points. Ground tracks of altimetry with repeated orbit missions generally do not coincide accurately with each other. Thus, collinear analysis is utilised to compute each SSH point of collinear tracks similar to the reference track. In this study, the collinear track of first cycle was treated as the reference track. Thus, from the reference track and corresponding collinear track, the formation SSH time series can be plotted as shown in figure 2.
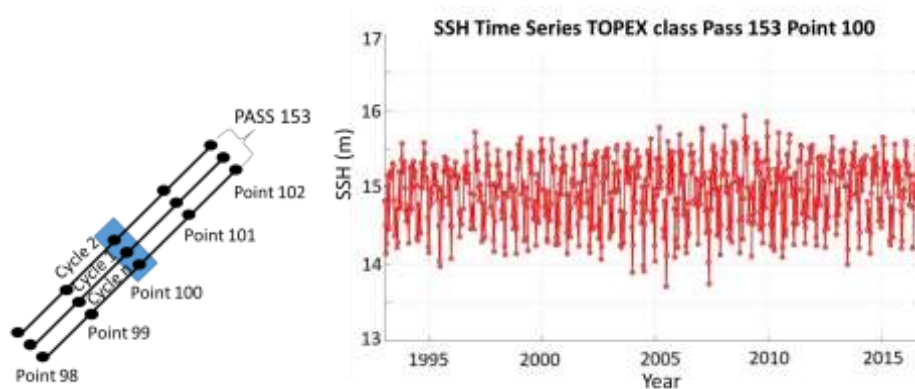
Figure 2. Schematic diagram on formation of SSH time series.

2.2.2 Tidal Aliasing.
TOPEX class and GFO missions have different repeated periods which are 9.9156 days and 17.0505 days, respectively. Thus, both missions suffer from tidal aliasing effect due to altimeter's long temporal sampling. According to Shannon sampling theorem, in order to completely rebuild the original signal, it must be sampled at least twice of the frequency, f_s. For instance, $f_N = 2f_s$, where f_N is the Nyquist frequency. A signal with period T_s can be completely rebuild if the samples are obtained at interval of less than $T_s/2$. If not, the signal of T_s are aliased to a longer period to T_a, which is aliased period [2,16]. The aliasing period can be computed by using the equation (2) [17].

$$T_a = \frac{2\pi \Delta s}{2\pi (f \Delta s - [f \Delta s + 0.5])} \qquad (2)$$

Where, f is the frequency of tidal component, Δs is the period sample and the bracket [.] in the formula of $[f \Delta s + 0.5]$ is the fix function that return greatest integer less than argument. The information of actual period and aliased period from TOPEX class and GFO missions are tabulated in Table 2. The aliased period obtained from both missions are calculated by using equation (2). The consequence of the aliasing effect on tide signals detected from altimetry mission is that the length of each tidal constituent appears to be longer than its actual period. The aliasing period of each constituent is used in harmonic analysis to estimate amplitude and phase as well as for tidal prediction.

Table 2. Actual and Aliased Tidal Period for TOPEX class (9.9156 days) and GFO (17.0505 days).

Tidal Constituents	Actual Period (cph)	Actual Period (cpd)	TOPEX Aliased Period (cpd)	GFO Aliased Period (cpd)
M2	12.42	0.52	62.11	317.11
S2	12.00	0.50	58.74	168.82
K1	23.93	1.00	173.19	175.45
O1	25.82	1.08	45.71	112.95
N2	12.66	0.53	49.53	52.07
K2	11.97	0.50	86.60	87.72
P1	24.07	1.00	88.89	4467.14
Q1	26.87	1.12	69.36	74.05
MF	327.86	13.66	36.17	68.71
MM	661.31	27.55	27.55	44.73
SSA	4382.92	182.62	182.62	182.62
SA	8765.74	365.24	365.26	365.26

Notes: cph = cycle per hour, cpd = cycle per day

2.3 Tidal Analysis and Prediction

Harmonic analysis approach was adopted for tidal analysis and prediction in this study. This analysis is performed using MATLAB package 'Unified Tidal analysis and prediction' or UTide, developed by [18]. Based on [18], the UTide was built on the foundation of T_TIDE by [19], integrating concepts from [20] and [21]. SSH time series from TOPEX and GFO missions were analysed to estimate the selected tidal harmonic constants at each point of along-track. Then, these estimated tidal harmonic constants (amplitudes and phase lags) were put into tidal harmonic prediction equation in order to predict the tides. A tidal prediction can be computed by summing up the oscillating contributions of some number of tidal constituents. The formula for tidal analysis and prediction used in this study are expressed in the equation (3) [16, 18, 22].

$$H(\varphi, \lambda, t) = Z_0(\varphi, \lambda) + \sum_{k=1}^{n} f_k A_k(\varphi, \lambda) \cos[\omega_k t + V_{0k} + u_k - G_k(\varphi, \lambda)] \qquad (3)$$

Where, $H(\varphi, \lambda, t)$ is the sea level for predefined time (t) at discrete location (φ, λ). $Z_0(\varphi, \lambda)$ is the mean sea level of analysed data and n represents the total number of tidal constituents used; A_k, ω_k and G_k represent the amplitude, frequency and delay phase of ith tidal constituents, respectively; V_{0k} is the astronomical argument, while f_k and u_k are nodal factor and nodal phase, respectively. Based on [23], LAT and HAT can be computed over a minimum of 19 years using harmonic constants estimated from at least 19 years of tidal data or other method known to produce reliable results. However, according to [24], using 19 years of tidal prediction to compute LAT and HAT are always reasonable. Thus, in this study, the tides were predicted for at least 19 years to determine the tidal datums.

2.4 Tidal Interpolation Method

The generation of tidal datums surfaces in this study involves two interpolation method namely Ordinary Kriging (OK) and a minimum curvature (MCr) technique called (regularised) spline. Both methods were used to interpolate the along-track altimetry data into a regular grid of 0.125°. Both were assessed to determine the best interpolation method for generation of tidal datums surfaces. Assessment was performed by comparing the interpolated points with the selected coastal tide gauges.

2.4.1 Ordinary Kriging

Kriging is a geostatistical interpolation method which is based on statistical models inclusive of autocorrelation. This method fits a mathematical function to specific points or all points within the specific radius to determine the output value of predicted locations. The formula is expressed in equation (4) [25, 26].

$$\hat{Z}(s_0) = \sum_{i=1}^{N} \lambda_i Z(s_i) \tag{4}$$

Where, $Z(s_i)$ is the measured value at the ith location; λ_i is an unknown weight for the measured value at the ith location; $\hat{Z}(s_0)$ is a predicted value and N is the total number of measured values.

2.4.2 Minimum Curvature Spline

This method is widely used in the earth sciences. The interpolated surface is equivalent to a thin, linearly elastic plate moving through each data with the minimum amount of bending [20]. The formula for spline interpolation is expressed in equation (5) [27, 28].

$$S(x,y) = T(x,y) + \sum_{j=1}^{N} \lambda_j R(r_j) \tag{5}$$

Where, N is the number of points, λ_j is the coefficient found by the solution of linear equations and r_j is the distance between point (x,y) and jth point. Since this study applied the regularised option, $T(x,y)$ and $R(r)$ were expressed in the equation (6) and (7).

$$T(x,y) = a_1 + a_2x + a_3y \tag{6}$$

Where, $a_1, a_2 \dots$ are the coefficient found by the solution of linear equations.

$$R(r) = \frac{1}{2\pi}\left\{\frac{r^2}{4}\left[\ln\left(\frac{r}{2\tau}\right) + c - 1\right] + \tau^2\left[K_o\left(\frac{r}{\tau}\right) + c + \ln\left(\frac{r}{2\pi}\right)\right]\right\} \tag{7}$$

Where, r is the distance between the point and sample, τ^2 is the weight parameter, K_o is the modified Bessel function and c is the constant equal to 0.577215.

2.5 Statistical Data Assessment

The Root Mean Square Error (RMSE) is used to measure the quality of the results where it computes the difference between the predicted values and the true values. In this study, there are two statistical data assessment were performed. First, the RMSE was calculated to determine the reliability of the predicted SSH derived from satellite altimetry by comparing with the observed SSH. Second assessment was performed by calculating the RMSE values between the interpolated points from two interpolation techniques and the selected coastal tide gauges which can be expressed in equation (8).

$$RMSE = \sqrt{\frac{\sum(x_p - x_t)^2}{n}} \tag{8}$$

Where, x_p is the predicted values (i.e., interpolated points), x_t is the true value which is the coastal tide gauges, and n is the total number of samples. However, for the first assessment, x_p is indicated as predicted SSH values while x_t is the observed SSH values.

3. Results and Discussion

3.1. Time Series Modelling and Residuals

SSH time series of TOPEX class and GFO missions were modelled by applying the equation (3). These time series were predicted at each point of along-track altimetry as illustrated in figure 1. Each point from the along-track of predicted SSH time series were randomly selected (labelled as red dots

in figure 1) at each Malaysian sea's regions namely the Malacca Straits, the South China Sea, the Sulu Sea, and the Celebes Sea. This is to visualise the modelled time series. It is noted that the point must be selected at the offshore area. Figure 3 shows the selected SSH modelled time series and its residuals from TOPEX class on the left column well as GFO mission on the right column. The observed and predicted SSH time series are plotted in blue and green lines, respectively. Meanwhile, the red plotted lines indicate as the residuals of SSH time series. These residuals were calculated by computing the differences between the predicted and observed SSH time series. Subsequently, the quality of the predicted SSH can be determined based on these residuals by using RMSE computation. It can be seen that the SSH time series data from TOPEX class is denser than GFO mission. This is because the repeated period of TOPEX class is shorter than GFO which is 9.9156 days and 17.0505 days, respectively. The highest RMSE value between observed and predicted SSH from TOPEX is at Malacca Straits which recorded 10.1cm, followed by Celebes Sea (9.8 cm), Sulu Sea (7.6 cm) and South China Sea (7.3 cm). This might be due that Malacca Straits is a closed sea area which the tidal characteristics would most likely have a large gradient. Nevertheless, the highest RMSE value from GFO mission is at Celebes Sea which recorded 10.9 cm, followed by Malacca Straits (7.9 cm), Sulu Sea (7.0 cm) and South China Sea (6.5 cm). Therefore, it can be inferred that the precision of tidal prediction from both missions were reasonable at offshore area since the RMSE is within 10.9 cm to 6.5 cm.
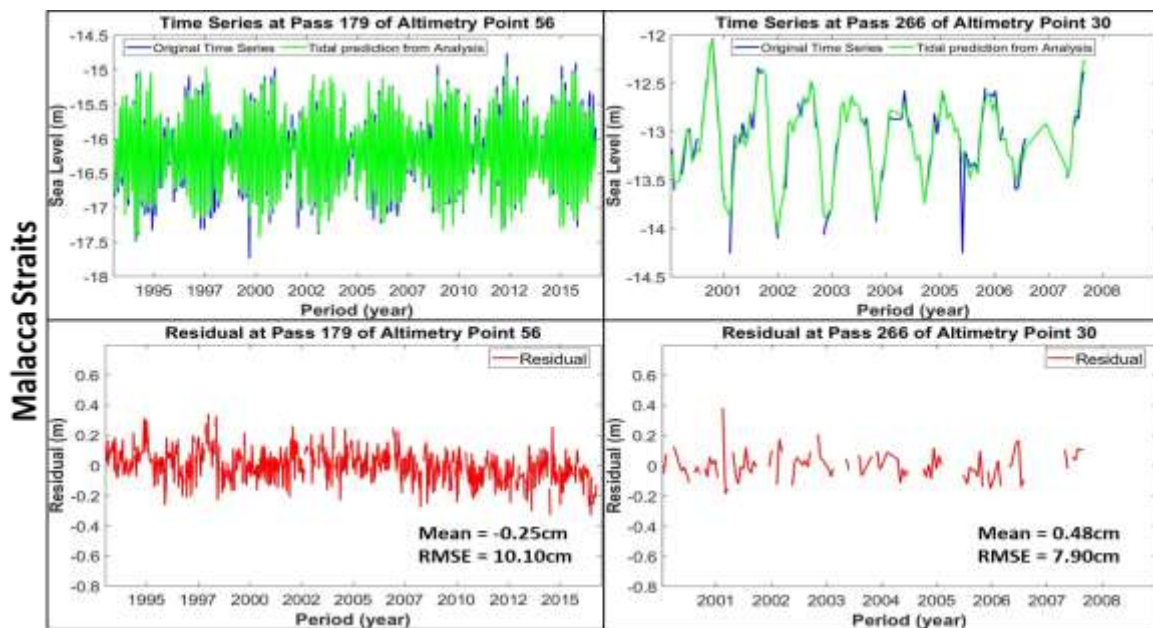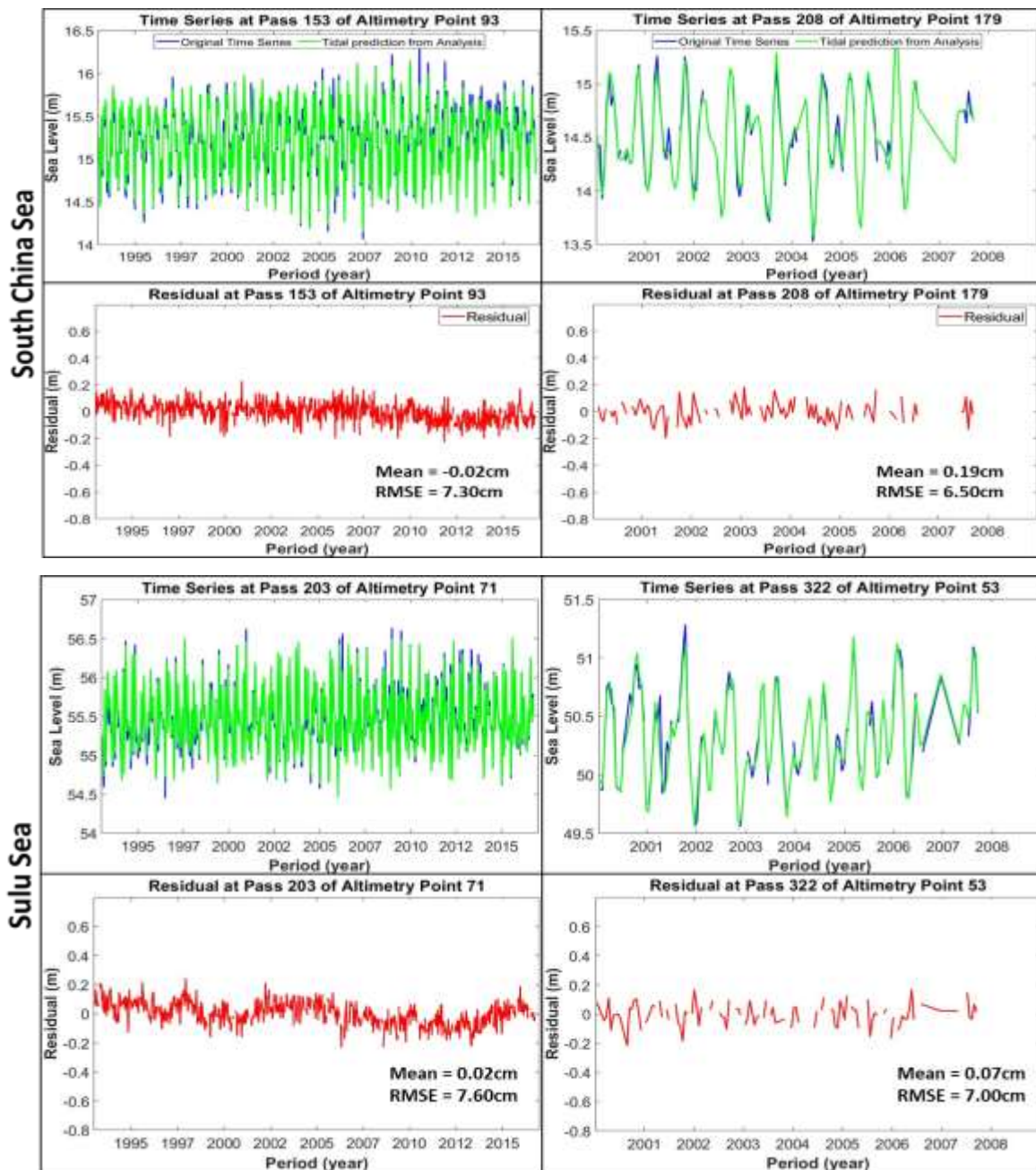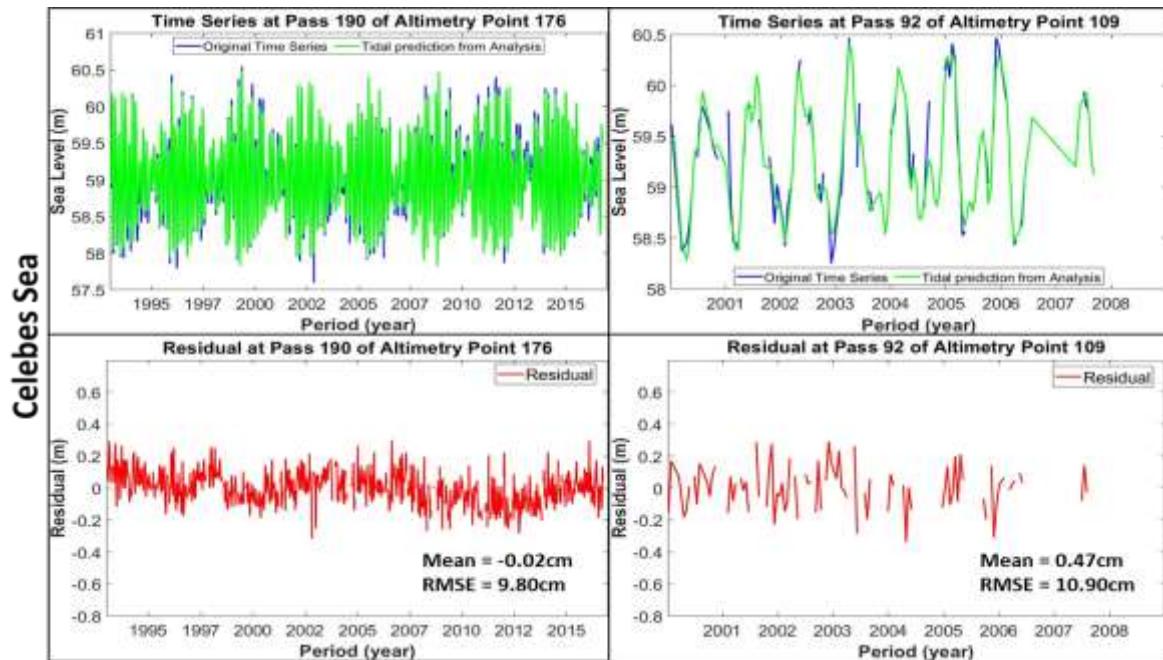
Figure 3. Observed (blue) and predicted (green) time series and residuals (red) of TOPEX class (left) and GFO (right) missions according to the areas (Malacca Straits, South China Sea, Sulu Sea and Celebes Sea).

3.2. LAT and HAT with respect to MSL

LAT and HAT can be defined as the lowest or (highest) water level which can be predicted to occur under average meteorological conditions as well any combination of astronomical conditions. Both may be derived by the analysis of a number of years of tidal data or predictions which is normally 18.6 years to account for the full nodal cycle. In this study, the SSH time series from both missions were predicted for at least 19 years or more where predicted time series from TOPEX class is between 1993 until 2019. Meanwhile, predicted time series from GFO is between 2000 until 2019. The lowest and highest predicted tide indicate the LAT and HAT, respectively. Later, the derived LAT and HAT from satellite altimetry were interpolated and validated against the selected coastal DSMM tide gauges as distributed in Figure 1. Before the results could be compared with the tide gauges, the derived data need to be converted with respect to MSL. The computation of LAT and HAT with respect to MSL was depicted in Figure 4.
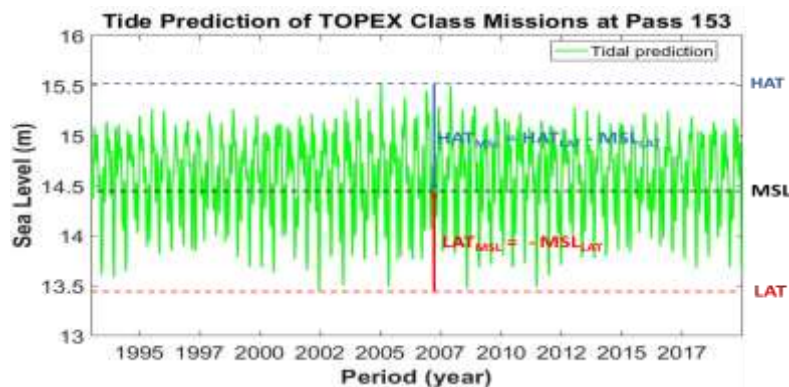
Figure 4. Computation diagram of LAT and HAT are relative to MSL.

Along-track satellite derived tidal datums from TOPEX class and GFO missions had to be merged together before being interpolated into a regular grid. Crossover offset was applied to the along-track

GFO mission to a TOPEX reference surface in order to minimise the orbital track errors and the discrepancy of satellite's orbit frame between two missions. The combination of TOPEX class and GFO along-track missions (LAT$_{MSL}$ and HAT$_{MSL}$) were then interpolated into a regular grid of 0.125° by using ordinary kriging and minimum curvature spline method as shown in Figure 5. Based on Figure 5, it can be seen that the middle of the Malacca Straits has the greatest tidal range of LAT$_{MSL}$ and HAT$_{MSL}$ compared to other regions which recorded up to -2.6 m and 3.0 m, respectively. The tidal range of LAT$_{MSL}$ and HAT$_{MSL}$ in the middle of South China Sea, Sulu Sea, and Celebes Sea show the values within -0.9 m to -1.1 m (LAT$_{MSL}$) and the values within 0.9 m to 1.2 m (HAT$_{MSL}$). The greatest tidal range of LAT$_{MSL}$ and HAT$_{MSL}$ also can be seen at the southwest of East Malaysia in the South China Sea which recorded up to -2.1 m and 2.2 m, proportionately. Meanwhile, at the north-western part of South China Sea, near to the Gulf of Thailand depicted the lowest tidal range of LAT$_{MSL}$ and HAT$_{MSL}$ which recorded the values near to zero meter. Apparently, the tidal ranges are mostly larger near to the coastal areas compared to the offshore areas. It is visible at the coastal part of Celebes Sea as shown in Figure 5. The reason is due to the satellite altimetry data acquired near the coastlines are contaminated by the inclusion of land in the footprint signal or by the fact that the tide is on the ebb [2]. Moreover, the tidal datum models using ordinary kriging method generated smoother contour lines as compared to minimum curvature spline method. However, these gridded offshore tidal datum models were validated with the selected coastal tide gauges in order to identify the best interpolation method.
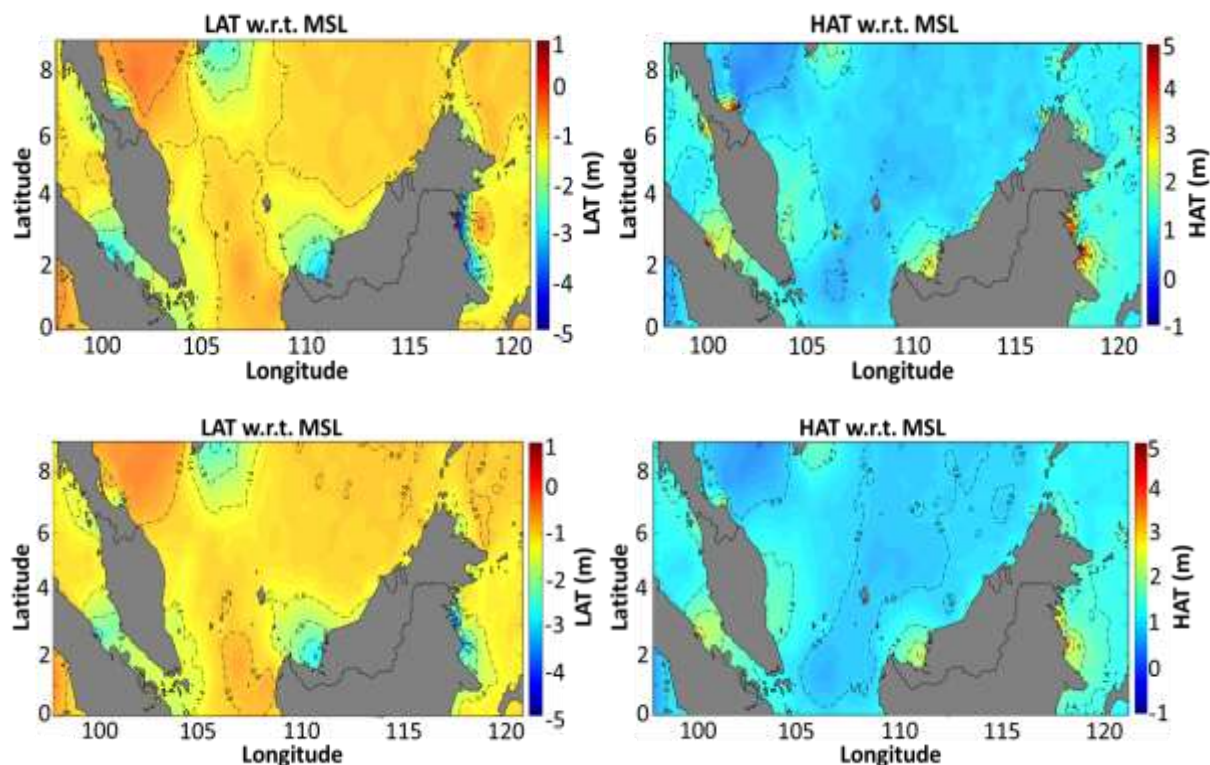
Figure 5. LAT$_{MSL}$ and HAT$_{MSL}$ models using ordinary kriging (Top) and minimum curvature spline (Bottom).

3.3. Statistical Assessment of Tidal Models

Generally, the best way to validate these offshore tidal datums are by comparing them with the offshore tide gauges. However, lack of deployment offshore tide gauges as well as difficulty in obtaining the offshore tidal data from the offshore authorities had hindered this validation method. Thus, this study adopted the statistical assessment of offshore tidal datums by validating the satellite

altimetry derived offshore tidal datums models with ten selected DSMM tide gauges. The results of the assessment were described in Table 3 (LAT$_{MSL}$) and Table 4 (HAT$_{MSL}$).

Table 3. Statistical results between satellite derived offshore LAT$_{MSL}$ (ordinary kriging and minimum curvature) and in situ tide gauge data (Units in meter).

Tide Gauge	Station	In Situ	Ordinary Kriging	Minimum Curvature	Ordinary Kriging – In Situ	Minimum Curvature – In Situ
1	P. Langkawi	-1.781	-1.758	-1.516	0.023	0.265
2	P. Pinang	-1.662	-1.117	-1.330	0.545	0.332
3	Lumut	-1.800	-1.293	-1.425	0.507	0.375
4	Tg. Sedili	-1.684	-1.389	-1.428	0.295	0.256
5	P. Tioman	-1.894	-1.584	-1.529	0.310	0.366
6	Cendering	-1.395	-1.210	-1.219	0.185	0.176
7	Geting	-0.717	-0.724	-0.919	-0.007	-0.202
8	Miri	-1.135	-1.212	-1.274	-0.077	-0.139
9	Bintulu	-1.389	-1.689	-1.528	-0.300	-0.139
10	K. Kinabalu	-1.223	-0.843	-1.089	0.380	0.134
				Mean	**0.186**	**0.142**
				STD	**0.258**	**0.211**
				RMSE	**0.318**	**0.255**

Table 4. Statistical results between satellite derived offshore HAT$_{MSL}$ (ordinary kriging and minimum curvature) and in situ tide gauge data (Units in meter).

Tide Gauge	Station	In Situ	Ordinary Kriging	Minimum Curvature	Ordinary Kriging – In Situ	Minimum Curvature – In Situ
1	P. Langkawi	1.751	1.915	1.482	0.164	-0.269
2	P. Pinang	1.391	1.508	1.413	0.117	0.022
3	Lumut	1.578	1.449	1.458	-0.129	-0.120
4	Tg. Sedili	1.429	1.045	1.189	-0.384	-0.240
5	P. Tioman	1.762	1.609	1.559	-0.153	-0.203
6	Cendering	1.527	1.472	1.429	-0.055	-0.098
7	Geting	1.012	1.020	1.027	0.008	0.015
8	Miri	1.182	1.180	1.173	-0.002	-0.009
9	Bintulu	0.977	1.901	1.298	0.924	0.321
10	K. Kinabalu	1.213	0.974	1.141	-0.240	-0.072
				Mean	**0.025**	**-0.065**
				STD	**0.337**	**0.161**
				RMSE	**0.338**	**0.174**

For offshore tidal datum of LAT$_{MSL}$, the RMSE values obtained between the minimum curvature spline model and in situ data is smaller than the ordinary kriging model which recorded 25.5 cm and 31.8 cm, respectively. Meanwhile, the RMSE values of HAT$_{MSL}$ between minimum curvature spline

and in situ data is also smaller than the ordinary kriging model which yielded 17.4 cm and 33.8 cm, respectively. Thus, it can be inferred that the offshore tidal datums models generated using minimum curvature spline method has better agreement with coastal tide gauges compared to ordinary kriging models despite ordinary kriging produced smooth contour surfaces.

4. Conclusion

This paper generally studies on deriving the offshore tidal datums using SSH satellite altimetry data from TOPEX class and GFO missions around Malaysian seas bounded to the latitude of $0°$ N - $9°$ N and longitude of $98°$ E - $121°$ E. SSH time series of both missions were analysed by adopting harmonic analysis approach to estimate the selected tidal constituents. The estimated tidal constituents were then used to predict the tides at each of along-track altimetry time series points. The outcomes from this study illuminated that the predicted and observed tides at offshore areas have good precision which yielded the RMSE values within 6.5 cm to 10.9 cm. The models of LAT_{MSL} and HAT_{MSL} were generated by using two different interpolation methods namely ordinary kriging and minimum curvature (regularised) spline and were assessed with selected coastal tide gauges. The results showed the models (LAT_{MSL} and HAT_{MSL}) adopting regularised spline method have the smallest RMSE values which indicates the best interpolation method. Therefore, it can be concluded that the regularised spline method is the best interpolation method in this study to predict the offshore tidal datum compared to the ordinary kriging method.

In conclusion, this study indirectly can create an awareness towards Malaysian hydrographic society especially regarding the importance of satellite altimetry in supporting hydrographic survey practice. The encouraging results from this study are capable in establishing seamless vertical datum by integrating the tidal datums between coastal and offshore area. Other than that, deriving tidal datum is necessary to support in the establishment of marine boundaries as well as the requirement for conducting shoreline mapping.

References

[1] Rahibulsadri R *et al* 2014a Determination of Tidal Datum for Delineation of Littoral Zone for Marine Cadastre in Malaysia. In: Abdul Rahman A., Boguslawski P., Anton F., Said M., Omar K. (eds) *Geoinformation for Informed Decisions*. Lecture Notes in Geoinformation and Cartography. 219-230

[2] Fok H S 2012 Ocean Tides Modeling using Satellite Altimetry *Ohio State University Geodetic Science Report no.* **501**

[3] Hands E B 2005 Tidal Datums. In: Schwartz M.L. (eds) Encyclopedia of Coastal Science. *Encyclopedia of Earth Science Series*. Springer, Dordrecht.

[4] Gill S K and Schultz J R 2001 Tidal datums and their applications. *Silver Spring MD, NOAA, NOS Center for Operational Oceanographic Products and Services*, 102pp. & Appendix. (NOAA Special Publication NOS CO-OPS 1).

[5] Rahibulsadri R *et al* 2014b Tidal Datum Consistency for Marine Cadastre Littoral Zone Commencement in Malaysia *FIG Congress 2014 Engaging the Challenges – Enhancing the Relevance*, Kuala Lumpur, Malaysia, 16-21 June 2014

[6] Haigh I D 2016 Tidal Datum. In: Kennish M.J. (eds) *Encyclopedia of Estuaries. Encyclopedia of Earth Sciences Series*. Springer, Dordrecht.

[7] Din A H M *et al* 2017 Malaysian sea water level pattern derived from 19 years tidal data *J. Teknol* **79** 137–145

[8] Gill S K and Porter D L 1980 Theoretical Offshore Tide Range Derived from a Simple Defant Tidal Model Compared with Observed Offshore Tides *International Hydrographic Review*, Monaco LVII (**1**)

[9] Daher V B *et al* 2015. Extraction of tide constituents by harmonic analysis using altimetry satellite data in the Brazilian coast. J. *Atmos. Ocean. Technol* **32** 614–626

[10] Ainee A 2016 Derivation of Tidal Constituents from Satellite Altimetry Data for Coastal Vulnerability Assessment In Malaysia. *Master of Science Thesis* Universiti Teknologi Malaysia Skudai

[11] Yahaya N A Z *et al* 2016 *Mean sea surface (MSS) model determination for Malaysian seas using multi-mission satellite altimeter*. International Archives of the Photogrammetry *Remote Sensing and Spatial Information Sciences - ISPRS Archives* **42** 247–252

[12] Zulkifle M. I *et al* 2019 Determination of a localised mean sea surface model for Malaysian seas using multi-mission satellite altimeter *ASM Science Journal* **12** 81-89

[13] Din A H M *et al* 2014 Derivation of sea level anomaly based on the best range and geophysical corrections for malaysian seas using radar altimeter database system (RADS) *Jurnal Teknologi*, **71** 4 83-91

[14] Din A H M *et al* 2019 Sea level trend over Malaysian seas from multi-mission satellite altimetry and vertical land motion corrected tidal data. *Advances in Space Research* **63** 11 3452-3472

[15] Hamid A I A *et al* 2018 Contemporary sea level rise rates around Malaysia: Altimeter data optimization for assessing coastal impact *Journal of Asian Earth Sciences* **166** 247-259

[16] Pirooznia M et al., 2016 The Time Series Spectral Analysis of Satellite Altimetry and Coastal Tide Gauges and Tide Modeling in the Coast of Caspian Sea *Open J Mar Sci* **06** 258–269

[17] Lindsley R D 2013 Fitting Tidal Constituents to Altimeter Data

[18] Codiga D L 2011 Unified Tidal Analysis and Prediction Using the UTide Matlab Functions. Technical Report 2011-01. Graduate School of Oceanography University of Rhode Island Narraganset RI **59**

[19] Pawlowicz R *et al* 2002. Classical tidal harmonic analysis including error estimates in MATLAB using T_TIDE.Comput Geosci **28** 929–937

[20] Leffler K E and Jay D A 2009. Enhancing tidal harmonic analysis: Robust (hybrid L1/L2) solutions. *Cont Shelf Res* **29**78–88.

[21] Foreman M G G 1977 Manual for tidal heights analysis and prediction *Institute of Ocean Sciences, Pacific Marine Science Report* **97** 77-10

[22] Fu Y *et al* 2020 Evaluation of satellite-derived tidal constituents in the South China Sea by adopting the most suitable geophysical correction models *J. Oceanogr* **76** 183–196

[23] IHO 2018 Resolution on datums and benchmarks A2.5 3/1919. *International Hydrographic Organization*. https://www.iho. int/iho_pubs/misc/M3-E-AUGUST18.pdf

[24] Byun D S and Hart D E 2019 On Robust Multi-Year Tidal Prediction Using T_TIDE *Ocean Sci J* **54** 657–671

[25] Yilmaz H M 2007 The effect of interpolation method in surface definition: an experimental study *Earth Surf. Process, Landforms* **32** 1346-1361

[26] Environmental Systems Research Institute 2016a. Raster Interpolation toolset concepts: How Kriging works. Available at https://desktop.arcgis.com/en/arcmap/10.3/tools/3d-analyst-toolbox/how-kriging-works.htm# (Accessed 1 November, 2020).

[27] Franke R 1982. Smooth Interpolation of Scattered Data by Local Thin Plate Splines. *Computer and Mathematics with Applications* **8** 4 273-281

[28] Environmental Systems Research Institute 2016b. Raster Interpolation toolset concepts: How Spline works. Available at https://pro.arcgis.com/en/pro-app/latest/tool-reference/3d-analyst/how-spline-works.htm#   (Accessed   1   November, 2020).