Evaluating satellite-derived bathymetry accuracy from Sentinel-2A high-resolution multispectral imageries for shallow water hydrographic mapping

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Abstract. The wide-ranging evolution of remote sensing technology has offered a promising application to the hydrographic surveying, the Satellite-Derived Bathymetry (SDB). SDB is a contemporary acquisition technique which derives bathymetric data from multispectral satellite imagery for various hydrographic purposes. The introduction and availability of the chargeless Sentinel-2A multispectral satellite data in the region, has inspired the National Hydrographic Centre (NHC) and Universiti Teknologi Malaysia (UTM) to collaborate in assessing the level of accuracy provided by Sentinel-2A imageries as a data sources for shallow water hydrographic mapping. The assessment is concentrating on both empirical algorithm methods, Lyzenga and Stumpf models in two different seabed topology conditions. Both Lyzenga and Stumpf model produced almost identical results for the area with normal gradient seabed. Conversely, for the rough and irregular seabed surface, results from Lyzenga model was much better compared to Stumpf’s. Lyzenga model has delivered better results where a total of 166,747 (36.23%) of depths samples achieved the IHO minimum survey order standard compared to 103,418 (22.47%) by Stumpf model. Thus, this paper would deliberate the detail findings from the study primarily on the accuracy level of the Sentinel-2A data for SDB hydrographic mapping application over the tropical environmental setting in Malaysia.

Keywords: Satellite-Derived Bathymetry, Sentinel-2A, Shallow Water Survey

1. Introduction

Geospatial data has received substantial attention globally. The growing demands also include the marine-base geospatial data. In recent years, more modern maritime space applications required more comprehensive bathymetric data [1]. The increasing demand for detailed bathymetric information ultimately has enhanced hydrographic surveying industry to diversify data collection techniques. The need for more comprehensive and accurate seabed topography outlook have evolved the bathymetry acquisition technique from shipborne platform to airborne and even using space-borne acquisition [2]. The massive development in the satellite technology especially the availability of the high-quality multispectral images materialised SDB as new acquisition method for hydrographic surveying industry in Malaysia. The enormous expansion of the remote sensing technology together with geographical information system (GIS) application has enabled this technique to be more accessible even for tropical environment [2, 3, 4, 5, 6, 7, 8, 9, 10].

SDB has become a new buzzword in the field of hydrographic surveying internationally. This SDB technique is capable of transforming traditional monochrome satellite images into more useful seabed
information by embracing mathematical algorithms. However, in Malaysia, the shipborne method is still the premium selection to provide high accuracy bathymetry data albeit time-consuming and the high cost of operation. Additionally, for shallow water survey activities, due to limited navigation space and high operational risk, the shipborne sonar typically small and can be fitted with a low draught survey platform. Nevertheless, the SBES incapable of producing a high spatial resolution.

In a recent year, with more sophisticated satellites being launched, it has generated a substantial number of research works to assess and analyse the SDB acquisition techniques [11]. The introduction of the European Space Agency (ESA) developed satellite, Sentinel-2A, which delivered chargeless high-resolution multispectral imageries within the region has generated new initiative to explore this contemporary growing method [12]. The availability of Sentinel-2A data directly has accessible an attractive option for hydrographic mapping data sources, especially in the Malaysian shallow water areas.

Although, there were few studies pertaining to SDB in Malaysia, unfortunately, these studies did not evaluate and discuss in detail on the level of accuracy assessment of SDB in hydrographic mapping applications. Since this subject is booming and has generated intense debate among academics and industry players globally, the National Hydrographic Center (NHC) and Universiti Teknologi Malaysia (UTM) jointly took the initiative to carry out an in-depth study of SDB. The aim of this study is assessing the SDB data quality in the Malaysian shallow water areas primary. Both organisations, NHC and UTM, have always inspired to be at the forefront of pioneering technology which closely related to hydrographic surveying and becomes the reference agency to industry players at the national level. This paper aims to quantitatively evaluate the depth accuracy that can be achieved using two different empirical methods that are commonly applied to SDB application. Then, these accuracies are compared with the international hydrographic surveys standards, and finally, the conclusion is made to address whether this dataset is acceptable for a hydrographic mapping application.

2. Methodology

2.1. Study Area

Two areas were identified for this study, Tawau Port (Sabah) and Pulau Kuraman (W.P Labuan). The rationale for choosing both locations as study areas are base on data availability. On the other hand, both area meeting the parameters required for this study where Tawau Port area is having a typical condition of relatively high water turbidity which capable to represent majority areas in Malaysia. Whereas, for Pulau Kuraman is due to the uniqueness of irregular seabed morphology surface condition. Figure 1 indicates the geographical location of both study area.

Figure 1. The geographical location of study areas; Pulau Kuraman, Labuan and Tawau Port, Sabah
2.2. Multispectral Satellite Image Data
This dedicated study has adopted two sets of Sentinel-2A high resolution multispectral data Level-1C product. This data was downloaded from ESA Earth Online official website. The data are provided with Top of Atmosphere (ToA) reflectance along with the parameters to transform them into radiance [17]. Only four bands, blue (447-545nm), green (538-582nm), red (645-682nm) and NIR (763-907nm) with 10-metre resolution, were used for this study. The Sentinel-2A image data for Tawau Port area was acquired on the 29 Nov 2016 while the image for Pulau Kuraman was on the 28 June 2017.

2.3. Bathymetry Data
Tremendous support received from the National Hydrographic Centre (NHC) for this study where two dedicated hydrographic surveys activities were conducted in both study areas. The rationale to acquire the latest bathymetric data is to minimise the ambiguity on the detail accuracy analysis for the SDB data. However, only data from Single Beam Echo Sounder (SBES) were acquired since the study areas are relatively very shallow. For Tawau Port, the hydrographic surveying works commenced on 30 November and completed on the 2 December 2016. Whereas, the survey activities for Pulau Kuraman was conducted from the 6 to 27 April 2017. The bathymetric data divided into two (2) dataset, the training dataset and full dataset. The training dataset is a set of randomly selected data used for the calibration process. The full dataset is the entire dataset which was used for the final detail accuracy analysis. Figure 2 shows the overview of the training dataset and full dataset in both study areas, Tawau Port and Pulau Kuraman.

Figure 2. The bathymetry dataset. Tawau Port (above) and Pulau Kuraman (below); (a) Full Dataset and (b) Training Dataset

2.4. Processing Software
ESRI ArcMap software Version 10.4.1 with the support of 3D Analyst Tool was the primary software used for the processing stage. ArcMap Raster Calculator and Model Builder features were used for the majority of the works which involved the geoprocessing. CARIS BASE Editor and MATLAB were the other supporting software utilised for accuracy analysis and statistical exploration. All data processing activities involve for this SDB study is described in Figure 3. For this study, the processing of the multispectral image data involved the correction of geometric, radiometric (Top-of-Atmosphere (ToA) Radiance), ToA Reflectance, Sun Glint Correction and Atmosphere Correction) and Radiometric Analysis to produce SDB.
2.5. Derivation Algorithms

There are several algorithm models developed for deriving bathymetry data from satellite images. This study only adopted the two (2) most accepted empirical algorithm models, Lyzenga and Stumpf. There is no new algorithm developed for this study, but some modification of Stumpf’s model was designed. The adjustment only involves the calibration stage. This improvement comprises additional elements including least square computation to form the best fit multi-layer linear derivative model.

2.5.1. Lyzenga Model (Log-Linear Model). This derivation model was introduced by Lyzenga [13] and developed through series of Lyzenga’s findings [6,14,15]. This log-linear derivation model can be adopted for a single band or combining with a number of wavelength bands. For this study, this Lyzenga model applied Blue, Green and Red band which adopted the multi-linear regression algorithm for the final bathymetry data derivation. The algorithm for this log-linear model is as Equation 1. Generally, the \( a_i \) is the constant coefficients, \( L(\lambda) \) is the radiance (atmospheric and sun-glint corrected), and \( L_\infty(\lambda) \) is the deep area radiance value.

\[
A = a_0 + \sum_{i=1}^{N} a_i \ln[L(\lambda_i) - L_\infty(\lambda_i)]
\]  

(1)

2.5.2. Stumpf Model (Band-Ratio Model). This model developed using the basic principle of water body’s absorption level delivered by every band. The diversity level of water body’s absorption theoretically will produce the ratio between bands. The ratio then will generate a simultaneous change when the depth change. The Equation 2 illuminates the Stumpf band-ratio model algorithm. The \( n \), \( m_1 \) and \( m_0 \) are the constant coefficients for the model. Where the \( L(\lambda_1) \) and \( L(\lambda_2) \) are the radiance for spectral \( \lambda_1 \) and \( \lambda_2 \).

\[
Z = m_1 \times \frac{\ln[mL(\lambda_2)]}{\ln[mL(\lambda_1)]} - m_0
\]  

(2)

3. Results and Discussion

At large, Lyzenga and Stumpf derivation algorithm models have delivered adequate results. Although Stumpf algorithm model is considered modest and straightforward during the processing stage, this model provides slightly noisy results. Lyzenga model produced higher clean samples outcome. Nevertheless, Lyzenga algorithm model demands additional skill and knowledge in the final processing stage as this model apply the multiple regression algorithms. Figure 4 presents the definitive overview delivered by both Lyzenga and Stumpf models for study area Tawau Port and Figure 5 is the SDB prediction outcomes for Pulau Kuraman area.

3.1. Descriptive Statistical Analysis

This study adopted the general descriptive statistical analysis in the first stage. This analysis used the outcomes of SDB data derived from both models as a predicted value and the real bathymetry data (Full Dataset) as a reference value. The results of the analysis are described in Table 1 (Tawau Port) and Table 2
(Pulau Kuraman). For Tawau Port, about 2119 samples of data were used in the analysis. The results in Table 1 show that the Stumpf model delivered slightly better results compared to the Lyzenga model. The Standard Deviation for Stumpf model produced 2.274m compared to 2.281m for Lyzenga’s.

![Image](image_url)

**Figure 4.** The result of SDB data derived by both algorithm models for both Tawau Port (left) and Pulau Kuraman (right); (a) Lyzenga Model; and (b) Stumpf Model

| Tawau Port          | Lyzenga | Stumpf |
|---------------------|---------|--------|
| Mean                | -1.030  | -1.026 |
| Standard Error      | 0.050   | 0.049  |
| Standard Deviation  | 2.281   | 2.274  |
| Sample Variance     | 5.205   | 5.170  |
| Range               | 12.226  | 12.214 |
| Minimum             | -7.147  | -7.115 |
| Maximum             | 5.079   | 5.010  |
| Count               | 2119    | 2119   |

For Pulau Kuraman, a total of 460252 samples were used for the analysis. The result shows significant differences in Mean value where Lyzenga model produced 0.800m compared to 2.287m by Stumpf. However, Lyzenga model shows a massive error range of 25.976m compared to 14.546m from Stumpf model. This was generated by the improbable values predicted by Lazenga model within the area of the inter-tidal zone. For the Standard Deviation, Stumpf model achieved a slightly better result of 2.027m compared to 2.342m by Lyzenga’s.
Table 2. The results from the descriptive statistical analysis for Pulau Kuraman study area

|                  | Lyzenga | Stumpf |
|------------------|---------|--------|
| Mean             | 0.800   | 2.287  |
| Standard Error   | 0.003   | 0.003  |
| Standard Deviation| 2.342  | 2.027  |
| Sample Variance  | 5.487   | 4.110  |
| Range            | 25.976  | 14.546 |
| Minimum          | -15.914 | -6.912 |
| Maximum          | 10.062  | 7.634  |
| Count            | 460252  | 460252 |

3.2. IHO Survey Standards Analysis

Pragmatically, the values provided by the descriptive statistical analysis purely ineffectual in illuminating the detailed assessment of the SDB accuracy level. Thus, the further quality assessment was made to analyse the outcome of the SDB. The 5th Edition of the International Hydrographic Organization (IHO) Standards for Hydrographic Surveys, Special Publication No 44 was referred for the detailed assessment [16]. Table 3 specifies the maximum allowable Total Vertical Uncertainty (TVU) for reduced depths to be achieved to meet each order of survey.

Table 3. The Total Vertical Uncertainty (TVU) minimum requirements established by IHO [16]

| Order   | TVU = \sqrt{a^2 + (b \times d)^2} \\ 
|---------|---------------------------------|
| For this IHO Standards Assessment, valu d = 10 (average depth) | \\ 
| Special | 1a | 1b | 2 |
|---------|----|----|---|
| Maximum allowable TVU (95% Confidence level) | a = 0.25m | a = 0.5m | a = 0.5m | a = 1.0m |
| b = 0.0075 | b = 0.013 | b = 0.013 | b = 0.023 |
| TVU     | ±0.261m | ±0.517m | ±0.517m | ±1.026m |

Feature Detection

- TVU = \sqrt{a^2 + (b \times d)^2}

3.2.1. Tawau Port Study Area. Table 4 describes the quantitative outcomes from the IHO hydrographic survey orders standard analysis for Tawau Port study area. From a total of 2119 depth samples, Stumpf model provided slightly higher with 822 samples meeting the minimum of Order 2 survey standard. Lyzenza model produced a total of 816 depth samples that were able to meet the minimum IHO Survey Standards Order 2.

Table 4. The quantitative analysis of the IHO Survey Standard for Tawau Port study area

|                  | Lyzenga | Stumpf |
|------------------|---------|--------|
| Samples          | %       | Samples| %       |
| Total Samples    | 2119    | 100    | 2119    | 100    |
| IHO Failed       | 1303    | 61.49  | 1297    | 61.21  |
| IHO Passed       | 816     | 38.51  | 822     | 38.79  |
| Special Order    | 203     | 9.58   | 203     | 9.58   |
| Order 1AB        | 292     | 13.78  | 297     | 14.02  |
| Order 2          | 321     | 15.15  | 322     | 15.20  |
Figure 5 describes the distribution of uncertainties (error) in Table 4 using the histogram graph. The green colour indicates the number of samples with the highest accuracy level and meeting the Special Order survey standard. The blue and yellow bar represents samples that meeting Order 1 ((a) and (b)) and Order 2 standards respectively. The red bar describes samples which failed to meet the minimum Order 2 standards.

**Figure 6.** Histogram graphs of error distribution for Tawau Port: achieved IHO Special Order (green), Order 1(a) and 1(b) (blue), Order 2 (yellow) and Failed (red); (a) Lyzenga; and (b) Stumpf

3.2.2. Pulau Kuraman Study Area. A total number of 460252 depth samples were used in assessing the quality of SDB predicted results from Pulau Kuraman study area with the IHO Survey Standards. The availability of bathymetric data in this area was due to the irregular condition of the seabed surface. A comprehensive survey operation was carried out in order to have a broad appreciation of the seabed layout. Table 5 shows the quantitative results of the analysis. The results were diverse compared with the descriptive statistic analysis where Lyzenga model provided much better outcomes. Lyzenga model delivered a total of 166747 samples (36.23%) capable of meeting the minimum requirements set by the IHO survey standard. Likewise, Stumpf model only achieved 103418 samples (22.47%) which passed the minimum IHO survey standard. The same ratio trend also occurred for every survey class order.

**Table 5.** The quantitative analysis of the IHO Survey Standard for Pulau Kuraman study area

|            | Lyzenga | Stumpf |
|------------|---------|--------|
| **Samples**| 460252  | 460252 |
| **IHO Failed** | 293505 | 356834 | 77.53 |
| **IHO Passed** | 166747 | 103418 | 22.47 |
| **Special Order** | 34245  | 18401  | 4.00 |
| **Order 1AB** | 67143  | 39617  | 8.61 |
| **Order 2** | 65359  | 45400  | 9.86 |

Figure 6 describes the histogram graph of the error distributions. The histogram shape from Lyzenga model exhibits a bell-shaped curve that is closely related to the normal distribution data as compared to Stumpf’s model. The error distribution histogram graph delivered from Stumpf model was skewed to the positive errors. This pattern might be caused by the single linear regression algorithm adopted by Stumpf model where for Pulau Kuraman study area, the majority of samples range from 2 to 6 meter are tending to be estimated at the higher depth values.
4. Conclusion
In general, this study has enlightened the accuracy level delivered from SDB technology which directly empowering the awareness amongst the hydrographic surveying industry in Malaysia. On the other hand, the outcomes from this study have also illuminated that empirical method capable of producing decent bathymetry data for shallow water hydrographic mapping. Stumpf model has provided a slightly better result for a normal seabed topography surface (Tawau Port) whereas Lyzenga has delivered a significantly superior result in irregular seabed surface (Pulau Kuraman).

As this study is still on-going, the promising results from this initial stage capable of creating a ripple to the hydrographic surveying industry in Malaysia. Although this study unable to provide a definite answer whether in future SDB is capable of replacing shipborne and airborne acquisition method, the outcomes certainly have to enlighten which level of accuracy does this SDB technology can offer. This information is indeed beneficial to the Malaysia hydrographic surveying industry players.

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**Figure 7.** Histogram graphs of error distribution for Pulau Kuraman: achieved IHO S-44 Special Order (green), Order 1(a)(b) (blue), Order 2 (yellow) and Failed (red); (a) Lyzenga; and (b) Stumpf
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