Multi-Layer Optimisation Technique (M-LOT) for Shallow Water Hydrographic Survey Mapping Using Satellite-Derived Bathymetry Application

Najhan MD SAID and Rozaimi CHE HASAN, Malaysia

Key words: Hydrography, Satellite-Derived Bathymetry

SUMMARY

Satellite-Derived Bathymetry (SDB), a new method which derives bathymetric data from multi-spectral satellite imagery, has yet to be recognised as a new acquisition method for shallow water hydrographic survey mapping. Currently, SDB has received substantial attention from researchers worldwide, but most of the studies primarily focused on remote sensing environments. The questions about precision and accuracy are always the subject of interest in the surveying field but went unreported in most of the studies. Therefore, the objective of this study is to develop an improved SDB algorithm model which is capable of delivering better accuracy for shallow water hydrographic survey mapping application in a tropical environment. High resolution multi-spectral satellite imageries from the Sentinel-2A, Pleiades and WorldView-2 of Tawau Port, Sabah and Pulau Kuraman, Labuan were derived. Both places have diverse seabed topography parameters. A conceptual model of Multi-Layer Optimisation Technique (M-LOT) was developed based on Stumpf derivation model. Accuracy assessment of M-LOT was carried out against derivation models of Lyzenga and Stumpf. The findings showed M-LOT model managed to achieve up to 1.800m and 1.854m Standard Deviation accuracy for Tawau Port and Pulau Kuraman respectively. In addition, M-LOT has shown a better derivation compared to Stumpf's, where a total of 13.1% more depth samples meeting the IHO minimum standard for Tawau Port. Furthermore, M-LOT has generated an extensive increment up to 46.1% depths samples meeting the IHO minimum standard for Pulau Kuraman. In conclusion, M-LOT has significantly shown improved accuracy compared to Stumpf, which can offer a solution for SDB method in shallow-water hydrographic survey mapping application.

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1. INTRODUCTION

The demand for bathymetry data has increased exponentially in recent years for maritime-related industries, especially for nearshore marine base activities. The demand has tremendously increased as more fields require the information primarily for the use of marine navigation, environment protection management, marine resources exploration and exploitation, fishing industry, marine science research, maritime defense, tourism and recreation, national spatial data infrastructure and maritime boundary delimitation (IHO, 2005).

The growing demands from various fields have shaped the evolution of the acquisition technique of bathymetric data; from a shipborne platform to airborne and even using space-borne acquisition (Pe'eri et al., 2014). The discovery of the electromagnetic spectrum (EMR) being able to penetrate water space leads to the breakthrough acquisition technique of extracting bathymetric data from space-borne platforms. The space-borne bathymetry acquisition technique for shallow water areas which is also known as Satellite-Derived Bathymetry (SDB) is more than just mere rhetoric. The rapid and vast development of remote sensing technology has brought in SDB as a new revolution to the hydrographic surveying (Stumpf et al., 2003; Lyzenga et al., 2006; Su et al., 2008; Bramante et al., 2013; Tang and Pradhan, 2015; Ehses and Rooney, 2015; and Chybicki, 2018).

2. SDB AS NEW OPTION IN MALAYSIA

The retribution of today's SDB technology inspired by Lyzenga (1978) through his study of deriving water depth estimation using airborne multispectral data with radiometric technique. The SDB technology is defined as a "passive" application technique, where it simply measures the reflected sunlight intensity. This application contrasts from the "active" depth measurement techniques such as echo sounders or LiDAR where the sensors are able to control the transmission and reception of the signal efficiently. This "passive" application technique requires a strict selection on the conditions of the imageries which the bathymetric data estimation can be derived (Mohamed et al., 2015; Toming et al., 2016; Jegat et al., 2016; Allen et al., 2017). The essential condition is the observed areas must be clear from cloud coverage. This includes the area being clear of the shadows of cloud coverage. Then, the water quality ideally must be as clear as possible or contains a minimum of substantially suspended sediment. Also, the sun-glint reflection from the water surface should not be excessive. Lastly, this application works only for shallow waters where the seabed can be seen in the imagery.

The topic related to SDB is relatively fresh and new in Malaysia. Since this subject has generated intense debate among academics and industry players globally, the National Hydrographic Center (NHC) of the Royal Malaysian Navy and Universiti Teknologi Malaysia (UTM) jointly took the initiative to carry out an in-depth study of SDB. Both organisations 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. Therefore, the ultimate aim of this study is assessing the SDB data quality in the shallow water area. The detailed analysis is emphasis on the level of precision and consistency of SDB results in typical Malaysia's climate environment.

3. DATA AND PRE-PROCESSING

3.1 Study Area

Two (2) areas with contradicting seabed parameters conditions were identified for this research. The selection of Tawau Port (Sabah) and Pulau Kuraman (Wilayah Persekutuan Labuan) as study areas are aligned in meeting the research objectives where at least two (2) areas with different coastal seabed topography parameters were fully tested. Beside the availability of data (bathymetry, tidal and satellite images), both areas perfectly met the parameters required for this research. The main feature for the Tawau Port study area is a protected coastal area with a low gradient condition which holds a typical condition of relatively high water turbidity. This condition is considered as the standard criteria for the majority of the coastal regions in Malaysia. Whereas, Pulau Kuraman study area consists of a very different water condition and different seabed topography parameter. Although the water clarity is better as compared to Tawau Port, Pulau Kuraman is an exposed coastal area which has an irregular seabed topography. The condition is due to the diversity of the seabed classifications which are a mixture of sand, coral, rock, seaweed and seagrass. Figure 3.1 indicates the geographical location of both study areas.

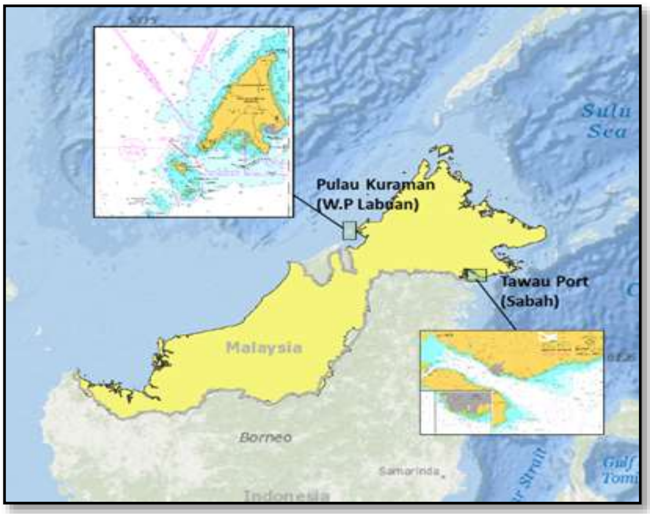

Figure 3.1 Geographical location of the study areas, the Tawau Port (Sabah) and Pulau Kuraman (W.P Labuan).

3.2 Satellite Image Data

This research optimised three (3) types of high-resolution multi-spectral satellite data which vary from a high resolution (HR) to very high resolution (VHR) images. The multi-spectral satellite data used for this research are the Sentinel-2 data (high resolution), Pleiades (VHR) and WorldView-2 images (VHR).

3.3 Bathymetry Data

With the great support delivered by the NHC for this research, two special hydrographic surveys were carried out in Tawau Port and Pulau Kuraman respectively. These surveys were conducted to collect the latest bathymetric data in the study area. The availability of the newest data certainly will enable to minimise noticeable ambiguity on the accuracy analysis for the SDB data. The majority of the bathymetry data adopted for calibration and accuracy analysis were from Singlebeam Echosounder data as the majority of the study areas are relatively very shallow.

The bathymetric dataset have been separated into two (2) categories. Firstly, the data which was adopted only for calibration purposes, the training data. This training dataset is a set of data which were randomly selected from every depth layer. Secondly, the complete bathymetry data, a full dataset, which were applied for the accuracy analysis processes over the studies area.

3.4 Depth Derivation and Model Enhancement

The radiometric analysis for the derivation of depth from satellite images was based on a radiative transfer model using in-situ bathymetry data (training dataset). This process referred to the depth calibration process. Before the depth calibration process, the tidal correction was applied to all bathymetry data. The reference level of the tidal correction might be different in other SDB application. The following process is the derivation of depth using the selected depth inversion model. For this research, log-linear (Lyzenga) and band-ratio (Stumpft) inversion models were adopted. Through a series of depth derivation processes, this research identified that the depth calibration adopted by Stumpf or the band-ratio inversion model could be enhanced by implementing the multi-layer linear regression technique. Therefore, besides the Lyzenga and Stumpf model, this study added the enhancement of Stumpf model, the Multi-Layer Optimisation Technique (M-LOT).

Generally, M-LOT is based on the assumption that the linear relationship between the depth and spectral radiance values alters as the depth increase. Since the rate of the alteration is significant in a tropical environment, a multi-layer linear regression is applied to minimise the gap left by the single linear regression calibration method adopted by the Stumpf model. The gap area (the uncertainty depth range) certainly will generate incorrect (false) depth as the single linear regression calibration does not cover the particular depth range in full. Figure 3.2 shows the workflow of the depth derivation process and the Model Enhancement phase.

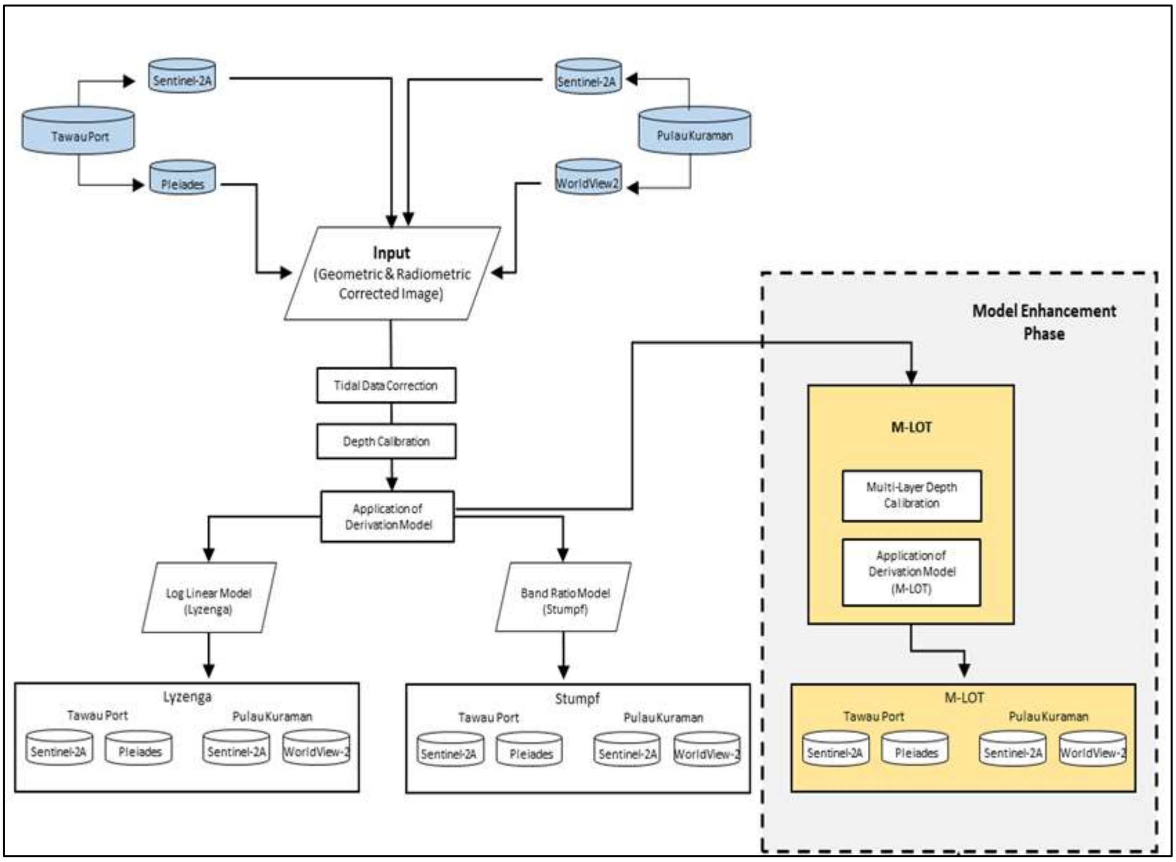

Figure 3.2 The flowchart of all processes required for depth derivation

4. RESULT AND ANALYSIS

The result analysis phase involves a comprehensive accuracy assessment of the SDB results from all inversion models adopted for this research including the M-LOT enhancement model. All the SDB model results were examined in two (2) parts, which are the Quantitative Evaluation and International Hydrographic Organisation (IHO) Survey Standards Assessment. The Quantitative Evaluation is the descriptive statistical analysis to evaluate the level of accuracy and precision of SDB data produced by all algorithm models. Additionally, the IHO Survey Standards Assessment was included to scrutinise the results quality emphasis in meeting the hydrographic surveying industry requirements.

4.1 Quantitative Evaluation

4.1.1 Tawau Port

The analysis for Tawau Port delivered exciting findings. Generally, the results produced by Lyzenga and Stumpf model are almost identical. Statistically, for Sentinel-2A dataset, the difference in Root Mean Square (RMSE) and Standard Deviation (SD) are only 0.005m and 0.007m respectively. However, M-LOT model has shown slightly better results for RMSE and SD. M-LOT provided a reading of 0.152m, a lower RMSE value compare to Stumpf's. While, for SD, M-LOT produced a reading of 2.171m which is 0.093m better than Stumpf's. Comparing with the Pleiades dataset, the RMSE and SD delivered by the Pleiades were not much different as compared to the Sentinel-2A dataset. The Lyzenga model of Pleiades provides a 4.323m RMSE which was only 0.142m lower from Sentinel-2A's result.

By analysing the overall summary, the Pleiades dataset provided mix outcomes. Although the Lyzenga model delivered the lowest RMSE value, M-LOT, on the other hand, produced the smallest SD value of 1.800m which is 0.198m lower than Lyzenga's. Table 4.1 describes the full results from the descriptive statistical analysis of the Sentinel-2A and Pleiades for Tawau Port. M-LOT has produced a better outcome for the majority of the statistical results. Generally, for both dataset, Sentinel-2A and Pleiades, M-LOT has consistently delivered better results as compared to Lyzenga and Stumpf.

Table 4.1 The descriptive statistical analysis of the Sentinel-2A and Pleiades for Tawau Port

	Tawau Port					
	Sentinel-2A			**Pleiades**		
	Lyzenga	**Stumpf**	**M-LOT**	**Lyzenga**	**Stumpf**	**M-LOT**
Mean	-1.043	-1.039	-0.667	-0.48	-0.414	-0.123
Sample Variance	5.159	5.124	4.713	3.992	3.963	3.24
RMSE	4.464	4.459	4.307	4.323	4.435	4.379
SD	2.271	2.264	2.171	1.998	1.991	1.8
Range	12.227	12.214	11.337	9.709	10.777	9.389

4.1.2 Pulau Kuraman

The outcomes from Pulau Kuraman study area demonstrated that the Lyzenga model has produced better results quantitatively which directly has enlightened the 'stability' of the Stumpf model over rugged and irregular seabed topography condition. The Lyzenga model delivered the smallest RMSE and SD value of 2.11m and 2.096m respectively. Correspondingly, M-LOT also provided a great improvement compared to Stumpf model where the RMSE and SD were reduced to 0.148m (6.1%) and 0.159m (6.3%) respectively. The WorldView-2 multi-spectral image are comparable to the Sentinel-2A outcomes.

Similarly, with Sentinel-2A results, the Lyzenga model had produced better results compared to Stumpf and M-LOT. The RMSE of Lyzenga model is 1.841m as compared to Stumpf's 2.975m and M-LOT's 1.958m. Likewise, for the SD value, Lyzenga delivered a reading of 1.634m which is lower than Stumpf and M-LOT that produced 1.972m (20.7%) and 1.854 (13.5%) respectively. Even though Lyzenga has prominently delivered the better outcome, from a statistical perspective, the results from M-LOT are still remarkable where it produced a substantial improvement as compared to Stumpf's results in almost all aspects. Table 4.2 defines the descriptive statistical analysis results of the Sentinel-2A and WorldView2 for Pulau Kuraman study area.

Table 4.2 The descriptive statistical analysis of the Sentinel-2A and WorldView2 for Pulau Kuraman

	Pulau Kuraman					
	Sentinel-2A			**WorldView2**		
	Lyzenga	Stumpf	M-LOT	Lyzenga	Stumpf	M-LOT
Mean	-0.308	0.035	-0.126	0.845	2.228	0.631
Sample Variance	4.393	5.813	5.105	2.676	3.887	3.437
RMSE	2.118	2.411	2.263	1.841	2.975	1.958
SD	2.096	2.411	2.259	1.634	1.972	1.854
Range	22.659	18.484	21.92	21.648	13.785	16.773

4.2 IHO Survey Standards Assessment

All analysis of IHO Survey Standards Assessment is referring to the 5th Edition of the International Hydrographic Organization (IHO) Standards for Hydrographic Surveys, Special Publication No 44 (IHO, 2008).The assessment of IHO Survey Standard was divided into two study areas, Tawau Port and Pulau Kuraman as described in the following sub-paragraph.

4.2.1 Tawau Port

The result of IHO Survey Standard Assessment of the Sentinel-2A multi-spectral image for Tawau Port described that M-LOT produced a better outcome where 906 samples meet the minimum requirement of the IHO Survey Standard from a total of 2113 samples,. The Stumpf and Lyzenga model were only able to achieve 826 and 822 respectively. However, M-LOT produced less samples to fulfil the Special Order survey class where only 198 samples meet the requirement compared to the Stumpf and Lyzenga model were both able to achieve higher numbers of 207 and 209 respectively.

The outcomes are similar for the Pleiades dataset where both Lyzenga and Stumpf delivered identical results where a total of 1019 and 1016 samples respectively achieved the minimum standard of IHO survey standard. M-LOT provided the better result with 1149 which are 133 samples more than Stumpf's. Diversely from the Sentinel-2A results, M-LOT delivered a higher number of samples for Special Order and Order 1A/1B survey class where a total of 283 and 500 samples met both survey standard respectively. These results are quite substantial as compared to Stumpf's results of 217 and 429 samples meeting the survey standards respectively. Table 4.3 together with Figure 4.4 and 4.5 illuminates in detail the results of the IHO Survey Standard Assessment of the Sentinel-2A and Pleiades for Tawau Port.

Table 4.3 The results from the IHO Survey Standards Assessment of the Sentinel-2A and Pleiades for Tawau Port

	Tawau Port					
	Sentinel-2A			**Pleiades**		
	Lyzenga	Stumpf	M-LOT	Lyzenga	Stumpf	M-LOT
Total Samples	2113	2113	2113	2213	2213	2213
IHO Passed	822	826	906	1019	1016	1149
IHO Failed	1291	1287	1207	1194	1197	1064
	IHO Survey Order Distribution					
Special Order	209	207	198	214	217	283
Order 1A/1B	297	299	399	417	429	500
Order 2	316	320	309	388	370	366

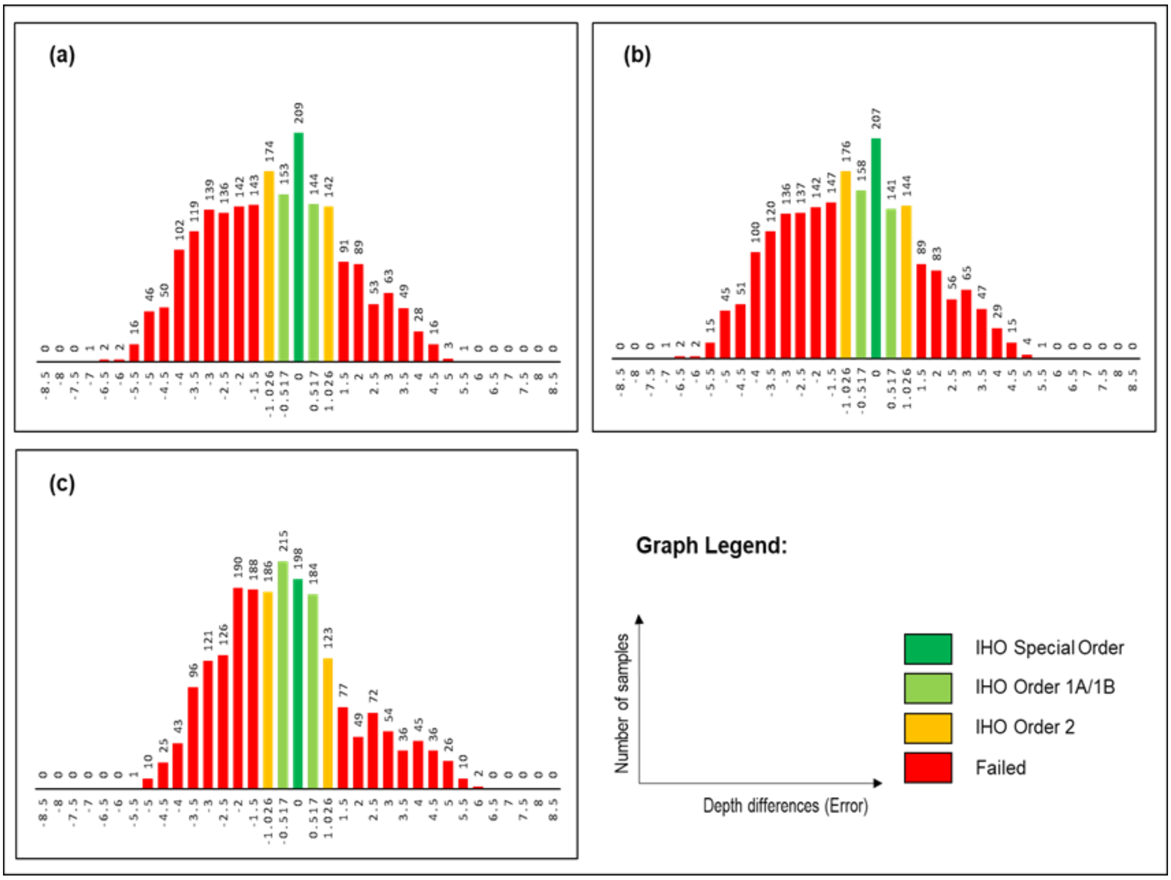

Figure 4.4 The IHO Survey Standard histogram graph outcomes delivered by all models for Sentinel-2A multi-spectral image in Tawau Port; (a) Lyzenga model; (b) Stumpf model; and (c) M-LOT model

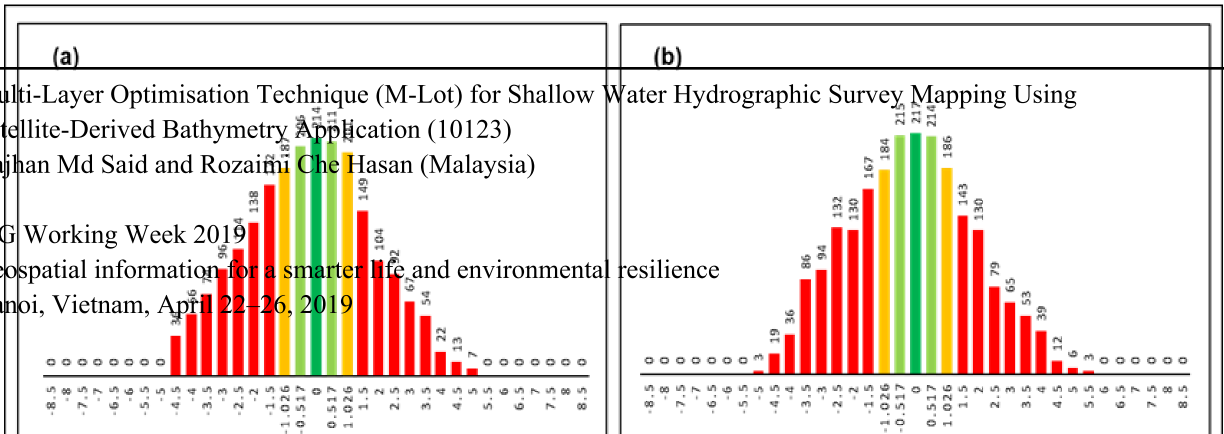

Figure 4.5 The IHO Survey Standard histogram graph outcomes delivered by all models for Pleiades multi-spectral image in Tawau Port: (a) Lyzenga model; (b) Stumpf model; and (c) M-LOT model

4.2.2 Pulau Kuraman

Similarly to Tawau Port outcomes, for the Sentinel-2A, the Lyzenga model had produced better results compared to Stumpf and M-LOT. The RMSE of Lyzenga model is 1.841m as compared to Stumpf's 2.975m and M-LOT's 1.958m. Likewise, for the SD value, Lyzenga delivered a reading of 1.634m which is lower than Stumpf and M-LOT that produced 1.972m (20.7%) and 1.854 (13.5%) respectively. Interestingly, the final assessment of the IHO survey standard for all derivation models from the WorldView-2 dataset is the most exciting part of this research. Since the WorldView-2 has the highest resolution, the number comparison sampling is also increased tremendously. The results show that the Lyzenga model was proven to deliver a better outcome as compared to the Stumpf and M-LOT models. Nevertheless, M-LOT had produced a total of 235260 depth samples which passed the minimum requirement of IHO survey standard compared to 123147 samples or 91% higher than the model origin, Stumpf.

Although the Lyzenga model is leading the results in all survey order categories, the results produced by M-LOT model are not much different from Lyzenga's. The differences between the Lyzenga model and the M-LOT model in all survey order categories are relatively small. For Special Order, the gap between these two models is only 525 samples. Likewisefor Order 1A/1B and Order 2 where the difference between the samples are only 399 and 3455. Evidently, for the WorldView-2 dataset, the M-LOT model has produced substantial outcomes as compared to Stumpf's. This outcomes had again validated the previous findings and reinforced the ability of M-LOT model. Table 4.6 together with Figure 4.7 and 4.8 elaborates in detail the results of the IHO Survey Standard Assessment of the Sentinel-2A and WorldView-2 multi-spectral image for Pulau Kuraman. Albeit Lyzenga has prominently delivered the better outcome, the results from M-LOT are still remarkable where it produced a substantial improvement as compared to Stumpf's results in almost all aspects.

Table 4.6 The results from the IHO Survey Standards Assessment of the Sentinel-2A and WorldView2 for Pulau Kuraman

	Pulau Kuraman					
	Sentinel-2A			**Worldview-2**		
	Lyzenga	Stumpf	M-LOT	Lyzenga	Stumpf	M-LOT
Total Samples	460252	460252	460252	502081	502081	502081
IHO Passed	166747	103418	151100	239639	123147	235260
IHO Failed	293505	356834	309152	262442	378934	266821
	IHO Survey Order Distribution					
Special Order	34245	18401	32311	50692	14364	50167
Order 1A/1B	67143	39617	61991	98634	43408	98235
Order 2	65359	45400	56798	90313	65375	86858

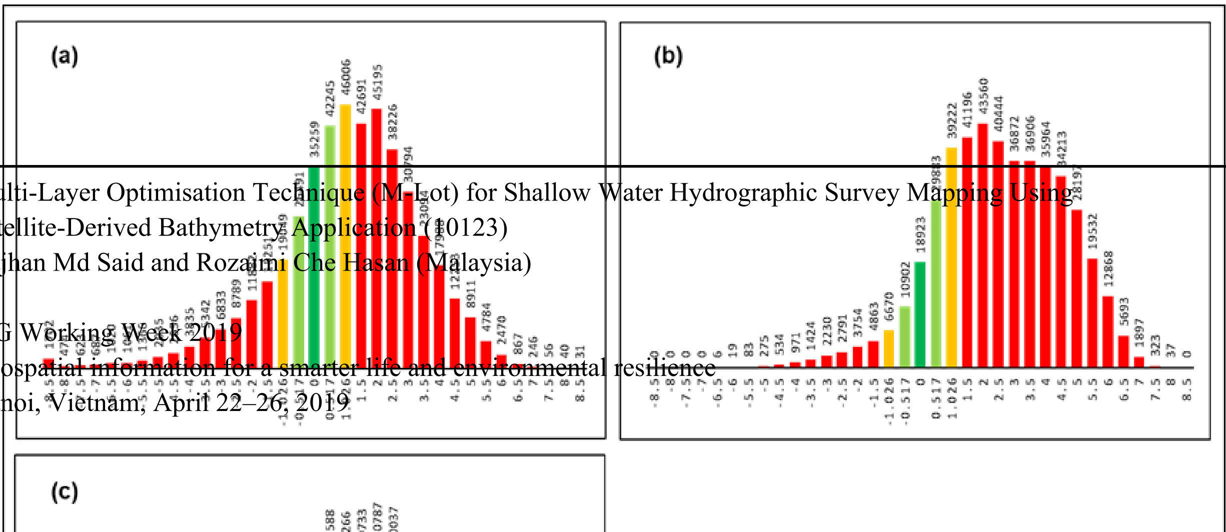

Figure 4.7 The IHO survey standard histogram graph outcomes delivered by all models for Sentinel-2A multi-spectral image in Pulau Kuraman: (a) Lyzenga model; (b) Stumpf model; and (c) M-LOT model

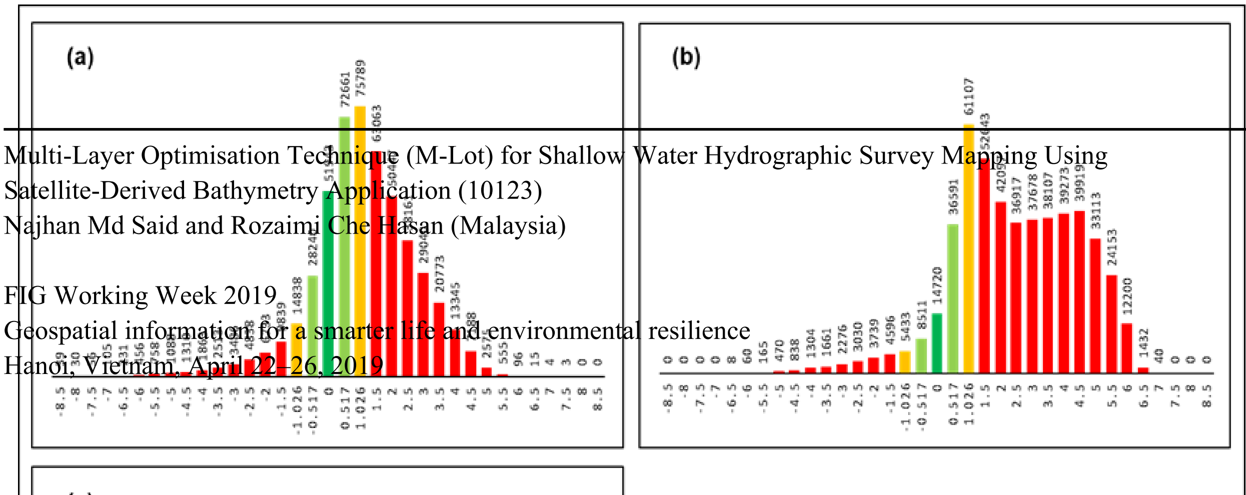

Figure 4.8 The IHO Survey Standard histogram graph outcomes delivered by all models for the WorldView-2 multi-spectral image in Pulau Kuraman: (a) Lyzenga model; (b) Stumpf model; and (c) M-LOT model

5. CONCLUSION

Generally this study has distinguished the performance of all derivation models over a low gradient seabed surface or regular seabed with the irregular seabed topography condition. Statistically, the M-LOT model produced better results over regular seabed while Lyzenga's perform slightly better on an irregular seabed topography surface. Likewise, similar findings were obtained from the IHO Survey Standard Assessment analysis outcomes. In general, the combination of the Pleiades multi-spectral image together with the M-LOT model has provided the best results on a regular seabed topography conditions. For the irregular seabed topography such as Pulau Kuraman, the Lyzenga model of the WorldView-2 with the combination of blue, green, yellow and coastal blue bands has produced the best results. A distinguished point to expel from both results is the instability outcomes delivered from Stumpf's derivation model over the irregular seabed surface. Nevertheless, the results have enlightened the consistent achievements made by M-LOT in improving the Stumpf model in both seabed conditions. Remarkably, M-LOT has also consistently improved the results for all multi-spectral images.

Besides of the M-LOT performance, principally, this study also has effectively illuminated the level of quality that the SDB technology can offer to the hydrographic surveying industry in

Malaysia. As the status of the hydrographic survey coverage percentage in this country is relatively small, sooner or later, this enormous gap of bathymetry data, especially in the shallow water area, need to be addressed by the relevant authority. Therefore, this study has aligned the methodology and scope into meeting the interest from hydrographic surveying industry. The approach of this study purposely designed to address the mind-blowing question amongst the hydrographic surveying community whether this SDB technology can deliver the level of accuracy required by the industry.

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BIOGRAPHICAL NOTES

First Admiral Dr. Najhan MD SAID is the Senior Director of National Hydrographic Centre, Royal Malaysian Navy (RMN). He graduated from the Naval College as Navy Officer before pursuing his post-graduate studies in local university and abroad. He holds a Master of Science (Hydrography) from Universiti Teknologi Malaysia (UTM) and a Master in Maritime Studies from the University of Wollongong, New South Wales, Australia. He attained his Doctor of Philosophy (Hydrography) quite recently from UTM. Admiral MD SAID is a professional hydrographic surveyor and very passionate in exploring hydrographic surveying technique and applications especially in multibeam echosounder and remote sensing hydrography. He also a member of the GEBCO Sub-Committee on Undersea Feature Name (SCUFN) and the Executive Committee of Malaysian Hydrography Society (MyHS).

Dr. Rozaimi CHE HASAN is a Senior Lecturer at the Razak Faculty of Engineering and Informatics, UTM, Kuala Lumpur, He holds a Bachelor of Geomatic Engineering and Master of Science (Hydrography), both from UTM. He obtained his Doctor of Philosophy in Environmental Sciences from Deakin University, Victoria, Australia with research topic in benthic habitat mapping using backscatter measurement from multibeam echosounder. His research interests include surveying and hydrographic mapping, multibeam data processing, backscatter data characterization and classification.

CONTACTS

First Admiral Dr. Najhan MD SAID

National Hydrographic Centre
Bandar Armada Putra
Pulau Indah
42009 PORT KLANG
Malaysia
Tel. +603 3169 4400
Email: najhan@navy.mil.my
Web site: https://hydro.gov.my

Dr. Rozaimi CHE HASAN
Universiti Teknologi Malaysia
Jalan Sultan Yahya Petra
54100 KUALA LUMPUR
Malaysia
Tel. +603 26154581
Email: rozaimi.kl@utm.my
Web site: www.utm.my