SATELLITE-DERIVED BATHYMETRY FOR SHALLOW WATER HYDROGRAPHIC MAPPING

NAJHAN BIN MD SAID

A thesis submitted in fulfilment of the
requirements for the award of the degree of
Doctor of Philosophy (Hydrography)

Faculty of Built Environment and Surveying
Universiti Teknologi Malaysia

NOVEMBER 2018

DEDICATION

To Allah Subhanahu Wa ta'ala, for the continuous strength. Physically and mentally.
To my parents, for giving me so much to be grateful for.
To my beloved wife, for endless supports and will always be there for me.
To my children, for aspirations and prayers. Indeed, this success story ain't easy.
May today's success be the beginning of your tomorrow achievements!
To the memories, for the hard times which made me much more determined to keep working hard.
To myself, for keep reminding me to be strong. Undeniably, I have fallen a lot along the journey.

ACKNOWLEDGEMENT

First and foremost, I would like to express my deepest gratitude to both my supervisors, Professor Sr. Dr Mohd Razali Mahmud and Sr. Dr Rozaimi Che Hasan for the valuable guidance, assistance and continuous encouragements until this work comes to existence. It is a great honour to work under their supervision.

My special thanks to the former Chief of Navy, Tan Sri Dato' Seri Dr. Abdul Aziz Hj Jaafar for the trust and granting me the Armed Forces Higher Education Scholarship award. Also to the Director-General of National Hydrographic Centre (NHC), Rear Admiral Hanafiah Hassan for the countless advices and continuously supporting me to accomplish my research.

My sincere appreciation to the Director General of Malaysian Remote Sensing Agency (MRSA), Tuan Haji Azlikamil Napiah and the fellow MRSA staffs who directly involved for providing me all the data required and for their support all the way through my study period.

I would like to place on record, my sense of gratitude to Madame Dr. France Floc'h, Madame Dr. Sophie Loyer as well as the fellow staffs in the Institut Universitaire Européen de la Mer (IUEM) and the Service Hydrographique et Océanographique de la Marine (SHOM), for their support and assistance while attending my doctorate internship in Brest, France.

Lastly, my thankfulness to the lecturers, staff and my fellow postgraduate students of the Faculty of Geoinformation and Real Estate (FGRE), especially to Mr. Mohd Hilmi Abdullah, Ms. Nur Hidayah Md Yusof, Mr. Ghazalli Khalid, and my colleagues at the Centre for Hydrographic Studies (CHS), who helped me in many ways throughout the course of my study in UTM. Indeed, words are powerless to express my sincere gratitude!

ABSTRACT

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. Hence, this study aims 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 Sumpf. Two types of accuracy assessment were involved: Statistical Assessment and International Hydrographic Organization (IHO) Survey Standard evaluation. The findings showed M-LOT model managed to achieve up to 1.800m and 1.854m Standard Deviation (SD) 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.

ABSTRAK

Batimetri Penghasilan Satelit (SDB), kaedah baru yang menghasilkan data batimetri dari imej satelit pelbagai spektral masih belum lagi diiktiraf sebagai kaedah baru untuk pemetaan pengukuran hidrografi di perairan cetek. Pada masa ini, SDB telah menarik perhatian ramai penyelidik dari seluruh dunia namun kebanyakan kajian memberi keutamaan dalam bidang penginderaan jarak jauh. Persoalan berkaitan ketepatan dan kejituan sentiasa menjadi perkara utama dalam bidang pengukuran, tetapi tiada pelaporan mengenainya dalam kebanyakan kajian. Oleh itu, kajian ini bertujuan untuk membangunkan model algoritma SDB yang mampu menghasilkan ketepatan yang lebih baik khususnya bagi aplikasi pemetaan pengukuran hidrografi kawasan cetek untuk persekitaran tropika. Imej-imej satelit pelbagai spektral beresolusi tinggi dari Sentinel-2A, Pleiades dan WorldView-2 bagi kawasan Pelabuhan Tawau, Sabah dan Pulau Kuraman, Labuan telah dihasilkan. Kedua-dua kawasan tersebut mempunyai parameter topografi dasar laut yang berbeza. Model konsep Teknik Pengoptimuman Pelbagai Lapisan (M-LOT) dibangunkan berasaskan model penghasilan Stumpf. Penilaian ketepatan M-LOT telah dilaksanakan dengan model Lyzenga dan Stumpf. Dua jenis penilaian ketepatan telah digunakan; Penilaian Statistik dan evaluasi Piawaian Pengukuran Pertubuhan Hidrografi Antarabangsa (IHO). Dapatan ini menunjukkan model M-LOT berjaya menghasilkan ketepatan 1.800m dan 1.854m sisihan piawai untuk Pelabuhan Tawau dan Pulau Kuraman. Di samping itu, M-LOT telah menunjukkan penghasilan yang lebih baik berbanding Stumpf di mana penambahan sebanyak 13.1% sampel kedalaman berjaya mencapai piawaian minimum IHO bagi kawasan Pelabuhan Tawau. Tambahan pula, M-LOT telah menghasilkan peningkatan yang lebih ketara iaitu sebanyak 46.1% sampel kedalaman mencapai piawaian minimum IHO bagi kawasan Pulau Kuraman. Kesimpulannya, M-LOT telah menghasilkan ketepatan yang lebih baik berbanding Stumpf dan mampu menawarkan penyelesaian bagi kaedah SDB untuk aplikasi pemetaan pengukuran hidrografi kawasan cetek.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

CARIS	-	Computer Aided Resource Information System
cm	-	centimetre
DOP	-	Depth of Penetration
DSMM	-	Department of Survey and Mapping Malaysia
EMR	-	Electromagnetic Spectrum
ENC	-	Electronic Navigation Chart
ESA	-	European Space Agency
GIS	-	Geographic Information Systems
HR	-	High Resolution
IHB	-	International Hydrographic Bureau
IHO	-	International Hydrographic Organization
IMO	-	International Maritime Organization
km		Kilometre
LADS	-	Laser Airborne Depth Sounder
LAT	-	Lowest Astronomical Tide
LiDAR	-	Light Detection And Ranging
LTE	-	Low Tide Elevation
LUT	-	Look-Up Tables
LWL	-	Low Water Line
MATLAB	-	Matrix Laboratory
m	-	metre
mm	-	millimetre
MBES	-	Multibeam Echo Sounder System
MRSA	-	Malaysia Remote Sensing Agency

MSI	-	Multi-Spectral Image
NASA	-	National Aeronautics and Space Administration
NHC	-	National Hydrographic Centre
NIR	-	Near-Infrared
nm	-	nautical mile
NOAA	-	National Oceanic and Atmospheric Administration
OLI	-	Operational Land Imager
RMSE	-	Root Mean Square Error
SBES	-	Single Beam Echo Sounder System
SD	-	Standard Deviation
SDB	-	Satellite-Derived Bathymetry
SHOALS	-	Scanning Hydrographic Operational Airborne LiDAR Survey
SOLAS	-	International Convention for the Safety of Life at Sea
SONAR	-	Sound Navigation and Ranging
SPOT	-	*Satellite Pour l'Observation de la Terre*
TIRS	-	Thermal Infrared Sensor
ToA	-	Top of Atmosphere
TS	-	Territorial Sea
TSB	-	Territorial-Sea Baseline
TVU	-	Total Vertical Uncertainty
UNCLOS	-	United Nation Convention on the Law of the Sea
VHR	-	Very High Resolution
V-NIR	-	Visible and Near-Infrared
WGS 84	-	World Geodetic System 1984

LIST OF SYMBOLS

A_d	-	Bottom upwelling radiance
a_i	-	Constant coefficients
b_i	-	Slope resulting from a regression of band *i*
DN_i	-	Pixel digital number for band i
g	-	Two-way attenuation coefficient
K_i	-	Absolute radiometric calibration
L_b	-	Bottom radiance
L_p	-	Atmospheric path radiance
L_s	-	Specular radiance
L_t	-	Total upwelling radiance
L_v	-	Subsurface volumetric radiance
L_∞	-	Optically-deep water radiance
min_{NIR}	-	Minimum near-infrared value
n	-	Total number of the samples
R^2	-	Coefficient of determination value
R'_i	-	Sun glint and atmosphere corrected image for band *i*
R_i	-	Uncorrected image (radiance) of band *i*
R_{NIR}	-	Near-infrared radiance
x_i	-	Real depth (reference depth)
$\hat{x}_i$	-	Derived depth (predicted depth)

$\bar{z}_i$	-	Mean of depth residual sample
z	-	Depth
z_i	-	Depth residual sample
$\Delta\lambda_i$	-	Effective band (band i)

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.1 Background of Study

According to the National Aeronautics and Space Administration (NASA), there are more complete maps of the surface of the Moon or Mars than the ocean floor of Earth (NASA, 2016). Geographical facts indicate that water covers close to 70 per cent of the earth's surface, yet only less than 15 per cent of the seafloor area worldwide have been appropriately surveyed using shipborne measurements (Copley, 2014). Apparently, the majority of such survey activities have been made along the major shipping routes of the world. This is because the production of navigational charts were originally regulated based on Chapter V of the International Convention for the Safety of Life at Sea (SOLAS), where there is an obligation under the Convention to provide safe routes for shipping (IMO, 1974). Therefore, it is of no surprise to find that the majority of the surveyed area globally only focused on the shipping routes of the world. This typical worldwide setting has left an expanse of unsurveyed territory, mainly in the very remote areas and shallow water spaces within nearshore which are unsafe for navigation. This situation also occurs in Malaysian waters, where the majority of hydrographic surveys conducted in Malaysia are only focused on the main shipping routes.

According to the database provided by the Malaysian National Hydrographic Centre (NHC), the majority of shallow water areas, both in Peninsular Malaysia and Sabah and Sarawak near the shorelines are still unsurveyed. The database map in Figure 1.1 shows the status of hydrographic survey data comprising of 4 categories as follows;

a. New data from Multibeam Echosounder System (MBES);

b. The new data from Singlebeam Echo Sounder System (SBES);

c. Old modern data (1950 – 1975), and;

d. Very old data (before 1950).

This database was updated until November 2017. The map shows significant gaps in the shallow water areas especially on the East Coast of Peninsular Malaysia and nearshore of Sarawak. There is no getting away from the fact that nearshore hydrographic data are imperative these days. Concurrently, 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).

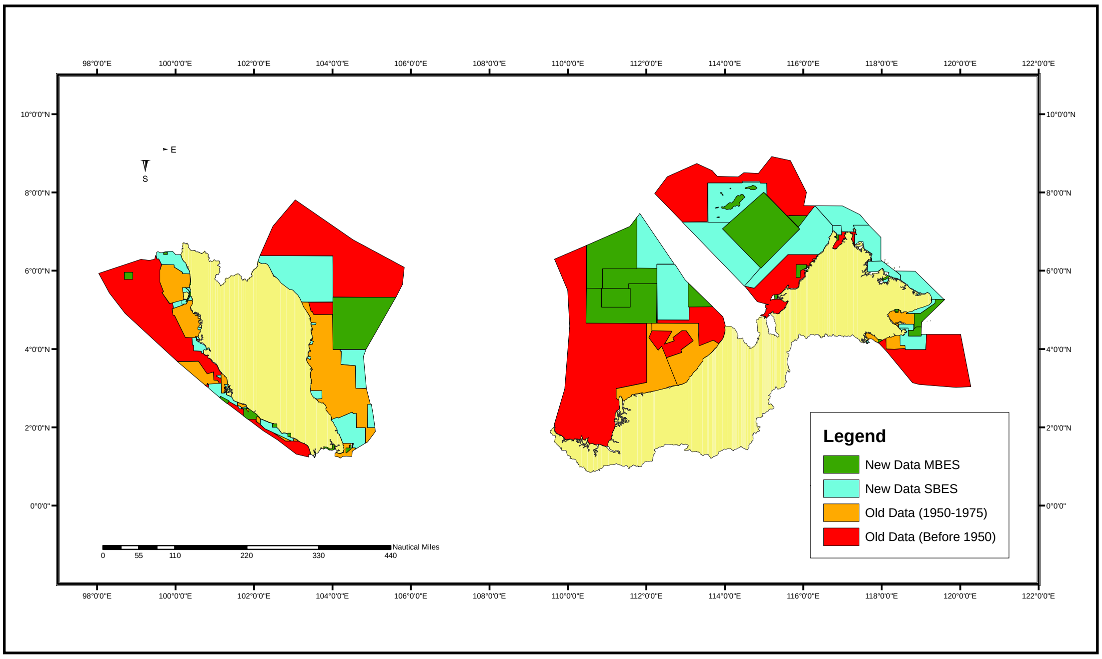

Figure 1.1 The hydrographic survey data status in Malaysia (NHC)

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. Figure 1.2 describes the evolution of the bathymetry data acquisition technique from shipborne to the space-borne platform. 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; Louchard *et al.*, 2003; Brando and Dekker 2003; Lyzenga *et al.*, 2006; Albert and Gege, 2006; Vanderstraete *et al.*, 2006; Su *et al.*, 2008; Bachmann *et al.*, 2012; Flener *et al.*, 2012; Doxani *et al.*, 2012; Bramante *et al.*, 2013; Pe'eri *et al.*, 2014; Tang and Pradhan, 2015; Ehses and Rooney, 2015; and Chybicki, 2018).

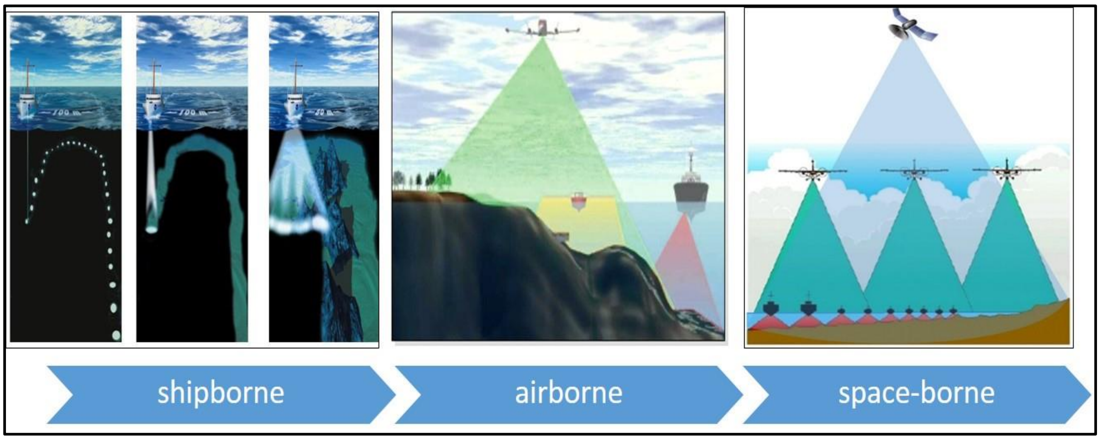

Figure 1.2 The evolution of bathymetry data acquisition technique

In recent years, remote sensing technology via the airborne acquisition has been accepted as an alternative technique in the bathymetric data acquisition process among the hydrography communities, especially in the shallow water area. Thus far, for seafloor mapping within shallow coastal waters, the Light Detection And Ranging (LiDAR) which is an airborne bathymetric acquisition technique, has been deployed in various countries including Malaysia. Indeed, LiDAR has produced reliable bathymetric data which is capable of achieving 20 cm vertical accuracy (Pe'eri *et al.*, 2014). In certain conditions, undoubtedly this technology is capable of meeting the International Hydrographic Organisation (IHO) Special Order survey requirements. Table 1.1 describes the nominal maximum detectable depth by various airborne bathymetric acquisitions (Lillycrop and Banic, 1993; Finkl *et al.*, 2005; Brock *et al.*, 2004). The data demonstrate clearly that these airborne acquisition techniques are commonly able to penetrate quite significant depths and achieve acceptable vertical accuracy. Nonetheless, there are still limitations in this airborne acquisition technique.

Table 1.1: LiDAR systems nominal maximum detectable depth

System	Developed By	Nominal Maximum Detectable Depth
SHOALS (Scanning Hydrographic Operational Airborne LiDAR Survey)	Teledyne Optech Incorporated, Canada	40 m
LADS (Laser Airborne Depth Sounder)	Tenix LADS Corporation, Australia	70 m
NASA EAARL (Experimental Advanced Airborne Research LiDAR)	NASA, United States	25 m

The major limitation of airborne bathymetric acquisition is not just on the maximum penetration range which depends heavily on water clarity, but the practicality in implementing this method on survey ground. The issuance of permits to operate a LiDAR system is the primary concern for the service providers while operating in a semi-enclosed maritime region like Malaysia. It is challenging to manage the flight path without entering the territory of neighbouring states, and the situation can trigger untoward incidents between both parties. With all the perilous issues, the operation cost of a LiDAR system in this region can be extremely high, especially when the application is for chart updating which requires more frequent flyovers (Minghelli-Roman *et al.*, 2009; Pe'eri *et al.*, 2014). Hence, with more new satellites being launched and new sensors developed every year, a noteworthy number of research whether international or local, have been conducted to assess and analyse the SDB acquisition techniques since this remote-sensing technology is considered as an attractive option for seafloor mapping (Bramante *et al.*, 2013; Pe'eri *et al.*, 2014; Chybicki, 2018).

1.2 Problem Statements

An operating surveying platform for bathymetry data acquisition in the shallow water area, which is defined as an area having a depth less than 15 meters, is always considered to be a high operational risk due to limited navigation availability. The shipborne soundings commonly in use is a Singlebeam Echo Sounder System (SBES) that often produces a low spatial resolution (Lyzenga, *et al.*, 2006; Kanno, *et al.*, 2011). Hence, considering the limitation of the shipborne acquisition remotely sensed data technique, either the active technique (airborne) or the passive technique (space-borne) would be the best available option to be utilised instead. In addition, bathymetry data derived from the remote sensing platform is not something new for hydrographic application (Gould *et al.*, 2001; Stumpf *et al.*, 2003; Louchard *et al.*, 2003; Brando and Dekker, 2003; Lyzenga *et al.*, 2006; Albert and Gege, 2006; Su *et al.*, 2008; Bachmann *et al.*, 2012; Flener *et al.*, 2012; Doxani *et al.*, 2012; Bramante *et al.*, 2013; Tang and Pradhan, 2015; Su *et al.*, 2015; Vinayaraj *et al*., 2015; Guzinski *et al.*, 2016; Toming *et al.*, 2016; Jegat *et al.*, 2016; Chybicki *et al.*, 2018).

Although SBD has received substantial attention by researchers in the recent decades, unfortunately, most of the studies have primarily focused on the development and enhancement of the established algorithms which are more inclined to remote sensing environments (Doxani *et al.*, 2012; Bramante *et al.*, 2013; Su *et al.*, 2015; Vinayaraj *et al.*, 2015; Guzinski *et al.*, 2016; Toming *et al.*, 2016; Jegat *et al.*, 2016; Mohamed *et al.*, 2015; Martins *et al.*, 2017; Allen *et al.*, 2017). Indeed, most of the outcomes from the above studies are indirectly beneficial to the hydrographic survey industry. However, most of the studies did not address a significant issue which mystifies the surveyor community in Malaysia; which is acknowledgement of the detail accuracy of the depth estimations produced by the SDB technique. Precision and accuracy are always the subject of interest to surveyors. However, this part went unreported in most of the studies.

To embrace the SDB technology in the hydrographic surveying industry, the depth estimations produced by the SDB need to be analysed with the requirements laid down in the IHO Standards for Hydrographic Surveys (IHO, 2008). Therefore, it is timely to have a detailed study in this country to assess, evaluate and analyse the capability and consistency of SDB outcomes in Malaysia's environment settings comprehensively together with the standards specified by the hydrographic surveying industry. Furthermore, the 'local settings' which refers to the tropical environment consist of entirely different parameter settings as compared to most of the above-mentioned studies that were cited.

1.3 Research Questions

Since the SDB technology is relatively new to the hydrographic industry in Malaysia, one question that was posed amongst surveyors about this technology is on the acceptability of the data provided from satellite remotely sensed technique concerning surveying industry practicality. Bramante *et al.* (2013), Pe'eri *et al.* (2014) and Tang and Pradhan (2015), used available soundings (depths) from the Electronic Navigation Chart (ENC) and bathymetric charts for the algorithm in deriving depths data. The results generated from the analysis might be sufficient enough and relevant to other field applications such as reconnaissance of chart adequacy, managing of the coastal zone and marine biodiversity modelling and so forth. However, in the surveying industry, the level of accuracy demanded is comparatively higher. In addition, the issue of consistency also needs to be addressed.

Therefore this research is addressing the gap identified from the reviews as above. The analysis of the gap has shaped a few fundamental research questions;

a. Which is the most practical algorithm model to adopt in this country's tropical weather and muddy water condition?

b. How reliable is the SDB technology in producing a consistent level of accuracy in the field of hydrographic surveying, especially for the shallow water area?

c. Which class of survey standard (IHO) that this technology is capable of achieving?

d. What improvement can be developed to simplify the current processing procedure that can be adapted into hydrographic surveying application?

1.4 Research Objectives

This research focuses more on utilising the technology of the optical remote sensing tools to derive bathymetry data for hydrographic surveying applications. In general, this research has successfully explored in detail the ability of light penetrating the body of water through various available techniques and algorithms in which it has provided a physical basis for modelling of bathymetry data from a few types of multi-spectral satellite data. As the field of SDB is still new in Malaysia, the primary objective that is set for this research is to identify, examine and develop the most practical SDB method which is capable of delivering the best outcomes for shallow water hydrographic mapping. In order to meet the desired aim, the research is focused on the following objectives.

a. Objective 1: To identify the performance of the empirical model algorithms, Lyzenga and Stumpf, in deriving bathymetry data modelling from multi-spectral satellite imageries in a tropical environment;

b. Objective 2: To determine the level of reliability produced from the algorithms focusing on the shallow water area which reflects on the hydrographic mapping applications.

c. Objective 3: To assess the degree of accuracy and standards of bathymetric data derived from SDB technology in meeting the standard and specifications laid by IHO.

d. Objective 4: To develop the new calibration of the SDB empirical method with an optimisation technique focusing on the tropical environmental parameter.

1.5 Scope of Study

The introduction of a high-resolution multi-spectral imagery satellite was a catalyst in the the SDB field for it to be a fast-growing technology and ultimately has fascinated a significant number of researchers around the globe. Consequently, the study scope has been reshaped and re-aligned in order to achieve the desired objectives. Thus, the study has placed emphasis at the critical stage of the processing part which deals in confronting the bottom reflectance in determining the bathymetric model in the shallow water area where the interest of the area will incline into identifying the TSB. Indirectly, this approach will minimise the discussions on the other processing parts, such as the sun glint removal and atmospheric correction stages. In deriving the bathymetric data from satellite imageries, this research focused on the capabilities of few satellite imageries. To have variety in evaluating the outcome of SDB, this research adopted three type of satellite imageries. Table 1.2 lists down in detail the kind of satellite imageries and the bands which will be used for the research.

Table 1.2: List of satellite imageries and bands used

Satellite Data/ Category	**Spatial Resolution**	**Wave Length Bands (nm)**	**Area/Date Captured**
Sentinel 2 (High-Resolution)	10 m	Blue: 447 to 545 Green: 538 to 582 Red: 645 to 682 Near IR: 763to 907	Tawau (29 Nov 2016) Labuan (28 June 2017)
Pleiades (Very High-Resolution)	2 m	Blue: 430 to 550 Green: 500 to 600 Red: 590 to 710 Near IR: 740 to 940	Tawau (12 July 2016)
WorldView2 (Very High-Resolution)	0.5 m	Coastal Blue: 400 to 450 Blue: 450 to 510 Green: 510 to 580 Yellow: 585 to 625 Red: 625 to 695 RedEdge: 705 to 745 Near IR: 770 to 895 Near IR2: 840 to 1040	Labuan (26 June 2015)

1.6 Study Areas

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. Availability of data (bathymetry, tidal and satellite images) was the primary criteria for choosing both locations as study areas. At the same time, 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 (coastal type 1P and 1M) 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. Thus, the results from Tawau Port is capable of representing the majority of shallow water conditions 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 (coastal type 2E and 3E) 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 1.3 indicates the geographical location of both study areas.

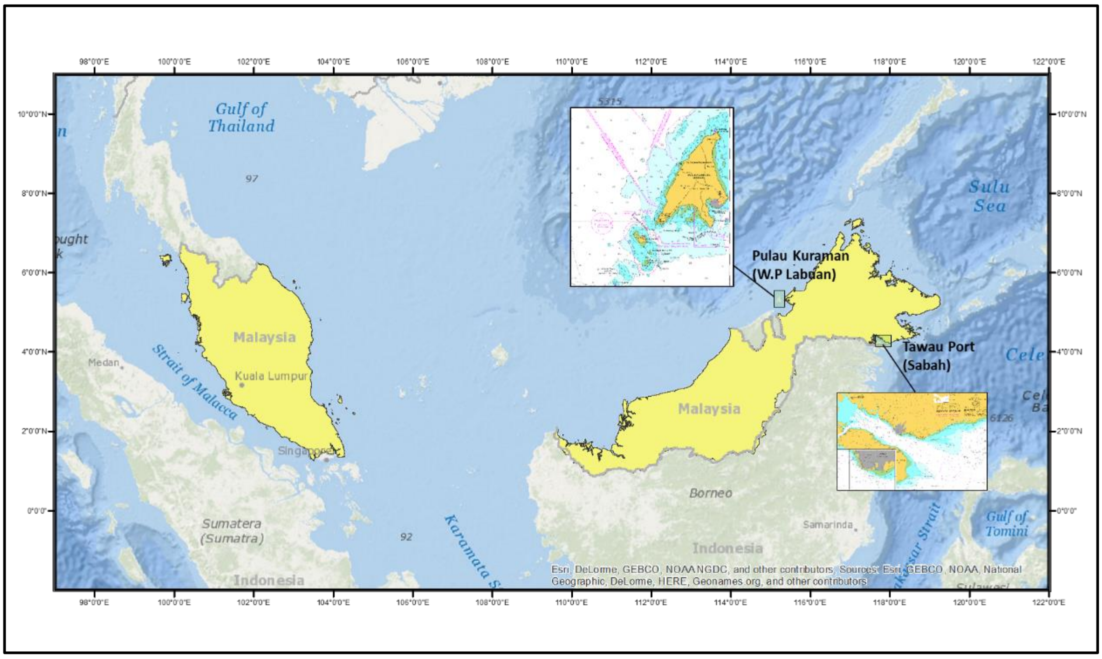

Figure 1.3 Geographical location of the study areas, the Tawau Port (Sabah) and Pulau Kuraman (W.P Labuan)

1.7 Significance of Study

This study has delivered a significant contribution to various fields, especially primary stakeholders such as NHC as the national focal point for all hydrographic surveying activities. Likewise, to the Department of Survey and Mapping Malaysia (DSMM), this research has provided a new approach in assisting the authority to update the national Territorial Sea Baselines (TSB). Nevertheless, this research did not fall short in delivering significant research novelty.

1.7.1 Delivering New Guidelines to Malaysian Hydrographic Industry

The most significant outcome of this research is the answer to whether the SDB technology is acceptable in the field of hydrographic surveying in this country. The SDB technology is considered as a new method for bathymetry data acquisition. There are a number of algorithms and techniques available in deriving bathymetry data. However, not all algorithms and technologies are suitable in term of practicality for the hydrographic surveying industry in Malaysia. Therefore, this research has successfully addressed the uncertainties and ambiguities by finding the suitable algorithm and technique to be adopted in Malaysia. This positive outcome will undoubtedly be able to assist in the challenging task of the NHC in filling in massive gaps of data on the very shallow water areas nationwide.

In conjunction with Universiti Teknologi Malaysia, a research university alongside the National Blue Ocean Strategy concept, this research has also facilitated the NHC as the national authority in developing a new set of guidelines in SDB acquisition technique and to provide the direction for the surveying industry in the country on this rapidly developing SDB technology. On top of that, this research has also assisted the NHC in participating with the IHO Technical Working Group under the Hydrographic Services and Standards Committee (IHO, 2015b), to study and develop the standards for the SDB technology as a new surveying method. As the standard for SDB technology is now in the pipeline, this research delivered a significant contribution to NHC as the outcomes have portrayed an accurate view of the capability of this promising technology to be adopted in this country.

1.7.2 Identifying The Nation's Territorial Sea Baseline (TSB)

The other stakeholder who directly benefited from this research is DSMM as the lead agency in maritime delimitation activities. Malaysia has a total of 55,6285 km^2 maritime area as compared to 329,960 km^2 of land area (NHC, 2016). This sizeable maritime area rationalises Malaysia to have more maritime neighbours as compared to the land neighbours (Haller-Trost, 1998; and Forbes and Basiron, 2008). Therefore, there is a necessity to address the question; where does the sea begin? Technically, under the Convention, the datum or the starting line for measuring the width of maritime jurisdictional zones encompassing from the coast seaward is the Territorial Sea Baseline (Forbes and Basiron, 2008).

According to Article 5 of the Convention, *"the normal baseline of a coastal state is the low-water mark as delineated on the large-scale charts adopted by the coastal state"* (United Nation, 1982). From this datum, the zone of jurisdiction, as provided in the UNCLOS 1982, namely the Territorial Sea (Article 3), the Contiguous Zone (Article 33), an Economic Exclusive Zone (Article 57) and the Continental Shelf (Article 76) are measured. Undeniably, all these articles demonstrate the importance for a coastal state to determine the TSB, which must then portrayed on charts (Reed, 2000; Prescott and Schofield, 2004 and Schofield, 2012). The only method of defining the national TSB is through bathymetry data collection. Therefore, the coastal state shall utilise the unsurpassed acquisition method available to produce the optimum outcomes.

Although DSMM had carried out a complete detail survey to identify national TSB, nevertheless, the surveying method which was adopted more than 14 years ago is arguably was not the best method to be applied as the Single Beam Echo Sounder System (SBES) was manifestly unable to provide comprehensive coverage. As better technology is now available, it is timely to revisit the whole process and implement the latest technology for the benefit of the country. Indeed, the positive outcomes from this research can undoubtedly be utilised by DSMM as a tool to assess our current TSB. Theoretically, by adopting this SDB technology, the data coverage becomes more substantial and a comprehensive coverage can be visualised. This approach is ideally capable of discovering some potential new low water line and low tide elevation within the whole nation shallow water areas. If this happens, this research certainly will be beneficial to Malaysia as we might gain more territory in our maritime zones.

1.7.3 Providing Significant Research Novelty

In the perspective of research novelty, this research has produced a new technique for SDB calibration. M-LOT is an in-house tool developed using MATLAB software which applies the combination of the least square adjustment method and linear correlation algorithm which has successfully improved the results in terms of quality and consistency. In general, the hardest part of the processing of the SDB application is the depth calibration process before applying the empirical inversion model. The conversational process is not only time-consuming but also requires additional skills and experiences of the hydrographic surveyor. M-LOT has simplified the painstaking element and has been proven in making the process easier in deriving bathymetry data from SDB application.

1.8 Thesis Outline

This research thesis consists of six (6) chapters which are Introduction, Literature Review, Research Methodology, Model's Calibration and Depth Derivation Results and the Results and Analysis. The detailed thesis outline of all chapters are elaborated in the following sub-paragraphs.

1.8.1 Introduction

The first chapter of this thesis is an introduction chapter. This chapter presents the general view of this research which covers Background of Study, Problem Statements, Research Questions, Research Objectives, Scope of Study, Study Areas, Methodology and Significance of the Study.

1.8.2 Literature Review

This chapter discusses the literature studies on related research works especially on SDB and divulges the research gaps. In addition, the technical information about multi-spectral images and remote sensing technology is also elaborated on. The topics discussed in this chapter are the Fundamentals of SDB, SDB for Hydrographic Mapping, types of Multi-spectral Satellite Imagery and Derivation Models used in SDB and the Research Gaps Finding.

1.8.3 Research Methodology

This chapter illuminates on the methodology adopted for the research. All work processes in meeting every single objective were discussed comprehensively. The topics illustrating the workflow of this research which consist of the five (5) phases involved are the Pre-Research Phase, Data Collection Phase, Data Processing Phase, Depth Derivation Phase and Data Analysis Phase.

1.8.4 Model's Calibration and Depth Derivation Using Multi-Spectral Satellite Imageries

This chapter discusses in detail the outcomes of the calibration and depth derivation processes. The calibration process that delivers the variables required for all three adopted model Lyzenga, Stumpf and M-LOT were described comprehensively. Consequently, this chapter also enlightens on the results that are obtained from models depth derivation. The subject discussed in this chapter are divided into Model's Depth Calibration Results and Depth Derivation Outcomes.

1.8.5 Result and Discussions

This chapter illuminates in detail the final findings of the research. The discussion covers the quantitative evaluation of all depth derivation model outcomes and the analysis of the IHO survey standards assessment process. Furthermore, this chapter also comprehensively elaborates on the findings and performance of every single model including the level of improvement achieved by M-LOT. The

REFERENCES

Adler-Golden, S. M., Acharya, P. K., Berk, A., Matthew, M. W., Gorodetzky, D. (2005) Remote Bathymetry of the Littoral Zone from AVIRIS, LASH, and QuickBird Imagery. *IEEE Transactions on Geoscience and Remote Sensing*, 43 (2), 337-347.

Airbus Defence and Space (2016). SPOT 6 | SPOT 7 High Resolution Broad Coverage. Intelligence. Available from <http://www.intelligence-airbusds.com/>. [3 May 2016]

Albert, A., and Gege, P. (2006). Inversion of Irradiance and Remote Sensing Reflectance in Shallow Water between 400 and 800 nm for Calculations of Water and Bottom Properties. *Applied Optics*, 45, 2331–43.

Allen, J. G., Nelson, N. B. and Siegel, D. A. (2017). Seasonal to Multi-Decadal Trends in Apparent Optical Properties in The Sargasso Sea. *Deep-Sea Research Part I-Oceanographic Research Papers 119(January)*.

Astrium (2010). Pléiades Imagery User Guide. Version 2.0, October 2012. Astrium GEO-Information Services, Toulouse, France.

Bachmann, C., Montes, M., Parrish, C., Fusina, R., Nichols, R., Li, R., Hallenborg, E., Jones, C., Lee, K., Sellars, J., White, S., and Fry, J. (2012). A Dual-Spectrometer Approach to Reflectance Measurements Under Sub-Optimal Sky Conditions. *Optics Express*, 20, 8959–8973.

Barale, V., Larkin, D., Fusco, L., Melinotte, J. M. and Pittella, G. (1999). OCEAN Project: The European Archive of CZCS historical data. *International Journal of Remote Sensing*. 20(70): pp. 1201-1218.

Benny, A. H., and Dawson., G. J. (1983). Satellite Imagery as an Aid to Bathymetric Charting in the Red Sea. *The Cartographic Journal*, 20:1983, 5–16.

Bramante, J. F., Raju, D. K. and Sin, T. M. (2013). Multi-spectral Derivation of Bathymetry in Singapore's Shallow, Turbid Waters. *International Journal of Remote Sensing*, 34:6, 2070-2088.

Brando, V. E., and Dekker, A. G. (2003). Satellite Hyperspectral Remote Sensing for Estimating Estuarine and Coastal Water Quality. *IEEE Transactions on Geoscience and Remote Sensing*, 41(6), 1378–87.

Brando, V. E., Anstee, J. M., Wettle, Dekker, A. G., Phinn, S.R., and Roelfsema, C. (2009). A Physics Based Retrieval and Quality Assessment of Bathymetry from Suboptimal Hyperspectral Data, *Remote Sensing of Environment*, 113(2009), 755-770

Brock, J. C., Wright, C.W., Clayton, T. D. and Nayegandhi, A. (2004). LIDAR Optical Rugosity of Coral Reefs in Biscayne National Park, Florida. *Coral Reefs*, 23, 48–59.

Carder, K. L., Cannizzaro, J. P. and Lee, Z. P. (2005). Ocean Color Algorithms in Optically Shallow Waters: Limitations and Improvements. The International Society for Optical Engineering Proceeding, SPIE 5885, Remote Sensing of the Coastal Oceanic Environment, 23 August 2005, 1–11.

Chybicki, A. (2018). Three-Dimensional Geographically Weighted Inverse Regression (3GWR) Model for Satellite-Derived Bathymetry Using Sentinel-2 Observations. Marine Geodesy, 41:1, 1-23.

Clark, R. K., Fay, T. H. and Walker, C. L. (1987). Bathymetry Calculations with Landsat-4-TM Imagery Under a Generalized Ratio Assumption. *Applied Optics.* 26(19): 4036–4038.

Conger, C. L., Hochberg, E. J., Fletcher, C. H., and Atkinson, M. J. (2006). Decorrelating Remote Sensing Color Bands from Bathymetry in Optically Shallow Waters. *IEEE Trans. On Geoscience and Remote Sensing*, 44, 1655–1660.

Copley, J. (2014). Just How Little Do We Know about the Ocean Floor? Available from Scientific American website <http://www.scientificamerican.com/>. [23 June 2016].

Corucci, L., Masini, A. and Cococcioni, M. (2011). Approaching Bathymetry Estimation from High Resolution Multi-spectral Satellite Images Using a Neuro-Fuzzy Technique. *Journal of Applied Remote Sensing*, 5(1):053515–053515-15.

Digital Globe, (2009). Worldview-2 Overview, Technical Note. 4th June 2009. Digital Globe, Westminster, Colorado, United States.

Doxani, G., Papadopoulou, M., Lafazani, P., Pikridas, C. and Tsakiri-Strati, M. (2012). Shallow-Water Bathymetry over Variable Bottom Types Using Multi-spectral Worldview-2 Image. ISPRS Congress Proceeding, 25 Aug – 1 Sept 2012, Melbourne, Australia. 159-164.

Drusch, M., Gascon, F. and Berger, M. (2010). GMES Sentinel-2 Mission Requirements Document, Issue 2 Revision 1. ESA: Paris, France.

Ehses, J. S. and Rooney, J. J. (2015). Depth Derivation Using Multi-spectral WorldView-2 Satellite Imagery. US Department of Commerce. NOAA Technical Memorandum NMFS-PIFSC-46.

Elvidge, C. D., Dietz, J. B., Berklemans, R., Andréfouët, S., Skirving, W., Strong, A. E. and Tuttle, B. T. (2004). Satellite observation of Keppel Islands (Great Barrier Reef) 2002 Coral Bleaching Using IKONOS Data. *Coral Reefs*, 23, 123–132

European Space Agency. (2015). Sentinel-2 User Handbook; ESA Standard Document; ESA: Paris, France.

Figueiredo, I. N., Pinto, L. and Goncalves, G. (2015). A Modified Lyzenga's Model For Multi-spectral Bathymetry Using Tikhonov Regularization. Pr´e-Publica¸c˜oes do Departamento de Matem´atica.

Finkl, C. W., Benedet, L. and Andrews, J. L. (2005). Interpretation of seabed geomorphology based on spatial analysis of high-density airborne laser bathymetry. Journal of Coastal Research 21:501–514.

Flamanc, D., and Maillet, G. (2005). Evaluation of 3D City Model Production from Pleiades High-Resolution Satellite Images And 2D Ground Maps. *URBAN*, Tempe, USA, 46-51.

Flener, C., Lotsari, E., Alho, P., and Kayhko, J. (2012). Comparison of Empirical and Theoretical Remote Sensing Based Bathymetry Models in River Environments. *River Research and Applications*, 28, 118–133.

Forbes, V. L. and Basiron, M. N. (2008). *Malaysia's Maritime Realm Atlas*. Kuala Lumpur: Maritime Institute of Malaysia (MIMA).

Forfinski-Sarkozi, N. A., and Parrish, C. E. (2016). Analysis of MABEL bathymetry in Keweenaw Bay and implications for ICESat-2 ATLAS. *Remote Sensing* 8(9), 772.

Freire, R., Pe'eri, S., Madore, B., Rzhanov, Y., Alexander, L., Parrish, C. E., and Lippmann, T. C. (2015). Monitoring Near-Shore Bathymetry Using a Multi-Image Satellite-Derived Bathymetry Approach. Proceeding of the US Hydrographic Conference 2015. March 16-19, 2015. National Harbor, Maryland: US Hydro 2015. 1-7.

Giardino, C., Candiani, G., Bresciani, M., Lee, Z., Gagliano, S. and Pepe, M. (2012). BOMBER: A Tool for Estimating Water Quality and Bottom Properties from Remote Sensing Images. *Computers & Geosciences*. 45(August):313–18.

Gordon, A. D. (1994). Identifying Genuine Clusters in a Classification. *Computational Statistics and Data Analysis*, 18: 561–81.

Gould, R. W. J., Arnorne, R. A. and Sydor, M. (2001). Absorption, Scattering, and Remote-Sensing Reflectance Relationships in Coastal Waters: Testing a New Inversion Algorithm. *Journal of Coastal Research*, 17, 328–41.

Green, E., Mumby P., Edwards A. and Clark, C. (2000). *Remote Sensing Handbook for Tropical Coastal Management.* Coastal Management Sourcebooks series, UNESCO Publication, Chapter 8.

Guzinski, R., Spondylis, E., Michalis, M., Tusa, S., Brancato, G., Minno, L. and Hansen, L. B. (2016). Exploring the Utility of Bathymetry Maps Derived with Multispectral Satellite Observations in the field of underwater archaeology. Open Archaeology 2(1):243–263.

Hamylton, S. M., Hedley, J. D. and Beaman, R. J. (2015). Derivation of high-resolution bathymetry from multi-spectral satellite imagery: a comparison of empirical and optimisation methods through geographical error analysis. Remote Sensing 7(12),16257–16273.

Haller-Trost, R. (1998). *The contested maritime and territorial boundaries of Malaysia: An international law perspective*. Cambridge, MA: Kluwer Law International.

Hedley, J. D., Harborne, A. R. and Mumby, P. J. (2005). Simple and Robust Removal of Sun Glint for Mapping Shallow-Water Benthos. *International Journal of Remote Sensing*, 26:10, 2107-2112.

Hedley, J., Roelfsema, C., Koetz, B. and Phinn, S. (2012). Capability of the Sentinel 2 mission for tropical coral reef mapping and coral bleaching detection. *Remote Sensing of Environment*, 120, 145–155.

Hengel, W. V. and Spitzer, D. (1991). Multi-temporal water depth mapping by means of Landsat TM. *International Journal of Remote Sensing*, 12:4, 703-712.

Hernandez, W. J. and Armstrong, R. A. (2016) Deriving Bathymetry from Multispectral Remote Sensing Data. *Journal of Marine Science and Engineering*, 4(8): 1–16

Hochberg, E. J., Andrefouet S. and Tyler, M. R. (2003). Sea Surface Correction of High Spatial Resolution IKONOS Images to Improve Bottom Mapping in Near-Shore Environments, *IEEE Transactions on Geoscience and Remote Sensing*, 41(7), 1724-1729.

Hoepffner, N. and Zibordi, G. (2009). *Remote Sensing of Coastal Waters. In Encyclopedia of Ocean Sciences*. Second Edition. Edited by Steele, J. H., Turekian, K. K. and Thorpe, S. A. pp 732–41. London.

Hogfe, K. R., Wright, D. J. and Hochberg, E. J. (2008). Derivation and Integration of Shallow-Water Bathymetry: Implications for Coastal Terrain Modeling and Subsequent Analyses. *Marine Geodesy*, 31, 299–317.

International Hydrographic Organization (1994). *International Hydrographic Dictionary (5th Edition)*. Monaco: IHO Publication S-32.

International Hydrographic Organization (2005). *Manual on Hydrography (1st Edition: Corrections to February 2011)*. Monaco: IHO Publication C-13.

International Hydrographic Organization (2008). *IHO Standards for Hydrographic Surveys (5th Edition).* Monaco: IHO Publication S-44.

International Hydrographic Organization (2015a). *The IHO-IOC GEBCO Cook Book.* Monaco: IHO Publication B-11.

International Hydrographic Organization (2015b). Report of 7th Meeting of the Hydrographic Services and Standards Committee in Busan, Republic of Korea, 9-13 November 2015.

International Hydrographic Organization (2015c). Report of 11th Meeting Chart Standardization and Paper Chart Working Group (CSPCWG)/Nautical Cartography Working Group (NCWG). Satellite-Derived Bathymetry Working Paper in Rostock, Germany, 27-30 April 2015.

International Maritime Organization, (1974). *International Convention for the Safety of Life At Sea, 1974*. London: SOLAS 1974.

International Ocean Colour Coordinating Group (2006). *Remote Sensing of Inherent Optical Properties: Fundamentals, Tests of Algorithms, and Applications*. Reports of the International Ocean-Colour Coordinating Group, edited by Z. Lee, 1–122. Canada: Dartmouth.

Jegat, V., Pe'eri, S., Freire, R., Klemm, A., Nyberg, J. (2016). Satellite-Derived Bathymetry: Performance and Production, Proceeding of 2016 Canadian Hydrographic Conference. Halifax.

Jena, B., Kurian, P. J., Swain, D., Tyagi, A. and Ravindra, R. (2012). Prediction of Bathymetry from Satellite Altimeter Based Gravity in the Arabian Sea: Mapping of Two Unnamed Deep Seamounts, *International Journal of Applied Earth Observation and Geoinformation*, 16(6), 1-4.

Jensen, J. R. (2007). Remote sensing of the environment: An earth resource perspective, 2nd Edition. Upper Saddle River, New Jersey: Prentice Hall.

Jupp, D. L. B. (1989). Background and Extension to Depth of Penetration (DOP) Mapping in Shallow Coastal Waters. Proceedings of Symposium on Remote Sensing of Coastal Zone, Gold Coast, Queensland, IV 2 (1) - IV 2 (19).

Kanno, A., Koibuchi, Y. and Isobe, M. (2011). Statistical Combination of Spatial Interpolation and Multispectral Remote Sensing for Shallow Water Bathymetry. *IEEE Geoscience and Remote Sensing Letters* 8(1):64–67.

Kanno, A., and Tanaka, Y. (2012). Modified Lyzenga's Method For Estimating Generalized Coefficients of Satellite-Based Predictor of Shallow Water Depth. *IEEE Geoscience and Remote Sensing Letters* 9:715–719.

Kay, S., Hedley, J.D. and Lavender, S. (2009). Sun Glint Correction of High and Low Spatial Resolution Images of Aquatic Scenes: A Review of Methods for Visible and Near-Infrared Band Wavelengths. *Remote Sensing*, 1:4, 697-730.

Kobryn, H. T., Wouters, K., Beckley, L. E. and Heege, T. (2013). Ningaloo Reef: Shallow Marine Habitats Mapped Using a Hyperspectral Sensor. *PLoS One*, 8(7).

Kramer, H. J. (2002). Observation of the Earth and Its Environment: Survey of Missions and Sensors. EO Portal Directory, Sharing Earth Observation Resources. Available from <https://directory.eoportal.org/web/eoportal/satellite-missions/p/pleiades>. [8 May 2017]

Kyriakidis, I., Karatzas, K., Ware, A. and Papadourakis, G. (2016). A generic preprocessing optimization methodology when predicting time-series data. *International Journal of Computational Intelligence Systems*, 9(4), 638–51.

Lee, Z. P., Carder, K. L., Mobley, C. D., Steward, R. G. and Patch. J. S. (1998). Hyperspectral Remote Sensing for Shallow Waters: 1. A Semi-Analytical Model. *Applied Optics* 37, 6329–38.

Lee, Z. P., Carder, K. L., Mobley, C. D., Steward, R. G. and Patch. J. S. (1999). Hyperspectral Remote Sensing for Shallow Waters: 2. Deriving Bottom Depths and Water Properties by Optimization. *Applied Optics*, 38, 3831–43.

Lee, Z. P., Carder, K. L., Chen, R. F. and Peacock, T. G. (2001). Properties of the water column and bottom derived from airborne visible imaging spectrometer (AVIRIS) data. *Journal of Geophysical Research*, 106, 639-651.

Lee, Z. P., Carder, K. L. and Arnorne, R. A. (2002). Deriving Inherent Optical Properties from Water Color: A Multiband Quasi-Analytical Algorithm for Optically Deep Waters. *Applied Optics*, 41, 5755–72.

Liu, Z. (2013). Bathymetry and bottom albedo retrieval using Hyperion: a case study of Thitu Island and reef. *Chinese Journal of Oceanology and Limnology*, 31(6), 1350–55.

Legleiter, C. J., Roberts, D. A., Marcus, W. A. and Fonstad, M. A. (2004). Passive Optical Remote Sensing of River Channel Morphology and In-Stream Habitat: Physical Basis and Feasibility. *Remote Sensing of Environment*, 93, 493–510.

Liew, S. C., Chang, C. W. and Kwoh, L. K. (2012). Sensitivity Analysis in the Retrieval of Turbid Coastal Water Bathymetry Using Worldview-2 Satellite Data, *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, Volume XXXIX-B7, XXII ISPRS Congress, 25 August – 01 September 2012, Melbourne, Australia

Lillycrop, W. J., and Banic, J. R. (1993). Advancements in the U.S. Army Corps of Engineers Hydrographic Survey Capabilities: The SHOALS system. *Marine Geodesy*, 15,177–185.

Liu S., Zang J. and Ma, Y. (2010). Bathymetric Ability of Spot-5 Multi-spectral Image in Shallow Coastal Water. Proceedings of the 18th International Conference on Geoinformatics: GIScience in Change, Peking University, Beijing, China.

Liu, Z. (2013). Bathymetry and bottom albedo retrieval using Hyperion: a case study of Thitu Island and reef. *Chinese Journal of Oceanology and Limnology*, 31(6):1350–55.

Louchard, E. M., Reid, R. P., Stephens, C., Davis, C. O., Leathers, R. A. and Downes, T. V. (2003). Optical Remote Sensing of Benthic Habitats and Bathymetry in Coastal Environments at Lee Stocking Island, Bahamas: A Comparative Spectral Classification Approach. *Limnology and Oceanography*, 48, 511–21.

Lyons, M., Phinn S. and Roelfsema, C. (2011). Integrating Quickbird Multi-Spectral Satellite and Field Data: Mapping Bathymetry, Seagrass Cover, Seagrass Species and Change in Moreton Bay, Australia in 2004-2007. *Remote Sensing*, 3, 42-64.

Lyzenga, D. R. (1978). Passive Remote Sensing Techniques for Mapping Water Depth and Bottom Features. *Applied Optics*, 17:3, 379-383.

Lyzenga, D. R. (1981). Remote Sensing of Bottom Reflectance and Water Attenuation Parameters in Shallow Water Using Aircraft and Landsat Data. *International Journal of Remote Sensing*, 2:1, 71-82.

Lyzenga, D. R. (1985). Shallow-Water Bathymetry Using Combined Lidar and Passive Multi-spectral Scanner Data. *International Journal of Remote Sensing*, 6:1, 115-125.

Lyzenga, D., Malinas, N. and Tanis, F. (2006). Multi-spectral Bathymetry Using a Simple Physically Based Algorithm. *IEEE Transactions Geoscience and Remote Sensing*, 44:8, 2251-2259.

Ma, S., Tao, Z., Yang, X., Yu, Y., Zhou, X. and Li, Z. (2014). Bathymetry Retrieval from Hyperspectral Remote Sensing Data in Optical-Shallow Water. *IEEE Transactions on Geoscience and Remote Sensing,* 52(2):1205–12.

Mahiny, A. S., and Turner, B. J. (2007). A comparison of four common atmospheric correction methods. *Photogrammetric Engineering & Remote Sensing*, 73(4), 361–68.

Maritorena, S., Siegel, D. A. and Peterson, A. R. (2002). Optimization of a Semi-Analytical Ocean Color Model for Global-Scale Applications. *Applied Optics*, 41: 2705–14.

Markus, I., Atzberger, C., and Koukal, T. (2012). Tree Species Classification with Random Forest Using Very High Spatial Resolution 8-Band WorldView-2 Satellite Data. *Remote Sensing*, 4(9), 2661-2693.

Martimort, P., Arino, O., Berger, M., Biasutti, R., Carnicero, B., Del Bello, U., Fernandez, V., Gascon, F., Greco, B., Silvestrin, P., Spoto, F. and Sy, O. (2007). Sentinel-2 Optical High Resolution Mission for GMES Operational Services. Proceedings of IGARSS 2007 (International Geoscience and Remote Sensing Symposium), Barcelona, Spain, July 23-27, 2007.

Martin, J., Eugenioa, F., Marcelloa, J., Medinaa, A. and Bermejo, J. A. (2012) Atmospheric correction models for high resolution WorldView-2 multi-spectral imagery: A case study in Canary Islands, Spain. The International Society for Optical Engineering Proceedings (SPIE), November 2012, SPIE Vol. 8534.

Martins, V. S., Barbosa, C. C. F., Carvalho, L. A. S., Jorge, D. S. F., Lucia Lobo, F. and Moraes Novo, E. M. L. (2017). Assessment of Atmospheric Correction Methods for Sentinel-2 MSI Images applied to Amazon floodplain lakes. *Remote Sensing*, 9(4):322.

McClain, C. R., Cleave, M. L., Feldman, G. C., Gregg, W. W., Hooker, S. B. and Kuring, N. (1998). Science Quality SeaWiFS Data for Global Biosphere Research. *Sea Technology*. September 1998: pp 10-15.

McIntyre, M. L., Naar D. F., Carder K. L., Donahue B. T., Mallinson D. J. (2006). Coastal Bathymetry from Hyperspectral Remote Sensing Data: Comparisons with High Resolution Multibeam Bathymetry. *Marine Geophysical Researches*, 27, 128-136.

Minghelli-Roman, A., Goreac, A., Mathieu, S., Spigai, M. and Gouton. P. (2009). Comparison of Bathymetric Estimation Using Different Satellite Images in Coastal Sea Waters. *International Journal of Remote Sensing*, 30, 5737–50.

Mishra, D. R., Narumalani, S., Lawson, M. and Rundquist, D. (2004). Bathymetric Mapping Using IKONOS Multi-spectral Data. *IEEE Transactions on Geoscience and Remote Sensing*, 41:4: 301-321.

Mishra, D. R., Narumalani, S., Rundquist, D., and Lawson, M. (2005). High-Resolution Ocean Color Remote Sensing of Benthic Habitats: A Case Study At The Roatan Island, Honduras. *IEEE Transactions on Geoscience and Remote Sensing*, 43(7):1592–1604.

Mishra, D. R., Narumalani, S., Rundquist, D., and Lawson, M. (2006). Benthic Habitat Mapping in Tropical Marine Environments Using Quickbird Multi-spectral Data. *Photogrammetric Engineering & Remote Sensing*, 72(9):1037–1048.

Mishra, D. R., Narumalani, S., Rundquist, D., Lawson, M. and Perk, R. (2007). Enhancing the Detection and Classification of Coral Reef and Associated Benthic Habitats: A Hyperspectral Remote Sensing Approach. *Journal of Geophysical Research: Oceans*, 112:C08014.

Mobley, C. D., Sundman, L. K., Davis, C. O., Bowles, J. H., Downes, T. V., Leathers, R. A., Montes, M. J. (2005). Interpretation of hyperspectral remote-sensing imagery by spectrum matching and look-up tables. Applied Optics 44(17): 3576–92.

Mohamed, H., Negm, A., Zahran, M. and Saavedra, O. C. (2015). Bathymetry Determination from High Resolution Satellite Imagery Using Ensemble Learning Algorithms in Shallow Lakes: Case Study El-Burullus Lake. Eighteenth International Water Technology Conference Proceeding, IWTC18, 12-14 March 2015, Sharm ElSheikh, Egypt.

Muslim, A. M., Komatsu, T. and Dianachia, D. (2012). Evaluation of classification techniques for benthic habitat mapping, The International Society for Optical Engineering Proceeding, SPIE 8525, Remote Sensing of the Marine Environment II, 21 November 2012, Kyoto, Japan.

NASA (2008). Landsat 7 Science Data Users Handbook. Available from NASA website:<http://landsathandbook.gsfc.nasa.gov/pdfs/landsat7_Handbook.pdf./> [6 July 2016]

NASA (2016). Seafloor Features are Revealed by the Gravity Field. Available from the NASA Visible Earth website: <http://visibleearth.nasa.gov/>.[29 June 2016].

NHC (2016). Maklumat Keluasan Zon Maritim Malaysia. Available from NHC website <https://www.hydro.gov.my/index.php/en/component/k2/item/274-maklumat-keluasan-zon-maritim-malaysia/>. [17 August 2016].

Nazrini Badarun. (2016). ESSCOM Tidak Pernah Berdiam Diri. *New Sabah Times*. Available from ESSCOM website <https://esscom.gov.my/.> [21 February 2016].

Paredes, J. and Spero, R. (1983). Water Depth Mapping From Passive Remote Sensing Data under a Generalized Ratio Assumption. *Applied Optics*, 22:8, 1134-1135.

Pe'eri, S., Parrish, C., Azuike, C., Alexander, L. and Armstrong, A. (2014). Satellite Remote Sensing as Reconnaissance Tool for Assessing Nautical Chart Adequacy and Completeness. *Marine Geodesy*, 37, 293–314.

Philpot, W. D. (1989). Bathymetric Mapping with Passive Multi-spectral Imagery. *Applied Optics*, 28, 1569–1578.

Pope, R. M., and Fry, E. S. (1997). Absorption spectrum (380–700 Nm) of Pure Water. II. Integrating Cavity Measurements. *Applied Optics* 36(33):8710–23.

Prescott, J. R. V. and Schofield, C. (2004) *The Maritime Political Boundaries of the World.* 2nd ed. Methuen, London, Brill Academic Publishers.

Recio, M. R., Mathieu, R., Hall, G. B., Moore, A. B. and Seddon, P. J. (2013). Landscape Resource Mapping For Wildlife Research Using Very High Resolution Satellite Imagery. *Methods Ecol Evol*, 4: 982–992.

Reed, M. W. (2000). *Shore and Sea Boundaries: The Development of International Maritime Boundary Principles Through United States Practice.* US Department of Commerce, Washington, D.C.

Roy, D. P., Li, Z., and Zhang, H. K. (2017) Adjustment of Sentinel-2 Multi-Spectral Instrument (MSI) Red-Edge Band Reflectance to Nadir BRDF Adjusted Reflectance (NBAR) and Quantification of Red-Edge Band BRDF Effects. *Remote Sensing*, 9(12), 1325

Sagawa, T., Sakata, E., Matsumoto Y., and Hiraiwa, T. (2016). Satellite based bathymetry measurements in shallow water. Techno-Ocean (Techno-Ocean), Kobe, pp. 97-100.

Schofield, C. (2012). Departures from the Coast: Trends in the Application of Territorial Sea Baselines under the Law of the Sea Convention. *International Journal of Marine and Coastal Law*, 27 (4), 723-732.

Spitzer, D. and Dirks, R. W. J. (1987). Bottom Influence on the Reflectance of the Sea. *International Journal of Remote Sensing*, 8:3, 279–290.

Stevens, J. P. (2009). *Applied Multivariate Statistics for the Social Sciences*.(5th ed.) Madison Avenue, New York: Taylor and Francis Group, LLC.

Stumpf, R. P., Holderied, K. and Sinclair, M. (2003). Determination of Water Depth with High-Resolution Satellite Imagery over Variable Bottom Types. *Limnology Oceanogr*., 48, 547-556.

Su, H., Liu, H. and Heyman, W. D. (2008). Automated Derivation of Bathymetric Information from Multi-Spectral Satellite Imagery Using a Non-Linear Inversion Model. *Marine Geodesy*, 31, 281-298.

Su, H., Liu, H., Wang, L., Filippi, A., Heyman, W. D., and Beck, R. A. (2014). Geographically adaptive inversion model for improving bathymetric retrieval from satellite multi-spectral imagery. IEEE Transactions on Geoscience and Remote Sensing 52(1):465–76.

Su, H., Liu, H. and Wu. Q. (2015). Prediction of Water Depth from Multi-spectral Satellite Imagery - The Regression Kriging Alternative. *IEEE Geoscience and Remote Sensing Letters* 12 (12), 2511–15.

Tang, K. K. W. and Pradhan, B. (2015). Converting Digital Number into Bathymetric Depth: A Case Study over Coastal and Shallow Water of Langkawi Island, Malaysia. Conference Paper for FIG Working Week 2015 in Sofia, Bulgaria.

Tarantino, C., Adamo, M., Pasquariello, G., Lovergine, F., Blonda, P., and Tomaselli, V. (2012). 8-Band Image Data Processing of the Worldview-2 Satellite in a Wide

Area of Applications, *Earth Observation*. Available from: the Intech Open website: <http://www.intechopen.com/books/earth-observation> [29 June 2017]

Toming, K., Kutser, T., Laas, A., Sepp, M., Paavel, B. and Noges, T. (2016). First Experiences In Mapping Lake Water Quality Parameters With Sentinel-2 MSI Imagery. *Remote Sensing,* 8(8), 640.

Updike, T. and Comp, C. (2010). *Radiometric use of WorldView-2 Imagery*. Technical Note, DigitalGlobe®, Inc.

United States Geological Survey (2015). *Landsat – Earth Observation Satellites.* Department of the Interior U.S. Geological Survey. Sioux Falls, South Dakota: Fact Sheet 2015–3081, November 2015.

United States Geological Survey (2016). *Landsat 8 (L8) Data Users Handbook (Version 2).* Department of the Interior U.S. Geological Survey. Sioux Falls, South Dakota: LSDS-1574 Version 2.0.

Vanderstraete, T., Goossens, R., and Ghabour, T. K. (2006). The Use of Multi-temporal Landsat Images for the Change Detection of the Coastal Zone Near Hurghada, Egypt. *International Journal of Remote Sensing*, 27(17), 3645–3655.

Vinayaraj, P., Raghavan, V., Masumoto, and Glejin, J. (2015). Comparative evaluation and refinement of algorithm for water depth estimation using medium resolution remote sensing data. International Journal of Geoinformatics 11(3), 17–29.

Vinayaraj, P., Raghavan, V., and Masumoto, S. (2016). Satellite-Derived Bathymetry Using Adaptive Geographically Weighted Regression Model. *Marine Geodesy*. 39(6):458–78.

Westfall, P. H., (2014). Kurtosis as Peakedness, 1905–2014. R.I.P. *The American Statistician*. 68(3): 191–195.

Winterbottom, S. J. and Gilvear, D. J. (1997). Quantification of Channel Bed Morphology in Gravel-Bed Rivers Using Airborne Multi-spectral Imagery and Aerial Photography. *Regulated Rivers-Research and Management*, 13, 489–49.

Zimmermann, G. and Neumann, A. (1997). Modular Optoelectronic Scanner (MOS) A Spaceborne Imaging Spectrometer for Ocean Remote Sensing. *Backscatter*. May 1997, pp. 9-13.