BATHYMETRY ESTIMATION FROM SATELLITE GEODETIC MISSIONS USING GRAVITY GEOLOGIC METHOD

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ASTINA BINTI TUGI

A thesis submitted in fulfilment of the
requirements for the award of the degree of
Master of Philosophy

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DEDICATION

Dedicated to my beloved Ibu and Ayah

And as an inspiration to my Along, Abang, Baby

And our little Sara

ACKNOWLEDGEMENT

بِسْمِ اللَّهِ الرَّحْمَٰنِ الرَّحِيمِ

In the name of Allah, the most Merciful and Beneficent

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ABSTRACT

Bathymetry information is essential in understanding the physics of the Earth and the ocean process. However, the bathymetry data are difficult to obtain at the restricted, complex and vast area. The conventional bathymetry surveys which used single beam echo sounder and multibeam echo sounder required high expenditure, consumed much time and the bathymetry data obtained were sparse. This study aims to map the bathymetry over the Malaysian seas by using the space-based approach. Six satellite missions namely Jason-1, Envisat1, ERS-2, Jason-2, Cryosat2 and Saral covering 11-year data period (2005-2015) have been used. Gravsoft software was utilised in the derivation of free air gravity anomaly (FAGA), using Fast Fourier Transform technique. Next, the derived FAGA was validated against the marine FAGA model developed by the Department of Survey and Mapping Malaysia. The Gravity-Geologic Method (G-G method) was then performed for the estimation of bathymetry and a density contrast of 1.67 g/cm^3 was used. Area of the estimated bathymetry was along the latitude and longitude of 5ºN – 10ºN and 107ºE – 114.6ºE, respectively. National Geophysical Data Center shipborne data was used utilizing 12362 bathymetry data points. 6584 points were used in the G-G method process while 5778 points as the validation points (check points). Minimum curvature interpolation was utilized in establishing the regional FAGA surfaces. The assessment on the accuracy of the results obtained was made using Root Mean Square Error (RMSE) and correlation coefficient analysis. The mean sea surface height (MSSH) obtained shows a strong correlation with Technical University of Denmark 2015 MSSH model with values of 0.9980. The RMSE for the computed FAGA achieved ±11.52606 mGal, with the use of EGM2008 (full degree and order) Global Geopotential Model and with this value, it gives a reliable derived FAGA information. The final estimated bathymetry produced the RMSE value of ±96.949 m, which is estimated to be large, perhaps due to the dynamic of the ocean and the depth variations. However, this estimated bathymetry can improve the depth accuracy by approximately 69% and 38% based on the comparison made with Earth Topography 1-minute and Technical University of Denmark 2010 global bathymetry model respectively. The final estimated bathymetry is known as Universiti Teknologi Malaysia 2018 bathymetry model. The study confirms that the estimation of bathymetry using the space-based approach is reliable and the mapping of the bathymetry is more effective and time-saving as it can cover non-accessible and restricted area in a mesoscale. The information collected from satellite altimeter can be delivered to the Malaysian Bathymetry Database System as the product from this study.

ABSTRAK

Maklumat kedalaman adalah penting dalam memahami fizik bumi dan proses lautan. Walau bagaimanapun data kedalaman sukar diperoleh di kawasan yang terhad, kompleks dan luas. Kajian kedalaman secara konvensional menggunakan pemerum gema alur tunggal dan pemerum gema berbilang alur memerlukan perbelanjaan yang tinggi, memakan masa dan data kedalaman adalah bersifat jarang. Kajian ini bertujuan untuk memetakan kedalaman bagi lautan Malaysia dengan menggunakan pendekatan berasaskan angkasa. Enam misi satelit iaitu Jason-1, Envisat1, ERS-2, Jason-2, Cryosat2 dan Saral merangkumi tempoh 11 tahun data (2005-2015) telah digunakan. Perisian Gravsoft digunakan dalam menghitung anomali graviti udara bebas (FAGA) menggunakan teknik Fast Fourier Transform. Seterusnya, pengesahan FAGA yang diperoleh dibuat terhadap model FAGA marin yang dibangunkan oleh Jabatan Ukur dan Pemetaan Malaysia. Kaedah Graviti-Geologik (kaedah G-G) kemudian dilakukan untuk menganggarkan kedalaman dan kepadatan kontras 1.67 g/cm^3 telah digunakan. Kawasan kedalaman anggaran adalah masing masing di sepanjang latitud dan longitud 5ºN - 10ºN dan 107ºE - 114.6ºE. Data kapal National Geophysical Data Center digunakan dengan menggunakan 12362 titik data kedalaman. 6584 titik digunakan dalam proses kaedah G-G manakala 5778 titik digunakan sebagai data validasi (titik semakan). Interpolasi lengkung minimum digunakan dalam penubuhan permukaan FAGA serantau. Penilaian keatas ketepatan keputusan yang diperoleh dibuat menggunakan analisis ralat punca min kuasa dua (RMSE) dan pekali kolerasi. Ketinggian permukaan laut purata (MSSH) yang diperoleh menunjukkan korelasi yang kuat dengan model MSSH Technical University of Denmark 2015 dengan nilai 0.9980. RMSE untuk FAGA yang dihitung mencapai ± 11.52606 mGal, dengan menggunakan Model Geopotential Global EGM2008 (berdarjah penuh) dan dengan nilai ini, ia memberikan maklumat FAGA yang boleh dipercayai. Kedalaman anggaran yang muktamat memberikan nilai RMSE sebanyak ± 96.949 m, yang mana nilai RMSE ini dianggarkan menjadi agak besar mungkin disebabkan oleh keadaan dinamik lautan dan variasi kedalaman. Walaupun begitu, kedalaman anggaran ini dapat meningkatkan ketepatan kedalaman dengan sekurang-kurangnya 69% dan 38% berdasarkan kepada perbandingan yang dibuat dengan model Bumi Topografi 1-minit dan model kedalaman global Technical University of Denmark 2010. Kedalaman anggaran yang terakhir dikenali sebagai model kedalaman Universiti Teknologi Malaysia 2018. Kajian ini menunjukkan anggaran kedalaman menggunakan pendekatan berasaskan angkasa adalah boleh dipercayai dan pemetaan kedalaman adalah lebih berkesan dan menjimatkan masa kerana ia boleh meliputi kawasan yang tidak boleh diakses dan terhad secara meluas. Maklumat yang dikumpul dari satelit altimeter boleh dipersembahkan melalui Sistem Pangkalan Data Kedalaman Malaysia sebagai produk dari kajian ini.

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LIST OF ABBREVIATIONS

ESA	–	European Space Agency
NASA	–	National Aeronautics and Space Administration
GFZ	–	German Research Centre for Geosciences
RADS	–	Radar Altimeter Database System
NGDC	–	National Geophysical Data Centre
G-G Method	–	Gravity-Geologic Method
FFT	–	Fast Fourier Transformation
MSSH	–	Mean Sea Surface Height
ETOPO1	–	Earth Topography 1-minute
DTU10	–	Technical University of Denmark 2010
DTU13	–	Technical University of Denmark 2013
DTU15	–	Technical University of Denmark 2015
GPS	–	Global Positioning System
GLONASS	–	Global Navigation Satellite System
SBES	–	Single Beam Echosounder
MBES	–	Multi-Beam Echosounder
NOS	–	National Ocean Service
DNSC	–	Danish National Space Center
LiDAR	–	Light Detection and Ranging
GRACE	–	Gravity Recovery and Climate Experiment
GOCE	–	Gravity-Field and Steady-State Ocean Circulation Explorer Mission
MATLAB	–	Matrix Laboratory
DSSM	–	Department of Survey and Mapping Malaysia
NGDC	–	National Geophysical Data Center
SALT	–	Satellite Altimeter
FAGA	–	Free Air Gravity Anomaly

GGM	–	Geopotential Global Models
ICGEM	–	International Centre for Global Earth Model
RMSE	–	Root Mean Square Error
GEBCO	–	Generic Bathymetry Chart of the Ocean
T/P	–	TOPEX/Poseidon
DORIS	–	Doppler Orbitography and Radiopositioning Integrated by Satellite
SSH	–	Sea Surface Height
MSL	–	Mean Sea Level
SLA	–	Sea Level Anomaly
MDT	–	Mean Dynamic Topography
ADT	–	Absolute Dynamic Topography
N	–	Geoid Height
CHAMP	–	Challenging Minisatellite Payload
LAGEOS	–	Laser Geodynamic Satellite
BGA	–	Bouguer gravity anomaly
NOAA	–	National Oceanic and Atmospheric Administration
WWT	–	Window Width Tapered
SDFM	–	Satellite-Derived FAGA Model
LAT	–	Lowest Astronomical Tide
IDW	–	Inverse Distance Weighting
EBK	–	Empirical Bayesian Kriging
IDTP	–	Inverse Distance to a Power
SIO	–	Scripps Institution of Oceanography

LIST OF SYMBOLS

R	–	Altimeter range
H	–	Satellite altitude
c	–	Speed of light
R'	–	Range computed
T	–	Disturbing gravity potential
W(P)	–	Constant gravity potential on the geoid surface
U(P)	–	Normal gravity potential
γ	–	Normal gravity at the ellipsoid surface
$\Delta\rho$	–	Density contrast between the seawater and bedrock
θ	–	Latitude
λ	–	Longitude
$s(\psi)$	–	Stokes function
g*	–	Total acceleration at the point of the airplane measured by the marine gravimeter
g	–	Total acceleration of the Earth's gravity field
a	–	Motion of the airplane with respect to the Earth surface
F	–	Free-air reduction
G	–	Gravitational constant
ρ	–	Standard density of the crustal mass
N_g	–	Geometric geoid
ΔN_{g_mdt}	–	N_g deducted by MDT
ΔN_{g_mss}	–	N_g without deducting the MDT value
Δg	–	Gravity anomaly
g_o	–	The average of the gravity or the normal gravity
ρ	–	Standard density of the crustal mass
ΔR_{Dry}	–	Dry tropospheric correction
ΔR_{Wet}	–	Wet tropospheric correction

ΔR_{Ion}	–	Ionospheric correction
ΔR_{SSB}	–	Sea-state bias correction
SSH_d	–	Dynamic sea surface height
h_T	–	Tidal height variations
h_a	–	Dynamic atmospheric correction
FA	–	Free air gravity anomaly
A_B	–	Infinite Bouguer plate
Δg_B	–	Bouguer anomaly
g_B	–	Bouguer gravity at geoid
g_{res} (j)	–	Residual gravity at site control point
g_{reg} (j)	–	Regional gravity at site control point
g_{obs} (j)	–	Observed gravity at site control point
g_{res} (i)	–	Residual gravity at site i
g_{reg} (i)	–	Regional gravity at site i
g_{obs} (i)	–	Observed gravity at site i

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CHAPTER 1

INTRODUCTION

1.1 Background of Study

Two thirds of the earth are covered by the ocean and the ocean floor is presumed to be a featureless and flat surface. This idea stated before the 19th century, however, in the 16th century, navigators discovered that the ocean is not as flat as was assumed. Moreover, most geologic processes that take place on land are eventually associated with ocean floor dynamics (Kious and Tilling, 2001). Additionally, the structures and profile of ocean basins, including seamounts and smaller ocean ridges, causes variabilities and fluctuations in tides and currents. Moreover, seafloor morphology such as the shape of the seafloor and its topographic features plays an important role in understanding the processes that form oceans and seas, such as glacial activity on high latitude continental shelves (Hell, 2011).

Topography is fundamental to understanding earth processes. On the land, topography varies from the small mountain valleys to large continental landmasses and this causes weather and climate variations. Land changes due to tectonic activity, erosion, and sedimentation transfer have stimulated the need for detailed topography to investigate geological occasions. In the ocean, with detailed bathymetry information, marine administrations can be organised and marine geology, biology, and physical oceanography can be discovered (Sandwell *et al.*, 2001; Rosmorduc *et al.*, 2006; Hell *et al.*, 2011). In other words, knowledge of ocean bathymetrics is important.

With the invention of satellite altimetry, bathymetry mapping from space can be achieved. This technology has benefited not only the geodesy community, but also the fields of oceanography and geophysics. Based on the measurements provided by satellite altimeters, this technique measures the height of the sea surface as reflected to its reference ellipsoid, which is the geometrical reference surface of the Earth. From sea surface heights measurements, ocean gravity can be obtained on a global scale and with this information, predictions of seafloor or ocean bathymetry can be executed. According to Guojun *et al.* (2003), another advantage of satellite altimeters is that they can determine marine geoids with a good accuracy and high resolution.

According to Xu *et al*. (2009), knowledge of the global ocean before the employment of satellite altimeter missions was spatially and temporally separated with scattered observations. Subsequently, this reflected inadequate information in global ocean observation components. With the implementation of satellite altimeter measurements, the measurement of sea surface height from global ocean circulation can be reliably and consistently obtained. Satellite gravity missions have provided information about the Earth's gravity, allowing marine gravity anomalies to be derived in order to explore the ocean basin (Yildiz, 2012; Sandwell *et al*., 2014). Gravity anomaly data can be used for many research purposes such as predicting bathymetry. Bathymetry predictions can be made with available gravity anomalies. Figure 1.1 depicts gravity anomaly maps derived from satellite altimeter measurements. Figure 1.2 shows the measurement of bathymetry from space by using satellite altimeter measurements.

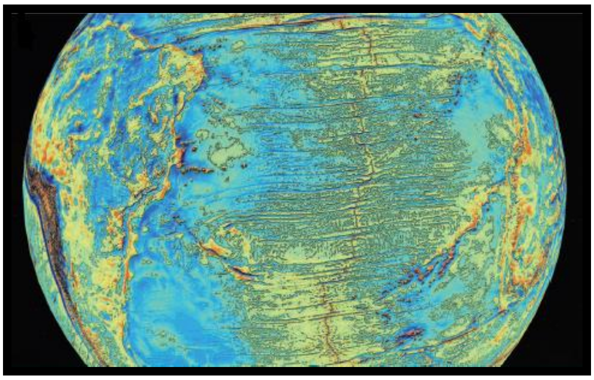

Figure 1.1: Satellite-derived gravity anomaly (Sandwell *et al*., 2014)

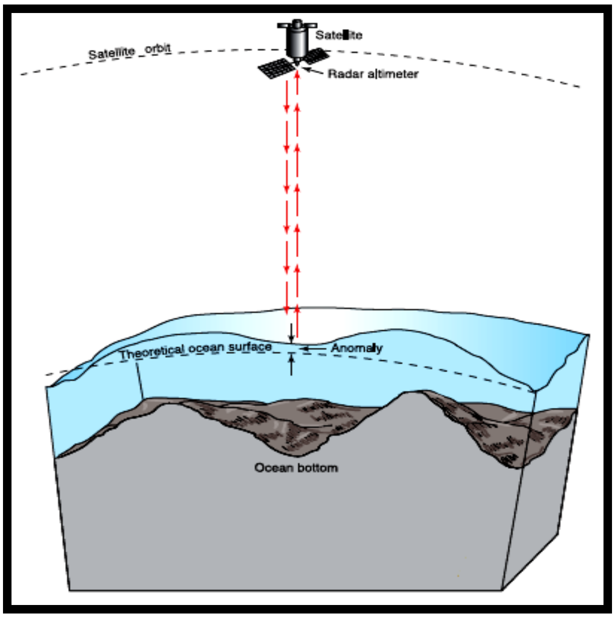

Figure 1.2: Bathymetry from space (Sandwell *et al.*, 2003)

Before the era of the space-based technology, early hydrographic surveyors used a hand-held rope to measure depth (Kious and Tilling, 2001; National Ocean Service, 2006). This technique used graduated depth markings that a leadsman lowered until it touched the bottom, after which he would manually read and record the depth in a process known as sounding. This technique was time-consuming and labour intensive, even though it can give accurate depths. According to the National Ocean Service (NOS) (2006), due to the limited number of depth measurements, information was missing between soundings, and therefore, mariners would often be unaware of bottom features and depth information necessary for safe navigation.

However, the technology for depth measuring has been splendidly improved. According to Hell (2011), the first echo sounder on a research vessel was installed on the German Meteor in the beginning of the 1920s. This echo sounder only gave single measurements, and later, single beam echo sounders provided continues seafloor profiles underneath the ship track. With this information, knowledge about previously unexplored parts of the world's oceans, especially during the 1960s and 1970s, was revealed when echo sounders were equipped to merchant ships (Hell, 2011). Echo sounders have improved ocean bathymetry. Nowadays, mapping bathymetry is carried out by using multi-beam echo sounders

These echo sounders measure bathymetry by fully covering a strip of the seafloor below the ship track using a fan of focused beams that are perpendicular to the ship track as well as measuring the time delay and direction of each beam. Together with improvements in depth measuring techniques, seafloor morphology and seafloor processes were improved (Mayer, 2006). Multi-beam technology has provided a better seafloor or bathymetry information and this technology has been possible with the support of the positioning satellite, namely the Global Positioning System (GPS) and Global Navigation Satellite System (GLONASS) (Mayer, 2006; Hell, 2011). Figure 1.3 illustrates the comparison of the seafloor coverage between leadline, single beam echosounder (SBES) and multi-beam echosounder (MBES).

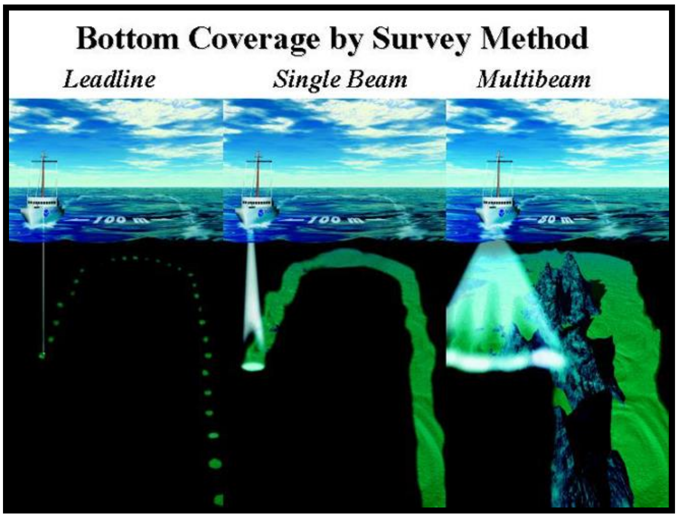

Figure 1.3: Comparison of bottom coverage by leadline, single-beam and multi-beam surveys method (NOS, 2006).

By using satellite altimeter, a large bathymetry coverage can be obtained. At present, nearly all high-resolution global bathymetry models are constructed from ship soundings and satellite altimetry gravity anomalies. The bathymetry model depends on gravity anomalies at the 20 – 200 km waveband and researchers must be careful when analysing the isostatic seafloor mechanisms with these models and gravity anomalies (Minzhang *et al.*, 2014). The combination of the sparse ocean depth from ship sounding measurements and dense satellite altimeter measurements creates a uniform resolution map of seafloor topography or bathymetry. While these maps might not be used in assessing navigational hazards due to their insufficient accuracy and resolution, however, they can be beneficial for diverse applications such as locating obstructions to major ocean currents and identifying shallow seamounts that have plentiful fish and lobster populations (Rosmorduc *et al.*, 2006).

Bathymetry information clarifies the cooling or subsidence of the oceanic lithosphere, mantle convection patterns, plate boundaries, oceanic plateaus, and the distribution of off-ridge volcanoes. This is due to the low erosion and sedimentation rates in the deep ocean (Sandwell and Smith, 2001; Hwang and Chang, 2014). Bathymetry also offers the necessary infrastructure for scientific, economic, political, educational, and managerial aspects such as the planning of pipeline routes and communication cables, habitat management, resource exploration, and legal claims related to territory expanses under the Laws of the Sea (Smith *et al.*, 2005; Rosmorduc *et al.*, 2006).

With satellite altimeter technology, many global models such as DTU10 bathymetry and gravity anomalies were produced. The global bathymetry model provides global ocean depths. In this study a local bathymetry map for Malaysian Seas was produced. The bathymetry map was generated using combination of gravity anomalies from satellite altimeters and satellite gravity missions to portray the depth of the Malaysian Seas including Malacca Straits, South China Sea, Celebes Sea, and Sulu Sea. This bathymetry map is intended to produce an estimation of bathymetry information with respect to any ocean exploration or other research activities.

1.2 Problem Statement

The technique used to obtain ocean floor models had varied over time with the development of new technologies. Echo sounders are commonly used for accurate ocean floor bathymetric mapping. Echo-sounding techniques have been classically used for accurate bathymetric ocean floor mapping and conventional single-beam echo sounder (SBES) was made obsolete by modern multi-beam echo sounder (MBES) techniques. According to Hell (2011), with the use of MBES, the accuracy, efficiency, and spatial resolution of coastal and ocean mapping was enormously increased (Hell, 2011). However, this technique is difficult to use to map vast areas of the ocean floor as it is very time consuming (Carron *et al*., 2001; Sandwell and Smith, 2001; Smith *et al*., 2005; Jena *et al.*, 2012; Minzhang *et al*., 2014). According to Jena *et al.* (2012), MBES bathymetry data collection for unexplored offshore areas is a challenging task. This is because these surveys required high expenditure and the bathymetry data is sparse (Sandwell and Smith, 2001; Smith *et al*., 2005, Kim *et al.*, 2010).

In shallow areas, bottom topography may be visible to airborne or space-borne optical or hyperspectral sensors, however, these systems are useful only in water depths less than tens of meters, at best (Smith *et al.*, 2005). According to Hsiao *et al*. (2016), in order to predict depths using optical images, images need to be analysed using the attenuation of sunlight in water, the reflectance of the bottom of the ocean, and water properties. The results from open publications show that a maximum depth of about 20 m can be obtained using optical images.

Therefore, space-borne radar altimetry is one of the techniques required for obtaining ocean surface height anomalies for globally uniform reconnaissance of deep-sea floor topography and for bathymetry modelling (Smith *et al*., 2005; Minzhang *et al*., 2014). These anomalies combine time-invariant signals reflected from the equipotential of the Earth's gravity field with other, mostly time-varying, signals associated with several physical oceanographic signals such as tides, currents, and climatic fluctuations (Smith *et al.*, 2005).

Recent progress in satellite altimetry has led to improvements in high-resolution marine gravity fields (Andersen *et al*., 2010) and global bathymetric models that provide refined depth resolutions for the South China Sea (SCS) (Sandwell *et al*., 2014). In addition, the latest altimeter-derived marine gravity and bathymetric models show hidden undersea tectonic features in SCS (Sandwell *et al*., 2014; Hwang and Chang, 2014). High-resolution bathymetry models are needed to study ocean geophysics, biology, and climate science as ship soundings still have sparse coverage even after decades of surveying. It will be very difficult to create a

1-minute bathymetry model using just ship soundings for the near future. The technological advance of satellite altimetry provides a new approach to high-resolution bathymetry model construction (Minzhang *et al*, 2014).

With a combination of satellite gravity missions, obtained data becomes denser compared to satellite altimeter data. Therefore, this research focuses on the generation of the ocean floor bathymetry for Malaysian Seas from space-borne techniques such as satellite altimeters and satellite gravity missions in order to derive gravity anomalies. From gravity anomalies, the estimation of the Malaysian seafloor was done using the Gravity-Geologic Method (G-G Method). An estimated bathymetry map was also produced.

1.3 Aim and Objectives

The aim of this study is to map the bathymetry over Malaysian Seas from Satellite Geodetic Missions by using Gravity Geologic Method (G-G method). From this goal, there were two specific objectives that were generated:

i. To derive gravity anomalies using multi-mission satellite altimeter and satellite gravity missions.
   The data measured from satellite altimeters (SALT) were computed in order to obtain the Mean Sea Surface Height (MSSH). From MSSH, satellite-derived gravity was computed using Gravsoft software using the Fast Fourier Transformation (FFT) technique.

ii. To estimate the bathymetry model over Malaysian Seas from satellite-derived gravity anomalies.
   Satellite-derived gravity anomalies were used to estimate bathymetry for Malaysian Seas by adopting the Gravity Geologic Method (G-G Method). Predictive bathymetry is evaluated with ground-truth bathymetry data from shipborne measurements gathered by the National Geophysical Data Centre (NGDC) to assess its accuracy. The final estimated bathymetry was mapped.

1.4 Scopes and Limitations of Study

The scope of this study includes the study area, used data, processing software, and processing analysis. The study area for this research featured the Malaysian Seas, which are the Malacca Straits, South China Sea, Sulu Sea, and Celebes Sea (refer to Figure 1.4). The study area limits were in between the latitude and longitude of 0º 0' 0" N to 14º 0' 0" N and 95º 0' 0" E to 126º 0' 0" E, respectively.

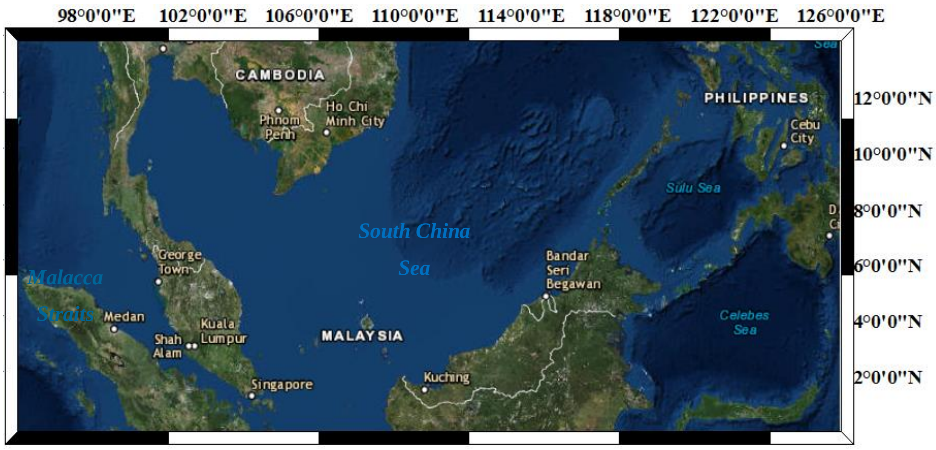

Figure 1.4: Limitation for the study area

Most data used in this study are from Satellite Altimeter and Satellite Gravity Missions. Satellite Altimeter data covered 2005 until 2015. This time period was chosen with consideration for the magnitude 9.3 earthquake that occurred in Sumatra, Indonesia on 26th December 2004 (Stein and Okal, 2005; Borrero, 2005). Therefore, the starting year of 2005 was chosen. The earthquake is also known as the Sumatra Andaman earthquake. According to Einarsson *et al*. (2010), Gravity Recovery and Climate Experiment (GRACE) satellite gravity missions was used to detect variations the gravity in the area during the earthquake.

Their study shows that changes in GRACE data were detectable after the earthquake (Einarsson *et al*., 2010). Moreover, it was assumed that Malaysia, as a neighbouring country of Indonesia, was also affected during the earthquake in the northern states of the west coast of Peninsular Malaysia (Mey, 2005; Siwar *et al*., 2006). Therefore, it was decided that the data used in this study would cover 2005 to 2015. With regards to the situation, it was assumed that gravity before and after the earthquake was changed. Tables 1.1 and 1.2 show the lists of the Satellite Altimeter Missions and Satellite Gravity Missions that have been used in this study, respectively. Table 1.3 depicts the study scope in term of complementary data and processing software.

Table 1.1: Satellite Altimeter Missions used in this study (summarised from Radar Altimeter Database System, 2017)

Satellite Altimeter	Phase	Mission Period	Cycle
ERS-2	A	29 Apr 1995 – 04 Jul 2011	000 – 169
JASON-1	A	15 Jan 2002 – 26 Jan 2009	110 – 260
	B	10 Feb 2009 – 03 Mar 2012	262 – 374
	C	07 May 2012 – 21 Jun 2013	382 – 425
ENVISAT1	B	14 May 2002 – 22 Oct 2010	033 – 113
	C	26 Oct 2010 – 08 Apr 2012	
JASON-2	A	04 Jul 2008 – 31 Dec 2015	000 – 276
CRYOSAT2	A	14 Jul 2010 – 31 Dec 2015	004 – 074
SARAL	A	14 Mar 2013 – 31 Dec 2015	001 – 030

Table 1.2: Satellite Gravity Missions used (summarised from European Space Agency (ESA), National Aeronautics and Space Administration (NASA) and German Research Centre for Geosciences (GFZ) Potsdam, 2017)

Satellite Altimeter	Altitude	Repeat Cycle	Mission Period	Provider
GRACE	485 km	30 days	2002 ~ 2015	NASA and German Aerospace Centre (DLR)
GOCE	268 km	61 days	2009 – 2013	ESA

Table 1.3: Description of the scope of this study in term of research data and data processing

<table>
<tr><td>Data Acquisition</td><td>Satellite Altimeter (SALT)</td><td>Geopotential Global Models (GGMs) from International Centre for Global Earth Model (ICGEM)</td></tr>
<tr><td>Satellite Mission used</td><td>• ERS-2
• Jason-1
• Envisat1
• Jason-2
• Cryosat2
• Saral</td><td>• Gravity Recovery and Climate Experiment (GRACE)
• Gravity Field and Steady-State Ocean Circulation Explorer (GOCE)</td></tr>
<tr><td rowspan="2">Processing Software</td><td>- Radar Altimeter Database System (RADS)
- Putty Application
- FileZilla</td><td>- ICGEM Calculator</td></tr>
<tr><td colspan="2">- Microsoft Excel
- ArcGIS
- Global Mapper
- Gravsoft
- Matlab
- Surfer</td></tr>
<tr><td>Data Processing</td><td colspan="2">- RADS Data Correction (To obtain MSSH)
- Gravity Anomaly derivation of satellite altimeter’s MSSH data
- Data Filtering using Crossover Adjustment
- Root Mean Square Error (RMSE) computation
- Bathymetry Estimation</td></tr>
<tr><td rowspan="3">Data Used</td><td>Free-Air Gravity Anomaly (FAGA)</td><td>- Global Geopotential Model (GGM) from International Centre for Global Earth Model (ICGEM)
- Department of Survey and Mapping Malaysia (Free-air gravity anomaly (FAGA) from airborne survey)</td></tr>
<tr><td>Bathymetric Model</td><td>- Generic Bathymetry Chart of the Ocean (GEBCO)
- Earth Topography 1 – minute (ETOPO1)
- Sandwell and Smith bathymetry model V18.1
- Technical University of Denmark 2010 (DTU10)</td></tr>
<tr><td>Ground Truth Data from Shipborne measurement</td><td>- Shipborne Bathymetry data from National Geophysical Data Center (NGDC)</td></tr>
</table>

There were 10 software programs used in this study, which is stated in Table 1.3. Generally, Radar Altimeter Database System (RADS) was used for SALT data processing, while data extraction was executed using the FileZilla application. Moreover, Microsoft Excel was utilised to sort the data. The computation of gravity anomalies was implemented using the processing module in the Gravsoft software. Outputs were interpreted using the ArcGIS, Global Mapper, and Matrix Laboratory (MATLAB) software. Surfer 8.0 software was used for in the selection of suitable interpolation methods for this study.

Based on the executed computation processes, there were two assessments conducted in this study to prove the reliability of each of the objectives. Below are the realisations of the validation process for each research objective.

1) Satellite derived gravity anomalies were examined with airborne gravity anomalies produced by Department of Survey and Mapping Malaysia (DSSM).

2) Estimated bathymetry was computed using the G-G method and validated with shipborne bathymetry data from the National Geophysical Data Centre (NGDC). Estimated bathymetry was mapped using MATLAB

1.5 Significance of Study

The significance of this study is as follows:

1) This study highlights the use of the multi-mission SALT in obtaining MSSH to derive the gravity anomalies. The gravity anomaly derived in this study are expected to provide a better understanding of ocean gravity anomalies, aiding local authorities such as geologists in exploration and research activities.

2) The aim of this study is to produce a bathymetry map for Malaysian Seas using space-borne techniques. The Malaysian Seas bathymetry map will benefit related agencies such as the oil and gas industry in resource exploration.

3) Moreover, ocean depth information from the generated bathymetry information will aid related government agencies in determining maritime boundaries.

1.6 General Research Methodology

This study is divided into four (4) phases in order to achieve the specified objectives. The purposes of each phase are explained. Figure 1.5 illustrates a flowchart of the research methodology used in this study.

PHASE 1

Literature Review

The literature review stage concentrates on the following topics:

1) An overview of satellite altimeter principles, satellite altimeter corrections, and satellite altimeter diversity.
2) Satellite gravity missions, satellite gravity concepts, and their applications.
3) The necessity of gravity anomalies, gravity measurements, and the airborne and space-borne gravity measurement methods.
4) Generation of the gravity anomalies from the sea surface height.
5) The relationship between gravity anomalies and geology.
6) Bathymetry interpretations as well as its relationship with gravity anomalies and bathymetry predictions using the G-G method.
7) The structure of the research design outlined in Figure 1.5.

Research Area Identification

The research area for this study was the Malaysian Seas and this area is depicted in Figure 1.4.

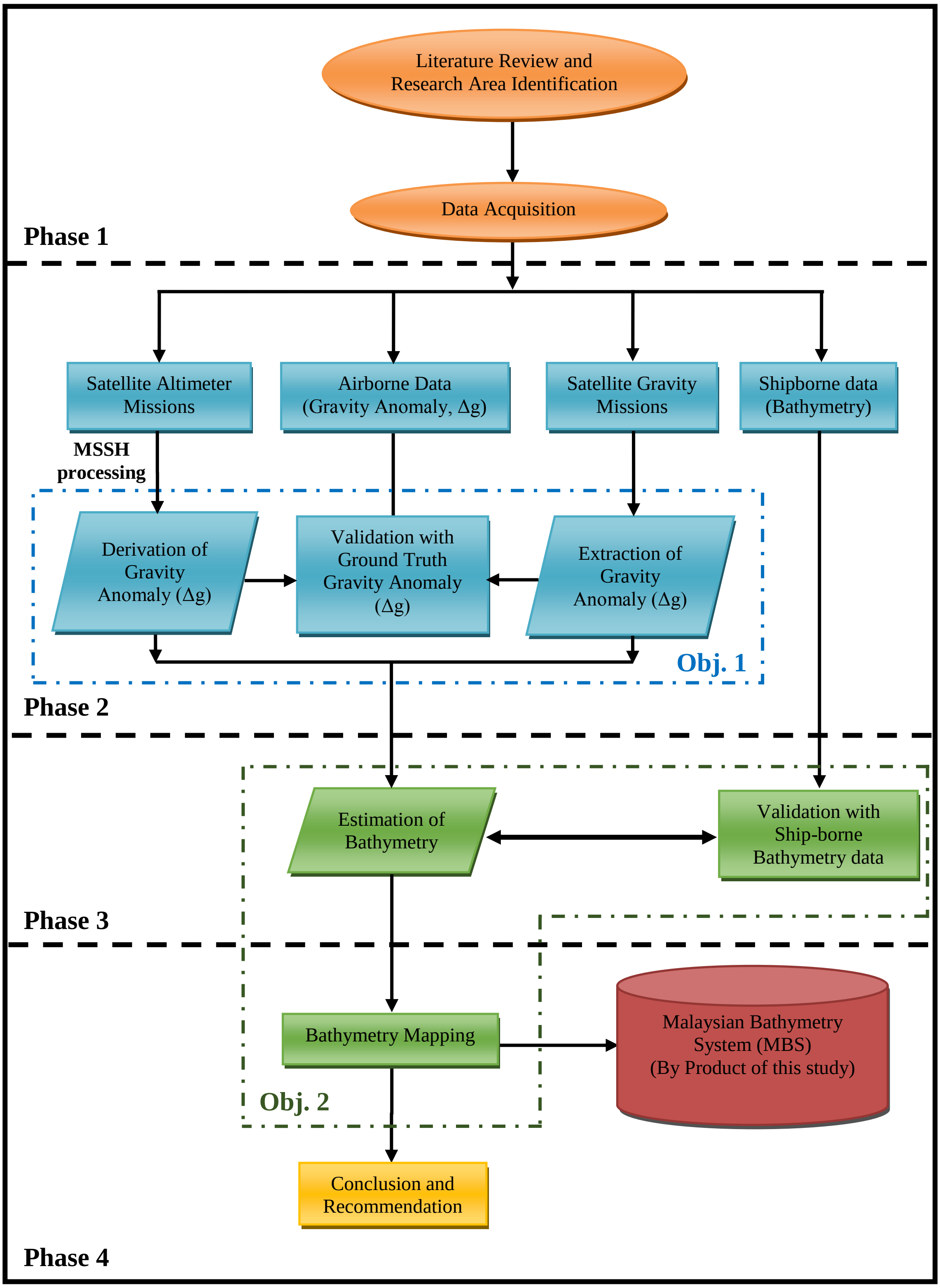

Figure 1.5: The research framework for this study

PHASE 2

Data Processing and Gravity Anomaly Derivation

Phase 2 involves data processing and the derivation of the gravity anomalies based on satellite altimeter missions and satellite gravity missions:

1) How all essential data (i.e.: MSSH, free air gravity anomaly (FAGA) data) in this research was gathered.
2) The computation of MSSH from satellite altimeters using RADS. The data provided by RADS was automatically processed according to user parameters.
3) Gravity anomalies from satellite gravity missions were extracted from Geopotential Global Models (GGM) based on the spherical coefficient of the models using the International Centre for Global Earth Model (ICGEM) calculator.
4) MSSH was used to derive gravity anomalies using Gravsoft software.
5) Derived FAGA was validated with airborne FAGA from DSMM and was used to estimate bathymetry.

PHASE 3

Estimation of the Bathymetry

In phase 3, derived FAGA from SALT was used with bathymetry information as a reference depth in order to estimate bathymetry for Malaysian Seas. There were two reference depth used in this study, which are bathymetry from global models and NGDC shipborne bathymetry data. There were four global bathymetry models used in this study. Bathymetry estimation was computed using the G-G method. Several interpolation methods bathymetry estimates were tested using Surfer software in order to obtain the best interpolation result. An evaluation of the estimated bathymetry was executed. The shipborne bathymetry data from NGDC was used to validate predicted bathymetry.

PHASE 4

Bathymetry Mapping and Malaysian Bathymetry System

This phase covers the mapping of estimated bathymetry and the generation of a Malaysian Bathymetry system. Bathymetry mapping was plotted using MATLAB software.

Conclusion and Recommendation

The conclusion in this study reflects its results and analysis. All of the achieved objectives are interpreted and summarized in this section. Moreover, due to some study limitations, a few recommendations have been proposed for the improvement of this study and future research.

1.7 Thesis Outline

This study is divided into five chapters.

The introduction of this study is thoroughly explained in **Chapter 1**. In this chapter, a brief explanation is given on the study background, problem statement, study goals, study objectives, study scope, and study significance.

The outline of the thesis followed by the literature review in **Chapter 2**, which uses studies from other researchers to support this study. The nature of space-borne bathymetry measurements, including SALT and gravity missions, and the relationship between bathymetry and gravity anomalies are described in this chapter. Moreover, the bathymetry prediction method is expressed in this section, which is the Gravity Geologic Method (G-G method).

Chapter 3 describes the methodology used in this study. The data processing of the SALT and satellite gravity missions is discussed in this chapter. Additionally, the deriving of SALT FAGA using the FFT technique as well as the experimental procedures used to predict bathymetry are explained. Moreover, each computation and the derived FAGA validation process are reported in this chapter.

Based on the methodology clarified in Chapter 3, the results and the analysis of SALT-derived FAGA and predicted bathymetry are elaborated in **Chapter 4.** The diagrams and the statistical values of the derived FAGA and predicted bathymetry are depicted. This chapter provides the result analysis and supporting details.

Chapter 5 is the last chapter in this thesis. This chapter summarize the results obtained from estimated bathymetry. It also includes suggestions for future work and study limitations.

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