DETERMINATION OF THE MEAN DYNAMIC TOPOGRAPHY OVER PENINSULAR MALAYSIAN SEAS USING MULTI-MISSION SATELLITE ALTIMETRY

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DEDICATION

I dedicate this work to God Almighty and my beloved family.

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To God be the glory, great thing He has done. When I look at your heavens, the work of your fingers, the moon and the stars, which you have set in place, what is man that you are mindful of him, and the son of man that you care for him? Thank you Jesus!

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ABSTRACT

Since the launch of the maiden altimetry satellites, altimetric data has enormously been used to better understand worldwide oceanic system and how it evolves at different temporal and spatial scales. The purpose of this study is to determine the mean dynamic topography (MDT) of the Peninsular Malaysian Seas covering the Malacca Strait and South China Sea using multi-missions satellite altimetry. The radar altimeter database system (RADS) was used to capture and process ENVISAT, CRYOSAT-2, SARAL, JASON-1 & JASON-2 satellite altimeter (SALT) data of five years spanning between 2011–2015. In the RADS processing, the 2016 upgraded geophysical and environmental corrections suitable for the Malaysian Seas were applied. The time series of monthly multi-mission SALT data showed estimated sea level trend of 3.6 mm/year, 1.0 mm/year, 2.4 mm/year, 12 mm/year and 2.4 mm/year at Cendering, Gelang, Port Kelang, Keling and Kukup respectively. The correlation analysis for the selected tide gauge stations produced satisfying results of R^2 with 0.968, 0.856, 0.911 and 0.89 for Geting, Cendering, Gelang and Sedili respectively. The ITG-Grace2010s geoid model was used to compute the MDT and plotted to a grid of 0.25° for the Malacca Strait and South China Sea of Peninsular Malaysia with Geting, Johor Bahru, Port Kelang, Keling and Sedili tide gauge stations having values determined by interpolation to be 1.2633m, 2.9109m, 1.1863m, 1.1406m and 1.8818m respectively. From the SALT computed MDT with respect to Port Kelang, the north-south sea slope ranges between -0.64 to 0.29 m/50km and between -0.01 to 0.52 m/50km along the east and west coasts of Peninsular Malaysia respectively. The computed SALT and Tidal MDTs were compared, resulting in centimeter differences at the selected tide gauge benchmarks, except at Johor Bahru having a difference of ~1.49m. The plotted grid of the derived MDT showed that the separation of the MSS and the ITG-Grace2010s geoid is smoother at the Malacca Straits, while the magnitude is larger and more undulated at the South China Sea. The determined MDT showed the huge potential SALT has in helping to fully map, study and understand the marine topography and environment.

ABSTRAK

Semenjak pelancaran satelit altimetry, data altimetric telah banyak digunakan untuk memahami sistem lautan dunia dan cara ia berkembang pada skala duniawi dan spatial yang berbeza. Tujuan kajian ini dijalankan adalah untuk menentukan min topografi dinamik (MDT) Lautan Semenjung Malaysia yang meliputi Selat Melaka dan Laut China Selatan menggunakan satelit pelbagai misi. Sistem pangkalan data radar altimeter (RADS) telah digunakan untuk mengambil gambar dan memproses data ENVISAT, CRYOSAT-2, Saral, JASON-1 & JASON-2 satelit altimeter (SALT) selama lima tahun merangkumi 2011-2015. Dalam pemprosesan RADS, pembetulan geofizik dan alam sekitar 2016 yang terkini dan sesuai untuk Lautan Malaysia telah diaplikasikan. Siri mata data bulanan bagi pelbagai misi SALT menunjukkan trend anggaran paras laut sebanyak sebanyak 3.6 mm/tahun, 1.0 mm/tahun, 2.4 mm/tahun, 12 mm/tahun dan 2.4 mm/tahun di Cendering, Gelang, Pelabuhan Kelang, Keling dan Kukup masing-masing. Analisis korelasi untuk stesen tolok air pasang surut yang terpilih menghasilkan keputusan R^2 yang memuaskan iaitu 0.968, 0.856, 0.911 dan 0.89 bagi Genting, Cendering, Gelang dan Sedili. Model geoid ITG-Grace2010s telah digunakan untuk mengira MDT dan diplot untuk grid 0.25° bagi Selat Melaka dan Laut China Selatan yang merangkumi Semenanjung Malaysia dengan stesen tolok air pasang Geting, Johor Bahru, Pelabuhan Kelang, Keling dan Sedili g yang mempunyai nilai yang dihasilkan melalui interpolasi iaitu 1.2633m, 2.9109m, 1.1863m, 1.1406m dan 1.8818m masing-masing. Kiraan MDT Port Kelang melalui SALT menunjukkan bahawa cerun laut utara-selatan berkisar antara -0.64 ke 0.29 m/50km di sepanjang timur Semenajung Malaysia dan antara -0.01 hingga 0.52 m/50km di sepanjang barat pantai Semenanjung Malaysia. Perbandingan kiraan SALT dan MDTs air pasang surut mengakibatkan perbezaan sentimeter di tanda aras tolok air pasang yang terpilih kecuali di Johor Bahru yang mempunyai perbezaan ~1.49m. Plot grid daripada MDT yang diperolehi menunjukkan bahawa pemisahan MSS dan geoid ITG-Grace2010s lebih halus di Selat Melaka, manakala magnitud yang lebih besar dan beralun dihasilkan di Laut China Selatan. MDT yang diperoleh menunjukkan potensi besar SALT dalam membantu pemetaan, kajian, dan pemahaman topografi marin dan alam sekitar.

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CHAPTER 1

INTRODUCTION

1.1 Background of Study

It is no secret that oceans play a major role in the outcome of the Earth's weather due to the fact that they heat, cool, humidify, dry the air, control wind speed and direction. Consequently, the weather affects various phenomena that ask questions such as crops getting sufficient rain for maturity, what clothes we should daily wear, the severity of the hurricane season – fierce or feeble, and many more. The patterns the weather takes over a long period of time have influence on various things like property valuation, food and water supply, trade, etc. It can be a double-edged sword in either being a tool for sporadic economic growth or responsible for its ruins. Though unpredictable, ability to forecast its occurrence, helps a great deal to manage its impact. If these predictions and forecasts of its societal impact are to be helpful, a comprehension of the ocean's characteristics and behavior is very key.

Since the launch of the maiden altimetry satellites sometime in the 1970s, the oceanographic community have enormously made use of altimetric data to better understand worldwide oceanic system and how it evolves at different temporal and spatial scales (Fu and Cazenave, 2000). With the successful launch of the JASON-3 satellite in January 2016, the quality of altimetric data available can only get better.

The development of satellite altimeters to more adequately sense ocean-surface topography has been one of the primary objectives of the National Aeronautics and Space Administration's (NASA) Ocean Processes Program for over four decades. Earth-revolving satellites, carrying passive and active remote sensing instruments, provide a capability for synoptic observation of the global oceans with temporal sampling that spans from a few days to a month. One of the sensors used by the satellites for oceanographic applications is the radar altimetry (Shum *et al.*, 1995).

A key instrument on both satellites is the radar altimeter, measuring the height of the satellite above the ocean surface. From this range measurement, the absolute sea level or the variations in sea level can be inferred. In order to do so, the range measurements must be subtracted from the altitude of the satellite, defined in a well-defined reference frame. The accuracy of the absolute sea level measurements by a radar altimeter is therefore always limited by the accuracy of the computed satellite altitude. It is the object of the precise orbit determination to provide the satellite position at any time during the mission with precision in the order of centimeters (Andersen and Scharroo, 2011; Scharroo *et al.*, 2013).

In accordance with the laws of physics, it is understood that the ocean surface is a surface of equal potential gravity field of the earth assuming there are no waves, winds, tides and currents for the moment. Ocean surface topography can be distinctly described as the distance between the separation of the mean ocean surface and the geoid. Ocean surface topography results from ocean currents, atmospheric pressure loading, ocean waves and tides. The main reason for measuring ocean surface topography, arguably is for understanding how the ocean circulate at a large-scale. The differences in height with regards to the ocean surface topography could be larger than two meters and these differences are affected by the ocean temperature, ocean circulation and saline content (Fu *et al.*, 1994).

In the context of examining satellite altimetry measurements for oceanographic studies, a frequently used term is marine geoid. The geoid is an equipotential surface of the Earth's gravity field, to which a motionless ocean would conform. Often, the geoid lies far away from the Earth's reference ellipsoid, which is the smooth mathematical surface that approximates the entire earth's shape. Because of Earth's gravity variations, the shape of the geoid is often irregular and in some cases significantly departs from the reference ellipsoid. The geoid surface is obtained quantitatively from models based on gravity measurements and long-term satellite data (Joseph, 2013).

The establishment of a consistent archive of worldwide data pertaining to satellite altimeter took off around the late 1980s. This awakened a conscious effort by the community of geodesists to develop unified global geoid with estimates of the MDT, while simultaneously reducing errors due to satellite orbit (Knudsen *et al.*, 2011). Although the data quality available fell short of what was needed to retrieve the more specific details regarding the general circulation of the ocean's, the determination and comparison could be made between the colossal scales (greater than 5000 km) of the ocean's MDT and early estimates of oceanographic MDT solely from hydrographic data, as in the case with Levitus and Boyer (1994). Through such comparisons, major issues were identified, chiefly among them happened to be how consistent are the impacts of permanent tidal corrections on the calculated MDT and the reference ellipsoids. In similar vein, marine gravity data obtained by mounting gravimeters on ships was used to regionally refine the spatial distribution of the gravity field and geoid. Improvements on the accuracy and detailed measurements of the MDT was achieved by a combination of locally improved geoids with altimeter data (Knudsen, *et al.*, 2011). Knowledge of the MDT would allow oceanographers to study the absolute circulation of the ocean and determine the associated geostrophic surface currents that help to regulate the earth's climate.

1.2 Justification of Study

A key tussle in oceanography is to rightly ascertain the MDT of the ocean time. To achieve this with adequate accuracy, one has to combine with elements of dynamic topography that are time-reliant, the absolute dynamic topography obtainable would be from altimetric data with an end product that accurately depicts the surface geostrophic currents and ocean transports (Bingham *et al.*, 2008). MDT also contributes to the understanding of heat movements globally via the oceans, an integral element of Earth's climate, and for global sea level change monitoring. Considering the fact that Malaysia is a coastal state, this information is very useful for studying various environmental concerns that relates to investigations of inundation and climate change, principally for an area that could do with more interests from the body of altimeter scientists.

1.3 Problem Statement

Sea surface variability and its effects in near coastal areas are an important aspect of climate change. In surveying, MDT is datum bias, that is, the difference between the mean sea level (MSL) and geoid. Conventional method of retrieving this information involves doing GPS ground observation on benchmark. Due to the sparseness of benchmarks, they cannot give adequate coverage as desired. However, satellite altimetry has very large ground coverage, hence its use globally for various oceanography purposes. In order to provide oceanographers and decision makers with adequate scientific data to improve understanding, prediction and policies that borders on environmental challenges that mostly relate to inundation investigations and climate change in a region that requires more attention from the altimeter science community, the determination of the MDT would be very useful scientific altimetry data in the hands of all stakeholders in the region.

1.4 Aim of Study

This project aims to determine the Mean Dynamic Topography (MDT) along the South China Sea and Malacca Strait of Peninsular Malaysia coastline.

To achieve the project's aim, the following objectives are to be undertaken:

1. Derivation of the instantaneous Height of the Sea Surface (SSH), by differencing the measured altimeter height above the sea surface from the satellite altitude above a reference ellipsoid;

2. To estimate the localized Mean Sea Surface (MSS) of the Malaysian Seas;

3. To quantify the localized MDT from the difference of the local MSS and the marine geoid and verify the results using data from some tide gauge stations within the region.

1.5 Scope

The project scope is limited to five (5) years (2011-2015) Saral, Jason-1, Jason-2, CryoSat-2, Envisat-1 satellite altimeter data covering the South China Sea and Malacca Straits of Peninsular Malaysia coastline. The satellite altimeter processing will be carried out using TUDelft's radar altimeter database system (RADS). From the RADS, sea level anomaly (SLA) and sea surface heights (SSH) are processed, extracted and used to compute the mean sea surface (MSS). The final product of this study is the MDT, computed from the MSS and the GRACE geoid model. Also, tidal data obtained from selected tide gauge stations would be used to validate the determined MDT. Figure 1.1 shows details of the study area.

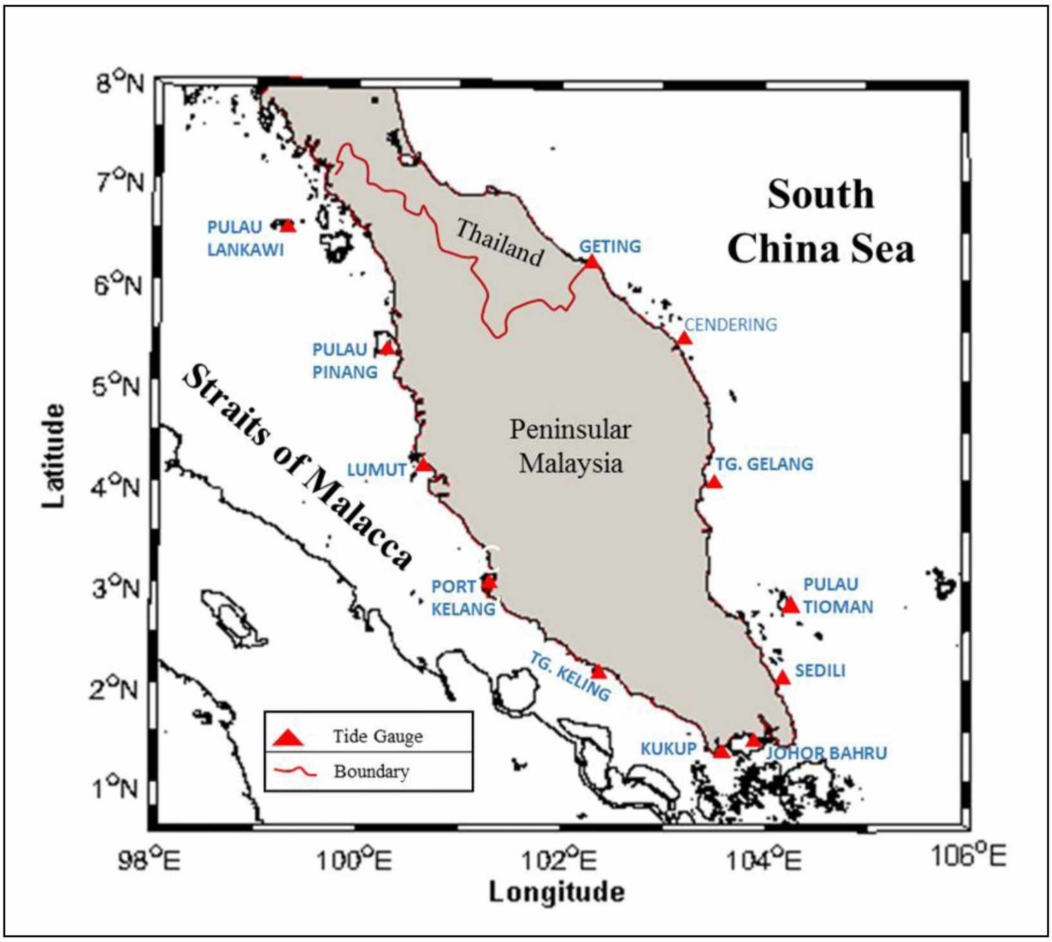

Figure 1.1: Coastline of Peninsular Malaysia Showing Tide Gauge Stations

1.6 Significance of Study

In marine geodesy, it is assumed and proven through various studies that the local vertical datum (MSS) does not coincide with and may not be parallel to the geoid. This separation is referred to as the vertical datum bias, sea surface topography or mean dynamic topography (MDT). The MDT helps to understand certain integral elements of the Earth's climate through the understanding of heat movements globally via the oceans, determining the directions of water flow and global sea level change monitoring. The MDT is one of the components of the marine profile and very useful in the determination of the marine geoid. Within the Malaysian coastline, the MDT has been estimated at tide gauge stations using the traditional tide gauge data combined with GPS observations and local gravimetric data. However, with satellite altimetry technique, an MDT with denser spatial coverage of the Malaysian seas that is not affected by land movements can be obtained. Hence, an altimeter determined MDT will be of immense benefit to all oceanography stakeholders and decision makers.

1.7 General Research Methodology

The general overview of this research entails the following sequence:

1. Using RADS to process, filter and extract the gridded altimeter SLA and SSH of the study area from satellite multi-missions from 2011 to 2015.
2. Determination of the MSS representing 2011 to 2015 altimetry data (referenced to the WGS84 ellipsoid) by computing the difference between the SLA from the SSH.
3. The computed MSS is transformed to GRS80 reference ellipsoid and used with the GRACE geoid model to determine the satellite altimetry (SALT) MDT of the study area.
4. The computed altimeter SLA and MDT are then validated by comparing with tidal MSL and MDT values at tide gauge benchmarks.
5. Data analysis and conclusions are drawn from the observed data.

The details of the general flow of the methodology is depicted in the Figure 1.2.

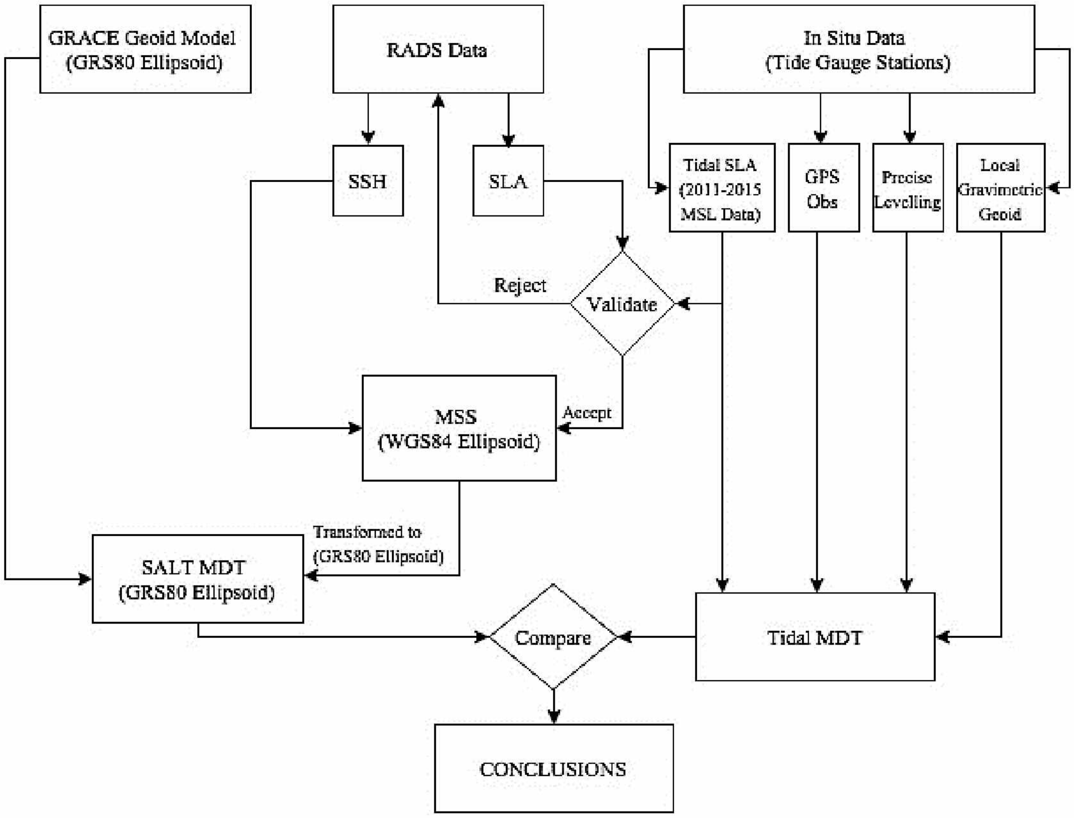

Figure 1.2: General Flow of the Methodology

1.8 Thesis Outline

This thesis report covers five chapters. Chapter 1 covered the general introduction of the research including the objective, justification, scope and general method to be used in achieving the aim of the research. Chapter 2 reviewed previous works related to the subject area, including the definition of various concepts and terms used in marine geodesy, satellite altimetry, etc. Chapter 3 focused on the various methods that would be applied in the research and their relationships, for example how RADS will be used to process altimeter data, etc. Chapter 4 presented and discussed all the results processed, which includes the SLA, SSH, MSS, MDT and verification of the satellite altimetry data with tidal data. The research write-up was concluded in Chapter 5, with conclusions and recommendations drawn from the research findings.

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