MARINE GEOID MODELING FROM MULTI-MISSION SATELLITE ALTIMETRY DATA USING LEAST SQUARES STOKES MODIFICATION APPROACH WITH ADDITIVE CORRECTIONS

NORNAJIHAH BINTI MOHAMMAD YAZID

UNIVERSITI TEKNOLOGI MALAYSIA

MARINE GEOID MODELING FROM MULTI-MISSION SATELLITE ALTIMETRY DATA USING LEAST SQUARES STOKES MODIFICATION APPROACH WITH ADDITIVE CORRECTIONS

NORNAJIHAH BINTI MOHAMMAD YAZID

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

Faculty of Built Environment and Surveying
Universiti Teknologi Malaysia

JULY 2018

DEDICATION

Special dedicated to my beloved parents (Mak Abah)

Mohammad Yazid Bin Bahari

Ramlah Binti Mohd Saad

My Brother

Mohammad Najib Bin Mohammad Yazid

This work is exclusively dedicated for you

ACKNOWLEDGEMENT

Having finished writing my MSc thesis, I realized that the best and most joyful part of this lengthy process has come; that is writing section where I can express my gratitude to those whose consciously and subconsciously, have helped me completed this part of my life.

Highest praised to Allah Almighty for His blessing in giving to me the strength, confidence and spirit to complete this study.

First and foremost appreciation goes to my supervisors, Sr Dr Ami Hassan Md Din, Assoc. Prof. Kamaluddin Mohd Omar and Mr Zainal Abidin Md Som for their expert guidance, valuables advice and supporting and assisting me in every positive way in completing this study.

I am extremely grateful to Dr Dudy Dermawan Wijaya and Dr Kosasih Prijatna (Institute of Technology Bandung, Indonesia) for all your scientific supports on fundamental geodesy and Matlab coding. You are both wonderful as you respond to any question posed by me, no matter how trivial. Thank you very much for the hospitality and treat me as your own student.

I would like to thank Mr Zainal Abidin bin Mohd Idris for reviewing this thesis and improving the content of this thesis as well as encouraging me to use proper English language. I would like to express my appreciation to all Geomatic Innovation Research Group (GnG) members for their help and friendship during my post graduate study. Not to be forgotten to my best friends (Jelitawan) and my lab sisters; Kak Nazirah, Kak Anim, Kak Fadila, Kak Astina, Kak Suraya and Amalina for your advice and encouragement. Special thanks also to my best friends Siti Khairiyah Azmi (schoolmate) for your support and motivation. Thank you for always lend me your ears and heart since 2004.

Most importantly, my gratitude goes to my beloved parents, Mohammad Yazid bin Bahari and Ramlah Bt Mohd Saad. Thank you mak abah for your moral support, financial support and always lift me up when I am almost give up. To all of my family members especially Mohammad Najib (brother), Hj Bahari (Grandfather) and all. Thank you for the love and support.To everyone that I do not reveal, believe me you are always in my mind and heart. Thank you so much.

ABSTRACT

Marine geoid is crucial for orthometric height determination. The airborne and shipborne surveys have been used for geoid and gravity surveys in marine areas, but they could only cover a limited coverage area due to the high cost and time constraints. Over the last 30 years, satellite altimeter has become an important tool for global geoid and gravity field recovery, with nearly 60% of the Earth's surface in relation to the height of the ocean could be covered. This enables researchers to replace the conventional marine geoid models, and surveys can be conducted faster with a larger coverage area at a reduced cost. This study presents an attempt to model marine geoid from multi-mission satellite altimetry data using Least Squares Stokes Modification Approach with Additive Corrections. Six altimetry data were used to derive the mean sea surface which was processed in the Radar Altimeter Database System. The gravity anomaly was computed using Gravity Software, and planar Fast Fourier Transformation method was applied. The evaluation, selection, blunder detection, combination and re-gridding of the altimetry-derived gravity anomalies and Global Geopotential Model data were demonstrated. The cross validation approach was employed in the cleaning and quality control of the data with the combination of the Kriging interpolation method. Marine geoid was computed based on the Least Squares Stokes Modification Approach with Additive Corrections. The optimal condition modification parameters of 4° spherical cap, 0.4 mGal terrestrial gravity data error and 0.1° correlation length were applied. Then, the additive corrections based on Downward Continuation, Atmospheric Effects and Ellipsoidal Corrections were combined with the estimated geoid to provide a precise marine geoid over the Malaysian seas. Three selected levelling observations at tide gauge stations at Geting, Cendering and Pelabuhan Klang were used to verify the accuracy of the computed marine geoid model. The derived mean sea surface represents -0.4945m mean error and 2.2592m root mean square error values after being evaluated with the mean sea surface of Denmark Technical University 13. The gravity anomaly data from tapering window width with block 300 from $h_{hawtimr4}$ assessments denotes the optimum gravity anomaly results with root mean square error value, 17.8329mGal. The accuracy of marine geoid model corresponds to the standard deviation, 0.098m and the root mean squared error value, 0.177m. The findings suggest that the marine geoid model can be utilized for the orthometric height determination in marine areas. The by-product of this research, the Malaysian Marine Geoid Calculator (MyMG) could assist users in extracting marine geoid in Malaysian seas.

.

ABSTRAK

Geoid marin adalah penting dalam menentukan ketinggian ortometrik. Pengukuran melalui udara dan kapal telah digunakan untuk menjalankan pengukuran geoid dan graviti di kawasan marin tetapi kaedah ini hanya terhad kepada luas kawasan yang tertentu disebabkan oleh kos yang tinggi dan kekangan masa yang terhad. Sejak 30 tahun yang lalu, altimeter satelit telah menjadi alat yang penting untuk pemulihan medan geoid dan graviti global dengan hampir 60% daripada permukaan bumi yang berkaitan dengan ketinggian laut boleh dilitupi. Ini membolehkan para penyelidik untuk menggantikan model geoid secara konvensional dan pengukuran boleh dijalankan dengan cepat dengan kawasan liputan yang luas dan pengurangan kos. Kajian ini menjelaskan satu usaha untuk memodelkan geoid marin dari data altimeter pelbagai misi dengan menggunakan *Least Squares Stokes Modification Approach with Additive Corrections*. Enam data altimeter digunakan untuk memperoleh purata permukaan laut yang diperoses dalam Sistem Pangkalan Data Altimeter Radar. Anomali graviti dihitung menggunakan perisian *Gravity* dan kaedah satah Transformasi Fourier Cepat digunakan. Penilaian, pemilihan, pengesanan kesilapan, gabungan dan pengumpulan semula anomali graviti perolehan altimeter dan data *Global Geopotential Model* telah dijalankan. Pendekatan pengesahan silang digunakan dalam pembersihan dan kawalan kualiti data dengan gabungan kaedah interpolasi Kriging. Geoid marin dihitung berdasarkan *Least Squares Stokes Modification Approach with Additive Corrections*. Parameter pengubahsuaian keadaan optimum 4° lingkungan sfera, 0.4 mGal ralat data daratan gravity dan 0.1° panjang korelasi telah digunakan. Kemudian, pembetulan tambahan berdasarkan Kesinambungan Ke Bawah, Kesan Atmosfera dan Pembetulan Ellipsoidal digabungkan dengan geoid yang dianggarkan untuk memberikan geoid marin yang tepat ke atas laut Malaysia. Tiga pemerhatian pengukuran aras yang terpilih di stesen tolok gelombang di Geting, Cendering dan Pelabuhan Klang telah digunakan untuk mengesahkan ketepatan ketinggian geoid marin yang dihitung. Purata permukaan laut yang diperoleh mewakili -0.4945m purata ralat dan 2.2592m nilai ralat quadrat rata akar selepas dinilai dengan purata permukaan laut di *Denmark Technical University 13*. Data anomali graviti dari lebar tirus yang melintang dengan blok 300 dari penilaian $h_{hawtimr4}$ menandakan keputusan anomali graviti optimum dengan nilai ralat quadrat rata akar, 17.8329mGal. Ketepatan model geoid marin sepadan dengan sisihan piawai, 0.098m dan nilai ralat quadrat rata akar, 0.177m. Dapatan kajian menunjukkan bahawa ketinggian geoid marin boleh diambil kira untuk penentuan ketinggian ortometrik di kawasan marin. Hasil sampingan kajian ini, Kalkulator Geoid Marin Malaysia (MyMG) dapat membantu pengguna dalam menghitung geoid marin di laut Malaysia.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS

Δg_{GGM}	-	GGM-derived gravity anomaly
N_{GGM}	-	GGM-derived geoid
$R_{corrected}$	-	corrected range
R_{obs}	-	observed range
ΔR_{wet}	-	wet tropospheric correction
ΔR_{dry}	-	dry tropospheric correction
ΔR_{ion}	-	ionospheric correction
ΔR_{SSB}	-	Sea-state bias correction
h	-	sea surface height
H	-	height of the spacecraft mass centre
h_D	-	Dynamic sea surface height
h_{geoid}	-	Geoid correction
h_{tides}	-	Tidal correction
h_{atm}	-	Dynamic atmospheric correction
R_{atm}	-	Atmospheric correction
R_{tides}	-	tide corrections
R_{geoid}	-	geoid correction
h_{sla}	-	sea level anomaly
P_0	-	Sea level pressure
hPa	-	hector-Pascal
∅	-	latitude
σ_{vap}	-	the vertical integration of the water vapour density
NO^+	-	Nitrogen
O_2^+	-	Oxygen
H^+	-	Hydrogen
N^+	-	Nitrogen
He^+	-	Helium
k	-	constant
U	-	the derived-wind speed from the backscatter coefficient
a_1	-	coefficients
a_2	-	coefficients

a_3	-	coefficients
a_4	-	coefficients
$\Delta h_{ocean\ tide}$	-	Ocean tide
$\Delta h_{load\ tide}$	-	Load tide
$\Delta h_{solid\ earth\ tide}$	-	Solid earth tide
$\Delta h_{pole\ tide}$	-	Pole tide
P_{ref}	-	The global “mean” pressure (reference pressure)
$\sum hD$	-	The summation of dynamic sea surface height
n	-	The total number of years
h	-	Ellipsoidal heights
H	-	The elevation relative to the geoid (orthometric heights)
N	-	Geoid height
W	-	Gravity Potential of the Earth
V	-	Gravitational potential
V_c	-	Potential
G	-	Gravity
dm	-	Element of mass
dv	-	Element of volume
ρ	-	Mass density of the element
l	-	distance between the mass element
Q	-	Point on the ellipsoid
$V_e\ (Q)$	-	Gravitational potential of the reference ellipsoid
$V_c\ (Q)$	-	Potential of the centrifugal force
Δg	-	Gravity anomaly on the geoid surface
g_p	-	Gravity value on the geoid surface
γ	-	Normal gravity on the selected reference ellipsoid
Δg_{FA}	-	Free-air gravity anomaly on the geoid surface
g_{surf}	-	Gravity value on the Earth’s surface
γ	-	Normal gravity on the selected reference ellipsoid
∂g_{FA}	-	Free-air reduction
n	-	degree
m	-	order
G	-	Newtonian gravitational constant
M	-	Mass of the Earth
$\bar{C}_{nm}\ \bar{S}_{nm}$	-	Fully normalized Stokes’ Coefficients
GM	-	Product of the Earth’s mass and the gravitational constant
r	-	Radial distance to the computational point
a	-	Semi-major axis of the reference ellipsoid

$\bar{P}_{nm}$	-	Fully normalized Legendre function
θ	-	Geodetic Latitude
γ	-	Geodetic Longitude
R	-	Earth sphere of radius
ψ	-	Geocentric angle
$S(\psi)$	-	Stokes' function
$d\sigma$	-	Infinitesimal surface element
σ	-	Sphere
$\sigma-\sigma_0$	-	Remote zone
c	-	Scale factor
Δg_n	-	Laplace harmonics of gravity anomaly
$S_L(\psi)$	-	The modified Stokes' function
L	-	Selected maximum degree
s_n	-	Arbitrary parameters
Δg^0	-	Observed or computed gravity anomaly
Δg_n^{GGM}	-	Gravity anomaly derived from Global Geopotential Model
Δg_{FA}	-	Free air gravity anomaly on the geoid surface
$N_{\Delta g_{red}}$	-	The residual geoid height
N_{ind}	-	The indirect effect of the terrain on the geoidal heights.
Δg_{red}	-	Reduced gravity anomaly
Δg_H	-	The terrain effect on gravity
ψ_0.	-	Spherical cap of geocentric angle
$\widetilde{N}$	-	Estimated geoid
δN_{dwc}	-	Downward continuation effect
δN_{tot}^{atm}	-	The combined atmospheric correction
δN_{tot}^{ell}	-	Ellipsoidal correction for the spherical geoid estimation in Stokes'
Δg^*	-	Quantity downward continued to the geoid
δN_{dwc}^1	-	The short wavelength of downward continuation gravity spectrum 1
δN_{dwc}^L	-	The long wavelength of downward continuation gravity spectrum L
δN_{dwc}^{L2}	-	The short wavelength of downward continuation gravity spectrum L2
$Fw\,(r)$	-	Gaussian distribution
$\Delta g_{GGM-airborne}$	-	Residual gravity anomaly is computed from GGM and airborne data
$\Delta N_{GGM-airborne}$	-	Residual geoid height computed from GGM and airborne
$\Delta g_{airborne}$	-	The airborne-derived gravity anomaly
$N_{airborne}$	-	The airborne-derived marine geoid height
h_{timr4}	-	Residual sea surface height

N_{timr4}	-	GGM-derived geoid height (from GO_CONS_GCF_2_TIMR4 model)
$h_{hawtimr4}$	-	Residual sea surface height
MDT_{hawaii}	-	Mean dynamic topography from Hawaii model
u, v, w	-	Spatial coordinates
x. y, z	-	coordinates
i	-	The image unit
$\Delta g_{\text{altimeter}}$	-	Altimetry-derived gravity anomaly
Δg_{GEBCO}	-	The gravity anomaly derived from depth of bathymetry (GEBCO)
h	-	The depth of bathymetry
Δg_{pre}	-	The estimated gravity anomaly (interpolated value)
$\Delta g_{estimated}$	-	The estimated gravity anomaly (known value)
$\Delta g_{residual}.$	-	The interpolated residual gravity anomaly information
$\sigma_{\Delta g}$	-	Terrestrial Gravity Data
ψ	-	Correlation length
s_n and b_n	-	The modification parameters value
N_0^{LM}	-	Estimated geoid height
δN_{dwc}	-	Downward continuation correction
δN_{tot}^{a}	-	Total atmospheric correction
δN_{tot}^{e}	-	Ellipsoidal correction
h_{GPS}	-	The GPS-derived ellipsoidal height for the tide gauge bench mark
ΔH_{Lev}	-	Height of the tide gauge bench mark above the zero of tide gauge
ΔH_{MSL}		Mean of yearly MSL from PSMSL data
R^2	-	Correlation
m	-	meter
km	-	kilometre

LIST OF ABBREVIATIONS

3D	-	3 Dimensional
AUNP	-	Asean-EU University Network Program
AVISO	-	Archiving, Validation and Interpretation of Satellite Oceanographic data
CHAMP	-	Challenging Minisatellite Payload
CLS01	-	Collecte Localisation Satellites 01
CNES	-	Centre National d'Etudes Spatiales
DEOS	-	Delft Institute for Earth-Oriented Space Research
DNSC08	-	Danish National Space Center 08
DORIS	-	Doppler Orbitography by Radiopositinoning Integrated by Satellite
DSMM	-	Department of Survey and Mapping Malaysia
DTM	-	digital terrain model
DTU10	-	Denmark Technical University 10
DTU13	-	Denmark Technical University 13
DWC	-	Downward Continuation
ECMWF	-	European Centre for Medium-Range Weather Forecasts
EGM	-	Earth gravity model
EGM 2008	-	Earth Gravity Model 2008
EM	-	electromagnetic
EnviSat	-	Environmental Satellite
ERA	-	ECMWF Re-Analysis
ERS	-	European Remote Sensing Satellite
ERS-1	-	European Remote Sensing Satellite 1
ERS-2	-	European Remote Sensing Satellite 2
ESA	-	European Space Agency
EUMESAT	-	European Organization for the Exploitation of Meteorological Satellites
FFT	-	Fast Fourier Transform
GEBCO	-	General Bathymetric Chart of the Ocean
GEOS-3	-	Geodynamics Explorer Ocean Satellite 3
GEOSAT	-	Geodetic Satellite
GGM	-	Global Geopotential Model

GOCE	-	Gravity Field and Steady-State Ocean Circulation Explorer
GOT	-	Global Ocean Tide
GPS	-	Global Positioning System
GPT	-	Global Pressure and Temperature Model
GRACE	-	Gravity Recovery and Climate Change
GRAVSOFT	-	GRAVity SOFware
GUIDE	-	Graphical User Interface Development Environment
IAG	-	International Association of Geodesy
ICGEM	-	International Center for Global Gravity Field Models
IGF	-	International Gravity Formula
IGS	-	International Geoid School
InSAR	-	Interferometic Synthetic Aperture Radar
ISRO	-	Indian Space Research Organisation
ITRF2000	-	International Terrestrial Reference Frame 2000
Jason-1	-	Joint Altimetry Satellite Oceanography Network 1
Jason-2	-	Joint Altimetry Satellite Oceanography Network 2
Jason-3	-	Joint Altimetry Satellite Oceanography Network 3
KTH	-	Royal Institute of Technology
LAGEOS	-	Laser Geodynamic Satellite
LSMS	-	Least Squares Modification of Stokes
LSMSA	-	Least-Squares of Stokes Modification with Additive Corrections
MAGIC	-	Marine Geodetic Infrastructures in Malaysian Waters
MASS	-	Malaysian Active GPS System
MATLAB	-	Matrix Laboratory
MDT	-	mean dynamic topography
MSL	-	mean sea level
MSS	-	mean sea surface
MyMG	-	Malaysian Marine Geoid Calculator
N	-	geoid undulation
NASA	-	The National Aeronautics and Space
NCEP	-	National Centers for Environmental Prediction
NKG	-	Nordic Geodetic Commission
NOAA	-	National Oceanic and Atmospheric Administration
NWM	-	Numerical Weather Model
OSTST	-	Ocean Surface Topography Science Team
PODAAC	-	Physical Oceanography Distributed Active Archieve Center
PSMSL	-	Permanent Service for Mean Sea Level
QWG	-	Quality working Group
RADS	-	Radar Altimeter Database System
RCR	-	Remove-Compute-Restore

RMSE	-	Root Mean Square Error
SARAL	-	Satellite with Argos and Altika
SLA	-	sea level anomaly
SLP	-	sea level pressure
SSB	-	sea-state bias
SSH	-	sea surface height
SST	-	sea surface topography
SWH	-	Significant Wave Height
TEC	-	Total Electron Content
TECU	-	Total Electron Content Unit
TOPEX	-	Topography Experiment
TP	-	TOPEX, Poseidon
TWW	-	tapering window width
UNIX	-	Uniplexed Information and Computing System
UTM	-	Universiti Teknologi Malaysia
VBP	-	Stokes's Classical boundary value problem
WGS84	-	World Geodetic System 1984

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.1 Background of the study

Geodesy has been interpreted by many scholars in accordance to their respective interest. For instance, in the case of classical geodesy, Helmert (1880) described geodesy as the discipline regards to the measurement and the mapping of the Earth's surface. In referring to this definition, geodesy plays a leading role in the determination of the position survey points as well as their variations over time on the Earth's surface. Lu *et al.*, (2014) described geodesy as studies about the shape and size of the Earth as well as its geodynamic phenomena. While Torge and Müller (2012) described the tasks of geodesy with respect to Earth surface as follows:

"To determine the figure and external gravity field of the Earth, as well as its orientation in space, as a function of time, from measurements on and exterior to the Earth's surface."

Another source to look at when discussing about geodesy and the role of geodesists is the reading materials furnished by the International Association of Geodesy (IAG). In one of the IAG publications, geodesy is defined as the science of the measurement and illustration of the Earth (geometry, physics, temporal variations) and other celestial bodies (Drewes, 2016). On the other hand, Panigrahi (2014) in his book "Computing in Geographic Information Systems GIS" outlines geodesy as 'the discipline of the techniques and methods for measuring the geometry of the Earth surface precisely'.

The role of geodesy has becoming more widen and its application been expanded even into marine with the creation of discipline known as marine geodesy. In marine geodesy, the main task initially was to ascertain geodetic control network on the surface of the Earth bordered by oceans. Such task plays an important role in accomplishing geodesists work to distinguish the position of the sea surface, as well as determining marine gravity field, measuring the dynamic ocean topography and computing the marine geoid. The task of computing the marine geoid is the topic of this research and will be discussed with more detail in this thesis.

Geoid determination is one of the main tasks of geodesy and becoming more important when survey works are done with Global Navigation Satellite System (GNSS) instruments, the use entrusted to geodesists and areas of responsibility of geodesy. After ellipsoid, geoid is the subsequent paramount estimation to the figure of the Earth.

The term geoid was initially introduced by Listing (1873) to describe the mathematical figure of the Earth. There are many ways of defining geoid can be quoted from more recent publications. For instance, Banerjee (2011) illustrates geoid as the level surface that corresponds with mean sea level (MSL) over the oceans and continents. In Jekeli (2016), geoid is interpreted as an equipotential surface of the Earth's gravity field closely approximates with mean sea level. The equipotential surface is described as a constant value of the gravity potential on the surface. While in Sj*ö*berg and Bagherbandi (2017), geoid is defined as the equipotential surface of the Earth's gravity field that best fits to the mean sea level. However, in marine areas, MSL can be interpreted as the mean sea surface (MSS) heights.

Conventionally, in marine areas the airborne and shipborne were used for measuring and acquiring the gravity data. Nevertheless, such gravity measurements for determining the gravity field information is limited only to the specific study area due to time constraint and the high cost required to handle the survey. Thus, a better option of getting comprehensive data especially for the purpose of marine geoid determination is required and the available option is by utilizing multi-mission satellite altimeter.

The satellite-based method provided by the satellite altimetry plays a crucial role in offering abundance of geodetic data for marine geodesy applications. Besides the amount in quantity the data provided by satellite altimeter are homogeneous and economic in nature. The launch of the recent satellite altimetry (i.e., Jason-3 and Sentinel-3a) presented a continuous, high-accuracy, high resolution and wide coverage of ocean monitoring, viable and easier lasting study. While, the earlier altimetry missions provide low accuracy in the true orbit and position of the satellite compared to the recent satellite missions.

Geoid determination is commonly accomplished with the utilization of gravimetric data by combining terrestrial gravity anomalies with gravity data derived from Global Geopotential Model (GGM) (Sjöberg, 2003). The approach of combining terrestrial gravity data with GGM-derived gravity to determine geoid requires the computation to be done by applying the modified Stokes' formula. The Stokes modification approach for geoid computation was originally introduced by M.S Molodensky as described in his seminal publication (Molodensky *et al.,* 1962). The modified Stokes' formula is proposed with the aim of reducing the truncation error as results of using gravity data over a limited area (Sjöberg, 2011).

Nowadays, there are various well-known geoid computational methods have been developed and proposed by geodetic institutions. For instance, one of the methods available is the Least-Squares Stokes Modification Approach (LSMSA) developed at the Royal Institute of Technology (KTH), Sweden. Research works on the development of LSMSA was led by Professor Lars Sjöberg in Geodesy Department at KTH. Hence, the geoid computation package using the method of LSMSA is also commonly known as the KTH method (Sjöberg, 2003). The work to develop LSMSA was started way back to 1984 (Sjöberg, 1984).

This study therefore presents an effort to determine and modelling marine geoid over Malaysian seas from multi-mission satellite altimetry data employing the method of LSMSA. In the process, the local mean sea surface (MSS) from multi-mission satellite altimeter starting from year 2005 to 2015 are derived. Then, the regional gravity anomaly data is computed covering the Malaysian seas, with the combinations of altimetry-derived gravity anomaly and GGM-derived gravity anomaly data. Finally, the local marine geoid model is estimated using multi-mission satellite altimetry data employing Least-Squares Modification of Stokes with Additive Corrections (LSMSA) approach or the KTH method.

1.2 Problem Statement

The marine geoid determination is necessary and its importance is for the creation of a high-accuracy and high-resolution marine geoid model. Such marine geoid model is very much needed will contribute significantly and used by geodesist, oceanographer and hydrographer (Sanso and Sideris, 2013). The marine geoid has also tremendous applications in offshore engineering works and dynamic applications. The applications example is such as bathymetry estimation, oil and mineral explorations, tsunami prediction, volcanoes and many more. For the case of Malaysia, the marine geoid model needed covers Malaysian region bordered by ocean areas of South China Sea, Malacca Straits, Sulu Sea and Celebes Sea.

At present there is already a geoid modeling project undertaken covering certain area of Malaysian seas. It is done by the Department of Survey and Mapping Malaysia (DSMM) under their special project known as Marine Geodetic Infrastructures in Malaysian Waters (MAGIC) project. The DSMM geoid model is determined based on terrestrial gravity data obtained from the airborne and shipborne techniques. However, the airborne-derived marine geoid conducted by MAGIC project (2015) only covered part of Malaysian sea; South China Sea region closer to Sabah within 10km. It is understood clearly that the cost to conduct airborne survey is too high and very time consuming besides the requirement of special logistic such as aircraft and dedicated gravimeter.

An alternative method in order to overcome these problems is to determine the marine geoid using space-based technique satellite altimeter. In terms of space-borne instrumentation only altimeters can measure the high-resolution gravity field from space (in the range of 5-100km) (Andersen, 2013). This is due to the satellite indirectly measures gravity by measuring the geoid height variations at the sea-surface. This means that satellite altimetry provides measurements implicitly at the sea surface which is distant nearer to the gravity field data in the Earth Crust accountable for the variations of gravity field in the 5-100km wavelength.

In order to achieve the aim of this study the sea surface height data is processed based on eleven years of altimetry data starting from 2005 to 2015. For this purpose, Radar Altimeter Database System (RADS) developed by geodetic team at the Technical University of Delft is used for altimeter data processing (Naeije *et al.*, 2000). To obtain high accuracy marine geoid model for the Malaysian seas region, firstly, the altimetry data of sea level anomaly (SLA) is verified with tidal data. Next, the mean sea surface is derived by averaging the sea surface heights data over eleven years of data. Subsequently, the derived mean sea surface is compared with DTU13 Mean Sea Surface (MSS) in order to compare the correlation between the regional and global mean sea surface.

In the next computation stage, after ready with the derived mean sea surface information, the regional gravity anomaly is computed using planar estimation of Stokes' function. This approach is commonly used in the frequency domain with spherical or planar Fast Fourier Transform techniques (FFT). In addition, the regional gravity anomaly data is crucial for computing the regional marine geoid data. Finally, the marine geoid heights are computed using LSMSA. Among the advantages of the LSMSA is that gravity reduction can be neglected and the prior geoid model can be updated and revised regularly as well.

To summarize, this research is to demonstrate a complete study on marine geoid determination and modelling using multi-mission satellite altimeter over Malaysian region. As a byproduct of this research, a Malaysian Marine Geoid Calculator (MyMG) for Malaysian seas is developed. This software product is limited to the study area and the users are able to determine the geoid heights based on specific location.

1.3 Research Questions

To address this peculiarity the main research question need to be answered in this study is:

Is marine geoid over Malaysian sea using multi-mission altimetry data represents good accuracy?

Hence, the secondary questions are:

i. What is the accuracy of the derived-mean sea surface (MSS) after compared with DTU13 MSS?
ii. How gravity anomaly can be derived based on tapering window width (TWW) examination?

1.4 Research Aim and Objectives

The aim of this research is to determine marine geoid over Malaysian seas using multi-mission satellite altimeter. In pursuit of this aim of this research, this study will specifically address several objectives as follows:

i. To derive local mean sea surface (MSS) from multi-mission satellite altimeter starting from year 2005 to 2015.

ii. To compute gravity anomaly by combining altimetry-derived gravity anomaly and GGM-derived gravity anomaly data.

iii. To estimate local marine geoid model over Malaysian seas by evaluating the accuracy of the derived geoid model with Global Positioning System (GPS) levelling observations.

1.5 Research Scope

This research is intended to determine the local marine geoid using multi-mission satellite altimeter and global gravity field model over Malaysian seas covering South China Sea, Sulu Sea, Celebes Sea and Malacca Straits. The altimetry data is processed for 11-year period starting 2005 to 2015. The research involves the following scope of work:

i. Study Area
The area under study is bounded between latitude from 0˚ up to 14˚ and longitude from 95˚ to 126˚ as shown in Figure 1.1. This study area is focused for the whole Malaysians sea covering Malacca strait, South China Sea, Celebes Sea and Sulu Sea.

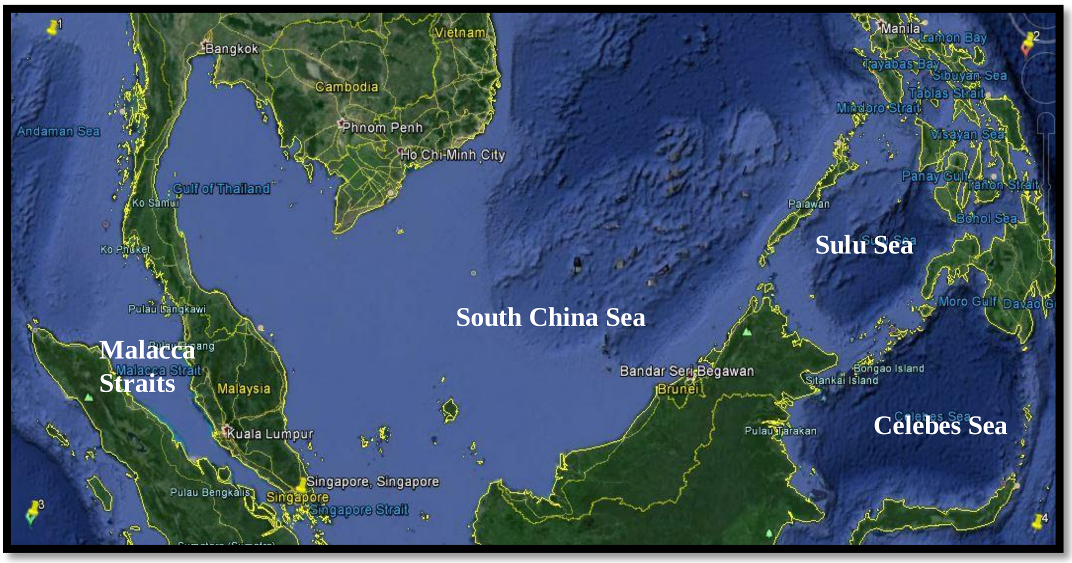

Figure 1.1: The map of the study area

ii. Satellite Altimeter Missions Data

This research involves six types of satellite altimeters; ERS-2, Jason-1, Jason-2, Envisat, Cryosat and Saral from year 2005 until 2015 (11 years). The data are processed by using Radar Altimeter Database System (RADS) for sea level anomaly (SLA) and sea surface height (SSH) derivation. The detailed descriptions regarding the satellite altimeter data (2005 to 2015) are as shown in Table 1.1.

Table 1.1: Satellite altimeter data missions

Satellite	**Phase**	**Cycle**	**Time Spends**
ERS-2	A	101-169	1 January 2005 to 4 July 2011
Jason-1	A,B and C	110-425	1 January 2005 to 21 June 2013
Envisat	B and C	6- 113	1 January 2005 to 8 April 2012
Jason-2	A	0-276	14 July 2008 to 31 December 2015
Cryosat	A	4-74	14 July 2010 to 31 December 2015
Saral	A	1-30	14 March 2013 to 31 December 2015

iii. Tidal Data

Monthly tidal data are taken from the Permanent Service for Mean Sea Level (PSMSL) website; http://www.psmsl.org/data/obtaining/. The tidal data cover the period from 2005 to 2015. Table 1.2 displays the list of tidal data adapted in World Geodetic System 1984 (WGS84) coordinate system that is involved in this study.

Table 1.2: Tide gauge stations involves in this study

Station Name	Latitude	Longitude
P. Langkawi	6°25'51.60"	99°45'50.40"
Lumut	4°14'24.00"	100°36'48.00"
Pelabuhan Klang	3° 2'60.00"	101°21'30.00"
Tanjung Keling	2°12'54.00"	102° 9'12.00"
Kukup	1°19'31.00"	103°26'34.00"
Johor Bharu	1°27'42.00"	103°47'30.00"
Tanjung Sedili	1°55'54.00"	104° 6'54.00"
Tanjung Gelang	3°58'30.00"	103°25'48.00"
Cendering	5°15'54.00"	103°11'12.00"
Geting	6°13'35.00"	102° 6'24.00"
Pulau Tioman	2°48'26.00"	104° 8'24.00"
Bintulu	3°15'44.00"	113° 3'50.00"
Kota Kinabalu	5°59'0.00"	116° 4'0.00"
Sandakan	5°48'36.00"	118° 4'2.00"
Tawau	4°14'0.00"	117°52'60.00"

iv. GPS Levelling data

A total of nine GPS levelling observation data extracted from Mohamed (2003) are used in this study. The marine geoid results are verified with GPS levelling in order to determine precise geoid for Malaysian seas. Further descriptions regarding GPS levelling data are discussed in Section 3.7.1.

v. Global Geopotential Model (GGM)

The GGMs are used for deriving the gravity-related information (i.e., gravity anomaly and marine geoid height). Selected GGMs are extracted from International Center for Global Gravity Field Models website (ICGEM) - http://icgem.gfz-potsdam.de/home. Table 1.3 displays the list of GGMs used in this study.

Table 1.3: The extracted GGMs from ICGEM website

Model	Year	Degree
ITG-GRACE2010s	2010	180
ITG-GOCE02	2013	240
GO_CONS_GCF_2_TIMR4	2013	250
Tongji-GRACE01	2013	160
ITSG-GRACE2014s	2014	200
EGM 2008	2008	2190

vi. Bathymetry data (GEBCO)

The bathymetry data from General Bathymetric Chart of the Ocean (GEBCO) model is used for the computation of the gravity anomaly from bathymetry depth. Besides, the contribution of bathymetry effect is applied for the additive corrections computation that will add to the geoid heights determination.

vii. Software

a) Radar Altimeter Database System (RADS)

RADS is employed in this study in order to extract the sea level anomaly (SLA) and sea surface height (SSH) data from multi-mission satellite altimeter in daily, monthly and climatology solution. The description regarding to RADS framework is further discussed in Section 2.4.

b) Global Mapper software

Global mapper software version 13 is important in order to emphasis on terrain layers and 3D data processing for mapping that are able to create the high-quality printed maps. Thus, there are the other applications that can be applied such as contour generation and customized gridding and terrain creation.

c) MATLAB Software

MATLAB is used for analyzing and handling the large number of data that has been extracted from RADS. Besides, this software is also used for computing the local mean sea surface (MSS) and mapping purpose such as the mapping of mean sea surface (MSS), estimated gravity anomaly and the computed marine geoid over Malaysian seas. Moreover, Matlab software is also used for developing Malaysian Marine Geoid (MyMG) calculator which will be the byproduct of this study.

d) GRAVSOFT software

Geofour program in GRAVSOFT software is employed for the computation of residual altimetry-derived gravity anomaly. This program is developed for gravity field modeling by planar Fast Fourier Transformation (FFT) program with many modes; upward continuation, gravity geoid, geoid to gravity and Molondesky's boundary value problem.

1.6 Research Significance

The significances of doing this research are:

i. This study aims to determine the marine geoid over Malaysian seas using multi-mission satellite altimeter. From marine geoid information, the unified vertical datum over Malaysian seas is particularly crucial for offshore engineering works. The marine geoid denoted information related to mineral exploration, oceanography and satellite dynamics importance for determining the orbits of the satellite (Ssengendo, 2015).

ii. The derivation of mean sea surface for Malaysian seas assimilates the oceanographic and geophysical studies such as global tide modelling, sea level rise study, vertical datum for offshore engineering and the derivation of mean dynamic topography (Yahaya *et al.*, 2016). In addition, mean sea surface heights is the key of gravity anomaly estimation and marine geoid determination.

iii. The estimation of gravity anomaly in this study is significantly required for the bathymetry estimation over Malaysian seas. Besides, the geodynamical phenomena modelling like polar motion, Earth rotation and crustal deformation can be predicted using gravity data (Bogusz *et al.*, 2015).

1.7 Research Methodology

The overall methodology of this study is divided into four phases as illustrated in Figure 1.2

1.7.1 Phase 1

i. Literature Review

This stage concentrated on reviewing the essential topics such as:

a) Understanding the fundamental and theory of geometrical data of the sea for instance sea surface height (SSH), mean sea surface (MSS), gravity anomaly and marine geoid.
b) The principle of satellite altimeter
c) Altimeter Processing Software: Radar Altimeter Database Software (RADS)
d) MATLAB programming language
e) GRAVSOFT software (Geofour program)

ii. Data Acquisition

There are three approaches employed to obtain the data as follows:

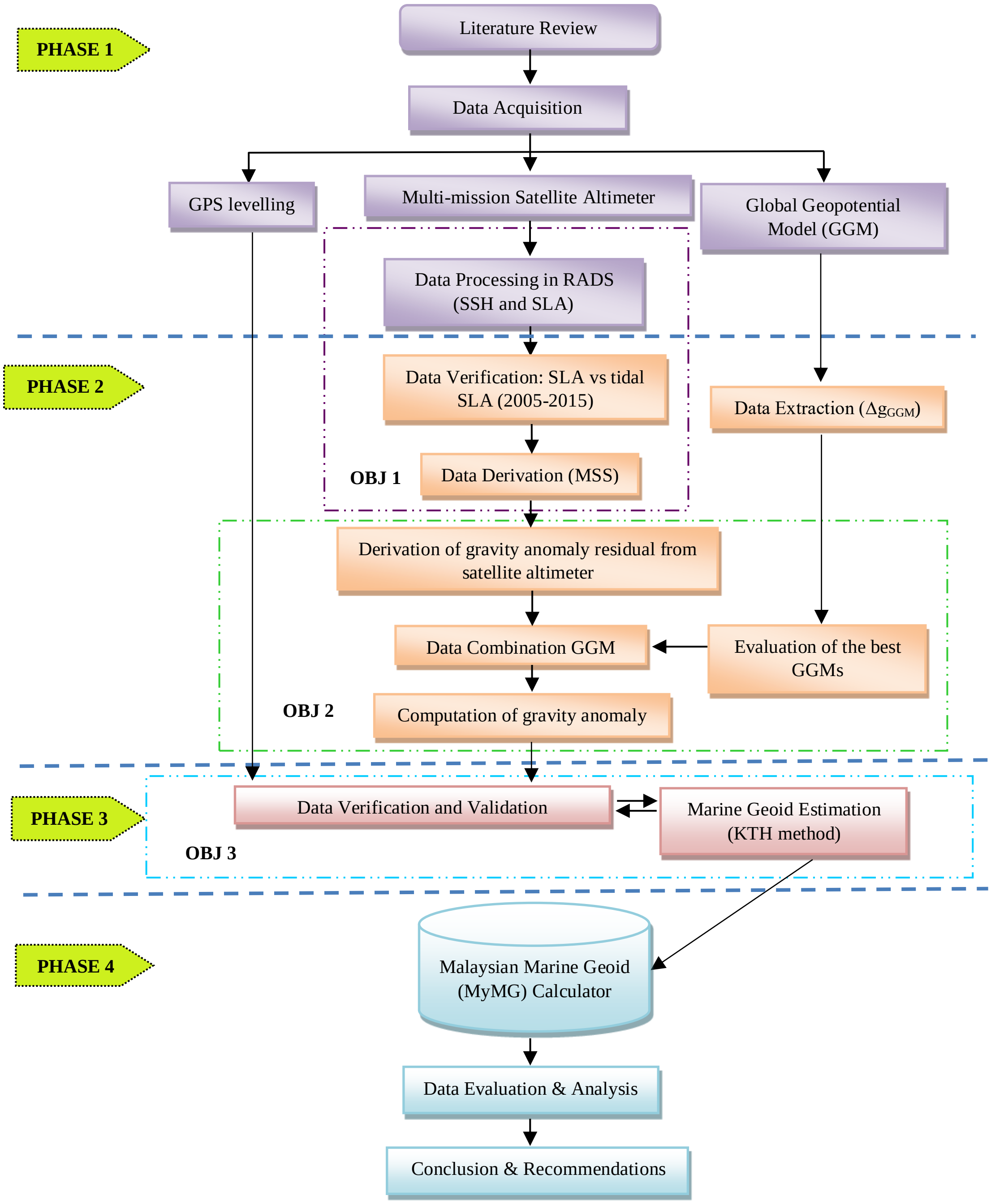

Figure 1.2: Schematic overview of the research methodology

a) GPS Levelling

There are nine GPS levelling observations data at tide gauges involve in this research; Geting, Lumut, Pelabuhan Klang, Tanjung Keling, Kukup, Johor Bharu, Tanjung Gelang and Chendering tide gauge stations. These data are used in the computed marine geoid verification.

b) Satellite Altimeter

Six satellite altimeter missions are involved for marine geoid determination; ERS-2, Jason-1, Envisat, Jason-2, Cryosat and Saral. In this study, Radar Altimeter Database System (RADS) is used for altimeter data processing. The sea level anomaly and sea surface height data are derived from RADS processing. The details regarding the processing methodology of RADS and enhancement are discussed in Section 3.2.

c) Global Geopotential Model (GGM)

GGMs data are used for gravity anomaly estimation and marine geoid determination using KTH approach. The evaluations of the selected GGMs must be performed in order to select the most suitable GGM for Malaysian region.

iii. Data Processing RADS (Sea Level Anomaly and Sea Surface Height)

The SSH and SLA data is processed by using RADS with the selected study area. By considering the spherical cap of the area, the SSH and SLA data are processed with extra 20° further than the study area. This is important for the evaluation of the initial modification parameter as discussed in Section 3.6.1 later.

1.7.2 Phase 2

i. Data Derivation MSS

Based on the SSH and SLA data, mean sea surface (MSS) height is derived by using two derivation approaches. The details description regarding to MSS derivation are discussed in Section 3.3.

ii. Residual Gravity Anomaly Derivation

The residual gravity anomaly is derived by using Geofour program in GRAVSOFT software. Gravity anomaly is the most significant data used in geoid determination.

iii. Data Extraction(Δg_{GGM})

GGM-derived gravity anomaly(Δg_{GGM}) and GGM-derived geoid(N_{GGM}) is extracted from the ICGEM Website.

iv. Evaluation of the Best GGM

Six selected GGM-derived gravity anomaly and GGM-derived geoid heights are evaluated with airborne-derived gravity data and airborne-derived marine geoid model. This is important in order to select the best GGMs for gravity anomaly estimation and marine geoid determination using KTH method.

v. Data combination

GGM-derived gravity anomaly(Δg_{GGM}) is combined with the residual altimetry-derived gravity anomaly in order to obtain the full spectrum of gravity anomaly.

vi. Computation of gravity anomaly

From the combination of GGM-derived gravity anomaly and altimetry-derived residual gravity anomaly, the cross validation and interpolation procedure is performed. The cross validation is vital for outlier detection in the data. Afterwards, the remaining data is interpolated using Kriging interpolation with the selected grid size and provide the final gravity anomaly information.

1.7.3 Phase 3

i. **Data verification and Validation**

The altimetry-derived gravity anomaly is evaluated with the airborne-derived gravity anomaly from Marine Geodetic Infrastructures in Malaysian Waters (MAGIC) project. While, the estimated marine geoid is evaluated and verified with the GPS levelling observation at tide gauge stations.

ii. **Marine Geoid Estimation (KTH approach)**

The marine geoid is determined by employing LSMSA approach based on KTH method.

1.7.4 Phase 4

i. **Malaysian Marine Geoid (MyMG)**

Based on the marine geoid estimation by using KTH approach, the Malaysian Marine Geoid (MyMG) software is developed. This is significant for the Malaysian users to obtain the marine geoid data at their specific location.

ii. **Data Evaluation and Analysis**

The evaluation and analysis are focused on analysing and discussing the MSS derivation, gravity anomaly computation and marine geoid determination over Malaysian seas.

iii. Conclusions and Recommendations

The conclusions are based on the findings and objective of the study. Hence, the suggestions and recommendations of the study are provided.

1.8 Outline of the Thesis

This thesis focussed on the marine geoid determination using multi-mission satellite altimeter over the Malaysian seas. The structure of the thesis composed of five chapters as follows:

Chapter 1 present the research topic, outlines of the research includes the aim and objectives. A general research methodology employed in this study is elaborated in this chapter.

Chapter 2 reviews the theory and principle of satellite altimeter in the derivation of ocean data. In addition, the fundamental and theory of geodesy is discussed with emphasis on the derivation of the mean sea surface, gravity anomaly estimation and marine geoid determination.

Chapter 3 discussed on how to derive mean sea surface, from multi-mission satellite altimeter employing Radar Altimeter Database System (RADS). The RADS processing methodology intensely for Malaysian seas are thoroughly discussed in this chapter. Moreover, this chapter discussed the gravity anomaly estimation and verification. The details corresponding to cross-validation are described in detail in this chapter which is significant for outlier detection. The marine geoid estimation is described particularly by using KTH approach with the additive corrections.

Chapter 4 discusses the final results of the mean sea surface derivation, gravity anomaly estimation and marine geoid determination over Malaysian seas. The results are then validated in order to assess the accuracy of the outcomes.

Chapter 5 outlines the findings and conclusions of this study. Then, the recommendations and suggestions for further studies are provided.

REFERENCES

Abbak, R. A., Erol, B., and Ustun, A. (2012). Comparison of the KTH and remove-compute-restore techniques to geoid modelling in a mountainous area. Computers and Geosciences, Volume 48, November, pp.31–40. http://doi.org/10.1016/j.cageo.2012.05.019.

Abdalla, A., and Green, C. (2016). Utilisation of Fast Fourier Transform and Least-squares Modification of Stokes formula to compile a gravimetric geoid model over Khartoum State: Sudan. *Arabian Journal of Geosciences*, *9*(3):236. http://doi.org/10.1007/s12517-015-2117-8

Ågren, J. (2004). *Regional Geoid Determination Methods for the Era of Satellite Gravimetry Synthetic Earth Gravity Models*. Doctoral Dissertation in Geodesy, Royal Institute of Technology (KTH).

Amos, M. J., and Featherstone, W. E. (2003). Comparisons of recent global geopotential models with terrestrial gravity field observations over New Zealand and Australia. *Geomatics Research Australasia*, 79:1-20.

Andersen, O. B. (2013). *Marine Gravity and Geoid from Satellite Altimetry*. Chapter 9, In Sanso, F., and Sideris M. G. (Eds) Geoid Determination: Theory and Methods (pp. 401-451). Heidelberg: Springer

Andersen, O. B., Woodworth, P. L., and Flather R. A. (1995*). Intercomparison of recent ocean tide models*. Journal of Geophys Res, 100(C12):25,261–25,282

Andersen, O.B., and Knudsen, P. (1998). *Global marine gravity field from the ERS-1 and Geosat geodetic mission altimetry*. Journal of Geophys Res 103(C4):8129-8137.

Andersen, O. B., Egbert, G. D., Erofeeva, S. Y., and Ray, R. D. (2006). *Mapping nonlinear shallow water tides: a look at the past and future.* Ocean Dynamics, 56(5-6):416–429. Springer, doi:10.1007/s10236-006-0060-7

Andersen, O.B., and R. Scharroo (2009). Range and geophysical corrections in coastal regions-Implications for mean sea surface determination, in *Coastal Altimetry*, edited by S.Vignidelli et al., Springer, Berlin.

Andersen, O.B., and Scharroo, R. (2011). *Range and Geophysical Corrections in Coastal Regions: And Implications for Mean Sea Surface Determination.* In

Vignudelli, S., Kostianoy, A., Cipollini P., and Benveniste J. (Eds) Coastal Altimetry (pp. 103-145). Heidelberg: Springer. doi:10.1007/978-3-642-12796-0.

Andersen, O. and Knudsen, P. (2013). The DTU13 MSS New global Mean sea surface from 20 years of satellite altimetry. Poster presented at the IAG Scientific Assembly 2013, Potsdam, 1- 6 September 2013

Andritsanos, V. D (2000). *Optimum combination of terrestrial and satellite data with the use of spectral techniques for applications in geodesy and oceanography*. Doctor Philosophy. Department of Geodesy & Surveying, School of Rural and Surveying Engineering, Faculty of Engineering, The Aristotle University of Thessaloniki, Greece.

AVISO(2017). AVISO Satellite Altimetry Data. Retrieved October 15. 2017, from http://www.aviso.oceanobs.com/

Balmino, G., Moynot, B., Sarrailh M, and Valès, N. (1987). *Free air gravity anomalies over the oceans from Seasat and Geos 3 altimeter data*. EOS Trans. AGU, 68(2):17-19.

Banerjee P. (2011). Geoid. In Gupta H. K. (Ed.), Encyclopedia of Solid Earth Geophysics, Encyclopedia of Earth Sciences Series, Springer Science & Business Media B.V., p. 353

Bertiger, W., Desai, S., Dorsey, A., Haines, B., Harvey, N., Kuang, D., Lane, C., Weiss, J. and Sibores, A. (2008). *Jason-2, Precision Orbit Determination Status*. OSTST workshop, Nice, Nov 2008

Bilitza, D. (2001). *International Reference Ionosphere 2000*. Radio Sci 36(2):261-275. doi:10.1029/2000RS002432

Bingham, C., Godfrey, M., and Tukey, J. (1967). Modern techniques of power spectrum estimation. *IEEE Trans. Audio Electroacoustic*, 15(2):55-66.

Bjerhammar, A. (1963). A new theory of gravimetric geodesy. Geodesy Division of the Royal Institute of Technology Report, Stockholm.

Bjerhammar, A. (1973). Theory of Errors and Generalized Matrix Inverses. Elsevier.

Bogusz, J., Brzezinski, A., Kosek, W., and Nastula, J. (2015). Earth rotation and geodynamics. *Geodesy and Cartography*, *64*(2), 201–242. http://doi.org/10.1515/geocart-2015-0013

Bracewell, R. N. (2000). The Fourier Transform And Its Applications. (3rd Edition) *New York: McGraw-Hill*. http://doi.org/10.1049/ep.1965.0268

Brown, G.S. (1997). *The Average Impulse Response of a Rough Surface and its*

Ellmann, A., and Sjöberg, L. E (2004). Ellipsoidal correction to the modified Stokes formula. *Bolletino di Geodesia e Scienze Affini, 63(3)*:153-172.

Engelis, T (1987). *Radial Orbit Error Reduction and Sea Surface Topography Determination Using One Year of GEOSAT Altimeter Data*. Report No. 377, Department of Geodetic Science and Surveying, The Ohio State University, Columbus, Columbus, Ohio, U.S.A.

Erol, B., Sideris, M. G., and Çelik, R. N. (2009). Comparison of global geopotential models from the champ and grace missions for regional geoid modelling in Turkey. Studia Geophysica et Geodaetica, 53(4):419-441.

Featherstone, W.E., and Dentith, M. C. (1997). A geodetic approach to gravity data reduction for geophysics. *Computers & Geosciences*, 23(10):1063-1070. doi.org/10/1016/S0098-3004(97)00092-7.

Forsberg, R. (1984). *A study of terrain reductions, density anomalies and geophysical inversion methods in gravity field modeling.* Report No. 355, Department of Geodetic Science and Surveying, The Ohio State University, Columbus, Ohio.

Fu, L.-L. (2010). *Determining Ocean Circulation and Sea Level from Satellite Altimetry: Progress and Challenges*. Oceanography from Space. Springer.

Fu, L.-L. and Cazenave, A. (2001). *Satellite Altimetry and Earth Sciences.* New York: Academic Press. 486p.

Fu, L.-L. and Chelton, D. B. (2001). *Largle Scale Ocean Circulation.* Chapter 2, In Fu, L.-L. and Cazenave, A. (Eds.) Satellite Altimetry and Earth Sciences. pp.133-169, New York: Academic Press.

Gaspar, P., Ogor, F., Le Traon, P.Y. and Zanifé, O. Z. (1994). Estimating the sea state bias of the TOPEX and Poseidon altimeters from crossover differences. Journal of Geophys Res, 99(C12):24981-24994

Geisser S., and Eddy W.F., (1979). A predictive approach to model selection. *Journal of the American Statistical Association*, 74(365), 153-160.

Giberson, W. E (1991). *Seasat-A: A Retrospective*. International Journal of Remote Sensing, 12(8), pp1613-1617.

Goldhirsh J., and Rowland JR., (1992). A tutorial assessment of atmospheric height uncertainties for high-precision satellite altimeter missions to monitor ocean currents. IEEE Trans Geosci Remote Sensing 20:418-434.

Gysen, V., H., and Coleman, R. (1997). On the satellite altimeter crossover problem. *Journal of Geodesy*, *71*, 83–96. http://doi.org/10.1007/s001900050077

Hackney, P. I., and Featherstone, W.E. (2003). *Geodetic versus geophysical perpectives of the 'gravity anomaly'*, Geophysical Journal International, 154:35-43.

Handoko, E. Y., Fernandes, M. J., and Lázaro, C. (2017). Assessment of altimetric range and geophysical corrections and mean sea surface models - Impacts on sea level variability around the Indonesian seas. *Remote Sensing*, *9*(2). 32 pages. http://doi.org/10.3390/rs9020102

Haxby, W. F. (1987). *Gravity Field of the World's Oceans. National Geophysical Data Center*, NOAA, Boulder, CO.

Heiskanen, W. A. and Moritz, H. (1967). Physical Geodesy. San Fransisco: W. H. Freeman and Co.

Helmert, F.R., (1880) *Die mathematischen und physicalischen Theorien der hoheren Geodasie*, Teubner, Leipzip, Frankfurt.

Hernandez, F., and Schaeffer, P. (2000). *Altimetric mean sea surfaces and gravity anomaly maps and inter-comparison.* AVISO Tech Rep, AVI-NT-011-5242, CLS CNES, Toulouse.

Hernandez, F., and Schaeffer, P. (2001). *The CLS01 Mean Sea Surface: A validation with the GSFC00.1 surface*. Technical Report, CLS, Ramonville, St Agne, France, 14 pp.

Hughes, C.W., and Bingham, R.J. (2008). *An Oceanographer's Guide to GOCE and the Geoid.* Ocean Science, Europen Geosciences Union. 4(1):15-29.

Hunegnaw, A. (2001). *Geoid Determination over Ethiopia with Emphasis on Downward Continuation of Gravity Anomalies*. Doctor Philosophy, Department of Geodesy & Photogrammetry, KTH, Stockholm, Sweden.

Hwang, C. (1998). *Inverse Vening Meinesz formula and deflection-geoid formula: applications to the predictions of gravity and geoid over the South China Sea*. Journal of Geodesy, 72(5):304–312

Hwang, C. (1999). *A Bathymetric Model for the South China Sea from Satellite Altimetry and Depth Data*. Marine Geodesy, 22(1):37-51.

Hwang C, Hsu, H.-Y, Jang, R.-J. (2002). *Global mean sea surface and marine gravity anomaly from multi-satellite altimetry: applications of deflection-geoid and inverse Vening Meinesz formulae*. Journal of Geodesy, 76(8):407-418.

ICGEM (2017). International Centre for Global Earth Models. Retrieved October 1 2017, from http://icgem.gfz-potsdam.de/home

Jamil, H. (2011). GNSS Heighting and Its Potential Use in Malaysia GNSS Heighting and Its Potential Use in Malaysia, Paper presented at the FIG Working Week 2011, Marrakech, Morocco, Paper No 5410, 19 pages.

Johannes, W. J., and Smilde, P. L. (2009). *Gravity Interpretation: Fundamentals and Application of Gravity Inversion and Geological Interpretation.* Heildelberg: Springer-Verlag.

Karpik, A. P., Kanushin, V. F., Ganagina, I. G., Goldobin, D. N., Kosarev, N. S., and Kosareva, A. M. (2016). Evaluation of recent Earth's global gravity field models with terrestrial gravity data. *Contributions to Geophysics and Geodesy*, *46*(1), 1–11. http://doi.org/10.1515/congeo-2016-0001

Kiamehr, R. (2006). *Precise Gravimetric Geoid Model For Iran Based on GRACE and SRTM Data and the Least-Squares Modification of Stokes' Formula with Some Geodynamic Interpretations*. Doctor Philisophy, Department of Transport and Economics, Royal Institute of Technology (KTH), Stockholm, Sweden.

Kiamehr, R. (2010). *Practical Concepts in Geoid Modelling with Geophysical and Geodynamical Interpretations*. Saarbrücken, Deutschlan: LAP Lambert Academic Publishing, 220 pages.

Kirby, J. F., and Featherstone, W. E. (1997). A study of zero-and first degree terms in geopotential models over Australia. *Geomatics Research Australasia*, (66):93-108.

Kirby, J. F, Featherstone W. E., and Kearsley A. H. W., (1998). Tests of the DMA/GSFC geopotential models over Australia. International Geoid Service Bulletin, (7):2-13.

Knudsen, P. (1993). *Integration of Gravity and Altimetr Data by Optimal Estimation Techniques*. In Satellite Altimetry for Geodesy and Oceanography, Lecture Notes in earth Sciences No 50, pp.453-466.

Koch, K. R. (1970). Gravity anomalies for ocean areas from satellite altimetry. *Proceedings of the Second Marine Geodesy Symposium*, Marine Technology Society, Washington DC.

Krige Danie G., (1951). A statistical approach to some basic mine valuation problems on the Witwatersrand. *J. of the Chem., Metal. And Mining Soc. of South Africa, 52(6*), 119-139.

Lambeck, K., and Coleman R., (1983). The Earth's shape and gravity field: a report of progress from 1958 to 1982. Geophysical Journal of the Royal Astronomical Society, 74, 25-54.

Le Traon, P. Y., and Morrow, R. (2001). Ocean Currents and Eddies, Chapter 3, In Fu, L.-L & Cazenave, A. (Eds) *Satellite Altimetry and Earth Sciences*, pp.71-215. New York: Academic Press.

Limpach, P.,(2010). *Sea Surface Topography and Marine Geoid by Airborne Laser Altimetry and Shipborne Ulttrasound Altimetry (Volume 80)*. Institut für Geodäsie und Photogrammetrie. ISBN-978-3-908440-24-6.

Listing, J.B., (1873). Uber unsere jetzige Kenntnis der Gestalt und Grosse der Erde, *Nachr. d. Kgl.*, Gesellsch. d. Wiss. und der Georg-August-Univ., 33-98, Gottingen.

Li, X., and Gotze, H-J. (2001). Tutorial on Ellipsoid, geoid, gravity, geodesy, and geophysic. Geophysics, 66(6):1660-1668. http://doi.org/10.1190/1.1487109

Lu , Z., Qu Y., and Qiao, S. (2014). Geodesy Introduction to Geodetic Datum and Geodetic Systems, Department of Survey and Mapping, Information Engineering University, Zhengzhou. Springer. ISBN 978-3-642-41244-8.

Talone, M., Meloni, M., Pelegri, J. L., Rosell-Fieschi, M. and Flobergaghen, R. (2014). *Evoulution of geoids in recent years and its impact on oceanography*. Scientia Marina, 78(2):155-164

Martinec, Z. (1998). *Topographical effects*. Chapter 3, In Boundary-Value Problems for Gravimetric Determination of a Precise Geoid. Lecture Notes in Earth Science, Vol 73, pp.34-49, Springer.

Martinec, Z., and Grafarend, E. (1997). Solution to the Stokes boundary-value problem on an ellipsoid of revolution. Studia Geophysica et Geodaetica, 41, 103-129. Retrieved from http://www.springerlink.com/index/ K3425K27504L1H26.pdf

Meissl, P. (1971). *A Study of Covariance Functions Related to the Earth's Disturbing Potential*, Report No. 151, Department of Geodetic Science, The Ohio State University, Columbus, Ohio.

Mohamed, A. (2003). *An Investigation of the Vertical Control Network of Peninsular Malaysia using a Combination of Levelling, Gravity, GPS and Tidal Data*. Doctor Philosophy, Universiti Teknologi Malaysia, Skudai.

Molodensky, M., Eremeev, V., and Yurkina, M. (1962). *Methods for study of the external gravitational field and figure of the Earth*. Jurusalem, Israel Program for Scientific Translations, 1962; [available from the Office of Technical Services, US Dept. of Commerce, Washington].

Moritz H., (1972). Advanced Least-Squares Methods, Dept of Geodetic Science, OSU, Report No. 175, 1972.

Moritz, H. (1980). Advanced Physical Geodesy. Herbert Wichmann, Karlsruhe/Abacus Press.

Naeije, M., Schrama, E. and Scharroo, R. (2000). *The Radar Altimeter Database System Project RADS*. Delft Institute for Earth Oriented Space Research, Delft University of Technology, The Netherlands.

Naeije, M., Doornbos, E., Mathers, L., Scharroo, R., Schrama, E. and Visser, P. (2002). *RADSxx: Exploitation and Extension*. NUSP-2 report 02-06, SRON/NIVR, Delft, The Netherlands.

Naeije, M., Scharroo, R., Doornbos, E. and Schrama, E. (2008). *Global Altimetry Sea Level Service: GLASS*. NIVR/SRON GO project: GO 52320 DEO.

Omar, K. M., Ses, S., Naieje, M., and Mustafar, M. A. (2006). *The Malaysian Seas: Variation of Sea Level Observed by Tide Gauges and Satellite Altimetry*. Paper presented at the SEAMERGES Final Symposium, 28-1 December 2005, Bangkok, Thailand.

Panigrahi, N. (2014). *Computing in Geographic Information Systems*. *CRC Press*. Boca Raton, Florida.

Picot, N., Case, K., Desai, S., and Vincent, P. (2003). *AVISO and PODAAC User Handbook.* IGDR and GDR Jason Products. SMM-MU-M5-OP-13184-CN (AVISO), JPL D-21352 (PODAAC).

Pilz, M., and Parolai, S. (2012), *Seismic Signal and Noise,* Helmholtz Centre Potsdam, GFZ German Research Centre for Geosciences, Helmholzstr, 7, 14473 Postdam

Pilz, M., Parolai, S., Picozzi, M., and Bindi, D. (2012). Three-dimensional shear wave velocity imaging by ambient seismic noise tomography. *Geophysical Journal International*, *189*(1):501–512. http://doi.org/10.1111/j.1365-246X.2011.05340.x

Radar Altimeter Database (RADS) Website. Retrieved September 9, 2016, from http://rads.tudelft.nl/rads/experts.shtml.

Sansó, F and Sideris, M. G. (2013). *Geoid Determination: theory and methods.* Lecture Notes in Earth Science, Vol. 110, Berlin: Springer-Verlag.

Scharroo, R., Leuliette, E., Lillibridge, J. , Doornbos, E., Naeije, M. and Schrama, E. (2011). *RADS 4: A New Interface to Precise and Fast-delivery Altimeter Data from Geosat to Cryosat*. Ocean Surface Topography Science Team (OSTST) Poster. San Dieogo, California.

Schwarz, K. P, Sideris, M. G, and Forsberg, R (1990). *The use of FFT techniques in physcial geodesy*. Geophys Journal Int 100:485-514.

Ses, S., and Mohamed, A. (2009). The second precise levelling network of Peninsular Malaysia. *Survey Review*, 41(314), 384-394.

Shum, C. K., Zhang, B. H., Schutz, B. E. and Tapley, B.D. (1990). *Altimeter Crossover Methods for Precision Orbit Determination and the Mapping of Geophysical Parameters*. J. Astron. Sci., 38, 355-368.

Sideris, M. G. (1997). *Geoid Determintion by FFT Techniques. In International School for the Determination and Use of the Geoid Lecture Notes, Rio de Janeiro,* September 10-16, International Geoid Service, DIIAR – Politecnico di Milano.

Sideris, ,M., Fei, Z., and Blais, J. (2002). Ellipsoidal corrections for the inverse Hotine/ Stokes formulas. *The Challenge of the 3rd Millennium*, 453-466.

Singh, M., Mandal, M. K, and Basu, A. (2005). *Gaussian and Laplacian of Gaussian weighting functions for robust feature based tracking.* Pattern Recognition Letters 26(13):1995-2005.

Sjoberg, L. E. (1984) *Least Square Modification of Stokes' and Vening Meinesz' Formulas by Accounting for Errors of Truncation, Potential Coefficients and Gravity Data*. The Department of Geodesy, Report No 27, The University of Uppsala, Upsalla, Sweden.

Sjöberg, L. E. (1986). Comparison of some methods of modifying Stokes' formula. *Bullettino di Geodesia e Science Affini*, 3(45):229-248.

Sjöberg, L. E. (1987). The estimation of the power spectrum and reliability of models of the Earth's gravity field by intercomparison of independent models. Manuscr. Geod. 12:104-112.

Sjöberg, L. E. (1991). Refined least squares modification of Stokes' formula. *Manuscripta Geodaetica*, 16, 367-375.

Sjöberg, L. E. (1998). The atmospheric geoid model and gravity corrections. *Bolletino Di Geodesia Scienze Affini*, 57(4), 421-435.

Smith, W. H. F., and Sandwell, D. T. (1997). *Global seafloor topography from satellite altimetry and ship depth soundings*. Science 277:1957–1962

Stokes, G. G. (1849). *On the variation of gravity at the surface of the earth. Trans. Cambridge Philos.* Soc. VIIII, 672-695.

Sulaiman, S. A. (2016). *Gravimetric Geoid Model Determination for Peninsular Malaysia Using Least Squares Modification of Stokes*, Doctor Philosophy, Universiti Teknologi Mara. Shah Alam.

Torge, W. and Müller, J. (2012) *Geodesy. 4th Edition*, Walter de Gruyter, Berlin. https://doi.org/10.1515/9783110250008

Trisirisatayawong, I., Naeije, M., Simons, W., and Femoglio-Marc, L. (2011). *Sea level change in the Gulf of Thailand from GPS-corrected tide gauge data and multi-satellite altimetry*. Global & Planetary Change, 76(3-4):137-151.

Tziavos, I. N., Forsberg, R., Sideris, M. G., and Andritsanos, V. D. (1997). *A comparison of satellite altimetry methods for the recovery of gravity field quantities*. In: Geodesy on the Move, R. Forsberg, M. Feissel, R. Diestrich (Eds.), IAG Symposia, Vol. 119, Springer.

Tziavos, I. N., Forsberg, R., and Sideris M. G. (1998). *Marine Gravity Field Modelling Using Shjipborne and Geodetic Missions Altimetry Data*. Geomatics Research Australasia, No. 69, pp.1-18.

Ulotu, P. E. (2009). *Geoid Model of Tanzania from Sparse and Varying Gravity Data Density by the KTH Method. Doctor Philosophy, Division of Geodesy, Department of Transport and Economics*, Royal Institute of Technology (KTH). Sweden.

Van Gysen, H., and Coleman, R. (1997). On the satellite altimeter crossover problem. *Journal of Geodesy*, *71*:83–96. http://doi.org/10.1007/s001900050077

Vergos, G. S. (2002). *Sea Surface Topography, Bathymetry and Marine Gravity Field Modelling*, UCGE Reports Number 20157, Univeristy of Calgary. Canada.

Vermeer, M. (1992). A frequency domain approach to optimal geophysical gridding. Manuscripta Geodaetica, 17:141-154.

Wang, Y. M. (2000). *The satellite altimeter data derived Mean Sea Surface GSFC98*. Geophysical Research Letters, 27(5):701-704

Watson, C. S. (2005). *Satellite Altimeter Calibration and Validation using GPS Buoy Technology*. Doctor Philosophy, Centre for Spatial Information Science, University of Tasmania, Australia, 264pp. Available at:http://eprints.utas.edu.au/254/