SEA LEVEL RISE ESTIMATION AND INTERPRETATION IN MALAYSIAN REGION USING MULTI-SENSOR TECHNIQUES

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

Faculty of Geoinformation and Real Estate
Universiti Teknologi Malaysia

SEPTEMBER 2014

DEDICATION

I dedicate this work to my beloved Mother, Wife, Children

and in memory of my late Father

ACKNOWLEDGEMENT

All praises to Allah, the Lord of the Universe. May the peace and blessings of Allah be upon Prophet Muhammad s.a.w, His last messenger.

Special thanks goes to my mentors, Prof. Dr. Sahrum Ses and Assoc. Prof. Kamaludin Mohd Omar for their tireless advice, constructive comments, great support and friendship during this long journey in completing my study. Working with them has improved my skills enormously. This work was possible through the financial aid from the *Skim Latihan Akademik Bumiputera* (SLAB), UTM.

I would also like to extend my gratitude to Assistant Prof. Marc Naeije (Delft University of Technology) for guiding me in the altimeter field and willing to spend his precious time answering even trivial questions posed by me. Thanks also to Prof. Dr. Andy Hooper and Dr. Miguel Caro Cuenca (Delft University of Technology) for introducing me to PS InSAR, particularly to the concept, algorithm and software.

I also very much appreciate Mr Soeb Nordin (DSMM Staff), Dr Mohd Effendi Daud (UTHM) and Mr Jhonny for their valuable discussions, recommendations and support in understanding Bernese processing during the early stages of my study.

I am deeply indebted to Mr Jespal Singh Gill for his assistance in proof reading this thesis. I am also grateful to my colleagues, especially Mr Mohamad Asrul Mustafar (UiTM), Mr Mohd Faiz Pa'suya, Mr Wan Aminullah Abdul Aziz and all friends in GNSS and Geodynamics Research Group, UTM who have provided assistance in various occassions. Unfortunately, it is not possible to list all of them in this limited space.

I would like to express my sincerest gratitude to My Late Father, Mother, Brothers and Sisters for their love, prayers and constant support. I also express my deepest appreciation for my family-in-law.

As for the utmost appreciation and gratitude, I would like to thank my lovely wife, Nadia Hartini Mohd Adzmi for her understanding, support and love during the past few years. To my daughter, Arina and my sons, Ahnaf and Afifi, with all their love they make me very happy. They are a major driving force and a great source of inspiration for completing my study. I am utterly grateful to them.

ABSTRACT

Rise in sea level is one of the disastrous effects of climate change. A relatively small increase in sea level could affect the natural coastal system. This study presents an approach to estimate before interpreting the precise sea level trend based on a combination of multi-sensor techniques in the Malaysian region over a period of 19 years. In the study, six altimeter missions were used to derive the absolute sea levels which were processed in the Radar Altimeter Database System. Next, 21 tide gauge stations along the coastlines of Malaysia were utilised to derive the rate of relative sea levels that took into account sea level changes and vertical land motions. To obtain absolute sea level at tide gauge, vertical land motions at these stations were removed by employing three techniques, namely GPS, Persistent Scatterers Interferometric Synthetic Aperture Radar and altimeter minus tide gauge. Bernese software with double difference strategy was employed to process data from 87 local and 30 international GPS stations. Using Persistent Scatterers Interferometric Synthetic Aperture Radar, the Stanford Method for Persistent Scatterer software processed 111 images. Besides that, the satellite altimeter and tide gauges were used to retrieve the differential rates estimated by altimetry and tidal data to obtain the rate of vertical land motion. Following that, absolute sea level rates from the tide gauge stations and multi-satellite altimeter missions were combined. This combination produced the regional sea level trend of the Malaysian seas. The findings from the multi-sensor techniques showed that the regional sea level trend has been rising at a rate of 2.65 ± 0.86 mm/yr to 6.03 ± 0.79 mm/yr for the chosen sub-areas, with an overall mean of 4.47 ± 0.71 mm/yr. Upon completion of the study, a Sea Level Information System for the Malaysian seas was developed to facilitate users in analysing, manipulating and interpreting sea level and vertical land motion data. This system is expected to be valuable for a wide variety of climatic applications to study environmental issues related to flood and global warming in Malaysia

ABSTRAK

Kenaikan paras laut adalah salah satu kesan buruk perubahan iklim. Peningkatan kecil dalam paras laut boleh menjejaskan sistem semula jadi pantai. Kajian ini membentangkan satu pendekatan untuk menganggarkan sebelum mentafsir trend paras laut tepat berdasarkan kombinasi teknik multi-sensor di rantau Malaysia dalam tempoh 19 tahun. Dalam kajian, enam misi altimeter telah digunakan untuk memperolehi paras laut mutlak yang telah diproses dalam Sistem Pangkalan Data Altimeter Radar. Seterusnya, 21 stesen tolok pasang surut di sepanjang garis pantai Malaysia telah digunakan untuk mendapatkan kadar paras laut relatif yang mengambil kira perubahan paras laut dan pergerakan tanah menegak. Untuk mendapatkan paras laut mutlak pada tolok pasang surut, pergerakan tanah menegak di stesen-stesen ini telah dikeluarkan dengan menggunakan tiga teknik, iaitu GPS, Radar Aperture Sintetik Interferometri Sebaran Berterusan dan altimeter tolak tolok pasang surut. Perisian Bernese dengan strategi perbezaan ganda dua telah digunakan untuk memproses data daripada 87 stesen tempatan dan 30 stesen GPS antarabangsa. Menggunakan Radar Aperture Sintetik Interferometri Sebaran Berterusan, perisian Kaedah Stanford untuk Sebaran Berterusan telah memproses 111 imej. Di samping itu, altimeter satelit dan tolok pasang surut telah digunakan untuk memperolehi kadar perbezaan anggaran dengan data altimeter dan tolok pasang surut untuk mendapatkan kadar pergerakan tanah menegak. Berikutan itu, kadar paras laut mutlak dari stesen tolok pasang surut dan misi altimeter multi-satelit telah digabungkan. Gabungan ini telah menghasilkan trend paras laut serantau di laut Malaysia. Penemuan daripada teknik multi-sensor menunjukkan trend paras laut serantau telah meningkat pada kadar 2.65 ± 0.86 mm/tahun kepada 6.03 ± 0.79 mm/tahun untuk sub-kawasan yang dipilih, dengan min keseluruhan 4.47 ± 0.71 mm/tahun. Dalam menyelesaikan kajian, Sistem Maklumat Paras Laut untuk laut Malaysia telah dibangunkan bagi membolehkan pengguna menganalisis, memanipulasi dan mentafsirkan data paras laut dan pergerakan tanah menegak. Sistem ini dijangka berharga untuk pelbagai aplikasi iklim untuk mengkaji isu-isu alam sekitar yang berkaitan dengan banjir dan pemanasan global di Malaysia.

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LIST OF SYMBOLS

$A_i x$	-	Orbital correction term
B	-	Baseline between master and slave
$B_\perp$	-	Perpendicular baseline
c	-	Speed of the radar pulse
D_A	-	Amplitude dispersion
d	-	Distance
e	-	Unit vector of the station
f	-	Frequency
F_{DC}	-	Doppler centroid frequency difference
$F_w(r,)$	-	Gaussian weighting function
GM_E	-	Gravitational constant of the earth
GM_j	-	Gravitational constant of the moon (j=2) and the sun (j=3)
h	-	Sea surface height
H	-	Satellite altitude
h_{atm}	-	Dynamic atmospheric correction
h_D	-	Dynamic sea surface height
h_{geoid}	-	Geoid correction
h_i	-	Instantaneous sea surface eight above the ellipsoid at the crossover point
h_{sla}	-	Sea level anomaly
h_{tides}	-	Tides correction
j	-	Represents 11 tidal harmonics
k	-	Constant of 0.40250 m GHz^2/TECU
K	-	Tuning constant whose default value of 4.685
m	-	Master image
N	-	Number of interferogram

$p(x,y)$	-	Interferogram pixel value at (x,y)
P	-	Average pressure anomaly
P_0	-	Sea level pressure
P_{ref}	-	Global mean pressure
r	-	Range from the satellite to the earth's surface
r_i	-	Residuals
$R_{corrected}$	-	Corrected range
R_{obs}	-	Observed range
t	-	Travel time
s	-	Slave image
$s_1(x,y)$	-	Master single look complex pixel value at (x,y)
S	-	Mean absolute deviation divided by a factor 0.6745
$SALT_{rate}$	-	Rate of sea level trend from satellite altimeter
SE	-	Standard Error
T	-	Temperature
TG_{rate}	-	Rate of sea level trend from tide gauge
$TG_{corr\ rate}$	-	Absolute sea level at tide gauge
U	-	Wind speed
v	-	Velocity of the SAR satellite
VLM_{rate}	-	Rate of vertical land motion
v_i	-	Single error term
χ_j	-	Reflect the position of the sun and moon
w_i	-	Observation weight
z	-	Satellite's height above the earth's surface
$\overline{h_i}$	-	Mean sea surface height
Δc	-	Displacement due to ocean tide loading
ΔF_{DC}	-	Difference in the Doppler centroid frequencies of the slave and master images
Δh_{dry}	-	Dry troposphere correction
Δh_{ib}	-	Dynamic atmosphere correction
Δh_{iono}	-	Ionosphere correction
$\Delta h_{load\ tide}$	-	Load tide
$\Delta h_{ocean\ tide}$	-	Ocean tide

$\Delta h_{pole\ tide}$	-	Pole tide
$\Delta h_{solid\ earth\ tide}$	-	Solid earth tide
Δh_{ssb}	-	Sea-state bias correction
Δh_{tides}	-	Tidal correction
Δh_{wet}	-	Wet troposphere correction
ΔR_{dry}	-	Dry tropospheric correction
ΔR_{iono}	-	Ionospheric correction
ΔR_{ssb}	-	Sea-state bias correction
ΔR_{wet}	-	Wet tropospheric correction
Δr	-	Vertical displacement of atmospheric loading
ΔX	-	Vector displacement of the station due to solid earth tides
ω	-	Angle between the baseline vector and the horizontal
ω_j	-	Angular velocities and astronomic arguments
ε_i	-	Measurement noise
$\xi_{instant\ i}$	-	Instantaneous component of sea surface height
ρ	-	Correlation
θ	-	Look angle
θ_i	-	Incident angle
λ	-	Wavelength
ϕ	-	Interferometric phase
ϕ_{atm}	-	Phase due to atmospheric delay effect
ϕ_{defo}	-	Phase due to ground deformation effect
ϕ_{int}	-	Interferometric phase of a pixel in a differential interferogram
ϕ_{noise}	-	Phase due to the scattering background and other uncorrelated noise terms
ϕ_{orb}	-	Orbit error due to inaccurate orbit information
ϕ_{topo}	-	Phase due to topography effect
$\sigma_{\emptyset}$	-	Phase standard deviation
σ_A	-	Standard deviation of amplitude
μ_A	-	Mean of a series of amplitude
α	-	Angle between baseline vector and perpendicular baseline
σ_{vap}	-	Vertical integration of the water vapour density
γ_x	-	Phase stability

LIST OF ABBREVIATIONS

AOGCM	-	Atmosphere-Ocean coupled Global Climate Models
ASAR/IM	-	Advanced Synthetic Aperture Radar Image Mode
AUNP	-	Asean-EU University Network Program
AVISO	-	Archiving, Validation and Interpretation of Satellite Oceanographic data
BP	-	Before Present
BPE	-	Bernese Processing Engine
CEOS	-	Committee on Earth Observation Satellites
CLAP	-	Combined Low-pass and Adaptive Phase
CLS	-	Collecte Localisation Satellites
CNES	-	Centre National d'Etudes Spatiales
CORS	-	Continuously Operating Reference Stations
CZH	-	Code Zero Header
CZO	-	Code Zero Observation
DBMS	-	Database Management System
DEM	-	Digital Elevation Model
DEOS	-	Delft Institute for Earth-Oriented Space Research
DoD	-	Department of Defense
DORIS	-	Delft Object-oriented Radar Interferometric Software
DORIS	-	Doppler Orbitography and Radiopositioning Integrated by Satellite
DSMM	-	Department of Survey and Mapping Malaysia
DSSH	-	Dynamic Sea Surface Height
DTU10	-	Denmark Technical University 10
ECMWF	-	European Centre for Medium-Range Weather Forecasts
EDM	-	Electronic Distance Measurement
EM	-	Electro Magnetic

ENSO	-	El Nino/Southern Oscillation
EnviSat	-	Environmental Satellite
EOLI-SA	-	Earth Observation Link Stand Alone
EOP	-	Earth Orientation Parameters
ERS-1	-	European Remote Sensing Satellite 1
ERS-2	-	European Remote Sensing Satellite 1
ESA	-	European Space Agency
EUMETSAT	-	European Organization for the Exploitation of Meteorological Satellites
FES2004	-	Finite Element Solution 2004
FTP	-	File Transfer Protocol
GEBCO	-	General Bathymetric Chart of the Oceans
GEOS-3	-	Geodynamics Explorer Ocean Satellite 3
GIA	-	Glacial Isostatic Adjustment
GIM	-	Global Ionosphere Map
GMSL	-	Global Mean Sea Level
GNSS	-	Global Navigation Satellite System
GPS	-	Global Positioning System
GRGS	-	Groupe de Recherche de Geodesie Spatiale
GUI	-	Graphical User Interface
GUIDE	-	Graphical User Interface Development Environment
IAG	-	International Association of Geodesy
IDW	-	Inverse Distance Weighting
IERS	-	International Earth Rotation Service
IGN	-	Institute Geographic National
IGS	-	International GNSS Service
InSAR	-	Interferometic Synthetic Aperture Radar
IPCC	-	Intergovernmental Panel on Climate Change
IRI	-	International Reference Ionosphere
IRLS	-	Iteratively Re-weighted Least Squares
ITRF	-	International Terrestrial Reference Frame
JPL	-	Jet Propulsion Laboratory
LOS	-	Line of Sight
MASS	-	Malaysian Active GPS System

MATLAB	-	Matrix Laboratory
MDT	-	Mean Dynamic Topography
MIT	-	Massachusetts Institute of Technology
MOG2D	-	Two Dimensions Gravity Waves Model
MSS	-	Mean Sea Surface
MyRTKnet	-	Malaysia Real Time Kinematic GNSS Network
NASA	-	National Aeronautics and Space Administration
NCEP	-	National Centre for Environmental Prediction
NOAA	-	National Oceanic and Atmospheric Administration
ONI	-	Oceanic Nino Index
OSTST	-	Ocean Surface Topography Science Team
PGR	-	Postglacial Rebound
PO.DAAC	-	Physical Oceanography Distributed Active Archive Center
PPP	-	Precise Point Positioning
PPS	-	Precise Positioning Service
PRARE	-	Precise Range and Range-Rate Equipment
PRN	-	Pseudo Random Noise
PS	-	Persistent Scatterer
PS InSAR	-	Persistent Scatterer Interferometric Synthetic Aperture Radar
PSMSL	-	Permanent Service for Mean Sea Level
PZH	-	Phase Zero Header
PZO	-	Phase Zero Observation
QIF	-	Quasi Ionosphere Free
QWG	-	Quality Working Group
Radar	-	Radio detection and ranging
RADS	-	Radar Altimeter Database System
RINEX	-	Receiver Independent Exchange
RMS	-	Root mean square
SAR	-	Synthetic Aperture Radar
SCR	-	Signal to Clutter ration
SEASAT	-	Sea Satellite
SIO	-	Scripps Institution of Oceanography
SLA	-	Sea Level Anomaly
SLC	-	Single Look Complex

SLIS	-	Sea Level Information System
SLP	-	Sea Level Pressure
SLR	-	Satellite Laser Ranging
SPS	-	Standard Positioning Service
SRES	-	Special Report on Emission Scenarios
SRTM	-	Shuttle Radar Topography Mission
SSB	-	Sea State Bias
SSH	-	Sea Surface Heights
SST	-	Sea Surface Temperature
StaMPS	-	Stanford Method for Persistent Scatterers
SCLA	-	Spatially Correlated Look Angle
SULA	-	Spatially Uncorrelated Look Angle
SWH	-	Significant Wave Height
TEC	-	Total Electron Content
TOPEX	-	Topography Experiment
UNIX	-	Uniplexed Information and Computing System
USO	-	Ultra Stable Oscillator
UTM	-	Universiti Teknologi Malaysia
VLBI	-	Very Long Baseline Interferometry
VLM	-	Vertical Land Motion
WGS84	-	World Geodetic System 1984
WH	-	Wave Height
WS	-	Wind Speed

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CHAPTER 1

INTRODUCTION

1.1 Research Background

In the recent report by the Intergovernmental Panel on Climate Change (IPCC), sea level rise has been explicitly named as one of the major challenges for human society in the 21st century. A rise of just 20 centimetres could result in the endangerment of more than 300 million people (Parry *et al.,* 2007). Scientific research has produced concrete evidence on sea level trends and the general public has observed, and often suffering from the consequences of coastal flooding, shoreline erosion, and storm damages. In the coming decades, sea level rise will impose a substantial burden on people and societies, especially for a country like Malaysia as it is surrounded by coastlines. Thus, effective mitigation and adaptation measures must be put in place to prevent and compensate for the impacts of sea level rise.

The impact of even a mild rate of sea level rise is disastrous, especially for islands and highly populated coastal regions. In fact, if there is an increment in sea level rate of about 2 mm per year in the 21st century, the economic and social burdens will be severely affected. This is based on the grounds that an increase in sea level significantly increases the impact of storms on low-lying coastal areas (Church *et al.,* 2008). It is a matter of immediate action needed to be taken to quantify the amount and causes of sea level rise so that mitigation activities are able to commence as soon as possible.

In the past, global sea level studies used tide gauges from all over the world to deduce sea level rate. However, for regional studies, quantifying such a threat is not simple as, additional issues related to the actual amount and cause of sea level rise requires an in-depth study. Though the rate of sea level from tide gauge data may be unequivocal, it may be affected by vertical movement due to active tectonic activities in the region. Therefore, a ‘next level’ comprehensive study on sea level change is needed which associates sea level change with regional geodynamics studies by utilising instruments such as tide gauges, satellite altimeter, InSAR and collocated GPS measurements.

This study presents an effort to quantify and interpret sea level rate in the region of Malaysia within a period of 19 years, beginning from 1993 to 2011 using multi-mission satellite altimeter, tide gauge, Global Positioning System (GPS) and Persistent Scatterer Interferometric Synthetic Aperture Radar (PS InSAR) techniques. This quantification and interpretation of sea level covers all sea level and vertical land motion information. For acquiring information on sea level, tide gauges and satellite altimeter are used to retrieve the relative and absolute sea level rate, respectively. Meanwhile, GPS and PS InSAR techniques are used to quantify the rate of vertical land displacement.

This study is the first systematic investigation on the sea level phenomena by combination of sea level and vertical land motion information for the Malaysian region, based on relatively long (~19 years) oceanographic and geodetic analysis. These results are expected to be valuable for a wide variety of climate applications and to study environmental issues related to flood and global warming in Malaysia.

1.2 Problem Statement

The Southeast Asian region is characterised by its unique geographical and geophysical settings. It shares continental and archipelago parts. The archipelago consists of thousands of islands. The entire area is located in the boundaries between two continents, Asia and Australia, and between two major oceans, the Pacific and Indian Oceans. Most of Southeast Asian countries are bordered by the sea and a large population inhabits low lands in coastal areas including Malaysia. Geographically, Malaysia is surrounded by water: the South China Sea, the Malacca Strait, the Sulu Sea and the Celebes Sea.

Due to the aforementioned facts, better knowledge on sea level behavior in this region is important. Currently, sea level rise and the threats related to it are receiving great attention across the globe. According to AVISO’s Sea Level Research Team, it is confirmed that since January 1993 to February 2012, the Global Mean Sea Level (GMSL) has increased to a rate of 3.11 ± 0.6 mm/yr (AVISO, 2013). Therefore, an understanding of past and future changes in sea level and related ocean dynamics are important, especially for coastal management.

For the past centuries, coastal tide gauges have been the main technique to measure sea level change. However, there are gaps in monitoring sea level changes using tide gauge data for the Malaysia region. The gaps are due to these two following issues:

i. Uneven geographical distributions of tide gauge stations installed at coastal areas and there are no long term tide records for the deep ocean (Azhari, 2003; Ami Hassan, 2010; PSMSL, 2014).

ii. As the tide gauges are attached to land, vertical land motion will be induced in the tide gauge records. The estimated sea level rate at any tide gauge is only able to produce relative sea level (Douglas, 2001; Church *et al.*, 2008).

An alternative method in order to overcome those problems is to measure the absolute sea level from space, i.e., satellite altimeter technique, as a complementary tool to the tide gauge. Satellite altimeter then provides good potential as a complementary tool to the traditional coastal tide gauge instruments for monitoring sea level change of Malaysian seas, especially for the deep ocean.

However, altimetry data contains geophysical effects such as undulation of geoid, tidal height variation, sea state bias and ocean surface response to atmospheric pressure loading. These geophysical effects must be modelled and removed from the sea surface height in order to derive the absolute sea level. In this study, the Radar Altimeter Database System (RADS), developed by the Technical University of Delft, is used for altimeter data processing (Naeije *et al.*, 2000). To obtain the best absolute sea level results for the Malaysian region, refinements in data processing parameters and algorithm have to be taken into account since most of the suggested corrections or models in RADS are for the global case.

Recently, much issues discussed are related to the cause of sea level rise; yet it must be understood that the cause may only be determined with accurate data. As mentioned, the rate of sea level from tide gauge data is influenced by vertical land movement due to active tectonic activities in the region (Church *et al.*, 2010; Din *et al.*, 2012). In this case, the impact of crustal motion has to be removed to obtain true or absolute measurements of sea level rate. This can be achieved by removing the estimated vertical land motion derived from Global Positioning System (GPS) records. This also reduces (though not completely removed) the impact of local and non-oceanographic processes in a regional analysis of tide gauge records.

Despite the tremendous advances in GPS measurements during the last decade, a major limitation of this technique is the lack of deformation data in many areas since GPS observations are station-dependent providing only point-wise data. Currently, in Malaysia, the only GNSS Continuously Operating Reference Stations (CORS) is the Malaysia Real Time Kinematic GNSS Network (MyRTKnet) which consists of 78 stations, with a spacing of between 30 to 100 km between one another in Peninsular Malaysia, and 30 to 200 km in Sabah and Sarawak (Mohamed, 2009).

In recent years, Interferometic Synthetic Aperture Radar (InSAR) has proven a very effective technique for measuring vertical crustal deformation for large areas. InSAR is a satellite-based remote sensing technique that is able to measure centimetre-level ground surface deformation over a 100 km^2 area (scene). As a result, a combination of GPS and InSAR techniques is an effective way to measure vertical changes of the land surface. The study by Watson *et al.* (2002) demonstrated the method of which GPS and satellite-based InSAR can be used to complement each other. Both InSAR and GPS show the same annual trends, but InSAR was able to spatially fill in the gaps.

A relatively recent analysis technique called the Persistent Scatterer (PS) InSAR is an extension to the conventional InSAR techniques, which addresses and overcomes the major limitations of repeat pass SAR interferometry: temporal and geometrical decorrelation, and variations in atmospheric conditions. In this study, a new persistent scatterer analysis method is used to compute the velocity of the vertical land deformation. The software used for identifying the PS points is known as Stanford Method for Persistent Scatterers (StaMPS). StaMPS is able to identify and extract deformation signals even in the absence of bright scatterers. StaMPS is also applicable in areas undergoing non-steady deformation, with no prior knowledge of the variations in deformation rate (Hooper, 2006).

Therefore, this research performs a comprehensive study on sea level interpretation in the region of Malaysia, by associating oceanographic and geodetic analysis, and including multi-sensor technology: tide gauges, satellite altimeter, PS InSAR and collocated GPS measurements. The byproduct of this research: a Sea Level Information System (SLIS) for Malaysian seas is developed. The system comprises of real-time data analysis of sea level and vertical land motion for the Malaysian region. Besides acting as a data archive and analysis platform for sea level and vertical land motion information, this system also facilitates users to analyse, manipulate and interpret the data for their own interest.

1.3 Research Objectives

The aim of this study is to interpret the precise sea level trend for the Malaysian region using a combination of multi-sensor technology: tide gauges, satellite altimeter, Global Positioning System (GPS) and Persistent Scatterers Interferometric Synthetic Aperture Radar (PS InSAR) techniques. In pursuit of the aim of this research, this study specifically addresses several objectives as follows:

1) To develop a method for deriving sea level anomaly from multi-satellite altimetry data using Radar Altimeter Database System (RADS) for Malaysian seas.

2) To determine the magnitude of vertical land motion using GPS and PS InSAR techniques to support sea level rise interpretation for the Malaysian region

3) To quantify and interpret the sea level rate within a 19-year period, beginning 1993 to 2011, for the region of Malaysia based on sea level and vertical land motion measurements.

1.4 Research Scope

This research intends to establish a complete methodology for quantifying and interpreting the sea level rate within a 19-year period, from 1993 to 2011, for the region of Malaysia based on sea level and vertical land motion measurements. Since the lunar nutation effect is able to be corrected by applying at least 18.6 years of data, thus a 19-year period of time series has been employed in this study in order to discover the actual rate of sea level rise in this region (Trisirisatayawong *et al.*, 2011; Din *et al.*, 2012). The research involves the following research scope:

1) Study area

The study area covered in this research is shown in Figure 1.1, it ranges between 0° N ≤ Latitude ≥ 12°N and 95° E ≤ Longitude ≥ 125°E, encompassing the entire Malaysian region. Satellite altimeter and tide gauge analysis are focused on Malaysian seas, which consists of the South China Sea, Malacca Straits, the Sulu Sea and the Celebes Sea. Meanwhile, GPS and PS InSAR analysis are concentrated on land areas, especially at tide gauges and GPS stations around Malaysia.

Figure 1.1 Study area

2) Satellite Altimeter Missions Data

Six satellite altimeter missions are used in this study: TOPEX, Jason-1, Jason-2, ERS-1, ERS-2 and EnviSat. The period of the altimetry data covers from January 1993 to December 2011 (~ 19 years). Detailed descriptions on the data are as follows:

a) TOPEX altimetry data (NASA/CNES Agency) are analysed for the Malaysian seas from January 1993 to July 2002 (cycle 11 – cycle 363).
b) Jason-1 altimetry data (NASA/CNES Agency) are analysed for the Malaysian seas from August 2002 to December 2011 (cycle 21- cycle 368).
c) Jason-2 altimetry data (NASA/CNES Agency) are analysed for the Malaysian seas from July 2008 to December 2011 (cycle 01- cycle 128).

d) ERS-1 altimetry data (ESA Agency) are analysed for the Malaysian seas from January 1993 to April 1995 (cycle 91 – cycle 156).
e) ERS-2 altimetry data (ESA Agency) are analysed for the Malaysian seas from May 1995 to September 2002 (cycle 1 – cycle 78).
f) EnviSat altimetry data (ESA Agency) are analysed for the Malaysian seas from October 2002 to December 2011 (cycle 10 – cycle 110).

The time period of the altimeter missions used in this study are almost different from one another due to the limited life time of altimeter missions. Hence, in order to continue retrieving the sea level data for a period of 19 years, six satellite altimeters from the different missions have been employed.

3) Tide Gauges Data

Monthly tide gauge data is taken from the Permanent Service for Mean Sea Level (PSMSL) website. The tide gauge data covers from 1993 until 2011, over 19 years of data span. The Malaysian coastal tide gauge stations used in this study is listed in Table 1.1.

4) GPS Data

9 Malaysian Active GPS System (MASS) stations (1999 to 2003) and 78 Malaysia Real Time Kinematic GNSS Network (MyRTKnet) stations (2004 to 2011) are used in this study. The GPS data is collected from the Department of Survey and Mapping Malaysia (DSMM). Additionally, 30 stations of GPS data from International GNSS Service (IGS) are downloaded from the IGS FTP (ftp://igscb.jpl.nasa.gov/network/netindex.html).

5) PS InSAR Data

SAR data from ERS-2 and EnviSat satellite missions are used in this research. There are 7 locations selected for PS InSAR analysis: Kota Bharu (Kelantan), Kuala Terengganu (Terengganu), Johor Bahru (Johor), Klang (Selangor), Sungai Petani (Kedah), Kuching (Sarawak) and Kota Kinabalu (Sabah). The total SAR satellite images processed in this study are 111 images, where 93 images are from ERS-2 and 18 images are from EnviSat.

Table 1.1: List of tide gauge stations and locations used in this study (PSMSL, 2014)

Number	Tide Gauge	Latitude	Longitude
1	Geting	6° 13’ 35”	102° 06’ 24”
2	Cendering	5° 15’ 54”	103° 11’ 12”
3	Tanjung Gelang	3° 58’ 30”	103° 25’ 48”
4	Pulau Tioman	2° 48’ 26”	104° 08’ 24”
5	Port Klang	3° 03’ 00”	101° 21’ 30”
6	Pulau Pinang	5° 25’ 18”	100° 20’ 48”
7	Lumut	4° 14’ 24”	100° 36’ 48”
8	Johor Bahru	1° 27’ 42”	103° 47’ 30”
9	Kukup	1° 19’ 31”	103° 26’ 34”
10	Pulau Langkawi	6° 25’ 51”	99° 45’ 51”
11	Tanjung Sedili	1° 55’ 54”	104° 06’ 54”
12	Tanjung Keling	2° 12’ 54”	102° 09’ 12”
13	Bintulu	3° 15’ 44”	113° 03’ 50”
14	Kudat	6° 52’ 46”	116° 50’ 37”
15	Kota Kinabalu	5° 59’ 00”	116° 04’ 00”
16	Sandakan	5° 48’ 36”	118° 04’ 02”
17	Tawau	4° 14’ 00”	117° 53’ 00”
18	Labuan	5° 16’ 22”	115° 15’ 00”
19	Lahat Datu	5° 01’ 08”	118° 20’ 46”
20	Miri	4° 32’ 00”	113° 58’ 00”
21	Sejingkat	1° 34’ 58”	110° 25’ 20”

6) Software

a) Radar Altimeter Database System (RADS).

Multi-mission satellite altimetry data are processed using RADS. The final output of altimetry processing is absolute sea level anomaly data with respect to DTU10 Mean Sea Surface (MSS) in daily and monthly solutions.

b) Bernese high precision GNSS processing software version 5.0.

GPS data are processed with Bernese version 5.0 using double-difference QIF strategy in daily, weekly and monthly solutions.

c) Delft Object-oriented Radar Interferometric Software (DORIS) Software.

DORIS software is used to carry out interferometric processing for interferogram formation.

d) Stanford Method for Persistent Scatterer (StaMPS) Software.
   Persistent scatterer points are identified using PS InSAR processing in StaMPS.
e) MATLAB Software
   MATLAB is used for analysing sea level and vertical land motion data. Besides, this software is also used to develop a system called Sea Level Information System (SLIS) for the Malaysian seas.

7) Data interpretation and analysis
   As for data analysis, it is to quantify and interpret the precise sea level rate within a 19-year period, from 1993 to 2011, in the region of Malaysia based on sea level and vertical land motion information. The scope of analyses is limited to:

a) Quantify and interpret a long time series of relative sea level rate using tidal data.
b) Quantify and interpret a long time series of absolute sea level rate using altimetry data.
c) Quantify and interpret the rate of vertical land motion derived from satellite altimeter and tide gauge via “altimeter minus tide gauge”.
d) Quantify and interpret the rate of vertical land motion using GPS at MASS and MyRTKnet stations.
e) Quantify and interpret the rate of vertical land motion using PS InSAR at selected areas.
f) Compare the rate of vertical land motion between ‘altimeter minus tide gauge’, GPS and PS InSAR techniques.
g) Quantify and interpret the regional sea level rate over the Malaysian seas from multi-satellite altimetry and vertical land motion corrected for tidal data.

1.5 Contribution of the Research

The contribution of this research is summarised as follows:

1) This study aims to highlight the importance of precise sea level information for Malaysia’s development, security and coastal management. From sea level information, government authorities are able to take effective mitigation and adaptation measures to prevent and compensate for sea-related or sea level impacts.

2) The initial step is to interpret and quantify the regional rate of sea level changes using a combination of multi-sensor technology: tide gauges, satellite altimeter, GPS and PS InSAR. This is also the first systematic investigation of sea level phenomena for the Malaysia region based on relatively long (~19 years) oceanographic and geodetic analysis. These results are expected to be valuable for a wide variety of climate applications, as well as to study environmental issues related to flood and global warming in Malaysia.

3) This study intends to demonstrate the potential of multi-mission satellite altimeter in deriving sea level data and to understand sea level trends over the Malaysian seas. This technology will evidently be a complementary tool to the traditional coastal tide gauge measurement in monitoring sea level change, especially in the deep ocean.

4) This research initiates the assessment to adopt the latest InSAR Persistent Scatterer (PS) algorithms in environmental, climatic and topographic conditions of the tropical area. Thus, it opens a gateway for the practice of PS InSAR technique in the Malaysian region.

1.6 Research Methodology

The general methodology of this study is divided into five (5) phases as illustrated in Figure 1.2.

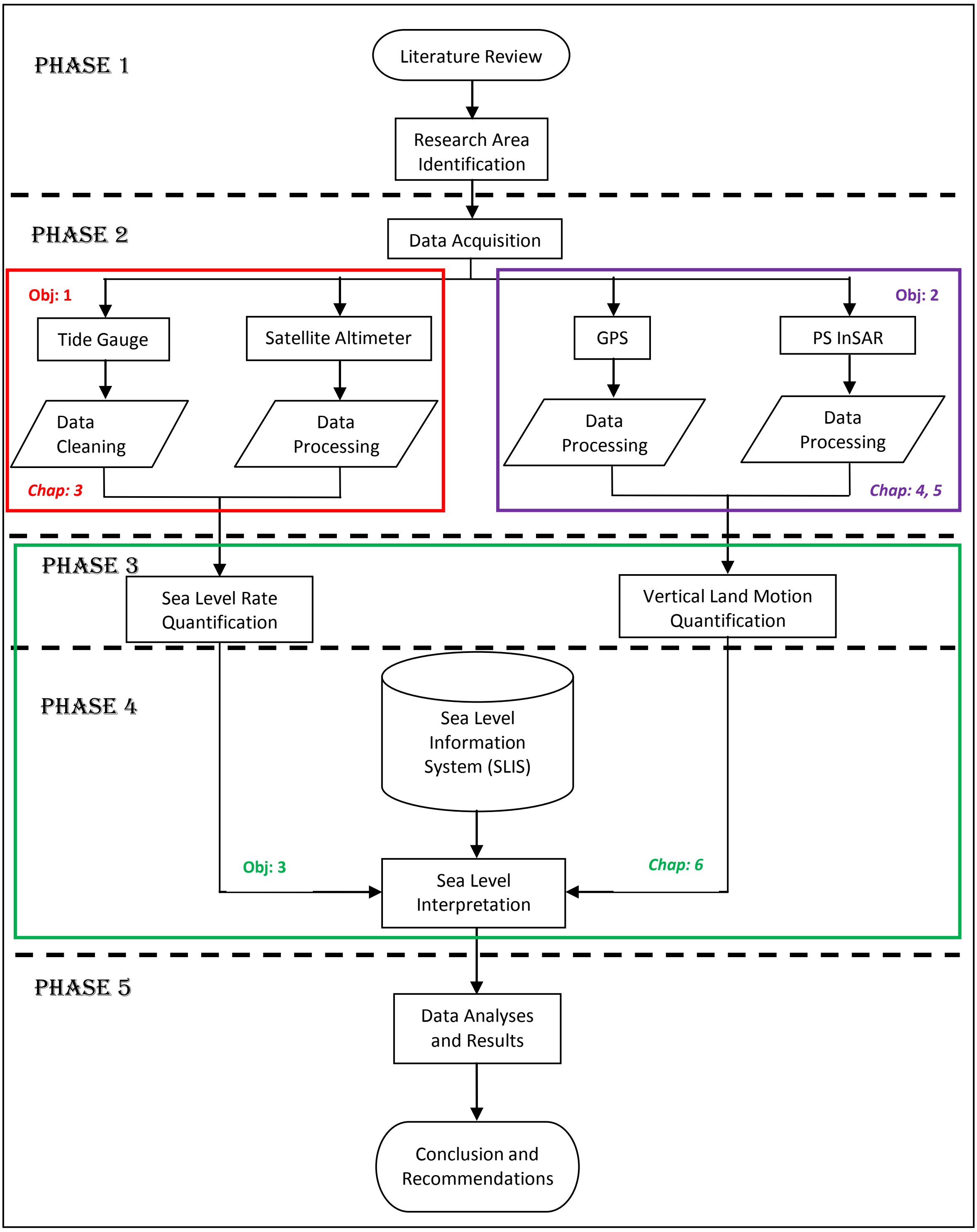

Figure 1.2 Overview of the research methodology

PHASE 1

Literature Review

This stage concentrates on reviewing essential topics such as:

i. Theory of sea level, vertical land motion, tides, satellite image and coordinate systems
ii. Principle of satellite altimeter, GPS, Persistent Scatterer InSAR and tide gauge
iii. Altimeter Processing Software: Radar Altimeter Database Software (RADS)
iv. High Precision GPS Processing software : Bernese version 5.0
v. PS InSAR Processing software: Delft Object-oriented Radar Interferometric Software (DORIS) and Stanford Method for Persistent Scatterers (StaMPS)
vi. MATLAB programming language
vii. Linux shell script, and
viii. Ubuntu operating system

Research Area Identification

The area of study covers the Malaysian region as shown in Figure 1.1.

PHASE 2

Data Acquisition and Processing

There are four techniques used to gather the data as follows:

1) *Tide Gauge*

There are 21 tide gauge stations involved in this research. List of tide gauges used is given in Table 1.1. This type of data does not require any complex processing unlike altimeter, GPS and PS InSAR techniques. Tidal data only requires cleaning any outlier or bad data before using them to perform analysis. Data cleaning is executed in Microsoft Excel and/ or Textpad.

2) *Satellite Altimeter*

In this study, Radar Altimeter Database System (RADS) is used for satellite altimeter mission data retrieval and processing, i.e., TOPEX, Jason-1, Jason-2, ERS-1, ERS-2 and EnviSat. The important data derived from altimeter processing is absolute sea level anomaly.The details regarding the processing methodology and enhancement of RADS are discussed in Chapter 3.

3) *Global Positioning System (GPS)*

For high precision GPS data processing, Bernese version 5.0 software is used. The details regarding the processing flow are discussed in Chapter 4. The GPS data are gathered from 9 MASS stations (1999 to 2003), 78 MyRTKnet stations (2004 to 2011) and 30 stations IGS stations (1999 to 2011).

4) *Persistent Scatterer Interferometric Synthetic Aperture Radar (PS InSAR)*

The SAR images are requested from European Space Agency (ESA) through EOLI-SA (as shown in Figure 1.3). Due to the declaration of SAR data as restrained dataset under ESA, a proper proposal has to be submitted for SAR data application (https://earth.esa.int/web/guest/data-access). Appendix A shows the list of ERS and EnviSat SAR data that is requested from ESA. The details on PS InSAR processing are further discussed in Chapter 5.

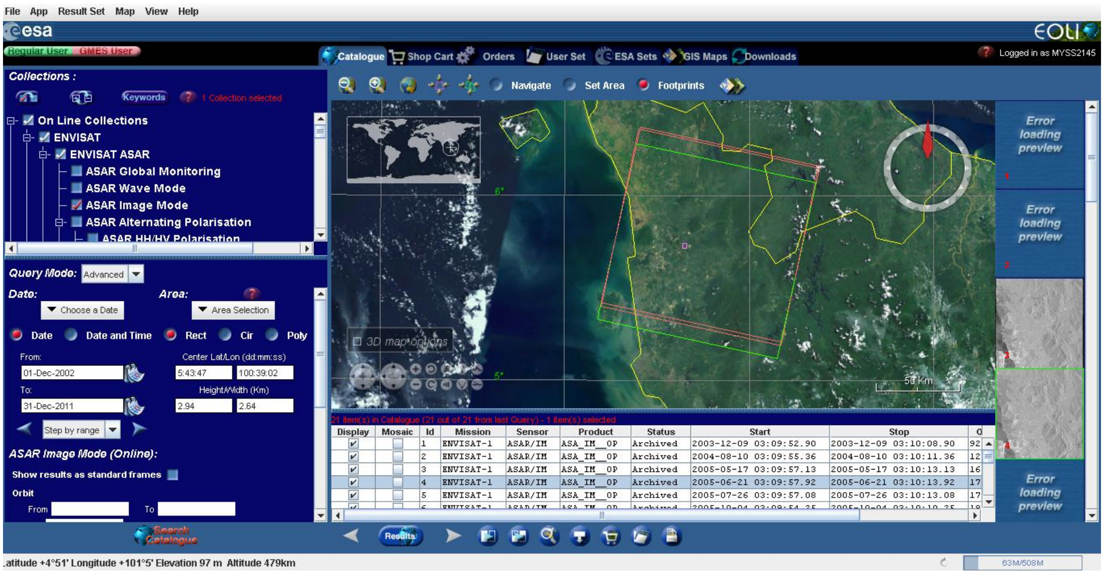

Figure 1.3 EOLI-SA interface for requesting SAR data

PHASE 3

Sea Level Rate Quantification

Altimetry data which is derived from RADS needs to be verified before performing analyses. In this study, sea level anomaly data is compared with ground-truth data, i.e., tidal data. The verification is focused on the sea level pattern and the correlation of the data comparison. The time series of the sea level trend for the Malaysian seas is quantified using robust fit regression analysis. Robust fit analysis is a standard statistical technique that simultaneously deals with solution determination and outlier detection. In this robust fit approach, a linear trend is fitted to the annual sea level time series of each station in an iteratively re-weighted least squares (IRLS) procedure (Holland and Welsch, 1977; Trisirisatayawong *et al.,* 2011).

Vertical Land Motion Quantification

In this study, vertical land motion of the Malaysian region was quantified based on GPS and PS InSAR techniques. The rate of vertical land motion is also computed using robust fit approach. For PS InSAR processing verification, the rate of vertical land changes was verified with the GPS results from MASS and MyRTKnet stations.

PHASE 4

Sea Level Interpretation

This stage will quantify and interpret the sea level rate within a 19-year period, from 1993 to 2011, for the region of Malaysia based on ocean and land information. The method of interpretation and quantification is as follows:

i. Relative sea level variation using tidal data
ii. Relative sea level rate using tidal data
iii. Absolute sea level variation using multi-mission satellite altimetry
iv. Absolute sea level rate using multi-mission satellite altimetry
v. Comparison of trend rates between tidal and altimetry data at coastal tide gauge stations
vi. Absolute sea level trend mapping over the Malaysian seas

vii. Vertical land motion rate from the difference of rates between the estimated altimetry and tidal data
viii. GPS-derived vertical land motion rate
ix. PS InSAR-derived vertical land motion rate
x. Comparison of vertical land motion rates from GPS and PS InSAR
xi. Vertical land motion rate comparison between "altimeter minus tide gauge", GPS and PS InSAR techniques
xii. Regional sea level rates over the Malaysian seas from multi-satellite altimetry and vertical land motion corrected tidal data

Sea Level Information System (SLIS)

Sea Level Information System (SLIS) for the Malaysian seas was developed in this study as a byproduct of the research. The system comprises of real-time data analysis of sea level and vertical land motion for the Malaysian region which are derived from tide gauges, satellite altimeter, GPS and PS InSAR data. Besides acting as data archive and analysis platform for sea level and vertical land motion information, this system will also provide opportunity to users to analyse, manipulate and interpret the data. The Graphical User Interface Development Environment (GUIDE) function in the MATLAB programming software is employed to develop the interface for manipulating the data. The capabilities of SLIS have been summarised in Appendix B.

PHASE 5

Data Analyses and Results

The analyses are focused on analysing and discussing sea level and vertical land motion rate, pattern and trend in the region of Malaysia.

Conclusion and Recommendation

The conclusions are based on the objectives and results of the study. Then, suggestions and recommendations for future studies are also provided.

1.6 Outline of the Thesis

The thesis focuses on the estimation and interpretation of sea level rise in the Malaysian region using tide gauges, satellite altimeter, Global Positioning System (GPS) and Persistent Scatterers Interferometric Synthetic Aperture Radar (PS InSAR) techniques. The structure of the thesis is divided into seven chapters as follows:

Chapter 1 introduces the research topic, and outlines the research aim and objectives. A general research methodology for this study is also discussed in this chapter.

Chapter 2 reviews the sea level changes associated with climate change and discussions on the scientific evidence of Holocene sea level rise: present and future projections globally and locally. At the end, a new approach to estimate sea level rise by combining sea level and vertical land motion information from multi-sensor technology is discussed in this chapter.

Chapter 3 describes how to derive sea level data from multi-mission satellite altimeter using Radar Altimeter Database System (RADS). Here, details on the RADS processing methodology particularly for the Malaysian seas are described extensively. Furthermore, this chapter discusses the derivation of tide gauge data for the determination of sea level anomaly and as verification for altimeter data. Besides, the robust fit regression analysis for computing the trend of sea level and vertical land motion is demonstrated in this chapter. Subsequently, a comparison of near-simultaneous altimeter and tide gauges data is assessed to verify the altimeter data processed from RADS.

Chapter 4 discusses on how to quantify the rate of vertical land motion from GPS measurements. The Bernese GNSS processing software framework and processing strategy employed in this study to achieve the high accuracy requirements of vertical land motion monitoring are described in detailss.

Chapter 5 describes the alternative technique that is applied to quantify the vertical land motion by using Persistent Scatterer (PS) InSAR. This chapter discusses the Stanford Method for Persistent Scatterer (StaMPS) framework as well as the Persistent Scatterer InSAR processing chain and parameter settings specifically suited for tropical regions such as Malaysia. The rate of vertical land motion derived in this chapter and the previous chapters are used to support sea level rise interpretation for the Malaysian region.

Chapter 6 discusses the final results and interpretation of sea level and vertical land motion trend over the Malaysian region based on various approaches. However, the primary focus of Chapter 6 is to provide the precise regional sea level trend over the Malaysian seas, based on multi-mission satellite altimetry and vertical land motion corrected tidal data.

Chapter 7 summarises the major findings and conclusions of this study, as well as provide suggestions and recommendations for future work.

adjustment algorithm, the estimation of nonlinear vertical land motion from "altimeter minus tide gauge" will yield a great improvement (Kuo *et al.*, 2007).

c) Conduct a study on sea level rise projection.

   The present study only focuses on the derivation of regional sea level trend from multi-sensor techniques. It is better if the regional sea level rate derived in this study can be extended to look into sea level rise projections for this region, particularly at flood prone areas, by including the vertical land motion effects as well. A solid and convincing result for the projections of sea level rise along Malaysian coasts is vital as it will become an important reference for the Malaysian coastal development in future.

d) Process additional SAR images

   Add more SAR images (more than 30 images in the same study area) in PS InSAR processing using StaMPS software in order to better remove phase unwrapping errors and also to obtain better results, particularly at rural and vegetated areas.

REFERENCES

Abdul-Hadi, A., Mansor, S., Pradhan, B. and Tan, C. K. (2012). *Seasonal Variability of Chlorophyll-a and Oceanographic Conditions in Sabah Waters in Relation to Asian Monsoon - A Remote Sensing Study*. Environ. Monit. Assess. DOI 10.1007/s10661-012-2843-2.

Agnieray, P. (1997). *The DORIS System Performances and Evolutions. Co-ordination of Space Techniques for Geodesy and Geodynamics*. Bulletin No. 14, In "Advanced Space Technology in Geodesy-Achievements and Outlook," (Rummel, R., Reigber, C. and Hornik, H. Eds.), pp. 73-80, Deutsches Geod/itisches Forschungsinstitut, Munich.

Agram, P. S. (2010). *Persistent Scatterer Interferometry in Natural Train.* Doctor Philosophy, Stanford University, California.

Akdag, C. (1996). *Tidal Analysis of the South China Sea*. Technical Report; Delft Hydraulics. Group of Fluid Mechanics, Faculty of Civil Engineering, Delft University of Technology.

Altamimi, Z., Angermann, D., Argus, D., Blewitt, G., Boucher, C., Chao, B., Drewes, H., Eanes, R., Feissel, M., Ferland, R., Herring, T., Holt, B., Johannson, J., Larson, K., Ma, C., Manning, J., Meertens, C., Nothnagel, A., Pavlis, E., Petit, G., Ray, J., Ries, J., Scherneck, H. G., Sillard, P. and Watkins, M. (2001). *The Terrestrial Reference Frame and the Dynamic Earth*, EOS, Transactions, Am. Geophys.U., Vol. 82(25), p. 273-279.

Altamimi, Z., Collilieux, X. and Métivier, L. (2012). *Analysis and Result of ITRF2008*. Journal of Geodesy. IERS Technical Note 37.

Aly, M. H. (2006). *Radar Interferometry for Monitoring Land Subsidence and Coastal Change in the Nile Delta, Egypt*. Doctor Philosophy, Texas A&M University, United States.

Ami Hassan Md Din (2010). *Sea Level Rise Estimation using Satellite Altimetry Technique*. MSc Thesis, Universiti Teknologi Malaysia, Skudai.

Andersen, O. B. (1995). *Global Ocean Tides from ERS-1 and TOPEX/Poseidon Altimetry*. J Geophys Res 100(C12):25,249-25,260.

Andersen, O. B. and Knudsen, P. (2010). *The DTU10 Mean Sea Surface and Mean Dynamic Topography – Improvements in the Arctic and Coastal Zone*. Ocean Surface Topography Science Team Meeting, Lisbon, Portugal.

Andersen, O. B. and Scharroo, R. (2011). *Range and Geophysical Corrections in Coastal Regions: And Implications for Mean Sea Surface Determination*. In Coastal Altimetry. Springer. doi:10.1007/978-3-642-12796-0.

Aobpaet, A, Caro Cuenca, M, Hooper, A. J. and Trisirisatayawong, I. (2009). *Land Subsidence Evaluation using Insar Time Series Analysis in Bangkok Metropolitan Area*. In M Engdahl (Ed.), *Proceedings of FRINGE09* (pp. 1-10). Frascati: ESA.

Arikan, M., Hooper, A. and Hanssen, R. (2010). *Radar Time Series Analysis over West Anatolia*. European Space Agency (Special Publication) ESA SP-677, 2010

AVISO (2013). *AVISO Satellite Altimetry Data.* Retrieved July 25, 2013, from http://www.aviso.oceanobs.com/

Azhari Mohamed (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.

Baek, S. (2006). *DEM Generation and Ocean Tide Modeling over Sulzberger Ice Shelf, West Antartica, using Synthetic Aperture Radar Interferometry*. Doctor Philosophy, The Ohio State University, Columbus.

Baker, T. F., Curtis, D. J. and Dobson, A. H. (1995). *Ocean Tide Loading and GPS*. GPS World 6 (3), 54-59.

Bamler, R. and Schattler, B. (1993). *SAR Data Acquisition and Image Formation*, in:Schreier, G., ed., SAR Geocoding: Data and Systems, pp. 53–102, Wichmann Verlag, Karlsruhe.

Barth, M. C. and Titus, J. G. (eds) (1984). *Greenhouse Effect and Sea Level Rise: A Challenge for this Generation*. Van Nostrand Reinhold, New York .

Bernese (2012). *Bernese Features*. Retrieved December 10, 2012 from http://www.bernese.unibe.ch/features.html

Bertiger, W. I., Bar-Server, Y. E. and Christensen, E. J. (1994). *GPS Precise Tracking of TOPEX/POSEIDON: Results and Implications*. J. Geophys. Res., 99, 24449-24464.

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.

Beutler, G., Moore, A. W. and Mueller, I. I. (2008). *The International Global Navigation Satellite Systems (GNSS) Service: Developments and Achievements.* J. Geodesy 83:297–307.

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

Bilitza, D. and Reinisch, B. W. (2008). *International Reference Ionosphere 2007: Improvements and New Parameters.* Adv Space Res 42(4):599–609. doi:10.1016/j.asr.2007.07.048

Bindoff, N., Willebrand, J., Artale, V., Cazenave, A., Gregory, J. M., Gulev, S., Hanawa, K., Le Quéré, C., Levitus, S., Nojiri, Y., Shum, C. K., Talley, L. D. and Unnikrishnan, A. (2007). *Observations: ocean climate change and sea level. In: Climate Chage 2007: The Physical Science Basis*. Contribution of Working Group 1 to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (Solomon, S., Qin, D., Manning, M., Marquis, M., Averyt, K., Tignor M. M. B. and Miller, H. L. (eds), pp. 385 – 432. Cambridge University Press , Cambridge.

Bingley, R. (2004). *GNSS Principles and Observables*. Nottingham, IESSG, University of Nottingham UK, M.Sc. Lecture Monograph.

Bock, Y. (1996). *Reference System*. In: Teunissen, P. J. G. and Kleusberg, A. (Eds.), GPS for Geodesy, Springer.

Bordi, J. J., Ries, J. C. and Tapley, B. D. (2000). *Precise Orbits for the ERS-2 Altimeter Satellite*. J. Astron. Sci., in press.

Boucher, C., Altamimi, Z., Feissel, M. and Sillard, P. (1996). *Results and Analysis of the ITRF94*, IERS Tech. Note 20, Obs. de Paris.

Boucher, C., Altamimi, Z. and Sillard, P. (1999). *The 1997 International Terrestrial Reference Frame (ITRF97)*. IERS Technical Note 27, Observatoire de Paris.

Brown, G. S. (1977). *The Average Impulse Response of a Rough Surface and its Applications*. IEEE Trans Antennas Propag AP-25(1):67–74.

Buble, G. (2012). *Microplate Kinematics, Intraplate Deformation and Sea Level Rise in Europe*. Doctor Philosophy, the University of Arizona, Tucson, United States.

Carrére, L. and Lyard, F. (2003). *Modeling the Barotropic Response of the Global Ocean to Atmospheric Wind and Pressure Forcing, Comparisons with Observations.* Geophysical Research Letter 30 (6), 1275 doi:10.1029/2002GL016473.

Cazenave, A., Dominh, K., Ponchaut, F., Soudarin, L., Cretaux, J. F. and Le Provost, C. (1999). *Sea Level Changes from Topex-Poseidon Altimetry and Tide Gauges, and Vertical Crustal Motions from DORIS*. Geophys. Res. Lett., 26, 2077-2080.

Chambers, D. P., Hayes, S. A., Ries, J. C. and Urban, T. J. (2003). *New TOPEX Sea State Bias Models and Their Effect on Global Mean Sea Level*. J. Geophys. Res., Vol. 108(C10), 3305-11.

Chelton, D. B. (1994). *The Sea State Bias in Altimeter Estimates of Sea Level From Collinear Analysis of TOPEX Data*. J Geophys Res 99(C12):24,995–25,008.

Chelton, D., Ries, J. C., Haines, B. J., Fu L. L. and Callahan, P. S. (2001). *Altimetry. In Satellite Altimetry and Earth Sciences* (Fu, L. L. and Cazenave A., eds). Academic Press , New York .

Church, J. A., Gregory, J. M., Huybrechts, P., Kuhn, M., Lambeck, K., Nhuan, M. T., Qin, D. and Woodworth, P. L. (2001). *Changes in sea level*. Pp. 639–694 in Climate Change 2001: The Scientific Basis. Contribution of Working Group 1 to the Third Assessment Report of the Intergovernmental Panel on Climate Change. Houghton, J. T., Ding, Y., Griggs, D. J., Noguer, M., van der Linden, P., Dai, X., Maskell, K. and Johnson, C. I. (eds.). Cambridge University Press, Cambridge, UK.

Church, J. A., White, N. J., Aarup, T., Wilson, S. T., Woodworth, P. L., Domingues, C. M., Hunter, J. R. and Lambeck, K. (2008). *Understanding Global Sea Levels: Past, Present and Future.* Integrated Research System for Sustainability Science and Springer. Sustain Sci., DOI 10.1007/s11625-008-0042-4.

Church, J. A., Woodworth, P. L., Aarup, T. and Wilson, W. S. (2010). *Understanding Sea Level Rise and Variability*. West Sussex, PO19 8SQ, UK: Blackwell Publishing Ltd.

Colesanti, C., Ferretti, A., Locatelli, R. and Savio, G. (2003). *Multi-platform Permanent Scatterers Analysis: First Results*. In: Second GRSS/ISPRS Joint Workshop on “Data Fusion and Remote Sensing over Urban Areas", Berlin, Germany, 22-23 May, 2003. pp. 52-56.

Cuenca, M. C. and Hanssen, R. F. (2008). *Subsidence and Uplift at Wassenberg, Germany due to Coal Mining using Persistent Scatterer Interferometry*. In: 13th FIG International Symposium on Deformation Measurements and Analysis, Lisbon, Portugal, 12 - 15 May, 2008. Lisbon, Portugal, pp. 1- 9.

Cumming, I. and Wong, F. (2005). *Digital Processing of Synthetic Aperture Radar Data: Algorithms and Implementation*. Artech House Publishers, New York.

Dach, R., Hugentobler, U., Fridez, P. and Meindl, M. (2007). *Bernese GPS Software Version 5.0*. Astronomical Institute, University of Bern, http://www.bernese.unibe.ch/docs/DOCU50.pdf.

Dach, R., Bock, H., Jäggi, A., Lutz, S., Meindl, M., Ostini, L., Prange, L., Schaer, S., Steinbach, A., Thaller, D., Walser, P. and Beutler, G. (2008). *Bernese GPS Software: Recent Developments and Plans*. EUREF–LAC–Workshop; Frankfurt; 22/23 October 2008.

Dancey, C. and Reidy, J. (2004). *Statistics without Maths for Psychology: using SPSS for Windows*. London: Prentice Hall.

Dasgupta, S., Laplante, B., Meisner, C., Wheeler, D. and Yan, J. (2007). *The impact of Sea Level Rise on Developing Countries; a Comparative Analysis.* New World Bank Working Paper.

Davis, J. L., Prescott, W. H., Svarc, J. L. and Wendt, K. J. (2012). *Assessment of Global Positioning System Measurements for Studies of Crustal Deformation*. Journal of Geophysical Research: Solid Earth (1978–2012), Vol 94 Issue B10 pages 13635–13650. DOI: 10.1029/JB094iB10p13635.

Degnan, J. D. (1985). *Satellite Laser Ranging: Current Status and Future Prospects.* IEEE Trans. Geosci. Remote Sens., GE-32, 398-413.

DeMets, C., Gordon, R. G., Argus, D. F. and Stein, S. (1994). *Effect of Recent Revisions to the Geomagnetic Reversal Time Scale on Estimates of Current Plate Motions*. Geophysical Research Letter, 21, 99. 2191 – 2194.

Din, A. H. M., Omar, K. M., Naeije, M. and Ses, S. (2012). *Long-term Sea Level Change in the Malaysian Seas from Multi-mission Altimetry Data*. International Journal of Physical Sciences Vol. 7(10), pp. 1694 - 1712, 2 March, 2012. DOI: 10.5897/IJPS11.1596.

Doornbos, E. and Scharroo, R. (2004). *Improved ERS and Envisat Precise Orbit Determination.* Proceedings of ERS/Envisat SymposiumSaltzburg 2004.

Douglas, B.C. (2001). Sea Level Change in the Era of the Recording Tide Gauges, in Douglas, B. C., Kearney, M. S. and Leatherman, S. P. (eds.) *Sea Level Rise—History and Consequences (*pp. 37–64). San Diego, Academic Press, International Geophysics Series.

DSMM (2012). *Department of Surveying and Mapping Malaysia*. Retrieved June 01, 2012, from http://www.geodesi.jupem.gov.my/

Farina, P., Colombo, D., Fumagalli, A., Marks, F. and Moretti, S. (2006). *Permanent Scatterers for Landslide Investigations: outcomes from the ESA-SLAM project*. Eng Geol 88:200–217.

Farr, T. G., Rosen, P. A., Caro, E., Crippen, R., Duren, R., Hensley, S., Kobrick, M., Paller, M., Rodriguez, E., Roth, L., Seal, D., Shaffer, S., Shimada, J., Umland, J., Werner, M., Oskin, M., Burbank, D. and Alsdorf, D. (2007). *The Shuttle Radar Topography Mission*. Rev. Geophys., 45(RG2004).

Ferretti, A., Prati, C. and Rocca, F. (1999). *Multibaseline InSAR DEM Reconstruction: TheWavelet Approach*. IEEE Transactions on Geoscience and Remote Sensing, 37(2 Part 1),705–715.

Ferretti, A., Prati, C. and Rocca, F. (2000). *Nonlinear Subsidence Rate Estimation using Permanent Scatterers in Differential SAR Interferometry*. IEEE Trans. On Geosci. Remote Sensing, 38(5), 2202–2212.

Ferretti, A., Prati, C. and Rocca, F. (2001). *Permanent Scatterers in SAR Interferometry*. IEEE Trans. on Geosci. Remote Sensing, 39(1), 8–20.

Forrest, N. D. (2010). *The Determination of Subtle Deformation Signals Using a Permanent CGPS Network in the Aegean*. Doctor Philosophy, University College London.

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). *Altimetry and Earth Science, A Handbook of Techniques and Applications.* Vol. 69 of International Geophysics Series. Academic Press, London.

Fu, L. L. and Holt, B. (1982). *Seasat View Oceans and Sea Ice with Synthetic Aperture Radar*. Tech. rept. Jet Propulsion Lab.

Gabriel, A. K., Goldstein, R. M. and Zebker, H. A. (1989). *Mapping Small Elevation Changes over Large Areas: Differential Radar Interferometry*. J. Geophys. Res., 94(B7), 9183–9191.

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*. J Geophys Res 99(C12):24981–24994.

Gaspar, P. and Florens, J. P. (1998). *Estimation of the Sea State Bias in Radar Altimeter Measurements of Sea Level: Results from a New Nonparametric Method*. J. Geophys. Res., 103, 15 803–15 814.

Gaspar, P., Labroue, S., Ogor, F., Lafitte, G., Marchal, L. and Rafanel, M. (2002). *Improving Nonparametric Estimates of the Sea State Bias in Radar Altimeter Measurements of Sea Level.* Journal of Atmospheric and Oceanic Technology. Volume 19, pp. 1690 – 1707.

GEBCO (2013). *General Bathymetric Chart of the Oceans*. Retrieved October 10, 2013, from http://www.gebco.net/

Geyh, M. A. and Kudrass, H. R. (1979). *Sea-level Changes During the Late Pleistocene and Holocene in the Strait of Malacca*. Nature 278, pp. 441–443.

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

Goldstein, R. M., Zebker, H. A. and Werner, C. L. (1988). *Satellite Radar Interferometry: Two-dimensional Phase Unwrapping*. Radio Science, 23 (4), 713 – 20.

Grinsted, A., Moore, J. C. and Jevrejeva, S. (2009). *Reconstructing Sea Level from Paleo and Projected Temperatures 200 to 2100AD*. Climate Dynamics 34, 461– 72 .

Gysen, H. and Coleman, R. (1997). *On the Satellite Altimeter Crossover Problem.* J. Geophys Res 71:83-96.

Hadikusumah (1995). *Study on Sea Level Rise in the Western Indonesia*. Marine Research in Indonesia No. 29, 1995. www.oseanografi.lipi.go.id.

Hanssen, R. F. (2001). *Radar Interferometry: Data Interpretation and Error Analysis*. Kluwer Academic Publishers, Dordrecht, 2001.

Hansen, J. E. (2007). *Scientific Reticence and Sea Level Rise*. Environ. Res. Lett., 2, 024002 (6 pp.)

Hassan, K. (2001). *Holocene Sea Level Changes in Kelang and Kuantan, Peninsular Malaysia*. Doctor Philosophy, Durham University. Available at Durham E-Theses Online: http://etheses.dur.ac.uk/3786/

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

Hofmann-Wellenhof, B., Lichtenegger, H. and Wasle, E. (2008). *GNSS-Global Navigation Satellite Systems, GPS, GLONASS, Galileo and more*. SpringerWien New York.

Hofton, M. A. (1995). *Anelastic Deformation in Iceland Studied using GPS: with Special ReferenceTtopost-tectonic Motion following the 1975-1985 Krafla Rifting Episode, and Isostatic Rebound.* Doctor Philosophy, Durham University, UK.

Holland, P. W. and Welsch, R. E. (1977). *Robust Regression using Iteratively Reweighted Least-squares*. Communications in Statistics—Theory and Methods 6 (9), 813–827.

Hooper, A. (2006). *Persistent Scatterer Radar Interferometry for Crustal Deformation Studies and Modeling of Volcanic Deformation.* Doctor Philosophy, Stanford University, California.

Hooper, A. (2008). *A Multi-temporal InSAR Method Incorporating Both Persistent Scatterer and Small Baseline Approaches*. Geophys. Res. Lett., 35, L16,302, doi:10.1029/2008GL03465.

Hooper, A., Zebker, H., Segall, P. and Kampes, B. (2004). *A New Method for Measuring Deformation on Volcanoes and other Natural Terrains using InSAR Persistent Scatterers*. Geophysical Research Letters, 31 (23), 5, doi:10.1029/2004GL021737, 2004.

Hooper, A., Segall, P. and Zebker, H. (2007). *Persistent Scatterer InSAR for Crustal Deformation Analysis, with Application to Volcano Alcedo, Galapagos*. J. Geophys. Res., 112(B07407), doi:10.1029/ 2006JB004763.

Hooper, A. and Pedersen, R. (2008). *Deformation at Katla, Eyjafjallajokull and Upptyppingar, Iceland, from Multi-temporal InSAR: A Combined Persistent Scatterer and Small Baseline Method*. IAVCEI 2008 General Assembly, Reykjavik .URL http://www.iavcei2008.hi.is

Hooper, A. Spaans, K., Bekaert, D., Cuenca, M. C., Arikan, M. and Oyen, A. (2010). *StaMPS/ MTI Manual version 3.2*. Delft Institute of Earth Observation and Space Systems, Delft University of Technology.

Horton, B. P., Gibbard, P. L., Milne, G. M., Morley, R. J. C., Purintavaragul, and Stargardt J. M. (2005). *Holocene Sea Levels and Palaeoenvironments, Malay-Thai Peninsula, Southeast Asia.* The Holocene, Volume 15, Number 8, December 2005, pages 1199-1213. doi.org/10.1191/0959683605hl891rp

Horton, R., Herdomjer, C., Rosenweig, C., Liu, J., Gornitz, V. and Ruane, A. (2008). *Sea Level Projections for Current Generation CGCMs based on semi-empirical method.* Geophysical Research Letters, 35, L02715

International GNSS Service (IGS). (2012a). About the IGS, retrieved June 8, 2012, from http://igscb.jpl.nasa.gov/overview/viewindex.html.

International GNSS Service (IGS). (2012b). IGS Tracking Network, retrieved January 8, 2012, from http://igscb.jpl.nasa.gov/network/complete.html.

Intergovernmental Panel on Climate Change (IPCC). (2001). In: McCarthy, J. J., Canziani, O. F., Leary, N. A., Dokken, D. J., White, K. S. (eds). *Climate change 2001: impacts, adaptation and vulnerability*. Cambridge University Press, Cambridge.

Intergovernmental Panel on Climate Change (IPCC). (2007). Fourth Assessment Report Working Group I Report (WGI): *Climate Change 2007: The Physical Science Basis*. Cambridge: Cambridge University Press.

Intergovernmental Panel on Climate Change (IPCC). (2012). Summary for Policymakers. In: *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation* [Field, C.B., V. Barros, T.F. Stocker, D. Qin, D.J. Dokken, K.L. Ebi, M.D. Mastrandrea, K.J. Mach, G.-K. Plattner, S.K. Allen, M. Tignor, and P.M. Midgley (eds.)]. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK, and New York, NY, USA, pp. 3-21.

Jeofry, M. H. and Rozainah, M. Z. (2013). *General Observations about Rising Sea Levels in Peninsular Malaysia*. Malaysian Journal of Science 32 (SCS Sp Issue): 363-370.

Jevrejeva, S., Moore, J. C., Grinsted, A. and Woodworth , P. L. (2008) *Recent Global Sea Level Acceleration Started over 200 Years Ago.*Geophysical Research Letters 35 , L08715.

Jhonny (2010). *Post-seismic Earthquake Deformation Monitoring in Peninsular Malaysia using Global Positioning System*. MSc Thesis, Universiti Teknologi Malaysia, Skudai.

Kampes, B. M. (2005) *Displacement Parameter Estimation using Permanent Scatterer Interferometry*. Doctor Philosophy, Delft University of Technology, Delft.

Kampes, B. M. (2006). *Radar Interferometry: Persistent Scatterer Technique*. First edn. P. O. Box 17, 3300 AA, Dordrecht, The Netherlands: Springer.

Kampes, B. M., Hanssen, R. F. and Perski, Z. (2003). *Radar Interferometry with Public Domain Tools*. In Third International Workshop on ERS SAR Interferometry, 'FRINGE03', pp. 6, Frascati, Italy.

Kampes, B. and Usai, S. (1999). *Doris: the Delft Object-oriented Radar Interferometric Software*, in: 2nd International Symposium on Operationalization of Remote Sensing, Enschede, The Netherlands, 16–20 August 1999.

Kee Tuan Chew (2007). *Global Positioning System for Earthquake Induced Deformation in Malaysia*. MSc Thesis, Universiti Teknologi Malaysia, Skudai.

Kemeling, I., van Leijen, F., Petley, D. N., Allison, R. J. and Long, A. J. (2004). *Monitoring Mining Subsidence in Rural Areas with a Temperate Climate using Radar Interferometry*. In: ENVISAT & ERS Symposium, Salzburg, Austria, 6-10 September, 2004. p. 7.

Ketelaar, V. (2009). *Satellite Radar Interferometry: Subsidence Monitoring Techniques*. Springer Verlag.

Kouba, J. (2009). *A Guide to Using International GNSS Service (IGS) Products*. http://igscb.jpl.nasa.gov/components/usage.html

Ku Kassim K. Y., Ahmad, A. and Mahyam, M. I. (2007). *Keadaan Laut Perairan Semenanjung Malaysia Untuk Panduan Nelayan*. Jabatan Perikanan Malaysia. 26 ms.

Kuo, C. Y., Shum, C. K., Braun, A. Cheng, K. C. and Yi, Y. (2008). *Vertical Motion Determined using Satellite Altimetry and Tide Gauges*. Terr. Atmos. Ocean. Sci., 19, 21-35, doi: 10.3319/TAO.2008.19.1-2.21.

Lazecký, I. M. (2011). *Monitoring of Terrain Relief Changes using Synthetic Aperture Radar Interferometry: Application of SAR Interferometry Techniques in a Specific Undermined Ostrava-Karviná District*. Doctor Philosophy, Technical University of Ostrava, Czech Republic.

Le Provost, C., Genco, M. L., Lyard, F., Vincent, P. and Canceil, P. (1994). *Spectroscopy of the World Ocean Tides from a Finite Element Hydrodynamic Model*. J Geophys Res 99(C12):24777–24,797.

Leick, A. (2004). *GPS Satellite Surveying*. (3rd ed.). New Jersey:John Wiley and Sons Inc.

Leighton, J. M. (2010). *GPS and PSI Integration for Monitoring Urban Land Motion*. Doctor Philosophy, University of Nottingham. UK.

Li, X., Rowley, R. J., Kostelnick, J. C., Braaten, D., Meisel, J. and Hulbutta, K. (2009). *GIS Analysis of Global Impacts from Sea Level Rise.* Photogrammetric Engineering & Remote Sensing. Vol. 75, No. 7, July 2009, pp. 807–818.

Liu, P. (2012). *InSAR Observations and Modeling of Earth Surface Displacements in the Yellow River Delta (China)*. Doctor Philosophy, University of Glasgow, Scotland.

Luthcke, S. B., Zelensky, N. P., Rowlands, D. D., Lemoine, F. G. and Williams, T. A. (2003). *The 1-centimeter orbit: Jason-1 precision orbit determination using GPS, SLR, DORIS and altimeter data*. In: Special issue on Jason-1 calibration/validation, Part 1. Mar Geod 26(3–4):399–421.

Low, K. C. (2006). *Application of Nowcasting Techniques Towards Strengthening National Warning Capabilities on Hydrometeorological and Landslides Hazards*. Public Weather Services Workshop on Warning of Real-Time Hazards by Using Nowcasting Technology. Sydney, Australia, 9 to 13 October 2006.

Lyard, F., Lefèvre, F., Letellier, T. and Francis, O. (2006). *Modelling the Global Ocean Tides: Modern Insights from FES2004.* Ocean Dyn 56(5–6):394–415. doi:10.1007/s10236-006-0086-x

Mackay, A. W., Battarbee, R. W., Birks, H. J. B. and Oldfield, F. (eds.) (2003). *Global Change in the Holocene*. London: Arnold. ISBN 0-340-76223-3.

Madi, N. B. (2009). *Groundwater Study for Shallow Alluvium Aquifer at Kota Bharu, Kelantan*. Msc Thesis, Universiti Teknologi Malaysia, Skudai.

Manaf, M. A., Rahman A. H., A., Talib, J. A. (2012). *Holocene Sea-level Change and The Development of Perak Coastal Plain, Perak, West Malaysia.* Second International Conference on Integrated Petroleum Engineering and Geosciences 2012 (ICIPEG2012). Universiti Teknologi Petronas, Tronoh, Perak. 12 – 14 June, 2012.

Massmann, E-H., Neumayer, K. H., Raimando, J. C., Enninghorst, K. and Li, H. (1997). *Quality of the D-PAF ERS Orbits Before and After Inclusion of PRARE Data*. Proc. 3rd ERS Scientific Symposium, ESA SP- 414, Florence, Italy.

Massonnet, D. and Feigl, K. L. (1998). *Radar Interferometry and its Application to Changes in the Earth's Surface*. Reviews of Geophysics, 36(4): 441 – 500.

MATLAB (2014). *MATLAB Online Tutorial*. Retrieved June 25, 2014, from http://www.mathworks.com/help/stats/robustfit.html

McCarthy, D. D. (1996). *IERS Standards 1996*. IERS Technical Note 21, Observatoire de Paris, Paris.

McCarthy, D. D. and Petit, G. (2003). *IERS Conventions (2003).* IERS Technical Note 32, Central Bureau of IERS, Observatoire de Paris.

Meehl, G. A., Stocker, T. F., Collins, W. D., Friedlingstein, P., Gaye, A. T., Gregory, J. M., Kitoh, A., Knutti, R., Murphy, J. M., Noda, A., Raper, S. C. B., Watterson, I. G., Weaver, A. J., Zhao, Z.-C. in: Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K. B., Tignor, M. and Miller, H. L. (2007). *Climate Change 2007: The Physical Sciences Basis*. Contribution of Working Group 1 to the Fourth Assessment of the Intergovermental Panel on Climate Change, Cambridge University Press, Cambridge, UK and New York, NY, USA. pp. 747 – 845.

Milliman, J. D., Broadus, J. M. and Gable, F. (1989). *Environmental and economic implications of rising sea level and subsiding deltas: the Nile and Bengal* examples. Ambio 18, 340 – 345.

Mitrovica, J. X. and Davis, J. L. (1995). *Present-day Post-glacial Sea Level Change Far from the Late Pleistocene Ice Sheets: Implications or Recent Analyses of Tide Gauge Records*. Geophys. Res. Lett., 22, 2529–2532.

MMD (2013). *Malaysian Meteorological Department-Monsoon*. Retrieved July 17, 2013, from http://www.met.gov.my/

Mohamed, A. (2009). *JUPEM GNSS Infrastructure*. Workshop on Surveying with a Single GPS Receiver in MyRTKnet Enviroment, 29-31 July. Kuching – Sarawak.

Morgan, J., Falorni, G., Bohane, A. and Novali, F. (2011). *Advanced InSAR Technology (SqueeSAR™) for Monitoring Movement of Landslides*. Technical Report, FHWA-CFL/TD-11-005. http://www.cflhd.gov.

Muhammad Faiz Pa'suya (2013). *Seasonal Surface Circulation of Southern South China Sea from Multi-mission Satellite Altimetry*. MSc Thesis, Universiti Teknologi Malaysia, Skudai.

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, Kluyverweg 1, 2629 HS Delft, 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. and Doornbos, E. (2007). *Next Generation Altimeter Service Challenges and Achievements*. 2007 ESA ENVISAT Symposium. 23 to 27 April 2007. Monteux, Switzerland.

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

NAHRIM (2010). *The Study of Impact of Climate Change on Sea Level Rise in Malaysia* (Technical Report), National Hydraulic Research Institute of Malaysia: 172pp.

Nerem, R. and Mitchum, G. (2002). *Estimates of Vertical Crustal Motion Derived from Differences of TOPEX/POSEIDON and Tide Gauge Sea Level Measurements*. Geophys. Res. Lett., 29, 1934, doi: 10.1029/2002GL015037.

Nguyen, P. K. (2009). *Climate Change, Sea Level Rise Scenarios for Vietnam*. Final Report. Ministry of Natural Resources and Environment, Vietnam.

Nicholls, R. J. and Tol, R. S. J. (2006). *Impacts and Responses to Sea-level Rise: a Global Analysis of the SRES Scenarios over the Twenty-first Century*. Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences, 364 (1841), 1073-1095.

Nicholls, R.J., Wong, P.P., Burkett, V.R., Codignotto, J.O., Hay, J.E., McLean, R.F., Ragoonaden., S. and Woodroffe, D.D. (2007). *Coastal systems and low-lying areas.* Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden and C.E. Hanson, Eds., Cambridge University Press, Cambridge, UK, 315-356.

Nicholls, R. J. and Cazenave, A. (2010). *Sea-Level Rise and Its Impact on Coastal Zones.* Science Magazine. June 18, 2010.

ONI (2014). *The Oceanic Niño Index*. Retrieved July 23, 2014, from http://ggweather.com/enso/oni.htm

Onn, F. and Zebker, H. A. (2006). *Correction for Interferometric Synthetic Aperture Radar Atmospheric Phase Artifacts using Time Series of Zenith Wet Delay Observations from a GPS Network*. J. Geophys. Res., 111(B09102).

Osmanoglu, B. (2011). *Applications and Development of New Algorithms for Displacement Analysis Using InSAR Time Series*. Doctor Philosophy, University of Miami, Florida.

Paganelli, F. and Hooper, A. (2008). *Deformation at Fogo Volcano, Cape Verde, Detected by Persistent Scatterer InSAR*. EGU General Assembly 2008, Vienna 10, EGU2008-A-07819.

Parkinson, B. W. (1996). *Introduction and Heritage of NAVSTAR, the Global Positioning System*. In "Global Positioning System Theory and Applications," Vol. 1, pp. 3-28, Progress in Aero. and Astro., 164, American Institute of Aerospace and Astro., Washington, D.C.

Parry, M. L., Canziani, O. F., Palutikof, J. P., Linden, V. D., Paul J. and Hanson, C. E. (2007). *Climate Change 2007: Impacts, Adaptation and Vulnerability*. Contribution of Working Group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change, IPCC (eds.). Cambridge University Press, Cambridge, United Kingdom, 1000 pp.

Perski, Z., Hanssen, R. and Marinkovic, P. (2008). *Deformation of the Margin of Sudety Mountains (Southern Poland), Studied by Persistent Scatterers Interferometry*. In: Fifth International Workshop on ERS/Envisat SAR Interferometry, `FRINGE07', Frascati, Italy, 26 Nov-30 Nov 2007. p. 4 pp.

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).

Pittock, A. B. (2009). *Climate Change: The Science, Impacts and Solutions*. 2nd edition. Collingwood, VIC. CSIRO Publishing.

PSMSL (2014). *Permanent Service for Mean Sea Level*. Retrieved June 20, 2014, from http://www.psmsl.org/

Pugh, D. (2004). *Changing Sea Level, Effects of Tides, Weather and Climate.* Cambridge University.

Rabus, B., Eineder, M., Roth, A. and Bamler, R. (2003). *The Shuttle Radar Topography Mission–A New Class of Digital Elevation Models Acquired by Spaceborne Radar*, ISPRS Journal of Photogrammetry and Remote Sensing, 57(4), 241–262.

Radar Altimeter Database (RADS) Website. Retrieved October 22, 2013, from http://rads.tudelft.nl/rads/experts.shtml.

Rahmstorf, S., Cazenave, A., Church, J. A., Hansen, J. E., Keeling, R.F., Parker, D. E. and Somerville, R. C. J. (2007). *Recent climate observations compared to projections*. Science 316, 709.

Ray, R. D., Koblinsky, C. J. and Beckley, B. D. (1991). *On the Effectiveness of Geosat Altimeter Corrections*. Int J Remote Sensing 12:1979–1984.

Rizos, C. (1999). *How Good is GPS?* [Online]. Sydney, Australia: The University of New South Wales. Available at: http://www.gmat.unsw.edu.au/snap/gps/gps_survey/chap2/241relb.htm.

Rosen, P. A., Hensley, S., Joughin, I. R., Li, F. K., Madsen, S. N., Rodriguez, E. and Goldstein, R. M. (2000). *Synthetic Aperture Radar Interferometry*. Proc. IEEE, 88(3), 333–382.

Rowley, R.J., Kostelnick, J.C., Braaten, D., Li, X. and Meisel, J. (2007). *Risk of Rising Sea Level to Population and Land Area*. EOS Transactions, 88:105, 107.

Saastamoinen, J. (1972). *Atmospheric Corrections for the Troposphere and Stratosphere in Radio Ranging of Satellites*. In: Hendriksen, S. W., Mancini, A. and Chovitz, B. H. (eds). The use of Artificial Satellites for Geodesy. Geophysical Monograph Series 15:247–251, AGU, Washington, DC

Sanli, D. U. (1999). *GPS Strategies for Tide Gauge Monitoring with Assessment of Sea Level Analysis Models*. Doctor Philosophy, University of Newcastle upon Tyne.

Sansosti, E., Berardino, P., Manunta, M., Serafino, F. and Fornaro, G. (2006). *Geometrical SAR Image Registration*. IEEE Trans. on Geosci. Remote Sensing, 44(10), 2861–2870.

Sathiamurthy, E. and Voris, H. K. (2006). *Maps of Holocene Sea Level Transgression and Submerged Lakes on the Sunda Shelf.* The Natural History Journal of Chulalongkorn University, Supplement 2: 1-44, August 2006 by Chulalongkorn University.

Schaeffer, M., Hare, W., Rahmstorf, S. and Vermeer, M. (2012). *Long-term sea-level rise implied by 1.5°C and 2° C warming levels.* Nature Climate Change Letters. Published online: 24 June, 2012.

Scharroo, R. and Lillibridge, J. (2004). *Non-parametric Se-state Bias Models and Their Relevance to Sea Level Change Studies*. Proc. of the 2004 Envisat & ERS Symposium, Salzburg, Austria 6-10 September 2004 (ESA SP-572, April 2005).

Scharroo R, and Smith W. H. F. (2010). *A GPS-based Climatology for the Total Electron Content in the Ionosphere*. Journal of Geophysical Research, 115, A10318, DOI: 10.1029/2009JA014719.

Scharroo, R. and Visser, P. (1998). *Precise Orbit Determination and Gravity Field Improvement for the ERS Satellites*. J. Geophys. Res., 103(B4), 8113–8127.

Scharroo, R., Leuliette, E., Lillibridge, J., Doornbos, Eelco., 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.

Scharroo, R., Leuliette, E. W., Lillibridge, J. L., Byrne, D., Naeije, M. and Mitchum, G. T. (2013). *RADS: Consistent Multi-mission Products*. In Proc. of the Symposium on 20 Years of Progress in Radar Altimetry, Venice, 20-28 September 2012, Eur. Space Agency Spec. Publ., ESA SP-710, p. 4 pp., 2013.

Scherneck, H. G. (1991). *A Parameterized Solid Earth Tide Model and Ocean Tide Loading Effects for Global Geodetic Baseline Measurements*. Geophysical Journal International, 106. Pp. 677 – 694.

Schrama, E. (1989). *The Role of Orbit Errors in Processing of Satellite Altimeter Data*. Netherlands Geodetic Commission, Publication of Geodesy 33, 167 pp.

Schreiner, W. S., Markin, R. E. and Born, G. H. (1997). *Correction of Single Frequency Altimeter Measurements for Ionosphere Delay*. IEEE Trans Geosci Remote Sensing 35(2):271–277. doi:10.1109/36.563266

Schutz, B. E., Zwally, H. J., Shuman, C. A., Hancock, D. and DiMarzio, J. P. (2005). *Overview of the ICESat mission*. Geophysical Research Letters 32, L21S01.

Seeber, G. (1993). *Satellite Geodesy*. ISBN Number-13: 978-3110175493.Walter de Gruyter, 10785 Berlin, second edition.

Shepard, D. (1968). *A Two-dimensional Interpolation for Irregularly-spaced Data*. Proceedings – 1968 ACM National Conference. pp. 517 – 524.

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.

Skolnik, M. L. (2001). *Introduction to RADAR Systems*. 3 edn. 1221 Avenue of the Americas, New York, NY 10020: Tata McGraw-Hill.

Smith, D. E., Kolenkiewicz, R., Dunn, P. J., Robbins, J. W., Torrence, M. H., Klosko, S. M., Williamson, R. G., Pavlis, E. C., Douglas, N. B. and Fricke, S. K. (1991). *Tectonic Motion and Deformation from Satellite Laser Ranging to LAGEOS*. J. Geophys. Res., 95, 22,013-22,041.

Sojisuporn, P., Morimoto, A. and Yanagi, T. (2010). *Seasonal Variation of Sea Surface Current in the Gulf of Thailand*. Coastal Marine Science. 34(1):91-102,2010.

Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K. B., Tignor, M. and Miller, H. L. (Eds.) (2007). *Climate change 2007: The physical science basis.* In Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge and New York: Cambridge University Press.

Soumekh, M. (1999). *Synthetic Aperture Radar Signal Processing*. First edn. New York: John Wiley and Sons, Inc.

Sousa, J. J., Hooper, A. J., Hanssen, R. F., Bastos, L. C. and Ruiz, A. M. (2011). *Persistent Scatterer InSAR: A Comparison of Methodologies Based on a Model of Temporal Deformation vs. Spatial Correlation Selection Criteria*. Remote Sensing of Environment 115, pp. 2652–2663. doi:10.1016/j.rse.2011.05.021.

Suchandt, S., Breit, H., Adam, N., Eineder,M., Schattler, B., Runge, H., Roth, A. and Mikusch, E. (2001). *The Shuttle Radar Topography Mission*. ISPRS 19-21 September, 2002. ISPRS. pp. 235–242.Workshop, High Resolution Mapping from Space, Hannover, Germany.

Tapley, B. D., Schutz, B. E., Eanes, R. J., Ries, J. C. and Watkins, M. M. (1993). *Lageos Laser Ranging Contributions to Geodynamics, Geodesy, and Orbital Dynamics.* In "Contributions of Space Geodesy to Geo- dynamics: Earth Dynamics, Geodynamics Series" (Smith, D. E. and Turcotte, D. L. Eds.), Vol. 24, pp. 147-173, American Geophysical Union, Washington, D.C.

Tapley, B. D., Ries, J. C., Davis, G. W., Eanes, R. J., Schutz, B. E., Shum, C. K., Watkins, M. M., Marshall, J. A., Nerem, R. S., Put- ney, B. H., Klosko, S. M., Luthcke, S. B., Pavlis, D., Williamson, R. G. and Zelensky, N. E. (1994). *Precision Orbit Determination for TOPEX/POSEIDON*. J. Geophys. Res., 99, 24,383-24,404.

Teh, T. S. and Voon, P. K. (1992). *Impacts of sea level rise in West Johor, Peninsular Malaysia*. Mal. Journ. Trop. Geog. 23(2): 93-102.

Tjia, H. D. (1996). *Sea-level changes in the tectonically stable Malay–Thai Peninsula*.
Quaternary International 31, pp. 95–101.

Tkalich, P. and Luu, Q. (2013). *Analysis of Sea Level Rise in Singapore Strait*. Geophysical Research Abstract. Vol. 15, EGU2013-4646, 2013. EGU General Assembly 2013.

Trisirisatayawong, I., Naeije, M., Simons, W. and Fenoglio-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: 137-151.

Usai, S. (2001). *A New Approach for Long Term Monitoring of Deformations by Differential SAR Interferometry*. Doctor Philosophy, Delft University of Technology, the Netherlands.

Van Dam, T. M., Blewitt, G. and Heflin, M. B. (1994). *Atmospheric Pressure Loading Effects on Global Positioning System Coordinate Determinations*. Journal of Geophysical Research 99 (B12) 23939-23950.

Vandemark, D., Tran, N., Beckley, B. D., Chapron, B. and Gaspar, P. (2002). *Direct Estimation of Sea State Impacts on Radar Altimeter Sea Level Measurements*. Geophys. Res. Lett., 29(24):2148–2153.

Vermeer, M. and Rahmstorf, S. (2009). *Global sea level linked to global temperature*. Proceedings of the National Academy of Sciences of the United States of America (PNAS), 106 (51), 21527-21532.

Wang, J., Qi, Y. and Jones, I. S. F. (2006). *An Analysis of the Characteristics of Chlorophyll in the Sulu Sea*. J. Mar. Syst., 59: 111-119.

Warren, M. A. (2007). *The Development of a 3-Pass Persistent Scatterer Algorithm Using the Integer Ambiguity Search Method*. Doctor Philosophy, University of Nottingham, UK.

Warrick, R. A., Barrow, E. M. and Wigley, T. M. L. (eds) (1993). *Climate and Sea Level Change: Observations, Projections, Implications*. Cambridge University Press, Cambridge.

Watkins, M. M., Eanes, R. J. and Ma, C. (1994). *Comparison of Terrestrial Reference Frame Velocities Determined from SLR and VLBI*. Geophys. Res. Lett., 21, 169-172.

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/

Watson, K., Bock, Y. and Sandwell, D. (2002). *Satellite Interferometric Observations of Displacements Associate with Seasonal Groundwater in the Los Angeles basin.* Journal of Geophysical Research. 107(B4) pp.2074

Wilhelm, H., Zurn, W. and Wenzel, H. G. (1997). *Tidal Phenomena*. Berlin: Springer Verlag.

Williams, S. D. P. (1995). *Current Motion on Faults of the San Andreas System in Central California Inferred from Recent GPS and Terrestrial Survey measurements.* Doctor Philosophy, Durham University, UK.

Willis, M. J. (2008). *Crustal Motion in the Antarctic Interior from a Decade of Global Positioning System Measurements.* Doctor Philosophy, The Ohio State University.

Woodard, G., Perkins, D. and Brown, L. (2010). *Climate change and freshwater ecosystems: impacts across multiple levels of organization.* Philos Trans R Soc Lond B Biol Sci., 365 (1549), 2093-2106.

Woodworth, P. L. and Player, R. (2003). *The Permanent Service for Mean Sea Level: An Update to the 21stCentury*. Journal of Coastal Research, Vol. 19, No. 2, Spring, 2003.

Worawattanamateekul, J., Adam, N., Hoffmann, J. and Kampes, B. M. (2003). *Urban Deformation Monitoring in Bangkok Metropolitan (Thailand) using Differential Interferometry and the Permanent Scatterer Technique.* In: Third International Workshop on ERS SAR Interferometry, `FRINGE03', Frascati, Italy, 1-5 Dec 2003. p. 22.

Wuriatmo, H., Koesuma, S. and Yunianto, M. (2012). *Analisa Sea Level Rise dari Data Satelit Altimetri TOPEX/POSEIDON, Jason-1 dan Jason-2 di Perairan laut Pulau Jawa Periode 2000 – 2010*. Indonesian Journal of Applied Physics (2012) Vol.2 No.7 halaman 73.

Wunsch, C. and Stammer, D. (1997). *Atmospheric Loading and the Oceanic "Inverted Barometer" Effect*. Rev Geophys 35:79–107.

Zebker, H. A. and Goldstein, R. M. (1986). *Topographic Mapping from Interferometric Synthetic Aperture Radar Observations*. Journal of Geophysical Research, 91 (B5), 4993-9, 1986.

Zebker, H. A. and Villasenor, J. (1992). *Decorrelation in Interferometric Radar Echoes*. IEEE Trans. on Geosci. Remote Sensing, 30(5), 950–959.

Zebker, H. A., Rosen, P. A. and Hensley, S. (1997). *Atmospheric Artefacts in Interferometric Synthetic Aperture Radar Surface Deformation and Topographic Maps*. J. Geophys. Res., 102, 7547{7563.

Zheng, Y. (2006). *Generation of Network-Based Differential Corrections for Regional GNSS Services*. Doctor Philosophy, Quensland University of Technology, Australia.

Zhou, X., Chang, N. and Li, S. (2009). *Applications of SAR Interferometry in Earth and Environmental Science Research*. Sensors 2009, 9, 1876-1912; doi:10.3390/s90301876.