VERTICAL LAND MOTION ESTIMATION DERIVED FROM SPACE-BASED GEODETIC TECHNIQUES

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DEDICATION

With genuine gratitude and warm regard, I dedicate this piece of work to my parents,

Sulaini binti A. Rahman

and

Zulkifli bin Yusof

Thank you for making me see this adventure through to the end.

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ABSTRACT

Vertical land motion is associated with land geohazards that portrays land movement in subsidence and uplift. As Malaysia is exposed to the tropical climate, heavy rain will cause the floodwater to submerge land or coastal areas, particularly in the presence of land subsidence. This could result in severe environmental consequences, such as inundation and economic losses. Therefore, this study presents an approach to estimate the rate of vertical land motion using multi-sensor technology, which are the Global Positioning System (GPS), Gravity Recovery and Climate Experiment (GRACE), and integrating them with the satellite altimeter minus tide gauge techniques. The four objectives of this study were to improve the accuracy of the vertical component on GPS measurement by mitigating the effects of seasonal variations, to derive the deformation of the Earth surface induced by hydrological loading and tectonic motion on GRACE measurement, to quantify the coastal vertical land motion using satellite altimeter minus tide gauge technique, and to integrate the vertical land motion rates within a 19-year period, from 1999 to 2017, for the region of Malaysia using space-based geodetic techniques. The methodology used was to firstly generate GPS vertical position time series from Bernese 5.2 software by considering the diverse geophysical sources on seasonal variations. Then, the vertical displacement of the Earth's surface was derived from the GRACE measurement. This was followed by the quantification of coastal vertical land motion using direct and advanced approaches. Finally, the rate of vertical land motion was then derived from each multi-sensor space-based geodetic technique before it was integrated using the least-squares collocation method over the Malaysian region. As Malaysia experiences land subsidence and uplift based on the integrated vertical land motion rates, as such the analysis of vertical land motion trend produced novel findings. The absolute motions indicated an overall displacement from a subsidence rate of -20 mm/yr. to an uplift of 5 mm/yr. A significant subsidence rate was observed at specific areas in Peninsular Malaysia due to groundwater extraction and natural compaction, except for Pantai Tok Jembal, which experienced coastal erosion. In East Malaysia, other areas encountered land subsidence due to peatlands, excluded Kota Belud and Kota Marudu as the groundwater development project had taken place at these areas, which gave proof of the dominant effect of land subsidence in Malaysia. In conclusion, the integration of multi-sensor technology in quantifying vertical land motion rates would not only help researchers obtain insight into the motion trends, but it also serves as a key to forecast the necessities of populations and environment, thus implementing appropriate monitoring and prevention measures for future geohazard risk assessment.

ABSTRAK

Pergerakan tanah menegak dikaitkan dengan kejadian bahaya geologi darat yang menggambarkan pergerakan tahap tanah secara menurun dan menaik. Oleh kerana Malaysia terdedah kepada iklim tropika, hujan lebat boleh menyebabkan air banjir menenggelami kawasan darat dan pesisir pantai, terutamanya dengan apabila berlaku pergerakan tanah secara menurun. Ini boleh mengakibatkan kesan kepada alam sekitar seperti banjir dan kerugian ekonomi. Oleh yang demikian, kajian ini dijalankan bertujuan untuk mengukur kadar pergerakan tanah secara menegak berdasarkan inetgrasi teknologi berbagai sensor: iaitu Sistem Kedudukan Global (GPS), *Gravity Recovery and Climate Experiment* (GRACE), dan mengintegrasikannya dengan altimeter satelit tolak tolok pasang surut. Empat objektif kajian ini adalah untuk meningkatkan ketepatan komponen menegak pada pengukuran GPS dengan mengurangkan kesan variasi bermusim, untuk memperoleh perubahan bentuk permukaan bumi yang disebabkan oleh beban hidrologi dan gerakan tektonik pada pengukuran GRACE, untuk mengukur pergerakan menegak bagi kawasan pantai menggunakan teknik altimeter satelit tolak tolok pasang surut, dan untuk mengintegrasikan kadar pergerakan menegak tanah dalam tempoh 19 tahun, bermula dari tahun 1999 sehingga 2017 di kawasan Malaysia menggunakan teknik geodetik berasaskan angkasa. Untuk mencapai objektif kajian, metodologi pertama adalah untuk menjana siri masa kedudukan menegak GPS menggunakan perisian Bernese 5.2 dengan mengambil kira pelbagai sumber geofizik variasi bermusim. Kemudian, anjakan menegak permukaan bumi diperoleh daripada ukuran GRACE, diikuti dengan pengukuran pergerakan menegak bagi kawasan pantai menggunakan pendekatan secara langsung dan lanjutan. Kadar pergerakan tanah menegak kemudiannya diperoleh daripada setiap teknik geodetik berasaskan angkasa berbagai sensor sebelum nilai tersebut diintegrasikan menggunakan kaedah kolokasi kuadrat terkecil di kawasan Malaysia. Analisis kadar pergerakan tanah menegak menghasilkan dapatan lepas. Khususnya, Malaysia mengalami pergerakan tanah secara menurun berdasarkan kadar pergerakan tanah menegak secara bersepadu. Gerakan mutlak menunjukkan anjakan keseluruhan dari kadar penurunan -20 mm/yr. hingga peningkatan 5 mm/yr. Kadar penurunan yang ketara dikenal pasti di kawasan tertentu di Semenanjung Malaysia disebabkan oleh pengeluaran air bawah tanah dan pemadatan semula jadi, kecuali Pantai Tok Jembal yang mengalami hakisan tanah. Di Malaysia Timur, kawasan lain yang mengalami penurunan tanah akibat tanah gambut, tidak termasuk Kota Belud dan Kota Marudu kerana pelaksanaan projek pembangunan air bawah tanah telah berlaku di kawasan ini yang membuktikan kesan dominan penurunan tanah di Malaysia. Kesimpulannya, penggabungan teknologi berbagai sensor dalam mengukur pergerakan tanah bukan sahaja dapat membantu penyelidik memberi gambaran terhadap trend pergerakan tanah, tetapi ia juga berfungsi sebagai kunci untuk meramalkan keperluan penduduk dan persekitaran agar pemantauan dan langkah pencegahan terhadap penilaian risiko bahaya geologi di masa akan datang dapat dilaksanakan.

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LIST OF ABBREVIATIONS

3D	-	Three-dimensional
AGSO	-	Australian Geological Survey Organisation
ACC	-	Accelerometers
ACC1B	-	Accelerometer Data Product
AIUB	-	Astronomical Institute of the University of Bern
AOD1B	-	Atmosphere and Ocean De-aliasing Level-1B
APC	-	Antenna Phase Centre
ARP	-	Antenna Reference Point
ATM	-	Non-tidal Atmosphere
AVISO	-	Archiving, Validation and Interpretation of Satellite Oceanographic data
BDS	-	BeiDou Navigation Satellite System
BPE	-	Bernese Processing Engine
CDDIS	-	Crustal Dynamics Data Information System
CE	-	Centre of Mass of the Solid Earth
CF	-	Centre of Figure
CLS	-	Collecte Localisation Satellites
CM	-	Centre of Mass of the Earth System
CNES	-	Centre National d'Etudes Spatiales
CORS	-	Continuously Operating Reference Stations
CRI	-	Coastal Resolution Improvement
CSR	-	Center for Space Research
CUT	-	Chalmers University of Technology
DCB	-	Differential Code Biases
DEOS	-	Department of Earth Observation and Space System
DLR	-	Deutsches Zentrum Für Luft und Raumfahrt
DoD	-	Department of Defense
DORIS	-	Doppler Orbitography and Radiopositioning Integrated by Satellite
DSMM	-	Department of Survey and Mapping Malaysia

DTU	-	Denmark Technical University
EnviSat	-	Environmental Satellite
EOP	-	Earth Orientation Parameter
EOSDIS	-	Earth Observing System Data and Information System
ERP	-	Earth Rotation Parameter
ERS	-	European Remote Sensing
ESA	-	European Space Agency
ESDIS	-	Earth Science Data and Information System
ESSP	-	Earth System Science Pathfinder
EUMETSAT	-	European Organisation for the Exploitation of Meteorological Satellites
FES	-	Finite Element Solution
FTP	-	File Transfer Protocol
GAMIT	-	GNSS at MIT
GeoSat	-	Geodetic Satellite
GFO	-	GeoSat Follow-On
GFZ	-	GeoForschungsZentrum
GGOS	-	Global Geodetic Observing System
GIA	-	Glacial Isostatic Adjustment
GIS	-	Geographic Information System
GLDAS	-	Global Land Data Assimilation System
GLONASS	-	Globalnaya Navigazionnaya Sputnikovaya Sistema
GNSS	-	Global Navigation Satellite System
GPS	-	Global Positioning System
GPS1B	-	GPS Data Product
GRACE	-	Gravity Recovery and Climate Experiment
GRAMAT	-	GRACE MATLAB Toolbox
GUI	-	Graphical User Interface
GUIDE	-	Graphical User Interface Development Environment
GWS	-	Groundwater Storage
IAG	-	International Association of Geodesy
ICA	-	Independent Component Analysis
IDW	-	Inverse Distance Weighting

IERS	-	International Earth Rotation and Reference Systems Service
IF	-	Ionosphere-free
IGS	-	International GNSS Service
ILRS	-	International Laser Ranging Service
IOC	-	Intergovernmental Oceanographic Commission
IPCC	-	Intergovernmental Panel on Climate Change
IPVPN	-	Internet Protocol Virtual Private Network
IRIS	-	Incorporated Research Institutions for Seismology
IRLS	-	Iteratively Re-weighted Least Squares
IRNSS	-	Indian Regional Navigation Satellite System
ISC	-	International Science Council
ITRF	-	International Terrestrial Reference Frame
ITRS	-	International Terrestrial Reference System
IUGG	-	International Union of Geodesy and Geophysics
JPL	-	Jet Propulsion Laboratory
JUPEM	-	Jabatan Ukur dan Pemetaan Malaysia
KBR	-	K-Band Ranging
KBR1B	-	K-Band Ranging Data Product
KPPP	-	Kinematic Precise Point Positioning
L3	-	Phase-based Narrowlane
L5	-	Phase-based Widelane
LAGEOS	-	Laser Geometric Environmental Observation Survey
LARES	-	Larets and Laser Relativity Satellite
LEGOS	-	Laboratoire d'Etudes en Géophysique et Océanographie Spatiales
LRR	-	Laser Retro Reflector
LSA	-	Laboratory for Satellite Altimeter
LSM	-	Land Surface Model
LWET	-	Liquid Water Equivalent Thickness
MASS	-	Malaysian Active GPS System
MATLAB	-	Matrix Laboratory
MIT	-	Massachusetts Institute of Technology
MMD	-	Malaysian Meteorological Department

MSL	-	Mean Sea Level
MSS	-	Mean Sea Surface
MyRTKnet	-	Malaysia Real-Time Kinematic GNSS Network
NAHRIM	-	National Water Research Institute of Malaysia
NASA	-	National Aeronautics and Space Administration
NetCDF	-	Network Common Data Form
NL	-	Code-based Narrowlane
NOAA	-	National Oceanic and Atmospheric Administration
NQ0	-	Normal Equation
N-S	-	North-South
NWS	-	National Weather Service
O	-	Observation
OBP	-	Ocean Bottom Pressure
OCN	-	Non-tidal Ocean
ONI	-	Oceanic Niño Index
OSTST	-	Ocean Surface Topography Science Team
PCA	-	Principal Component Analysis
PCF	-	Process Control File
PCO	-	Phase Centre Offset
PCV	-	Phase Centre Variation
PNT	-	Positioning, Navigation and Timing
PO.DAAC	-	Physical Oceanography Distributed Active Archive Center
PS InSAR	-	Persistent Scatterer Interferometry Synthetic Aperture Radar
PSMSL	-	Permanent Service for Mean Sea Level
QIF	-	Quasi-Ionosphere-Free
QWG	-	Quality Working Group
QZSS	-	Quasi-Zenith Satellite System
R	-	Correlation Coefficient
RADS	-	Radar Altimeter Database System
RDC	-	Raw Data Center
RF	-	Reference Frame
RFWG	-	Reference Frame Working Group

RINEX	-	Receiver Independent EXchange
RL06	-	Release 06
RLR	-	Revised Local Reference
RMS	-	Root Mean Square
RVLM	-	Relative Vertical Land Motion
S3A	-	Sentinel-3A
SARAL	-	Satellite with Argos and ALtiKa
SBAS	-	Satellite-based Augmentation System
SCA	-	Star Camera Assembly
SCA1B	-	Star Camera Data Product
SDS	-	Science Data System
SHC	-	Spherical Harmonic Coefficients
SINEX	-	Solution Independent Exchange
SLA	-	Sea Level Anomaly
SLM	-	Surface Loading Model
SLR	-	Satellite Laser Ranging
SM	-	Soil Moisture
SST	-	Satellite-to-Satellite Tracking
SW	-	Surface Water
SWE	-	Snow Water Equivalent
SWH	-	Significant Wave Height
TIN	-	Triangulation Irregular Network
TN	-	Technical Note
TPn-J1n	-	TOPEX/Poseidon tandem tracks – Jason-1 tandem tracks
TWS	-	Terrestrial Water Storage
UCAR	-	University Corporation for Atmospheric Research
USGS	-	United States Geological Survey
UTCSR	-	University of Texas Center for Space Research
VLBI	-	Very Long Baseline Interferometry
VLMIS	-	Vertical Land Motion Information System
WDS	-	World Data System
WL	-	Code-based Widelane
ZPD	-	Zenith Path Delay

LIST OF SYMBOLS

X, Y, Z	-	Coordinates of the station at observation epoch t
$\hat{R}_j, R_j$	-	Unit vector and magnitude of vector of the celestial body from the geocentre
$\bar{C}_{lm}, \bar{S}_{lm}$	-	Fully-normalised spherical harmonic coefficients
$\bar{P}_{lm}$	-	Fully-normalised Legendre function for degree and order
$\bar{P}_{lm}(\sin\varphi)$	-	Fully-normalised Associated Legendre Polynomials of degree and order
h_2, l_2	-	Nominal degree 2 of Love number and Shida number
h_{MSS}	-	Mean sea surface
h_{atm}	-	Dynamic atmospheric correction
h_{sla}	-	Sea level anomaly
h_{ssb}	-	Sea state bias correction
h_{tides}	-	Tides correction
$\hat{r}$	-	Unit vector of the station from the geocentre
R_e	-	Equatorial radius of the Earth
A_{cj}, ϕ_{cj}	-	Tidal amplitude and phase lag
C_0	-	Covariance when the distance from the observation is 0
GM_E	-	Gravitational parameter of the Earth
GM_j	-	Gravitational parameter of the Moon and the Sun
$R_{corrected}$	-	Corrected range
R_{obs}	-	Observed range
X_0, Y_0, Z_0	-	Coordinates of the station at the reference epoch t_0
a_e	-	Mean equatorial radius
f_j, u_j	-	Varying functions of the mean longitudes of the moon's ascending node
k'_l, h'_l, l'_l	-	Load Love numbers
l_0, β	-	Defined by the coordinates of the two ends of the curve
$\tilde{p}$	-	Average pressure over a circular region with a 2000 km radius

$\hat{s}$	-	Signal to be estimated at a specific point
x_j	-	Astronomical argument
x_p, y_p	-	Polar motion
$\Delta C_{lm}^h, \Delta C_{lm}^h$	-	Spherical harmonic coefficients of the height deformation
$\Delta C_{lm}^g, \Delta S_{lm}^g$	-	Spherical harmonic coefficients of the gravity field
$\Omega_x, \Omega_y, \Omega_z$	-	Vector of plate rotation at the reference epoch t_0
$\omega_j t$	-	Tidal angular velocity at reference time t
h	-	Sea surface height
r	-	Averaging radius
ΔTWS	-	Terrestrial Water Storage changes
μ	-	Gravitational constant of the Earth
A	-	Fixed empirical parameter
ASL	-	Absolute sea level trend
C	-	Covariance matrix between two variables
H	-	Height of the mass centre of the satellite estimated through orbit determination above the reference ellipsoid
K	-	Empirically calculated parameter
R	-	Radius of the Earth
RSL	-	Relative sea level trend
$RVLM$	-	Relative vertical land motion
$V(r, \varphi, \lambda; t)$	-	Gravitational geopotential at geographical latitude, longitude, time and geocentric radius
VLM	-	Vertical land motion
$W(\alpha)$	-	Global weighting function of the spherical distance
b	-	Dimensionless parameter
b	-	Parameter controls the bandwidth of the filter
d	-	Correlation length/scaling parameter
j	-	11 periods of tidal constituents
l	-	Observed data point
l, m	-	Degree and order of spherical harmonic coefficients
max	-	Function that chooses the larger argument
p	-	Local pressure anomaly

p	-	Empirically calculated parameter
s	-	Distance between two points
s	-	Interpolated data point
Δh_{dry}	-	Dry tropospheric correction
Δh_{iono}	-	Ionospheric correction
Δh_{wet}	-	Wet tropospheric correction
ΔR_{dry}	-	Dry troposphere range
ΔR_{iono}	-	Ionospheric range
ΔR_{ssb}	-	Sea state bias range
ΔR_{wet}	-	Wet troposphere range
$\Delta \vec{r}$	-	Displacement of the station due to Earth body tide
$\Delta GLDAS\ TWS$	-	Terrestrial Water Storage changes derived from GLDAS
$\Delta GRACE\ TWS$	-	Terrestrial Water Storage changes derived from GRACE
ΔGWS	-	Groundwater Storage changes
Δc	-	Site displacement component due to ocean tide loading
Δr	-	Vertical displacement due to atmospheric pressure loading
$\Delta\lambda, \Delta\theta, \Delta r$	-	Horizontal and vertical displacement due to pole tide
$\beta(\alpha)$	-	Normalised Gaussian averaging function in the spatial domain
γ	-	Empirically calculated parameter
$\delta\varepsilon$	-	Common trend error
ε	-	Trend error
λ, θ	-	Longitude and colatitude of station
ϵ	-	Random error

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CHAPTER 1

INTRODUCTION

1.1 Research Background

Vertical land motion can be defined as the vertical movement of land, generally associated with land subsidence and uplift. These two movements are closely related as the land will act upon the dynamic of the Earth based on the foundation underneath the ground. This ground deformation might occur due to geophysical processes, known as natural causes and/or artificial processes due to anthropogenic activities. Generally, vertical land motion is a part of land geohazard, and it can be referred to as an event caused by any process happening on the surface of the Earth that is most likely to harm humans, structures, and the environment (AGSO, 2020). These processes might develop instantly or could take thousands of years to respond (Culshaw, 2018). Therefore, in land areas, vertical land motion is an important aspect to be considered in order to prevent extensive damage jeopardising human life and property. Meanwhile, it is fundamental to understanding sea level behaviours in coastal areas, given that the coastal subsidence can exacerbate the impact of sea level rise. Even though the land deformation has become a prominent issue in sea level rise studies over the past period of ten to hundred years (Douglas, 2001; Woodworth, 2006; Blewitt et al., 2010; Din et al., 2019), how exactly the rising sea levels play out locally are not well understood especially when the ground itself is moving (Strelich, 2016). To highlight this event, the vertical land motion is significant not only in flat and low land, but also in coastal areas.

Furthermore, attributable to the location of Malaysia close to the equator, it is exposed to tropical climate dealing with the effect of El-Nino, which reduces rainfall in the dry season and increases rainfall during monsoon season. The heavy rain will cause the floodwater to submerge, specifically the flat and low areas. This could result in severe environmental consequences and economic losses, especially in urban areas.

The vertical land motion at flat and low land would get worse, particularly with the existence of uncontrollable anthropogenic activities and the effect of seismic activities resulting from the Eurasian tectonic plate motion. The effect of vertical land motion will eventually contribute to inundation, threatening the nearby communities and ecosystems in the coming century.

Despite the attention given to the estimation of vertical ground displacements of the Earth surface using the most developed geodetic techniques in the past quarter-century, it is yet a challenging part of research in geodesy (Carter et al., 1989; Carter, 1994; Schone et al., 2009; Blewitt et al., 2010, Woppelmann & Marcos, 2016). Previously, the vertical deformation of the Earth surface only depends on the instrumental data, either from the Global Positioning System (GPS) or Gravity Recovery and Climate Experiment (GRACE) in land areas and GPS or satellite altimeter and tide gauge in coastal areas. Based on the study conducted by Woppelmann and Marcos (2016), they implemented the techniques of GPS, satellite altimeter, and tide gauge to measure the vertical land motion only in the coastal area. Consequently, with the emergence of space-based geodetic technologies, such as GPS, GRACE, and satellite altimeter missions, such as TOPEX, Jason-1, Jason-2, and Environmental Satellite (Envisat), the dynamical phenomena, namely vertical land motion, can be quantified by integrating those approaches.

Therefore, this study demonstrates an endeavour to estimate the vertical land motion using an integration of multi-sensor technology comprising GPS, GRACE, and satellite altimeter minus tide gauge techniques for a period of 19-year, beginning from 1999 to 2017 in the Malaysian region as illustrated in Figure 1.1. The effect of seasonal variations on GPS measurement for the vertical component is hardly reduced during data processing which would downgrade the precision of the GPS observations. Hence, this study attempts to mitigate the effect of ocean tide loading by executing the combination of local and global models in GPS processing, as well as performing moving average filtering for the excess variations. On GRACE measurement, the deformation of the Earth surface is derived based on the hydrological loading and the effect of crustal motion due to earthquake. Meanwhile, in the coastal area, the vertical land motion is measured using the satellite altimeter minus tide gauge technique.

Consequently, it is expected that quantifying the vertical land motion would be vital in forecasting the essentials of communities and ecosystems by adopting appropriate monitoring and prevention measures for future geohazards. The findings contributed by this study would also help disaster risk assessment and the level of planning and preparedness in Malaysia.

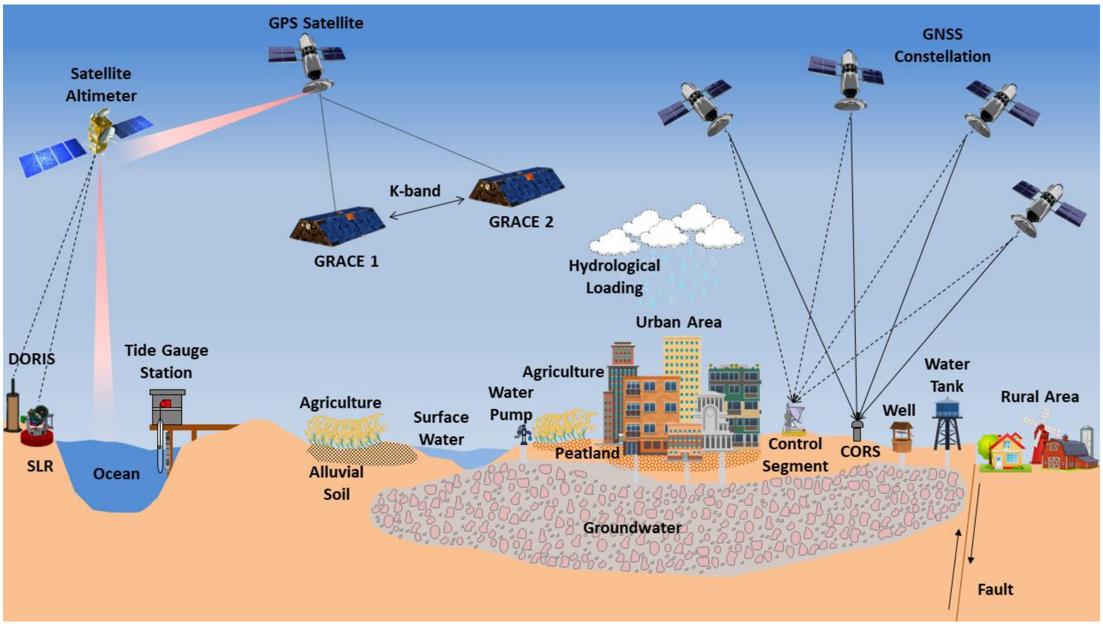

Figure 1.1 Conceptual model of this study

1.2 Problem Statement

Malaysia is geographically located in the northern hemisphere near the equator, which is bounded by water, specifically the South China Sea, Malacca Strait, Sulu Sea, and the Celebes Sea, with a large number of inhabitants populated lands and coastal areas. For that reason, Malaysia only deals with tropical climate, hot and humid climate throughout the year with the rainy period during monsoon season. In land areas, rainfall contributes a part towards hydrological; hence, increasing the risk of flood, specifically with the existence of vertical land movement (Miller & Shirzaei, 2019). Whereas, in coastal areas, Strelich (2016), Martinez-Asensio et al. (2019), Din et al. (2019), and Nandika et al. (2019) mentioned that with the existence of vertical land motion, the impact of sea level rise can be exacerbated. Both land and coastal areas will eventually encounter inundation, particularly at the flat and low surface in the presence of land subsidence. Due to the forenamed evidences, better comprehension of the vertical land motion is essential to estimate the necessities of human and ecological communities for geohazard risk assessment.

Vertical deformation might happen as the consequences of natural causes and/or anthropogenic activities, for examples crustal movement, groundwater or gas extraction (Cenni et al., 2013). During monsoon season, rainfall that acts as the surface mass load would be a major factor in the deluge, specifically at flat and low land in the presence land subsidence. In Kelantan, 47% of the public water supply is extracted from groundwater; the other 53% is from the source of surface water (Suratman, 2012). Besides, Suratman (2012) and Karim et al. (2014) also stated that the local communities had used around 38% of the total year-long national groundwater usage, and due to that, Md Din et al. (2015a) had analysed extensive land subsidence existed in Pintu Geng, Tanjung Mas, and Tumpat which are -1.78 mm/yr., -2.39 mm/yr., and -1.87 mm/yr., respectively. This has proven that land subsidence is one of the factors of the massive flood in 2014, apart from the heavy rainfall brought by the northeast monsoon.

Moreover, the information on vertical land movement is highlighted to be prominent in coastal areas as the long-term vertical motion can be equivalent or bigger than the local absolute sea level; hence, concealing the climatic-related information of the tidal data (Peltier & Tushingham, 1989; Baker, 1993; Klos et al., 2019; NASA, 2021; IPCC, 2021). Woppelmann and Marcos (2016), in their study, revealed that ground deformation should be defined preferably with standard errors that are one order of magnitude smaller than contemporaneous climate signals of 1 to 3 mm/yr. for long-term sea level studies showing how significant the precise value of vertical ground movement should be quantified. Moreover, the effect of vertical land motion can be clearly observed from the enormous coastal flooding in Torres Islands (Ballu et al., 2011), a significant sea level fall in Fennoscandia (Johansson, 2002), a continuous shrinking of coastal zone in Semarang (Nandika et al., 2019), and an inestimable damage in Venice (NASA, 2021). Eventually, the low-lying islands, coasts, and communities will experience extensive and diverse damage (Martinez-Asensio et al., 2019; IPCC, 2021).

Therefore, this study demonstrates an attempt to quantify the vertical land motion using a combination of multi-sensor space-based geodetic approaches: GPS, GRACE, and satellite altimeter minus tide gauge. To increase the accuracy and precision in measuring vertical land deformation, the effect of seasonal variations on GPS measurements should first be mitigated. Seasonal variations that correlated to GPS measurement include ocean tide loading and Earth body tide, reflecting the up-component cycle in the GPS time series, as eloquently stated by Din (2014) and Din et al. (2019). This situation could result in an error of up to 6 cm per year in Peninsular Malaysia (Alihan et al., 2019). Ocean tide loading is one of the geophysical loadings triggered by the gravitational pull of the Moon and the Sun due to the mass of the ocean tide, which, in turn, initiates the deformation of the Earth (Agnew, 2015; Bos et al., 2015). The deformation caused by this element varies based on location, tidal frequency or constituent, and sidereal time. The effect of ocean tide loading on GPS measurement is not as large as the effect of the Earth tide or the Earth body tide for the horizontal (5 cm) and the vertical component (20 – 30 cm) (Heroux & Kouba, 2001; Zheng, 2006; Cai, 2009; Bastos et al., 2010; Peng et al., 2020; Abbaszadeh et al., 2020) but poses a huge issue if the geodetic station is located near the shore (Pagiatakis, 1988; Lysaker et al., 2008; Yuan et al., 2010). Therefore, by using the combination of local and global ocean tide loading models, the effect of seasonal variations due to this geophysical effect can be minimised to increase the precision of the GPS measurement's vertical component. Previous studies have suggested implementing the moving average technique to filter excess seasonal variations caused by other sources, namely solid Earth body tide, pole tide, atmospheric pressure loading, nontidal oceanic mass, and groundwater loading.

Furthermore, to derive the deformation of the Earth surface from GRACE observation, the seasonal variation, namely hydrological loading, should be considered. The environmental mass loading in Malaysia is influenced by the tropical climate throughout the year. The climate type, along with the influence of terrestrial water storage (TWS), including groundwater storage (GWS), which can be measured by GRACE, would also contribute to the impact of seasonal loading deformation (Gu et al., 2017). Besides, the effect of tectonic motion from the seismic event of the Sumatra-Andaman earthquake that struck on 26th December 2004 in Indonesia has caused local tsunami travelling towards a dozen countries (Geist et al., 2007).

Peninsular Malaysia is no exception to receive the impact of secondary tsunami waves originating from the undersea earthquake (Ghobarah et al., 2006; Tun et al., 2006; Ahmadun et al., 2020). The vertical displacement regarding the earthquake can be derived from the GRACE measurement reflecting fluctuations in vertical time series before and after the event.

Additionally, both the direct and advanced approaches between altimetric and tide gauge data are implemented to quantify the coastal vertical land motion. The particular reason for this circumstance is to estimate the vertical deformation along the coast better. As stated by Searle (2006) and Foster et al. (2006), the earthquake that hit Indonesia has led to land uplift and caused severe damage to coral reefs, which has been raised out of water up to 2 m in the Andaman Islands, resulting in the changes of shoreline. Besides, this information would also indirectly be beneficial for sea level rise studies. Due to the uneven physically-allocated tide gauge stations in the coastal areas, there will be a gap in sea level data (Mohamed, 2003, Hamid et al., 2018; Din et al., 2019). Therefore, the advanced method of double-difference will not only overcome the geographically limited to semi-enclosed oceans, but it can also be implemented at stations in coastal area with adequate quality data (Santamaria-Gomez et al., 2014). In addition, the mutual trend errors and most of the spatially correlated signals can be cancelled if the double-difference approach is to be executed (Santamaria-Gomez et al., 2014).

Consequently, this research performs a comprehensive study on estimating the vertical land motion in the Malaysian region by associating the integration of space-based geodetic approaches: GPS, GRACE, and satellite altimeter minus tide gauge. With the limitations of each technique, such as station dependent offering point-wise data from GPS measurement (Md Din et al., 2015b; Din et al., 2019), limited data availability due to the active battery management during the certain period on one of the GRACE satellites (Fu et al., 2015), and restrained to only vertical land motion along the coast as altimetric and tidal data only provide information relative to sea level changes, can be conquered. Eventually, these three methods can complement each other; hence, providing better accuracy in vertical land motion quantification. Moreover, by integrating GPS, GRACE, satellite altimeter, and tide gauge measurement, denser information on the vertical land motion rates covering land and coastal areas can be obtained in the Malaysian region.

1.3 Research Questions

The research questions closely associated with the research objectives are foreseen to be significant in developing the main ideas of this research. The research questions are as follows:

1. How can the accuracy of the vertical component on GPS measurement be improved?
2. What is the measurement used to derive deformation of the Earth surface induced by hydrological loading and tectonic motion?
3. What is the method adopted to quantify the coastal vertical land motion?
4. How does the vertical land motion rates from the space-based geodetic techniques are combined?

1.4 Research Aim and Objectives

The aim of this research is to estimate the vertical land motion using an integration of multi-sensor space-based geodetic technology: GPS, GRACE, and satellite altimeter minus tide gauge techniques. Four objectives are outlined in order to realise the aim of this research. The objectives are as follows:

1. To improve the accuracy of the vertical component on GPS measurement by mitigating the effect of seasonal variations.
2. To derive the deformation of the Earth surface induced by hydrological loading and tectonic motion on GRACE measurement.

3. To quantify the coastal vertical land motion using satellite altimeter minus tide gauge technique.

4. To integrate the vertical land motion rates within a 19-year period, from 1999 to 2017, for the region of Malaysia using space-based geodetic techniques.

1.5 Research Scope

This research seeks to measure the vertical land motion using an integration of multi-sensor technology within a 19-year period, beginning from 1999 to 2017, for the region of Malaysia by mitigating the effect of seasonal variations on GPS time series, deriving ground deformation from GRACE measurement induced by hydrological loading and tectonic motion, and implementing satellite altimeter minus tide gauge technique for coastal vertical land motion estimation. Therefore, this research is limited to the following scope:

1.5.1 Research Area

The area covered in this research is shown in Figure 1.2. It is approximately range between 0.5° ≤ Latitude ≤ 8.0° and 98.5° ≤ Longitude ≤ 120.5°, comprising the whole Malaysian region including land and coastal areas. GPS and GRACE data interpretations are focused on land areas, whereas satellite altimetry and tidal data measurement are emphasised in the Malaysian coastal region for coastal vertical land motion.

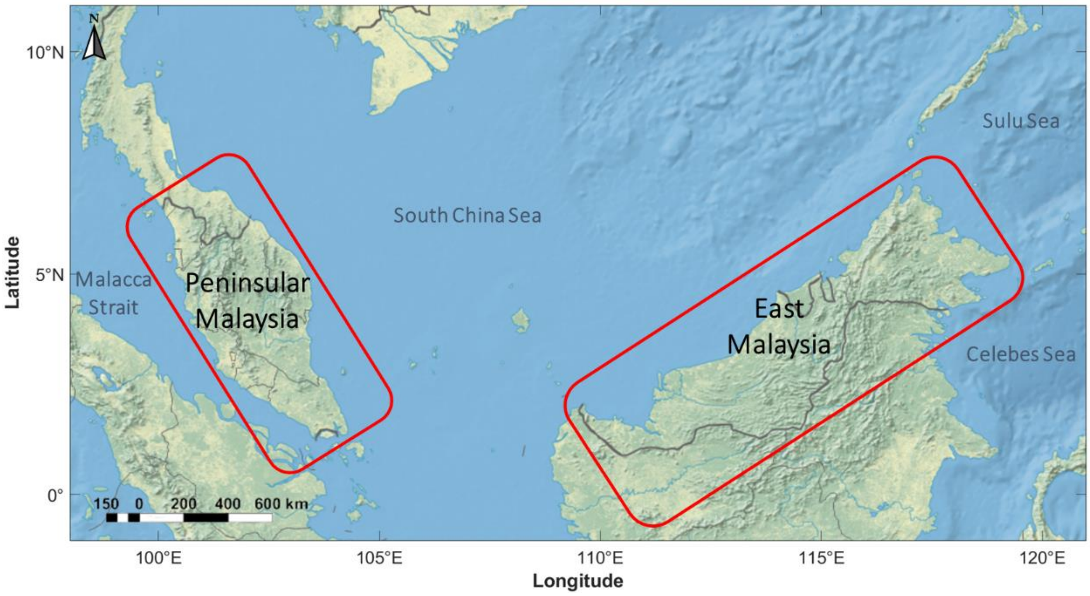

Figure 1.2 Study area comprising Malaysian region. Red boxes emphasis Peninsular and East Malaysia

1.5.2 GPS Data

The daily GPS data used in this research are gathered from nine Malaysian Active GPS System (MASS) stations (from 1999 – 2003), 78 Malaysia Real-Time Kinematic Global Navigation Satellite System (GNSS) Network (MyRTKnet) stations (from 2004 – 2017), and 53 International GNSS Service (IGS) stations (from 1999 – 2017). The GPS data of MyRTKnet and MASS stations are obtained from the Department of Survey and Mapping Malaysia (DSMM). Meanwhile, the GPS data of IGS stations are downloaded from the Crustal Dynamics Data Information System (CDDIS) data archive (https://cddis.nasa.gov/archive/gnss/data/daily/). CDDIS serves as a global data centre for IGS data and products.

1.5.3 GRACE Data

GRACE data involved in this research are divided into two categories which are the products of Level-2 and Level-3 Release 06 (RL06). GRACE products of Level-2 consist of spherical harmonic coefficients (SHC) during specific timespan from three different data providers: University of Texas Center for Space Research (UTCSR), GeoForschungsZentrum (GFZ), and Jet Propulsion Laboratory (JPL). The products of Level-3 give information on the liquid water equivalent thickness (LWET) covering the TWS of GWS, soil moisture (SM), snow water equivalent (SWE), and surface water (SW). Both data in monthly solutions are acquired from the Physical Oceanography Distributed Active Archive Center (PO.DAAC) drive (https://podaac-tools.jpl.nasa.gov/drive/files/GeodeticsGravity/grace), a National Aeronautics and Space Administration (NASA) Earth Observing System Data and Information System (EOSDIS) data centre managed by the Earth Science Data and Information System (ESDIS) Project, for a period of 16-year (from April 2002 – June 2017).

1.5.4 Global Land Data Assimilation System (GLDAS) Model

Global Land Data Assimilation System (GLDAS) is the land surface modelling developed from the assimilation techniques, which consists of hydrological products of SM, SWE, and SW. It is used in this research to obtain information on GWS. The monthly GLDAS data are downloaded from the PO.DAAC drive (https://podaac-tools.jpl.nasa.gov/drive/files/GeodeticsGravity/tellus/L3/gldas_monthly), beginning from April 2002 until June 2017.

1.5.5 Satellite Altimeter Missions' Data

Ten satellite altimeter missions used in this research are TOPEX, Poseidon, Jason-1, Jason-2, Jason-3, European Remote Sensing (ERS)-2, Envisat, CryoSat-2, Satellite with Argos and ALtiKa (SARAL), and Sentinel-3A (S3A), covering the period from January 1999 to December 2017. Even though the period of each satellite altimeter mission is dissimilar due to the limited life span of the satellite, nevertheless, by utilising the 10 multi-mission satellite altimeters, denser coverage of the monthly absolute sea level data can be retrieved continuously for a period of 19-year.

1.5.6 Tide Gauges Data

The monthly tidal data collected by DSMM are downloaded from the Permanent Service for Mean Sea Level (PSMSL) website (https://www.psmsl.org/data/). The tide gauge data used in this research covers from 1999 to 2017, for a period of 19-year. The list of selected Malaysian coastal tide gauge stations is tabulated in Table 1.1.

Table 1.1 Coordinates of tide gauge stations used in this research (PSMSL, 2018)

Number	Tide gauge Station	Latitude	Longitude
1	Geting	6° 13’ 34”	102° 06’ 25”
2	Cendering	5° 15’ 54”	103° 11’ 13”
3	Tanjung Gelang	3° 58’ 30”	103° 25’ 48”
4	Pulau Tioman	2° 48’ 26”	104° 08’ 24”
5	Pelabuhan Kelang	3° 03’ 00”	101° 21’ 30”
6	Pulau Pinang	5° 25’ 19”	100° 20’ 49”
7	Lumut	4° 14’ 24”	100° 36’ 47”
8	Kukup	1° 19’ 31”	103° 26’ 34”
9	Pulau Langkawi	6° 25’ 52”	99° 45’ 50”
10	Tanjung Sedili	1° 55’ 55”	104° 06’ 54”
11	Tanjung Keling	2° 12’ 54”	102° 09’ 11”
12	Bintulu	3° 15’ 43”	113° 03’ 50”
13	Kudat	6° 52’ 44”	116° 50’ 38”
14	Kota Kinabalu	5° 58’ 59”	116° 04’ 01”
15	Sandakan	5° 48’ 36”	118° 04’ 01”
16	Tawau	4° 14’ 00”	117° 53’ 00”
17	Labuan	5° 16’ 23”	115° 15’ 00”
18	Lahat Datu	5° 16’ 22”	118° 20’ 46”

1.5.7 Software

1.5.7.1 High-precision Bernese GNSS Processing Software Version 5.2

GPS data are processed using the double-difference approach in daily, weekly, and monthly solutions with respect to the International Terrestrial Reference Frame (ITRF) 2014 using Bernese 5.2 software.

1.5.7.2 Matrix Laboratory (MATLAB) Software

Matrix Laboratory (MATLAB) programming language is used to derive vertical displacement of the surface of the Earth from GRACE SHC. This software is also used to integrate the vertical land motion rates obtained from GPS, GRACE, and satellite altimeter minus tide gauge techniques. Furthermore, analysis and interpretation of vertical land motion rates, as well as sea level data are also executed using MATLAB software; thus, developing the Vertical Land Motion Information System (VLMIS) for the Malaysian region as by-product of this study.

1.5.7.3 Radar Altimeter Database System (RADS)

Multi-mission satellite altimetry data are processed using Radar Altimeter Database System (RADS) with absolute sea level anomaly (SLA) as the final output with respect to Denmark Technical University (DTU) 15 Mean Sea Surface (MSS) in daily and monthly solutions.

1.5.7.4 Surfer Software

The surfer software is used to interpolate vertical land motion rate during mapping in Peninsular and East Malaysia (Sabah and Sarawak), incorporated into MATLAB software.

1.5.8 Data Interpretation and Analysis

At this stage, the vertical land motion rate within 19 years period, beginning from 1999 to 2017 in the Malaysian region is interpreted and analysed based on each technique that has been implemented, which is GPS, GRACE, and satellite altimeter minus tide gauge. The scope of data analyses is limited to:

(a) Quantification and interpretation of vertical land motion rate using GPS at MASS and MyRTKnet stations.

(b) Quantification and interpretation of vertical land motion rate derived from GRACE measurement, induced by hydrological loading and tectonic motion.

(c) Quantification and interpretation of vertical land motion rate derived from satellite altimeter and tide gauge via altimeter minus tide gauge technique.

(d) Comparison of vertical land motion rates between those derived from GPS, GRACE, and altimeter minus tide gauge techniques.

(e) Interpretation of integrated vertical land motion rates from GPS, GRACE, and satellite altimeter minus tide gauge technique.

1.6 Research Significances

The significances of this research are recapitulated as follows:

1. This research emphasises the importance of the vertical land motion information for Malaysia's development, security, and geohazard risk assessment in land and coastal areas. The information on the vertical land motion is able to help disaster risk assessments and increase the level of planning and preparedness in Malaysia. Additionally, the authorities can characterise the areas affected by geological hazards and forecast the regions that are potentially susceptible to land subsidence, therefore reducing and compensating for the impact of land deformation.

2. As the accuracy of the vertical components on GPS measurement is still substandard, this research initiates an improvement to reduce the effect of seasonal variations by implementing the combination of local and global ocean tide loading models in GPS processing and performing moving average filtering against GPS vertical position time series.

3. This research endeavours to specify the significant factors that contribute to the deformation of the Earth surface based on GRACE measurement in the Malaysian region. The impact of hydrological loading and tectonic motion towards vertical land deformation are highlighted in this research.

4. This research demonstrates the direct and advanced 'altimeter minus tide gauge' techniques in deriving the rate of vertical land motion. These approaches exemplify the potential estimation of vertical land motion rate not only at tide gauge stations, but also along the coastal in between the pair of tide gauge stations, based on the information on absolute and relative sea level data.

5. This research intends to originate an integration of multi-sensor space-based geodetic approaches: GPS, GRACE, and satellite altimeter minus tide gauge in order to quantify and interpret the vertical land motion rates in the Malaysian region based on relatively long (~19 years) geodetic analysis. These methods evidently complement each other to obtain denser information on vertical land motion in Malaysia, hence generating the spatial map. The results are anticipated to be beneficial for geohazard risk assessments, specifically land subsidence, as well as for precise long-term sea level rise study from the information of coastal vertical land motion.

1.7 General Research Methodology

The flowchart of general research methodology consists of five phases, as justified in Figure 1.3.

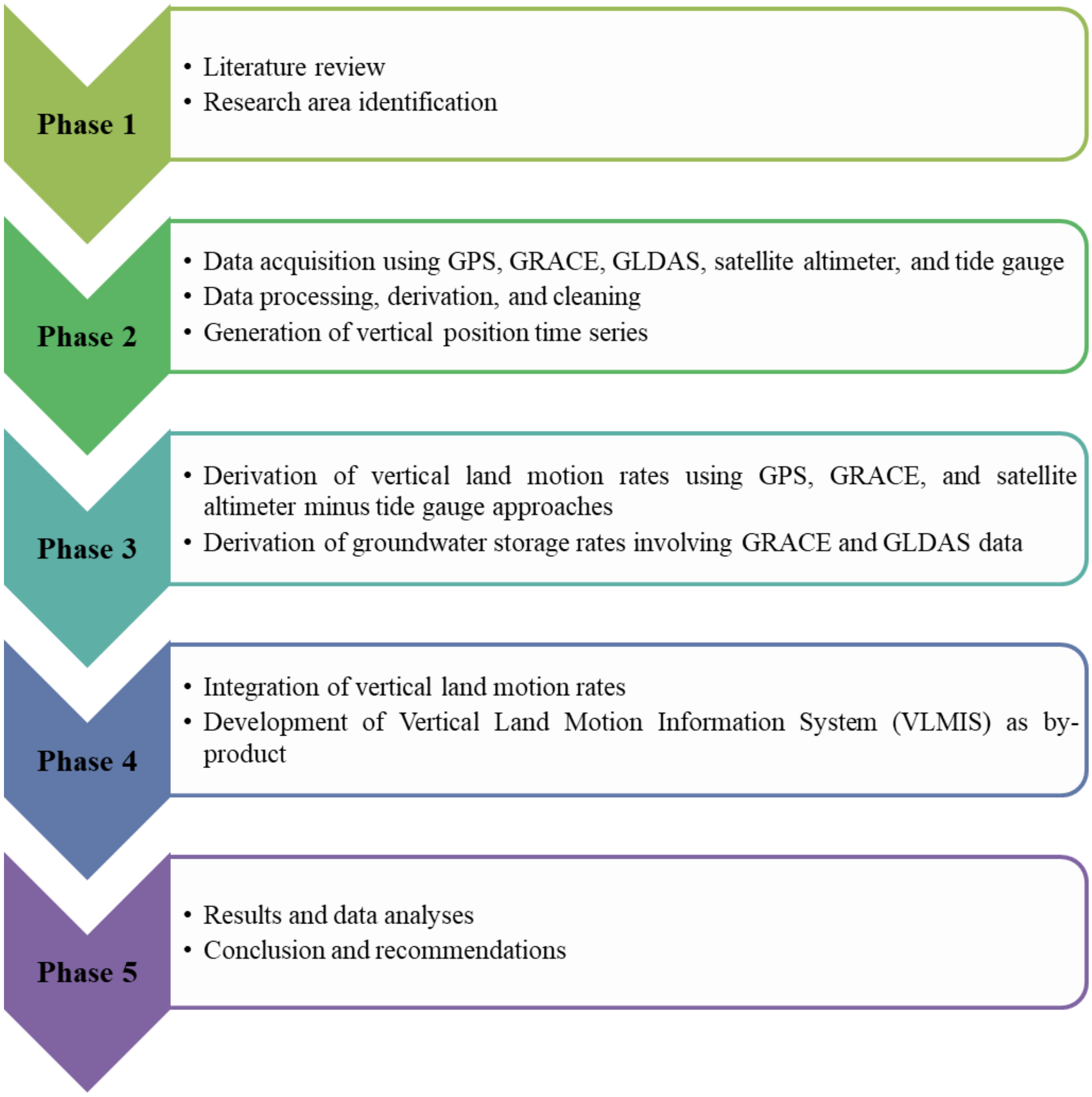

Figure 1.3 Flowchart of general research methodology

1.7.1 PHASE 1

1.7.1.1 Literature Review

Literature review is a significant stage to have a better understanding in completing this research. There are the topics highlighted for further improvisation on the research methodology, such as:

(a) Theories of vertical land motion, seasonal variations, hydrological loading, tectonic motion, and sea level.

(b) Principle of GPS, GRACE, satellite altimeter, and tide gauge.

(c) Derivation of vertical land motion rates from the measurement of GPS, GRACE, and satellite altimeter minus tide gauge techniques.

(d) High precision GNSS processing software: Bernese version 5.2.

(e) MATLAB programming language.

(f) Altimeter processing software: RADS

(g) Filtering and least squares methods.

1.7.1.2 Research Area Identification

The area of this study covers the whole Malaysian region comprising land and coastal areas, as shown in Figure 1.2.

1.7.2 PHASE 2

1.7.2.1 Data Acquisition and Processing

Five techniques involved in data gathering are enlisted as follows:

(a) GPS

The GPS data are gathered from nine MASS stations (from 1999 – 2006), 78 MyRTKnet stations (from 2004 – 2017), and 53 IGS stations (from 1999 – 2017). These data are further processed in Bernese version 5.2 using double-difference strategy in daily, weekly, and monthly solutions. In addition, to increase the accuracy of the vertical component, the combination of local and global ocean tide loading models is incorporated in the Bernese processing. Once the time series of vertical position are generated, the moving average method is executed to filter the residue of the seasonal variation effect.

(b) GRACE

GRACE products of Level-2 and Level-3 (from April 2002 – June 2017) RL06 are downloaded from the PO.DAAC drive. The Level-2 products consist of SHC of cosine and sine coefficients for specific degrees, and order is used in the MATLAB programming platform. The calculation involves certain mathematical equations, such as Legendre function and load Love numbers to derive the displacement of the Earth surface in the radial direction. Meanwhile, the Level-3 ready-to-use products can directly be used to derive mass changes from the information on the LWET. The LWET reflects the information of TWS, including GWS, SM, SWE, and SW, which more or less influence the occurrence of vertical deformation.

(c) GLDAS

The land surface modelling, namely GLDAS, is downloaded from PO.DAAC drive as well, covering a period from April 2002 until June 2017. It comprises information on SM, SWE, and SW, dissimilar to the GRACE product of Level-3, which includes information on GWS. GLDAS data are used in conjunction with the Level-3 data of GRACE products to derive information on GWS, involving simple mathematical calculation.

(d) Satellite altimeter

Data retrieval and processing of multi-mission satellite altimeter: TOPEX, Poseidon, Jason-1, Jason-2, ERS-2, Envisat, CryoSat-2, SARAL, and S3A are performed in RADS. Any corrections applied to the data during processing are also executed in RADS. The output obtained from the processing is sea level anomaly, where it is used to quantify absolute sea level rate for a period of 19-year, beginning from January 1999 until December 2017 using robust fit regression in MATLAB software.

(e) Tide gauge

Tidal data gathered and archived by DSMM are downloaded from PSMSL (from 1999 – 2017) involving 18 stations, as listed in Table 1.1. The tide gauge data only requires cleaning process to remove outliers and bad data before tidal analysis is performed. Unlike GPS, GRACE, and altimetry data, tidal data do not entail complicated processing. Data cleaning is easily performed in Microsoft Excel and/ or TextPad. Subsequently, the relative sea level rate is derived from the SLA of tidal data.

1.7.3 PHASE 3

1.7.3.1 Derivation of Vertical Land Motion Rate

In this research, the rate of vertical land motion is quantified from the three space-based geodetic approaches: GPS, GRACE, and satellite altimeter minus tide gauge. The rates are acquired from the GPS vertical position time series, displacement of the Earth surface in radial direction derived from GRACE, and rate of sea level via satellite altimeter minus tide gauge, using robust fit regression analysis in MATLAB software.

1.7.3.2 Derivation of Groundwater Storage Rate

The derivation of GWS rate requires input from the GRACE products: Level-3 and the GLDAS surface model. Since GRACE measurement consists of all information on TWS, including GWS, for GLDAS measurement, it is necessary to compute the anomaly of GWS since it does not include GWS in the observation data. Only simple mathematical calculation is involved in obtaining the information on GWS before the rate is calculated using robust fit regression in the MATLAB programming platform.

1.7.4 PHASE 4

1.7.4.1 Integration of Vertical Land Motion Rates

This phase integrates the rate of vertical land motion within a period of 19-year, from 1999 to 2017, in the Malaysian region based on land and coastal areas derived from GPS, GRACE, satellite altimeter, and tide gauge measurements. The integration is executed using MATLAB programming language by adopting the least-squares collocation method. Prior to the integration, the assessment and interpretation of each measurement technique in deriving the rate of vertical land motion are evaluated such follows:

(a) Evaluation of vertical land motion rate using GPS at MASS and MyRTKnet stations after implementing the combination of local and global ocean tide loading models in GPS processing.

(b) Evaluation of GPS vertical time series after performing moving average method to filter the effect of the seasonal variation.

(c) Evaluation of vertical land motion rate derived from GRACE measurement.

(d) Evaluation of GWS rate derived from the ready-to-use GRACE data and GLDAS land surface model.

(e) Evaluation of absolute sea level rate derived using multi-mission satellite altimeter.

(f) Evaluation of relative sea level rate derived using tidal data.

(g) Evaluation of coastal vertical land motion rate derived from satellite altimeter and tide gauge via altimeter minus tide gauge.

(h) Comparison of vertical land motion rates between those derived from GPS, GRACE, and satellite altimeter minus tide gauge techniques.

1.7.4.2 Development of Vertical Land Motion Information System (VLMIS)

VLMIS is developed as a by-product of the research. The system consists of updated data analysis on vertical land motion rates for the Malaysian region estimated from GPS, GRACE, satellite altimeter minus tide gauge, and the combination of the three geodetic techniques for 19-year, from 1999 to 2017. The VLMIS allows users to analyse and interpret the data in spite of serving as a data cache and analysis medium for vertical land motion rates. MATLAB programming language involving the App Designer to lay out the visual components of a graphical user interface (GUI) and program app behaviour.

1.7.5 PHASE 5

1.7.5.1 Results and Data Analyses

This phase concentrates on the analyses and discussions based on the results obtained from this research. The findings include vertical land motion rate, pattern, and trend in the Malaysian region comprising land and coastal areas. The outputs from each measurement method and the outcomes on the parameters or strategies incorporated during data processing to achieve the optimum results are presented in this section.

1.7.5.2 Conclusion and Recommendations

The conclusion is made relative to the objectives and outputs of the research. Then, suggestions and recommendations to enhance future studies are provided.

1.8 Thesis Outlines

This thesis aims to estimate and interpret the vertical land motion in Malaysia using an integration of GPS, GRACE, and satellite altimeter minus tide gauge techniques. To realise the aim, this thesis is composed of five chapters as follows:

Chapter 1 introduces the definition of this research comprising of research background, problem statement, research aim, and objectives. Research scope, significances and a brief general research methodology for this research are also discussed in this chapter.

Chapter 2 reviews the theory on the vertical land motion related to the seasonal variations, hydrological loading, tectonic motion, and sea level. The explanation on how each measurement technique (GPS, GRACE, and satellite altimeter minus tide gauge) is translated into vertical land motion rate is also included. Eventually, a novel method to quantify the rate of vertical land motion by combining the three multi-sensor space-based geodetic technology techniques is discussed in this chapter.

Chapter 3 details the methodology on the derivation of vertical land motion rates for each space-based geodetic method: GPS, GRACE, and satellite altimeter minus tide gauge, as well as the integration of those methods. Moreover, Chapter 3 also describes data acquisition, preparation, and processing using Bernese version 5.2, MATLAB, and RADS software for every method implemented. Any mathematical equation and calculation involved to derive vertical land motion are also demonstrated.

Chapter 4 discusses the results and interpretation of the vertical land motion for each technique implemented, namely GPS, GRACE, and satellite altimeter minus tide gauge. The data that have been processed are presented as evidence of the research methodology. Subsequently, the assessment of vertical land motion rates derived from every method is conducted before the output is integrated to attain the best accuracy of the vertical land motion rates. Nevertheless, the main focus of Chapter 4 is to provide the rate and trend of vertical land motion over the Malaysian region for a period of 19-year based on the three multi-sensor technologies in the form of spatial map and vertical position time series.

Chapter 5 summarises the whole research idea, major findings, and conclusion of the research. The suggestions and recommendations for future studies are also outlined.

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AWARD

1. Best presenter of Department of Geoinformation, Faculty Built Environment and Surveying, Universiti Teknologi Malaysia, for paper title, The Differences

between Coordinates in GDM2000 based on Revision in 2009 & 2016, in virtual International Graduate Conference of Built Environment and Surveying (GBES 2021).

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1. Impact of Different International Terrestrial Reference Frames on Positioning and Mapping in Malaysia. Inventors: Ami Hassan Md Din and Nur Adilla Zulkifli. *Copyright.* Innovation and Commercialisation Centre (ICC, UTM). 2nd July 2017. Filing Number: LY2017005586.

2. Derivation of Vertical Land Motion Rates around Malaysia based on Optimisation of GPS Observation. Inventors: Ami Hassan Md Din and Nur Adilla Zulkifli. *Copyright.* Innovation and Commercialisation Centre (ICC, UTM). 22nd September 2020. Filing Number: LY2020007060.