ESTIMATION OF GEOPHYSICAL LOADINGS OVER THE MALAYSIAN REGION BASED ON KINEMATIC PRECISE POINT POSITIONING GPS TECHNIQUE

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DEDICATION

Special dedicated to
my dearly loved family

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In the name of Allah, the most Merciful and Beneficient

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ABSTRACT

The earth's crust undergoes natural deformation due to the geophysical loadings that consist of the earth body tide, ocean tide loading, atmospheric pressure loading and pole tide. This periodic displacement is generated by the changes of the gravitational attraction between the moon and the sun acting upon the earth's rotation, along with the temporal atmospheric changes and the variability of the ocean tide. The study of the geophysical loadings is important in the geodesy field as the magnitude of the signals is significant and can contribute to errors in space geodetic measurements such as Global Positioning System (GPS), Very-Long Baseline Interferometry (VLBI) and Altimeter. This study aims to estimate the spatio-temporal variation of the geophysical loadings due to the earth body tide, ocean tide loading and the total signals of the earth tide over the Malaysian region, based on the GPS observations by using a Kinematic Precise Point Positioning (KPPP) GPS approach. Continuous GPS observations over a one-year period in the year 2013 have been utilised to observe the diurnal, semi-diurnal and long-term periods of tidal constituents. The tidal analysis of harmonic and spectral are conducted to examine the characteristic of the geophysical loadings as well as to estimate the tidal parameters of the tidal constituents. The results of the geophysical loadings derived from the KPPP GPS solutions correlate well with the predictions of the theoretical models, IERS2003 and NAO.99b, with the correlation coefficient above 0.90 at three components: north, east and up. The root mean square error (RMSE) is less than ±1 cm at north and east components and around ±6 cm at up component for both earth body tide and earth tide. The RMSE is minimal at all components of ocean tide loading. The presence of the geophysical loadings indicates that as many as 76% to 93% of the geophysical loadings signal are contained in the GPS time series. The findings reveal that earth body tide signals are more significant if compared to ocean tide loading signals because the magnitude of the earth body tide is greater than that of the ocean tide loading and it affects the coordinate system particularly at up component. The spatio-temporal variation of the geophysical loadings is generated during the apogee and perigee phenomena, monsoon seasons and throughout the year 2013 to provide the information on the temporal changes from the geophysical loadings response. Results have widened the understanding of geophysical loadings variations in equatorial regions and illustrated the potential of GPS to provide the local parameters of the geophysical loadings that are beneficial for earth tidal modelling and that can be used to improve the quality of space geodetic measurements.

ABSTRAK

Permukaan kerak bumi mengalami deformasi semula jadi disebabkan oleh beban geofizik yang terdiri daripada pasang surut kerak bumi, beban pasang surut air laut, beban tekanan atmosfera dan pasang surut kutub. Anjakan berkala ini terhasil daripada perubahan tarikan graviti antara bulan dan matahari yang bertindak ke atas putaran bumi di samping perubahan atmosfera dan perubahan pasang surut air laut. Kajian mengenai beban geofizik adalah penting dalam bidang geodesi kerana magnitud isyarat yang dinyatakan adalah ketara dan boleh menyumbang kepada kesalahan pengukuran geodetik angkasa seperti Sistem Penentududukan Global (GPS), Interferometri Asas Sangat Panjang (VLBI) dan Altimeter. Kajian ini adalah untuk menganggarkan variasi ruang-masa beban geofizik akibat daripada pasang surut kerak bumi, beban pasang surut air laut dan jumlah isyarat pasang surut bumi di rantau Malaysia berdasarkan pemerhatian GPS dengan menggunakan pendekatan ketepatan titik penentududukan kinematik jitu (KPPP) GPS. Cerapan GPS yang berterusan sepanjang tempoh setahun pada tahun 2013 digunakan untuk memerhatikan juzuk pasang surut diurnal, separuh diurnal dan juzuk jangka panjang. Analisis pasang surut harmonik dan spektral dijalankan untuk mengkaji ciri-ciri beban geofizik dan juga untuk menganggarkan parameter juzuk pasang surut. Hasil beban geofizik yang diperoleh daripada KPPP GPS berkorelasi baik dengan ramalan model teori, IERS2003 dan NAO.99b, dengan pekali korelasi di atas 0.90 bagi komponen utara, timur dan ketinggian. Minimum selisih punca kuasa dua (RMSE) adalah kurang daripada ±1 cm bagi komponen utara dan timur dan dalam anggaran ±6 cm bagi komponen ketinggian untuk pasang surut kerak bumi dan pasang surut bumi. RMSE adalah minimum di semua komponen beban pasang surut air laut. Kewujudan beban geofizik menunjukkan bahawa sebanyak 76% hingga 93% isyarat beban geofizik terkandung dalam siri masa GPS. Hasil kajian menunjukkan bahawa isyarat pasang surut kerak bumi adalah lebih ketara berbanding dengan beban pasang surut air laut kerana magnitud pasang surut kerak bumi lebih besar daripada beban pasang surut air laut dan ia memberi kesan kepada sistem koordinat terutamanya di komponen ketinggian. Variasi ruang-masa beban geofizik dihasilkan semasa fenomena apogee dan perigee, musim tengkujuh dan sepanjang tahun 2013 untuk memberikan maklumat tentang perubahan masa dari tindak balas beban geofizik. Keputusan dapat meluaskan pemahaman mengenai variasi beban geofizik di kawasan khatulistiwa dan ia menunjukkan potensi GPS dalam menyediakan parameter beban geofizik tempatan yang bermanfaat untuk pemodelan pasang surut bumi dan dapat digunakan untuk meningkatkan kualiti pengukuran geodetik.

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LIST OF ABBREVIATIONS

3D	-	three-dimensional
ATX	-	antenna phase variation center
CLK	-	IGS final clock
CORS	-	Continuously Operating Reference System
CPD	-	cycle per day
CUI	-	Comment User Interface
DCB	-	Differential Code Bias
DORIS	-	Doppler Orbitography and Radiopositioning Integrated by Satellite
DSMM	-	Department of Survey and Mapping Malaysia
ERP	-	Earth Rotation Parameter
FFT	-	Fast Fourier Transform
GIS	-	Geographic Information System
GMT	-	Generic Mapping Tools
GNSS	-	Global Navigation Satellite System
GOTIC2	-	Global Oceanic Tidal Correction
GPS	-	Global Positioning System
IGS	-	International GPS/GNSS Service
IHO	-	International Hydrographic Organization
K1	-	luni-solar diurnal
K2	-	luni-solar semi-diurnal
KPPP	-	Kinematic Precise Point Positioning
M2	-	principal lunar semi-diurnal
Mf	-	lunar fortnightly
Mm	-	lunar monthly
MyRTKnet	-	Malaysian Real-Time Kinematic GNSS Network
N2	-	larger lunar elliptic semi-diurnal

O1	-	principal lunar diurnal
P1	-	principal solar diurnal
Q1	-	larger lunar elliptic diurnal
RMSE	-	root mean square error
RTKLIB	-	Real-Time Kinematic Library
S2	-	principal solar semi-diurnal
SP3	-	precise ephemeris
Ssa	-	solar semi annual
VLBI	-	Very Long Baseline Interferometry

LIST OF SYMBOLS

F_a	-	the attraction force of particle A
F_b	-	the attraction force of particle B
F	-	the attraction force between both particle A and B
G	-	the gravitational constant (6.674×10^{-11} N m^2 kg^{-2})
M_a	-	mass of particle A
M_b	-	mass of particle B
c	-	the distance between the center of the mass of both particle A and B
E	-	center of the earth
M	-	center of the moon
Q	-	the point on the earth's surface
F_Q	-	the attraction force of particle at point Q
M_m	-	mass of the moon (7.35×10^{22} kg)
b	-	the distance of the particle at point *Q* to the center of the moon
a	-	the distance of particle at point *Q* from the center of the earth
θ	-	the angle at the center of the earth between *EM* and *EQ*
A_o	-	the coefficient
n	-	the tidal constituents
A_n	-	amplitude of the tidal constituent n
ω_n	-	angular frequency of the tidal constituent n
t	-	time epoch
θ_n	-	the phase of the tidal constituent n
a_n	-	coefficients of series
b_n	-	coefficients of series
X	-	unknown parameter
L	-	observation data
A	-	design matrix
E_{Total}	-	total energy
f_s	-	sampling frequencies

f_h	-	highest frequencies
$f(\eta)$	-	frequency in cycles per unit time
Δt	-	sampling interval
Z	-	the length of data
j	-	the j^{th} tidal data
E_s	-	Energy Spectral Density
n, m	-	degree and order
h_{mn}	-	Love numbers
l_{mn}	-	Shida numbers
$\Delta\vec{r}$	-	the vector displacement of the station
GM_e	-	the gravitational parameter of the earth
GM_j	-	the gravitational parameter of the moon *(j=2)* or the sun *(j=3)*
$\hat{R}_j, R_j$	-	the unit vector from the geocenter of the earth to the moon or sun, and it's magnitude
R_e	-	equatorial radius of the earth ($R_e = 6\,378\,136.6\,m$)
$\hat{r}, r$	-	the unit vector from the geocenter of the earth to station, and it's magnitude
h_2	-	the nominal degree 2 Love number ($h_2 = 0.6078$)
l_2	-	the nominal degree 2 Shida number ($l_2 = 0.0847$)
Δc_k	-	the tidal displacement of component k
Δr	-	vertical displacement
p	-	local air pressure anomaly
$\bar{p}$	-	average of the pressure anomaly
$\Delta\lambda$	-	displacement longitudinal
$\Delta\theta$	-	displacement latitudinal
$\widehat{EBT}$	-	earth body tide derived from KPPP GPS
$\widehat{OTL}$	-	ocean tide loading derived from KPPP GPS
$\widehat{ET}$	-	earth tide derived from KPPP GPS
$\overline{EBT}$	-	earth body tide model, IERS2003
$\overline{OTL}$	-	ocean tide loading model, FES2012
$\varepsilon_{\overline{EBT}}$	-	earth body tide model error
$\varepsilon_{\overline{OTL}}$	-	ocean tide loading model error

UCL	-	upper control limit
CL	-	control limit
LCL	-	lower control limit
χ	-	mean
σ	-	standard deviation
R	-	linear correlation coefficient
h	-	number of pairs data
x	-	the predictions of the theoretical model data
y	-	the observations of geophysical loadings based on KPPP GPS solutions
v_χ	-	residuals of data x
v_γ	-	residuals of data y
m	-	gradient of the straight line
V_e	-	residual vector
l_i'	-	the second iterations of observations
l_i	-	original observations
v_i	-	residuals of the observations
P_{EBT}	-	presence of the earth body tide
P_{OTL}	-	presence of ocean tide loading
P_{ET}	-	presence of earth tide

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CHAPTER 1

INTRODUCTION

1.1 Background of the Study

Malaysia, geographically located in the Sunda Plate, is surrounded by the South China Sea, the Andaman Sea and the Straits of Malacca towards the north and the south of Peninsular Malaysia, respectively, while the Sulu Sea along with the Celebes Sea and the Makassar Strait are located near Sabah and Sarawak as shown in Figure 1.1. This country is exposed to various types of natural hazards such as land subsidence, landslides, earthquakes and natural deformation phenomena as it close to the one of the most active seismic plate boundaries between the Indo-Australian and Eurasian Plate (Yong, 2013). This exposure indicates the implication toward the coordinate system, geodetic positioning, and deformation study in Malaysia.

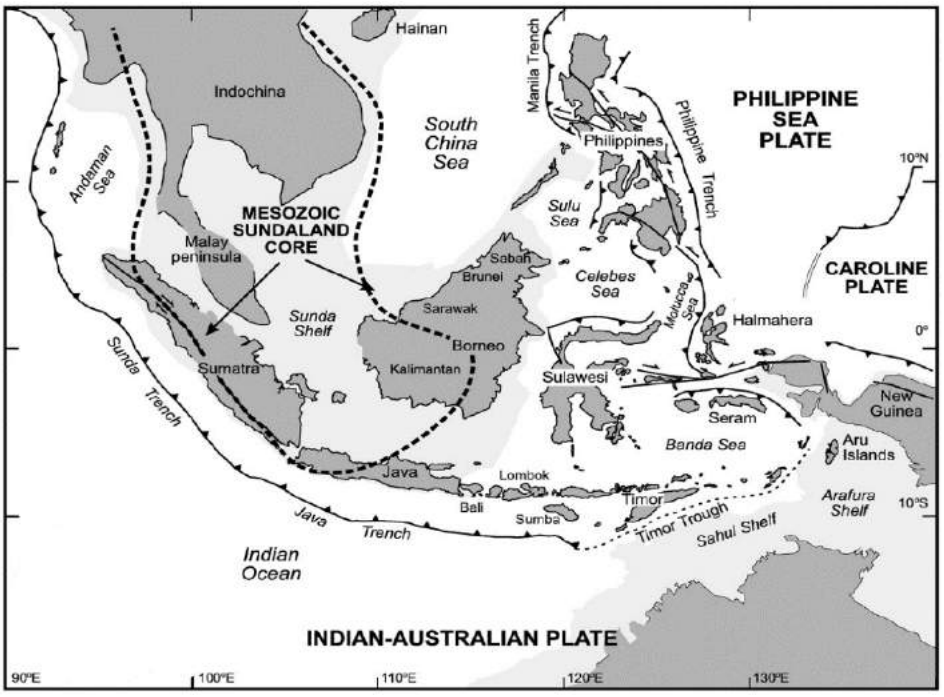

Figure 1.1 The geophysical setting of Malaysia (Hall *et al.*, 2008).

Generally, the realization of the reference coordinate system used in the satellite geodesy demands a good understanding about the dynamic of the earth. As eloquently stated by Abidin (2001), the dynamic of the earth has a wide spectrum from the scale of the galaxy to the scale of the local movement underneath the earth's crust. There are three types of earth dynamic that affect the coordinate system in satellite geodesy, which are the earth orbit around the sun alongside with the other planets, the earth rotation about its axis and the relatively slow movement of the earth's crust. The rotation of the earth has been affected by the gravitational force between the moon and the sun, the geophysical movement of mass distribution within the solid earth, ocean tide loading, atmospheric loading, and plate tectonic motions (Dickey, 1995; Abidin, 2001). Figure 1.2 illustrates the forces that perturb the rotation of the earth and the coordinate system.

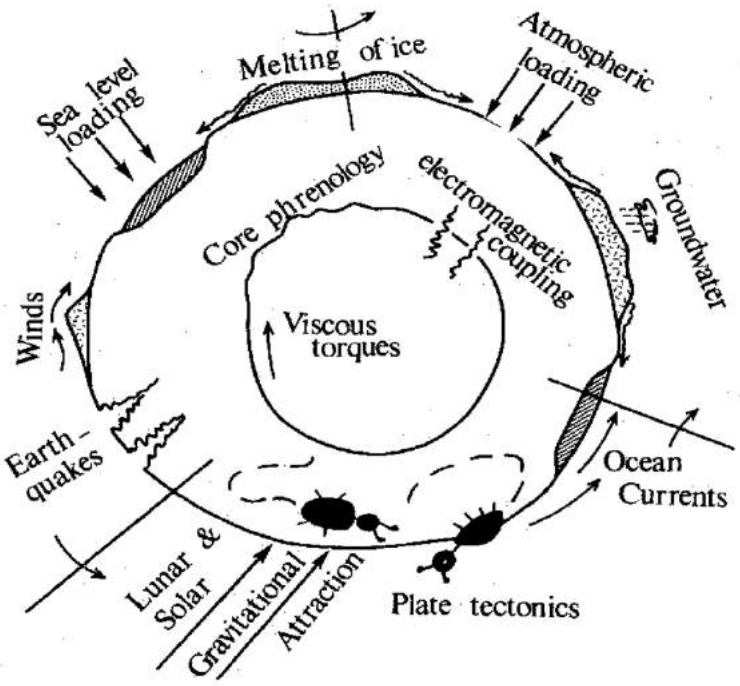

Figure 1.2 The forces that affect the earth rotation and the coordinate system (Dickey, 1995).

Recently, with the high demand for precise measurement, the knowledge of the dynamic of the earth has become important in the field of geodesy. Thus, this study widened the understanding of the dynamic of the earth due to the geophysical loadings phenomena in the Malaysian region. The periodic ground displacements due to the changes of gravitational attraction between the moon and the sun along with the

varying of the ocean tide referred as earth body tide and ocean tide loading, respectively (Agnew, 2009; Bos *et al.*, 2015). The earth body tide is the largest periodic motion of the earth's crust compared to ocean tide loading which it can reach in the centimeter (cm) level of displacements, about 5 cm in the horizontal plane and 20-30 cm in the vertical component (Héroux and Kouba, 2001; Zheng, 2007; Cai, 2009). However, the loading effect of the ocean tide loading can be large as the geodetic stations are very close to the shore (Pagiatakis, 1988). As explained by Agnew (2009), there are three important parts of the tidal deformations in geophysics. First, the facts about the earth will be obtained from the measurement of the tidal deformations. Second, the tidal effects against the geodetic measurement can be eliminated by using the models of the tidal deformations. Third, these models can be used to investigate the impact of the tidal variations towards the geophysical phenomenon such as earthquakes, tsunami and volcanic activity (Agnew, 2009).

Conventionally, the precise point measurement of tidal response is commonly measured by various instruments such as super-conducting gravimeters, strain meter and tilt observations. However, the rising cost of operation, the less data provided, the sparse distribution of station and the difficulty of accessing the best location for low-noise site causes inconsistent observations to expose the spatial heterogeneity of the solid earth tidal field (Ito *et al.*, 2009). With the advent of precise space geodetic techniques such as Very Long Baseline Interferometry (VLBI) and Global Positioning System (GPS), it is possible to determine geophysical characteristics of tidal deformations *i.e*. earth tide (the sum of earth body tide and ocean tide loading), ocean tide loading, and earth body tide (Vey *et al.*, 2002; Ito *et al.*, 2009; Bos *et al.*, 2015). Furthermore, the studies that used the technology of GPS have achieved millimeter-level accuracy in tidal measurements which have better precision than superconducting gravimeter (Yuan *et al.*, 2013).

Since the VLBI stations are limited worldwide, the study utilised the operational GPS Continuously Operating Reference System (CORS) existing in Malaysia which is the Malaysian Real-Time Kinematic GNSS Network (MyRTKnet) operated by the Department of Survey and Mapping Malaysia (DSMM). These GPS CORS networks currently are widely used to support various applications such as

precise positioning, surveying, navigation, mapping and research studies. Furthermore, the GPS CORS does not drift during strong ground motion, provide an absolute measurement and is cheaper in terms of installation and maintenance. These advantages lead to the study of using GPS to investigate the spatio-temporality of earth tidal deformations in the Malaysian region.

1.2 Statement of the Problem

Malaysia's crust undergoes periodic displacements due to the gravitational attraction between the moon and the sun, temporally varying atmospheric, surface loads, oceanic and continental water mass. The gravitational force and ocean tide water movement periodically load and unload the earth causing the changes of displacement, tilt and gravity. The most significant changes are directly underneath the load such as on the sea floor (Pagiatakis, 1988). This periodic ground displacement affects the coordinate system and has gained importance in geodesy as the high precision of space geodetic measurements (*e.g.* GPS, VLBI, Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS) and Altimeter) required the correction from the tidal effects to maximize their extensive use in geodesy and geophysical studies such as monitoring the variations of mean sea level and quantifying the vertical land motion (Agnew, 2009). Thus, to increase the accuracy of satellite positioning and geodetic measurement techniques to sub-millimeter level, a good knowledge of the tidal deformation is imperative.

Equation (1.1) represented the example of the mathematical model for GPS positioning (El-Rabbany, 2002; Hofmann-Wellenhof *et al.*, 2007).

$$L_{L2} = \rho + c\,(dt^s - dt_R) - dion_{L2} + dtrop + (dH^S + dH_R)_{L2} + dmp_{L2} + \lambda_{L2}N_{L2} + E_{L2} \qquad (1.1)$$

where L_{L2} is the carrier phase measurement on L2 frequency, ρ is pseudorange, *dion* is ionospheric delay, *dtrop* is troposheric delay, dH^S and dH_R are satellite and receiver hardware, respectively, *dmp* is the multipath effect and *E* is the measurement noise.

From the equation (1.1), there are parameter known as pseudorange that estimated from satellite position (χ^s, γ^s, Z^s) and initial receiver position $(\chi_{R^0}, \gamma_{R^0}, Z_{R^0})$ that can be expressed as follows (El-Rabbany, 2002; Hofmann-Wellenhof *et al.*, 2007):

$$\rho_{R^\circ}^{S} = \sqrt{\left(\chi^s(t) - \chi_{R^0}(t)\right)^2 + \left(\gamma^s(t) - \gamma_{R^0}(t)\right)^2 + \left(Z^s(t) - Z_{R^0}(t)\right)^2} \qquad (1.2)$$

If the GPS observation in the static mode, it can be assumed that the initial of the receiver position is remain unchanged. However, due to the existing of the geophysical loadings, the initial of receiver position are actually displaced to $(\chi_{R'}, \gamma_{R'}, Z_{R'})$ as shown in Figure 1.3.

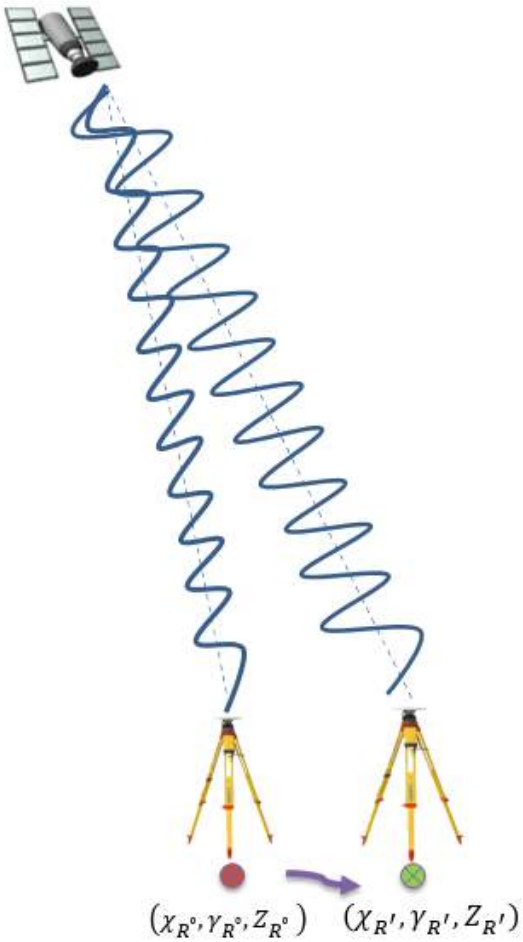

Figure 1.3 The initial of the receiver position is displaced from $(\chi_{R^0}, \gamma_{R^0}, Z_{R^0})$ to $(\chi_{R'}, \gamma_{R'}, Z_{R'})$ due to the geohysical loadings effect.

Therefore, the site displacement should be corrected by using equation (1.3) to (1.5) where $(\Delta X, \Delta Y, \Delta Z)$ is estimated from the tidal effects of the geophysical loadings.

$$\chi_{R'} = \chi_{R^0}(t) + \Delta X \tag{1.3}$$

$$\gamma_{R'} = \gamma_{R^0}(t) + \Delta Y \tag{1.4}$$

$$Z_{R'} = Z_{R^0}(t) + \Delta Z \tag{1.5}$$

With the advent of precise space geodetic techniques such as GPS and VLBI, the study of the interior of the earth from the surface observations of the loading effects can provide the consistency of observations in revealing the spatial heterogeneity of the solid earth tidal field. In this study, the technology of GPS is utilised to investigate the characteristic of the tidal displacement as Malaysia has 78 GPS CORS stations distributed between 30 to 120 km apart since the VLBI stations are limited in number, with only 35 stations available worldwide. Furthermore, several studies have utilised the GPS since around 2000 to validate the tidal displacement based on GPS with the predictions from both earth body tide models and ocean tide loading model (Ito *et al.*, 2009; Penna *et al.*, 2015).

1.3 Research Objectives

The aim of this study is to estimate the spatio-temporal variation of geophysical loadings over the Malaysian region based on GPS observations. This study has undertaken to pursue three objectives as follows:

i. To estimate the correlation between the GPS solutions and the predictions from the theoretical earth tidal model.
ii. To determine the tidal parameters of the earth body tide, ocean tide loading and earth tide.
iii. To examine the characteristics of geophysical loading over the Malaysian region.

1.4 Scope of the Study

The scopes of this study are described as follows:

1. This study utilised the Malaysian Real-Time Kinematic GNSS Network (MyRTKnet) operated by the Department of Survey and Mapping Malaysia (DSMM). MyRTKnet consists of 50 and 28 GPS Continuously Operating Reference Station (CORS) over Peninsular Malaysia and East Malaysia, respectively. However, only 70 GPS observation stations with intervals of 30 seconds can be used in this study due to the other eight (8) stations having bad observations in 2013. The distribution of the MyRTKnet stations is shown in Figure 1.4.

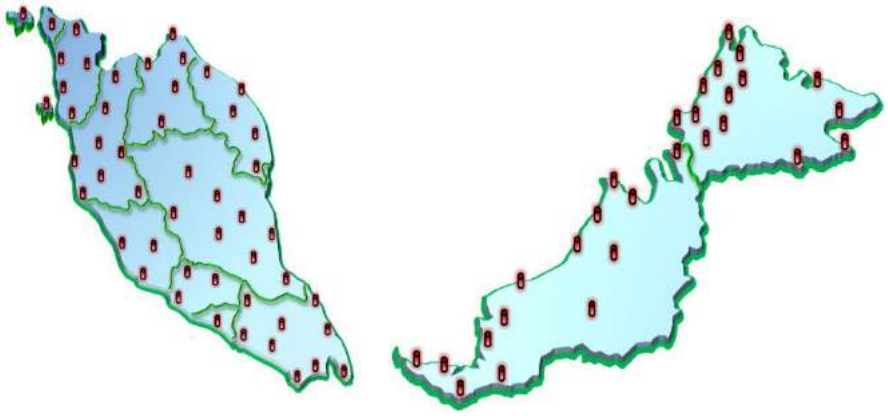

Figure 1.4 The distribution of MyRTKnet stations around Malaysia.

2. An open source software RTKLIB with Comment User Interface (CUI) is employed to process the GPS data from MyRTKnet stations using Kinematic Precise Point Positioning (KPPP) solutions.

3. This study estimates the geophysical loadings of the earth body tide, ocean tide loading and earth tide based on GPS observations. The tidal displacements observed by GPS are validated with the predictions from the theoretical model which are IERS2003 and NAO.99b for earth body tide model and ocean tide loading model, respectively.

4. The tidal spectral analysis using Fast Fourier Transform (FFT) method is performed to determine the characteristic of geophysical loadings in GPS observations. A total of 11 tidal constituents from the diurnal, semi-diurnal and long-term periods is observed. The tidal parameters, amplitude and phase of each tidal constituents are estimated using the tidal harmonic analysis method.

5. The hourly snapshots of earth tidal displacements are generated by using the Generic Mapping Tools (GMT) version 5.3.1 to investigate the spatial and temporal variations of geophysical loadings response in the Malaysia region during the perigee and apogee phenomenon, monsoon seasons and throughout the year 2013.

1.5 Significance of the Study

This study is essential for several purposes:

1. This study widened the understanding of earth tidal variations in equatorial regions. It is beneficial for earth tide modelling that include both earth body tide and ocean tide loading for improving the quality of space geodetic measurements.

2. This study provides the local tidal parameters of earth body tide, ocean tide loading and earth tide from the GPS observations that can be used in further research such as to investigate the impact of the geophysical loadings against the geohazards monitoring, to quantify the actual vertical land motion in the local region and to study the dynamics of the solid earth.

3. This study could be used to support authorities, institutions and researchers in various aspects such as providing the information of geophysical loadings over Malaysian region.

1.6 Research Framework

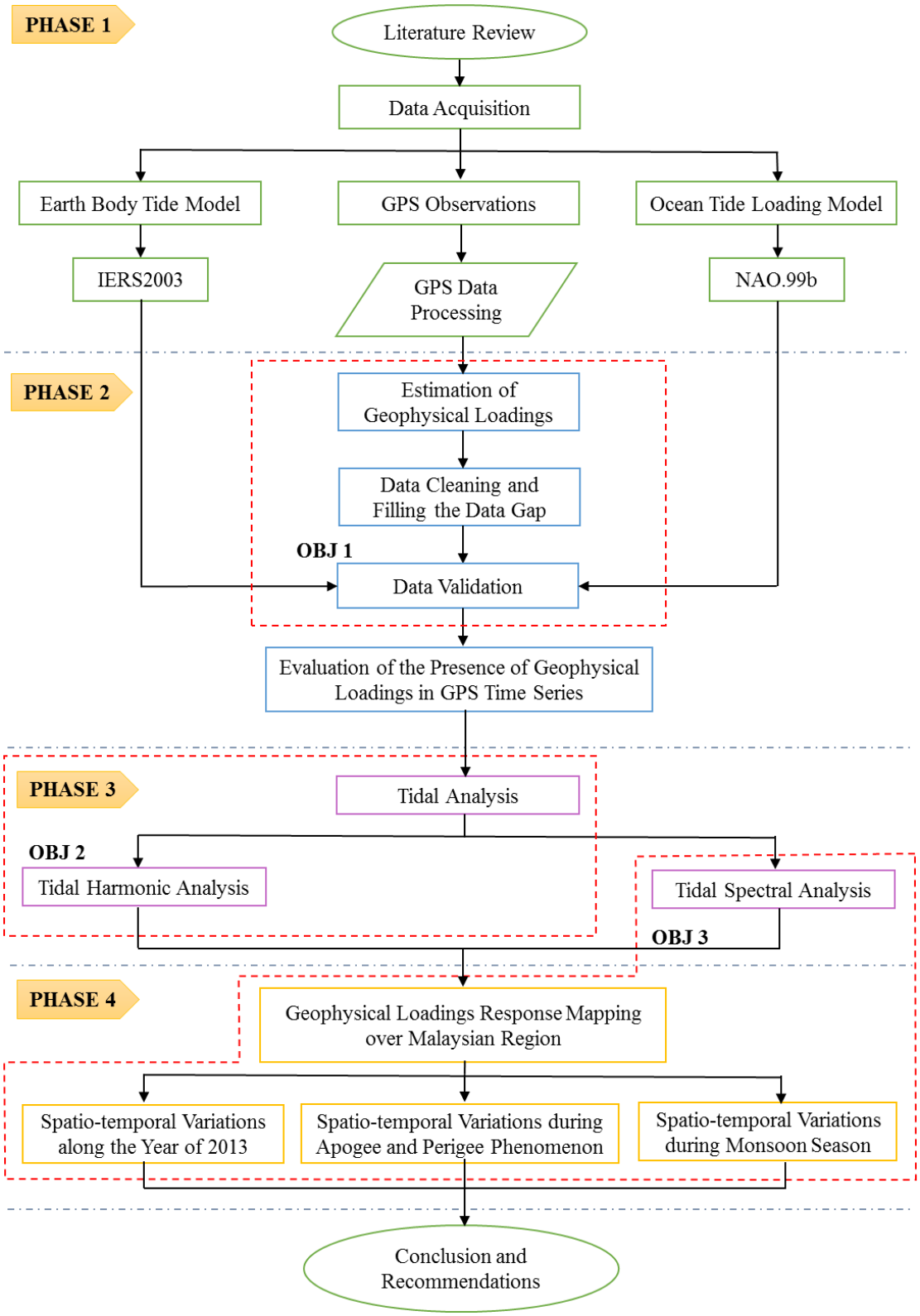

Figure 1.5 The research framework of the study.

The research methodology of this study is conducted in four phases. Phase 1 of the study is focused on the literature review of related issues such as the theory of tides, tidal analysis, the geophysical loadings and the existing sensor in Malaysia along with the data acquisition and data processing used in this study. Next, phase 2 is concerned with the estimation of the geophysical loadings from the GPS solutions and the post-data processing, which consists of the data cleaning and filling the data gap. The data validation is conducted to verify the outcome of the geophysical loadings from the GPS with the theoretical models used in this study. In addition, the presence of the geophysical loadings contained in the GPS observations is evaluated in this phase. Phase 3 concentrated on the tidal analysis of the harmonic and the tidal spectral to estimate the tidal parameters of amplitude and phase of the tidal constituents and to examine the characteristics of the geophysical loadings of the earth body tide, ocean tide loading and earth tide from the GPS observations. Lastly, phase 4 visualised the geophysical loadings response over the Malaysian region during the year 2013, during the apogee and perigee phenomenon and during the monsoon seasons. The research framework of this study is illustrated in Figure 1.5.

1.6.1 Phase 1: Literature Review and Planning

The literature review is concentrated on a few topics that are related to understanding the fundamentals of tides including the tides generating potential, the techniques of tidal analysis and the mechanism of the tides. The tidal effect of the geophysical loadings consisting of the earth body tide, ocean tide loading, atmospheric loadings and pole tides along with the sensor used to estimate this kind of geophysical loadings are also discussed in the literature review. The design of the planning phase involved the data acquisition and the processing strategy used in this study. There are three types of data acquired (1) the GPS observations along the year 2013 with the sampling rate of 30 seconds (2) the data predictions from the earth body tide model, IERS 2003 and (3) the data predictions from the ocean tide loading model, NAO.99b. In this study, the open source GPS/GNSS processing software known as Real-Time Kinematic Library (RTKLIB) is utilised for kinematic precise point positioning data processing. The programming language of MATLAB is also utilised to run the

solid.exe program to generate the IERS2003 model and the command prompt to run the GOTIC2 (Global Oceanic Tidal Correction) program to generate the NAO.99b model. Further details of the GPS processing method are discussed in Section 3.2.

1.6.2 Phase 2: The Correspondence of the Geophysical Loadings with the Theoretical Models

Phase 2 involved the estimation of the geophysical loadings that consist of the earth body tide, ocean tide loading and earth tide based on the GPS observations. This output undergoes data cleaning to remove noise as well as fill the gap contained in the time series for requirement of the tidal analysis purposes in phase 3. The outcome from the GPS is validated with the prediction from the theoretical models IERS2003 and NAO.99b to evaluate the agreement of correlation. Then, the presence of the earth body tide, ocean tide loading and earth tide is evaluated using the general least squares approach as discussed in Section 3.5 to discover the significance of the geophysical loading contribution to the GPS time series.

1.6.3 Phase 3: The Tidal Analysis

In this phase, the tidal assessment is performed by using the tidal harmonic analysis and tidal spectral analysis approaches to determine the amplitude and phase of the tidal constituents and to examine the characteristics of the earth body tide, ocean tide loading and earth tide. The computation of the tidal harmonic analysis and the tidal spectral analysis is elaborated in Section 2.2.2 and Section 2.2.4, respectively.

1.6.4 Phase 4: The Visualisation of the Geophysical Loadings Response over the Malaysian Region

Phase 4 is focused on the visualisation of the geophysical loadings response over the Malaysian region. The hourly snapshots of the geophysical loadings response are visualised using GMT 5.3.1 with surface interpolation. This spatio-temporal map is generated in several conditions, (1) the geophysical loadings variations along the year of 2013, (2) the geophysical loadings variations during the apogee and perigee phenomenon and (3) the geophysical loadings variations during the monsoon seasons. The conclusion of the study is based on the findings related to the aim and objectives achieved and the recommendation is provided to improve this study in the future.

1.7 Structure of the Thesis

This dissertation contains six chapters and these chapters are constructed as follows:

Chapter 1 Introduction

This chapter provided a background of the study on the implications of geohazard activities such as geophysical loadings in Malaysia towards the realization of the coordinate system in the geodesy field. The problem statement, aim and objectives of the study, the scope of the study and the significance of the study are also outlined in this chapter.

Chapter 2 Literature review

This chapter describes the basic theory of geophysical loadings and tides including tide generating potential and tidal analysis. The implementing of existing GPS CORS to support the understanding of earth tidal variations that consist of the earth body tide and ocean tide loading in the Malaysia region are discussed as well.

Chapter 3 Research methodology

This chapter discussed the GPS processing method and analysis technique used to achieve the objectives of the study. The estimation of the geophysical loadings from the GPS observations and the applicability of the prediction from the theoretical models, IERS2003 and NAO.99b is also elucidated in this chapter. Moreover, the details of the linear regression approaches for the data validation and the method of general least squares to estimate the presence of the geophysical loadings contained in the GPS observations is discussed.

Chapter 4 The correlation of GPS observations with the predictions of theoretical models

This chapter presents the results of the correlation of the earth body tide, ocean tide loading and earth tide from the GPS observations with the prediction from the theoretical models. The presence of geophysical loadings including earth tide, earth body tide and ocean tide loading in GPS observations is clarified in this chapter.

Chapter 5 The characteristics of earth body tide, ocean tide loading and earth tide observed by GPS

This chapter is the continuation from Chapter 4 which involves the tidal harmonic and tidal spectral analysis to determine the tidal parameters and the characteristic of geophysical loadings in GPS observations. The spatio-temporal variations of Earth tide displacements are generated in this chapter.

Chapter 6 Conclusions and recommendations

Finally, this chapter presents the conclusion of this study and the recommendations for further improvement in the future related study.

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