SPATIO-TEMPORAL ESTIMATION OF INTEGRATED WATER VAPOUR OVER THE PENINSULAR MALAYSIA

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DEDICATION

This thesis is dedicated to my precious parents, Salihin B Md Zin & Mashitah Bt Murad, my loving husband, Mohd Ilmi Izzuddin B Jamaludin and my sweet daughter, Nur Izzatul Ulya Bt Mohd Ilmi Izzuddin

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ABSTRACT

Located at a low latitude region, Peninsular Malaysia experiences extreme rainfall and hot weather over various places. The region has a large amount of water vapour in the atmosphere, and its variation shows a close relationship with the monsoon season, leading to severe flood events in some states during the season. Hence, it is important to classify the homogenous characteristic of atmospheric water vapour over this region. However, observing atmospheric water vapour over climatology time period is difficult to enumerate due to its high variability in time and space. Thus, characterizing the water vapour behaviour in the troposphere based on horizontal profile by using Global Positioning System (GPS) meteorology approach has been widely adopted by researchers. However, in this low-latitude region, only a few studies have been conducted due to the lack of GPS Continuously Operating Reference Stations (CORS) infrastructure co-located with the meteorological sensors in this area. Therefore, the aim of this study is to define the behaviour of water vapour in Peninsular Malaysia by utilizing ground-based GPS networks. Three objectives were established for three different research phases. The first objective is to estimate the Zenith Path Delay (ZPD) and Integrated Water Vapour (IWV) from the network of GPS stations. The estimation process of ZPD was performed in post-processed mission and the results were validated with ZPD product by International GNSS Service (IGS). The Root Mean Square (RMS) errors of the GPS-derived ZPD lie between 6 mm to 19 mm. From ZPD, the value of GPS-derived IWV was further extracted and validated with IWV from selected radiosonde stations. Based on the findings, Peninsular Malaysia has high amount of water vapour with an average of >50 kg/m^2 over the year. Three GPS stations close to radiosonde stations were assessed and the RMS errors of the GPS-derived IWV were 9.914 kg/m^2, 11.154 kg/m^2 and 9.865 kg/m^2. The results present a good relationship between GPS and radiosonde IWV with linear correlation coefficients of 0.9116, 0.8245 and 0.8369, respectively. The validation results are then addressed in the second phase of the study to fulfil the second objective, which is to assess the estimated GPS ZPD and IWV. The third objective is to characterize the spatio-temporal variability of water vapour in Peninsular Malaysia during monsoon seasons. Two-dimensional (2D) water vapour mapping was generated from IWV results to achieve this objective. Based on the mapping, it was found that the high amount of water vapour can be seen over the west coast of Peninsular during First Inter Monsoon (FIM) with a mean average ranges from 45.482 kg/m^2 to 52.973 kg/m^2. During the Second Inter Monsoon (SIM) the value of GPS-derived IWV depicts a higher amount of water vapour with a maximum value recorded at 57.429 kg/m^2. Further analysis show that North and Northeast of Peninsular Malaysia experienced more water vapour during South West Monsoon (SWM): the mean average lies between 50.505 kg/m^2 to 53.305 kg/m^2. During North East Monsoon (NEM), less amount of water vapour was recorded in the Northwest and East of Peninsular Malaysia (a mean average of 43.851 kg/m^2 to 54.548 kg/m^2). However, heavy rain is common in the season, possibly due to the strong monsoon wind that caused the affected area to receive substantial high amount of rainfall. This study has successfully demonstrated the positive trend between GPS-derived IWV and rainfall data.

ABSTRAK

Terletak di kawasan berlatitud rendah, Semenanjung Malaysia mengalami hujan lebat dan cuaca panas di banyak kawasan. Kawasan ini mempunyai sejumlah besar wap air dalam lapisan atmosfera, dan variasinya menunjukkan hubungan rapat dengan musim monsun yang mengakibatkan banjir teruk di beberapa buah negeri sepanjang musim. Oleh itu, adalah sangat penting untuk mengklasifikasikan sifat homogenes wap air di lapisan atmosfera di kawasan ini. Namun begitu, pemerhatian ke atas wap air di atmosfera terhadap perubahan masa klimatologi adalah sukar untuk dijangka disebabkan perubahan yang pelbagai dalam masa dan ruang. Oleh itu, pencirian sifat wap air di troposfera adalah berdasarkan profil mendatar dengan menggunakan pendekatan metereologi Sistem Kedudukan Sejagat (GPS) yang digunakan oleh para pengkaji secara meluas. Walaubagaimanapun, di kawasan beraltitud rendah ini, hanya sedikit kajian yang telah dijalankan disebabkan oleh kekurangan infrastruktur GPS Stesen Rujukan Operasi Berterusan (CORS), GPS bersama deria meteorologi yang terhad. Oleh itu, tujuan kajian ini adalah untuk mentakrifkan sifat wap air di Semenanjung Malaysia dengan menggunakan jaringan GPS kawalan bumi. Tiga objektif telah ditetapkan untuk tiga fasa kajian yang berbeza. Objektif pertama adalah menilai Lengah Basah Zenit (ZPD) dan Integrasi Wap Air (IWV) daripada jaringan stesen-stesen GPS. Proses menilai ZPD dijalankan dalam misi pasca proses dan hasilnya disahkan dengan produk ZPD daripada Perkhidmatan GNSS Antarabangsa (IGS). Ralat punca min kuasa dua (RMS) untuk GPS ZPD yang diperoleh adalah dalam lingkungan 6 mm hingga 19 mm. Daripada ZPD, nilai IWV GPS diekstrak dan disahkan dengan IWV daripada stesen belon kaji cuaca terpilih. Daripada hasil kajian, Semenanjung Malaysia mengandungi jumlah wap air yang tinggi dengan purata >50 kg/m^2 sepanjang tahun. Tiga stesen GPS yang berdekatan dengan stesen belon kaji cuaca telah dinilai dan ralat RMS untuk IWV GPS yang diperolehi adalah 9.914 kg/m^2, 11.154 kg/m^2 and 9.865 kg/m^2. Keputusan ini menunjukkan hubungan yang baik antara IWV GPS dan IWV belon kaji cuaca dengan pekali kolerasi linear masing-masing adalah 0.9116, 0.8245 and 0.8369. Pengesahan tersebut turut dinyatakan dalam objektif kedua kajian ini iaitu untuk menilai keputusan GPS ZPD dan IWV. Objektif ketiga adalah untuk mencirikan sifat perubahan masa spatial wap air di Semenanjung Malaysia pada musim monsun. Pemetaan 2-Dimensi (2D) wap air dihasilkan daripada keputusan IWV untuk mencapai objektif ini. Berdasarkan kepada pemetaan, didapati jumlah wap air yang tinggi di kawasan pantai barat Semenanjung Malaysia sepanjang musim Peralihan Monsun Pertama (FIM) dengan kadar purata dalam lingkungan 45.482 kg/m^2 to 52.973 kg/m^2. Pada musim Peralihan Monsun Kedua (SIM), nilai wap air dihasilkan oleh IWV GPS menunjukkan bacaan lebih tinggi dengan catatan jumlah wap air tertinggi adalah 57.429 kg/m^2. Analisis seterusnya menunjukkan kawasan Utara dan Tenggara Semenanjung Malaysia mengalami jumlah lebih wap air sepanjang musim Monsun Barat Daya (SWM): nilai purata wap air ialah antara 50.505 kg/m^2 to 53.305 kg/m^2. Pada musim Monsun Timur Laut (NEM), sedikit jumlah wap air direkodkan di kawasan barat laut dan timur Semenanjung Malaysia (jumlah purata antara 43.851 kg/m^2 to 54.548 kg/m^2). Namun begitu, hujan lebat kerap berlaku pada musim ini kemungkinan disebabkan oleh tiupan monsun yang kuat menyebabkan kawasan terlibat menerima jumlah hujan yang tinggi. Kajian ini berjaya menunjukkan tren positif di antara data terbitan GPS IWV dan data hujan.

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LIST OF ABBREVIATIONS

IWV	-	Integrated Water Vapour
NEM	-	North East Monsoon
SWM	-	South West Monsoon
GPS	-	Global Positioning System
ZTD	-	Zenith Total Delay
ZPD	-	Zenith Path Delay
MRI	-	Magnetic Resonance Imaging
SWD	-	Slant Wet Delay
WVR	-	Water Vapour Radiometer
CORS	-	Continuously Operating Reference Stations
NWP	-	Numerical Weather Prediction
MyRTKnet	-	Malaysian Real-Time Kinematic GNSS Network
PW	-	Precipitable water
RO	-	Radio occultation
LEO	-	Low-Earth-Orbit
UHF	-	ultra-high frequency
PRN	-	pseudo-random noise
C/A-code	-	coarse acquisition code
P-code	-	precision code
DoD	-	Department of Defence
RF	-	Radio frequency
EMR	-	Electromagnetic radiation
SPD	-	Slant Path Delay
ZHD	-	Zenith Hydrostatic Delay
ZWD	-	Zenith Wet Delay
RINEX	-	Receiver Independent Exchange
DID	-	Department of Irrigation and Drainage
RMS	-	Root Mean Square

LIST OF SYMBOLS

n	-	Refractive Index
v	-	Velocity
N	-	Atmospheric refractivity
K_1, K_2, K_3	-	Refractivity constants
P_d	-	partial pressure of dry air
T, T^2	-	Absolute temperature
Z_d^{-1}	-	Compressibility factors for dry air
Z_w^{-1}	-	Compressibility factors for water vapour
N_h	-	Dry component
N_w	-	Wet component
S	-	Observed path
G	-	Geometry path
ΔL	-	Excess delay
ΔL_h	-	Dry delay
ΔL_w	-	Wet delay
$\Delta L(\theta)$	-	Total delay
θ	-	Satellite elevation angles
ΔL_h^z	-	Zenith hydrostatic delay
mf_h	-	Hydrostatic mapping function
ΔL_w^z	-	Zenith wet delay
mf_w	-	Non-hydrostatic mapping function
P_s	-	Surface pressure
$\emptyset,$	-	Latitude of the station
h	-	Height above the ellipsoid
R_v	-	Gas constant for water vapor
T_M	-	Weighted mean temperature
T_s	-	Surface temperature
mbar	-	millibar
K	-	Kelvin

mm	-	millimetre
m	-	metre
km	-	kilometre

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CHAPTER 1

INTRODUCTION

1.1 Background

Water vapour is a crucial parameter in the atmosphere as it plays as a major role in global heat and hydrological cycle, thus affects the global climate and weather condition. Therefore, it is crucial to have accurate measurement of atmospheric water vapour to provide the actual weather condition; and to improve the weather forecasting model. However, high variability of water vapour makes it difficult to capture in high spatio-temporal resolution due to the limitations of the existing measurement techniques.

GPS (Global Positioning System) meteorology is rapidly developed and have been used since the 1990s as a meteorological observing system. GPS measurement is able to estimate the amount of water vapour overlying a point on the Earth's surface which is usually state as the vertically integrated mass of water vapour per unit area (*e.g.*, kg/m^2); called as Integrated Water Vapour (IWV); or as the height of an equivalent column liquid water known as Precipitable Water (PW) (Bevis *et al*., 1992). However, the term "GPS meteorology" in this research focuses on estimating atmospheric water vapour content in state of IWV only.

1.1.1 Role of Atmospheric Water Vapour and It's Measurement Technique

Water vapour (water in its gaseous state) in the atmosphere is a prominent constituent on the climate system that saturated in lower part of atmosphere known as troposphere (see Figure 1.1). In fact, more than 90% of the water vapour is contained in the lower 5km and less than 6% of the water vapour is contained above 5km of the stratosphere (Tao, 2008). All the weathers conditions occur in this layer.

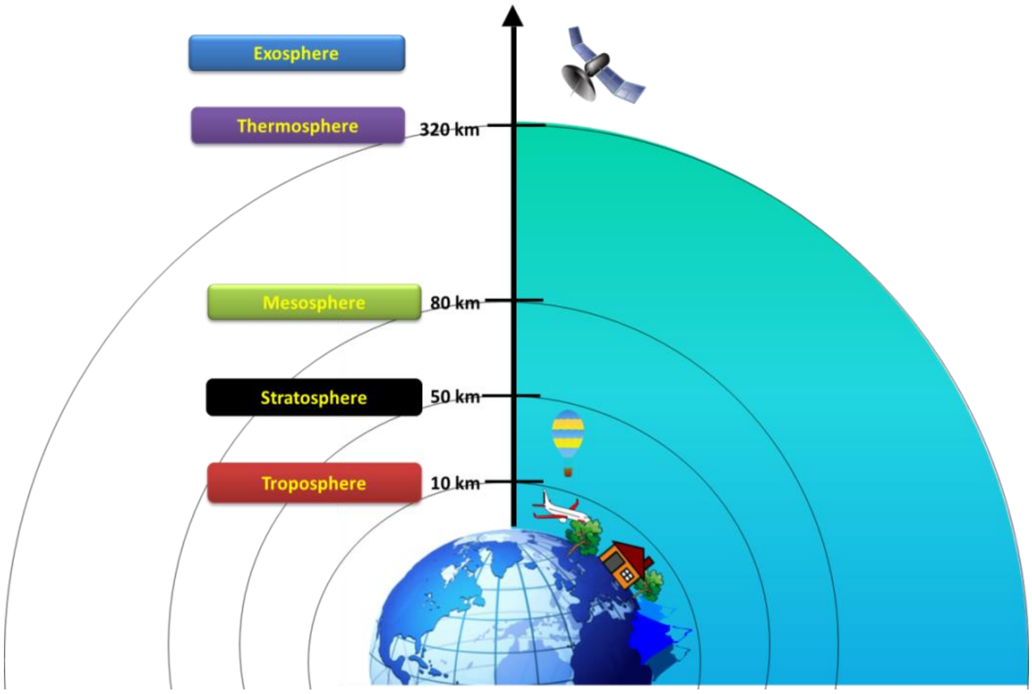


Figure 1.1 The layer of atmosphere.

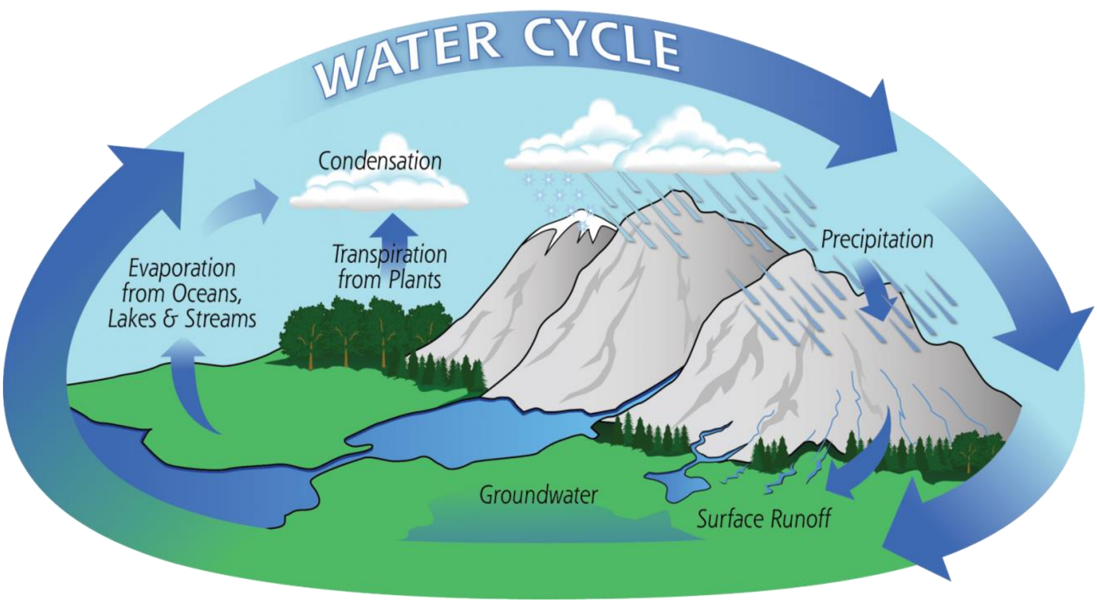


Figure 1.2 Illustration of hydrological cycle on Earth (NASA, 2014).

Water vapour affects the climates in two ways. Firstly, it plays an important role in atmospheric processes, which acts upon a wide range of spatio-temporal scales of the hydrological cycle on Earth (see Figure 1.2). In this cycle, liquid water from land and sea surface evaporates to form water vapour when heat is absorbed. All of the evaporated water vapour from the Earth's surface will ultimately return as precipitation that recognizable as snow and rain. Secondly, water vapour is also highly important since it is the strongest greenhouse gases. While being a key element in atmosphere, accurate measurement of atmospheric water vapour needs to be proposed and utilized. The research on improving and enhancing the existing measurement technique in measuring water vapour have been conducted since years ago. A detailed and accurate measurement of water vapour can improve the ability to model and predict the Earth's climate and weather forecast.

Techniques used to estimate vertical and horizontal atmospheric water vapour distribution have been discussed in many studies (Bevis *et al*., 1992; Guerova, 2003; Agustan, 2004; Coster *et al*., 1996). Currently, there are several instruments were utilized to monitor atmospheric water vapour such as radiosonde, Water Vapour Radiometer (WVR) and weather satellite (see Table 1.1).

i) Radiosonde

Radiosonde is a balloon-borne instrument package that used to measure temperature, pressure, wind speed and dew point temperature together with its direction through a profile of Earth's atmosphere up to the altitude of 30 km (Wang *et al*., 2005). A radio transmitter were used and attached with the instruments package to transmit the measured and recorded data to the ground station by radio signal. According to Durre *et al*., (2006), the radiosonde was launched daily since 1940's by meteorologist. This instrument has become a major tool for climate research due to the largest data archived availability (Wang and Zhang, 2008); and it is one of the major meteorological instruments over the world. However, radiosonde has limitation in terms of high cost to operate; low in spatial coverage and only launched two times daily.

ii) Water Vapour Radiometer

The WVR provides measurement of water vapour along a given line of sight through the atmosphere. WVR provide low spatial resolution of water vapour but high in temporal resolution. However, this instrument has limitations which requires regular calibration and is affected by rain and clouds with high cost to operate (Turner *et al*., 2007; Geurova, 2003).

iii) Weather Satellite

The weather satellite can be classified into two which are geostationary and orbiting satellites. Satellite is affective to monitor atmospheric water vapour in large spatial coverage up to global scales including the difficult access region such as ocean and mountainous area. However, the limitations of this techniques are that the geostationary satellite observes at very far distance from Earth's elevation; and is less accurate. In addition, the orbiting satellite is difficult to improve temporal resolution because the orbiting satellite take time to complete the orbit and revisit same area (Agustan, 2004).

The knowledge of the nature on these parameters is also worthwhile and significance since it creates a variety weather pattern over various places on the Earth. Hence, evaluation of its spatio-temporal distribution is fundamental for improving meteorological forecasting and climate monitoring. The continuous study on time series of water vapour can be used to detect and quantify spatio-temporal variations in seasonal and diurnal time scales

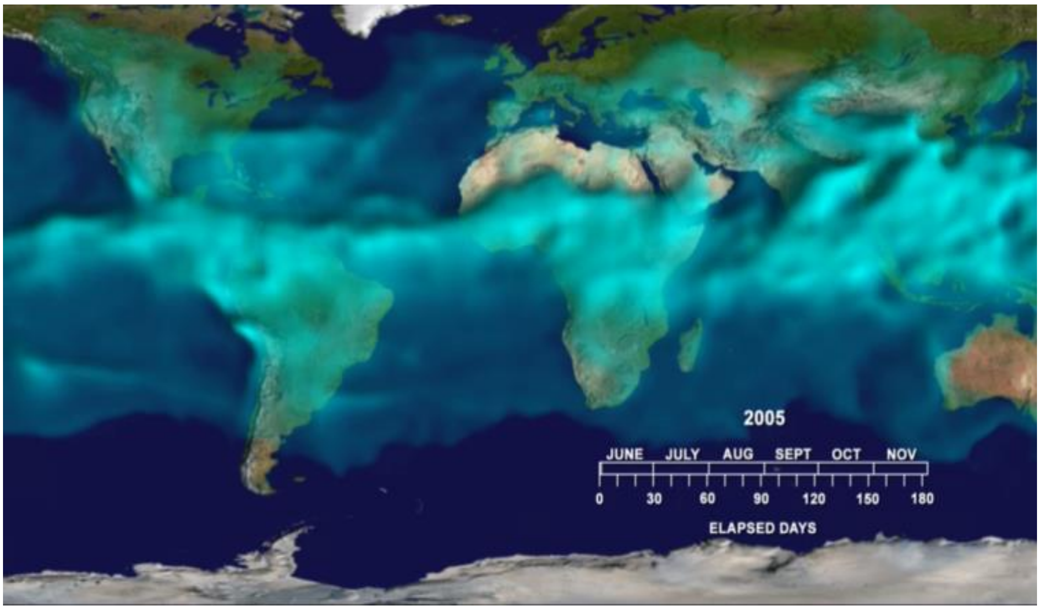
Table 1.1 The comparison between techniques in atmospheric water vapour monitoring (Wolfe and Gutman,2000; Wang *et al*., 2007; Faiz, 2016)

	Radiosonde	WVR	Satellite weather	GPS/GNSS
Availability	Except in heavy rainfall and thunderstorm	Not functional in heavy rainfall	All weather	All weather condition and weatherproof
Cost	Expensive	Expensive	Expensive	Relatively low cost
Spatial resolution	1,000 sites	Sparse	Global	More than 1,000 sites (IGS+EUREF+National Network)
Temporal resolution	Average twice daily	High	High (Geostationary) Low (polar orbit)	High
Calibration	Frequent	Frequent	Free-calibrate	Free-calibrate
Accuracy	Low. Various, biases	Depends on weather condition	Low	High

1.1.2 The Climate of Peninsular Malaysia

The global distribution of atmospheric water vapour has a significant latitudinal dependence. It is highly concentrated in low-latitude region compare to high latitude region (see Figure 1.3). Peninsular Malaysia is geographically located in the low-latitude region that lies in the range of 1^o to 6^o north and longitude of 100^o to 105^o east. Situated near the equator, climate in Peninsular Malaysia is categorized as equatorial, which experiences hot, humid and rainy throughout the year. The temperature in this region are uniform with high annual temperature extending from 25.5^oC to 35^oC. As a tropical country, this region quantify high amount of precipitation with annual rainfall, normally around 2,000 mm and relative humidity commonly exceeding 70%. The seasonal wind flow patterns and the local topographic features determine the rainfall distribution over this region. On the other hand, this pattern of rainfall is influenced by monsoon season that occurs over the year.

Figure 1.3 The visualization of global distribution of atmospheric water (NASA, 2008).



The precipitation climate in this region is categorized by two rainy seasons that influenced by two annual monsoons known as North East Monsoon (NEM) and South West Monsoon (SWM). NEM occurs from November to February and SWM occurs from early of May to August. March to April and September to October form transitional periods (known as inter monsoon) which the substantial rainfall occurs between the monsoon seasons. These monsoons bring more precipitation abundant and frequent to the areas that directly exposed to these winds. East coast of Peninsular Malaysia was much affected during NEM and North East of Borneo much affected during SWM. These heavy rainfall can lead to the extensive flood event over the affected areas.

1.1.3 Atmospheric Sensing using Global Positioning System (GPS) Technique

The ability of GPS in measuring atmospheric water vapour has been discussed since years ago. Previous study have shown that GPS meteorology offers detailed coverage and continuous observations regardless of weather conditions such as rainfall and clouds (Amir, 2012). GPS Meteorology is an innovation that has led to the possibility of using GPS for remote sensing to complement the limitations of the existing techniques. GPS tools provide a better spatio-temporal resolution, low cost system, have global coverage, are practical in any weather condition, give reliable and stable results, unaffected by rain and clouds (GPS use radio frequencies); and have high accuracy measurement (Awange and Grafarend, 2005; Gutman *et al*., 2004; Amir, 2012). According to Tao (2008), this technique provides high measurement accuracy; and is low-cost for water vapour observing system. The use of GPS signals has been suggested to enhance the existing weather-monitoring systems since this GPS technology hold a promise to provide the detail necessary and significant increase in forecast accuracy (Bevis *et al*., 1994).

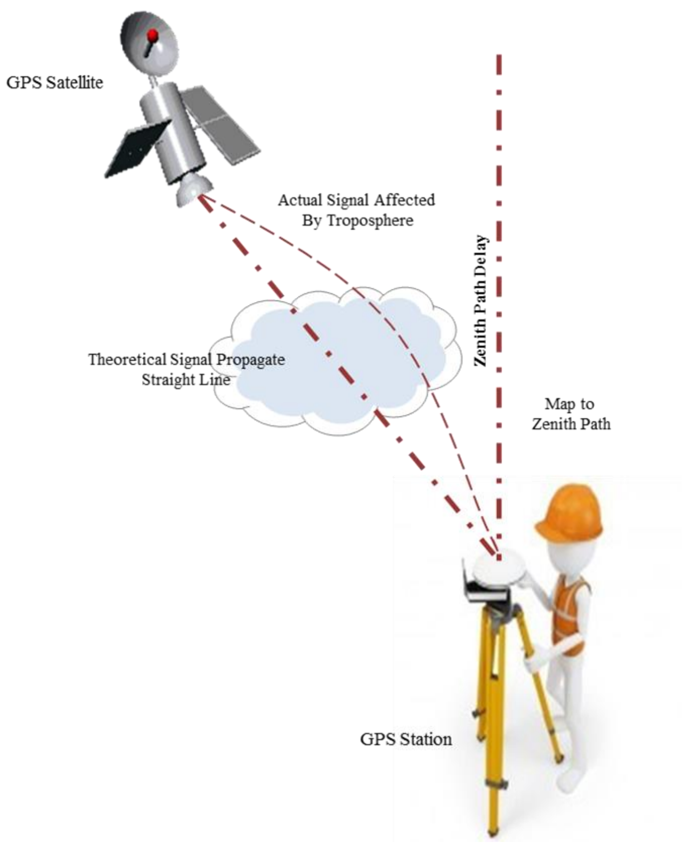


Figure 1.4 Zenith Path of GPS signals over a GPS Station.

GPS allows the continuous remote monitoring of atmosphere by analyzing the satellite signal noise (Hordyniee, 2014). The main source of the GPS signal noise is caused by the troposphere which is determined in zenith direction between a satellite and receiver known as Zenith Total Delay (ZTD) and Zenith Path Delay (ZPD). ZPD or ZTD consists of two components; the dry (hydrostatics) due to dry gases and the wet component due to dipole component of water vapour (Flores *et al*., 2000). Figure 1.4 shows the zenith path direction over the GPS station. IWV is a total atmospheric water vapour contained in a vertical columnar of unit cross-sectional area extending from the earth surface to the top of the atmosphere that can be derived from ZPD by accounting meteorological parameters. However, the GPS IWV only has two dimensional characters (Haan and Marel, 2008). IWV two-dimensional maps based on a dense network of GPS stations provide detailed information on the water vapour distribution without information on vertical profiles (Bender *et al*., 2010).

1.2 Problem Statement

In order to quantify the behavior of atmospheric water vapour, there are three questions need to be answered;

i. What is the homogenous characteristic of water vapour in Peninsular Malaysia?

ii. Why the information of water vapour is very important in Peninsular Malaysia?

iii. How to define the behavior of water vapour over the Peninsular Malaysia?

The Earth’s weather and climate are heavily influenced by the amount of water vapour. The amount of water vapour varies widely, both in latitude and height, and cannot be accurately predicted with surface measurements. The instrument such as radiosonde, WVR, satellite-based radiometry is widely used in measurement of water vapour, but all these existing techniques have their own limitations to provide accurate, dense and continuous observation of water vapour in the atmosphere.

GPS can be utilized as a tool to complement the limitations of the existing techniques as it provides a better spatio-temporal resolution; is a low-cost system; and able to operate in all-weather condition. The existing of dense GPS Continuously Operating Reference Stations (CORS) over the Peninsular Malaysia could be utilized to estimate the amount of atmospheric water vapour in horizontal and vertical distribution.

Lately, Peninsular Malaysia experienced extreme rainfall and hot weather over various places. As a tropical country, this region has a large amount of water vapour in the atmosphere. According to Musa (2007), the high amount and variation of atmospheric water vapour in Malaysia show a close relationship with its monsoon seasons. This phenomenon leads to a flash flood in the eastern part of Malaysian Peninsular and west coast of Sabah and Sarawak (Amir, 2012). Hence, the homogenous characteristics of water vapour for this region is important to be classified. By estimating the atmospheric water vapour, it helps to define the behavior of water vapour in horizontal and vertical profile over Peninsular Malaysia.

1.3 Aim and Objectives

The main aim of this research is to define the behavior of water vapour in Peninsular Malaysia by utilizing ground-based GPS networks in this region. In order to support the aim, there are three main objectives to be achieved;

1. To estimate the GPS-ZPD and GPS-derived IWV from the network of GPS stations.
2. To assess the estimated GPS-ZPD and GPS-derived IWV, and
3. To characterize the spatial-temporal variability of water vapour in Peninsular Malaysia.

1.4 Scope of Study

The scope of this study includes:

i. The research is focusing on the water vapour distribution in Peninsular Malaysia which is in low latitude region and has abundant of water vapour in its atmosphere.

ii. Recently, there are two primary techniques for sensing atmospheric water vapour by using GPS; space-based and ground-based techniques. This study is focusing on atmospheric water vapour estimation using ground-based technique.

iii. The study was conducted using GPS observation data from Malaysian Real-Time Kinematic GNSS Network (MyRTKnet) that consists of 58 GPS stations over Malaysian Peninsular. However, this study utilized 49 stations that were selected for GPS-derived IWV estimation.

iv. The value of atmospheric water vapour cannot be estimated directly by using GPS networks. Hence, it is necessary to involved along with surface meteorological stations that closely located to the corresponding GPS stations. Surface meteorological data was obtained from five (5) selected stations. Radiosonde observations was acquired to validate the GPS-derived IWV.

v. Estimation of GPS-derived ZPD from GPS observations data can be conducted by using a variety of software that available from open source, commercial and scientific software. However, every software has its own limitations and advantages. In this study, GPS observation data were processed by using high scientific Bernese software version 5.0. Bernese software has the capability to handle high precision processing; and contained various modelling to estimate high quality of GPS-derived ZPD.

1.5 Significance of Study

The significance of this study is as follows:

1. This study contributes in understanding on the spatio-temporal variation of atmospheric water vapour over Peninsular Malaysia. The knowledge of this variation parameter can be utilized towards improving the weather monitoring and forecasting in this region.

2. The outcome from this study can support the monitoring of the atmospheric water vapour during disaster event such as monsoon, flood and heavy rainfall over this region.

3. The application of GPS meteorology technique demonstrated as alternative technique to observe atmospheric water vapour in Peninsular Malaysia. This study indicates that GPS system has a potential to complement existing techniques in this region for measuring water vapour.

1.6 Thesis Structure and Organization

This study is structured into five (5) chapters which are;

Chapter 1 provides a brief review on the introduction of the role of water vapour and its measurement technique, the climate of Peninsular Malaysia region, and GPS meteorology. The problem statements, aim and objectives, scopes and significance of this study is clearly stated in this chapter.

Chapter 2 provides relevant literature that defines the study context. The topics reviewed in this chapter is aimed to provide an insight into the sensing of atmospheric water vapour by using GPS observation technique. Detailing information on the ground-based GPS meteorology and GPS signal refractivity involve in this study is provided in this chapter.

Chapter 3 discussed the technical aspect of the study by presenting the research methodology. The methodology was briefly reviewed and arranged in accordance to the objectives of the study.

Chapter 4 presents the results and analysis of this study. In this chapter, all the findings in this study are discussed and presented.

Finally, in **chapter 5**, the outcomes of this study were evaluated, and the conclusions were constructed. This chapter also discusses the suggested future outlook of this study.

LIST OF PUBLICATIONS

Salihin, S., Musa, T. A., and Mohd Radzi, Z.: SPATIO-TEMPORAL ESTIMATION OF INTEGRATED WATER VAPOUR OVER THE MALAYSIAN PENINSULA DURING MONSOON SEASON, Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci., XLII-4/W5, 165-175, https://doi.org/10.5194/isprs-archives-XLII-4-W5-165-2017, 2017