MODELLING ATMOSPHERIC WET REFRACTIVITY PROFILE USING GROUND AND SPACE-BASED GLOBAL POSITIONING SYSTEM

OPALUWA YUSUF DRISU

UNIVERSITI TEKNOLOGI MALAYSIA

MODELLING ATMOSPHERIC WET REFRACTIVITY PROFILE USING GROUND AND SPACE-BASED GLOBAL POSITIONING SYSTEM

OPALUWA YUSUF DRISU

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DEDICATION

With much glory to **Allah S.W.T** for the gift of life, grace and wisdom, this work is dedicated to my late Father, Idrisu Opaluwa of blessed memory.

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ABSTRACT

Precise measurement of atmospheric water vapour has been very challenging due to some limitations of the conventional meteorological systems. Hence, there is a need for Global Positioning System (GPS) for meteorology or GPS meteorology. Therefore, the ground-based GPS meteorology and the space-based GPS Radio Occultation (GPS RO) techniques have been used. The major challenges of ground-based GPS meteorology approach include the lack of surface meteorological data collocating with the location of the ground-based GPS receivers as well as its inability to profile the atmosphere. Whereas the GPS RO technique has a problem of generating profile for the lower tropospheric region which holds the largest amount of water vapour. This research investigates an approach for estimating wet refractivity profile using GPS data. Three specific objectives were set for the study which was conducted in three phases. The first objective assessed GPS Integrated Water Vapour (GPS IWV) in which GPS IWV from interpolated meteorological data and the applicability of Global Pressure and Temperature (GPT2w) model for GPS meteorology was evaluated. The results revealed that the GPS IWV from Automatic Weather Station (AWS) presents good correlation with the radiosonde IWV, the standard deviation of the biases vary spatially from 3.162kg/m^2 to 3.878 kg/m^2. The actual influence of the errors of GPT2w meteorological parameters on GPT2w-based GPS IWV lies between 2kg/m^2 and 3kg/m^2, translating to an average relative accuracy of 1.2%. Meanwhile, the sensitivity of the GPS RO data to equatorial water vapour trend was evaluated to achieve second objective. It was found that the GPS RO IWV is highly comparable with the ground-based GPS IWV, having average bias of 1.8kg/m^2. Finally, a methodology for GPS wet refractivity retrieval was developed towards achieving the third objective of this research. The Modified Single Exponential Function (MSEF) model for retrieving wet refractivity profile from ground-based GPS Zenith Wet Delay (ZWD) was realised. The output validation using profile from radiosonde and GPS RO observations showed high correlation in each case. In order to improve the performance of the MSEF model, an approach for integrating the ground-based and the space-based GPS data (GIWRef) was formulated. The GIWRef profile is highly correlated with the GPS RO profile, which showed an average improvement of 41% over the initial MSEF method with average correlation coefficient of 0.99. It can be concluded from the foregoing results of the study that the MSEF and GIWREF concepts developed in this work, presents a potential for augmenting weather forecasting and monitoring water vapour system.

ABSTRAK

Pengukuran kandungan wap air di atmosfera yang jitu adalah begitu mencabar disebabkan oleh keterbatasan sistem meteorologi secara konvensional. Maka, sistem penentududukan sejagat (GPS) untuk meteorologi atau GPS meteorologi ini menjadi satu keperluan. Oleh itu, teknik GPS meteorologi kawalan di bumi dan GPS radio hijaban di angkasa (GPS RO) telah digunakan. Cabaran utama bagi kaedah GPS meteorologi kawalan di bumi adalah kekurangan data meteorologi permukaan khususnya di lokasi penerima GPS dan seterusnya menyebabkan ketidakupayaannya untuk menjana profil atmosfera. Manakala teknik GPS RO mempunyai masalah untuk menjana profil meteorologi bagi lapisan troposfera rendah yang mengandungi jumlah wap air yang tinggi. Kajian ini menyiasat suatu pendekatan untuk menganggar profil kebiasan basah dengan menggunakan data GPS. Tiga objektif khusus telah ditetapkan untuk kajian ini dan dilaksanakan dalam tiga fasa. Objektif pertama adalah menilai integrasi wap air berasaskan GPS (GPS IWV) dengan menggunakan GPS IWV di mana hasil daripada interpolasi data meteorologi dan kesesuaian model tekanan dan suhu sejagat (GPT2w) untuk GPS meteorologi telah dinilai. Hasil kajian mendapati bahawa GPS IWV daripada stesen kajicuaca automatik (AWS) menunjukkan korelasi yang baik dengan IWV daripada *radiosond* dengan sisihan piawai bias berbeza secara spatial sebanyak 3.162kg/m^2 hingga 3.878kg/m^2. Punca sebenar yang mempengaruhi ralat parameter meteorologi pada GPT2w terhadap GPT2w yang berasaskan GPS IWV adalah di antara 2kg/m^2 dan 3kg/m^2 diterjemahkan sebagai ketepatan purata relatif sebanyak 1.2%. Sementara itu, sensitiviti data GPS RO terhadap arah aliran kandungan wap air di kawasan Khatulistiwa telah dinilai untuk mencapai objektif kedua. Kajian mendapati bahawa GPS RO IWV yang dibandingkan dengan GPS IWV kawalan di bumi adalah hampir sama iaitu dengan purata bias sebanyak 1.8kg/m^2. Akhirnya, metodologi untuk memperolehi kebiasan basah daripada GPS telah dibangunkan bagi mencapai objektif ketiga. Model fungsi eksponen tunggal (MSEF) untuk mendapatkan profil kebiasan basah daripada lengah basah zenit (ZWD) berasaskan GPS kawalan di bumi telah direalisasikan. Hasil pengesahsahihan menggunakan profil daripada cerapan *radiosonde* dan GPS RO menunjukkan korelasi yang tinggi dalam setiap kes. Bagi meningkatkan prestasi model MSEF ini, suatu pendekatan dengan integrasi data GPS kawalan di bumi dan di angkasa (GIWRef) telah dirumuskan. Profil GIWRef menunjukkan korelasi yang tinggi dengan profil GPS RO, yang memberikan kadar purata peningkatan sebanyak 41% berbanding kaedah awalan MSEF dengan kadar purata pekali korelasi sebanyak 0.99. Kesimpulannya, hasil kajian ini menunjukkan bahawa konsep MSEF dan GIWREF yang dibangunkan oleh kajian ini berpotensi untuk membantu sistem ramalan kajicuaca dan sistem pemantauan kandungan wap air.

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LIST OF ABBREVIATIONS

AWS	-	Automatic Weather Station
BDSS	-	BeiDou Satellite System
CDAAC	-	Cosmic Data Analysis and Archival Centre
CHAMP	-	Challenging Mini Payload
CORS	-	Continuous Operating Reference Station
COSMIC	-	Constellation Observing System for Meteorology, Ionosphere and Climate
DSMM	-	Department of Survey and Mapping Malaysia
ECMWF	-	European Centre for Medium Weather Forecast
FFT	-	Fast Fourier Transform
GIWRef	-	GPS data Integration for Wet Refractivity
GLONASS	-	Globalnaya Navigatsionnaya Sputnikovaya Sistema
GM	-	Gravitational Constant
GMF	-	Global Mapping Function
GPS	-	Global Navigation Satellite System
GPS	-	Global Positioning System
GPT	-	Global Pressure and Temperature
GRACE	-	Gravity Recovery and Climate Experiment
GWReMS	-	GPS wet refractivity monitoring system
IGS	-	International GPS Service
InSAR	-	Interferometry Synthetic Aperture Radar
IRNSS	-	Indian Regional Navigational Satellite System

IWV	-	Integrated Water Vapour
LEO	-	Low Earth Orbiter
LSP	-	Lomb-Scargle Periodogram
MMD	-	Malaysia Meteorological Department
MSEF	-	Modified Single Exponential Function
MyRTKnet	-	Malaysia Real-Time Kinematic network
NMF	-	Neill Mapping Function
NWM	-	Numerical Weather Model
NWP	-	Numerical Weather Prediction
PCO	-	Phase Centre Offset
PCV	-	Phase Centre variation
POD		Precise Orbit Determination
PPP	-	Precise Point Positioning
PWV	-	Precipitable Water Vapour
QZSS	-	Quasi-Zenith Satellite System
SAC-C	-	Satellite de Aplicaciones Cientificas-C
SHD	-	Slant Hydrostatic Delay
SPD	-	Slant Path Delay
SWD	-	Slant Wet Delay
TACC	-	Taiwan Analysis Centre for Cosmic
USA	-	United States of America
UK	-	United Kingdom
UTLS	-	Upper Troposphere Lower Stratosphere
UTM	-	Universiti Teknologi Malaysia
VLBI	-	Very Long Baseline Interferometry
VMF	-	Vienna Mapping Function
RMS	-	Root Mean Square

WVR	-	Water Vapour Radiometer
ZHD	-	Zenith Hydrostatic Delay
ZWD	-	Zenith Wet Delay
ZPD	-	Zenith Path Delay

LIST OF SYMBOLS

n - Refractive index
c - Speed of light
v - Velocity
K_1, K_2, K_3 - Refractivity constants
P_d - Partial pressure of dry atmosphere
T - Temperature
K - Kelvin
Z_d^{-1} - Compressibility factors for dry components
Z_w^{-1} - Compressibility factors for wet component
R - Specific gas constant
R_v - Gas constant for water vapour
ρ - Partial pressure of gas
e, p_w, p_v - Partial pressure of water vapour (mbar)
L_1 - GPS frequency of 1575.42 MHz
L_2 - GPS frequency of 1227.60 MHz
dt^S - Satellite clock delay
dt_R - Receiver clock delay
g_m - Mean gravity
dB - Signal strengths in decibel
$d^{ion}L_1$ - Ionospheric delay on L_1 frequency
$d^{ion}L_2$ - Ionospheric delay on L_2 frequency
d^{trop} - Tropospheric delay
dH_R - Receiver hardware delay
dH^S - Satellite hardware delay

d^{mp} - Multipath

d^{sys} - Synchronisation effect

d^{rel} - Relativistic effect

d^{orien} - Receiver and transmitter orientation correction

d^{pcv} - Antenna phase centre offset

λ - Wavelength

N - Carrier phase integer ambiguity

ε - Carrier phase signal noise

L_3 - Ionospheric-free linear combination

L_4 - Geometry-free linear combination

L_w - Wide-lane linear combination

S - Observed path

G - Geometry path

v - GPS signal propagation

ΔL - Excess phase

ΔL_1 - Excess path on L_1 frequency

ΔL_2 - Excess path on L_2 frequency

θ - Satellite elevation angles

$mf_h(\theta)$ - Hydrostatic (dry) mapping function

$mf_w(\theta)$ - Wet (non-hydrostatic) mapping function

H_S - Orthometric height of GPS station

h_t - Height correction

P_S - Surface pressure

ϕ - Latitude

h - Ellipsoidal height

$l_{f,a,b}^{i}$ - The difference of two observation equations from two (2) GPS stations

T_d - Dew temperature

T_m - Weighted mean temperature of the atmosphere

T_s - Surface temperature

$\bar{K}$ - Water vapour scale factor

H_w - Water vapour scale height

H_{tropo} - Troposphere height

H_h - Height of neutral atmosphere

RH - Relative humidity

e_s - Saturated vapour pressure

α - Signal bending angle

a - Atmospheric impact parameter

N - Refractivity

N_h - Refractivity for hydrostatic

N_w - Refractivity for wet

$N_w(h)$ - Vertical profile of wet refractivity

ΔN_w - Wet refractivity gradient

nr - Fractional radius

q - Specific humidity in g/kg

P_T - Pressure at the top of troposphere

A_d - Diurnal anomaly of water vapour

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CHAPTER 1

INTRODUCTION

1.1 Background of Study

Atmospheric water vapour plays a crucial role in Earth's energy and hydrological cycles due to its high instability. In general, as the air gets warmer, more water vapour is trapped in the atmosphere (Musa, 2007) and such vapour can be transported over a large spatial extent before releasing its latent heat during condensation of water vapour into precipitation, which dominates the structure of the tropospheric adiabatic heating (Lutz, 2008). This phenomenon gives the tropical climate dynamics much of its distinct flavour and complexity (Giannini *et al.*, 2008). Due to its large variability both temporally and spatially, accurate measurement of atmospheric water vapour has been very challenging in meteorology, according to Wang *et al.* (2012), it can vary vertically on three orders of magnitudes from ~10 g/kg to less than 0.01 g/kg in mixing ratio.

Measurements of water vapour may be expressed in terms of the precipitable water vapour (PWV) or integrated water vapour (IWV). Atmospheric scientists have developed a variety of means for measuring the vertical and horizontal distribution of atmospheric water vapour. Figure 1.1 shows the various conventional meteorological platforms for measuring atmospheric water vapour. The radiosonde, a balloon-borne instrument package that sends temperature, humidity, and pressure data to the ground by radio signal, is the cornerstone of the operational analysis and prediction system at most operational weather forecast centres worldwide. Contemporary radiosonde instruments measure temperature and relative humidity with accuracies of ~0.2°C and ~3.5%, respectively, with diminishing performance in cold, dry regions (Rocken *et al.*, 1993).

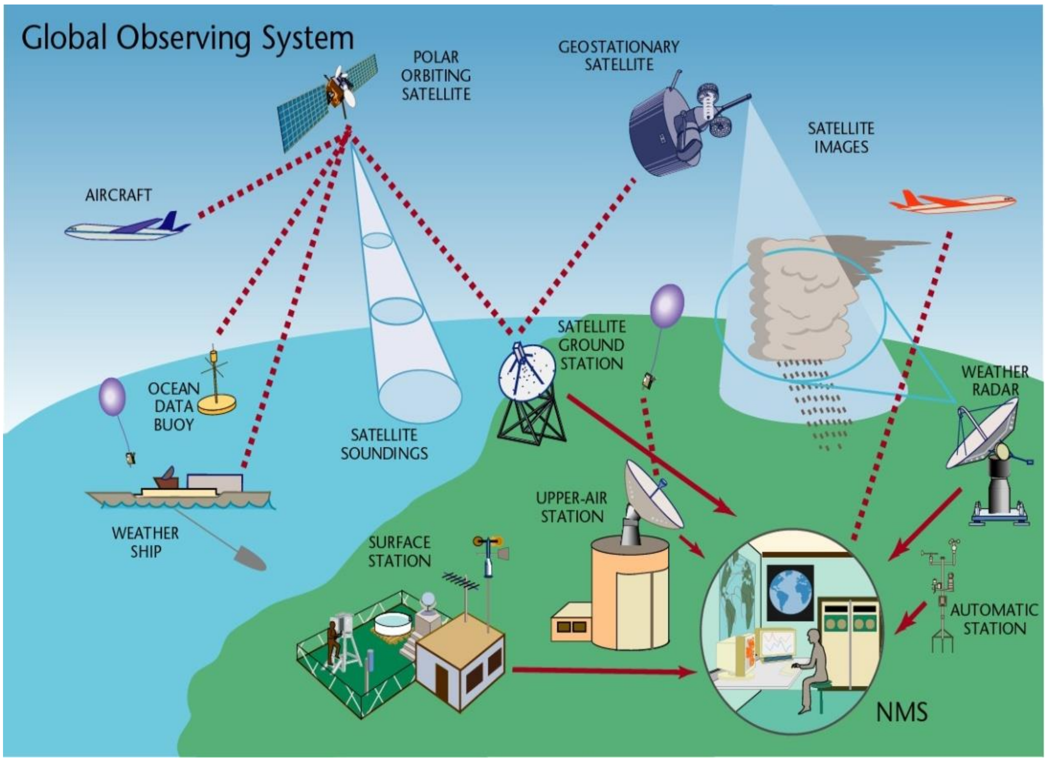

Figure 1.1 Conventional Water Vapour Measurement Platforms and Sensors (MetService, 2013).

Although the radiosonde measurements have been known to provide good vertical resolution of atmospheric profile, it still presents some serious disadvantages which include:

1. *Cost ineffectiveness:* Radiosondes are expensive, and this restricts the number of launches to twice daily at a limited number of stations.

2. *Poor spatio-temporal resolution:* Because of these restrictions, radiosonde measurements inadequately resolve the temporal and spatial variability of water vapour, which occurs at scales much finer than the spatial and temporal variability of temperature or winds (Deng, 2012).

Two other techniques used to routinely measure the atmospheric water vapour other than radiosonde, are Ground-based and Space-borne remote sensing (Bevis *et al*., 1992).

(i) Ground-based radiometry measures the background radiation emitted by atmospheric constituents. A water vapour radiometer (WVR) measures the intensity of the water vapour spectral line centred at 22,235 GHz, which can be converted into line-of-sight IWV. The WVR can provide high temporal resolution. However the WVR also has limitations because during heavy rainfall or observation close to sun, the WVR cannot measure the sky brightness temperature, in addition, it is also expensive (Deng, 2012). Hence only a few of these instruments are used today (Pacione *et al.*, 2001).

(ii) Downward-looking WVRs are also found on board satellites to measure microwave emissions from the atmosphere and the Earth's surface. The application of downward-looking WVRs is greatly affected by the complications of the background surface brightness temperature and the results are limited to cloud-free conditions (Deng, 2012; Bevis *et al.*, 1992). Otherwise satellite-based radiometry provides good spatial but poor temporal resolution.

These drawbacks suggest that traditional water vapour measurements are very coarse in time and space, thus, quality problems are usually prevalent with some being systematic. In view of this, the capability of observing or modelling water vapour in sufficient detail is limited (Bevis *et al.*, 1992; Vedel, *et al.*, 2008; De Haan *et al.*, 2009; Bursinger, 2009; Anthes, 2011). Therefore, the search for a robust measurement system that could augment these limitations became essential hence, the use of Global Navigational Satellite System (GNSS) for meteorology.

1.1.1 GNSS Geodesy and the Atmospheric Dynamics

The GNSS consists of a constellation of satellites orbiting at about 20,200km above Earth's surface, continuously transmitting signals that enable users to determine their three-dimensional (3D) position with global coverage. These include; the United State of America’s Global Positioning System (GPS), Russian’s Globalnaya Navigatsionnaya Sputnikovaya Sistema (GLONASS), European’s Galileo, Japanese Quasi-Zenith Satellite System (QZSS), China’s Beidou Satellite System (BDSS), Indian Regional Navigational Satellite System (IRNSS) and a host of others (Li *et al.*, 2015).

However, GPS being the first type of GNSS infrastructure developed, first for military purpose and later made partly accessible to civilian users has been widely used by many professionals all over the world to support various applications such as navigation, surveying, mapping and engineering, due to its capability as an all-weather satellite-based positioning tool. Figure 1.2 represents the GPS constellation, which consists of 24 space vehicles (SVs) at 20,200 km altitude distributed in six circular orbital planes inclined at 55o to the equator and having four operational satellites in each plane.

Figure 1.2 GPS Constellation (University of Colorado, 2015).

The GPS tracking network was established to provide high precision navigation and geodetic positioning. Four satellites are visible anywhere in the world, at any time. The network uses GPS receivers (which constitute the user segment) to track and decode the transmitted signals from the satellites. High quality dual frequency receivers are essentially needed for accurate estimation of tropospheric delay and in order to effectively eliminate ionospheric propagation delay (Li *et al.*, 2015).

A global network of GNSS stations equipped with such high quality receivers is maintained by the International GNSS Service (IGS), Figure 1.3 depicts the global distribution of the network. The IGS, formerly referred to as the International GPS Service, presently has about four hundred and twenty seven (427) sites and three hundred and sixty (360) active stations worldwide equipped with dual frequency receivers as well as about two hundred (200) data processing and analysis centres (ACs) spread in over ninety (90) countries worldwide (Rizos, 2012). Using data from this global network of continuously operating GNSS stations, each AC computes products such as precise GPS ephemerides and adjusted clock parameters and recently, global ZPD product has been added for GPS meteorology. A list of IGS products is shown in Table 1.1.

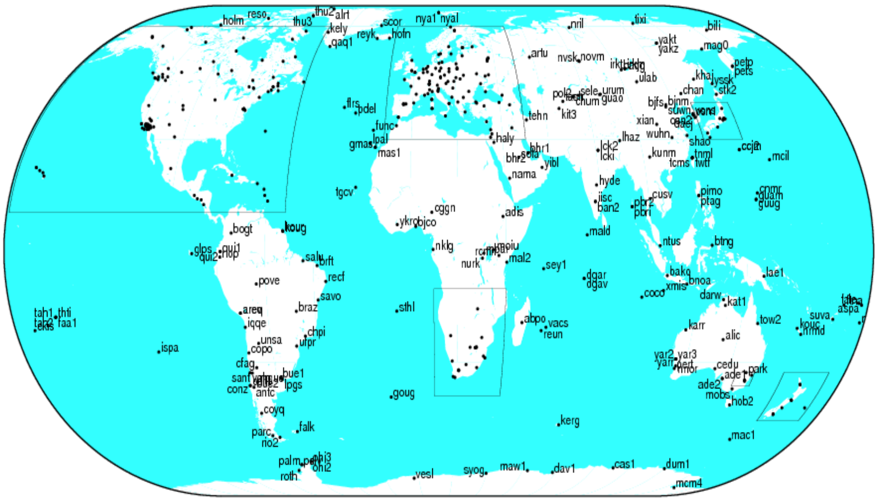

Figure 1.3 Global Distribution of IGS Tracking Stations (International GNSS Service, 2013).

Table 1.1 Broadcast Values and IGS Combined Orbit and Clock Products (International GNSS Service, 2013).

Products Type		Orbit		Clock		Latency	Update intervals
		RMS	Interval	RMS	Interval		
Broadcast		~100cm	Daily	~5ns	Daily	Real time	
IGU	Ultra-Rapid predicted half	~5cm	15 min	~3ns	15 min	Real time	Four times each day
	Ultra-Rapid observed half	<3cm	15 min	~150ps	15 min	3-9 h	Four times each day
IGR	Rapid	~2.5cm	15 min	~75ps	5 min	17-41 h	Daily
IGS	Final	~2.5cm	15 min	~75ns	30 s	12-18 days	Weekly

Furthermore, the last decade of the 20th century witnessed the development of Low Earth Orbiting (LEO) satellite such as the German Challenging Mini-satellite Payload (CHAMP), Gravity Recovery and Climate Experiment (GRACE), for other geodetic applications such as gravity field determination (Hofmann-Wellehof and Moritz, 2005). The LEO satellites are equipped with GPS receiver to enable them track GPS satellite at a higher orbit in order to fix their in-orbit location, thus the concept of satellite-to-satellite tracking.

1.1.2 GPS Meteorology

The use of GPS to measure water vapour in the atmosphere for the application of weather predictions and study of climate change is currently referred to as GPS meteorology. The principle behind GPS meteorology was first introduced by Bevis *et al*. (1992) and has gained wide acceptability and usage since then with more areas of applications emerging. The continuous availability of GPS satellites and the increasing spatial distribution of the Continuously Operating Reference Stations (CORS) worldwide, coupled with the deployment of numerous Low Earth Orbiting (LEO) satellites carrying GPS receivers on-board have tremendously enhanced this concept of GPS atmospheric measurement platform. Figure 1.4 depicts the GPS meteorology platform

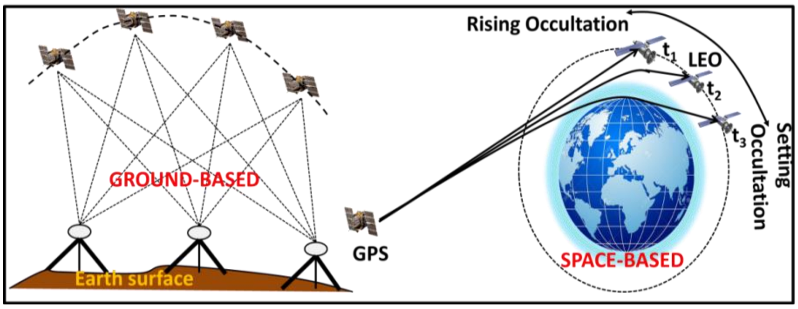

Figure 1.4 GPS-based Meteorological Observing Platforms.

GPS meteorology is sensitive to the total atmospheric delay of GPS radio signals and hence can provide atmospheric information (e.g. Hajj *et al*., 1997; Liou *et al*., 2007; 2010, Lin, 2010; Rizos, 2012). There are two main categories of GPS meteorology (Berbeneva *et al*., 2001; Bai, 2004), based on the reception of the GPS signals, these are the ground-based GPS meteorology (Figure 1.4, left column) and the space-based GPS radio occultation (Figure 1.4, right column).

Basically, in GPS data analysis, the total delay of GPS radio signals along the line of sight from each satellite are conventionally mapped to the zenith direction to yields a single average parameter known as the zenith total delay or zenith path delay (ZPD). Figure 1.5 shows the slant ray path in relation to the zenith direction.

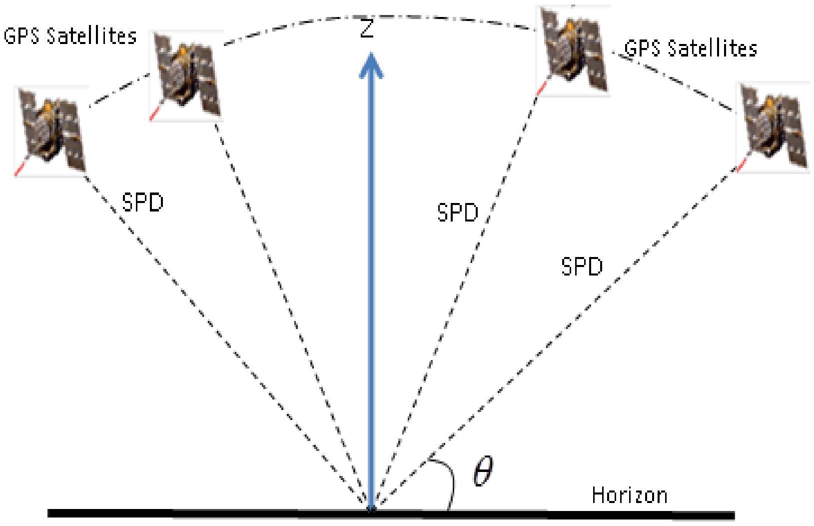

Figure 1.5 Slant and Zenith Path of GPS Signals Over a GPS Station.

The ZPD is a crucial parameter for meteorological and climatological study; for instance, it serves as an additional input parameter in NWP models for synoptic meteorology, while for now-casting; it is a standard real time product used as a measure of the state of the atmosphere (Awange, 2012; Bosy *et al.* 2010). Nevertheless, the vertical variation of atmospheric refractivity is most desirable to meteorologists and atmospheric scientists. Realising this through GPS meteorology concepts has remained a subject of research over the last few years.

1.2 Problem Statement

The equatorial region (low latitude or tropical region), is exposed to intensive sunlight all year round due to the relatively low zenith distance of the sun in the region, with temperatures in the ranges of 20°c to 35°c (Musa *et al.*, 2011). Since water vapour is responsible for atmospheric stabilisation, the warmer the air, the more water vapour it can hold to form droplets that eventually produce rain. This circumstance is responsible for the peculiar atmospheric dynamics and climatic uncertainty in the tropics (Lystad, 2011; Deng, 2012). This great uncertainty has hitherto limited the ability of global circulation models to properly resolve the atmospheric dynamics in the tropical region.

The need to address the challenges of GPS radio signal attenuation and its attendant effects on various applications due to the presence of water vapour in the atmosphere cannot be over emphasised. Application of GPS meteorology concept to study the variability of the water vapour to allow for proper modelling of its effects on positioning and navigation, as well as for weather and climate applications have been advanced in the last two decades. As a requirement for GPS meteorology, surface meteorological data (e.g. temperature and pressure) should be preferably obtained from in-situ measurements co-locating with or close to the GPS antenna (Bai, 2004; Musa *et al.*, 2011; Norazmi, 2016). Availability of meteorological data in such a manner still remain a challenge especially in the data sparse equatorial region.

To address this challenge, gridded meteorological data are interpolated from NWP models, but this facility is yet to be adopted in most developing countries due to its cost. However, Böhm *et al.* (2015) has developed the Global Pressure and

Temperature (GPT2_1w) model for generating approximate meteorological information for GPS meteorology application. A detail study on the applicability of the model as recommended is yet to be explored. Investigation into the use of this model for GPS meteorology may not only benefits meteorological application but also geodesy to improve the up-component of GPS positioning.

Furthermore, the benefits of the ground-based GPS meteorology to weather and climate applications have been highlighted in the previous section. But the major challenge lies in the mapping of the slant observations to the zenith direction which has hindered its ability to adequately generate profiles of atmospheric refractivity. This explains why most meteorological institutions prefer assimilation of only the ZPD parameters from GPS data analysis. Therefore, how to generate atmospheric refractivity profile from GPS data analysis still remains a challenge.

Although, the technique of GPS tomography remain the most potent option, but the problem with the tomography solution as stated earlier, ranges from the imposition of constraint to the use of NWP models refractivity as a-priori in order to handle the ill-conditioness and rank deficiency of the coefficient matrix. This introduces errors of unknown sources and the solution is not an independent GPS solution.

In addition, the concept of site specific tropospheric profiling has been developed. The concept is still being investigated as a result of instability of the solutions as well as heavy computational task. There is the need to search for an approach that could deliver stable solution and be easily implemented. Therefore, Hurter and Maier (2013) have reconstructed atmospheric wet refractivity profiles and humidity by combining ZPD obtained from surface meteorological data, GPS, radiosonde profiles as well as wet refractivity from radio occultation profiles using least square colocation approach. Although the methodology was said to compare considerably well with radiosonde profiles but it is a solution from heterogeneous data background. It is essential to still investigate a GPS-only solution for retrieval of refractivity profile.

Fortunately, the space-based GPS radio occultation technique has been developed to provide the profiles of the atmosphere at a global scale, but the degradation of the L2 signal in the lower troposphere region due to high atmospheric moisture gradients, which causes atmospheric ducting, atmospheric multipath of GPS signals and low signal-to-noise ratios (Scherllin-Pirscher *et al.*, 2011) also limit the capability of the occultation profiles to penetrate the lower troposphere. However, the bulk of atmospheric water vapour is located within the lower tropospheric region and this is responsible for the atmospheric variability which is known to be very high in the equatorial region. Furthermore, the spatio-temporal distribution of GPS RO events in equatorial region is still very sparse. Interestingly, recent improvements in retrieval models has enhanced the penetration of the GPS RO soundings to the nearest 1km layers hence, profiles are now available at altitudes as low as 100m in the lower troposphere (Huang *et al.*, 2013). It will be remarkable therefore, to seek how best to utilise the GPS RO infrastructure in order to improve the ground-based GPS meteorology output.

Therefore, the key challenge drawn from the foregoing issues is how to adequately measure the vertical structure of tropospheric column water vapour and its spatial distribution. It is thus, essential to ascertain the extent to which GPS meteorology can be reliable for retrieving atmospheric wet refractivity profile especially in the data sparse equatorial region.

As this research attempt to address these challenges, a combination of the space-based GPS RO and ground-based GPS data may be beneficial to that effect. Thus, the following questions need to be properly addressed:

(i) How can GPS observations be utilised for sensing the variability of atmospheric water vapour?

(ii) Can ground-based GPS meteorology be used for wet refractivity profile retrieval without combining with data from other conventional meteorological systems or using tomography concept?

(iii) How may data from surface network of GPS receivers be combined with the space-based GPS radio occultation (RO) data for optimum estimation of atmospheric water vapour?

1.3 Aim and Objectives of the Study

The overall aim of this research is to investigate a methodology for GPS-based retrieval of atmospheric water vapour profile. Therefore, the following specific objectives were set towards achieving this aim:

(i) To evaluate ground-based GPS IWV while investigating alternative sources of surface meteorological data for GPS meteorology.

(ii) To investigate the sensitivity of space-based GPS RO data to water vapour trend.

(iii) To develop a GPS-based wet refractivity retrieval model through integration of the ground- and space-based GPS observations.

1.4 Scope and Limitations of the Study

This study focuses mainly on assessing the effects of tropospheric variability on GPS positioning so as to explore the potential of GPS meteorology in understanding the tropospheric dynamics and its uncertainty in equatorial region. Therefore, this research utilised data from GPS; focusing on measurements from L1 and L2 frequency bands only. However, measurements from other GNSS infrastructure such as GLONASS, Galileo, BDSS etc. was not considered in this study.

The study was conducted using GPS observations over Peninsular Malaysia. Surface meteorological data based on Automatic Weather Station (AWS) measurements was obtained as auxiliary information; Radiosonde observations was acquired for benchmarking the GPS derived atmospheric parameters.

The ground-based GPS data was processed using Bernese version 5.0 software, while Matlab programming codes was developed to handle other processing strategies that are not supported by Bernese software. The RO data was accessed at the online archive of GPS radio occultation mission centres (e.g. Cosmic Data Analysis and Archival Centre (CDAAC) and the Taiwan Analysis Centre for Cosmic (TACC)).

Finally, a methodology for GPS-based wet refractivity retrieval using a combination of data from the ground-based GPS and the GPS RO was developed; the performance of the method developed was statistically evaluated. However, this study does not cover the application of the model in a specified case study (to study water vapour events).

1.5 Contributions and Significance of the Study

This research has investigated approaches for GPS-based wet refractivity retrieval. Thus, the applicability of GPT 2w model for GPS meteorology as well as the sensitivity of GPS RO data to water vapour variation in Peninsular Malaysia has been conducted.

A new approach for GPS wet refractivity profile retrieval have been realised in this study. This is the Modified Single Exponential Function (MSEF) model for site-specific ground-based GPS wet refractivity profile. In addition, the concept of GPS data Integration for Wet Refractivity (GIWRef) profile retrieval have also been realised towards improving the MSEF methodology. These constitute the key contribution of the research. This achievement could aid the development of GPS Wet Refractivity Monitoring System (GWReMS). The realisation of such system would be remarkable for understanding the equatorial monsoon system and also contributes towards development of residual tropospheric error reduction model for improved positioning/navigation solutions.

Therefore, the significance of this study can be viewed from a tripodal perspective of geodesy/space science, meteorology/atmospheric science and hydrology/environmental science applications. This is envisaged from the following possible benefits derivable from the outcome of this study:

(i) Tropospheric ducting has remained a serious challenge in space infrastructure deployment and reception. The MSEF/GIWRef approaches realised in this study will allow the use of GPS CORS for tropospheric characterisation in space applications and telecommunication.

(ii) Also, the site-specific GPS approach (MSEF) would be of great need in air space management system. This is because; it has the potential for operational implementation for providing continuous information about water vapour distribution at the airport environments.

(iii) Furthermore, the new GPS wet refractivity model can be used to generate apriori refractivity values for GPS tomography. This will address the challenges of using external observations to tune tomography solution. It can also be useful for developing residual wet delay field to support precision GPS positioning.

(iv) The wet refractivity from the MSEF/GIWRef method could be useful for assimilation into NWP model for improved weather forecasting and possible early warning of severe events such as flood.

(v) The study outcome can support monitoring of equatorial water vapour system and of course the tropical monsoon system.

1.6 The Structure of the Thesis

This thesis is organised into six chapters. The intoroduction to the study and research definition has been detailed in Chapter 1; meanwhile, the summary of the remaining chapters is outlined subsequently.

Chapter 2 reviewed literatures on GPS observation for sensing atmospheric water vapour, it starts with an overview of atmospheric delay on GPS signals. Relevant studies on ground-based GPS meteorology, covering GPS observations and data processing strategies for accurate estimation of ZPD, the space-based GPS RO technique detailing the processing strategy for accurate estimation of atmospheric excess phase and the subsequent inversion to generate refractivity profiles were covered. Then, the approaches for ground-based GPS tropospheric profiling is also discussed before presenting a preliminary study on GPS wet refractivity profile retrieval

Chapter 3 presents the research methodology. Thus, a methodology for assessing GPS-derived IWV over Peninsular Malaysia is discussed, including the use of empirical tropospheric model (GPT2w) to generate approximate meteorological information for GPS meteorology. this is to achieve the Objective 1 of this study. Then, a methodology to evaluate the GPS RO-derived IWV was discussed. This is towards achieving the Objective 2 of this research. The chapter also detailed the formulation and retrieval strategy for the Modified Single Exponential Function (MSEF) approach for ground-based GPS wet refractivity retrieval, while the method for integrating the ground- and space-based GPS observations for tropospheric profiling was covered to achieve Objective 3 of the research.

Chapter 4. dwells on the results and discussions for the first two objectives. Thus, the results of the evaluation of ground-based GPS IWV as well as the space-based GPS RO IWV were discussed.

Chapter 5 presents the MSEF profile results its performance evaluation. The validation of the GIWREF approache for improve MSEF wet refractivity profile retrieval is also covered.

Finally, Chapter 6 presents the conclusion and future outlook of the study.

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