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TREND IN GROUND-BASED GPS SENSING OF ATMOSPHERIC WATER VAPOUR: THE MALAYSIAN PERSPECTIVE

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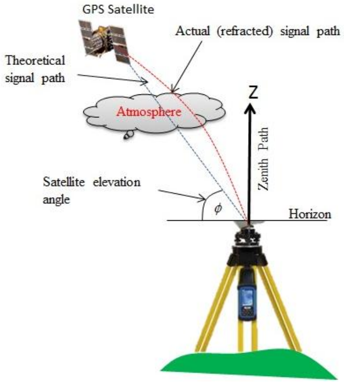

Abstract

Atmospheric water vapour is the most variable component of the atmosphere. It plays a crucial role in ogical cycles. Because of its temporal and spatial variability, accurate measurement of atmospheric water in meteorology. However, the Global Positioning System (GPS) offers detailed coverage, all weather and re, exploring this potential to deliver atmospheric information is now termed 'GPS meteorology'. This of global trend in GPS meteorology while discussing GPS meteorology research efforts in Malaysia. A ctivity towards realisation of operational use of GPS meteorology in Malaysia is also highlighted.

Keywords: GPS meteorology, Atmospheric water vapour, Zenith path delay, Slant path delay, integrated

Abstrak

Wap air merupakan komponen atmosfera paling ketara berubah. Ia memainkan peranan yang penting ni dan kitaran hidrologi. Oleh kerana wap air sering berubah-ubah bergantung pada masa dan lokasi, sfera adalah merupakan perkara yang paling mencabar dalam meteorologi. Walau bagaimanapun, Sistem ırkan liputan yang terperinci, operasi dalam pelbagai keadaan cuaca dan cerapan yang berterusan. Maka ia erolehi maklumat atmosfera dan boleh dikenali sebagai 'GPS meteorologi'. Kertas ini membentangkan dalam GPS meteorologi sambil membincangkan usaha penyelidikan GPS meteorologi di Malaysia. rkini ke arah merealisasikan operasi penggunaan GPS meteorologi di Malaysia juga diketengahkan.

Kata kunci: GPS meteorologi, wap air atmosfera, lewatan laluan zenith, lewatan laluan condong, integrasi

■1.0 INTRODUCTION

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 and such vapour can be transported over a large spatial extent before releasing its latent heat This phenomenon gives the tropical climate dynamics much of its distinct flavour and complexity [13]. Due to its large variability both temporally and spatially, accurate measurement of atmospheric water vapour has been very challenging in meteorology, it can vary vertically on three orders of magnitudes from ~10 g/kg to less than 0.01 g/kg in mixing ratio [40]. Traditionally, water vapour measurements are very coarse in time and space. Quality problems are usually prevalent with some being systematic. Hence, the capability of observing or modelling water vapour in sufficient detail is limited [1, 4, 6, 8, 39].

The development of Global Positioning System (GPS) meteorology as a modern meteorological observing system out of geodetic expedition has been well detailed in literature since the last two decades. A number of studies have shown that "GPS meteorology" offers continuous observations and detailed coverage irrespective of weather conditions (such as heavy rainfall and clouds) and it is cost effective in complementing other remote-sensing techniques to measure water vapour content [2, 15, 35]. However, bulk of these researches has been concentrated around the mid-latitude to near tropical region. Unfortunately, the tropical region noted for its peculiar climatic dynamics and uncertainty has hitherto not reflected adequately on this research platform. The possible reason could be the near absence of GPS infrastructure in the region for a long time. Within the last decade, the network of GPS Continuously Operating Reference Stations (CORS) has been established in most countries in the tropical region including Malaysia. This infrastructure is expected to have set the stage for researches focussed on GPS atmospheric sensing in the region.

This paper briefly reviews the global trend in ground-based GPS meteorology utilizing the CORS and presents a summary of similar research efforts in Malaysia.

■2.0 CONCEPT OF GPS WATER VAPOUR SENSING

As GPS signals travel from space to receivers on the earth surface, the two principal layers of the atmosphere (ionosphere and troposphere) affect the radio signals thereby bending the signal path and delaying their time of arrival hence, atmospheric delay [16]. Although, ionospheric delay is more severe but because of its dispersive nature, the delay can be minimise using linear combination of dual-frequency GPS observation. The troposphere on the other hand, is non-dispersive and thus cannot be minimised with dual frequency GPS receivers. More so, large amount of atmospheric water vapour is trapped in the troposphere. Tropospheric delay contains information on the total water vapour and mass of the atmosphere along the signal path [19]. The process of estimating the total tropospheric delay or zenith path delay (ZPD) from GPS observations and derivation of Integrated Water Vapour (IWV) is further discussed.

2.1 Zenith Path Delay (ZPD) Estimation

The total zenith path delay in GPS signal is given by [2, 4, and 28]:

$$\Delta L = \int_L n(s)\,ds - G \qquad (1)$$

where *n(s)* is the refractive index as a function of position s along the curved ray path *L*, and *G* is the straight-line geometrical path length through the atmosphere. Equation (1) is further re-written as [2, 16, 19]:

$$\Delta L = \int \left[n(s) - 1 \right] ds + \left[S - G \right] \qquad (2)$$

where S is the path length along *L*. The first term on the right is due to the slowing effect, and the second term is due to bending of the signal. Equation (2) is often formulated in terms of atmospheric refractivity *N*, rather than the index of refraction, *n*. Thus,

$$N = 10^6 (n-1)$$

N is a function of atmospheric temperature, pressure, and water vapour pressure, their relationship is [2, 4, 31 and 32]:

$$N = k_1 \left({}^{P_d}\!/_{T} \right) + k_2 \left({}^{P_v}\!/_{T} \right) + k_3 \left({}^{P_v}\!/_{T^2} \right) + k_4 \left({}^{P_c}\!/_{T^2} \right) \qquad (3)$$

where P_d, P_V, and P_c are the partial pressure of dry air, water vapour and carbon dioxide respectively (in millibars) and *T* is the absolute temperature (in Kelvin). While k_2, k_2, k_3 and k_4 are the refraction coefficients given as [2, 3, 14 and 20]:

$$k_1 = (77.607 \pm 0.013)\, Kmbar^{-1},$$
$$k_2 = (71.6 \pm 8.5)\, Kmbar^{-1} and$$
$$k_3 = (3.747 \pm 0.031) \times 10^5 K^2 mbar^{-1}$$
$$k_4 = \left({}^{5}\!/_{3} \right) . k_1$$

Considering the non-ideal gaseous behaviour of the atmosphere, [36] gave a more precise form of Equation (3) as [2 and 4]:

$$N = (n-1)10^6 = k_1 \left({}^{P_d}\!/_{T} \right) Z_d^1 + k_2 \left({}^{P_v}\!/_{T} \right) Z_v^1 + k_3 \left({}^{P_v}\!/_{T^2} \right) Z_v^1 \qquad (4)$$

where Z_d^{-1} and Z_v^{-1} are the inverse compressibility factors for dry air and water vapour, respectively. The refraction coefficients for Equation (4) are given by [5] as:

$$k_1 = (77.604 \pm 0.05)\, Kmbar^{-1},$$
$$k_2 = (70.4 \pm 2.2)\, Kmbar^{-1} and$$
$$k_3 = (3.739 \pm 0.012) \times 10^5 K^2 mbar^{-1}$$

Since the troposphere is neutral and non-dispersive, its refractive index depends on temperature, pressure, humidity, compressibility and electric characteristics of the molecules [41]. However, the total tropospheric delay depends on the zenith distance or elevation angle of the satellite. If zenith distance is *z* then the propagation path delay is proportional to 1/cos *z*. The interactions between the GPS radio signal and the atmosphere is depicted in Figure 1.

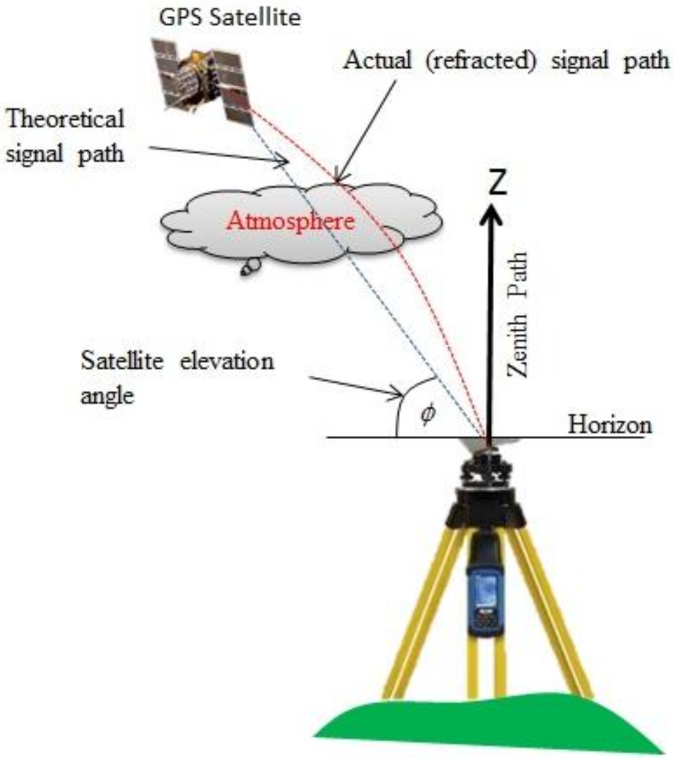

Fig.1 Atmospheric effect on GPS signal.

From Figure (1), the zenith distance,

$$z = 90^0 - \phi \quad \text{hence,}$$

$$1/\cos z = 1/\sin\phi \qquad (5)$$

where ϕ is the satellite elevation angle. This is the concept for the mapping-functions [24].This unique signature makes it possible to solve separately for the total tropospheric delay in zenith direction in GPS computations including station coordinates and receiver clock delays. The *ZPD* consists of two components: the zenith hydrostatic or dry delay (*ZHD*) and the zenith wet (non-hydrostatic) delay (*ZWD*) components. Therefore, the total effect of the two components gives the total zenith delay over the station, which can be expressed as [2, 9, 21 and 41]:

$$ZPD = mf_h(z).HD + mf_w(z).WD \qquad (6)$$

where, $mf_h(z)$ and $mf_w(z)$ are the dry and wet mapping functions respectively while, *HD* and *WD* are the dry and wet delay.

2.2 Integrated Water Vapour (IWV) Estimation

The *ZHD* is about 90% of the *ZPD*. It varies smoothly with surface pressure therefore, it can be effectively modelled as [*e.g.* 10, 29].

$$ZHD = (2.2779 \pm 0.0024)\, P_s / f(\phi, h) \qquad (7)$$

where P_s is the total pressure (in millibars) at the Earth's surface, and

$$f(\phi, h) = (1 - 0.00266\cos 2\phi - 0.00028h) \qquad (8)$$

Equation (8) accounts for the variation in gravitational acceleration with latitude ϕ and the height *h* of the surface above the ellipsoid (in kilometres). If the surface pressure and temperature at the GPS stations are measured or known, then the integrated water vapour (IWV) can be derived as follows:

$$IWV = \bar{K}(T_m).ZWD \qquad (9)$$

where, $\bar{K} = \dfrac{10^6}{\left((R_3/T_m) + k_2\right)R_v}$ and

R_v is a gas constant for the water vapour, p_w is the partial water vapour k_2 and k_3 are as defined earlier while, T_m is the weighted mean temperature of the atmosphere given as [7]:

$$T_m = \frac{\int\left(\frac{e}{T}\right)dz}{\int\left(\frac{e}{T^2}\right)dz} \qquad (10)$$

where *e* is water vapour pressure, *T* is as defined earlier.

The commonly used global T_m parameters are usually derived from radiosonde and surface temperature (T_s) in Kelvin (K) using linear regression technique, [4] derived the global T_m parameters as:

$$T_m = 70.2 + 0.72T_s \tag{11}$$

■3.0 GPS METEOROLOGY: THE GLOBAL LANDSCAPE

Since the introduction of the concept of GPS meteorology in 1992 [4], it has find global acceptability with more areas of applications emerging. Numerous experimental studies have been performed all over the globe to demonstrate the potential of GPS measurement of atmospheric water budget.

Starting with the GPS/STORM experiment as a proof-of-concept study in high-tornado risk mid-western region of United State, the validity of GPS meteorology was demonstrated by comparing the GPS derived water vapour to radiosonde measurements during the period of over six (6) major storm events in that region [2]. In a follow-up project, the National Oceanic and Atmospheric Administration (NOAA) established 291 GPS sites for studying the impact of GPS water vapour on numerical weather modelling.

Currently, there are about four hundred and twenty seven (427) International GNSS Service (IGS) sites and three hundred and sixty (360) active stations with about two hundred (200) data processing and analysis centres spread in over ninety (90) countries worldwide [27] This data set which is being updated continuously is now used to generate global ZPD distribution, for instance [21] used the IGS troposphere products to assess the global ZPD variability (Figure 2).

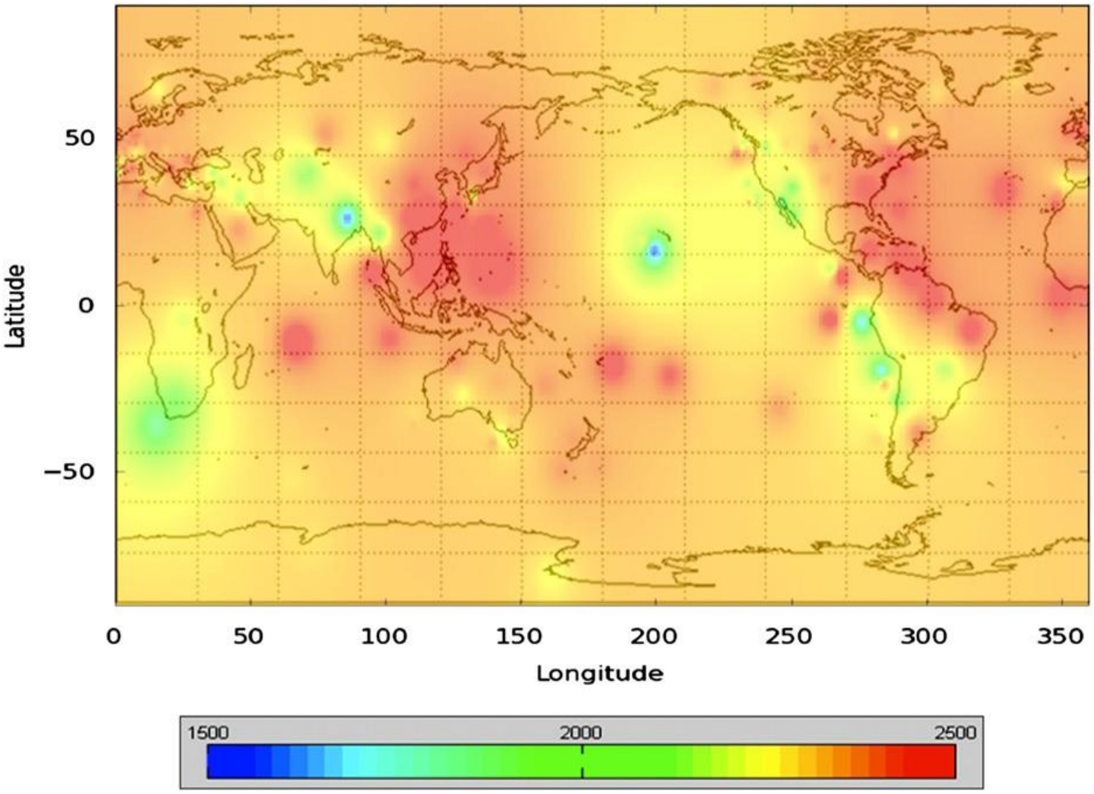

Fig.2 Global ZPD as derived from the International GNSS Service (IGS) troposphere products [21].

Over the years, at National Centre for Atmospheric Research (NCAR) in Boulder U.S.A, a global precipitable water vapour (PWV) map has been created and continuously updated by using the ZPD data from IGS, Suominet and from Geonet global water vapour maps [40]. Figure 3 shows global analysis of PWV from IGS network reflecting the diurnal anomalies in the southern and northern hemisphere (S. H and N. H) as compared to the global situation.

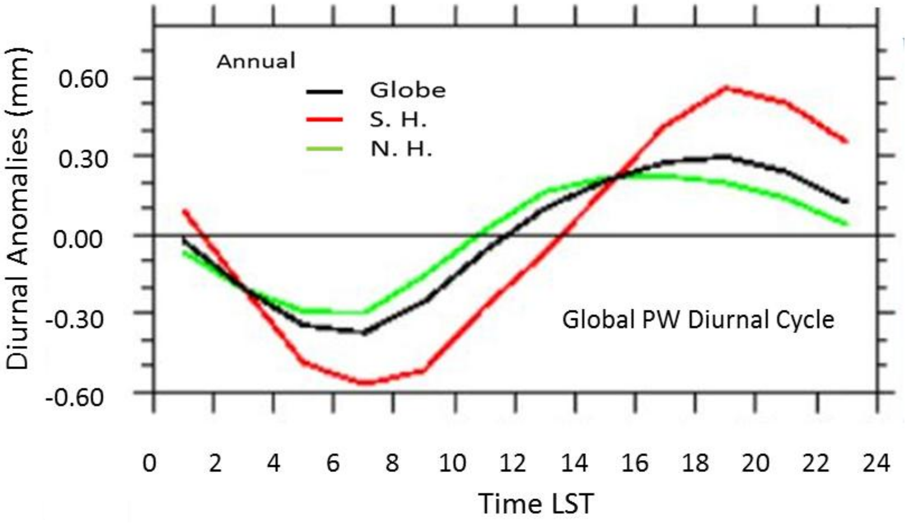

Fig.3 Global PWV analysis from IGS GPS data of January, 1995 to December, 2011 [40]

In Europe, the European Community (EC) developed a number of projects which were run in succession sponsored by member countries; these are GPS WAter Vapour Experiment For Regional Operational Network Trials (WAVEFRONT), the Baltic Sea Experiment (BALTEX), European Co-operation in the field of Scientific and Technical (COST) Research Action 716, Meteorological Applications of GPS Integrated Column (MAGIC) Water Vapour Measurements in the Western Mediterranean and Targeting Optimal Use of GPS Humidity (TOUGH) measurements in meteorology.

In order to consolidate on the gains from these researches, project E-GVAP I (EUMETNET GPS Water Vapour Programme I) was launched in 2005 to develop the operational application of GPS meteorology in Europe [38]. Several IGS stations and analysis centres across Europe and beyond (*e.g.* see Figure 4) were networked into the research project with strong relationship among stake holders *e.g.* geodesists, meteorologists and hydrologists [11]. Before the end of the project in 2009, full operational use of GPS water vapour had commenced in UK Met Office (METO).

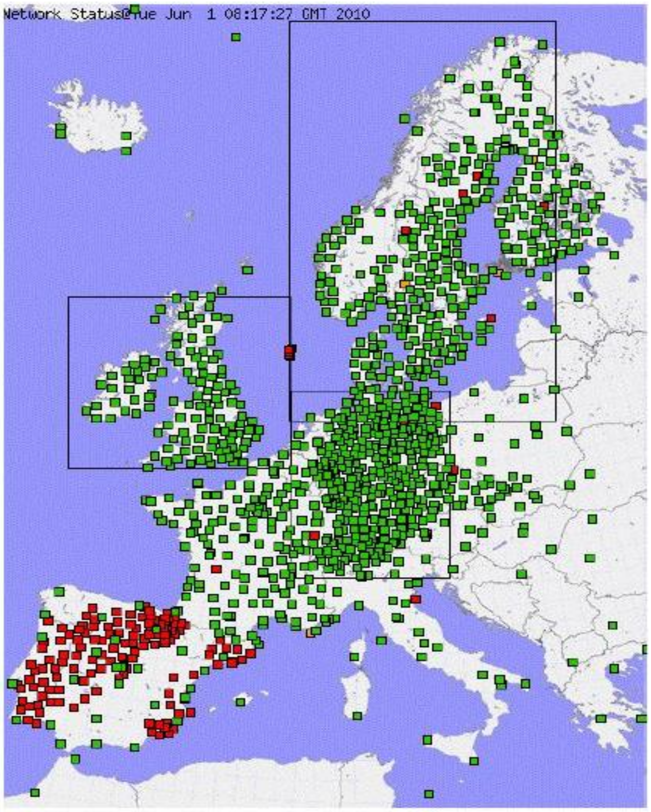

Fig.4 Map of the European GNSS ground stations included in the E-GVAP programme [38].

Based on the ZPD estimates that are continuously delivered from these collaborations and additional pressure and temperature information from in-situ meteorological systems, maps of integrated water vapour (IWV) over Europe are made (Figure 5).

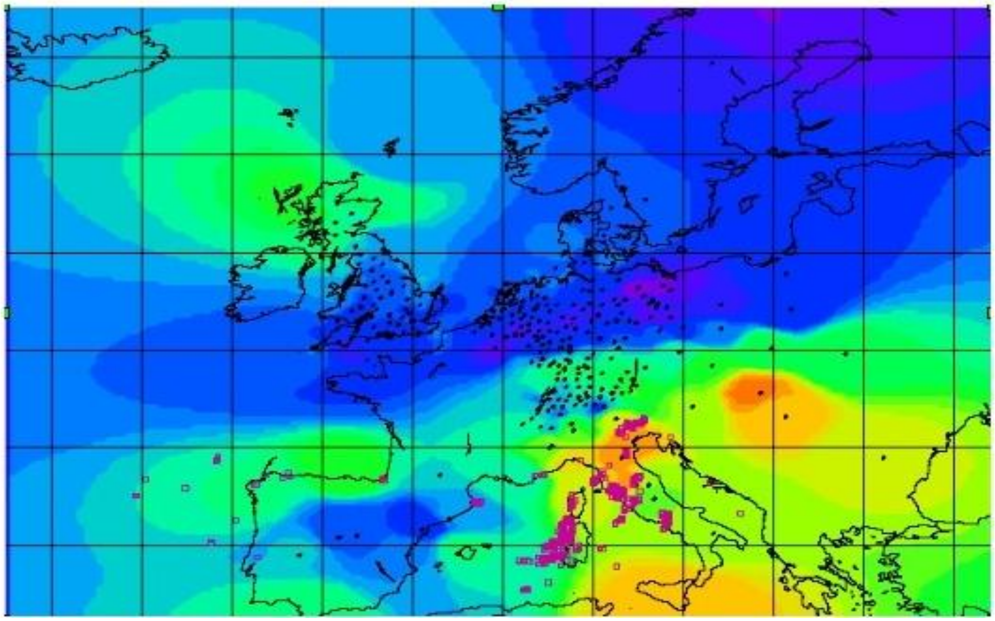

Fig.5 IWV map over Europe [39].

In Asia-Oceania region, application of GPS water vapour has also moved from experimental study to operational use since 2005 [17]. In Japan, the one thousand (1000) GPS array tagged "GPS Earth Observation Network (GEONET)" operated by the Geographical Survey Institute (GSI) was used to developed GPS meteorology project of Japan (GPS/MET) since 1997 [37] .

■4.0 GPS METEOROLOGY RESEARCH IN MALAYSIA

Located in the tropical equatorial region, Malaysia exhibits a bi-monsoonal seasons. These are the North-East monsoon (November to early March) and the South-West monsoon (early May to August). The two monsoons bring heavy rain, which sometimes causes extensive flooding in the country. Generally, the mean monthly rainfall in this area indicates drier weather conditions from May to early July and wetter conditions from November to January [22]. Therefore, the monsoon seasons highly influence the rainfall distribution in the area. Consequently, the climate and weather conditions in the country reflect the strong influence of the atmospheric water vapour. [42] assessed the impact of monsoon circulations on the performance of space-based radio navigation satellites for surveying applications; high influence of the North-East monsoon compared to the South-West monsoon was reported.

The evaluation of low latitude troposphere using the CORS in Southeast Asia by [23] served as the gateway to GPS atmospheric study in Malaysia. To set the platform for full research on GPS meteorology, [26] further examined the challenges of atmospheric remote sensing in the Australasian region. ZPD estimates from two CORS networks; the Australian Regional GPS Network (ARGN) including the Sydney CORS network (SydNET) in the temperate zone, and the Malaysian Real-Time Kinematic network (MyRTKnet) in the tropics were analysed. The preliminary results indicated a higher and shorter-term variability of the estimated ZPD over MyRTKnet (see Figure 6) which conform to their initial evaluation of IGS ZPD (Figure 2).

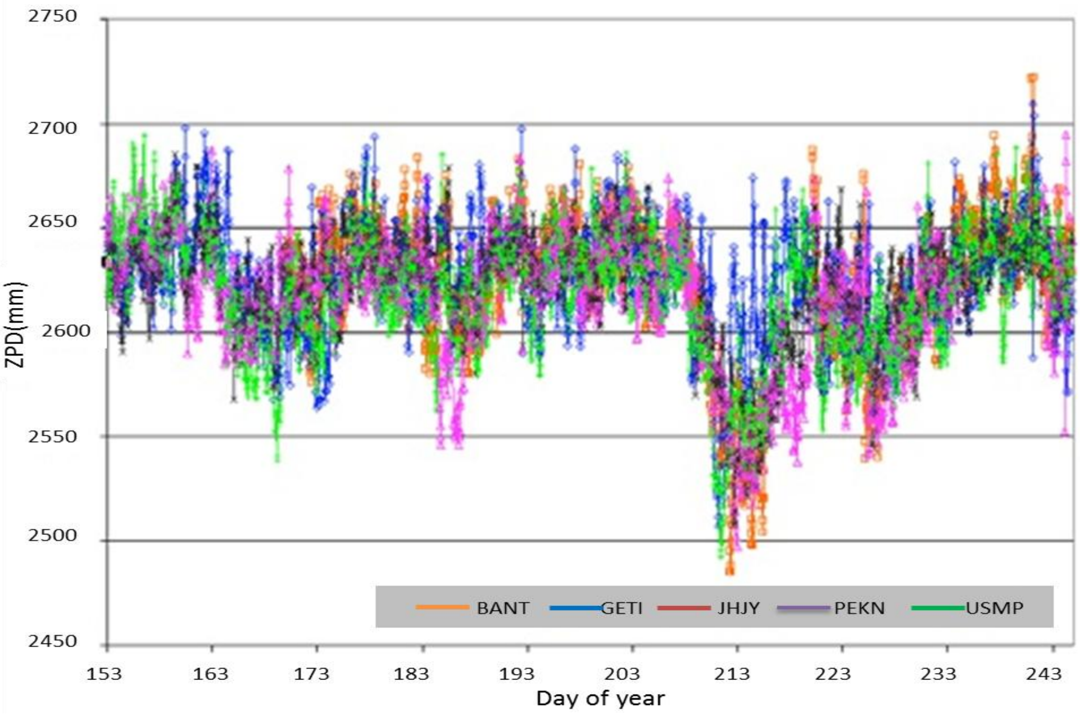

Fig.6 Time series of estimated ZPD from MyRTKnet [26].

Investigating the potential of GPS meteorology in the tropics with focus on Peninsular Malaysia, [21] assessed GPS-derived IWV for four MyRTKnet stations closed to radiosonde stations. In conformity with [26] findings, a high and short term variability of the IWV values was observed (Figure 7).

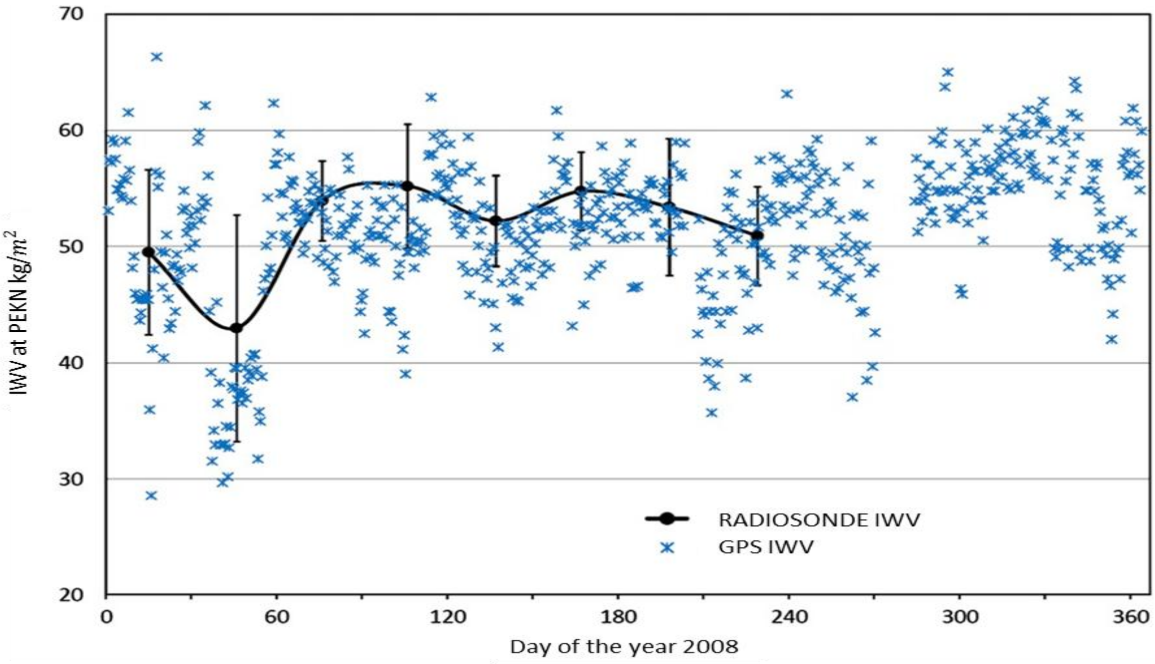

Fig.7 GPS and radiosonde-derived IWV for the PEKN station [21].

Furthermore, [33] monitored the lightning activity associated with water vapour changes during the 2009 winter monsoon over Bangi Malaysia and PWV derived from a GPS CORS was used. Their results suggest that GPS data can be utilized further as a guide to predict the occurrence of lightning. In order to evaluate the severe flooding activity in Kelantan, [34] also used PWV derived from a GPS CORS data and meteorological observations to monitor the heavy rainfall occurrences associated with water vapour changes recorded during the winter monsoon in November 2009 at Kuala Krai, Kelantan. Low PWV was observed which they attributed to the influence of heavy rainfall within the period of study. These two cases reported from [33 and 34) presented a good background for GPS Meteorology over Malaysia.

Nevertheless, there is still room for improvement in all of these efforts. This is because, all research efforts so far are focused on Peninsular Malaysia, the eastern states of Sabah and Sarawak are not covered in each of the experiments reported. In addition, the use of near real time GPS meteorology and space-based GPS radio occultation is yet to be experimented.

4.1 Moving Ahead: Developing Near Real-Time GPS meteorology in Malaysia.

Currently, the research effort at the GNSS and Geodynamics (G&G) research group, Universiti Teknologi Malaysia (UTM) is targeted at the development of near real-time GPS meteorology for operational use over Malaysia. This is aimed at characterising the tropospheric variability in the tropical region. To achieve this goal, the following issues formed the key objectives:

i. Multi-year ground-based GPS data re-processing (in a post-mission mode) and analysis.
ii. Processing and analysis of space-borne GPS radio occultation data.
iii. Assessment of atmospheric parameters using ground-based and space based GPS meteorology, thus generating the refractivity profile of the neutral atmosphere.
iv. Developing a near real-time atmospheric monitoring system.

Consequently, the research seeks to design and establish experimental GPS/MET stations as well as validating its near real time operational capability as a water vapour monitoring system in Peninsular Malaysia. Therefore, the challenges with operational use of near real time GPS meteorology have to be identified and the strategy for overcoming these challenges developed. Some of these challenges are - near real time GPS data streaming and handling; obtaining accurate information on orbits of the GPS satellites; accessing near real time data from surface meteorological sensors collocated with GPS stations; and software issues, product delivery and visualization.

In order to adress these challenges, and meet the main goal of the research, we present the highlight and concept for each of the key objectives as follows:

(i) GPS data re-processing:

This is to allow for long term analysis of ZPD variability and to further evaluate the stability and/or oscillation of atmospheric water vapour. The challenges at this level include availability of data infrastructure and access.

Available infrastructure

The G&G research group has established a GPS network called ISKANDARnet since 2010; it consists of four GPS stations distributed over the metro-area of Iskandar Malaysia, Johor, mainly for real time surveying applications [30]. One of the stations (ISK1) is equipped with a surface meteorological sensor which collects and records meteorological data in real-time mode (Figure 8). Currently, this network is undergoing expansion to cover entire Penisular Malaysia through research collaboration with some government agencies. This is expected to increase the station number to about ten and most of their locations are strategically considered to be co-located with meteorological infrastructure. This constitutes a key infrastructure for this study.

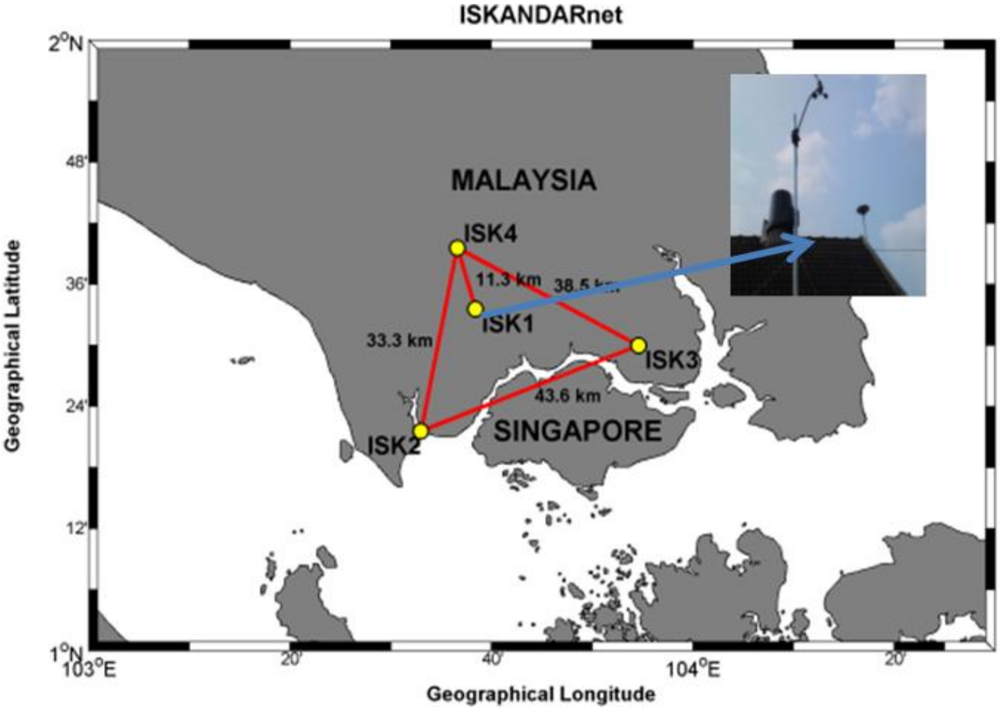

Fig.8 ISKANDARnet RTK with meteorological sensor at ISK1.

Also, Department of Survey and Mapping Malaysia (DSMM) is maintaining 78 stations (50 in Peninsular Malaysia and 28 in Sabah and Sarawak) GPS network called MyRTKnet [25], see Figure 9. In order to improve the spatial and temporal resolution of IWV estimations, the data set from MyRTKnet would be utilised in this study.

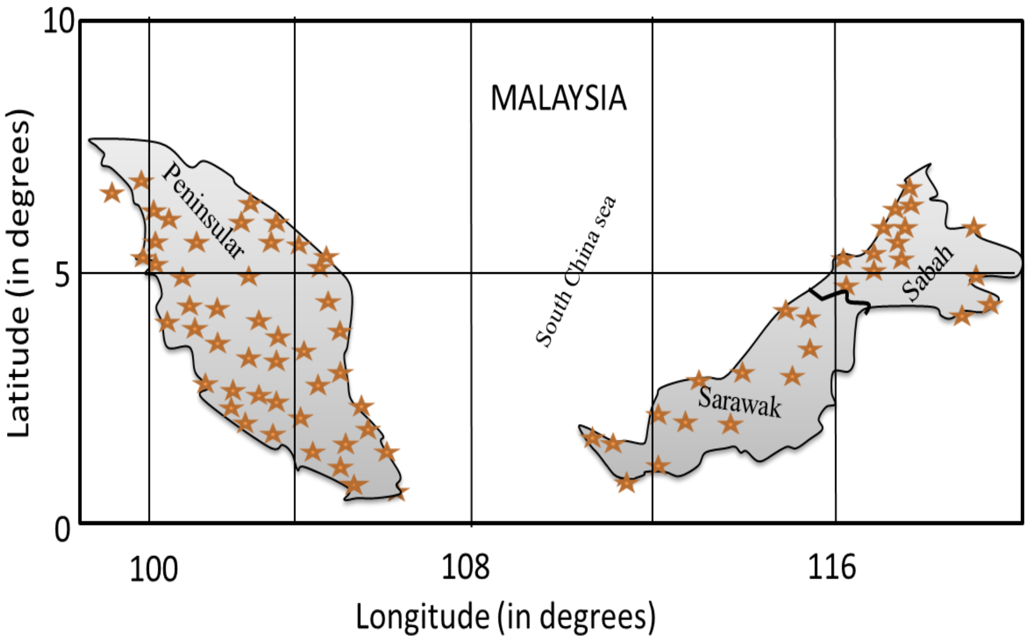

Fig.9 A sketched map of Malaysia showing MyRTKnet (modified after [25]; available at: http:// www.fig.net/pub/vietnam/).

Some IGS stations in Asia-Oceania region will be included so as to extend the network size for absolute ZPD estimation. Data for these set of stations shall be accessed at IGS website via http://igs.bkg.bund.de/root_ftp/NTRIP/streams/streamlist_igs-ip.htm. Ideally, it is required that surface meteorological sensors are established adjacent to each GPS station, but this condition does not exist. Therefore, interpolation from the nearest weather station as proposed by [2] will be adopted. Fortunately, there are Automatic Weather Stations established and maintained by Malaysian Meteorological Department (MMD) with good spatial coverage over Malaysia, some of these stations are also equipped with radiosonde facilities.

Data Access

The next challenge at this phase is access to both GPS and the meteorological data. The proposed option is to enhance a purposeful collaboration amongst the key professionals; three professional groups were identified (see Figure10).

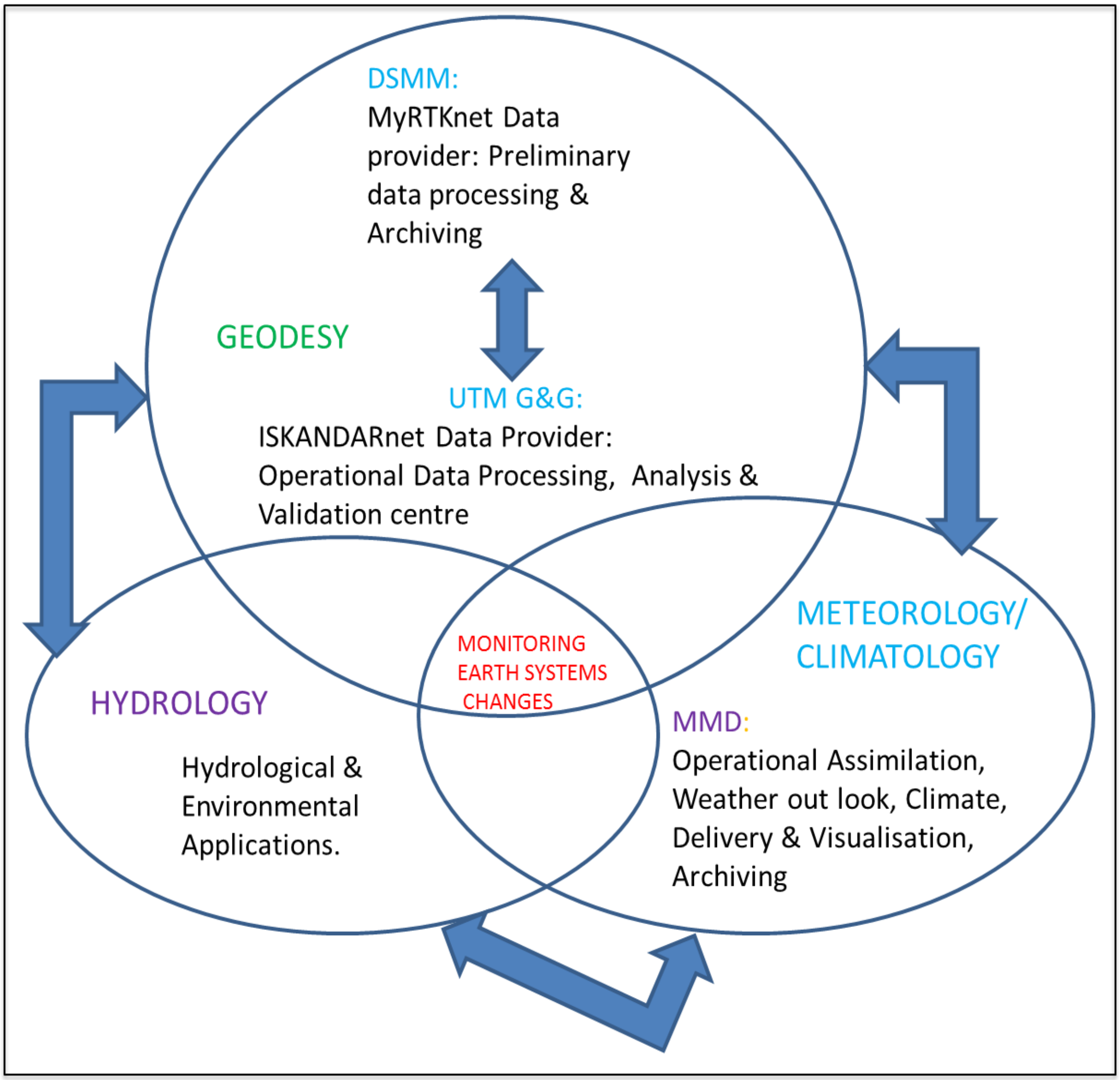

Fig.10 Professional collaboration

Consequently, institutional framework will be required to specify the mode of operations. Thereafter, the operational monitoring scheme can be developed and allow to function in a relational mode as shown in Figure 11.

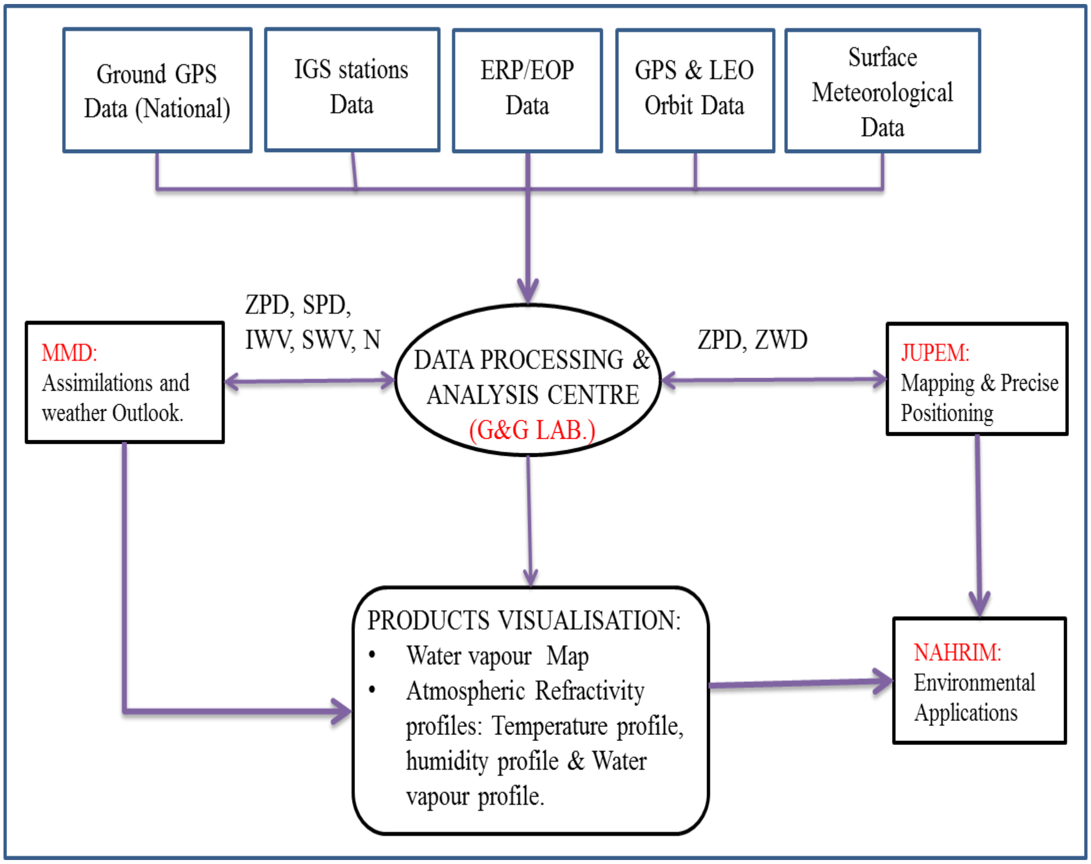

Fig.11 Operational Monitoring Model

(ii) Space-borne GPS radio Occultation:

The potential of GPS radio occultation in delivering accurate near-vertical profiles of atmospheric variables has been detailed in literature [*e.g.* 1, 12, 18, 41]. However, this technique is yet to be experimented in Malaysia. This challenge will be explored in this research to generate wet refractivity profile as background information. There are a number of GPS occultation missions currently orbiting the earth for meteorological and other geodetic applications. In this study, data from FORMOSAT-3/COSMIC mission is proposed. The mission satellite data is available at COSMIC Data Analysis and Archival Centre (CDAAC) which can be accessed at http://cosmic-io.cosmic.ucar.edu/cdaac/product.html#cosmic.

(iii) Assessment of atmospheric parameters:

Estimated parameters from (i) shall be examined side by side with the estimation from (ii). Thereafter, estimation from in-situ meteorological system (*e.g.* radiosonde and global weather field such as ECMWF model) will be used to judge the two approaches. The result will be used to build a background for benchmarking the near real-time system.

(iv) Developing a near real-time atmospheric monitoring system:

This involves designing and establishment of near real-time GPS meteorology network. While focusing on the strategy for mitigating effects of orbital errors in the near real-time processing of GPS data, the processing technique that will minimise processing time without degrading the output quality will be explored. Finally, the monitoring system will be developed by integrating the ground-based GPS data with the space-based GPS occultation data.

■5.0 CONCLUSIONS

In this paper, the concept of deriving atmospheric water vapour from GPS geodetic positioning has been discussed. A brief review of the global trend in ground-based GPS meteorology and similar research efforts in Malaysia was presented. Finally, a summary of the current research activity towards realisation of operational use of GPS meteorology in Malaysia has also been highlighted. In view of the temporal and spatial complexity of atmospheric water vapour especially in the equatorial region, developing a near real time water vapour monitoring system over Malaysia as proposed in this paper will be essential for predicting the variability of tropical monsoon. This may be a pointer towards understanding the equatorial atmospheric dynamics.

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