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RESEARCH ARTICLE - EARTH SCIENCES

The Concept of Operational Near Real-Time GNSS Meteorology System for Atmospheric Water Vapour Monitoring over Peninsular Malaysia

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Abstract The operational system from near real-time global navigation satellite system (NRT GNSS) meteorology is crucial for supplying information about climate and meteorological activities over Malaysia. As demonstrated by many researchers all over the world, the applicability of NRT GNSS meteorology has proved as a valuable tool for capturing high spatio-temporal resolution of atmospheric water vapour. This study discusses a design of NRT GNSS meteorology system for future development in Malaysia. There are three major components of this system which cover the architecture of GNSS meteorological station, the engine processor and data flow management. This paper provides the functional illustration for each component and discusses several challenges in the development of NRT GNSS meteorology system.

Keywords Zenith path delay · Integrated water vapour · ISKANDARnet · Tropical region

1 Introduction

The monsoon season country such as Malaysia is noted for frequent rainfall which is essential for economic and domestic growth. Normally in Peninsular Malaysia, the rainfall volume and distribution are mainly influenced by the two monsoon seasons known as south-west (May to September) and north-east (November to March). However, the frequency and intensity of rainfall in recent time are becoming more extreme, especially during the north-east monsoon, which contributes to severe flooding at low land areas and induces many landslide events at the high land areas. This has caused extensive damages on live and properties which has adversely affected the economy of the country.

There are many factors that influence the extreme rainfall. For example, climate change and El Niño Southern Oscillation amplified the extreme rainfall over tropical region [1]. In addition, the global warming also increases the acceleration in the natural hydrological cycle and intensity of rainfall rate which occur specifically during annual monsoon season throughout Asia [2–5]. Since various sources have been disturbing the rainfall pattern over tropical region which includes the Peninsular Malaysia, it can be inferred that the climate of this region is nowadays becoming particularly sensitive. Thus, a comprehensive measurement to monitor the tropical rainfall is essential, for example, monitoring the highly variable tropical water vapour.

Several efforts to monitor the atmospheric water vapour have been conducted by meteorologists. Nevertheless, proper monitoring of the water vapour in mesoscale has been limited by the deficiency of meteorological instruments [6,7]. Nowadays, availability of GNSS networks worldwide is being used to contribute a new parameter known as precipitable water vapour (PWV) or integrated water vapour (IWV) for meteorology [8]. The continuous observation with GNSS network allows for better representation of atmospheric water vapour in high spatio-temporal resolution. This can improve the numerical weather prediction for providing more integrity information about weather condition and forecast-

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ing as demonstrated by Vedel and Huang [9] and Van Baelan et al. [10].

In Peninsular Malaysia, there are several GNSS continuously operating reference station (CORS) network such as Malaysian Real-Time Kinematic Network (MyRTKnet) (see Jamil et al. [11]) and a university-based GNSS network (ISKANDARnet) (see Shariff [12]). Nevertheless, the potentialities of these networks have not been exploited for near real-time (NRT) monitoring of atmospheric water vapour. This paper presents the conceptual design of the operational NRT GNSS meteorological system for Peninsular Malaysia. In the future, this design will be physically developed in phases.

2 Estimation of Integrated Water Vapour

Accordingly to Musa et al. [13], the source of IWV parameter is from the total tropospheric delay which can be written as follow:

$$\Delta LM_{\mathrm{total}}(\theta) = L_{\mathrm{h}}^{0} M_{\mathrm{vh}}(\theta) + L_{\mathrm{w}}^{0} M_{\mathrm{w}}(\theta) \quad (1)$$

where $\Delta LM_{\mathrm{total}}$ is the total tropospheric delay, L_{h}^{0} is the hydrostatic delay, L_{w}^{0} is the wet delay, M_{h} is the hydrostatic mapping function, M_{w} is the wet mapping function and (θ) is the satellite elevation angle. The tropospheric delay is measured in the zenith direction of the GNSS receiver that also can be simplified as,

$$\mathrm{ZPD} = \mathrm{ZHD} + \mathrm{ZWD} \quad (2)$$

where ZPD is the zenith path delay (in millimetre, mm), ZHD is the zenith hydrostatic delay (in mm) and ZWD is the zenith wet delay (in mm). The ZHD is directly proportional to the atmospheric pressure and can be accurately modelled by Elgered et al. [14],

$$\mathrm{ZHD} = (2.2779 \pm 0.0024)\; p_{\mathrm{s}}/f(\lambda, H) \quad (3)$$

where p_{s} is the surface pressure (in millibar, mb), λ is the latitude and H is the height above ellipsoid in kilometre (km). The variation in gravitational acceleration with λ and H is accounted as:

$$f(\lambda, H) = (1 - 0.00266 \cos 2\lambda - 0.00028H) \quad (4)$$

Meanwhile, the second part of tropospheric delay is ZWD which depends on atmospheric water vapour. The ZWD can be written according to Bevis et al. [15],

$$\mathrm{ZWD} = 10^{-6}\left[k_2' \int \left(\frac{e}{T}\right) \mathrm{d}z + k_3 \int \left(\frac{e}{T^2}\right) \mathrm{d}z\right] \quad (5)$$

where $k_2' = (17 \pm 10)\,\mathrm{K\,mbar}^{-1}$, $k_3 = (3.776 \pm 0.004) \times 10^5\,\mathrm{K}^2\,\mathrm{mbar}^{-1}$, e is the partial pressure of water vapour (in mb) and T is the temperature (Kelvin, K). The unit z is the delay along the zenith direction of troposphere. Note that, the Eq. 5 is only useful for estimation of IWV from radiosonde which is required for validation of the GNSS-derived IWV. Hence, the ZWD from GNSS can be obtained by subtracting the ZHD from ZPD.

In GNSS meteorology, the ZWD is a crucial parameter because it conveys the information of atmospheric water vapour [16,17]. To retrieve water vapour information from ZWD, a conversion constant is required. This conversion constant is multiplied by the ZWD as given by Askne and Nordius [18]:

$$\mathrm{IWV} = \overline{K} \cdot \mathrm{ZWD} \quad (6)$$

The IWV is defined as an absolute amount of water vapour in the vertical column of the atmosphere in unit $\mathrm{kg}^{-1}\,\mathrm{m}^{-2}$. Meanwhile, $\overline{K}$ is written as,

$$\overline{K} = 10^6\left[R_{\mathrm{v}}\left(\frac{k_3}{T_{\mathrm{M}}} + k_2'\right)\right]^{-1} \quad (7)$$

where R_{v} is the gas constant for water vapour (461.51 $\mathrm{J\,kg}^{-1}\mathrm{K}^{-1}$), $and T_{\mathrm{M}}$ is the weighted mean temperature of atmosphere (in Kelvin) defined as [19],

$$T_{\mathrm{M}} = \frac{\int \left(\frac{e}{T}\right) \mathrm{d}z}{\int \left(\frac{e}{T^2}\right) \mathrm{d}z} \quad (8)$$

where e and T are as earlier defined.

Generally, the T_{M} parameter is estimated using radiosonde data (see detail Bevis et al. [15]; Wang et al. [17]). However, less redundancy of radiosonde observation (twice daily) may limit the NRT GNSS meteorology to estimate IWV in highly spatio-temporal resolution. Due to this reason, Bevis et al. [15] introduced relationship between surface temperature, T_{S} and T_{M}, through the linear regression function,

$$T_{\mathrm{M}} = 0.72T_{\mathrm{S}} + 70.2 \quad (9)$$

Recently, Musa et al. [13] have demonstrated the potential use of GNSS meteorology in Peninsular Malaysia. They utilized four global positioning system (GPS) CORS (Banting, Bayan Lepas, Geting and Pekan) from MyRTKnet station to estimate GPS ZPD. Due to lack of operational surface meteorological station close to these stations, they have utilized the interpolation technique for obtaining surface pressure and temperature in conversion of ZPD to IWV (see Bai and Feng [20]). They found that the pattern of the estimated GPS-derived IWV was highly correlated with the monsoon season (see Fig. 1). In addition, they confirmed that the accuracy of GPS-derived IWV has strong correlation with the radiosonde-derived IWV which varied from 0.797 to 0.877.

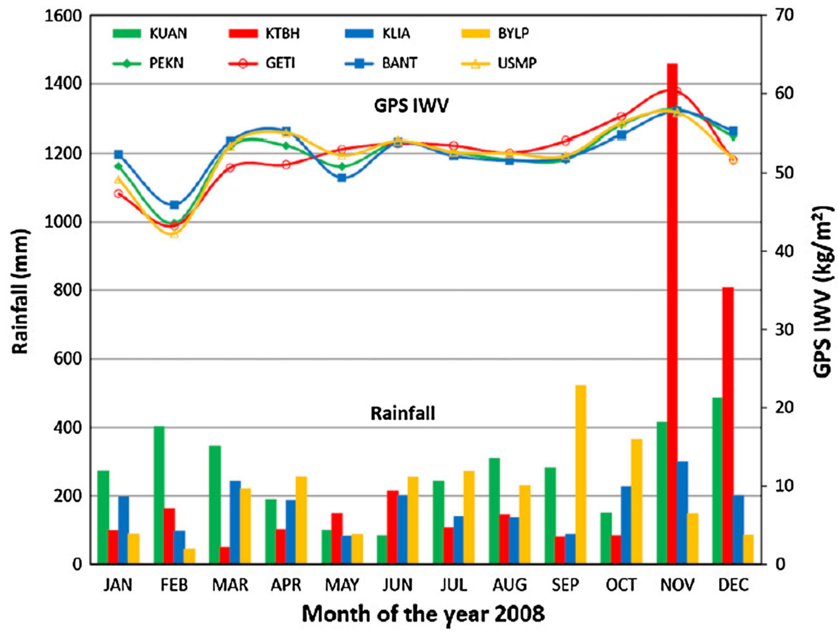


Fig. 1 The statistical analysis of monthly means shows trend of GPS-derived IWV (*lines*) and the total amounts of rainfall (*bars*) for year 2008 (*Source*: [13])

Table 1 List of local GNSS meteorological station

No.	Location	State	Abbreviation
1.	Banting	Selangor	AGKS
2.	Pulau Langkawi	Kedah	AGLG
3.	Kuantan	Pahang	JLKU
4.	Kota Bahru	Kelantan	AGKB
5.	Sungai Udang	Melaka	JLML
6.	ISK 1	Johor	ISK1

3 Field Campaign of NRT GNSS Meteorology

The ISKANDARnet that initially covers only the most southern part of Peninsular Malaysia is now gradually extending its coverage area and are strategically distributed over peninsular. In this study, the ISKANDARnet will be classified as local network (Table 1). Furthermore, there are several GNSS CORS around the Asia and Australia (see Fig. 2; Table 2). These GNSS CORS are being operated by the International GNSS Service (IGS) and will also be utilized to strengthen the local network. Detail information about these IGS stations can be found via http://igscb.jpl.nasa.gov/network/netindex.html. On the other hand, this study will also utilize several meteorological stations (radiosonde station) which are located at Kota Bahru, Kuantan and KLIA (see Fig. 2). These stations are operated by the Malaysian Meteorological Department. The purpose of radiosonde station is to benchmark the quality of the IWV from GNSS.

4 Planning on Design NRT GNSS Meteorology System

In general, the conceptual design of the operational NRT GNSS meteorology system will consist of three major components: (1) data entry, (2) data process and (3) output data as depicted in Fig. 3. The data entry refers to the data supply from the GNSS receivers and surface meteorological sensors to the control centre. The GNSS receiver will receive the transmitted GNSS signal continuously; meanwhile, surface meteorological sensor will measure surface meteorological parameters such as pressure and temperature. This component covers the establishment of the GNSS receivers, surface meteorological sensors and communication system to enable the real-time data streaming to the control centre. The data process refers to the component of the GNSS data processing which processes the raw data to estimate IWV by using the NRT processing engine (see Sect. 4.3). The output data refers to the estimated IWV from the component of data process. The estimated IWV will be utilized to construct 2-dimensional (2-D) map in such a manner that allows for a continuous update.

4.1 Architecture of GNSS Meteorology Station

As compared to the regular GNSS CORS station, the ground-based GNSS meteorology station is equipped with surface meteorological sensors (i.e. weather station) (see Fig. 4; Table 3). In GNSS meteorology, there are three types of data required which are GNSS data, surface pressure and temperature. All these data will be integrated inside the processing engine for producing GNSS-IWV.

1. GNSS components
   The GNSS components consist of a GNSS antenna and receiver. The GNSS antenna utilizes the geodetic receiver type which has hundred channels that can support mul-

Fig. 2 The spatial distribution of GNSS CORS and radiosonde stations

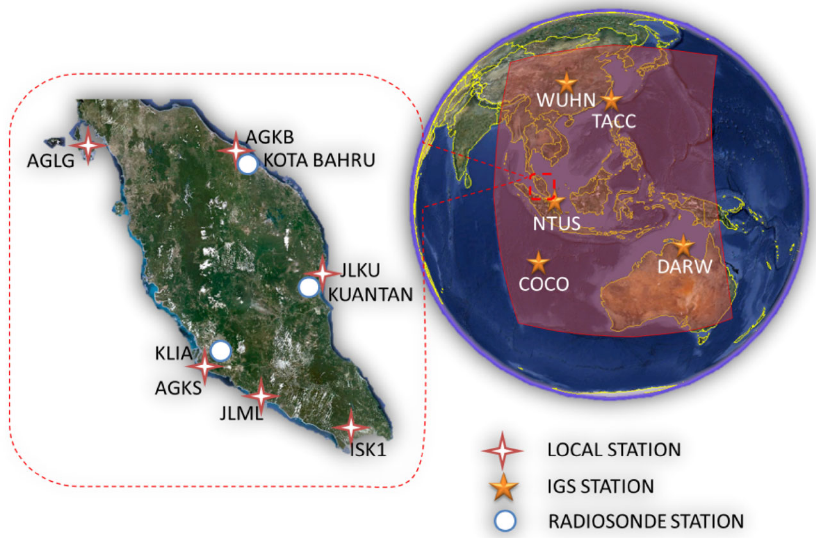


Table 2 List of IGS CORS stations

No.	Location	Country	Abbreviation
1.	Nanyang Technology University	Singapore	NTUS
2.	Cocos Island	Australia	COCO
3.	Darwin	Australia	DARW
4.	Wuhan	China	WUHN
5.	Taipei	Taiwan	TACC

tiple GNSS constellation tracking. The receiver also can support the remote management and real-time data transfer. Meanwhile, the GNSS antenna will be positioned in a suitable location such as on top of roof for obtaining a clear sky-view and void of any obstruction in order to minimize the impact of multipath.

2. Surface meteorological components
Normally, the ideal practice in GNSS for meteorology is that a GNSS station must be co-located adjacently to surface meteorological sensors. The performances of surface meteorological sensors are very critical to the accuracy of derived IWV (approximately $1\,\text{kg m}^{-2}$) [21]. In order to achieve $1\,\text{kg m}^{-2}$ accuracy level, the surface meteorological sensor will be allocated with an error budget dependent upon pressure and temperature sensors accuracy, which must be less than 0.3 hPa (milibar) and $\pm 1\,^{\circ}\text{C}$ (Celsius), respectively [22].

4.2 Data Flow Management

The internet connection is the key factor for running an operational system of the NRT GNSS meteorology system. The local communication infrastructure which is local area network (LAN) will be established for interconnecting entire components of the whole system. The LAN will allow for real-time data streaming to the control centre and continuously feed the processing engine for GNSS-IWV. This can briefly be explained as follows (see Fig. 5):

1. Streaming real-time raw observation data
The entire ISKANDARnet station will stream the raw observation data to the control centre at Universiti Teknologi Malaysia (UTM) via ISKANDARnet server. Also, several selected IGS stations will stream the raw observation data to the control centre via the IGS server.
2. Establishing NTRIP caster for supporting data stream
One computer will be set up with the NTRIP caster program which will be at the control centre in UTM. This NTRIP caster will not save any raw data but serve as a main component in support of the real-time data stream from entire ISKANDARnet stations to processing engine.
3. Initiating the NRT GNSS meteorology processing engine
The streamed data from ISKANDARnet stations will be stored in the specific directory of the processing engine. Once data is available, it will be ready to feed the processing engine and trigger the processing engine to quickly estimate NRT GNSS-IWV (see detail in Sect. 4.3).
4. Dissemination of results
The main product from processing engine is GNSS-derived IWV. The product will be channelled out for atmospheric water vapour monitoring purposes by constructing the 2-D IWV map in such a manner that allows for a continuous update at a pre-defined interval. The platform for data sharing of NRT GNSS-IWV will be a web-based system. Therefore, the system will be developed to implement the visualization in automated format.

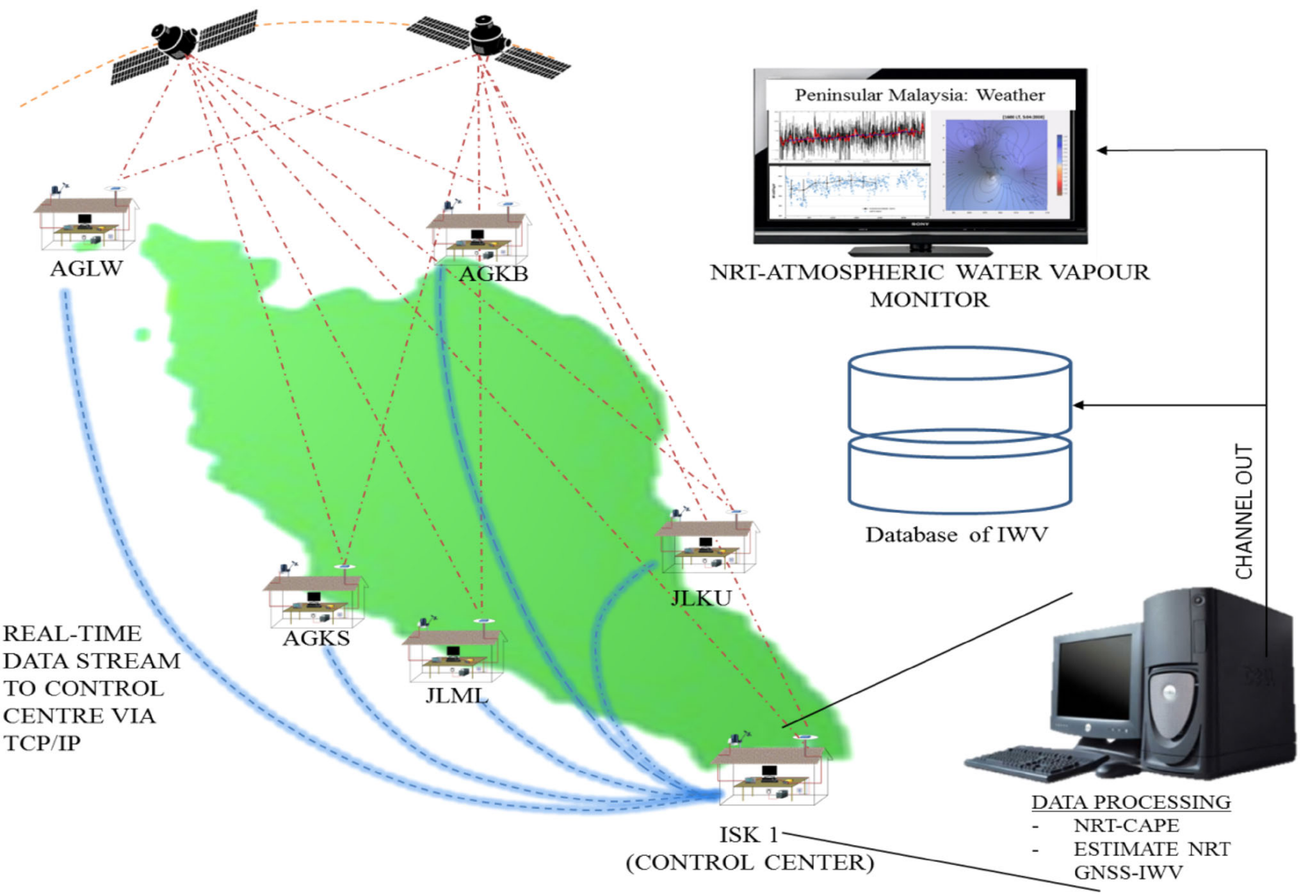
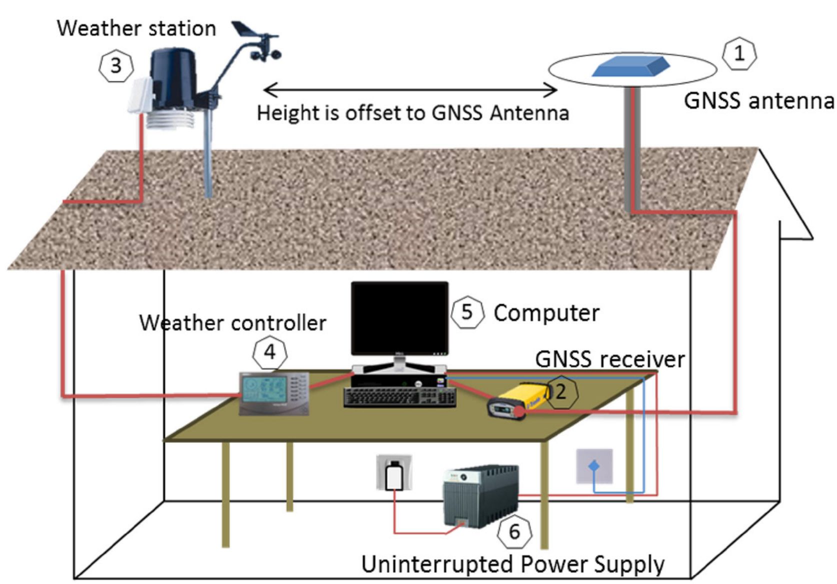


Fig. 3 Illustration of conceptual design of NRT GNSS meteorology system

Fig. 4 The hardware components of the GNSS meteorological station



Conventionally, the file transfer protocol (FTP) is used to upload or download the GNSS Receiver INdependent EXchange (RINEX) format from the server. However, the use of FTP is only limited for post-processing purpose and does not support the RINEX data stream application. In order to support the real-time data stream, the radio technical commission for maritime (RTCM) service has introduced a new RINEX data stream protocol to support the RINEX data stream which is known as the networked transport of RTCM via Internet Protocol (NTRIP). Both

Table 3 Detailed description of each component

No.	List of hardware	Description
1.	GNSS antenna	Capability to track the transmitted GNSS signal
2.	GNSS receiver	Receive the transmitted GNSS signal
3.	Weather station	The integrated surface meteorological sensors which include surface pressure, temperature and relative humidity
4.	Weather controller	To monitor the sensors and record the observations
5.	Computer	Gather and store the GNSS raw data and surface meteorological data. Latter, it will stream the data in real-time mode to the control centre
6.	Uninterrupted power supply	As an emergency supply for electricity in case of failure of main electricity power

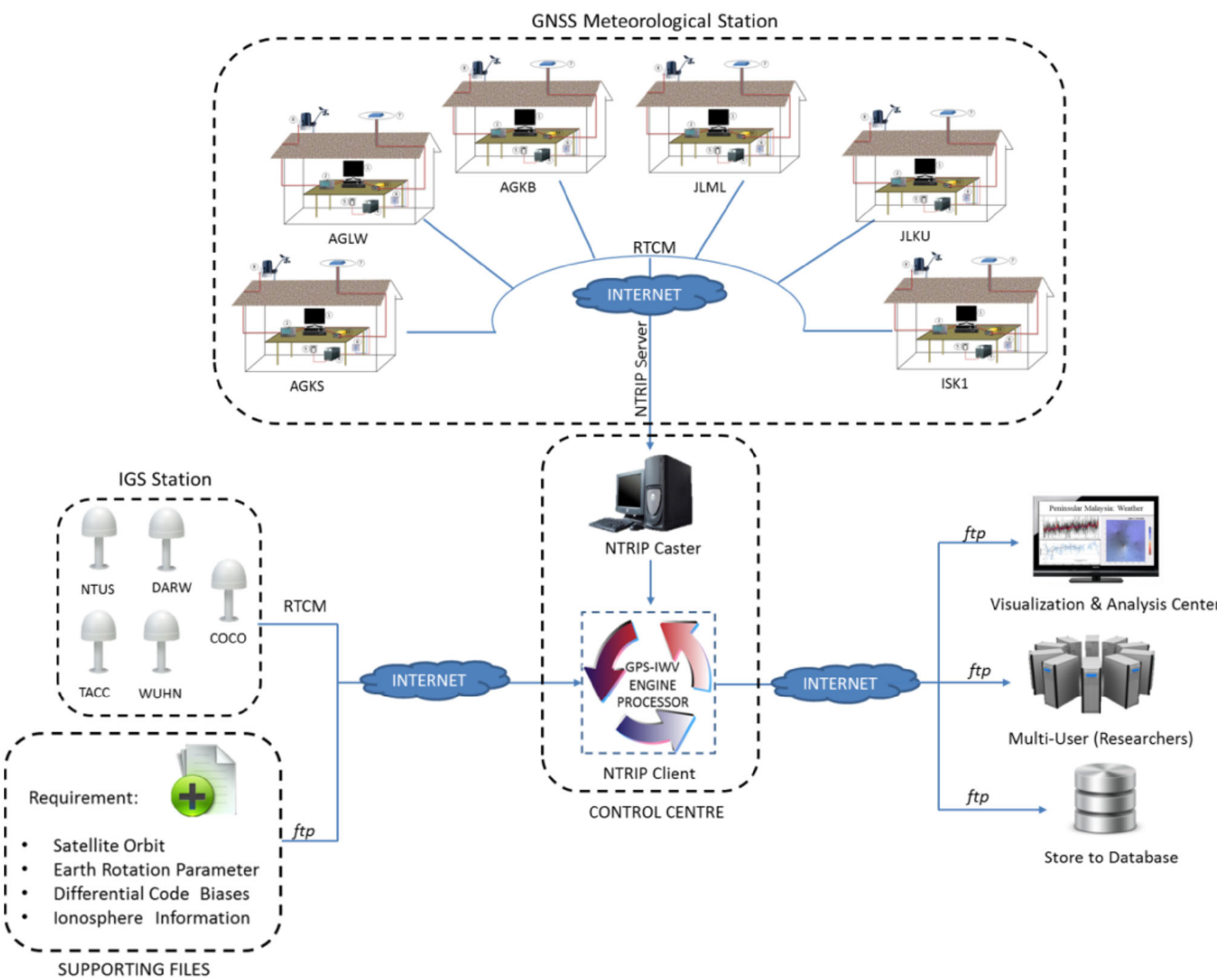


Fig. 5 Data flow management

communication protocols work on the basic protocol of internet which is called Transmission Control Protocol/Internet Protocol (TCP/IP). For this study, the NTRIP is used to stream the RINEX observation files. Meanwhile, the FTP is utilized to download the supporting GNSS data from the IGS server such as satellite orbit, pole information, ionosphere information and differential code biases information (DCB).

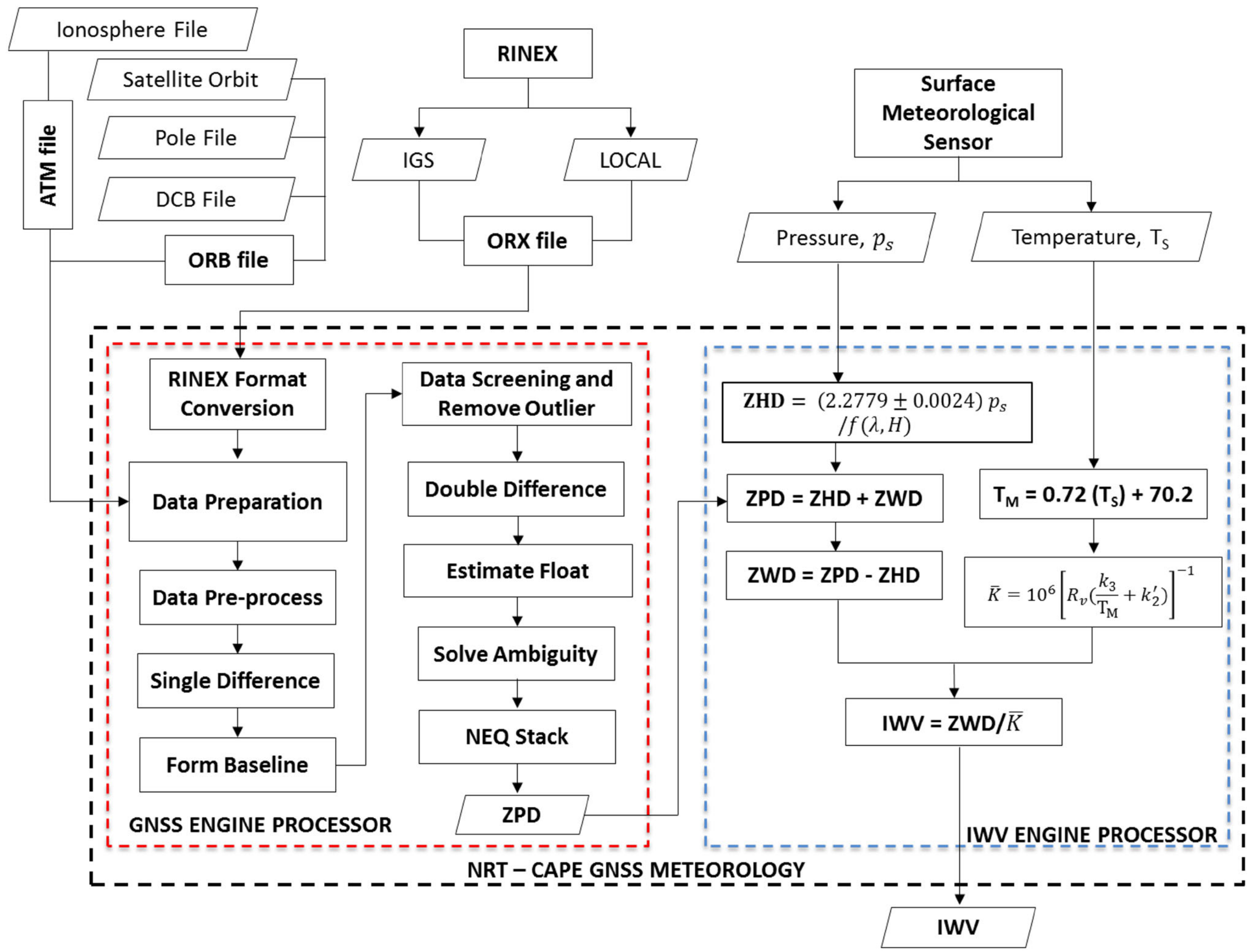


Fig. 6 The schematic design of data flow inside the NRT–CAPE

This study will utilize Bundesamt für Kartographie und Geodäsie (BKG) NTRIP Client or BNC software to capture a real-time stream of the RINEX observation via NTRIP system [23]. There are three basic elements of NTRIP system, namely NTRIP server, NTRIP caster and NTRIP client [24]. The NTRIP server is established at the ISKANDARnet station which enhances the real-time streaming of the observation data to the control centre. The NTRIP caster is established at the control centre to serve as a bridge that connects the ISKANDARnet stations and processing centre. Furthermore, the NTRIP client is also established at the control centre to grab the data from the NTRIP caster for data processing purposes.

4.3 The NRT GNSS Meteorological Engine Processor

The NRT GNSS meteorology will utilize the Bernese version 5.0 software for the GNSS data processing. The Bernese software is high-precision software that was developed by the Astronomical Institute of University of Bern [25]. This software supports various scientific applications such as plate tectonic monitoring, multi-GNSS data processing including troposphere estimation.

Due to high volume of data collected from daily RINEX observation, the automated processing script was developed to reduce task of manual processing. This script is known as Bernese Processing Engine or (BPE). Basically, the BPE was designed for manual post-processing mode and not supporting the NRT processing. For the BPE to perform in NRT mode, the BNC software is used to feed the BPE files with RINEX data and the pearl programme has to be modified to automatically download the supporting data from IGS server (see detail in Fig. 6). The BPE will be run continuously as long as the data is feed to the processing engine. Therefore, this processing system is referred to as NRT—continuously automated processing engine or NRT–CAPE.

The NRT–CAPE consists of two major parts: (1) the estimation of ZPD parameter from GNSS data processing and

(2) the derivation of GNSS-IWV with the aid of surface meteorological data. Based on Fig. 6, the flow of data processing from the two sources (e.g. RINEX data and surface meteorological sensor) inside the processing engine can be further illustrated:

1. Estimation of ZPD parameter with the GNSS Engine Processor
   The GNSS data processing begins once RINEX data are streamed to the GNSS Engine Processor. In the NRT–CAPE, there are several stages involved to produce the ZPD parameter (see Fig. 6). The end product from the GNSS Engine Processor is ZPD parameter that will be channelled out to IWV Engine Processor for estimating GNSS-IWV.
2. Derivation of GNSS-IWV at IWV Engine Processor
   The information about surface meteorological data such as surface pressure and temperature will be directly used to extract the component of ZPD parameter. The surface pressure is required to compute ZHD and will leave the ZWD as the key variable. Meanwhile, the surface temperature T_S is required to compute the T_M parameter and so as to solve for the conversion constant, $\overline{K}$ (see Fig. 6). After the ZWD parameter and $\overline{K}$ are solved, the GNSS-IWV will be processed.

5 Discussion

This NRT GNSS meteorology system can be considered as first experience for Malaysia. Before the NRT GNSS meteorology system was proposed, several exploratory studies has been conducted to determine the potentiality of GNSS meteorology in Malaysia. Results of studies by Musa et al. [13] and Amir [26] suggested the need to develop the NRT GNSS meteorological system for capturing early information about monsoon and several meteorological events in Malaysia. However, being the first attempt at developing the NRT GNSS meteorology system in Malaysia, there will be several challenges such as:

1. Financial challenge
   In this study, only five GNSS meteorological stations can be realized over Peninsular Malaysia from ISKANDARnet CORS infrastructure. These stations are not enough to represent the highly variable water vapour field over this region. Although, there is MyRTKnet CORS that is maintained by Department of Survey and Mapping Malaysia (DSMM) whose distribution can be considered to significantly cover Malaysia. But, the main purpose of MyRTKnet is specifically for supporting survey and mapping activities in Malaysia and not for meteorological application. In order to utilize MyRTKnet CORS, institutional policy through Agencies collaboration will be required; this is not within the scope of this study.
2. Technical challenge
   (a) Availability of surface meteorological data: The surface meteorological observation (i.e. pressure and temperature) is basic parameter to convert ZPD parameter to IWV. In Malaysia, the MMD is the responsible authority that operates the surface meteorological stations. The surface meteorological stations are also sparsely distributed and are relatively far from the ISKANDARnet CORS. Utilization of these meteorological stations could be a possible source of systematic errors in the estimation of GNSS-IWV. Even though some studies (e.g. Bai and Feng [20]; Bosy et al. [27]) demonstrated the applicability of interpolation technique to obtain the pressure and temperature at GNSS CORS, the quality of interpolated pressure and temperature is still a topical issue in research within the low-latitude region due to high spatio-temporal variability of the troposphere in the region. Thus, this study proposes to install the surface meteorological sensors adjacent to each GNSS CORS to be utilized in this experiment.
   (b) GNSS data processing: The precise satellite orbits are important to accurately estimate ZPD parameter [28,29]. However, the precise satellite orbits are not available in the NRT mode. To produce precise satellite orbits, specifically final orbit, the IGS spend about 2 weeks before it is available to be downloaded (see http://igscb.jpl.nasa.gov/components/prods_cb.html). Nonetheless, there is a predicted (ultra-rapid) orbit that is updated every 6 h daily and supports a real-time GNSS data processing. The ultra-rapid orbit is not as accurate as the final orbit, and the use of it can degrade the accuracy of GNSS-IWV. For example, the (European Meteorological Network) EUMETNET GPS Water Vapour Programme (E-GVAP) has confirmed that the latency of 6 h from ultra-rapid orbit can increase the post-fit residual which ranges from 5 to 8 mm and standard deviation ranging from 0.5 to 1 mm and these increases 4–6 times before 1 h switch to the next batch of the ultra-rapid products [30]. Thus, the latency and accuracy of the orbit need to be addressed in this study.
   Meanwhile, in the NRT processing, the GNSS carrier phase ambiguity is extremely difficult to be resolved because of low data redundancy from satellite which have risen above or set below the

GNSS receiver horizon in last hour. During collaboration between European countries in NRT GPS meteorology project known as COST-176, the European Analysis Centres attempted to resolve the phase ambiguity. However, the repeatability of ZPD parameter became worse [31]. On the other hand, Bosy et al. [27] also attempted to resolve the ambiguity, and they affirmed that this procedure delayed the processing time by about 4 min. In NRT mode, the available data have less redundancy and hence, will lead the GNSS data processing algorithm to become unstable. This might contribute to a systematic error in the estimated troposphere parameter. One way to handle this problem is by introducing the relative troposphere constraint. The function of relative constraint is to reduce the variability of ZPD estimation between two consecutive epochs [26,32]. However, the suitability value of relative constraint has to be determined for the first attempt processing of the NRT ZPD parameter.

6 Conclusion

The conceptual design of NRT GNSS meteorology system for operational application in Peninsular Malaysia has been discussed. There are three major components considered for this system which include the architecture of GNSS meteorological station as input data source, the engine processor (i.e. the NRT–CAPE) and data flow management which detailed the strategy for data flow from source to processor and to output display, sharing and visualization. The functional illustration for each of these components has been presented; thus, the expected output from the system is the GNSS-derived IWV which will be visualized in 2-D IWV map and shared using web-based platform. Since this study is the first attempt in Malaysia, there are some key expected challenges to be addressed in developing the NRT GNSS meteorology system, and these include the insufficient finances for acquisition of the system infrastructure, technical challenges such as availability of surface meteorological stations collocating with the GNSS CORS and GNSS data processing and handling for accurate estimation of ZPD parameter. In order to address these challenges, full utilization of the ISKANDARnet CORS infrastructure and installation of meteorological sensors adjacent to each CORS have been proposed; this will be achieved through research support from Malaysian government. Meanwhile, the challenge in GNSS data processing for estimation of the GNSS-derived IWV could be overcome through extensive experimental study.

The promise of GNSS meteorology as an alternative tool for augmenting the existing atmospheric water vapour observing system is highly valuable. Owing to its location in the tropical region, Malaysia experiences high atmospheric vapour content with corresponding large amount of rain fall annually; therefore, accurate weather forecasting is very essential for mitigating vulnerability to any severe events such as flooding. Thus, developing the NRT GNSS meteorology is critical to Malaysian economy as it leads to improved forecasting and enhances nowcasting, sustainable agriculture as well as environmental prediction. The performance evaluation of the NRT GNSS meteorology system will be discussed in our subsequent publication.

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