The development of GPS TroWav tool for atmospheric – terrestrial studies

W Suparta1,*

1Institute of Space Science (ANGKASA), Universiti Kebangsaan Malaysia, 43600 Bangi, Selangor Darul Ehsan, Malaysia

Email: wayan@ukm.my

Abstract. We have developed an efficient tool to process dual-frequency Global Positioning System (GPS) signals and the surface meteorological data, called the Tropospheric Water Vapor (TroWav) program. TroWav is a stand-alone program to compute atmospheric precipitable water vapor (PWV). The source of the program is developed using Matlab TM and the graphical user interface for the system was developed using a Visual Basic. The algorithms of the program capable to compute satellite elevation angle, Zenith Tropospheric Delay (ZTD), Zenith Hydrostatic Delay (ZHD), Zenith Wet Delay (ZWD) and mapping function. The tool is very practical and useful for sustainable atmospheric management.

1. Introduction

Precipitable water vapor (PWV) is one of the paramount importance parameters for atmospheric studies that can improve numerical weather prediction (NWP), nowcasting and forecasting, and viable use to study the thunderstorms, flooding, natural climate variability (global warming, climate change and El Niño–Southern Oscillation), precipitation budget, teleconnections, terrestrial coupling, etc. Global Positioning System (GPS) has an established reputation as a reliable technique of positioning equipment and has a complete turnkey capability in all areas of process equipment and space supply from integrated design through to engineering, fabrication, commissioning and testing. In contrast to atmospheric science applications, improvement of the system should be carried out to solve the data complexity with good practices and useful to support sustainable development.

GPS Meteorology technique has been developed since 1990s to measure PWV with superior in temporal and spatial resolution [1],[2]. Suparta and Alhasa [3] has proposed to estimate the PWV using an adaptive neuro-fuzzy inference system (ANFIS) due to the GPS data are not always available for a full 24-hour. However, as for a comparison of PWV from ANFIS, PWV derived from GPS data is necessary. Therefore, a suitable tool at low-cost and with high accuracy, named as the Tropospheric water vapor (TroWav) has been initiated since 2003 and the study was first started from the polar region. The tool is to compute PWV using GPS signals and the surface meteorological data [4]. The result of the PWV has been validated with radiosonde data [5]. Since then, the program has been updated that suitable for ENSO studies over the Borneo region [6]. In this paper, we updated the
development of TroWav program for atmospheric-terrestrial studies in the equatorial region, so-called the TroWav 2.0.

2. Concept and System Design

In this state-of-art, we first develop a concept of determination of PWV from GPS signals perspective. Setup of measurement system and data processing are then constructed. Implementation of the designing system will be realized in the Matlab program. Testing and analysis result will be conducted to do the best performance to the system. In the following is describing the first step.

2.1. Deriving PWV from Ground-Based GPS Meteorology

When the radio signals traveling through the Earth’s atmosphere to a receiver on the ground, it is retarded and affected significantly by the presence of free electrons in the ionosphere and the refraction (see Figure 1). The refraction of the GPS signal is induced by refractivity of gases, hydrometeors, and other particulates in the neutral atmosphere (the troposphere and stratosphere). Suparta et al. [7] described in detail propagation delays in the troposphere, where total delays can be expressed as the sum of the hydrostatic and wet components. In general, the total tropospheric delay following Davis et al. [8] and modified by Suparta [9] as

$$ZTD = m_{hyd}(\theta) \cdot SHD + m_{wet}(\theta) \cdot SWD$$  \hspace{1cm} (1)$$

where $ZTD$ is zenith tropospheric delay or equal to total tropospheric delay ($D_{Trop}^s$), $SHD$ is the slant hydrostatic delay, $SWD$ is the slant wet delay, $\theta$ is the satellite elevation angle that can be extracted from the GPS signals, and $m_{hyd}(\theta)$ and $m_{wet}(\theta)$, hydrostatic and wet mapping functions, respectively. On the other hand in equilibrium state, the $ZTD$ can be expressed as [9]

$$ZTD = ZHD + ZWD$$  \hspace{1cm} (2)$$

In practices, $ZTD$ is computed using Modified Hopfield model [4,10]:

$$ZTD = 10^{-12} N_{j,0}^{Trop} \left[ 1 + 4a_j \frac{r_j^2}{2} + (6a_j^2 + 4b_j) \frac{r_j^3}{3} + 4a_j (a_j^2 + 3b_j) \frac{r_j^4}{4} + (a_j^2 + 12a_j^2 b_j + 6b_j) \frac{r_j^5}{5} + \ldots \right]$$  \hspace{1cm} (3)$$

$$a_j = -\frac{\sin \theta}{h_j} \quad \text{and} \quad b_j = -\frac{\cos^2 \theta}{2h_j R_E}$$  \hspace{1cm} (4)$$
where for the hydrostatic component subscript $j$ is replaced by $h$ and for the wet component subscript $j$ is replaced by $w$ respectively. In (3) and (4), $h_j$ (in meters) represent $h_{h_1} = 40136 + 148.72T$ and $h_{w}$ (set to 11 km) is the effective height for the hydrostatic and wet components respectively. $R_e$ is radius of the Earth and taken as 6378137 meters. $N_{j,0}^{Trop}$ is the total refractivity at the surface of the Earth.

Figure 1. Ground-based GPS measurements system for PWV

The ZHD in (2) is calculated using the Saastamoinen model [11]. The model uses the surface pressure ($P_s$) and a correction factor to correct the local gravitational acceleration at the center mass of atmospheric column, which can be expressed as,

$$ZHD_{Saas} (P_s, \lambda, h) = \frac{(2.2768 \pm 0.0024)P_s}{(1 - 0.00266 \cos(2\lambda) - 0.00028 h)}$$

(5)

where $\lambda$ is the latitude of site (in degree), $P_s$ is the total surface pressure (hPa) and $h$ is the height of the site above the ellipsoid (in km) measured by GPS receiver.

The ZWD is calculated from GPS measurements by separating the ZTD from ZHD. Note that the ZTD was mapped to satellite elevation angle. PWV now can be calculated using Bevis et al. [1] equation:

$$PWV = \pi(T_m)ZWD_{GPS}$$

(6)
where the dimensionless \( \pi(T_m) \) is a conversion factor that varies with the summation on the local climate (e.g. location, elevation, season and weather) and depend on a weighted mean temperature \( (T_m) \) as given by

\[
\pi(T_m) = \left[ \rho_{lw} R_v \left( k_2 + k_3 / T_m \right) \right]^{-1} 10^6
\]  

(7)

where \( \rho_{lw} \) and \( R_v \) are the density of the liquid water and specific gas constant for water vapor, respectively. From (13), \( k_2 \) and \( k_3 \) are the refraction constants, \( k_2 = (22.1 \pm 2.2) \text{ K mbar}^{-1} \) and \( k_3 = (3.739 \pm 0.012) \times 10^5 \text{ K}^2 \text{ mbar}^{-1} \), respectively. The mean temperature \( T_m \) is estimated linearly by [12],

\[
T_m = 70.2 + 0.72 T_K
\]  

(8)

where \( T_K \) is surface temperature (Kelvin) measured at the site of GPS receiver. Measuring of PWV from ground-based GPS receiver is depicted in Figure 1. GPS data is recorded every 30s.

2.2. System Design
The system is constructed to properly work with faster process and accurate quantification. Data cleaning in terms of time series missing and errors were solved properly by using MATLAB. Matlab is used as a versatile tool to efficiently perform tasks, simply by providing a toolbox and can simulate different signals, and the processing involved. Figure 2 shows the flowchart for designing of PWV obtained from ground-based GPS and the surface meteorological data. GPS receiver from Trimble product will produce the raw data in *.dat file. This file can be extracted to RINEX (Receiver Independent Exchange) format (*.*obs and *.*nav) by using a Translate/Edit/Quality Check (TEQC) routine developed by UNAVCO (http://www.unavco.org). In case the GPS data is obtained from another source like SOPAC (Scripps Orbit and Permanent Array Center), we need to convert the GPS data from Hatanaka format (*.d) to RINEX using software that has been provided at the http://terras.gsi.go.jp/ja/crx2rnx.html.

As seen in Figure 2, we required the surface meteorological data (pressure (P), temperature (T) and relative humidity (H)) near or co-located with the GPS receiver to process PWV. Note that propagation signal in the ionosphere is complex than in the troposphere. On the other hand, neutral atmosphere is independent on the GPS frequencies. Before PWV is computed, the position of the reference station, which using the World Geodetic System 1984 (WGS84) frame is determined. The next task is to compute the satellite position by using Keplerian equation. Satellite elevation angle is strongly important in the processing of GPS data. This parameter is used to map the delay into zenith direction, known as the mapping function. In (1), \( m_{hyd}(\theta) \) and \( m_{wet}(\theta) \) are computed using the Vienna Mapping Function (VMF1) [13]. Updated Niell mapping function with VMF1 and use the same \( T_m \) equation in (8), the TroWav program for this update is called the TroWav 1.0. \( T_m \) in (8) is very suitable for mid-latitude regions. The latest tool is TroWav 2.0, which updating the following \( T_m \) equation that capable use for equatorial region [14]:

\[
T_m = 0.83663 T_s + 48.103
\]  

(15)

where \( T_s \) is similar to \( T_K \). Finally, the surface meteorology data (P, T and H) should be the same size matrix with the GPS data to produce PWV.
3. System Testing and Analysis Result

The graphical user interface (GUI) of the *TroWav* system is developed using Microsoft Visual Basic 7.0. The program is currently running in a 32-bit version of Windows. There are six menus in the top left side of Figure 3. The GPS menu will take input of GPS data or RINEX files (*obs and *.nav), and converted into *.mat or ASCII files to easier processed in Matlab. In the processing menu, the satellite elevation angle will be processed. Source code for GPS data cleaning and to fix the data errors have been developed with Matlab program. Satellite elevation angle is computed based on the input of GPS position (latitude, longitude and ellipsoidal height), pseudorange (C1, P2), ephemeris and epoch. All these parameters are obtained from RINEX files. The input of surface meteorological data (P, T and H) is processed in the surface meteorology menu. In this menu, the system was also capable to plot the three of parameters. The hearth of this program is GPS MET menu, which compute the ZHD, ZTD, ZHD and PWV as demonstrated in Figure 4. The program is also designed capable to select the interval data based on the availability of meteorology data for possible computation of above four parameters: 30s (default), one-min, 10-min, one-hour and 3-hour. Explanation on how to use the *TroWav* program is compiled in the about menu.
The testing result from the TroWav screen is demonstrated in Figure 4. Example data used here is collected from Casey station (CAS1) in Antarctica with period of testing is on September 7, 2013. This station is managed by Australian Antarctic Division. From the figure, the four GPS meteorology parameters (ZHD, ZTD, ZWD and PWV) showed a similar pattern. The processing results are in 30 seconds resolution (default), means that the daily size of data is 2880. The ZHD demonstrated very clear and smooth. Their pattern is clearly dependent on the surface pressure and position of GPS receiver. For the three another parameter showed noisy from 00:00 to 08:00 UT, which possibly degrading the GPS signals due to atmospheric conditions. On the other hand, the ZTD pattern closely followed the ZHD trend which clarified that the hydrostatic part is contributed about 90% in the total of ZTD component, and the rest is contribution from the wet part. Note that not all the GPS meteorology parameters will show a similar pattern or trend as in Figure 4. This depends on the atmospheric conditions of the station, geography and typical weather or current climate.
4. Conclusion

In this paper, a promising tool with effective-cost to process GPS and the surface meteorological data to produce PWV as a climate indicator for the atmospheric and terrestrial studies was developed. The program, namely TroWav is capable to plot the processing data (ZHD, ZTD, ZWD and PWV) and also save the data and the figure for future use. The system is currently running under a 32-bit of Windows platform. By this tool, GPS user capable to improve the positioning accuracy via atmospheric effects quantification as well as utilize the GPS signals for sustainable development.

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