Precipitable water vapor estimated using GPS precise point positioning

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Abstract. Precipitation water vapor is an important indicator of climate change. It is related to the moisture in the atmosphere. Atmospheric water vapor is one of the primary greenhouse gases, and it plays a critical role in weather forecasting, micrometeorology, and global climate change. Due to their high operational costs, sparse station distribution, and lack of all-weather availability, certain conventional methods of measuring water vapor, such as microwave radiometers and radio-sounding balloons, are limited in their application to modern meteorology. The precipitation water vapor values are can be obtained using Global Positioning System signal delays. The objective of this study is to estimate the zenith wet delay using the Global Positioning System precise point positioning method. Water Vapor can be presented by zenith wet delay. To estimate the strength of the relationship between zenith wet delay from GPS data, the computation of correlation with in situ data from meteorology data has been performed. Using two pair stations (Global positioning system and meteorology station): CMLG-Malang and CPAS-Tretes, the correlation coefficients are strong 0.85 and 0.79, respectively. Finally, GPS data measurement can be a complement to obtain the zenith wet delay and water vapor.

1. Introduction

Water vapor is the most prevalent greenhouse gas on the planet. Water vapor feedback can further increase the warming impact of other greenhouse gases, allowing more water vapor to enter the atmosphere as a result of rising carbon dioxide levels. Warmer temperatures result from more water vapor, which causes more water vapor to be absorbed into the air. In a spiraling cycle, warming and water absorption rise.

The water vapor content in the low atmosphere cycle is one of the most important metrics for water vapor control and precipitation forecasting; nevertheless, owing to its quick rate of change, it is difficult to measure; yet, appropriate water vapor content is a necessity for any precipitation occurrence. A large-scale, successive, or concentrated precipitation event will cause flooding, putting lives and livelihoods in danger. Precipitation is also one of the most important sources of water for many countries. As a result, a short-term precipitation monitoring and forecasting service, particularly for high-intensity rainfall, is essential for reducing the risks to life and property.

Traditional water vapor detection systems cannot follow and forecast precipitation events due to their tempo-spatial resolution limitations. For small-scale tracking and forecasting, for example, the distance between adjacent radiosonde stations is roughly 200–300 km, and the sounding balloon is launched two to four times a day: such spatial and temporal resolutions are insufficient. Microwave radiometers are
costly and can’t operate in the rain, so they’re not widely used in practice. Ground-based GNSS has increasingly become one of the most effective ways of acquiring consolidated water vapor (IWV) data and analyzing precipitation events. Bevis [1] proposed the definition of GPS meteorology. Many countries have developed their own Continuously Operating Reference Station (CORS) networks after more than two decades of growth for the Global Navigation Satellite System (GNSS). The tropospheric delay (TD) is a measurement of the amount of water vapor in the direction between a GPS satellite and a receiver. The tracking of microwave radiometers onboard altimeter spacecraft, atmospheric science and meteorology, and the calibration of Synthetic Aperture Radar photographs have both used GNSS-derived tropospheric delays.

The troposphere is found in practically all water vapor and aerosols in the atmosphere, accounting for more than 80% of the total molecular mass. Dry molecules (such as N2, O2, Ar, CO2, Ne, and He) and water vapor make up the electrically neutral atmosphere (H2O). Many space-based electromagnetic ranging techniques, such as very long baseline interferometry, one-way and two-way satellite-based positioning systems, satellite altimetry, satellite laser ranging, radio science tests, and planetary spacecraft monitoring, have been identified as having a significant simulation flaw due to neutral atmosphere propagation delay [2]. Refraction, a characteristic of the environment, affects the speed of microwave transmissions. The refractive index (n) of any substance is included because the velocity and ray bending of light varies between media.

\[ n = \frac{c_0}{c} \]  

In a vacuum, the speed of light is \( c_0 \), while in a given medium, the speed of light is \( c \). The refractivity \( N \), which is proportional to \( n \) and equivalent to, is used to compute the refractive index.

\[ N = (n - 1) \times 10^6 \]  

The zenith total delay (ZTD), or In the zenith direction, the total path delay amounting to troposphere can be expressed as [3]

\[ ZTD = \int_0^h (n - 1) \, dh = 10^{-6} \int_0^h N \, dh \]  

where \( n \) is the troposphere's refractive index, \( h \) is the atmosphere's height, and \( N \) is the refractivity. [4] calculated the refractive index (N) as follows:

\[ N = \left( \frac{k_1 \frac{P_d}{T^2}}{Z_d} \right) + \left( \frac{k_2 \frac{P_w}{T} + k_3 \frac{P_w}{T^2}}{Z_w} \right) \]  

\[ \frac{1}{Z_d} = 1 + P_d \left[ 57.97 \times 10^{-8} \left( 1 + \frac{0.52}{T} \right) - \frac{9.4611 \times 10^{-4} \, t}{T^2} \right] \]  

\[ \frac{1}{Z_w} = 1 + 1650 \left( \frac{P_w}{T^3} \right) \left( 1 - 0.01317 \, t + 1.75 \times 10^{-4} \, t^2 + 1.44 \times 10^{-6} \, t^3 \right) \]  

Whereas, \( k_1 \) and \( k_2 \) are microwave refractivity constants related to polar and non-polar molecule induced polarization, respectively, and \( k_3 \) is a microwave refractivity constant related to polar molecule orientation polarization (water vapor). The partial pressures of dry air and water vapor in millibars are \( P_d \) and \( P_w \), respectively, while the temperature is \( T \) in Kelvin. The pressures have the same subscripts as
the compressibility variables $Z_d$ and $Z_w$. The temperature in degrees Celsius is represented by $t$. In Equation (4), the dry tropospheric delay is the first term, whereas the wet tropospheric delay is the second and third terms. Laboratory tests and theoretical measurements were used to derive the values for $k_1$, $k_2$, and $k$.

Integrated water vapor (IWV) is the entire amount of water vapor contained in an air column from the Earth's surface to the top of the atmosphere, and it is measured in kilograms per square meter (kg/m²) or millimeters (mm) as the length of an equivalent column of liquid water. According to Bevis [1], PW can be estimated as following the Equation:

$$PW = \Pi \cdot ZWD$$  \hspace{1cm} (7)

and,

$$\Pi = \frac{10^6}{\rho \cdot R_v \left[ \frac{k_3}{T_m} + k_2 \right]}$$  \hspace{1cm} (8)

Where, $T_m$ is the mean temperature of the troposphere, which may be in turn modeled from the surface temperature ($T_0$) [5].

$$T_m = 50.40 + 0.789 \cdot T_0$$  \hspace{1cm} (4.11)

With, $T_0$ in kelvin.

### Table 1. Empirical values of the microwave refractivity constants [1].

| Reference                    | $k_1$ (K/hPa)            | $k_2$ (K/hPa)            | $k_3 \times 10^3$ (K²/hPa) |
|------------------------------|--------------------------|--------------------------|----------------------------|
| Essen and Froome (1951) [6]  | 77.636 ± 0.03            | 64.69 ± 0.2              | 371.8 ± 0.4                |
| Essen (1953) [7]             | 77.636 ± 0.03            | 74.99 ± 0.2              | 368.2 ± 0.4                |
| Thayer (1974) [8]            | 77.60 ± 0.014            | 64.79 ± 0.08             | 377.6 ± 0.4                |

Instead of dry and water vapor components, it is more convenient to express refractivity as hydrostatic and non-hydrostatic, or wet part, components. The ZTD is made up of two components: a hydrostatic (dry) component called the zenith hydrostatic delay (ZHD) and a wet component called the zenith wet delay (ZWD) (ZWD). Over 90% of the ZTD is made up of hydrostatic components. Although the wet component only accounts for roughly 10% of the overall route delay, it is significantly more unpredictable in terms of area and time, making it more difficult to model. [9].

The goal of this study is to quantify precipitation water vapor using the Global Positioning System's precise point positioning method. The GPS measurement results will be compared to meteorological data. In the next part, we'll go through the data and techniques utilized in this study. The results are presented in Section 3, which include zenith wet delay from GPS and Meteorology, a connection between the two, and a discussion of the findings. The study's findings are summarized in the final section.

### 2. Data and method

This section contains the study's data as well as the methodology utilized.

#### 2.1. GPS and meteorology data

In this study, several data are used, such as GPS and meteorology data. GPS data were downloaded from the Indonesian Geospatial Agency (BIG) (http://inacors.big.go.id). Data cover the period 2015 to 2018. Meanwhile, the meteorology data also have the same period as GPS data (http://dataonline.bmkg.go.id).
The meteorology data were requested from local meteorology stations. For this research, only two stations of GPS and Meteorology were used, are Malang (CMLG) and Pasuruan (CPAS), the location as shown in Table 2 and Figure 1.

**Table 2.** Coordinates of GPS and meteorology stations.

| GPS Station | Latitude (deg) | Longitude (deg) | Height (meter) | Meteorology Station | Latitude (deg) | Longitude (deg) | Height (meter) |
|-------------|----------------|-----------------|----------------|---------------------|----------------|-----------------|----------------|
| CMLG        | -7.980         | 112.663         | 474.6          | Malang              | -7.901         | 112.598         | 590            |
| CPAS        | -7.651         | 112.901         | 43.5           | Tretes              | -7.705         | 112.635         | 832            |

**Figure 1.** Area study. The insert of the blue box is a particular area study and the distribution of GPS stations (Black dot) and Meteorology stations (Blue triangle).

2.2. *Precise point positioning*

GAMIT [10], GIPSY-OASIS [11], and Bernese [12] are GNSS software packages that may be used to calculate ZTD. At least one of the GNSS receivers must be at a known position inside a given reference frame for GAMIT to handle simultaneous observations from a series of GNSS. Precision point positioning (PPP), unlike differential positioning, comprises mm-cm placement of a GNSS station using a single receiver. The PPP is a commonly used absolute positioning method that estimates the position of a single GPS station using un-differenced dual-frequency pseudo-range and carrier-phase data, as well as accurate satellite orbit and clock information. [11]. Many scientific GPS software packages, such as the Jet Propulsion Laboratory's (JPL) GIPSY/OASIS program and the Astronomical Institute of the University of Berne's Bernese GPS software, use the PPP approach. PPP has become a popular option for positioning in many distant locations when adjacent base stations are absent or the installation of base stations is difficult or expensive. The ZTD and ZWD were calculated using the GIPSY/OASIS program in this study.
2.3. Correlation GPS and meteorology
A calculation of a monotonic relationship between two variables is the correlation. A monotonic relationship between two variables is one in which the value of one variable increases in lockstep with the value of the other variable, or the value of one variable decreases in lockstep with the value of the other variable. Pearson’s linear correlation was used, with degrees of correlation ranging as following in Table 3 [13].

| Absolute Magnitude of the Observed Correlation Coefficient | Interpretation       |
|-----------------------------------------------------------|----------------------|
| 0.00–0.10                                                 | Negligible correlation|
| 0.10–0.39                                                 | Weak correlation      |
| 0.40–0.69                                                 | Moderate correlation  |
| 0.70–0.89                                                 | Strong correlation    |
| 0.90–1.00                                                 | Very strong correlation|

In this study, the correlation of two variables between ZWD from GPS data and ZWD from Meteorology data were computed. The correlation value was be interpreted based on Table 1.

3. Results and discussion
This section presents the results of the ZWD time series from GPS measurement and Meteorology station data. Moreover, a linear relationship between 2 variables: GPS and Meteorology, is indicated by correlation value.

3.1. ZWD time series
In this sub-section, the ZWD from GPS data and Meteorology data for each station is presented in Figures 2 and 3. Figures 2 and 3 show that the pattern of ZWD values between GPS and Meteorology data are close to similar. The distance of the CMLG GPS station and Malang Meteorology station about 12 km, so the results of ZWD are very close. Meanwhile, the CPAS and Tretes meteorology stations have a 30 km of distance. Due to the long distance between GPS and Meteorology station, the tropospheric condition can be a different situation, such as temperature, humidity, pressure, and wind.

Figure 2. The time series of ZWD at the CMLG GPS station (in blue) and the Malang Meteorology station (in red).
3.2. Correlation between GPS and Meteorology data

The correlation between ZWD from GPS and Meteorology data is shown in figure 4.

According to Figure 4, we can interpret the linear relationship between two variables: ZWD from GPS and ZWD from Meteorology data. The correlation coefficient for CPAS – Tretes (Figure 4 - left) and CMLG – Malang (Figure 4 – right) are 0.79 and 0.85, respectively. Both of the coefficients are different, as mentioned in the previous sub-section, the differences in troposphere conditions due to considerable distance (CPAS – Tretes ± 30 km and CMLG – Malang ± 12 km). However, the correlation coefficients (0.79 and 0.85) based on Table 1 have the meaning “Strong” correlation. This result indicates that ZWD from GPS is very close to the in situ measurement from meteorology data.

4. Conclusion

This research involved estimating ZWD from GPS data using Precise Point Positioning (PPP). The ZWD derived from GPS and Meteorology data (in situ) show a strong correlation (0.79 and 0.85 for CPAS-Tretes and CMLG-Malang, respectively). GPS measurement data can be used as a complement for computing ZWD and Water Vapor. By translating the ZWD to PWV, precipitable water vapor (PWV) may be estimated using GPS data as a critical indicator of climate change. By combining both
GPS measurement and Meteorology data, estimation of water vapor might be a satisfactory result in terms of geographical and temporal variability.

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