GNSS PRECIPITABLE WATER VAPOR

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Received: December 12, 2023
Revised: December 15, 2023
Accepted: December 20, 2023

ABSTRACT

This review article centers on tropospheric delays in Global Navigation Satellite System (GNSS) positioning and the methodology for estimating Zenith Total Delay (ZTD), which encompasses Zenith Hydrostatic Delay (ZHD) and Zenith Wet Delay (ZWD). The precise modeling and estimation of these delays are paramount for achieving high-precision GNSS positioning and valuable tools for tropospheric monitoring. The process of GNSS Precipitable Water Vapor (PWV) retrieval entails the calculation of ZWD by subtracting ZHD from ZTD. The Weighted Mean Temperature (Tm) stands out as a crucial parameter influencing the calculations of GNSS PWV, and the accuracy of GNSS PWV hinges on the precision of both Tm and ZHD.

Keywords: Precipitable water vapor, GNSS, ZTD, ZHD, ZWD

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I. INTRODUCTION

Water vapor plays a crucial role in Earth's atmospheric processes, influencing weather patterns and contributing to the overall climate system. Accurate measurement and monitoring of atmospheric water vapor content are essential for understanding weather dynamics, climate variability, and improving weather forecasting capabilities. One advanced technique for obtaining precise information about water vapor in the atmosphere is through the use of Global Navigation Satellite System (GNSS) technology.

GNSS, encompassing satellite constellations such as Global Positioning System (GPS), GLObalnaya NAvigatsionnaya Sputnikovaya Sistema (GLONASS), Galileo, BeiDou Navigation Satellite System (BeiDou), Quasi-Zenith Satellite System (QZSS), and Indian Regional Navigation Satellite System (IRNSS), has evolved beyond its primary role in navigation to become a valuable tool in atmospheric science. One significant application is the estimation of Precipitable Water Vapor (PWV), a key parameter characterizing the amount of water vapor present in the troposphere. The fundamental principle underlying GNSS PWV estimation lies in the analysis of signal delays experienced by GNSS signals as they traverse the Earth's atmosphere. When GNSS signals pass through the troposphere, they encounter delays due to atmospheric conditions, with water vapor being a major contributor to these delays. Leveraging the dual-frequency signals transmitted by GNSS satellites, researchers can differentiate and quantify the tropospheric delay associated with water vapor.

The process involves calculating the Zenith Total Delay (ZTD), which represents the total delay experienced by GNSS signals from the satellite to the receiver, including contributions from water vapor. By employing mathematical models and algorithms, scientists can separate the dry component of the atmosphere and isolate the water vapor-related delay. Furthermore, a mapping function is applied to account for variations in the atmosphere's refractivity, ensuring accurate corrections. The final result is a precise estimation of the Integrated Water Vapor (IWV), which represents the total amount of water vapor along the vertical column above a specific location. The capability to continuously monitor GNSS signals allows for real-time tracking of changes in atmospheric water vapor content. This information proves invaluable in various fields, including meteorology, climate research, and environmental monitoring. GNSS-derived PWV data contribute to improving weather forecasts, understanding climate patterns, and enhancing our ability to respond to and mitigate the impacts of extreme weather events (Bevis et al.,1992, pp. 15787-15801; Domingo & Macalalad, 2022, pp. 1-13; Han et al., 2023, pp. 1-14; Huang et al., 2021, pp. 1-18).

In this review, the integration of GNSS technology into atmospheric studies represents a remarkable advancement, offering a non-intrusive and globally accessible means to observe and quantify one of the most influential components of Earth's atmosphere – water vapor. As researchers continue to refine GNSS-based techniques, the potential for enhanced understanding and prediction of atmospheric phenomena continues to grow, ushering in new possibilities for scientific inquiry and practical applications.

II. WATER VAPOR

Water vapor is the gaseous form of water and is an essential component of Earth's atmosphere. It plays a crucial role in the planet's weather and climate systems. Understanding the principles of water vapor involves recognizing its unique properties and the processes that govern its presence in the atmosphere.

Phase transition: Water exists in three primary phases-solid (ice), liquid (water), and gas (water vapor). The transition between these phases is governed by temperature and pressure. When water absorbs heat, it undergoes a phase transition from liquid to vapor, a process known as evaporation.

Evaporation and condensation: Evaporation is the process by which water molecules gain enough energy to break their bonds and become vapor. This occurs primarily at the surface of bodies of water, such as oceans, lakes, and rivers. Conversely, condensation is the process where water vapor loses energy and transitions back to liquid form, forming clouds and precipitation.

Water vapor in the atmosphere: Water vapor is present in varying concentrations in the Earth's atmosphere. It is most abundant in the troposphere, the lowest layer of the atmosphere, where weather events occur. The amount of water vapor the air can hold depends on its temperature; warmer air can hold more water vapor than cooler air.

Role in the water cycle: Water vapor is a central player in the Earth's water cycle. As the sun heats the Earth's surface, water evaporates into the atmosphere. Once in the atmosphere, water vapor can be transported over great distances by atmospheric currents. When conditions are right, it can condense to form clouds and participate in precipitation events.

Greenhouse gas: Water vapor is also a significant greenhouse gas, contributing to the natural greenhouse effect. While carbon dioxide and other greenhouse gases are often discussed in the context of climate change, water vapor's role is critical. It amplifies the warming effect by increasing as the atmosphere warms, creating a feedback loop.

Humidity: Humidity is a measure of the amount of water vapor present in the air. It can be expressed as absolute humidity (the actual amount of water vapor per unit volume of air) or relative humidity (the percentage of water vapor present compared to the maximum amount the air could hold at a given temperature).

III. GNSS PRECIPITABLE WATER VAPOR

Tropospheric delays are commonly recognized as a primary source of errors in GNSS positioning, and as such, they are typically modeled and estimated in the GNSS analysis process. The estimation of these delays not only enables high-precision GNSS positioning but also serves as a valuable tool for tropospheric monitoring. Traditionally, the zenith total delay (ZTD) comprises two components: the zenith hydrostatic delay (ZHD) and the zenith wet delay (ZWD). These components are linked to individual satellite observations and their associated slant delays through specific mapping functions. The ZTD depends on the hydrostatic (Air pressure-related) part and, crucially, on the partial water vapor pressure in the lower atmosphere. By estimating the wet component of the delay (i.e., the ZWD), GNSS observations provide a direct means to observe the quantity of atmospheric water vapor. This water vapor is an active and abundant component of the climate system.

A. Methodology

As GNSS signals traverse the lower atmosphere, they encounter the atmospheric delay effect, resulting in a decrease in signal propagation speed and the bending of the signal path-a phenomenon commonly referred to as atmospheric delay. This delay predominantly occurs in the troposphere and is specifically known as tropospheric delay. The delay amount in the zenith direction is termed zenith total delay (ZTD), which comprises two primary components: zenith hydrostatic delay (ZHD) and zenith wet delay (ZWD). In GNSS data processing, accurate estimation of ZTD is achievable, with ZHD calculated primarily using the Saastamoinen model based on station latitude and surface pressure or derived from numerical weather models (NWM). ZWD, essential for GNSS meteorology, is computed by subtracting ZHD from ZTD.

In the realm of GNSS meteorology, the weighted mean temperature (Tm) assumes a critical role as a parameter for computing GNSS Precipitable Water Vapor (PWV). PWV is a significant factor influencing the calculation of high-precision PWV values. Consequently, the accuracy of GNSS PWV is heavily contingent on the precision of both Tm and ZHD (Huang et al., 2021, pp. 1-18).

Domingo and Macalalad (2022, pp. 1-13) studied on temporal analysis of GNSS-based precipitable water vapor during rainy days over the Philippines from 2015 to 2017. They employed a globally accepted model, the Tm model by Bevis, as shown in Figure 1.

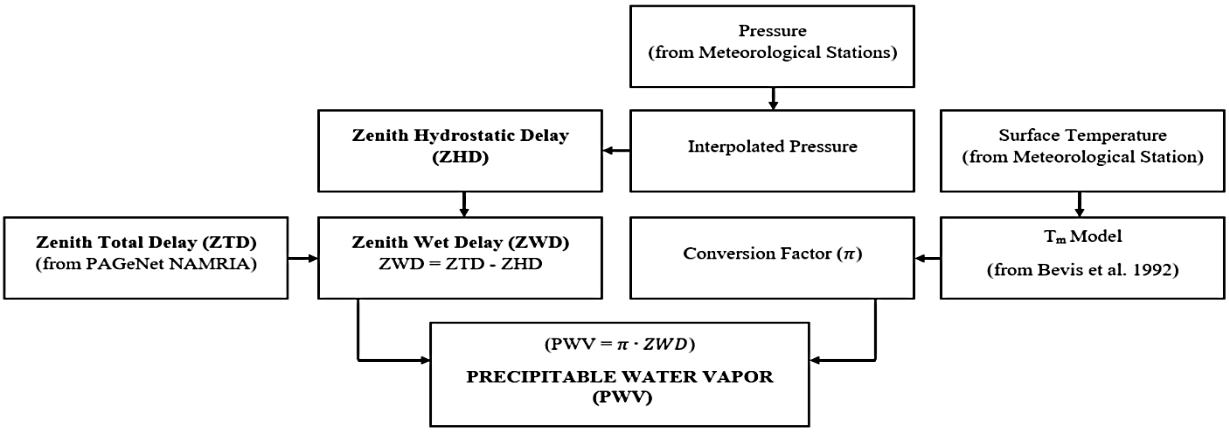

Figure 1 Flow chart for obtaining GNSS PWV
Source: Domingo and Macalalad (2022, p. 4)

B. Equations

Bevis et al. (1992, pp. 15787-15801) introduced the concept of GPS meteorology, wherein ZTD is obtained from GNSS observations. ZHD is typically estimated using the Saastamoinen model based on surface pressure measurements or derived from Numerical Weather Models (NWM). Subsequently, the ZWD value is determined by subtracting ZHD from ZTD (Domingo & Macalalad, 2022, pp. 3-4; Han et al., 2023, pp. 3-4; Huang et al., 2021, pp. 3-7).

The procedure for GNSS PWV calculating is outlined as follows:

$$\mathrm{ZWD} = \mathrm{ZTD} - \mathrm{ZHD} \tag{1}$$

$$\Pi = \frac{10^6}{\rho_w R_v \left[\frac{k_3}{T_m} + k'_2\right]} \tag{2}$$

$$\mathrm{PWV} = \Pi \,.\, \mathrm{ZWD} \tag{3}$$

where Π is the dimensionless atmospheric water vapor conversion factor, ρ_w is the density of liquid water, R_v represents the universal gas constant for water vapor, and k'_2 and k_3 are atmospheric physical constants.

The weighted mean temperature (Tm) can be calculated using the equation as:

$$T_m = \frac{\int \left(\frac{e}{T}\right) dH}{\int \left(\frac{e}{T^2}\right) dH} \tag{4}$$

where e indicates the water vapor pressure, T refers to the corresponding temperature, and dH indicates the atmosphere thickness.

The Vertical correction investigation for ZHD, the vertical adjustment holds significant importance in the development of tropospheric delay and Tm models. Numerous successful investigations have emphasized that the precision of the correction model significantly influences the accuracy of high-precision positioning. Crétaux et al. (2009, pp. 723–735) identified various challenges associated with these corrections, particularly in the context of dry tropospheric corrections. Previous research has indicated that the vertical adjustment of ZHD can be accomplished by considering the height dependence of atmospheric pressure, as utilized by Kouba 2008 (Huang et al., 2021, pp. 3-7), expressed as:

$$P_s = P_0[1- 0.0000226 \,.\, (h_s - h_0)]^{5.225} \tag{5}$$

$$\text{ZHD} = \frac{0.0022768 \,.\, P_s}{1\text{-}0.0000226 \cos(2\varphi) - 0.28.10^{-6} .\, h_s} \tag{6}$$

where P_s and P_0 are the atmospheric surface pressures (in hPa) at heights h_s and h_0 (in m), φ is the geodetic latitude, and ZHD results in meters. The P_0 is obtained from GPT2w.

$$\text{ZHD} = \text{ZHD}_{\text{grid}} + 0.0022768 \,.(\frac{g \,.\, P_{grid}}{R \,.\, T_{grid}}).\, (h\text{-}h_{grid}) \tag{7}$$

where g is the gravity acceleration (9.8 m s^{-2}), and R is the gas constant (8.314 JK^{-1} mol^{-1}). p_{grid} and T_{grid} have been extracted from the new GPT2w model.

IV. RESULT REVIEW

GNSS signals passing through the lower atmosphere experience tropospheric delays, primarily due to atmospheric water vapor. Tropospheric delays, specifically ZTD, are modeled and estimated to enable high-precision GNSS positioning and tropospheric monitoring. ZTD consists of two main components: ZHD and ZWD. ZHD is traditionally estimated using models like the Saastamoinen model based on surface pressure or derived from Numerical Weather Models (NWM). ZWD is then obtained by subtracting ZHD from ZTD. PWV is calculated as the product of the atmospheric water vapor conversion factor (Π) and ZWD: PWV=Π·ZWD. Tm is a critical parameter influencing PWV calculations. Tm is determined by integrating water vapor pressure (e) over temperature (T) and its square over the atmosphere's thickness (dH).

V. CONCLUSION AND DISCUSSION

This review focuses on tropospheric delays GNSS positioning and the methodology for estimating ZTD, comprising ZHD and ZWD. The accurate modeling and estimation of these delays are crucial for high-precision GNSS positioning and serve as valuable tools for tropospheric monitoring. The procedure for GNSS PWV retrieval involves calculating ZWD by subtracting ZHD from ZTD. The weighted mean temperature (Tm) is a critical parameter influencing GNSS PWV calculations. The accuracy of GNSS PWV is contingent on the precision of both Tm and ZHD. Equations are provided for calculating ZWD, PWV, and Tm, with a focus on the vertical adjustment of ZHD. The height dependence of atmospheric pressure is considered, and a correction model is presented, emphasizing its importance in high-precision positioning. Temporal analyses of GNSS-based PWV during specific periods may be conducted to understand variations. Globally accepted models, such as the Tm model by Bevis, can be employed for comprehensive temporal studies. Vertical adjustment for ZHD, precision in the vertical adjustment of ZHD significantly influences high-precision positioning. Challenges, particularly in dry tropospheric corrections, are acknowledged. Vertical adjustment methods, considering the height dependence of atmospheric pressure, are proposed for accurate ZHD estimation.

AKNOWLEDGEMENT

We would like to thank Assistant Professor Dr. Prasert Kenpankho from Space, Satellite, and Study Laboratory (SSS Lab), Department of Engineering Education, King Mongkut's Institute of Technology Ladkrabang, Thailand for consulting on this review article.

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