QUANTIFYING PRECIPITABLE WATER VAPOR USING THREE-DIMENSIONAL RADIOSCOPY FROM OBSERVATIONS WITH GPS, BDS, AND GLONASS SATELLITES

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ABSTRACT

This review article presents information and academic documents related to measuring precipitable water vapor in the atmosphere using 3D radioscopy by three satellite systems: GPS, BDS, and GLONASS. The review article presented the three methods to compare the differences in using a single satellite system, two satellite systems, and three satellite systems, respectively, which can measure the amount of precipitable water vapor in the atmosphere using 3D radioscopy. In addition to being beneficial for measuring precipitable water vapor in the atmosphere through photographic methods, it can also serve as a tool for research in forecasting precipitable water vapor for agricultural crop cultivation by farmers according to different seasons, predicting air humidity, rainfall, meteorological department reports, and monitoring global climate change.

Keywords: GNSS, Global positioning system, 3-D water vapor precipitable, Precipitable water vapor, ZTD, ZHD, ZWD

I. INTRODUCTION

The atmosphere contains water vapor, which is a crucial variable for all living things on this planet. Water vapor is extremely important as it drives the life processes of living organisms (National Aeronautics and Space Administration [NASA], 2025, Online). It regulates the body temperature of humans, animals, plants, and others. It is essential for farmers in the agricultural sector, such as in crop cultivation and livestock raising. The hydrological cycle of water vapor depends on the variable amount of water vapor and the average concentration in the atmosphere, which is influenced by factors such as geographical characteristics or different seasons. The measurement of water vapor in the atmosphere has been ongoing for a long time, with meteorologists seeking various methods and techniques to calculate the amount of water vapor.

From the study of the Global Positioning System (GPS) by Bevis et al. (1992, pp. 15787-15801), which serves as a guideline for estimating atmospheric water vapor using GPS satellites, this method has been explored due to its cost-effectiveness. The amount of water vapor in the atmosphere can be inferred from the signal propagation errors of GPS satellites passing through the tropospheric layer. These errors are considered parameters and are eliminated in the process of estimating the coordinates of the surveying station. The estimation of the tropospheric layer's wet part from Very Long Baseline Interferometry (VLBI) and GPS surveying is close to the estimates from radiosondes and microwave radiometers (Lu et al., 2016, pp. 703-713). However, the measurement using microwave radiometer and radiosonde requires a significant budget and only provides data in certain areas. Therefore, these methods have become another option that meteorologists use.

In this review study, GNSS technology is integrated and applied to the study of precipitable water vapor in the atmosphere using 3D radioscopy with GNSS satellite systems (Dong et al., 2018, pp. 1-15). The applications include single-system, dual-system, and triple-system approaches, which demonstrate that more satellites in GNSS systems such as GPS, BeiDou, and GLONASS increase accuracy.

II. WATER VAPOR

Steam refers to water that has evaporated, characterized by its purity and colorlessness, resembling mist. At normal pressure, water turns into steam at a temperature of 100 degrees Celsius, expanding to about 1,600 times its liquid volume. Steam can reach very high temperatures (above 100 degrees Celsius), known as superheated steam, when liquid water comes into contact with high-temperature objects such as hot metals or lava. Water can instantly turn into vapor (Ahrens, 2012, pp. 91-93).

Humans cannot see water vapor with the naked eye, but on clear days, there is water vapor everywhere. This is because water vapor is a colorless, odorless gas, so it cannot be directly perceived through touch, which may differ from clouds formed by liquid water droplets. It is nothing more than the change in the state of water vapor when the phase changes from liquid to gas. This water vapor is colorless and odorless, although it usually appears white and cloudy when mixed with small liquid water droplets. The visibility decreases depending on the factor of density. For example, we can see that steam can be quite visible when we leave the bathroom and close the bathroom window. This is where the steam accumulates and turns into liquid when it condenses on the walls.

III. 3-D WATER VAPOR TOMOGRAPHY

3D radioscopy with satellite systems for capturing images to determine the amount of water vapor in the atmosphere, using pixel observation methods. The observation model assumes a spatial relationship between the water vapor in specific pixels and the surrounding pixels. General constraints are applied, including horizontal constraints, vertical constraints, and boundary constraints.

METHODOLOGY

The principle tomography technique is to use the integral observation reconstruct the detailed information to the studied object through a certain mathematical constraint. In GNSS meteorological, the integral observation of tropospheric tomography are SWV, with the movement of satellites system in space and the rotation of Earth, and dense GNSS observations can retrieve the 3-D water vapor over interested area with the tomography technique.

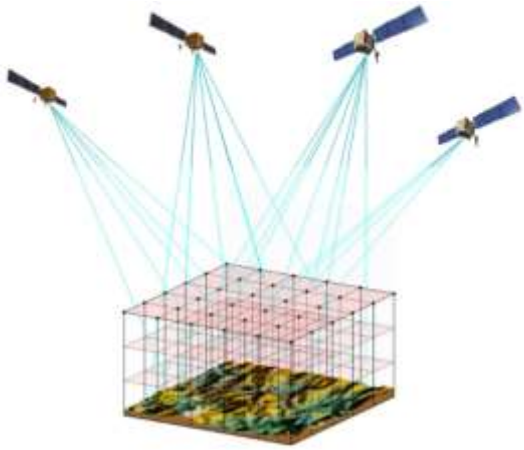

Figure 1: The principle of GNSS tropospheric water vapor tomography

B. EQUATION

Determination of dry vertical tolerances.The value can be calculated if we know the air surface pressure (Ps) at the station location from the equation (Bevis et al., 1992, pp. 15787-5801) and wet vertical tolerances.

$$ZHD = \frac{2.2768\ XPs}{1-0.00266\cos(2\ \emptyset)-0.00000028H} \quad (1)$$

This is caused by the amount of water vapor present in the atmosphere, which can be calculated from the equation (Bevis et al., 1992, pp. 15787-15801).

$$ZWD = ZTD - ZHD \quad (2)$$

ZWD (Zenith Wet Delay) is in millimeters.

The resulting ZWD value can be used to calculate the amount of water vapor in the atmosphere from the relationship from the equation getting the amount of water vapor in the atmosphere in millimeters.

$$PWV = ZWD * \prod \quad (3)$$

Where the coefficient $\prod$ can be estimated from the equation (Bevis et al., 1992, pp. 15787 - 15801).

$$\prod = \frac{10^6}{Pw\ x\ \mathrm{Rv} + (\frac{K3}{Tm} + k'2)} \quad (4)$$

where as

P_w = density of water in liquid state. (999.97 kg/m^3)
R_v = Steam constant (461.525 joules/kg*Kelvin)gg
k'_2 = refractive constant in the troposphere (22.1 Kelvin/mbar)
k_3 = refractive constant in the troposphere (3,739 $Kelvin^2$/mbar)
T_m = Average temperature of the troposphere (Kelvin)h

In the process of determining the T_m value at any given time, it is difficult to make accurate measurements. It also requires processing time. Another option is to estimate using mathematical models, which take the form of linear relationships with surface temperature data at station locations.

The observations of the tropospheric water vapor tomography are the integration of water vapor in the direction of the ray – path slant water vapor (SWV) which can be expressed as:

$$SWV = \int_l p\,(l)dl = PWV * M_w + R \tag{5}$$

where

p (l) = represent the water vapor density
dl = Specifies the length of a signal element
M_W = is the wet mapping coefficient
R = the non - homogeneous variation of the water vapor

IV. RESULTS REVIEW

The research findings indicate that, based on the comparison of root mean square (RMS) values and relative errors between the water vapor density obtained from ERA5 and the GNSS tomography results, which differ from UTC 6:00 to 18:00 over a seven-day period across various layers, the amount of water vapor tends to decrease with increasing altitude. It was also found that the RMS values using two and three satellite systems are better than those using only the GPS satellite system. This demonstrates that a multi-satellite system increases accuracy even further in Figure 2. It is using the GPS satellite system alone (G), the GPS system with BDS (G+C), the GPS and GLONASS satellite systems (G+R), and the GPS, BDS, and GLONASS satellite systems (G+R+C).

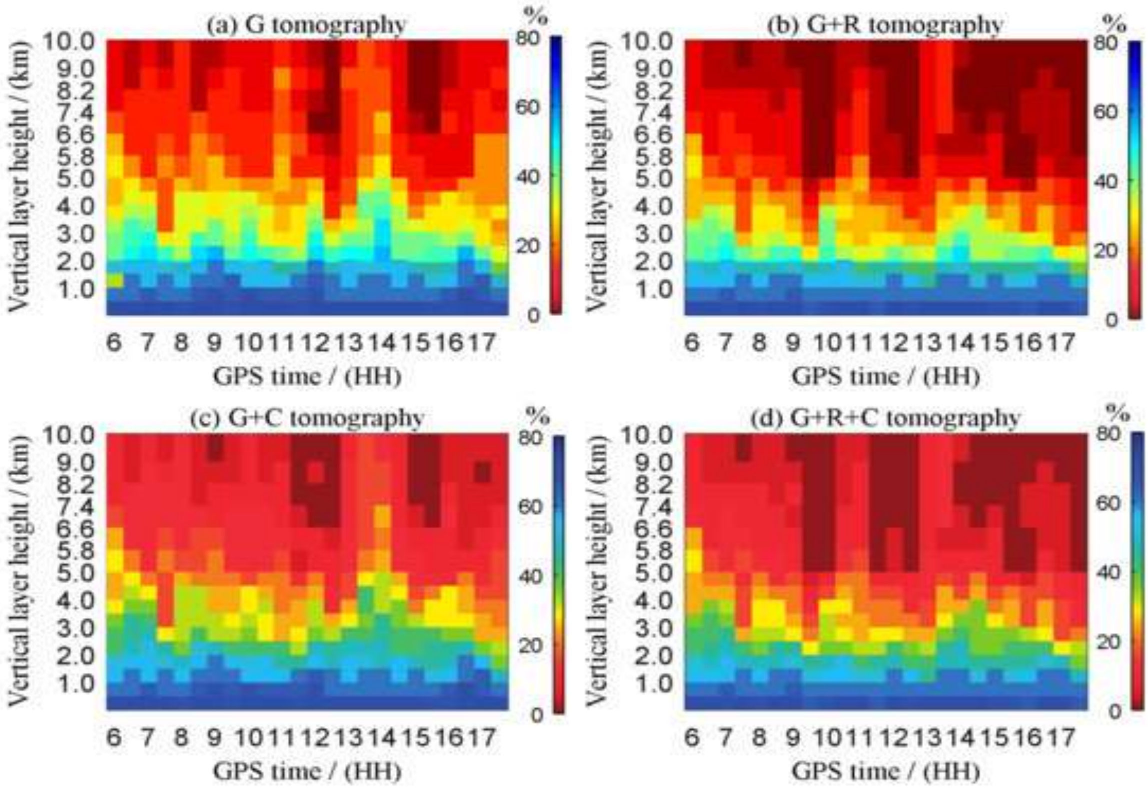

Figure 2: The percentage of empty voxels with different combined GNSS in different layers

V. CONCLUSION AND DISCUSSION

The conclusion from the study of the above article, which has the same objective of water vapor tomography using three satellite systems, namely GPS, BDS, and GLONASS. All four methods use different satellite systems, but they share the same objective: to determine the water vapor density through imaging (Tomography). It was found that as the height of the atmosphere increases, the amount of water vapor tends to decrease. Additionally, the RMS values of the two-system and three-system satellite configurations are better than using the GPS satellite system alone. This indicates that more satellite systems increase accuracy in determining atmospheric water vapor density. Changes in atmospheric water vapor are partly due to human activities, which in turn can lead to global changes. This study is interesting and may serve as a good method and guideline for future research. From this study, it is interesting and may be another good method that is suitable and can be used as a guideline for research by Dong et al. (2018, pp. 1-15).

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