environmental sciences proceedings

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Proceeding Paper

Evaluation of Water Vapor-Weighted Mean Temperature Models in GNSS Station ACOR †

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† Presented at the IV Conference on Geomatics Engineering, Madrid, Spain, 6–7 July 2023.

Abstract: The delay of GNSS signals in the neutral atmosphere allow the determination of atmospheric water vapor. The conversion factor of the delay in the water vapor uses the water vapor-weighted mean temperature, T_m, which is a crucial parameter to improve the quality of conversion. This study analyzed two different types of models: linear models such as Bevis, Mendes and Ortiz de Galisteo, and empirical models such as GPT2w, GPT3 and GWMT_D. The performance of the models was analyzed using the models as the source of T_m to obtain the precipitable water vapor (PWV), which was compared to a reference set of PWV obtained from a matched radiosonde site. The results show a better performance of the linear models, with the Bevis model achieving the best performance.

Keywords: precipitable water vapor; GNSS; water vapor-weighted mean temperature

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Citation: Perdiguer-López, R.; Valero, J.L.B.; Garrido-Villen, N. Evaluation of Water Vapor-Weighted Mean Temperature Models in GNSS Station ACOR. *Environ. Sci. Proc.* **2023**, *28*, 31. https://doi.org/10.3390/environsciproc2023028031

Academic Editors: María Belén Benito Oterino, José Fernández Torres, Rosa María García Blanco, Jorge Miguel Gaspar Escribano, Miguel Ángel Manso Callejo and Antonio Vázquez Hoehne

Published: 7 March 2024

1. Introduction

Water vapor is one of the most important atmospheric parameters due to its contribution to the hydrological cycle and its role as a natural greenhouse gas that significantly contributes to the regulation of the temperature of the Earth/atmosphere system. The measuring and modeling of water vapor is essential because of its contribution to both the climate and weather. Global Navigation Satellites Systems observations have become a powerful tool to retrieve the atmospheric water vapor. High temporal and spatial resolution as well as low costs and all-weather capability are some of the characteristics of the GNSS technique.

The retrieval of water vapor from GNSS observations is based on the delay the signal suffers in the neutral part of the atmosphere, mainly in the troposphere. This delay is usually calculated from GNSS observations and once it is mapped onto the zenith, it is called Zenith Total Delay, ZTD. This can be divided in two parts: the Zenith Hydrostatic Delay, ZHD, and the Zenith Non-hydrostatic or Wet Delay, ZWD. Thanks to its small variability, ZHD can be accurately obtained from models like the Saastamoinen model, which depends on the latitude and height of the GNSS site as well as the atmospheric site pressure [1]. ZWD, nevertheless, has great variability both in space and time, which makes its modeling difficult, so it is often calculated via the subtraction of the ZTD and ZHD. Once the ZWD is calculated, it can be converted into PWV by multiplying it with a factor, Π, as demonstrated by Bevis et al. [2]:

$$\Pi = \frac{10^6}{\rho R_V \left[\frac{k_3}{T_m} + k_2 - m k_1 \right]} \tag{1}$$

where ρ is the density of liquid water, R_V is the specific gas constant for water vapor, m is the ratio of the molar masses of water vapor and dry air, and T_m is the water vapor-weighted mean temperature. The values and uncertainties of the physical constants are k_1 = (70.60 ± 0.05) Kmb^{-1}, k_2 = (70.40 ± 2.2) Kmb^{-1} and k_3 = (3.7390 ± 0.0012) 10^5K^{2}mb^{-1} [2]. Relative error in Tm can determine the uncertainty of conversion, Π, and, consequently, the quality of the PWV retrieved. The correct determination of T_m is thus the key for the improvement of conversion, Π.

The water vapor-weighted mean temperature can be obtained via different approaches. One of the most widely used is the application of linear models that explain the relationship between the surface temperature and the water vapor-weighted mean temperature. Another approach is the use of empirical blind models. In this study, these two approaches are applied to obtain water vapor-weighted mean temperature values. The models of Ortiz de Galisteo, Mendes and Bevis are used as well as GPT2w, GPT3 and GWMT_D as empirical blind models. Then, water vapor, expressed as Precipitable Water Vapor, is calculated from these different series of T_m values, and compared to a reference set of PWV provided by radiosonde records to analyze their performance as a source of T_m upon PWV retrieval.

The outline of this paper is as follows: Section 2 explains the different data sets used in the study as well as the methodology of the calculation of T_m and PWV. Section 3 explains the results while Section 4 focuses on the discussion of the results.

2. Materials and Methods

2.1. Data Sets

The GNSS station located in A Coruña, ACOR, was chosen in this study. This station contributes to the EUREF Permanent Network and is managed by the National Geographic Institute of Spain. The series of the ZTD of ACOR were obtained from the website https://igs.bkg.bund.de/root_ftp/EUREF/products/ (assessed on 1 February 2023).

The needed atmospheric parameters for this study, pressure, and temperature, were obtained from a meteorological station called Coruña-Dique, which belongs to the meteorological station network Meteogalicia, managed by the Xunta of Galicia. According to the limit distance between the GNSS site and a meteorological station of 5 kilometers, as claimed by Li et al. 2022, the two sites could be considered co-located [3]. The data of the meteorological station were downloaded from the Meteogalicia website (https://www.meteogalicia.gal/, accessed on 1 February 2023).

The radiosonde is a traditional technique to retrieve the water vapor present in the atmosphere and it is used as a reference to validate other techniques due to its high precision. The State Meteorological Agency of Spain (AEMET) managed a station in the area known as A Coruña. This radiosonde site is under the limit distance between a GNSS site and a radiosonde site, both in the horizontal and vertical component, as suggested by some studies [4], and can be used to validate the PWV retrieved from GNSS observations with the different models of water vapor-weighted mean temperature. The data of the radiosonde were downloaded from the Integrated Global Radiosonde Archive web site (ftp://ftp.ncdc.noaa.gov/pub/data/igra, accessed on 1 February 2023).

2.2. T_m Linear Models

Bevis et al. [5] proposed a model between T_m and surface temperature, T_s, analyzing two-year data of 8718 radiosonde profiles from sites in the United States, achieving a root mean square (rms) in the T_m calculation of 4.7k:

$$T_m = 70.2 + 0.72T_s \tag{2}$$

Another well-known model is the one proposed by Mendes [6]. The model was developed using 32,467 profiles of 50 radiosonde sites distributed worldwide, achieving a rms on T_m of 3.07k:

$$T_m = 50.4 + 0.789T_s \tag{3}$$

In Spain, Ortiz de Galisteo [7] proposed a relation based on the analysis of 37,179 profiles of 8 radiosonde sites from 2000 to 2008, achieving a rms in the determination of T_m of 3.07k:

$$T_m = 61.92 + 0.75T_s \tag{4}$$

From Equations (2)–(4), it is clear that the only needed parameter to obtain T_m in this approach is the surface temperature of a co-located meteorological station.

2.3. Empirical Blind Models

Empirical blind models are characterized by very simple input data. Moreover, non-meteorological in situ measurements are needed to derivate the water vapor-weighted mean temperature.

Global Pressure and Temperature 2 wet, GPT2w and Global Pressure and Temperature 3, GPT3, are empirical models that were developed by the Technical University of Vienna [8,9]. These models are a full empirical troposphere models providing all the parameters required for troposphere modeling. GPT3 was developed using monthly mean pressure levels from ERA-Interim reanalysis data from 2001 to 2010 and can be used just with the coordinates of the site and the day as inputs. Each model provides different atmospheric parameters including pressure and water vapor-weighted mean temperature. The GPT2w and GPT3 models considered the characteristics of annual and semiannual cycles in the atmospheric parameters. However, diurnal variations are not taken into account so only a value of each atmospheric parameter is provided by day. In this study, the GPT2w and GPT3 models were used on the $1^\circ \times 1^\circ$ grid version with the time variation option. The scripts of the models can be downloaded from http://vmf.geo.tuwien.ac.at/codes/ (accessed on 1 February 2023).

The Global Weighted Mean Temperature with Diurnal variation, GWMT-D, model was developed using 4-year data from 2010 to 2013, namely NCEP2 reanalysis data [10]. This model only provides the water vapor-weighted mean temperature. However, the model considered not only the annual and semiannual cycles of T_m but also the diurnal cycle.

2.4. PWV Retrieval

Precipitable water vapor from December 2021 to November 2022, covering the four seasons, was calculated using the different models of water vapor-weighted mean temperature. The starting point of GNSS PWV retrieval is the series of ZTDs of the ACOR site. Then, using the records of pressure from the meteorological station, the series of ZHDs could be calculated using the Saastamoinen model. ZWD was calculated via the subtraction of ZTD and ZHD. The last step, the calculation of PWV, was conducted using the conversion factor, Π, calculated from the different T_m series.

In the case of GPT2w and GPT3 models, because they also provided pressure, the value of ZHD was obtained from the Saastamoinen model but using the value of pressure derived from each model.

3. Results

The statistical results of the comparisons between the reference set of PWV from the radiosonde and the six series of PWVs obtained from the different sources of T_m are shown in Table 1.

Table 1. Statistical results of the comparison between the different sets of GNSS-retrieved PWV using different T_m models and PWV from radiosonde as the reference value.

PWV set	T_m model	Correlation coefficient	Mean Bias Error (mm)	Standard Deviation (mm)	RMS (mm)
PWV_O	Ortiz de Galisteo	0.99	1.162	1.157	1.640
PWV_M	Mendes	0.99	1.145	1.157	1.628
PWV_B	Bevis	0.99	1.134	1.151	1.616
PWV_GPT2w	GPT2w	0.94	1.469	2.493	2.893
PWV_GPT3	GPT3	0.94	1.468	2.491	2.891
PWV_GWMT_D	GWMT_D	0.99	1.216	1.197	1.707

4. Discussion

According to the statistical results (Table 1), the performance of the linear models, which related surface temperature with the water vapor-weighted mean temperature, are better than the performance of the empirical models. Even the results between the three models studied are similar, though the Bevis model has slightly better performance. However, these models require surface temperature for their application, which could make their use in stations without a co-located meteorological station difficult. Related to the performance of empirical blind models, GWMT_D, which considers the diurnal cycle of $\mathrm{T_m}$, has better results than GPT2w and GPT3 models. However, this model is not a full troposphere model, so it requires the measurement of the pressure to be able to calculate the necessary ZHD. The two empirical blind models, GPT2w and GPT3, have very similar performance, which is worse than that of the rest of the models, with a slightly improvement in the use of GPT3 as a source of T_m. However, these two models provide all the information required for the conversion of ZTD into PWV without in situ meteorological measurements, so they could be easily used in stations without a meteorological co-located station or in real-time PWV retrieval.

Author Contributions: Conceptualization, methodology, validation, writing and formal analysis, R.P.-L., J.L.B.V. and N.G.-V. Software and resources, R.P.-L. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Conflicts of Interest: The authors declare no conflict of interest.

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