

DETERMINATION OF ZENITH TROPOSPHERIC DELAY AND PRECIPITABLE WATER VAPOR USING GPS TECHNOLOGY

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Abstract: In order to be able to be process GPS data, the GPS signal it has to pass the entire terrestrial atmosphere – both neutral atmosphere and ionosphere – which may cause an alteration of the GPS receiver to perform, resulting in large errors in the final position estimate. The dual frequency GPS receivers are affected by the influence of the atmosphere, especially by the troposphere. To estimate the delay caused by the troposphere and to obtain a high degree of accuracy, mapping function has to be used in the estimation process, which opens the door for remote sensing the atmosphere.

Because the wet component from the hydrostatic and non-hydrostatic part, is only 10% of the total neutral atmospheric part, its influence is considerate significant in the application of high-precision positioning in which GPS receivers are employed. The article presents the determination of the precipitable water vapor using relative using four permanent GPS stations. The estimation were done by using the Global Mapping Function - GMF and the apriori pressure and temperature from the GPT2 model.

Keywords: GPS, ionosphere, water vapor, GPT2

1. Introduction

The GPS technique over the past two decades were employed in different activities such as: ocean tide measurements [1], geodynamics applications [2] and none the less atmospheric water vapor sensing [3].

Since the inception of space geodesy, the tropospheric delay of signals propagating through the atmosphere of the Earth has affected geodetic estimations of coordinates on the surface of the Earth. The amount of precipitable water vapor (PW) contained in the neutral atmosphere can be inferred from the propagation delay of the Global Positioning System (GPS) signals passing through the troposphere. For many years, geodesists have treated such delays as nuisance parameters to be removed in the process of estimating station coordinates [4].

The tropospheric delay is one of the main error sources in the analysis of space geodetic techniques operating at microwave frequencies, such as global navigation satellite systems (GNSS), very long baseline interferometry (VLBI), or Doppler orbitography and radiopositioning integrated by satellite (DORIS) [5].

The neutral atmosphere, called the troposphere, is the lowest part of the Earth's atmosphere up to about 80 km altitude. The neutral atmosphere consists of a combination of several gases. The signal propagation on this layer depends on the temperature, pressure and water vapor [6].

The ability to remote sensing the atmosphere using geodetic techniques was dramatically improved over the past decade, primarily as a result of advances in satellite-borne technologies, large-scale and dense geodetic Global Navigation Satellite System (GNSS) networks, new dedicated space missions and developments of new algorithms and innovative methodologies [7].

Space-geodetic and remote sensing applications suffer from the fact that electromagnetic waves are delayed and bended when they propagate through the Earth's atmosphere, an effect known as tropospheric refraction [8].

Global Navigation Satellite System (GNSS) was originally designed for positioning and navigation. Among other possible applications it can be used to derive information about the state of the atmosphere, what is now recognized as GNSS meteorology [9].

Recent developments in both ground-based and satellite-borne geospatial infrastructure have opened exciting new opportunities for geodesists to contribute to issues such as weather, climate, global warming, environment and sustainability [7]. Radio signals transmitted from the GPS satellites are delayed by the atmosphere before they are received on the Earth's surface. The delay due to the presence of water vapor in the troposphere offers an opportunity to observe precipitable water (PW) using ground-based GPS [10].

The dynamics of WV have a strong influence on weather and climate due to the large energy transfers in the hydrological processes. This is particularly so during the formation and life cycle of severe mesoscale convective storm and precipitation systems. Contrary to its importance, WV remains poorly understood and inadequately measured both spatially and temporally, especially in the southern hemisphere, where meteorological data are sparse [6].

The possibility of using GNSS technology for remote sensing the atmospheric water vapor results from the development of "deterministic" least-square and Kalman filtering technique, where the effect created by zenith tropospheric delay that influence the GNSS receiver results from the recorded observation [11]. The basic idea is to calculate the tropospheric delay from GPS pseudoranges when station coordinates with high accuracy is known [6].

Ground-based GPS meteorology was introduced by [11]. The technique consists of using the tropospheric products estimated from permanent ground-based GPS receivers for Numerical Weather Prediction (NWP). This requires a close collaboration between geodetic and meteorological communities since GPS data are usually observed and processed by the former and the tropospheric products assimilated into NWP models by the latter [12].

Over more than a decade, such collaboration has been developed in Europe, namely within the former projects WAVEFRONT, MAGIC, COST-716 and TOUGH. During 2004–2009, the EUMETNET Economic Interest Group (EIG) Global Navigation Satellite System (GNSS) Water Vapour Programme (E-GVAP) was responsible for the coordination of near real time GNSS Zenith Total Delay [12].

Recent research has shown that the estimates of the wet tropospheric delay from very long baseline interferometry (VLBI) and GPS observations agree closely with estimates from radiosonde and microwave radiometer (MWR) measurements [13]. It has been demonstrated through much research that GPS observations allows us to estimate atmospheric PWV with an accuracy of 1.5 mm and temporal resolution of about 30 min under all-weather condition [14].

2. Materials and methods

With the development of the continuously operating geodetic GPS networks, the data provided by them can be used in different areas of geodesy, hence the possibility of remote sensing the atmosphere, by determining the zenith wet delay (ZWD) and precipitable water vapor (PWV). This can be obtain by using the concept of "deterministic" least-square technique and Kalman filtering. By using this technique and continuous operating GPS system we are able to estimate the ZWD with less than 10 mm of long-term bias in equivalent excess path lengths and less than 10 mm (rms) of random noise [11].

The difference between the true electrical path length and the assumed straight line of the GPS signal that travels from the satellite to the receiver throughout the Earth's atmosphere bears the name of "atmospheric delay". The electrical path of the signal "suffers" a delay and its path changes from a straight line to a curved one. Depending on the meteorological condition and the location of the GPS receiver, the atmospheric delay varies from about 6 to 8 nanosecunds or 10-12 cycles of phase at L1-band or 190 to 240 cm. For the computation of the total zenith delay, the atmospheric delay is broken into two components: dry or hydrostatic delay - ZHD and wet delay - ZWD. So, the zenith tropospheric delay is:

$$ZTD = ZHD + ZWD = 10^{-6} \int_{H}^{\omega} N(s) ds$$
⁽¹⁾

where ds has units of length in the zenith, H is the surface height and N(s) is the refractivity of air given parts per million (ppm):

$$N = k_1 \left(\frac{P_d}{T}\right) Z_d^{-1} + k_2 \left(\frac{e}{T}\right) Z_{\omega}^{-1} + k_3 \left(\frac{e}{T^2}\right) Z_{\omega}^{-1}$$
(2)

where P_d is the dry air pressure, T is the air temperature in (K) e is the partial pressure of water vapor (hPA) Z_d and Z_{ω} are the dry air and water vapor compressibility factors, that consider the departure of air from an ideal gas.

In the dry component – ZHD it is assumed that the mean molar mass is equal to the mean molar mass of only the "dry" components excluding the water vapor. If it is assumed that the atmosphere is in hydrostatic equilibrium, the zenith dry delay is very well modelled - with an RMS of approximately 0.5 mm. The hydrostatic part is describe by:

$$ZHD = 10^{-6}k_1 \int \frac{P_d}{T} Z_d^{-1} ds$$
(3)

The wet component – ZWD is due to the water vapor, and includes a correction for the "dry mean molar mass". Due to the fact that the water vapor is present in the form of water drops which causes the "unmixed" condition of the troposphere, the wet delay estimation is very inaccurate and can have RMS errors of several centimeters. The wet part is describe by:

$$ZWD = 10^{-6}k_2 \int \left(\frac{e}{T}\right) Z_{\omega}^{-1} ds + 10^{-6}k_3 \int \left(\frac{e}{T^2}\right) Z_{\omega}^{-1} ds$$
(4)

The relationship between zenith wet delay – ZWD and to water vapor – PW is given by:

$$PW = \Pi * ZWD \tag{5}$$

where ZWD is given in units of length and Π is a dimensionless constant of proportionality.

3. Processing and Results

The study is presenting the determination of the total zenith delay, wet delay and the precipitable water vapor in the west part of Romania by estimating the delay caused by the troposphere over the GPS signal. The determination was possible with the help of 4 GPS permanent stations situated on the West part of Romania. The chosen method for processing was relative positioning. To be able to determine the zenith tropospheric delay by using the GPS technique we have used Gamit-Globk software [15]. We can also use the VLBI technique for the determination of zenith wet delay from which we can determine the precipitable water vapor [16]. When we imply the GPS technique we can also use different approaches like precise point positioning – PPP [17] or relative positioning.

For the analysis we have used the GMF – global mapping function and the apriori pressure and temperature was from the GPT2 model.

Although the troposphere is composed by "hydrostatic – dry" part and "wet" part, the largest effect on the pseudorange bias is due to the presence of the "wet" part of the troposphere. This

one consist only of 10% of the tropospheric refraction while the dry portion is represented by 90%. Due to this difference we are incline first to determine the dry portion of the troposphere. Using mapping function we can determine this part of the troposphere more accurate than the wet part and the effect of this delay on the GPS estimates.





Fig. 1 - Zenith wet delay for the 4 stations

For avoiding one of the largest effect of the troposphere on GPS estimates is to allow data from the satellites with low elevation to "fully" participate on the estimation process and therefore we have set the elevation mask for the GPS receiver to 15 degrees. The satellite trajectories and Earth orientation was provided by IGS – International GNSS Service. Also the IGS08 absolute phase center offset and variation model for Satellite and receiver antenna phase center calibration was used and for the N-S and E-W horizontal gradients a temporal resolution of 2 hours has set.

Taking into account the other 90% of the tropospheric refraction represented by the hydrostatic delay we continue by analyzing the total zenith delay -wet delay + hydrostatic delay which is presented in fig .2.



Fig. 2 - Total zenith delay - wet zenith delay+ hydrostatic delay

In the computation part we have estimated the PWV and also the standard deviation for each station. Due to the fact that the Romania does not have great latitude variation – is only between 43° and 48° and the chosen 4 GPS stations were between 45° and 48° , the variation between stations in terms of precipitable water vapor was negligible. Also we have to understand the fact that the west part of Romania does not border with a sea and the temporal variation of precipitable water vapor concentration in the atmosphere depends on the season and other climate condition. The results of the precipitable water vapor is presented in figure 3.



Fig. 3 - The variation of the precipitable water vapor

The standard deviation can be interpreted as being the spread of the precipitable water vapor differences or taking the definition into account - variation from the mean. The mean of the standard deviation for the 4 station is around 6.92 mm. To have concrete data concerning the precipitable water vapor in Romania it is recommended to use different permanent GPS station placed in different parts in the country[18].

4. Conclusions

The estimation of tropospheric delays play's a crucial factor in high precision position even if the position is determinate by relative technique or by precise point positioning.

The paper is presenting an overview of the GPS atmospheric remote sensing with the focus on the influence of the troposphere on the GPS signals using state of the art GPS processing software with a resolution of 2 hours. The computed precipitable vapor is important for determining the greenhouse effect.

The paper is presenting the possibility to compute the zenith tropospheric delay using GPS technology but the paper is focused only on four GPS station situated in the West part of Romania. A recommendation is to compute for the entire country due to the fact that the country has many different types of relief. Also a comparison between the results obtained in the summer and in the winter would be of great interest.

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