Continuous precipitable water vapor monitoring using GNSS

M. Igondová, J. Hefty
Department of Theoretical Geodesy, Faculty of Civil Engineering, Slovak University of Technology[1]

Abstract: Permanent GNSS (Global Navigation Satellite Systems) observations are performed at hundreds of stations all over the world. If surface measurements of pressure and temperature are available the Precipitable Water Vapor (PWV) can be computed. It requires the values of ZTD (Zenith Total Delay) derived from continuous processing of GNSS observations and the dry component modeling using e.g. the Saastamoinen model. PWV time series from years 2002 to 2007 are computed and presented for GNSS stations GOPE and ZIMM. The annual seasonal effects within Central Europe have amplitude of about 7 mm and phase shift of 249 days. Comparison of PWV values derived from GNSS and radiosonde observations shows agreement with bias 1.2 mm and standard deviation 3.1 mm.

Key words: GNSS, troposphere, Precipitable Water Vapor (PWV), time series, radiosonde measurements

1. Introduction

Global Navigation Satellite Systems - GNSS including Global Positioning System – GPS (*Hefty and Husár, 2003; website GPS*), GLONASS (*website GLONASS*) and proposed Galileo (*website GALILEO*) are powerful tool for positioning, navigation and time determining. Long-term position monitoring allows determining position changes in time which can contribute to research activities focused on plate and regional tectonics (*Hefty, 2007*), solid Earth and ocean tides (*Hrčka and Hefty, 2006*) and also troposphere and ionosphere monitoring (*Igondová, 2006*).

Troposphere is the lowest layer of atmosphere, which extends from the Earth's surface to an average altitude ranging from 20 km at the equator

[1] Radlinského 11, 813 68 Bratislava, Slovak Republic
e-mail: miroslava.igondova@stuba.sk, jan.hefty@stuba.sk

down to 8 km at the poles (*Moran and Morgan, 1989*). Most weather occurs within the troposphere and water vapor content is one of the weather indicators. Precipitable Water Vapor (PWV) can be derived from combination of GNSS and meteorological measurements. There are hundreds of GNSS stations over the world *(websites IGS, EUREF)* providing continuous, weather independent observations. If ground temperature and pressure measurements at the stations are available, the PWV values can be derived with relatively high time resolution (1 to 2 hours) and space resolution (tenths to hundreds of kilometers) in comparison to classical meteorological observations, such as radiosonde or WVR (Water Vapor Radiometer) measurements.

2. Deriving PWV using GNSS observations

Observation parameters in position determination using GNSS are pseudoranges R from code measurements and carrier phases or phase differences $\psi(t)$ from phase measurements. There are several systematic effects affecting observations including tropospheric refraction T caused by propagation delay in troposphere. It leads to extension of time span between transmitting and receiving signal.

The fundamental observation equations for code (1) and phase (2) measurements are

$$R = \rho + c \cdot \Delta\delta + T + I + \varepsilon \tag{1}$$

$$\lambda \cdot \psi(t) = \rho + c \cdot \Delta\delta + N \cdot \lambda + T - I + \varepsilon, \tag{2}$$

where ρ is geometric distance, c is the speed of light, $\Delta\delta$ corresponds to difference between satellite and receiver clock correction $(\delta^s - \delta_r)$, I is ionospheric refraction and T tropospheric refraction, λ wavelength, N ambiguity and ε includes observation noise.

In contrast to the ionosphere, no dispersion effects are present with respect to the delay caused by the troposphere, making an elimination of this systematic error using two frequencies impossible. However, tropospheric refraction in zenith direction called Zenith Tropospheric Delay (ZTD) can be estimated or modeled as additional parameter within processing of permanent GNSS observations (*Beutler et al., 2007*).

It is convenient to divide the tropospheric delay into dry T_d and wet T_w component. The large majority of the delay (typically about 90 percent, which corresponds to delay about 2.3 m in zenith direction) is due to the dry component of the air (mainly nitrogen and oxygen). Dry delay T_d [m] in zenith can be easily derived from surface pressure p [hPa], latitude φ and ellipsoidal height H_{el} [km] using Saastamoinen model (*Saastamoinen, 1972*)

$$T_d = \frac{2277 \cdot p}{1 - 0.00266 \cdot \cos(2\varphi) - 0.00028 \cdot H_{el}}. \tag{3}$$

Distribution of atmospheric water vapor is highly inhomogeneous and almost unpredictable, therefore wet tropospheric delay cannot be modeled. The amount of water vapor varies from few millimeters in dry regions up to 40 centimeters in humid regions and varies also according to time of year (*Bevis et al., 1992*).

Subtracting dry component T_d from total tropospheric delay ZTD gives wet component in zenith direction T_w [m] and subsequently IWV (Integrated Water Vapor) [kg.m^{-2}] and PWV (Precipitable Water Vapor) [m] can be computed using formulae (*Bevis et al., 1992*):

$$PWV = \frac{IWV}{\rho}, \tag{4}$$

where ρ is water density.

$$IWV = \kappa \cdot T_w \tag{5}$$

IWV is derived from wet component T_w multiplied by "constant" κ given by

$$\kappa = \frac{10^6}{R_v \cdot (c_3/T_m + c_2' - m \cdot c_1)}, \tag{6}$$

where $c_1 = (77.604 \pm 0.014) K \cdot hPa^{-1}$, $c_2' = (17 \pm 10)\, K \cdot hPa^{-1}$, $c_3 = (3.776 \pm 0.004) \cdot 10^5 K^2 \cdot hPa^{-1}$, $R_v = R/M_w$ is the specific gas constant for water vapor, R is gas constant and M_w is molecular weight of water vapor. Weighted "mean temperature" of the atmosphere T_m is given by

$$T_m = \frac{\int \frac{e}{T_a} dz}{\int \frac{e}{T_a^2} dz}, \tag{7}$$

where e [hPa] is partial pressure of water vapor and T_a [K] is atmospheric temperature. According to (*Bevis et al., 1992*) linear regression

$$T_m = 70.2 + 0.72 \cdot T_s, \tag{8}$$

where T_s is surface temperature, can be used with a latitude range of 27° to 65° and a height range of 0 to 1.6 km with relative error less than 2%.

3. PWV time series

Network of permanent GNSS stations localized in central Europe is permanently processed at Department of Theoretical Geodesy of Faculty of Civil Engineering, Slovak University of Technology. Network consists of 54 stations and continually processed data are available from year 2002. In addition to standard outputs in form of coordinates and covariance matrixes are determined also Zenith Tropospheric Delays for each station in one-hour interval (*Igondová, 2006*).

Surface temperature and pressure measurements are available for 22 from 54 processed stations and using formulas (2) to (6) and (8) Precipitable Water Vapor is derived. Behavior of PWV time series during several years is demonstrated by example of station GOPE - Geodetic observatory Pecný, near Prague, Czech Republic (see Fig. 1) and ZIMM – Zimmerwald, Switzerland (see Fig. 2).

The most dominant component for each PWV time series is annual seasonal effect, which can be described using formula

$$PWV(t) = a + b \cdot \sin(t + \varphi), \tag{9}$$

where t means time of measurement, a is sinus function mean position, b is amplitude and φ is phase shift. For station GOPE variables reach values $a = 14.8$ mm, $b = 7.7$ mm and $\varphi = 249$ days.

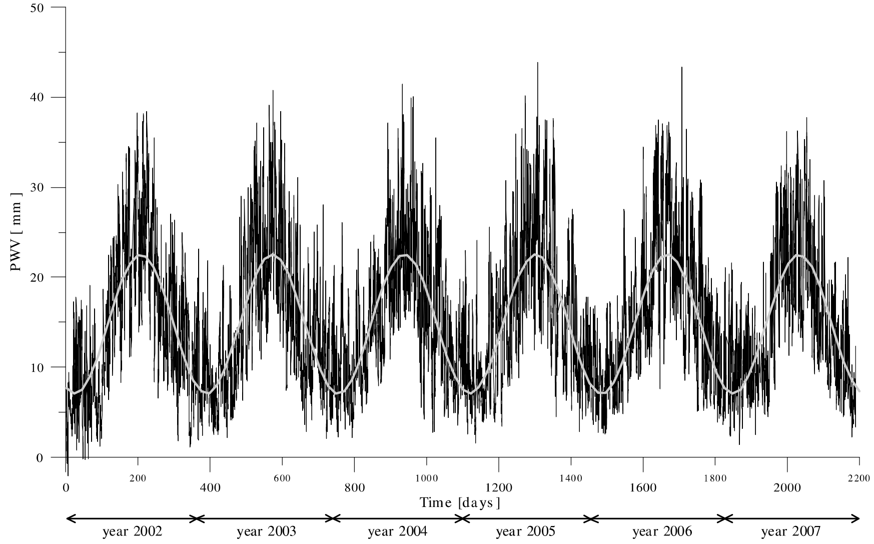

Fig. 1. Precipitable Water Vapor at station GOPE (latitude: 49°54′49.33″, longitude: 14°47′08.23″, ellipsoidal height: 592.6 m) during years 2002 to 2007. Grey line represents estimated annual seasonal effect.

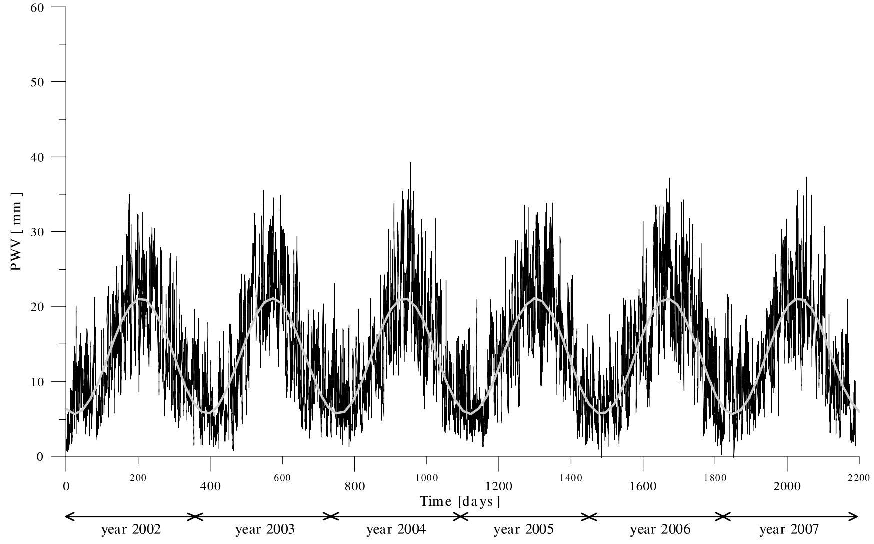

Fig. 2. Precipitable Water Vapor at station ZIMM (latitude: 46°52′37.56″, longitude: 7°27′55.08″, ellipsoidal height: 956.7 m) during years 2002 to 2007. Grey line represents estimated annual seasonal effect.

4. Comparison of PWV based on GNSS and radiosonde measurements

Validation of PWV values based on GNSS and meteorological measurements was done using independent radiosonde measurements at station GANP – Gánovce near Poprad, Slovakia (see Figs. 3 and 4). PWV is derived as integrated value from measuring of dry-bulb temperature and pressure during ascending of meteorological balloon, equipped with radiosonde. Radiosondes are launched twice a day at 0 and 12 hours UTC. GNSS observations are available at the same place with 1-hour time resolution.

It was 408 pairs of PWV values obtained from November 11, 2003 to June 19, 2004 used for analysis. The mean value of PWV differences is 1.2 mm with standard deviation (RMS) 3.1 mm. Correlation between GNSS and radiosonde based PWV values is 0.90, which indicates very good agreement.

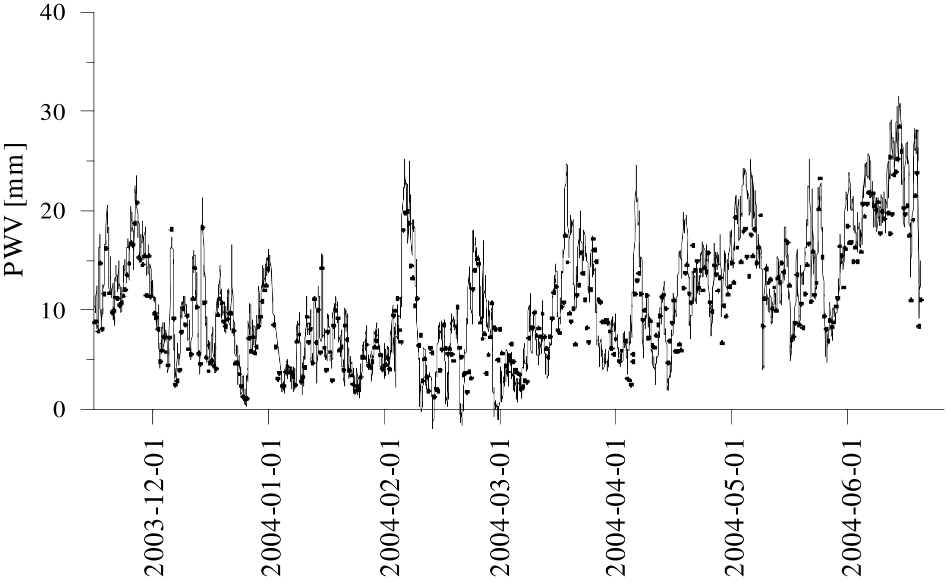

Fig. 3. Comparison of Precipitable Water Vapor derived from GNSS observations (line) and from radiosonde measurements (dots) at station GANP from November 11, 2003 to June 19, 2004.

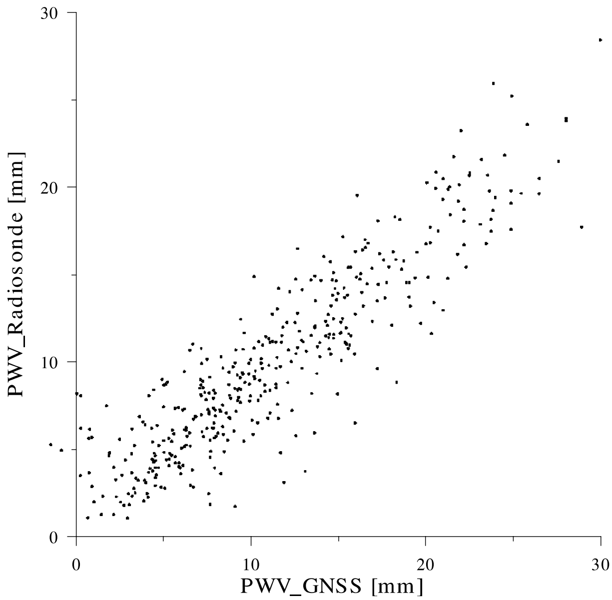

Fig. 4. Correlation of Precipitable Water Vapor derived from GNSS observations with radiosonde measurements at station GANP.

5. Conclusions

Worldwide network of permanent GNSS stations can serves as basis for continual monitoring of Precipitable Water Vapor if surface pressure and temperature is available. Processing GNSS observations leads to computing Zenith Total Delay. Dry component is easily modeled; therefore wet component and then PWV can be derived.

WVR and radiosonde also provide PWV values but the frequency of measurements is lower with higher costs then GNSS observations. Realized comparison between GNSS and radiosonde based PWV values shows very good agreement with mean value of PWV differences 1.2 mm and standard deviation 3.1 mm.

Acknowledgments. This work was supported by the Slovak Research and Development Agency under the contract No. LPP-0176-06.

Thanks are due to the British Atmospheric Data Centre for providing access to the Met Office Global Radiosonde Data.

References

Beutler G., Bock H., Dach R., Fridez P., Gäde A., Hugentobler U., Jäggi A., Meindl M., Mervart L., Prange L., Schaer S., Springer T., Urschl C., Walser P., 2007: Bernese GPS Software, Version 5.0. User manual, Bern. 640 p.

Bevis M., Businger S., Herring T. A., Rocken CH., Anthes R. A., Ware R. H., 1992: GPS Meteorology: Remote Sensing of Atmospheric Water Vapor Using the Global Positioning System. Journal of Geophysical Research, **97**, D14, 15,787–15,801.

Hefty J., Husár L., 2003: Satellite Geodesy, Global Positioning System. Slovak University of Technology, Bratislava (in Slovak).

Hefty J., 2007: Geo-kinematics of Central and South-Eastern Europe Resulting from Combination of Various Regional GPS Velocity Fields. Acta Geodynamica et Geomaterialia. **4**, 4 (148), 169–185.

Hrčka M., Hefty J., 2006: Diurnal and Semi-Diurnal Coordinate Variations Observed in European Permanent GPS Network: Deterministic and Stochastic Constituents. Contr. Geophys. Geod., **36**, 7–16.

Igondová M., 2006: Modeling Troposphere and Ionosphere Using Permanent GPS Networks. Slovak University of Technology, Bratislava, Series of scientific monographs, **35**, 94 p. (in Slovak).

Moran J. M., Morgan M. D., 1989: Meteorology: the Atmosphere and the Science of Weather, 2nd ed., Macmillan Publishing, New York, 560 p.

Saastamoinen J., 1972: Atmospheric correction for the troposphere and stratosphere in radio ranging of satellites. In: The Use of Artificial Satellites for Geodesy in Geodesy. Volume Geophys. Monogr. Ses. 15, 247–251. AGU, Washington, D. C.

EUREF: `http://www.epncb.oma.be`

GALILEO: `http://www.esa.int/esaNA/galileo.html`

GLONASS: `http://www.spaceandtech.com/spacedata/constellations/glonass_consum.shtml`

GPS: `http://www.gps.gov`

IGS: `http://igscb.jpl.nasa.gov`