Near Real Time Estimation of Integrated Water Vapour from GNSS Observations in Hungary

Sz. Rózsa, A. Kenyeres, T. Weidinger, and A.Z. Gyöngyösi

Abstract

Meteorological products derived from Global Navigation Satellite Systems (GNSS) observations have been routinely used for numerical weather prediction in several regions of the world. Hungary would like to join these activities exploiting meteorological usage of the dense GNSS CORS (Continuously Operating Reference Station) network operated by the Institute of Geodesy, Cartography and Remote Sensing for positioning applications.

This paper introduces the near real-time processing system of GNSS observations for meteorological purposes in Hungary. The hourly observations of 35 Hungarian permanent GNSS CORSs are processed. This network is extended beyond the country with about 50 stations covering Eastern and Central Europe. The data analysis is being done using the Bernese V5.0 GPS data processing software. The Hungarian CORS network has an average baseline length of 60 km, thus the precipitable water vapour (PW) can be estimated with a high spatial resolution.

The estimation of the PW from the zenith wet delay (ZWD) is carried out in near real-time. Firstly, the zenith hydrostatic delays (ZHD) are subtracted from the total delays. The wet delays are then scaled to precipitable water vapour values.

The GNSS derived PW values were validated using radiosonde observations over Central Europe using the observations of a 47-day-long period (April 14–May 31, 2011). The results showed that the estimated PW values agree with radiosonde observations at the level of ±1.5 mm in terms of standard deviation. In this comparison a bias of +1.0 mm was observed. Following the validation phase, our analysis will be connected to the continental E-GVAP project (GNSS Water Vapour Programme of the Network of European Meteorological Services, EUMETNET).

Keywords

CORS • GNSS meteorology • Integrated water vapour • Numerical weather prediction • Radiosounding

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1 Introduction

The water vapour content of the atmosphere plays an important role in many meteorological applications. On a short term it is applied for numerical weather predictions to predict the intensity of rainfalls. However, on a long term the water vapour plays a significant role in climatic analyses, since it is the most important greenhouse gas.

The atmospheric water vapour content can be measured with different techniques, like radiosoundings, microwave radiometers and GNSS, etc. Currently the most reliable technique is the radiosounding. In this case the vertical temperature, pressure and humidity profiles are measured, and the water vapour content of the atmospheric column is computed by vertically integrating the water vapour density. However, radiosondes have significant disadvantages: they are quite costly and they are also prone to systematic biases and calibration problems. Due to the high costs, radiosonde profiles are measured with the period of 24 h at only two stations in Hungary (Budapest and Szeged).

Since the active GNSS network has been established in Hungary, the feasibility of the estimation of the PW from GNSS observations is studied in this paper. Similar studies have been reported by researchers from the Central European countries (e.g. Karabatic et al. 2011; Bosy et al. 2010; Igondova and Cibulka 2010). Our study focuses on the development of a near real-time processing and validation system, which automatically processes the hourly observations of the GNSS stations. Moreover, it also validates the estimates with the PW values and other parameters computed from the radiosonde profiles.

The purpose of this work is to take the first step towards the integration of PW values estimated from GNSS observations in the numerical weather prediction (NWP) models used in Hungary. The near real-time estimation of PW from GNSS data would significantly improve the spatial and temporal resolution of the observed PW values. Thus the highly variable atmospheric water vapour could be modelled with a higher accuracy without additional costs. This could improve the accuracy of predicting heavy rainfall in Hungary. The establishment of a near real-time processing facility would also enable us to join the EUMETNET E-GVAP Programme (Vedel 2006).

The first part of this paper introduces the structure of the processing software. The methodology of the PW estimations is then discussed, followed by the methodology of the validation. The validation is carried out using all of the quantities used in the estimation of the PW. The results of these validations are also presented in the last part of the paper.

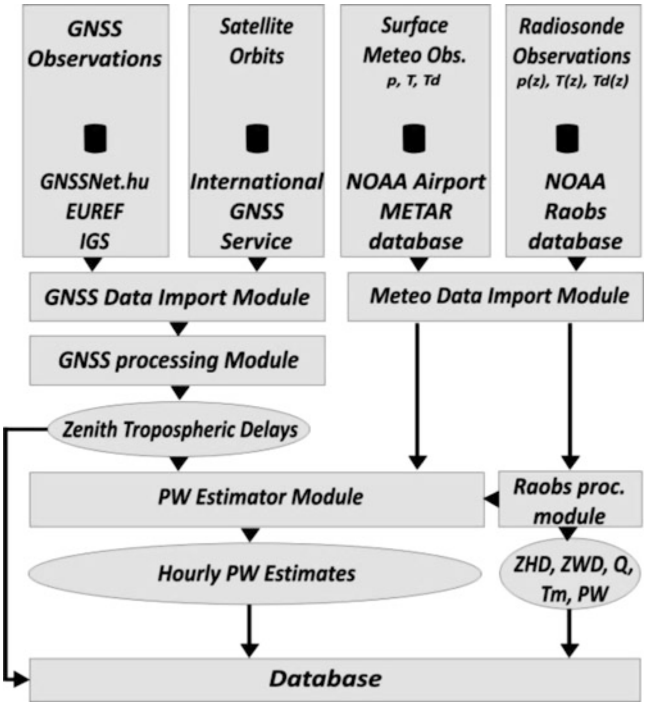

Fig. 1 The block scheme of the near real-time data processing and validation system

2 The Near Real-Time Processing and Validation System

The processing system is responsible for collecting and processing the GNSS observations in near real-time. Apart from that, surface meteorological observations are collected and processed routinely for the estimation of PW, and the observed radiosonde profiles are used to compute the PW for validation purposes. The most important features of the system are briefly introduced in this section.

In order to evaluate the potential of the PW derived from the active GNSS CORS network, a near real-time processing and validation system has been developed. The core functionality is provided by the Bernese GNSS data processing software version 5.0 (Dach et al. 2007). The block scheme of the system can be seen in Fig. 1.

Firstly, the *GNSS Import Module* collects the GNSS observations from various data centres:

- The GNSS CORS network of Hungary consisting 50 stations (GNSSNet.hu);
- The GNSS Data Centre maintained by the German Federal Agency for Cartography and Geodesy (BKG), where altogether 20 EPN (EUREF Permanent Network) stations and 23 IGS (International GNSS Service) stations where chosen for the data processing.

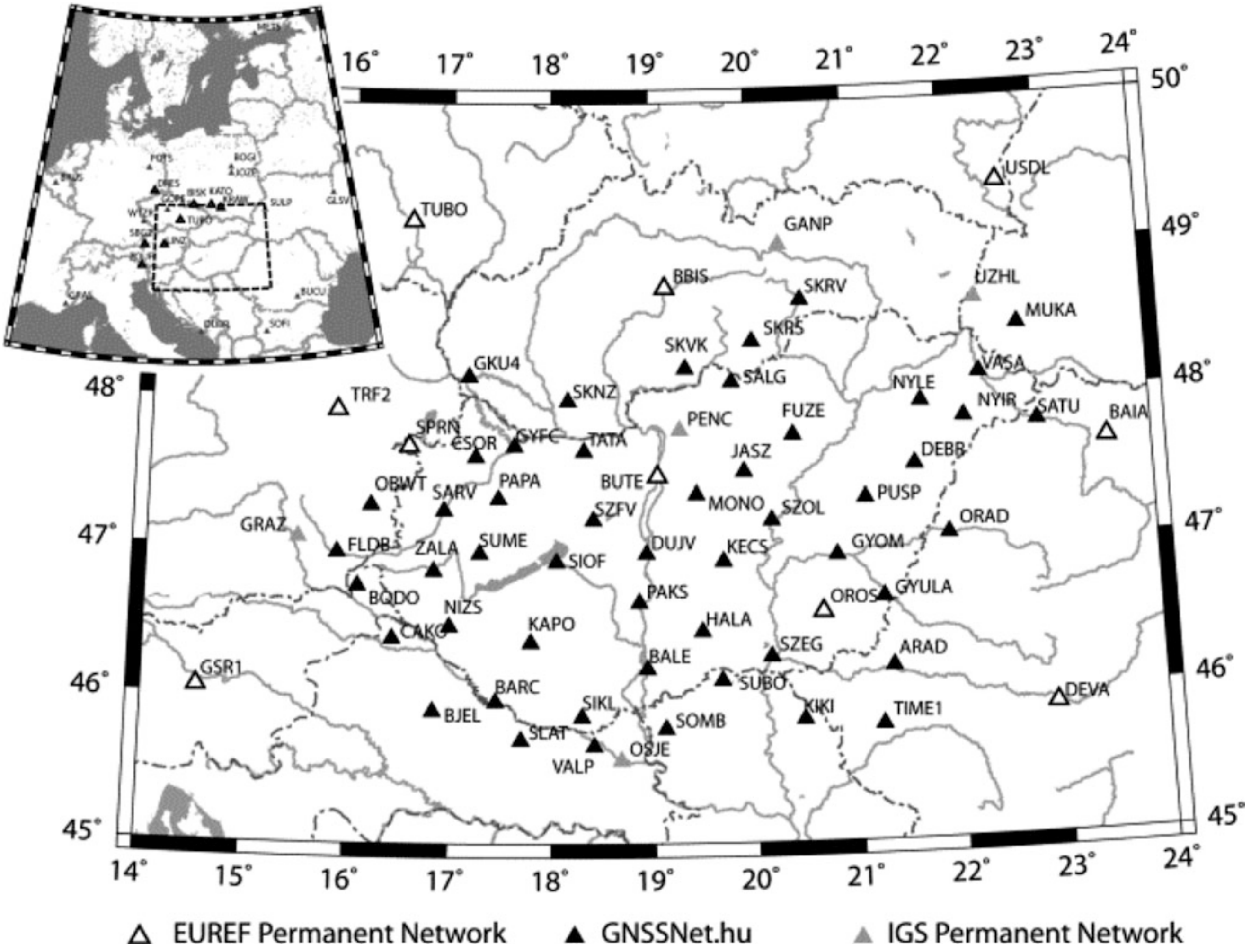

Fig. 2 The GNSS CORS network processed

The processed CORS network consists of 93 stations. The network can be seen in Fig. 2.

Secondly the ultra-rapid products (orbits, clocks and Earth orientation parameters) are collected from the IGS. Afterwards the GNSS data are processed by the *GNSS Processing Module*. In each hour, the observations of the previous 12 h are concatenated and processed using fixed station coordinates. Although both GPS and GLONASS observations are collected in the network, currently only the GPS observations are processed routinely. Zenith tropospheric delays (ZTD) are estimated on an hourly basis using the Saastamoinen model (Saastamoinen 1972, 1973) for modelling the "a priori" zenith hydrostatic delay (ZHD) and the Niell mapping function to map the zenith delays to the satellite direction. Horizontal tropospheric gradients are estimated along with the ZWDs using a 0° elevation mask. Currently the GNSS data processing starts 15 min after the full hour and lasts for approximately 50 min.

The *Meteo Data Import Module* is responsible for collecting surface meteorological observations including total air pressure (p), surface temperature (T) and dewpoint (T_d) from the Airport METAR (**ME**teorological **T**erminal **A**viation **R**outine Weather Report) Database maintained by the National Oceanic and Atmospheric Administration (NOAA). The hourly METAR observations are decoded and stored in a database for further use. Furthermore, the radiosonde profiles are collected on a daily basis from the NOAA Raobs (Radiosonde Observations) database. Altogether the profiles from 23 radiosonde launching sites are used for validation purposes (Fig. 3).

The *PW Estimator Module* computes the PW based on the estimated ZTD from the GNSS data processing and the surface total air pressure. In order to validate the estimated PW, the collected radiosonde profiles are processed by the *Raobs Processing Module*. All of the results are stored in a relational database for further analysis.

Fig. 3 The processed radiosonde launching sites

3 Methodology

This section focuses on the methodology of the estimation of PW. Moreover various aspects of the validation process are also discussed here.

3.1 The Estimation of PW

The *ZTD*s are used as an input for the *PW Estimator Module*. In order to convert the estimated *ZTD* to *PW*, firstly the *ZHD* must be subtracted:

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

where *ZWD* is the zenith wet delay. The *ZHD* is computed from the total air pressure (p) at the mean sea level using the Saastamoinen-model (Saastamoinen 1972, 1973):

$$ZHD = 0.002277\,p \tag{2}$$

Since the total air pressure is not observed at the majority of GNSS stations, it should be either estimated using NWP models or it should be interpolated from the observations of the automatic meteorological stations of the meteorological services.

Currently our system utilizes the first option, namely the DBCRAS (Direct Broadcast CIMSS Regional Assimilation System) NWP model (Aune et al. 2008) from the Department of Meteorology of the Eötvös Lóránd University, that provides hourly forecasts of the total air pressure at the mean sea level, the surface total air pressure as well as the surface temperature. This NWP model has a resolution of 48 km × 48 km, which is suitable for the computation of ZHDs. In the near future the integration of a second NWP model is planned, since the Department of Meteorology runs the WRF (Weather Research and Forecasting) model with a higher resolution but with a smaller coverage (covering an area of 100 km beyond the borders of Hungary).

Based on the computed value of the ZWD, the PW can be estimated using an appropriate scaling factor (Q) (Haase et al. 2003):

$$PW = \frac{ZWD}{Q}. \tag{3}$$

The scaling factor Q is dimensionless, since both the PW and the ZWD are expressed in mm. In our computation Q is computed as a direct function of the surface

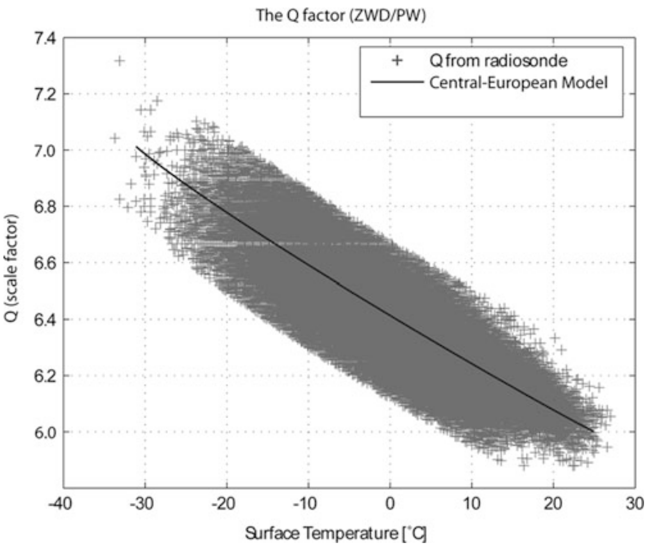

Fig. 4 The second order polynomial of surface temperature fitted to the scale factor values computed from radiosonde observations

temperature based on a regression analysis of more than 150,000 radiosonde observations in the area (Fig. 4):

$$Q = a_0 + a_1\left(T - \bar{T}\right) + a_2\left(T - \bar{T}\right)^2 \tag{4}$$

where T is the surface temperature in Kelvin, while a_0, a_1, a_2 and $\bar{T}$ are empirical constants with the following values (Rózsa et al. 2012):

$$\begin{aligned} a_0 &= 6.3953 \pm 0.0003, \\ a_1 &= -1.75 \times 10^{-2} \pm 2.7 \times 10^{-5} \ \ [1/\mathrm{K}], \\ a_2 &= 7.5 \times 10^{-5} \pm 2.5 \times 10^{-6} \ \ \left[1/\mathrm{K}^2\right], \\ \bar{T} &= 283.17 \quad [\mathrm{K}] \ . \end{aligned} \tag{5}$$

A similar model has been proposed by Emardson and Derks (2000) based on more than 100,000 radiosonde observations in Europe. However other investigations showed that the locally fitted model performs better than the Emardson–Derks model in the area of Hungary (Rózsa et al. 2012).

It must be noted that Bevis et al. (1992) proposed a different method for the computation of the scale factor Q:

$$Q(T_m) = \frac{10^6}{R_v\left(-\frac{R_d}{R_v}k_1 + k_2 + \frac{k_3}{T_m}\right)}, \tag{6}$$

where R_v and R_d are the specific gas constants of water vapour and dry air respectively and T_m is the mean temperature of water vapour. Bevis et al. (1992) proposed the following formula for the computation of T_m as a function of the observed surface temperature:

$$T_m = 70.2 + 0.72T, \tag{7}$$

Since this approach is widely used in practice, both the Q and T_m parameters are computed from radiosonde profiles for validation purposes.

3.2 Validation with Radiosonde Observations

Our aim was to provide the near real-time PW estimates from the GNSS observations. Besides the automatic validation of these results was carried out. In order to achieve this, the available radiosonde observations are routinely acquired from the NOAA Raobs database. In order to be able to validate the computational procedure and the results of PW estimations, a number of parameters are computed from the radiosonde observations. The most important ones are the *PW*, *ZWD*, *ZHD* values and the scale factor Q. Since this scale factor is computed as a function of the surface temperature, the approaches introduced in the previous section can be evaluated, too.

Computation of PW from Radiosonde Profiles

Radiosonde observations provide the vertical temperature, dew point and pressure profiles (along with the wind speed and wind directions). The PW in a layer between two radiosonde observations $i-1$ and i can be computed using the mixing ratio and the total air pressure:

$$PW_i = \frac{1}{g}\left(p_{i-1} - p_i\right)\frac{MR_{i-1} + MR_i}{20}, \tag{8}$$

where g is the gravity gradient at the mean altitude of the layer, and *MR* is the mixing ratio, which can be computed from the observed total air pressure and the partial pressure of water vapour (e) (WMO 2008):

$$MR = 622 \times \frac{e}{p - e}, \tag{9}$$

The total *PW* in a vertical column can be computed by summing up the *PW* in the layers of the atmospheric column.

Computation of ZHD and ZWD from Radiosonde Profiles

The tropospheric delay (TD) can be computed by integrating the refractivity (N) along the path of the incoming satellite signal (Thayer 1974). Introducing the Essen and

Froome (1951) formula for the refractivity, the following equation is obtained:

$$TD = 10^{-6} \int N \; \mathrm{ds} = 10^{-6} \int \left(k_1 \frac{p_d}{T} + k_2 \frac{e}{T} + k_3 \frac{e}{T^2} \right) \mathrm{dz}, \qquad (10)$$

where p_d is the partial pressure of dry air, k_1, k_2 *and* k_3 are empirical constants with the values of 0.7760 K/Pa, 0.704 K/Pa and 0.03739×10^5 K^2/Pa respectively. The refractivity can be split into the dry and the wet parts (Smith and Weintraub 1953). Since the partial pressure of the dry air is not observable, the *TD* in the zenith direction (*ZTD*) can be written as:

$$ZTD = ZHD + ZWD = 10^{-6} \int \left[k_1 \frac{p}{T} \right] \mathrm{dz} + 10^{-6} \int \left[(k_2 - k_1) \frac{e}{T} + k_3 \frac{e}{T^2} \right] dz \, . \qquad (11)$$

Although the PW stemming from radiosonde profiles is comparable with the GNSS based estimations, it is not true for the ZHD. Radiosonde profiles terminate at the pressure level of approximately 100 hPa (approximately the altitude of 35 km). However, the neutral upper atmosphere has a non-negligible effect on the ZHD. This must be taken into account, when the ZHDs computed from radiosonde observations and the values estimated by (2) are compared. The correction can be computed from standard atmosphere models as well as from radio occultation observations (Kursinski and Hajj 2001).

The processing system uses the former option based on the International Standard Atmosphere (ISO 2533:1975). Figure 5 shows the ZHD at different elevations. It can be seen that the hydrostatic delay still reaches the level of 1.3 cm even at the elevation of 35 km, where the radiosonde observations usually terminate. This error would cause approximately 2 mm error in the PW estimates. The *Raobs Processing Module* computes the correction of ZHD, thus this effect is taken into account in the estimations.

Computation of the Scale Factor *Q* from Radiosonde Profiles

Since both the PW and the ZWD can be computed from the radiosonde profiles, the reference values of the scale factor *Q* can be computed using (3). Due to the fact that *Q* is usually computed either from a polynomial model (4) or a model proposed by Bevis et al. (1992) in (6), the T_m temperature is also computed directly from the radiosonde observations using the following equation:

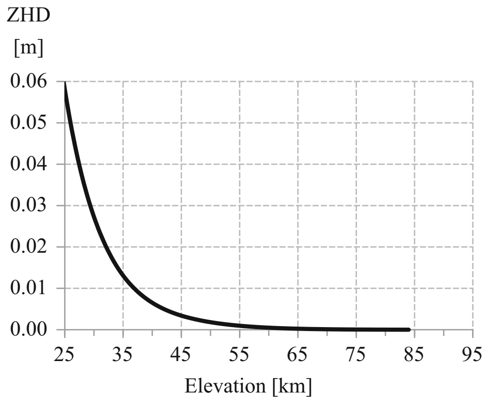

Fig. 5 Zenith hydrostatic delays computed from the International Standard Atmosphere (m)

$$T_m = \frac{\int \rho_v \, \mathrm{dz}}{\int \frac{\rho_v}{\mathrm{T}} \, dz}, \qquad (12)$$

where ρ_v is the water vapour density:

$$\rho_v = \frac{e}{R_v T}. \qquad (13)$$

The computation of the T_m values from radiosonde observations enables us to study various models used for the estimation of the scale factor *Q*.

The reference values of the aforementioned parameters are automatically computed from the radiosonde profiles, and they are stored in a database along with the lowest observed total pressure and the burst altitude of the sonde. The latter variables are used to assess the reliability of the *ZHD* values derived from the radiosonde observations.

4 Results and Validation

The near real-time data processing system has been established in the premises of the Satellite Geodetic Observatory in Penc. The system started to operate on April 14, 2011. In the following sections the first results of the validation process are presented. This validation has been done using the radiosonde observations taken at Budapest in the period of April 14–May 31.

After processing the GNSS observations, the PW was computed using the predicted surface meteorological parameters obtained from the DBCRAS NWP model. The radiosonde observations were processed according to Sect. 3.2. The results of are shown in the next sections.

Table 1 The statistical properties of the residuals of the zenith hydrostatic delays computed from the Saastamoinen model with respect to radiosonde observations (mm)

	Min	Max	Mean	Std. dev.
Radiosonde-Saastamoinen	−4.1	2.3	−1.4	±1.2

Table 2 The statistical properties of the residuals of the zenith wet delays estimated from the GNSS observations with respect to radiosonde observations (mm)

	Min	Max	Mean	Std. dev.
Radiosonde-GNSS	−30.9	29.2	+1.7	±10.6

4.1 Estimation of the Hydrostatic and Wet Delays

Due to the fact that the processing facility computes various tropospheric parameters from the radiosonde observations, the performance of the "a priori" ZHD estimation can also be evaluated. The Saastamoinen model provided a nice fit to the radiosonde observations. The statistical properties of the residuals can be found in Table 1. The table shows that the ZHD is slightly overestimated by the model (−1.4 mm of bias) in the study period. However this bias would cause a systematic error of only −0.2 mm in the PW estimates, since the scale factor Q has the approximate value of 6.5 [see (5)]. This value is well below the expected 1–1.5 mm error of the PW estimations.

On the other hand the GNSS estimated zenith wet delays show a worse fit compared to the radiosonde observations (Table 2.). Although the bias is still in the order of few millimetres, the standard deviation reaches the level of ±1 cm, which would mean that the accuracy of the PW estimation would be in the order of ±1.5 mm.

4.2 Validation of the Estimation of Scale Factor Q

The PW values are computed from the ZWDs using the scale factor Q (3), that is usually estimated from the surface temperatures using (4) or (6). Since both the PW and the ZWD values are also computed from the radiosonde observations, reference values can be computed from the radiosonde profiles using (3). Thus the scale factor Q estimated from the surface temperatures and computed from the profiles can be compared, too.

The statistics of the comparison can be found in Table 3. The results show that the value of Q is overestimated by 3 % in the study period. This would lead to the underestimation of the PW by 3 %. Since the PW had the mean value of approximately 20 mm during this period, that would mean a bias of −0.6 mm in the estimated value, which is much larger than the effect of the "a priori" model of the hydrostatic delays.

Table 3 The statistical properties of the Q factor computed from the surface temperature with respect to the radiosonde observations (the values in brackets are relative values)

	Min	Max	Mean	Std. dev.
Radiosonde-GNSS	−0.36 (−5.5 %)	−0.03 (−0.5 %)	−0.20 (−3.1 %)	±0.08 (±1.2 %)

4.3 The Effects of the Coordinate Fixing

Tropospheric delays are estimated based on the fixed coordinates of the GNSS stations. In order to study the effects of the coordinate fixing strategy, different scenarios have been studied. The observations of the period of April 14, 2011 to May 31, 2011 were processed with various strategies. The station coordinates were fixed on:

- The ITRF coordinates computed from ITRF coordinates and station velocities (ITRF);
- The weekly coordinate solutions of the network (ITRF_WK, where the weekly coordinates are computed using all the observations taken from the previous GPS Week);
- A running window combination of the daily observations, where the length of the window varies between 4 and 11 days (RW_LL, where LL is the length of the window in days).

In the last two cases, the normal equations of the least square adjustment of the 12-h-sessions are combined with a minimal constraint approach using IGS stations for datum definition. The major difference between the weekly and the running window strategies is, that the running window strategy with the length of seven days combines the normal equations of the previous 7 days on a daily basis, while the weekly coordinate solutions are generated once a week from all the observations of the previous GPS week.

The PW has been estimated using the aforementioned approaches, and the estimates have been compared to the reference values computed from the radiosonde observations. The standard deviation of the residuals did not show significant differences between the various fixing strategies (the maximal observed difference was only 0.05 mm). However the bias of the PW estimation decreased by 15 %, when the weekly coordinate solutions have been used (Fig. 6). A similar performance was experienced, when a running window of more than 7 days was applied. This window size fits to the average residence time of the water molecules in the atmosphere (Pidwirny 2006).

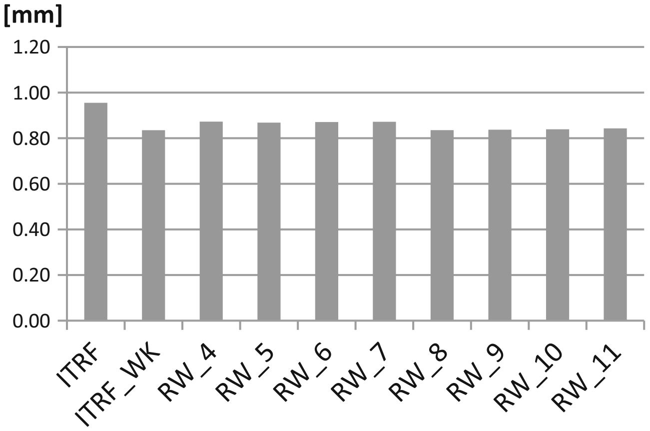

Fig. 6 The bias of the PW estimations using different coordinate fixing strategies

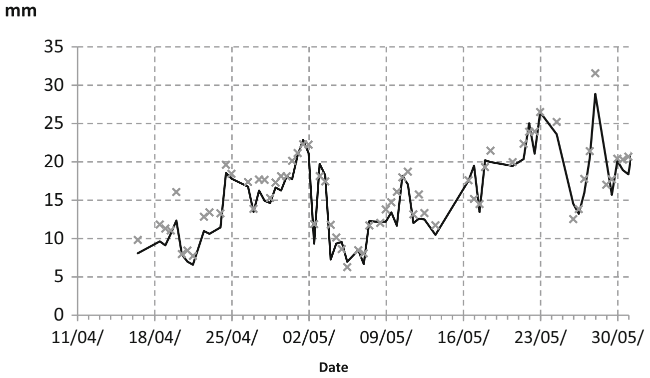

Fig. 7 The precipitable water vapour in the study period (*black line*—GNSS estimates; *grey crosses*—radiosonde observations)

Table 4 The statistical properties of the residuals of the GNSS estimates and ECMWF analysis of PW with respect to the radiosonde observations

	Min	Max	Mean	Std. dev.
Radiosonde-GNSS	−4.2	4.6	1.0	±1.5
Radiosonde-ECMWF	−4.6	4.7	0.4	±1.6

4.4 PW Comparison with Radiosonde Observations and NWP Model

The PW estimates have been compared with radiosonde observations and predictions from ECMWF analysis in the study period. The results can be seen in Fig. 7, while the statistical properties can be found in Table 4.

The results show a remarkable agreement between GNSS estimates and radiosonde observations. The experienced bias of +1.0 mm and standard deviation of ±1.5 mm shows that GNSS tends to underestimate the precipitable water vapour.

The PW estimates have also been compared to the results of ECMWF analysis, too. Table 4. shows that although the ECMWF analysis reproduces the radiosonde based PW estimation with a smaller bias of 0.4 mm, the standard deviations are on the same level in both cases.

5 Conclusions and Outlook

Based on the validation results it can be stated that the PW estimates fit to the radiosonde observations on a similar level compared to other results in the literature (e.g. Karabatic et al. 2011; Bosy et al. 2010; Igondova and Cibulka 2010). It must be noted that the observed standard deviation of the residuals with respect to the radiosonde observations (±1.5 mm), is quite close to the results obtained during the recent radiosonde intercomparison campaigns (±1.0 mm) according to Nash et al. (2011).

Our results provided the best fit, when the fixed coordinates were computed by the weekly combination or the combination of the prior 8–11 days of GNSS observations. This is in a good agreement with the average residence time of the water molecules in the atmosphere.

Based on the validation with radiosonde observations, it can be concluded that the data processing facility is capable of providing tropospheric delay and PW estimates with sufficient accuracy to the EUMETNET E-GVAP project (Vedel 2006).

The investigations showed that the systematic bias of the PW estimations is mainly caused by the model used for the determination of the scale factor Q. Thus further refinement of the model is necessary to remove this systematic effect from the estimations. However it must also be noted that further independent observations should be used (such as microwave radiometers) in order to assess the performance of GNSS in the estimation of precipitable water vapour.

The results also showed the advantage of GNSS based PW estimations with respect to the radiosonde observations. GNSS is able to provide PW with a higher temporal and spatial resolution, which could lead to an improvement in predicting severe storms in the area of Hungary.

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