Estimation of the Tropospheric Delay from GNSS Data over the Austrian Territory

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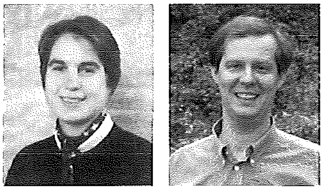

Abstract

GPS has become an important tool both in navigation and in precise point positioning. One of the nuicance parameters limiting the accuracy of point determination is the water vapor content of the troposphere. On the other hand meteorologists are interested in the wet component of the troposphere as a valuable tool for Numerical Weather Prediction. Therefore GPS offers a low cost monitoring of water vapor with high temporal resolution.

We make use of continuous measurements of the GPS/GLONASS reference station network in Austria, which currently consists of about 30 sites with distances ranging from 50 km to 120 km. We calculate the zenith wet delays for a period of 2 months (February and March 2002). Subsequently the results are compared to contributions of different processing centers of the COST-716 project 'Exploitation of Ground Based GPS for Climate and NWP' [2] and with zenith path delay estimates provided by the IGS. As meteorologists need the water vapor within less than two hours, special attention is paid to the availability, reliability and especially to the quality of the satellite orbits used for the network calculations. For this reason we try to use rapid ephemeris instead of the IGS final orbits, whereby we perform a quality control of the rapid orbits. If one or more satellites show poor quality or if one satellite is missing at all we include the broadcast ephemeris information instead.

Zusammenfassung

In den vergangenen Jahren wurde in Österreich durch verschiedene Betreiber ein dichtes GPS-Permanentnetz mit einem Punktabstand zwischen 50 km und 120 km aufgebaut. Bisher war die Nutzung der Messdaten der GPS-Referenzstationen auf die geodätische Positionierung und diverse Navigationsaufgaben beschränkt. Die Brechung der GPS-Signale in der Troposphäre und der Ionosphäre wird dabei in der Datenauswertung üblicherweise als Störgröße behandelt und durch geeignete Algorithmen eliminiert oder zumindest reduziert.

Der gesamte Feuchtegehalt der Atmosphäre ist in den untersten Troposphärenschichten (bis zu einer Höhe von 10 km) in Form von Wasserdampf gespeichert. Die Verteilung des Wasserdampfes ist wesentlich für das Wettergeschehen verantwortlich und somit auch für Wettervorhersagen von großer Bedeutung. Seit wenigen Jahren versucht man deshalb das GPS-Positionierungsverfahren zu invertieren und das hohe Genauigkeitspotential der Messgrößen zur Beobachtung der Atmosphäre heranzuziehen. Man nutzt die Kenntnis der Stationskoordinaten und der GPS-Bahndaten um die troposphärische Verzögerung zu berechnen. Weiters erlauben genaue Messungen von Druck und Temperatur an der Bodenstation den hydrostatischen Anteil vom Feuchtanteil zu trennen, woraus der IWV (Integrated Water Vapour) berechnet werden kann. Als Integral über den gesamten Messstrahl liefert das Verfahren keine vertikale Auflösung der IWV Werte, was als Nachteil gegenüber den üblichen Ballonsondenmessungen gelten mag. Demgegenüber stehen aber sowohl die hohe zeitliche (30 min bzw. 1 Stunde) als auch räumliche Auflösung (horizontal alle 50 km) der Schätzwerte.

Unser Ziel ist es, aus den kontinuierlichen Messungen des österreichischen GPS-Permanentnetzes, welches zur Zeit aus beinahe 30 Stationen besteht, möglichst rasch nach Datenaufnahme meteorologische Parameter für numerische Wettervorhersagen abzuleiten. Dies verlangt einen schnellen Datenfluss, präzise Satellitenbahnen in beinahe Echtzeit (Internationales GPS Service - IGS) und eine Automatisierung der GPS-Auswertung mit Hilfe der Berner Software.

In dieser Arbeit werden für zwei Monate (Februar und März 2002) ZPDs (Zenith Path Delays) berechnet und sowohl mit Abgaben des IGS, als auch mit Ergebnissen von Auswertezentren, die im Rahmen des COST-716 Projekts „Exploitation of Ground Based GPS for Climate and NWP" entstanden [2], verglichen. Da Meteorologen die Ergebnisse innerhalb von zwei Stunden benötigen, befassen wir uns mit der Verfügbarkeit, der Zuverlässigkeit und speziell mit der Genauigkeit der präzisen Satellitenbahnen. Es werden die Ergebnisse basierend auf den präzisen IGS ‚Final Orbits' den mit Hilfe von prädizierten ‚Ultra-Rapid' Bahnen (IGU) gewonnenen Resultaten gegenübergestellt. In verschiedenen Testszenarien werden in den IGU Bahnen gänzlich fehlende Satelliten oder Satelliten mit schlechter Bahnqualität durch die Broadcast-Information ersetzt.

1. Introduction

For weather forecasts meteorologists are in need of accurate and timely observations of water vapor. This is primarily because significant changes in the vertical and horizontal distribution of water vapor can occur rapidly (hours to minutes) during active weather processes. The majority of information about the vertical distribution of water vapor in the atmosphere comes from radiosondes that make in-situ measurements twice daily at widely spaced locations. The vertical resolution is good, but the spatial and temporal coverage is rather sparse. Alternatively the amount of water vapor can be measured by a water vapor radiometer. This instrument provides usually very accurate data, but its measurements are unreliable during precipitation and the device is also fairly expensive. GPS networks are capable of providing a rather dense and nearly continuously measured water vapor data.

Consider the GPS observation equation for code and phase measurements:

Code: $\rho_k^s + \Delta\rho_{k,\,Ion}^s + \Delta\rho_{k,\,trop}^s + c\Delta t_k + c\Delta t^s = P_k^s + v_k^s$ (1a)

Phase: $\rho_k^s - \Delta\rho_{k,\,ion}^s + \Delta\rho_{k,\,trop}^s + c\Delta t_k + c\Delta t^s + \lambda \cdot N_k^s = L_k^s + v_k^s$ (1b)

where

L_k^s	is the carrier phase observation in units of length between satellite s and receiver k
ρ_k^s	is the geometric distance between receiver k and satellite s
c	is the speed of light in vacuum
Δt_k, Δt^s	are receiver and satellite clock offsets
$\Delta\rho_{k,\,Ion}^s$	is the ionospheric path delay
$\Delta\rho_{k,\,trop}^s$	is the tropospheric path delay
N_k^s	is the initial phase bias
λ	is the wavelength of the carrier
v_k^s	is the error or residual

The time delay imposed by the variable tropospheric refraction due to varying amounts of water vapor constitutes a limiting error source for this technique. Under the assumption that the ambiguities are successfully resolved, and the remaining error sources are well modelled, the tropospheric slant delay can be estimated from equation (1b). This slant delay $\Delta\rho(z)$ is usually mapped into the zenith $\Delta\rho(0)$ by means of an appropriate mapping function m(z):

$$\Delta\rho(0) = m(z) * \Delta\rho(z)$$

The total tropospheric delay can be separated into a hydrostatic and a wet delay, whereby it is preferable to use different mapping functions for the dry and wet part of the tropospheric delay:

$$\Delta\rho(0) = m_d(z) * \Delta\rho_d(z) + m_w(z) * \Delta\rho_w(z) \qquad (2)$$

where

$\Delta\rho(0)$	is the total zenith path delay
$\Delta\rho_d$	is the dry tropospheric delay
$\Delta\rho_w$	is the wet tropospheric delay
$m_d(z)$	is the mapping function of the dry component
$m_w(z)$	is the mapping function of the wet component

As meteorologists are interested in the Integrated Water Vapor (IWV) or the Precitable Water Vapor (PW), we use the surface pressure and the station height to remove the hydrostatic zenith delay $\Delta\rho_d(0)$. This term may reach values up to 2.1 m at low altitudes and can be calculated with an accuracy of a few millimeters. The resulting zenith wet delay $\Delta\rho_w(0)$, which is mostly small (few cm up to 40 cm) but very variable, can be converted to IWV by the following expression

$$IWV = k * \rho_{H_2O} * ZWD \qquad (3)$$

where

k	is an empirically determined factor (k~0.16)
ρ_{H_2O}	is the density of liquid water

To calculate ZPDs over the Austrian region we make use of the network of permanent GPS sites in Austria. The Austrian GPS network was established primarily for real-time positioning over the past years and consists at present (February 2003) of about 30 stations. The geographical distribution of stations is shown in figure1.

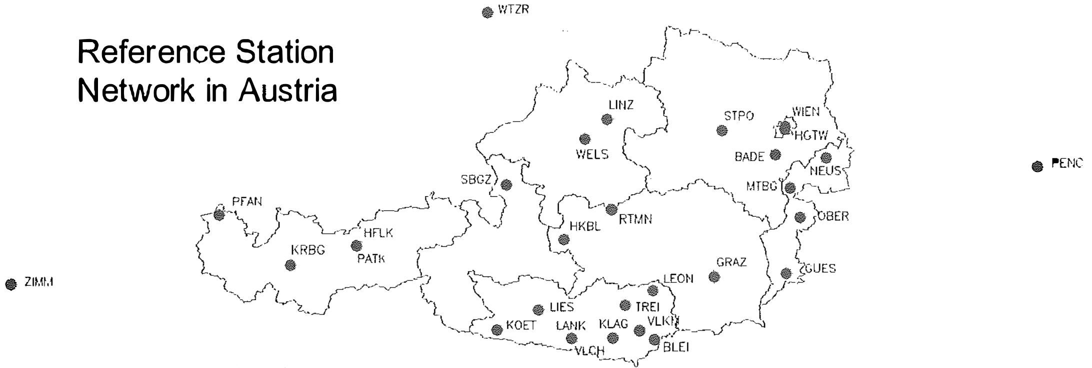

Figure 1: Reference Station Network in Austria

The receivers are operated by the Austrian Academy of Science, several local power supply companies (BEWAG, KELAG, WIENSTROM) in cooperation with the University of Technology Vienna and the Federal Office for Metrology and Surveying (BEV).

2. IGS Products

The International GPS Service, formed in 1992, has consistently improved and expanded the quality of its products. The IGS collects, archives, and distributes GPS observation data sets of sufficient accuracy to meet the objectives of a wide range of scientific and engineering applications and studies. The data sets are used to generate products like GPS satellite ephemeris, Earth rotation parameters, coordinates and velocities of the IGS tracking stations, GPS satellite and IGS tracking station clock correction information and last but not least tropospheric and ionospheric delay estimates.

Three types of GPS ephemeris are provided. While the final combinations are available within 13 days after observation, the Rapid orbit file is issued with approximately 17 hours latency. Both orbit products are of high quality as listed in table 1 but latencies are clearly inadequate for weather prediction applications, where data are assimilated in cycles of several hours duration. In order to be useful for weather predictions the precise orbits must be available in near realtime with an accuracy of at least ±30 cm. The Ultra-Rapid combinations are generated twice each day (at 0300 and 1500 UT) and contain 48 hours worth of orbits; the first 24 hours are based on observations and the second 24 hours are predicted orbits. Currently this product, which combines estimates from seven IGS analysis centers, can achieve an orbit accuracy of better than ±25 cm with respect to the highest quality final orbits (IGS).

Product	Final (IGS)	Rapid (IGR)	UltraRapid (IGU)
Delay	13 days	17 hours	3 hours
Ephemerides	< 5 cm	5 cm	< 25 cm
Sat. Clocks	0.1 ns	0.2 ns	5 ns

Table 1: IGS product accuracies

Figure 2 shows delivery times and the proportion between observed and predicted orbit part contained in the IGR and the IGU files.

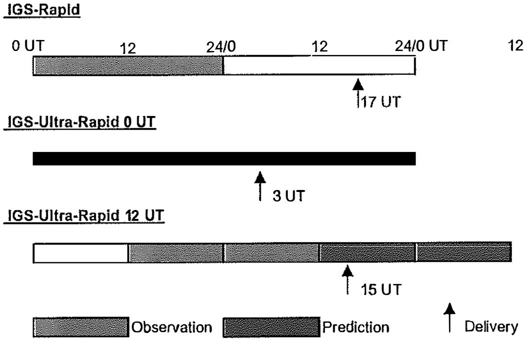

Figure 2: Latency of IGS products

3. Analyses

The main objective of this work was to investigate the impact of the quality of the satellite ephemerides on the estimated tropospheric delays. The near realtime product with less accurate satellite positions on the one side is opposed to the precise final orbits which were used as reference. We have calculated the total zenith delays (ZPD) of 27 permanent stations in Austria plus the neighboring stations PENC, WTZR and ZIMM over a period of 2 months (February and March 2002). The network was processed with the Bernese Software V 4.2 using the BerneseProcessingEngine (BPE), which allows a very automated data processing [5]. Data modeling was carried out under the following specifications:

- IGS final orbits/ IGS Ultra Rapid orbits
- 8 degrees cutoff elevation angle and height dependent observation weighting (cos z)
- no a priori troposphere model (full delay was estimated using Dry Niell Mapping Function)
- 2-hourly estimation of troposphere parameters
- ambiguity resolution: L5/L3

4. Results

The total ZPD at 3 stations (Graz, Hafelekar, Pfänder) is shown in figures 3 to 5 over a 10 days period (doy 032 - 041/2002) for both investigated orbit types, IGS Final (IGS) and IGS Ultra Rapid (IGU) orbits. For comparison, graphics 4 and 5 additionally display the ZPD estimates delivered by the IGS. These ZPD's are regularly generated on a weekly basis by IGS as a combined tropospheric product since 1997. They are based on the submissions of the individual IGS Analysis Centers. Furthermore our results were compared with those provided by four Processing Centers delivering Near Real Time (NRT) data in association with the European COST-716 action (using UltraRapid orbits)[2], which are

GFZ (Potsdam, Germany)
GOP (Pency, Czech Republic)
ASI (Matera, Italy)
LPT (Wabern, Switzerland)

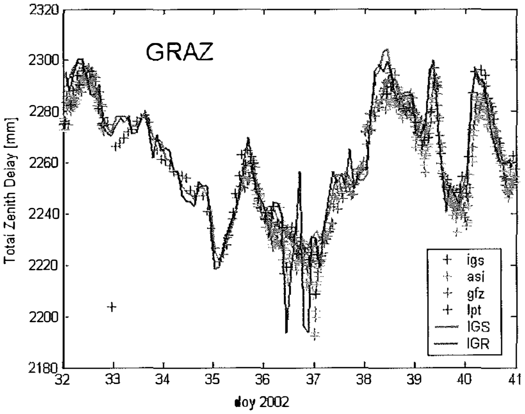

Figure 3: ZPD, Station GRAZ, doy 032 - 040

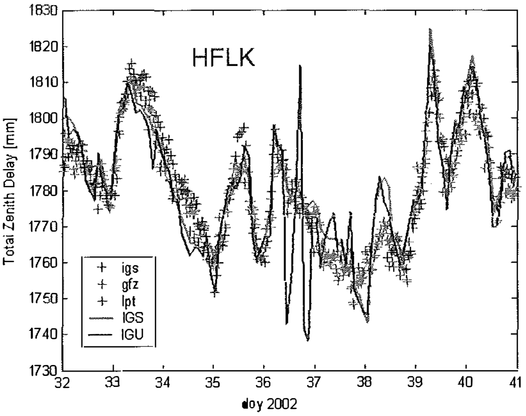

Figure 4: ZPD, Station HFLK, doy 032 - 040

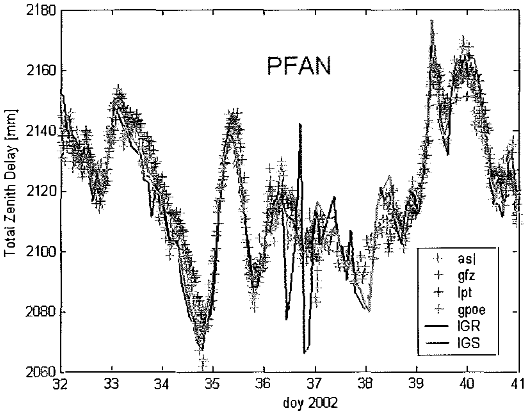

Figure 5: ZPD, Station PFAN, doy 032 - 040

As shown in the diagrams the two different orbit types result in small ZPD discrepancies with one remarkable exception during doy (day of year) 36. That day solutions show remarkable differences of up to 3.8 cm at all examined stations. The rms of the differences is ±7.5 mm over the whole week but decreases to ±4 mm when eliminating doy 36. A closer inspection of doy 36 points towards a poor orbit quality of GPS satellite PRN29 (flagged in the header by a high acuracy code number) which influences the results in a detrimental manner. The header of the standard GPS orbit format SP3 contains satellite specific accuracy information. The accuracy code has to be interpreted as the exponent of 2 (in millimetres), e.g. 5 implies an overall position accuracy of $\pm 2^5$ mm (~3.2 cm).

In a second step we solely focus on day 36. A number of test scenarios (SC1-SC4) with different modifications of the IGS Ultra-Rapid orbits were investigated.

SC1: We replaced all IGU satellite orbits with an accuracy code > 8 (PRN29, PRN 2) by the broadcast ephemeris information (Solution: IGU-B1).

SC2: We replaced all IGU satellite orbits with an accuracy code > 7 (PRN29,PRN 2, PRN 4, PRN24) by the broadcast ephemeris information (Solution: IGU-B2).

SC3: We replaced all IGU satellite orbits with an accuracy code > 7 AND included for all satellites missing in the IGUs the broadcast ephemeris information (Solution: IGU-B3).

SC4: We included for all satellites missing in the IGUs the broadcast ephemeris information (Solution: IGU-B4).

Considering these 4 scenarios the results for the same 3 stations and the computations made using the IGS and IGU orbits are shown in figures 6 to 8 and summarized in table 2.

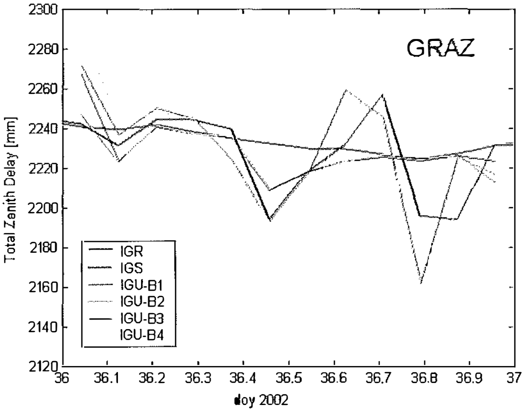

Figure 6: ZPD, Station GRAZ, doy 036

	all days but doy 36	doy 36	SC1	SC2	SC3	SC4
maximum deviation	1.1 cm	3.8 cm	3.0 cm	3.5 cm	6.4 cm	8.5 cm
rms	4 mm	20 mm	11 mm	13 mm	26 mm	34 mm

Table 2: Maximum deviation and rms error of ZPD differences between IGU test scenarios (initial solution excl. doy 36, doy 36, SC1-SC4) w.r.t. IGS solutions.

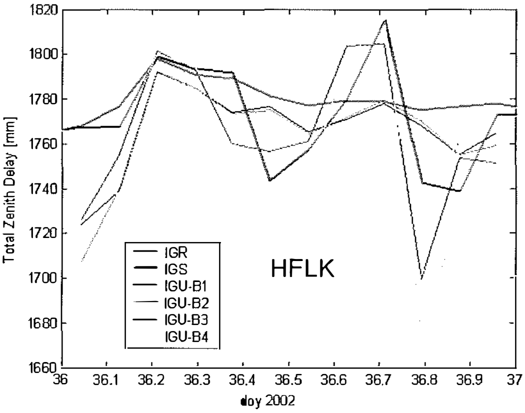

Figure 7: ZPD, Station HFLK, doy 036

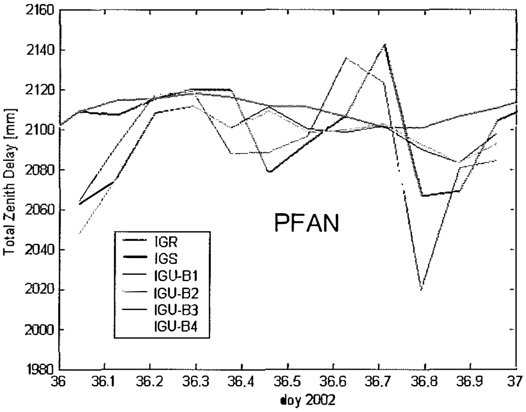

Figure 8: ZPD, Station PFAN, doy 036

We conclude that replacing satellites orbits of poor quality by the relevant broadcast information improved our estimated ZPD's. On the other hand, to add broadcast ephemeris information for missing satellites, has a negative effect. In most cases the included satellites degrade our results.

A closer look at the orbital representation of satellites PRN2,PRN4,PRN24 and PRN29 can clarify the situation. Under the assumption that the along track component is affected most by orbit mismodelling, we calculated the difference in along track of the IGU orbit (IGU) w.r.t. the IGS Final orbit. While PRN2,PRN4 and PRN24 show moderate deviations up to a few meters at the end of the prediction interval of 24 hours (see figure 9), the deviations of the PRN29 IGU ephemeris are quite huge (see figure 10). For comparison the accompanying broadcast information (BRD) of PRN2 and PRN29 is provided, too. Especially in case of satellites with accuracy codes > 8 the broadcast information can be a more relevant data source, especially in the second half of the considered prediction interval.

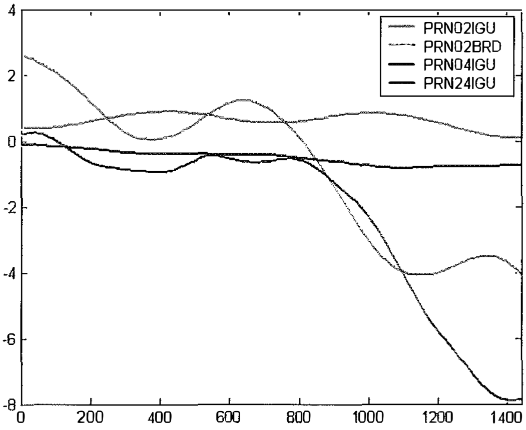

Figure 9: Orbital difference in along track of IGU orbit (IGU)/ Broadcast orbit(BRD) w.r.t. IGS Final orbit (PRN 2,4,24)

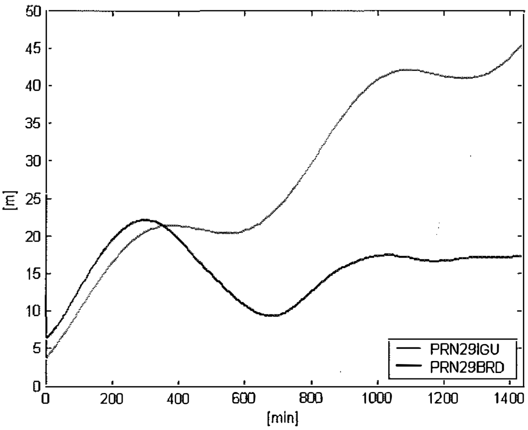

Figure10: Orbital difference in along track of IGU orbit (IGU)/ Broadcast orbit(BRD) w.r.t. IGS Final orbit (PRN 29)

5. Summary

As expected the time series show discrepancies between the zenith path delays estimated by using IGS and IGU orbits in the order of several mm up to 4 cm. These differences are mainly caused by the lower quality of the Ultra-Rapid orbits.

As a consequence we made an apriori quality check of the available IGS UltraRapid orbits and in case of bad orbit quality we replaced these satellites by those stemming from the broadcast ephemeris. In scenario 1 we clearly obtained better results. When including all missing satellites with their broadcast ephemeris information (SC3, SC4) no improvements in ZPD calculation can be reported. In some cases the added erroneous satellite orbit information propagated into huge deviations of the ZPD estimates.

Upcoming studies have to determine in more detail the accuracy code range (less than 8 or 9) which still provides satellite positions accurate enough for ZPD calculation at the 5mm level. Moreover they have to deal with questions like how reliable is such a simple one-digit characterisation of the extrapolated orbits and how useful are orbit extrapolations over periods longer than 12 hours? Hopefully useful in this context is the modified standard format for satellite orbits (SP3c), which should become effective very soon. The new format provides enhanced accuracy information, because it contains the calculated or predicted standard deviation of each position component (X, Y, Z) per epoch. Furthermore the update cycle of the IGU orbits will be reduced from 12 hours to 3 hours in the near future, which will support essentially the fast ZPD determination.

References

[1] *Beutler G., Schaer S., Rothacher M., 1999,* Wide Area Differential GPS, Astronomical Institute, University of Berne, 1999.
[2] COST-716 hompage: http://www.knmi.nl/samenw/cost716/index.html , Smith A., Exploitation of Ground Based GPS for Climate and NWP.
[3] *Fang P., Gendt G., Springer T., Mannucci T. (2001):* IGS Near Real-Time Products and Their Applications. GPS Solutions, Vol.4, No.4, pp 2–8.
[4] *Fragner E. (2003):* Estimation of the integrated water vapor from GNSS data over the Austrian territory. GPS Solutions, Vol.4, No.4, pp 2–8.
[5] *Hugentobler U., Schaer S., Fridez P. (Eds.), 2001,* Bernese GPS Software Version 4.2 documentation, Astronomical Institute, University of Berne, 2001.
[6] *Zhang J., Lachapelle G., 2001,* Precise estimation of residual tropospheric delay using a regional GPS network for real-time kinematic applications, Journal of Geodesy (2001) 75, pp 255–266.

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