Precipitable Water Vapour and Zenith Total Delay time series and models over Slovakia and vicinity

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Abstract: More than 50 permanent GNSS (Global Navigation Satellite Systems) stations are processed continually within the Central European Permanent Network. Zenith Total Delay (ZTD), one of the processing outputs, reflects a delay of the GNSS signal caused by troposphere. Precipitable Water Vapour (PWV) is calculated when ground meteorological observations are available. Model of PWV over Slovakia and its vicinity is produced using digital elevation model data for height correction. Real variation of PWV over the area shows a model of normalized PWV (nPWV), which is created from PWV values reduced by theoretical PWV values corresponding to altitude and latitude of the station. Time series of ZTD and PWV since 1996 and models of PWV and nPWV are published on the web page, using Web Map Service and other web technologies. Data are continually updated and can be downloaded for free.

Key words: Zenith Total Delay (ZTD), Precipitable Water Vapour (PWV), model of PWV and nPWV, automated processing, world wide web

1. Introduction

A network of 58 permanent GNSS stations in Central and South-East Europe (CEPER) is processed automatically at the Department of Theoretical Geodesy, Faculty of Civil Engineering, Slovak University of Technology in Bratislava (Hefty et al., 2009) – see Fig. 1. Two independent solutions using Bernese GPS Software are available – final and rapid. Final solution is based on daily GNSS data files and final satellite orbits. Rapid solution uses four one-hour GNSS data files and ultra-rapid satellite orbits. Final solution is more precise and reliable then rapid but it is available with 2 weeks delay contrary to rapid solution which is available with approximately
2 hour delay. Characteristics of the used satellite orbits are summarized in Table 1.

Table 1. Characteristics of Final and Ultra-rapid orbits used for GNSS data processing
(IGS website)

<table>
<thead>
<tr>
<th>Orbits</th>
<th>Accuracy</th>
<th>Latency</th>
<th>Updates</th>
</tr>
</thead>
<tbody>
<tr>
<td>Final</td>
<td>2.5 cm</td>
<td>12 – 18 days</td>
<td>every Thursday</td>
</tr>
<tr>
<td>Ultra-rapid</td>
<td>5 cm</td>
<td>Real Time</td>
<td>at 03, 09, 15, 21 UTC</td>
</tr>
</tbody>
</table>

Fig. 1. Distribution of stations processed in CEPER network.
Zenith Total Delay (ZTD), one of the outputs from both types of processing, represents tropospheric refraction in zenith direction. Wet part of the ZTD (ZWD – Zenith Wet Delay) is caused by water vapour in the troposphere. The amount of water vapour in [mm] is called Precipitable Water Vapour (PWV) and can be derived from ZWD and ground meteorological measurements of dry temperature T and air pressure p (Igondová and Hefty, 2008; Bevis et al., 1992). Using Saastamoinen model (Saastamoinen, 1972) for hydrostatic component of ZTD (ZHD – Zenith Hydrostatic Delay) and information on station position - latitude ϕ and ellipsoidal height H_{el} in [km], Precipitable Water Vapour is

\[ PWV = \kappa' ZWD = \kappa' \left( ZTD - \frac{0.002277 p}{1 - 0.00266 \cos(2\phi) - 0.00028 H_{el}} \right). \]  

(1)

Dimensionless constant factor \( \kappa' \) is

\[ \kappa' = \frac{10^8}{\rho R_v \left( c_3/T_m + c'_2 - m c_1 \right)}, \]  

(2)

where the laboratory determined constants are \( c_1 = (77.604 \pm 0.014) \text{K hPa}^{-1}, c'_2 = (17 \pm 10) \text{K hPa}^{-1}, c_3 = (3.776 \pm 0.004) \cdot 10^5 \text{K}^2 \text{hPa}^{-1}, m = 0.62198 \) is the ratio of molar weight of the water vapour to molar weight of the dry air, \( \rho = 998 \text{ kg m}^{-3} \) is the density of the water and \( R_v \) is the specific gas constant for the water vapour. The weighted “mean temperature” of the atmosphere \( T_m \) in [K] is assumed within a latitude range from 27° to 65° and a height range from 0 to 1.6 km to be given by the linear regression (Bevis et al., 1992)

\[ T_m = 70.2 + 0.72 T, \]  

(3)

where \( T \) in [K] is the surface temperature (2 m above the ground).

Wide network of GNSS stations providing continual and regular GNSS observations and ground meteorological data, allows automated processing of data and computing discrete PWV values and models over selected area subsequently. The present article describes a software solution for determining time series of ZTD and PWV, and models of PWV and \( nPWV \) and web page for dissemination of these data.
2. Software solution

Large number of processed data, necessary for continual PWV determination and various expected outputs, leads to creating own software solution based on a series of Perl scripts and configuration files. Software is running under operating system Linux Fedora and enables automated processing as well as user-defined requested processing. Processing scheme contains four basic scripts, with series of input configuration files and four possible output formats (see Fig. 2).

The script `get_met.pl` downloads meteorological data in format of RINEX (Receiver Independent Exchange Format) from data centres using FTP (File Transfer Protocol) service, archives them and creates time series of pressure $p$, temperature $T$ and relative humidity $RH$ separately for each processed station. It is running every hour in order to download newest files.

The script `tro2ztd.pl` creates time series of $ZTD$ from tropospheric SINEX (Solution Independent Exchange Format) – TRO files generated
by Bernese GPS Software. There are TRO files from final solution used, supplemented with rapid solution TRO files at the end of the series. It is running hourly right after `get_met.pl` script and also after availability of new final solution.

The script `ztd2pwv.pl` is the main universal script for computing PWV from ZTD and meteorological data. It creates time series of PWV or input data files for model of PWV and nPWV, according to information specified in the input configuration file (see Fig. 3). Configuration file (`input.cfg`) contains much input information – time span of processed data, list of processed stations, output directory, e-mail address for sending requested data and information on type of processing (routine final/not routine/routine rapid). There are three additional configuration files containing used constants (`const.cfg`), automatically updated list of station coordinates (`coord.cfg`) and list of height differences between ARP (Antenna Reference Point) and meteorological sensors (`Met_corH.cfg`). Output files intended for downloading from web page (see Section 5) are converted to format correctly readable for Windows users because the end of lines in text files created under Unix/Linux and Windows operation system differs. Example of PWV time series is in Fig. 3. The same structure has ZTD time series created by `tro2ztd.pl` script. The script is running hourly and once a week when new final solution is available.

<table>
<thead>
<tr>
<th>START_YEAR (YYYY)</th>
<th>START_MONTH (01-12)</th>
<th>START_DAY (01-31)</th>
<th>STOP_YEAR (YYYY)</th>
<th>STOP_MONTH (01-12)</th>
<th>STOP_DAY (01-31)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1998</td>
<td>01</td>
<td>01</td>
<td>2010</td>
<td>01</td>
<td>01</td>
</tr>
</tbody>
</table>

 assurance that PWV will be included in processing.

# END of list of processed stations (one station in one line)
# Name of directory
# Data for PWV or ZTD, ZTD input from TRO files
# Additional configuration files
# Constants
# Height differences between ARP and meteorological sensors
# Additional constants
# End of list of processed stations (one station in one line)
# Name of directory
# Data for PWV or ZTD, ZTD input from TRO files
# Additional configuration files

Fig. 3. Left – example of input configuration file. Upper right – example of output PWV time series. Lower right – example of output grid file in .asc format.
The script `pwv2asc.pl` is used if PWV and nPWV models are requested. It creates models from discrete data prepared by `ztd2pwv.pl` script in the form of input text file (data.txt). It contains name of station, coordinates, PWV, p, T and RH for all stations available at selected epoch. Simple linear interpolation is used for computing nPWV model. On the contrary, PWV model is generated using linear interpolation with additional correction to real height obtained from Digital Elevation Model GTOPO30 (website GTOPO30) with 30′′ × 30′′ resolution (for more information on creating models, see Section 4). Output files are in standardized interchange ArcInfo ASCII Grid .asc format. It consists of header that specifies the geographic domain and resolution, followed by the actual grid cell values (website ASC) (example in Fig. 3).

3. Time series of ZTD and PWV over Slovakia and vicinity

Time series are formed using software described above. ZTD data are available for all stations included in primary processing of CEPER network. Final solution of ZTD is extended with rapid ZTD solution up to two hours before actual epoch. For stations providing ground meteorological measurements, PWV data are calculated and PWV time series are formed. Time series are updated right after availability of new final or rapid solution. The beginning of each time series differs according to start of GNSS and/or meteorological observations at the station and it is also limited by the availability of ZTD solutions from processing of CEPER network which starts at 2006-01-01.

Output format for storing time series data is the same for both ZTD and PWV series. Name of file contains 4 character abbreviation of station standardly used in GNSS data processing and extension is ZTD or PWV according to type of data. Each line in file starts with date and time described in two different ways. First is common form of YEAR-MONTH-DAY HOUR:MINUTE and second is Modified Julian Day (MJD) where days are computed continually and time is described as decimal part of MJD. Date in MJD format allows easy plotting of data with any suitable software. Time is displayed in Universal Time Coordinated (UTC) system. It differs from Central European Time (CET) in minus 1 hour
(UTC − CET = −1 hour) and from Central European Summer Time (CEST) in minus 2 hours (UTC − CEST = −2 hours). Last two columns of file contain information on ZTD or PWV value and corresponding precision. Data are available in one hour intervals. List of GNSS stations providing ZTD and PWV time series is summarized in Table 2. Example of plotted ZTD and PWV time series with corresponding standard deviation.

Fig. 4. Example of ZTD time series at station GOPE from 1996-01-02 to 2010-07-21 and the corresponding standard deviation (bottom line, scale on the right).

Fig. 5. Example of PWV time series at station GOPE from 1999-11-05 to 2010-07-21 and the corresponding standard deviation (bottom line, scale on the right). Meteorological data were not available before 1999-11-05 (MJD 51487).


Table 2. List of GNSS stations included in processing – availability of ZTD and PWV time series

<table>
<thead>
<tr>
<th>Station</th>
<th>ZTD Series</th>
<th>PWV Series</th>
<th>Station</th>
<th>ZTD Series</th>
<th>PWV Series</th>
</tr>
</thead>
<tbody>
<tr>
<td>ASIA – Asiago, Italy</td>
<td>Yes</td>
<td></td>
<td>MATE – Matera, Italy</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>BAILA – Baia Mare, Romania</td>
<td>Yes</td>
<td>Yes</td>
<td>MEDI – Medicina, Italy</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>BAST – Banská Štiavnica, Slovakia</td>
<td>Yes</td>
<td>Yes</td>
<td>MOP1 – Modra – Piesok, Slovakia</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>BBYS – Banska Bystrica, Slovakia</td>
<td>Yes</td>
<td>Yes</td>
<td>MOP2 – Modra – Piesok, Slovakia</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>BISK – Zlaté Hory, Czech Republic</td>
<td>Yes</td>
<td></td>
<td>OBE3 – Oberpfaffenhofen, Germany</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>BOGI – Borowa Góra, Poland</td>
<td>Yes</td>
<td></td>
<td>ORAD – Oradea, Romania</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>BOGO – Borowa Góra, Poland</td>
<td>Yes</td>
<td></td>
<td>ORID – Ohrid, Macedonia</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>BORI – Borowice, Poland</td>
<td>Yes</td>
<td></td>
<td>OROS – Orosháza, Hungary</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>BRAI – Brášňa, Romania</td>
<td>Yes</td>
<td></td>
<td>OSJE – Osijek, Croatia</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>BUCU – Bucuresti, Romania</td>
<td>Yes</td>
<td></td>
<td>PACO – Padova, Italy</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>BUTE – Budapest, Hungary</td>
<td>Yes</td>
<td></td>
<td>PENC – Pécs, Hungary</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>BZRG – Bolzano, Italy</td>
<td>Yes</td>
<td></td>
<td>POTS – Potsdam, Germany</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>CLUJ – Cluj-Napoca, Romania</td>
<td>Yes</td>
<td></td>
<td>RISO – Rimavska Sobota, Slovakia</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>COST – Constanța, Romania</td>
<td>Yes</td>
<td></td>
<td>ROVI – Rovigo, Italy</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>CRAI – Craiova, Romania</td>
<td>Yes</td>
<td></td>
<td>SBG2 – Salzburg, Austria</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>DRES – Dresden, Germany</td>
<td>Yes</td>
<td></td>
<td>SIBI – Sibiu, Romania</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>DUBR – Dubrovnik, Croatia</td>
<td>Yes</td>
<td></td>
<td>SOFI – Sofia, Bulgaria</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>GANP – Gávocz, Slovakia</td>
<td>Yes</td>
<td></td>
<td>SRJV – Sarajevo, Bosnia and Herzegovina</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>GOPE – Ondřejov, Czech Republic</td>
<td>Yes</td>
<td>Yes</td>
<td>SUCE – Suceava, Romania</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>GRAZ – Graz, Austria</td>
<td>Yes</td>
<td></td>
<td>SUME – Sümeg, Hungary</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>GSRJ – Ljubljana, Slovenia</td>
<td>Yes</td>
<td></td>
<td>SULP – Lviv, Ukraine</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>JOZ2 – Józefosław, Poland</td>
<td>Yes</td>
<td></td>
<td>TUBO – Brno, Czech Republic</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>JOZE – Józefosław, Poland</td>
<td>Yes</td>
<td>Yes</td>
<td>USDL – Ustrzyki, Poland</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>KATO – Katowice, Poland</td>
<td>Yes</td>
<td></td>
<td>UZHL – Uzhorod, Ukraine</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>KLOP – Kloppenheim, Germany</td>
<td>Yes</td>
<td></td>
<td>VACO – Vacov, Czech Republic</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>KRAW – Kraków, Poland</td>
<td>Yes</td>
<td></td>
<td>WROC – Wroclaw, Poland</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>LAMA – Lankówko, Poland</td>
<td>Yes</td>
<td></td>
<td>WZT – Wettzell, Germany</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>LOMS – Lomnický Štít, Slovakia</td>
<td>Yes</td>
<td></td>
<td>ZIMM – Zimmerwald, Switzerland</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>MARJ – Jáchymov, Czech Republic</td>
<td>Yes</td>
<td></td>
<td>ZYW1 – Žywiec, Poland</td>
<td>Yes</td>
<td></td>
</tr>
</tbody>
</table>

tions are in Figs. 4 and 5.

Data gaps, if present, are caused by unavailability of GNSS or mete-
orological data. Station GANP does not provide ground meteorological data automatically to accessible data centres; therefore PWV data are updated non-regularly and longer gaps may occur at the end of series. Station PENC stops providing meteorological data at 2007-03-20; therefore no current PWV data are available.

4. PWV and nPWV models

Values of PWV are altitude dependent, the higher altitude the lower PWV value. It implies two problems connected with PWV models generated over the area of interest. The first one is that interpolation of discrete PWV data cannot use any standard interpolation technique. It has to take into account height conditions at the point of interpolation. And the second problem arises from need of interpretation of achieved model. PWV data are correlated with height, therefore it is hard to assess if difference of PWV values between two places is connected with real change of PWV values or only with height difference of the places. This leads to defining new “normalized” PWV (nPWV) value

\[ nPWV = PWV - PWV_{\text{theor}}. \]  

computed as a difference of PWV value and theoretical value of PWV (PWV_{\text{theor}}).

\[ PWV_{\text{theor}} = \kappa' ZWD_{\text{theor}}. \]  

Saastamoinen model (Saastamoinen, 1972) for computing theoretical value of ZWD is applied

\[ ZWD_{\text{theor}} = \frac{0.002277 \left( \frac{1225}{T_{\text{theor}}} + 0.05 \right) e_{\text{theor}}}{1 - 0.00266 \cos(2\varphi) - 0.00028 H_{el}}, \]  

where theoretical, instead of real, meteorological data are applied (Dai et al., 2006). Partial water vapour pressure \( e \) in [hPa] can be calculated from relative humidity \( RH \) in [%], temperature \( T \) in [K], the specific gas constant for the water vapour \( R_v \) and latent heat of vaporization \( L = 2.5 \cdot 10^6 \text{ J kg}^{-1} \).
\[ e_{\text{theor.}} = e_0 \exp \left[ \frac{L}{R_e} \left( \frac{1}{T_0} - \frac{1}{T_{\text{theor.}}} \right) \right] \frac{RH_{\text{theor.}}}{100}, \quad (7) \]

\[ T_{\text{theor.}} = T_0 - 0.0065 \frac{\circ C}{m} H, \quad (8) \]

\[ RH_{\text{theor.}} = RH_0 \exp (-0.0006396 H), \quad (9) \]

where \( T_0 = 18 \circ C, H_0 = 7000 m, \ RH_0 = 50\% \) are reference values at the sea level.

Theoretical PWV values \( PWV_{\text{theor.}} \) are not time, day or season dependent. There is only one \( PWV_{\text{theor.}} \) value for each place, because the only two variables used are the station height and latitude. Value of \( nPWV \) is altitude independent therefore one of the standard interpolation techniques can be used for creating \( nPWV \) model. We used the Inverse distance weighted interpolation with distance squared (Waelder, 2008).

Interpolation of PWV data starts with standard interpolation of discrete PWV values and also \( T \) and \( RH \) values together with computing interpolated altitude in point of interpolation. Let us mark the values referred to this altitude with subscript \( 1 - PWV_1, T_1 \) and \( RH_1 \). Interpolated temperature and relative humidity are corrected to real altitude at the place using formulas (8) and (9) and it produces values marked with subscript \( 2 - T_2 \) and \( RH_2 \). Then theoretical values of \( e, ZWD_{\text{theor.}}, T_m \) and subsequently \( PWV_{\text{theor.}} \) are computed using formulas (7), (6), (2), (5) and values \( T_1, RH_1, T_2, RH_2 \) in interpolated and real altitude, respectively. Height correction to interpolated \( PWV_1 \) value is then

\[ dPWV = PWV_{\text{theor.2}} - PWV_{\text{theor.1}} \quad (10) \]

and final corrected value of PWV in point of interpolation is

\[ PWV = PWV_1 + dPWV. \quad (11) \]

Computed models of PWV and \( nPWV \) are stored in form of .asc files. Models are related to specific date and time, which is indicated in the file name: \( YEAR-MONTH-DAYTHOUR_PWV \) (or \( nPWV \) instead of \( PWV \)). Time is expressed in UTC system described in Section 3.
5. Web page

Time series and models over Slovakia and its vicinity are available at the hourly updated web page http://147.175.80.68 (website PWV). Web page is divided into 5 sections: Introduction, PWV and ZTD, Specific request, Legend and Contact information. The introduction contains information on type of available data, their precision and list of related publications. Displayed models can be downloaded, as well as the time series of PWV and ZTD for selected stations. Specific user requests are managed through special form and data are sent to users’ e-mail address.

Server containing Web Map Service (WMS) and the data is built on operating system Linux Fedora 9. Technologies used on server side are (Cibulka, 2010):

- Apache 2.2.9 – open-source HTTP (Hypertext Transfer Protocol) server for operating systems including UNIX and Windows NT (APACHE website),
- MapServer 4.10.0 – open-source platform for publishing spatial data and interactive mapping applications to the web (MAPSERVER website),
- PHP (Hypertext Preprocessor) – general-purpose scripting language especially suited for web development; can be embedded into HTML (PHP website),
- BASH (Bourne Again Shell) – command-line interpreter.

Web client for communication between user and server is based on technologies (Cibulka, 2010):

- HTML (Hypertext Markup Language) – language for web pages,
- JavaScript – object-oriented scripting language, implemented as part of a web browser in order to provide enhanced user interface and dynamic website,
- CSS (Cascading Style Sheets) - enables the separation of document content from document presentation,
- OpenLayers – open-source JavaScript library for easy putting a dynamic map in any web page (OPENLAYERS website).
Web page is optimized for Internet Explorer, Mozilla Firefox, Opera and Google Chrome Web browsers. Example of web page design is in pictures 6 and 7. Texts are written in Slovak language. There are not expected non-Slovak users due to limited area of provided data.

Fig. 6. Example of web page http://147.175.80.68 design – time information on displayed model, list of stations contributing to displayed model generation and link for downloading the model on the left side; satellite image background, $PWV$ model and stations with $ZTD$ and $PWV$ time series on the right side.

Fig. 7. Example of web page http://147.175.80.68 design – legend and colour scales on the left side; Google hybrid background map and $nPWV$ model on the right side.
Data are displayed on the background of satellite image or hybrid Google image. User can switch on one or more of available layers: PWV model, \(nPWV\) model, state boundaries, stations providing ZTD data and stations providing PWV data.

Models of PWV and \(nPWV\) for the last year can be displayed. All models, including models older then one year, are available for downloading in .asc format together with text file containing discrete input data. Each .asc file contains grid of 900 × 420 points. To accelerate speed of visualization on web page, models are pre-converted to .tif format. Exact time span for downloading and displaying models is given on the web page.

Time series of ZTD and PWV are available for downloading after switching to relevant layer and clicking on the station mark.

6. Conclusions

Continual processing of GNSS data and the availability of ground meteorological measurements allow determining Precipitable Water Vapour (PWV) values subsequently. Software solution for determining time series of ZTD and PWV, and models of PWV and \(nPWV\) is described. It is based on a series of Perl scripts and configuration files. Final solution is available in two weeks therefore it is supplemented with rapid solution available with only two hours delay.

Detailed method of creating PWV and \(nPWV\) models is presented. Interpolation of PWV discrete data requires additional information on altitude at the point of interpolation; therefore Digital Elevation Model GTOPO30 (GTOPO30 website) is used. Interpretation of PWV model is problematic due to altitude dependency of PWV values. Therefore, altitude independent \(nPWV\) values were defined.

Web page http://147.175.80.68 for publication of ZTD and PWV time series and models of PWV and \(nPWV\) was created, and is available for interested persons. It allows displaying and downloading data, and creating specific user requests.

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References


APACHE: http://httpd.apache.org/
ASC: ArcInfo ASCII Grid Format: http://docs.codehaus.org/display/GEOTOOLS/ArcInfo+ASCII+Grid +format
GTOPO30: Digital Elevation Model from Earth Resources Observation and Science Center. http://eros.usgs.gov/# /Find+Data/Products+and+Data+Available/gtopo30_info
MAPSERVER: http://mapserver.org/
OPENLAYERS: http://openlayers.org/
PHP: http://php.net/
PWV: PWV and ZTD in Slovakia: http://147.175.80.68