

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

Miroslava IGONDOVÁ¹, Dušan CIBULKA¹

¹ Department of Theoretical Geodesy, Faculty of Civil Engineering,
Slovak University of Technology; Radlinského 11, 813 68 Bratislava, Slovak Republic
e-mail: miroslava.igondova@stuba.sk; dusan.cibulka@stuba.sk

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 than 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*)

Orbits	Accuracy	Latency	Updates
Final	2.5 cm	12 – 18 days	every Thursday
Ultra-rapid	5 cm	Real Time	at 03, 09, 15, 21 UTC

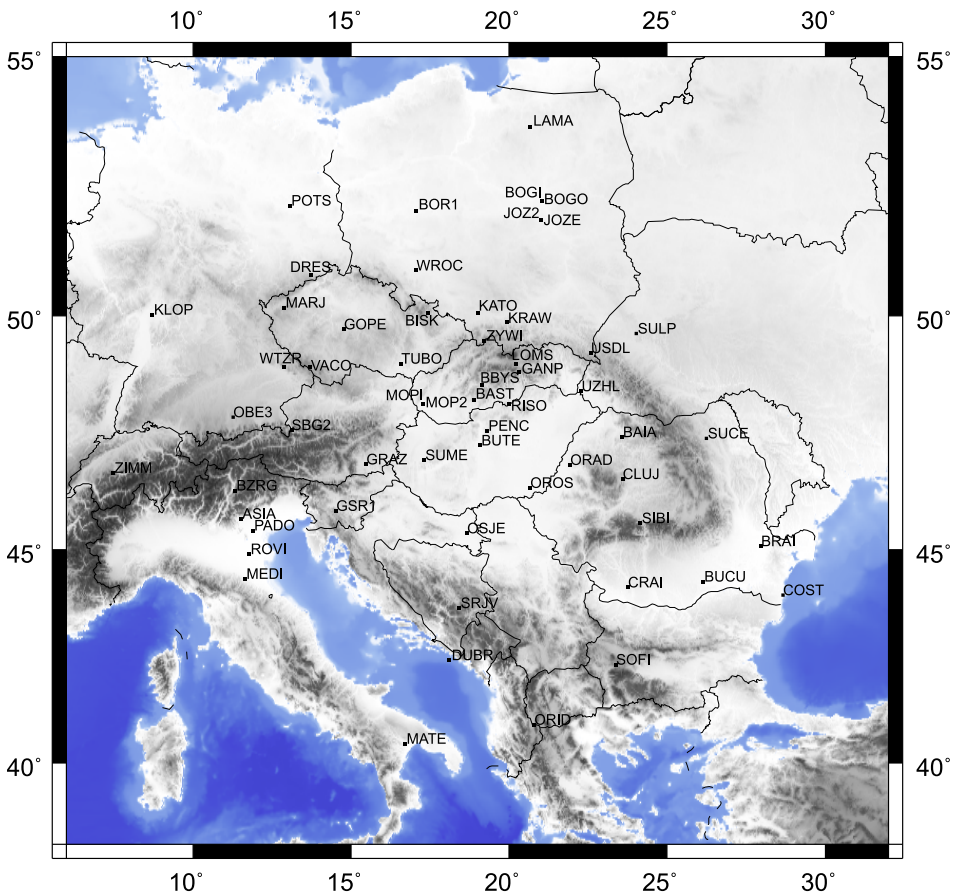


Fig. 1. Distribution of stations processed in CEPER network.

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

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

Dimensionless constant factor κ' is

$$\kappa' = \frac{10^8}{\rho R_v (c_3/T_m + c'_2 - m c_1)}, \quad (2)$$

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*)

$$T_m = 70.2 + 0.72 T, \quad (3)$$

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).

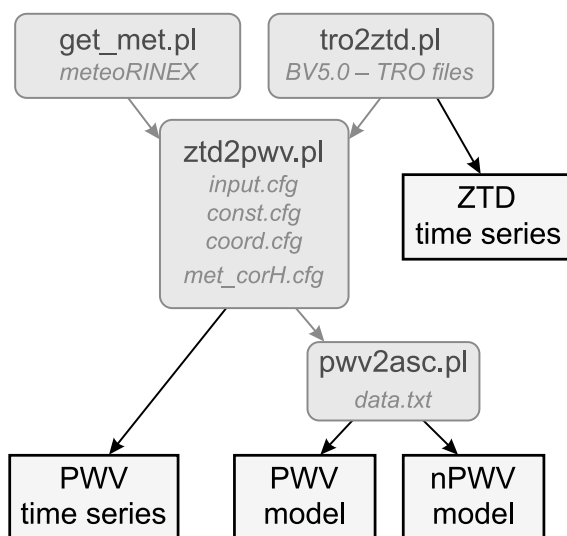


Fig. 2. Processing scheme – scripts, input files (gray) and output files (rectangle form).

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.

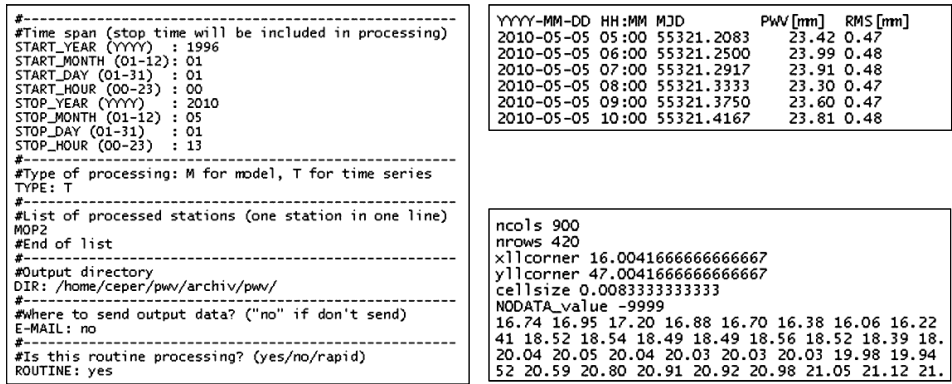


Fig. 3. Left – example of input configuration file. Upper right – example of output *PWV* time series. Lower right – example of output grid file in .asc format.

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 $30'' \times 30''$ 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 devia-

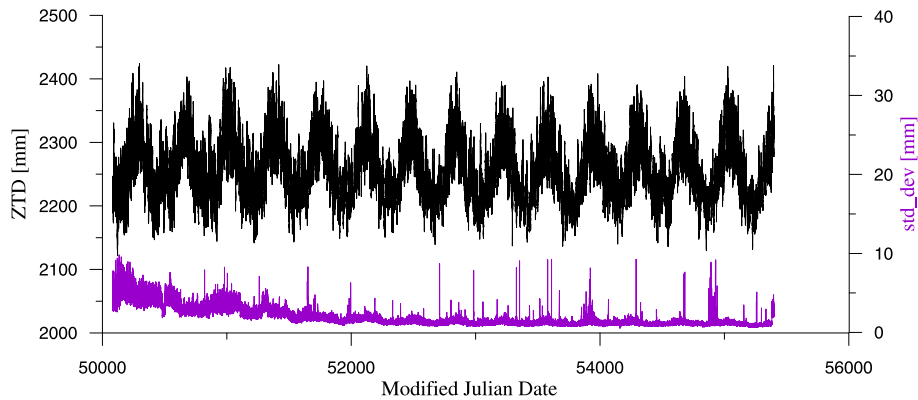


Fig. 4. Example of *ZTD* time series at station GOPE from 1996-01-02 to 2010-07-21 and the corresponding standard deviation (bottom line, scale on the right).

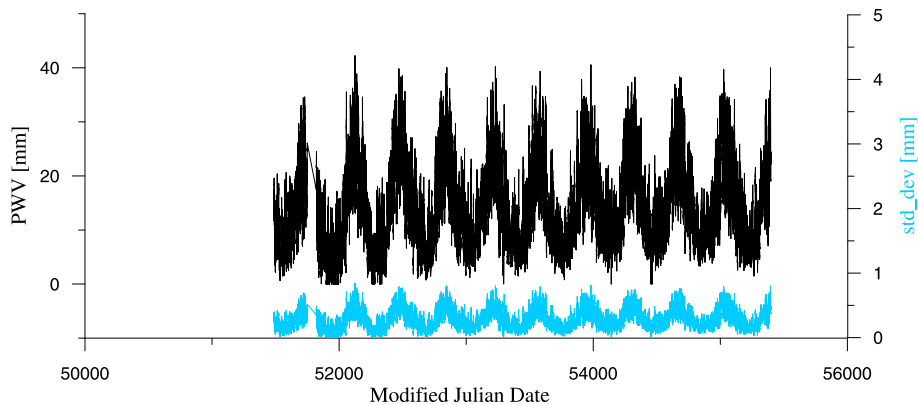


Fig. 5. Example of *PWV* time series at station GOPE from 1999-11-05 to 2010-07-21 and the corresponding standard deviation (bottom line, scale on the right). Meteorological data were not available before 1999-11-05 (MJD 51487).

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

Station	ZTD Series	PWV Series	Station	ZTD Series	PWV Series
ASIA – Asiago, Italy	Yes		MATE – Matera, Italy	Yes	
BAIA – Baia Mare, Romania	Yes	Yes	MEDI – Medicina, Italy	Yes	
BAST – Banská Štiavnica, Slovakia	Yes		MOPI – Modra – Piesok, Slovakia	Yes	Yes
BBYS – Banská Bystrica, Slovakia	Yes	Yes	MOP2 – Modra – Piesok, Slovakia	Yes	Yes
BISK – Zlaté Hory, Czech Republic	Yes		OBE3 – Oberpfaffenhofen, Germany	Yes	
BOGI – Borowa Góra, Poland	Yes		ORAD – Oradea, Romania	Yes	
BOGO – Borowa Góra, Poland	Yes		ORID – Ohrid, Macedonia	Yes	
BOR1 – Borowiec, Poland	Yes		OROS – Orosháza, Hungary	Yes	
BRAI – Brăila, Romania	Yes		OSJE – Osijek, Croatia	Yes	
BUCU – Bucuresti, Romania	Yes		PADO – Padova, Italy	Yes	
BUTE – Budapest, Hungary	Yes		PENC – Penc, Hungary	Yes	Yes
BZRG – Bolzano, Italy	Yes		POTS – Potsdam, Germany	Yes	
CLUJ – Cluj-Napoca, Romania	Yes		RISO – Rimavská Sobota, Slovakia	Yes	Yes
COST – Constanța, Romania	Yes		ROVI – Rovigo, Italy	Yes	
CRAI – Craiova, Romania	Yes		SBG2 – Salzburg, Austria	Yes	
DRES – Dresden, Germany	Yes		SIBI – Sibiu, Romania	Yes	
DUBR – Dubrovnik, Croatia	Yes		SOFI – Sofia, Bulgaria	Yes	
GANP – Gánovce, Slovakia	Yes		SRJV – Sarajevo, Bosnia and Herzegovina	Yes	
GOPE – Ondřejov, Czech Republic	Yes	Yes	SUCE – Suceava, Romania	Yes	
GRAZ – Graz, Austria	Yes		SUME – Sümeg, Hungary	Yes	
GSRI – Ljubljana, Slovenia	Yes		SULP – Lviv, Ukraine	Yes	
JOZ2 – Józefosław, Poland	Yes		TUBO – Brno, Czech Republic	Yes	Yes
JOZE – Józefosław, Poland	Yes	Yes	USDL – Ustrzyki, Poland	Yes	Yes
KATO – Katowice, Poland	Yes		UZHL – Uzhgorod, Ukraine	Yes	
KLOP – Kloppenheim, Germany	Yes		VACO – Vacov, Czech Republic	Yes	
KRAW – Kraków, Poland	Yes	Yes	WROC – Wrocław, Poland	Yes	Yes
LAMA – Lamkówko, Poland	Yes		WTZR – Wettzell, Germany	Yes	Yes
LOMS – Lomnický štít, Slovakia	Yes		ZIMM – Zimmerwald, Switzerland	Yes	
MARJ – Jáchymov, Czech Republic	Yes		ZYWI – Żywiec, Poland	Yes	

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

$$nPWV = PWV - PWV_{\text{theor.}} \quad (4)$$

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

$$PWV_{\text{theor.}} = \kappa' ZWD_{\text{theor.}} \quad (5)$$

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

$$ZWD_{\text{theor.}} = \frac{0.002277 \left(\frac{1225}{T_{\text{theor.}}} + 0.05 \right) e_{\text{theor.}}}{1 - 0.00266 \cos(2\varphi) - 0.00028 H_{el}}, \quad (6)$$

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 $L = 2.5 \cdot 10^6 \text{ J kg}^{-1}$

$$e_{\text{theor.}} = e_0 \exp \left[\frac{L}{R_v} \left(\frac{1}{T_0} - \frac{1}{T_{\text{theor.}}} \right) \right] \frac{RH_{\text{theor.}}}{100}, \quad (7)$$

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

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

where $T_0 = 18^{\circ}\text{C}$, $H_0 = 7000 \text{ m}$, $RH_0 = 50\%$ 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.

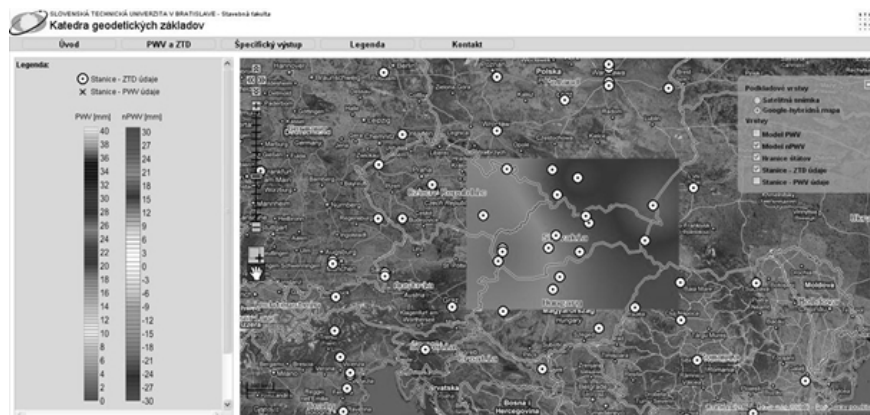


Fig. 7. Example of web page <http://147.175.80.68> design – legend and colour scales on the left side; Google hybrid background map and *nPWV* model on the right side.

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 than 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.

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

References

- 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 Geophys. Research*, **97**, D14, 15,787–15,801.
- Cibulka D., 2010: Web Map Service Time – Client and Server. In: *Juniorstav 2010*, VUT Brno.
- Dai X. J., Ding X. L., Li Z. W., Kwok K. C. S., Campbell S., 2006: Tropospheric Effects on GPS Measurements. *Location (magazine)*, Nov.–Dec., 36–41.
- Hefty J., Igondová M., Droščák B., 2009: Homogenization of Long-Term GPS Monitoring Series at Permanent Stations in Central Europe and Balkan Peninsula. *Contrib. Geophys. Geod.*, **39**, 1, 19–42.
- Igondová M., Hefty J., 2008: Continuous Precipitable Water Vapour Monitoring Using GNSS. *Contrib. Geophys. Geod.*, **38**, 2, 151–167.
- 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.
- Waelder O., 2008: *Mathematical methods for Engineers and Geoscientists*. Springer-Verlag Berlin Heidelberg, 176 p.
- 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
- IGS: IGS products: <http://igsceb.jpl.nasa.gov/components/prods.html>
- MAPSERVER: <http://mapserver.org/>
- OPENLAYERS: <http://openlayers.org/>
- PHP: <http://php.net/>
- PWV: PWV and ZTD in Slovakia: <http://147.175.80.68>