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)*

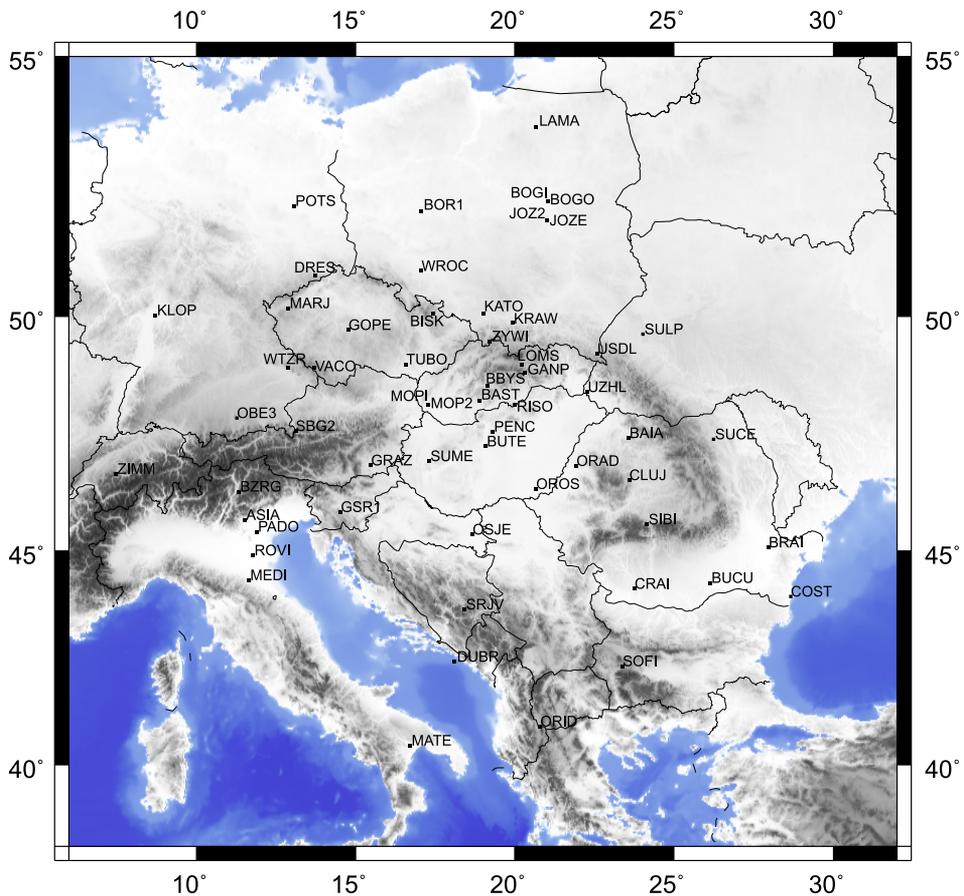| Orbits	Accuracy	Latency	Updates
Final	2.5 cm	12 − 18 days	every Thursday
Ultra-rapid	5 cm	Real Time	at 03, 09, 15, 21 UTC

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

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

Dimensionless constant factor κ' is

$$\kappa' = \frac{10^8}{\rho\, R_v\, \left(c_3/T_m + c_2' - m\, c_1\right)}, \qquad (2)$$

where the laboratory determined constants are $c_1 = (77.604 \pm 0.014)\mathrm{K\ hPa^{-1}}$, $c_2' = (17 \pm 10)\,\mathrm{K\ hPa^{-1}}$, $c_3 = (3.776 \pm 0.004) \cdot 10^5\,\mathrm{K^2\ hPa^{-1}}$, $m = 0.62198$ is the ratio of molar weight of the water vapour to molar weight of the dry air, $\rho = 998\ \mathrm{kg\,m^{-3}}$ 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 ($Bevis\ et\ al.,\ 1992$)

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

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).
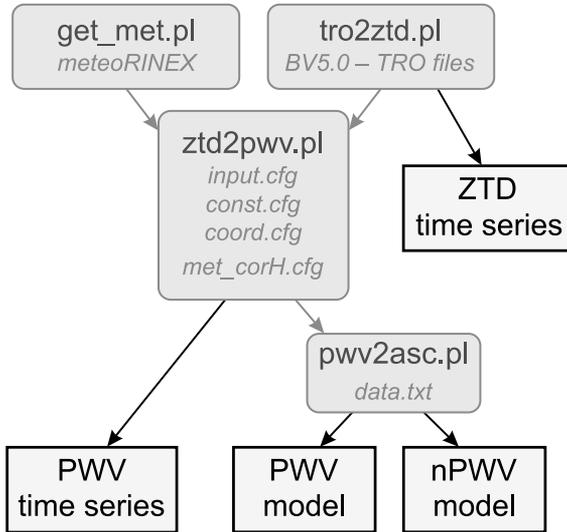

Fig. 2. Processing scheme – scripts, input files (gray) and output files (rectangle form).

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.

```
#-----------------------------------------------
#Time span (stop time will be included in processing)
START_YEAR (YYYY)  : 1996
START_MONTH (01-12): 01
START_DAY (01-31)  : 01
START_HOUR (00-23) : 00
STOP_YEAR (YYYY)   : 2010
STOP_MONTH (01-12) : 05
STOP_DAY (01-31)   : 01
STOP_HOUR (00-23)  : 13
#-----------------------------------------------
#Type of processing: M for model, T for time series
TYPE: T
#-----------------------------------------------
#List of processed stations (one station in one line)
MOP2
#End of list
#-----------------------------------------------
#Output directory
DIR: /home/ceper/pwv/archiv/pwv/
#-----------------------------------------------
#Where to send output data? ("no" if don't send)
E-MAIL: no
#-----------------------------------------------
#Is this routine processing? (yes/no/rapid)
ROUTINE: yes
```

```
YYYY-MM-DD HH:MM MJD          PWV[mm]   RMS[mm]
2010-05-05 05:00 55321.2083    23.42 0.47
2010-05-05 06:00 55321.2500    23.99 0.48
2010-05-05 07:00 55321.2917    23.91 0.48
2010-05-05 08:00 55321.3333    23.30 0.47
2010-05-05 09:00 55321.3750    23.60 0.47
2010-05-05 10:00 55321.4167    23.81 0.48
```

```
ncols 900
nrows 420
xllcorner 16.0041666666666667
yllcorner 47.0041666666666667
cellsize 0.0083333333333
NODATA_value -9999
16.74 16.95 17.20 16.88 16.70 16.38 16.06 16.22
41 18.52 18.54 18.49 18.49 18.56 18.52 18.39 18.
20.04 20.05 20.04 20.03 20.03 20.03 19.98 19.94
52 20.59 20.80 20.91 20.92 20.98 21.05 21.12 21.
```

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 pre-
cision. Data are available in one hour intervals. List of GNSS stations
providing ZTD and PWV time series is summarized in Table 2. Example
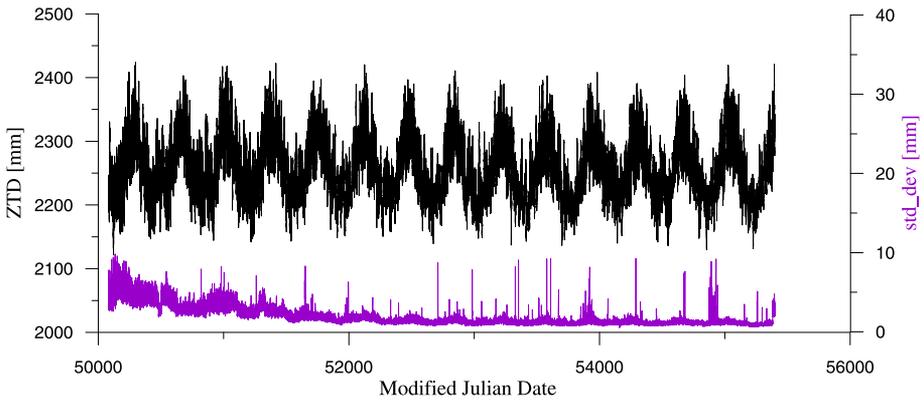of plotted ZTD and PWV time series with corresponding standard devia-

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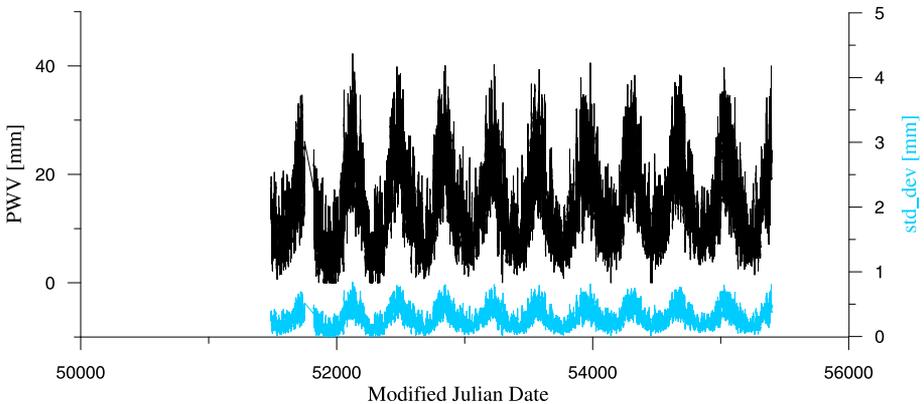the corresponding standard deviation (bottom line, scale on the right).

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 – Constanţa, 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	
GSR1– Ljubljana, Slovenia	Yes		SULP – Ľviv, 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 up-
dated non-regularly and longer gaps may occur at the end of series. Station
PENC stops providing meteorological data at 2007-03-20; therefore no cur-
rent 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

$$nPWV = PWV - PWV_{\text{theor.}} \tag{4}$$

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

$$PWV_{\text{theor.}} = \kappa' \, ZWD_{\text{theor.}}. \tag{5}$$

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

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

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

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

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

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

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

$$dPWV = PWV_{\text{theor.2}} - PWV_{\text{theor.1}}\tag{10}$$

and final corrected value of PWV in point of interpolation is

$$PWV = PWV_1 + dPWV.\tag{11}$$

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-DAY_HOUR_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.
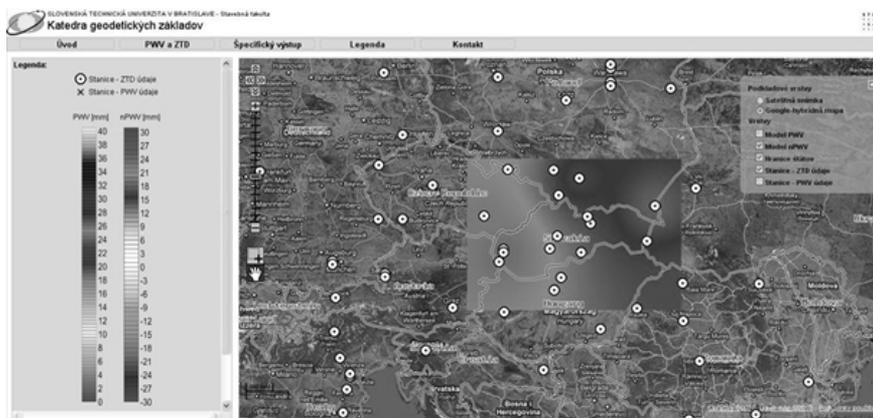

Fig. 7. Example of web page http://147.175.80.68 design – legend and colour scales on the left side; Google hybrid background map and $nPWV$ model on the right side.

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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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APACHE: `http://httpd.apache.org/`

ASC: ArcInfo ASCII Grid Format: `http://docs.codehaus.org/display/GEOTOOLS/Arc Info+ASCII+Grid +format`

GTOPO30: Digital Elevation Model from Earth Resources Observation and Science Center. `http://eros.usgs.gov/# /Find_Data/Products_and_Data_Available/gtopo 30_info`

IGS: IGS products: `http://igscb.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`