The network of permanent GPS stations in Central Europe analysed for purpose of regional geodynamics and troposphere studies

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A b s t r a c t : The results from analysis of the four-year interval of GPS observations in the network of more than 30 permanent stations situated in Central Europe, Alpine-Adriatic region and Balkan Peninsula are presented. The time series of site coordinate variations and zenith total delays (ZTD) are the analysis products which characterize the behaviour of the individual network stations. The main features of both series are the long-term drift and seasonal variability at the millimetre level for local coordinates and at the level of 50 millimetres for the troposphere induced ZTD.

Key words: GPS, permanent networks, regional geokinematics, zenith total delays, coordinate time series

1. Introduction

The satellite surveying techniques using the Global Positioning System (GPS) are worldwide applied for precise positioning where millimetre precision of 3-dimensional position is required. The most accurate and effective results are obtained by the permanently installed GPS equipment at relevant sites and continuous monitoring of all GPS satellites in view. The sets of GPS permanent stations are forming networks of various hierarchy, purpose and extent. The global network processing of GPS code and carrier phase observations, like the International GNSS Service network (IGS, 2008) results to actual station coordinates and other relevant parameters such as the

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troposphere and ionosphere models, satellite orbit and clocks corrections, receiver clocks corrections, etc. *(Hugentobler et al., 2001).* The continental permanent networks, like the EUREF Permanent Network *(EPN, 2008)* use partly the IGS products (satellite clocks and orbits) and the station coordinates and local troposphere parameters are solved in the network adjustment. However the global or continental networks are not sufficiently dense for solving the regional and local phenomena. In this situation, the regional permanent GPS networks are formed, aimed at investigation of detailed local and regional features on the basis of dense set of permanent stations.

In the Central Europe, Alpine – Adriatic region and Balkan Peninsula are situated some stations included in IGS and EPN. Besides, some new stations were established in late years which are not included in global or continental networks or they were included after some delay. At the Slovak University of Technology (SUT) is performed since 2001 the regular analysis of regional network comprising recently about 50 permanent stations. Part of them is analysed now by IGS and/or EPN, the remainder of about 10 stations are not included in these networks, or were added after longer period of observations. We will present here the main outputs of the regional network analysis at the SUT focusing on geodynamic applications and the troposphere zenith total delay (ZTD) estimates relevant for monitoring of water vapour content variations.

2. The network analysed and the processing strategy

In the paper will be presented results of the regular processing of GPS permanent stations in the network configuration shown in Fig. 1 which started at the SUT in January 2003 (GPS week 1200). The majority of the 29 stations were at that time the EPN sites in the region. Progressive enlarging of the network resulted in the new situation shown in Fig. 2 with 55 analyzed stations in end of 2006 including 10 new non-EPN stations. The paper will describe the results of the self-contained period of analysis from 4-year interval 2003.0 – 2007.0 (GPS weeks 1200-1407). The outputs represent a homogeneous set of coordinates and ZTD time series as the whole period was processed in the unique coordinate frame, namely the ITRF2000

(Boucher et al., 2004) and the uniform solution strategy was applied using the Bernese GPS Software, Version 4.2 – BV42 *(Hugentobler et al., 2001)*. The continuation of these activities is based on ITRF2005 referencing and the usage of the Bernese GPS software, Version 5.0. The superposition of ITRF2000 and ITRF2005 referenced series in 2007.0, which are moreover processed with different versions of analysing software brings the discontinuities of coordinates and ZTDs. The prolongation of the time series after 2007.0 will be presented elsewhere. Processing of the permanent observation data follows the standard procedure rules applied for analysis at EPN

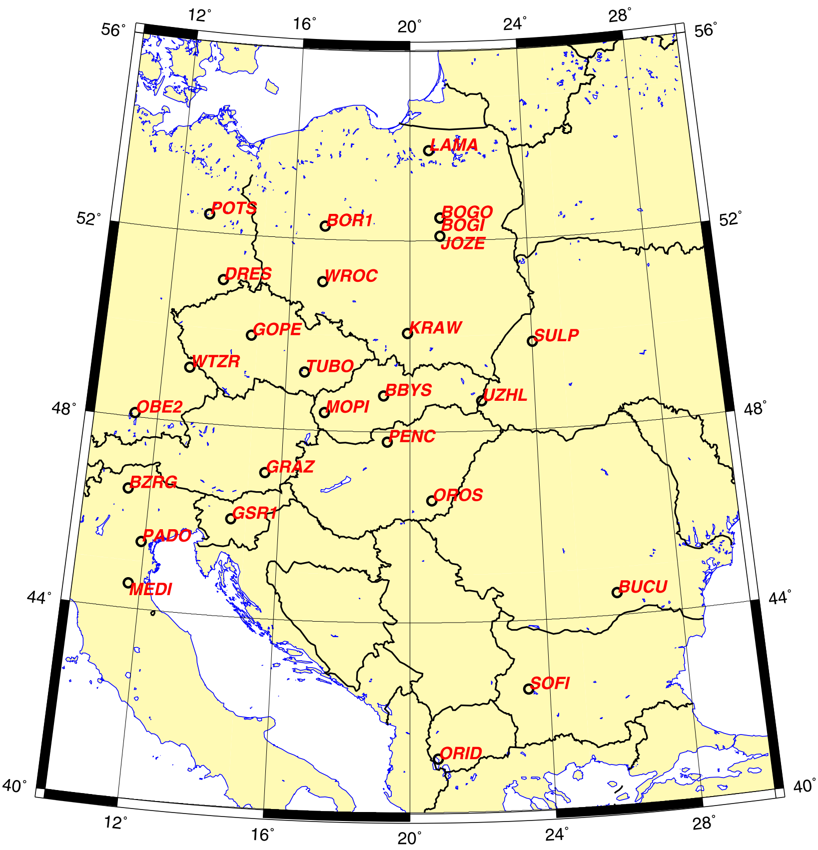

Fig. 1. Network of permanent GPS stations analyzed since 2003.0.

Local Analysis Centres *(Bruyninx et al., 2003)* with some slight modifications. The input data are the daily RINEX files of observing stations, IGS orbit and clock products, and the Earth Orientation Parameters from the International Earth Rotation and Reference System Service. The outputs of the analyses are the daily products of network adjustment: files with station coordinates and their covariance matrices covering 24-hour intervals (from 0 to 24 h UT), troposphere zenith total delays with one- and two-hour

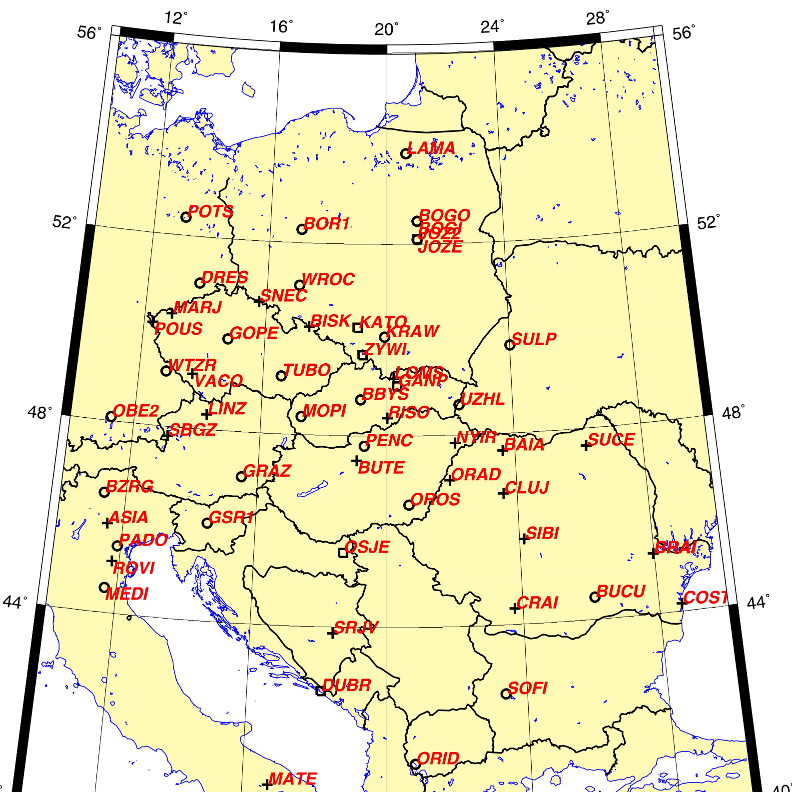

Fig. 2. Status of the analysed network of permanent stations in December 2006. o – stations processed during the whole 4-years interval since 2003.0, ▫ – stations processed from 2 to 3 years, + – stations processed one year or less.

resolution, troposphere gradients, ionosphere models for 24-hour intervals and coordinates with sub-daily (4-hour) resolution. The daily coordinate outputs are combined to the weekly coordinate solutions corresponding to GPS week intervals (from Sundays 0 h UT to Saturdays 24 h UT). All the solutions are obtained with constraining X, Y and Z coordinates of the reference site Borowiec (BOR1) to 0.0001 m. This means that the daily, sub-daily and weekly coordinate outputs can be treated as free network solutions without any deformation due to primary referencing. In this paper we analyse their weekly coordinate combinations and the troposphere zenith delays in 2-hour intervals.

3. Mathematical model for referencing time series of permanent network coordinates

The common coordinate variations of the whole network which are due to variations of the constrained reference station (BOR1) and due to systematic regional influences will be eliminated by referencing of the whole network to a set of selected stations. The stations which appear as a most stable from the long-term point of view are used as the reference. This step means that the station residuals from this referencing will reflect only the relative station variations. The residual time series of local station coordinates will be further analyzed for linear trend and seasonal variations at the individual network sites.

The aim of the referencing procedure is to obtain series containing detailed information about time variations of permanent station coordinate components. The elimination of coordinate changes common to the whole network analysed (the network is situated on one tectonic plate) will enable refined investigation of local station behaviour. We will briefly describe here the procedure of transformation of the daily stations coordinates referenced to the ITRF 2000 through constraining the fiducial station BOR1 to the relative station coordinates related to the "mean" position of the network at the epoch of observation t. Further details are in *(Hefty et al., 2005)*.

The network solution, which is output of the weekly network combination related to the actual epoch t yields the set of Cartesian coordinates

$$\mathbf{X}(t) = \begin{bmatrix} \mathbf{X}_1(t) \\ \mathbf{X}_2(t) \\ \vdots \\ \mathbf{X}_n(t) \end{bmatrix} \tag{1}$$

and their covariance matrix $\Sigma_X(t)$. The elements of (1) are the coordinates $\mathbf{X}_i(t) = \left[X_i(t)\, Y_i(t)\, Z_i(t) \right]^T$, $(i = 1,\, 2,\, \ldots n)$ of n stations included in the actual network solution in the epoch t.

Geocentric coordinates $\mathbf{X}_j(t)$ of subset of m $(j = 1, 2, \ldots m,\, m \leq n)$ selected stable stations will be further reduced for mean station position $\mathbf{X}_{0j}$ at reference epoch t_0 and the a-priori station velocity $\mathbf{v}_{0j}$ as

$$\Delta\mathbf{X}_j(t) = \mathbf{X}_j(t) - \mathbf{X}_{0j} - \mathbf{v}_{0j}(t - t_0) \tag{2}$$

In the case of well-predicted mean position $\mathbf{X}_{0j}$ and velocity $\mathbf{v}_{0j}$, the value $\Delta\mathbf{X}_j(t)$ should vary only due to random errors of coordinates of the station j and due to random errors of the reference station. For sites included in ITRF 2000 (*Boucher et al., 2004*) we use their ITRF related $\mathbf{X}_0$ and $\mathbf{v}_0$, for the other sites their most reliable values estimated by iterations are used. The common part of the $\Delta\mathbf{X}_j(t)$ variations reflects the whole network drift and actual network orientation at the epoch t. It can be modelled by three translation parameters $T_X(t)$, $T_Y(t)$, $T_Z(t)$ and three rotation angles $\omega_X(t)$, $\omega_Y(t)$, $\omega_Z(t)$.

The relation among the differences $\Delta\mathbf{X}_j(t)$ of the individual stations and the common parameters $\mathbf{T}(t)$ could be written as

$$\Delta\mathbf{X} = \begin{bmatrix} \Delta\mathbf{X}_1(t) \\ \Delta\mathbf{X}_2(t) \\ \vdots \\ \Delta\mathbf{X}_n(t) \end{bmatrix} = \begin{bmatrix} \mathbf{A}_1 \\ \mathbf{A}_2 \\ \vdots \\ \mathbf{A}_n \end{bmatrix} \begin{bmatrix} T_X(t) \\ T_Y(t) \\ T_Z(t) \\ \omega_X(t) \\ \omega_Y(t) \\ \omega_Z(t) \end{bmatrix} = \mathbf{AT}(t) \tag{3}$$

where submatrices of the design matrix $\mathbf{A}$ are given as

$$\mathbf{A}_i = \begin{cases} \begin{bmatrix} 1 & 0 & 0 & 0 & Z_{0i} - Z_B & -(Y_{0i} - Y_B) \\ 0 & 1 & 0 & -(Z_{0i} - Z_B) & 0 & X_{0i} - X_B \\ 0 & 0 & 1 & Y_{0i} - Y_B & -(X_{0i} - X_B) & 0 \end{bmatrix} \star \\ \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \star\star \end{cases} \tag{4}$$

$\star$ if the station is among the selected reference
$\star\star$ for other stations

X_B, Y_B, Z_B are coordinates of barycentre of the network. The estimate of parameters $\hat{\mathbf{T}}(t)$ is obtained by least square adjustment and the residuals of all network stations (the reference ones as well as the non-reference) are defined then as

$$\delta\mathbf{X}(t) = \Delta\mathbf{X}(t) - \mathbf{A}\hat{\mathbf{T}}(t) \tag{5}$$

The time series $\{\delta\mathbf{X}_i(t_k)\}$, $k = 1, 2, \ldots p$, where p is number of observed epochs, describes the station behaviour in the time domain.

For better interpretation the residuals of each station i expressed in geocentric system X, Y, Z are transformed to the local system n, e, u (n – north-south, e – east-west, and u – up component) according to

$$\delta\mathbf{N}_i(t) = \begin{bmatrix} \delta n_i(t) \\ \delta e_i(t) \\ \delta u_i(t) \end{bmatrix} = \begin{bmatrix} -\sin\varphi_i\cos\lambda_i & -\sin\varphi_i\sin\lambda_i & \cos\varphi_i \\ -\sin\lambda_i & \cos\lambda_i & 0 \\ \cos\varphi_i\cos\lambda_i & \cos\varphi_i\sin\lambda_i & \sin\varphi_i \end{bmatrix} \begin{bmatrix} \delta X_i(t) \\ \delta Y_i(t) \\ \delta Z_i(t) \end{bmatrix} =$$

$$= \mathbf{R}(\varphi_i, \lambda_i)\ \delta\mathbf{X}_i(t) \tag{6}$$

Then the $\{\delta\mathbf{N}_i(t_k)\}$ series represent the time dependent station evolution expressed in horizontal coordinate components n, e and ellipsoidal heights u. These variations are influenced mainly by effects, which are characteristic for each individual station with ellipsoidal coordinates φ_i and λ_i. The station variations common to the whole network were eliminated by the procedure described above. In this way the $\{d\mathbf{X}_i(t_k)\}$ and $\{d\mathbf{N}_i(t_k)\}$ series reflect the relative variations of each site.

Systematic behaviour of the $\{\delta n(t)\}$, $\{\delta e(t)\}$ and $\{\delta u(t)\}$ series can be described according to the model (the station index i and time index k are omitted for simplicity)

$$\begin{aligned}
\delta n\,(t) &= n_0 + dv_n\,(t-t_0) + b_n \sin\left(2\pi\,(t-t_0)\right) + c_n \cos\left(2\pi\,(t-t_0)\right) + \\
&\quad + d_n \sin\left(4\pi\,(t-t_0)\right) + e_n \cos\left(4\pi\,(t-t_0)\right) + \sum_{k=1}^{r} f_{nk}\vartheta\,(t-t_0) \\
\delta e\,(t) &= e_0 + dv_e\,(t-t_0) + b_e \sin\left(2\pi\,(t-t_0)\right) + c_e \cos\left(2\pi\,(t-t_0)\right) + \\
&\quad + d_e \sin\left(4\pi\,(t-t_0)\right) + e_e \cos\left(4\pi\,(t-t_0)\right) + \sum_{k=1}^{r} f_{ek}\vartheta\,(t-t_0) \qquad (7) \\
\delta u\,(t) &= v_0 + dv_u\,(t-t_0) + b_u \cos\left(2\pi\,(t-t_0)\right) + c_u \cos\left(2\pi\,(t-t_0)\right) + \\
&\quad + d_u \sin\left(4\pi\,(t-t_0)\right) + e_u \cos\left(4\pi\,(t-t_0)\right) + \sum_{k=1}^{r} f_{uk}\delta\vartheta\,(t-t_0)
\end{aligned}$$

where dv_n, dv_e, dv_u are the residual velocity components representing the linear station movement relative to reference station mean (the intraplate velocities). The amplitude coefficients b_n, b_e, b_u, c_n, c_e, c_u describe the annual and d_n, d_e, d_u, e_n, e_e, e_u the semi-annual variation of station positions. Sudden changes of position due to station arrangements or equipment alterations are modelled using the known function $\vartheta\,(t-t_0)$ with estimated amplitudes f_n, f_e, f_u. The epoch t and the reference epoch t_0 are expressed in years.

4. Coordinate time series and the geokinematical implications

The mean feature of $\{\mathbf{X}_i(\mathrm{t})\}$ series in (1) are the linear drift due to Eurasia tectonic plate motion which is in Central Europe manifested as global motion in north-eastward horizontal movement with observed magnitude about 25 mm/year *(Boucher et al., 2004).* The referencing and reduction procedure using the model given by (2) – (5) results in time series $\{\delta n_i(t)\}$, $\{\delta e_i(t)\}$ and $\{\delta u_i(t)\}$ which are free from global tectonic plate motion. Only the intraplate motions and local stations variations are expected to be present in the series.

In Fig. 3 are shown examples of local coordinate variation at some selected sites. We will point out to some typical situations in the station behaviour.

The station BOGO is an example showing consistent series of weekly coordinates with intraplate drift less than 1 mm/year. Station TUBO has similar behaviour; however a jump about 10 mm in the height component at the end of 2005 is clearly visible. The effect of the change of GPS receiver and antenna at TUBO resulted in the series discontinuity which has to be modelled by the term $f\vartheta\,(t-t_0)$ in (7).

The stations DRES and KRAW are typical examples of sites with seasonal variations of horizontal station position. The e-component of DRES and n-component of KRAW have annual variations with amplitudes nearly 3 mm. The origin of these local phenomena is not fully explained yet, but very probably is due to monumentation and/or instrumental reasons.

The GSR1 and ORID stations situated in Slovenia and Macedonia are examples of significant horizontal intraplate motion. Their linear drifts are about 3mm/year in north-south coordinates and in nearly opposite directions. The seasonal variations of the u-component are clearly visible at both stations.

The above examples clearly demonstrate the very individual behaviour of the analyzed stations if the millimetre accuracy is reached. The application of station analysis using the model (6) – (7) gives detailed information about all the network stations. Detection of series discontinuities relies on the site log information which allow to set the $\vartheta\,(t-t_0)$ function and consecutively to estimate the f_n, f_e, f_u amplitudes of jumps simultaneously with linear drifts and seasonal terms in station coordinates variations. We will further shortly demonstrate the outputs of the 4-year series analysis on two examples: the intraplate horizontal station drifts and annual components of horizontal coordinates variations.

Graphical representation of horizontal intraplate velocities is in Fig. 4. In the central part of the network the horizontal velocities are at the level about 1 mm/year or less. The only one exception is the velocity of KATO which clearly indicates that it is a local phenomenon. For the southern part of the network are characteristic velocities with larger amplitudes reaching from 1 to 4 mm/year. The orientation of the velocities is towards to northwest in Mediterranean-Alpine region, towards north in central Balkan and

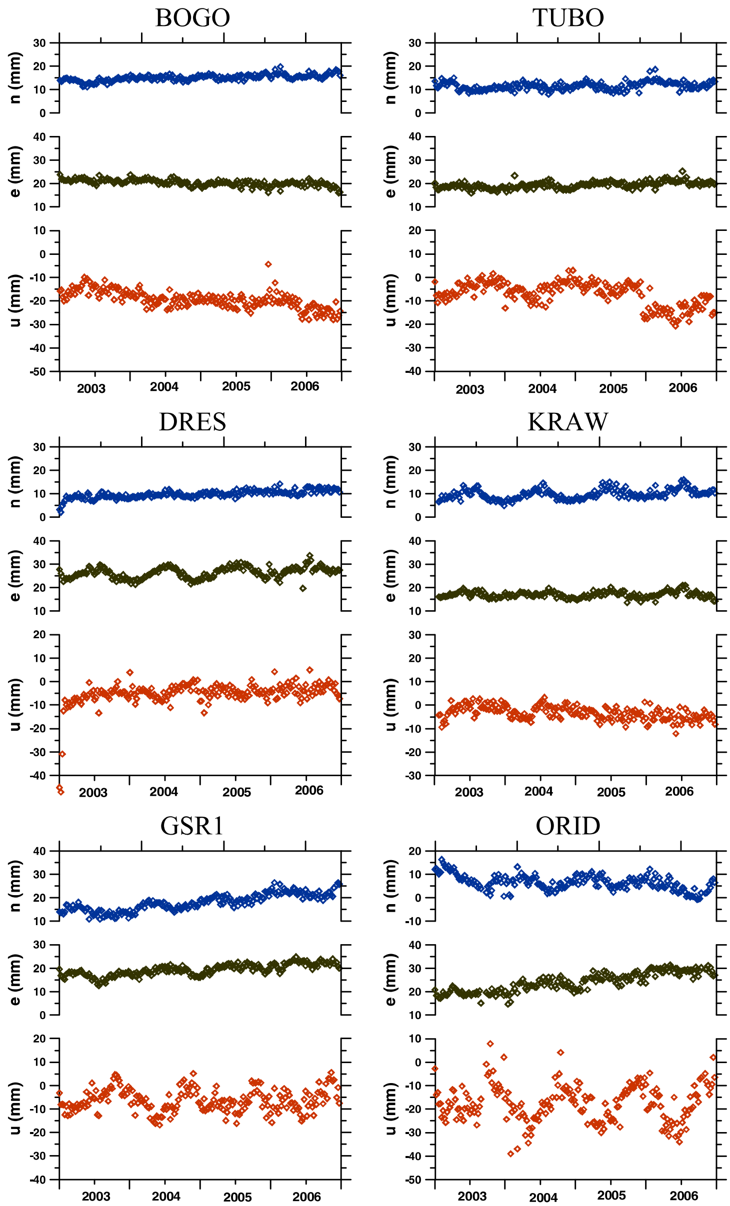

Fig. 3. Examples of local station coordinate variations in the n, e and u component at some selected sites.

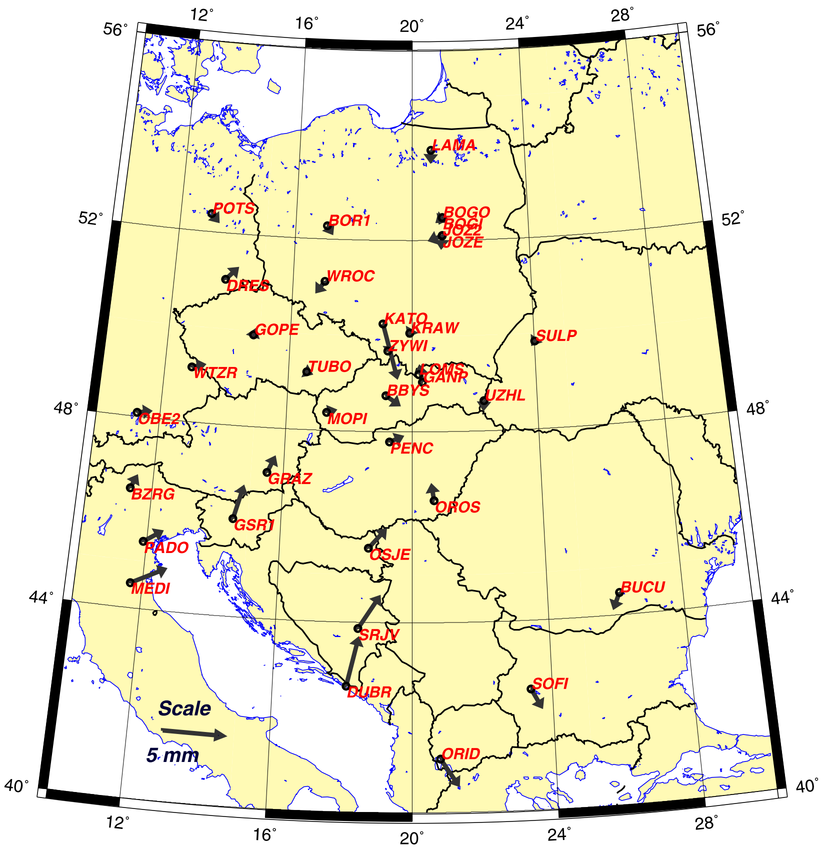

Fig. 4. Estimated horizontal intraplate velocities of the analyzed permanent stations.

towards south in the eastern Balkan. These tendencies are consistent with data obtained by other GPS derived velocities analysed in *(Hefty, 2007a)*.

The advantage of our approach to intraplate velocity estimation is the independence of the ITRF velocity field and possibility to estimate the intraplate velocities of non-EPN stations. However the consistency with ITRF 2000 velocities *(Boucher et al., 2004)* reduced for the APKIM modelled velocities *(Drewes, 1998)*, the EPN intraplate velocities *(Kenyeres, 2006)* and the CERGOP velocities evaluated from CERGOP epoch observations from 1994 to 2005 *(Hefty and Gerhátová, 2006)* was proved at the 1mm/year level *(Hefty, 2006)*.

Periodical variations of horizontal coordinates and ellipsoidal heights are besides the long-term drift the most pronounced phenomenon of permanent station behaviour. The origin of seasonal variations with amplitudes reaching from 1 to 5 mm is not fully explained. It is partly a regional phenomenon with some local anomalies. We estimated the annual and semi-annual terms according to model (7) for all stations with observation history longer than two years. Fig. 5 documents the amplitudes and phases of annual variations

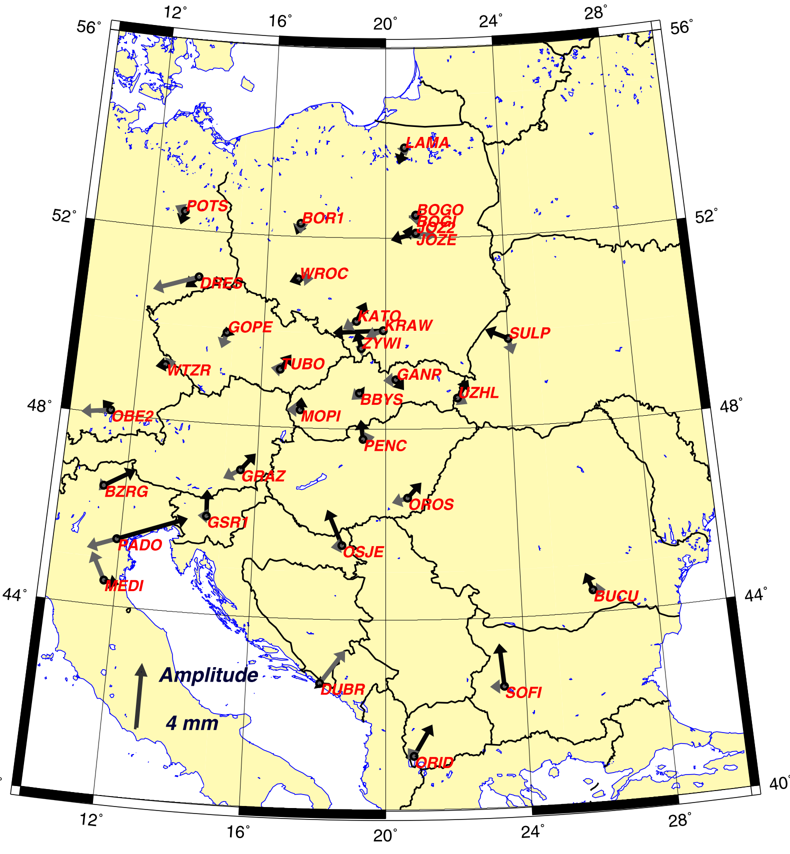

Fig. 5. Amplitudes of annual variations in north-south direction (black) and in east-west direction (gray). The orientation of vectors gives phases: direction to east means maximum in January, orientation to east maximum in July.

in north-south and east-west components. The orientation of vectors is giving the phase of the variation with east direction indicating maximum in January and west direction indicating the maximum in July. Local anomalies are characteristic for stations PADO, KRAW in north-south constituent, and DRES, DUBR and MEDI in east-west constituent. They exhibit variations with amplitudes above 2–3 mm and phases not consistent with the regionally distributes phases of other neighbouring stations. A regional pattern is visible e.g. for stations ORID, OSJE, SOFI and BUCU.

5. Zenith total delays time series

Simultaneously with the processing of daily batches aimed to coordinate adjustment are estimated zenith total delays for each participated permanent station. Zenith delays presented here are the results for 2-hour subintervals. They represent the actual effect of troposphere on GPS carrier phase propagation. ZTD is a sum of the dry and wet components with the dominant part of the dry component (about 90%). However, the time variability of ZTD in mainly caused by the wet part related to water vapour content in the troposphere.

Fig. 6 shows examples of ZTD for four-year interval for two stations MOPI and PENC. The annual signal is clearly visible and is dominating to all station ZTD series. The ZTD actual data serve as the input for precibitable water vapour modelling *(Igondová and Hefty, 2008).* Here we will restrict ourselves on pointing on some peculiarities of the ZTD series at the individual GPS sites. As the annual and semi-annual terms are dominating to ZTD series, the parameters of these terms were estimated for all the network sites. In Tab. 1 are summarized the mean values of ZTDs and amplitudes of annual and semi-annual terms at four Slovakian stations and two stations close to Slovakian borders.

Mean of the ZTDs at individual stations is in general inversely proportional to the station height. This is implied in the modelling of the troposphere influence on the GPS observations. However such dependence is not as clearly pronounced for annual and semi-annual terms as it could be expected. It is remarkable that the long-term drift of ZTD on all stations in Table 1 has a positive value.

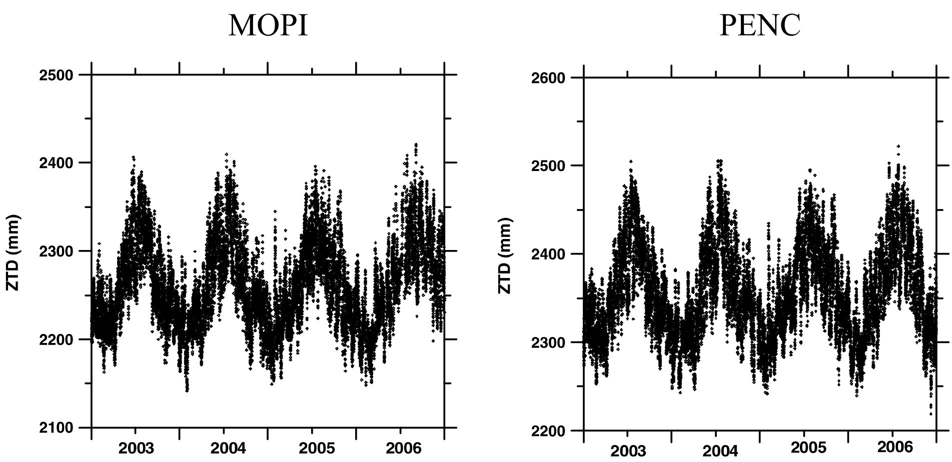

Fig. 6. Examples of four years of zenith total delays estimates from the GPS permanent observations.

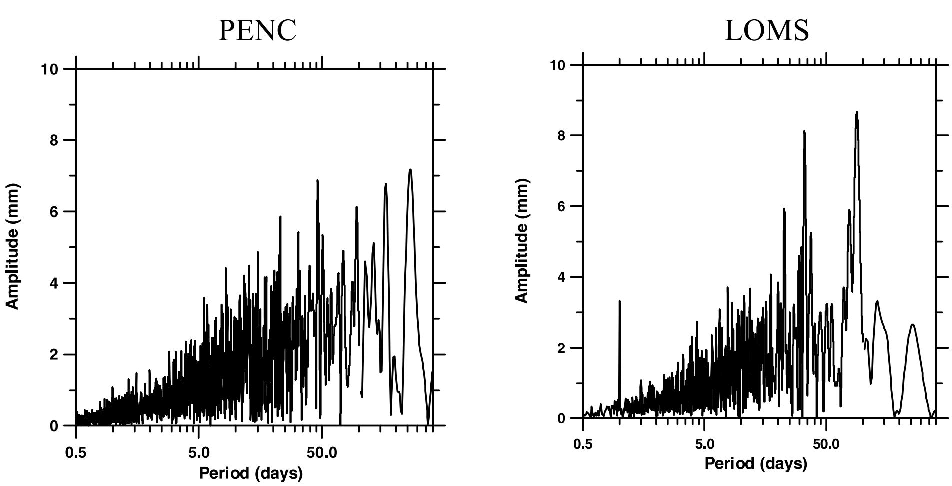

Fig. 7. Examples of amplitude spectra of ZTD residuals after eliminating the long-term and seasonal changes. Note the peak at 1 day period in LOMS series.

Table 1. Mean, drift and amplitudes of annual, semi-annual and diurnal periodic terms of ZTD at permanent sites in Slovakia and close to Slovakian borders

Site	Interval of data (years)	Height above WGS84 ellipsoid (m)	Mean ZTD and annual drift (mm) (mm/year)	Amplitude and mean error of Annual term (mm)	Semi-annual term (mm)	Diurnal term (mm)	RMS of ZTD residuals (mm)
BBYS	4.0	487.9	2296.0	51 3	8.2	0.5	35.1
			+0.4	0.5	0.5	0.5	
GANP	3.8	746.0	2209.9	53.3	7.2	2.9	30.4
			+1.8	0.5	0.5	0.6	
LOMS	2.3	2676.3	1710.0	37.2	5.1	3.4	23.1
			+1.8	0.4	0.4	0.4	
MOPI	4.0	578.9	2256.7	48.3	8.1	0.8	32.9
			+2.5	0.5	0.5	0.5	
PENC	4.0	291.7	2352.8	54.1	8.5	0.8	32.7
			+1.3	0.5	0.5	0.5	
UZHL	4.0	231.7	2359.3	51.5	6.8	1.1	34.9
			+3.8	0.5	0.5	0.5	

The ZTD residuals after eliminating seasonal variations were analysed by least-squares spectral analysis. Fig. 7 shows spectra in interval from 0.5 to 400 days. We observe the noise decrease towards higher frequencies, which is typical for coloured noise models of GPS coordinates (Williams, 2003, Hefty, 2007b). The exception of this rule is diurnal term observed in LOMS spectra. Therefore we additionally estimated the term with exactly 24-hour period for all the series. Results in Table 1 show that from the 6 stations it is significant in GANP and LOMS ZTD series only. There are several peaks in range from 20 to 150 days with no preference for some certain periods. The local character of ZTD is visible and will be further analysed.

6. Conclusions

The analysis of GPS permanent stations in Central Europe and adjacent regions has shown that the individual behaviour of the sites monitored can be deduced from the four-year interval of data analysis. The homogeneous set of station coordinate and ZTD time series was obtained by using of the unique analysis procedures, consistent reference frame and standard software application. From the bulk of the analysis output data we were concentrated on weekly station coordinates and 2-hour troposphere induced ZTDs.

In the coordinate analysis the main feature are the intraplate motions at the mm/year level and the annual variations. Significant differences are among the individual network stations. While the majority of the long-term station drifts can be interpreted as the consequence of intraplate tectonics, the seasonal variations have no clear interpretation yet.

The ZTD series exhibit annual variability with about 50 mm amplitude, visible at all stations. However the local differences occur, which cannot be explained by the station height dependence. Also the diurnal term was detected at some stations; its interpretation has to be examined in future.

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