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Homogenization of long-term GPS monitoring series at permanent stations in Central Europe and Balkan Peninsula

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Abstract: The network of 54 permanent GPS stations situated in Central Europe, Alpine-Adriatic region and Balkan Peninsula is analyzed by unified processing strategy, using homogeneous models for reduction of physical effects, and is uniformly referred to as the International Terrestrial Reference Frame – ITRF2005. The resulting time series of observed site coordinates and site troposphere parameters from interval 1999.5 to 2008.5 are inspected for their continuity, homogeneity, long-term drift, and seasonal variations.

Key words: GPS permanent stations in Central Europe, GPS reprocessing, time series of site coordinates, zenith total delays and precipitable water vapor

1. Introduction

Continuous observation series at permanent GPS stations provide information about changes of position due to lithosphere continental plate motions, regional and local geodynamics, periodic variations of geocentric coordinates as well as about the ionosphere and troposphere variability. The quality of outputs obtained strongly depends on processing strategies, used reference frames, and modeling of physical effects when analyzing the satellite observations – GPS code pseudoranges and carrier phases. There is a common practice to apply the most recent software packages, actual reference frames realizations and the best models available when analyzing the actually observed data. The consequence of such approach is that the resulting time series of site coordinates, troposphere and ionosphere characteristics and station parameters are not fully homogeneous from the long-term view due to changes in the processing strategy and different reference frame realizations.

The most reasonable way how to homogenize the whole period of observations is to reprocess the past available observed data with unified models and software applied for recent routine network analysis. The possibility of application of such approach to continental or regional networks is supported now by the fact that the global GPS tracking network analyzed in the framework of the International GNSS Service (IGS) was completely reprocessed until 2006.0 *(Steinberger et al., 2006)*. The strategy applied was similar with the analyzing process used recently by IGS *(IGS, 2009)*, so that all the global products based on IGS network which are available now were processed in the unified way. The final products – precise satellite orbits, Earth orientation parameters, and satellite clock corrections are mutually consistent and appropriate for application within the continental and regional networks.

In this paper the strategy and some results of analysis of network of permanent Global Navigation Satellite System (GNNS) stations situated in Central and South-East Europe *(Hefty and Igondová, 2008)* will be outlined. Data from 1999.5 to 2008.5 were processed by Bernese GPS analysis software, version 5.0 – BV50 *(Dach et al., 2007)* applying the homogeneous procedure and models. We will concentrate on the station coordinate series used for site velocities estimates and the zenith total delays (ZTD) applied for determination of precipitable water vapor (PWV) over the observing stations. The use of other products from the homogenized processing will be discussed elsewhere.

2. Processing scheme

The applied GPS data analysis is consistent with recent strategies used for global or large regional networks. The input data used for daily network solutions are the RINEX observational data covering the intervals from 0 h to 24 h UT. All the computations are performed by BV50 installed in the LINUX FEDORA 2.6.12.3 environment. Main attributes of the processing strategy are:

- Processing in daily intervals (0–24 h UT), final solutions are based on carrier phases only.
- Use of IGS orbits and corresponding ERPs since 2006.0, before this date the IGS reprocessing data are used.
- Sampling rate 30 s for pre-processing and ambiguity resolution, 180 s for final coordinate estimates.
- Simultaneous daily network processing of all the network stations (from 18 to 53 sites).
- 3 degrees elevation angle.
- Reference point BOR1 with ITRF2005 coordinates reduced to epoch of observation. In the case of unavailability of complete or correct BOR1 observations, the ZIMM is used as reference. Such approach leads to free network solution.
- Troposphere zenith total delays are estimated at each station in hourly intervals, Dry Niell and Wet Niell mapping function *(Dach et al., 2007)* are applied with elevation dependent weighting, troposphere gradients are estimated for 24-hour intervals.
- Baseline geometry is usually fixed, only in the case of data gaps slight modification of baseline geometry is performed.
- For ambiguity fixing the QIF strategy *(Dach et al., 2007)* is applied.
- Satellite and receiver antenna eccentricities are from the IGS05 absolute calibration model.
- Ocean loading model FES2004.

For the final solution the resolved ambiguities are pre-eliminated, and the final parameterization includes the daily site coordinates, ZTDs for one-hour intervals and troposphere gradients for 24-hour intervals. The coordinates from 24-hour solutions are finally combined to weekly solutions which are used in further analyses.

The routine processing according to the above mentioned strategy started in GPS week 1400, which is corresponding to epoch 2006.86. All the observations before week 1400 were reprocessed (the reprocessing interval reported here started in GPS week 1016). The main advantage of the routine processing and reprocessing products is the fact that no reference frame changes occurred and the same models for troposphere, solid earth and ocean tides, and antenna phase centers corrections are applied, as well as the constant cut-off angle and observation weighting strategy is used.

3. Analyzed network and its evolution

As the number of permanent GNSS stations available in the region of our interest was continually increasing from the time of establishing first stations in 1994, the reprocessed network has gradually increased from 20 stations in 1999 to 54 selected stations in 2008. Fig. 1 shows the network status in 2008.5 with 45EUREF Permanent Network (EPN) stations (EPN, 2009) and 9 non-EPN sites. The increase of number of stations is documented by Fig. 2. The network has been enlarged gradually till 2006.86 when 10 stations were added. After this completion the network remained stable.

Figure 3 documents the availability of relevant final weekly coordinate solutions at network stations. There were 19 stations which had observa-

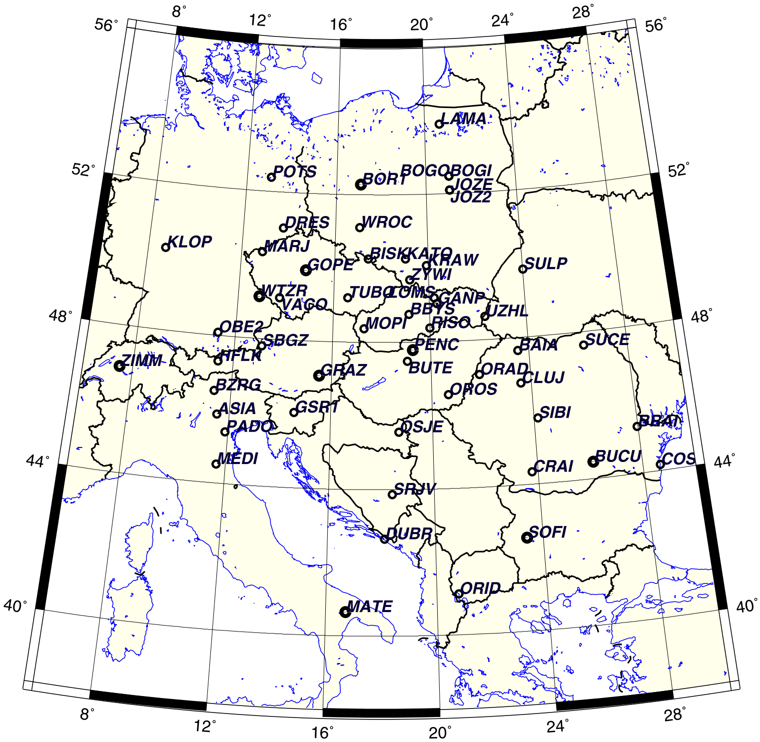

Fig. 1. Network of GNSS stations analyzed. Sites which are used for referencing to ITRF2005 are highlighted with full circles.

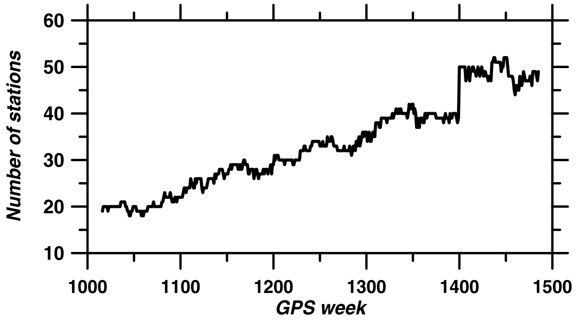

Fig. 2. Number of stations included in weekly combinations.

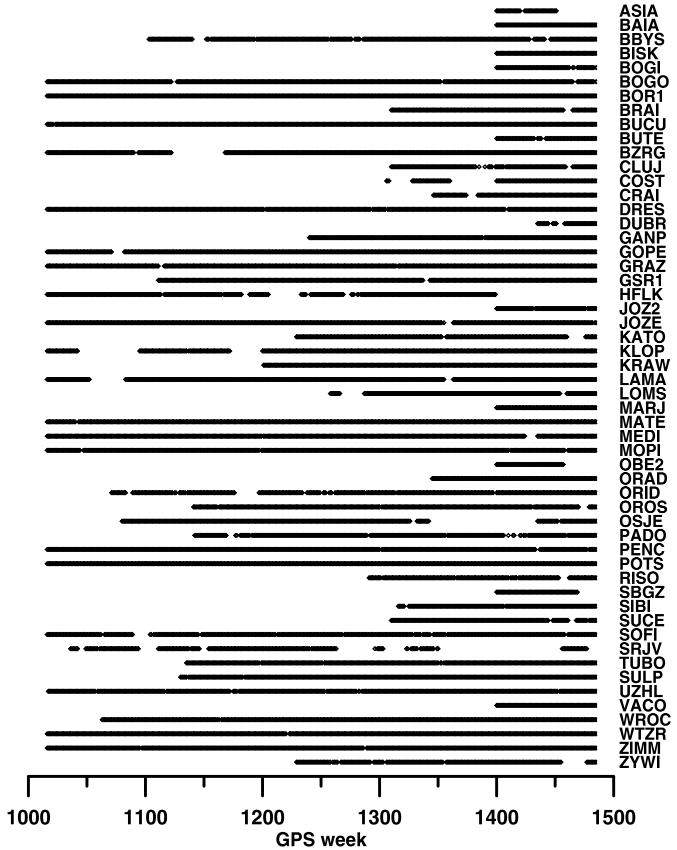

Fig. 3. Availability of weekly coordinate solutions at analyzed stations.

tions during the whole 9-year interval analyzed (some of them with several minor gaps). It is evident that more gaps of data have to be expected in all the station series. The reasons of lack of final weekly site coordinates are the unavailability of observations as well as exclusions of computed coordinates from weekly solutions after statistical testing of outliers. The gaps in the series (if the observing facilities remain unchanged) make no difficulties for velocity estimates, although they can slightly involve the estimation of seasonal variation parameters. For relevant velocity and seasonal term estimations we take as minimum the 3-year interval of data with 90% coverage at least. Applying these criteria, the number of sites suitable for analysis in this paper is reduced to 40. We apply these strict criteria due to previous experience with permanent stations analysis, where irregular variations with 2-year or longer effect were observed to strongly influence the station parameter estimates.

For ZTD and Precipitable Water Vapor (PWV) series in which the subdaily resolution is necessary, the continuity of the series is of primary importance. Moreover, the availability of site atmosphere pressure and temperature data is necessary for PWV, so the number of relevant sites is reduced to 10 stations.

4. Method of the compilation of coordinate time series

The fact that the whole 9-year period was analyzed with the unchanged strategy allows applying a simple strategy to referencing the weekly free network solutions to the ITRF2005. Following the transformation model in described *(Hefty, 2004)* we can write

$$\mathbf{x} = \begin{bmatrix} \mathbf{x}^{(ITRF)} \\ \mathbf{x}_I^{(obs)} \\ \mathbf{x}_N^{(obs)} \end{bmatrix} = \begin{bmatrix} \mathbf{I}_I & \mathbf{0} & \mathbf{0} \\ \mathbf{I}_I & \mathbf{0} & \mathbf{T}_I \\ \mathbf{0} & \mathbf{I}_N & \mathbf{T}_N \end{bmatrix} \begin{bmatrix} \mathbf{y}_I \\ \mathbf{y}_N \\ \Theta \end{bmatrix} + \begin{bmatrix} \varepsilon^{(1)} \\ \varepsilon_I^{(2)} \\ \varepsilon_N^{(2)} \end{bmatrix} = \mathbf{A}\,\mathbf{y} + \varepsilon, \tag{1}$$

where $\mathbf{x}^{(\mathrm{obs})}$ are the observed coordinates resulting from the weekly combination procedure and $\mathbf{x}^{(\mathrm{ITRF})}$ are the ITRF2005 coordinates at the epoch of observations. The ITRF2005 reference data are computed using the coordinates and velocities in *(ITRF, 2009)*. For simplicity we omit at this moment the time factor t related to the observed coordinates. The global vectors of coordinates $\mathbf{x}$ are composed from 3D coordinates X_1, X_2, X_3 of p sites as

$$\mathbf{x} = \begin{bmatrix} \mathbf{x}_1 \\ \mathbf{x}_2 \\ \vdots \\ \mathbf{x}_p \end{bmatrix}, \quad i = 1,\, 2,\, \ldots p,\ \mathbf{x}_i = \begin{bmatrix} X_{1_j} \\ X_{2_j} \\ X_{3_j} \end{bmatrix}. \tag{2}$$

Indices I in (1) indicate the reference sites with known predicted ITRF2005 positions and N is used to denote the non-identical points. The number p of sub-vectors $\mathbf{x}_i$ in (2) reflects the number p_I of reference sites with ITRF coordinates or number p_N of sites for which the ITRF coordinates are determined. Symbols $\mathbf{I}_I$ and $\mathbf{I}_N$ denote the identity matrices of relevant dimensions and $\mathbf{T}_I$ and $\mathbf{T}_N$ are the design matrices of the form

$$\mathbf{T} = \begin{bmatrix} \mathbf{T}_1 \\ \mathbf{T}_2 \\ \vdots \\ \mathbf{T}_p \end{bmatrix},$$

$$\mathbf{T}_i = \begin{bmatrix} 1\,0\,0\, X_{1_j} - X_{1B} & 0 & -\left(X_{3_j} - X_{3B}\right) & X_{2_j} - X_{2B} \\ 0\,1\,0\, X_{2_j} - X_{2B} & X_{3_j} - X_{3B} & 0 & -\left(X_{1_j} - X_{1B}\right) \\ 0\,0\,1\, X_{3_j} - X_{3B} & -\left(X_{2_j} - X_{2B}\right) & X_{1_j} - X_{1B} & 0 \end{bmatrix}. \tag{3}$$

Values X_{1B}, X_{2B}, X_{3B} are the barycentre coordinates of the network. Parameters of the model (1) are: ITRF coordinates of identical and non-identical sites $\mathbf{y}_I$ and $\mathbf{y}_N$, and the transformation parameters Θ comprising from 3 translations, scale factor and 3 rotations angles

$$\mathbf{\Theta} = \left[dX_1\, dX_2\, dX_3\, \Delta\, \omega\, \psi\, \vartheta \right]^T. \tag{4}$$

The vector $\boldsymbol{\varepsilon}$ represents the random errors of observed coordinates. The covariance matrix of observations has the form

$$Var\left(\boldsymbol{\varepsilon}\right) = \mathbf{\Sigma}_x = \begin{bmatrix} \mathbf{\Sigma}^{(ITRF)} & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{\Sigma}_I^{(obs)} & \mathbf{\Sigma}_{IN}^{(obs)} \\ \mathbf{0} & \mathbf{\Sigma}_{NI}^{(obs)} & \mathbf{\Sigma}_N^{(obs)} \end{bmatrix}. \tag{5}$$

The estimate $\hat{\mathbf{y}} = \begin{bmatrix} \hat{\mathbf{y}}_I \\ \hat{\mathbf{y}}_N \\ \hat{\Theta} \end{bmatrix}$ of parameters $\mathbf{y}$ is obtained according to the standard least-squares model, see e.g. *Kubáčková (1990).*

The coordinate residuals reduced by reference frame shift, orientation and scale are given by

$$\delta\mathbf{x} = \begin{bmatrix} \delta\mathbf{x}_I \\ \delta\mathbf{x}_N \end{bmatrix} = \begin{bmatrix} \mathbf{x}_I^{(obs)} - T_I\hat{\Theta} - \mathbf{x}_I^{(0)} \\ \mathbf{x}_N^{(obs)} - T_N\hat{\Theta} - \mathbf{x}_N^{(0)} \end{bmatrix}, \tag{6}$$

where $\mathbf{x}_I^{(0)}$, $\mathbf{x}_N^{(0)}$ are the apriori coordinates of identical and non-identical sites.

If we now introduce the time factor of the observations related to the epoch t_j then the time series of coordinate residuals is $\{\delta\mathbf{x}(t_j)\}$, $j = 1, 2, \ldots r$, where r is the number of observed epochs (the number of weekly combinations available).

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

$$\mathbf{n}_i\left(t_j\right) = \begin{bmatrix} n_i\left(t_j\right) \\ e_i\left(t_j\right) \\ u_i\left(t_j\right) \end{bmatrix} = \begin{bmatrix} -\sin\varphi_i\cos\lambda_i & -\sin\varphi_i\sin\lambda_i & \cos\varphi_i \\ -\sin\lambda_i & \cos\lambda_i & 0 \\ \cos\varphi_i\cos\lambda_i & \cos\varphi_i\sin\lambda_i & \sin\varphi_i \end{bmatrix} \begin{bmatrix} \delta X_{1i}\left(t_j\right) \\ \delta Y_{2i}\left(t_j\right) \\ \delta Z_{3i}\left(t_j\right) \end{bmatrix} =$$

$$= \mathbf{R}\left(\varphi_i, \lambda_i\right)\delta\mathbf{x}_i\left(t_j\right). \tag{7}$$

These variations are influenced by the effects which are characteristic for each individual station (the station i has ellipsoidal coordinates φ_i and λ_i). Values $\mathbf{n}_i\left(t_j\right)$ relate the actual ITRF position at the epoch t_j to the initial site positions given by sub-vectors in $\mathbf{x}_I^{(0)}$, $\mathbf{x}_N^{(0)}$.

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

$$
\begin{aligned}
n(t) &= n_0 + v_n (t - t_0) + b_n \sin(2\pi (t - t_0)) + c_n \cos(2\pi (t - t_0)) + \\
&+ \ d_n \sin(4\pi (t - t_0)) + e_n \cos(4\pi (t - t_0)) + \sum_{k=1}^{r} f_{nk} \phi (t - t_0), \\
e(t) &= \ldots, \\
u(t) &= \ldots .
\end{aligned} \tag{8}
$$

The expressions for $e(t)$ and $u(t)$ are analogous to the expression for $n(t)$. The values of v_n, v_e, v_u are the ITRF velocity components representing the global linear annual station movement. 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 $\phi(t - t_0)$ with unknown amplitudes f_n, f_e, and f_u. It is worth mentioning that no jumps due to reference frame alteration have to be introduced. The epoch t and the reference epoch t_0 are expressed in years.

The principal difference from the approach of referencing the observations presented in *(Hefty and Igondová, 2008)* is that here the absolute, rather than relative, velocities are determined. The estimation of velocities v_k, amplitudes b_k, c_k, d_k, e_k of seasonal variations and amplitudes f_k of offsets in the series is performed separately for $k = n$, e, u components.

5. Velocities and seasonal variations obtained from homogenized coordinate time series

The stability of the referencing procedure can be evaluated by inspecting the time series of transformation parameters in (4). To maintain the original scale of observations of the Central European GPS network, the scale factor Δ was not estimated. For referencing we have selected a set of 9 stations with site coordinates and velocities determined in the ITRF2005, namely the stations: BOR1, BUCU, GOPE, GRAZ, MATE, PENC, SOFI, WTZR and ZIMM. The criterion for selection of the stations was their long-term stability and the optimum geometry of the network of identical points (Fig. 1).

Figure 4 shows the time series of transformation parameters estimated for linking the weekly coordinate solutions to ITRF2005. The drifts of the translation parameters which are below 0.5 mm/year and of the rotation

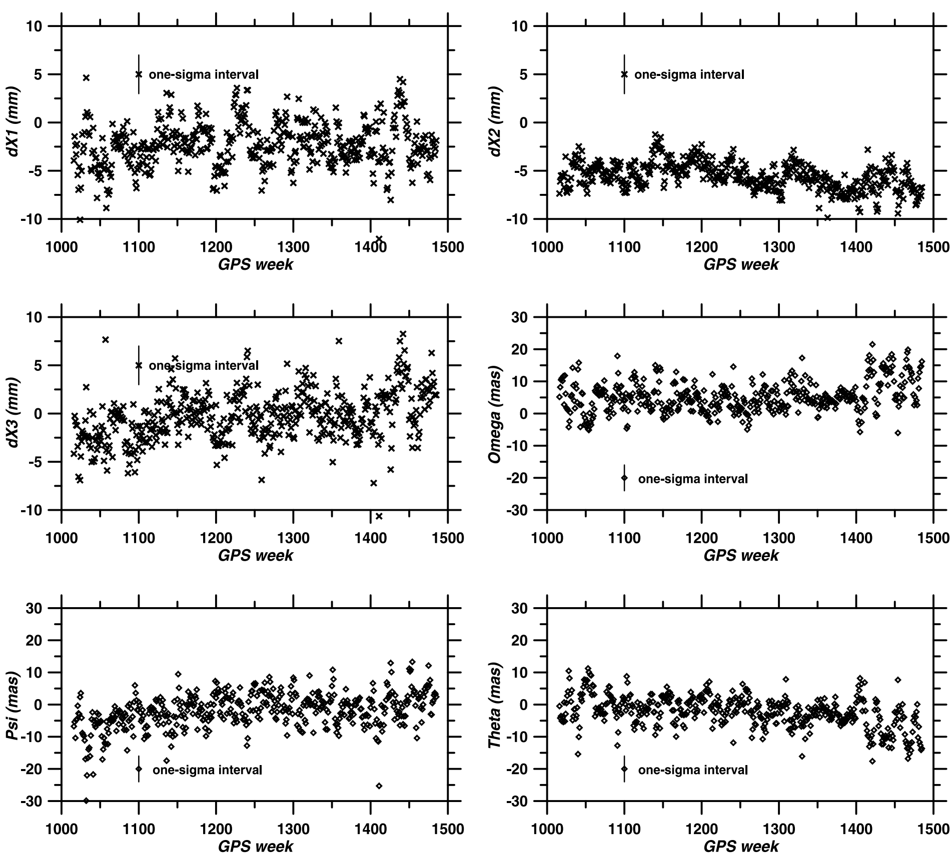

Fig. 4. Time series of transformation parameters estimated for linking the weekly coordinate solutions to ITRF2005. The one-sigma intervals show the mean values reflecting the consistency of estimated coordinates with ITRF2005 at identical points.

parameters which are below 1 mas/year can be explained by the inconsistency of BOR1 velocity with the velocities of other sites used for referencing. Tight constraining of BOR1 station was used for linking the network to ITRF within the processing when the coordinates are computed using the BV50 software. Spurious are the non-negligible annual variations of the transformation parameters, namely the variation of dX_1 with 1.2 mm amplitude and variations of ω, ψ, ϑ with amplitudes of 1.6 mas.

After aligning the weekly network solutions to ITRF2005 the local coordinates time series according (6)–(7) were compiled. The coordinate offsets – the last terms in (8) – were adjusted in two ways: Firstly, for situations where the reason of the offset was apriori known, e.g. the change of GPS antenna, the amplitudes of the coordinate changes were simultaneously estimated by solving eqs (8). We estimated the parameters of 32 discontinuities of this kind. Subsequently, the residuals time series obtained from the approximation by the linear trend, seasonal terms and estimated offsets was inspected. Secondly, if there were observed some significant offsets with clearly distinguished epoch of the discontinuity, their amplitudes were additionally estimated. However, such kind of discontinuities was discovered only for 5 sites in the set of stations in Fig. 3.

We then apply the following three criteria for evaluation of the homogeneity of the long-term observational series.

- Estimated velocities are evaluated by comparing the obtained data with other geo-kinematical information of the site or of the wider region.
- Estimated seasonal variations are evaluated with respect to the generally accepted fact that the significant strictly periodic seasonal coordinate variations are usually a local phenomenon related to antenna monumentation, multipath and/or atmospheric (mainly troposphere) effects and no regional seasonal pattern is observed.
- Evaluation of residual RMS errors after approximation of coordinate time series by (8), as they are a measure of the repeatability of observations and of fidelity with the model, and consequently reflect the quality of site, instrumentation and monumentation.

For better interpretation of the station coordinates behavior some typical time series are demonstrated in Fig. 5 and Fig. 6. In graphs are plotted the series obtained according to (7) with elimination of the estimated offsets f in (8). From the residual ITRF2005 coordinates the motion model *(Drewes, 1998)* was subtracted, so the series in Figs. 5–6 represent the change of station coordinates relative to the uniform rotation of European tectonic plate.

The series for two stations in Fig. 5 exemplify the case when only linear drift is observed and the variability of the weekly coordinates is small – about 1 mm in n and e and about 2.5 mm in u components. However, it is worth to mention that the height component is not strictly linear and the

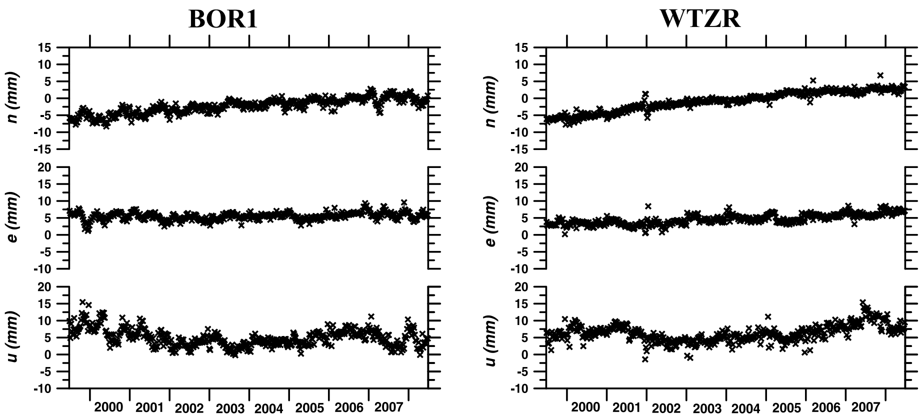

Fig. 5. Examples of stations where the linear change is dominated by the relatively slight coordinate variability.

long-term deviation from the linear approximation can be noticed.

Time series in Fig. 6 are the examples of stations at which a specific behavior is observed. For the station BUCU the u-component has a stable value in the first half of the observed interval, afterwards it has ascending trend. For the station HFLK strong annual variations in n and also in e and u are visible. At the MEDI station non-linear behavior of u and strange variability of e after 2006.8 is visible. For the MOPI station the strong variability of u is characteristic, but without any significant trend. The PADO station has strong annual variability of n and e, and increasing trend in all three constituents. The u component of RISO has a trend of – 3.3 mm/year during 3 years.

Velocities for stations with the observing interval longer than 3 years are summarized in Table 1. The table contains estimated velocities related to ITRF2005 expressed in the local horizontal system as well as the velocities reduced for plate motion model APKIM2000 which represent the intraplate velocities on the Eurasian tectonic plate. The RMS errors in the table are obtained using the white noise error model and therefore are underestimated. In future the real accuracy of velocities has to be evaluated. The colored noise site behavior of GPS data *(Bos et al., 2008)* and its influence on the velocity estimates will be studied elsewhere. In the right-hand columns of Table 1 the original ITRF2005 velocities *(ITRF, 2009)* are

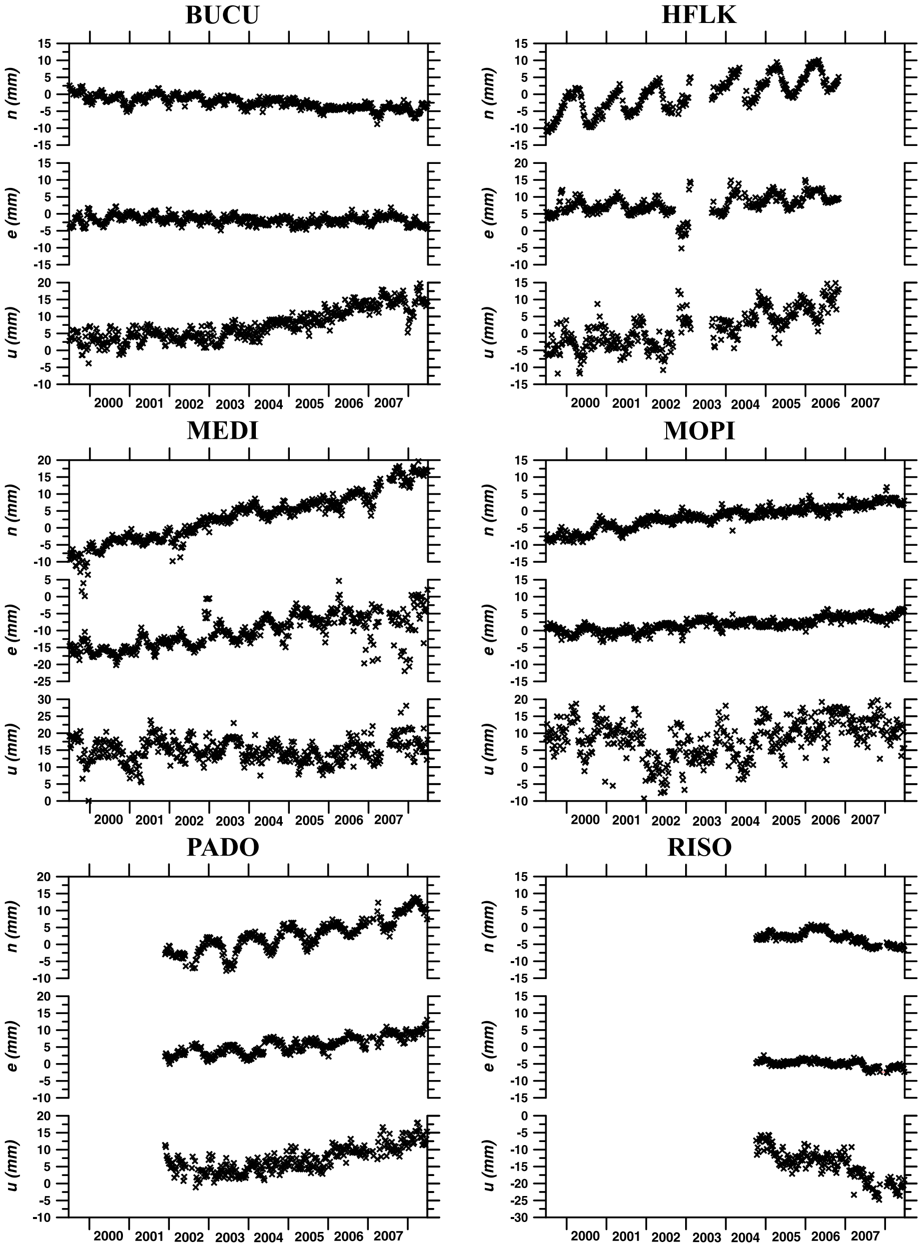

Fig. 6. Examples of stations where one or more coordinate components have a specific behavior.

Table 1. Estimated velocities related to ITRF2005 (v_n, v_e, v_u), intraplate velocities (δv_n, δv_e, δv_u) and their uncertainties (σ_{vn}, σ_{ve}, σ_{vu}). In the right-hand columns the original ITRF2005 velocities *(ITRF, 2009)* are indicated if available. The unit for all data is mm/year

Site	v_n	δv_n	σ_{vn}	v_e	δv_e	σ_{ve}	v_u	δv_u	σ_{vu}	ITRF2005		
										v_n	v_e	v_u
BBYS	14.08	0.38	0.03	21.60	0.31	0.03	0.52	0.47	0.09	-	-	-
BOGO	14.22	0.75	0.02	20.48	-0.12	0.02	-1.20	-1.25	0.06	13.82	21.02	-1.79
BOR1	14.68	0.75	0.02	20.01	0.11	0.01	-0.22	-0.27	0.05	14.81	19.81	0.54
BRAI	10.28	-2.23	0.11	26.89	2.46	0.11	-7.73	-7.77	0.28	-	-	-
BUCU	12.24	-0.54	0.02	23.21	-0.08	0.02	1.55	1.51	0.04	12.67	22.97	1.22
BZRG	15.65	1.16	0.04	20.00	-0.34	0.04	4.30	4.26	0.11	-	-	-
CLUJ	39.22	28.08	0.20	24.76	2.35	0.05	-2.41	-2.46	0.19	-	-	-
DRES	15.66	1.38	0.02	19.69	0.10	0.03	0.58	0.53	0.07	-	-	-
GANP	14.59	1.03	0.08	19.53	-1.81	0.05	-0.42	-0.46	0.12	-	-	-
GOPE	15.26	1.09	0.02	19.68	-0.41	0.02	1.55	1.50	0.05	14.33	21.17	2.57
GRAZ	15.27	1.17	0.02	21.25	0.31	0.02	0.74	0.80	0.69	15.53	21.90	0.16
GSR1	17.26	3.06	0.02	21.10	0.08	0.03	0.78	0.74	0.07	-	-	-
HFLK	16.07	1.57	0.04	20.64	0.51	0.05	1.93	1.88	0.07	16.44	20.66	1.70
JOZE	14.36	0.89	0.03	20.97	0.28	0.02	0.69	0.65	0.08	14.16	20.76	2.40
KATO	10.82	-2.90	0.05	21.99	1.19	0.04	-0.52	-0.57	0.08	-	-	-
KLOP	15.28	0.59	0.02	19.00	0.16	0.03	3.85	3.80	0.10	-	-	-
KRAW	14.63	1.02	0.04	21.10	0.10	0.03	-0.31	-0.35	0.07	-	-	-
LAMA	14.20	0.69	0.04	20.02	-0.12	0.03	-0.74	-0.78	0.07	14.55	19.97	0.27
LOMS	13.99	0.41	0.07	21.81	0.53	0.06	-0.66	-0.70	0.20	-	-	-
MATE	19.03	5.05	0.03	23.19	0.64	0.02	1.21	1.16	0.06	19.40	23.15	1.18
MEDI	17.13	2.66	0.04	22.16	1.30	0.06	0.22	0.18	0.00	17.65	22.28	-2.26
MOPI	15.08	1.17	0.02	21.55	0.61	0.02	0.66	0.62	0.09	-	-	-
ORID	11.75	-1.75	0.03	23.61	0.51	0.04	-0.06	-0.10	0.07	-	-	-
OROS	14.62	1.10	0.03	22.53	0.56	0.03	-0.88	-0.92	0.06	-	-	-
OSJE	15.22	1.46	0.02	22.24	0.40	0.02	-0.17	-0.22	0.07	-	-	-
PADO	16.72	2.28	0.04	21.75	1.06	0.03	1.61	1.56	0.07	-	-	-
PENC	14.45	0.77	0.02	22.03	0.59	0.01	-0.36	-0.41	0.05	14.62	22.14	-0.57
POTS	15.00	0.66	0.02	19.14	0.05	0.02	0.10	0.05	0.06	15.11	18.86	0.21
RISO	12.45	-1.15	0.19	20.87	-0.56	0.05	-3.36	-3.41	0.15	-	-	-
SIBI	14.45	1.39	0.08	22.19	-0.52	0.13	-1.84	-1.88	0.27	-	-	-
SUCE	13.45	0.69	0.08	23.11	0.45	0.13	-3.49	-3.53	0.20	-	-	-
SRJV	16.26	2.47	0.08	22.74	0.57	0.08	0.13	0.08	0.15	-	-	-
SOFI	12.17	-1.00	0.03	23.84	0.61	0.02	-0.79	-0.83	0.05	11.86	23.91	0.82
TUBO	14.70	0.71	0.02	20.68	0.07	0.02	1.32	1.28	0.05	-	-	-
SULP	13.80	0.72	0.03	21.91	0.12	0.03	-0.92	-0.96	0.09	-	-	-
UZHL	13.73	0.42	0.02	21.81	0.04	0.02	-0.14	-0.19	0.05	-	-	-
WROC	14.45	0.52	0.02	20.15	-0.06	0.02	1.71	1.67	0.04	15.05	20.33	3.78
WTZR	15.43	1.08	0.02	20.34	0.41	0.02	0.38	0.33	0.04	15.67	20.23	1.51
ZIMM	16.11	1.32	0.02	19.71	0.20	0.02	2.65	2.60	0.04	16.08	19.58	2.33
ZYWI	14.63	0.94	0.04	21.24	0.28	0.04	-0.83	-0.00	0.13	-	-	-

shown, if available.

Comparison of individual velocities given in Table 1 with the data derived from the smoothed intraplate velocity field obtained from the combination of regional and local velocity fields in *(Hefty, 2007)* is shown in Fig. 7.

We observe generally good consistency of the two types of data; however, some significant discrepancies can be stated. The most evident is the station CLUJ, where the local land slide is reported. The velocity of KATO is also anomalous where apparently the local phenomenon is observed.

The consistency of our estimates with the original ITRF2005 horizontal velocities v_n and v_e is better than 0.5 mm/year. Only for the station GOPE the difference of about 1.5 mm/year is observed which can be explained by larger number of equipment alterations and subsequent offsets (5 reported antenna changes during the period analyzed). The consistency of up component velocities is below 1 mm/year for majority of stations. Larger differences are for JOZE, MEDI, SOFI and WROC.

In Table 2 we list the stations for which the estimated amplitudes of annual or semiannual variations are larger than 1 mm for horizontal component and 1.5 mm for vertical component. It is evident that in the homogenized time series there was significantly reduced by the seasonal variability of all the three coordinate components when compared to previous results e. g. *(Hefty and Igondová, 2008)*. We can state here that all the observed seasonal variations are purely local phenomena and no regional effects are

Table 2. Estimated amplitudes and their RMS errors of annual and semi-annual periodic variations (in mm) for sites where either n or e coordinate component exceeds 1 mm or u component exceeds 1.5 mm. The last column shows the number of weekly files used in the analysis

Site	North - south				East – west				Up				Number of weeks
	annual		semi-annual		annual		semi-annual		annual		semi-annual		
	amp	σ_{amp}	*amp*	σ_{amp}	*amp*	σ_{amp}	*amp*	σ_{amp}	*amp*	σ_{amp}	*amp*	σ_{amp}	
BRAI	1.54	0.21	0.95	0.21	1.30	0.22	0.43	0.22	1.04	0.41	0.96	0.41	169
BZRG	1.07	0.16	0.21	0.16	0.65	0.16	0.21	0.16	0.59	0.41	1.25	0.41	422
CLUJ	1.09	0.40	0.95	0.40	1.23	0.16	0.35	0.16	0.53	0.37	0.92	0.37	160
DRES	0.98	0.10	0.17	0.10	2.13	0.14	0.27	0.14	0.99	0.36	0.14	0.36	465
GANP	0.78	0.22	0.48	0.22	0.59	0.15	0.22	0.15	1.62	0.40	0.50	0.40	245
HFLK	4.17	0.19	1.30	0.19	2.05	0.23	0.82	0.23	3.16	0.43	0.77	0.43	336
KATO	0.95	0.13	0.26	0.13	0.74	0.11	0.07	0.11	1.52	0.24	0.16	0.24	239
KLOP	0.31	0.14	0.22	0.14	0.87	0.14	0.03	0.14	2.23	0.51	0.23	0.51	390
KRAW	2.37	0.13	0.84	0.13	1.21	0.13	0.34	0.13	1.66	0.28	0.61	0.28	285
LOMS	1.04	0.17	0.90	0.17	0.30	0.15	0.53	0.15	0.98	0.49	0.55	0.49	203
MEDI	0.41	0.22	0.12	0.22	1.62	0.31	0.56	0.31	1.40	0.48	1.28	0.48	459
MOPI	0.85	0.12	0.17	0.12	0.77	0.13	0.12	0.13	3.04	0.46	1.15	0.46	464
ORID	1.01	0.16	0.39	0.16	1.17	0.16	0.30	0.16	2.02	0.38	0.33	0.38	373
PADO	2.95	0.17	0.86	0.17	1.40	0.14	0.39	0.14	0.96	0.37	0.27	0.37	318
SRJV	1.41	0.32	0.75	0.31	0.48	0.32	0.31	0.32	0.19	0.39	0.16	0.39	247
SUCE	1.94	0.16	1.01	0.16	1.80	0.22	0.09	0.22	0.21	0.32	0.37	0.32	166

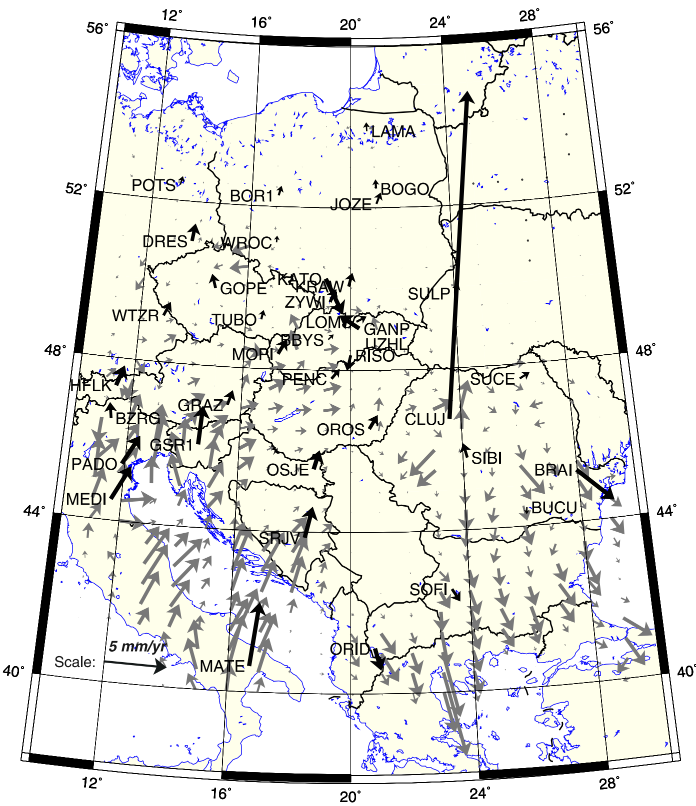

Fig. 7. Comparison of intraplate velocities obtained from the analysis in this paper (black vectors) with the interpolated velocity field (gray vectors) generated on the basis of various GNNS data in *Hefty (2007)*.

observed.

The consistency of observed coordinate variations with the adopted model (8) is documented by RMS errors of unit weight of station weekly coordinates n, e, u. Figure 8 shows that for the horizontal component the RMS errors are below 1.5 mm with exception of several more scattered stations, like CLUJ, HFLK, MEDI and SRJV. The stations HFLK and SRJV have gaps in the observation series and non-reported station equipment and monumentation manipulations can be expected. Station MEDI has peculiar behavior only for limited period (cf. the e-component in Fig. 6). All the sites mentioned can be considered as problematic. The RMS errors of the

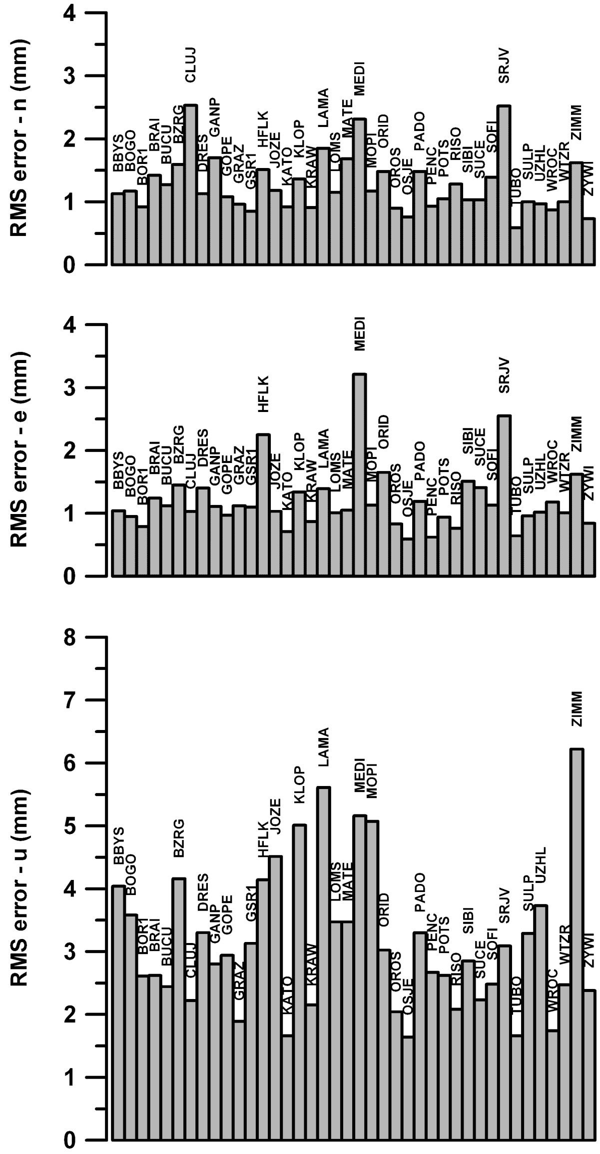

Fig. 8. Post-fit RMS errors of n, e and u coordinate components of weekly solutions for sites exceeding 3-year interval of observations.

vertical component have no strict limit; for majority of stations it is less than 4 mm. However, also the stations exceeding this limit cannot be considered as problematic, because the vertical component is very sensitive to troposphere variability, antenna and radome related effects etc. The homogenized series of height component still exhibit the behavior which cannot be satisfactorily interpreted.

6. Total zenith delays and precipitable water vapor data from the homogenized GPS analysis

The parameterization of daily GPS network processing includes besides the site coordinates also the troposphere related parameters – Zenith Total Delays and troposphere gradients *(Dach et al., 2007; Igondová and Hefty, 2008)*. These parameters are sensitive to the apriori troposphere modeling and setting of the cut-off elevation angle. Application of the homogenized processing scheme provides series which enable reliable evaluation of the long term troposphere variability. Knowing the actual surface pressure at the observing site, the dry component of ZTD can be computed and subsequently used to determinate the precipitable water vapor. The PWV value characterizes the condensed amount of water vapor over the observing site.

The long-term behavior of ZTD and PWV is shown in Fig. 9 with examples of two sites where both series almost completely cover the interval 1999.5 – 2008.5.

As it is known from previous studies, for ZTD and PWV the variations with annual, semi-annual and diurnal periods *(Hefty and Igondová, 2008)* are characteristic. In Table 3 the estimates of amplitudes of the three periodic constituents mentioned for 7 representative sites with good coverage of both ZTD and PWV data are shown. Besides the amplitudes a_{an}, a_{sa}, a_d also the mean values ZTD_0, PWV_0 and their annual drifts $\delta\, ZTD$, $\delta\, PWV$ are given. In all the ZTD series the dominant annual signal is observed and less distinct is the semi-annual one. Also the significant diurnal variation is presented in all the series. Notice, the different amplitudes of semi-annual and diurnal terms for MATE stations when compared to other sites. Similar pattern is manifested in the PWV series, althoug with amplitudes smaller by two orders. The differences among amplitudes at various sites are pure

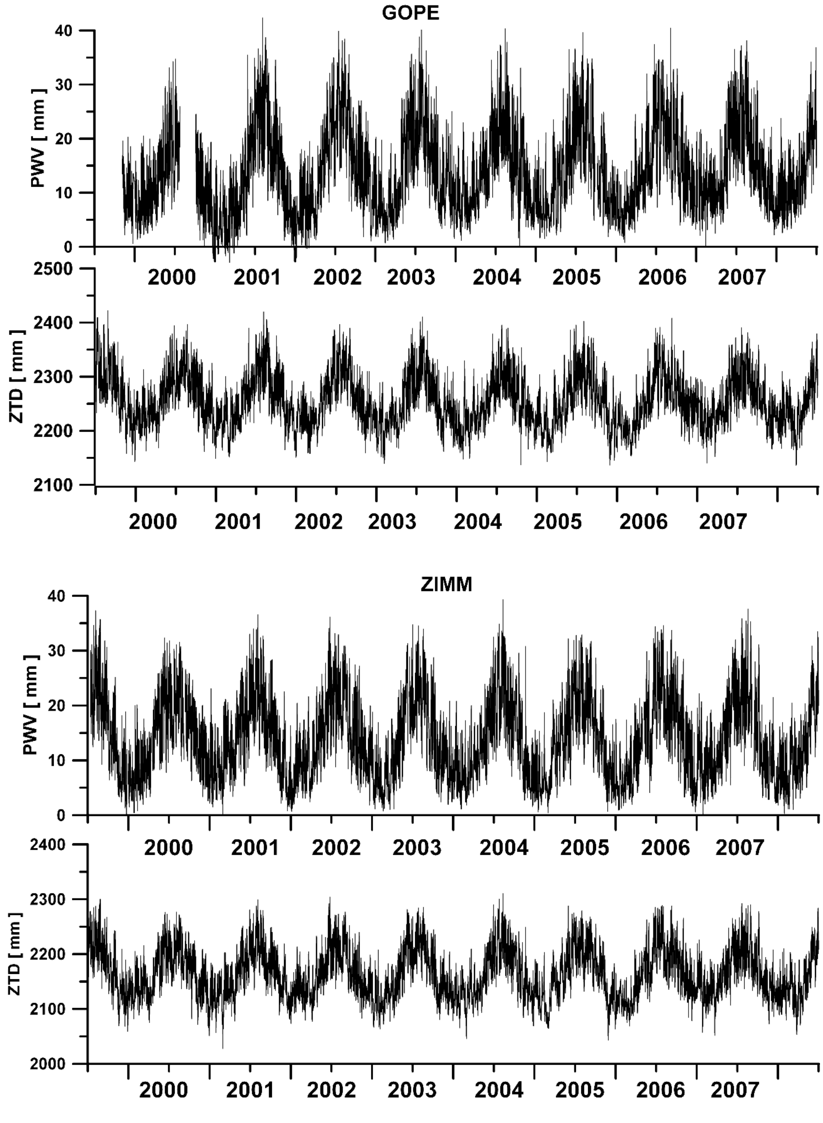

Fig. 9. ZTD and PWV variations for stations GOPE and ZIMM.

local phenomena reflecting the altitude of the site and regional meteorological environment. A linear trend of ZTD about –1 mm/year is observed for

Table 3. Estimated parameters of approximation of ZTD and PWV series by the linear, annual, semi-annual and diurnal periodic terms. All values are in mm, except $\delta\, ZTD$ and $\delta\, PWV$ which are in mm/year. The last column shows the number of days for which ZTD and PWV values are available

Site	ZTD					PWV					N_{ZTD}
	ZTD_0	δZTD	a_{an}	a_{sa}	a_d	PWV_0	δPWV	a_{an}	a_{sa}	a_d	N_{PWV}
	σ_{ZTD0}	$\sigma_{\delta ZTD}$	σ_{an}	σ_{sa}	σ_d	σ_{PWV0}	$\sigma_{\delta PWV}$	σ_{an}	σ_{sa}	σ_d	
GOPE	2254.3	-1.04	48.2	8.5	1.4	14.20	0.19	7.91	1.41	0.29	3206
	0.1	0.04	0.2	0.2	0.2	0.02	0.01	0.05	0.05	0.05	2926
MATE	2282.1	-0.01	40.8	1.2	4.3	16.11	0.03	7.27	0.35	0.84	3180
	0.1	0.04	0.2	0.2	0.2	0.06	0.06	0.05	0.05	0.01	2788
POTS	2378.3	-0.01	48.8	8.7	1.3	15.23	-0.37	8.88	1.78	0.38	3180
	0.1	0.05	0.2	0.2	0.2	0.04	0.02	0.07	0.07	0.07	1441
TUBO	2336.4	-0.13	51.1	10.5	0.5	16.06	-0.04	9.23	1.54	0.30	2384
	0.1	0.07	0.2	0.2	0.2	0.02	0.01	0.05	0.05	0.05	2277
WROC	2376.7	-0.90	51.2	9.6	1.0	15.73	-0.29	9.09	1.60	0.34	2780
	0.1	0.05	0.2	0.2	0.2	0.03	0.01	0.06	0.06	0.06	2142
WTZR	2236.4	-0.10	47.5	9.2	1.3	14.22	0.02	7.69	1.39	0.32	3222
	0.1	0.04	0.2	0.2	0.2	0.03	0.03	0.05	0.05	0.05	2265
ZIMM	2163.37	-0.07	47.0	7.4	2.2	3.87	-0.03	7.56	0.78	0.38	3199
	0.1	0.04	0.2	0.2	0.2	0.02	0.02	0.04	0.04	0.04	3058

the GOPE and WROC stations.

The residual ZTD and PWV series after elimination of estimated terms in Table 3 for two sites – GOPE and ZIMM are plotted in Fig. 10. It is evident, especially for PWV, that the residual signal is not purely random but has a significantly seasonally modulated amplitude. As for the GPS data themselves such behaviour is not typical, we can conclude that this is a phenomenon related to variability of meteorological parameters.

An independent check of quality of PWV obtained from processing the GPS is possible by comparison with PWV values derived from radiosonde meteo observations. This type of measurements is performed daily at the Gánovce meteorological observatory at 0 h and 12 h UT. The GPS GANP permanent station is situated directly in the area of meteorological observatory. Mean differences between PWV_{GPS} and $PWV_{radiosonde}$ from 2004.0 to 2007.0 are plotted in Fig. 11. The distribution of differences is not random and two kinds of dependencies are visible. Firstly, the systematic difference between midnight and noon values, and secondly, the seasonal dependence of noon values. These phenomena are well documented in Fig. 11, where quarterly means are plotted separately for 0 h UT and 12 h UT values. Note

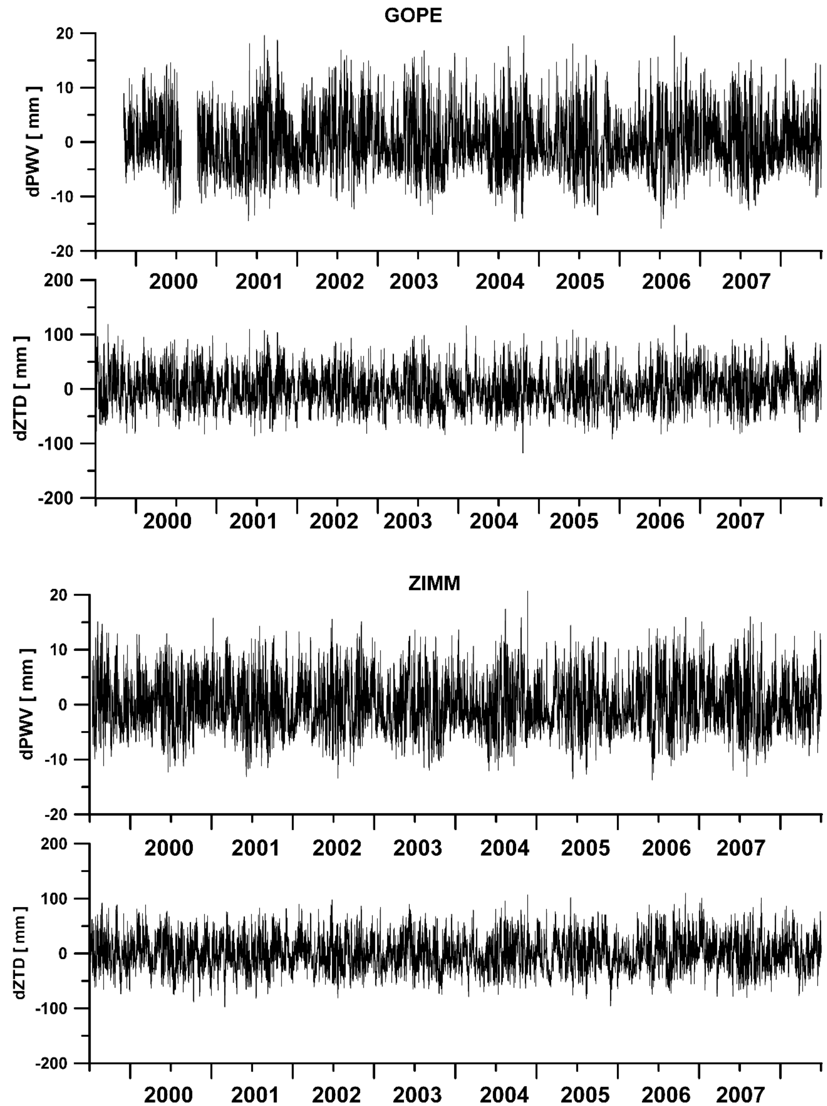

Fig. 10. Residual ZTD and PWV variations for stations GOPE and ZIMM after elimination of seasonal and diurnal periodic terms.

also more the stable and less scattered 0 h UT values as well as the 1 mm bias among the midnight and noon values.

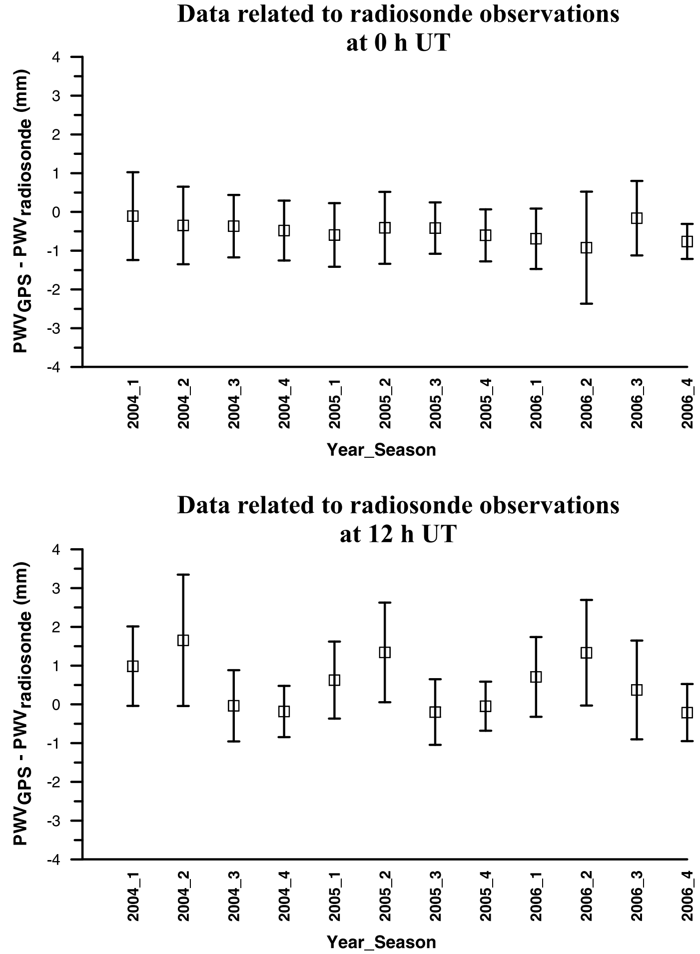

Fig. 11. Mean difference between PWV derived from GPS observations at GANP stations and PWV obtained from radiosonde measurements at Gánovce meteorological observatory.

7. Conclusions

A homogenized analysis of nine years of permanent GPS observations at sites situated in Central Europe, Alpine-Adriatic region and Balkan Peninsula provide new and improved information about geokinematics of the region as well as about the troposphere parameters at the observing sites. Unified processing scheme and linking the final coordinates to ITRF by using a stable set of reference stations enabled to obtain continuous and homogeneous coordinate series as well as the compact ZTD series and subsequently also the PWV values. It is evident that the strategies applied to routine GPS analysis after 2006.68 and the reprocessing of the older data are capable of providing the position, velocity, seasonal variations, and PWV with millimeter or even better accuracy.

The main achievements of the analysis of 54 permanent stations in the region of interest which have been observed in the period from 1999.5 to 2008.5 can be summarized as follows:

- The analysis method applied allowed obtaining the coordinate time series of horizontal coordinates without significant offsets, with dominating linear drift due to tectonic plate motion, and occasionally also the seasonal variations. The typical variability of weekly station coordinates is characterized by the RMS errors of about 1 mm for stable stations and is generally not exceeding 3 mm. We have not observed other types of station behavior than the linear and seasonal changes.
- The RMS error of weekly coordinates for the height component is below 3 mm for stable stations and can reach 4–6 mm for less stable stations. Besides the linear trend, annual and semi-annual variations at several stations, also the non-linear behaviour is observed with has no clear physical interpretation.
- The obtained horizontal velocities coincide with the ITRF2005 velocities as well as with the intraplate velocity trends in the region. Only for the two stations – CLUJ and KATO the significant local anomalies are observed. The velocities summarized in Table 1 can be used as a reference for other regional and local geo-kinematic investigations.
- Coordinate seasonal variations which have in the extreme case amplitudes up to 4 mm, but usually below 2 mm, have to be considered as pure local phenomena, there is no evidence of regional patterns.
- The ZTD and PWV series have a strong seasonal signal, but also intraseasonal variability. The slightly weaker diurnal term is also present in majority of the sites analyzed. The coincidence of GPS - derived PWV and radiosonde values prove the high quality of data from the homogenized GPS processing. Seasonal and night-day dependence was

recognized for the difference between GANP PWV GPS data and PWV derived from radisonde values.

The data obtained from the reprocessing period coupled with the recently performed routine processing form a solid basis for further applications in geodynamics, troposphere studies and seasonal effects analyses.

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