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SITE VELOCITIES FROM LONG-TERM EPOCH GPS OBSERVATIONS – CASE STUDY: CENTRAL EUROPE REGIONAL GEODYNAMIC PROJECT 1994-2005

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ABSTRACT
Series of repeated epoch-wise GPS campaigns performed in Central European region are used for estimation of site velocities. The main features of campaign processing and combination of network solutions are outlined. The velocities obtained from epoch observations within the Central Europe Regional Geodynamic Project covering the 11-year time span are compared at some sites with velocities derived from permenent GPS observations.

KEYWORDS: epoch GPS network, Central Europe Geodynamic Reference Network, site velocities – horizontal and vertical, intraplate velocity field in Central Europe

1. INTRODUCTION

The series of regularly repeated GPS campaigns occupying several days are frequently used for estimation of site velocities, in particular in regions where permanent sites are not available or the density of permanent stations is not sufficient. These, so-called epoch campaigns were widespread in the early nineties when GPS started to be applied as the generally available space technique well suitable for geo-kinematical investigations. In Central Europe region such activities motivated in 1994 establishment of the Central Europe Regional Geodynamic Project (CERGOP, Fejes and Sledzinski, 1998) as the research collaboration of 11 countries. As the observational background for CERGOP serves the Central European GPS Geodynamic Network (CEGRN). The continuations of these activities are realized in follow-up project CERGOP-2/Environment (Fejes and Pesec, 2003) involving 13 countries. The CEGRN, which was originally consisting of 24 sites, distributed in Central and southeast Europe was observed for the first time in May 1994. At that time the network was comprised mainly of epoch stations. Since that time the CEGRN was significantly enlarged from originally observed 24 sites to 92 network sites observed in 2005. Part of the originally epoch stations were gradually transformed to permanent ones. We emphasise that not all new permanent stations in the region became the part of CEGRN. The epoch-wise observing campaigns of CEGRN comprising of five 24-hour simultaneous sessions were performed in late spring annually in 1994, 1995, 1996, 1997 and then bi-annually in 1999, 2001, 2003 and 2005.

Results of separate processing of individual epoch campaigns are consecutively used for combination of all available data and for estimation of site coordinates and velocities. Time span of 11 years at CEGRN sites with longest observational history is a challenge to obtain valuable information about geo-kinematics in the region. The network of CEGRN epoch stations is referenced to the ITRF 2000 (Boucher et al., 2004) through 8 European collocated ITRF stations where the velocity is obtained at least from two separate space techniques (GPS, SLR and/or VLBI). In the paper we will demonstrate results of estimation of velocity field comprising of all relevant sites where epoch observations were performed three times at minimum and the observing interval covers four and more years. The combination is based on epoch network solutions obtained at Slovak University of Technology using the Bernese GPS software, version 4.2 (Hugentobler et al., 2001). Results obtained from epoch solutions delivered by several processing centres (individual network solutions independently computed at 3 up to 6 various institutions, Hefty et al., 2006) and subsequently combined into one common product will be published elsewhere.

The intraplate velocities based on CEGRN observations will be compared at the non-reference permanent sites where the ITRF 2000 velocities are available. Besides, at the permanent GPS stations will be the CEGRN outputs compared with velocities obtained from analysis of European Permanent Network (Kenyeres, 2006) and with velocities determined for GPS permanent sites in Central Europe within activities of CERGOP2/Environment (Hefty and Igondová, 2006).

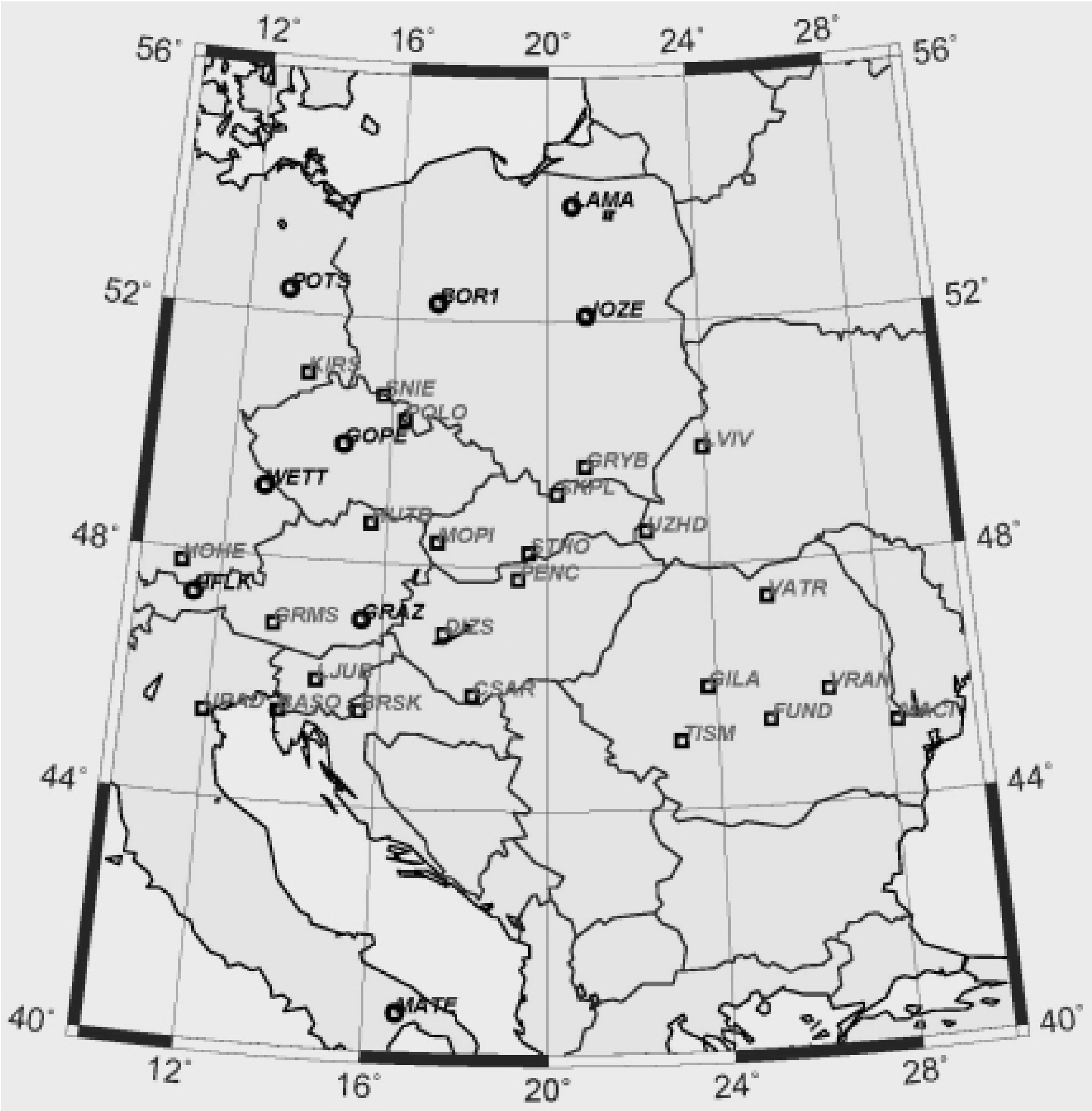

Fig. 1 CEGRN constellation in the second observing campaign performed in 1995 (○ permanent stations, □ epoch stations).

2. OBSERVATIONS OF CEGRN FROM 1994 TO 2005 AND THE EPOCH NETWORK SOLUTIONS

The number of observed stations included in CEGRN was gradually increased. First epoch campaign in 1994 included 23 stations. Status of the network observed in 1995 is shown in Fig. 1. Set of 32 CEGRN stations (9 of them observed at that time already permanently) which include 4 IGS reference stations (BOR1, GRAZ, MATE and WETT) was processed with other 4 additional IGS stations outside the network (KOSG, METS, ONSA, ZIMM) to enable reliable referencing to ITRF. Status of network observed in 2005 is shown in Fig. 2. The set of network stations comprises of 72 officially adopted CEGRN permanent and epoch stations, 4 IGS outside stations and 19 so-called candidate stations. It is intended that some of candidate stations will be adopted later as official CEGRN stations. The reason of this selection procedure is to keep the number of CEGRN stations reasonable (the whole network hast to be simultaneously observed and processed) and to ensure the sites quality.

All the 8 epoch campaigns were processed using the same principles and methods. The main features of the applied strategy:

- GPS software Bernese BV 4.2 (Hugentobler et al., 2001).
- Use of final IGS orbits and corresponding Earth orientation parameters.

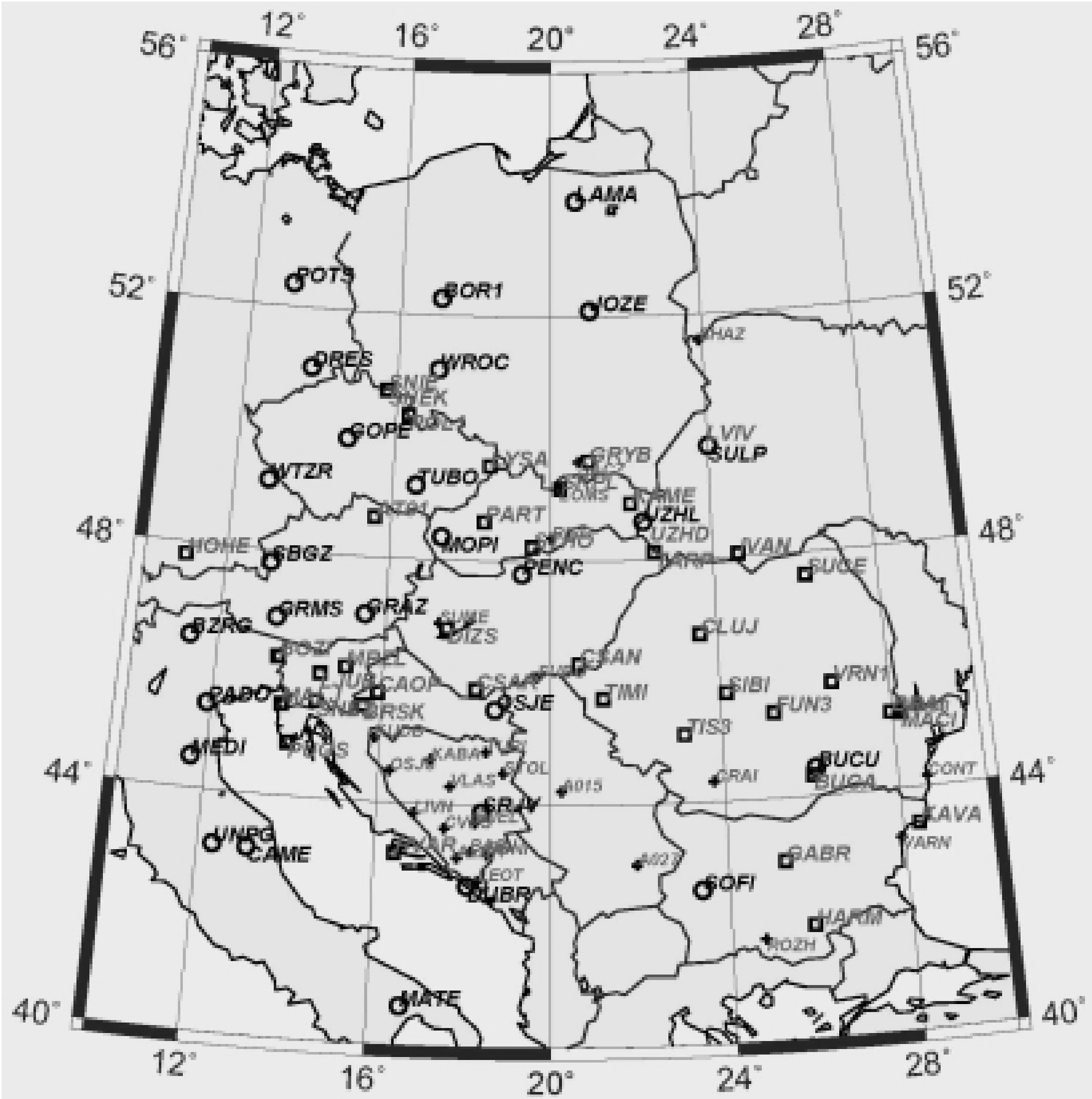

Fig. 2 CEGRN constellation in epoch campaign in 2005 (○ permanent stations, □ epoch stations, + candidate CEGRN stations).

- 10 degrees elevation angle.
- Reference point GRAZ at the epoch of campaign consistent with the effective ITRF realisation. Free network solution constraining GRAZ to 0.0001 m in each coordinate constituents.
- Independent processing of daily intervals (0-24 h UT).
- Ionosphere effects were eliminated by using L3 iono-free combination.
- Niel mapping function applied, hourly zenith delays estimated, elevation dependent weighting.
- Ambiguity fixing using the QIF strategy.
- Antenna eccentricities and phase centre variations using the IGS model.

Summary with characteristics of solutions of eight epoch CEGRN observing campaigns processed at Slovak University of Technology is given in Tab. 1. The number of observed sites clearly demonstrates their progressive increase. In 1994 CEGRN comprised of 23 sites and 4 additional IGS sites were included in the final campaign processing. Till 2005 the network was observed 8 times, in the last campaign were 18 identical sites for which the original monumentation from 1994 remained unchanged. These sites are promising the most reliable velocity estimation. The values of residual RMS in Tab. 1 are larger for 2003 and 2005 campaigns than in previous campaigns. We suppose that this fact is due to significant extension of the network. There are 50 CEGRN non-reference sites where three or more epoch campaigns interval were performed at the identical position and the observing span is at least four years.

Table 1 Main characteristics of CEGRN epoch campaign solutions obtained at the Slovak University of Technology.

Observing campaign	Epoch of observation	Number of sites included in the final solution	Residual RMS of the final solution
CEGRN'94	1994.34	27	0.0026 m
CEGRN'95	1995.31	36	0.0025 m
CEGRN'96	1996.45	37	0.0025 m
CEGRN'97	1997.43	45	0.0023 m
CEGRN'99	1999.46	61	0.0025 m
CEGRN'01	2001.47	55	0.0027 m
CEGRN'03	2003.46	72	0.0030 m
CEGRN'05	2005.47	95	0.0031 m

3. MATHEMATICAL MODEL FOR ESTIMATION OF SITE COORDINATES AND VELOCITIES FROM EPOCH CAMPAIGNS

The mathematical model for combination of epoch campaigns with aim to estimate site coordinates at reference epoch and site velocities is based on statistically correct approach given in (Hefty, 2004). The idea is based on generalisation of the methods of combination of local geodetic networks described in (Dobeš et al., 1990).

Results of individual CEGRN epoch observations are obtained in the form of vector geocentric coordinates $\mathbf{X}_i$ and their covariance matrix $\mathbf{\Sigma}_i$. They refer to the epoch of observing campaign t_i. The coordinates of reference ITRF sites $\mathbf{X}_{ITRF}$ and velocities $\mathbf{v}_{ITRF}$ referred to epoch t_0 are considered as pseudo-observations. They are characterized by their covariance matrix composed from covariance matrices $\mathbf{\Sigma}_{XITRF}$, $\mathbf{\Sigma}_{vITRF}$ and cross-covariance $\mathbf{\Sigma}_{XvITRF}$.

The estimated parameters - geocentric coordinates of CEGRN sites are denoted as $\mathbf{Y}$ and the respective site velocities as $\mathbf{v}_Y$. Parameters $\mathbf{Y}$ and $\mathbf{v}_Y$. formally include also coordinates and velocities of reference sites. To align the CEGRN free-network solutions referred to epoch t_i to the reference at epoch t_0, the 7-parameter spatial transformation with transformation parameters $\mathbf{\Theta}_i$ has to be included into the model. Then the observation model relating observed values (results of CEGRN processing and ITRF coordinates and velocities) to estimated parameters (coordinates $\mathbf{Y}$, velocities $\mathbf{v}_Y$ and transformation parameters $\mathbf{\Theta}_i$) can be written in the form

$$\begin{bmatrix} \mathbf{X}_1 \\ \mathbf{X}_2 \\ \vdots \\ \mathbf{X}_n \\ \mathbf{X}_{ITRF} \\ \mathbf{v}_{ITRF} \end{bmatrix} = \begin{bmatrix} \mathbf{A}_1 & \mathbf{D}_1 & \mathbf{T}_1 & \cdots & \mathbf{0} \\ \mathbf{A}_2 & \mathbf{D}_2 & \mathbf{0} & \cdots & \mathbf{0} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ \mathbf{A}_n & \mathbf{D}_n & \mathbf{0} & \cdots & \mathbf{T}_n \\ \mathbf{A}_{ITRF} & \mathbf{0} & \mathbf{0} & \cdots & \mathbf{0} \\ \mathbf{0} & \mathbf{D}_{ITRF} & \mathbf{0} & \cdots & \mathbf{0} \end{bmatrix} \begin{bmatrix} \mathbf{Y} \\ \mathbf{v}_Y \\ \mathbf{\Theta}_1 \\ \vdots \\ \mathbf{\Theta}_n \end{bmatrix} + \begin{bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \vdots \\ \varepsilon_n \\ \varepsilon_{XITRF} \\ \varepsilon_{vITRF} \end{bmatrix} \tag{1}$$

$\mathbf{A}_i$ design matrix relating observed coordinates with estimated coordinates (its elements are 1 or 0)

$\mathbf{A}_{ITRF}$ design matrix relating ITRF coordinates with estimated coordinates (its elements are 1 or 0).

$\mathbf{D}_i$ design matrix relating observed coordinates with estimated velocities (its elements are $t_i - t_0$ or 0)

$\mathbf{D}_{ITRF}$ design matrix relating ITRF velocities with estimated velocities (its elements are 1 or 0).

$\mathbf{T}_i$ design matrix for transformation of epoch campaigns to ITRF

$\mathbf{Y}$ coordinate parameters: coordinates of epoch sites as well as of reference sites

$\mathbf{v}_Y$ velocity parameters: velocities of epoch sites as well as velocities of reference sites

$\mathbf{\Theta}_i$ transformation parameters from i-th epoch t_i to reference epoch t_0

$\boldsymbol{\varepsilon}$ vectors of errors of observed quantities

n number of epoch campaigns

Stochastic properties of observed quantities can be characterized by global covariance matrix

$$\text{var}\begin{pmatrix} \mathbf{X}_1 \\ \mathbf{X}_2 \\ \vdots \\ \mathbf{X}_n \\ \mathbf{X}_{ITRF} \\ \mathbf{v}_{ITRF} \end{pmatrix} = \begin{bmatrix} \vartheta\Sigma_1 & \mathbf{0} & \cdots & \mathbf{0} & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \vartheta\Sigma_2 & \cdots & \mathbf{0} & \mathbf{0} & \mathbf{0} \\ \vdots & \vdots & \ddots & \vdots & \vdots & \vdots \\ \mathbf{0} & \mathbf{0} & \cdots & \vartheta\Sigma_n & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \cdots & \mathbf{0} & \Sigma_{XITRF} & \Sigma_{XvITRF} \\ \mathbf{0} & \mathbf{0} & \cdots & \mathbf{0} & \Sigma_{XvITRF}^T & \Sigma_{vITRF} \end{bmatrix} \tag{2}$$

where ϑ is the variance factor scaling the covariance matrices from epoch solutions $\mathbf{\Sigma}_i$ to be consistent with reference ITRF coordinates and velocities. The observations in various epochs t_i are considered as mutually independent. Estimation of parameters – coordinates, velocities and transformation parameters an their covariance matrix is based on standard least-squares approach (Koch, 1999).

4. CEGRN EPOCH VELOCITIES AND THEIR COMPARISON WITH VELOCITIES OBTAINED FROM PERMANENT OBSERVATIONS

Setting of the coordinate and velocity parameters in (1) was restricted to sites, where at least three epochs at identical position were observed. As the reference the ITRF 2000 coordinates and velocities of 8 IGS stations with their covariance matrix at the epoch 1997.0 were extracted from the ITRF 2000 SINEX file. The selection of the reference sites was determined by the requirement, that their velocities are obtained from combination of two space techniques at least (GPS and VLBI and/or SLR). This criterion meets IGS stations BOR1, GRAZ, KOSG, MATE, WTZR, ONSA and ZIMM, which were included in CEGRN epoch campaign processing. Velocities at 51 non-reference sites were determined on the basis of 1002 coordinate observations included in vectors $\mathbf{X}_i$ on the left-hand side of (1). The variance factor ϑ was determined iteratively by fulfilling the criterion to obtain the a posteriori variance of unit weight close to one. The final solution was obtained with $\vartheta = 47$.

To obtain information about intraplate velocity field the estimated velocities $\mathbf{v}_Y$ evaluated in geo-centric system were reduced for model velocities from Actual Plate Kinematic Model APKIM 2000 (Drewes, 1998). The reduced velocities and their covariance matrices were then transformed to local horizontal coordinates n , e and h. Resulting velocities and their RMS errors are summarized in Tab. 2, where also the number of epoch campaigns used and observation time span are given. Also is given the indication if the station was epoch or permanent in 2005. The horizontal velocities for sites, which have RMS errors less than 1 mm/year for both constituents, are represented with their 2σ error ellipses in Fig. 3. Vertical velocities of sites with which have RMS smaller than 5 mm/year are plotted in Fig. 4. For sake of better resolution they are represented with 1σ intervals.

The distribution of CEGRN intraplate horizontal velocities can be roughly characterized by three regional groupings:

- Central European part with velocities with small amplitudes (generally up to 1 mm/year) and not uniform orientation (about 30 stations). Amplitudes on sites with observation history longer than 8 years only slightly exceed their 2σ error ellipses. The only station in the region, which has different behaviour, is SNIE with its southwest oriented velocity with 4 mm/year magnitude. It is very probable that this is a local phenomenon, which will be explained after relevant information of permanent station situated close to SNIE will be available. Stations in Panonian Basin and stations close to this region have velocities about 2 mm/year oriented to east (GRAZ, DISZ, PENC, STHO, UZHD).
- Stations close to Adriatic region with velocities directed to north and northeast (MEDI, MALJ, BOZI, LJUB, BRSK, HVAR, SRJV). Their magnitudes are from 2 to 4 mm/year and the velocity vectors are exceeding the 2σ confidence.
- Balkan stations situated in Bulgaria (SOFI, HARM) and Romania (VRN1, FUN3, MACI, BUCU, BUCA) with velocities oriented to south and southeast. Magnitude of the velocities is from 2 to 4 mm/year and all the vectors are exceeding the 2σ intervals.

The vertical velocities are above 1σ level only occasionally. The dominant direction is decrease of height, however it can be hardly interpreted as geodynamic phenomenon. Few exceptions like POTS, VRN1 and HVAR are very probably of local nature or originate from instrumental biases.

The relevance of estimated horizontal velocities obtained from epoch observations will be examined by their comparison with velocities evaluated on the basis of permanent GPS observations. We will use three sources of information:

- ITRF 2000 velocity field, epoch 1997 (Boucher et al., 2004), reduced for APKIM 2000.
- European permanent network station velocities expressed in ETRF 2000, epoch 1997 (Kenyeres, 2006). The uncertainties of these velocities are extremely small and unreliable when compared to other sources. We expect that not accounting for coloured noise of permanent time series (see e.g. Williams, 2003) is responsible for this anomaly.
- Velocities inferred from 3-year interval of permanent observations in Central Europe region (Hefty and Igondová, 2006).

Although the mentioned velocities do not relate to the same reference we will use them for comparison with CEGRN velocities as all of them represent in some manner the intraplate velocities within the Eurasian tectonic plate. Plots for 12 CEGRN stations where some of the three kinds of velocities previously mentioned are available in Fig. 5. We see in general good agreement of the compared velocities. At least at sites where velocities are above 2 mm/year coincide the vectors in direction (SOFI, SRJV, MEDI, DUBR, BUCU) what proves that the main tendencies observed in CEGRN intraplate velocities are real phenomenon. The uncertainty of CEGRN velocities is generally larger than for velocities derived from permanent observations. This is obvious consequence of significantly smaller number of observations at epoch sites when compared to number of observations at permanent sites even the time span covered by epoch observations is longer. The other phenomenon negatively influencing the uncertainties is alteration of observing equipment at the epoch sites. Nevertheless the results in Fig. 5 proves the reliability of information gained from epoch campaigns and confirm, that epoch observations can provide valuable

Table 2 Estimated velocities and their RMS errors of the non-reference CEGRN sites. Velocities are reduced for APKIM 2000 and expressed in local horizontal system.

Site	Number of campaigns	Time span of observations	Epoch (E) or permanent (P) station	v_n (mm/year)	σ_{vn} (mm/year)	v_e (mm/year)	σ_{ve} (mm/year)	v_h (mm/year)	σ_{vh} (mm/year)
BASO	4	3	E	4.3	1.6	-2.7	2.3	29.9	8.5
BOZI	4	6	E	2.9	0.8	-0.5	0.6	-2.9	4.0
BRSK	8	11	E	1.6	0.4	1.0	0.3	-2.2	1.9
BUCA	6	10	E	-2.8	0.5	0.7	0.4	-0.7	2.5
BUCU	4	6	P	-2.3	0.8	-0.5	0.6	-0.5	4.0
BZRG	4	6	P	-0.3	0.8	0.1	0.6	-0.7	4.1
CSAN	4	6	E	0.2	0.9	-0.0	0.9	-2.6	4.4
CSAR	8	11	E	0.2	0.4	0.4	0.3	-2.2	2.0
DISZ	8	11	E	-0.5	0.4	2.1	0.3	-2.5	1.9
DRES	4	6	P	1.5	0.7	0.1	0.6	5.5	3.2
DUBR	3	4	P	2.9	1.2	-1.0	0.9	-5.2	5.6
FUN3	4	6	E	-2.7	0.8	-1.0	0.6	-0.6	4.1
GOPE	8	11	P	-0.1	0.4	-0.1	0.3	-0.7	1.7
GRMS	4	4	E	-0.1	3.2	4.7	2.6	-0.9	18.0
GRYB	8	11	E	-0.2	0.4	0.8	0.3	-1.1	1.8
HARM	4	9	E	-3.4	0.6	1.3	0.5	-3.3	3.0
HFLK	6	10	P	0.6	0.5	0.5	0.4	0.2	2.3
HOHE	7	11	E	1.5	0.4	0.7	0.3	-0.0	1.8
HUTB	8	11	E	0.8	0.7	2.5	0.5	0.0	3.2
HVAR	5	8	E	4.0	0.6	2.6	0.5	-7.0	3.0
IAS3	3	4	E	0.6	1.8	0.5	1.4	-1.0	10.5
JOZE	8	11	P	-0.3	0.4	0.1	0.3	-0.3	1.8
KAME	4	6	E	-0.6	0.8	0.6	0.6	-1.0	4.4
KIRS	5	5	E	1.1	0.9	-1.0	0.7	-0.9	5.1
LAMA	8	11	P	-0.6	0.4	-0.7	0.3	-3.0	1.7
LJUB	8	11	E	1.8	0.4	-0.1	0.4	-1.2	2.0
LVIV	7	10	E	-0.6	0.5	-0.1	0.4	1.5	2.6
LYSA	4	6	E	0.2	0.8	0.2	0.8	-0.8	3.7
MACI	3	3	E	-1.1	0.7	0.9	0.6	-4.5	3.9
MALJ	4	6	E	2.9	0.8	0.6	0.7	-4.4	4.2
MEDI	4	6	P	1.7	0.8	1.8	0.6	-4.2	4.1
MOPI	8	11	P	-0.0	0.4	0.1	0.3	0.8	2.0
PART	4	6	E	2.1	0.8	-0.9	0.6	-2.3	3.7
PENC	8	11	P	-0.5	0.4	1.2	0.3	-1.6	1.6
POL1	4	6	E	-0.9	1.2	0.3	0.9	2.0	5.6
POTS	7	10	P	-0.0	0.4	0.2	0.3	-0.0	1.5
SBGZ	4	6	P	0.4	0.7	0.5	0.6	0.5	3.1
SKPL	8	11	E	-0.9	0.5	0.3	0.4	0.6	2.2
SOFI	6	9	P	-2.4	0.6	1.0	0.5	-2.3	2.9
SRJV	4	6	P	1.3	0.8	0.5	0.7	-2.8	4.2
STHO	8	11	E	-0.3	0.5	1.9	0.4	-1.9	2.3
SULP	5	8	P	-0.3	0.6	0.1	0.5	0.8	3.3
TARP	4	6	E	-0.6	0.8	-0.3	0.6	-2.8	4.3
TIS3	5	9	E	-2.5	0.6	0.7	0.5	-0.3	3.1
TUBO	5	10	P	0.3	0.6	0.5	0.5	-1.6	2.7
UNPG	3	4	E	-1.4	1.2	-2.9	1.0	-6.1	6.3
UZHD	8	11	E	-1.1	0.4	0.6	0.3	-1.1	1.9
UZHL	3	4	P	-0.9	1.8	0.1	1.4	-2.2	10.1
VRN1	5	8	P	-2.7	0.9	-0.4	0.7	-11.9	4.6
WROC	4	6	P	-0.1	0.7	-0.2	0.6	-0.8	3.2

results for sites where no permanent observations are available.

5. CONCLUSIONS

Epoch observations at more than 50 sites in Central Europe and in the Balkan region, which result to intraplate velocity estimates, are performed within the Central Europe Regional Geodynamic Project. The uncertainties of horizontal velocities are for majority sites below 1 mm/year what is sufficient accuracy for identification of regional intraplate movements exceeding 2 mm/year in Adriatic and Balkan region.

The region covered by monitored stations can be divided according observed horizontal movements roughly into three parts: Central European region with small velocities, usually at the level of their uncertainties, East Alpine - Adriatic region with velocities exceeding significantly their uncertainties directed to north and East Balkan region with significant velocities oriented predominantly to south.

The agreement of horizontal velocities obtained from epoch-wise observations with velocities inferred from permanent GPS observations proves the quality of information based on epoch data. We stress that application of the combination procedure, which respects the complete stochastic modelling of observations is necessary for obtaining reliable estimates of velocities and their uncertainties. The epoch-wise observations could result to valuable geodynamic information mainly in the regions where no permanent observations are available or where the density of monitored network has to be increased.

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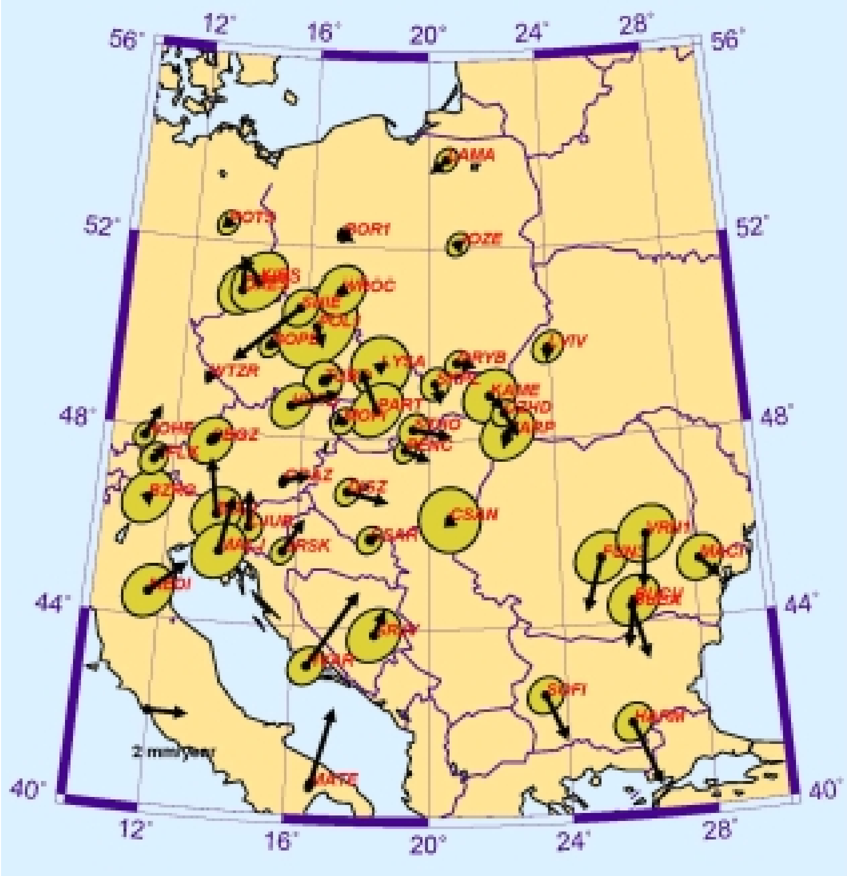

Fig. 3 Estimated horizontal velocities and their 2σ error ellipses of CEGRN sites observed more than 3 times and covering time span longer than 4 years.

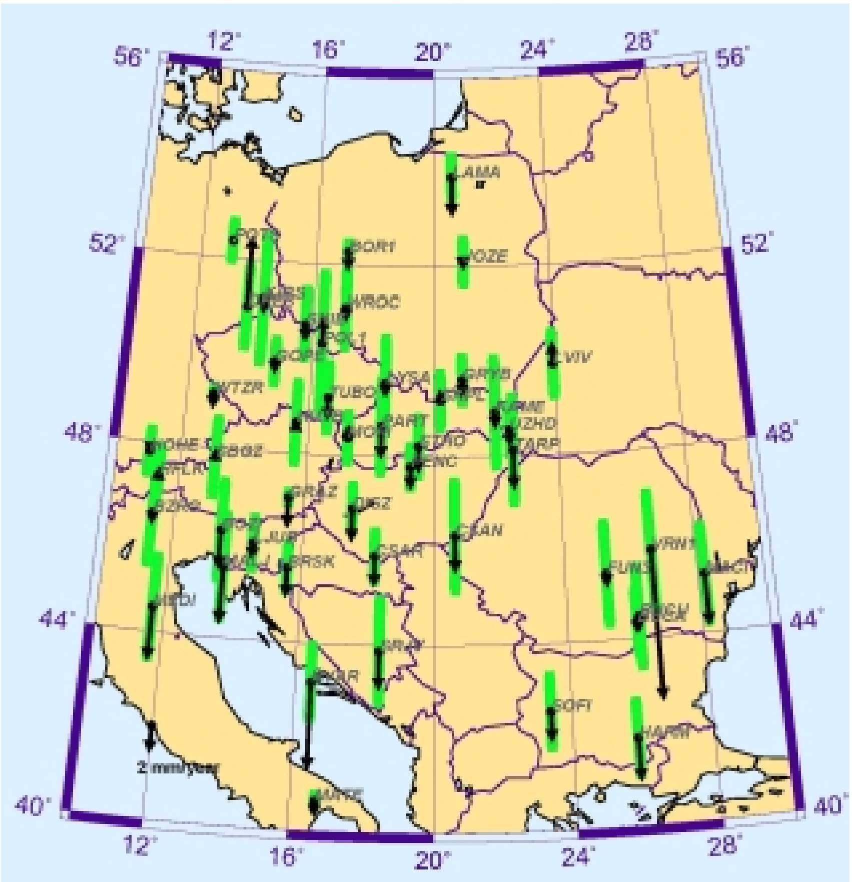

Fig. 4 Estimated vertical velocities and their 1σ confidence intervals of CEGRN sites observed more than 3 times and longer than 4 years.

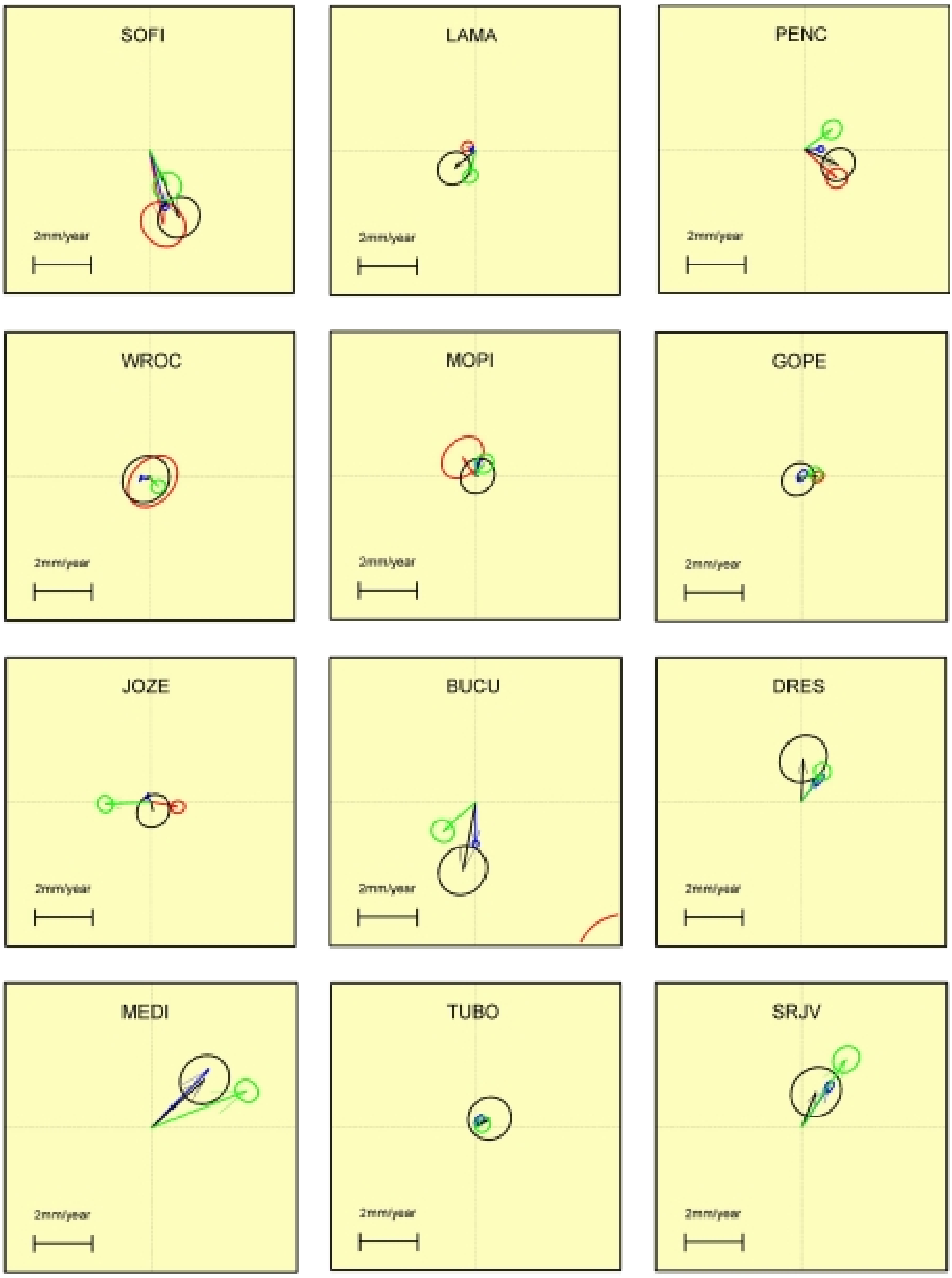

Fig. 5 Comparison of velocities obtained from CEGRN epoch campaigns (black lines) with ITRF 2000 velocities reduced for APKIM 2000 (red lines), EPN velocities (blue lines) and velocities obtained from analysis of permanent stations in Central Europe (green lines).