Acta Geodyn. Geomater., Vol. 7, No. 3 (159), 303–315, 2010

RECENT GEO-KINEMATICS OF SLOVAKIA BASED ON HOMOGENIZED SOLUTIONS OF PERMANENT AND EPOCH GPS NETWORKS

Ján HEFTY [1)]*, Linda HIPMANOVÁ [1)], Ľubomíra GERHÁTOVÁ [1)], Miroslava IGONDOVÁ [1)] and Branislav DROŠČÁK [2)]

[1)] *Department of Theoretical Geodesy, Faculty of Civil Engineering, Slovak University of Technology in Bratislava, Radlinského 11, 813 68 Bratislava, Slovakia*
[2)] *Institute of Geodesy and Cartography in Bratislava, Chlumeckého 4, 827 45 Bratislava, Slovakia*
**Corresponding author's e-mail*: jan.hefty@stuba.sk

(*Received* March 2010*, accepted* May 2010)

ABSTRACT
The paper is focused to the analysis of permanent and epoch-wise GPS networks extending over the region of Slovakia. We considered almost all available GPS data measured in Slovakia and its close surroundings over the period of last 17 years. Our analysis is based on combination of homogenized permanent and epoch-wise network solutions leading to the ITRF2005 related coordinates, velocities and their global covariance matrix. Estimated velocities were further reduced for APKIM2005d plate motion model and submitted to the velocity filtering and smoothing using the least square collocation approach. The obtained homogenized intra-plate velocity field is then used for the surface deformation analysis. The final and partial results of this procedure are discussed in order to extend information about recent regional geo-kinematics of Slovakia.

KEYWORDS: GPS, geo-kinematics, regional horizontal and vertical velocity field, surface deformation analysis

1. INTRODUCTION

Slovakia is considered from the geo-kinematical point of view as a relatively stable region without significant drifts and faults. Since 1993 at this territory various GPS networks of continental, national and local importance were devoted to the geo-kinematical investigations. This paper is chiefly focused to the combination of one permanent and four epoch-wise GPS networks extending over this region. The obtained sites velocities are later on used for the surface deformation analysis. We took advantage from 10 years of permanent and almost 17 years of epoch-wise GPS observations performed within the five networks namely: CEPER (Central European Permanent Network), CEGRN (Central European Geodynamic Reference Network), SGRN (Slovak Geodynamic Reference Network), local network TATRY and local monitoring network EMO, all of them briefly described in this paper. We operated uniquely with the GPS reprocessed data using the Bernese GPS software version 5.0 (Dach et al., 2007) and respecting the general rules applied for reprocessing activities. Combination of resulting SINEX (Solution Independent Exchange Format) files was ensured by the CATREF (Combination and Analysis of Terrestrial Reference Frames) software (Altamimi et al., 2009) developed in LAREG (Laboratiore de Recherches en Géodésie) in France for the purpose of ITRF (International Terrestrial Reference Frame) combinations. Final output set contained 74 points (11 permanent stations and 63 epoch-wise points) with ITRF2005 related coordinates, velocities and their global covariance matrix. Global velocities were reduced for APKIM2005d plate motion model and submitted as input data for velocity filtering and deformation analysis which are also discussed in the paper.

2. AVAILABLE DATA

The complex analysis of relevant GPS observations performed on the territory of Slovakia is based on combination of homogenized long-term GPS measurements provided by permanent and epoch-wise GPS stations. We analyzed the data from 11 permanent and 63 epoch-wise GPS stations covering reasonable time span to estimate the geo-kinematical behavior of Slovakia and its nearby areas. These data originate from one permanent and four epoch-wise GPS networks extending over the region of Slovakia (Table 1, Fig. 1).

Quality of input data could be evaluated from many points of view. First of all we have to mention that all of the data included to this experiment were reprocessed respecting the rules given by CEGRN (Central European Geodynamic Reference Network) consortium and applied e.g. in (Hefty et al., 2009). The main features of reprocessing realized by Bernese GPS software version 5.0 (Dach et al., 2007) were as

Table 1 The main features of the investigated network.

Name	Total number of points	Number of used points for analyses over Slovakia	Time span [year]	Number of campaigns	From - To [year]	Length of observing campaigns
CEPER	19 - 56	11	9.76	510 weeks	2000.00 - 2009.76	permanent
CEGRN	27 - 95	6	13.14	9	1994.33 - 2007.47	120 h
SGRN	17 - 33	28	13.82	9	1993.66 - 2007.48	36 - 120 h
TATRY	13 - 23	18	10.02	12	1998.67 - 2008.69	72 - 96 h
EMO	14 - 22	11	7.75	7	2001.87 - 2009.62	48 h

follows: Processing at daily intervals (0-24 h UT), celestial reference frame realized by IGS (International GNSS Service) orbits and the corresponding Earth Rotation Parameters since 2006. Before this date the reprocessed global GPS network data were used (Steinberger et al., 2006). The elevation cut off angle of 10° was applied in case of CEGRN, TATRY, EMO and SGRN networks, 3° elevation cut off was applied in case of CEPER permanent network. Constraints of 0.0001 m were applied to station positions of the fiducial point in order to reference the network solutions to the ITRF2005. As concerns the troposphere modeling the Niell mapping function was applied with elevation dependent weighting and station zenith delays were estimated at hourly intervals. Satellite and receiver antenna eccentricities were taken from the IGS05 absolute calibration model, the ocean loading model FES2004 was used.

The above mentioned strategy assures the homogenization of the results in terms of employed software, processing parameters, unified models, reference frame, etc. On the other hand we can state considerable discrepancies in quality of input data in terms of number of reference points, its long-term quality, length of observation campaign, network size, and time span used for velocity estimation, etc.

The highest quality data are provided by CEPER (Central European Permanent Reference Network) permanent network. This network started to be analyzed in 1996 at the LAC SUT (Local Analytic Center of Slovak University of Technology) comprising only 19 points. The main features of the GPS networks dedicated to this experiment are summarized in table 1. Later on the CEPER network was significantly enlarged over the time and now consists of 56 permanent stations but only 11 permanent stations are situated in Slovakia and its surroundings. Routine processing strategy respect the rules for reprocessing described above. For the purpose of this experiment we selected the data covering the time span of 9.76 year of permanent GPS observation starting from 2000.00 to 2009.76.

The CEGRN (Central European Geodynamic Reference Network) was established in 1994 in frame of CERGOP and CERGOP-2/Environment projects. We selected 9 observation campaigns realized in 1994, 1995, 1996, 1997, 1999, 2001, 2003, 2005 and 2007 in order to perform the combination. CEGRN is the largest network in our experiment containing about 95 points in Central and Southeastern Europe. Despite of this fact only 6 epoch-wise points are located in investigated area. Each epoch campaign took 120 hours of simultaneous observations at all network sites.

Slovakia is covered by various networks of national and local importance. The most significant is the SGRN (Slovak Geodynamic Reference Network) regularly extending over the whole territory of Slovakia (Klobušiak et al., 2002). About 28 epoch-wise points were available for this experiment. Length of observation campaign varies from 36 to 120 hours per campaign. The campaigns were realized in 1993, 1995, 1998, 1999, 2000, 2001, 2003, 2005, and 2007. We excluded the SGRN 2001 observation campaign from the processing because of antennas rotations which were realized in the middle of observation campaign in order to eliminate uncertainties of a real position of the antenna phase centre (Klobušiak et al., 2002).

Local network Tatry was established in 1997 and first successful observation campaign was realized in 1998 (Mojzeš and Papčo, 2004). This network extends in Tatra Mountains and was established in order to investigate local geodynamics in this area. It consists of 23 points located in Slovakia and Poland. This network was re-observed 12 times and all of the observation campaigns were included to the combination. Observation campaigns reach the length varying from 72 to 96 hours.

Local monitoring network EMO extends in close surroundings of Mochovce Nuclear Power Plant. This network was established in 1985 for the purpose of monitoring of lithosphere stability of this area using terrestrial geodetic observing techniques. Since 2001 the network was observed by GPS on the base of 48 h epoch campaigns (Hefty et al., 2008). Network consists of 30 pillars located in proximity (up to 30 km) of the power plant. Since 2001 till 2009 seven GPS campaigns were performed in 2001, 2002, 2003, twice in 2006, then in 2008 and 2009. For this experiment 11 points of epoch-wise observation were kept at disposition.

3. COMBINATION STRATEGY AND ESIMATED VELOCITY FIELDS

The combination model of CATREF software (Altamimi et al., 2009) is based on 7-parameters similarity transformations assuming that for each individual solution *s* and each point *i*, we have position $\mathbf{X}_s^i$ at the epoch t_s^i and velocity $\dot{\mathbf{X}}_s^i$ expressed in a given reference frame *k* (Altamimi et al., 2009). The general combination model is given by following equations

$$\begin{aligned}\mathbf{X}_s^i &= \mathbf{X}_c^i + (t_s^i - t_0)\dot{\mathbf{X}}_c^i + \mathbf{T}_k + \mathbf{D}_k\mathbf{X}_c^i + \\ &+ \mathbf{R}_k\mathbf{X}_c^i + (t_s^i - t_k)[\dot{\mathbf{T}}_k + \dot{\mathbf{D}}_k\mathbf{X}_c^i + \dot{\mathbf{R}}_k\mathbf{X}_c^i]\end{aligned}, \quad (1)$$

$$\dot{\mathbf{X}}_s^i = \dot{\mathbf{X}}_c^i + \dot{\mathbf{T}}_k + \dot{\mathbf{D}}_k\mathbf{X}_c^i + \dot{\mathbf{R}}_k\mathbf{X}_c^i \quad (2)$$

Parameter $\mathbf{T}_k$ represents the translations, $\mathbf{R}_k$ is rotation matrix and $\mathbf{D}_k$ scale factor of each individual frame *k*. The dotted parameters designate their derivations with respect to time (Altamimi et al., 2007). The estimated parameters are: stations positions $\mathbf{X}_c^i$ expressed in epoch t_0 and appropriate velocities related to the combined frame *c*, transformation parameters $\mathbf{T}_k$, $\mathbf{R}_k$, $\mathbf{D}_k$ and their rates $\dot{\mathbf{T}}_k$, $\dot{\mathbf{R}}_k$, $\dot{\mathbf{D}}_k$ between combined frame *c* and individual frame *k*.

General combination strategy is based on two steps. In the first step the individual combination is performed and stations positions $\mathbf{X}_c^i$ related to given epoch t_0, velocities $\dot{\mathbf{X}}_c^i$ expressed in combined frame *c* are estimated. The transformations parameters $\mathbf{T}_k$ and their rates $\dot{\mathbf{T}}_k$ between two frames: individual *k* and combined *c* are estimated. In the second step the individually processed solutions are combined together and homogeneous velocity field is estimated. All the input and output data are provided in SINEX format. The datum definition is ensured by minimum constraint approach supposing the minimization of transformation parameters between individual and combined frame. The most delicate procedure of the combination is the discontinuities identification. These phenomena are most commonly caused by antennas manipulations, receiver changes, monumentation modification, radome changes, earthquakes etc. Discontinuities are relatively easy to identify in time series of permanent stations but they are almost undetectable in case of epoch-wise points because of insufficient length of observation. Nevertheless we decided to take the significant discontinuities into account also in case of epoch-wise networks. In the process of combination we eliminated the outliers exceeding the value of 0.05 m.

The final solution was related to the ITRF2005 over the set of reference points. Unfortunately the distribution of reference points is not very favorable in terms of velocity estimation. Combined network solutions are not fully surrounded by reference points because no fiducial stations present in official ITRF2005 solution occur easterly from Slovakia and only the stations with prevailing western location could be used. Namely we can speak about points BOR1, GRAZ, JOZE, MATE, METS, ONSA, PENC, POTS, WTZR and ZIMM. We aspired to use only the points with smooth long-term history where no unexplained discontinuities occur.

Finally, the APKIM2005d reduced individual site velocities $\dot{\mathbf{X}}_c^i$ and their covariance matrices were transformed into the vector of horizontal velocity components $\mathbf{h}$ and its covariance matrix $\mathbf{\Sigma_h}$ and the vector of up velocity components $\mathbf{u}$ and its covariance matrix $\mathbf{\Sigma_u}$.

3.1. RELIABILITY OF COMBINATION PROCEDURE

The reliability of partial results was evaluated by its comparison to the reference value represented by results of permanent GPS stations if available. Unfortunately only 11 permanent stations occur in our experiment and the reliability of the results could be evaluated only in terms of precision in many cases. Figure 2 illustrates the residual comparison resulting from individual combination of five above mentioned networks.

These sub-results indicate pretty nice agreement at 4 mm level in horizontal and up to 10 mm in vertical component. As mentioned previously the significant discontinuities were taken into account also in case of epoch-wise measurements. Based on our partial results we can state that unified reprocessing strategy significantly contributed for homogenization of the results.

Independently estimated velocities were compared to each other in order to evaluate the quality and consistency of partial results. Velocities resulting from permanent observations are available only in 11 cases. These velocities are supposed to represent the reference values for epoch-wise observations. Generally we can state that our results are reciprocally consistent. Some inconsistencies are very probably due to insufficient length of observation campaign or number of repeated observations. Please notify that only the station satisfying the following criteria were considered as suitable for the purpose of this experiment: three years of continuous permanent observation (in case of permanent stations) and at least two repeated observation during the period of three years (in case of epoch-wise points). Global velocities were reduced for APKIM2005d plate motion model. Figure 3 illustrates the comparison of independently estimated intra-plate velocities at GPS sites MOPI, LOMS, PENC and SKPL. The highest consistency of the partial results was achieved in case of permanent station MOPI. This station takes part of EPN (EUREF Permanent Network) network and has long observation history in CEPER permanent network. Others permanent stations LOMS and PENC are also shown in above mentioned figure. Permanent station LOMS is located on the top of Lomnický štít in Tatra Mountains 2634 m above sea level showing the largest inconsistencies in horizontal and also in vertical component.

Permanent station PENC is located south of Slovak boundary and is included in EPN and IGS networks. The official ITRF2005 velocity is also shown as reference value. We can see that blue arrow representing the velocity of permanent observation is very close to this value. Remaining inconsistencies are due to insufficient length of observation and numerous discontinuities identified in time series of this station. Epoch-wise point SKPL is also situated in Tatra Mountains but no data from permanent GPS station are available. In case of this station we can observe the inconsistencies in combination resulting from SGRN network which is very probably due to insufficient number of repeated observations.

3.2. ESTIMATED HORIZONTAL VELOCITY FIELD

The estimated horizontal velocities obtained from final combination of the five mentioned networks are shown in Figure 4. Final combination set contains ITRF2005 related coordinates, velocities and appropriate covariance matrix of 74 stations. The presented velocities were obtained after reduction for APKIM2005d plate motion model which is supposed to be the most representative for the investigated area. As it is visible from the plotting, the orientation and magnitude of the velocity vectors is variable and inhomogeneous. Magnitude of estimated velocities varies from 1 to 3 mm/year. Velocity field and its long-term evolution is influenced by main stress sources in Central and Southeastern Europe particularly rotation of Adria micro-plate around its pole of rotation with coordinates (46° N, 6° E) (Kováč et al., 2002). Generally, the mentioned stress source imposes the interposition of Adria micro-plate under the Eastern Alps. These phenomena involve the W-E oriented drift in the region of Panonian basin (Caporalli et al., 2008). As visible from Figure 4, the velocity vectors are oriented randomly and it is entirely delicate at this moment to assume some correlation between our results and general assumptions inferred from geological and geophysical investigations.

Possibly there are some drifts having the connection with above mentioned phenomena in south-western part of Slovakia indicating W-E movement with magnitude up to 2.5 mm/year. Please notify that we combined all the available GPS data which are characterized by variable quality. Magnitude and orientation of estimated velocities depends on many factors particularly: length of observation campaign, time span used for velocity estimation, number and long-term quality of reference points, number of discontinuities identified and modeled in combination, network size, plate motion model, etc. We suppose that length of observation was not sufficient to determine reliable velocity vectors in many cases especially if length of observation in regional network reaches the 36 – 48 h level. Generally reliable velocities are supposed to be achieved if length of observation is 96 – 120 h. Estimated velocities in Tatra Mountains indicate generally south and southeastern drifts with magnitude varying from 1 to 2.5 mm/year. Resembling orientation of velocity vectors is indicated in area of Mochovce Nuclear Power Plant with magnitude up to 3 mm/year.

Figure 5 illustrates the precision of estimated horizontal velocities resulting from final combination of the five mentioned networks. As visible from this figure the highest precision was achieved in case of permanent stations (marked blue) and oscillates from 0.05 to 0.20 mm/year. Precision of epoch-wise points vary from 0.22 to 2.68 mm/year. These values are partially influenced by insufficient number of observations and length of observation which is no longer than 36 – 48 h in especially in case of SGRN (marked pink) and EMO (marked orange) networks.

3.3. ESTIMATED VERTICAL VELOCITY FIELD

The estimates of vertical velocities are obviously less precise than the horizontal ones, namely due to satellite geometry, troposphere modeling limitations, antenna elevation dependence, etc. When combining the permanent and epoch networks the phenomenon of GPS equipment alteration, on epoch sites diminishes the reliability of estimated vertical velocities. The effect of antenna changes cannot be estimated from the observations themselves as it is used when antenna is replaced on permanent sites. Nevertheless we will analyze also the vertical component as the geographical distribution of sites is promising to estimate the general pattern of height deformations at least. Figure 6 shows the final vertical velocities with their one-sigma intervals. We may observe that irrespective of the scatter of the vertical velocities some trends are visible. The vertical changes within the local networks EMO and TATRY have similar pattern.

4. ANALYSIS

The raw velocities in Figures 4 and 6 are not immediately convenient for further geo-kinematical analysis. In the following part we will firstly perform the filtering of evaluated site velocities, then their interpolation to regular grid, and finally the

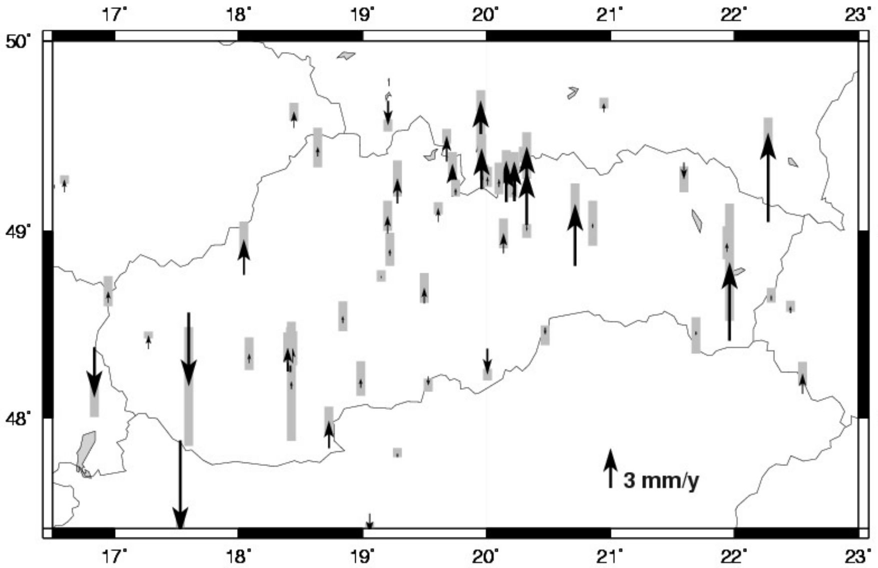

Fig. 6 Estimated vertical velocities with one-sigma interval (in grey) resulting from the final combination of one permanent and four epoch-wise networks.

deformation analysis of the horizontal surface deformations.

4.1. SMOOTHING AND INTERPOLATION OF OBSERVED VELOCITY FILEDS

The observed velocities obtained from (1) and (2) are irregularly distributed and their accuracy is significantly varying as is documented in Figures 4 – 6. Moreover, the random constituent of the velocities is sometimes at the same level as the observed velocities themselves. To obtain more realistic information about the significant geo-kinematical trends in the territory of Slovakia it is necessary to evaluate the signal part of the site velocities and to filter out the noise part. We used the Least squares collocation approach (Moritz, 1973) for this purpose. Due to significant differences in accuracy of estimated horizontal velocity constituents **h** and vertical constituents **u** we will separately process the horizontal and vertical velocity fields.

The signal part of the horizontal ($\mathbf{h}_s$) and vertical ($\mathbf{u}_s$) velocities are obtained as

$$\mathbf{h_s} = \Sigma_{\mathbf{sh}} \left(\Sigma_{\mathbf{h}} + \Sigma_{\mathbf{sh}} \right)^{-1} \mathbf{h} \quad ,$$
$$\mathbf{u_s} = \Sigma_{\mathbf{su}} \left(\Sigma_{\mathbf{u}} + \Sigma_{\mathbf{su}} \right)^{-1} \mathbf{u} \tag{3}$$

The elements of the covariance matrices of horizontal and vertical signal $\mathbf{\Sigma_{sh}}$ and $\mathbf{\Sigma_{su}}$ are generated on the basis of isotropic covariance functions

$$\mathrm{cov}\left(s_i, s_j\right) = C\left(d_{i,j}\right) = \sigma_s^2 \exp\left(-a^2 d_{i,j}^2\right) \tag{4}$$

where i and j are indices related to pair of observed sites separated by distance $d_{i,j}$. Coefficient σ_s^2 is representing the variability of the signal part and the choice of a^2 influences the degree of smoothing. The appropriate value of a^2 was determined iteratively by fulfilling the requirement to obtain the post-fit weighted sum of horizontal residuals $\mathbf{r_h} = \mathbf{h} - \mathbf{h_s}$ and post-fit weighted sum of vertical residuals $\mathbf{r}_u = \mathbf{u} - \mathbf{u_s}$ close to unity, i.e.

$$\mathbf{r_h}^T \Sigma_{\mathbf{h}}^{-1} \mathbf{r_h} \approx 1 \quad \text{and} \quad \mathbf{r_u}^T \Sigma_{\mathbf{u}}^{-1} \mathbf{r_u} \approx 1 \tag{5}$$

From studies related to the noise modeling of permanent GPS coordinate time series (Williams, 2003, Kenyeres, 2005) it is known that the behavior of the observing station could not be properly interpreted if only the white noise model is adopted. More appropriate approach is considering for permanently monitored GPS sites a colored noise model. Acceptance of colored noise model is significantly influencing the velocity estimation from long-term observed site coordinates and namely its uncertainties. The analysis in (Williams, 2003) is resulting to relatively simple function for a scale factor which increases the uncertainties of velocity estimates obtained by applying pure white noise model. The scaling factor is function of adopted noise model expressed by noise spectral index and by length of the series. As the procedure that we used in Ch. 3 for velocity determination is based on pure white noise approach we scaled the uncertainties of velocities of permanent stations in Figures 4 and 6 by the factors from 2 to 6 according to the length of the series used for velocity estimates. Actual scale factors were determined according to procedure described in (Williams, 2003) using the average value of spectral

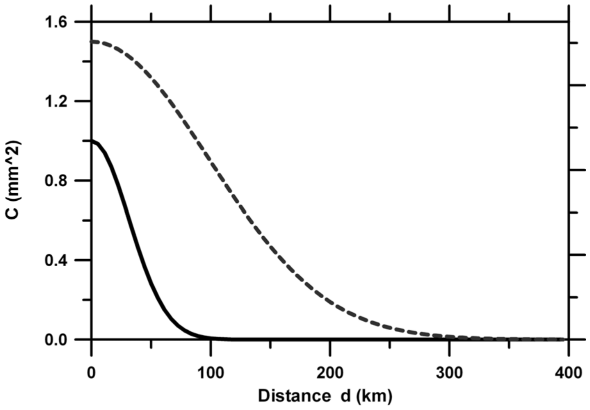

Fig. 7 The covariance functions used for generate the covariance matrices of horizontal (full line) and vertical signals (dashed line).

index k = -0.7 (Kenyeres, 2005). The velocities at epoch stations were not scaled. The introduced scaling factors were used to modify the covariance matrices Σ_h and Σ_u in (5). In this way the parameter a^2 of covariance function (4) is respecting the more reliable velocity uncertainties modeling. The covariance functions for horizontal and vertical constituents obtained for velocities in Figures 4 and 6 with the scaled uncertainties are plotted in Figure 7. Degree of smoothing is significantly larger for vertical velocities due to larger uncertainties for vertical component when compared to the horizontal constituents.

The signal parts of horizontal and vertical velocities are plotted in Figures 8 and 9. As the collocation procedure allows evaluating the uncertainties of estimated signal the plotting shows also their one-sigma error ellipses and one-sigma

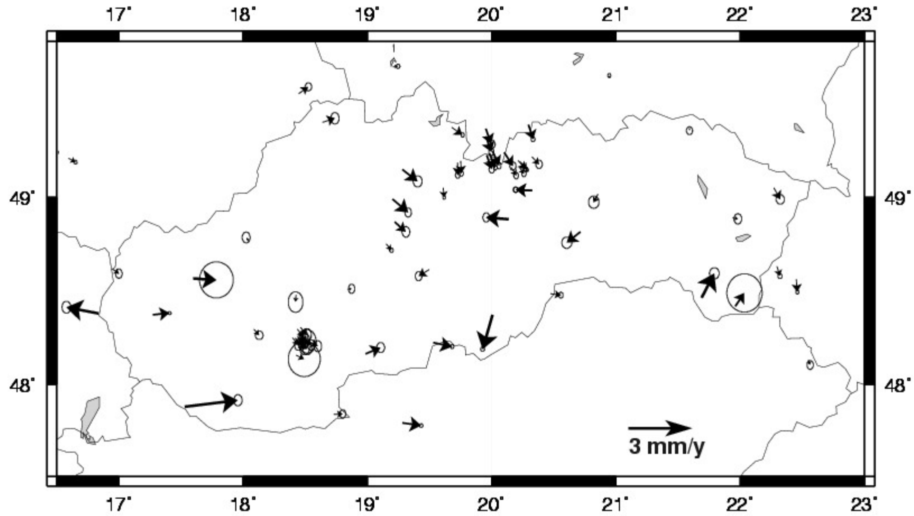

Fig. 8 Estimated signal part of horizontal velocities at observed sites with one-sigma error ellipses.

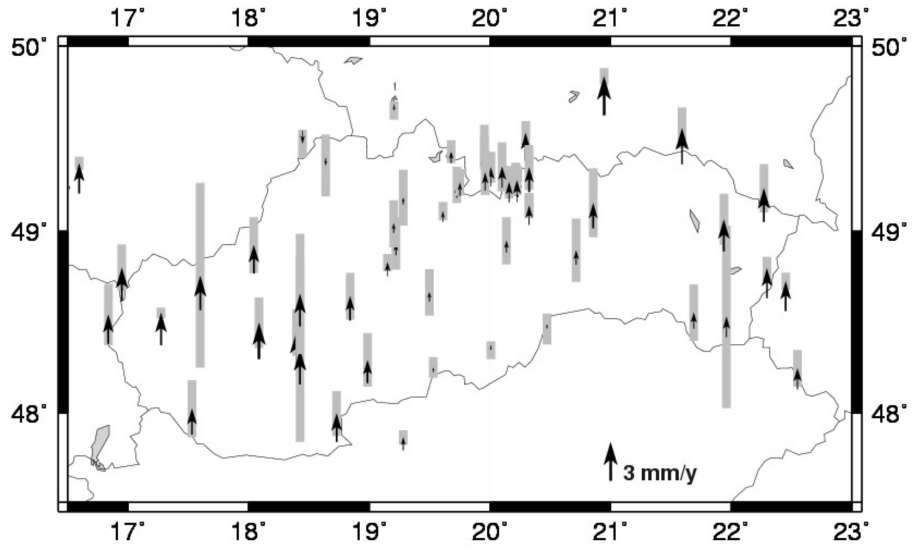

Fig. 9 Estimated signal part of vertical velocities at observed sites with one-sigma error intervals.

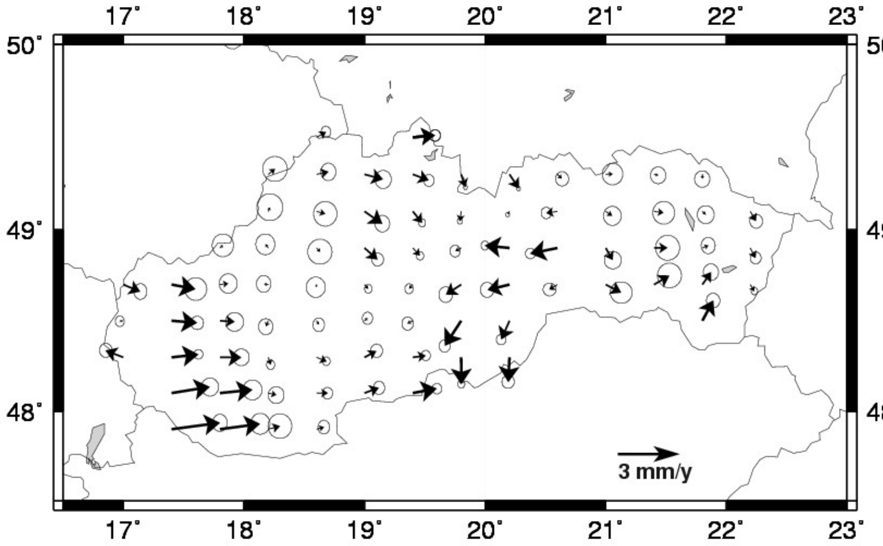

Fig. 10 Interpolated signal part of horizontal velocities in 0.4° × 0.2° grid with one-sigma error ellipses.

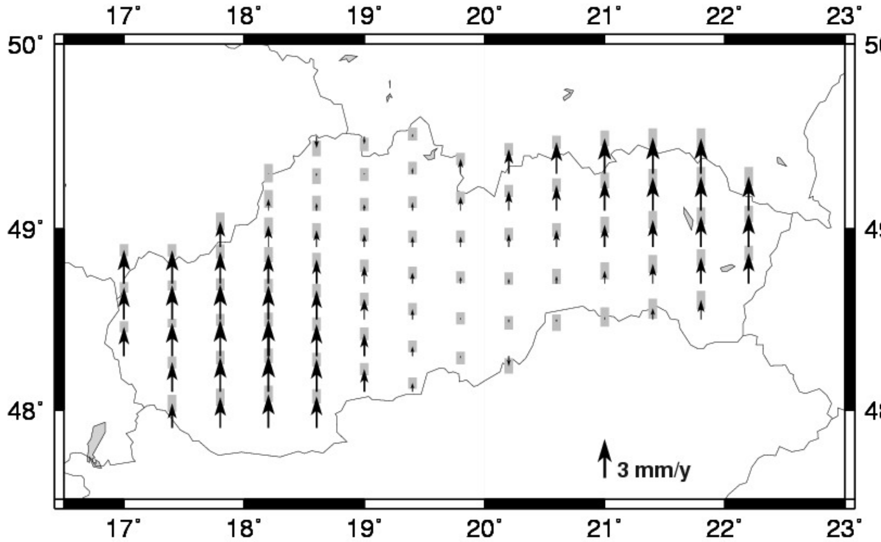

Fig. 11 Interpolated signal part of vertical velocities in 0.4° × 0.2° grid with one-sigma error intervals.

intervals respectively. It is evident that even the horizontal signal is relatively weak some regional pattern are distinguishable after the smoothing procedure. The horizontal velocity trends exceptionally are exceeding 1 mm/year but at majority of sites they are larger than one-sigma level.

Concerning the vertical signal part of velocities it is generally up to 2 mm/year with prevailed uplift. The most remarkable phenomenon is the regional systematic behavior of vertical velocities separating the ~ 2 mm uplift in western part of Carpathians, the almost zero uplift in Central Slovakia and 1 – 2 mm uplift in northern and eastern part of Carpathians.

Collocation procedure allows estimation of signal and its uncertainties also for positions where no observations were performed. We apply the interpolation procedure for 0.4° × 0.2° grid to better visualize the regional velocity trends. The method used is the same as described by (3). However, instead of covariance matrices of horizontal and vertical signal $\mathbf{\Sigma_{sh}}$ and $\mathbf{\Sigma_{su}}$ related to points with observed velocities only, there are used the matrices $\mathbf{\Sigma_{shp}}$ and $\mathbf{\Sigma_{sup}}$ relating the signal at observed and predicted points. We stress that for generating of these matrices the same covariance functions plotted in Figure 7 were applied. The resulting regularized velocity fields are shown in Figures 10 and 11.

Concerning the interpretation of general pattern of horizontal and vertical velocities it is worth to mention that is it strongly dependent on the model applied for reducing the global Eurasia plate motion and the selection of fiducial sites used for referencing. As we used the APKIM2005d plate motion model the residual horizontal velocities in Figures 4, 8 and 10 represent the possible motions relatively to the stable part of Europe and mainly are focused on the possible intra-plate motions on the territory of Slovakia. It is the zone with northern part of Carpathians and can be considered as the boundary between Adriatic micro-plate and European platform. The detailed geo-kinematics of the region is still poorly known.

The vertical pattern is influenced mainly by the non uniform distribution of used outside reference sites which are concentrated in the western side of Slovakia and missing are the reference sites on the east. So, the conclusions relating to vertical velocities should be limited to relative regional pattern and not as general uplift of the monitored territory. In this sense we can observe a phenomenon of non-uniform vertical movement of the territory of Slovakia.

4.2. *CHARACTERISTICS OF HORIZONTAL SURFACE DEOFRMATIONS INFERRED FROM GPS VELOCITIES*

The mathematical background for transformations of 3D velocity field into the parameters characterizing surface deformation under the assumption that the investigated territory is a continuous environment is developed and consistently evaluated in (Altiner, 1999). If the covariance matrix of estimated velocities is available, it can be efficiently used for stochastic modeling of the inferred deformation characteristics. The procedure of consecutive stochastic transformations starting from 3D velocities covariance matrix and resulting in the covariance matrices of elements of deformation tensor is described in (Hefty and Duraciova, 2003). We will apply this approach to the velocities from the territory of Slovakia interpolated into 0.4° × 0.2° grid shown in Figures 10 and 11. The deformation characteristics and their covariance matrices are evaluated from interpolated velocities in four vertices and they are relating to centers of these grid elements.

In Figure 12 are visualized estimated values of surface compression or extension with their one-sigma interval. Their uncertainties are variable depending on the density and accuracy of input velocities and they range from 8 nanostrain/year (1 nanostrrain = 1 mm/1000 km) to 45 nanostrain/year. Distribution of compression and extension areas is varying from east to west but their amplitudes only exceptionally exceed the 2-sigma interval. It is evident that the territory of Slovakia cannot be treated as homogeneous from the point of view of surface compression or extension.

The orientation and magnitude of main axes of deformations are shown in Figure 13. In larger part of the territory of Slovakia the observed deformations are not significant. Only the north-south oriented extension in west Slovakia and compression and extension areas in central Slovakia are above the 2-sigma level. The accuracy of estimated quantities is varying similarly to surface compression/extension data from 8 nanostrain/year in High Tatra to 45 nanostrain/year north-west Slovakia. The global deformation pattern of the territory cannot be reliably defined due to lack of relevant homogeneous velocity field. However the upper limit of deformation is firmly determined and in no case is the maximum deformation exceeding 80 nanostrain/year.

5. CONCLUSIONS

The homogeneous velocity field based on combination of one permanent and four epoch GPS networks were estimated in this experiment. We summarize the results of long-term GPS monitoring performed in Slovakia over the period of 17 years. Homogenization of the input data was ensured by unified reprocessing strategy applied uniformly over each network solution. Despite of this fact we suppose some quality discrepancies connected with different length of observation campaign, long-term quality of reference points, number of modeled discontinuities, etc. We aspired to include almost all data available in region of Slovakia. Combination strategy adopted in CATREF software was used in this experiment.

The final solution consists of ITRF2005 related coordinates, velocities and covariance matrix of 74 sites extending over the region of Slovakia. Global velocities were reduced for APKIM2005d plate motion model in order to obtain intra-plate velocities of the investigated area. Estimated velocity field does not indicate some explicit and uniform drifts in terms of orientation and magnitude of velocity estimates. Generally our velocities are oriented randomly with magnitude up to 3 mm/year. We suppose some correlation between our results and general drifts involved by main stress sources in Central and Southeastern Europe particularly in southwestern part of Slovakia where W-E oriented velocities with magnitude up to 2.5 mm/year predominates. Vertical velocity estimates were also analyzed in this experiment. Generally the horizontal velocity estimates are more precise than verticals ones. Vertical component is more sensitive to satellite geometry, troposphere modeling, antenna elevation dependence, etc. From our raw vertical velocity field some drifts could be indicated. Estimated intra-plate velocities were used as an input data for next analysis.

The velocity filtering was ensured by the Least square collocation approach in order to obtain reliable information about geo-kinematics of Slovakia with stressing the systematics of the motions. The signal parts of horizontal and vertical velocities were evaluated by applying the optimum filtering procedure suppressing the noise influence. The horizontal signal is considered as indistinctive exceptionally exceeding 1 mm/year level. In case of vertical signal component we state general uplift up to 2 mm/year. The remarkable systematic behavior up to 2 mm/year is indicated in western, northern and eastern Carpathians.

ACKNOWLEDGEMENT

This work was supported by the Grant No. 1/0569/10 of the Grant Agency of Slovak Republic VEGA.

REFERENCES

Altamimi, Z., Collilieux, X., Legrand J., Garayt, B. and Boucher, C.: 2007, ITRF2005: A new release of the International Terrestrial Reference Frame based on time series of station positions and Earth Orientation Parameters. Journal of Geophysical Research, 112, B09401, doi: 10.1029/2007JB004949.

Altamimi, Z., Sillard, P. and Boucher, C.: 2009, CATREF software – Combination and Analysis of Terrestrial Reference Frames. Marme la Vallée, France. LAREG laboratory (Laboratoire de Recherches en Geodesie). January 2009.

Altiner, Y.: 1999, Analytical Surface Deformation Theory. Berlin Heidelberg New York: Springer Verlag.

Caporali, A., Aichhorn, C., Becker, M., Fejes, I., Gerhatova, L., Ghitau, D., Grenerzcy, G., Hefty, J., Krauss, S., Medak, D., Milev, G., Mojzes, M., Mulic, M., Nardo, A., Pesec, P., Rus, T., Simek, J., Sledzinsky, J., Solaric, M., Stangl, G., Vespe, F., Virag, G., Vodopivec, F. and Zablotskyi, F.: 2008, Geokinematics of Central Europe: New insights from the CERGOP-2/ Environment Project, Journal of Geodynamics, 45, 246–256.

Dach, R., Hugentobler, U., Fridez, P., Meindl, M.: 2007, Bernese GPS Software Version 5.0, User manual, January 2007, Astronomical Institute, University of Bern, Produced in Digital Print by Stampfli Publications AG, Bern.

Hefty, J. and Duraciova, R.: 2003, Stochastic properties of deformation characteristics obtained from GPS site velocities. Reports on Geodesy, 1 (64), 33–40.

Hefty, J., Igondová, M. and Droščák, B.: 2009, Homogenization of long-term GPS monitoring series at permanent stations in Central Europe and Balkan Peninsula. Contributions to geophysics and Geodesy, 39/1, 19–42.

Hefty, J., Gerhátová, Ľ. and Papčo, J.: 2008, Recent kinematics in area of Mochovce Nuclear Power Plant inferred from the GPS epoch observations. Conference INGEO – 4th International Conference on Engineering Surveying, Bratislava, Slovakia, October 23–24, 2008.

Kenyeres, A.: 2005, EPN time series analysis SP status report. Presented at the EUREF Symposioum, Vienna 1–3 July, 2005. Available at: http://www.euref-iag.net/symposia/2005/Vienna/2-03.pdf

Klobušiak, M., Leitmannová, K., Priam, Š. and Ferianc, D.: 2002, Slovak Terrestrial Reference Frame SKTRF 2001 – Its Computation and Connection to the EUREF, 2002, Bratislava, Geodetic and Cartography Institute in Bratislava.

Kováč, M., Bielik, M., Hók, J., Kováč, P., Kronome, M., Plašienka, D. and Šujan, M.: 2002, Seismic activity and neotectonic evolution of the Western Carpathians (Slovakia), EGU Stephan Mueller Special Publication Series, 3, 167–184, 2002, European Geosciences Union 2002.

Mojzeš, M. and Papčo, J.: 2004, The analysis of GPS measurements in Tatra Mountain. Acta Geodyn. Geomater., 1, No. 3 (135), 115–124.

Moritz, H.:1973, Least-squares Collocation, DGK, Reihe A/75, München.

Steinberger, P., Rothacher, M., Dietrich, R., Fritsche, M., Rülke, A, Vey, S.: 2006, Reprocessing of global GPS network. J. Geophys. Res., III, B05402, doi: 10.1029/2005JB003747.

Williams, S.D.P.: 2003, The effect of coloured noise on the uncertainties of rates estimated from geodetic time series. Journal of Geodesy, 76, 484–494.

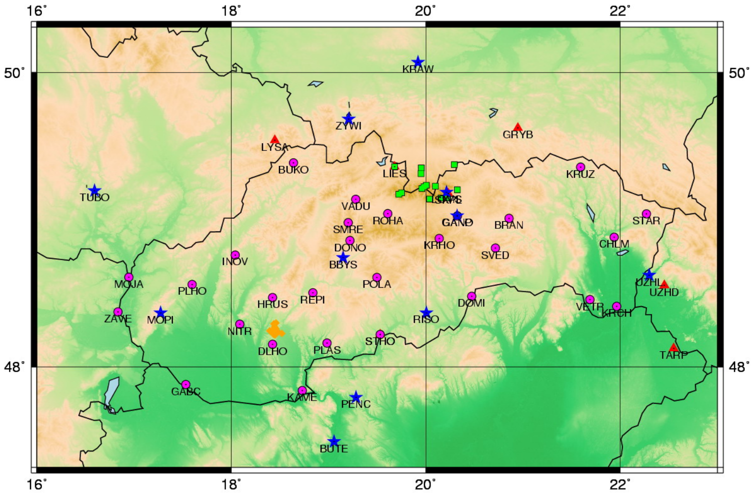

Fig. 1 Permanent and epoch-wise GPS networks included to the experiment. Blue stars – permanent stations of CEPER network, red triangles – CEGRN network, pink dots – SGRN network, green squares – local network TATRY, orange diamonds – local monitoring network EMO.

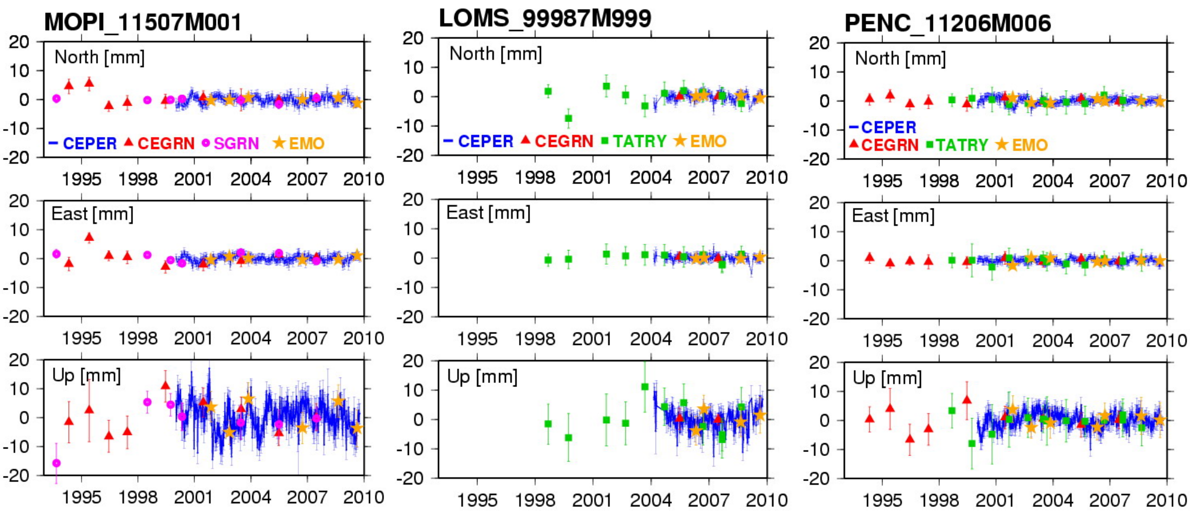

Fig. 2 De-trended time series of permanent stations MOPI, LOMS and PENC resulting from various network solutions. Blue line – CEPER permanent network, red triangles – CEGRN network, pink dots – SGRN, green squares – local network TATRY, orange stars – local monitoring network EMO.

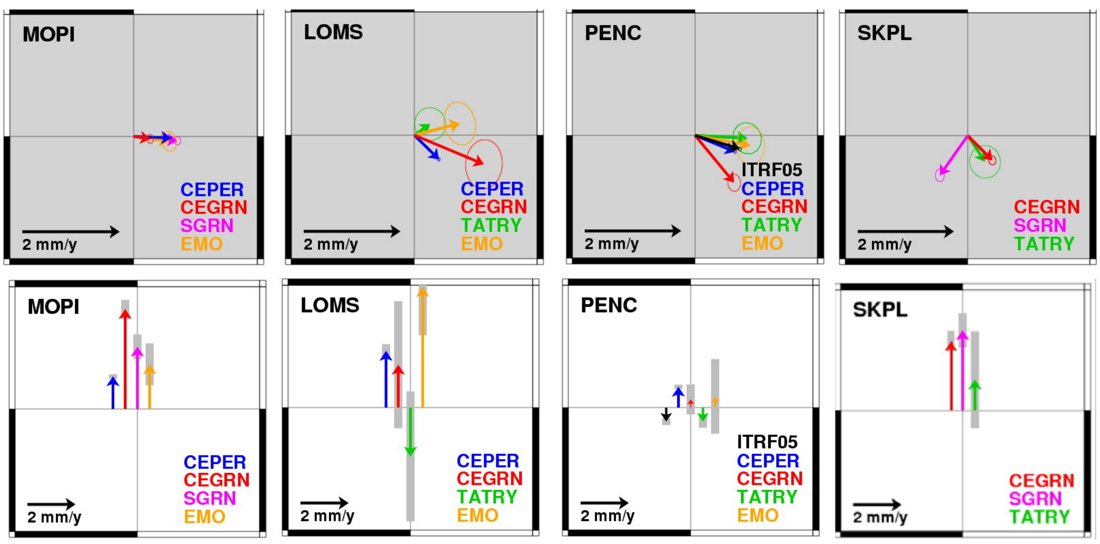

Fig. 3 Estimated intra-plate velocities and their uncertainties as results from individual combinations of five investigated networks.

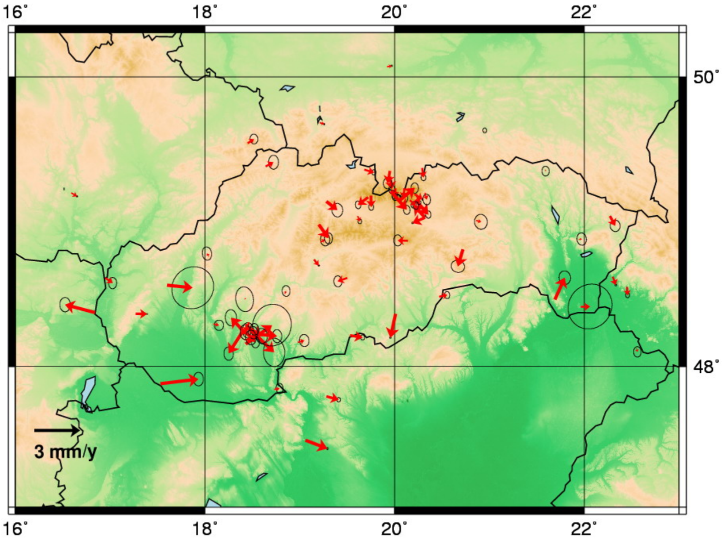

Fig. 4 Estimated horizontal velocity field with one-sigma confidence ellipse resulting from the final combination of one permanent and four epoch-wise networks.

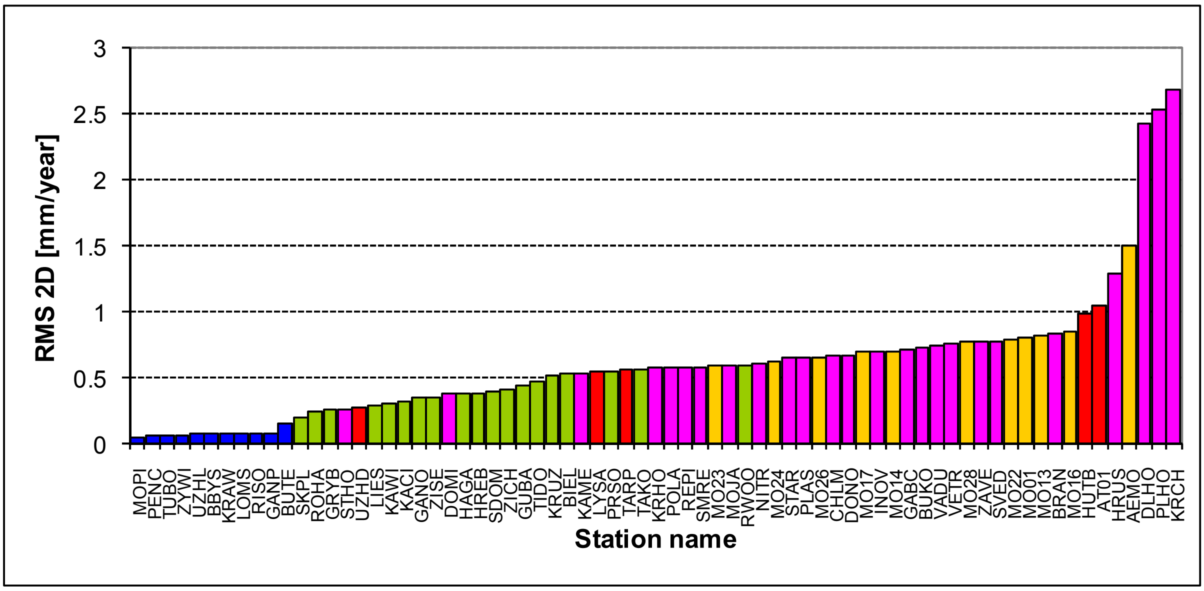

Fig. 5 Precision of horizontal velocity estimates resulting from the final combination of five networks: CEPER permanent network is marked blue, CEGRN network – red, SGRN network – pink, local network TATRY – green, local monitoring network EMO – orange.

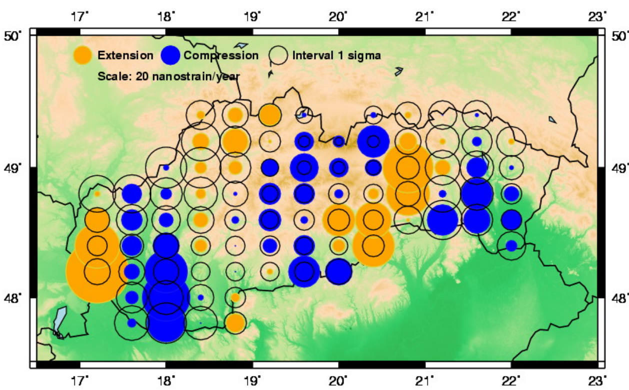

Fig. 12 Surface extension or compression inferred from horizontal velocities and their one-sigma intervals.

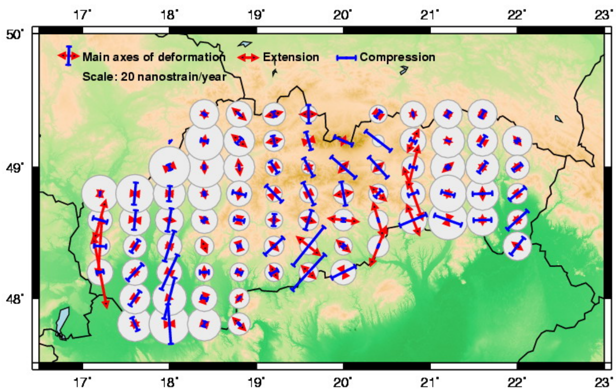

Fig. 13 Orientation and magnitude of main axes of deformation. The ellipses indicate the one-sigma uncertainties of deformation axes.