GEO-KINEMATICS OF CENTRAL EUROPE INFERRED FROM LONG-TERM MONITORED REGIONAL AND LOCAL GPS NETWORKS

Jan Hefty

Department of Theoretical Geodesy, Slovak University of Technology,
Radlinskeho 11, 813 68 Bratislava, Slovakia

1. INTRODUCTION

History of detailed geokinematical monitoring in Central Europe started about 1992 when the GPS observation technique became broadly available. Since that time the countries in Central Europe and Balkan Peninsula are covered by many regional and national or local epoch, and later on also by permanent GPS networks related to geokinematical investigations. The history, purpose, observing schedule, instrumentation, etc. of these networks is variable, dependent on scientific intents, methodology, financial ability, etc. Usually these networks were processed and analyzed completely independently and were yielding to regional or local velocity fields not fully mutually comparable.

It is evident that for geokinematical research is necessary to have complex homogeneous information about the whole region of interest. The EPN (EPN, 2008) or CEGRN (Fejes and Pesec, 2003) velocity fields are examples of such homogeneous networks but they are not sufficiently dense concerning the regional distribution of sites with velocities. Simple combination of various individual velocity fields into unique system is not straightforward because of different realizations of reference frames, different sets of reference sites, different epochs and various accuracy and quality of the input data. The optimum choice is a combination using the SINEX formatted results; however such outputs from ‘historical’ data are mostly not available. In this paper we will discuss the geokinematics of Central Europe and Balkan Peninsula on the basis of results from individual networks using the combination method of horizontal velocity fields described in (Hefty, 2007). The velocity field discussed in this paper is obtained by compiling 10 sets of velocities. After combination procedure the velocities will be smoothed and interpolated by least squares collocation and finally used for evaluation of horizontal surface deformations.

2. VELOCITY FIELDS USED FOR COMBINATION

Firstly we will shortly describe the velocity fields which were used for homogenisation into one set of velocities referred to the unified reference. We emphasise that the input velocity fields are of different origin, epoch, resulting from various observing schedules and analysis procedures; however, the combination method will consider majority of the individual behaviour of the input velocity data sets. The more detailed information about the input data is summarized in (Hefty, 2007).

EUROPEAN PERMANENT NETWORK

In the region of our interest are situated more than 50 EPN permanent stations for which the site velocities are estimated within the project The EPN Coordinate Time Series Analysis (EPN, 2008). These data represent the most stable and homogeneous velocity field in the region; the sites are distributed all over the whole territory, even though not quite uniformly. These velocities will be further used as the reference for linking other velocity fields as there is available a sufficient number of identical sites included in EPN and in local velocity fields.

CERGOP VELOCITY FIELD

The velocities evaluated from epoch-wise observations within the CERGOP and CERGOP-2/Environment (Fejes and Pesec, 2003) are covering the whole territory of Central Europe and Balkan. The solution based on observations from 1994 to 2007 is summarized in (Caporalli et al., 2008). Totally 9 epoch network campaigns performed annually or biannually were combined to yield site coordinates and velocities. The final combined solution contains velocities of 61 sites related to ITRF2000, among them are 29 permanent EPN stations; their data were processed in the same mode as other epoch stations.

NETWORK OF PERMANENT STATIONS IN CENTRAL EUROPE AND BALKAN PENINSULA

The network of permanent stations situated in Central Europe and Balkan Peninsula is analyzed within the CERGOP-2/Environment project since the beginning of 2003 (Hefty, 2006). The network comprises more than 50 permanent stations, mainly EPN, but there are also 12 non-EPN stations included. The intraplate velocities are evaluated according to the method described in (Hefty et al., 2005). Generally four-year intervals of observations are used for velocities estimation, however also shorter datasets are used to fill in the gaps in regions covered by newly established permanent stations (the minimum interval used was 1.5 year of continuous observations).

NETWORK OF PERMANENT STATIONS IN ITALY AND CLOSE REGIONS

Weekly solutions from 45 permanent GPS stations covering Alpine Mediterranean area (ALPMED) are used in (Caporali et al., 2003) for estimation of horizontal velocity field aligned with the ITRF2000. Horizontal velocities and their uncertainties are evaluated for 36 EPN and 9 non-EPN stations.

VELOCITIES OF CROATIAN AND SLOVENE GEODYNAMIC NETWORK

We used the results form the epoch-wise network CRODYN (Croatian and Slovene Geodynamic Network) published in (Altiner et al., 2006). The velocities of 17 stations are computed on a basis of three epoch campaigns performed from 1994 to 1998, 16 further sites were observed only in two epochs separated by two years. The network analysis included also seven EPN stations.

VELOCITIES OF BULGARIAN EUREF STATIONS

On the territory of Bulgaria two epoch observing campaigns in 1993 and 2003 within the EUREF activities were performed. The set of 15 stations forms the Bulgarian reference network (BULREF). The ITRF2000 referenced velocities of 11 BULREF sites together with 5 outside EPN stations are evaluated in (Milev et al., 2005).

INTRAPLATE VELOCITIES OF HUNGARIAN GEODYNAMIC NETWORK

The velocities obtained form processing of Hungarian Geodynamic Reference Network (HGRN) are analyzed in (Generczy, 2002). The intraplate velocity field comprising of 13 HGRN sites is based on 5 epoch campaigns performed from 1991 to 1999 in two-year intervals.

VELOCITIES OF SLOVAK GEODYNAMIC REFERENCE NETWORK

The basis of Slovak Geodynamic Reference Network (SGRN) comprising 17 points was established in 1993. Since the first epoch campaign in 1993 the network was gradually enlarged and re-observed 8 times (Leitmannova et al., 2001). The velocities of 29 sites were obtained in complex coordinate and velocity estimation procedure yielding also the global covariance matrix (Hefty and Kovac, 2004).

AUSTRIAN MONITORING NETWORK

Network of about 90 permanent stations in Alpine region, Balkan Peninsula and Near East. Network is analyzed by OLG Graz (Pany et al., 2001). Velocities are based on 2-7 year span of observations.

GPS EPOCH NETWORK IN ROMANIA

Velocities from the GPS network in Vrancea seismogenic zone (Hoeven et al., 2004). Epoch observations are performed since 1996 on about 30 sites.

3. THE COMBINATION PROCEDURE AND THE HOMOGENIZED VELOCITY FIELD IN THE REGION

The principle of homogenisation of various horizontal fields into a unique reference is in elimination of systematic differences among the velocity fields by rotating them around Euler pole. The position of Euler pole and angular velocity of rotation are estimated on the basis of set of identical sites with velocities in both systems. As the reference was chosen the EPN velocity field and all the other velocities were aligned to this reference set. The details of the procedure are described in (Hefty, 2007). In addition, the method was completed in (Hefty, 2008) by stochastic modelling of input velocities to consider their various origins (epoch or permanent, length of time series, number of observing epoch campaigns and the time span of epoch observations). For the velocities from permanent networks the effect of coloured noise model was applied.

The combined velocity field containing all available site velocities in our region of interest is shown in Fig. 1. The vectors represent intraplate velocities which were obtained by reducing the ITRF2005 related velocities for the APKIM 2000 model. In (Hefty, 2007) is analysed the consistency of velocities from individual networks at the sites where more velocities are available. The conclusion is that the individual velocities at the identical sites coincide mostly at the level of 1 mm/year.

The velocity field in Fig. 1 includes velocities of about 300 sites referred to the same reference. The RMS of velocities of permanent stations is in range 0.2 -1.5 mm/year, the RMS of epoch station is in range 0.2 – 2.0 mm/year. It is evident that the accuracy of velocities is variable because of various origin (epoch/permanent), various observation history which is from 1 year (permanent) to 14 years (epoch) and various approach to processing; however the uncertainty estimates are modeled sufficiently reliable to be respected in the combination process.

It is evident that the distribution of sites with velocities is still non-homogeneous. But it is significantly improved when compared to individual regional velocity fields like EPN or CEGRN.

In Fig. 1 there can be generally distinguished four characteristic features according to the magnitude and orientation of the velocities:

- Predominantly northward oriented velocities of 3 – 5 mm/year in the Adriatic region.
- Eastward oriented velocities in East Alpine region, North Carpathian region and Pannonian Basin with magnitude up to 2 mm/year.
- The stable region of Bohemian Massive and North European Platform.
- Southward oriented velocities in the Southern Carpathian and East part of Balkan Peninsula with magnitude around 3 mm/year.

In addition to the general velocity trends several outliers (local anomalies) are clearly visible. For separation of the systematic part of the velocity trends from the random constituents of the individual velocities and from the local anomalies we filtered the velocity field using the least collocation method. The parameters of the applied covariance function are discussed in (Hefty, 2007). The systematic part shown in Fig. 2 emphasizes the main character of the velocity trends in Central and South-East Europe. The most significant pattern is the clock-wise rotation of Adria, Pannonian Basin, South Carpathian and North-East Greece. However it is evident that the rotation rate is not uniform.

The station velocities which do not follow the general trends are plotted in Fig. 3. We detected these ‘outliers’ on the iterative basis. The selection of the velocity as outlying is dependent on degree of smoothing by the least square collocation and is given by parameters of covariance function. We detected about 50 sites which may be considered as not consistent with the estimated trends (if the velocity differences between interpolated and observed velocities are larger than 2 mm/year). The ‘outliers’ are a very sensitive phenomenon for geokinematic interpretation. The origin of anomalous velocity vectors has to be analyzed in detail; the main reasons are site monumentation, land slides, local technogene phenomena, etc.

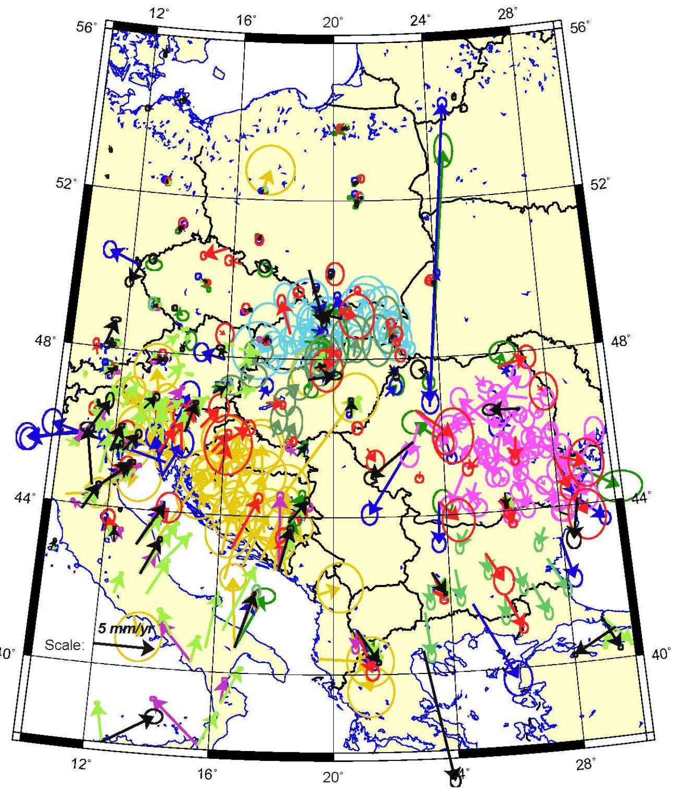

Fig. 1. The combined velocity field based on compilation of 10 individual velocity fields.

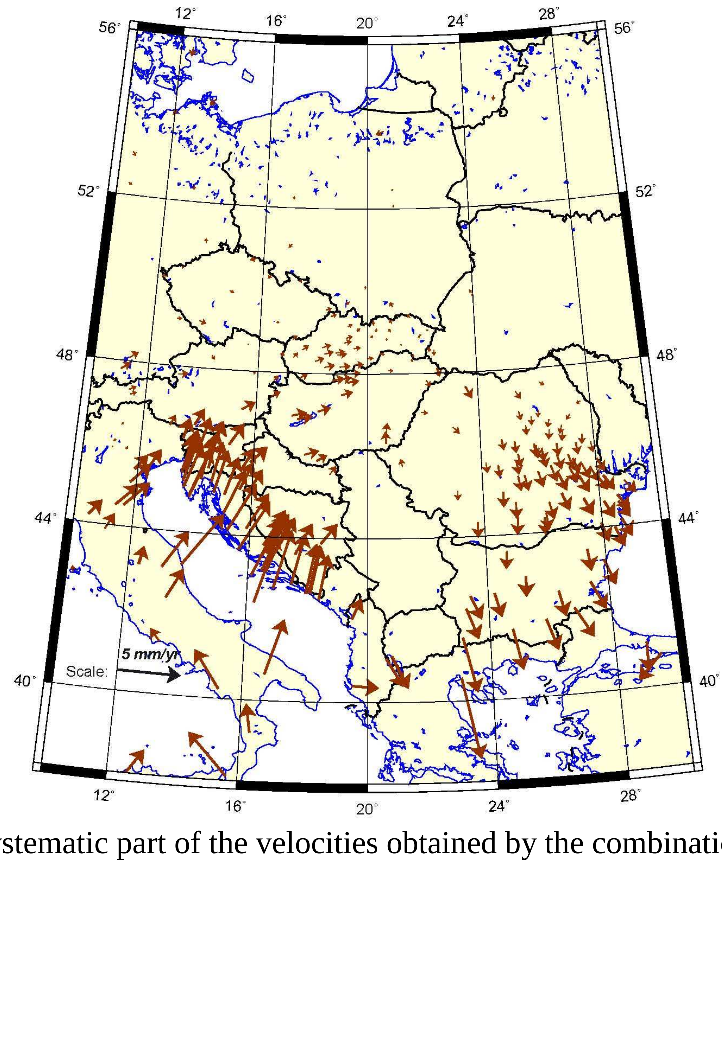

Fig. 2. The systematic part of the velocities obtained by the combination procedure.

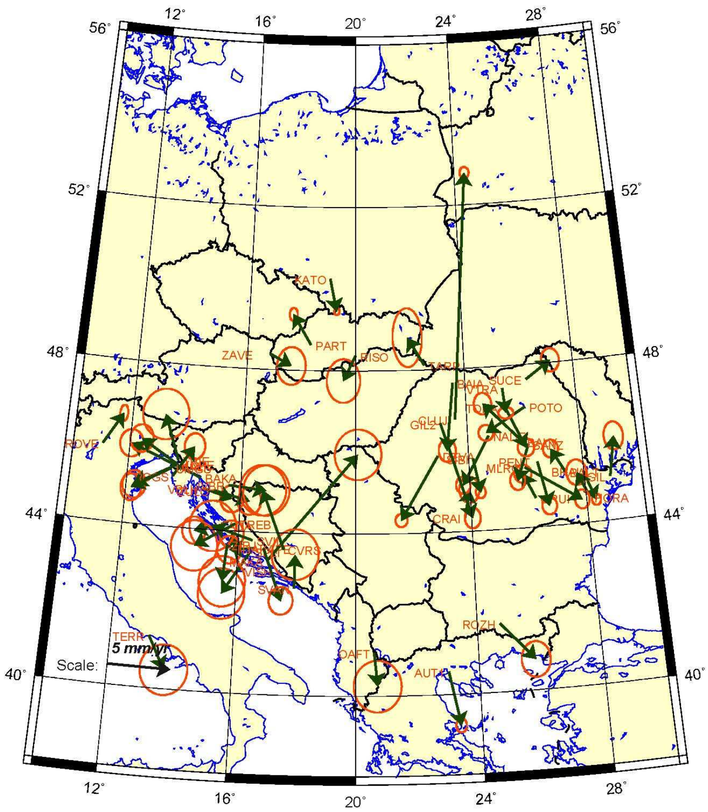

Fig. 3. The detected 'anomalous' velocities not following the general pattern.

Fig. 4 shows the interpolated velocities in the 1.0° ×0.5° grid obtained by the least square collocation. In order to get more detailed structure of the velocities, the data are less smoothed when compared to Fig. 2 and only the most significant outliers were excluded. The general patterns visible in Fig. 2 are in Fig. 4 completed by slight regional phenomena reflecting the possible peculiarity of some territories. These velocities are further used for deformation analysis.

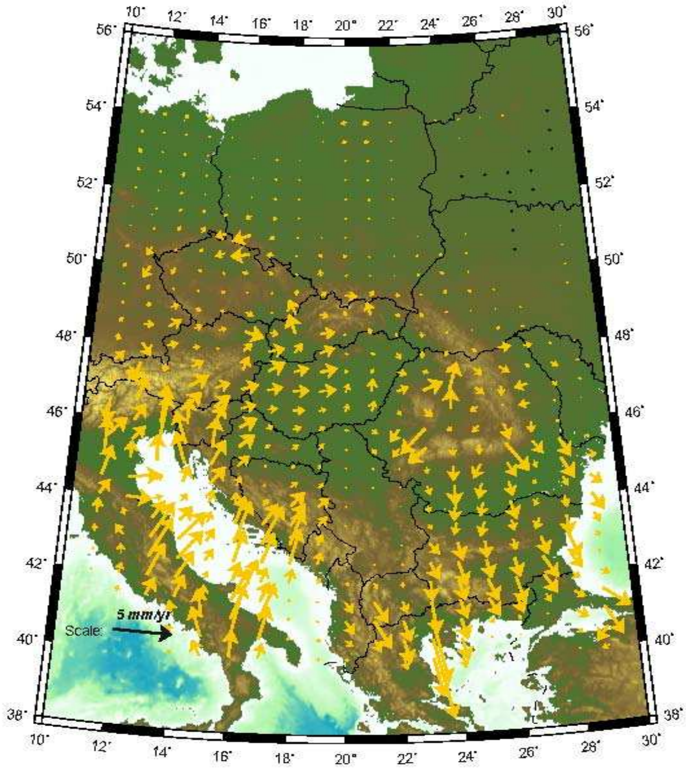

Fig. 4. The velocity field interpolated into 1.0° ×0.5° grid.

4. SURFACE DEFORMATIONS INFERRED FROM INTERPOLATED INTRAPLATE VELOCITIES

The interpolated horizontal velocity field in regular grid was used for surface deformation analysis. In Figs 5 – 7 are examples from some outputs. The surface compression and surface extension is visualized in Fig. 5. The deformation rates are in range from 0 to 30 nanostrain/year (10 nanostrain/year corresponds to deformation 1mm/100km/year). The circles represent the one-sigma uncertainty. The deformation fields are scattered and regionally distributed. The ~10 nanostrian/year and larger surface deformation situated mainly in Adria and Balkan are exceeding the one-sigma level. The extension and compression regions are varying what points out on complicated and complex surface deformation situation.

In Fig. 6 are plotted the amplitudes of shear deformation. As concerns their magnitude which reaches 50 nanostrain/year, they are pronounced as most significant deformation characteristics exceeding more times their uncertainties. However it should be remarked that this type of deformation is mostly influenced by random errors of observations and of the interpolated velocities.

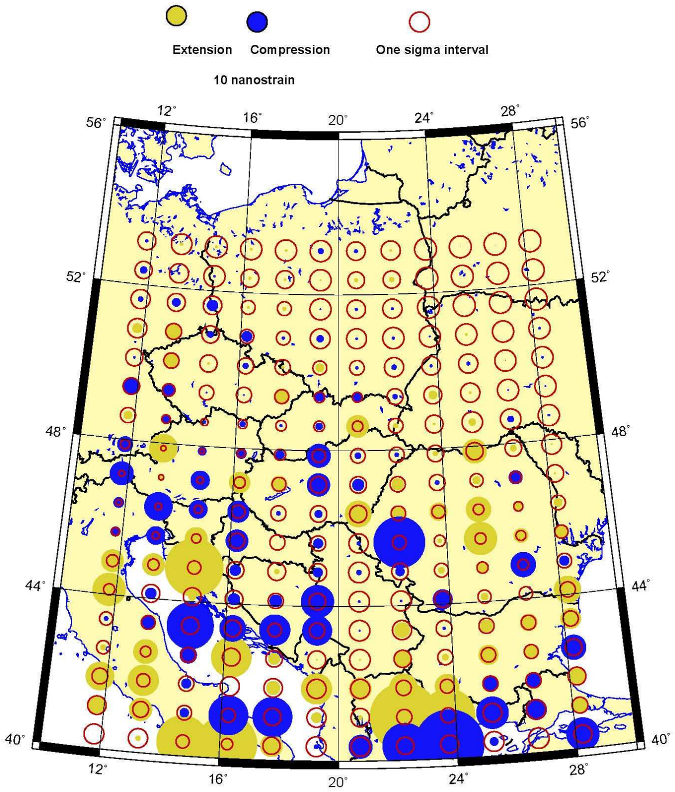

Fig. 5. Extension and compression obtained from interpolated velocity field.

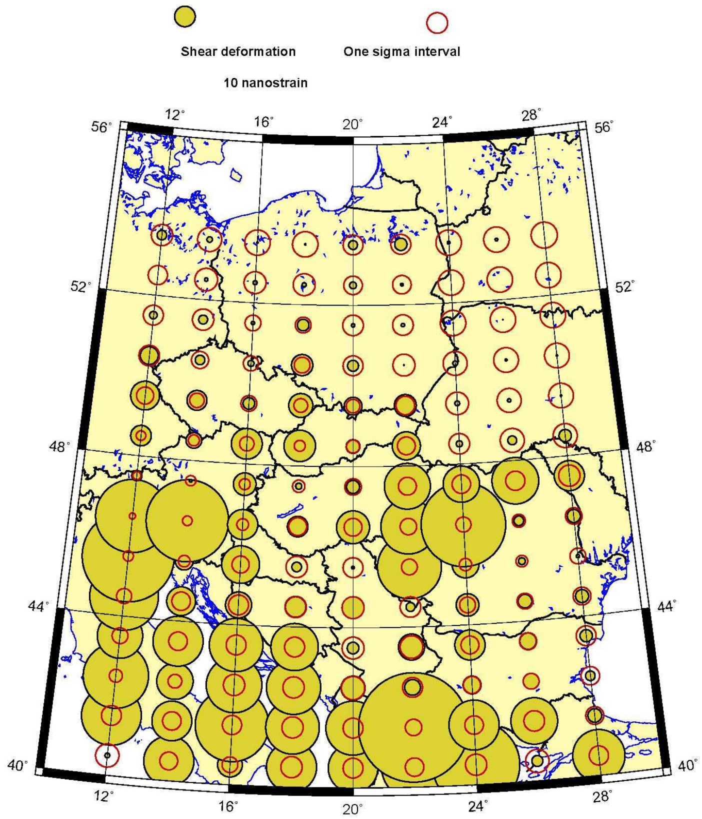

Fig. 6. Amplitude and one-sigma uncertainty of shear deformation.

Fig. 7 shows the detailed picture of orientation of main axes of extension and compression based on velocities interpolated 0.5° ×0.25° grid. This figure documents the complicated deformation structure visible also in the relatively less deformed regions like Carpathians and Pannonian Basin.

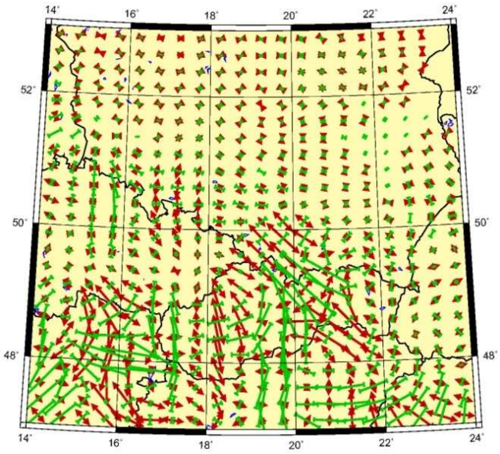

Fig. 7. Main axes of extension and compression obtained from detailed gridded velocity field.

5. CONCLUSIONS

- There are more national or regional velocity fields in Central Europe and Balkan region reported in literature. However the data are not published in numerical form or there are not available velocities for sites which can enable the referencing. As example we can mention the GPS networks in west and north Greece, Black Sea region, Bohemia, Austria, etc., as well as velocities derived from the private/commercial permanent networks.
- The main problem of combination of heterogeneous data is correct modeling of velocity uncertainties. We applied a model which considers the main characteristics of the input data used for velocity estimation like length of series, number of epoch campaigns and stochastic modeling using the colored noise approach. It is worth to mention that the rigorous SINEX based combination is also not fully adapted for correct combination of epoch and permanent observations because of assuming the white noise error models.
- The presented study was aimed to complex modeling of velocity field in Central and South-east Europe using velocity fields from various databases. We obtained velocities for more than 300 sites. The regional trends are manifested at the 1 mm/level and are well pronounced in general. The surface deformations derived from the velocities interpolated into regular grid are regionally distributed with maximum values reaching 50 nanostrain/year in Adriatic and Balkan regions.
- The presented information has to be considered as the contribution to regional modeling, of surface geo-kinematics thanks to significant densification of the velocity field. However, the coverage for homogeneous local modeling is not sufficient yet. The study of velocities for sites which are not consistent with global trends is challenge for further research. Special attention has to be paid to local phenomena, like monumentation, environment, landslides, geology, etc.

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BIBLIOGRAPHY

1. Altiner, Y., Bačič, Ž, Bašič, T., Coticchia, A., Medved, M., Mulič, M., Nurce, B. (2006) Present-day tectonics in and around the Adria plate inferred from GPS measuremets. Geological Society of America Special Paper 409. pp. 43 – 55.
2. Caporali, A., Martin, S., Massioroni, M. (2003) Average strain rate in the Italian crust inferred from a permanent GPS network – II. Strain rate versus seismicity and structural geology. Geophys. J. Int. 155. pp. 254 – 268.
3. Caporali, A. et al. (2008) Geokonematics of Central Europe: New insight from the CERGOP/2 Environment project. Journal of Geodynamics, Vol. 45, 4-5, 246-256.
4. EPN (2008) The EPN Coordinate Time Series Analysis Special Project. Available at www.epncb.oma.be.
5. Fejes, I. and Pesec, P. (2003) CERGOP-2/Environment – a challenge for the next 3 years. Proc. Of EGS-AGU-EUG G17 Symposium, Nice, 2003. Reports on Geodesy No.1 (64), 13-22.
6. Grenerczy, Gy. (2002) Tectonic Processes in the Eurasian-African Plate Boundary Zone Revealed by Space Geodesy. Plate boundary zones, AGU Monograph Geodynamic Series Volume 30.
7. Hefty, J. (2006) Work Package 5 of the CERGOP-2/Environment: GPS data analysis and the definition of reference frames. Final report: April 2003 – July 2006. Reports on Geodesy 3 (78), pp 51-84.
8. Hefty, J. (2007) Geo-kinematics of Central and South-east Europe resulting from combination of various regional GPS velocity fields. Acta Geodyn. Geometer., Vol. 4 (148), 173-189.
9. Hefty, J. (2008) Densification of the Central Europe velocity field using velocities from local and regional geokinematical projects. Geophysical research abstracts, Vol. 10/2008, Abstracts of the Contributions of the EGU GA, Vienna, Austria, 13-18 April, 2008.
10. Hefty, J. and Kovac, M. (2004) Detection of intraplate motion within the territory of Slovakia and their importance for reference frame realisation. Recent status and progress in reference frames, Brno, Institute of Geodesy, Technical University in Brno, pp 60 – 68 (in Slovak).
11. Hefty, J., Igondová, M., Hrčka, M. (2005) Contribution of GPS permanent stations in Central Europe to regional geo-kinematical investigations. Acta geodynamica et geomaterialia 2, No. 3, (139), pp 75-86.
12. Hoeven, A., Scmitt, G., Dinter, G., Mocanu, V. and Spakman, W. (2004) GPS probes the kinematics of the Vrancea seismogenic zone. EOS transactions, 19, 85, 185-196.
13. Leitmannova, K., Klobusiak, M., Priam, S., Ferianc, D.: (2002) SKTRF 2001 – Reference frame for national spatial network. Geodetic reference systems, Bratislava, Slovak University of Technology, pp 137 – 148 (in Slovak).
14. Milev, G., Vassileva, K., Becker, M., Kirchner, M. (2005) Analysis of the EUREF stations stability on the territory of Bulgaria. EUREF Symposium 2005, Vienna, Austria.
15. Pany, T., Pesec, P., Stangl, G. (2001) Network monitoring at the OLG Analysis Centre. Presented at the Euref Symposium 2001, Dubrovnik, Croatia.

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