International Symposium on Strong Vrancea Earthquakes and Risk Mitigation
Oct. 4-6, 2007, Bucharest, Romania

THREE DIMENSIONAL PLATE KINEMATICS IN ROMANIA

Günter Schmitt [1], Andre Nuckelt [1], Andreas Knöpfler [1], Constantin Marcu [2]

ABSTRACT

The geodetic subproject B1 of the CRC 461 „Strong Earthquakes“ focuses on the determination of the three dimensional movement of the Romanian investigation area. For the actual project phase the research activities were concentrated on the improvement of the data processing and development of new strategies for the interpolation of velocity fields including deformation analyses.
The observation data of 14 GPS campaigns performed from 1995 to 2006 have been reprocessed using the Bernese GPS Software. To improve the station quality detailed analyses of multipath effects and GPS antenna calibrations were performed. The alternative processing strategy besides the traditional baseline processing, “Precise Point Positioning” was tested, but the accuracy could not satisfy the demands of a high-precision deformation analysis.
Station velocities were obtained from the GPS daily coordinate solutions using the kinematic model of geodetic deformation analyses. Based on these station velocities a three dimensional velocity field was estimated using the technique of multilevel B-spline approximation. Principal strains and shear strains were derived directly from the B-spline approximation surfaces. The application of the law of variance propagation to velocity field approximation and strain calculation allows the qualitative analysis for all obtained results.
The final results of the research project are detailed information about the three dimensional movement of the investigation area. Regions of significant uplift or subsidence were identified.

INTRODUCTION

The aim of the geodetic subproject B1 “Three dimensional plate kinematics” of the COLLABORATIVE RESEARCH CENTER (CRC) 461 “STRONG EARTHQUAKES” is the determination of three dimensional plate movements for Romania as well as strain rates of the tectonic units.

At the beginning of the CRC 461 the effort was focused on the establishment and densification of the GPS network. In the second and third project phase the research was concentrated on improvement of the strategies for GPS data processing and deformation analysis.

The research tasks of the last project phase are distinguished in two working areas:

I. Reprocessing of all observed GPS data. Updates of the used GPS processing software, continually improving of GPS processing strategies as well as changes of the global GPS reference frames require the reprocessing of the GPS observations. Furthermore a complete analysis of the database optimizes the data processing. The reprocessing should help to solve problems, which were detected during previous data analysis.

[1] Geodetic Institute, University of Karlsruhe
[2] Faculty of Geodesy, Technical University of Bucharest

II. Approximation of the three dimensional velocity field with included propagation of variances. Based on these results principal strains and shears strain have to be computed.

Beside these tasks the project work dealed also with time series analyses of permanent GPS stations and the development of a project information system.

GPS NETWORK

One main aspect of geodynamic measurements is the network which is used. In this case a regional GPS network was established and used.

Overview

Three dimensional movements of the earth's surface can be determined by regional GPS networks. In the framework of the CRC 461 in cooperation with the Department of Earth Observation and Space Systems (DEOS) of the TU Delft a network including roughly 50 stations was established in Romania between 1997 and 2003 (see Fig. 1) (Nuckelt et al., 2005) (van der Hoeven et al., 2005). Station velocities are estimated using observations of 14 GPS field campaigns between 1995 and 2006.

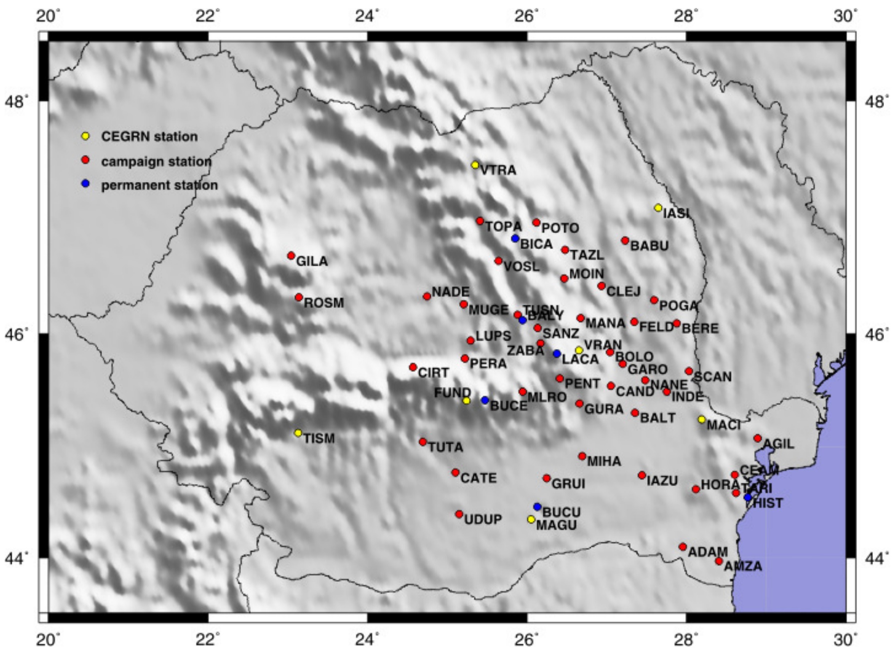


Figure 1: GPS network used in CRC 461

An overview about all campaigns is given in table 1.

Table 1: GPS campaigns

Year	Institution	GPS-Days	Number of Stations	Occupation Time
1995	CEGRN[3]	148-154	6	24 h
1996	CEGRN	162-167	6	24 h
1997	CEGRN	155-161	6	24 h
	CRC	270-275	26	7 h
1998	CRC	232-239	27	7 h
1999	CEGRN	165-170	6	24 h

[3] Central European GPS Geodynamic Reference Network

Year	Institution	GPS-Days	Number of Stations	Occupation Time
	NATO	184-195	11	24 h
2000	CRC	232-240	34	8 h
2001	NATO	130-138	12	24 h
2002	DEOS	184-207, 250-268	50	24 h
2003	CRC	224-234	63	24 h
2004	CRC+DEOS	221-231	58	24 h
2005	DEOS	184-198	32	24 h
2006	CRC+DEOS	226-236	51	24 h

Signalisation of the sites

The marking of the sites in such a big project causes different problems. One the one hand, two institutions marked their sites in a different way (CRC, CEGRN) and on the other hand the markers of some sites have been destroyed during the project. Both institutions used metal bolts which are fixed in bedrock or concrete. The difference between these bolts is that at the CEGRN-bolt the thread sticks out of the bedrock or concrete and at the CRC-bolt the thread is inside the bolt. So the CEGRN one can be easily damaged and the CRC one is rather secure. When the bolts are not in use, the thread can be covered by a special cap. For an easy setup of the equipment, special adapters were developed by the Geodetic Institute Karlsruhe (GIK). With special attachments they fit both CRC-marker and CEGRN-bolt. After screwing them into the CRC-bolt or on the CEGRN-marker, they can be set vertical by a special hinge. For each version of the setup, they have a predefined, fixed height.

Unfortunately many bolts were damaged during the long period, especially the CEGRN-bolts, because they stick out of the ground. In order to be able to continue the time series on a damaged site, an alternative setup with a triangular plate with a fix height component was used. It is necessary to mention that even if the measurements can be continued with a different setup on a destroyed site, the time series is broken. Both the offset between the intact bolt and the damaged one is not known and because of a different setup, a different surrounding to the GPS-equipment is given whose behaviour is not known. A view on the two different setups is given in fig. 2.

Figure 2: Different setups: CRC-adapter (left) and triangular plate (right)

In addition to the main bolts of a site, backup bolts were placed some meters beside and offset-measurements were made. Normally the measurements during the campaigns were performed on the main bolt but unfortunately some teams in every campaign used the backup bolt. Even with the offset measurements no satisfying result could be reached in this way.

DATA REPROCESSING

In the last period of the CRC, all available data was reprocessed using identical settings for consistent results.

Data and Data Problems

For the reprocessing the available data of all occupied stations of all 14 field campaigns has been used. Beside the raw files of the stations a lot of other data is necessary for a processing of the GPS-data. In order to achieve best possible results, final orbit data for the GPS satellites had to be included. These final orbits are determined by different institutions and available on internet. In this case, final orbits of the IGS (International GNSS Service) have been used. Further parameters of the earth rotation and of the ionosphere activity have been downloaded and integrated in the processing.

A problem in terms of a deformation analyses covering such a long period is to use one geodetic reference frame during the whole time. All the products (orbits, coordinates, earth rotation parameters) that are used within the processing depend on the current reference frame. Changes during the period of available data can be seen in table 2.

Table 2: ITRF changes IGS products

Date	Change from:	To:
30.06.1996	ITRF93	ITRF94
01.03.1998	ITRF94	ITRF96
01.08.1999	ITRF96	ITRF97
02.12.2001	ITRF97	IGS00

For consistent results of the deformation analyses the used external products like orbits or earth rotation parameters had to be transformed to one reference frame: in this case ITRF2000 [Boucher et al., 2004] was chosen. Also the coordinates of the IGS reference stations that were chosen for the geodetic datum were used in ITRF2000.

Software and Strategy

The Software used for data reprocessing was the Bernese GPS Software Version 5.0 of the Astronomical Institute, University of Berne (Switzerland) (Dach et al., 2007). Former processing has been performed with earlier versions of this software package. For the final deformation analysis, all available campaigns were reprocessed using the latest version of this software with the same settings for all campaigns. Bernese GPS Software is a scientific software package which offers much more possibilities for special settings to the user than other commercial products.

In order to process all campaigns in the same way, a so called Bernese Processing Engine (BPE) can be created. Within this part of the software, all important settings can be stored and the processing can be run in a kind of batch-mode.

The processing can be separated in 4 steps: data preparation, definition of baseline & preprocessing, float solution and ambiguity fixed solution. In the first step the different information of earth rotation, orbits and the RINEX-Files [Gurtner, 2001] of the stations are converted into proprietary formats. Within this process, some checks are performed. The first part of the next step is to form baselines out of the stations. In this case single difference observation files of the carrier phase are used. Further existent cycle slips are detected and corrected as well as unpaired observations flagged as unusable. The last step of this part of the processing is the double difference phase residual screening. Within this step, the double difference residual files are created, screened for outliers, the outliers are marked and final residual files are created. One main step is the solving of the ambiguities. First, a network solution with real valued ambiguities is performed and the coordinates and troposphere estimates are stored for further processing. Next, the estimates of the previous part are introduced and fixed and the L1 and L2 ambiguities are solved and stored. In the final part of the processing, an ambiguity-fixed solution is computed, using the ambiguities of the previous part.

VELOCITY FIELD

The velocity field is derived from the daily coordinate solutions of the GPS network. In the first step a kinematical model is used to estimate the station velocities, afterwards a regular velocity field is generated using B-spline techniques.

Estimation of station velocities

The station velocities are calculated relatively to the movement of the European continent. To assume a stable European plate all daily coordinate solutions have to be transformed from their epoch to epoch 1997.0. Using the usual kinematic model for deformation analyses should deliver the best fitted linear velocity.

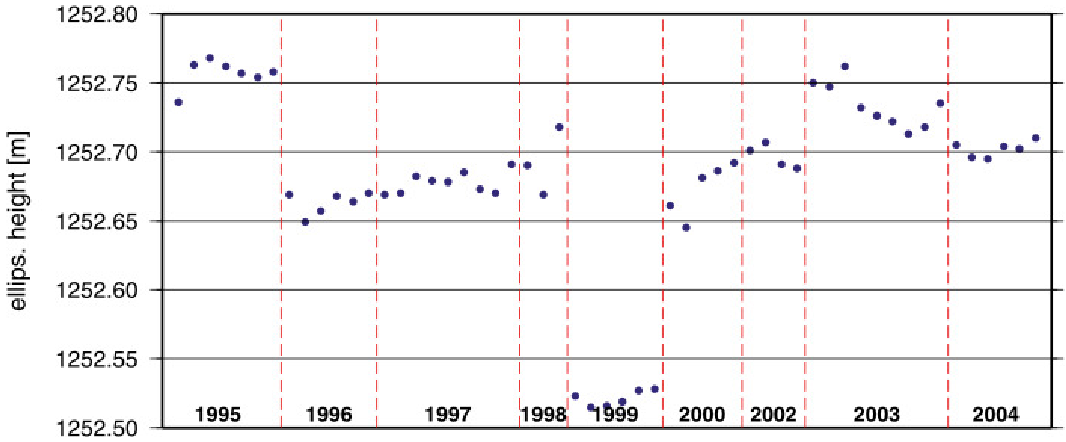


Figure 3: GPS station Fundata, daily solution for height coordinate for observations in campaigns between 1995 and 2004

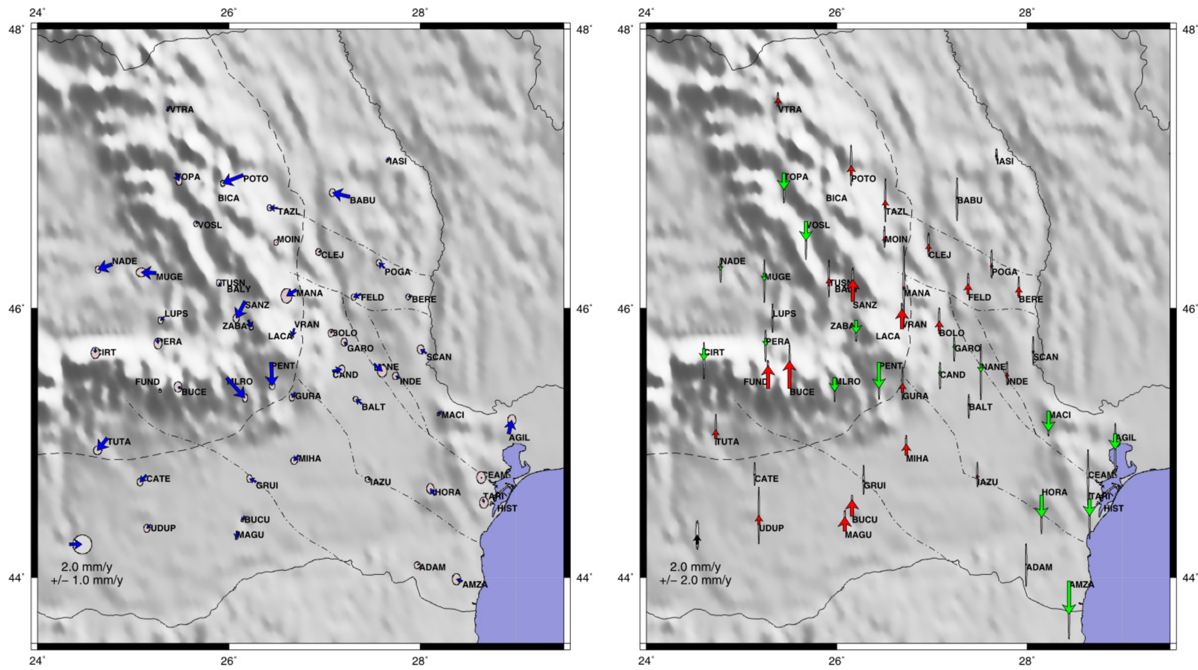
There are significant differences for the height coordinates caused by different receiver equipments, shown in figure 3. Leaps for the station height coordinate occur even within a single campaign, e. g. campaign 2003: the first three dots belong to the first occupation block; there is a significant difference to the solutions of block two and three (the following 6 dots, different equipments were used for each occupation block).

State of the art GPS processing includes also antenna phase center models to handle different properties of equipments. But even the best antenna models could not eliminate these leaps (Knöpfler et al., 2007). The height differences due to different equipments should be caused by their different sensitivity for multipath signals. Actually it’s not possible to eliminate multipath influences, they only can be detected.

To handle the leaps of the height component the kinematic model was extended by a term for offset estimation.

$$\begin{pmatrix} B \\ L \\ h \end{pmatrix}_{i,t} + \begin{pmatrix} v_B \\ v_L \\ v_h \end{pmatrix}_i = \begin{pmatrix} B \\ L \\ h \end{pmatrix}_{i,t_0} + \begin{pmatrix} \omega_B \\ \omega_L \\ v_h \end{pmatrix}_i (t - t_0) + \begin{pmatrix} dB(B,L,h,d) \\ dL(B,L,h,d) \\ dh(B,L,h,d) \end{pmatrix}_i + \begin{pmatrix} O_B \\ O_L \\ O_h \end{pmatrix} \quad (1)$$

Using this model the linear velocities in north, east and up direction can be estimated. The results for the GPS stations are shown in figure 4.



(a) Plane velocities (b) Vertical velocities

Figure 4: Estimated velocities of GPS stations

Velocity field approximation

As usual the GPS stations are located very scattered. For analysing the movement and deformation of the investigation area it is necessary to determine a regular grid or continuous surface using approximation techniques. The methods of freeform surfaces and scattered data interpolation provide both lots of possibilities for the estimation of approximation surfaces. The multilevel B-spline approximation unifies both methods and provides the possibility to include a computation of strain rates. Due to application of the law of propagation of variances to the approximation algorithm standard deviations can be obtained for the velocity field.

The basic theory is to define rectangular control lattice Φ to overlay the domain Ω , which contains the scattered data points P . To approximate the scattered data an approximation function *f* is formulated as an uniform bicubic B-spline function, which is defined by a control lattice Φ (see Fig. 5), each point on the approximation surface is computed depending on the control points in its 4×4 neighbourhood.

The approximation problem is solved by calculating the control points of the lattice $\boldsymbol{\Phi}$. In this opposite way every computation of a control point corresponds to all data point in its $\mathbf{4 \times 4}$ neighbourhood.

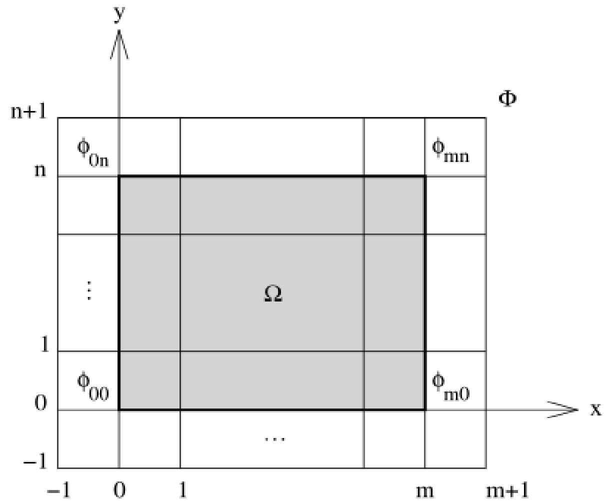


Figure 5: The configuration of control lattice Φ

Fig. 4 depicts the complete multilevel B-spline approximation (MBA) algorithm to generate the approximation function *f*. The algorithm consists of four main operations in each refine level:

I. Compute a control lattice $\boldsymbol{\Phi}$ from the data points $\boldsymbol{P}$
II. Compute the deviation $\boldsymbol{P} = \boldsymbol{P} - \boldsymbol{F}(\boldsymbol{\Phi})$ at the data points
III. Compute $\boldsymbol{\Psi} = \boldsymbol{\Psi}' + \boldsymbol{\Phi}$
IV. Refine $\boldsymbol{\Psi}$ into $\boldsymbol{\Psi}'$

During the approximation process a number of control lattices is generated. At the left side of Fig. 6 a set of control lattices $\boldsymbol{\Phi}$ is shown, which are derived directly from the data points using B-spline techniques. For each control lattice the deviations at the data points (original value minus approximated value) are determined. These deviations are the input values for the next finer control lattice. Thus the final approximation function is defined on the sum of all lattices. The characteristic of the computation of a new control lattice $\boldsymbol{\Phi}$ is, that only control points in the neighbourhood of the data points are computed.

To allow an addition of the control lattices, the configuration of the control points has to be equal. Thus the coarse control lattice has to be refined to the refinement level of the finer lattice. Hence the final control lattice as well as all intermediate results is obtained by addition of refined coarser intermediate results and a new finer control lattice.

The law of propagation of variances has to be applied to the four main operations of the MBA algorithm to obtain information about the accuracy of the approximated function *f*, in our case the approximated velocity field. The determination of the so called *Jacobi* matrix *F* can be implemented directly into the approximation algorithm. Each operation consists of linear functions, thus differentiations and Taylor expansions are not necessary. Using the matrix *F* the law of propagation of variances can be applied to calculate the covariance matrices. A detailed description of the propagation of variances for multilevel B-spline approximation is given in (Nuckelt, 2007).

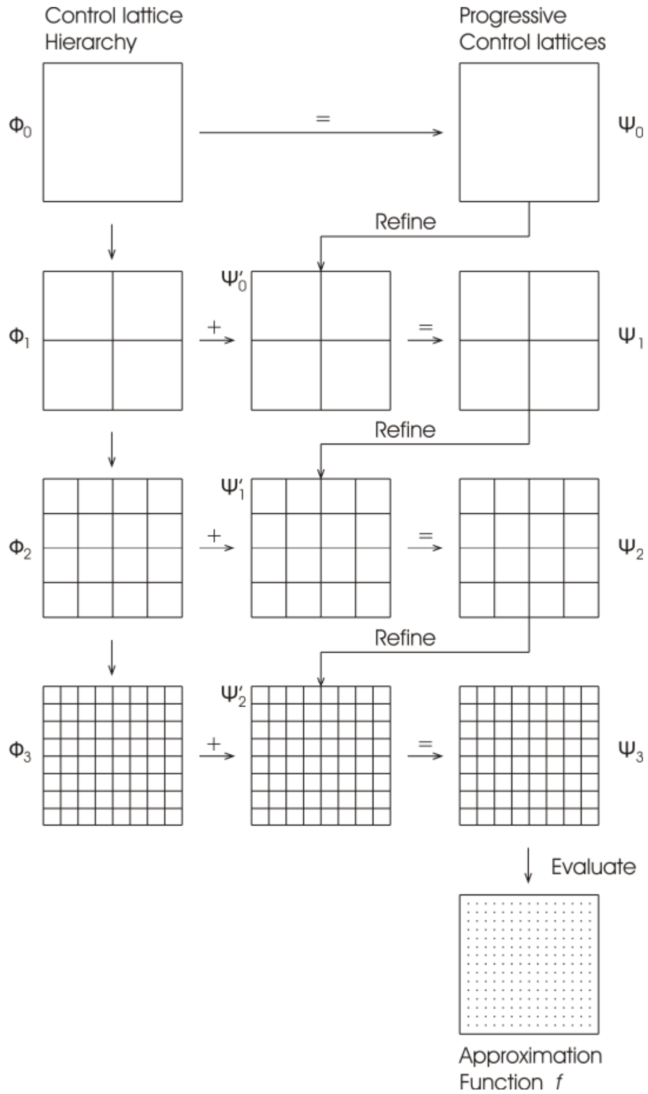


Figure 6: Approximation function evaluation in the MBA algorithm

Final velocity field

The obtained velocity field plus standard deviations are shown in Fig. 7 and 8. The obtained velocity field fits very well the station velocities. Fig. 7 depicts areas of significant horizontal movements. The Moesian platform moves clearly direction southwest. For the part in the north a west movement is shown. The area between Intramoesian Fault and Peceneaga Camena Fault moves to the Northwest, this is the opposite direction of previous publications (Nuckelt et al., 2005) and (van der Hoeven et al., 2005). The Transylvanian Basin inside the Carpathian arc performs a shift to the west. The biggest velocities (up to 5 mm/year) are shown for the south-eastern part of the Carpathian arc.

The vertical velocity field in Fig. 8 visualises areas of significant uplift and subsidence. Transylvanian Basin, Brasov Basin, Focsani Basin and the areas close to the Black Sea are evidently subsiding regions. In opposition to this areas the Carpathian arc, Moesian platform and European platform are uplift areas.

The horizontal as well as the vertical movements match more or less with geological studies (Tarapoanca et al., 2003)**.** The moderate uplift of Vrancea area coincides with a geodynamic model developed in the CRC 461. This model proposes the progressive delamination of a soft coupled vertical slab beneath this area (Sperner et al., 2005), (Heidbach et al., 2007).

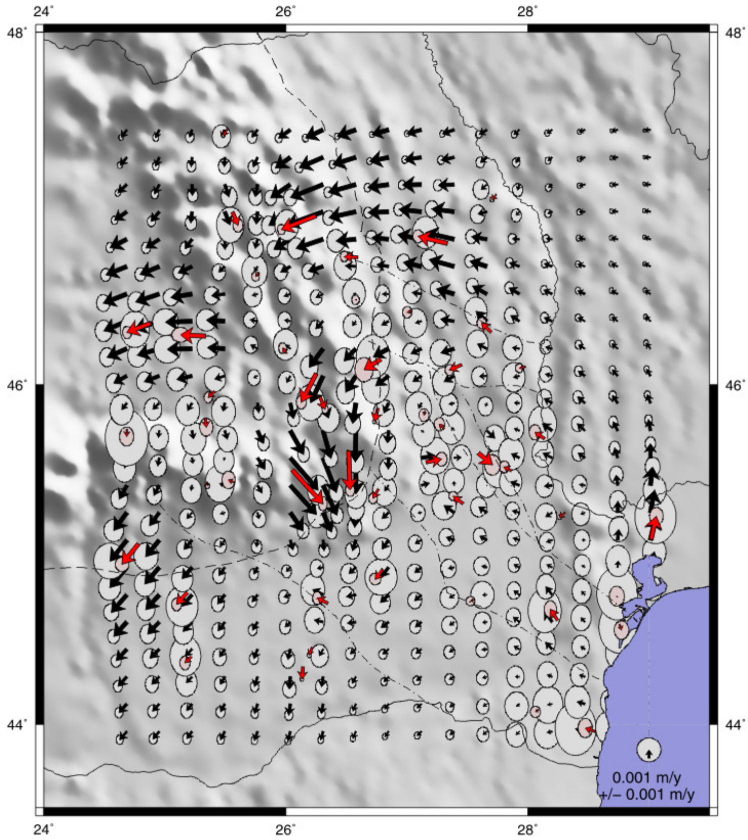
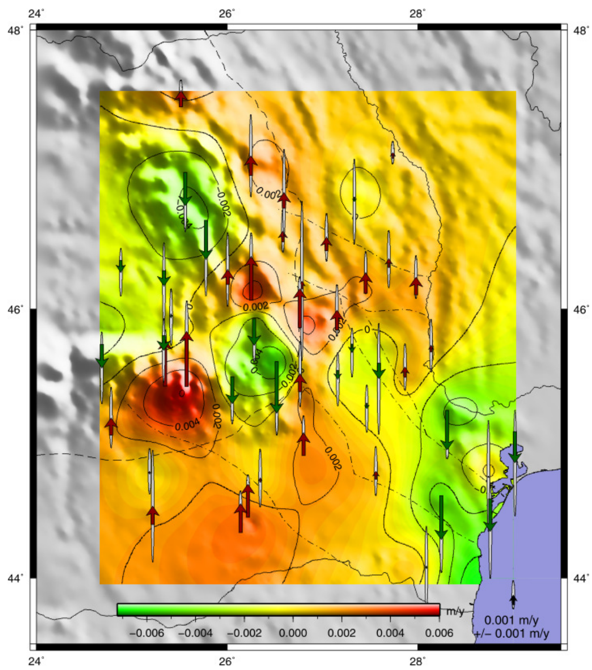
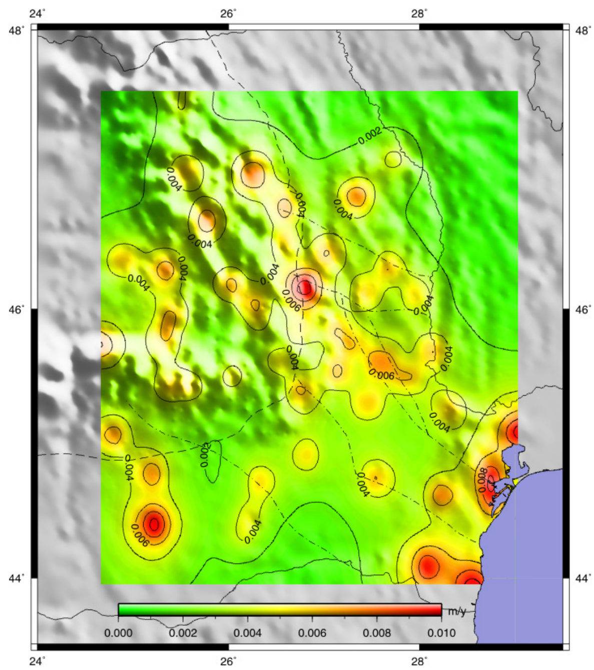


Figure 7: Plane velocity field plus standard deviations



(a) Velocities



(b) Standard deviations

Figure 8: Vertical velocity field

The approximation with multilevel B-splines generates smooth best fitting surfaces which represent the velocity field. The accuracies of the GPS stations propagate to the velocity field. Due to the properties of the algorithm areas close to the data points (GPS stations) obtain bigger standard deviation than other areas, because control points within the 4×4 neighbourhood of the data points are more often included into the approximation process than the other control points. The areas of biggest standard deviations surround the most inaccurate GPS stations. More detailed analyses in terms of accuracy are given in (Nuckelt, 2007)

Strain Analysis

Based on the continuous description of an object the theory of continuum mechanics can be applied to perform strain analyses for this object. The necessary continuous description is provided by the velocity field generated by multilevel B-spline approximation algorithm. The displacement gradient tensor $\boldsymbol{Grad\,\overline{u}}$ with

$$\boldsymbol{Grad\,\overline{u}} = \begin{bmatrix} \frac{\partial v_{north}}{\partial X} & \frac{\partial v_{east}}{\partial X} & \frac{\partial v_{up}}{\partial X} \\ \frac{\partial v_{north}}{\partial Y} & \frac{\partial v_{east}}{\partial Y} & \frac{\partial v_{up}}{\partial Y} \\ \frac{\partial v_{north}}{\partial Z} & \frac{\partial v_{east}}{\partial Z} & \frac{\partial v_{up}}{\partial Z} \end{bmatrix} \qquad (2)$$

can be obtained directly from the control lattice of the approximation function. The vertical gradient can not be determined, because geodetic observations are provided only for the earth surface. If the movement for a surface point and its corresponding points beneath the surface is assumed, the vertical gradient can be set to

$$\frac{\partial v_i}{\partial Z} = 0\,. \qquad (3)$$

With this assumption it is not possible to describe vertical deformations. Thus authentic strain analyses can be performed only for the two dimensional surface.

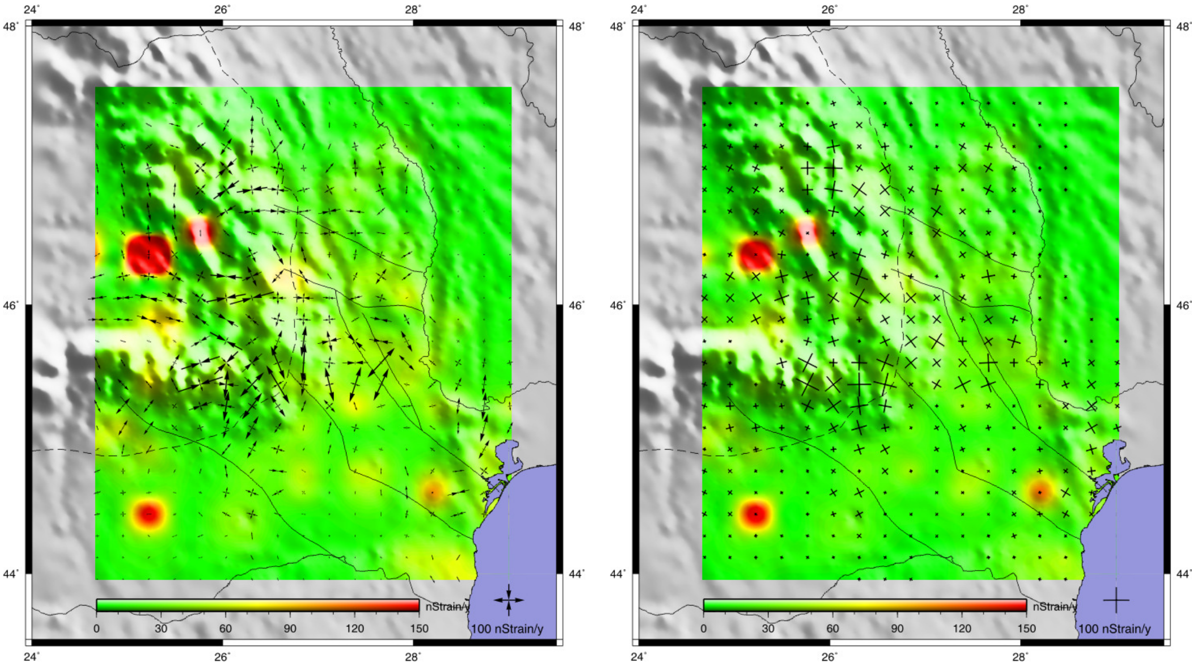
The infinitesimal deformation tensor $\underline{\boldsymbol{\varepsilon}}$ and the infinitesimal rotation tensor $\underline{\boldsymbol{\Omega}}$ can be derived from $\boldsymbol{Grad\,\overline{u}}$. The principal strains are the results of computing eigenvalues and eigenvectors of $\underline{\boldsymbol{\varepsilon}}$. The shear strains can be derived also from $\underline{\boldsymbol{\varepsilon}}$ and $\underline{\boldsymbol{\Omega}}$. The law of propagation of variances is applied also to each computation of the strain analysis.

For a complete explanation of the propagation of variances for the determination of $\boldsymbol{Grad\,\overline{u}}$, the tensor calculation and the determination of principal and shear strains is referred to (Nuckelt, 2007).

The computed principal and shear strains are shown in Fig. 9. The coloured surfaces put under the strain crosses represent their formal errors. The pattern of these surfaces is similar to Fig. 8(b). The areas of bigger errors coincide, because the velocity field as well as the strain parameter are based on the same control lattice of the multilevel B-spline approximation. This lattice itself depends on the GPS stations. That's why you can see the station configuration and their different accuracies also in these figures.

Large principle and shear strain are observable in the centres of both Figures 9 (a) and (b). Strains are obtained for regions where different movements occur, e. g. the most south-eastern part of the Carpathian arc. Large extensions and shear strains are shown in this zone. In the adjacent area to the east large extensions in different directions are observable.

In areas of uniform displacement strains do not occur, e. g. the Moesian platform and the whole southern area, respectively.



(a) Principal strain (b) Shear strain

Figure 9: Horizontal strains plus standard deviations

CONCLUSIONS

The defined project aims are partially achieved. The quality of the obtained velocities of the GPS stations could be improved due to extension of the timeline and number of measurement campaigns. The situation in the investigation area requires a large number of observations within a long time span, because the horizontal as well as the vertical movements are quite small.

Nevertheless the movements of the Carpathian arc and the adjacent basins were determined. While the Carpathians are uplifted the Transylvanian Basin and Focsani Basin are clearly subsidence areas. (The actual configuration of the monitoring network does not allow detailed studies of the faults.)

All activities and effort for improving the GPS data processing did not solve the problem of discrepancies of the coordinate time series (see fig. 3). The reprocessing of all observations, the investigation of GPS antenna phase centre variations and multipath signals as well as the PPP strategy for the data processing could not eliminate the occurred coordinate leaps.

Due to the application of B-spline techniques including error propagation a velocity field with accuracy information were generated. Based on the horizontal velocities principal and shear strains were computed. The analysis of the obtained standard deviation for velocities as well as for the strains points up the reliability of the associated values.

ACKNOWLEDGMENTS

This study was carried out in the Collaborative Research Center (CRC) 461 “Strong Earthquakes: a challenge for Geosciences and Civil Engineering” at the Universität Karlsruhe (TH), which is funded by the Deutsche Forschungsgemeinschaft (German Research Foundation) and supported by the state of Baden-Württemberg and the Universität Karlsruhe (TH).

We thank our Dutch and Romanian colleagues and specially the big number of students participating in the field campaigns; without them, this project would not have been possible.

REFERENCES

Boucher, C., Altamimi, Z., Sillard, P. and Feissel-Vernier, M., 2004: The ITRF2000. IERS Technical Note No. 31, http://www.iers.org/documents/publications/tn/tn31/tn31.pdf (viewed on 2006-05-03)

Dach R., Hugentobler U., Fridez P. and Meindl M., 2007: Bernese GPS Software Version 5.0, Astronomical Institute University of Berne (Switzerland)

Gurtner, W., 2001: RINEX: The Receiver Independent Exchange Format Version 2.10. http://www.ngs.noaa.gov/CORS/Rinex2.html (viewed on 2006-05-03)

Heidbach, O, Müller, B., Sperner, B., Kurfeß, D., Buchmann, T., Peters G., Ledermann, P., Nuckelt, A. and Schmitt, G., 2007: Attached or not attached: slab dynamics beneath Vrancea, Romania, this volume

Knöpfler, A., Mayer, M., Nuckelt, A., Heck, B. and Schmitt, G., 2007: Untersuchungen zum Einfluss von Antennenkalibrierwerten auf die Prozessierung regionaler GPS-Netze, Universität Karlsruhe, Schriftenreihe des Studiengangs Geodäsie und Geoinformatik, No. 2007/1

Nuckelt, A., Nutto, M., Schmitt, G., van der Hoeven, A. G. A., Marcu, C. and Mocanu V., 2005: Status report of the CRC 461 subproject "Three dimensional plate kinematics in Romania", Geophysical Research Abstract, 7, 00120

Nuckelt, A., 2007: Dreidimensionale Plattenkinematik: Strainanalyse auf B-Spline-Approximationsflächen am Beispiel der Vrancea-Zone/Rumänien, University of Karlsruhe, Schriftenreihe des Studiengangs Geodäsie und Geoinformatik, No. 2007/5

Sperner, B. & the CRC 461 team, 2005: Monitoring of Slab Detachment in the Carpathians, in: Wenzel, F. (ed.): Perspectives in Modern Seismology, Springer-Verlag, p. 187-202

Tarapoanca, M.; Bertotti, G., Matenco, L., Dinu, C. and Cloetingh, S., 2003: Architecture of the Focsani depression: A 13 km deep basin in the Carpathians bend zone (Romania), Tectonics, Vol. 22, No. 6

van der Hoeven, A.G.A., Mocanu, V., Spakman, W., Nutto, M. Nuckelt, A., Matenco, L., Munteanu, L., Marcu, C. and Ambrosius, B. A. C., 2005: Observation of present-day tectonic motions in the Southeastern Carpathians: Results of the ISES/CRC-461 GPS measurements, Earth and Planet. Sc. Lett., 239, 177-184