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GEODETIC NETWORK DEFORMATION BASED ON GPS DATA IN THE BALTIC REGION

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Abstract. For investigating horizontal deformations of geodetic networks, the data of GPS measurements of the epochs about 1992 and 2003 were used. To avoid the impact of the discrepancy of the systems of coordinates upon the parameters of the deformations, the method of tensor analysis was applied using the method of finite elements. A geodetic network consists of 19 triangles; 15 geodetic ground benchmarks observed by GPS method were used. The horizontal deformations of geodetic network in the territory of the Baltic Sea region were calculated. The maximum relative strain in the territory of the Baltic Sea region varies between $+0{,}03\times10^{-6}$ and $+0{,}58\times10^{-6}$ and is positive within the whole territory; the minimum relative strain varies between $-0{,}93\times10^{-6}$ and $+0{,}03\times10^{-6}$; and the dilatation varies between $-0{,}35\times10^{-6}$ and $+0{,}16\times10^{-6}$.

Keywords: finite element method, GPS, strains, tensor analysis.

1. Introduction

Horizontal deformations of the Earth's crust can be identified from the changes of the geodetic coordinates and other elements of the benchmarks of geodetic networks by performing the repeated geodetic measurements (El-Fiky, Kato 2006; Lagios *et al.* 2007; Lidberg *et al.* 2006, 2007; Masson *et al.* 2007; Riguzzi *et al.* 2006; Šliaupa *et al.* 2006; Zakarevičius, Stanionis 2007, Zakarevičius *et al.* 2007). The measurements can be performed in the continuous or differential regimes.

Among the latest geodetic network measurement technologies the GPS is the most widely used investigation system (Skeivalas 2008). The repeated measurements of those networks enables an investigation of horizontal deformations.

The objective of the presented study is to evaluate the applicability of tensor analysis and finite element modelling for evaluation of the horizontal strains by geodetic measurements. The geodetic network of the Baltic regions was investigated. Relative maximum and minimum horizontal strains, direction of maximum strain and dilatation were calculated.

2. Data

Data of GPS campaigns of 1992 and 2003 GPS were used. The network consists of 19 triangles (Fig. 1) comprising 15 geodetic ground benchmarks.

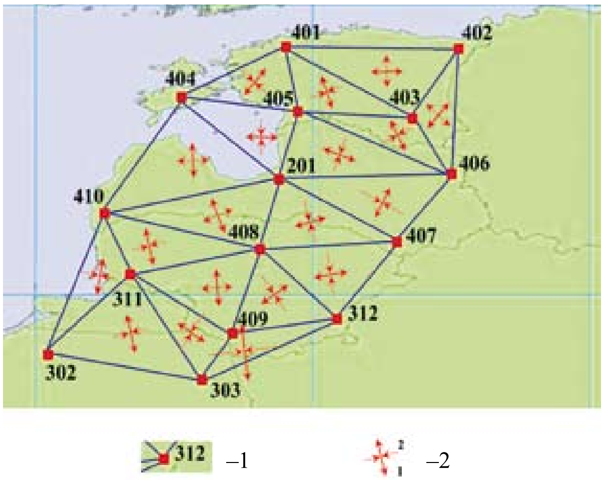

Fig. 1. GPS network and orientation of the horizontal principal strain axis: 1 – GPS benchmark, 2 – principal strain direction (1 – maximum principal strain (extension), 2 – minimum principal strain (compression)

The EUREF-BAL´92 campaign was carried out from August 29 to September 4, 1992 (Madsen F.; Madsen B. 1993; Ehrnsperger 1995). Each day the morning and afternoon sessions of approximately 5 hours duration took place. The observations were performed by Norwegian, Swedish, Finish, and Danish geodesists using Ashtech

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dual frequency receivers. 24 geodetic sites were measured by 20 GPS receivers. In Estonia, the sites Landskrone (401), Vaivara (402), Tartu (403), Ohtja (404) and Saarde (405) were measured; in Latvia – Riga (201), Kaugari (406), Indra (407), Arajas (410); in Lithuania – Akmeniškiai (311), Meškonys (312), Šašeliai (408), Dainavėlė (409). The to EUREF network was tied geodetic stations in Poland (Borowiec (216), Barowabora (217), Lamkowko (302), Masze (303), in Germany (Wettzell (035), Karlsburg (313)), in Finland (Metsähovi (011), in Sweden (Mårtsbo (013), Klinta (015), Visby (411)), in Denmark (København (412). Stations 011, 013, 015, 035, 313, 412 were kept fixed at EUREF-89 geodetic coordinates. The processing was performed as a traditional network densification of the original EUREF- 89 campaign. The TOPAS software was used for reducing the observations, and the FILLNET – for the vector adjustment.

EUREF-POL´2001 GPS campaign was carried out in September 2001 (Jaworski *et al.* 2002). Five 24 hour-duration sessions were performed for a quality assurance of the Polish part of the EUREF-POL´1992 campaign (Zielinski *et al.* 1994). The solution was computed in ITRF 2000 epoch 2001.74 and then transformed to ETRS89. Data of sites 302 and 303 were used for the deformation analysis of the geodetic network.

The 2003 GPS campaign under the framework of the Nordic Geodetic Commission (NKG) was carried out in GPS-week 1238 (September 28 to October 4 2003) (Jivall *et al.* 2005a, 2005b; 2007). The campaign included mainly permanent GPS stations in the Nordic and Baltic areas as well as Island, Greenland and Svalbard. In Latvia, Lithuania and Denmark also geodetic points of ETRS 89 were included. The processing of the NKG GPS 2003 campaign was carried out by 4 analysis centres using 3 different software packages (Bernese version 4.2, version 5.0, Gamit/Globk, Gipsy/Oasis II). The final solution in ITRF 2000 epoch 2003.75 is an average of the four solutions after aligning them all to the average of the two global solutions (Gipsy and Gamit). The estimated accuracy on the 95 % level is 0,5–1 cm in the horizontal components and 1–2 cm in the vertical. New ETRS 89 coordinates based on the NKG 2003 campaign have been calculated.

Finally all coordinates were converted to plane coordinates of the Transverse Mercator projection (Table 1).

3. Method of calculating the horizontal deformations

Horizontal deformations of the geodetic network are determined by repeated measurements of the geodetic network. The method of determining the horizontal deformations is based on the comparison of site coordinates calculated according to measurements done at different time (Stanionis 2005; Zakarevičius 2003; Zakarevičius, Stanionis 2006).

When having plain coordinates of geodetic network points *(x, y)* and changes of geodetic network coordinates calculated according to the data of repeated measurements Δx, Δy it is possible to describe horizontal deformations of the geodetic network by the second-rank tensor (Zakarevičius 2003; Zakarevičius, Stanionis 2004):

$$\| T \| = \left\| \begin{matrix} \frac{\partial u}{\partial x} & \frac{\partial u}{\partial y} \\ \frac{\partial v}{\partial x} & \frac{\partial v}{\partial y} \end{matrix} \right\| = \left\| \begin{matrix} e_{11} & e_{12} \\ e_{21} & e_{22} \end{matrix} \right\|, \tag{1}$$

where

$$u = \Delta x = u(x, y), \tag{2}$$

$$v = \Delta y = v(x, y), \tag{3}$$

here: u, v – shifts of coordinates in rectilinear functions of coordinates in the Cartesian Coordinate System, e_{11}, e_{12}, e_{12}, e_{22} – tensor elements, $\Delta x_i = x_i^/ - x_i$, $\Delta y_i = y_i^/ - y_i$, x_i, y_i – are the coordinates of benchmarks of geodetic network obtained by the first measurements, $x_i^/$, $y_i^/$ – are the coordinates of benchmarks of geodetic network obtained by the second measurements, $i = 1, 2, ..., n$ – are numbers of benchmarks.

The tensor elements (1) are calculated by finite element approach (Zakarevičius 2003).

Table 1. Plane rectangular coordinates of GPS benchmarks and their changes

GPS benchmark	x_{1992} (m)	y_{1992} (m)	x_{2003} (m)	y_{2003} (m)	Δx (m)	Δy (m)
201	6312913.3231	503565.2750	6312913.3052	503565.2747	–0.0179	–0.0003
302	5977885.3672	281147.2077	5977885.3597	281147.1945	–0.0075	–0.0132
303	5972821.0726	414581.4432	5972821.0609	414581.4523	–0.0117	0.0091
311	6133606.0460	362420.3672	6133606.0354	362420.3593	–0.0106	–0.0079
312	6089118.3447	584389.8085	6089118.3320	584389.7969	–0.0127	–0.0116
401	6590192.0115	541864.6581	6590192.0041	541864.6568	–0.0074	–0.0013
402	6589613.4649	718703.8336	6589613.4522	718703.8348	–0.0127	0.0012
403	6475325.8898	658701.1614	6475325.8732	658701.1584	–0.0166	–0.0030
404	6478886.3818	404611.4777	6478886.3672	404611.4691	–0.0146	–0.0086
405	6444302.5676	559477.0009	6444302.5600	559476.9926	–0.0076	–0.0083
406	6334917.5992	717738.2104	6334917.5771	717738.2073	–0.0221	–0.0031
407	6199760.1464	725911.0411	6199760.1608	725910.9935	0.0144	–0.0476
408	6156799.5186	481318.6422	6156799.4958	481318.6496	–0.0228	0.0074
409	6015165.7893	460745.2649	6015165.7673	460745.2578	–0.0220	–0.0071
410	6264461.9294	363483.8445	6264461.9091	363483.8345	–0.0203	–0.0100

Maximum and minimum relative strains are the main characteristics describing deformation of the geodetic network:

$$\begin{bmatrix}\varepsilon_1\\ \varepsilon_2\end{bmatrix}=\frac{1}{2}\left(e_{11}+e_{22}\right)\pm \sqrt{\left(e_{11}-e_{22}\right)^2+\left(e_{12}+e_{21}\right)^2}\ , \qquad (4)$$

here: ε_1 – maximum principal strain, ε_2 – minimum principal strain.

Relative dilatation:

$$\Delta = e_{11} + e_{22}. \qquad (5)$$

Maximum and minimum strains are perpendicular to each other. The direction of maximum strain with respect to abscissas axes is defined:

$$\varphi=\frac{1}{2}\text{arctg}\left(-\frac{e_{12}+e_{21}}{e_{11}-e_{22}}\right)+ \begin{bmatrix}90°,\text{when } \left(e_{11}-e_{22}\right)>0\\ 0°,\ \text{when } \left(e_{11}-e_{22}\right)<0\end{bmatrix}. \qquad (6)$$

The relative errors of the network chords (zero class) do not exceed $\approx 0{,}1\times10^{-6}$.

4. Horizontal deformations of GPS network

The repeated GPS measurements revealed the horizontal changes in the coordinates of benchmarks; in other words, the network was deformed during the period of 1992–2003.

Using the afore-described approach the two-dimensional (2-D) model was constructed.

The horizontal deformation parameters of 19 geodetic network triangles were calculated using equations (1–6) (Fig. 1). The maximum and minimum principal strains, the direction of the maximum relative strain, the dilatation were calculated. The parameters of horizontal deformations are calculated for the gravity centre of a finite element (triangle).

The horizontal geodetic network parameters have been calculated applying *Mathcad* program (Table 2).

The relative maximum strain ε_1 is in the range of $+0{,}03\times10^{-6}$ / $+0{,}58\times10^{-6}$, ε_2 vary from $-0{,}93\times10^{-6}$ to $+0{,}03\times10^{-6}$, the relative dilatation Δ changes from $-0{,}35\times10^{-6}$ to $+0{,}16\times10^{-6}$ (Table 2).

Relative maximum strains ε_1 are with a positive symbol, ε_2 – are negative (except for 5 triangles), Δ – are positive (except for 6 triangles).

5. Geodynamic interpretation

Three different regions, i.e. West Lithuanian–West Latvian, East Lithuanian–East Latvian, and NW Estonian, are identified as showing different deformation regimes. These provinces closely correlate with the major lithotectonic domains of the crystalline basement. In the western province the calculated horizontal strain is dominated by NNW–SSE extension at a rate $-0{,}5\times10^{-8}$ to $-1{,}5\times10^{-8}\text{yr}^{-1}$, while the second principal strain rate axis is compressional. The eastern strain province is dominated by contractional deformation regime; the strain rate reaches $-3\times10^{-8}\text{yr}^{-1}$ with a N(N)W–S(S)E orientation of maximum compression. The north-eastern part of Estonia is subject to a bi-axial extension, which is also revealed in the Middle Lithuanian transitional zone.

The identified strain rates are compatible to those obtained from other cratonic areas (e.g. Fennoscandian Shield, North America, and India). Furthermore, the domination of extensional deformations in the western and northern parts of the Baltic region correlate with the GPS data from Fennoscandia.

Table 2. Parameters of horizontal deformations

Node of finite element			$\varepsilon_1\times10^{-6}$	$\varepsilon_2\times10^{-6}$	φ°	$\Delta\times10^{-6}$
GPS benchmark	GPS benchmark	GPS benchmark				
401	402	403	0.05	0.01	89	0.06
404	401	405	0.06	−0.04	41	0.02
401	403	405	0.04	−0.02	−19	0.02
403	402	406	0.04	0.03	42	0.07
405	403	406	0.06	−0.02	−28	0.04
404	405	201	0.05	−0.01	91	0.05
405	406	201	0.10	−0.02	111	0.08
404	201	410	0.07	0.02	−2	0.10
201	406	407	0.04	−0.36	28	−0.32
410	201	408	0.11	0.02	−22	0.13
201	407	408	0.03	−0.24	75	−0.21
410	408	311	0.15	−0.08	−13	0.07
408	407	312	0.08	−0.22	81	−0.15
410	311	302	0.11	−0.08	11	0.04
311	303	302	0.18	−0.02	−13	0.16
311	409	303	0.06	−0.31	124	−0.24
311	408	409	0.12	0.01	−4	0.13
408	312	409	0.05	−0.17	56	−0.12
409	312	303	0.58	−0.93	−7	−0.35

6. Conclusions

1. The maximum relative strain in the Baltic region varies between $+0,03\times10^{-6}$ and $+0,58\times10^{-6}$; the minimum relative strain changes from $-0,93\times10^{-6}$ to $+0,03\times10^{-6}$; the dilatation is in the range of $-0,35\times10^{-6}$ to $+0,16\times10^{-6}$.
2. The calculated greatest relative deformations exceed the relative accuracy of chord measurements up to approximately 10 times.
3. Three different provinces were identified that show different deformation regimes. It implies different geodynamic mechanisms involved in the Baltic area. The obtained strain rates are compatible to other cratonic regions.

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References

Ehrnsperger, W. 1995. *Adjustment of the 1992 – GPS – Network in the Baltic Countries.* Report on the Symposium of the IAG Subcommission for Europe (EUREF) in Helsinki 3–6 May 1995, 282–292.

El-Fiky, G.; Kato, T. 2006. Secular crustal deformation and interplate coupling of the Japanese Islands as deduced from continuous GPS array, 1996–2001, *Tectonophysics* 422(1–4): 1–22.

Jaworski, L. *et al.* 2002. *Results of the EUREF-POL´2001 GPS Campaign.* Report on the Symposium of the IAG Subcommission for Europe (EUREF) in Ponta del Gada, 5-8 June 2002, 185–198.

Jivall, L. *et al.* 2005a. *Processing of the NKG 2003 GPS Campaign.* Report on the Symposium of the IAG Subcommission for Europe (EUREF) in Vienna, 1–3 June 2005 (draft).

Jivall, L. *et al.* 2005b. *Processing of the NKG 2003 GPS Campaign. Reports in Geodesy and Geographical Information Systems.* Lantmäteriet, Sweden: LMV-rapport 2005:7. 104 p.

Jivall, L.; Kaminskis, J.; Paršeliūnas, E. 2007. Improvement and extension of ETRS 89 in Latvia and Lithuania based on the NKG 2003 GPS campaign, *Geodezija ir kartografija* [Geodesy and Cartography] 33(1): 13–20.

Lagios, E.; Sakkas, V.; Papadimitriou, P.; Parcharidis, I.; Damiata, B. N.; Chousianitis, K.; Vassilopoulou, S. 2007. Crustal deformation in the Central Ionian Islands (Greece): results from DGPS and DInSAR analyses (1995–2006), *Tectonophysics* 444(1–4): 119–145.

Lidberg, M.; Johansson, J. M.; Scherneck, H.-G.; Davis, J. L. 2007. An improved and extended GPS-derived 3D velocity field of the glacial isostatic, *Journal of Geodesy* 81(3): 213–230.

Lidberg, M.; Johansson, J. M. 2006. *A new GPS derived velocity field of the postglacial adjustment in Fennoscandia, and its implications for the maintenance of the European geodetic reference frame.* Report of the Symposium of the IAG Subcommission for Europe (EUREF) in Vienna, 1-4 June 2005, 38: 102–107.

Madsen, F.; Madsen, B. 1993. *A new GPS-network in the Baltic Countries.* Report on the Symposium of the IAG Subcommission for Europe (EUREF) in Budapest, 17–19 May 1993, 83–91.

Masson, F.; Anvari, M.; Djamour, Y.; Walpersdorf, A.; Tavakoli, F.; Daignières, M.; Nankali, H.; Van Gorp, S. 2007. Large-scale velocity field and strain tensor in Iran inferred from GPS measurements: new insight for the present-day deformation pattern within NE Iran, *Geophysical Journal International* 170(1): 436–440.

Riguzzi, F.; Pietrantonio, G.; Piersanti, A.; Mahmoud, S. M. 2006. Current motion and short-term deformations in the Suez–Sinai area from GPS observations, *Journal of Geodynamics* 41(5): 485–499.

Skeivalas, J. 2008. *GPS tinklų teorija ir praktika* [Theory and practice of GPS networks]. Vilnius: Technika. 288 p. ISBN 978-9955-28-228-0.

Šliaupa, S.; Zakarevičius, A.; Stanionis, A. 2006. Strain and stress fields of the Ignalina NPP area from GPS data and thin-shell finite element modelling, NE Lithuania, *Geologija* 56: 27–35.

Stanionis, A. 2005. *Research of the Earth's crust horizontal movements in the Ignalina nuclear power plant region by geodetic methods:* Summary of Doctoral Dissertation. Vilnius Gediminas Technical University. Vilnius: Technika. 24 p.

Zakarevičius, A. 2003. *Dabartinių geodinaminių procesų Lietuvos teritorijoje tyrimas* [Investigation of the recent geodynamic processes in the territory of Lithuania]. Vilnius: Technika. 195 p. ISBN 9986-05-691-8.

Zakarevičius, A.; Šliaupa, S.; Stragys, V.-V.; Stanionis, A. 2007. Deformations of the Earth crust in Lithuania and seismic risk for buildings and structures, in *The 9th International Conference "Modern Building Materials, Structures and Techniques"*: Selected papers, vol. 3. Ed. by M. J. Skibniewski, P. Vainiūnas, E. K. Zavadskas. May 16–18, 2007, Vilnius, Lithuania. Vilnius: Technika, 1134–1142.

Zakarevičius, A.; Stanionis, A. 2004. Horizontaliųjų Žemės plutos poslinkių ir deformacijų modeliavimas baigtinių elementų metodu [Modelling the horizontal movements and deformations of the Earth crust by the finite element method], *Geodezija ir kartografija* [Geodesy and Cartography] 30(2): 35–40.

Zakarevičius, A.; Stanionis, A. 2006. Žemės plutos erdvinių deformacijų nustatymas taikant GPS matavimų duomenis [Deformation of spatial strains of the Earth crust using GPS measurements], *Geodezija ir kartografija* [Geodesy and Cartography] 32(4): 88–91.

Zakarevičius, A.; Stanionis, A. 2007. Erdvinių geodinaminių įtempių tyrimas pagal geodezinių matavimų rezultatus [Research into spatial geodynamic stresses according to results of geodetic observations], *Geodezija ir kartografija* [Geodezy and Cartography] 33(1): 21–25.

Zielinski, J. B. *et al.* 1994. *Final report about the EUREF-POL´ 1992 GPS Campaign.* Report on the Symposium of the IAG Subcommission for Europe (EUREF) in Warsaw, 8–11 June 1994, 92–99.

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