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

| GPS benchmark | x1992 (m) | y1992 (m) | x2003 (m) | y2003 (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 | 414581.4523 | 5972821.0609 | 414581.4523 | -0.0117 | 0.0091 |
| 311           | 6133606.0460 | 362420.3672 | 6133606.0354 | 362420.3593 | -0.0106 | -0.0079 |
| 312           | 6089118.3447 | 541864.6581 | 6089118.3320 | 541864.6581 | -0.0127 | -0.0116 |
| 401           | 6590192.0115 | 541864.6581 | 6590192.0041 | 541864.6581 | -0.0074 | -0.0013 |
| 402           | 6589613.4649 | 7118703.8336 | 6589613.4522 | 718703.8348 | -0.0127 | 0.0012 |
| 403           | 6473525.8898 | 658701.1614 | 6473525.8732 | 658701.1584 | -0.0166 | -0.0030 |
| 404           | 647886.3818 | 404611.4691 | 647886.3672 | 404611.4691 | -0.0146 | -0.0086 |
| 405           | 6444302.5676 | 559477.0009 | 6444302.5600 | 559477.9926 | -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 | 481318.6439 | -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 |

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), Kauguri (406), Indra (407), Arajas (410); in Lithuania – Ąkmeniškiai (311), Meškonys (312), Šašeliai (408), Dainavėlė (409). The to EUREF network was tied geodetic stations in Poland (Borowiec (216), Barowobra (217), Lambowko (302), Masze (303), in Germany (Wettzel (035), Karlburg (313)), in Finland (Metsähovi (011), in Sweden (Märtsbo (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-durations sessions were performed for a quality assurance of the Polish part of the EUREF-POL’92 campaign (Zielinski et al. 1994). The solution was computed in ITRF 2000 epoch 2001.74 and then transformed to ETR589. 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 vertical 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 \( \Delta x, \Delta y \) it is possible to describe horizontal deformations of the geodetic network by the second-rank tensor (Zakarevičius 2003; Zakarevičius, Stanionis 2004):
Maximum and minimum relative strains are the main characteristics describing deformation of the geodetic network:

\[
\begin{align*}
\varepsilon_1 &= \frac{1}{2} \left( e_{11} + e_{22} \right) \\
\varepsilon_2 &= \frac{1}{2} \left( e_{11} - e_{22} \right) \\
\Delta &= \frac{1}{2} \sqrt{\left( e_{11} - e_{22} \right)^2 + \left( e_{12} + e_{21} \right)^2},
\end{align*}
\]  

(4)

here: \( e_1 \) – maximum principal strain, \( e_2 \) – minimum principal strain.

Relative dilatation:

\[ \Delta = e_{11} + e_{22}. \]

(5)

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

\[
\varphi = \frac{1}{2} \arctan \left( -\frac{e_{12} + e_{21}}{e_{11} - e_{22}} \right) +
\begin{align*}
90^\circ, & \text{ when } \left( e_{11} - e_{22} \right) > 0 \\
0^\circ, & \text{ when } \left( e_{11} - e_{22} \right) < 0.
\end{align*}
\]

(6)

The relative errors of the network chords (zero class) do not exceed \( 0.1 \times 10^{-6} \).

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

| Node of finite element | GPS benchmark | GPS benchmark | GPS benchmark | \( \varepsilon_1 \times 10^{-6} \) | \( \varepsilon_2 \times 10^{-6} \) | \( \varphi \) | \( \Delta \times 10^{-6} \) |
|-----------------------|---------------|---------------|---------------|-----------------|-----------------|---------|-----------------|
| 401                   | 402           | 403           |               | 0.05            | 0.01            | 89      | 0.06            |
| 401                   | 402           | 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 $+0.03 \times 10^{-6}$ and $+0.58 \times 10^{-6}$; the minimum relative strain changes from $-0.93 \times 10^{-6}$ to $+0.03 \times 10^{-6}$; the dilatation is in the range of $-0.35 \times 10^{-6}$ to $+0.16 \times 10^{-6}$.
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 crustal regions.

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Algimantas ZAKAREVIČIUS. Professor, Doctor Habil. Dept of Geodesy and Cadastre, Vilnius Gediminas Technical University, Saulėtekio al. 11, LT-10223 Vilnius, Lithuania (tel. +370 5 274 4703), e-mail: Algimantas.Zakarevicius@ap.vgtu.lt. A graduate of Kaunas Polytechnic Institute (now Kaunas University of Technology), geodetic engineer, 1965. Doctor’s degree at Vilnius University, 1973. Dr Habil degree at VGTU, 2000. Member of the Geodetic Commission of Estonia, Latvia and Lithuania. Research training at Geodetic Institute of Nor-
Saulius ŠLIAUPA. Doctor Habil., Institute of Geology and Geography, T. Ševčenkos g. 13, LT-03223 Vilnius, Lithuania (Ph +370 5 210 4698, Fax +370 5 210 4695), e-mail: sliaupa@geo.lt.

Author of 3 monographs, more than 100 research papers; participated in many internal conferences.

Research interests: regional geology, tectonics, geodynamics, lithology, petrophysics.

Arminas STANIONIS. Associate Professor, Doctor. Dept of Geodesy and Cadastre, Vilnius Gediminas Technical University, Saulėtekio al. 11, LT-10223 Vilnius, Lithuania (Ph +370 5 210 4698, Fax +370 5 210 4695), e-mail: Arminas.Stasionis@ap.vgtu.lt.

A graduate of Vilnius Gediminas Technical University (VGTU) (Master of science, 2002). Doctor’s degree at VGTU, 2005. Author and co-author of more than 20 research papers. Participated in many internal conferences.

Research interests: investigation of geodynamic processes, GIS, investigations of deformations.

Eimuntas PARŠELIŪNAS. Associate Professor, Doctor. Dept of Geodesy and Cadastre, Vilnius Gediminas Technical University, Saulėtekio al. 11, LT-10223 Vilnius, Lithuania (Ph +370 5 274 4703, Fax +370 5 274 4705), e-mail: eimis@ap.vgtu.lt.

Doctor (1992). Author of 2 teaching books and more than 40 research papers. Participated in many internal conferences.

Research interests: graphs theory in geodesy, adjustment of geodetic networks, geoinformation systems.