Investigation of Crustal Deformation by the Means of Directly Defined Spatial Chords – Possibility or Predeterminancy

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Abstract. The possible effect of the reductions to the measured distances between the points in a geodynamic geodetic network on the reliability of the subsequently calculated deformations has been analysed. Experimental investigations on the basis of doubly measured spatial chords from the real network and their analogues in UTM-projection have been planned and implemented. Reduction adjustments have been indisputably found to lead to distortion of the deformation model. The problem about block-determined Earth crust deformation has been discussed. A method for calculation of the elements of deformation by geodetic determined linear deformations has been proposed.

1. Introduction
Organized and applied in an appropriate way, geodetic methods are inseparable and essential part of the sophisticated complex of investigations in the field of geodynamics. These investigations cover areas varying in territorial range, which are characterized with enhanced intensity of deformation processes.

Rapid development of the modern geodetic technique and geodetic technologies are a prerequisite for obtaining more and more detailed, comprehensive and accurate information on the dynamic behaviour of the earth crust. What is essential in the case is to ensure the prerequisites which are necessary for obtaining reliable to the highest degree information reflecting the peculiarities of the earth dynamics. From this point of view a comprehensive redefinition of the approach of organization and processing of geodetic measurements for the purposes of geodynamics is necessary.

2. Reduced on the ellipsoid chords – necessity or inertia?
Most possibly, because of the conservatism or by the professional force of habit, the application of conventional geodetic methods and approaches in the process of geodynamic investigations is too common. The fact that the object of observation has specific peculiarities and is non-stationary in time is ignored. The priority of reliability of the obtained information, naturally defined by the accuracy maximal for the given moment, in the geodynamic investigations, is not taken into account.

Given the foregoing, the common practice that geodetic surveyors who work in the field of geodynamics use reduced [2,7,8] (to the surface of a referent ellipsoid or a map projection) geodetic
measurements, is somewhat strange and ungrounded. Such an approach, which is imperatively applicable in the regular geodesy, would lead to significant manipulations of the deformation model. The main reasons for such a statement are the following [4,6]:

• geodetically determined elements which are reduced on the referent ellipsoid (today – most frequently lengths), depend directly on the over ellipsoid heights of the defining points. The great possibility that sections with different height can be in fact subjected to the same intensity of deformation processes is not taken into account.
• the length of the reduced chord depends on the parameters of the chosen referent ellipsoid.
• the length of the distance in projection is definitively influenced by the remoteness of the main meridian (parallel).

Thus, following the route of tradition and routine practice, geodetic surveyors often use elements which have undergone deformations of fully geometric nature, and these deformations are not of geodynamic origin. In this way, whether deliberately or not, a manipulated deformation model with modified sensitivity and reliability is created.

3. Purpose and organization of experiment
In the context of the stated above, it would be interesting to find a practical confirmation of the stated opinion supporting the use of directly measured values [1,4,9], mainly spatial chords. For the purpose, the results from GPS-measurements (2002, 2004) (Table 1) between the points in the local geodynamic network in the area of Krupnik, South-West of Bulgaria (Figure 1) are used.

The components of the symmetric tensor of deformation and main deformation axes (Table 2.) [9], as well as the area deformations and shear deformations (Table 3), referred to the centre of gravity of each finite element of the network, are calculated on the basis of registered linear deformations of the chords [5].

Table 1. Spatial GPS-chords network in the area of Krupnik – Kresna geodynamic network

| № side | S₁ [m] - 2002 | S₂ [m] - 2004 |
|--------|---------------|---------------|
| 1 - 5  | 2494.693      | 2494.683      |
| 1 - 15 | 1670.814      | 1670.812      |
| 5 - 15 | 2086.616      | 2086.612      |
| 5 - 11 | 3214.730      | 3214.729      |
| 15 - 11| 2024.799      | 2024.804      |
| 1 - 16 | 2528.508      | 2528.516      |
| 15 - 16| 1026.307      | 1026.320      |
| 16 - 11| 1307.287      | 1307.295      |
| 1 - 12 | 3975.577      | 3975.583      |
| 12 - 16| 1737.655      | 1737.660      |
| 12 - 11| 1870.379      | 1870.377      |
3.1. Calculation of the deformation parameters by the means of spatial chords for the period 2002 - 2004, defined by GPS measurements

Table 2. Elements of the symmetric tensor of deformation and main deformation axes

| № | Δ   | Triangle | Eₓₓ, \ .10° | Eᵧᵧ, \ .10° | γₓᵧ, \ .10° | E_max, \ .10° | E_min, \ .10° | Φ, [g] |
|---|-----|----------|-------------|-------------|-------------|--------------|--------------|-------|
| 1 | Δ 1 5 15 | -1.708    | -2.558      | -3.782      | 1.673       | -5.939       | 442.9577    |
| 2 | Δ 5 11 15 | 3.084     | -2.143      | -0.507      | 3.133       | -2.192       | 403.0746    |
| 3 | Δ 15 11 16 | 2.592     | 25.818      | 10.191      | 29.656      | -1.246       | 213.1615    |
| 4 | Δ 16 11 12 | 8.184     | -0.214      | -7.198      | 12.318      | -4.348       | 422.5540    |
| 5 | Δ 16 12 15 | 7.665     | 5.942       | 10.579      | 17.418      | -3.811       | 44.8617     |
| 6 | Δ 1 15 16 | -2.062    | 18.364      | -3.293      | 18.882      | -2.579       | 205.0872    |

Table 3. Area deformations and shear deformations, calculated by the method of finite elements

| № | Δ   | X, [m] | Y, [m] | Eₓₓ + Eᵧᵧ, \ .10° | Eₓₓ - Eᵧᵧ, \ .10° |
|---|-----|--------|--------|--------------------|--------------------|
| 1 | 4635553.645 | 677053.312 | -4.266 | 0.851 |
| 2 | 4636621.292 | 677635.574 | 0.941 | 5.228 |
| 3 | 4636551.161 | 678606.179 | 28.410 | -23.226 |
| 4 | 4636799.946 | 679468.722 | 7.970 | 8.398 |
| 5 | 4635732.299 | 678886.459 | 13.607 | 1.723 |
| 6 | 4635483.514 | 678023.917 | 16.302 | -20.426 |

Figures 2, 4, 6, 8, 10, 12 and 14 show graphically the main deformation axes, the angular deformations, the areas of area deformations and shear deformations, for the different periods of measurement.

3.2. Calculation of the deformation parameters by the means of distances in UTM – projection for the period 2002 - 2004

Directly measured chords between the points of the earth surface, obtained as a result of GPS measurements, are reduced to distances in UTM – projection.

All the necessary reductions for converting to chords from the ellipsoid, geodetic line and ultimately to distances in UTM – projection, respectively, are made on the measured bases.

The data from the reduction of spatial chords to distances in UTM – projection are given in Tables 4 and 5.

From the distances reduced in this way, similar calculations for determining the deformation parameters for each cycle of measurements are made.

The components of the symmetric tensor of deformations and main deformation axes are given in Table 6. Area deformations and shear deformations (Table 7), are also calculated for the centre of gravity of each finite element of the network.

The results obtained by the performed calculations are graphically presented as follows: main deformation axes (Figure 2 and 3), angular deformations (Figures 5 and 7), areas of area deformations (Figures 9 and 11) and shear deformations (Figures 13 and 15) for each epoch of measurement.
Table 4. Reduction of spatial chords to distances in UTM – projection

| № side | S - 2002 r., [m] | № p. | H, [m] | ∆h, [m] | chord from the ellipsoid | geodetic line | distance in UTM projection |
|--------|-----------------|------|--------|---------|-------------------------|--------------|-------------------------|
| 1 - 5  | 2494.683        | 1    | 719.199| -373.911| 2277.178                | 2289.474     | 2288.559                |
| 1 - 15 | 1670.814        | 5    | 345.288| -356.157| 1505.118                | 1508.640     | 1508.036                |
| 1 - 16 | 2528.508        | 11   | 501.664| -290.760| 2304.706                | 2317.458     | 2316.531                |
| 1 - 12 | 3975.577        | 12   | 836.994| 117.795  | 3541.444                | 3588.626     | 3587.190                |
| 5 - 15 | 2086.616        | 15   | 363.042| 17.754   | 1976.659                | 1984.673     | 1983.880                |
| 5 - 11 | 3214.730        | 16   | 428.439| 156.376  | 3010.998                | 3039.725     | 3038.509                |
| 11 - 15| 2024.799        |      |        |         | -138.622                | 1891.772     | 1898.032                |
| 11 - 16| 1307.287        |      |        |         | -73.225                 | 1216.458     | 1218.313                |
| 11 - 12| 1870.379        |      |        |         | 335.330                 | 1665.609     | 1670.389                |
| 12 - 16| 1737.655        |      |        |         | -408.555                | 1537.017     | 1540.769                |
| 15 - 16| 1026.307        |      |        |         | 65.397                  | 964.333      | 965.256                 |

Table 5. Comparison between ellipsoidal chords and distances in UTM projection

| № side | S - 2004 r., [m] | № p. | H, [m] | ∆h, [m] | chord from the ellipsoid | geodetic line | distance in UTM projection |
|--------|-----------------|------|--------|---------|-------------------------|--------------|-------------------------|
| 1 - 5  | 2494.683        | 1    | 719.199| -373.911| 2277.169                | 2289.465     | 2288.549                |
| 1 - 15 | 1670.814        | 5    | 345.288| -356.160| 1505.116                | 1508.638     | 1508.035                |
| 1 - 16 | 2528.516        | 11   | 501.658| -290.762| 2304.714                | 2317.466     | 2316.539                |
| 1 - 12 | 3975.577        | 12   | 836.987| 117.795  | 3541.451                | 3588.631     | 3587.196                |
| 5 - 15 | 2086.616        | 15   | 363.032| 17.751   | 1976.656                | 1984.670     | 1983.876                |
| 5 - 11 | 3214.729        | 16   | 428.430| 156.377  | 3010.997                | 3039.724     | 3038.508                |
| 11 - 15| 2024.804        |      |        |         | -138.626                | 1891.777     | 1898.036                |
| 11 - 16| 1307.295        |      |        |         | -73.228                 | 1216.465     | 1218.321                |
| 11 - 12| 1870.377        |      |        |         | 335.329                 | 1665.607     | 1670.387                |
| 12 - 16| 1737.660        |      |        |         | -408.555                | 1537.022     | 1540.774                |
| 15 - 16| 1026.307        |      |        |         | 65.398                  | 964.345      | 965.268                 |

Table 6. Elements of the symmetric tensor of deformation and main deformation axes

| № Δ  | Triangle | E_XX , .10^6 | E_YY , .10^6 | E_ZZ , .10^6 | E_max , .10^6 | E_min , .10^6 | Φ, [g] |
|------|---------|--------------|--------------|--------------|---------------|---------------|--------|
| 1 Δ  | 1 5 15  | -0.621       | -3.010       | -0.278       | -3.042        | -0.589        | 403.683|
| 2 Δ  | 5 11 15 | 0.996        | -3.570       | -3.337       | 2.757         | 5.330         | 420.089|
| 3 Δ  | 11 16 16| 4.408        | 14.315       | 12.291       | 22.613        | 3.891         | 228.409|
| 4 Δ  | 11 16 12| 6.714        | 3.061        | 5.244        | 10.441        | -0.666        | 30.6366|
| 5 Δ  | 1 16 12 | -2.223       | 0.480        | -5.349       | 4.646         | -6.389        | 235.111|
| 6 Δ  | 1 15 16 | -0.411       | 10.120       | 3.067        | 10.948        | -1.239        | 209.0212|

Table 7. Area deformations and shear deformations, calculated by the method of finite elements

| № Δ  | X, [m] | Y, [m] | E_XX + E_YY, .10^6 | E_XX - E_YY, .10^6 |
|------|--------|--------|---------------------|---------------------|
| 1 Δ  | 4635553.645 | 677053.312 | -3.631 | 2.389 |
| 2 Δ  | 4636621.292 | 677635.574 | -2.574 | 4.566 |
| 3 Δ  | 4636551.161 | 678606.179 | 18.723 | 9.970 |
| 4 Δ  | 4636799.946 | 679468.722 | 9.775 | 3.652 |
| 5 Δ  | 4635732.299 | 678886.459 | -1.743 | -2.702 |
| 6 Δ  | 4635483.514 | 678023.917 | 9.709 | 10.531 |
Main axes of deformations, calculated by directly measured chords and distances in UTM projection

Figure 2. Main axes of deformations, calculated by directly measured chords

Figure 3. Main axes of deformations, calculated by directly measured chords distances in UTM projection

Intensity of the field of the angular deformations $\gamma \cdot 10^{-6}$

Figure 4. With directly measured chords

Figure 5. With distances in UTM – projection
2D presentation of the area of the angular deformations $\gamma_{xy} \cdot 10^6$

Figure 6. With directly measured chords

Figure 7. With distances in UTM – projection

Intensity of the field of the area deformations $E_{xx} + E_{yy} \cdot 10^6$

Figure 8. With directly measured chords

Figure 9. With distances in UTM – projection

2D presentation of the field of the area deformations $E_{xx} + E_{yy} \cdot 10^6$

Figure 10. With directly measured chords

Figure 11. With distances in UTM – projection
Intensity of the field of the shear deformations $E_{xx} + E_{yy} \cdot 10^6$

![Diagram](image1.png)

**Figure 12.** With directly measured chords

![Diagram](image2.png)

**Figure 13.** With distances in UTM – projection

2D presentation of the field of the shear deformations $E_{xx} + E_{yy} \cdot 10^6$

![Diagram](image3.png)

**Figure 14.** With directly measured chords

![Diagram](image4.png)

**Figure 15.** With distances in UTM – projection

4. **Block determined earth crust deformation and a possibility for their calculation**

Often, specialists, working in the area of geodynamics, assume, for practical reasons or due to the lack of information, theories, which presuppose a very simplified and integrated model of the Earth crust [10,11,12]. At the same time, methods and approaches to accumulate information are used, which do not provide for the essential aspects of the main purpose—timely, authentic and precise information. Thus, often geodetic measurements for geodynamic purposes are prepared, carried out and processed meeting the main requirements to regular geodetic works, designed for the solution of routine problems.

The major lapse, made usually in such cases, is not to take into consideration the specifics of the task and the specifics of the surveyed site—the Earth crust with its structure and its dynamic behavior in time. According to the most-widely spread lately theories of the Earth crust is the theory of block structure, i.e. that the Earth crust is structured of individual, hierarchically arranged and autonomous blocks, which vary in dimension and according to rheological properties.

On this background, a question is coming: How, in the course of preparation and performance of the repeated geodetic surveys, the divergences of the rheological properties of the individual consolidated quasy-continual blocks can be given account of?
A possible answer of this question can be found in a well-known connection in the theory of deformations [5, 9]:

$$
\epsilon_i = \cos^2 a_i x + \sin^2 a_i y + \cos a_i \sin a_i \gamma
$$

(1)

where:

$$
\epsilon_i = \frac{L_i - L_0}{L_0} \quad \text{- is linear deformation of segment } i;
$$

$$
a_i \quad \text{- specified angle of segment } i;
$$

$$
L_0 \quad \text{- initial length of segment } i;
$$

$$
L_i \quad \text{- actual length of segment } i.
$$

If segment $i$ falls simultaneously into two different quasi-continual blocks and the part lying in block $I$ is signified with $I_1$ and the part lying in block $II$ - respectively with $II_1$ for the relative linear deformation it can be written [5]:

$$
\epsilon_i = \frac{\delta L_i^I - \delta L_i^{II}}{L_i^I}
$$

(2)

where:

$$
\delta L_i^I \quad \text{- variation of length } L_i^I;
$$

$$
\delta L_i^{II} \quad \text{- variation of length } L_i^{II}.
$$

For the part of the segment $i$, lying in block $I$, the representations shall be used:

$$
L_i^I = k L_i^0
$$

(3)

where:

$$
k \quad \text{- coefficient of proportionality.}
$$

Then, after non-complex transformations, for $\epsilon_i$ is obtained:

$$
\epsilon_i = k \epsilon_i^I + (1 - k) \epsilon_i^{II},
$$

(4)

where:

$$
\epsilon_i^I \quad \text{- relative linear deformation of part of segment } i, \text{ lying in block } I;
$$

$$
\epsilon_i^{II} \quad \text{- relative linear deformation of part of segment } i, \text{ lying in block } II;
$$

The obtained result is:
\[
\epsilon_i = k \cos^2 a_i e'_{xx} + k \sin^2 a_i e'_{yy} + k \cos a_i \sin a_i \gamma'_{xy} + \\
(1 - k) \cos^2 a_i e''_{xx} + (1 - k) \sin^2 a_i e''_{yy} + (1 - k) \cos a_i \sin a_i \gamma''_{xy}
\]  

(5)

where:

- \(e'_{xx}, e'_{yy}, e'_{zz}\) are components of symmetric tensor of deformations of block \(I\);
- \(e''_{xx}, e''_{yy}, e''_{zz}\) - components of symmetric tensor of deformations of block \(II\).

Obviously for the calculation of all the six components of deformation are necessarily six measured chords and their linear deformations. Several possible configurations of chords are shown on Figure 16. On the Figure 17 are presented area, shear and angle deformations of Earth crust, calculated for a real object by linear deformations of six chords, situated as a geodetic quadrangle (Figure 16).

**Figure 16:** Possible configuration of geodetic measured chords

**Figure 17:** Graphic presentation of area, shear and angle deformations for a real object
5. Conclusions

1. Bearings, modules and directions of the main deformation axes, calculated by the means of distances in projection, are different from the ones, calculated by directly measured chords between the points.

2. The field of the area deformations for the period 2002 – 2004, calculated by linear deformations of the distances in UTM-projection, is considerably different by the field, obtained by direct chords.

3. The extreme points of the shear deformations coincide in location with those, determined by spatial chords, but are opposite in sign.

4. In consideration of reliability, it is preferable to calculate the deformation components by directly measured elements (lengths) with appropriately chosen accuracy and frequency of measurements.

5. The reporting of the block structure of the Earth crust is a way to realistic interpretation of the results of the geodetic measurements.

6. Is not necessary to use an ordinary geodetic network for a successful realization of repeated geodetic measurements for geodynamics purposes. I needs only a right configuration of chords.

7. With an already designed and stabilized geodetic network for geodynamic investigations a choice of various combinations of different configurations of chords is possible.

References

[1] Antova G., “Visualization of geoinformation in dam deformation monitoring”, III International Conference on Cartography and GIS – conference proceedings, Nesebar, Bulgaria, 2010.
[2] Azzouzi R., Ettarid M., Semlali El H. et Rimi A., “Contribution à la détermination des déplacements horizontaux récents et des déformations des plaques Africaine et Eurasienne dans l'Ouest Méditerranéen, au cours de la période 1997 – 2003”, 2nd FIG Regional Conference, Marrakech, Marocco, 2 – 5 December, 2003.
[3] Fadev A. B., “The finite element method in geomechanics”; Moskow, Nedra, 1987.
[4] Gospodinov Sl., “An opportunity to track area crust distortions by direct geodetic observations”, Annual of UASEC, Sofia, volume XXXVI, III, 1991 – 1992.
[5] Gospodinov Sl., Basic geodetic networks for geodynamics realisations /Dissertation/, Sofia, 1989.
[6] Gospodinov Sl., “Determination of Block Deformations of the Earth's Crust by Measured Spatial Chords”, Sofia, 2011.
[7] Rukieh M. et al.; “Recent geodynamics as a source of geological and seismic hazards for Western part of Syria”, International symposium on „Modern technologies, education and professional practice in Geodesy and Related fields”. Sofia, 3 – 4 November, 2005.
[8] Sylvester A. G., “Near - field tectonic geodesy. In Active Tectonics”, National Academy Press, Washington, D. C., pp. 164 – 80, 1986.
[9] Varbanov Hr., Tepavicharov A., Ganev T., “Applied theory of elasticity and plasticity”, Sofia, 1992.
[10] Yavasoglu H. et al.; “GPS measurements on the Western Marmara segment of North Anatolian fault”, International symposium on „Modern technologies, education and professional practice in Geodesy and Related fields”. Sofia, 3 – 4 November, 2005.
[11] Yeats R. S., Sieh K., Allen Cl. R.; “The geology of earthquakes”, New York – Oxford University press, chapter 5, pp. 88 – 113, 1997.
[12] Zakarevicius A., Slaupa S., Stanionis A., „Strain and stress modelling of the Earth's crust of the GPS polygon of the Ignalina nuclear power plant”, International symposium on „Modern technologies, education and professional practice in Geodesy and Related fields”. Sofia, 3 – 4 November, 2005.