Geodetic Contribution to the Determination of Recent Tectonic Activities at the Area of Croatia

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In der Arbeit werden Ergebnisse aus geodätischen GPS-Messungen mit geotektonischen Informationen gemäß der Bewegungstheorie lithosphärischer Platten miteinander verglichen. Alle Ergebnisse bestätigen die geologischen Erfahrungen über die tektonischen Bewegungen. Die Verdichtungszonen kann man auf Grund von umgekehrten Verwerfungen und umfangreicher tektonischer Aktivität erkenn, d.h. die Epizentren der stärksten Erdbeben befinden sich in diesem Gebiet, und diese Zonen sind ziemlich identisch mit den Verdichtungszonen im geodätischen Modell. Obwohl die GPS-Messungen nur über einen Zeitraum von zwei Jahren durchgeführt wurden, bestätigen die erhaltenen Ergebnisse ohne Zweifel die Korrelation zwischen dem geodätischen und dem geologischen Modell in der Bestimmung von Bewegungen und Deformationen der äußeren Erdkruste.

1 Introduction

The role of geodesy in geosciences has been significantly increased with the appearance of satellite methods VLBI (Very long basis Interferometry), SLR (Satellite Laser Ranging), and especially with GPS (Global Positioning System) being widely applied. Classical geodetic measurements used to be of fundamental significance only in statical model. Today it is, however, possible to determine with geodetic methods the relative movements between distant points with the accuracy below one centimetre, and these quantities can be used in dynamic models as well. Geodesy can, by applying adequate methods of deformation analysis, explain a lot of global and local phenomena on the Earth. The basic global phenomenon on the Earth is the appearance of the tidal movements caused by the attraction forces of the Moon and the Sun. These forces affect the change of the gravity acceleration and thus cause the deformation of geoid (see e.g. Heitz 1980–83; Melchior 1983).

Apart from those global answers, geodesy can explain many local phenomena on the Earth, either those connected with defining the deformations of the parts the Earth's external surface in accordance with the theory of lithosphere plate movements (see e.g. Altiner et al. 1998; Altiner 1999; Brunner 1990; Cigrovski-Detelić, 1998; Freeden et al. 1995; Mervart, 1995; Miller 1992.; Müller 1996; Vogel 1995), or those associated with the deformations of special object surfaces, as dams, bridges, tunnels, buildings, machines, and even human bodies (Reinking 1994). If we want to use the results of geodetic measurements (coordinates) as the basic ones for *dynamic models*, then it is necessary to use three-dimensional coordinate presentation of the topography of the external part of the Earth's crust. Mathematically speaking, the external surface of the Earth should be presented as generally curved surface using the coordinates of characteristic relief points in three-dimensional Euklid space. High accuracy of geodetic measurements requests indispensably the renewed testing of so far used mathematical bases for deformation analysis.

2 Mathematical basis for deformation analysis

2.1 Geodetic application of deformation theory

Discrete observation station firmly connected to the Earth's body are presented mathematically by means of three-dimensional coordinates (X, Y, Z *ili* L, B, H) in global geocentric or ellipsoid coordinate system. For the complete presentation of surface deformation it is necessary to take into consideration both external and internal changes of the Earth's body geometry. It is quite sure that for three-dimensional satellite GPS-measurements one cannot use two-dimensional deformation theories based on Cartesian coordinate geometry (Caspary 1987). Such analyses do not yield sufficient accuracy, not even in the case of small mountain areas, and for larger areas they are unacceptable, even if those areas are approximately horizontal.

In the geodetic application of the deformation theory (Altiner 1999; Cigrovski-Detelić 1998) one starts with discretely distributed measuring station (P) on the Earth's surface F: $\{P\} \in F$, where geodetic GPS-measurements have been carried out in two time points $t\bar{t}$. These time points relate in a concrete case for this paper, to GPS-campaigns CRODYN 94 (t) and CRODYN 96 ($\bar{t}$). The results

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for all points are three ellipsoidal coordinates ($q^a,\ \bar{q}^a$) in both time periods (t *and* $\bar{t}$), i.e.:

$$q^a := q^a(t), \quad \bar{q}^a := q^a(\bar{t}), \quad a \in \{1,2,3\}. \tag{2.1}$$

On the basis of these coordinates the requested movement coordinates (z^a), are determined,

$$z^a := \bar{q}^a - q^a, \tag{2.2}$$

making the *movement field* for the entire observed area. *The changes of lengths or coordinates* between the points being the element of uninterrupted point field on the Earth's physical surface F are the basis for all *deformation analyses*. We presume thereby that the coordinates of surface points q^a and movement coordinates z^a, and they can be modelled as analytical functions of surface coordinates $u_a, \alpha \in \{1,2\}$:

$$q^a = q^a(u^\alpha), \quad z^a = z^a(u^\alpha) \tag{2.3}$$

The main part of the regional geodetic (geometric analysis) of surface deformation referring to the surface of the selected ellipsoid is as a rule considered only a partial aspect of three-dimensional deformation. However, in the wholesome spatial solution of the problems, the deformations on the ellipsoid surface are significant because of two reasons: they are geodetically *measurable quantities* and are the only target quantities that can be *defined mathematically.* The intact three-dimensional dynamic solution is not possible in most of cases because of insufficiently accurate knowledge about the material properties, e.g. already in near-surface internal part of the Earth. The surface deformities give significant contribution to the process of solving all dynamic problems of three-dimensional bodies being of marginal geometric value (Heitz 1983; Heitz 1988).

2.2 Theory of surface deformations

2.2.1 Internal surface deformations derived from ellipsoid coordinates

The primary surface deformation measure is the difference of linear elements squares that reads as follows in the isoparametric presentation:

$$d\bar{s}^2 - ds^2 = \left(\bar{f}_{\alpha\beta} - f_{\alpha\beta}\right) du^\alpha du^\beta = 2D_{\alpha\beta}\ du^\alpha du^\beta, \tag{2.4}$$

where it denotes:

u^α = Coordinates of the point P in the time points t and $\bar{t}$
$f_{\alpha\beta}$ = Measuring tensor in the time point t (2.5)
$\bar{f}_{\alpha\beta}$ = Measuring tensor in the time point $\bar{t}$
$D_{\alpha\beta}$ = *Surface deformation tensor*

For small movements that are considered in this paper, the linear deformation tensor, i.e. $D_{\alpha\beta} \approx \varepsilon_{\alpha\beta}$ can be applied with sufficient accuracy. The measures of internal surface deformation will be for that case: maximum linear movement of ***elongations*** and *deformations* in the direction $r^\alpha := du^\alpha / ds$:

$$q := (d\bar{s} - ds)/ds = \varepsilon_{\alpha\beta} r^\alpha r^\beta \tag{2.6}$$

$$m = 1 + q,$$

and the surface dilatation:

$$\bar{q} = f^{\alpha\beta} \varepsilon_{\alpha\beta}. \tag{2.7}$$

For the purpose of computing elongations and dilatations from geodetic GPS-measurements the *surface* coordinates will be ellipsoidal coordinates:

$$u^\alpha = (L, B), \quad \alpha \in \{1,2\}, \tag{2.8}$$

so that the surface presentation for successive time points, $\bar{t}, t$ according to (Cigrovski-Detelić 1998) is the following:

$$q^a(u^\alpha) = [L, B, H(u^\alpha)]^a \quad \bar{q}^a(u^\alpha) = [\bar{L}(u^\alpha), \bar{B}(u^\alpha), \bar{H}(u^\alpha)]^a, \tag{2.9}$$

and hence, the movement coordinates will be:

$$\delta q^a(u^\alpha) = [\delta L(u^\alpha), \delta B(u^\alpha), \delta H(u^\alpha)]^a. \tag{2.10}$$

The metrics of geographic, ellipsoid coordinates is according to (Heitz 1988) determined by means of the expression:

$$g_{ab} = (R_1 + H)^2 \cos^2 B \delta^1_a \delta^1_b + (R_2 + H)^2\ \delta^2_a \delta^2_b + \delta^3_a \delta^3_b, \tag{2.11}$$

where: $R_1 = N$ *– the radius of curvature by the first vertical*, $R_2 = M$ *– the radius of curvature by meridian*, $H =$ *ellipsoid (geodetic height).*
Applying the transformation expression for the measuring tensor

$$f_{\alpha\beta} = q^c_{,\alpha} q^d_{,\beta} g_{cd}, \tag{2.12}$$

we obtain the measuring tensor $f_{\alpha\beta}$ for the first time point t, in the isoparametric surface presentation:

$$f_{\alpha\beta} = \left[(R_1 + H)^2 \cos^2 B + (H_{,1})^2\right] \delta^1_\alpha \delta^1_\beta + (\delta^1_\alpha \delta^2_\beta + \delta^2_\alpha \delta^1_\beta) H_{,1} H_{,2} + \left[(R_2 + H)^2 + (H_{,2})^2\right] \delta^2_\alpha \delta^2_\beta. \tag{2.13}$$

In the same way the tensor $\bar{f}_{\alpha\beta}$ in another time point $\bar{t}$, and the linear surface deformation tensor $\varepsilon_{\alpha\beta}$. On the basis of these quantities the other measures of the internal surface have been computed as well according to (Cigrovski-Detelić 1998): maximum linear movement, so called linear surface *elongation and dilatation* (– depression) surface, according to the formulas (2.6) and (2.7).

2.3.2 External surface deformations

The external surface deformations are according to (Altiner 1999; Cigrovski-Detelić 1998 Chapter 6.3.2) defined by means of changes of mean curvatures:

$$\delta H = \bar{H} - H = \frac{1}{2}\left(\bar{f}^{\alpha\beta} \bar{L}_{\alpha\beta} - f^{\alpha\beta} L_{\alpha\beta}\right) = f^{\alpha\beta} \delta L_{\alpha\beta} + \bar{L}_{\alpha\beta} \delta f^{\alpha\beta}, \tag{2.14}$$

that are computed on the basis of the changes of the first and the second fundamental tensor:

$$\bar{f}_{\alpha\beta} - f_{\alpha\beta}\ ;\ \bar{L}_{\alpha\beta} - L_{\alpha\beta}. \tag{2.15}$$

The changes of the first fundamental tensor will for small movements $\bar{z}_{i,\alpha}| << |x_{i,\alpha}|$, be:

$$\delta f_{\alpha\beta} = \bar{f}_{\alpha\beta} - f_{\alpha\beta} = x_{i,\alpha} z_{,\beta} + x_{i,\beta} z_{i,\alpha} \ldots = 2\varepsilon_{\alpha\beta},$$

$$\delta f = \bar{f} - f = 2(f_{11}\varepsilon_{22} + f_{22}\varepsilon_{11} - 2f_{12}\varepsilon_{12} + \ldots). \tag{2.16}$$

Tab. 3.1: The Points included into the interpolation of the movement vector for relative adjustment model: GRAZ control station

CRODYN 94 – CRODYN 96								
Name of the point	B^0	L^0	dL (mm)	dB (mm)	dH (mm)	Δd (mm)	Δs (mm)	ν^0
GRAZ	47.067129	15.493478	0.0	0.0	0.0			
PULA	44.865490	13.846150	– 0.4	4.3	7.2	4.31	8.40	– 5.31
MALIJA	45.503787	13.643390	– 5.5	1.1	6.9	5.60	8.89	– 78.69
VELI VRH	45.006986	14.675847	– 1.3	2.4	12.9	2.72	13.19	– 28.44
ZADAR	44.119101	15.230142	– 3.0	6.0	3.1	6.70	7.39	– 26.56
HUM-VIS	43.029954	16.113619	– 1.7	9.2	4.1	9.35	10.21	– 10.47
PALAGRUŽA	42.392661	16.254939	– 0.4	10.5	11.7	10.50	15.73	– 2.18
BAKAR	45.255447	14.585909	1.0	6.6	19.5	6.67	20.61	8.61
KAPELA	43.600031	16.592637	2.6	7.7	12.6	8.13	14.99	18.65
HVAR	43.144463	16.597636	– 1.2	9.4	4.9	9.48	10.67	– 7.28
ŽUTA LOKVA	44.969365	15.062199	– 2.6	5.7	9.1	6.26	11.05	– 24.52
DUBROVNIK	42.657867	18.060766	– 1.9	7.9	11.5	8.12	14.08	– 13.52
UČKA	45.308357	14.215910	– 2.7	2.7	16.6	3.82	17.03	– 45.00
SPLIT	43.506620	16.438460	0.4	7.1	14.3	7.11	15.97	3.22
ROVINJ	45.084026	13.629350	– 3.2	3.0	2.8	4.39	5.20	– 46.85
LASTOVO	42.751614	16.860520	– 1.0	8.0	0.5	8.06	8.08	– 7.12
TIJARICA	43.608377	16.876403	– 3.3	3.7	– 1.9	4.96	5.31	– 41.73
SVETI IVAN	42.873767	17.457443	0.4	7.4	7.6	7.41	10.62	3.09
BLEGOŠ	46.164802	14.113509	– 1.7	3.6	6.4	3.98	7.54	– 25.28
KOPER	45.548162	13.724109	– 4.9	7.2	4.5	8.71	9.80	– 34.24

$\Delta d = \sqrt{(dL)^2 + (dB)^2}$ = horizontal movement; $\nu = arctg \frac{dL}{dB}$ = grid bearing of the horizontal movement

$\Delta s = \sqrt{(dL)^2 + (dB)^2 + (dH)^2}$ = spatial movement

Taking into consideration the expressions for other fundamental tensors in F i $\bar{F}$, for all time points t and $\bar{t}$, according to (Heitz 1988):

$$L_{\alpha\beta} = n_i . x_{i,\alpha\beta} = \varepsilon_{ijk.} x_{j,1} x_{k,2} x_{i,\alpha\beta} f^{-1/2};$$

$$\bar{L}_{\alpha\beta} = \bar{n}_{i.} x_{i,\alpha\beta} = \varepsilon_{ijk.} \bar{x}_{j,1} \bar{x}_{k,2} \bar{x}_{i,\alpha\beta} \bar{f}^{-1/2}, \tag{2.17}$$

the change of the other fundamental tensor will be:

$$\delta L_{\alpha\beta} = \bar{L}_{\alpha\beta} - L_{\alpha\beta}$$

$$\delta L_{\alpha\beta} = \frac{\varepsilon_{ijk.}}{\sqrt{f}} \left[x_{j,1}, x_{k,2} z_{i,\alpha\beta} + (x_{j,1} z_{k,2} + x_{k,2} z_{j,1}) x_{i,\alpha\beta} \right] - $$

$$- \frac{L_{\alpha\beta} \delta f}{(2f)}, \tag{2.18}$$

$$\delta L = \bar{L} - L = L_{11} \delta L_{22} + L_{22} \delta L_{11} - 2 L_{12} \delta L_{12} + \delta L_{11} \delta L_{22}$$

$$+ \delta L_{12}^2 .$$

Partial derivation necessary for the presentation of external surface deformation in geographic ellipsoidal coordinates: $q^a = (L, B, H)$, are obtained according to (Altiner 1999); Cigorvski-Detelić 1998) from internal normal surface coordinates $\tilde{p}^a = (L, B, h)$, by applying the formula:

$$q^d_{,\tilde{a}} = c^d_{i.} b_{i.\tilde{a}}, \tag{2.19}$$

and a special case defined with the formula

$$q^{\gamma}_{,\tilde{\alpha}} = \delta^{\gamma}_{\alpha}, \quad q^3_{,\tilde{\alpha}} = H_{,\alpha}; \quad q^d_{,\tilde{3}} = c^d_{i.} n_{i.} = n^d = \frac{g^{cd}}{\sqrt{f}} \varepsilon_{abc} q^a_{,\tilde{1}} q^b_{,\tilde{2}}, \tag{2.20}$$

where:

$$f_{\alpha\beta} = q^a_{,\tilde{\alpha}} q^b_{,\tilde{\beta}} g_{ab}, \quad f = |f_{\alpha\beta}| = f_{11} f_{22} - f_{12}^2,$$

$n_{i.} = b_{i.\tilde{3}}$ = *normal of the reference surface of the* p^a*-system.* (2.21)

3 Geodetic model of tectonic movements

3.1. Horizontal and vertical components of vector movement

To define a geodetic model of tectonic movements means to determine the change of external Earth's surface geometry in two time points. That means that it is necessary to define the functional connections between the geometry change and numerous, often unknown forces that affect the body subjected to deformations as it is the Earth. The end result of the activity of all these forces is manifested in the change of body geometry that can be explained with the changes of point coordinates in two time points, and surveyors can determine these coordinates with necessary accuracy.

All measures of ***internal and external surface deformations*** that are necessary for the presentation of tectonic movement geodetic model are computed according to (Cigrovski-Detelić 1998). The obtained results have been analysed and presented by means of tables and images. The ellipsoid surface coordinates have been used in these computations. The input data for the extensive mathematical processing were the differences of adjusted coordinates in two GPS campaigns: *CRODYN 94 and CRODYN 96* (Rašić, Marjanović 1997), table 3.1, on the basis of which the change of geometry of the external Earth's surface has been determined.

The greatest significance of such data processing lies in the fact that it is possible to define one uninterrupted deformation surface on the basis of geodetic measurements on discrete observation stations, which makes it possible to obtain information about deformations for each point in the observed area, and not only for measuring station.

When the function F that connects geodetic measurements and the deformations looked for is defined, further procedure of adjustment and accuracy estimation belongs to geodetic routine. Positional and height components of movement speed vector is presented in the table 3.1 and in the figure 3.1. The arrow indicates the direction of positional components that are the result of the movement in the direction of longitude and latitude. It is obvious that there is a systematic quality in the orientation of both horizontal (north, north-west) and vertical movement vector component (height increase) as it is shown on the Figure 3.1. One can also see the change of the direction on the northwest part of the observed area from the north direction northwestwards, which indicates mild rotation of the Adriatic micro plate.

3.2 Internal surface deformations determined on the basis of GPS measurements

3.2.1 Surface dilatation

For the purpose of computing internal and external surface deformations the area between 42.4 and 46.4 degree of the northern latitude and between 13.6 and 17.7 degree of the eastern longitude has been observed. This area is divided with raster network having the spaces of 0.1 degree each. Thus, the coordinates for 1681 points have been obtained for which the heights, speed vectors have been interpolated, and then all surface deformation measures computed. On the basis of thus computed values, the obtained results are presented graphically as well. The results based on the analytical surface deformation theory (Altiner 1999) indicate three different deformation zones (See Fig. 3.2).

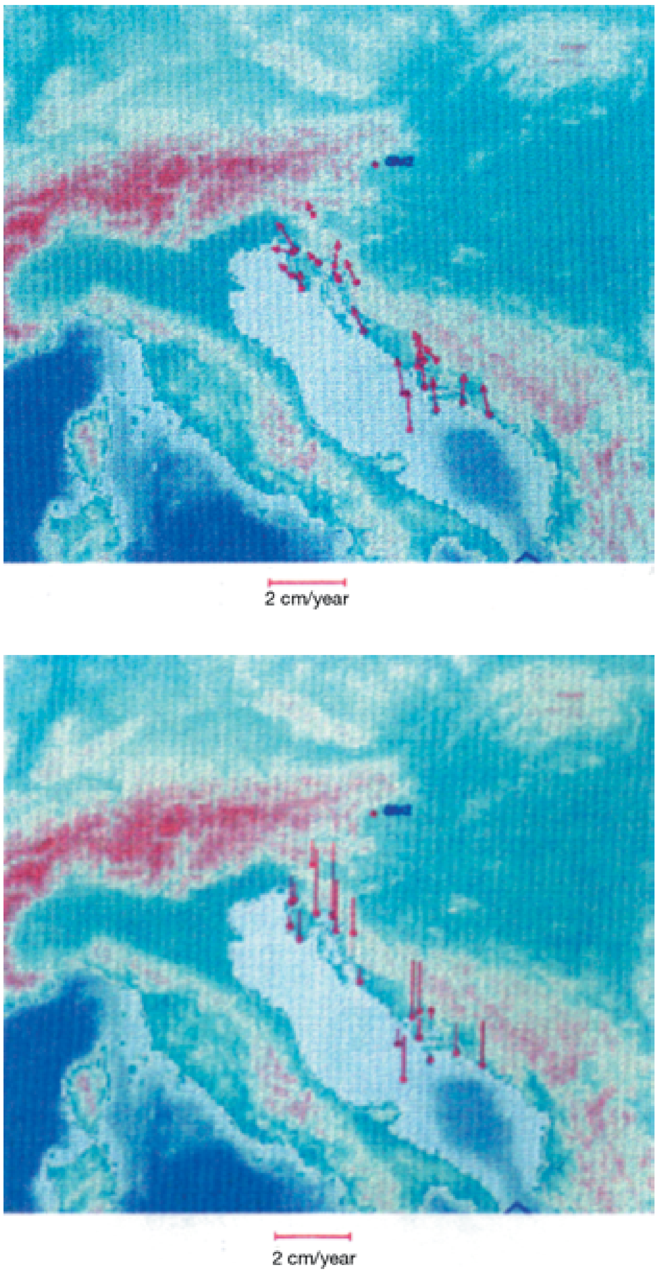

Fig. 3.1: Horizontal and vertical components of the movement vector

Maximum deformation zone has been detected in the northwestern part of the observed area, between 45 and 46 degree of the latitude and between 13.6 and 15 degree of the longitude. In this area the sign is positive which means that it is the dominant ***extension*** zone. The extension zones are marked with red colour on Fig. 3.2. Another zone with smaller positive dilatation (extension) values is located in the southeastern part of the observed area, between 43.6 and 44 degrees of the latitude and between 16 and 16.2 degrees of longitude. On Fig. 3.2 these areas are indicated in light red colour.

The negative sign of dilatation indicates the compression of the area, between two observation time points. Dark blue colour indicates the zones of maximum compression, light blue indicates the zones with smaller compression

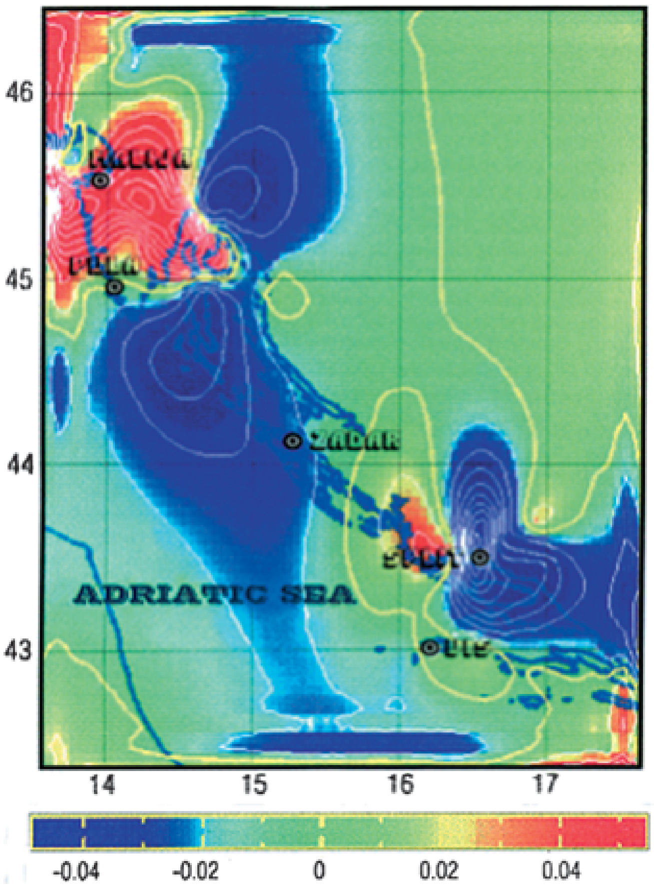

Fig. 3.2: Presentation of surface dilatation

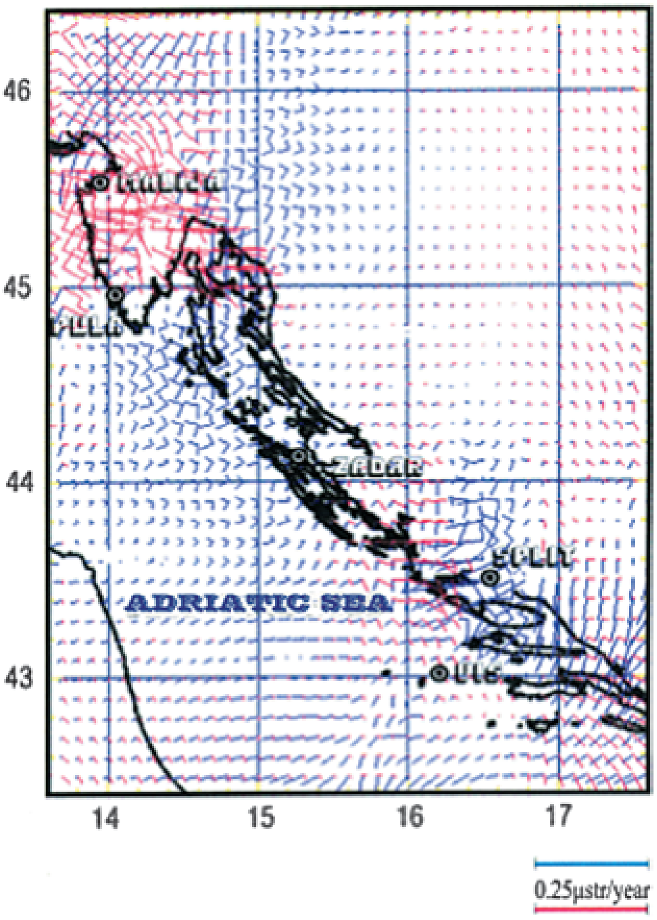

Fig. 3.3: Presentation of elongation – maximum linear deformation

values. As it can be seen from the Fig. 3.2, there are two larger compression zones: one being in the northwestern part, and the other in the southeastern part of the observed area. Light green and yellow colours indicate stable zones. In these areas the dilatation values are very small, or equal to zero.

3.2.1 Surface elongation

Fig. 3.3 shows the results of maximum linear deformation; the so-called elongation. Positive sign of elongation means the extension, and negative sign means the compression of lengths in the observed area. Maximum values of ***extensions*** run up to 6 mm at the distance of 10 km. They are located in the northwestern part of the observed area that has been at the same time detected as the area of the largest total deformations. Smaller zones of length extensions are observable in the eastern and southeastern part and they run up to 1.3 mm at the distance of 10 km. The values of ***compression*** are from 3 to 5 mm at 10 km, for the period of one year. The northeastern part of the observed area has been detected as stable, i.e. the length change is very small or equal to zero (light-green and yellow colour on Fig. 3.3).

3.2.2 External surface deformation

The external surface deformation is determined on the basis of length changes of radius-vectors of points in the time points t and $\bar{t}$, i.e. of changes of mean (δH) surface curvature, in two time epochs. As it is shown on the Fig. 3.4, the maximum changes of the main curvatures with positive sign marked with red colour are located as follows: one is located in the south-eastern (between 43.0 and 44.2 degree of northern latitude and between 15.2 and 16.8 degrees of eastern longitude) and two smaller zones in the north-western part of the observed area (between 45.0 and 45.7 degree of latitude and 14.2 and 14.7 degrees of longitude). The positive sign of the curvature change means the reduction of the mean Earth radius, and hence, the increase of the elevation difference between the neighbouring point pairs. With negative signs, the mean Earth radius is larger, and hence, the curvature is smaller which can be considered as the reduction of elevation difference between the neighbouring points, i.e. coming closer to the shape of the plane.
The area of maximum curvature changes with negative sign (blue on Fig. 3.4) is concentrated in three zones in the narrow area between 16.8 and 17 degrees of longitude and 42.7 and 43.8 degrees of latitude. This area is located immediately near the area with maximum positive changes of curvature, which leads us to the conclusion

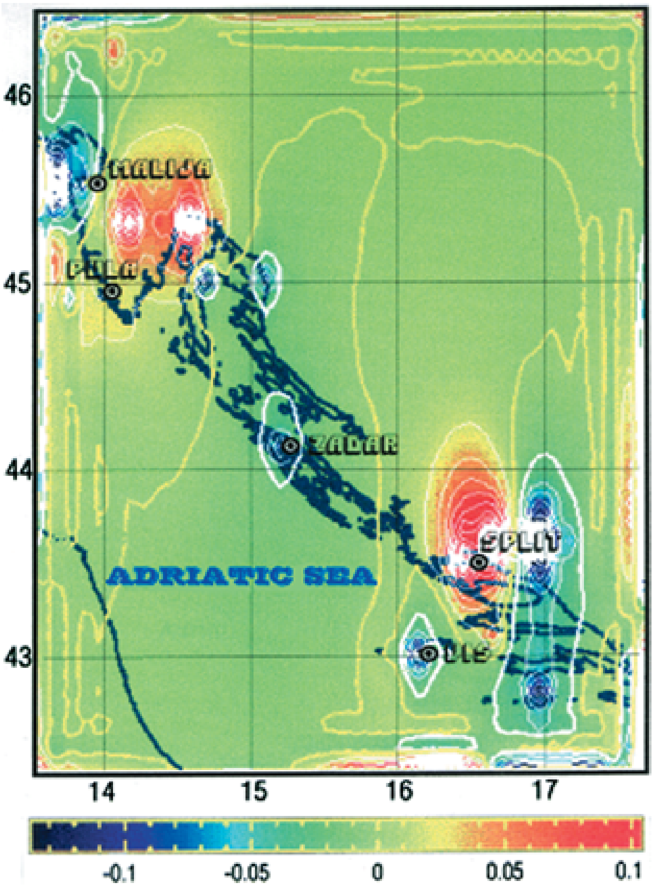

Fig. 3.4: External surface deformations – elevation changes

that this is area of maximum change of the external Earth's surface geometry. There were also four other smaller areas with negative curvature sign detected (se Fig. 3.4) and the rest of the observed territory can be regarded as stable.

4 Geological model of tectonic movements on the observed territory

4.1 Selection of observation stations in geodynamic networks

One of more important conditions in selecting the place for the points of geodetic-geodynamic network that should be the basis for the control of movements and deformations of the external Earth's crust part is the familiarity with the characteristics or properties of recent geological structural set. It is quite clear that vertical and horizontal changes of the position of any point are the consequence of tectonic movements of individual structural unit parts. It is therefore necessary to select the observation stations in geodynamic networks in such a way that they meet two basic terms: *correlation possibility* for geodetic and geological data and *defining tectonically most active zones*. These terms have been taken into consideration, as far as it could have been achieved in the field, already at the time of designing the Croatian geodynamic network CRODYN.

For the presentation of recent geological structural set and tectonic movements, faults and shifts of structures there were numerous published scientific and professional works used in which essential structural and geological, geophysical and seismological conclusions about tectonic dynamics of the area included into the geodynamic network CRODYN are dealt with (Čolić et al. 1996b). The most comprehensive basic geological data can be found on the sheets of the Base Geological Map at the scale of 1:1 000 000 (Croatian Geological Research 1969–1980). The geological base for studying possible correlation between so far known geodetic and geological data about recent tectonic movements is the map of geological structural set, Fig. 4.1. The map contains important geological specific features of the observed area: structural units, faults, tectonic dynamics. Especially the figure 4.2 shows the epicentres of earthquakes in Croatia with neighbouring areas. The focus of all these earthquakes in Croatia is in the Earth crust (Čolič et al. 1996 a), i.e. above the Mohorovičič discontinuity as its lower border. The most destructive earthquakes at the territory of Croatia are shown on Fig. 4.2.

5 Comparison between geodetic and geological model of tectonic movements

Comparing *the movement directions* of structures close to the surface, obtained by means of geological and geodetic methods one can see their diversity. According to geological measurements, the direction of structure movements close to the surface caused by the activity of regional stress is generally southwards, south-westwards, and the movement vector speeds obtained from geodetic measurements are in most cases directed northwards, northwestwards. Hence, there is a *general conclusion* that the southern part of the Adriatic micro plate is leaning on the African plate that is moving in the direction north, northwest. The movement in that direction is dominant, so that it is larger than the movement of structures close to the surface presenting the force of reaction, i.e. the force by which the Dinaric Alps mass resisted to the pressure force of the African plate, and thus of the Adriatic micro plate, and the middle parts were considered stable. Because of the influence of regional stress, the theory and practice can be remarkably different. Therefore, the regional stress should be eliminated from the measuring results before the global tectonic movements and deformations are determined.

The change of the speed vector direction in the geodetic model, from the north-northwest to the west could be the indication of mild *rotation* of the northwestern part of the Adriatic micro plate. It is also confirmed by the geological discoveries.

Tectonically most active areas where the epicentres of the strongest earthquakes are located, Fig. 4.2, coincide very well with the compression zones in the geodetic model of tectonic movements (Fig. 3.2, 3.3 and 3.4).

It should be pointed out that Fig. 4.1 shown the movements along the most important faults bordering with geo-

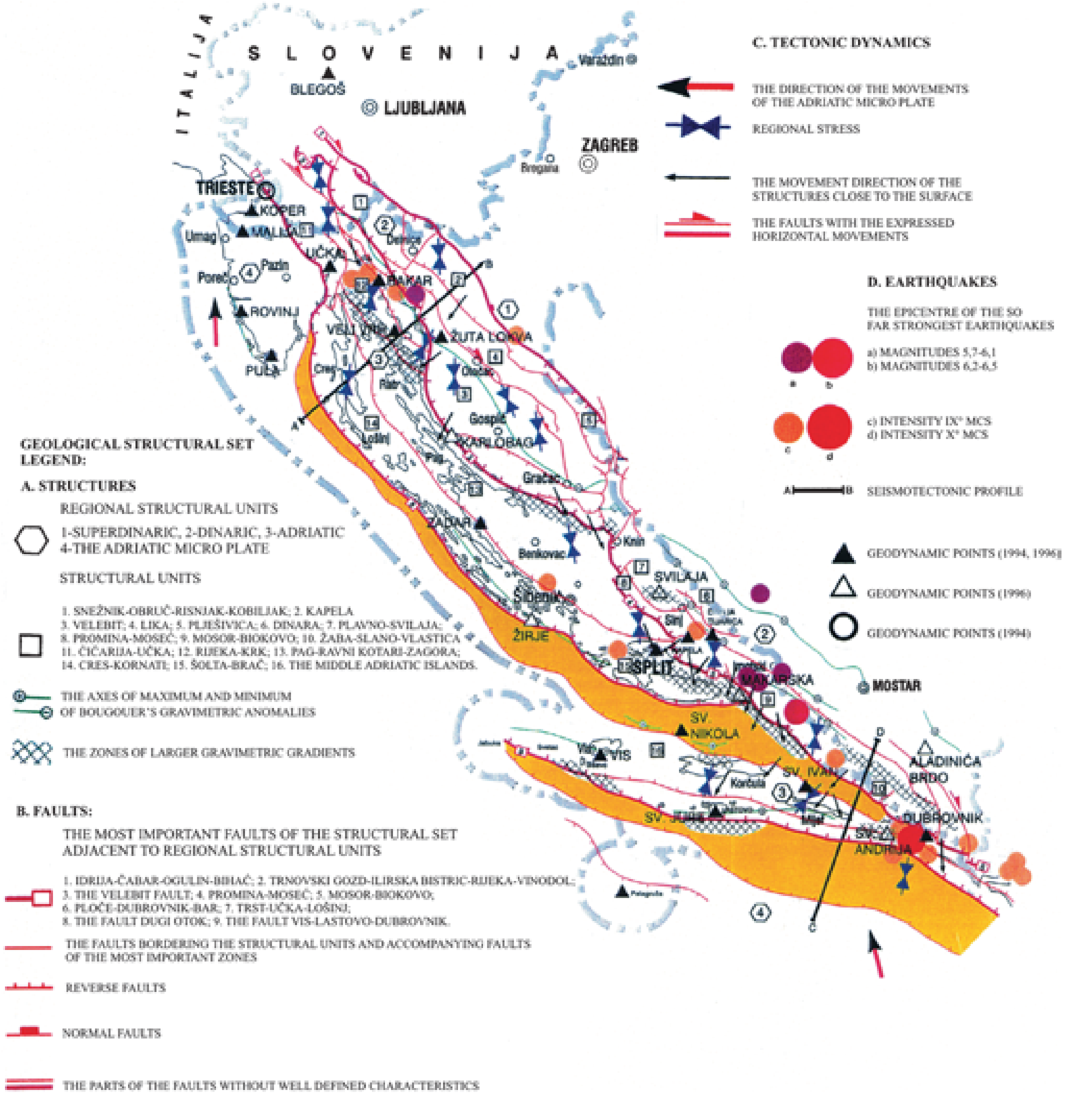

Fig. 4.1: Geological structural set: made according to the data: Buljan, Prelogović 1997; Croatian Geological Research 1969–1980; Cvijanović et al. 1979; Herak 1991; Prelogović et al. 1997a, b, 1995, 1994; Prelogović Buljan 1998

logical structural units. However, in wide zones of reverse faults or in the zones of expressive compression, the gravity or reverse movements opposite to those indicated might crop up. One should also bear in mind that there are no structural and geological measurements around all geodetic points included into the project CRODYN. Specially important seems to be the position of geodetic points within the geological structural units because of the need to notice possible geological local terms that cause various movements of the parts of structural units or fault wings. The comparison of geodetic and geological model of tectonic movements for the observed area is therefore given for individual points.

Rovinj and Pula: they are located on the Adriatic micro plate. In the zone around these points there are no more important faults or deformations of the micro plate which is fully confirmed by the results of deformation analysis carried out on the basis of geodetic measurements, i.e. the points are located in the stable zone marked in the geodetic model with yellow-green colour on Fig. 3.2, 3.3 and 3.4.

Učka is located within the structural unit Ćićarija-Učka (11). This unit is placed in so-called transpression zone, which means that there is a very extensive space compression present there, as well as the right transcurrent movements. The structures located on the northern side of the observed area move eastwards, and the movements of the Adriatic micro plate are generally westwards. The compression in the point Učka is confirmed also by geodetic indicators: altitude increase of 0.0166 m, and large surrounding extension zone presented on Fig. 3.2–3.4. as well as the vector orientation of horizontal movements, Fig. 3.1

Bakar is located in the fault zone Trnovski Gozd-Ilirska Bistrica-Rijeka-Vinodol (2). The geological data indicate the right transcurrent movement, but also the compression of structures. The same characteristic are indicated by geodetic data as well, see, as earlier, Fig. 3.2–3.4.

Žuta Lokva is located exactly in the fault zone with the emphasized transcurrent (horizontal) right movements. The results of the deformation analysis based on geodetic GPS-measurements confirm this fact.

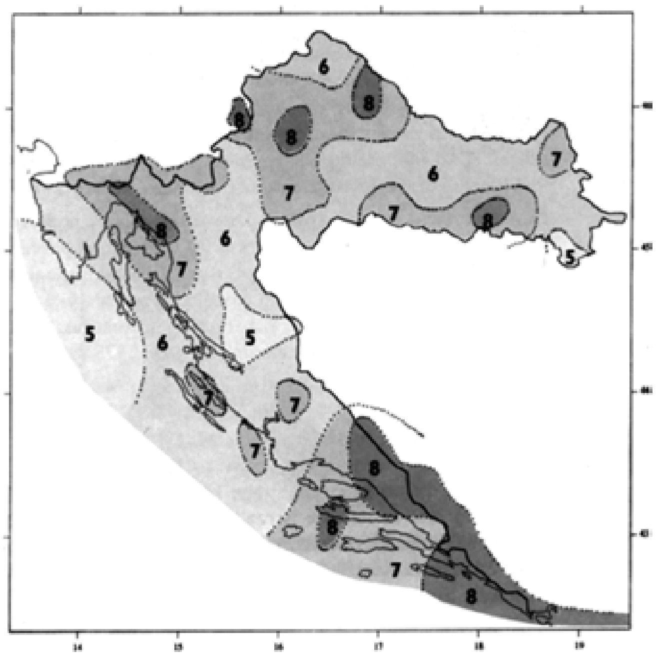

Fig. 4.2: The map of maximum earthquake intensities (Medvedev-SponheuerKarnikov scale from 1964) at the territory of Croatia for the period of 100 years (Skoko-Mokrovic 1998)

Veli Vrh is located in the seismologically active zone and has got very similar characteristics as the area of Učka. The changes of stress show the rotation of the Adriatic micro plate. Geodetic measurements completely confirm the above stated.

Zadar is located in the regional structural unit of the Adriatic area (3). In this area there is a reverse fault on the surface, which indicates the space compression. According to the geodetic indicators, this is the zone with small compression values, as shown on Fig. 3.2 – 3.4

Žirje has got the similar position in the structural set as Zadar. Apart from the space compression in the zone of Dugi otok fault (8), there are smaller extensions appearing in this area that are probably created behind the folding zone of the middle Dalmatian islands. All above stated is confirmed by geodetic data as well that have been graphically presented earlier on apostrophe figures.

Split is located according to geological information in the structural unit of large compression. It is confirmed by geodetic measurements as well, since the height increase in this point runs up to 0.0143 m. The movements obtained by structural and geological measurements indicate the rotation of Mosor, which can be seen from geodetic measurements as well.

Kapela and Donja Tijarica are located along the border of the geological structural units Plavno-Svilaja (7), Dinara (6) and Mosor-Biokovo (9). The greatest compression is present in Mosor and Biokovo. The data for this area show the height reduction in the point Donja Tijarica, and different positional movement than all other points between Split and Dubrovnik. Since the point is located in the wider zone of reverse fault, the gravitation movements of the rock “package” are possible where the geodetic point is located. This leads us to the conclusion that the structural unit of the Dinaric Alps represents a separate density mass that is different from the surrounding area.

Vis, Sveti Nikola, Sveti Ivan and Sveti Jure are located within the structural unit of middle Dalmatian islands (16). Every island is separated with reverse fault visible on the surface. The directions of the movements of these islands are almost perpendicular to the direction of the movement of the Adriatic micro plate. There is compression in this structural unit, and the rotation can also be noticed confirmed by the changes in the stress orientation in this area. This rotation is completely confirmed by the geodetic data as well. Because of consecutive reverse faults, the gravitation movements are also possible in their zones, as well as the formation of reverse faults of opposite orientation because of rock folding.

Palagruža is located in the marginal zone of the Apennine Mountains, so there are no structural and geological data for this area. According to general geological information there must be space compression present there which is completely confirmed by the geodetic measurements.

From all above state it is to be seen that the mathematically defined deformation zones determined on the basis of *geodetic GPS-measurements* and presented on Fig. 3.1 – 3.4, show *high degree of correlation* with geological information about deformation zones in the research area.

6 Conclusion

The researches presented in this work undoubtedly show that GPS-measurements performed on the external Earth’s surface with the application of adequate deformation analysis can be used as the basis for the control of tectonic movements and deformations of the Earth crust that are caused by many, often unknown forces in the internal structures of the Earth. On the basis of highly accurate GPS-measurements it is possible to define mathematically the changes of three-dimensional surface geometry that is used for describing the deformation of the external Earth crust. In this way, the geodetic measurements have become the basis not only for static, but also for kinematic, i.e. dynamic models.

The results of deformation analysis show that the majority of the speed vectors are oriented north north westwards which is in accordance with the movement direction of the African plate. It leads us to the conclusion that the southern part of the Adriatic micro plate is leaning on the African plate that moves in that direction. In the points Bakar, Split and Sveti Ivan, the positional speed vector in the northwestern part of the observed area, from the north-northwest towards west can be the indication of mild rotation of this part of the Adriatic micro-plate. All signs are positive, except in the point Donja Tijarica, where this sign is negative. According to geological information, the Adriatic micro plate is slipping under the Dinaric Alps, which could mean that the opposite edge of the plate is rising.

The comparison of the zones of maximum surface deformations obtained on the basis of GPS-measurement with the map of maximum earthquake intensities in Croatia, Fig. 4.2, it is to be seen that the zones of maximum earthquake intensities are located exactly at the place that have been defined in the geodetic model as the zones of the largest compressions. These results, although obtained on the basis of the measurements done in the period of only two years, undoubtedly confirm the correlation between geodetic and geological models of tectonic movements. All *deformation zones determined on the basis of geodetic GPS-measurements* indicate *high degree of conformity* with geological information regarding the deformation zones in the research area. It should be specially pointed out in this case that the research results depend essentially on the selection of the points of geodynamic network and their manner of stabilization. Is also desirable to stabilize the points by means of especially constructed, brass marks for forced centring of GPS-device antennas.

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Abstract

The paper presents a method for determining the model of the Earth's external surface deformation on the basis of geodetic GPS-measurements, and the comparison of obtained results with geotectonic information for the observed area in accordance with the movement theory of lithosphere plates. The geodetic model has been produced referring to the difference of adjusted ellipsoid coordinates of mutual points in two GPS campaignes: CRODYN 94 and CRODYN 96. The results of surface deformation analysis obtained in the tested area placed between 42.4 and 46.4 degree of northern latitude and between 13.6 and 17.6 of eastern longitude indicate the zones of various deformations. There have been two zones of extensions and two zones of compressions detected, and between these zones there have been no zones with larger deformation detected. The zone with maximum extension value: 6 mm for the distance of 10 km in period of one year has been detected in the north-west part of the observed area, and the other zone with somewhat smaller extension values: 3–5 mm/10 km is placed westward from Split. The values of length compressions are a bit smaller than the extensions and run from 3–5 mm at the distance of 10 km in both above stated zones.

All these results confirm completely the geological notions about the tectonic movements and the existence of these zones at the tested area. Compression zones can be recognized on the basis of reverse faults and extensive tectonic activity, i.e. the epicentres of the strongest earthquakes are placed in this areas, and these zones are pretty identical with the compression zones in the geodetic model. Although the GPS-measurements have been observed only in the period of two years, the obtained results confirm undoubtedly the correlation between geodetic and geological models in determining the movements and deformations of the external part of the Earth's crust.

Zusammenfassung

In der Arbeit ist die Methode für die Bestimmung des Models der Erdoberflächedeformation auf Grund der geodätischen GPS-Messungen dargestellt, wie auch der Vergleich von erhaltenen Ergebnissen mit geotektonischen Informationen für das beobachtete Gebiet gemäß der Bewegungstheorie der lithosphärischen Platten. Das geodätische Model wurde mit Bezug auf den Unterschied der ausgeglichenen Ellipsoidkoordinaten von gemeinsamen Punkten in zwei GPS-Kampagnen hergestellt: CRODYN 94 und CRODYN 96. Die Ergebnisse der Oberflächedeformationsanalyse, die im Testgebiet zwischen dem 42.4 und 46.4 Grad nördlicher Breite und zwischen dem 13.6 und 17.6 Grad östlicher Länge erhalten wurden, zeigen die Zonen unterschiedlicher Deformationen. Zwei Ausdehnungs- und zwei Verdichtungszonen wurden entdeckt, und zwischen diesen Zonen gab es keine Zonen mit größerer Deformation. Die Zone mit dem maximalen Ausdehnungswert: 6 mm für die Entfernung von 10 km in der Zeit von einem Jahr wurden in dem nord-westlichen Teil des beobachteten Gebiets gefunden, und die andere Zone mit etwas kleinerem Ausdehnungswert: 3–5 mm/10 km befindet sich westwärts von Split. Die Werte von Längenverdichtungen sind etwas kleiner als die Ausdehnungen und betragen 3–5 mm auf der Entfernung von 10 km in beiden oben genannten Zonen.

Alle diese Ergebnisse bestätigen im Ganzen die geologischen Erfahrungen über die tektonischen Bewegungen und die Anwesenheit dieser Zonen in dem Testgebiet. Die Verdichtungszonen kann man erkennen auf Grund von umgekehrten Verwerfungen und umfangreicher tektonischer Aktivität, d.h. die Epizentren der stärksten Erdbeben befinden sich in diesem Gebiet, und diese Zonen sind ziemlich identisch mit den Verdichtungszonen im geodätischen Model. Obwohl die GPS-Messungen nur in der Zeit von zwei Jahren beobachtet wurden, bestätigen die erhaltenen Ergebnisse ohne Zweifel die Korrelation zwischen dem geodätischen und dem geologischen Model in der Bestimmung von Bewegungen und Deformationen der äußeren Erdkruste.