SOME PRELIMINARY RESULTS AND ANALYSIS OF DIFFERENT GEODYNAMIC TECHNIQUES WITH SPECIAL REMARK ON GPS AND TILTMETER MEASUREMENTS IN CROATIA

Yüksel ALTINER[1], Krešimir COLIC[2] And Radovan MARJANOVIC - KAVANAGH[3]

SUMMARY

Croatia lies in a region, which is seismotectonically very active. The main reasons for this are the Adriatic microplate movements towards the Dinarides, with its different specific densities of rock masses in the crust. There are several zones in the Adriatic Sea but also along the Adriatic Coast experiencing in the past heavy earthquakes with damages in cities (Dubrovnik, Makarska, Rijeka, Ston, and Zadar). Also, there are some local zones in the inland regions (Gospiæ, Knin, Zagreb and others) which are not directly coupled with the above mentioned dynamics. Therefore, several different measuring methods and techniques applied in different zones are used (and others are planned) to determine the changes in position, height, tilting, and gravity, which will enable the creation of better earthquake prevention models. Two main projects for deformation monitoring are still running. The first project is: a) The monitoring of the Adriatic Sea area deformations with a part of the inner land, and the other is b) the local deformation net of the broader area of Zagreb. The monitoring is based on GPS measurements. For the investigation of the present tectonic activities in the Adriatic Sea area, a wider GPS network was established. The network consists of 22 stations that are distributed over Croatia (17), Slovenia (3) and Italy (2). In 1996, the network was extended towards the south and west with 7 stations in Albania (4) and Italy (3). The GPS network has to be remeasured several times and from the repeated data, velocity vectors will be calculated.

The results of the deformation analysis, based on the analytical surface deformation theory, indicates three different deformation zones in the investigated area.

Tilt measurements in combination with gravity measurements in the future along the coast will have to prove the theory of three separate microplates in the Adriatic basin.

To observe earthquake precursors (if they occur), continuously on-line tiltmeter measurements are planned. Since the Geophysical Institute in Zagreb has been recording earthquakes for more than hundred years till now, these data are to be included as well. Also an absolute gravity network with selected measuring points which will cover the main part of Croatia as well as a GPS permanent network is planned in the future. The combination of data from different origin will enable the usage of crust behaviour models in future. Based on such models a better understanding of earthquake origins and prevention, especially around cities could be obtained.

INTRODUCTION

The movements of the African plate towards the Eurasian plate induce strong tectonic activity in the Adriatic Sea area and the inner part of the Croatian coast. Several seismological and geological studies proved this theory, and several researching teams worked on this phenomenon. After Mantovani (Mantovani et al., 1992) the Adriatic Sea is a promontory of the African plate which moves with a relative velocity of 5 mm/year towards north to northeast. Several other authors are of the opinion that the Adriatic Sea is a separate independent microplate, and the earthquakes in this region are caused by the local deformations of the Adriatic microplate (Anderson & Jackson, 1987). According to short duration of time there is not enough data for final conclusions to decide

[1] *Bundesamt für Kartographie und Geodäsie, Frankfurt am Main, Germany, Europe, Email: altiner@ifag.de*
[2] *Geodetic Faculty of the University of Zagreb, Croatia, Europe, Email: kresimir.colic@jagor.srce.hr*
[3] *Faculty of Mining, Geology and Petroleum engineering, University of Zagreb, Croatia, Email: ramaka@rudar.rgn.hr*

between these theories. However it gives a solid base for investigations which will proceed in future. Based on analytical surface deformation theory (Altiner, 1999), taking in account other geological and geophysical results, the deformations of the Adriatic region and a part of the inner land of Croatia are calculated (Altiner et al., 1999).

From the year 1977, a local 3D-Geodynamic project is running around the capital city of Zagreb with about one million inhabitants. A strong tectonic activity of the mountain Medvednica with its different geological structures, and many faults, caused a lot of strong earthquakes in the past. The position of the city of Zagreb that is situated just on the edge of the mountain Medvednica, gives special importance to this project. A carefully designed GPS network consisting of 42 points was established, in accordance with geological and other parameters. The points are covering stable positions and even those where movements are to be expected. A special point stabilisation was done to achieve high accuracy avoiding local micro-movements of the pillars. The distances between the points are about 7 km.

At the present moment only the results of the first measurement phase are available. The remeasurements of the network will follow in some years. A deformation calculation of that region based on repeated GPS measurements is therefore not possible but from the measered data, a local geoid for this test area with a cm accuracy was calculated (Èoliæ et al., 1999).

THE MEASUREMENT STRATEGY

For measuring present crust deformations in the Adriatic region and in the inner land of Croatia, the main idea was to establish a net of GPS points, where after a certain period of time, remeasurements could be done. The GPS network was established in the year 1994 in co-operation between the Bundesamt für Kartographie und Geodäsie, Frankfurt am Main (Germany), The Geodetic Faculty of the University of Zagreb, The State Geodetic Administration in Zagreb (both Croatia) and the Surveying and Mapping Authority in Ljubljana (Slovenia). The net from the year 1994 consisted of 22 points distributed over Croatia (17), Slovenia (3) and Italy (2).

The measuring campaign called CRODYN' 94 started on June the 7th until June the 10th. The campaign was divided in three sessions with a session length of 24 hours. The second measuring campaign CRODYN' 96 was carried out from September the 9th till September the 12th in the year 1996 and the third campaign in the year 1998, which started on September the 4th till September the 7th. In all campaigns the same observation strategy has been applied. A cut-off angle of 15 degrees and a sampling rate of 15 seconds were used for data collection (Altiner et al., 1999). To avoid variations in the phase centre from different receiver antennas, all stations were equipped with the same type of receivers: Trimble 4000 SSE, (exempt Bassoviza and Trieste, where Leica SR 299 were used).

At the present moment only data from the first and second campaign are completely calculated using the Bernese post-processing GPS Software (Version 4.0). CODE orbits (Centre for Orbit Determination in Europe) were used for precise orbits. Coordinates of the ITRF (International Terrestrial Reference Frame) sites Graz, Matera, Zimmerwald and Wettzell were shifted to the observation epochs of the CRODYN'94 and CRODYN'96 campaigns, using the coordinates and velocities published in the IERS Technical Note for the ITRF92 and ITRF94 (Altiner et al., 1999).

DATA PROCESSING

Firstly a data pre-processing was applied, where the raw data were converted to RINEX (Receiver INdependent EXchange) format, and the measured antenna heights were corrected on the basis of the L1/L2 antenna phase centre for the used antenna type. Using pseudorange data the receiver clock correction for each observation epoch was performed. Triple difference screening for the determination of a priori coordinates has been performed. For data quality checking daily solutions for each campaign were determined separately. Free daily solutions were combined for each campaign separately to create a free campaign solution.

A multi campaign solution - combination of CRODYN'94 and CRODYN'96 was used for calculating station velocities. The NUVEL1-A model has been used for the IGS stations (International GPS Service for Geodynamics) on the European Plate. The final coordinates and velocities were determined in the mean observation epoch of the two GPS campaigns (ITRF94, epoch 1995.6). Two different solutions for the determination of the station velocities were computed:

a) Absolute Coordinate Solution and

b) Relative Solution

Ad a) In the first solution, the coordinates and velocities of 4 IGS sites (Wettzell, Matera, Graz and Zimmerwald) were chosen as fixed for the computation of the coordinates and velocities of the other stations. The results obtained from this calculation indicate a significant north-east movement with velocities between 2.5 and 3.0 cm/year with an accuracy in order of ± 2mm/year, for the horizontal component and an amount of about 1.0 cm /year for the vertical component, with an accuracy of ± 4mm/year. The results are shown in figure 1.

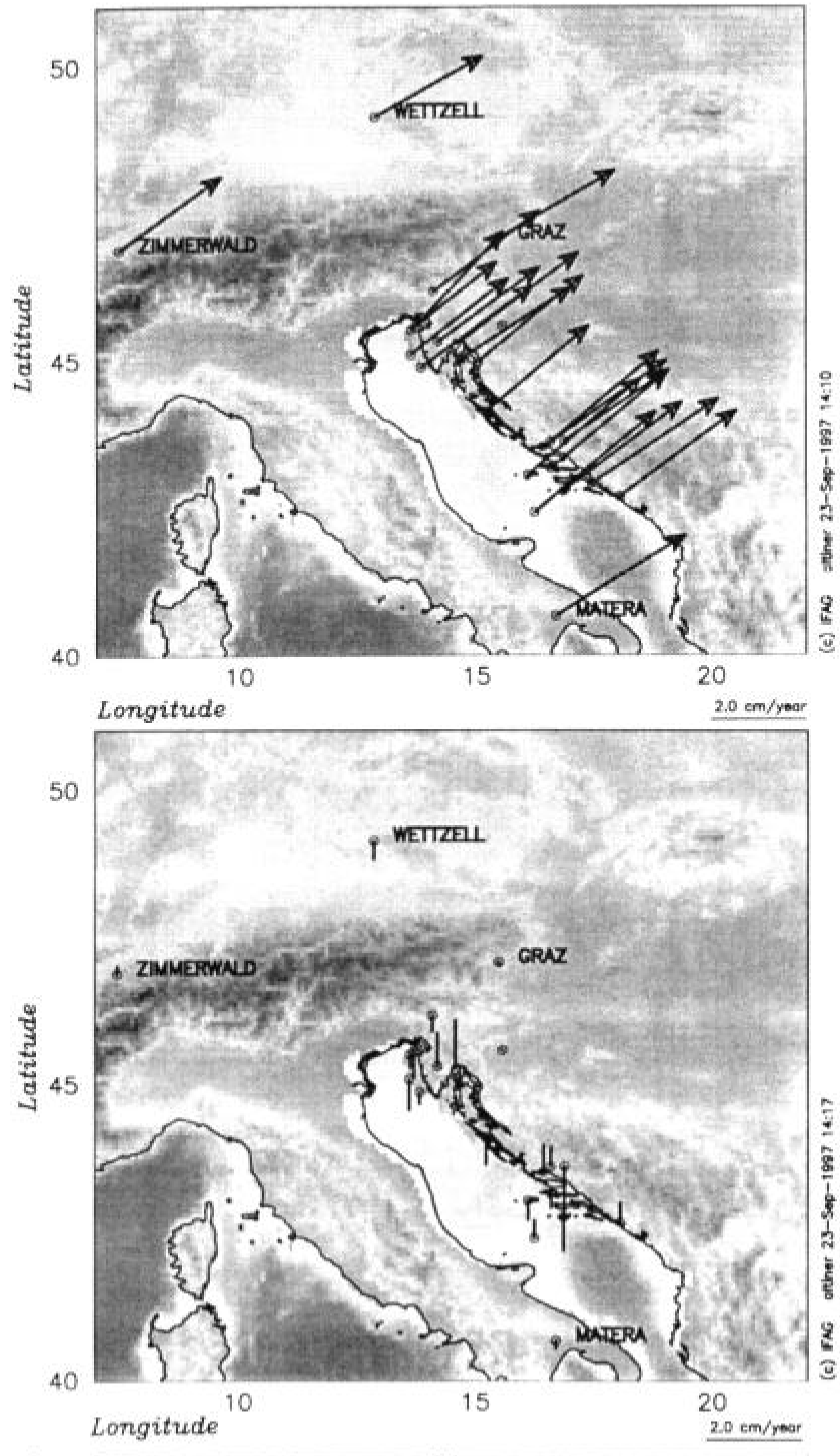

Figure 1: The station velocities for the absolute model.

Ad b) The relative model was calculated on the basis that the a-priori velocities were set to zero, and the station Graz with the ITRF94 coordinates were fixed as a reference site to determine the coordinates and velocities of all other stations. The accuracy of the velocities of these calculations is about ± 3mm/year for the horizontal component and about ± 5mm/year for the vertical component. The velocity amount of the horizontal component is in the order of 0.5 cm/year in the southern part and ca. 1.0 cm/year in the northern part. The vertical component has a value of about 2.0 cm/year in average for the whole investigated area. The results are shown in figure 2.

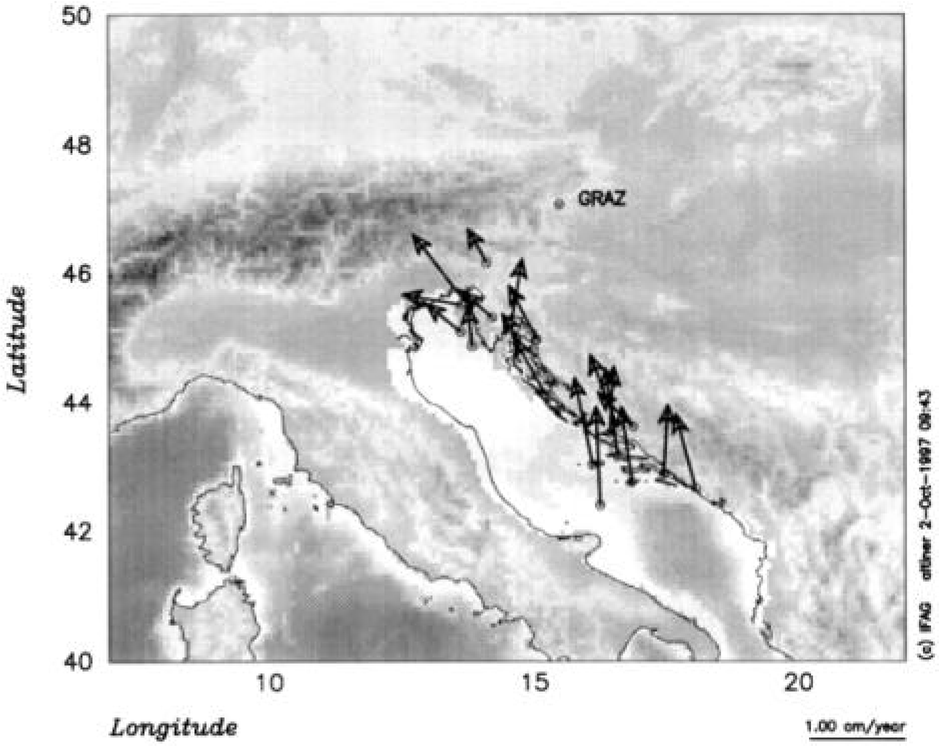

Figure 2: The station velocities for the relative model.

THE CALCULATION OF INTERNAL AND EXTERNAL DEFORMATIONS

As the results of a deformation model calculation are dependent of the fixed-point geometry, the absolute model was not used but only the relative one. With an increment of 0.1 degree, from 42.4 degrees to 46.4 degrees of northern latitude, an area-wide grid was established, based on the observed points. The collocation method was used for the interpolation of heights, horizontal and vertical velocities, as well as the derivatives of heights and velocities for the surface coordinates of the grid points, (Altiner, 1998). The results from the analytical surface deformation analysis indicate three different deformation zones, which are partially in accordance with the presumption given earlier by Cvijanoviæ (Cvijanoviæ & Labaš, 1990). It is therefore of great importance to compare similar results of other working teams from neighboured countries like from the Bovec-Tolmin earthquake region (Miškoviæ, D., et al., 1999).

The deformations of the Adria area calculated as curvature change are shown in figure 3.

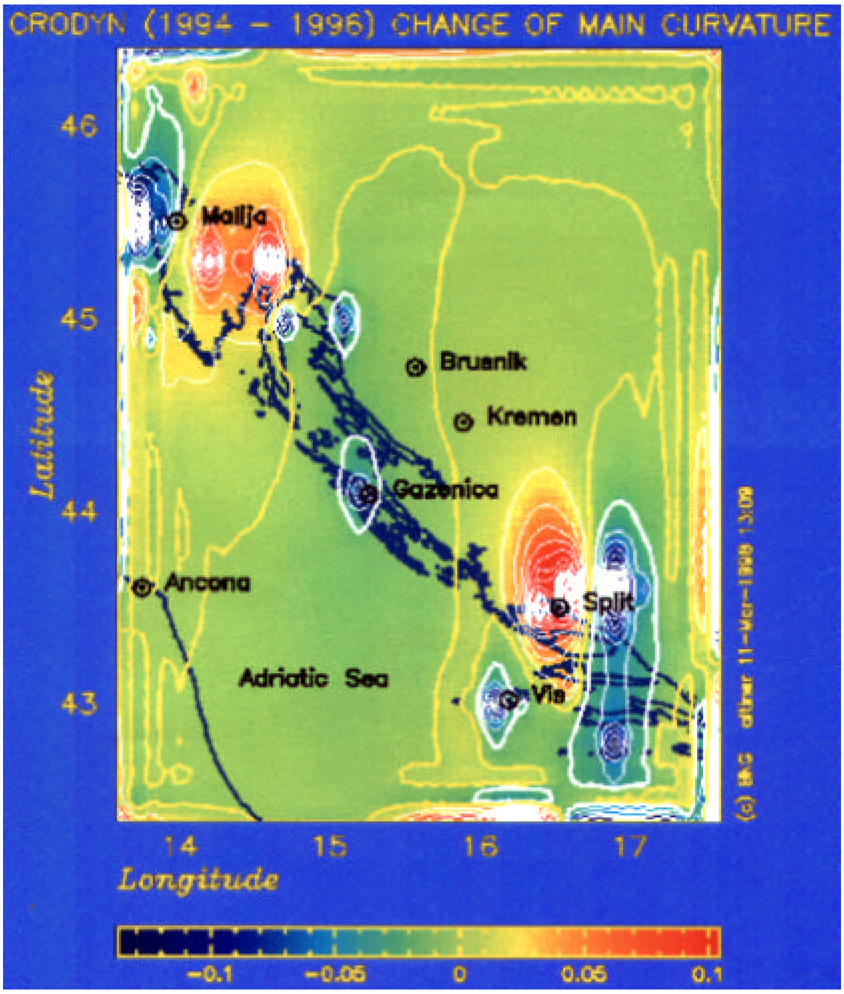

Figure 3 :Three different deformation zones, and the curvature change for the measured period

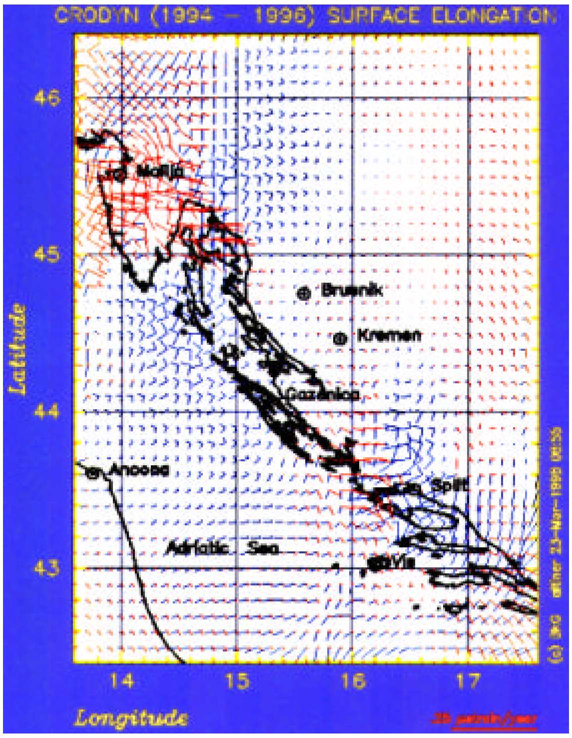

Figure 4: Surface deformations shown as elongation

In the north-western part of the investigated area a maximum of extension deformation with an amount of 3mm/year/10km was found, and in the south to south-east part of the investigated area the extensions are smaller with an amount of 1-2-mm/year/10 km. The results of the calculations of the surface elongation are shown in figure 4

THE 3D NETWORK ARROUND ZAGREB

In the inner land several projects for deformation measurements are still running. In the broader area of the City of Zagreb, which is a strongly menaced seismic zone, a GPS test net was established. In this region the occurrence of earthquakes even with strong destruction in the past was often (Èoliæ et.al.,1999). A large number of earthquake recordings, and those epicentres from a period of more than 120 years are known, figure 5.

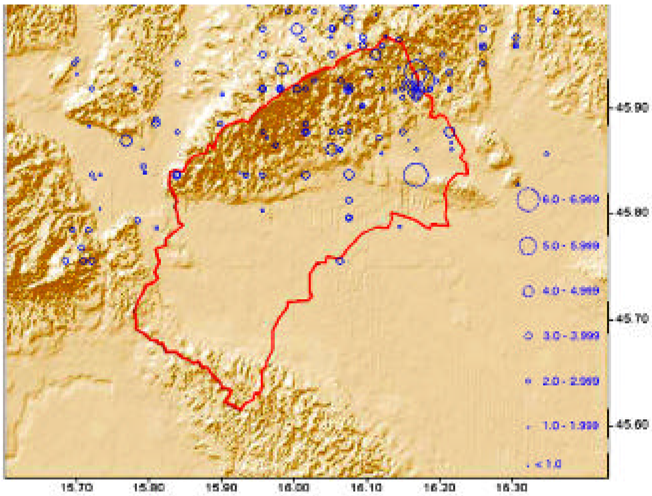

Figure 5: Epicentres of earthquakes at the territory of Zagreb

according to Richter scale (Èoliæ et al., 1999)

Also the most active seismic zones and the most significant faults in the near mountain Medvednica have been derived which divide the mountain in several separate tectonic units. (Cvijanoviæ et al., 1980). Seismologists and neotectonists have observed that the highest frequencies of earthquake occurrence are at the points of intersections of transversal and diagonal faults with the main longitudinal fault on the mountain Medvednica. That proves the hypothesis that these faults are active, and they directly cause the increased seismicity. The fault system of the mountain Medvednica is shown in figure 6. The longitudinal faults are signed as 1,3,and 8, and the transversal and diagonal faults are signed as 2,4,5,6,and 7.

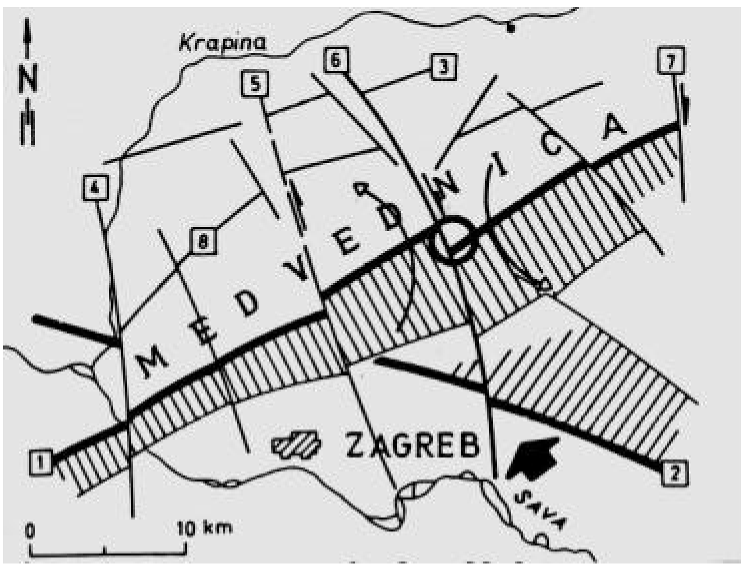

Figure 6: The main faults of the mountain Medvednica after (Cvijanoviæ et al., 1980)

For the area of Zagreb the most of the earthquakes originate at two significant depths over Moho. The first characteristic depth is about 10km, and the second a depth between 10-20 km. At the depth of 10 km the strongest known earthquake in this region happened in the year 1880 with the intensity of IX^0 of MCS, when strong damages on buildings occurred. From the available data the magnitude of 6.3 according to Richter's scale was later determined. However the earthquakes mostly occur in the region of the mount Medvednica, caused by tectonic movements also the broader area is an earthquake hazardous region. So in the year 1909 again an earthquake of IX^0 of the MCS happened with its epicentre about 39 km in the southeast direction from Zagreb. Several authors predict an earthquake with a maximum magnitude of M=6.5 ± 0.2 of Richter's scale, somewhere in that broader location, for the next period of 500 years.

From the mentioned above a GPS network with 42 measuring points was established (Èoliæ et al., 1999). The point distribution was carefully chosen to cover both sides of the most significant faults. A special pillar construction was used (to 10 m deep) to achieve stabile contact with the subsurface geological structures, which in the southern part beneath the mount Medvednica consists mostly of sediments from the river Sava.

The observations have been carried out with 25 Trimble 4000SSI/SSE and two Astech Z-12 receivers. For that reason the measurements have been divided in two phases, where some points have been used for both sessions.

Apart from the first stage of geodynamic research, the data of these GPS measurements have been used for a test computation of a cm-geoid (Èoliæ et al.,1999), and also to determine 4000 GPS points for cadastral purposes.

The second stage of this measuring campaign will follow in several years

Because GPS measurements (even permanent stations) can only particularly give continuous data, an on-line tiltmeter array is planned. Investigations of several tiltmeter constructions have been done and a new digitally tiltmeter construction is developed (Marjanoviæ, 1998). A test of long-term instrument stability showed acceptable results. The main problem using tiltmeter and similar instruments is still the separation of extern influences such as temperature, air-pressure, and humidity changes. A sufficient insulation (dry boreholes), and a continuous data transfer from several instruments to a computing centre extremely enlarges the costs of such a project. Therefore the tiltmeter-measurement project is still in the developing stage, and the data analysis is at the moment not available for a comparation with other results.

CONCLUSIONS

1. For the seismotectonically very active region, of Croatia a continuous monitoring system also in future is of special importance, and therefore these projects have to be continued.

2. As the geological circumstances are not equal with the political border it is necessary that this projects are international, covering wider regions of the neighboured countries.

3. The most important zones for such investigations in Croatia are still the Adriatic coast and local zones around cities (Zagreb).

4. As the accuracy of the GPS coordinates of points is in order of about few mm in all three directions it is of great importance to improve the stabilisation of points, and to preserve them for a long period of time while the remeasurements will take place again.

5. To get data of earthquake precursors (if they occur) the period of remeasurements has to be shortened and also other measuring techniques have to be applied.

6. To get better deformation models which are now based firstly on GPS techniques in future it will be necessary to include all available geophysical, geological and geodetic data.

ACKNOWLEDGMENTS

At the end of this paper we would like to offer special thank to the assistants at the Geodetic faculty of the University of Zagreb to Mr Boško Pribiæeviæ and Draž en Švehla for their help during the measurements, and the calculations of the digital terrain model.

REFERENCES

1. Altiner, Y., (1998). "Nutzung von GPS - beobachtungen für die Strainanalyse in der Ebene und ein neues Verfahren zur Darstellung von äusseren Flächenänderungen", *Vermessungswesen und Raumordnung,* Dümmler Verlag, Heft 1 pp.42-50, Februar 1998

2. Altiner, Y., Cigrovski-Deteliæ B., Èoliæ, K., Seeger, H., (1999) "Present crustal deformations in the Adriatic Sea area on the basis of GPS observations", *Second International Symposium Geodynamics of the Alps-Adria by means of Terrestrial and Satellite Methods*, Dubrovnik, Croatia, 28th September - 2nd October 1998

3. Altiner, Y, (1999) *Analytical Surface Deformation Theory for detection of Earth's Crust Movements,* Springer Verlag , Frankfurt,1999

4. Andersen, H., Jackson, J, (1987) "Active tectonics of the Adriatic Region", *Geophys. J. R. astr. Soc. (1987) 91*, pp. 937 - 983

5. Cvijanoviæ, D., Prelogoviæ, E., Skoko, D., Mariæ, K, Miškoviæ, D., (1980) "Seizmotektonska rajonizacija Medvednice","(Seismotectonic zoning of Medvednica)", *Zbornik referata 6. Jugoslavenskog simpozija o hidrologiji in inžennirski geologiji*, Portorož , Vol.2, pp. 13-25

6. Cvijanoviæ, D., Labaš V., (1990) "Comparison of Seismic Activity and Residual Anomalies of Gravity in the wider Knin area", *Proceedings of the first international symposium: Gravity field determination and GPS-Positioning in the Alps-Adria area*, Dubrovnik-Hvar, 2nd - 7th October 1989, Graz 1990

7. Èoliæ, K., Pribièeviæ B., Švehla, D., (1999) "3D - Geodynamic Network of Broader Area of the City of Zagreb", *Second International Symposium Geodynamics of the Alps-Adria by means of Terrestrial and Satellite Methods,* Dubrovnik, Croatia, 28th September - 2nd October 1998

8. Mantovani, E., Albarello, D., Babbucci, A, Tamburelli, C., (1992) *Recent Geodynamic Evolution of the Central Mediterranean Region*, Department of Earth Sciences - University of Siena. (1992)

9. Marjanoviæ-Kavanagh, R. (1999) "*Some Experiences with a new digitally Tiltmeter*", *Second International Symposium Geodynamics of the Alps-Adria by means of Terrestrial and Satellite Methods,* Dubrovnik, Croatia, 28th September - 2nd October 1998

10. Miškoviæ, D., Pesec P., Stangl G., (1999) "GPS Remeasurements in the Bovec-Tolmin Earthquake Region", *Second International Symposium Geodynamics of the Alps-Adria by means of Terrestrial and Satellite Methods,* Dubrovnik, Croatia, 28th - September 2nd 1998