Determination of Horizontal and Vertical Movements of the Adriatic Microplate on the Basis of GPS Measurements

M. Marjanović, Ž. Bačić
State Geodetic Administration, Gruška 20, 10 000 Zagreb, Republic of Croatia

T. Bašić
Croatian Geodetic Institute, Savska cesta 41/XVI, 10 000 Zagreb, Republic of Croatia

Abstract. The paper describes the determination of horizontal and vertical movements of the Adriatic microplate on the basis of GPS measurements carried out in the period between 1994 and 2005 within the frame of the 21 measuring campaigns organized at the research territory. The role of geodetic measurement methods particulary GPS method is essential in applications that requires high accuray and precision as in the velocity field estimation of tectonic plates. The processing of GPS data as well as computation of the coordinates of points and their velocities was performed by Bernese GPS Software Ver. 5.0 based on 140 daily solutions. The mean standard deviations of estimated coordinates from repeatability of daily solutions and combined solution are $\sigma_\varphi = 2.0$ mm, $\sigma_\lambda = 2.2$ mm and $\sigma_h = 5.6$ mm. In purpose to determine and present the trend of height component the comparison of the data obtained by monitoring the change of sea level and the results of GPS measurement data was investigated. On the basis of the computed relative velocities of points as related to the Euro-Asian plate, the parameters of Euler rotation vector and Euler pole of the Adriatic microplate have been calculated and compared with other solutions. Also, the kinematic research area model has been determined on the basis of the combined solution results and compared with with global kinematic models NNR-NUVEL-1A and APKIM2000.

Keywords. GPS, geodynamic, Euler pole, plate kinematic models

1 Introduction

In recent years GPS become one of the most used methods in applications that requires high positioning precision such as in velocity field estimation and computation of plate tectonic models. The coordinates of geodetic points on Earth's surface change with time due to plate tectonics and therefore they are dependent on epoch of their determination. If we have measurements at least in two epochs it is possible to compute the change of point coordinates as a function of time.

The Adriatic microplate is a plate or litosphere block which includes the area of Adriatic sea, eastern part of Italy, river Po valley and the area of western Dinarides. The microplate is situated on the border between two major tectonic plates, Euro-Asian and African plate. The main cause for the deformation processes in whole area is the moving of African plate in north direction [Krijgsman, 2002]. The most part of Adriatic microplate is covered by the Adriatic sea and it is not possible to perform field measurements directly on the microplate, because of that the investigation of microplate movements have to be carried out based on the measurements made in surroundings area.

At the begining of the 1990's, Croatia starts to participate in international geodynamic projects and GPS campaigns, but the measurements were carried out just on one or two points. In year 1994 the project CRODYN started in cooperation of Faculty of Geodesy in Zagreb, State Geodetic Administration of Croatia and Institute of Applied Geodesy from Frankfurt (Germany) for the geodynamic research of Adriatic microplate based on GPS method [Čolić et al., 1996].

Table 1: GPS Campaigns

No.	Campaign	Sessions	Year	Points
1	CEGRN94	5	1994	8
2	CEGRN95	5	1995	11
3	CEGRN96	6	1996	9
4	CEGRN97	5	1997	14
5	CEGRN99	6	1999	13
6	CEGRN01	6	2001	16
7	CEGRN03	6	2003	13
8	CEGRN05	6	2005	15
9	CRODYN94	3	1994	21
10	CRODYN96	3	1996	38
11	CRODYN98	3	1998	34
12	CROSLO94	4	1994	20
13	CROREF95	7	1995	28
14	CROREF96	6	1996	44
15	CROREF05	2	2005	50
16	EUVN97	7	1997	17
17	SLOVEN02	4	2002	12
18	SLOVEN03	3	2003	14
19	RTREAT03	22	2003	24
20	RTREAT04	25	2004	24
21	RTREAT05	7	2005	16

The main objective of paper is the computation of coordinates and velocities of points and computation of Euler rotation vector and Euler pole of the Adriatic microplate based on relative velocities of points to the Euro-Asian plate. The processing of GPS data as well as computation of the coordinates of points and their velocities was performed by Bernese GPS Software Ver. 5.0.

2 Data Set

The computation of coordinates and velocities of points were performed based on 21 GPS campaigns observed in the period between 1994 and 2005 (Table 1). In the processing of the data 140 sessions (24 hour) of 81 points were included. The GPS campaigns were carried out within international and national geodynamic projects, EUREF projects and national projects for establishment reference GPS networks. Also, 15 IGS points were included for datum definition and control of data processing.

3 Data Processing

The software used for the processing of GPS data was Bernese GPS Software Ver. 5.0 [Dach et al., 2007]. The strategy of data processing followed:

- Recommendations of EUREF Technical working group [Boucher and Altamimi, 2001],
- Specifications for the computation of EUREF/EPN network [URL 1],
- Guidelines for using of IGS products [Kouba, 2003].

The computation of combined solution based on all 140 session solutions was done in ITRF2000, at the middle epoch of all measurements 2000.04 (Table 2). The IGS point Graz was used for datum definition for coordinates as well as for velocities (Figure 1).

Table 2: Computation of Combined Solution

Number of input NEQ files	140
Number of points	81
Number of vectors	2148
Number of observations	40 236 729
Number of parameters	81 592
σ_0 [mm]	1.4

The mean standard deviation of 21 GPS campaigns derived from the comparison of daily solutions of each GPS campaign shows very good quality and accuracy of computed coordinates what is very important for the computation of velocities (Figure 2).

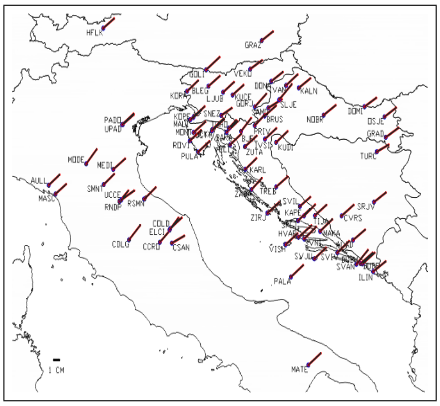

Fig. 1: Computed velocity vectors

The mean standard deviations of estimated coordinates from repeatability of 140 daily solutions and combined solution are $\sigma_\varphi = 2.0$ mm, $\sigma_\lambda = 2.2$ mm and $\sigma_h = 5.6$ mm.

4 Results

4.1 Euler Rotation Vector and Euler Pole of the Adriatic Microplate

The relative movement or rotation of one plate respect to the another plate is described by relative kinematic plate model or with rotation for angle Ω around the point on Earth's surface or Euler pole.

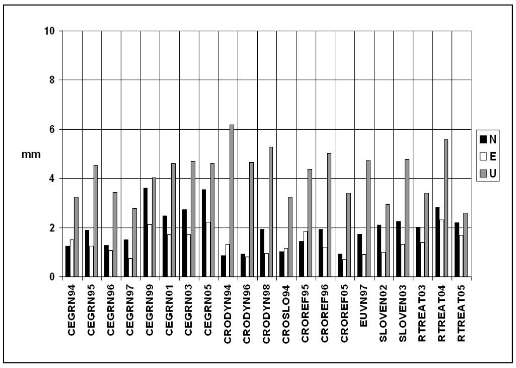

Fig. 2: Repeatabilites of Daily Solutions

Each tectonic plate included in some kinematic plate model (absolute or relative) has altogether six parameters: Euler rotation vector (Ω_X, Ω_Y, Ω_Z) and Euler pole (φ, λ, Ω). Using the estimated relative velocities and coordinates of GPS points it is possible to estimate relative plate kinematic model of Adriatic microplate respect to Euro-Asian plate in least square adjustment process [Perez et al., 2003]. The Euler theorem gives the linearized observation equation for one station in which we have relation between estimated (V_X, V_Y, V_Z, X, Y, Z) and unknown values (Ω_X, Ω_Y, Ω_Z)

$$\begin{bmatrix} V_X \\ V_Y \\ V_Z \end{bmatrix} = \begin{bmatrix} 0 & Z & -Y \\ -Z & 0 & X \\ Y & -X & 0 \end{bmatrix} \begin{bmatrix} \Omega_X \\ \Omega_Y \\ \Omega_Z \end{bmatrix} \qquad (1)$$

if

$$n_f = n - u > 0 \qquad (2)$$

where n is number of measurements and u is number of unknown parameters. The computed parameters of Euler rotation vector are

$$\begin{aligned} \Omega_X[\text{rad/mil years}] &= 0.0023 \\ \Omega_Y[\text{rad/mil years}] &= 0.0003 \\ \Omega_Z[\text{rad/mil years}] &= 0.0023 \end{aligned} \qquad (3)$$

and then the parameters of Euler pole are

$$\begin{aligned} \varphi &= \tan^{-1}\left(\frac{\Omega_Z}{\sqrt{\Omega_X^2+\Omega_Y^2}}\right) = 45.4^\circ \\ \lambda &= \tan^{-1}\left(\frac{\Omega_Y}{\Omega_X}\right) = 8.1^\circ \qquad (4) \\ \Omega &= \sqrt{\Omega_X^2+\Omega_Y^2+\Omega_Z^2} = 0.2^\circ/mil\,years. \end{aligned}$$

The estimated Euler pole of Adriactic microplate was compared with the results of investigations carried out between 1987 and 2005 (Table 3). The values in table 3 shows good agreement, althougth different type of measurements and computation methods were used.

Table 3: Comparison of Euler Pole Parameters

Solution	φ [°]	λ [°]	Ω [$^\circ/mil\,years$]
1*	45.8	10.2	-
2*	44.5	9.5	0.3
3*	46.8	6.3	0.3
4*	45.3	9.1	0.5
5*	46.7	9.7	0.4
6*	45.4	8.1	0.2

1* Anderson and Jackson [1987]; 2* Westaway [1990]; 3* Ward [1994]; 4* Calais et al. [2002]; 5* Weber et al. [2005a,b]; 6* This study

4.2 Comparison of Computed and Global Plate Kinematic Models

The kinematic plate model of research area computed based on the results and processing of GPS measurements was compared with two global plate kinematic models NNR-NUVEL-1A and APKIM2000 [DeMets et al., 1994; Drewes and Angermann, 2001] of the Euro-Asian tectonic plate parameters (Table 4).

Using the parameter values from table 4 and equation 1 the velocities of points can be computed for all three kinematic plate models (e.g. Brusnik, Table 5).

Table 4: Kinematic Plate Model Parameters Ω_{XYZ} [$^\circ/mil\,years$]

Model	Ω_X	Ω_Y	Ω_Z
1*	-0.0010	-0.0024	0.0032
2*	-0.0003	-0.0024	0.0038
3*	0.0003	-0.0020	0.0046

Table 5: Velocities of Point Brusnik V_{NEU}

Model	V_N [mm]	V_E [mm]	V_U [mm]
1*	13.0	21.3	0.0
2*	14.1	21.3	0.0
3*	13.0	21.7	0.0

1* NNR-NUVEL-1A; 2* APKIM2000; 3* This study

The comparsion of three models (Tables 4 and 5) shows good agreement if we know that global models are based on geological and geophysical data (NNR-NUVEL-1A) and various satellite geodesy methods (APKIM2000), while this regional model was determined on GPS measurements carried out in the period between 1994 and 2005.

4.3 GPS Results and Sea Level Changes Data

The monitoring of sea level changes and data analysis helps in determination of vertical movements of the Earth's surface [Lambeck et al., 2004]. The change of sea level is caused by eustatic, glacial and tectonic effects. The most interesting from geodynamic point of view are tectonic effects which have regional character caused by tectonic processes. During the planning of CRODYN project five GPS points (GPS) were established on or near tide gauges (TG) which are also included in GPS campaigns and data processing (Table 6).

For the determination of vertical movements of every tide gauge and GPS points the data of sea level changes and the values of elipsoidal heigths were analysed (e.g. Bakar, Figures 3 and 4).

Table 6: Tide Gauges and GPS Points

TG/GPS	TG [year]	GPS [session]	V_U [mm]
BAKAR	62	17	-1.2
DUBROVNIK	47	17	-1.2
ROVINJ	48	19	-0.4
SPLIT	50	17	-2.1
ZADAR	10	11	-0.9

In purpose to investigate the relationship between two series of data the correlation coefficients were computed based on both data series using

$$r = \frac{P_1}{\sqrt{P_2 \cdot P_3}} \tag{5}$$

where

$$\begin{aligned} P_1 &= \sum_{i=1}^{m}\sum_{i=1}^{n}\left(A_{mn}-\overline{A}\right)\left(B_{mn}-\overline{B}\right) \\ P_2 &= \sum_{i=1}^{m}\sum_{i=1}^{n}\left(A_{mn}-\overline{A}\right)^2 \\ P_3 &= \sum_{i=1}^{m}\sum_{i=1}^{n}\left(B_{mn}-\overline{B}\right)^2 \end{aligned} \tag{6}$$

m and n are number of each data series with condition $m = n$, A_{mn} and B_{mn} are matrices of data and $\overline{A}$ and $\overline{B}$ matrices of mean values (Table 7).

Table 7: Correlation of TG and GPS Data

Tide gauge/GPS point	r
BAKAR	-0.99
DUBROVNIK	-0.99
ROVINJ	-0.99
SPLIT	-0.99
ZADAR	-0.99

The trends of sea level changes and computed elipsoidal heigths on all tide gauges and GPS points as well as sign of determined V_U velocites shows their relative movement in vertical sense, the rise of sea level or descending of coast. Also, the values of correlation coefficients in table 7 shows perfect correlation between two series of data in time ($r \approx 1$).

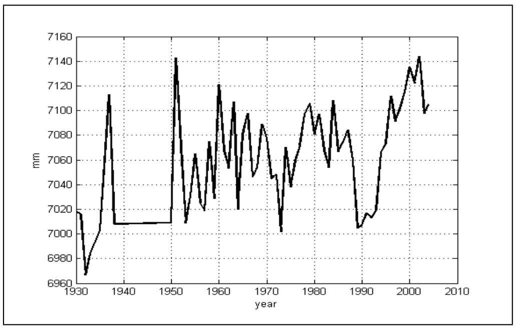

Fig. 3: MSL of Bakar Tide Gauge

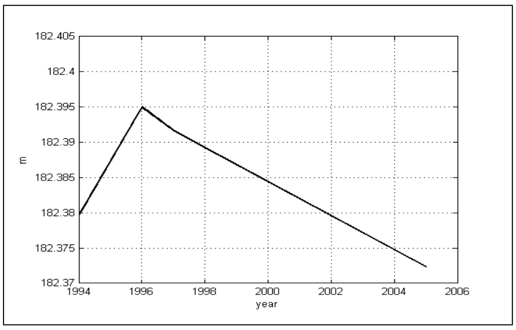

Fig. 4: Elipsoidal Heigth of Bakar GPS

5 Conclusion

The determined parameters of Euler pole and plate kinematic model of research area computed on the basis of GPS measurements have good agreement with the results of previous investigations and global plate kinematic models NNR-NUVEL-1A and APKIM2000. The analysis of mean sea level data of five tide gauges and computed elipsoidal heigths of corresponding GPS points made possible to determine the direction of relative movement in vertical component by two independent methods. At the begining of december 2008 the CROPOS (CROatian POsitioning System) was launched. The system has 30 reference GNSS stations and apart from applying CROPOS system for the the state survey and cadastre, the data also will be used for further geodynamic research.

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