Research of the Horizontal Crustal Motions, Based on GPS Data for the Territory of Bulgaria and the Balkans (7093)

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Key words: GNSS, velocity, Euler pole, earth crust movement

SUMMARY

The present study is focused on the used GPS data from free available GNSS stations on the territory of the Balkans. Applying velocities and respective coordinates of the stations estimated from GPS data processing, it is possible to estimate the rotation Euler vector by Least Squares Method. For determination of Euler parameters the author accepts a set of GPS stations as stable. Several different rotation poles have been estimated in order to test the proposed kinematics model for Bulgaria. The presented velocity gradient clearly indicates the increase of the motion from north to south. The GPS derived velocity field from GPS stations covering the territory of Bulgaria has been analysed and discussed in the context of tectonic block models. The investigation in the present publication is focused on the South Balkan extensional region using Global Positioning System (GPS) technique. The horizontal velocities in North Bulgaria, north of the Stara planina mountain, confirm the suggestion that North Bulgarian territory is part of the Eurasian plate. Our results show that the Southern Balkans do not belong to the Eurasian plate and seem to be dragged toward the south with the velocities relative to Eurasia gradually increase in N-S direction from 1.5-2 mm/yr in Western Bulgaria to 10mm/yr in Greece.

РЕЗЮМЕ

Настоящото изследване е фокусирано върху използването на GPS данни от наличните перманентни GNSS станции на територията на Балканите, свободно предоставящи и разпространяващи информация.. Използваики скоростите и координатите на GPS точките получини при обработката на тези данни, е възможно да се оцени Ойлеровия вектор на ротация по методът на най-малките квадрати. За определяне на Ойлеровите параметри авторът приема групи от GPS станции като стабилна. Няколко различни полюси на ротация са били оценени, за да се тества предложения кинематиен модел за територията на България. Представеният скоростен градиент ясно показва увеличаване на преместванията от север на юг. Полученото поле на скоростите от GPS станции, за територията на България е анализирано и дискутирано в контекста на тектонични блокови модели. Изследването в настоящата статият се фокусира върху екстензионния регион на Южните Балкани , използвайки Global Positioning System (GPS) технология. Хоризонталните скоростите на север от Стара планина, потвърждават предположението, че територията на Северна България е част от Евроазиатската плоча. Нашите резултати показват, че южните Балкани не принадлежат към Евроазиатската плоча и се преместват от север на юг със скорост спрямо Евразия, постепенно увеличаващасе от 1.5-2 mm / год в Западна България до 10mm/yr в Гърция.

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1. INTRODUCTION

Since the launching, geodetic techniques for monitoring crustal motion, advanced satellite techniques and systems, including GPS, significantly simplified the procedure for determining the parameters of crustal motions since it allowed during a short period of time to receive precise of data that helped to determine with greater accuracy the parameters of crustal movement for definite time.

This paper covers an important topic, where GPS data has now been collected for enough years to be able to be used for reviewing plate movements. The main purpose of this article is to estimate and infer coordinates and velocity vectors of a set of stations, and to determine rotation parameters, using GPS data. For determination of Euler parameters the author accepts a set of GPS stations as stable and uses Least Squares Method. Different parameters of Euler pole have been estimated in least squares adjustment process on the base of obtained coordinates and velocities of several sets of GNSS permanent stations

The territory of Bulgaria and particular the region of Balkan Peninsula characterizes with active tectonics and seismotectonics. Repeated GPS surveys in Bulgaria provide a direct measurement of current crustal motions. GPS surveys have been carried out in this region since 1996.

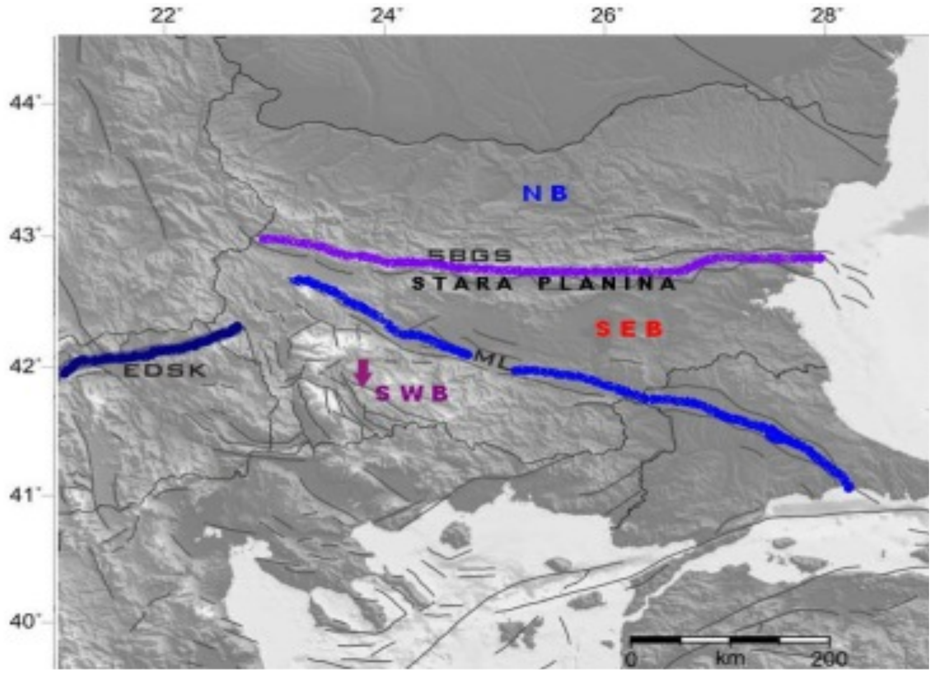

Figure 1. *Position fault from territory of Bulgaria and the part of Balkans, Southern Balkan Extensional Region (SBER) (Kotzev et al, 2008, Matev K., 2011) and Maritza lineament (ML) (Georgiev I., (2009)*

The horizontal crustal movement and seismicity have been studied by GPS analysis in (Burchfiel et al., 2006, Georgiev et al., 2013, Kotzev et al, 2008, Matev K., 2011).
The region of South Bulgaria, especially Southwest Bulgaria and Rhodopes Mountains and Northern Greece is an active tectonic and seismotectonic area in the South Balkans with proved recent active tectonic structures and crustal motions.
Based on these alleged boundaries, geological structures and faults, the author this article formed the contours of the blocks structure, in it research.
The GPS velocity fields are estimated and they are used to estimate the block rotation motions. Blocks rotations are discussed in details by the study of GPS measurements, geology structural, and seismicity and paleomagnetic measurement, which contribute to more precise and clear determination of the transition zone.

2. METHODS

The velocity field of blocks can be determined by their relative displacement field of stable point groups. According to rigid kinematics theory and regarding the crust as a rigid body, we can establish kinematics model.
Using the velocities v^x, v^y and v^z and the respective coordinates of the stations estimated by GPS, it is possible to estimate the rotation Euler vector (Ω_x, Ω_y, Ω_z) in a Least Square adjustment. Using the very well known Euler theorem, the movement of blocks can be described by Euler vector, and the vector can be gotten from the linearized observation equation for one station (Perez et al., 2003):

$$\mathbf{V} = \Omega.\mathbf{X}\text{, or} \tag{1}$$

$$\begin{bmatrix} v_i^x \\ v_i^y \\ v_i^z \end{bmatrix} = \begin{bmatrix} 0 & -\Omega_z & \Omega_y \\ \Omega_z & 0 & -\Omega_x \\ -\Omega_y & \Omega_x & 0 \end{bmatrix} . \begin{bmatrix} X_i \\ Y_i \\ Z_i \end{bmatrix} . \tag{2}$$

It is also possible to write an observation equation similar to eq. (2) based on the spherical coordinates and so also north, east and vertical components in velocity. Because of the poor precision of GPS in vertical direction, we discard v^u and only use east velocity v^e and north velocity v^n to compute $\mathbf{\Omega}$ (Xu Caijun et al., 2000)

$$\begin{aligned} v_i^n &= R.\sin\lambda_i.\Omega_x - R.\cos\lambda_i.\Omega_y \\ v_i^e &= -R.\sin\varphi_i.\cos\lambda_i.\Omega_x - R.\sin\lambda_i.\sin\varphi_i.\Omega_y + R.\cos\varphi_i.\Omega_z \end{aligned} \tag{3}$$

Here R is mean radius of Earth.
Ω_x, Ω_y, Ω_z are respectively angle velocity in coordinate axes X,Y,Z;
φ_i, λ_i are respectively longitude and latitude of the point i.
Euler vector parameters can be expressed by Ω_x, Ω_y, Ω_z:

$$\Omega = \sqrt{\Omega_x^2 + \Omega_y^2 + \Omega_z^2} \tag{4}$$
$$\Phi = \arcsin \frac{\Omega_z}{\Omega}$$
$$\Lambda = \arctan \frac{\Omega_y}{\Omega_x}$$

Here Ω is angle velocity and Φ , Λ are Euler polar coordinates.
The results and their precisions are showed in Table 3. We have estimated the Euler parameters of each block with v^e and v^n .

3. GPS DATE

Two different kinds of GPS networks are used to monitor and determine present-day displacements on the territory of Bulgaria and the Balkans.
The networks include observation from permanent stations IGS (http://igscb.jpl.nasa.gov/), and EPN sites (most of the IGS sites are part of EUREF), HemusNet and other permanent stations.

Figure 2. *Locations of IGS, EPN, HemusNet and other parmanent sites and BULREF point*

HemusNet permanent GPS network (http://www.hemus-net.org/) was established in 2007 under international project “Science for Peace Program”, NATO: SFP 981881 (Monitoring Crustal deformation in West Central Bulgaria and Northern Greece using GPS). The aim of the project is to provide basic infrastructure in both Bulgaria and Northern Greece for space-aided navigation, surveying, science, engineering, and atmospheric sensing. The network contains 8 permanent stations that cover West-Central Bulgaria and Northern Greece. Locations of the sites are presented on Figure 2

For purposes of the study data from 15 GNSS permanent stations are used as 8 of them are on the territory of Bulgaria, 2 permanent stations in Romania, 3 permanent stations in Northern Greece, 1 permanent station in North-East Turkey and 1 permanent station in Macedonia (Figure 2).

The second kind GPS data, who are used are campaigns measurements for the15 points (table 1) of the precise BULREF network, adopted for officially realization of ETRS89 in Bulgaria. The initial observations were carried out in two campaigns – 1992 and 1993 (Altiner Y. et al., 1996). Seven points from this network are officially accepted as extension of EUREF with accuracy class B. The points from the BULREF network were measured during the period 1993-2005, for the various projects and campaigns by several author's groups (Altiner et al., 1996, Kotzev V., et. al. 2001, Vasileva K. et. al. 2004, Georgiev I. et al. 2009).

Table 1. *BULREF stations using in campaign processing*

NAME	1992.7	1993.4	1996.74	1997.74	1998.74	2003.46	2005.0
PETR	X	X	X	X	X	X	X
HARM	X	X				X	X
GABR	X	X		X	X	X	X
VIDI	X	X				X	X
KAVA	X	X			X	X	X
SOFI	X	X	X	X	X	X	X
BURG	X	X		X	X	X	X
SAPA		X	X	X	X	X	X
SATO		X	X	X	X	X	X
GULI		X				X	X
SHUM		X		X		X	X
KERM		X				X	X
MAMA		X				X	X
BERK		X	X	X	X	X	X
PANA		X	X			X	X

To estimate current displacements, we have used data for the 15 BULREF points. GPS measurements carried out in 1996, 1997, 1998 within the frames of international project with Massachusetts Institute of Technology (MIT) (Geodynamic settings of Bulgaria in the active and young Near East-Balkan geotectonic system) (Kotzev et. al. 2001). In epoch 2005.0 this 15 points are observation, adjustment and include of the National GPS network-based class system ETRF2000 (Georgiev I., et al. 2005). Stations were processed with the same software, in the one same coordinate system ETRF2000. For the local movements of the stations, which are more important for their behaviour, the ETRF horizontal station velocity vectors have been obtained by applying ETRF components of the Eurasia plate rotation pole (Boucher, Altamimi, 2008) to the obtained ITRF2005 velocity vectors. Then they have been transformed into ETRF2000 (Atanasova M,. 2013a, . Atanasova M,. 2013b)

Table 2. *GPS coordinates and velocities and their mean square errors with respect to the stable Eurasian*

name	λ_i	φ_i	v^n	σ_{v^n}	v^e	σ_{v^e}	v	α
Block NB								
BUCU	26.1257	44.4639	-1.20	0.4	-0.12	0.4	1.20	185.71
VIDI	22.7334	44.0772	-1.00	0.4	-1.02	0.4	1.42	225.59
COST	28.4334	44.1639	-0.30	0.4	-0.20	0.4	0.36	213.70
BERK	23.1378	43.1095	-0.42	0.4	-0.83	0.4	0.93	243.19
SHUM	26.725	43.4878	-0.29	0.4	-0.81	0.5	0.86	250.33
GABR	25.2768	42.9629	-0.01	0.4	-0.13	0.4	0.13	265.64
GULI	24.6781	43.6029	-0.38	0.4	-0.55	0.4	0.66	235.38
KAVA	28.3734	43.4135	0.00	0.4	0.18	0.4	0.18	266.86
VATG	27.9093	43.1927	-1.95	0.4	0.89	0.5	2.14	155.45
Block SEB								
HARM	25.8463	41.8844	0.18	0.4	-0.12	0.4	0.21	146.29
KERM	26.3246	42.5185	0.10	0.4	-0.11	0.4	0.14	132.24
MAMA	26.7854	42.1041	-0.30	0.4	-0.25	0.4	0.39	219.82
PANA	24.1593	42.5947	-0.51	0.4	-0.13	0.4	0.52	165.69
PAZA	24.3400	42.2310	0.37	0.4	-0.54	0.4	0.65	124.39
BURG	27.4419	42.6664	-1.47	0.4	0.56	0.4	1.57	159.13
ISTA	29.0193	41.1044	-2.11	0.4	0.42	0.4	2.15	168.73
Block SWB								
SOFA	23.2685	42.6678	-1.81	0.4	0.70	0.4	1.94	158.84
SOFI	23.3947	42.5560	-1.97	0.4	0.30	0.5	1.99	171.33
DRAG	22.9335	42.9318	-1.70	0.4	1.82	0.4	2.49	133.02
KUST	22.7131	42.2837	-1.58	0.4	0.90	0.5	1.82	149.77
SAPA	23.2460	42.2817	-2.72	0.5	0.26	0.5	2.73	174.53
PETR	23.1247	41.4588	-3.71	0.5	0.61	0.5	3.76	170.65
SATO	23.9125	41.5981	-3.04	0.5	0.45	0.5	3.07	171.57
SAND	23.2678	41.5505	-2.82	0.4	-0.40	0.5	2.84	188.07
YUND	23.8538	42.0643	-2.06	0.4	0.28	0.4	2.07	172.25
ROGH	24.6872	41.6334	-2.47	0.4	0.31	0.5	2.48	172.84
ORID	20.7940	41.1273	-2.55	0.4	0.52	0.4	2.60	168.46
Northern Greece								
AUT1	23.0037	40.5668	-7.91	0.6	0.86	0.4	7.95	173.79
TEIS	23.5640	41.2476	-4.31	0.6	-8.20	0.5	9.30	208.08
LEMN	25.1805	39.8972	-11.7	0.5	-16.7	0.5	20.39	235.01

4. VELOCITY FILD

The obtained velocity field of the Earth's crust is represented by 30 points in Bulgaria and encompassing the region. (Figure 2).The results show southward displacements between 0.5-3.8 mm/yr. GPS results give detailed information on the displacements. The presented velocity gradient clearly indicates the increase of the motion from north to south and reaches the Hellenic arc with values of up to 30mm/yr. In concordance with the geological and seismological data, the results confirm the contemporary activity in the region.
The extensional zone passes through Central Bulgaria along an approximately east-west trend separating a northern region with insignificant motion relative to Eurasia from south-western region characterized by E-W extensional grabens and increasing southward velocities between 2 - 3mm/yr

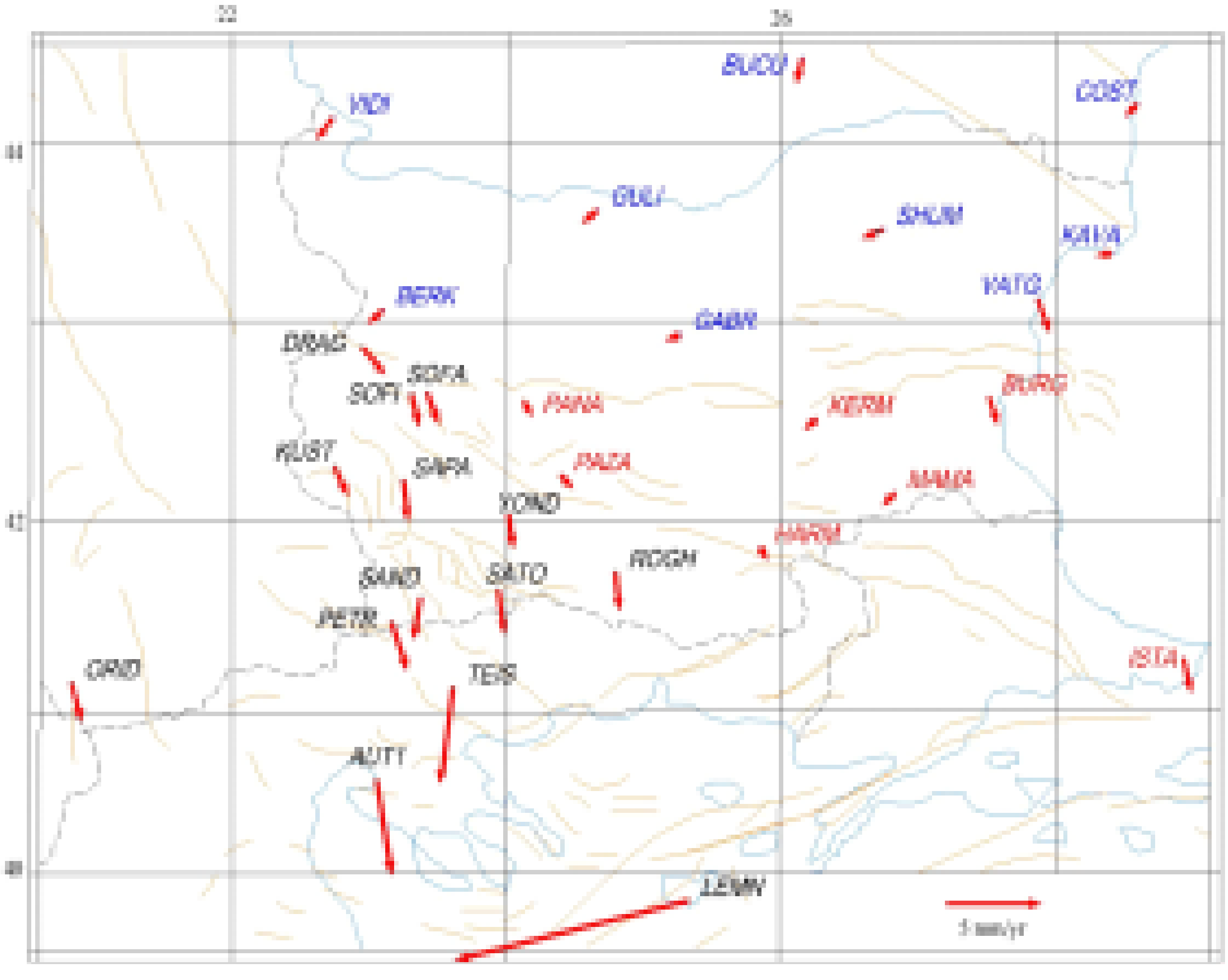

Figure 2. *The obtained velocities represented by 30 points in Bulgaria and the region Balkans.*

5. ESTIMATION OF THE EULER ROTATION VECTOR

Several different rotation poles covering different scale of areas have been tested to fit better with the observed velocities. As mentioned above, the zone of extension passes obliquely trough the east-west trending Stara Planina Mountain of central Bulgaria. By this reason two main sets are configured from all stations in Northern Bulgaria and two stations in Romania and respectively from all stations in Southern Bulgaria, Northern Greece and Northern Turkey and Macedonia. Obtained results for Euler pole (Φ, Λ, Ω) of all sets are given in Table 3

Table 3. *Euler Parameters of Blocks deduced from the velocities*

Name of Blocks	Euler Longtitude Λ ° E	Euler latitude Φ ° N	Ω °/Ma.
1.Northern Bulgaria - NB	31.57	39.00	0.138
2.Southern Bulgaria - SB	32.77	43.07	0.381
2.1 South-East - SEB	26.28	-43.03	0.438
2.2 South-West - SWB	11.13	-39.11	0.369
2.2.1. Block " SOFI"	19.13	-40.68	0.842
2.2.2. Block "PETR"	75.67	33.23	0.104

Using 9 GPS points the author suggest a Block to name NB, which reaches the Stara Planina Mountain of south. On Figure 2 is shown proposed NB block (red points) defined with Euler pole of rotation around 39.00°N/31.57°E with angular rate of 0.138 °/Ma.

First we tried to find a large single block SB, which consists of stations only in southern Bulgaria, Northern Greece and Northern Turkey and Macedonia, calculating rotation pole using 21GPS stations and the following parameters have been estimated: 43.07°N, 32.77°E, and 0.318°/Ma. The obtained misfits do not confirm the existence of rigid block, which is in agreement with the geological aspect that the SBER consists mainly of active normal faults (Burchfiel et al., 2008). The obtained misfits between the observed and model velocities are very big. The presented by the misfits results are not consistent with the proposed and clearly show that there is no rigid block which can perform the current displacement shown through our study as single stable block within such large area.

The author divided this large area into two small blocks and boundaries suggest that it passes through Maritza lineament passing NW-SE. The block situated east of the Maritsa lineament is named SEB and its boundaries to the north is Stara planina Mountain and the Black Sea to the east. With 7 GPS stations (blue points) located of SEB rotation pole (-43.03°N, 26.28°E, and 0.438°/Ma) relative to Eurasia is obtained. But for a few of the stations from block SEB it could be assumed that they also belong to the Eurasia plate. Therefore the results obviously show not quite clear distinction between the transition zones, which is also an assumption of other studies (Stangl, 2011).

The region of Southwest Bulgaria (SWB) has the most pronounced tectonic and seismotectonic activity on the whole Bulgarian territory (Shanov et al. 2001). The investigated area exhibits diverse relief structures, which are subjected to horizontal and vertical movements of various intensity. Southwest Bulgaria falls within a zone of contemporary extension of the Earth's crust with complex interaction between horizontal and vertical movements of the geological structures (Zagorchev, 2001).

Using 10 GPS stations (black points) on smaller areas in SWB and 2 GPS stations on NG territory, 1 GPS stations on territory Macedonia we estimated rotation pole -39.11°N, 11.13°E, and 0.369°/Ma respectively. With those areas the obtained misfits are between 0.09 mm/yr and 2..07 mm/yr These results still do not provide good fitting..

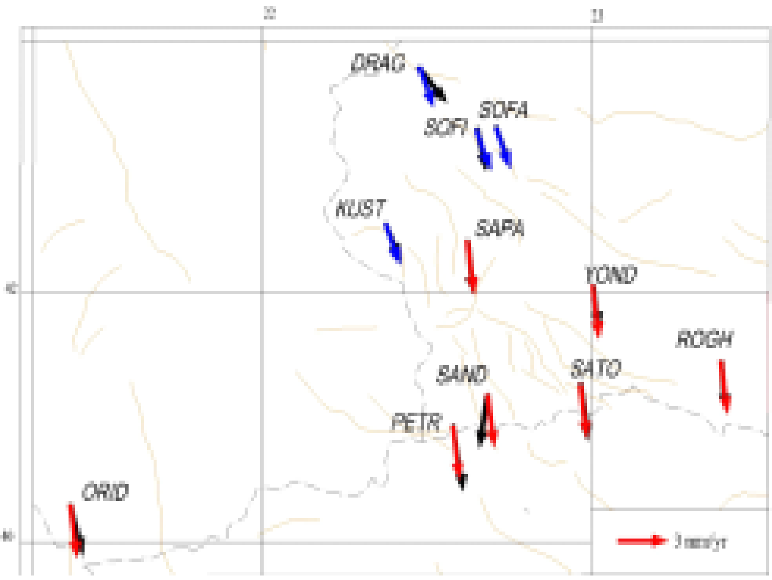

Figure 3. *Schematic mapping of block structure SWB inferred from GPS results. Black arrows show observed velocities. The red, blue arrows present the predicted model velocities for Block "SOFI" and, Block "PETR",*

The misfits decrease with the decreasing the scale of blocks area. We indicated 2 blocks that present better fitting between observed and model vectors - plotted on Figure 3. The estimated parameters of the rotation pole are listed in Table 3. A set of 4 points (DRAG, SOFA, SOFI, KUST) are used to define a block corresponding to the observed velocities (SWB blok "SOFI") and a set of 7 points (PETR, SAND, SAPA, SATO YOND, ROGH, ORID) are used to define a block corresponding to the observed velocities (SWB block "PETR")
The smaller on block size gives better fitting between observed and model velocities
These results obtained by analysis of GPS data set are in agreement with the obtained by result of other scientists (Georgiev et al., 2011, Matev K., 20111)

6. CONCLUSION

The GPS velocity fields are estimated and they are used to estimate the block rotation motions. Blocks rotations are discussed in details by the study of GPS measurements, geology structural, and seismicity measurement, what contribute to more precise and clear determination of the transition zone.
The obtained velocities from the GPS data processing indicate an overall motion to the south. The results show an increasing rate from 1-1.5 mm/y in Central-west Bulgaria to 10 mm/y for the Northern Greece confirming the north-south extensional regime in the region. The

horizontal velocities in North Bulgaria, confirm the suggestion that North Bulgarian territory is part of the Eurasian plate. From the analysis of the obtained parameters of the Euler rotation poles it can be assumed that excepting, the North Bulgarian territory and probably a small part of the central-eastern Bulgaria belong to the Eurasia plate Our results show that the Southwest Bulgaria do not belong to the Eurasian plate and seem to be dragged toward the south with the velocities relative to Eurasia gradually increase in N-S direction from 1.5 mm/yr in western Bulgaria to 10mm/yr in the Northern Greece.

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BIOGRAPHICAL NOTES

Assistant Professor Mila Atanasova-Zlatareva
Since 1998 I study the global and local coordinate systems and coordinate transformations for the Bulgarian territory. In October 2013 I obtained a PhD degree on thesis "Transformations models in contemporary geodetic coordinate systems". My studies are focused on application of GPS technology in geodesy and geodynamics. This includes determination of plate motions, deformation analysis and GPS data processing. Up to now I have 12 publications. Since 2010 I am visiting assistant lecturer at the University of Architecture, Civil Engineering and Geodesy, Sofia.

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