GNSS Monitoring of Geodynamics in the Region Around Sofia and South-Western Bulgaria

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Abstract: For more than 25 years, the monitoring of geodynamic processes with modern GNSS technology in the region of Sofia and Southwestern Bulgaria continues. To investigate modern crustal motions in the area, Global Positioning System (GPS) data obtained between 1996 and 2022 are analyzed to obtain the velocity field for southwestern Bulgaria. For this period, monitoring covered 28 stations. The active strain in the region is also estimated from analysis of the results for velocity solutions. Some correlation between modern earth crust movements, seismic events and tectonic structures is established. The obtained results in a general way confirm previously data, but with much better accuracy and details at local level. The results can be used for a detailed geodynamic and geological study of the active fault structures in the area.

1 INTRODUCTION

The area around Sofia and Southwestern Bulgaria is characterized by a large number of active geological fault structures, and the presence of tectonic and seismic activity predetermines the development of dangerous geodynamic processes. These processes have the greatest impact on the changes (deformations) of the geodetic networks built specifically for their study. Using GNSS technology for estimating natural destructive processes provides specific quantitative values of recent crustal movements. The area of interest of this study is limited to the north by the southern slopes of Stara Planina, to the south to the border of Bulgaria with Greece, to the west - the western border of Bulgaria and to the east - the beginning of the Upper Thracian Plain (Fig. 1). The historical review of earthquake activity shows that a significant number of strong earthquakes have been recorded in the Sofia area. The above shows the social importance of the studied territory and the need to obtain geodetic data on its current geodynamic activity in order to assess the geological hazard. The main goal of the geodynamic monitoring is to clarify the geodynamic setting of the region and behavior of suggested active faults.

2 GPS NETWORK AND DATA

For more than 25 years, the monitoring of geodynamic processes with modern GNSS technology in the region of Sofia and Southwestern Bulgaria continues. In order to study the modern crustal movements in 1996, a geodynamic network was built in the area around Sofia, covering SW Bulgaria. The network is designed for high-precision GNSS measurements, determination of coordinates and velocities of points, calculation of active stress in the area and long-term monitoring geodynamic processes. The points are stabilized so that the grid covers the main tectonic structures in the area. The first GPS measurements of the Sofia Geodynamic Network were made in 1996. GPS measurement of all points of the network with processing and analysis of the results first been performed only in two epochs 1997 and 2000 (Kotzev et al., 2001, Kotzev et al., 2006). A new comprehensive measurement of the geodynamic network was accomplished in the summer of 2020 (Dimitrov and Nakov, 2020, Dimitrov and Nakov, 2022). A new campaign was performed in the summer of 2021. Three additional points were measured – BELM, SATO and LOZ2 (Fig. 1). Point BELM was measured previously in 1997 and 2020, point SATO was measured in 1996 and 2003. Because the original point LOZE was

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destroyed after the measurements in 2000, in 2021 we measured the duplicating point LOZ2, which was measured in 1997 but with shorter period of observation. In this reason the obtained result for velocity of this point has greater error, but still is reliable (Dimitrov and Nakov, 2021). In the summer of 2022, we measured the next epoch at 9 network points. These points now have at least four measurement epochs over a period of 25 years. The epochs of all GPS measurements included in this study are shown in Table 1.

3 VELOCITIES AND STRAIN RATE ESTIMATION

The measurements were processed/reprocessed in a two-step procedure using the GAMIT/GLOBK software v10.71 (Herring et al., 2015, Herring et al., 2018) to ensure the quality and homogeneity of the solutions. In the first step, loosely constrained estimates of station coordinates, Earth orientation, orbital parameters, and atmospheric zenith delays were determined using GAMIT. Major models and parameters used in GAMIT GPS data processing are given in Table 2.

Table 1: Epochs of GPS measurements.

Point		Year of measurements										number
ID	1996	1997	2000	2001	2002	2003	2004	2012	2017	2020	2021	2022	of epochs
BANK		*	*					*		*			4
BELI		*	*							*			3
BELM		*	*								*		3
BERK		*	*	*						*			4
BOGS		*	*	*			*			*			5
BOSN		*	*				*			*			5
BUHO		*	*							*			3
CARV		*	*				*			*		*	5
DELA		*	*				*			*		*	5
DOB1	*	*	*	*						*		*	6
DSEC		*	*							*			3
FROL		*	*							*			3
GURM						*				*			2
KRAL		*	*				*	*		*		*	6
LOZ2		*									*		2
MALC		*	*							*		*	4
MECH						*				*			2
MUHO		*	*							*			3
PADA		*	*							*			3
PLA1		*	*	*		*		*	*	*	*		9
SATO	*					*					*		3
SLI1		*	*							*			3
SOFI		*	*	*	*	*	*	*	*	*	*	*	11
VERI		*	*							*		*	4
VETR		*	*							*		*	4
VITI		*	*							*			3
VLAD		*	*	*						*			4
ZEME		*	*							*		*	4

Table 2: Major models and parameters used in GAMIT GPS data processing.

Cutoff angle and data weighting	10º, depending on the elevation angle
Data sampling and data weighting	30 s for data editing, and 120 s for parameter estimation
Antenna phase center	IGS ANTEX files to correct absolute PCVs of satellite and receiver
Ionospheric refraction	Iono-free linear combination
Troposphere refraction	VMF1 for dry delay and parameter estimation in 2-hour intervals for wet delays. Troposphere horizontal gradients in 24-hour interval are estimated. Atmospheric tidal loading corrections VMF1.
Ocean tide	FES2004 model [12] with correction for the center-of-mass motion
Solid Earth tide, pole tide	Models recommended by IERS Conventions 2010

In the second step, a global Kalman filter was applied using GLOBK, to the combined, loosely constrained solutions and associated covariances in order to estimate a consistent set of station coordinates and velocities. Six parameter transformation was estimated by minimizing the horizontal velocities of 10 globally distributed IGS stations with respect to the IGS14 realization of the ITRF2014 reference frame (Altamimi et al., 2016). In the region is located the IGS station Class A – SOFI which is included in the estimation and analysis. The obtained results for the velocities of the point from geodynamic network are shown in Fig. 1.

In the analysis we examined the time series for all of the stations, removing obvious outliers and further

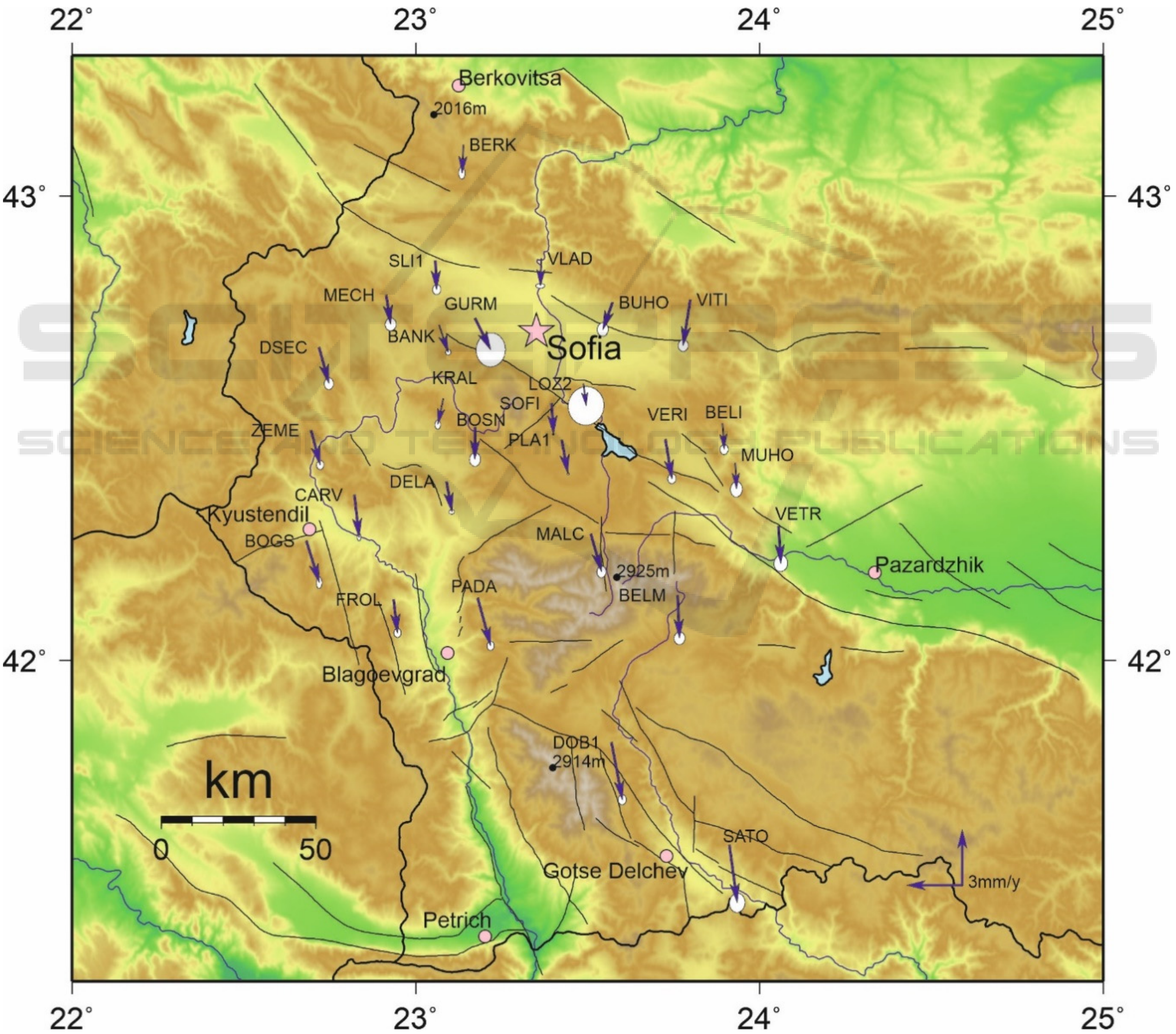
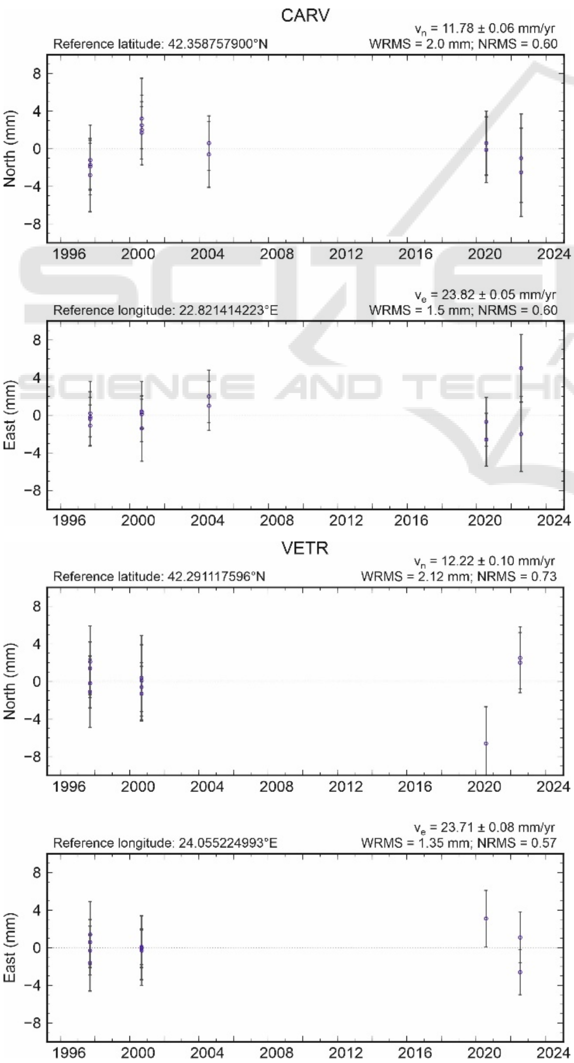


Figure 1: Horizontal GPS velocity with respect to Eurasian plate with 95% confidence. Slim lines show suggested active faults in the area. The topography is shown from green to brown – lower to higher elevation. The elevation of the highest peaks in the area is given in meters.

downweighting those for which the normalized root-mean-square (nrms) was greater than 0,7. Four of these time series are shown in Fig. 2. It should be noted that unlike full velocity solution, the time series do not account rigorously for all correlations.

For this study all measurements were reprocessed with the GAMIT/GLOBK software, to obtain loosely constrained daily solutions saved in SINEX (Solution Independence Exchange format). For estimation of strain rate, the QOCA software (https://qoca.jpl.nasa.gov/) is used to model site displacements, which involve all the campaign sites. We use velocities adjustment in strain rate analysis. Coseismic jumps and post-seismic deformations are removed in the time series. Principal strain axes of the horizontal strain rate tensors are estimated over the Delaunay triangles (Fig. 3).



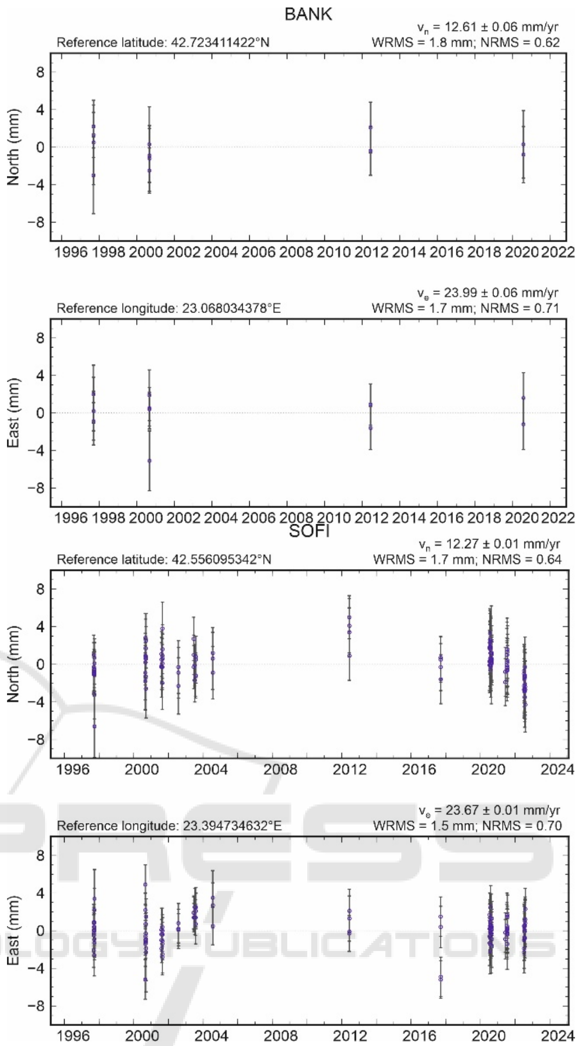


Figure 2: Long-term repeatabilitie of the horizontal station positions.

4 DISCUSSIONS

The present-day geodynamics of the area as well as the entire territory of South-West Bulgaria is defined by the neotectonic extensional processes in the South Bulgarian Extensional Region (Burchfiel et al., 2000), part of the broad East-Mediterranean – Balkan Extensional system. Presently, based on geological data the extension is suggested to be in a general N-S direction, which results in tectonic structures with general trend NW-SE to E W (Dimitrov and Nakov, 2020). For a period of more than 25 years the monitoring has covered 28 stations. They have been measured in different years and in different number of campaigns (Table 1). Despite the different number of measurements, the obtained results are quite

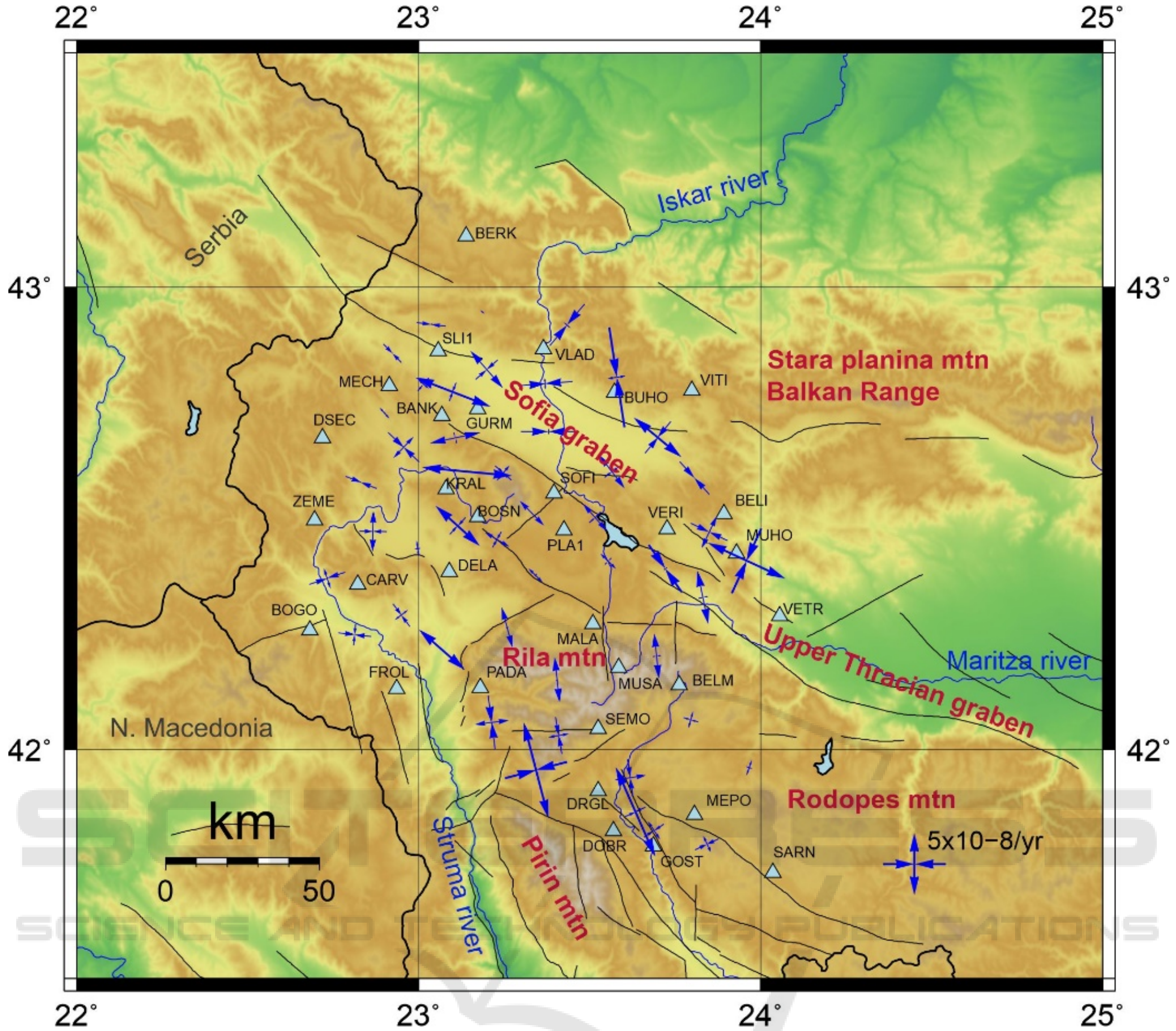


Figure 3: Topography (brown elevated areas, green low lands) and suggested active faults with black lines (Barrier et al., 2004) with principal axes of the horizontal strain rate tensor with blue arrows.

homogeneous in the different deposits of the studied territory and show clear uniform trends. In this regard, the velocities of stations PLA1 and SOF1 with the largest number of measurements, which suggests very high reliability, do not differ significantly from the surrounding stations.

Recently obtained velocities are extremely reliable because theirs 3σ errors are very small. All velocities are in southern direction. All velocities clearly exceed 1.5 - 2 mm/y reaching up to 3 - 4 mm/y. They are in the limits of 1.5 mm/year up to slightly over 3 mm/year, almost reaching 4 mm/year (stations DOB1, SATO). The velocities of the stations tend to increase from north to south, passing through an intermediate locality, clearly increasing in the southernmost part of the country.

This velocity field motivates N-S expressed extension with increasing rates from North to South. The difference in the velocity rates tends to change along geologically suggested active fault zones. This result point to the significance of the GPS monitoring for the identification and evaluation of active faults.

5 CONCLUSIONS

The newly acquired velocities from three campaigns 1997, 2000, 2020, 2021 years, complemented with the new results from 2022 confirm that the general tendency of movement of the stations in the region of Central West Bulgaria is in the south direction with respect to stable Eurasia. The velocities tend to increase from north to south. This pattern is in agreement with the extensive movement of southern Bulgaria and northern Greece.

The results obtained for the strain rate show that the strain field is not uniform in direction and intensity. In the area located to the north of the Sub-Balkan fault (north of Sofia graben) dominates the compression strain. However, the limited number of stations may require further observations for more accurate results. The intermediate area is characterized by the NW-SE trend of the strain with dominating extension. The southernmost area is characterized by a general NNW – SSE (almost N-S) direction of the extensional strain and higher values compared to the northern area.

The newly obtained results in a general way confirm previous data, but with much better accuracy and details at local level and can be used for a detailed geodynamic and geological study of the area. Further extension of geodynamic network will provide new details on the geodynamics of the area.

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