UNIVERSITY OF ARCHITECTURE, CIVIL ENGINEERING AND GEODESY

FACULTY OF GEODESY

Research and Analysis of Horizontal Crustal Deformation for the Territory of Bulgaria Based on GNSS Data

Marineli Dancheva
mpdancheva@gmail.com

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ABSTRACT

This research is focused on analyzing the horizontal intraplate crustal motions of the territory of Republic of Bulgaria, derived from GNSS solutions. It aims to demonstrate the possibility of practical realization of European Terrestrial Reference System 89 (ETRS89) for the mentioned territory. For this purpose the behavior of 30 permanent GNSS stations, representing one of the licensed CORS networks on the territory of Republic of Bulgaria is analyzed. GNSS measurements with duration of 8 days from three campaigns are used (April 2014, 2016 and 2018). Considering the long distance between the stations from the network, the determination of their coordinates and velocities is implemented in Bernese GNSS Software v5.2. A processing strategy is defined, based on the most contemporary concepts, proposed by the International GNSS Service – IGS. As a result, high precision coordinates and velocities of the stations are obtained. The adjusted coordinates and velocities are transformed into European Terrestrial Reference System – ETRS89, whereat in addition to the obtained absolute velocities in ITRF2014 - relative velocities are derived. The assessment of the horizontal velocities and deformation axes provides information on the location of fault and block-defined structures of the earth's crust, illustrated by graphical representation. The resulting deformation axes allow localization of anomalous areas and an evaluation of the current activity of the tectonic structure. The estimated horizontal velocities of the stations have not only scientific, but also highly applicable significance in terms of determination of real station coordinate for the epoch of observation. A comparison between the results of the current analysis and existing geological data is made, as consistency between them is proven.

Keywords: ETRS89, GNSS, deformation, intraplate velocities

Contents

1. Introduction

The territory of Bulgaria is located near the edge of the Eurasian plate, which is an indication of active tectonics and seismotectonics. Many studies have been conducted over the years, some of which conclude that the territory is divided into several micro-plates. The intra-plate velocities of the southern micro-plates in Bulgaria are up to several times higher than those of the northern ones. For many years the determination of these velocities was a challenge. Nowadays, thanks to the presence of Continuously operating reference station (CORS) networks and modern GNSS methods of measurement and analysis, it is possible to monitor crustal motions with high accuracy and precision.

The aim of this study to determine and understand horizontal velocity model for the territory of Bulgaria, derived from ETRS89 coordinates and velocities of a CORS network. For reliable analysis on intraplate crustal motions, it is required that the coordinates and velocities of each station from the network are obtained with very high accuracy. Therefore, the results are based on a solution for 30 permanent GNSS stations with precise coordinates and absolute velocities derived by using the scientific product Bernese GNSS Software v5.2. For the first time in the geodynamical studies for the territory of Bulgaria is used such a dataset of 30 evenly distributed stations comprising the whole country.

The final analyses are based on velocities relative to the Eurasian plate. Since the rotation of the Eurasian tectonic plate is excluded, analyses on the intraplate horizontal motions can be conducted. Horizontal velocity field is defined.

2. GNSS data processing and analysis

2.1 Definition of output data

For the purpose of this research the behaviour of 30 permanent GNSS stations, evenly covering the country is being analysed. The data used is obtained from 3 measuring campaigns, conducted at same period (23-30 April 2014, 23-30 April 2016 and 23-30 April 2018) as the duration of each of them is 8 days. The data provided is raw 24-hour RINEX format files with 30 sec sampling rate for each station in each campaign, antenna information (type, offsets, etc.) and receiver information for each site.

2.2 Strategy for precise GNSS data processing

In consideration of the long distance between the stations and in order to ensure best possible solution for coordinates and velocities of the stations, a baseline network adjustment has been performed using the Bernese GNSS Software v5.2. Bernese GNSS Software v5.2 is a scientific package developed at the Astronomical University of Bern, Switzerland and is used in the processing of global and regional networks. The software meets highest quality standards for geodetic and further applications based on GNSS. Moreover, it meets the most up-to-date requirements for accuracy and reliability of the results which are obtained using the most effective ambiguity resolution strategies.

Before using the Bernese GNSS Software, a specific processing strategy, in accordance with the aim of the research, has to be defined. The current strategy has been implemented in correspondence with the latest and most advanced concepts in processing of regional networks, recommended by EUREF, namely:

- the reference system in which the initial results were obtained is International Terrestrial Reference System (ITRS) at its realization - ITRF2014;
- code and phase observations on both frequencies are processed;
- single and double carrier phase differences are simultaneously processed with application of ionosphere models
- absolute antenna phase centre variations models are used;
- precise satellite ephemerides, clock data, Earth orientation parameters (EOP) are used;
- in the ambiguity resolution, successive floating and fixed solutions are obtained as initially the uncertainties being treated as unknown parameters and their values evaluated as real numbers using statistical tests of their covariance matrices;
- for obtaining a final solutions the normal equations for all daily solutions are combined to evaluate the coordinates and actual tectonic velocities of all stations. The concept of minimum constraints on fiducial stations is used;
- The EPN stations used are: Bucuresti (BUCU), Kiev (GLSV), Graz (GRAZ), Matera (MATE), Mendeleevo (MDVJ), Kirkkonummi (METS), Onsala (ONSA), Sofia (SOFI), Koetzting (WTZR) and Zimmerwald (ZIMM), considering their official coordinates and velocities.

2.3 Some remarks on the formulation of the strategy for accuracy improvement

2.3.1 Precise ephemerides and reference frame

For the precise data processing are used precise satellite ephemerides, delivered by the CODE ftp server. Additional data, such as atmospheric models, earth rotation parameters, clock corrections etc., is used. Without such data is impossible to achieve high accuracy in processing long vectors. When using IGS products, the station coordinates are being obtained in ITRS. In order to obtain optimal coordinates and velocities, it is recommended to provide a connection between ITRF stations and the processed network during processing itself. The applied method for this is to tightly constrain the coordinates of the selected stations to their ITRF values for the middle of the observation period.

2.3.2 Rotational Pole of the Eurasian Tectonic Plate and the steady part of Europe

For the network stations, a priori annual yearly tectonic velocities are derived from the NUVEL-1A-NNR. Thus, the movement of the stations due to tectonic motion, tides in the hard earth crust and ocean tides is modelled.

It is recommended that the NUVEL-1A-NNR rotational velocity is replaced by that determined by ITRF2000 in the transformation formulas between ETRS89 and ITRS.

2.3.3 Troposphere

Specific attention is paid to the impact of the troposphere, as tropospheric refraction and multipath effect can cause significant deterioration in the observation quality, especially low above the horizon. A tropospheric model for tropospheric gradient evaluation is estimated for each network station. A weight function, developed by CODE, is used. It depends on the height of the observed satellite. Also, CODE develops a function to measure the impact of tropospheric delay at low altitudes above the horizon.

Thus, by using weights dependent on the height of the satellites, the accuracy of the determined vertical component is significantly improved.

2.3.4 Antennas

The correct input of each antenna type for each station is essential due to offset and variation of the phase center of the antennas. Also, the measured pseudo-ranges are corrected with the displacement of the phase center as well as its variations. Absolute models of offset variations of GNSS phase antenna centers are used. They are obtained from the ANTENNA EXchange format files provided for free download from the IGS website.

2.3.5 Ambiguity resolution strategy

There are numerous strategies for fixing the ambiguities, depending on the length of the vectors. The strategy used here is the so-called Quasiionosphere-Free strategy (QIF), which analyzes and fixes observations simultaneously on both L1 and L2 frequencies, as well as uses the ion-free linear combination L3. The baselines are comprised of the OBS-MAX strategy, which selects an optimal combination of independent vectors, taking into account maximum number of simultaneous observations and minimum distance between stations.

3. Results

The daily solutions for each day from the three campaigns are obtained as the coordinates of the permanent stations are estimated for the middle of the observation epoch. Normal equations are combined from the daily solutions for each individual campaign, as the obtained coordinates for the permanent stations are estimated for the middle epoch for the individual campaign. Thus station coordinates for each of the campaigns - for 2014, 2016 and 2018 - are obtained.

These coordinates are obtained in the latest implementation of the International Terrestrial Reference System, ITRS - ITRF2014 and brought to the middle epoch of each measurement campaign - YYYY.MM.DD 00:00:00 hours.

A final network solution is obtained by combining the normal equations of all daily solutions (with data from the three campaigns for the period 2014-2018), giving coordinates and station velocities in ITRS coordinate system, realization ITRF2014.

The RMS error of the final combined network solution, as well as for the network processing of each campaign, is presented in the following table:

Table 1. RMS Error

RMS Error, [mm]			
Campaign April 2014r.	Campaign April 2016r.	Campaign April 2018r.	Final Solution for the period 2014-2018r
1.44	1.40	1.51	2.16

The results are shown on Table 2.

Table 2: Coordinates (2a) and velocities (2b) of the stations in ITRS, ITRF 2014, eph. 2010.0

Station №	X, [m]	Y, [m]	Z, [m]	mx, [m]	my, [m]	mz, [m]
100	4248897.6247	2103368.7192	4252768.3888	0.00014	0.00008	0.00014
101	4199905.8237	2156615.6703	4274151.2974	0.00013	0.00008	0.00014
102	4068599.4815	2212190.2610	4370982.6786	0.00034	0.00021	0.00035
103	4314502.6219	2072139.2397	4201953.8955	0.00015	0.00009	0.00015
104	4137766.5888	2189470.6821	4317625.2131	0.00013	0.00008	0.00014
105	4218174.6429	1874640.1057	4387010.7851	0.00014	0.00008	0.00014
106	4341530.3019	1997851.4185	4211110.2697	0.00016	0.00009	0.00015
107	4183336.8921	2201319.6056	4267631.0890	0.00014	0.00008	0.00014
108	4375001.8836	1923051.0886	4210717.6356	0.00015	0.00009	0.00015
109	4360742.6694	1823032.5321	4269166.5730	0.00016	0.00008	0.00015
110	4093424.6863	2161021.3282	4373678.8568	0.00014	0.00009	0.00015
111	4283628.4360	1919687.0128	4304706.3534	0.00016	0.00009	0.00015
112	4328995.5329	1887446.3406	4274069.3654	0.00014	0.00008	0.00014
113	4265868.6472	1971643.7542	4298529.0167	0.00016	0.00009	0.00015
114	4158028.5457	2119814.0739	4332798.6712	0.00013	0.00008	0.00014
115	4307578.6623	1846494.7079	4312558.8202	0.00014	0.00008	0.00014
116	4246010.1461	1897787.3499	4350302.6567	0.00014	0.00008	0.00014
117	4264924.6412	1830366.1861	4360658.6313	0.00013	0.00007	0.00014
118	4235209.4623	1786946.6730	4406908.7219	0.00014	0.00008	0.00014
119	4209631.9640	2081711.8516	4301803.2587	0.00014	0.00009	0.00014
120	4251394.3161	2039679.8533	4280885.4827	0.00013	0.00008	0.00014
121	4076970.3233	2100835.1231	4417562.1113	0.00013	0.00008	0.00014
122	4287501.3210	2049951.0044	4239994.6381	0.00014	0.00008	0.00014
123	4234714.9141	1949342.2571	4338663.9350	0.00014	0.00008	0.00015
124	4144415.0447	2068492.9380	4370394.1375	0.00013	0.00008	0.00014
125	4142643.4378	2016133.5732	4396064.0026	0.00013	0.00008	0.00014
126	4207110.8353	2018169.5946	4334110.4784	0.00016	0.00010	0.00015
127	4185302.5802	1962741.0117	4379874.7569	0.00013	0.00008	0.00014
128	4301266.5033	1982685.7434	4257880.8853	0.00014	0.00008	0.00014
129	4312694.0875	1950083.5795	4261393.0010	0.00015	0.00008	0.00015

a

Station №	Vx, [m]	Vy, [m]	Vz, [m]	mvx, [m]	mvy, [m]	mvz, [m]
100	-0.0187	0.0176	0.0110	0.00005	0.00003	0.00005
101	-0.0196	0.0170	0.0096	0.00005	0.00003	0.00005
102	-0.0204	0.0167	0.0028	0.00011	0.00007	0.00011
103	-0.0187	0.0184	0.0101	0.00006	0.00003	0.00006
104	-0.0205	0.0168	0.0096	0.00005	0.00003	0.00005
105	-0.0179	0.0172	0.0088	0.00005	0.00003	0.00005
106	-0.0165	0.0197	0.0107	0.00006	0.00003	0.00006
107	-0.0201	0.0173	0.0084	0.00006	0.00003	0.00006
108	-0.0157	0.0199	0.0091	0.00006	0.00004	0.00006
109	-0.0161	0.0188	0.0090	0.00007	0.00003	0.00006
110	-0.0197	0.0163	0.0089	0.00005	0.00003	0.00006
111	-0.0169	0.0179	0.0097	0.00006	0.00003	0.00006
112	-0.0161	0.0184	0.0085	0.00006	0.00003	0.00006
113	-0.0181	0.0182	0.0090	0.00006	0.00003	0.00006
114	-0.0197	0.0167	0.0083	0.00005	0.00003	0.00005
115	-0.0173	0.0183	0.0086	0.00005	0.00003	0.00005
116	-0.0175	0.0173	0.0091	0.00005	0.00003	0.00006
117	-0.0170	0.0178	0.0096	0.00005	0.00003	0.00005
118	-0.0182	0.0174	0.0068	0.00005	0.00003	0.00005
119	-0.0190	0.0174	0.0091	0.00006	0.00003	0.00006
120	-0.0185	0.0178	0.0098	0.00005	0.00003	0.00005
121	-0.0197	0.0161	0.0080	0.00005	0.00003	0.00005
122	-0.0180	0.0183	0.0102	0.00005	0.00003	0.00005
123	-0.0193	0.0170	0.0101	0.00006	0.00003	0.00006
124	-0.0194	0.0162	0.0086	0.00005	0.00003	0.00005
125	-0.0217	0.0155	0.0086	0.00005	0.00003	0.00005
126	0.0591	0.0482	-0.2012	0.00007	0.00004	0.00007
127	-0.0195	0.0173	0.0087	0.00005	0.00003	0.00005
128	-0.0176	0.0183	0.0095	0.00005	0.00003	0.00006
129	-0.0174	0.0185	0.0091	0.00006	0.00003	0.00006

b

3.1 Quality control

3.1.1 Quality verification of the solution

In order to minimize the inaccuracies in the course of work, particular attention is paid to the control and validation of the results. In order to obtain reliable end products, every step is being checked. Some of these steps will be presented below.

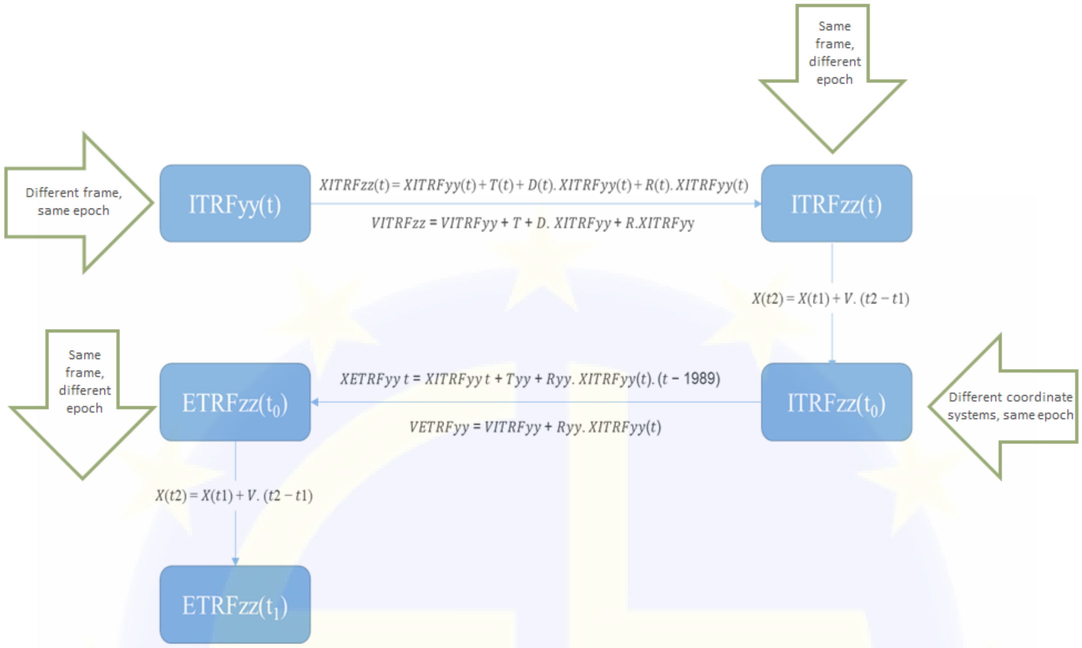
For the control and quality of the daily solutions, a Helmert transformation is applied between the coordinates of the reference stations with known coordinates in ITRF2014 and the obtained from the free-constraints. The accuracy assessment is based on the estimated root-mean-square deviation in plane position (North and East) and Up / Height (Up) of these stations.

3.1.2 Coordinate transformation

Any analysis associated with the motion of points located on the Eurasian tectonic plate, should be conducted in European Terrestrial Reference System – ETRS89.

Through known transformation parameters and velocities, the coordinates of the 30 stations are transformed into the European Terrestrial Reference System ETRS89, realization ETRF2005. A short representation of the steps for transformations of these coordinates is given on the Figure 1. For coordinate transformations from ITRF2014 to ETFR2005 are use the velocities obtained in Bernese v5.2.

Figure 1. Coordinate transformation scheme between ITRFyy(t) and ETRF(t_1)



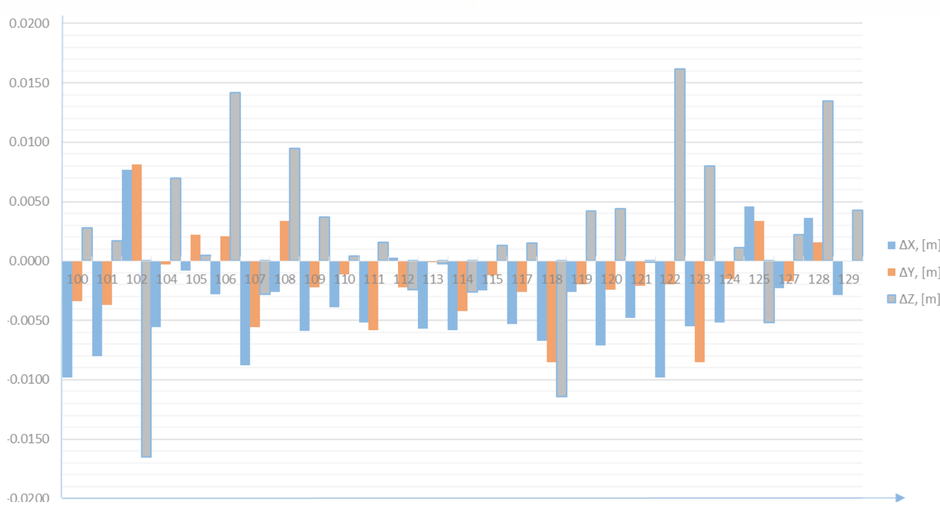
3.1.3 Coordinates quality control

A comparison of the ETRS89 coordinates for each campaign (2014, 2016 and 2018) is made. The aim is to draw conclusions about problematic stations.

The analysis found that a change of station 126 was done between April 2014 and April 2016, after which its values show consistency. That's why the station is excluded from the 2014 campaign processing. Therefore, in the processing for the calculation of velocities and horizontal deformations, this station will only be included in the campaign processing 2016-2018.

Figure 2 presents a graph for visual interpretation of the results.

Figure 2. Coordinate differences derived by comparison of station coordinates along axis X, Y and Z

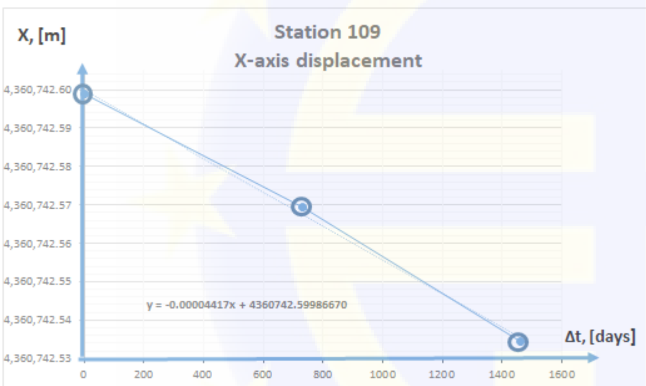


3.1.4 Velocities quality control

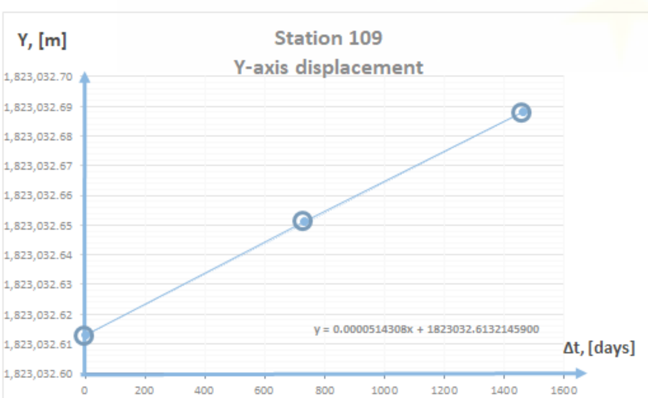
A verification of absolute velocities is performed based on comparison of the results obtained by two independent methods. The first one is processing the velocities in Bernese v5.2 software. The second – by estimating linear independence between variables – time and displacement for axis X, Y and Z. This calculation leads to finding a regression line for movement of each point on the respective axes. The regression line is used to calculate the velocity of axial displacement. A comparison between velocities obtained in Bernese v5.2 and these calculated by regression line in MS Excel is made. The aim is to check whether the results obtained for the direction and the magnitude of the points correspond to the published data for Eurasian movement.

A displacement graph and subsequent estimation table for station 109 are presented on figure 3.

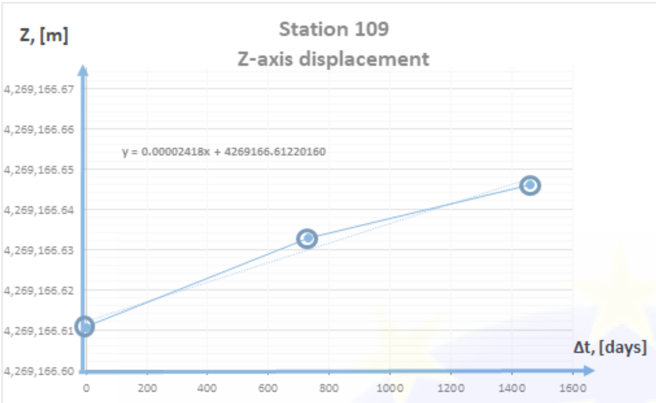
Figure 3. Regression line and station coordinates for station 109



№	X [m]		
109	2014	2016	2018
	4360742.5989	4360742.5695	4360742.5344
regression line	4360742.5999	4360742.5676	4360742.5353
Δt, [days]=	0	731	1461
ΔX, [mm]=	-64.5		
V=	-0.04417	mm/day	
V=	-16.1	mm/yr	
V=	-0.01612	m/yr	
V_0=	-1.0	mm	
V_1=	1.9	mm	
V_2=	-1.0	mm	
[v]=	0.0	mm	
[vv]=	5.615		
m_v=	1.37		



№	Y [m]		
109	2014	2016	2018
	1823032.6130	1823032.6513	1823032.6881
regression line	1823032.6132	1823032.6508	1823032.6884
Δt, [days]=	0	731	1461
ΔX, [mm]=	75.1		
V=	0.051	mm/day	
V=	18.8	mm/yr	
V=	0.01877	m/yr	
V_0=	-0.3	mm	
V_1=	0.5	mm	
V_2=	-0.3	mm	
[v]=	0.0	mm	
[vv]=	0.389		
m_v=	0.36		



№	Z [m]		
109	2014	2016	2018
	4269166.6107	**4269166.6329**	**4269166.6460**
regression line	4269166.6122	4269166.6299	4269166.6475
Δt, [days]=	**0**	**731**	**1461**
ΔX, [mm]=	35.3		
V=	0.024	mm/day	
V=	8.8	mm/yr	
V=	0.00883	m/yr	
V_0=	-1.5	mm	
V_1=	3.0	mm	
V_2=	-1.5	mm	
[v]=	0.0	mm	
[vv]=	13.728		
m_v=	2.14		

3.2 Velocity models

3.2.1 Definition of absolute velocities

The final geocentric coordinates are transformed to UTM, zone 35N. This aims to ensure good visual perception, geometric accuracy and practical significance of the results. Further, in to avoid reduction in the estimated velocities and their directions, due to the projection, the velocities for each axis (X,Y,Z) are transformed to topocentric velocities (v_E, v_N, v_U). For the purpose of this transformation is used GRS80 ellipsoid. The velocity vector is estimated using the following formulas:

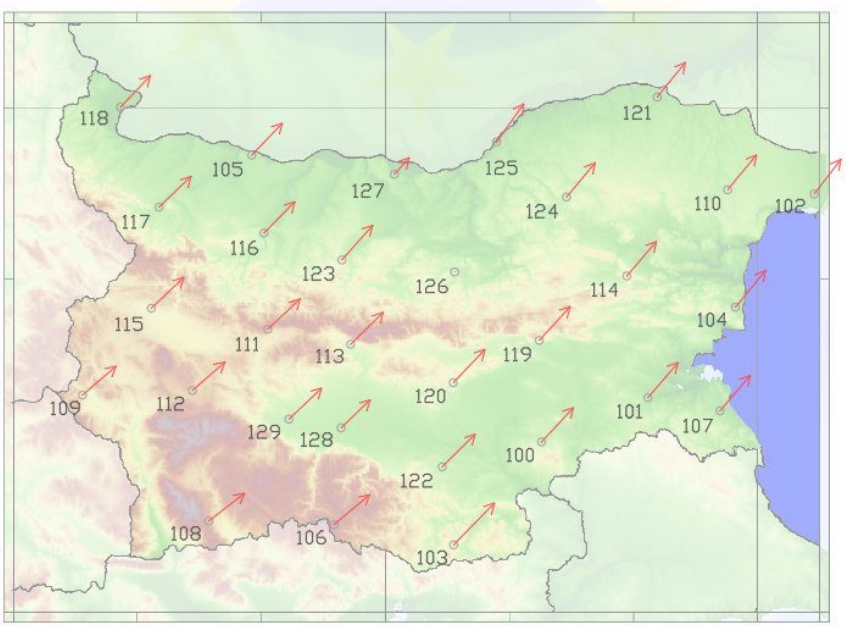
$$v_E = -v_X.\sin L + v_Y.\cos L \tag{1}$$

$$v_N = -v_X.\cos L.\sin B - v_Y.\sin L.\sin B + v_Z.\cos B \tag{2}$$

$$v_U = v_X.\cos B.\cos L + v_Y.\sin L.\cos B + v_Z.\sin B \tag{3}$$

Figure 4 presents the absolute ITRS velocities of the stations.

Figure 4. Absolute velocities in ITRS, ITRF2014 (vectors scale: 1 cm ≈ 0.025 m/y)



3.2.2 Definition of horizontal intraplate velocities

The relative velocities refer to intraplate movements of the territory. They are obtained as the rotation of the plate is excluded from the absolute velocities for the analyzed stations.

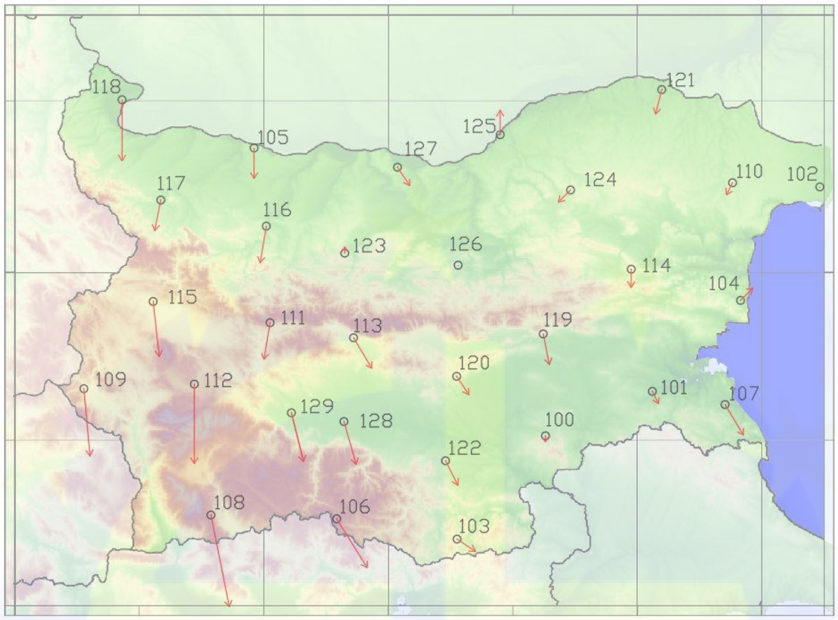
Therefore the obtained coordinates and velocities from the final solution are further transformed into ETRS89, ETRF2000, epoch 2005.0. This is the official reference system in Bulgaria. This procedure follows the official transformation recommendations published by EUREF. The results are presented on Table 3.

Table 3: Geocentric coordinates and velocities and topocentric velocities of the stations in ETRS89, ETRF2000, eph. 2005.0

Station №	X, [m]	Y, [m]	Z, [m]	Vx, [m/y]	Vy, [m/y]	Vz, [m/y]	vE, [m/y]	vN, [m/y]	vU, [m/y]
100	4248898.0766	2103368.4064	4252768.1362	0.00042	0.00050	0.00095	0.00026	0.00030	0.00108
101	4199906.2845	2156615.3635	4274151.0543	-0.00027	0.00005	-0.00038	0.00017	-0.00013	-0.00042
102	4068599.9532	2212189.9632	4370982.4752	-0.00060	0.00026	-0.00686	0.00052	-0.00470	-0.00502
103	4314503.0703	2072138.9195	4201953.6447	0.00010	0.00100	-0.00016	0.00086	-0.00047	0.00029
104	4137767.0575	2189470.3801	4317624.9725	-0.00090	0.00007	-0.00018	0.00048	0.00039	-0.00068
105	4218175.0826	1874639.7962	4387010.5442	0.00064	0.00014	-0.00129	-0.00013	-0.00138	-0.00043
106	4341530.7351	1997851.0897	4211110.0143	0.00208	0.00226	0.00039	0.00118	-0.00159	0.00238
107	4183337.3577	2201319.2983	4267630.8525	-0.00060	0.00043	-0.00148	0.00066	-0.00087	-0.00124
108	4375002.3081	1923050.7570	4210717.3868	0.00262	0.00228	-0.00135	0.00103	-0.00321	0.00158
109	4360743.0923	1823032.2065	4269166.3249	0.00196	0.00122	-0.00145	0.00037	-0.00261	0.00071
110	4093425.1515	2161021.0309	4373678.6217	-0.00008	-0.00025	-0.00083	-0.00018	-0.00047	-0.00071
111	4283628.8703	1919686.6964	4304706.1055	0.00157	0.00058	-0.00055	-0.00011	-0.00154	0.00085
112	4328995.9600	1887446.0187	4274069.1216	0.00220	0.00098	-0.00190	0.00002	-0.00303	0.00050
113	4265869.0902	1971643.4374	4298528.7732	0.00060	0.00096	-0.00120	0.00062	-0.00152	-0.00012
114	4158029.0068	2119813.7708	4332798.4360	-0.00032	-0.00009	-0.00154	0.00007	-0.00090	-0.00129
115	4307579.0944	1846494.3877	4312558.5762	0.00096	0.00093	-0.00169	0.00048	-0.00209	-0.00023
116	4246010.5837	1897787.0382	4350302.4129	0.00103	0.00018	-0.00101	-0.00026	-0.00143	0.00005
117	4264925.0728	1830365.8707	4360658.3842	0.00127	0.00060	-0.00060	0.00005	-0.00140	0.00061
118	4235209.8989	1786946.3616	4406908.4900	0.00008	0.00021	-0.00339	0.00016	-0.00255	-0.00224
119	4209632.4182	2081711.5420	4301803.0175	0.00013	0.00042	-0.00093	0.00032	-0.00089	-0.00041
120	4251394.7647	2039679.5393	4280885.2360	0.00037	0.00067	-0.00032	0.00044	-0.00066	0.00024
121	4076970.7870	2100834.8277	4417561.8811	-0.00027	-0.00042	-0.00171	-0.00025	-0.00093	-0.00150
122	4287501.7658	2049950.6859	4239994.3876	0.00088	0.00103	0.00004	0.00055	-0.00080	0.00095
123	4234715.3631	1949341.9477	4338663.6870	-0.00055	-0.00008	0.00001	0.00016	0.00037	-0.00038
124	4144415.5028	2068492.6382	4370393.9010	-0.00015	-0.00059	-0.00120	-0.00046	-0.00060	-0.00111
125	4142643.9055	2016133.2768	4396063.7663	-0.00263	-0.00127	-0.00127	0.00001	0.00111	-0.00299
126	4207110.8963	2018169.1310	4334111.2881	0.07809	0.03121	-0.21117	-0.00564	-0.21155	-0.08294
127	4185303.0327	1962740.7038	4379874.5182	-0.00060	0.00036	-0.00129	0.00058	-0.00066	-0.00117
128	4301266.9430	1982685.4239	4257880.6379	0.00102	0.00099	-0.00077	0.00047	-0.00147	0.00048
129	4312694.5242	1950083.2585	4261392.7548	0.00113	0.00108	-0.00117	0.00052	-0.00186	0.00031

Based on the above estimations, the graphical presentation of the velocities of the stations relative to Eurasia, are shown on Figure 5. Formulas 1-3 are applied. A velocity vector indicating the magnitude and direction of the corresponding stations is presented. This allows formulation of tendencies through which comparisons the results in relation to the crust motion can be interpreted. Moreover, the visual representation of these vectors allows defining the nature of movements and characteristics of its distribution.

Figure 5: Relative velocities of stations - ETRS89 (vector scale: 1 cm ≈ 0.005 m/y)



4. Results and discussion

4.1 Crustal deformation and kinematics

4.1.1 Network configuration

In the current research the crustal motion is examined throughout a horizontal deformation model. These are deformations of horizontal compressional and tensional stress. The solution strategy is based on the Finite element method (FEM). The geometry of the territory is divided into a number of discrete sub-regions, called 'elements', connected at discrete number of points called 'nodes'. Each of these nodes is presented by a station from the network. The aim is to define the magnitude and direction of rotation in the network of **simple** triangles, as result of strain and rotation estimations. The distribution of the deformation parameters is obtained inside of each finite element. The configuration of each finite element is chosen to be as close to equilateral as possible.

The currents estimations are made for all stations for the period 2014-2018; except for stations 102 and 126 due to established problems with them (i.e. change of location). The results for these are included in the final solution only for the period 2016-2018.

4.1.2 Estimation of horizontal intraplate deformations

In this study, the crustal deformations analysis is based on two-dimensional plane strain model. Thus two-dimensional strains are defined for the description of the geometric alterations in the position of the projections of the surface points onto the local reference plane.

Under the assumption of small displacement gradients, three independent variables can be used to describe the deformation. These variables correspond to the extensional strains e_{xx} and e_{yy} as well as the shear strain - $\gamma_{x\,y}$. The last one measures the change in angle between the unit vectors in the x and y directions. The extensional strain in given by:

$$\varepsilon_{i\,j}^{(x\,y)} = e_{xx} \,.\cos^2 a_{i\,j}^{(x\,y)} + e_{yy} \,.\sin^2 a_{i\,j}^{(x\,y)} + \cos a_{i\,j}^{(x\,y)} \,.\sin a_{i\,j}^{(x\,y)} .\gamma_{x\,y}, \tag{4}$$

Where

$a_{i\,j}^{(x\,y)}$– is the angle between the X axis and the projection L_{ij} in plane XY;

$e_{xx},\ e_{yy}, \gamma_{x\,y}$ – strain elements.

Equation (4) shows how the elongation varies with orientation.

The strain tensor, being symmetric, takes a diagonal form, presented by the following matrix:

$$\lambda E = \begin{bmatrix} E_{max} & 0 \\ 0 & E_{min} \end{bmatrix}. \tag{5}$$

The quantities E_{min} and E_{max} represent the principal strains. In order to compute the principal strains from the components of the strain tensor, the following matrix is applied:

$$E = \begin{bmatrix} e_{xx} & \gamma_{xy} \\ \gamma_{xy} & e_{yy} \end{bmatrix}. \tag{6}$$

The principal strains E_{min} and E_{max} are computed as the roots of the following equation:

$$E^2 - J_1 \,.E + J_2 = 0, \text{ where} \tag{7}$$

$$J_1 = e_{x\,x} + e_{yy} \tag{8}$$

J_2 is the determinant of matrix (5).

Thus the determinant of (7) is estimated by the following characteristic equation:

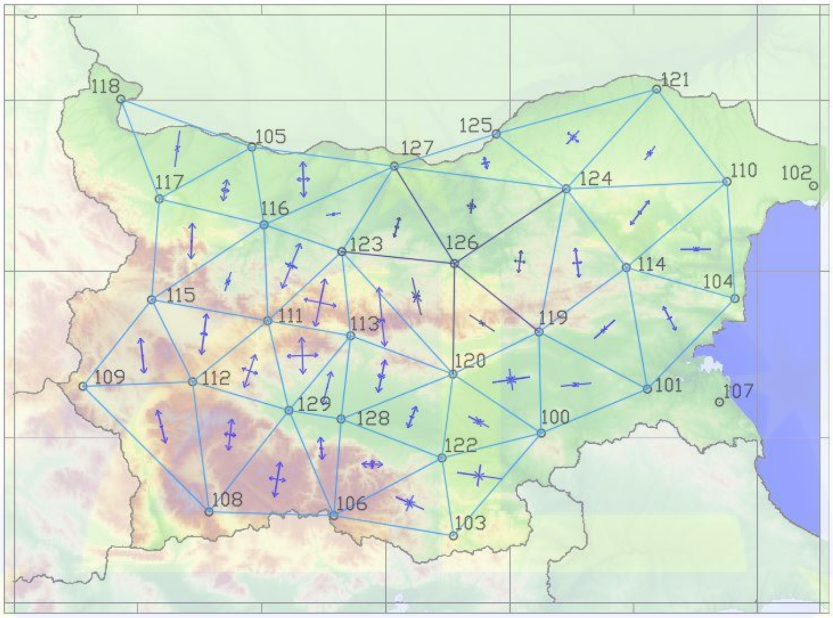
$$D = \left(E_{x\,x} + E_{y\,y}\right)^2 - 4E_{x\,x}\,E_{y\,y} + \gamma_{x\,y}^2. \tag{9}$$

Thereafter, the orientation of each strain is computed. The angle of rotation of E_{max} is presented by the following formula:

$$tg2\Phi = \frac{\gamma_{x\,y}}{E_{x\,x} - E_{y\,y}}. \tag{10}$$

Thus the extension and compression related to the center of gravity of each finite element is graphically presented on figure 6 by the principle strain distribution:

Figure 6: Two-dimensional plane strain distribution



4.1.3 Localization of fault zones

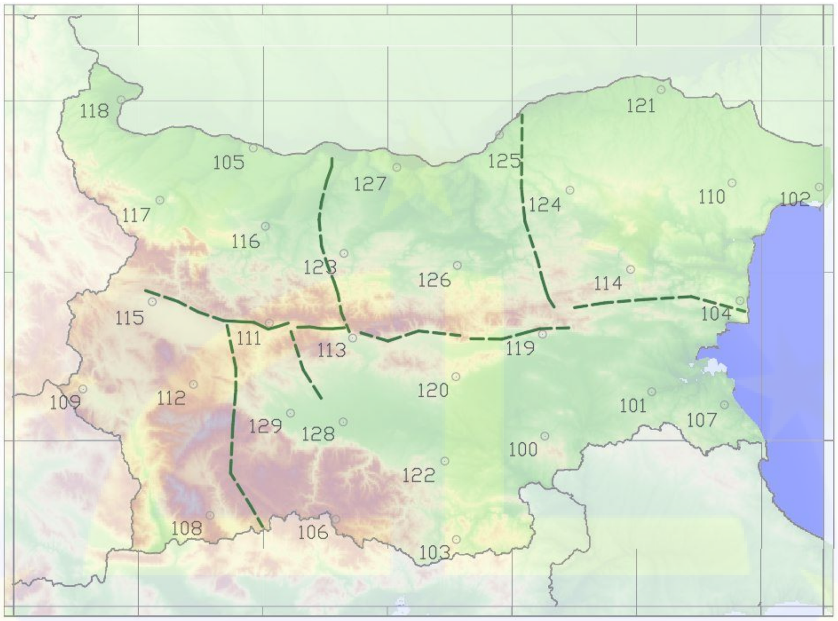
Based on the results, it's visible that the movement of stations at south-west part of Bulgaria is faster than the others. The stations in north-west Bulgaria are characterized by most even (regular) movements – direction south, south-west. In south Bulgaria the direction is again north-south, but the velocity of the point at this area increases significantly. Therefore southwestern Bulgaria appears to be moving more intensively than the northern.

The plane strain distribution gives more clearness regarding the horizontal movement of crust. In southern Bulgaria - the Rhodope and Sakar regions, there is a reversal of the main axes of deformation relative to the horizontal velocities, probably due to the fact that the area is at the end of Eurasia. According to geological data at this area are localized multiple faults.

For the territory of the western part of the country, its complex nature is clearly visible. Central-West Bulgaria dominates the processes of extension with north-south direction.

Based on the characteristic movements of the stations, as well as the results shown by two- dimensional plane strain distribution, a proposed scheme for potential fault zones is presented on Figure 7.

Figure 7. Localization of fault zones



Several faults are localized based on the obtained horizontal velocities and deformation axes. These faults are located in the adjacent zones, separating distinct block structures.

The results and conclusions obtained in the study are compared with current geological data. Consistency between the current analysis and detailed geological surveys in achieved.

5. Conclusions

Within the current research was presented a suggested strategy to locate and monitor contemporary activity of the tectonic structure throughout a combination of GNSS methods, based on Continuously Operating Reference Stations. With the existence of certain cyclic precise coordinates and velocities, a kinematic coordinate system could be defined, taking into account the intra-plate motion of each station. A research of such a scale could only be carried out using research scientific software (such as Bernese GNSS Software), ensuring high accuracy and reliability of the obtained results.

During the precise data processing, orbit related files are applied, such as precise satellite ephemerides and earth rotation parameters, as well as atmosphere related files, downloaded from ftp server of CODE. In order to obtain optimal final coordinate solution, a relation between ITRF stations and the stations from the network is established. Thus the geodetic datum is defined based on the reference ITRF sites using tight constrains.

Based on the estimated horizontal velocities as well as the calculated horizontal deformations via FEM, the localization of block-defined structures and the boundary between them is achieved. Some of the performed studies in the article coincide with existing published geological hypotheses, while others

(North and Central Bulgaria) show the existence of an unexplored geotectonics. Particular attention should be paid to these areas, since the deformations identified there could be due both to the geodynamics of the area and to the relocation of the physical permanent station and the adjacent infrastructure.

All the conclusions presented in this study define the contemporary geodynamic activity on the territory of Bulgaria. For more detailed information on crustal motion and division of block structures, a dense network of points is required.

It is particularly important that the geodynamic information is kept up to date.

For successful monitoring of the contemporary Earth crust movements, it is necessary to have both continuously operating permanent GNSS stations and periodically measured ones with sufficient density.

In areas with more frequent seismic activities, the availability of such a network is crucial for the ongoing assessment of geodynamic activity. In Bulgaria there are such networks at some specific regions. The stations used for densification of such a network should be located so that they encompass the main faults, some of which are defined in this study. Further, the establishment of GNSS stations for geodynamic purposes requires that they are stabilized on positions where local movements are excluded (e.g. not on infrastructural sites).

The integration of GNSS data along with geological, tectonic and seismological data is an important step in assessing seismic risk for a given territory. The contribution of geodetic means is significantly and undoubtedly important.

The results obtained from the presented periodic GNSS measurements and subsequent analyzes can be used for further geodynamic analyzes and interpretations in other Earth-related sciences.

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