Practical Application of a Horizontal Intraplate Velocity Field Model for the Territory of Bulgaria

Yuri Tsanovski1, Tsocho Danchev1

1The University of Architecture, Civil Engineering and Geodesy (UACEG), Bulgaria
tsdanchev@gmail.com

Abstract. The Republic of Bulgaria is situated on the edge of the Eurasian tectonic plate. This is defined by active tectonic and seismic activity, which is an issue in the implementation of the official coordinate reference system in the country - the ETRS89, as far as precise solutions are concerned. The reason is that the intraplate, relative to Eurasia, tectonic movements south of Stara Planina are about 5 times larger than those north of it. Over a period of time (about 10 years), the coordinate errors of the points from a static network become bigger than the uncertainties of GNSS measurements and thus limit their potential. Thanks to the presence of networks of continuously operating reference GNSS stations (CORS networks), and advanced methods of processing and analysis of the results, it is possible to monitor the crustal deformations with sufficient precision. A model of horizontal intraplate velocities was developed based on measurements from different epochs of the CORS networks operating on the territory of Bulgaria. Precise coordinates and velocities of the stations were estimated using the Bernese GNSS Software v5.2, and the deformation modeling was performed using a method of determining parameters of local deformation and Euler poles of distinctive tectonic blocks to which the country is divided according to the authors. This paper presents the practical applicability of this model for interpolation the velocities of stations from static networks and verification of the official results for the points of the National GPS Network. The results are encouraging for the practical realization of ETRS89 on the territory of Bulgaria.

1. Introduction
The territory of Bulgaria is characterized by its high tectonic and seismic activity which is investigated by many authors [1-5]. 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 in terms of the fact that for most of them the values are close to the achievable accuracy of the geodetic measurements. Thanks to the presence of CORS networks and modern GNSS methods of processing the data and analysis of the results, it is now possible to accurately monitor the crustal deformations with sufficient precision.

The purpose of this study is to examine the possibility of the practical application of a derived horizontal intraplate velocity field model for the territory of Bulgaria which was based on a solution for 30 permanent GNSS stations with precise coordinates and velocities derived by using the scientific product Bernese GNSS Software v5.2. The deformation modeling was performed using a method of determining parameters of local deformation and Euler poles of distinctive tectonic blocks to which the country is divided according to the authors. Each of the blocks is considered to behave as a rigid body with similar deformations for the whole area.

Verification of the model has been processed using a solution for 45 permanent GNSS stations not included in the model definition. Their coordinates and velocities were also determined using the same strategy as in the processing of the stations, used to derive the model. A comparison of the horizontal intraplate velocities obtained as a result of the Bernese processing and of the interpolation using the
A model was made. In addition, provided velocities of stations of the National GPS Network of Bulgaria were also compared to the interpolated via the model. A statistic of the results of the obtained CORS network and National GPS Network velocities was compiled.

2. GNSS data processing

In the velocity field model determination, we conducted an analysis of the behavior of 30 permanent GNSS stations, covering evenly throughout the country, based on 6 measuring campaigns. 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. The duration of each campaign is as follows:

- 1st - 7 days (24 - 30 April 2016);
- 2nd - 4 days (1 - 4 November 2016);
- 3rd - 8 days (23 - 30 April 2017);
- 4th - 8 days (15 - 21 October 2017);
- 5th - 8 days (23 - 30 April 2018);
- 6th - 8 days (15 - 21 October 2018).

In order to ensure the best possible solution for coordinates and velocities of the stations, a baseline network adjustment has been performed using the Bernese GNSS Software v5.2. This is a scientific software package meeting the highest quality standards for geodetic and further applications based on GNSS [6]. It is developed at the Astronomical University of Bern, Switzerland and is used in the processing of global and regional networks. The software package meets the most up-to-date requirements for accuracy and reliability of the results which are obtained using the most effective ambiguity resolution strategies that allow processing of baselines up to several thousand kilometers long. The processing strategy has been implemented taking into account the most advanced concepts in the processing of regional networks, recommended by EUREF [7]. The processing strategy is described in details in [8].

As it is described in [8], the obtained results (geocentric coordinates and velocities) were initially in ITRF2014, epoch 2010. Thereafter they were transformed to the official reference system in Bulgaria - ETR89, ETRF2000, epoch 2005.0, considering the transformation recommendations by EUREF [7]. The ETR89 coordinates and velocities were then transformed to geodetic coordinates (B, L, H) and the velocities for each axis (X, Y, Z) to topocentric velocities (v_E, v_N, v_U), to make it easier to visualize the velocity vector for each station. For the transformation is used the GRS80 ellipsoid and the following formulas:

\[ v_E = -v_X \sin L + v_Y \cos L \]
\[ v_N = -v_X \cos L \sin B - v_Y \sin L \sin B + v_Z \cos B \]
\[ v_U = v_X \cos B \cos L + v_Y \sin L \cos B + v_Z \sin B \]

The vectors that visualize the horizontal intraplate velocities of the stations, involved in the definition of the model are shown in Figure 1:
Figure 1. Relative horizontal velocities of the stations, defining the model (vectors scale: 1 cm ≈ 0.005 m/year)

The results from this processing were used in the subsequent modeling of the intraplate velocity field. The exact same strategy was used in the data processing of another CORS network composed of 45 permanent GNSS stations. The data used is again raw 24-hour RINEX format files with 30 sec sampling rate for each station. The results from the second CORS network were used for verification of the velocity field model in the subsequent analyses.

3. Local deformation estimation and micro-plate diversification

For determining the horizontal intraplate velocity field is used an algorithm for estimating median strain rate tensors ($\varepsilon$) and median rotation rate vectors ($\omega$), based on MELD (Median estimation of local deformation) by Kreemer et al. [9]. As it is described in [8], the median strain rate tensors and rotation rate vectors are estimated from a set of N local estimates of strain rate tensors ($\varepsilon$) and vectors ($\omega$), each of them determined from four horizontal velocity vectors at the vertices of a local spherical quadrangle (instead of triangle), specified by their velocities ($v_e, v_n$). It is possible to estimate ($\dot{\varepsilon}$) and ($\dot{\omega}$) from the velocities at a triangle's three vertices, but these estimates have no robustness because there is no redundancy in the data. Any noise in the velocity gets directly onto the model estimates which led us to the idea to use approximately equal to the area, overlapping quadrangles. For every quadrangle's reference point (its center of mass) the six parameters are estimated. The local rotation rate vectors are expressed as a rotation around Cartesian Euler vector. 34 spherical overlapping quadrangles were compiled with vertices coinciding with the station of the CORS network from Figure 1. The matrix formulation used in MELD algorithm is:
\[
\begin{pmatrix}
\nu_x \\
\nu_y \\
\nu_z
\end{pmatrix} = R
\begin{pmatrix}
(\hat{r}.\hat{e}_0)(\hat{e}.\hat{e}_0) (\hat{r}.\hat{n}_0)(\hat{e}.\hat{n}_0) (\hat{r}.\hat{n}_0)(\hat{e}.\hat{e}_0) + \\
(\hat{r}.\hat{e}_0)(\hat{n}.\hat{e}_0) (\hat{r}.\hat{n}_0)(\hat{n}.\hat{e}_0) (\hat{r}.\hat{n}_0)(\hat{n}.\hat{e}_0)
\end{pmatrix}
\begin{pmatrix}
\hat{n}_x \\
\hat{n}_y \\
\hat{n}_z
\end{pmatrix}
\begin{pmatrix}
\hat{e}_e \\
\hat{e}_m \\
\hat{e}_n
\end{pmatrix}
\begin{pmatrix}
\hat{\omega}_x \\
\hat{\omega}_y \\
\hat{\omega}_z
\end{pmatrix}
\]

(4)

More information about MELD and the designations used can be found in [9].

The local strain rate tensor and rotation vector were obtained for each of the 34 quadrangles where after quadrangles with similar values for the rotation vectors were defined and then merged into polygons. Because the polygons are composed of figures with very close values, we can assume that the behavior for each of them will be as a rigid body and thus has the same Euler rotation pole. Once they have been grouped again, the components of the strain rate tensor and rotation vector were determined again, but for the whole figures.

A division of the territory of Bulgaria into 5 blocks (Figure 2) with similar values of the components of deformation was carried out - North-east (NE), North-west (NW), Central (CE), South-east (SE) and South-west (SW).

![Figure 2. Determined microplates with Euler pole parameters for each of them.](image)

Of the results visualized in Table 1, it can be seen that the determination of the parameters in the newly formed polygons is reliable. There is an exception - the SW block, where the number of stations - 4, is totally insufficient, which is why the \(\sigma\) values of the parameters exceed them [8].
Table 1. Calculated parameters for each block with their respective σ

| BLOCK | εee | σee | εnn | σnn | εen | σen | Ωx | Ωy | Ωz | Ωx | Ωy | Ωz |
|-------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| NW    | -0.011 | 0.006 | 0.018 | 0.001 | 0.002 | 0.000 | 0.007 | 0.001 | 0.015 | 0.001 | 0.006 | 0.000 |
| NE    | 0.012 | 0.005 | 0.004 | 0.000 | 0.011 | 0.005 | -0.005 | 0.001 | 0.014 | 0.001 | -0.012 | 0.006 |
| CE    | -0.043 | 0.010 | -0.037 | 0.011 | -0.042 | 0.010 | 0.009 | 0.004 | -0.064 | 0.015 | 0.048 | 0.010 |
| SW    | -0.082 | 0.139 | -0.182 | 0.314 | -0.123 | 0.206 | 0.000 | 0.008 | -0.238 | 0.408 | 0.112 | 0.188 |
| SE    | -0.026 | 0.001 | -0.023 | 0.014 | -0.030 | 0.013 | 0.004 | 0.002 | -0.042 | 0.002 | 0.033 | 0.013 |

4. Practical application of the model

The segmentation of the territory of Bulgaria into 5 micro-plates with similar intra-plate movements was done as well as determining the components of the local deformation for each of them. By using the values of these components and the geodetic coordinates of a given point (B, L) it is possible to interpolate the relative velocity of this point, depending on which block it is located.

In order to evaluate the obtained model of the intra-plate velocities of the territory of Bulgaria, 45 CORS stations (used as control points) with their coordinates and velocities in the ETRF2000 realization of ETRS, epoch 2005, were used. Their coordinates and velocities were obtained as a result of a processing using the Bernese GNSS software, applying the same strategy as with the points, used to generate the model. Once the components of deformation are determined (Equation 4), for the interpolation of horizontal intra-plate velocities, only the geodetic coordinates of the points are required - geodetic latitude and longitude (B, L). As a result of the processing of the control points with the Bernese GNSS software and the interpolation of their intra-plate velocities using the derived model, Table 2 is composed.

5. Results and discussion

As a result of the processing of the control points with the Bernese GNSS software and the interpolation of their intra-plate velocities using the derived model, Table 2 is composed.

Table 2. Horizontal velocity comparison for the control stations

| Station № | From MODEL | From Bernese | Differences |
|------------|------------|-------------|-------------|
|            | V_e MODEL [m/y] | V_n MODEL [m/y] | V_e BERNESE [m/y] | V_n BERNESE [m/y] | ΔV_e [m/y] | ΔV_n [m/y] |
| NORTH - WEST | | | | | | |
| 4          | 0.000 | -0.002 | 0.000 | -0.001 | 0.001 | -0.001 |
| 7          | 0.000 | -0.002 | -0.001 | 0.002 | 0.001 | -0.004 |
| 19         | 0.000 | -0.002 | -0.001 | 0.002 | 0.001 | -0.004 |
| 22         | 0.000 | -0.002 | -0.005 | 0.002 | -0.004 | -0.004 |
| 25         | 0.000 | -0.002 | 0.004 | -0.004 | 0.000 | 0.000 |
| 38         | 0.000 | -0.002 | 0.000 | -0.004 | 0.000 | 0.000 |
| 40         | 0.000 | -0.002 | 0.000 | -0.004 | 0.000 | 0.000 |
| 43         | 0.000 | -0.002 | 0.000 | -0.004 | 0.000 | 0.000 |
| 45         | 0.000 | -0.002 | 0.000 | -0.003 | 0.000 | 0.000 |
From MODEL | From Bernese | Differences
| Station № | V_N^ MODEL [m/y] | V_E^ MODEL [m/y] | V_N^ BERNESE [m/y] | V_E^ BERNESE [m/y] | ΔV_N^ M-B [m/y] | ΔV_E^ M-B [m/y] |
|------------|----------------|----------------|----------------|----------------|----------------|----------------|
| NORTH - EAST | | | | | | |
| 6 | 0.000 | -0.002 | 0.002 | -0.001 | -0.002 | -0.001 |
| 14 | 0.000 | -0.001 | -0.066 | -0.349 | 0.066 | 0.348 |
| 16 | 0.000 | -0.002 | 0.002 | -0.001 | -0.002 | -0.001 |
| 33 | 0.000 | -0.001 | 0.001 | -0.002 | -0.002 | 0.001 |
| 34 | 0.000 | -0.002 | 0.001 | -0.003 | -0.001 | 0.001 |
| 35 | 0.000 | -0.002 | 0.001 | -0.003 | -0.001 | 0.001 |
| 42 | 0.000 | -0.002 | -0.001 | -0.001 | 0.001 | -0.001 |
| CENTRAL | | | | | | |
| 2 | 0.000 | -0.002 | 0.001 | -0.004 | -0.001 | 0.002 |
| 10 | 0.000 | -0.003 | -0.001 | -0.005 | 0.001 | 0.002 |
| 13 | 0.000 | -0.002 | 0.006 | -0.012 | -0.006 | 0.011 |
| 20 | 0.000 | -0.003 | 0.000 | -0.003 | 0.000 | -0.001 |
| 21 | 0.000 | -0.004 | -0.004 | -0.003 | 0.004 | -0.001 |
| 23 | -0.001 | -0.002 | 0.000 | -0.001 | -0.001 | -0.001 |
| 24 | 0.000 | -0.004 | 0.033 | -0.014 | -0.033 | 0.010 |
| 26 | 0.000 | -0.002 | 0.005 | -0.004 | -0.004 | 0.002 |
| 29 | 0.000 | -0.003 | 0.001 | -0.004 | -0.002 | 0.001 |
| 30 | 0.000 | -0.002 | -0.002 | -0.001 | 0.001 | 0.000 |
| 41 | 0.000 | -0.003 | 0.002 | -0.004 | -0.002 | 0.001 |
| SOUTH - EAST | | | | | | |
| 1 | 0.000 | -0.002 | 0.010 | -0.006 | -0.010 | 0.004 |
| 5 | 0.000 | -0.002 | 0.000 | -0.002 | 0.000 | 0.000 |
| 8 | 0.000 | -0.002 | -0.001 | -0.002 | 0.000 | 0.000 |
| 9 | 0.000 | -0.003 | 0.002 | -0.010 | -0.002 | 0.007 |
| 12 | 0.000 | -0.003 | -0.001 | -0.003 | 0.001 | 0.000 |
| 15 | 0.000 | -0.003 | -0.001 | -0.003 | 0.001 | 0.000 |
| 18 | 0.000 | -0.003 | 0.005 | -0.003 | -0.005 | -0.001 |
| 27 | 0.000 | -0.003 | 0.012 | -0.009 | -0.013 | 0.007 |
| 36 | 0.000 | -0.002 | 0.000 | -0.003 | 0.000 | 0.000 |
| 39 | 0.000 | -0.002 | 0.001 | -0.004 | -0.001 | 0.001 |
| SOUTH - WEST | | | | | | |
| 3 | 0.000 | -0.006 | 0.001 | -0.004 | -0.001 | -0.002 |
| 11 | 0.000 | -0.006 | 0.001 | -0.005 | -0.001 | -0.001 |
| 17 | 0.000 | -0.005 | 0.001 | -0.003 | -0.001 | -0.002 |
| 28 | 0.000 | -0.006 | 0.003 | -0.003 | -0.003 | -0.003 |
| 31 | 0.000 | -0.004 | 0.000 | -0.004 | 0.000 | -0.001 |
| 32 | 0.000 | -0.006 | 0.002 | -0.006 | -0.002 | 0.000 |
| 37 | 0.000 | -0.005 | 0.000 | -0.003 | 0.000 | -0.002 |
| 44 | 0.000 | -0.005 | 0.001 | -0.005 | -0.002 | 0.000 |

The results obtained for the velocities of the 45 control stations are satisfactory. As shown in Table 3, most of them differ by up to 2 mm/y (in any direction) from the precisely defined by using
the Bernese GNSS software. There is clearly some issue with one of the stations (#14) since the calculated via Bernese velocity is with such a great value (perhaps the whole station has been relocated) and that's why it shouldn't be taken into account for evaluating the model.

### Table 3. Difference between Model and Bernese processed velocities

| Criteria            | # of stations |
|---------------------|---------------|
| up to 1 mm/y        | 19            |
| from 1 mm/y to 2 mm/y | 13            |
| from 2 mm/y to 1 cm/y | 9             |
| exceeding 1 cm/y    | 4             |

Besides the 45 control stations, interpolation of the velocities of 109 points from the National GPS Network in Bulgaria was made. They are then compared with derived velocities of these points in the same reference system for the period 2004-2018 [10]. Comparison between the provided and interpolated values are shown in Table 4.

### Table 4. Difference between interpolated and provided National GPS Network velocities

| Criteria            | # of stations |
|---------------------|---------------|
| up to 1 mm/y        | 67            |
| from 1 mm/y to 2 mm/y | 33            |
| from 2 mm/y to 3 mm/y | 7             |
| exceeding 3 mm/y    | 4             |

It can be seen that the results for the interpolated velocities of the State GPS Network stations are even better than those from the control CORS network. Most of their values differ up to 1mm on both directions (East, North) from the provided. For static networks, velocities with an average of 2mm/y values ensure correct results for the coordinates over a period of about 5 years. After there 5 years, the error generated by the intraplate deformations will exceed the accuracy of the station's position. So it is important that these velocities are taken into account and defined with sufficient precision.

### 6. Conclusions

The paper presented the practical applicability of the model for interpolation the velocities of stations from static networks and verification of the official results for the points of the National GPS Network. The division of the territory of Bulgaria into 5 microplates (or blocks, as referred in this study) is justified. In order to improve the velocity field model, it is necessary to include more stations with precisely calculated velocities on the periphery of the defined blocks. The results are encouraging for the practical realization of ETRS89 on the territory of Bulgaria.

### Acknowledgment(s)

We would like to thank the Bulgarian CORS networks - GeoNET and 1Yocto for providing the raw measurement GNSS data from their stations, which are used in this research and the Military Geographic Service for their valuable help in processing this data with the Bernese software. We also would like to thank the University of architecture, civil engineering and geodesy (UACEG, Sofia) for the opportunity to perform this study.

### References

[1] K. Vassileva, and M. Atanasova, “Inferred plate tectonic transition boundaries in Bulgaria from
GPS”, 8th National conference on Geophysics, 25th November, 2016.

[2] K. Vassileva, and M. Atanasova, “Study of transition boundaries in Bulgaria from GPS”. International symposium on modern technologies, education and professional practice in geodesy and related fields, Sofia, 06-07 November, 2014.

[3] I. Georgiev, D. Dimitrov, P. Brio and E. Botev. “Velocity field in Bulgaria and northern Greece from GPS campaigns spanning 1993-2008”. Proceedings of 2nd INQUA-IGCP-567 International Workshop on Active Tectonics, Earthquake Geology, Archaeology and Engineering, Corinth, Greece, 54-56, 2011.

[4] S. Gospodinov. “Determination of block deformations of the Earth's crust by measured baselines”, monography, 2011.

[5] I. Zagorchev. “Cenozoic Block Rotations in the Balkan Peninsula”. Proceedings of 3th International Symposium of the Black Sea region, 1-10 October, 2011, Bucharest, Romania, 220-222, 2011.

[6] R. Dach, S. Lutz, P. Walser and P. Fridez. “Bernese GNSS Software Version 5.2. User manual”, University of Bern, 2015.

[7] Z. Altamimi, “EUREF Technical Note 1: Relationship and Transformation between the International and the European Terrestrial Reference Systems”, 2018.

[8] Y. Tsanovski and Ts. Danchev, “Horizontal intraplate velocity field model for the territory of Bulgaria derived from GNSS solution”, SGEM 2019 Conference Proceedings, ISSN 1314-2704, 2019.

[9] C. Kreemer, W. C. Hammond and G. Blewitt. “A robust estimation of the 3-D intraplate deformation of the North American plate from GPS”. Journal of Geophysical Research: Solid Earth, 123, pp. 4388–4412, 2018. https://doi.org/10.1029/2017JB015257.

[10] I. Georgiev, “Deputy director of National Institute in Geophysics”, Geodesy and Geography, Bulgarian Academy of Sciences, Private communication, 2019.