TRIKOTNIŠKO ZASNOVANA DATUMSKA TRANSFORMACIJA V BOSNI IN HERCEGOVINI

TRIANGLE-BASED HORIZONTAL GEODETIC DATUM TRANSFORMATIONS IN BOSNIA AND HERZEGOVINA

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IZVLEČEK

V članku je opisan postopek transformacije med starim in novim horizontalnim geodetskim datumom v Bosni in Hercegovini. Uporabljeni sta bili dve metodi, ki temeljita na – nepravilni in pravilni – trikotniški mreži. Za razvoj modelov transformacije sta bila uporabljena dva nabora točk, en za razvoj modelov (približno 1200 točk) in drug za testiranje (približno 850 točk). Pred razvojem so bile vse točke preizkušene na prisotnost odstopanj, ta so označena v podatkovni bazi točk. Rezultati kažejo, da je mogoče z uporabljenima metodama modelirati velik del izkrivljanj v stari trikotniški mreži. Največje standardne deviacije položaja z najboljšim modelom znašajo 4,5 in 6,4 centimetra za dva nabora točk, največje razlike v položaju pa so 30 in 40 centimetrov za dva nabora točk. Vsaka metoda ima svoje prednosti in slabosti, ki so tudi predstavljene v članku. Pokazano je, da so število, prostorska porazdelitev in kakovost vhodnih podatkov ključnega pomena za razvoj visoko natančnih modelov transformacije. Kot pomemben prispevek tega dela so bila prepoznana nekatera problematična področja z nepravilnimi izkrivljanji. Na koncu je podanih nekaj priporočil za izboljšanje razvitih modelov.

ABSTRACT

The article describes the procedure for transformation between old and new horizontal geodetic datum in Bosnia and Herzegovina. Two triangle-based methods were used for transformation, which are based on irregular and regular triangular network. For development of transformation models two set of points were used, one for developing models (around 1200 points), and other for testing (around 850 points). Prior to development, all points were tested at presence of outliers, and outliers are marked in the points database. Results shows that large part of distortions in old triangulation network can be modeled with used methods. Maximal positional standard deviations with best model are 4.5 and 6.4 cm for two sets of points, respectively, while maximal positional discripencies are 30 and 40 cm for two sets of points. Each method has some advantages and disadvantages which are shown in this article. It is shown that the number, spatial distribution and quality of input data are crucial for development of highly accurate transformation model. Also, as an important contribution of this work, some problematic areas with irregular distortions are identified. Finally, some recommendations are given for improvement of developed models.

KLJUČNE BESEDE

geodetski datum, triangulacija, modeli transformacije, odstopanja položaja, izstopajoče točke, položajne razlike, nepravilne distorzije, prostorska distribucija

KEY WORDS

geodetic datum, triangulation, transformation models, outliers, positional discrepancies, irregular distortions, spatial distribution

1 INTRODUCTION

The current official geodetic datum used in Bosnia and Herzegovina is known as the Hermannskogel datum, with its origin located in a point on the hill of Hermannskogel near Vienna. The Bessel ellipsoid was selected as the reference ellipsoid and the Gauss-Kruger projection was adopted. The establishment of the first-order trigonometric network in the former Yugoslavia lasted, with interruptions, for about 50 years (Begić, 2012). Of the total of 341 first-order trigonometric points, 36 points were taken from the Austrian triangulation. The lower-order networks were based on the first-order network and used for surveying. The entire network has many shortcomings in terms of internal accuracy and homogeneity.

For the new geodetic datum in Bosnia and Herzegovina, the ETRS89 (European Terrestrial System 1989) with the Transverse Mercator projection was adopted. This datum was realized through two campaigns BIHREF98 and BIHREF2000 (Mulić et al., 2015). After these campaigns, in 2011, the BIHPOS (BiH Positioning Service) was established, initially consisting of 34 permanent stations, whose coordinates were determined in ETRF2000 (European Terrestrial Reference Frame 2000), epoch 2011.307 (Mulić, 2018).

Most GNSS (Global Navigation Satellite Systems) measurements taken since 2011 were made through the BiHPOS system. To obtain coordinates in the State Coordinate System of Bosnia and Herzegovina (bos. Državni Koordinatni Sistem Bosne i Hercegovine), a 7-parameter transformation or localization was usually performed. Users were forced to determine the transformation parameters themselves, as there was no official transformation model. The transformation parameters determined by using the 7-parameter transformation are only applicable to smaller areas. In fact, the position residuals after the 7-parameter transformation in Bosnia and Herzegovina reach values of up to 2 meters (Krdžalić, 2021).

The transformation between geodetic datums is the most important aspect in the field of surveying and cadastre, geospatial information systems, and other fields that use spatial data.The process of geodetic datum transformation has been the subject of numerous studies and research initiatives, with various methods proposed and tested in different regions around the world. Triangle-based methods are used e.g. in Great Britain (Greaves, 2004; Greaves et al., 2016), Switzerland (Kistler and Ray, 2007), Kosovo (Kohli and Jenni, 2008), Slovenia (Berk and Komadina, 2010, 2013) and it was tested also in Croatia (Šljivarić, 2010).

In this article, we will focus on two triangle-based methods for geodetic datum transformation: the FINELTRA (FINite ELement TRAnsformation) method developed by Carosio and Plazibat (1995) and the transformation using regular triangular network (RTN) developed by Berk and Komadina (2010, 2013). We will evaluate the applicability of these methods in Bosnia and Herzegovina and compare their results in the transformation of geodetic data in the country.

The aim of this article is to provide a comprehensive understanding of the first-time application of FINELTRA and the RTN transformation method in Bosnia and Herzegovina. Through a critical analysis of their advantages, limitations, and potential future developments, we will gain insight into their effectiveness in the context of geodetic datum transformation in Bosnia and Herzegovina.

The decision to exclude heights from transformation was based on the standard practice of establishing horizontal and vertical datums separately in traditional geodetic surveys. The horizontal geodetic datum is established through classical triangulation methods, and the vertical datum is determined using precise geometric leveling techniques. Additionally, there is a newly created geoid model for Bosnia and Herzegovina, as reported in the work of Krdžalić and Abbak (2023).

The models that have been developed can effectively transform various spatial data where is required transformation accuracy better than 0.5 meters. These models have the ability to adapt to the demands of various mapping and surveying projects, ensuring that the transformed data is accurate and reliable. With a precision of better than 0.5 meters, the models can support a wide range of applications in fields such as surveying, mapping, and geographic information systems. These developments have greatly improved the ability to accurately capture, store, and utilize spatial data, which is critical for numerous industries and applications. It is also necessary to determine the optimal model of datum transformation in order to connect and use national spatial data (NSD) from both national geodetic datum, but also to meet requirements for accession to the European Union through the INSPIRE Directive (Infrastructure for Spatial Information in the European Community).

2 METHODS AND DATA

2.1 Transformation of coordinates using triangles

The method of transformation using triangles is based on dividing the transformation area into regular or irregular triangles. If the transformation area is divided into regular triangles, the triangle vertices are defined by virtual points (points that do not exist on the ground). If the transformation area is divided into irregular triangles, the triangle vertices are defined by control points (which exist on the ground), whose coordinates are known in two coordinate systems. In both cases, the transformation is performed point by point, based on the surrounding points in its neighborhood.

Transformation using a triangle grid can be done in two ways:

1. By calculating transformation parameters for each triangle.
2. By modeling the distortion within each triangle based on the distortion in the points that define the vertices of the triangle.

In the first method, transformation parameters can be calculated for each triangle using a Helmert 2D or affine 2D transformation. This treats each triangle separately, and the accuracy of the transformation within the triangle depends solely on the quality of the coordinates of the triangle vertices. An increased number of points in one area does not affect the accuracy of the transformation in another area. Affine transformation is more suitable for several reasons (Carosio and Plazibat, 1995):

– it is a continuous linear function,
– transformation is reversible,
– it preserves lines, parallel lines, etc.
– the residuals are significantly smaller compared to Helmert's transformation.

In the second method, residuals are first calculated using a simple transformation model (e.g., by calculating translations or a Helmert 2D transformation) based on all known points. Modeling residuals (distortion) is done using the so-called sector method.

2.1.1 Regular triangular network

The coordinate transformation using a regular triangular network was developed by Berk and Komadina (2013).

In the entire country, a regular triangular network is developed which extends beyond the borders (Figure 1). The vertices of the triangles are assigned coordinates in a new coordinate system. The transformation of the triangle vertices is performed using nearby common points, which are selected based on a predefined search radius (10 km), using Helmert's 2D or affine 2D transformation.

The flow diagram of the coordinate transformation using the regular triangular network is shown on Figure 2. First, it is necessary to define the coordinates of the triangle vertices that will form the regular triangular network. The surface area of the triangle is directly related to the number and distribution of points.

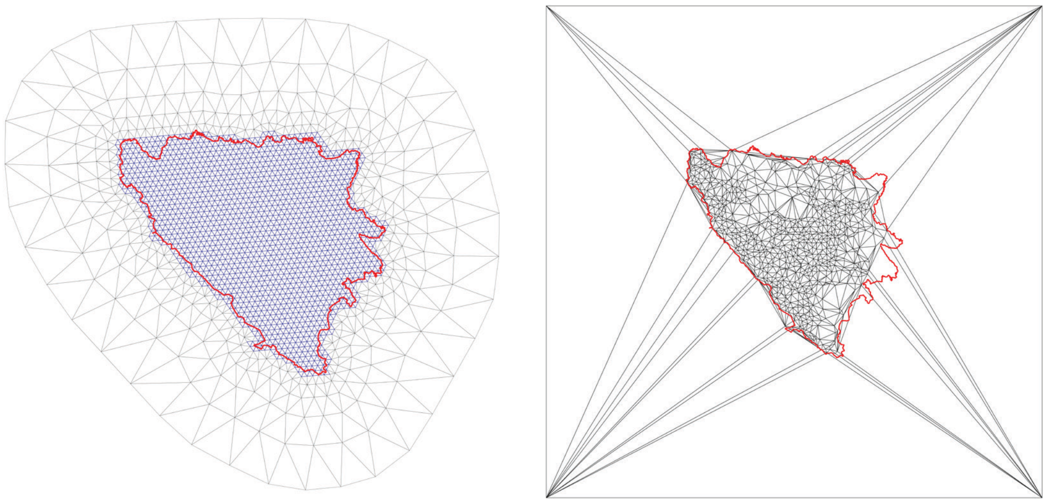

Figure 1: Regular triangular network (left) and irregular triangular network (right)

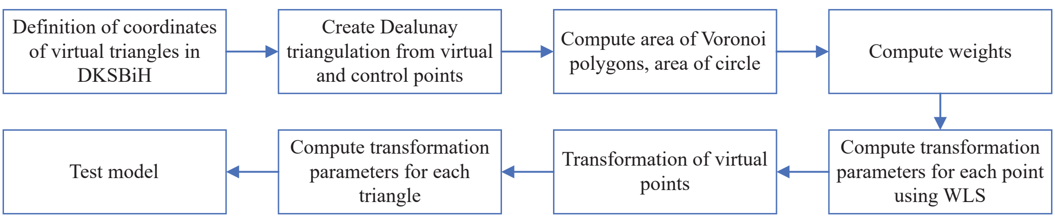

Figure 2: Diagram of transformation flow using a regular grid of triangles

The neighborhood between given and virtual points is defined by Delaunay triangulation. For each virtual point, a triangulation is created with surrounding given points. The minimum number of points with which each virtual control point must be connected is 3, in order to calculate the transformation parameters in the case of affine or 2 in the case of Helmert transformation. If there are less than 4 points located within the defined radius of 10 km, then the closest 4 points will be selected instead.

The given points are assigned weights to eliminate the influence of uneven point distribution and uneven distances between given and virtual points (Berk & Komadina, 2013). During the weighted least square

(WLS) transformation, weights are calculated in two ways: based on the ratio of the Voronoi polygon area to the area of the circle defined by the distance between the virtual tie point and the given point, and as the inverse values of the squared distances between the given and virtual points.

2.1.2 Irregular triangular network

In this method, an irregular triangle network is created based on given points using Delaunay triangulation. In order to cover the border areas of Bosnia and Herzegovina, it would be necessary to use points from neighboring countries. Since such data is not available, virtual points were added outside of Bosnia and Herzegovina. The coordinates of these additional points in the ETRS89 system were determined using Helmert's 2D transformation, using all given points. Four points were added, located approximately 200 km from the border of Bosnia and Herzegovina, with coordinates assigned in the DKSBiH (Figure 1).

The model transformation using irregular triangle networks was developed using the FINELTRA method. The FINELTRA method was developed by Carosio and Plazibat (1995). The residuals at the vertices of the triangles are the differences in coordinates between the DKSBiH and ETRS89 coordinate systems. The sector method (Swisstopo, 2008) is used to interpolate the residuals within the triangles. In this method, interpolation of residuals within a triangle is performed by calculating weights based on the areas of the triangles formed by the new point with the given points. Let T be a new point whose coordinates are being transformed, and let T_1,T_2,T_3 be the given points that form the triangle in which point T is located (Figure 3).

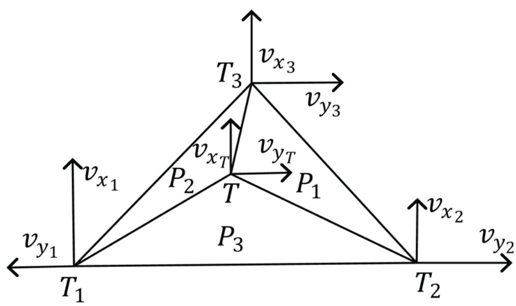

Figure 3: Computing distortion within a triangle

Using the new point, three new triangles are formed. Modeling of the distortion at point T is performed using areas. The area of a triangle can be calculated using the following formula:

$$P = ½ \,[x_1 \,(y_2 - y_3) + x_2 \,(y_3 - y_1) + x_3 \,(y_1 - y_2)] \tag{1}$$

The interpolation of residuals is calculated based on the residuals of control points and the surface areas of the three new triangles:

$$v_{y_T} = \frac{\sum_{i=1}^{3} v_{y_i} P_i}{\sum_{i=1}^{3} P_i} \qquad v_{x_T} = \frac{\sum_{i=1}^{3} v_{x_i} P_i}{\sum_{i=1}^{3} P_i} \tag{2}$$

where v_{y_i} and v_{x_i} are translations or coordinate differences between the old and new systems.

2.2 Data

The majority of input data for this research was provided by the Federal Administration for Geodetic and Property Affairs (bos. Federalna uprava za geodetske i imovinsko-pravne poslove-FUGIPP – https://www.fgu.com.ba/). These data are the result of two projects: "Digital orthophoto maps" (Federal Administration for Geodetic and Property Affairs, 2012) and "Determination of models for transformation between old and new reference coordinate system in BiH" (Federal Administration for Geodetic and Property Affairs, 2015). Within the first project, 412 points (DOF points) were determined, while in the second project it was measured 999 points (FGU GRID points) (Figure 4). In the following text, this set of points is referred to as SET1.

In addition to the points determined in the two mentioned projects, FUGIPP provided testing points that were determined in urban geodetic networks or by municipalities or companies (mostly using the RTK method with the BIHPOS service). A total of 1223 points were provided, including 192 points determined in urban networks, which are mostly trigonometric and tie points, and the rest are points determined by the RTK method. Some data were collected from other sources (faculty archives, surveying companies, colleagues, etc.). This way, 68 points were collected. In the following text, this set of points is referred to as SET2.

Figure 4 shows that the points are unevenly distributed over the territory of Bosnia and Herzegovina.

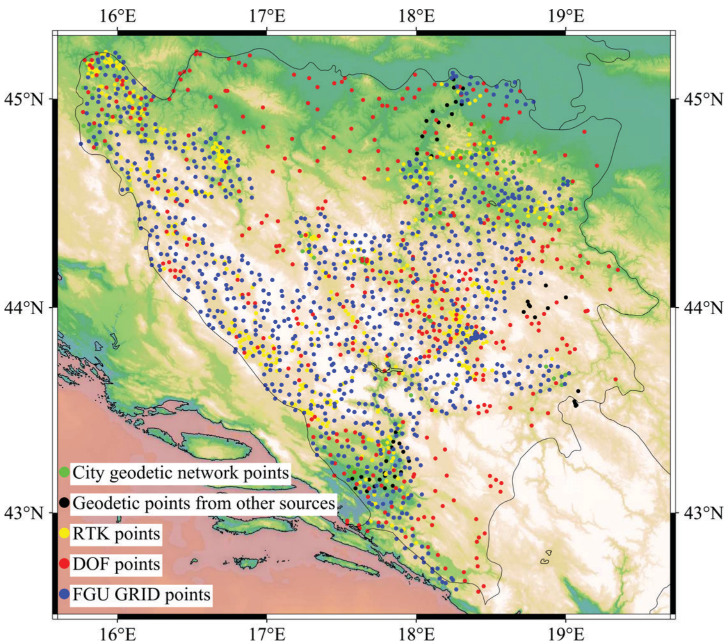

Figure 4: Distribution of input data

2.2.1 Analysis of input data

The preprocessing of input data, which took place in the development and calculation of transformation models, was carried out in the following stages:

– Checking the delivered coordinates (in the national coordinate system) by comparing them with the coordinates in the so-called point cards,

– Checking for duplicate points,
– Detecting gross errors using the Helmert 2D transformation.

The testing was performed separately on both defined sets of points, SET1 and SET2.

2.2.2 Filtering

Filtering residuals is the most important step in the process of calculating transformation models. The assumption is that residuals at neighboring points should not differ significantly, either in direction or intensity.

There are various methods for eliminating residuals. Classical methods of filtering residuals using statistical tests do not provide adequate results in the case of coordinate transformation over larger areas (e.g. country-wide). Therefore, a method based on comparing the intensity and orientation of the residual vectors with neighboring points (Table 1) was applied. For each point, the residual vector is converted from Cartesian to polar coordinates. Then, by defining a suitable radius, nearby points are selected to calculate the mean value of the intensity and orientation of the residual vector, as well as the standard deviation of these components. Based on a predefined criterion ($m * \sigma$), the differences between the mean values and the values at the observed point are compared separately for both components of the residual vector. If the difference between the values is greater than the tolerance, the point is marked as an error. Finally, a visual inspection of the results is carried out.

Table 1: Pseudo cod for resiudals filtering method based on magnitude and angle

Input: *coordinates in old and new datum; R – search radius; k-threshold form minimum number of neighbors; m – factor for sigma multiplication*
Step 1: *compute Helmert 2D transformation parameters from all points*
Step 2: *compute residuals* v_y, v_x *and convert them to polar coordinates* d, θ
Step 3: *search points inside predefined radius R*
for *each point* P_i, $i \in 1,\dots, s$ **do**
    if $n_{points} < k$
        increase radius
    else
    endif
    compute mean value of magnitude vectors of neighbors $\overline{\boldsymbol{d}_n}$
    compute standard deviation of $\overline{\boldsymbol{d}_n}$: $\sigma_{\overline{d_n}}$
    compute difference $\Delta d_i = |d_i - \overline{\boldsymbol{d}_n}|$
    compute mean value of angle θ *of neighbors* $\overline{\theta_n}$
    compute standard deviation of mean value $\overline{\theta_n}$: $\sigma_{\overline{\theta_n}}$
    compute difference $\Delta\theta_i = |\theta_i - \overline{\theta_n}|$
    if $\Delta d_i < m * \sigma_{\overline{\theta_n}}$
        mark point as outlier
    else
    endif
    if $\Delta\theta_i < m * \sigma_{\overline{\theta_n}}$
        mark point as outlier
    else
    endif
endfor

It is important to note that the distribution of points can have a significant impact on the results, and that the possibility of user intervention is left open.

3 RESULTS

After checking the point coordinates and removing duplicate points in the SET1, 1397 points remained for further processing, while in the SET2 dataset, 948 points remained.

3.1 Outliers detection and filtering

The question is how to determine whether a point is erroneous or not? Here, we assumed that residuals at neighboring points should be approximately consistent with each other, both in terms of intensity and direction. However, it remains an open question whether and to what extent such points were used for, e.g., surveying or collecting geospatial data.

After the visual inspection, 25 points were removed from SET1, and then 140 points were removed by applying the filtering method (Table 1). After the filtering, a visual check was performed, and an additional 17 points were removed. After filtering and visual inspection, 1204 points remained for further processing out of 1397, i.e. 13.1% of points were marked as gross errors.

From SET2, 27 points were removed by visual inspection, 63 by filtering, and 9 by the final visual check. Out of 948 points, 99 or 10.4% were marked as gross errors. Figure 5 shows the residuals of SET1 and SET2, both for the remaining and removed points.

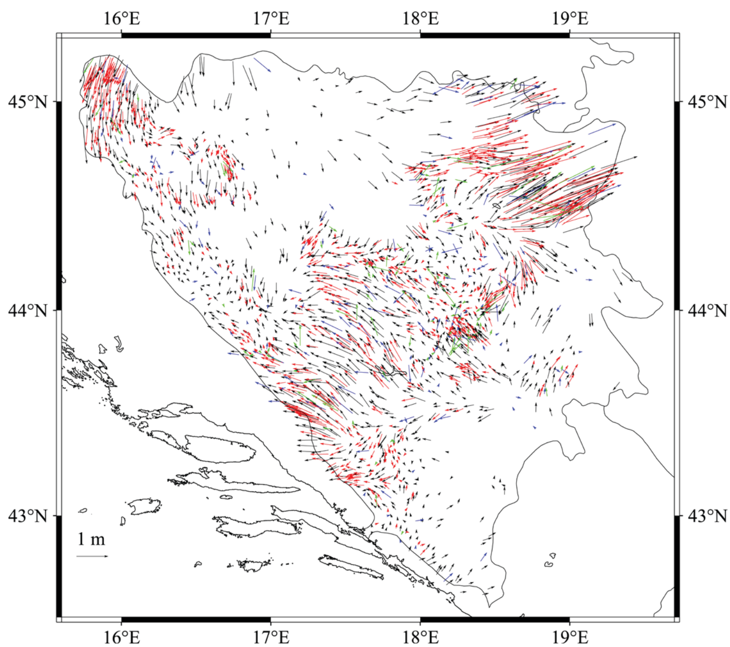

Figure 5: Residuals at points (black – SET1, red – SET2, blue – outliers SET1, green – outliers SET2)

3.2 Regular triangular network

When determining the ETRS89 coordinates of FGU GRID points, the territory of Bosnia and Herzegovina was divided into a 5 km x 5 km grid. At least one point was observed in each grid cell so that it would be as close as possible to the center of the cell. Considering that the area of the cell is 25 km2, an area of 20 km2 was chosen for the triangle area. For a smaller triangle area, a larger number of points would be required.

The Helmert and affine 2D transformations were used for transforming virtual points. Weights were calculated using the two mentioned methods. The affine 2D transformation was used for transforming coordinates within the triangle. Thus, considering the two transformation methods and the two methods for calculating weights, four transformation models were obtained:

1. P20hd (Helmert 2D transformation of virtual points with inverse distance weight)
2. P20ad (afine transformation of virtual points with inverse distance weight)
3. P20hp (Helmert 2D transformation of virtual points with area ratio weight)
4. P20ap (afine transformation of virtual points with area ratio weight)

Three criteria were used to estimate the optimal transformation model:

1. standard deviation of positional residuals,
2. maximum positional residual, and
3. percentage of positional residuals greater than 10 cm.

These criteria were applied to both sets of points. Results based on the first two criteria are shown in Figure 6. According to the first two criteria, the results for points in SET2 are almost identical. However, the results of the SET1 testing are better for the first two models.

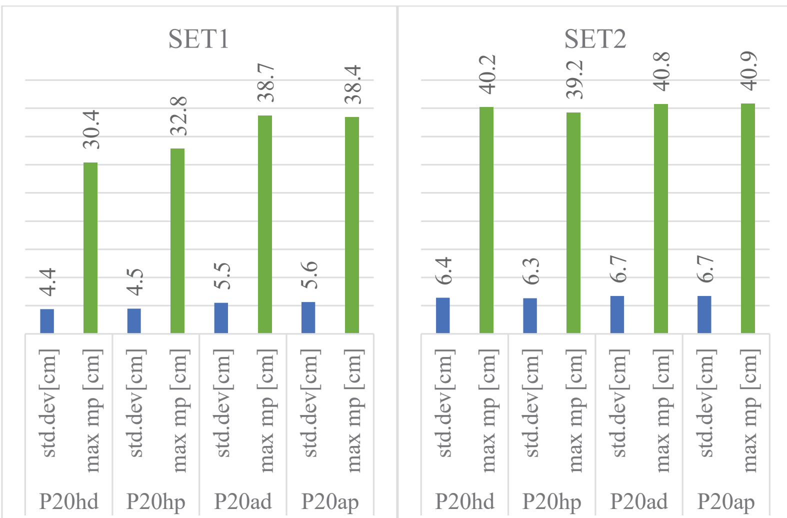

Figure 6: Standard deviation of positional residuals and maximal positional discrepancies (left – SET1, right – SET2)

According to the third criterion, the best results for SET1 are obtained by applying the second model, while the best results for SET2 are obtained by applying the first model (Figure 7).

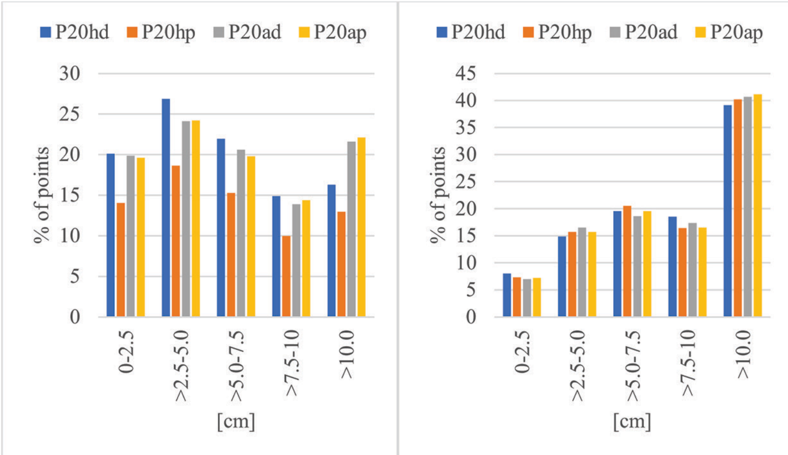

Figure 7: The percentage of discrepancies left- SET1, right SET2

Based on the set criteria, it can be said that the first two models (P20hd and P20hp) are better compared to the other two models (P20ad and P20ap). For the final model, the P20hd model was adopted here because it gives almost identical results as the P20hp model, but the computer implementation is much simpler.

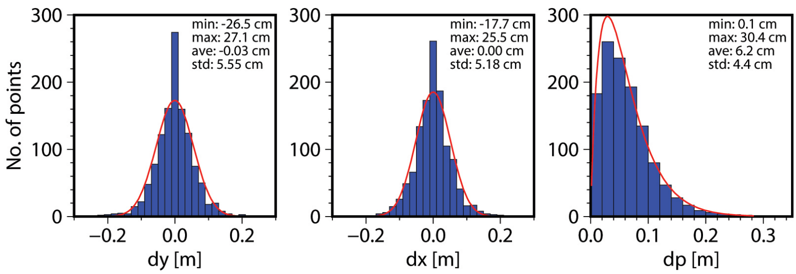

Figure 8: Histogram of differences between transformed and given coordinates for SET1

From Figure 8, it can be seen that the residuals after transforming points from SET1 using the P20hd model are centered and follow a normal distribution. The standard deviations are about 5 cm for both components. The maximum positional discrepancies dp (Figure 8 - right) is 30.4 cm, while the standard deviation is 4.4 cm. Positional discrepancies follow a chi-squared distribution.

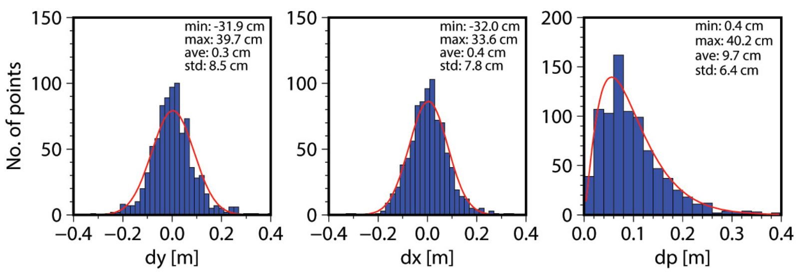

Figure 9: Histogram of differences between transformed and given coordinates for SET2

Figure 9 shows histograms of the deviations between the transformed and given coordinates for points in SET2. The standard deviations, as well as the minimum and maximum discrepancies, are slightly higher compared to the values for SET1, which is expected since these points were not used in creating the transformation model. The maximum positional discrepancies is 10 cm higher than the maximum positional discrepancies for the points in SET1.

3.3 Irregular triangular network

During the implementation of the FINELTRA method for forming an irregular triangle network, points from SET1 were used. One weakness of this method is the inability to directly test the developed model using the points used to compute the model. For this reason, virtual points from a regular grid were transformed using the FINELTRA method and then used to calculate discrepancies at given points. Discrepancies at independent points (SET2) were calculated directly using the developed FINELTRA model. The standard deviations and maximum positional discrepancies for points in both sets are almost the same as when using regular triangulation (see Figure 10).

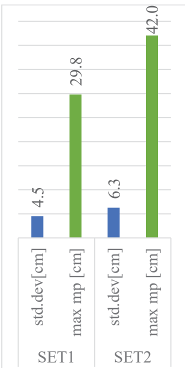

Figure 10: Standard deviation of positional residuals and maximal positional discrepancie with FINELTRA method

Figure 11: The percentage of discrepancies for SET1 and SET2 (FINELTRA)

The percentage of discrepancies greater than 10 cm for SET1 is 17.0%, while for SET2 it is 37.1% (see Figure 11). These values are almost the same as those obtained using the P20hd model.

The histograms of discrepancies for points from SET1 (Figure 12) and SET2 (Figure 13) show that the values obtained using FINELTRA model are very similar to those obtained using the P20hd model.

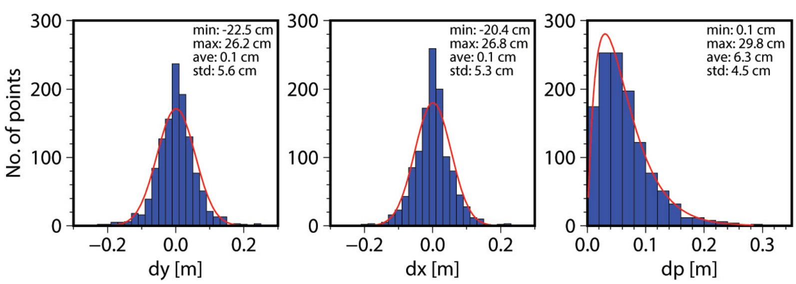

Figure 12: Histogram of differences between transformed and given coordinates for SET1 after FINELTRA transformation

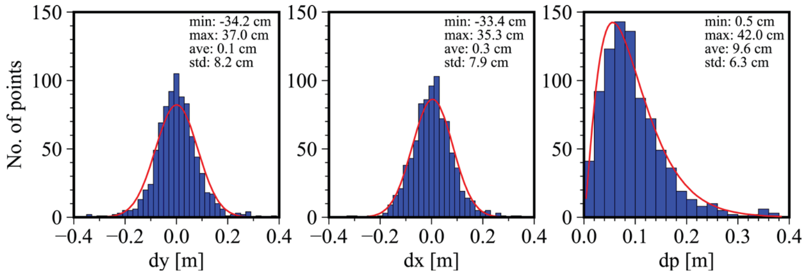

Figure 13: Histogram of differences between transformed and given coordinates for SET2 after FINELTRA transformation

4 DISCUSSION

The triangulation network in Bosnia and Herzegovina was developed through a hierarchical process that involved starting with larger triangles and gradually refining them to smaller ones. The first step was to create a first-order network, consisting of 82 points. This was followed by the development of a second-order network, which contained 424 points. If one includes points from the third and fourth orders, as well as connecting points, the network contains roughly 28,500 trigonometric points (Krajinić, 1976; Begić, 2012; Mulić et al., 2015).

The development of the triangulation network in Bosnia and Herzegovina spanned almost nine decades, and it was never adjusted as a one network. Instead, adjustment was done by blocks (Delčev et al., 2015) (refer to Figure 14).

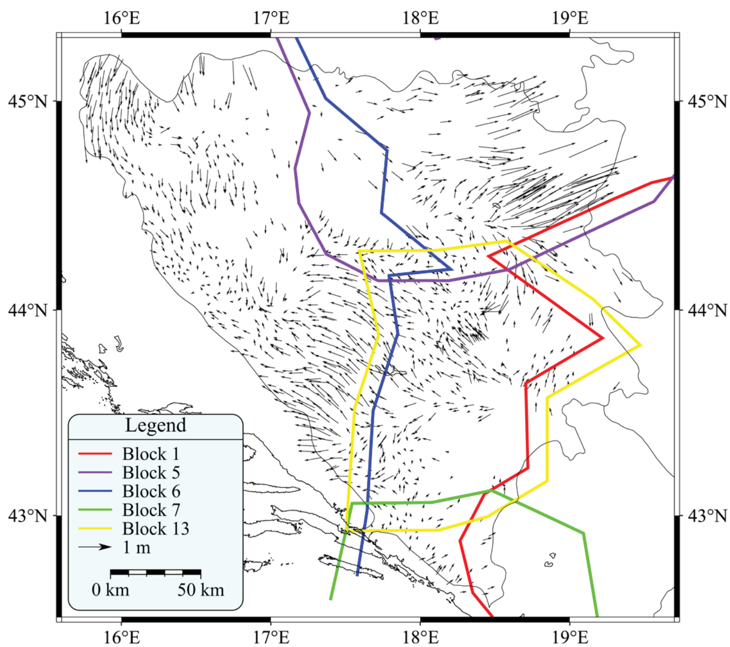

Figure 14: Correlation between blocks of triangulation networks and residuals

The accuracy of the trigonometric network in Bosnia and Herzegovina has never been established. However, Delčev's (2001) analysis of the trigonometric network in Serbia, Macedonia, and Montenegro found an average positional error of 0.6 meters. Therefore, it is clear that the trigonometric network, and thus the polygonal networks, are affected by distortion, which is neither uniform in direction nor intensity. Based on the available data used in this study, several areas that need further investigation have been identified (Figure 15). In these areas, residuals show a sudden change in both direction and intensity. It would be best to observe additional points in these areas to better model the change in the direction and intensity of the residuals.

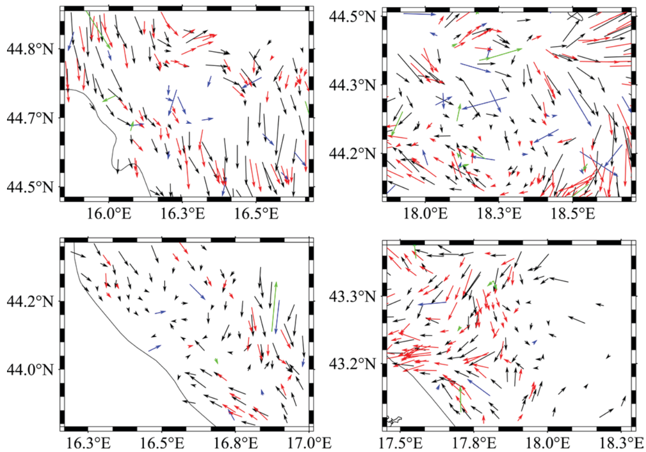

Figure 15: Areas with very problematic distortions

Looking at the results after transformation using regular and irregular triangular network, it is evident that the direction and intensity of residuals are almost identical (as shown in Figure 16).

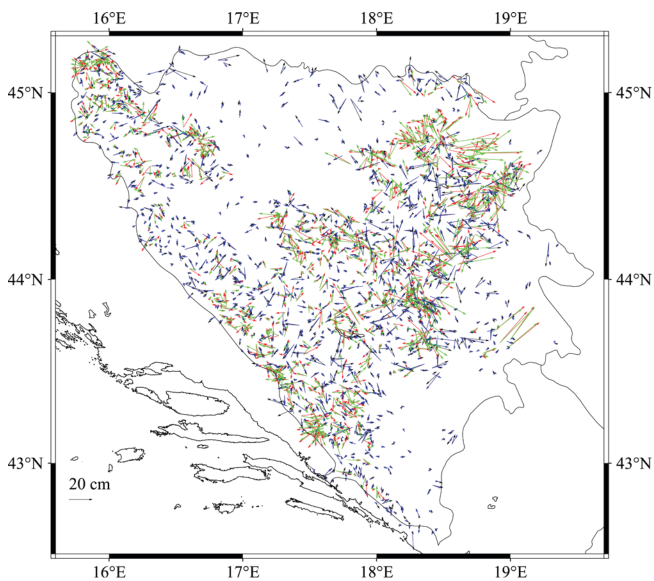

Figure 16: Residuals comparison after transformation (black – FINELTRA SET1, red – FINELTRA SET2, blue – P20hd SET1, green – P20hd SET2)

5 CONCLUSION

Based on the established criteria for selecting the best transformation model, it cannot be conclusively determined which method produces the best results. Research has shown that there are minor differences in the results obtained by the two transformation methods. The residuals after transformation are almost identical both in intensity and direction.

The obtained results indicate that satisfactory results can be achieved with the investigated methods in applications where extremely high transformation accuracy (sub-decimeter) is not required, such as agriculture, forestry, hydrology, etc.

Each of the tested methods has its own advantages and disadvantages. The advantage of the FINELTRA method over the regular triangulation method is that no virtual point network needs to be created, making it simpler to implement. On the other hand, the disadvantage of the FINELTRA method is the inability to test the accuracy of the transformation based on given points. However, every method must be tested with a set of independent points. One disadvantage of both methods is the inability to implement them in widely used GIS software such as QGIS or ArcGIS. To apply these transformation models in these software programs, GRID files must be developed, which reduces the accuracy of the models, although only slightly.

Comparing the obtained accuracy of the transformation with the results of research in the region (Kohli and Jenni, 2008; Šljivarić, 2010; Berk and Komadina, 2013), it can be concluded that the results are very similar. In the mentioned research, the maximum positional differences after the transformation are around 20 cm, while in this study, these differences are around 30 cm for SET1 and around 40 cm for SET2. Only 16 out of 1204 points (1.32%) from SET1 have positional differences greater than 20 cm, while 60 out of 849 (7.07%) points from SET2 have positional differences greater than 20 cm. It is important to note that the test points were mostly collected by RTK method, but it is unknown how the measurement was performed, i.e., how long the measurements were taken, what was the registration interval, and whether there were multiple repetitions.

The study also revealed areas where distortions are highly variable, and as such, they are difficult to model adequately. For these areas, additional testing is recommended, primarily by re-measuring the same points and measuring additional points.

The non-homogeneous distribution of input data greatly affects the practical applicability of the calculated models. The number of points in the northern and eastern parts of Bosnia and Herzegovina is significantly lower compared to other parts, and therefore, it is not possible to perform an adequate analysis of the accuracy of the models, and thus their practical application.

To investigate the possibility of using these models in the transformation of cadastral data, it is necessary to study the surface deformations that occur after the transformation in the future.

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