http://dx.doi.org/10.15576/GLL/2021.4.169

GLL

Geomatics, Landmanagement and Landscape No. 4 • 2021, 169–183

ANALYSIS OF THE GEOMETRY OF THE TPI NETPRO REFERENCE STATION NETWORK IN POLAND

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Summary

Active geodetic networks currently perform many important tasks, including supporting satellite measurements with relative methods (e,g. Real Time Kinematic, Network Real Time Kinematic). For this reason, the geometries of reference station networks should meet certain standards both in terms of optimal distances between the reference stations as well as their spatial distribution. The paper presents a spatial analysis of the TPI NETpro commercial active geodetic network and a comparison of the obtained geometric parameters with the values calculated in relation to the national ASG-EUPOS network. Voronoi polygonization (also known as Dirichlet tessellation) and Delaunay triangulation were applied to assess the geometric dependence of the location of reference stations, while the nearest neighbour analysis was used to determine the degree of clustering of reference stations. The conducted analyses showed that the analysed network of TPI NETpro reference stations is characterised by a geometry similar to the national network ASG-EUPOS. The average distance between the neighbouring stations of the TPI NETpro network, expressed as the average length of the sides of Delaunay triangles built on this network, is 64.93 km, while the analysis of the nearest neighbour showed an average distance between stations of 41.97 km. The average distance connecting the TPI NETpro network points with the nearest neighbour from the ASG-EUPOS network is 25.20 km, and 41.06 km in the case of the three nearest neighbours. It has also been demonstrated that the ASG-EUPOS network points are more dispersed than the TPI NETpro network points.

Keywords

active geodetic network • TPI NETpro • ASG-EUPOS • Voronoi polygons • Delaunay triangulation

1. Introduction

In recent years, there has been an increase in the accuracy and precision of positioning based on Precise Point Positioning (PPP) and Precise Point Positioning – Real-Time Kinematic (PPP-RTK) [e.g. Bahadur and Nohutcu 2018, Marques et al. 2018]. However, determining the position with the PPP technique requires a measurement over at least several minutes to achieve the decimetre positioning accuracy [Banville et al. 2014]. Therefore, techniques of relative positioning using corrections generated based on reference station networks continue to be very popular for surveying works.

Reference station networks for geodetic measurements distinguish between national and commercial networks. These networks serve as active geodetic networks that mainly support, among others, measurements using the Network Real Time Kinematic (NRTK) and Real Time Kinematic (RTK) techniques. Recently, the NRTK measurements have been particularly popular. Existing studies [Mora et al. 2020] prove that the location and density of reference stations, the coverage of the cellular network and the investment of space significantly impact the accuracy of the vertical position determination in NRTK measurements. Research [Mora et al. 2020] showed when there is insufficient network density, the vertical component of the position is determined by the NRTK technique with 2–4 times worse accuracy than analogous measurements with the RTK technique.

Most of the national networks in Central and Eastern Europe were created under the guidelines and technical standards of The European Position Determination System (EUPOS) [EUPOS 2021]. The national networks established in accordance with the EUPOS standards include ASG-EUPOS (Poland), SK-POS (Slovakia), CZEPOS (Czech Republic), LIT-POS (Lithuania), MOLDPOS (Moldova), EUPOS-RIGA (Latvia), ROMPOS (Romania), gnssnet.hu (Hungary), SAPOS (Germany). EUPOS standards specify that the average distance between nearest neighbouring stations should be less than 75 km, although the desired network density depends on topography and network software performance, and higher density may be useful in conurbations [EUPOS 2014]. The maximum distance between the two closest reference stations cannot exceed 100 km [EUPOS 2014], which is also confirmed by numerous studies [Wübbena and Willgalis 2001, Grejner-Brzezinska et al. 2005, El-Mowafy 2005]. As to the ASG-EUPOS network, it has been shown that typical distances between neighbouring reference stations are up to 65 km [Calka et al. 2017]. It is, therefore, possible to combine national networks created and operating based on the same EUPOS standards and consider them as a regional network located in central Europe.

Existing studies suggest designing a network dedicated to NRTK/RTK measurements so that the average values of baseline lengths between stations and mobile receivers are in the range of 50–70 km [El-Mowafy 2005, Tang et al. 2013]. The suggested optimal baseline lengths are influenced in particular by ionospheric, tropospheric and multipath errors in satellite signals. As demonstrated by Murrian et al. [2016], a network with a density of more than 5 stations per 1000 km^2 or the average distance between stations below 18 km allows obtaining values of these errors at a level lower than the multipath error of the mobile receiver. In the case of NRTK measurements, an important issue is also the spatial relationship of positioning accuracy and baseline lengths, determined with the use of FKP (German: Flächenkorrekturparameter) and VRS (Virtual Reference Station) [Gökdaş and Özlüdemir 2020] network solutions. In the case of base vectors with a length of 1.6 km to 42.8 km, no significant correlation was found between the RMSE (Root Mean Square Error) value and the variance with the baseline length. To achieve the required accuracy when using multi-frequency receivers with the possibility of working with several satellite systems, an optimal distance between the reference stations should not exceed 100 km [Wanninger 1998, Petovello et al. 2011]. In a reference network, in which the distance between the stations does not exceed 100 km, it is considered that the change of the network geometry does not lead to significant differences in positioning by the NRTK technique with the use of various types of corrections (VRS, FKP and MAC). Whereas in the case of less dense networks, i.e. distances over 100 km between stations, the obtained results of NRTK measurements may not be reliable [Dardanelli and Pipitone 2021, Wanninger 1998, Petovello et al. 2011].

In addition to national networks managed by state institutions, commercial networks developed and managed by leading geodetic companies have also developed successfully. In Poland itself, apart from the ASG-EUPOS national network, which has already been extensively covered in the literature [Bosy et al. 2007, 2008, Uznański 2012, Figurski et al. 2009], there are as many as 4 networks commercially covering the entire territory of Poland. These networks include TPI NETpro [TPINet 2021], VRSNet [VRSNet 2021], HxGN SmartNet [SmartNet 2021] and RtkNet [RTKNet 2021]. The NadowskiNet [NadowskiNet 2021] network also operates in the Śląskie, Opolskie, Małopolskie, Świętokrzyskie and Podkarpackie voivodeships. Commercial networks in Poland are differentiated by their technical parameters and available services. Nevertheless, the directors of all these networks declared in 2020 that the relative positioning services they provide allow for the determination of the horizontal position with an accuracy of ± 0.03 m and ± 0.05 m for the vertical position. The conducted research on the assessment of the accuracy of position determination in NRTK/RTK measurements with the use of corrections from all active geodetic networks in Poland showed that in most cases the achievable positioning accuracy is 1 cm for horizontal positions and 2 cm for vertical positions [Prochniewicz et al. 2020]. However, in some cases, depending on both the network and on the available corrections, the accuracy was twice lower [Prochniewicz et al. 2020].

The TPI NETpro network is the first nationwide commercial network of reference stations operating in Poland. The owner and director of the TPI NETpro network is TPI Sp. z o. o. In 2010, the TPI NETpro network consisted of 12 reference stations, while by the end of 2012 it had already 115 reference stations. The TPI NETpro network has been designed so that its reference stations would densify the existing national ASG-EUPOS network. Moreover, the research on the stability of the stations of the TPI NETpro network and the ASG-EUPOS network was carried out according to the same strategy [Figurski et al. 2015]. Figure 1 shows the spatial distribution of the reference stations of the ASG-EUPOS national network and the TPI NETpro network. As part of the concluded agreement, the alignment of the entire TPI NETpro network, the monitoring of the work of its stations and the testing of the accuracy of the services offered were entrusted to the Centre for Applied Geomatics of the Military University of Technology [GEOForum 2012]. At the turn of 2012/2013, 8 stations located in the Czech Republic (Turnov, Rychnov nad Kneznou, Krnov, Ostrava, Lysa Hora, Sluknov, Upice and Vidnava) were connected to the network, which improved the geometry of the network in border areas. In 2013, according to the reports of the network owner, the surface correction was available in 80% of the territory of Poland [GEOForum 2013a]. In the first quarter of 2013, after adding 3 new stations to the network, located in the Mazowieckie, Podkarpackie and Dolnośląskie voivodeships, the network consisted of 118 stations. In May 2013, 5 stations from Ukraine (Szack, Lviv, Velykyi Beryznyi and Sambor) were connected to the TPI NETpro network [GEOForum 2013b]. The precise coordinates of the TPI NETpro network points have been determined in relation to the points of the International GNSS Service (IGS), EUREF Permanent GNSS Network (EPN) and ASG-EUPOS. At the end of 2013, more than half of the network points were introduced to the national geodetic resource [GEOForum 2013c] as points of the detailed horizontal geodetic network meeting the requirements set out in the provisions of the law in force in Poland [Regulation of the Ministry of Regional Development of 6 July 2021/ Rozporządzenie MRPiT z dnia 6 lipca 2021 r.]. Successively, at the beginning of 2014, 3 German reference stations (Gellin, Grossraschen and Lindenberg) [GEOForum 2014] were added to the network. In mid-2014, the amendments were made available to all interested parties. Along with the development of the network, from November 2019 the TPI NETpro users can benefit from four-system adjustments, i.e. for the following systems: GPS, GLONASS, Galileo and BDS. The official website of TPI NETpro [TPINet 2021] informs that it consists of 136 reference stations evenly distributed in Poland and the border areas of neighbouring countries (Germany, Czech Republic, Ukraine). Meanwhile, the website dedicated to users of TPI NETpro network services [TPI RTK 2021] claims that the network consists of 139 reference stations (current state as of October 13, 2021). TPI NETpro network reference stations are equipped with NET-G5 receivers and CR-G5 choke ring antennas with TA-5 module based on Topcon technology. The data recorded by TPI NETpro network stations are processed by the TopNet software. There are seven types of corrections available for TPI NETpro network users in the NRTK and RTK measurement mode [TPINet 2021]. More information about the TPI NETpro network can be found on the website dedicated to this network [TPINet 2021].

The research presented in this paper aimed to analyse the geometry of the TPI NETpro reference stations network and to verify the hypothesis of whether this network may form a density of the national ASG-EUPOS network. For this purpose, spatial analyses were carried out with the use of GIS tools. In particular, Voronoi polygons and Delaunay triangulation were applied to assess the geometric relationships between the station locations. The nearest neighbour analysis was also used to determine the degree of clustering of network points. Moreover, the paper compares the geometrical parameters of the TPI NETpro network with the parameters specified for the ASG-EUPOS network. The research used data in the form of station positions of the TPI NETpro and ASG-EUPOS networks.

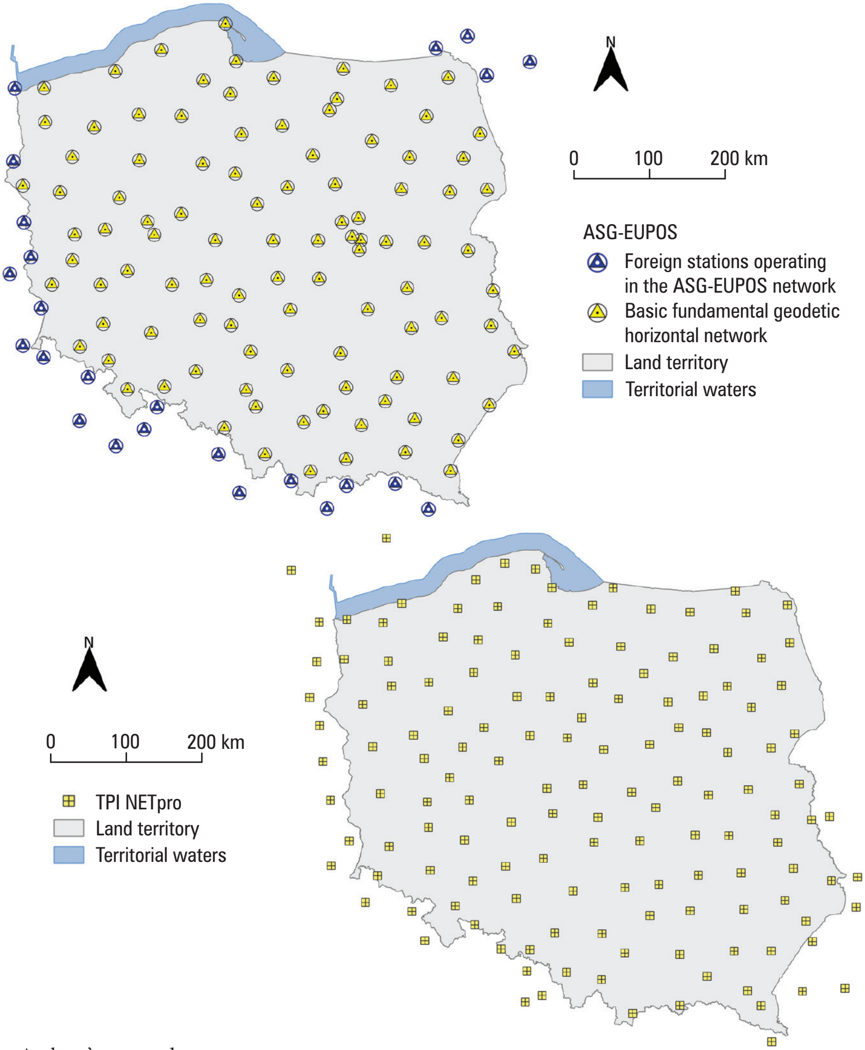

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Fig. 1. Location of stations of ASG-EUPOS network (top) and TPI NETpro network (bottom)

2. Material and methods

Voronoi diagrams with Delaunay triangulation were used to determine the geometrical relationships between the locations of the TPI NETpro network reference stations. Voronoi polygonization, which is a dual graph in relation to Delaunay triangulation, made it possible to divide the land territory and the territory of Poland, taking into account territorial waters, in relation to the location of the stations of the analysed network. Voronoi polygonization was chosen in this study due to its previous use for spatial analysis of geodetic networks [Lim and Rizos 2008, Calka et al. 2017, Kudas et al. 2020].

A Voronoi diagram consists of a mesh of polygons that is constructed around a point so that every place inside the polygon is closer to the central point than to any other point. Such a polygon is also called a Thiessen polygon or a Voronoi cell. The first step is to define the points around which the polygon will be formed. Then, based on these points, a triangle mesh is constructed, which is usually built using Delaunay triangulation. Delaunay triangulation requires meeting the condition of the so-called empty circumcircle. This condition means that the vertices of another triangle cannot be found in the circle described on each triangle. Thus, the internal angles will be at their maximum values. The range of Voronoi polygons is determined by perpendicular lines dividing the sides of Delaunay's triangles symmetrically.

In this study, Delaunay triangulation was used to build a network of triangles that were created based on points that represent the locations of the reference stations of the analysed network. Then, the side lengths of the Delaunay triangles were classified and characterized in terms of the desired distances between points in the reference network for NRTK/RTK measurements. The average length of the sides of Delaunay's triangles built on the points of the reference network can be used to describe the density of this network [Kudas 2020]. An evaluation criterion was adopted in line with the EUPOS [EUPOS 2014] standard, that the maximum distance between neighbouring stations should not exceed 100 km, while the average distance between stations should be 75 km.

Next, spatial buffers were created around the points of the analysed network. Considering the aforementioned average distance between stations in EUPOS networks, the contribution of buffers with a radius equal to half of this value, i.e. 37.5 km, should be mainly considered. Thus, the use of buffers with a radius of 37.5 km made it possible to delimit the area of Poland, including optimal conditions that should be fulfilled by the network to perform RTK measurements in any place.

The paper also conducts a Nearest Neighbour (NN) analysis, which uses the Euclidean metric and provides information on the degree of clustering of network points and the randomness of point distribution. Using the distance matrix, it is possible to analyse the average value of the distance to the nearest reference station and subsequent neighbours. NN is related to the Nearest Neighbor Index (NNI) [Clark and Evans 1954], which compares the observed average distance between the nearest points and the distances that would appear for a random distribution of points [Lian et al. 2013]:

$$NNI = \frac{d(NN)}{d(random)} \tag{1}$$

where:

$d(NN)$ – the observed average distance between the nearest points (neighbours),

$d(random)$ – a random average distance.

NNI value <1 indicates that the distances between the nearest points are smaller than in the random distribution, forming clusters. The NNI value >1, on the other hand, shows that points are more regularly positioned than in a random distribution, thereby demonstrating an even distribution.

Clark and Evans [1954] also proposed a *Z*-test to verify the null hypothesis that the spatial pattern reflects the Complete Spatial Randomness (CSR) pattern. For this purpose, the statistics defined by the following equation were applied:

$$Z = \frac{d(NN) - d(random)}{SE_{d(random)}} \quad (2)$$

where:

$SE_{d\,(random)}$ – standard error of random average distance.

For the significance level of 0.05, the statistic value read from the tables for the normal distribution is +/- 1.96. Obtaining a negative statistic value of the *Z* and lower than the tabular value indicates a more concentrated pattern. A positive value of the Z statistic and greater than the tabular value indicates a dispersed pattern. On the other hand, if the Z statistic reaches values from -1.96 to +1.96, then there is no reason to reject the null hypothesis with a theoretical random pattern.

The analyses were carried out using the QGIS program and geoprocessing tools available in the program (spatial buffer), geometry tools (Delaunay triangulation, Voronoi polygons) and analysis tools (distance matrix, NNI analysis, sum of line lengths). The research used station coordinates available to logged-in users via the network's internet system [TPI RTK 2021] available on 13 October 2021.

3. Results

Regarding the connections of the points that make up the TPI NETpro network and the ASG-EUPOS network using Delaunay triangulation, it can be noticed that distances in the range of 75-100 km between stations are more frequent within the ASG-EUPOS network than in the TPI NETpro network (Fig. 2). In addition, the average length of the sides of the Delaunay triangles for the TPI NETpro network is 64.93 km, with a standard deviation value of 30.65 km. Whereas, the value of the average length of the sides of Delaunay's triangles in the ASG-EUPOS network is 69.03 km, with a standard deviation of 36.73 km and a median value of 64.24 km. The variance value analysis showed that the side lengths' variability is greater by approx. 44% in the ASG-EUPOS network than in the TPI NETpro network. The shortest connection in the TPI NETpro network is 23.82 km, while in the ASG-EUPOS network it is 12.01 km. If the side lengths of Delaunay's triangles that exceed 125 km, i.e. those that connect the network's extreme stations, are rejected, the average length for TPI NETpro is 59.88 km with a standard deviation of 15.72 km, and the ASG-EUPOS network obtains an average value of 62.56 km with a standard deviation of 17.71 km. The obtained results concerning the average distances between the reference stations meet the recommendations for distances between stations up to 100 km, which is required to calculate accurate measurements with the use of multi-frequency receivers [Wanninger 1998, Petovello et al. 2011].

Regarding delimitation of buffer zones around network points, it can be stated that 97.6% of Poland's area (including territorial waters) is characterized by the length of the base to the TPI NETpro network reference station less than 37.5 km, and in the case of the base to the ASG-EUPOS network station, it is 92.3% of the land territory and territorial waters.

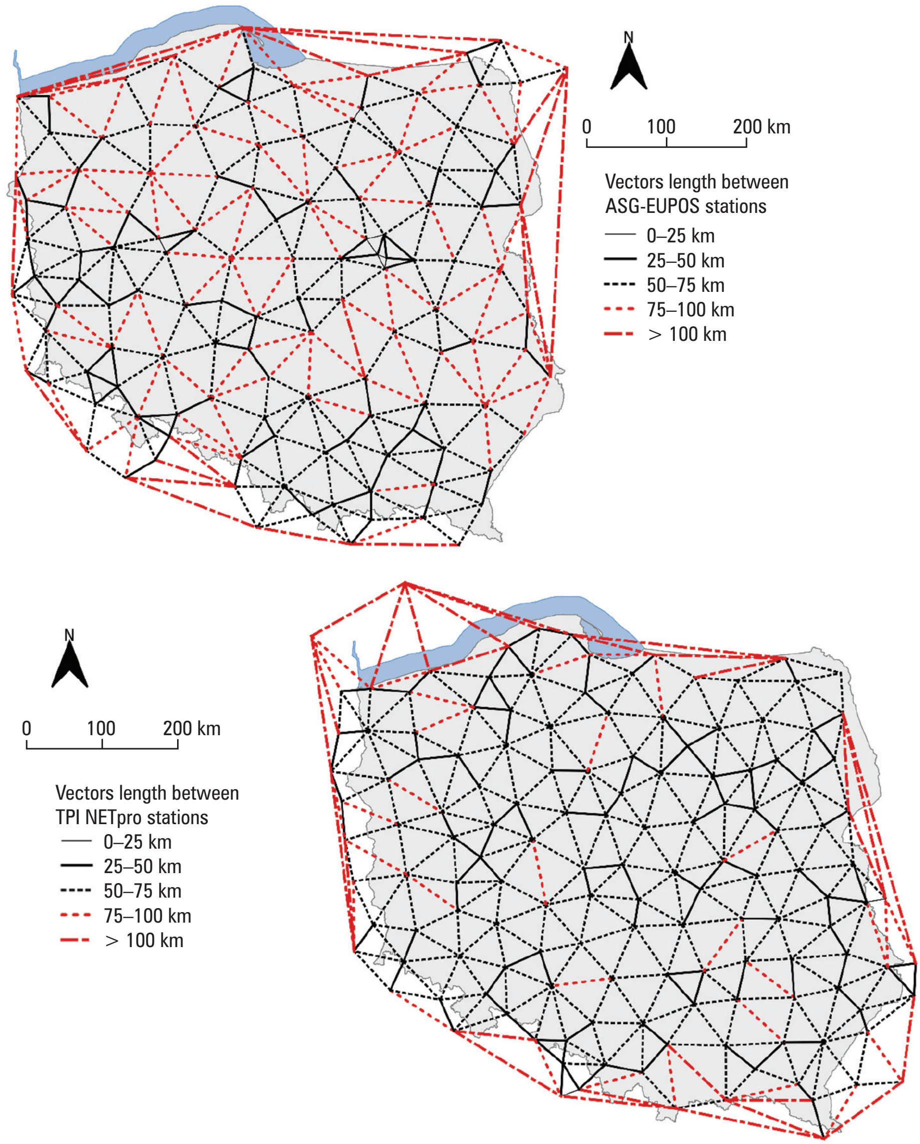

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Fig. 2. Classification of horizontal distances between points in the ASG-EUPOS network (top) and TPI NETpro (bottom) using the side lengths of Delaunay triangles

The Voronoi polygons were used to determine the adaptation of the TPI NETpro station network to the territory of Poland. Voronoi polygons were limited to the administrative borders of Poland, taking into account both the land area and the total area including territorial waters. Thus, the area of the country attributable to each reference station was determined. In the case of the TPI NETpro network and the land territory of Poland, the average area of a Voronoi cell is 2332 km^2, and its standard deviation is 907 km^2, with the areas of Voronoi cells ranging from 9 to 4054 km^2. For the ASG-EUPOS network, the average area of the created polygons is 2583 km^2, with a standard deviation of 1210 km^2, confirming previous research in this regard [Calka et al. 2017]. The values of the areas of Voronoi cells in this case range from 9 to 4905 km^2. In the case of the division of Poland with its territorial waters in relation to the TPI NETpro stations, the average area of the Voronoi cell takes the value of 2371 km^2 with a deviation of 946 km^2 and values ranging from 3 to 4054 km^2. For the set of ASG-EUPOS stations and the total area of Poland, the average area of the created polygons was 2665 km^2, with a deviation of 1268 km^2. The span of the surface of Voronoi cells stretches from 9 to 6023 km^2. Figures 3 and 4 present, respectively, histograms of the Voronoi polygon surfaces in respect to Poland's land territory and its total area.

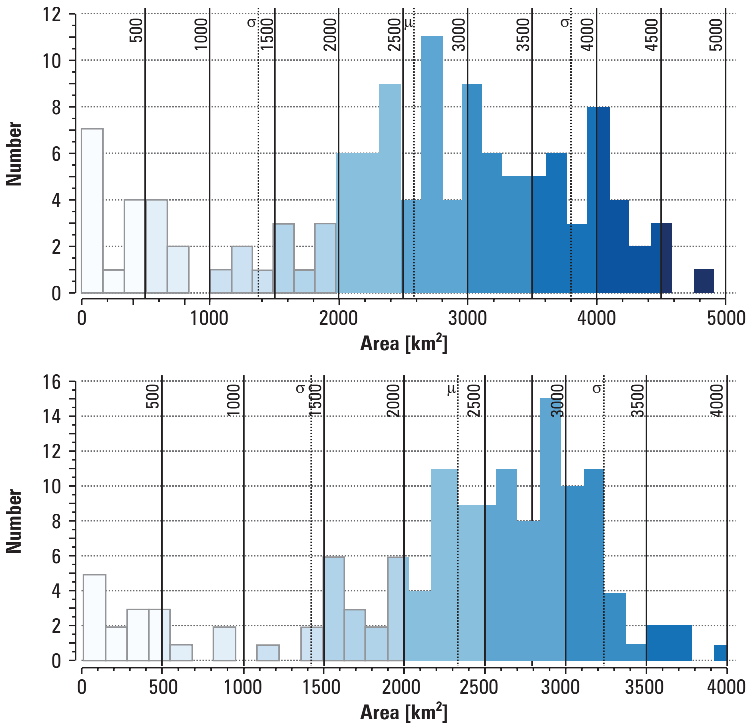

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Fig. 3. Histograms of the Voronoi polygon surfaces in respect to Poland's land territory: ASG-EUPOS (left), TPI NETpro (right)

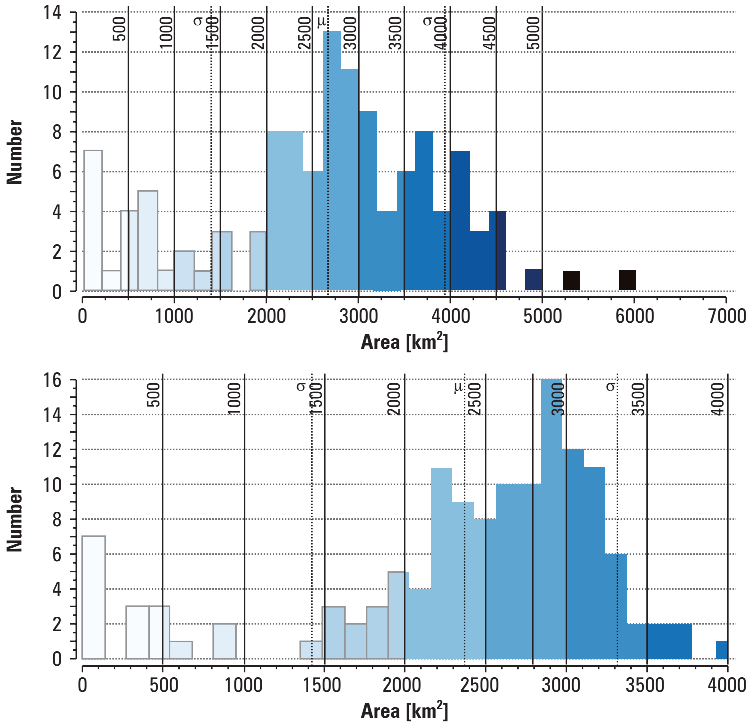

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Fig. 4. Histograms of the Voronoi polygon surfaces in respect to Poland's total area: ASG-EUPOS (left), TPI NETpro (right)

Visualization of the spatial distribution of the surface value of the Voronoi polygons (Fig. 5) makes it possible to notice that the points of the TPI NETpro network are more favourably located relative to the borders of the territory of Poland than the ASG-EUPOS network stations. Especially the configuration of TPI NETpro stations is more favourable in the northern part of Poland and provides better access to NRTK corrections in the territorial waters area.

Verification of the obtained values of the average area of Voronoi cells for the ASG-EUPOS network allows us to conclude that an analysis of Poland's land territory demonstrates that its density is in accordance with the guidelines for the points of the basic fundamental horizontal geodetic matrix (1 point per 5000 km^2 is recommended). While in the case of territorial waters this condition is not met (Fig. 5).

The NN analysis indicates that the average distance between stations in the TPI NETpro network is 41.97 km and the expected value is 30.10 km. In the case of ASG-EUPOS, this parameter is 42.27 km, with an expected value of 29.67 km. the NNI value for the TPI NETpro network is 1.39 with the *Z* statistic of 8.99, while for ASG-EUPOS, according to existing studies, the NNI is 1.42 [Kudas 2020], with the *Z* statistic of 9.08. A comparative summary of statistics based on the analysis of the nearest neighbour is included in Table 1. Analysing the value of the statistic *Z* and comparing it with the value of +/−1.96 for the normal distribution, it should be concluded that at the significance level of 0.05, the observed spatial patterns of the analysed networks feature distribution, which is not random. Similar conclusions for the ASG-EUPOS network were obtained by Calka et al. [2017].

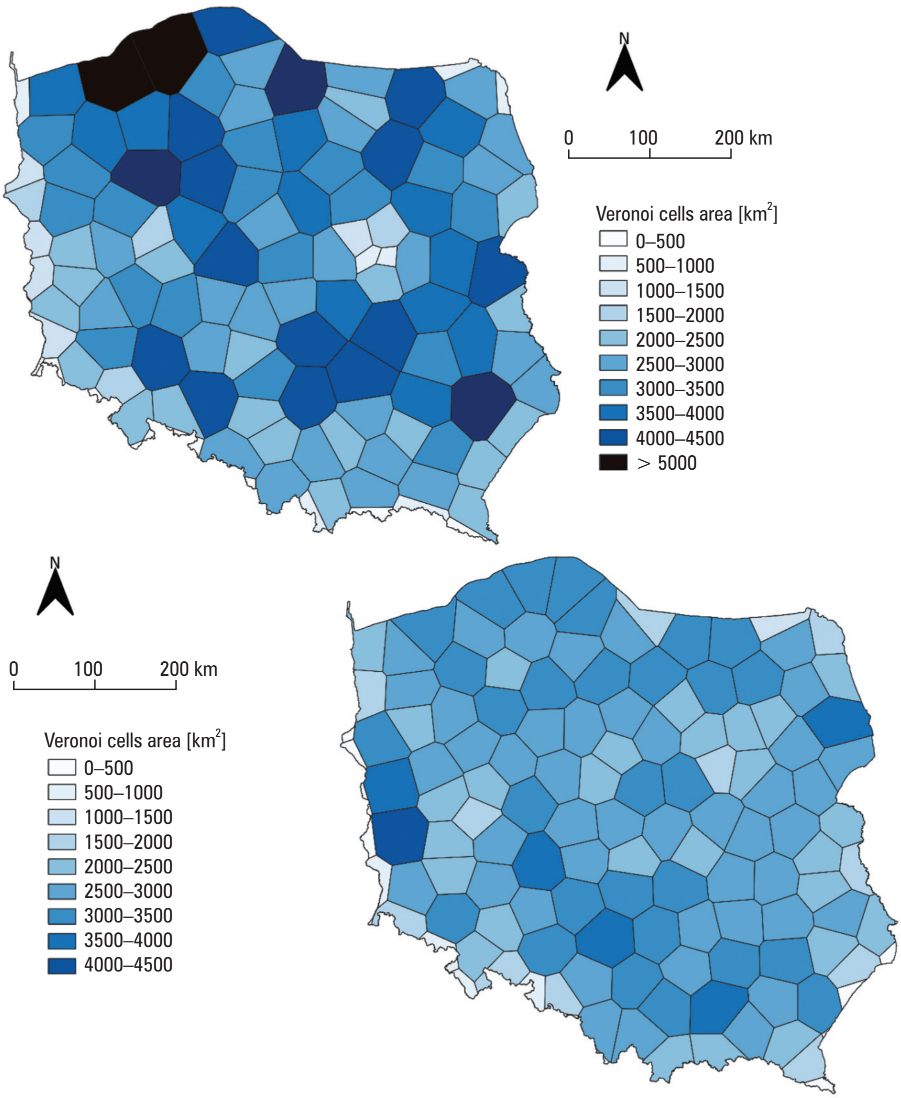

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Fig. 5. Spatial differentiation of the surface of Voronoi cells constructed by the points of the ASG-EUPOS network (top) and TPI NETpro (bottom)

Table 1. Results of the nearest neighbour (*NN*) analysis for the ASG-EUPOS and the TPI NETpro networks stations

	ASG-EUPOS	TPI NETpro
Observed average distance [km]:	42.27	41.97
Expected average distance [km]:	29.67	30.10
Nearest neighbour index:	1.42	1.39
Number of points:	125	142
Statistics *Z*:	9.08	8.99

To investigate the alignment of the location of the TPI NETpro station with the ASG-EUPOS network points, the value of the average distance connecting the TPI NETpro network points with the nearest neighbour from the ASG-EUPOS network, as well as with two and three nearest neighbours was examined. The change of distance to the nearest neighbour and the three nearest neighbours for each station from the TPI NETpro network is presented in Figure 6.

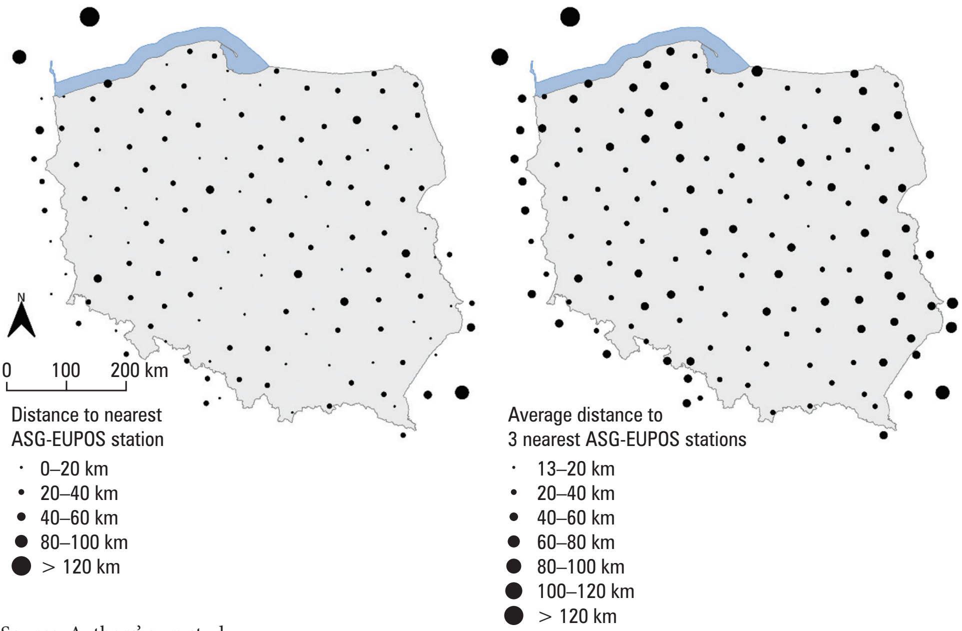

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Fig. 6. The distance of a TPI NETpro station to the nearest neighbour from the ASG-EUPOS network (left) and the average distance to the three nearest neighbours (right)

The analysis showed that the average distance is 25.20 km, with a standard deviation of 15.93 km. For the average distance to the two nearest neighbours from the ASG-EUPOS network, the distance is 34.21 km, and the deviation is 13.48 km. However, in the case of an average distance to the three nearest neighbours from the ASG-EUPOS network, the average distance is 41.06 km, with a standard deviation of 13.46 km. Thus, it can be concluded that the calculated average distance between TPI NETpro and ASG-EUPOS network points is close to half the value of the average distance between stations recommended by EUPOS standards, i.e. 37.5 km. This demonstrates the correct densification of the ASG-EUPOS network with the TPI NETpro stations.

4. Conclusions

Currently, reference stations of commercial networks on the territory of Poland are classified as detailed networks points. This does not mean, however, that commercial reference networks are to be characterized by a density of points corresponding to the classic geodetic network, because the average length of a side of a classic detailed network is about 250 m [Oleniacz and Skrzypczak 2012]. In the case of active geodetic networks, it is crucial to select the right distance between stations to ensure appropriate conditions for the provision of services, in particular in the form of providing corrections for real-time measurements NRTK/RTK. The research presented in this paper has shown that the commercial reference station network TPI NETpro has a spatial geometry similar to the national network ASG-EUPOS. Furthermore, the TPI NETpro was proven to have a more regular geometry (Fig. 5) and smaller values for horizontal distances between stations (Fig. 2). The analysis of distances of the TPI NETpro network points to the three nearest neighbouring points from the ASG-EUPOS network showed that the average distance is 41.06 km. Therefore, the hypothesis that the TPI NETpro network densifies the national ASG-EUPOS network was verified. It was also shown that the spatial patterns of both analysed reference station networks are dispersed and do not form clusters. The research showed that the ASG-EUPOS network points are slightly more dispersed than the TPI NETpro network points. This fact is also confirmed by the analysis using the lengths of sides of Delaunay triangles, which provided information that in the ASG-EUPOS there is a larger number of sides with lengths exceeding 75 km than is the case in the TPI NETpro.

Financed by a subsidy from the Ministry of Education and Science for the University of Agriculture in Krakow for 2021.

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