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GEODYNAMIC STUDIES IN THE PIENINY KLIPPEN BELT IN 2004–2020

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ABSTRACT. The Pieniny Geodynamic Test Field is situated in the middle of the region between the Inner and Outer Carpathians. Geodynamic research conducted in the past in the Pieniny Klippen Belt (PKB) region were suggestive of neotectonic activity. The goal of the investigation was to determine whether the nearby structures, the Podhale Flysh (FP) and the Magura Nappe (MN), are affected by neotectonic activity in the PKB. The goal of the study was to ascertain the velocity and direction of motion of stations situated close to the Pieniny Geodynamic Test Field's 3 main structures. Twelve GNSS stations, including 6 in the PKB, 3 in the MN, and 3 in the FP, make up the Pieniny Geodynamic Test Field. Three GNSS sites in the Tatra Mountains (TM) complete the entire geodynamic test field. The satellite observations made between 2004 and 2020 (excluding the year 2005 due to lack of observation) were investigated to identify the horizontal movements. Using the IGb14 reference system, the station's positions and velocities were calculated. First, daily sessions were used to process the horizontal coordinates of the points for an average observation epoch in a given year. Sixteen measurement epochs were included in the long-time solution. Based on the horizontal velocity residues in the north–south and east–west directions, the station's movement was calculated. The collected results were compared to information from the EUREF Permanent GNSS Network (EUREF) and to the findings of prior research on the tectonic activity of the PKB. The results of horizontal displacements calculated using GNSS measurements in the area of the PKB and nearby structures—the MN and the FP are presented and analyzed in this article.

Keywords: The Pieniny Klippen Belt, geodynamics, horizontal movements monitoring

1. INTRODUCTION

The Pieniny Klippen Belt (PKB) is a zone with a width of several hundred meters to 20 kilometers. The length of the PKB is about 900 kilometers. The PKB consists of Mesozoic and Paleogene rocks. It runs among the rocks surrounding it and sediments coming from the tertiary order. It is part of a narrow arc-shaped zone that stretches from Marmosha in the Romanian Carpathians to Vienna in the Eastern Alps. It separates two significant structural units of the Carpathians, namely: the Outer Carpathians and the Inner Carpathians. The Outer Carpathians are located north of the PKB, while the Inner Carpathians are located on its south side (Figure 1). The part of the PKB located on the territory of Poland is about 60 kilometers long. In the Pieniny it reaches the widest width of 5 kilometers (Birkenmajer, 1974).

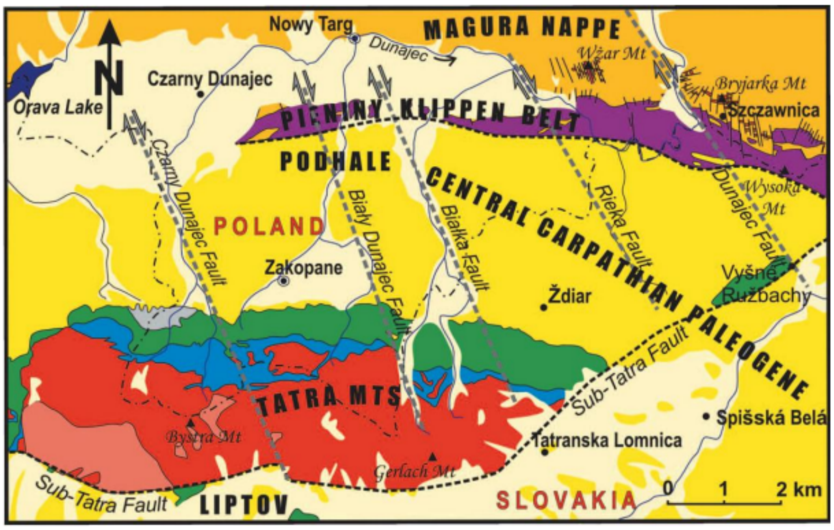

Figure 1. The geological structure of the Pieniny Klippen Belt (Jurewicz, 2005)

Its distinctive feature is a very diversified morphology. This is because some stratigraphic cells—mostly Jurassic—are built of hard layers, which morphologically are marked as ridges and hills. On the other hand, where there are solinks–mostly from the Cretaceous period–you can meet passes, valleys, and other types of terrain depressions (Birkenmajer, 1986). Tectonics in the area of the PKB is closely related to the Carpathian an orogen of the localization type. The main feature of localization type orogens is forceful compression, as well as the resulting tectonic transport. During the tertiary movements of the tectonic plates, the phenomenon of subduction of the European plate under the Pannonian plate occurred. A subduction zone in the Carpathians ran along the PKB. The sedimentary structures in this zone have been strongly compressed into a narrow strip of scales and folds. During the studies, which were carried out using the method of seismic refractive profiling on the 5 international profiles, a significant change in the flesh of the Earth crust was documented. This occurred in the bedrock at a depth of 35 kilometers in the area of the FP, while in the area of the MN at a depth of 50 kilometers width of several hundred meters to 20 kilometers (Czarnecki, 2004). Based on the known geological structure of the PKB, it can be concluded that there will be increased tectonic activity in this region (Birkenmajer, 1986).

The Pieniny Test Field in the area of the PKB was established in the year 1978. The location of the points was chosen in such a way that it was possible to study the changes in the position of the points located in the PKB in relation to the MN and the FP. In the year 2001, the existing horizontal network was modified for Global Navigation Satellite Systems (GNSS) observations. New points have been stabilized in locations where GNSS observations were possible for longer sessions, as well as to replace some points of the classic network with satellite points in the future. Currently, GNSS measurements on network points have been carried out since 2004. Measurements are carried out annually at the beginning of September. Until the year 2008, satellite surveys were based solely on GPS. Currently, observations are made using 3 systems—GPS, GLONASS, and Galileo. The study carried out in 2016, covering 11 measurement epochs (years 2004–2015) showed submillimeter movement of units of the PKB and its surrounding units. In a recent publication (Walo et al., 2016), the following recommendations were made: continuation of GNSS satellite surveys in the network points existing to date and repetition of the observations within this area every 3 to 5 years. According to them, after the lapse of 5 years, another study was carried out, aimed at confirming or excluding horizontal movements of the PKB relative to the surrounding structures. The current studies used data from a larger number of reference stations (i.e. 24 reference stations were used instead of previous 5), determined the velocity of motion of points in a two-track way—based on strict time series of horizontal coordinates and horizontal velocity residues. The first of these is approximate, although it allows determining the direction of movement of individual points. A comparative analysis was also carried out with the EUREF model and with the results of previous studies, coming from the year 2016.

2. DATA AND METHODS

The Pieniny Geodynamic Test Field has a meridian course, which is perpendicular to all units on which GNSS stations are located, the MN, the FP, and the PKB. The location of the test field points, not only in the area of the PKB but also in the area of its contact zones, is significant. It allows determining how the position of the PKB changes in relation to the MN, surrounding the PKB from the north and the FP, located to the south of the PKB (Figure 2).

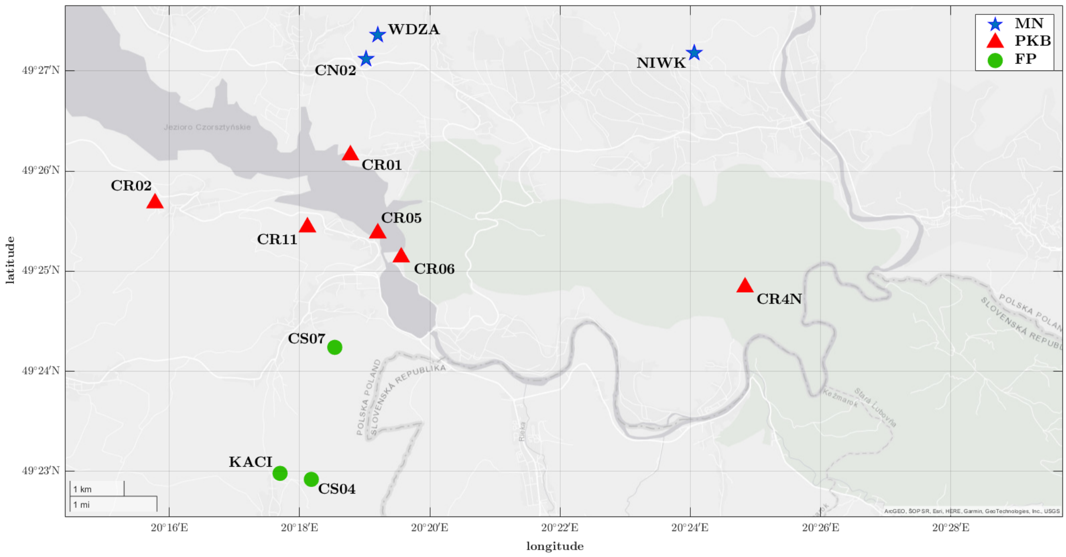

Figure 2. The map points of the Pieniny Klippen Belt (red triangles), the Magura Nappe (blue stars), and the Podhale Flysh (green circles)

The Pieniny Test Field includes 12 GNSS stations:

- 6 stations inside the PKB,
- 3 stations within the MN,
- 3 stations within the FP.

The Pieniny Geodynamic Test Field is supplemented by 3 stations situated in the TM (GUBA, HAGA, KAWI). The GNSS network is stabilized in the form of brass bushings located in the native rock, allowing for forced centering of GNSS antennas. Since 2004, observations have been made annually in the first decade of September. The duration of observations at individual points in the network is varied. For base points measurements last 72 hours, while for other points the observation session lasts from 6 hours. The informations of measuring epochs for each point in the Pieniny Test Field area are presented in Table 1.

Table 1. List of measuring epochs for each point in the Pieniny Test Field area

Station	Unit	Duration of the measurement session [hours]	Measuring epochs	Number of epochs
CR01	**PKB**	6.0	2004, 2006 – 2020	16
CR02		6.0	2004, 2006 – 2020	16
CR4N		6.0	2006, 2008 – 2020	16
CR05		6.0	2004, 2006 – 2020	16
CR06		6.0	2004, 2006 – 2020	16
CR11		6.0	2004, 2006 – 2014	10
NIWK	**MN**	6.0	2004, 2006 – 2020	16
WDZA		72.0	2004, 2006 – 2020	16
CN02		6.0	2004, 2006 – 2015	11
KACI	**FP**	72.0	2004, 2006 – 2020	16
CS04		6.0	2004, 2006 – 2015	11
CS07		6.0	2004, 2006 – 2020	16
GUBA	**TM**	72.0	2004, 2006 – 2014	10
HAGA		72.0	2004, 2006, 2008 – 2020	15
KAWI		72.0	2004, 2006 – 2020	16

Measurements are carried out using two measuring sets: Trimble 4007 receiver and Trimble Micro-Centered L1/L2+GP antenna and Leica GX1230GG antenna and LEIAX1202GG antenna. Individual antennas are assigned to specific points so that it is possible to eliminate the error associated with the antenna offset. Observations are performed at intervals of 30 seconds. The elevation out-off angle equals 5 degrees each time.

Data from the years 2004–2020 (excluding the year 2005—observations in that year were made, although data from that year were lost) were developed to determine the velocities of horizontal movements of network points. Analyze time intervals covering 4 days in the first week of September each year. Detailed dates of development were related to measurements at the points of the Pieniny Geodynamic Test Field. The least observed are at points where measurements are no longer performed (CN02—since year 2015) or were added to the network later (CR4N—in year 2006), what is shown in Figure 3. The following Figure 4 shows the number of observations for each of the points forming the GNSS network. Most observations were made at base points.

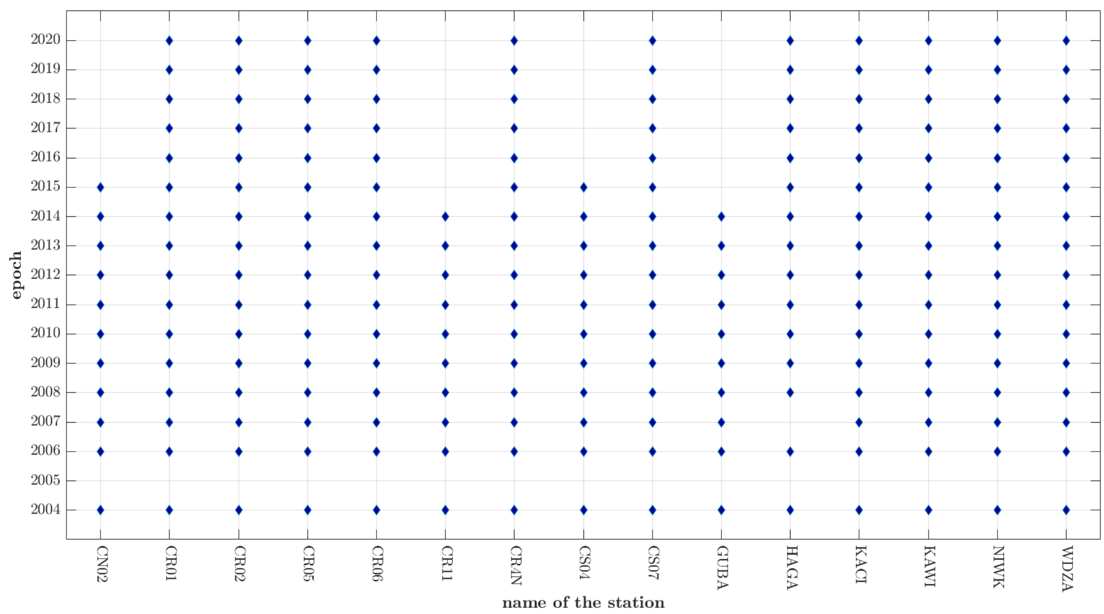

Figure 3. The plot showing the measuring epochs for each point in the Pieniny Test Field area

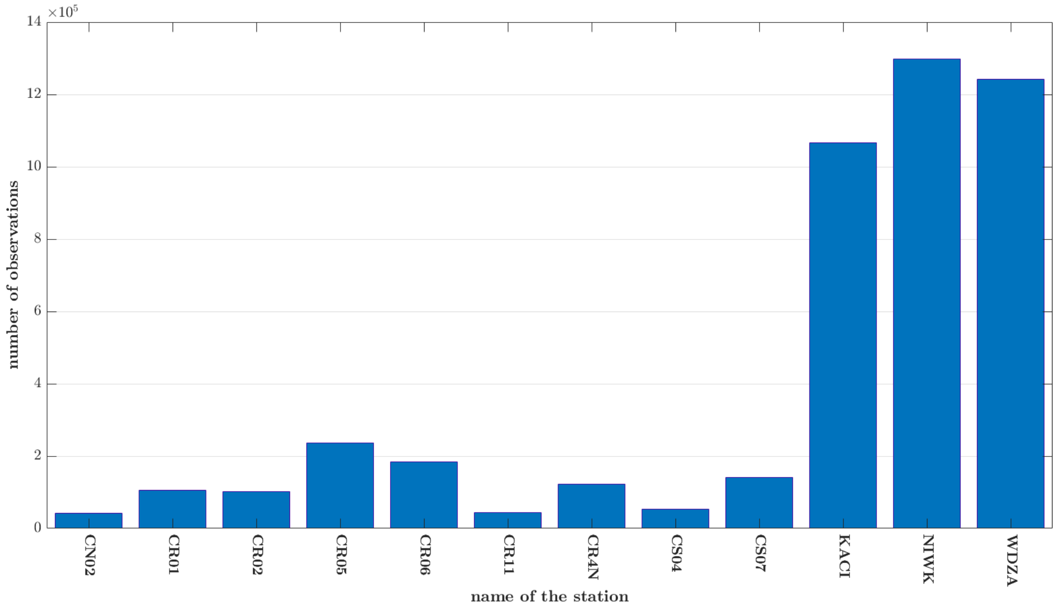

Figure 4. The histogram of the number of observations at each point of the Pieniny Geodynamic Test Field

The study uses Reprocessing 2 products from the Analysis Center at the Institute of Astronomy at the University of Bern (CODE) (Dach et al., 2015). The second reanalysis of the full history of GPS data collected by the International GNSS Service (IGS) global network since 1994. The data included Earth rotation parameters, GNSS orbit coordinates, satellite clock corrections, coordinates, and station velocities. In the adjustment in the IGb14 system, the consistency between the IGS products and the reference system was not maintained—the orbital data came from the Reprocessing 2, which was associated with the IGS08 system (Völksen, 2013). The reference frame file is IGb08.snx in SINEX format. The Reprocessing 2 uses updated igs08.atx ”absolute” antenna calibrations and GPS time is used for all output analysis products. The igs08.atx includes phase center offsets and direction-dependent phase center variations. However, for small local area networks, this approach is acceptable (Liwosz, 2017). The measurements are developed using Bernese GNSS Software 5.2 (Dach et al., 2015).

To define the IGb14 system, 24 stations EUREF (Euref Permanent GNSS Network) were used. The points were selected based on the following criteria: location, length of available data and as few gaps in measurement series as possible (gaps mean lack of observation). The stations were selected so that they were located at the shortest distance from the Pieniny Geodynamic Test Field, as well as to be evenly distributed. For evenly spaced reference stations, the results of the determination of the horizontal coordinates should not differ by more than 1 cm for the horizontal components and by more than 2 cm for the vertical components to achieve the ETRS89 system. Used stations are shown in Figure 5.

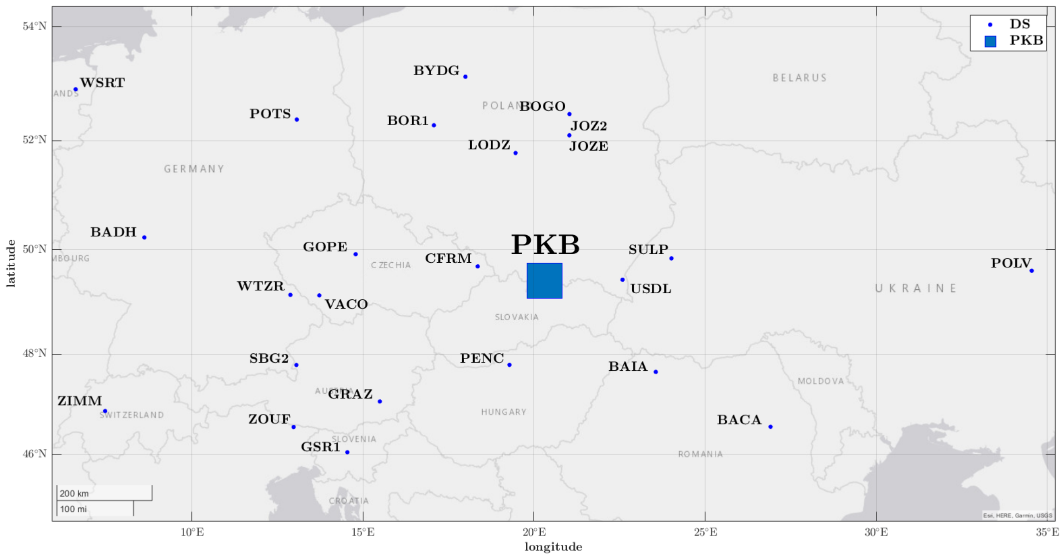

Figure 5. The map of datum definition sites

A large number of noncontinuities, which most often result from hardware changes—antennas or receivers, when determining the velocity of points in long-time solutions, affects a significant decrease in accuracy (Dach et al., 2015). Therefore, the stations that have the least discontinuities were selected. The number of discontinuities for EUREF's stations is shown in Table 2.

Table 2. Number of discontinuities for EUREF's stations

Number of discontinuities	Station
0	BOGO ZIMM ZOUF
1	BACA BADH BAIA BOR1 CFRM GSR1 JOZ2 LODZ PENC POLV SULP USDL VACO WSRT
2	BYDG GOPE JOZE SBG2 WTZR
4	GRAZ POTS

The development was done in the IGb14 system. To check with the results of existing studies, the calculations were also performed in the IGS08 system. In the IGS14 system, antenna calibrations (igs14.atx) have been updated compared to the previous ones (igs08.atx). Satellite antenna calibrations have also been updated. In addition to the medium models, igs08.atx and igs14.atx, the stations of the EUREF Permanent GNSS Network (EPN) and the Active Geodetic Network

(ASG-EUPOS) have individual antenna calibrations. The results of these calibrations have been included in this study. Changes in the position of the phase center of the antenna are one of the dominant sources of errors associated with the measuring station. Ignoring the change in the position of the phase center of the antenna may cause errors in the determination of individual position parameters, especially the vertical component (Rothacher and Mader, 1996; Mader, 1999; Hofmann Wellenhof et al., 2008; Kersten and Schön, 2016). The first stage of the study was to determine approximate coordinates for the stations forming the Pieniny Geodynamic Test Field. The Precision Point Positioning (PPP) method was used for the processing. Then, using the template of the next procedure, RNX2SNX.PCF—which was modified accordingly, the whole network was adjusted. The RNX2SNX.PCF script allows calculation of station coordinates and determination of troposphere parameters for all stations included in a given reference system. It also allows you to generate normal equations. The RNX2SNX is part of the Bernese Software. The parameters used to determine approximate coordinates using the RNX2SNX. Ephemerides were used to process GNSS data and parameters of the pole expressed in IGb08. In addition to the properly marked observation files, it was necessary to enter a number of data concerning the stations and their equipment, satellites, and orbits, as well as parameters related to geodynamics, atmosphere, and reference system. The first stage of the development was to determine errors of GPS receivers on the basis of code observations, using the values from the telegraph satellite navigation. The study was based on double differences of observation for each independent vector, using double frequencies. Process control file (PCF) procedure is shown in Table 3.

Table 3. The GNSS processing parameters

Observation modeling	
Epoch	01 01 2010
Observations	GPS, GLONASS, Galileo
Satellite orbits	CODE, IGS Reprocessing 2
Baseline creation strategy	max. number of common obs.
Amibiguity observation strategy	QIF
Sampling interval	300
Ionospheric model	CODE
Phase center variations	igs14.atx
Reference frame	IGb14
PCV model	I14
Earth orientation parameters	
Nutation model	IERS2010
UT1–UTC	IGS (IERS)
Orbit modeling	
Coeff. of Earth potential	EGM 2008
Subdaly pole model	IERS 2010
Ocean loading corrections	FES2004
Planetary ephemeris file	DE405
Station movement	
Ocean tidal loading	FES2004
Subdaily pole model	IERS 2010

The solutions were determined with the imposition of the conditions of a free network. The orbit parameters of the satellites have been found to be error-free. Based on the coordinates of GNSS stations assigned for each epoch, velocity vectors in the geodynamic network have been determined. After calculating daily GPS solutions, annual (cumulative) solutions were

also created, covering the days on which measurements were made at network points in a given year. When determining the cumulative coordinates, the only external information was the data on the orbits of the satellites. Using this approach, the network geometry is created only based on GPS, GLONASS, and Galileo's observations and is not burdened with station errors. Thanks to this solution, it is possible to analyze time series, which are interpreted as geophysical phenomena (Dach et al., 2015). The measurements were developed in one-day sessions. After the first adjustment, the a priori coordinates obtained from PPP have been corrected. The end coordinates for the stations were determined with minimal limitations on the translation parameters for the measured epoch. There are no minimum restrictions on all 7 parameters (translation, rotation, and scale) connected with the Helmert transformation, as this introduces too many degrees of freedom for local networks. The selection of translation parameters only to the geometric center of the network is conditioned by the fact that in this case the errors of the station coordinates do not reduce the accuracy of the reference system and do not distort the geometry of the network (Blewitt, 2013). The introduction of minimum restrictions serves to eliminate the peculiarities of the matrix of normal equations. Choosing the right free network conditions has an impact on the predetermined coordinates and velocities of points in the network, especially for small local networks, where the correlation between transformation parameters is quite high (Liwosz, 2017). In the long-time solution, discontinuities at reference stations were enabled—here data EPN08.SCC and EPN14.SCC were used (https://epncb.oma.be/ftp/station/coord/EPN/).
Based on the results obtained in the process of balancing the residues between the daily and the long-time (multiyear) solutions, time series of coordinates changes and time series of the velocity residues of the GPS stations were developed. A 3-parameter Helmert transformation, which defines only translation, was used to check the quality of the system independently for each solution. The following criteria were adopted for the reference stations defining the system: 8 mm for the topocentric elements N and E and 15 mm for the coordinate U (Dach, et al., 2015). If any of the stations exceeded the declared limits, it was eliminated from the definition of the reference system. For the selected 24 stations, the above criteria have been met, so each solution is homogeneous in terms of its reference. Long-time solutions were computed using ADDNEQ2. Based on the obtained time series of residuals, it was possible to exclude outliers, as well as to introduce discontinuities at the stations of the Pieniny Geodynamic Test Field.

The horizontal velocities were determined in two ways—using the **[1]** formula and using the EPN CB Coordinate Transformation Tool app provided by EPN.

$$\dot{X}^E_{yy} = \dot{X}^I_{yy} + \begin{pmatrix} 0 & -\dot{R}3_{yy} & \dot{R}2_{yy} \\ \dot{R}3_{yy} & 0 & -\dot{R}1_{yy} \\ -\dot{R}2_{yy} & \dot{R}1_{yy} & 0 \end{pmatrix} \times X^I_{yy} \tag{1}$$

where:

X^I_{yy} – vector of station coordinates in ITRS;
$\dot{X}^I_{yy}$ – vector of station velocity in ITRS;
$\dot{X}^E_{yy}$ – vector of station velocity in ETRS.

The rotation velocity parameters $\dot{R}1_{yy}$, $\dot{R}2_{yy}$, $\dot{R}3_{yy}$ are the 3 components of the Eurasian Euler vector expressed in ITRF$_{yy}$.

The ETRS definition defines only station horizontal traffic conditions. The vertical velocities of the stations are the same in both the ITRS and the ETRS. It is also worth noting that the values of interpolate velocities determined in the ETRF system for the area of Poland do not reach too high values (Szafranek, 2012).

The station velocities were determined in two ways—using the diagram contained in ”EUREF Technical Note 1: Relationship and Transformation between the International and the European Terrestrial Reference Systems” (Altamimi, 2018) and using the EPN CB Coordinate Transformation Tool provided by the EUREF Permanent Network (EPN) at http://epncb.oma.be/_productsservices/coord_trans/ (Bruyninx, 2016).

3. HORIZONTAL MOVEMENTS

This study described only horizontal movements because there was no adequate data to determine the vertical coordinates. Horizontal coordinates have been determined for a range of 16 measurement epochs. It is obvious that the greater the number of epochs, the greater the reliability of the determination of horizontal or vertical movements. Horizontal coordinates were determined in both ways—in daily and in long-time solutions covering 16 measurement epochs. The longer the observation sessions at the points of the network, the greater the certainty of determining the coordinates. Based on the coordinates of the reference stations defining the reference system, the coordinates of the stations on the Pieniny Geodynamic Test Field for each epoch were determined, as well as the vectors of horizontal velocities. The horizontal coordinates of the points for a given observation period were determined as a weighted average from daily solutions. The inverse of the squares of the mean errors (RMS) for the individual coordinate components were taken as weights. On this basis, it was possible to determine the linear trend of coordinate changes in the topocentric system. Residues were marked north–south (North component) and east–west (East component). They were calculated by subtracting the velocity of the Eurasian Plate, which was determined based on model ITRF2014. For the development of IGS08 the model ITRF2008—Plate Motion Model was used (Altamimi et al., 2016). Coordinates and their velocities are expressed in ETRF2010 for the epoch 01.01.2010.
In the first step, the observed velocities of the reference stations from the IGb14 system were compared with the actual velocities from the EUREF model to check the correctness of the calculations. The linear trend of coordinate changes was then calculated based on the strict time series of coordinates of the network of points constituting the Pieniny Geodynamic Test Field. In the next step, time series of horizontal velocity residues were developed and on this basis the velocities of the stations included in the Pieniny Geodynamic Test Field were determined. Additionally, an adjustment of the observations in the IGS08 system was also performed for the first 11 measurement epochs. Analysis in the IGS08 system was carried out to check the correctness of the obtained results, as it could be compared with the previous analysis of data from the year 2016.

3.1. Comparison with the EUREF model

To check the correctness of the performed adjustment, the velocities calculated for the reference stations were compared with the data from the model provided by EUREF (https://epncb.oma.be/ftp/station/coord/EPN/). The average differences between the adjustment values and the model values are at the level of one-hundredths of a millimeter. Highest differences in our case are equal to ± 0.1 mm/year and concern reference stations with a high number of discontinuities (e.g. GRAZ, POLV, LODZ). Discontinuities were directly related to hardware changes and were introduced into adjustment. There are not any spatial coherency between residuals and stations location. Differences of residual horizontal velocity values for each component (north and east) between the EUREF model and the adjustment results are shown in Figure 6.

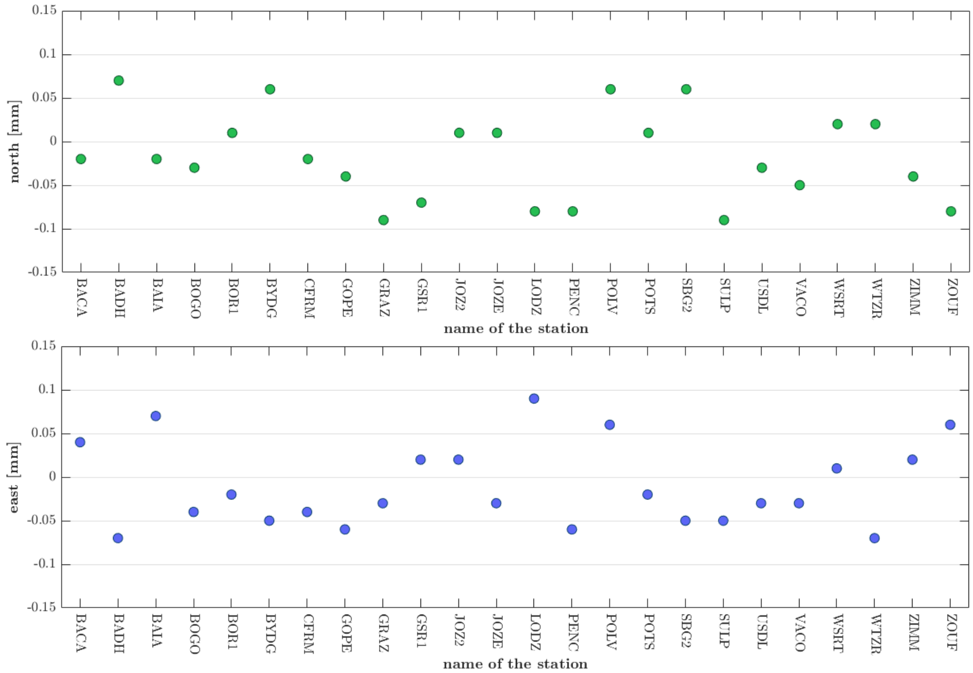

Figure 6. The residual horizontal velocity values from EUREF model for the North (upper plot) and East (bottom plot) components

Based on the comparison, it can be concluded that the calculations made are numerically correct, because the obtained values are not significant. The results of calculations may be used in the further part of the study.

3.2. Horizontal velocity residues analysis

Based on the time series of horizontal velocity residues, linear trends of residue changes were determined for each of the stations, separately for the northern and eastern components. For points where the measuring sessions were longer (KACI, KAWI, NIWK, WDZA, GUBA, HAGA), the average residue is ±3 mm, while for points with shorter sessions (CR01, CR02, CR4N, CR05, CR06, CR11, CS04, CS07, and CN02), the average residue value oscillates around ±4–5 mm. Maximum residue values shall not exceed ±10 mm. It can be noted that the residues at the points where observations were made 72 - hours (KACI, KAWI, NIWK, WDZA, GUBA, HAGA) are definitely lower than at the other points where the measurement sessions were 6 hours. Figure 7 shows the north–south and east–west residue plots for the four exemplary stations.

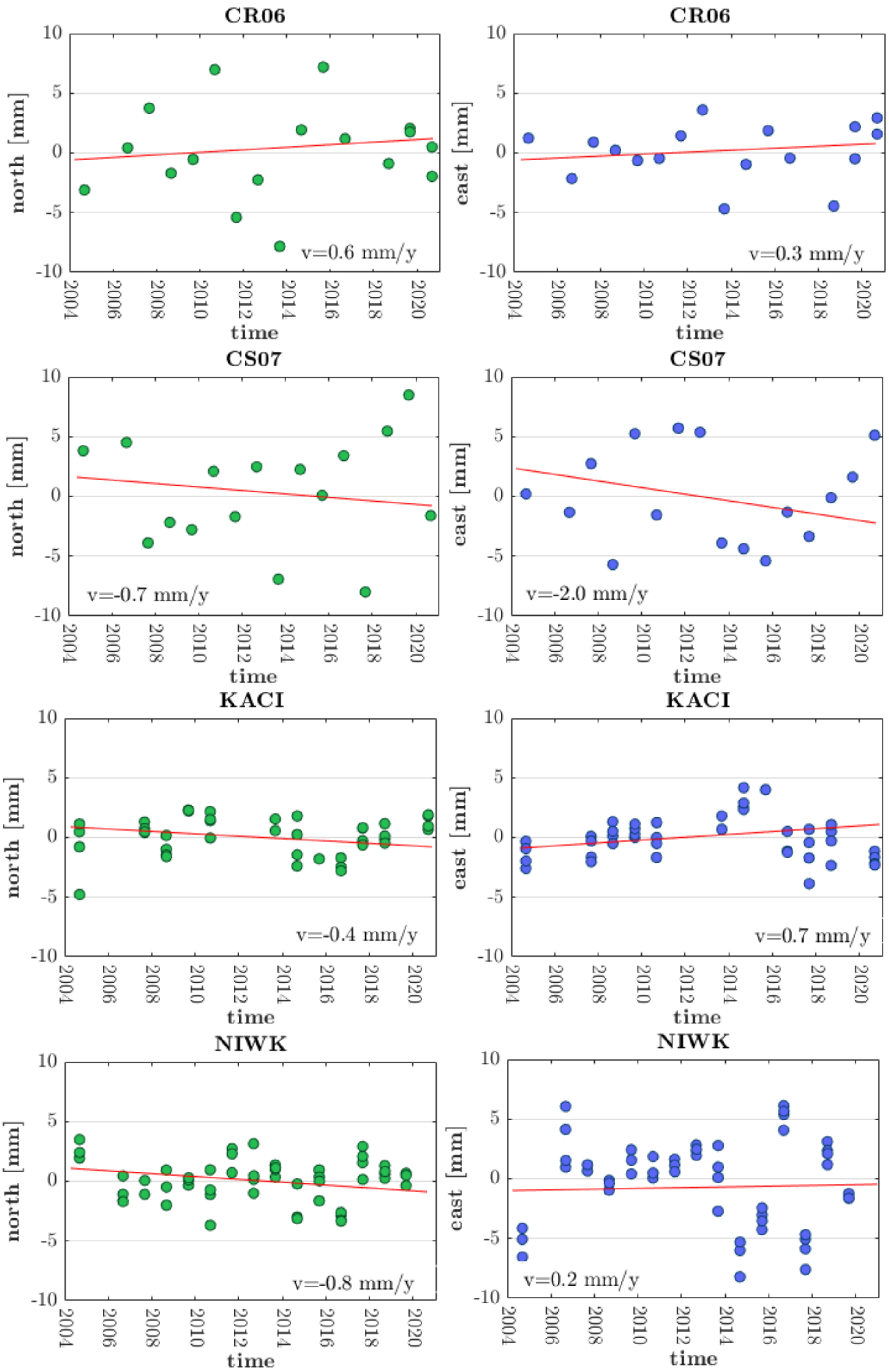

Figure 7. The residual horizontal velocities with trend line for the CR06, CS07, KACI and NIWK stations in each direction (north–south and east–west)

The KACI and the NIWK points are stations where observations were made for 72 hours, while at the CR06 and CS07 the measurement time was 6 hours. Based on Figure 7 it can be concluded that the linear trend is only noticeable periodically for several stations, i.e. the KACI (northern component), and the NIWK (northern component). For most of the stations, the changes in the velocity residue values are nonlinear. High residual values may be because the points on the Pieniny Geodynamic Test Field are not permanent stations. Each year the antennas are repositioned at points and their position may vary slightly from year to year; therefore, discontinuities should be introduced for all epochs. After the first adjustment was calculated, they were entered and the adjustment was repeated. The criterion used was to change the type of antenna. However, discontinuities were not recorded with each new stabilization of the antenna at the point, as it would be necessary to account for discontinuities at each subsequent measurement epoch. It is also important to strictly follow the technical recommendations regarding the measurements performed, such as pointing north of the antenna point regarding which the parameters of the phase center have been determined, starting the receiver a few minutes before the start of the measurement (for the summer season), performing the centering and leveling of the antenna with the correct accuracy for the carried out measurement task. This is also influenced by the short observation time and the small number of measurement sessions. Conducting several measurement sessions would make it possible to check the measurements carried-out, for example, by creating daily solutions and carrying out their comparative analysis. Table 4 contains the residual velocity in each direction for all stations constituting the Pieniny Geodynamic Test Field, as well as their errors for individual components. The data were divided according to their location on tectonic units, e.g. the MN, the FP, the PKB, and in the TM.

Table 4. The summary of residual horizontal velocity

Station	Unit	Residual velocity		Residual velocity error	
		North [mm/year]	East [mm/year]	North [mm/year]	East [mm/year]
CR01	**PKB**	0.1	−0.3	±0.30	±0.14
CR02		−0.5	−0.5	±0.38	±0.20
CR4N		−0.4	1.6	±0.41	±0.14
CR05		−1.3	−0.7	±0.39	±0.20
CR06		0.6	0.3	±0.16	±0.08
CR11		−1.0	1.5	±0.43	±0.23
Mean		−0.4	0.3	±0.35	±0.17
NIWK	**MN**	−0.8	0.2	±0.07	±0.04
WDZA		−0.4	0.5	±0.06	±0.04
CN02		0.2	0.4	±0.40	±0.28
Mean		−0.3	0.4	±0.21	±0.12
KACI	**FP**	−0.4	0.7	±0.05	±0.03
CS04		−0.8	−0.2	±0.55	±0.28
CS07		−0.7	−2.0	±0.27	±0.12
Mean		−0.6	−0.5	±0.29	±0.14
GUBA	**TM**	−0.4	0.0	±0.14	±0.07
HAGA		−0.1	−0.3	±0.09	±0.05
KAWI		0.8	0.5	±0.13	±0.06
Mean		0.1	0.1	±0.12	±0.06

The residual horizontal velocities for points located within the PKB toward the north reach similar values in the range ±0.2–0.7 mm/year. Larger values take only points CR05 toward the north -1.3 mm/year, CR11 toward the east 1.4 mm/year, and CR02 toward the north. The average the PKB velocity for IGb14 is -0.4 mm/year to the north and 0.3 mm/year to the east. For points located on the MN, northward velocities were about -0.3 mm/year to the north and about 0.4 mm/year to the east. Velocities of points located on the FP are about -0.6 mm/year to the north and -0.5 mm/year to the east. On the other hand, the points located in the TM reach average velocities of 0.1 mm/year toward the north and 0.1 mm/year toward the east. On each of the described tectonic units (except the TM), the northern component usually assumes negative values in the range -1.9–0.4 mm/year. For the eastern component, the values are usually positive. For points where they were performed in sessions 72 hourly differences do not exceed ±0.4 mm/year. At the other points of the network the differences are on average ±0.4–0.5 mm/year, and their maximum differences are ±1.0 mm/year.

For each tectonic unit, the mean velocities in mm/year and their mean errors were calculated based on the data in Table 4. The velocity vectors, calculated based on the velocity residues in each direction, are shown in Figure 8. The graph also plotted ellipses of mean point position errors for the velocity of points of the Pieniny Geodynamic Test Field. The position error takes the shape of an ellipse with variable flattening depending on the strength of the coordinate correlation. Therefore, the area within which the point lies may take on different sizes and shapes. The magnitude and direction of the flattening of the ellipse indicates the nature of the correlation between the coordinates, but they are dependent on the structure of the grid. The uncertainty of the location of the point is one of the basic indicators of accuracy. The point location error is the result of a combination of coordinate uncertainties. The error ellipse axes for points where 6 hourly sessions were conducted—are no longer than 1.5 mm. For points where sessions were 72 hours long, the ellipse axes are less than 0.2 mm long. This difference allows us to see that a longer observation time has a significant impact on the determination of the velocity of the point. At the points NIWK and CN02 the ellipses have a shape similar to a circle, which indicates a low correlation between the components of the designated velocities.

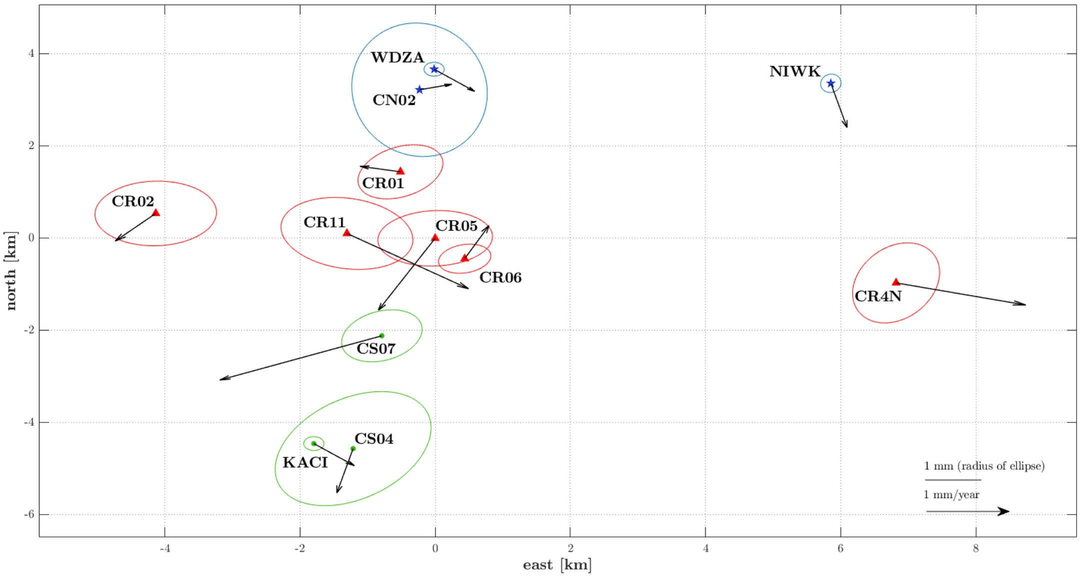

Figure 8. The map of the residual horizontal velocity vectors end of the velocity error ellipses for stations in the Pieniny Klippen Belt (red triangles), the Magura Nappe (blue stars), and the Podhale Flysh (green circles)

Another accuracy characteristic is the residual velocity error. Errors are included in Table 4. The smallest error values had the velocities of the points at which measurements were made in 72-hour sessions. Errors at stations: KACI, KAWI, NIWK, WDZA, GUBA and HAGA oscillated around ±0.1 mm/year. In other cases, the errors were much higher—the average value is about ±0.25 mm/year. The largest mean square error is about ±0.6 mm/year. It is also possible that the error values were greater for the coordinate in the east direction than in the north direction. After a detailed analysis of the calculated compensation, it can be concluded that the period of the investigation so far was stable and did not show major changes.

3.3. Comparison with the previous study

Data for the first 11 measurement epochs (2004, 2006–2015) were also used for calculations in the IGS08 reference system, in order to compare them with the results presented in the previous study on the geodynamics of the PKB. The previous study (Walo et al., 2016) used data from 5 EUREF reference stations closest to the Pieniny Geodynamic Test Field (UZHL, GRAZ, WTZR, JOZ2, and BOR1). For the current calculations in the IGS08 system, the same parameters as in the existing study were adopted to make the comparison as reliable as possible.

Table 5. The comparison residual horizonal velocities from the current study and from the previous one in the IGS08 system

Station	Study 2016		Study 2022		Difference	
	North [mm/year]	East [mm/year]	North [mm/year]	East [mm/year]	North [mm/year]	East [mm/year]
CN02	0.0	0.5	0.1	0.5	0.1	0.0
CR01	0.1	−0.2	0.1	−0.3	0.0	−0.1
CR02	−0.2	−0.3	−0.4	−0.3	−0.2	0.0
CR05	−1.1	−0.4	−1.2	−0.5	−0.1	−0.1
CR06	0.4	0.2	0.4	0.3	0.0	0.1
CR11	−1.1	1.8	−1.2	1.6	−0.1	−0.2
CR4N	−0.3	1.8	−0.4	1.7	−0.1	−0.1
CS04	−0.9	−0.2	−0.8	−0.3	0.1	−0.1
CS07	−0.9	−2.2	−0.7	−2.0	0.2	0.2
KACI	−0.2	0.6	−0.3	0.6	−0.1	0.0
NIWK	−0.8	0.4	−0.8	0.3	0.0	−0.1
WDZA	−0.3	0.5	−0.2	0.4	0.1	−0.1

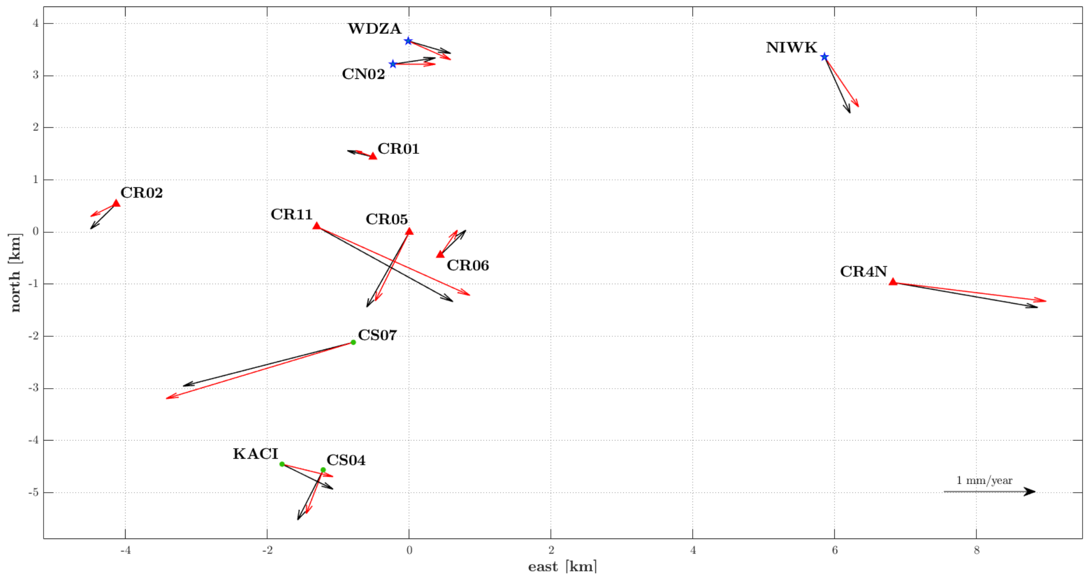

Figure 9. The differences between residual horizonal velocities from the current study (black vectors) and from the previous one (red vectors) for stations in the Pieniny Klippen Belt (red triangles), the Magura Nappe (blue stars), and the Podhale Flysh (green circles)

A comparison of the calculated velocity residues with the results of the adjustment from the year 2016 showed differences at the mean level of ±0.3 mm/year. The most considerable differences concern the points where observations were made 6 hours, i.e., CR4N, CR01, CR02, and CR11. However, the differences are characterized by the same sign in almost all cases, both for the northern and eastern components. The maximum difference is -0.2 mm/year. It should be noted that the 2016 equalization used data from only 5 reference stations (UZHL, GRAZ, WTZR, JOZ2, BOR1), whereas UZHL did not participate in the 2022 equalization. This change was because a different set of reference stations was used in the IGb14 data processing. This change may have led to discrepancies between the results of the two studies. The differences between the values of the horizontal velocity residues in each direction for both equations are shown in Table 5. Both studies show almost the same direction of stations' movements. This is related to local effects, particularly since the network of points located on the PKB and surrounding units is a small local network (Preweda et al., 1997). The changes are consistent for almost all stations located in the Pieniniy Test Field area. Figure 9 shows a comparison of horizontal velocity vectors. The red vectors correspond to the previous study, while the black vectors have been determined based on current studies.

4. SUMMARY

Based on the conducted studies, it is possible to determine the changes in the position of the PKB relative to the adjacent tectonic units. The studied area shows low tectonic activity, which confirms the correctness of the conclusions from the previous study that the PKB exhibits minor neotectonic activity. Units of the PKB, the MN, and the FP have negative velocities for the northern component—at the level of ± 0.5–0.7 mm/year. For the eastern component, the average unit velocities are positive, although for the PKB there are also negative velocities for points such as: CR01, CR02, and CR05. However, it should be considered that these are points where observations are made in sessions lasting 6 hours once a year. Another issue is the fact that the antenna is installed every year, and any minimal change in its position negatively affects the measurement results. Therefore, in subsequent measurement epochs, it is worth paying attention to the lengthening of observations at such points, or increasing the number of sessions. The obtained results indicate little tectonic activity of the PKB and its surrounding units. Velocities for both the north and east components are at submillimeter level. After incorporating into the adjustment in the IGb14 system further 5 measurement epochs, it can be seen that the position changes in the same direction. The trend in the magnitude of these changes is also maintained, but these changes are not linear. Referring to the results of the previous study, the differences in the obtained results are at the level of less than 0.3 millimeter. On the other hand, it is recommended to pay attention to the use of the same equipment at individual points in subsequent measurement periods. In geodynamic studies, where we observe changes in the position of the point at the submillimeter level, it is important that the measurement conditions in each epoch are analogous. It would also they be necessary to extend the measurement sessions, because when are short—i.e. they last 6 hours, there is very little margin to remove outliers. Another issue is to standardize the time of observation at the points of the network, so that each takes 72 hours. A larger number of measurement epochs allows the implementation of daily solutions and comparison of the obtained results to control them. It is also worth increasing the number of measurement sessions by performing GNSS observations twice a year, and then comparing weekly solutions.To maintain the continuity of the studies and to be able to make a more complete interpretation, it is recommended a repetition of the observations within this area every 4 to 5 years and then repeat the calculations considering the most recent observations. The comparison of the calculations allowed to conclude that the made adjustment does not differ from the solutions presented in the model and in the previous study, as well as that the determined directions of the velocities of the points are similar.

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