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ORIGINAL PAPER

THE CREATION OF A MODEL OF RELATIVE VERTICAL CRUSTAL MOVEMENTS IN THE POLISH TERRITORY ON THE BASIS OF THE DATA FROM ACTIVE GEODETIC NETWORK EUPOS (ASG EUPOS)

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ABSTRACT

Since the satellite systems have been operative, the data from permanent stations have been used for modelling the changes of the coordinates of the stations. One of the components of the changes is the change of the location of the Earth's crust surface. Both horizontal and vertical changes are analysed, as well as their velocities are determined. The system of ASG EUPOS station has been operative in Poland since 2008. The longer the system operates, the more possible it will be to create a model of the vertical crustal movements on Polish territory. The vertical movements can be determined as absolute, or relative. In order not to include the influence of transformation errors, the changes of geoid and eustasic, the changes of velocity between the chosen ASG EUPOS stations can be used to the creation of the model. The purpose of this article is to determine various models of the relative vertical movements from satellite data, as well as their evaluation. The author of the article concentrated mainly on the determination of the relative velocities, on their equalisation and visualisation. Relative vertical movements between the stations were determined on the basis of various data and for various epochs. They were equalised in several versions. As a result, several models of relative vertical movements were created and evaluated. In addition, there were established the accuracy possibilities of determining the model of the relative vertical movements on the basis of the data from ASG EUPOS.

INTRODUCTION

In the area of Poland three major tectonic units adjoin: Eastern European Precambrian platform, young western and middle Paleozoic platform and Carpatian region (Mizerski, 2002). In the joint of this three areas there is a Teisseyre'a – Tornquist zone (Fig. 1), which is geologically active in moderate degree (Mizerski, 2002).

Diverse geological structure may suggest, that the vertical crustal movements may occur in the area of Poland.

The movements are outlines using repeatable measurements of precise levelling (Kowalczyk, 2006a), using permanent satellite observations (Vestøl, 2007; Kontny and Bogusz, 2012) or the combined data (Ågren and Svensson, 2007). Estimating the expected accuracy is as essential factor in outlining vertical crustal movements. During analyzing observations from the last three years using linear regression, it was stated that the differences in ellipsoid heights come to 0.5 mm/year (Ihde and Augath, 2000). As it was shown in the work (Kowalczyk, 2006b), for Polish stations the period comes to 4 years.

The regression line with exponential distribution was used with the results. The coefficient of determination R2 grew to 0.997 which indicates on proper determination of the line. As a result, a formula (eqn. 1) for the theoretical standard deviation $\sigma\Delta\upsilon_{GNSS}^{N}$, depending on the amount of available epochs, was obtained.

$$\sigma\Delta\upsilon_{GNSS}^{N} = 2.908\Delta T^{-1.349} \tag{1}$$

where: ΔT – epochs differences ($T_i - T_e$)

Among others, absolute vertical movements calculated at permanent GPS stations were employed in the abovementioned works. In order to determine the absolute movements, the knowledge of the values of eustatic movements and the changes of geoid through time is essential. To create the model with the use of vertical movements data from the satellite, levelling and tide-gauge input, one needs to know the relations between those movements. The relation between the ellipsoidal height and the height with relation to the average sea level (Fig. 2) must be the onset of the study. This relation is as follows:

$$h_e = h + N \tag{2}$$

where: h_e – ellipsoidal height, h – height with relation to the average sea level, N – the distance between the geoid and ellipsoid.

One needs to consider whether the changes of the ellipsoidal height at permanents stations can be identified with the changes of height from geometric levelling. The following reasoning has been employed.

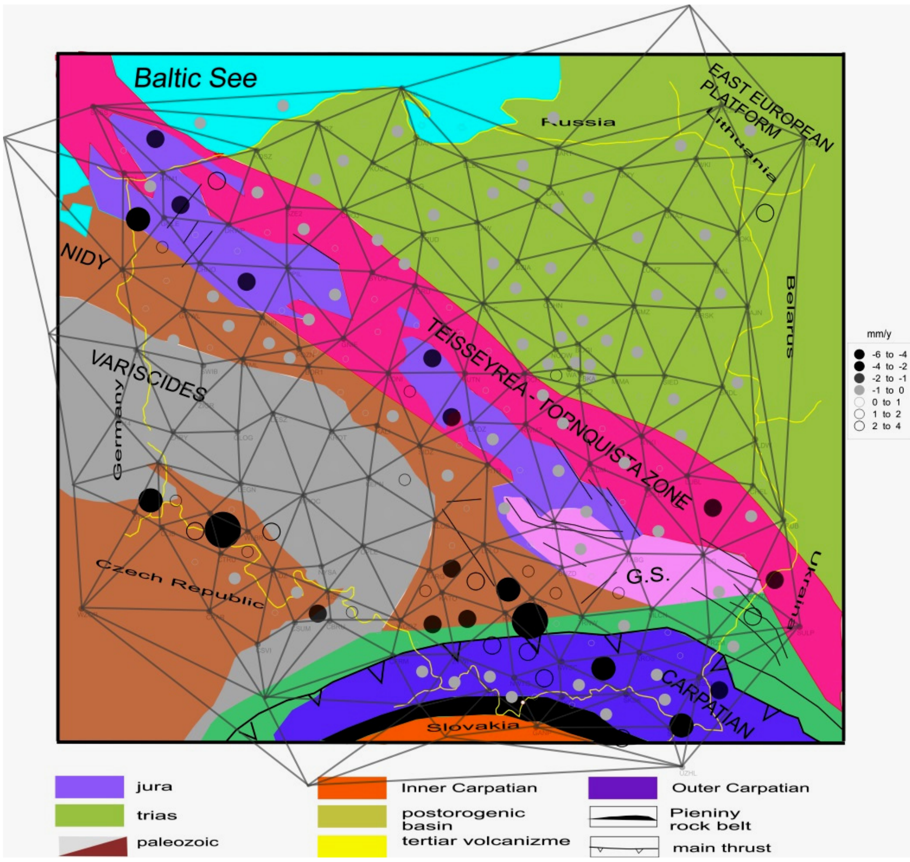

Fig. 1 Tectonic sketch Teisseyre-Tornquist Zone and adjacent areas, the development of their own on the basis of (Guterch and Grand, 2001) and the connections of the ASG EUPOS stations with the use of Delaunay triangulation and the loop misclosures.

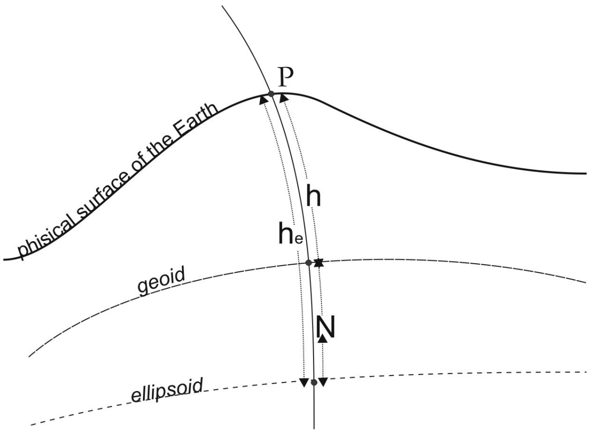

Fig. 2 The relations between the ellipsoidal height and the "levelling" height.

It results from Eqn. (2) (Torge, 1989) that the changes of ellipsoidal height, with reference to the average sea level and to the distance between the geoid and the ellipsoid, remain in the following relation:

$$\partial h_e = \partial h + \partial N \tag{3}$$

The change in ∂N consists of: the movement caused by the geoid uplift and eustatic movement.

According to the Eqn. (3) one can write that:

$$v_a = v_o + v_e + v_g \tag{4}$$

where:

v_a – the total vertical crustal movements (absolute), it is related to the ellipsoid,

v_g – the movement caused by the geoid uplift,

v_o – observed vertical movement with relation to the mean sea level,

v_e – eustatic movement.

It results from the Eqn. (4) that the absolute vertical movement, i.e., the one relating to the ellipsoid, consists of: the observed movement v_o, the eustatic movement v_e and the geoid uplift v_g. The observed movement is presented by the formula:

$$v_o = v_r + v_m \tag{5}$$

where:

v_m – uplift nodal point refened to the mean sea level,

v_r – vertical movements determined with relation to the established permanent benchmark (relative movements).

Taking into consideration the above relations, one can assume that the absolute movement reduced by the eustatic movement, the change of geoid through time (Sjoberg, 1982) and the change of the sea level would be identical with the levelling movement.

The determination of the eustatic movement is a complicated task. Within the region of the Baltic Sea, the eustatic changes are estimated from 0.8 mm/year to 1.1 mm/year (Ekman, 1986; Lisitzin, 1974). The ongoing changes, among others changes of the climate, result in a constant change of this movement. The creation of a regional model of the vertical movements based on the permanent stations requires a series of long observations, as well as a dense network of such stations. If the distances between the stations are too great, the stations are not mutually correlated which, in turn, requires the use of properly chosen interpolation models.

Having various time series and a dense network of permanent stations, one can employ the movements calculated between the particular stations to determine the model of vertical crustal movements. On the basis of these movements, one can conduct the process of adjustment of the network by assigning them properly chosen weight functions. The movements calculated in this way will be the relative movements $\boldsymbol{v_r}$, calculated with the use of satellite data. The eustatic movement and the changes of the geoid through time are eliminated from this approach.

The above approach requires a well-prepared and reliable research material. Various periods when the stations are operational, external conditions and other unidentified factors influence the quality of the data (Bogusz et al., 2011; Rapiński, 2014). At the a priori stage of material analysis, it is possible to determine the weight functions adopted in the later adjustment process, as well as to eliminate random and systematic errors. It is also possible to determine which stations should not be included in the subsequent adjustment.

The main aim of the research is to create the first in Poland and reliable model of vertical crustal movements using levelling data, GNSS data and mareographic data. In order to achieve the goal, one must define the prospect problems, do different adjustment variants, estimate expected and gained accuracies and minimize the influence of the frame of reference. The article answers some questions connected with including GNSS data into the planned model. It also indicates on the assumed problems that can be solved in the future.

In Poland there have been attempts on creating a model of vertical crustal movements using GNSS data (Kontny and Bogusz, 2012) using the absolute method. The test, however, did not give a hundred per cent certainty in the aspect of replacing the levelling data by GNSS data with the given accuracy. The problems connected with combining levelling and GNSS data include:

- various reference frame,
- various measuring methods,
- various expected accuracies of determining vertical crustal movements,
- lack of common points,
- various measurement time,
- various types of networks (scale and scale-free networks),
- various types measurements verification,
- various measurement interval.

A part of the issues is eliminated by using the relative method (e.g. various systems of reference). So far in Poland no one has drawn up assumptions and adjusted vertical crustal movements with the relative method using GNSS data. Consequently, one ought to look for answers to questions connected with the theoretical basis of the analysis:

- estimating directives for choosing a point or points that are constant in the adjustment process,
- estimating a procedure of creating a model,
- working-out a rule of connecting stations GNSS into vectors,
- choose or working-out a method (procedure) of setting a trend on vectors,
- estimating the quality of measurement materials, including those from neighboring countries,
- verifying and estimating the predicted accuracy of the model,
- determining time frames for data collected in various stations in creating a model of vertical crustal movement,
- determining the criterion of loops misclosures, using the information in the process of eliminating vectors that include too profound errors or implementing the information to position weight matrix and stations that are suspected of vertical movements not connected with any changes in crustal surface,
- estimating predicted and acquired accuracies of determining linear trends in vectors,
- determining if one can automate the process of data preparation, data verification and adjustment,
- determining the weights used in adjustment processes,
- determining the expected accuracy after adjustment with the use of the relative method.

Due to the research problems outlines above, the aim of the article is an attempt to use the relative method in estimating vertical crustal movements using GNSS data as an alternative to the absolute method.

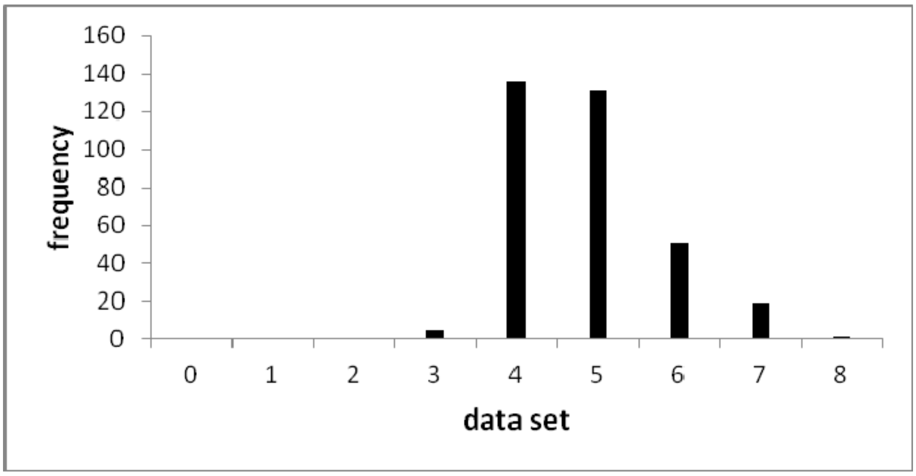

Fig. 3 Histogram of the standard deviation of height differences for particular vectors.

The aim was achieved by the following tasks: determining vectors between stations, selection of adjustment units of weight, statistic evaluation vertical movement on the vectors, analyzing loops misclosure created in polygon triangulation and determining criterion loops misclosure, trial network adjustment in different variations, statistic evaluation of the adjustment and drawing up selected procedures and criteria and the directions of gaining optimal levelling conditions.

DATA

The research material consists of the diurnal height differences from 343 ASG-EUPOS stations determined in the Military University of Technology EPN Local Analysis Centre (MUT LAC) using Bernese 5.0 software (Dach et al., 2007). The height differences were calculated between the stations of the neighbouring countries as well, in order to obtain a full coverage for Polish area. The connections of permanent stations for calculating the height differences were chosen with the use of Delaunay triangulation (Delaunay, 1934) (Fig. 5).

Within the research material (the files as time series), due to temporal modernisations of the stations, there were present height changes caused by, among others, installation of new aerials. The series were adjusted to the latest antenna value.

Prior to the analysis, outliers influencing the standard deviation were pre-eliminated from the research material using 3σ criterion. The data from the measurement epochs featured by major variations from the general characteristics of the series was eliminated. These were, mainly, the initial epochs of stations with great intervals.

The research material was characterised by a large number of measurement epochs for each defined pair (vector) of permanent stations. This resulted from a gradual launch of the particular ASG EUPOS stations, as well as from initial selection of the data. Despite the fact that the amount of information on some vectors varied greatly from the rest of them, they were included in further analysis for cognitive purposes. The number of vectors on which the period of registration did not exceed 3 years equals about 6 %. A standard deviation of the sample was calculated for particular vectors. At first, the calculated standard deviation of the height differences at particular pairs (vectors) of permanent stations was analysed. Figure 3 depicts the distribution of standard deviation. The calculated standard deviations of height differences at vectors vary from 2.7 mm to over 7 mm.

At tested and adjusted data were calculated linear trend and the standard deviation of the trend. The linear trend $\Delta\upsilon_{GNSS}^{N}$ of the height changes in time was calculated at particular vectors. Alongside, the standard deviation of this trend was computed (Eqn. 1). The obtained values of the standard deviation of the linear trend are presented in Figure 4. On average, they equal to 0.5 mm/y and the maximum value equals to 2.2 mm/y.

The greatest values of the trend were observed within the vicinity of Krakow, Warsaw, within Silesia and within the vicinities of north-eastern Poland. On the average linear trend $\Delta\upsilon_{GNSS}^{N}$, it equal to 0.0mm/y and the maximum value equals to -7.0 mm/y (NWSC-KRA1) and -3.7 mm/y to 3.7 mm/y. Small values of the trend having an incommensurably great error of determination can be observed, e.g., between the stations KRA1 – PROS. And conversely, there can be observed a relatively great trend value with a small error value (BILG-CHEL).

Another phase constituted the calculation of loops misclosure φ_{L}^{GNSS}. Moreover, kurtosis and skewness were computed too. Maximum misclosure is equal to ~5.5 mm/year. Most of the set has a misclosure up to 1mm/year (193 loops); 13 loops have a misclosure from 1mm/year to 2 mm/year and 16 loops have a misclosure over 2 mm/year. The obtained misclosures have a normal distribution

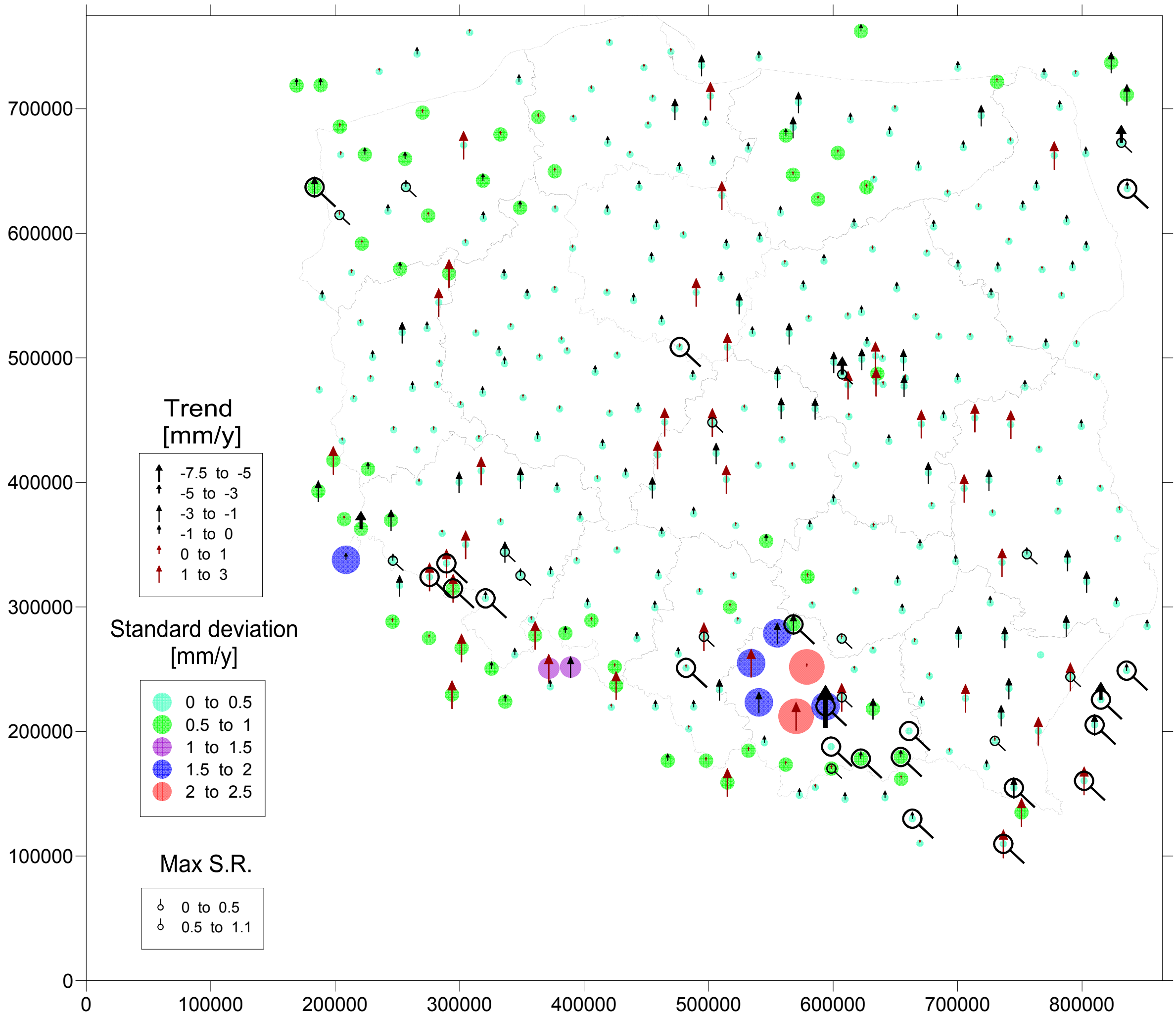

Fig. 4 Standard deviation of the trends at the vectors. Max S.R. variant A.

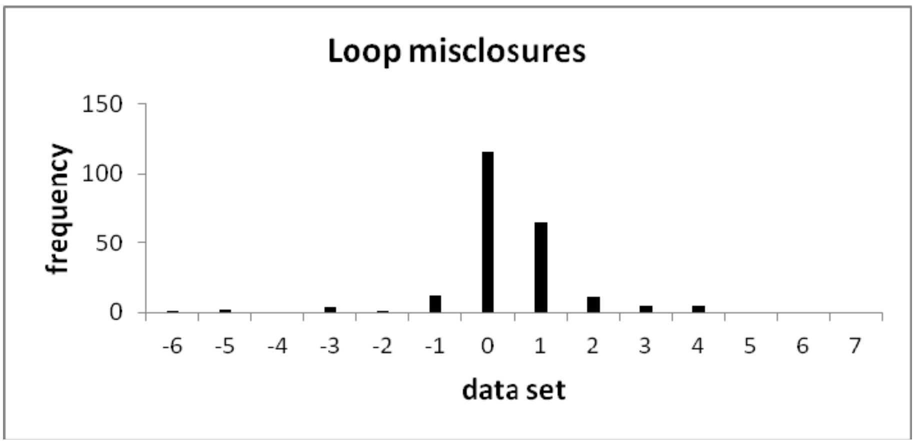

Fig. 5 The distribution of the loop misclosures.

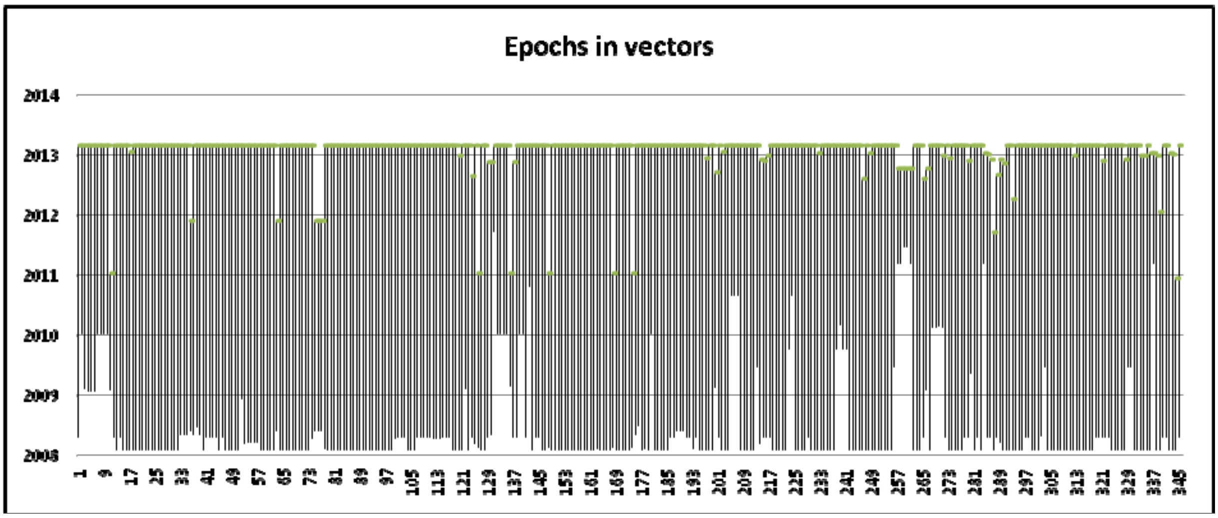

Fig. 6 Epoch in vectors.

(kurtosis equals to 7), greatly prolonged (high concentration of a similar values), however no symmetrical – left skewness equals to -0.9. The distribution of the loop misclosures is presented in Figure 1 and Figure 5.

The greatest values of loops misclosure are visible along the southern border, as well as within the vicinity of Krakow (triangle KRA1-NWSC-PROS, -5.5mm/y) and Wałbrzych (triangle JLGR-WLBR-CTRU, -5.1mm/y). The accepted value of loops misclosure does not depend on the distance. The formula used for levelling data cannot be used in this case (Wyrzykowski, 1987). It seems legitimate to determine the triple standard deviation as the criterion. The criterion eliminates the following triangles in the subsequent work: KRA1-NWSC-PROS, JLGR-WLBR-CTRU, KRA1-LELO-PROS, CLIB-0147-139.

As a criterion one can suggest using a pattern based on the quantity of sides in a loop assuming that determining a trend on a vector depends on the quantity of epochs (eqn. 1). One should also acknowledge a constant parameter of 1.5 as it has already been presented in the work (Wyrzykowski, 1987).

The pattern:

$$\varphi_L^{GNSS} = 1.5 \sum_{i=1}^{n} \left(\sigma \Delta \upsilon_{GNSS_i}^{N} \right) \tag{6}$$

where:
n - the number of vectors in the loop

The testing of the suggested criterion (6) and the parameter value depends on the choice or drawing-up the final method (procedure) of determining vertical velocity on vectors.

ADJUSTMENT AND RESULT ANALYSIS

The GNSS data are collected permanently. The differences between the stations come as follows: the time of launching the station (Fig. 6), place of stabilization and distance between the stations. In the relative method of estimating vertical crustal movements, the attitude to adjusting networks influenced by network optimization (Niemeier and Rohde, 1982; Meissl, 1980) and the aim of their determination may vary. Concerning these factors, three test adjustments were conducted. In adjustments to estimate the weights theoretical standard deviation $\sigma \Delta \upsilon_{GNSS}^{N}$ (Fig. 4) was used. The test adjustments include:

- variant A – adjustment of networks with one adjustment point (KUNT) in the middle of the network (Fig. 7a)
- variant B - adjustment of networks with one adjustment point (KUNT) in the middle of the network, vectors with observation period below 3 years and loops misclosures that do not fulfill the 3σ criterion (triangles: KRA1-NWSC-PROS -5.5 mm/y, JLGR-WLBR-CTRU -5.1 mm/y, KRA1-LELO-PROS -3.6mm/y, CLIB-0147-139 -3.5 mm/y) (Fig. 7b),
- variant C – adjustment of network with four adjustment points (OPLU, MYSZ, GOLE, WROC) (Fig. 7c).

In adjustment the velocity in nodes was taken as zero.

To calculate the relative vertical movements the SNAP v. 2.3.44 software was used (Survey Network Adjustment Program), developed by Land Information New Zealand, successfully implemented in the work (Kowalczyk and Rapiński, 2013). Figures 7a,b,c show the adjustment results as a isolines of vertical velocities of points network.

The results in variants A and B are similar. The differences appear in the places where vectors, which do not fulfill variant B criteria, were removed. The mean difference $\overline{\Delta V_{GNSS}^{A}}$ comes to 0.0mm/y,

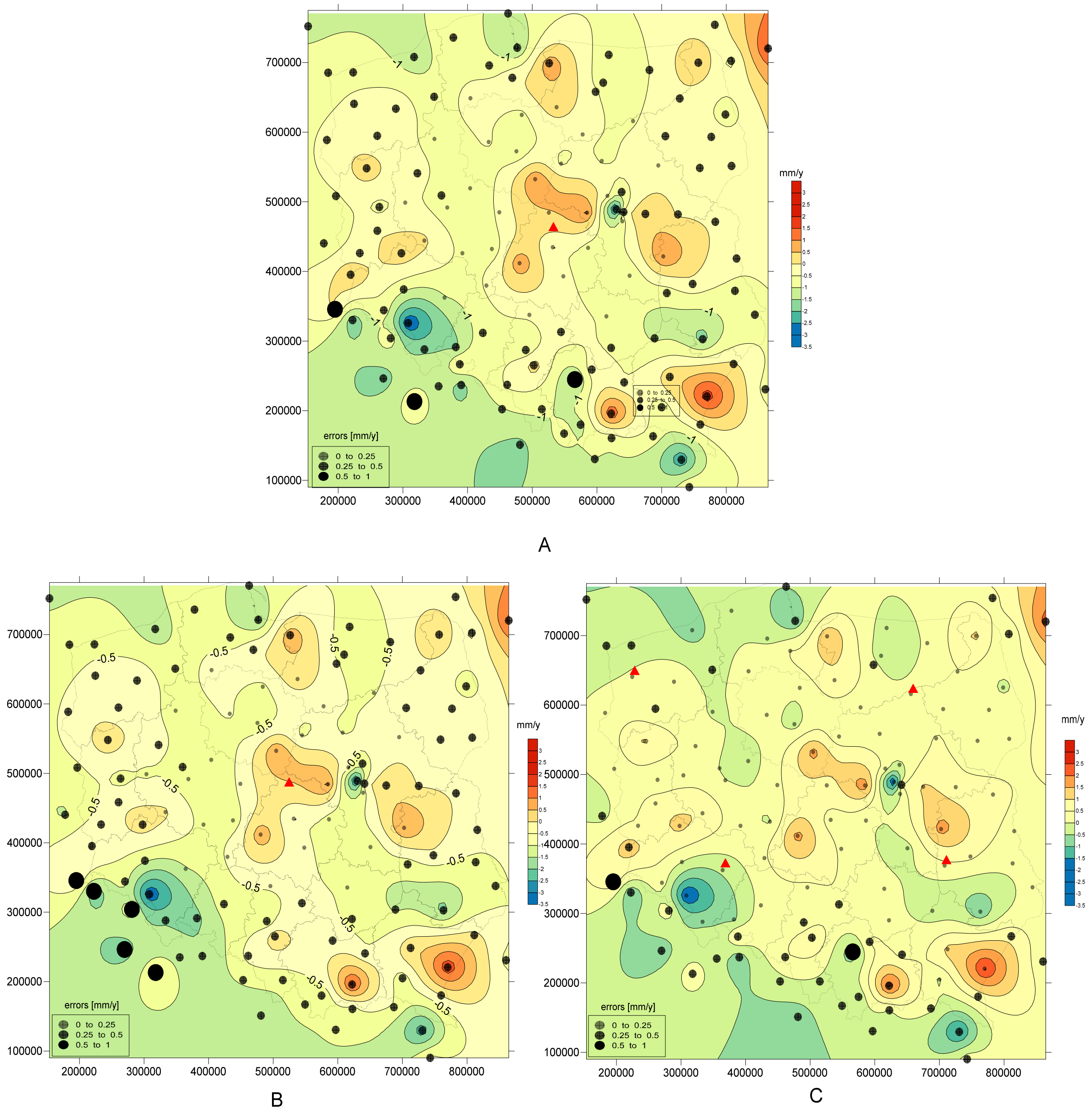

Fig. 7 The isolines of relative vertical crustal movements in the area of Poland after adjustment in three variants. The red triangle is nodal point.

however, the highest value of the difference ΔV_{GNSS}^{A} was observed in stations WAT1 (-0.7 mm/y) and NWSC (0.4 mm/y). In the remaining cases, the differences fluctuate from -0.3 mm/y (0139) to 0.3 mm/y (CBKA). The very high kurtosis (16.5) may indicate on a very good models adjustment. The models covariance comes to 0.6.

The results in variants A and C are slightly divergent. The differences ΔV_{GNSS}^{A} in most cases fluctuate from 0.5 mm/y to 1.0 mm/y. The average difference $\overline{\Delta V_{GNSS}^{A}}$ comes to 0.7 mm/y, however, the smallest value was noticed in stations WAT1 (0.0 mm/y) and KUTN (0.3 mm/y), the highest in station BISK (1.1 mm/y). The high kurtosis (4) may indicate on a very good models adjustment and even distribution of residuals. The models covariance comes to 0.6. From the statistical point of view and the expected accuracy of the models, it can be stated that the models from variants A and B are better adjusted. Variant C indicates on a greater diversification in comparison to variant A. It is caused by various conditions of networks adjustment (the amount and distribution of adjustment points). The issue (network optimization) requires further analysis concerning the aim and the use of the created models of vertical movements. A posteriori models statistical evaluation is presented in Table 1.

For all variants mean error a posteriori comes to 0.8 mm/y and the mean error of an individual

Table 1 A posteriori models statistical evaluation.

	A		B		C	
	v	**σ**	**v**	**σ**	**v**	**σ**
mean [mm\y]	-0.5	0.3	-0.5	0.3	0.2	0.3
error [mm\y]	0.8		0.8		0.8	
kurtosis		6.7		8.2		7.7
skewness		1.9		2.2		2.2
min [mm\y]	-3.1	0.2	-3.2	0.2	-2.3	0.2
max [mm\y]	1.8	0.7	1.9	0.8	2.6	0.7
Number of parameters	123	123	121	121	120	120
Number of observations	343		319		343	
Degrees of freedom	220		198		223	

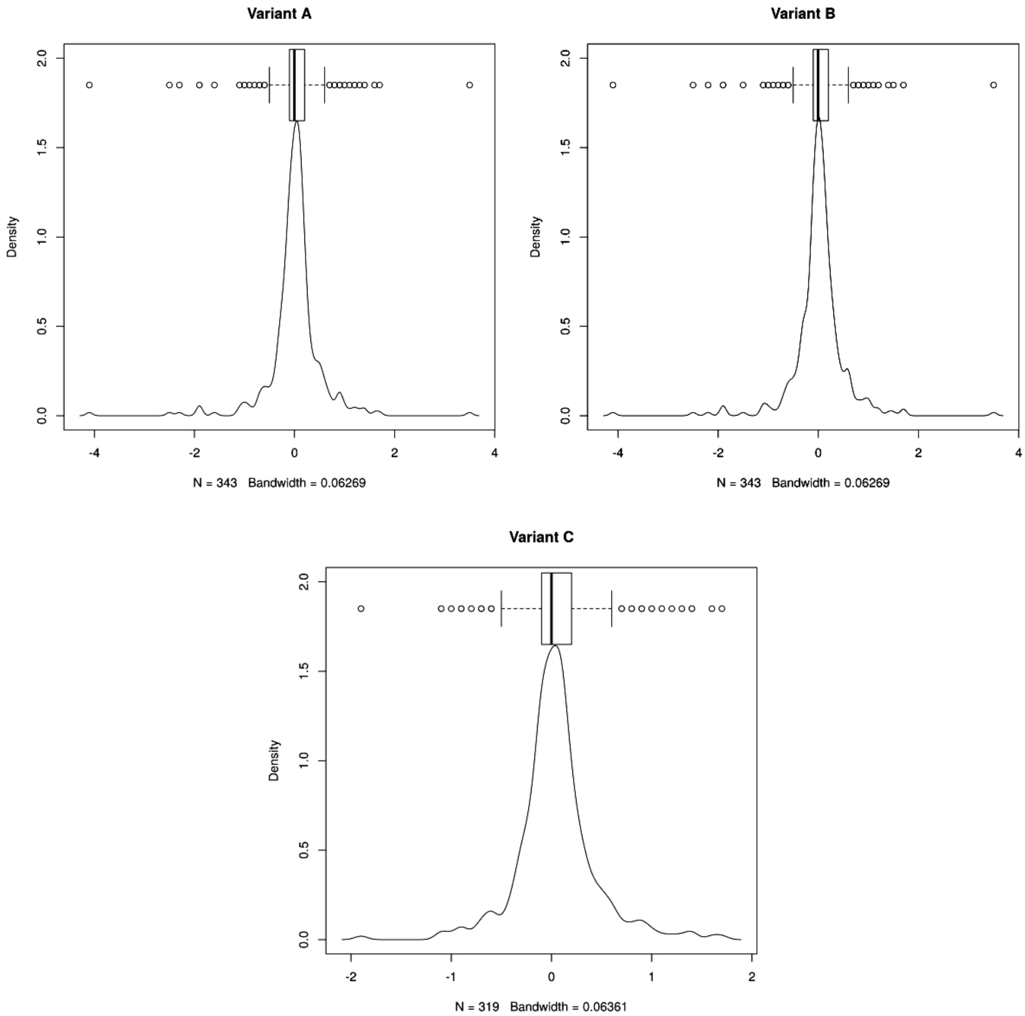

Fig. 8 Residuals distribution as a box plot along with corresponding density function.

observation is 0.3 mm/y, the minimum error is 0.2 mm/y and the maximum error is 0.7 mm/y. Kurtosis of the three sets is high which is understood as the data had undergone an initial filtration. Skewness for all sets is similar. For variants A and B means, maximum and minimum vertical crustal movements ΔV_{GNSS}^{A} in nodes are similar. The mean of vertical crustal movements in variant C is lower, $\overline{\Delta V_{GNSS}^{A}}$ (0.2 mm/y), however, the minimal and maximal values are 0.8 mm/y higher than in variants A and B.

Standard error of unit weight was estimated for each variant and it comes to 1.2 mm/y. It proves the proper selection of allowances to priori errors. Residuals outside a confidence limit for all variants come to: under 95 % (90 %), under 99 % (5 %), over

99 % (5 %). That indicates on proper preparation of data and adjustment. Slight relocations between ranges in the variants. In most cases the same vectors were selected for the ranges. The maximum S.R. value in variant A is presented in Figure 4.

The solutions for further statistical evaluation were presented in the work ((Kowalczyk and Rapiński, 2013).

The suitability analysis of the data from three variants were based on the observation residuals. To complete this task the following statistical methods and graphs based on statistical methods were used: box-plots, Pearson's, Kendall's, and Sperman's correlation tests and QQ plots. Figure 8 depicts the distributions of observation residuals as a box-plot (Benjamini, 1988). It allows enclosing in one drawing the information on the location, dispersion and shape of the empirical distribution of the test characteristics (Benjamini, 1988).

Shown in figure that the residuals from the three variants have normal distribution. Only single points do not fulfil the criterion of triple mean error. Density for the three wariants is equals 1.7, data with slight offset to the left. Criterion of triple mean error is not fulfilled by even: variants A and B - 20 residuals, variant C - 17 residuals.

To see if the residuals between campaigns variants are correlated, two tests were performed - Pearson and Spearman correlation tests. The null hypothesis in the above tests is „the correlation is equal to 0" with the alternative hypothesis "the correlation is different than 0" (Hollander and Wolfe, 1973). Both tests results show that the data are very linearly correlated.

The performed test was the QQ test (Wilk and Gnanadesikan, 1968). In this test the differences between normal distribution (horizontal axis) and standardized residuals (vertical axis) are depicted. From Figure 9 it is clear that for variant C the distribution has larger variance than the residuals for the variants A and B.

CONCLUSIONS

The main aim of the work was an attempt to use the relative method in estimating vertical crustal movements with the use of GNSS data as an alternative to the absolute method.

The GNSS station does not measure the distance and that is why a well-tried method of a Delaunay triangulation was used. Altogether 343 vectors had been estimated and they were then analyzed and correlated.

The number of vectors on which the period of registration did not exceed 3 years equals about 6 %. The calculated standard deviations of height differences at vectors vary from 2.7 mm to over 7 mm. A linear trend was set on each vector as not adjusted vertical movement $\Delta\upsilon_{GNSS}^{N}$.

The greatest values of the trend were observed within the vicinity of Krakow, Warsaw, within Silesia and within the vicinities of north-eastern Poland. On the average linear trend, it equal to 0.0 mm/y and the maximum value equals to -7.0 mm/y (NWSC-KRA1) and -3.7 mm/y to 3.7 mm/y.

Another phase constituted the calculation of loops misclosure φ_{L}^{GNSS}, where the greatest values of loops misclosure are visible along the southern border, as well as within the vicinity of Krakow (triangle KRA1-NWSC-PROS, -5.5 mm/y) and Wałbrzych (triangle JLGR-WLBR-CTRU, -5.1 mm/y). For adjustments one used estimated theoretical standard deviation $\sigma\Delta\upsilon_{GNSS}^{N}$. The suggested solution of the estimations will be then verified in due time (the verification of eqn. 6 criterion, the elimination of vectors with too profound errors or counting the information in weight matrix). The estimated standard error of unit weight (1.2mm/y) proves the correctness of the applied solutions.

The adjustment was implemented in three variants A, B and C. The results in variants A and B are similar (apart from the spots of removed vectors that do not fulfull the criteria in variant B). The results in variants A and C are slightly divergent. The differences in most cases fluctuate from 0.5 mm/y to 1.0 mm/y. The average difference $\overline{\Delta V_{GNSS}^{A}}$ comes to 0.7 mm/y, however, the smallest value was noticed in stations WAT1 (0.0 mm/y) and KUTN (0.3 mm/y), the highest in station BISK (1.1mm/y). The main factor that influenced the result was the optimization of network which will be more deeply analyzed in due time. For the three variants the mean error a posteriori comes to 0.8mm/y, the mean error of an individual observation is 0.3mm/y, the minimum error is 0.2mm/y and the maximum error is 0.7 mm/y.

The residuals from the three variants have normal distribution. Criterion of triple mean error is not fulfilled by even: variants A and B - 20 residuals, variant C - 17 residuals. The null hypothesis in the above tests is „the correlation is equal to 0" with the alternative hypothesis "the correlation is different than 0" (Hollander and Wolfe, 1973). From the statistical point of view the results of Pearson and Spearman tests show that the data were profoundly linearly correlated. The QQ test proved for variant C the distribution has larger variance than the residuals for variants A and B.

As a result, a procedure that enables to draw up relative vertical crustal movements using GNSS data was obtained. The issues connected with statistical evaluation of input data, the process of trend evaluation and its verification, verification of theoretical standard deviation a priori and optimization of network. The estimated values do not indicate on the necessity of adjustment with several adjustment points, the problem occurs with the choice of the points and evaluating their constancy, as in the

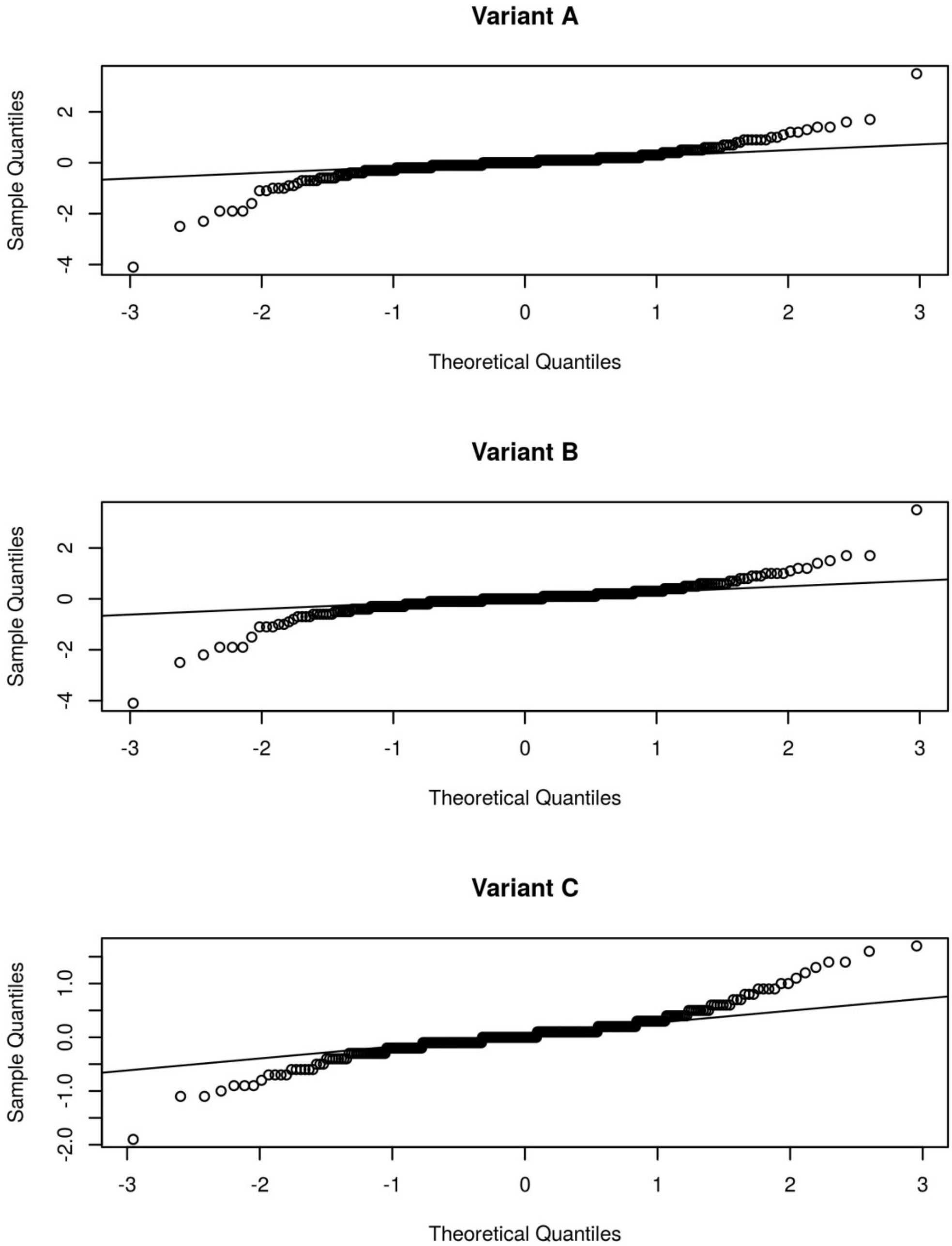

Fig. 9 Results of QQ test.

aspect of vertical crustal movements, the location must not be the only criterion. In optimization it is of paramount importance to set the aim for drawing up a relative model of vertical crustal movements using GNSS data, for instance the join estimation of the model using GNSS data and the precise levelling, or introducing allowances in national levelling networks on account of vertical crustal movements. In the further research, it is planned to use a free adjustment without assuming the constancy of cardinal points.

It seems that the process of drawing-up the vertical crustal movements using GNSS data can be automated, however, it requires establishing satisfying criterion as well as verifying given criteria on every level of adjustment.

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