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Original Research Article

ACCURACY CHARACTERISTICS OF THE SELECTED DIAGNOSTICS METHODS AND THE ADJUSTMENT OF GEODETIC OBSERVATIONS

Martyna KULUPA[1], Paulina MAGDA[1], Maria MRÓWCZYŃSKA[2]
[1]Faculty of Geographical and Geological Sciences Adam Mickiewicz University, Poznań, Poland
[2] Faculty of Civil Engineering, Architecture and Environmental Engineering, University of Zielona Góra, Poland

A b s t r a c t

The article presents the results of the adjustment of the experimental horizontal geodetic network using the classical method and the estimation of strengths in identifying observations with gross error and analyzing the accuracy of the obtained results. The presented analyses were made considering the possibility of their use in implementation networks and measurement and control networks used for monitoring building structures. The paper's subject was a horizontal network established on the Morasko campus (Poznań). While creating it, the practical needs and economics of measurements were taken into account. The obtained results of numerical analyzes confirmed the benefits of using the methods of estimating strengths in the equalization process, which give satisfactory results in the case of outliers.

Keywords: geodetic observations, gross errors, strong estimation, horizontal network, accuracy analysis

[2] Corresponding author: Faculty of Civil Engineering, Architecture and Environmental Engineering, University of Zielona Góra, m.mrowczynska@ib.uz.zgora.pl, +48 68 3282636

1. INTRODUCTION

Classic geodetic networks (horizontal and vertical) are the basic scheme for geodetic measurements and their use in engineering and research. Geodetic networks are used as an essential tool for obtaining information for monitoring displacements and deformations of building objects [1,7,12,20,32], in geodetic planning, and agricultural management works [13,23], in spatial and geographic information systems [18,23,33], in engineering geodesy [5,9,10,17,24] or photogrammetry and remote sensing [2,3,25,29,30]. It is essential to determine the coordinates of geodetic networks characterized by a high level of confidence and with identified mean errors considering the wide application of geodetic measurements in various fields of knowledge.

In the classic approach, determining the coordinates of points in horizontal geodetic networks requires carrying out excess linear and angular elements measurements, appropriately designed in geometry and economics [19]. The measurement results are subject to the equalization process, which is the domain of these calculations. As a primary tool for solving computational problems in geodesy, this calculation aims to statistically elaborate the measurement results by estimating parameters and analyze the accuracy of the obtained estimators using artificial intelligence methods [16]. Currently, estimating parameters in geodetic networks most often used in geodesy is the least-squares method, characterized by the simplicity of calculations and obtaining estimators that are the best linear unbiased estimators [27].

The least-squares method also has limitations, ensuring that the functional and statistical model is close to the measurement reality [4]. If there are gross errors (outliers) in the observations, alternative approaches should be sought to align geodetic networks. First, statistical tests can be used to detect and eliminate outliers, and then the observations can be adjusted using the classical method of the least-squares [21]. However, suppose the gross error cannot be identified, or the elimination of the observation would disturb the geometry of the network. In that case, we can apply methods using strong estimation (M-estimate) [6,31]. The use of robust estimation methods eliminates the influence of outliers on the estimated parameters [8,22]. The M-estimation method assumes that the random errors of observations are acceptable (according to the assumed statistical or probabilistic model) or unacceptable (gross errors). M-estimators are usually determined in an iterative process. Their favourable properties result from the modified objective function and its derivative, i.e. the influence function and associated weighting function [28,29].

The study aimed to carry out analyses indicating an alternative approach that can be used to align geodetic observations, use methods based on strong estimation, and diagnose the set of observations in terms of outliers and the accuracy of the results obtained. The entire process was carried out on actual measurement data obtained as part of field measurements carried out on the Morasko campus (Adam Mickiewicz University in Poznań) [11,15].

2. MATERIALS AND METHODS

2.1. Case study

The adjustment of observations in a horizontal geodetic network and an accuracy analysis and diagnostics of observations with a large error was carried out on the example of linear and angular observations made in a network established on the Morasko campus (Adam Mickiewicz University campus in Poznań). The implementation of the aim of the work required the design and field stabilization of an experimental angular-linear network, which was related to the network points in the national PL-2000 geodetic coordinate system. The field conditions guided the points' location, the redundancy of observations, and the network's optimization in terms of the economics of the measurements and the significance of individual observations [19]. The location of the network points and reference points was presented in Fig. 1.

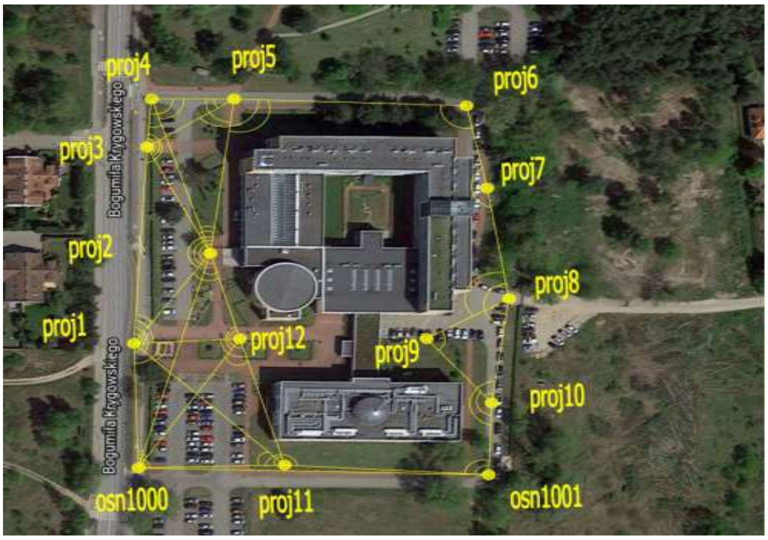

Fig. 1. Location points of experimental network on campus Morasko [15]

A mechanical total-station - Trimble M3 with Trimble Access software was used to measure the observations in the experimental horizontal network. The instrument measures distance from 1.5m to 3000m using a standard 6.25cm prism. The standard deviation of the measurement based on the ISO 17123-4 standard is

± 3mm with the measurement interval every 1.6 sec.. In contrast, the horizontal and vertical accuracy of the angle measurement is 3''/10^{cc}. The total station has a two-axis compensator with a compensation range ±3.5'. Due to the research nature of the measurements, all linear and angular observations were made in two series. The Trimble M3 allows you to work without additional instrument errors at temperatures from -20ºC to +50ºC. Finally, 25 horizontal angles and 20 distances were measured; the graphical arrangement of the observations is shown in Fig. 2 [11,15].

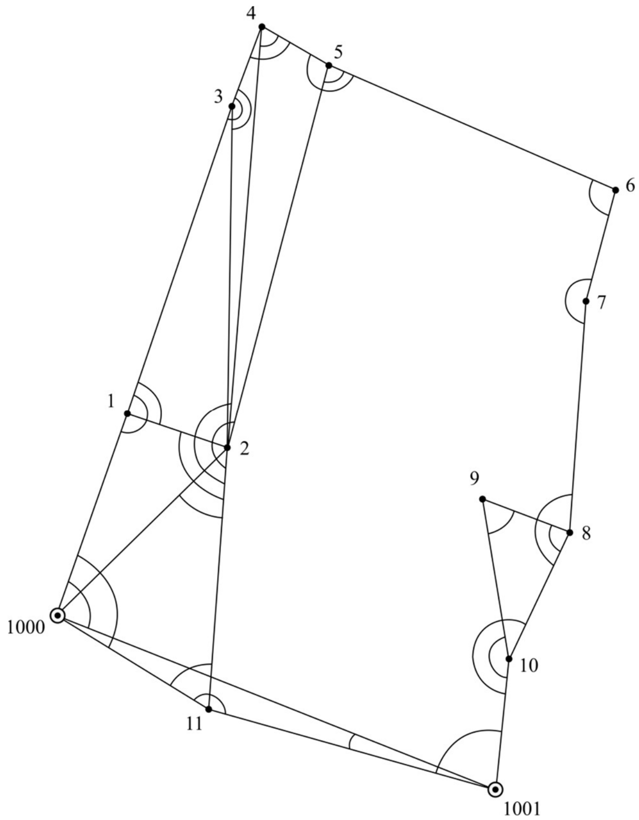

Fig. 2. Diagram of observations made in the experimental network [11]

2.2. Numerical processing of measurement results

The observations were measured in the experimental network (25 horizontal angles and 20 distances). Then the strict adjustment was carried out using the indirect method to verify the correctness of the measurements made initially and to identify observations with a gross error. Basic diagnostics of the observation system was performed in the form of:

$$\frac{v}{m_v} > 2 \tag{2.1}$$

where: v – correction for observation, m_v – correction error. The assumption made in a formula (2.1) allows for identifying observations with a gross error. The elimination of outliers from the observation system is not always desirable due to the necessity to maintain the redundancy of observations. At the same time, in the classic approach to the least-squares method, it is assumed that each measurement result is a random variable with the same standard deviation, which means that each observation is assigned the same weight. In practice, this means that if the observation has a gross error, then despite the different values, it is as important as the others and has an impact on the final result [4, 29]. Those observations cause false measurement results. The methods that are resistant to their occurrence are used to prevent this, to compensate for the observations suspected of gross errors. These methods belong to the class of strong estimation (M-estimation) [14, 26]. They allow to eliminate the influence of outliers on the process of equalization and thus obtain more accurate results [27]. An important part of the estimation process is selecting the appropriate damping function, which allows modifying the weights of observations and minimizing the impact of defective observations on the calculation results.

The most commonly used damping functions are [2]:

– Huber function, for which the damping function and the resulting weighting function can be written as:

$$t(\bar{v}) = \begin{cases} 1, & \bar{v} \in \Delta\bar{v} \\ 0, & \bar{v} \notin \Delta\bar{v} \end{cases} \tag{2.2}$$

where: $\bar{v} = v/\sigma$ – standardized correction with a normal distribution; $\Delta\bar{v} = < -k; k >$, where k is the most common factor in the range <0.5;3.0> depending on the adopted level of probability.

However, its weight function has the form:

$$\hat{p} = t(\bar{v})p = \begin{cases} p, & \bar{v} \in \Delta\bar{v} \\ 0, & \bar{v} \notin \Delta\bar{v} \end{cases} \tag{2.3}$$

– Hampel function:

$$t(\bar{v}) = \begin{cases} 1, & \bar{v} \in < -k; k > \\ \frac{|\bar{v}| - k_b}{k - k_b}, & |\bar{v}| \in (k; k_b > \\ 0, & |\bar{v}| > k_b \end{cases} \tag{2.4}$$

$$\hat{p} = t(\bar{v})p = \begin{cases} p, & \bar{v} \in < -k; k > \\ \left(\frac{|\bar{v}| - k_b}{k - k_b}\right) p, & |\bar{v}| \in (k; k_b > \\ 0, & |\bar{v}| > k_b \end{cases} \tag{2.5}$$

where: $k_b -$ a number that sets the limits of additional intervals

– Danish function:

$$t(\bar{v}) = \begin{cases} 1, & \bar{v} \in < -k; k > \\ \exp\{-l\,(|\bar{v}| - k)^g\}, & |\bar{v}| > k \end{cases} \tag{2.6}$$

$$\hat{p} = t(\bar{v})p = \begin{cases} p, & \bar{v} \in < -k; k > \\ \exp\{-l\,(|\bar{v}| - k)^g\}\, p, & |\bar{v}| > k \end{cases} \tag{2.7}$$

2.3. Modified least squares method

As previously noted, the classic form of the least-squares equation is not resistant to gross errors that may appear in the set of observations. The modified least-squares method can be used to align a set with such observations. This modification assumes, among other things, a change of weights for individual observations. It is an iterative method, requiring several repetitions until the result meets the adopted criteria [28].

The initial stage is to carry out the classical adjustment of observations with the use of the initially adopted **P** weight matrix and to check whether the calculated corrections belong to the accepted acceptable range $\Delta\bar{v}$. The formula can express this requirement:

$$\bar{\hat{v}}_i \in \Delta\bar{v} \tag{2.8}$$

where: $\bar{\hat{v}}_i = \frac{\hat{v}_i}{m_{\hat{v}_i}}$ – correction estimator; $m_{\hat{v}_i} = \sqrt{[\hat{\mathbf{C}}_{\hat{\mathbf{v}}}]_{ii}}$ – correction estimator error.

Each subsequent step is to perform the equalization using the least-squares method, using modified weights suppressed by functions, the values of which are determined based on standardized corrections calculated in the previous iterations [27]. The course of the compensatory task can be formulated in the form of a linear equation:

$$\begin{gathered} \mathbf{V} = \mathbf{Adx} + \mathbf{L} \\ \mathbf{C}_{\mathbf{x}^{\mathbf{ob}}} = \sigma_0^2 \mathbf{Q}_{\mathbf{x}^{\mathbf{ob}}} = \sigma_0^2 \mathbf{P}^{-1} \\ \min_{\mathrm{dx}}\{\xi(\mathbf{dx}) = \mathbf{V}^T \hat{\mathbf{P}} \mathbf{V} = \mathbf{V}^T [\mathbf{T}(\bar{\mathbf{V}})\mathbf{P}]\mathbf{V}\} = \hat{\mathbf{V}}^T [\mathbf{T}(\bar{\hat{\mathbf{V}}})\mathbf{P}]\hat{\mathbf{V}} \end{gathered} \tag{2.9}$$

where: $\hat{\mathbf{P}} = \mathbf{T}(\bar{\mathbf{V}})\mathbf{P}$ – equivalent weight matrix;

$\hat{\mathbf{C}}_{\mathbf{x}^{\mathbf{ob}}}$ – equivalent covariance matrix;

$\widehat{\mathbf{Q}}_{\mathbf{x}^{\mathbf{ob}}}$ – equivalent cofactor matrix;

$$\mathbf{T}(\overline{\mathbf{V}}) = \begin{bmatrix} t(\bar{v}_1) & & & \\ & t(\bar{v}_2) & & \\ & & \ddots & \\ & & & t(\bar{v}_n) \end{bmatrix} \text{ – diagonal damping matrix.}$$

Having dependency $\hat{p}_i = t(\hat{v}_i)p_i$, where $i = 1, \dots, n$, the equivalent matrix of weights for independent variables takes the form:

$$\widehat{\mathbf{P}} = \mathbf{T}(\overline{\mathbf{V}})\mathbf{P} = \begin{bmatrix} \hat{p}_1 & & & \\ & \hat{p}_2 & & \\ & & \ddots & \\ & & & \hat{p}_n \end{bmatrix} = \begin{bmatrix} t(\bar{v}_1)p_1 & & & \\ & t(\bar{v}_2)p_2 & & \\ & & \ddots & \\ & & & t(\bar{v}_n)p_n \end{bmatrix} \quad (2.10)$$

On the other hand, the covariance matrix of the correction vector ($\widehat{\mathbf{V}}$) can be described by a formula:

$$\hat{\mathbf{C}}_{\widehat{\mathbf{V}}} = m_0^2[\mathbf{P}^{-1} - \mathbf{A}(\mathbf{A}^T\mathbf{P}\mathbf{A})^{-1}\mathbf{A}^T] \quad (2.11)$$

The equalization ends with an iteration in which the obtained values of standardized corrections belong to the accepted acceptable range. The resulting damping matrix does not introduce any changes to the weight matrix. The final weight matrix thus obtained is equivalent. In this matrix, the values of weights of observations with gross errors are reduced or even equal to zero, which results from applying the damping function [27]. The algorithm diagram for adjusting the set of observations with the modified least-squares method is shown in Fig. 3.

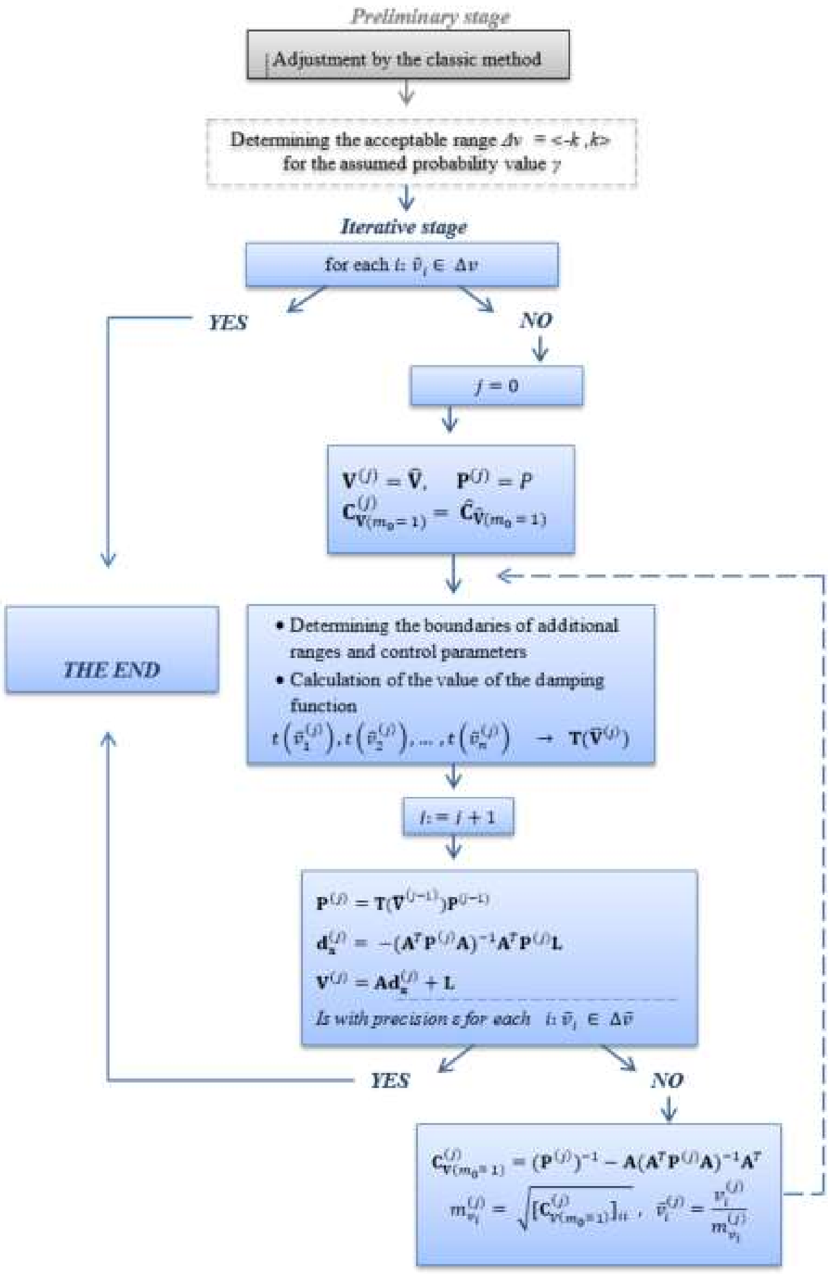

Fig. 3. Algorithm of resistance adjustment with the modified least-squares method [11]

3. RESULTS AND DISCUSSION

To analyze the accuracy of observations made in the experimental network, identify outliers and use the method of estimating strengths as an alternative approach to equalize the set of observations, three approaches were used:

- adjustment I – preliminary stage - adjustment of all observations using the indirect method and analysis of the accuracy of the measurements taken;
- adjustment II - adjustment of the network after eliminating outliers from it, also using the indirect method;
- adjustment III - adjustment resistant to coarse errors, using the modified least-squares method and the Hampel damping function.

The first analyzed variable was the mean error value m_0, obtained in the process of adjustment I. At the same time, it is worth noting that the previously performed diagnostics of gross errors and the rejection of two angular observations and one linear observation resulted in a significant reduction of the mean error value. The mean error value m_0, which is a determinant of the geometric correctness of geodetic networks, decreased by as much as 59% after eliminating three outliers. On the other hand, the lowest mean error value was achieved in adjustment III; this value decreased by 66% compared to the adjustment I. Between the 2nd and 3rd adjustments, a decrease in the mean error was also noticed. It is to be noted not as large as between the 1st and 3rd adjustments.

An accuracy analysis was also carried out the equalization using the classical method of the least squares (adjustment I). The parameters of the error ellipse were determined for individual points of the experimental network, with the assumed confidence level of 0.95. A graphical representation of the error ellipse parameters for all network points is shown in Fig. 4, and for selected points, the error ellipses are shown in Fig. 5.

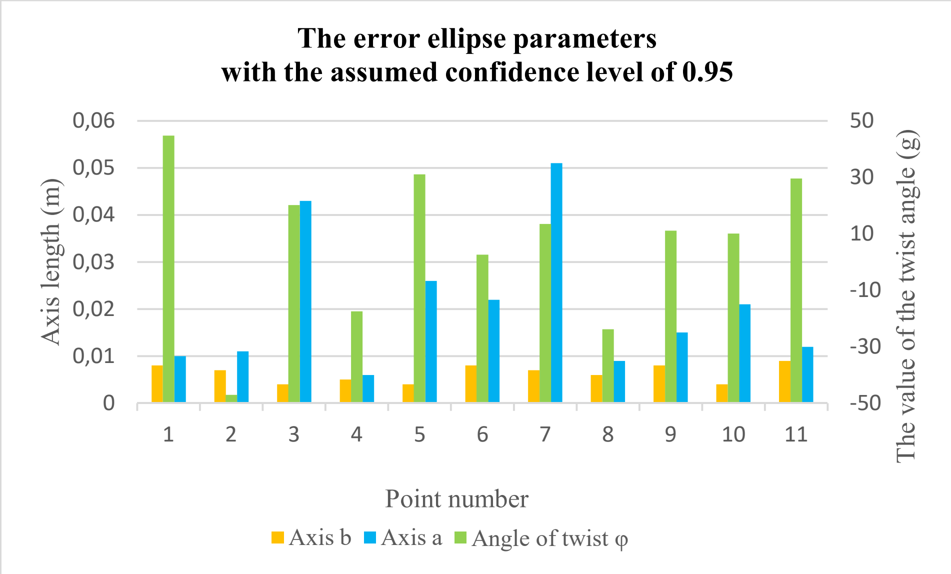

Fig. 4. The error ellipse parameters for points of the experimental network with the assumed confidence level $\gamma = 0.95$ [15]

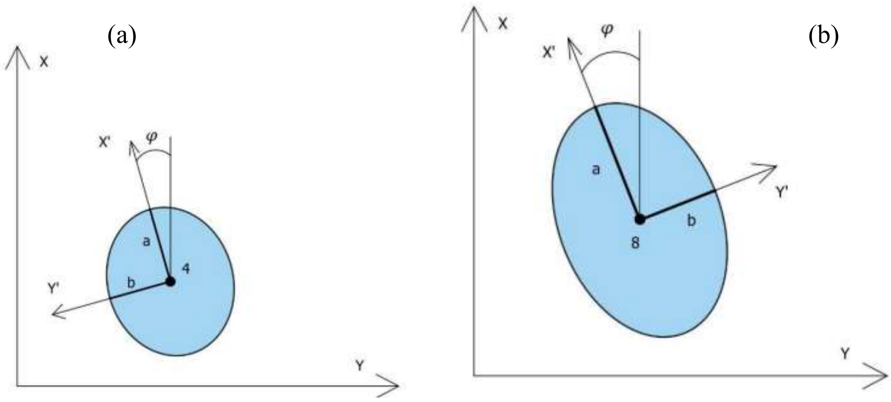

Fig. 5. Confidence ellipse for point 4 (a) and for point 8 (b) [15]

The performance of coarse error-tolerant adjustment by the modified least-squares method and the applicable suppression functions are detailed in Section 2.2. and 2.3. The damping function was used - the Hampel function - to equalize the experimental network. In the equalization resistance to gross errors, all observations with appropriate mean errors constituting elements of the weight matrix and the ε precision of introducing standardized corrections to the permissible range were assumed for equalization. The precision was dependent on the accuracy of the measurements made and adopted a priori on the level ε=0.0015. The process of adjustment by the modified least-squares method was as follows for the experimental network (a detailed diagram is presented in Fig. 3):

– *Step 0* – preliminary stage - classical adjustment with the least-squares method, the result of which are the values of estimated parameters and the mean errors of observations and coordinates. If we assume that γ=0,95, then the value of k for the assumed probability is 2, i.e. by calculating the numerical ratio of the correction to the correction error, standardized values of correction estimators were obtained. Received values allowed for the identification of three observations that did not fall within the acceptable range. The Hampel damping function defined by formula (2.4) was introduced to estimate parameters in the process. The damping function value was calculated based on formula (2.5), and the damping matrix was created, which is a diagonal matrix containing the damping function values on the main diagonal. It was also assumed that k=2 and k_b=6 to calculate the value of the damping function.
– *Step 1* and the next steps – the weight matrix **P** was multiplied by the damping matrix from *Step 0*, the least-squares equalization was performed. As a result of the equalization, the **V** matrix was determined, and the mean errors of observations were calculated based on the matrix $\mathbf{C_x}$. The iteration process is complete after running 12 iteration steps. The final adjustment in the observation corrections is shown graphically in Fig. 6 and Fig. 7.

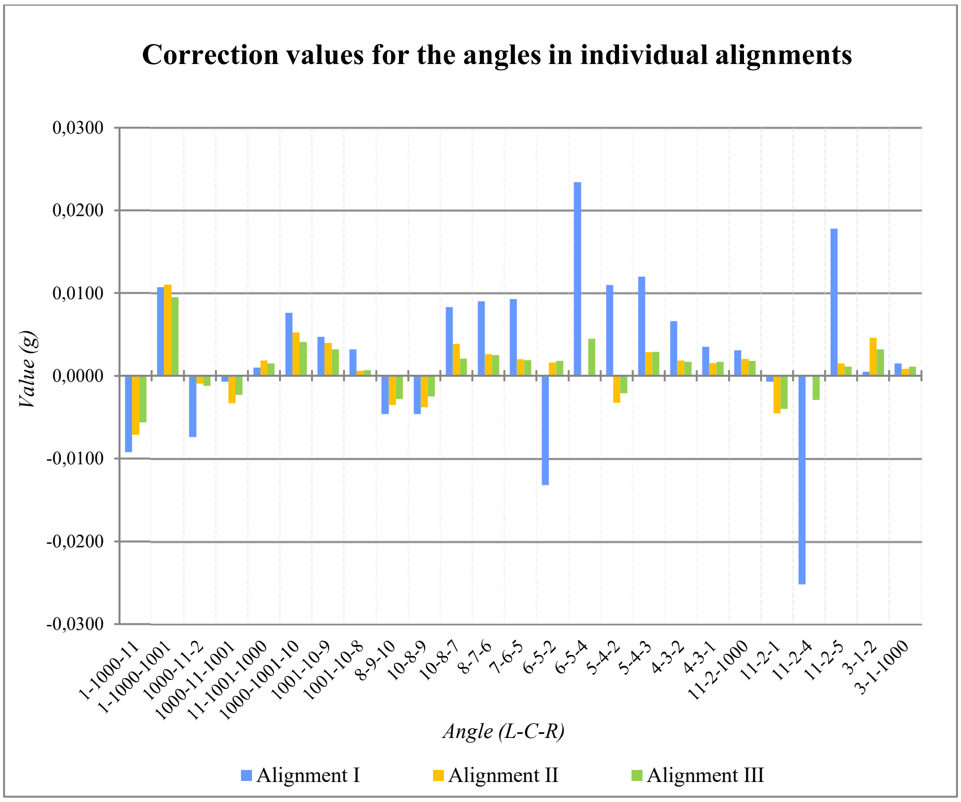

Fig. 6. Correction values for angles [11]

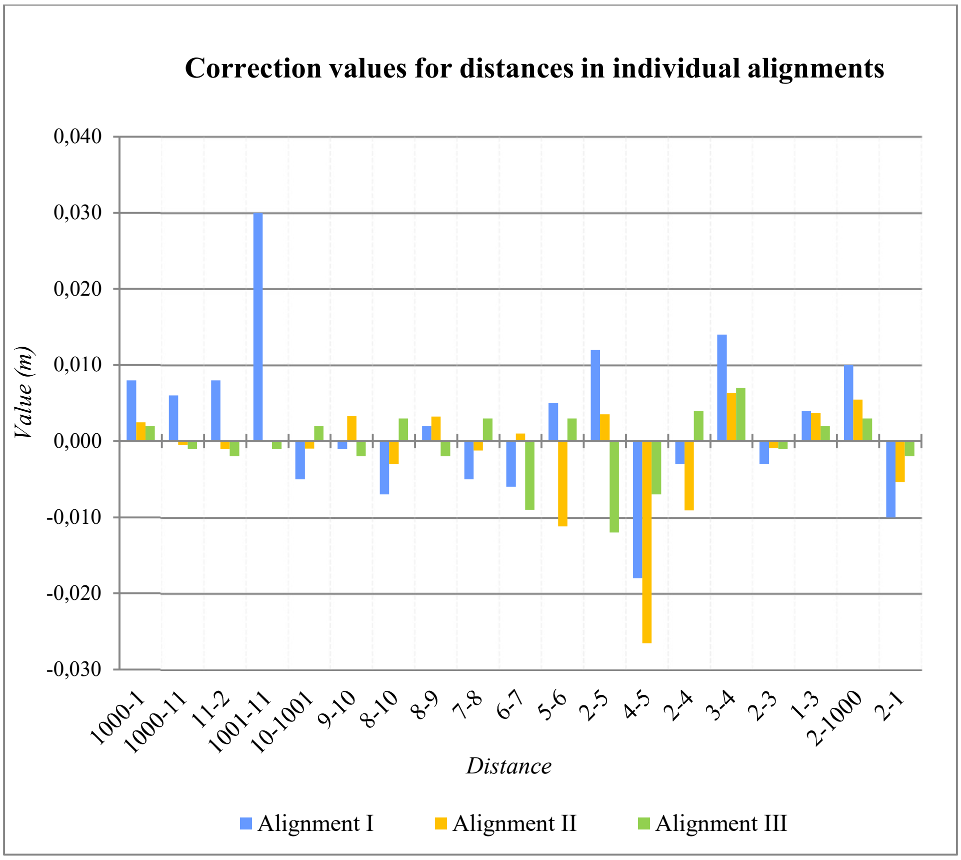

Fig. 7. Correction values for distance [11]

Comparing the data presented in Fig. 6, it can be stated that the highest correction values were recorded in the first adjustment, while the smallest was in adjustment III. Particular attention is paid to the correction values for observations 6-5-4 and 11-2-4, i.e. observations rejected due to the suspicion of gross errors; they assume the highest values among those presented and significantly differ from the others. In the case of corrections for distances (Fig. 7), as in angles, the highest values were obtained during I compensation, but not for all observations. In observations 5-6, 4-5 and 2-4, the highest correction values were recorded in adjustment II. It is also worth mentioning that the highest value among the presented corrections concerned observations 1001-11, i.e. the observation that was rejected during adjustment II. The smallest corrections values for linear and angular observations were obtained by adjusting resistance to coarse errors (adjustment III). Table 1 summarizes the values of the coordinates of the points after adjustment for all the variants of network alignment presented in the paper. The obtained coordinate values confirm the usefulness of the network adjustment using the modified least squares method.

Table 1. Coordinate values

Point number	Coordinate values [m]					
	adjustment I		adjustment II		adjustment III	
	X	*Y*	*X*	*Y*	*X*	*Y*
1	5815050.696	6428037.548	5815050.691	6428037.546	5815050.690	6428037.547
2	5815041.877	6428064.231	5815041.869	6428064.232	5815041.851	6428064.231
3	5815132.842	6428065.948	5815132.837	6428065.946	5815132.833	6428065.947
4	5815153.549	6428073.246	5815153.535	6428073.243	5815153.528	6428073.244
5	5815143.533	6428091.295	5815143.520	6428091.282	5815143.527	6428091.280
6	5815110.296	6428167.963	5815110.317	6428167.947	5815110.303	6428167.944
7	5815080.700	6428159.875	5815080.713	6428159.864	5815080.742	6428159.861
8	5815019.264	6428155.368	5815019.272	6428155.366	5815019.254	6428155.367
9	5815027.996	6428132.383	5815028.004	6428132.380	5815028.009	6428132.381
10	5814985.276	6428139.477	5814985.280	6428139.476	5814985.318	6428139.477
11	5814979.354	6428061.787	5814979.355	6428061.781	5814979.337	6428061.782

4. CONCLUSION

The analyses show that the adjustment resistance to coarse errors with the modified least-squares method allowed to obtain results similar to the measured network adjustment after eliminating outliers. The robust equalization method obtained the lowest mean error value for the investigated experimental network. Implementing the network equalization after eliminating outliers reduced the mean errors for unknowns and observations significantly.

An essential feature of coarse error-tolerant adjustment is that it does not require eliminating outliers, which is particularly important in networks where many overtime observations have not been made. The conducted research allowed for the objectives' implementation of the work - the establishment and measurement of the implementation network on the Morasko campus and the analysis of the possibility of diagnosing and eliminating gross errors in the completed observations. Thanks to the analysis of the results, it is possible to confirm the effectiveness of both methods in detecting and eliminating gross errors. The advantages of M-estimation methods, which with the help of specific mathematical operations, allow for processing the obtained spatial data satisfactorily, were also confirmed. After determining the aligned coordinates of the points, the experimental geodetic network established on the Morasko campus can constitute a solid test base for further geodetic works.

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