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MODIFIED PARAMETER METHODS OF RESEARCHING GNSS NETWORKS WITH CORRELATIVE MEASUREMENTS AND SYSTEMATIC ERRORS

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1. Introduction

The application of GNSS measuring method for monitoring pumped hydroelectric energy storage (PHES) and hydroelectric station deformations which are located in mountainous districts need to be observed using geodetic observation programs. A technological equipment and the relief of the territory of hydroelectric stations considerably limit an access to satellite during GNSS of measurements. Thus, the influence of errors on the results of GNSS rises. The basic sources of GNSS errors measurements are divided into three groups. The errors are known to be caused by a space segment, signal passing through the layers of ionosphere and troposphere. There are also instrumental errors [Shaw of et al.,2000]. Besides GNSS errors of measurements can be of accidental and systematic character. Accidental errors equalized due to balanced networks and doing additional measurements. Therefore, systematic errors are hard to get rid of the results of the measurements. Doing simultaneous vector measurements increases displacement of systematic errors, which are connected with their correlation. For the research of deformation processes at hydroelectric power stations the modern systems of the automated monitoring are applied. In Ukraine the leaders of development and exploitation of such systems are some companies producing geodesic devices (Trimble, Leica Geosystems AG), some hi-technological companies, which create complexes for information management (Stock Company "Bankomsviaz") and companies specialized exactly in monitoring integral state buildings (SolDATA Group). Such systems have already been worked at five the greatest Ukrainian hydroelectric power stations (Dnipro, Kaniv, Kamianske, Dnister HES and PHES). It is going to be set at Kahovka HES too [Projects., 2016]. In automatic systems all measurements are practically conducted simultaneously and thus the displacement of their systematic errors is maximum. Systems of automated deformation monitoring are absent at the hydroelectric power stations. The repeated measurements of hydrotechnic networks are regularly conducted. As a rule, the less number of GNSS receivers are used than network sets. Thus, not at every set the simultaneous GNSS measurings are done. In the whole all measurements are executed at all network sets and have enough extra measurement data necessary for their monitoring. The influence of systematic errors is less for such measuring scheme but never the less it exists within every measurement.

The value of systematic error of the measuring vectors depends on signal passing through troposphere and ionosphere, their lengths, measuring duration, GDOP index and its changing in time, open territory during the measurements and other factors.

In the research [Trevoho of et al., 2014] authors have learnt a standard basic geodesic GNSS observation method. Having based on the received results of observations in different days it has been learnt that systematic error of 20 km length line is 2mm.

Troposphere and ionosphere delays of signal passing from satellite to receiver are the basic sources of systematic errors [Zhang of et al., 2011, Petrie of et al., 2011, Fritsche of et al., 2005]. Two-frequency GNSS receivers allow to remove errors only of the first serial, at the same time permanent errors of 2nd and higher serials can be of a few centimeters. It is set that these errors in majority depend on the angle of cutoff of satellite [Lau of et al., 2006]. If the angle of cutoff is diminished the errors of troposphere and ionosphere delays will decrease too and, vice versa, an error of multi-ways will increase.

To diminish the error of multi-ways the authors [Lau of et al., 2006] suggested to change the length of the reflected signal for the half of wave-length. Such manipulations with phases frequencies will decrease the influence of this error. Another characteristic of the method [Kadaj 2008] is reducing the error of multi-ways by algorithm of additional post-processing of the measured networks using the complete set of Shraiberg observation differences applying diagonal gravimetric matrices.

Another systematic error of GNSS of measurement is an error of setting off aerial phase center. Its neglecting can considerably distort the observations results. In the research [Mader 1999] authors state that the height error can be up to 10 cm. Calibration of GNSS-aerial [Rothacher2001] allows partly to detect the value of the error, but during the work it can be changing. In their research [Church of et al., 2011] the authors offer to use the system of equation that during "post-processing" can remove this error partly. The quality of the received observations results depends on the error reflected signal.

No less important systematic errors are errors of space satellites orbits. These errors mainly depend on a chosen file that contains information about Ephemeris of satellites and allow to detect their location [Schmid of et al., 2007]. The least errors are so-called «Final» GNSS files of satellite orbits [Eckl of et al., 2001].

Except the mentioned above systematic errors the errors of atomic clock depend on the accuracy of GNSS measurements [Weiss of et al., 2007]. These errors are partly got rid of during the differential measurements [Macii of et al., 2004] and in the process of network balancing, that is why their final influence can be set to accidental.

Determination of set coordinates is done by using combinative method of pseudo-distances and measuring of bearing phases. Each of these methods separately does not set out the systematic errors considerably and thus, the received GPS measurements are distorted [Shaw of et al., 2000, Mosavi of et al., 2014]. Having used a combination of suggested methods authors have improved the observation results to 45 % but this is not enough for high-accuracy researches.

Based on analysis of scientific sources it may be stated that applying methods of setting off of GNSS systematic errors, their influence on the final results of the measured values are substantial and they become accurate after fulfilling the simultaneous measurements under the restrict access to the satellite signals during the measuring process. The classic parameter method of balancing allows mainly to set off accidental error only. That’s why it is necessary to improve geodesic network balancing method in order to get rid of systematic errors of the measuring results.

2. Metodology

To reduce the influence of systematic errors the differential method of GNSS network balancing has been suggested. This balancing method is a modification of classic parameter balancing method. To get rid of systematic errors partly the equations of difference correcting of these vectors have been suggested.

For the classic parameter method the equation of correcting projections of measured GNSS (having applied vector method) at the coordinative axes are as follows:

$$\begin{aligned} d_{x_i}\frac{\partial f}{\partial_{x_i}}+d_{x_j}\frac{\partial f}{\partial_{x_j}}+l_{x_{ij}}&=u_{x_{ij}}\\ d_{y_i}\frac{\partial f}{\partial_{y_i}}+d_{y_j}\frac{\partial f}{\partial_{y_j}}+l_{y_{ij}}&=u_{y_{ij}}\\ d_{z_i}\frac{\partial f}{\partial_{z_i}}+d_{z_j}\frac{\partial f}{\partial_{z_j}}+l_{z_{ij}}&=u_{z_{ij}} \end{aligned} \quad (1)$$

Application of classic balancing method for a triangle formed by three simultaneously measured vectors nine equations are conducted (1). For differential method the equation of correcting may be of two types, exactly, the equation of measured vectors correcting (1) and the equation of vectors differences correcting. In the same triangle two vectors for the equation of their differences (2) and one vector remains in a form of equation (1).

$$\begin{aligned} d_{x_i}\frac{\partial f}{\partial_{x_i}}-d_{x_m}\frac{\partial f}{\partial_{x_m}}+\left(l_{x_{ij}}-l_{x_{mj}}\right)&=u_{x_{im}}\\ d_{y_i}\frac{\partial f}{\partial_{y_i}}-d_{y_m}\frac{\partial f}{\partial_{x_m}}+\left(l_{y_{ij}}-l_{y_{mj}}\right)&=u_{y_{im}}\\ d_{h_i}\frac{\partial f}{\partial_{h_i}}-d_{h_m}\frac{\partial f}{\partial_{h_m}}+\left(l_{h_{ij}}-l_{h_{mj}}\right)&=u_{h_{im}} \end{aligned} \quad (2)$$

where

$$\begin{aligned} l_{x_{ij}}&=\Delta x_{ij_{meas}}-\Delta x_{ij_{apr}}\\ l_{x_{mj}}&=\Delta x_{mj_{meas}}-\Delta x_{mj_{apr}}\\ l_{y_{ij}}&=\Delta y_{ij_{meas}}-\Delta y_{ij_{apr}}\\ l_{y_{mj}}&=\Delta y_{mj_{meas}}-\Delta y_{mj_{apr}}\\ l_{h_{ij}}&=\Delta h_{ij_{meas}}-\Delta h_{ij_{apr}}\\ l_{h_{mj}}&=\Delta h_{mj_{meas}}-\Delta h_{mj_{apr}} \end{aligned} \quad (3)$$

i, j, m – are the set points of triangle between measured vectors. Two equations of differences (2) can be done for a triangle but in both of them correlative result of vector differences equation exists.

Thus, differential method unlike classical parameter method has the value of correcting equations for each triangle less in one point and that makes the result worse. It negatively influences on the estimation of accuracy of the balanced network. But nevertheless it gives an opportunity to set off the systematic errors. The further network balancing is done using the differential method of the least squares. Having done balancing it is necessary to estimate efficiency (E) of differential balancing method in comparing to classic parameter one. It gives an opportunity to estimate the received results. Efficiency is calculated by formula:

$$E=\frac{\left|d_{class}\right|-\left|d_{diff}\right|}{\left|d_{class}\right|}\cdot 100\% \quad (4)$$

where d_{class} – is the difference between the coordinates set by classic parameter method and «the truth», d_{diff} – is the difference between the coordinates set by differential method and «the truth».

3. Results

Having learnt the facts above it is worth investigating the efficiency of differential GNSS balancing method of measurement for standard networks which, first of all, have satisfactory conditions of open territory. For this purpose, the network has been chosen consisting of 8 permanent stations (Fig. 1)which are located in the south-west of the USA network (in the southern part of California) at the Pacific Ocean coast. Every point of the network has two-frequency GNSS receivers with observation frequency 15 seconds. Signal access to the receiver is set by such parameters: angle of set off of satellite which is 10^0 and the observation duration which is limited by 12 hours. A network consists of stations: p181, MONB, p222, p228, p229, p230, p248, p262.The minimum distance between the points is 13.2 kilometers, and the average distance is 31.4 kilometers, and the maximum one is 64.5 km. Basic data for the vectors calculation and network balancing have been RINEX-files of GNSS measuring results at these stations. They are in free access at the following website http://sopac.ucsd.edu/ dataBrowser.shtml, and also the exact value of Ephemeris is at the following website http://rvdi.com/freebies/ gpscalendar.html.

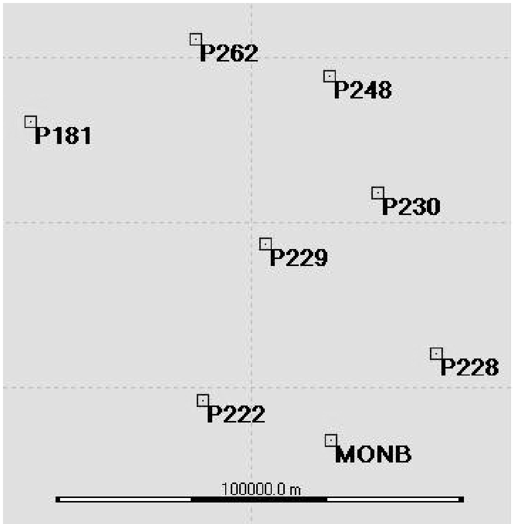

Fig. 1. Scheme of GNSS Stations Network

The scheme of network measurements has been set by combination of all possible triangles formed by three simultaneously measured vectors. Vectors measurements of each triangle has been conducted in different day, thus the measuring period is 56 days. The fragment of observation calendar plan is shown at Table 1.

Special feature of the result comparison of balancing network is the vector calculation which has been done twice. First, using LGO software (Leica Geo Office), secondly, using TBC software (Trimble Business Centre). It has been set to have applied these softwares because they showed good results at processing network vectors with small distances between the set points. For determination of the set coordinate accuracy and the advantages or disadvantages of the received results based on the both methods it is necessary to know "the truth" of the set coordinates. As "the truth'' of the set of coordinates has been taken balanced coordinates with the center determined basing on processing durative observation, applying independent methods and softwares. To get the exact station coordinates which are accepted as "the truth" during the processing correcting data have been maximum taken into account as possible sources of GNSS measurement errors. The received results are kept in the archive of SOPAC center and are in free access. Stations coordinates are truly reflected in the middle epoch of measurements. It is shown at Table 2.

Table 1

Fragment of Calendar Plan of the Set Network Measurements

№ day	Observation date	stations	№ day	Observation date	stations	№ day	Observation date	stations	№ day	Observation date	stations
1	1.04.2014	p181, p262, p248	2	2.04.2014	p181, p262, p230	3	3.04.2014	p181, p262, P228	4	4.04.2014	p181, p262, MONB
5	5.04.2014	p181, p262, P222	6	6.04.2014	p181, p262, p229	7	7.04.2014	p181, p248, p230	8	8.04.2014	p181, p248, P228

Table 2

"The Truth" of Set Network Coordinates

Station	Coordinates, м		
	X	Y	Z
MONB	–2675632.3943	–4304129.2434	3860728.5356
P181	–2697941.0782	–4255089.3931	3898009.6121
P222	–2689640.3005	–4290437.3144	3865050.9137
P228	–2657816.9211	–4305567.6477	3870768.3557
P229	–2674302.7553	–4283445.1433	3883668.1839
P230	–2657625.5245	–4288583.7177	3889987.4778
P248	–2657969.5330	–4275411.2632	3903451.5648
P262	–2673021.9692	–4261799.1186	3907637.9453

Balancing is done by differential and classic parameter methods. The first set of the network coordinates has been chosen by SOPAC center, the rest set of coordinates have been chosen taken into account the balancing results. On the basis of the balanced network coordinates the differences between certain corresponding sets and these of SOPAC center have been set. These set differences are for classic parameter and differential methods. They are transformed on the plane of the Universal Merkator project. Differences are set in accordance with SOPAC center coordinates and can be interpreted as determination errors of the set coordinates based on the balancing results. Therefore these differences may be called the errors of the set coordinates based on the corresponding method of balancing. The results of determination of set coordinates errors for a network d_x, d_y, d_h (vectors are calculated using LGO software) by two balancing methods. They are shown at Table 3. But in the last but one line of the table the sum is shown and in the last line the average value of corresponding errors is shown too. In column 8 and in column 9 errors are shown at each point of the plan, and in column 10 and in column 11 of the territory. Table 4 shows a pre-learnt accuracy of the set coordinates based on the balancing result of differential and classic parameter methods. The last line shows the average square errors of determination of the set coordinates.

As the result, out of Fig. 2a, 2b and 2c and Table 3 it is evidently, that errors of set coordinates applying differential method are considerably less than the errors of set coordinates based on classic method for the axes x and y (the exception is point 3 at axis x) and at axis h are approximately identical. Changing of determination coordinates errors in the plan and the territory are represented at Fig. 2d and 2e. It should be noted that the errors, having got by differential method are less than errors set out of the balancing by applying classic parameter method. The average efficiency of the suggested method is 15 % in the plan and 4 % in the spatial.

The researching results of the pre-learnt accuracy of coordinate determination applying two methods are presented at Table 4. Comparing the average square errors and errors of set network coordinates where vectors are calculated using LGO software, it is possible to state that errors determined by differential method are less in 20 % than the errors determined by classic parameter method. They are less in 60 %. Thus, it confirms the presents of systematic errors.

Table 3

The Errors of the Set Network Coordinates Determined by Differential and Classic Parameter Methods (Vectors Are Calculated Using LGO Software)

№ point	d_x diff. mm	d_x class. mm	d_y diff. mm	d_y class. mm	d_h diff. mm	d_h class. mm	d_{plan} diff. mm	d_{plan} class. mm	$d_{spatial}$ diff. mm	$d_{spatial}$ class. mm
1	2	3	4	5	6	7	8	9	10	11
2	–8.0	–27.8	3.7	18.6	15.9	38.2	8.8	33.5	18.2	50.8
3	10.4	–1.6	–0.2	–2.1	10.5	39.9	10.4	2.6	14.8	39.9
4	19.8	18.7	–5.4	–9.5	–15.2	11.8	20.6	21.0	25.6	24.1
5	18.1	23.0	–5.6	–9.3	–42.8	–31.3	18.9	24.8	46.8	39.9
6	7.9	13.2	–2.3	–6.2	–31.5	–20.7	8.2	14.6	32.6	25.3
7	–8.2	–3.7	–8.0	–6.7	–122.6	–96.8	11.5	7.7	123.1	97.1
8	–29.3	–26.3	19.7	17.0	–3.4	–5.4	35.3	31.3	35.5	31.7
$\lvert\Sigma\rvert$	101.7	114.4	44.9	69.2	241.9	244.1	113.7	135.4	296.5	308.9
|midel|	14.5	16.3	6.4	9.9	34.6	34.9	16.2	19.3	42.4	44.1
E%	11		35		1		16		4	

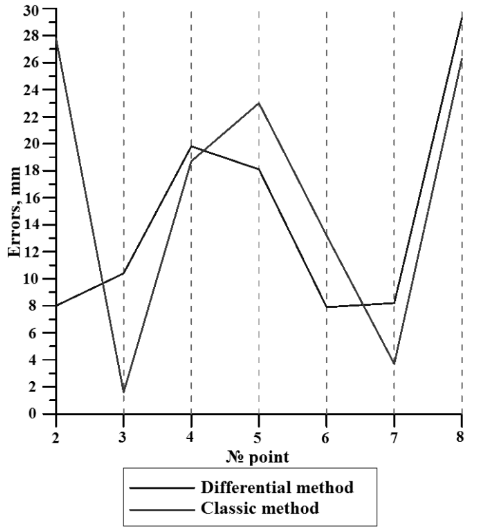

Fig. 2a

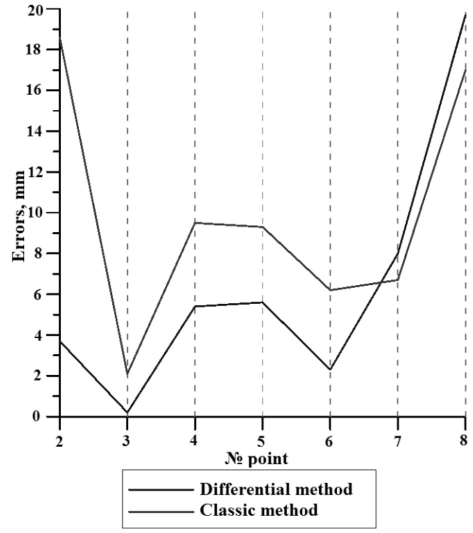

Fig. 2b

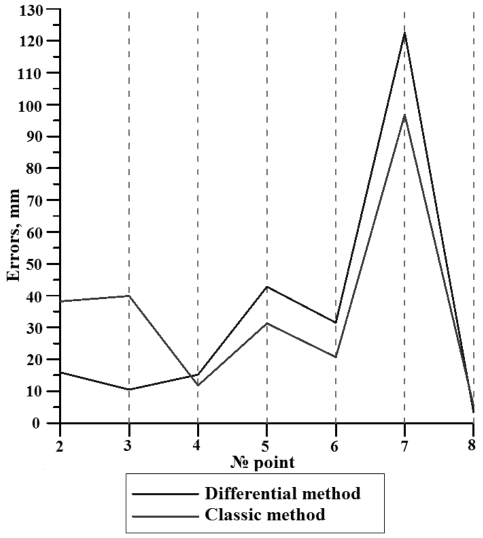

Fig. 2c

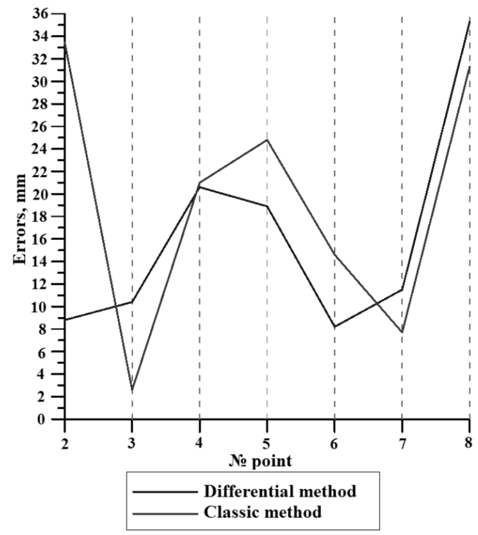

Fig. 2d

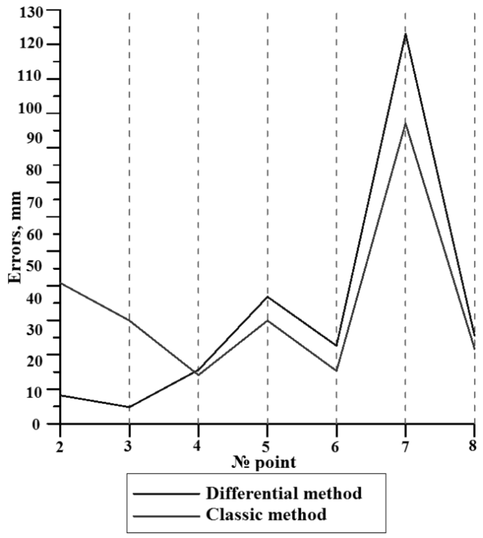

Fig. 2e

Fig. 2. Changing of determination of the set coordinate errors applying differential and classic parameter methods (Fig. 2a. Errors d_x *; Fig. 2b. Errors* d_y *; Fig. 2c. Errors* d_h *; Fig. 2d. Errors in the plan; Fig. 2e. Errors in the spatial)*

Table 4

The Average Square Errors of the Set Network Coordinates Determined by Differential and Classic Parameter Methods (Vectors Are Calculated Using LGO Software)

№ point	m_x diff. mm	m_x class. mm	m_y diff. mm	m_y class. mm	m_h diff. mm	m_h class. mm	m_{plan} diff. mm	m_{plan} class. mm	$m_{spatial}$ diff. mm	$m_{spatial}$ class. mm
1	2	3	4	5	6	7	8	9	10	11
2	9.7	1.1	8.2	8.7	21.5	21.2	12.7	8.7	25.0	23.0
3	10.7	1.2	4.3	5.1	23.5	23.1	11.6	5.3	26.2	23.7
4	11.5	1.2	3.9	4.9	22.3	20.2	12.1	5.0	25.4	20.8
5	11.2	1.0	4.2	5.3	24.9	22.4	12.0	5.4	27.6	23.0
6	11.4	1.1	4.4	5.5	23.5	15.8	12.2	5.6	26.5	16.7
7	11.8	1.1	6.3	5.0	28.2	22.6	13.4	5.1	31.2	23.2
8	15.9	1.1	10.3	5.4	31.4	20.5	19.0	5.5	36.7	21.2
midel	11.7	1.1	5.9	5.7	25.1	20.8	13.3	5.8	28.4	21.7

Tables 5 and Table 6 , Fig. 3a, 3b, 3c, 3d, 3e show the results of network processing (vectors are calculated using TBC software) applying differential and classic parameter methods. Fig. 3c shows evidently, that at axis h the results are approximately identical (Fig. 3c), except for point 8. If the results of network processing in the plan and the spatial (Fig. 3d, 3e) are considered then the average efficiency of differential method is 15 % comparing to classic parameter method.

Table 6 shows the researches of the pre-learnt determination accuracy of coordinates based on two methods of network where vectors are calculated using TBC software. The results show that accuracy of determination coordinates applying classic method is higher, than that one done by the suggested differential method. These results, as well as for previous networks are determined by the fact that the number of correcting equations applying classic method is more than when the differential method is used. As the result of the network processing (vectors are calculated using TBC software) by two methods it is set that having average square errors determined by differential method are 7 % less than errors determined by classic parameter method. They are 45 % less. Thus, it confirms the existing of systematic errors in measurements and the efficiency of network balancing applying differential method.

Table 5

The Errors of the Set Network Coordinates Determined by Differential and Classic Parameter Methods (Vectors Are Calculated Using TBC Software)

№ point	d_x diff. mm	d_x class. mm	d_y diff. mm	d_y class. mm	d_h diff. mm	d_h class. mm	d_{plan} diff. mm	d_{plan} class. mm	$d_{spatial}$ diff. mm	$d_{spatial}$ class. mm
1	2	3	4	5	6	7	8	9	10	11
2	–8.1	–26.5	3.2	16.3	–1.7	–1.8	8.7	31.1	8.9	31.2
3	11.3	0.6	–0.8	–3.1	–3.4	–5.9	11.3	3.2	11.8	6.7
4	20.2	20.3	–5.6	–10.3	–0.3	–3.7	20.9	22.7	20.9	23.0
5	17.3	22.8	0.0	–4.6	–1.9	–4.9	17.3	23.2	17.4	23.8
6	6.8	12.5	–2.4	–6.0	4.6	–1.3	7.2	13.8	8.5	13.9
7	–13.8	–9.1	–6.0	–4.2	–55.1	–56.3	15.0	10.1	57.1	57.2
8	–29.3	–26.3	17.6	16.9	14.0	–0.4	34.2	31.2	36.9	31.2
$\|\Sigma\|$	106.8	118.0	35.6	61.5	80.9	74.4	114.7	135.4	161.6	187.0
|midel|	15.3	16.9	5.1	8.8	11.6	10.6	16.4	19.3	23.1	26.7
E%	9		42		–9		15		13	

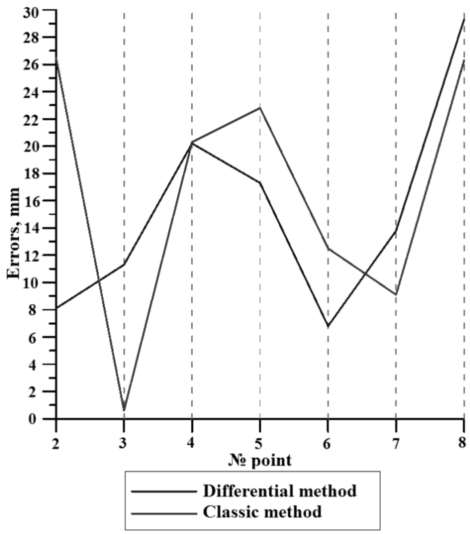

Fig. 3a

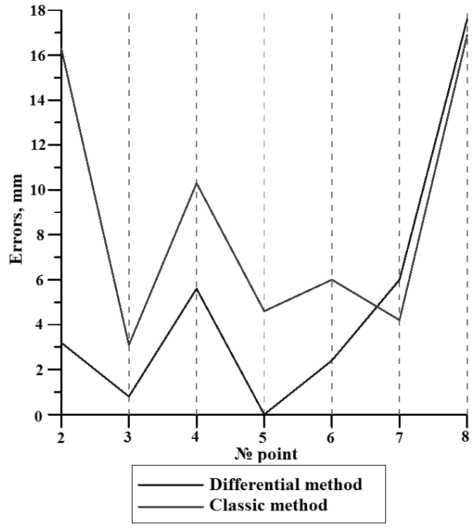

Fig. 3b

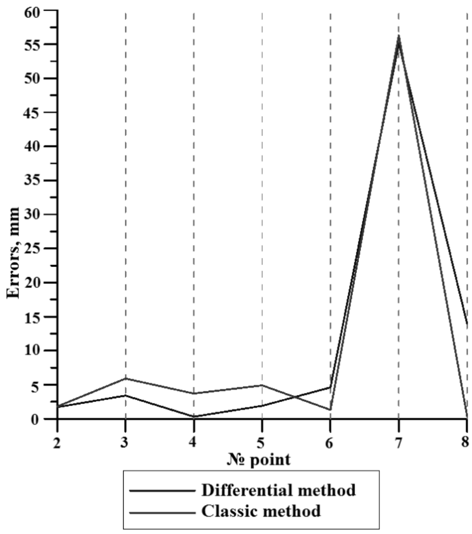

Fig. 3c

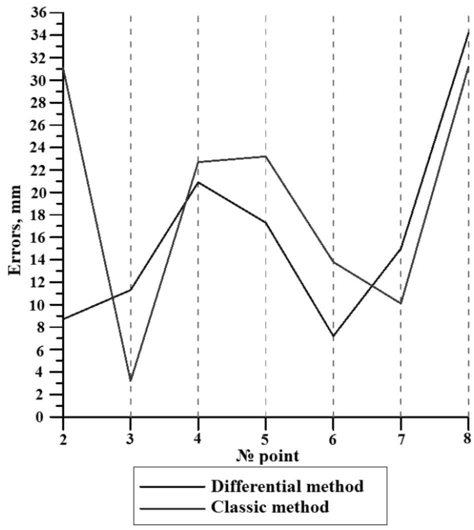

Fig. 3d

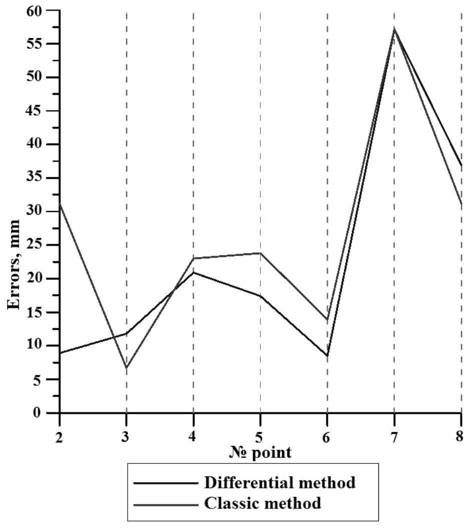

Fig. 3e

Fig.3. Changing of determination of the set coordinate errors applying differential and classic parameter methods (Fig. 3a. Errors d_x ; Fig. 3b. Errors d_y ; Fig. 3c. Errors d_h ; Fig. 3d. Errors in the plan; Fig. 3e. Errors in the spatial)

Table 6

The Average Square Errors of the Set Network Coordinates Determined by Differential and Classic Parameter Methods (Vectors Are Calculated Using TBC Software)

№ point	m_x diff. mm	m_x class. mm	m_y diff. mm	m_y class. mm	m_h diff. mm	m_h class. mm	m_{plan} diff. mm	m_{plan} class. mm	$m_{spatial}$ diff. mm	$m_{spatial}$ class. mm
1	2	3	4	5	6	7	8	9	10	11
2	9.7	1.2	7.9	9.1	11.2	13.1	12.6	9.2	16.9	16.0
3	10.8	1.3	4.2	5.4	12.3	14.3	11.6	5.5	16.9	15.3
4	11.6	1.2	3.8	5.2	11.7	12.5	12.2	5.3	16.8	13.6
5	10.7	1.0	4.1	5.6	12.9	13.7	11.4	5.7	17.2	14.8
6	11.0	1.1	4.3	5.7	11.6	9.7	11.8	5.9	16.6	11.3
7	12.3	1.2	6.1	5.3	14.5	13.8	13.7	5.4	20.0	14.8
8	16.4	1.1	9.5	5.7	18.7	12.9	18.9	5.8	26.6	14.2
midel	11.8	1.1	5.7	6.0	13.3	12.9	13.2	6.1	18.7	14.3

Fig. 4 summarises the results of average error determination only by processing the networks applying differential and classic methods and at Table 7 the average square errors are shown as the balancing results. As the result the average errors of determination of set network coordinates are 10–20 % less than the results of set coordinates applying differential balancing method comparing to classic one. Thus, the efficiency of the suggested differential balancing method has been shown again even when vectors have been calculated using different softwares.

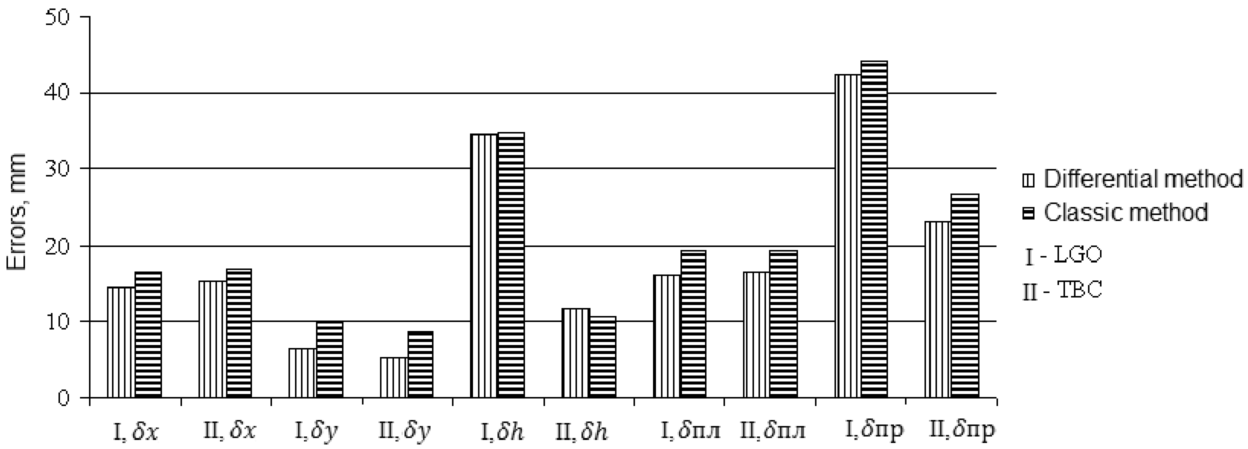

Fig. 4. The average errors of set coordinates determined by differential and classic parameter methods (based on the results of network processing by two softwares)

Table 7

The Average Square Errors of the Set Network Coordinates Determined by Differential and Classic Parameter Methods

Determination in software	m_x diff. mm	m_x class. mm	m_y diff. mm	m_y class. mm	m_h diff. mm	m_h class. mm	m_{plan} diff. mm	m_{plan} class. mm	$m_{spatial}$ diff. mm	$m_{spatial}$ class. mm
1	2	3	4	5	6	7	8	9	10	11
Midel										
LGO	11.7	1.1	5.9	5.7	25.1	20.8	13.3	5.8	28.4	21.7
TBC	11.8	1.1	5.7	6.0	13.3	12.9	13.2	6.1	18.7	14.3

On the basis of the done researches it can be concluded that the results of GNSS network measurements studied in observation conditions and with applying differential method allow partly to set off the processing systematic errors which exist during the processing of GNSS networks by classic method. The average efficiency of differential method of balancing comparing to classic parameter one is 10–20 % but these ideal conditions exist only for satellite visibility.

The errors of set coordinates determination based on differential method are co-measurable to the average square errors which have been got out of network balancing. But processing networks by classic method considerably exceed the set parameters of error accuracy. The results of processing of network by two softwares are co-measurable and the same results are practically found. This fact in future allows to do the research using only one software.

Taking into account, that the majority of hydroelectric power stations are located in the complicated relief it is necessary to investigate the efficiency of differential method at difficult conditions of satellite signal access. To realize such investigation the network has been chosen which consist of 8 permanent stations, with a limited signal access to GNSS receiver (the angle of cutoff of satellite is 20° and observation duration is limited by 4 hours). The chosen permanent stations are located in the south -west of the USA (in the southern part of California) at the Pacific Ocean coast. Each network set has two-frequency GNSS receivers. A network consists of 8 permanent stations: p254, p229, p230, p228, MONB, p226, MHCB, p221. The minimum distance between points is 16.3 kilometers, the average distance is 36.2 kilometers, and the maximum one is 60.2 km. Basic data for the vectors calculation and network balancing have been RINEX-files of GNSS measuring results at these stations. They are in free access at the following website Scripps Orbit and Permanent Array Center (SOPAC, Institute of Geophysics and Planetary Physics, USA) [http://sopac.ucsd.edu/dataBrowser.shtml], and also the exact value of the Ephemeris is at the following website http://rvdi.com/freebies/gpscalendar.html.

The scheme of network measurements has been set by combination of all possible triangles formed by three simultaneously measured vectors. Thus for the first network four triangles of the measured vectors are leaned on every possible vector. Vectors measurements of each triangle has been conducted in different day, thus the measuring period is 56 days. Created measuring scheme had the correlated vectors only within the limits of each separate triangle. Application of classic balancing method for these networks is a balance of correcting equation within separate triangle where correlative connection exists. But correcting equation based on differential method will have no correlation. To set advantages and disadvantages and accuracy of determination of the set coordinates applying both methods it is necessary to have “the truth” of the set coordinates.

Fig. 5a shows schematic location of sets at the chosen network which have been used for the research.

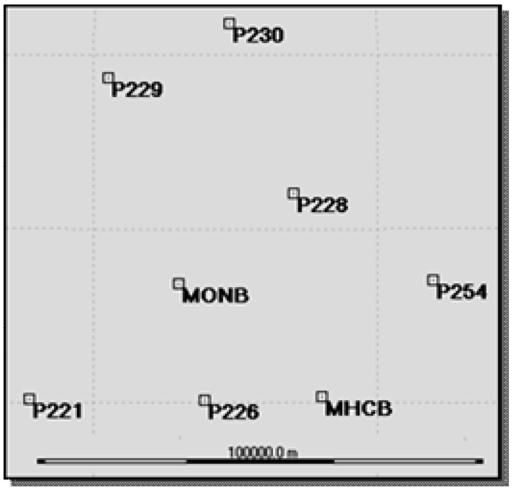

Fig. 5. Scheme of network

Calculation of vectors has been conducted by using LGO software (Leica Geo Office) taking into account the exact Ephemeris and files of the displacement of aerial phase centers. For the imitation of difficult conditions of satellite signal access and strengthening of systematic errors influence the angle of satellite cutoff has been accepted as 20^0 and the observation duration has been limited by 4 hours. For the calculation of vector correctings of the troposphere delay have been calculated in accordance with the model of Hopfield network and ionosphere delay was determined out of two frequencies L1 and L2.

After vector calculation the correcting equations for the measured vectors have been conducted basing on the classic method of balancing (1) and differential method (1), (2). The common value of the correcting equation based on differential balancing method is 112, and for classic parameter it is 168. The further balancing has been executed by using the same methodology, as well as in the previous research. The results of determination of set coordinate errors d_x, d_y, d_h for network by two balancing methods are showed at Fig. 6a-6e and at Table 8 and Table 9. Fig. 6a-6c and Table 8 show evidently, that set coordinate errors based on differential method are considerably less than set coordinate errors based on classic method (the exception is point 7 at axis y and point 3) and point 7 at axis h. The total errors are 4 times less at axes x and y and 1,5 times less at axis h. Comparing the set coordinates errors using two methods in the plan and the territory (Fig. 6d, 6e), it is possible to assert that differential method of balancing gives to 73 % better result in the plan and to 53 % in the territory than classic parameter method (the exception is point 7). Comparing the average errors of determination of the set coordinates and the average squared errors of the set coordinates applying differential and classic parameter methods it is obviously that when applying differential method they coincide practically, and when applying classic parameter method the average error is 40 % less than other errors.

Table 9 pre learned estimation of accuracy of set coordinates is done by two methods. Analyzing Table 8 it can be asserted that accuracy of coordinates determination by classic parameter method is higher, than by differential one and that is due to the fact of the less number of equation (like in the first network).

Comparing the average errors of set coordinates determination the average square errors of determination set network coordinates applying differential and classic parameter methods, it should be noted that using differential method the error is less than 20 % but classic parameter method the average error is less than 70 %.

Table 8

The Errors of Set Network Coordinates Determined by Differential and Classic Parameter Methods

№ point	d_x diff. mm	d_x class. mm	d_y diff. mm	d_y class. mm	d_h diff. mm	d_h class. mm	d_{plan} diff. mm	d_{plan} class. mm	$d_{spatial}$ diff. mm	$d_{spatial}$ class. mm
1	2	3	4	5	6	7	8	9	10	11
2	5.5	66.1	2.3	–30.2	–16.7	–66.1	5.9	72.7	17.7	98.3
3	–10.7	47.5	3.4	–22.5	20.8	–8.1	11.2	52.6	23.6	53.2
4	8.6	70.0	–3.4	–33.5	–8.9	–44.1	9.3	77.6	12.8	89.2
5	–5.0	57.2	–3.0	–33.6	–5.8	–31.5	5.9	66.3	8.2	73.4
6	–13.7	42.3	7.8	–25.3	–71.7	–96.4	15.8	49.3	73.4	108.3
7	–5.5	18.2	23.0	–6.4	76.1	23.6	23.6	19.3	79.7	30.5
8	35.5	59.0	–12.1	–39.5	2.3	–52.7	37.5	71.1	37.6	88.4
$\lvert\Sigma\rvert$	84.6	360.4	54.9	191.0	202.2	322.5	109.2	408.9	253.1	541.4
|midel|	12.1	51.5	7.8	27.3	28.9	46.1	15.6	58.4	36.2	77.3
E %	77		71		37		73		53	

Table 9

The Average Square Errors of the Set Network Coordinates Determined by Differential and Classic Parameter Methods

№ point	m_x diff. mm	m_x class. mm	m_y diff. mm	m_y class. mm	m_h diff. mm	m_h class. mm	m_{plan} diff. mm	m_{plan} class. mm	$m_{spatial}$ diff. mm	$m_{spatial}$ class. mm
1	2	3	4	5	6	7	8	9	10	11
2	7.9	7.8	5.7	5.5	20.9	20.3	9.7	9.5	23.0	22.5
3	9.8	10.1	4.7	4.5	17.2	15.2	10.9	11.0	20.4	18.8
4	10.1	10.3	4.2	4.6	19.8	18.9	11.0	11.3	22.6	22.0
5	9.8	9.6	4.4	4.6	20.7	17.8	10.7	10.6	23.3	20.8
6	13.6	8.2	4.9	4.5	24.6	19.9	14.5	9.4	28.6	22.0
7	4.9	1.1	6.4	4.5	25.2	16.1	8.1	4.7	26.4	16.8
8	4.9	2.2	10.8	4.8	33.0	21.3	11.9	5.3	35.1	22.0
midel	8.7	7.0	5.9	4.7	23.0	18.5	11.0	8.8	25.6	20.7

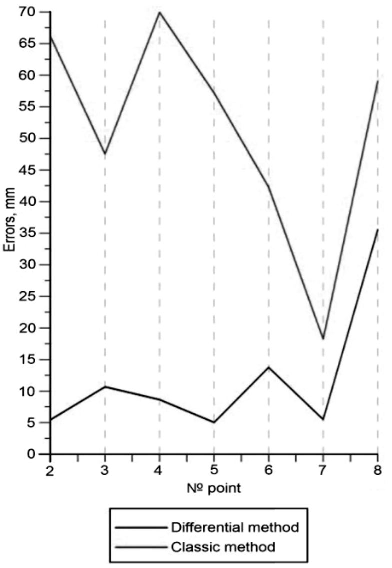

Fig. 6a

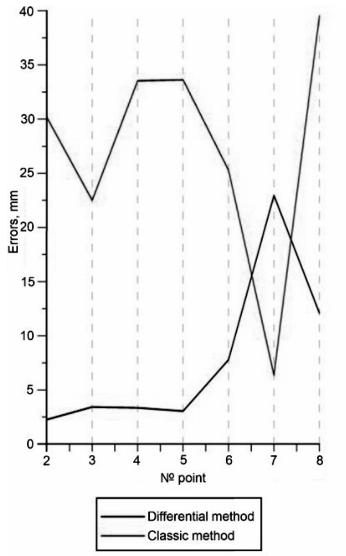

Fig. 6b

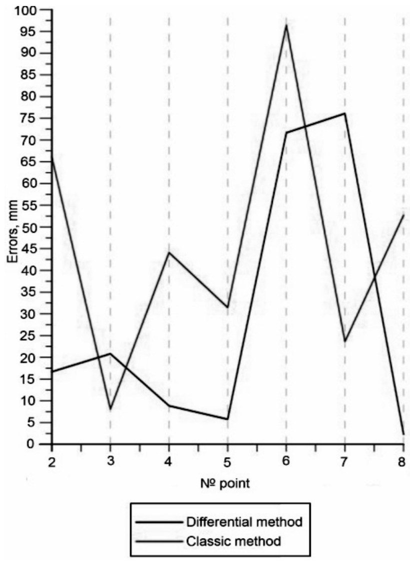

Fig. 6c

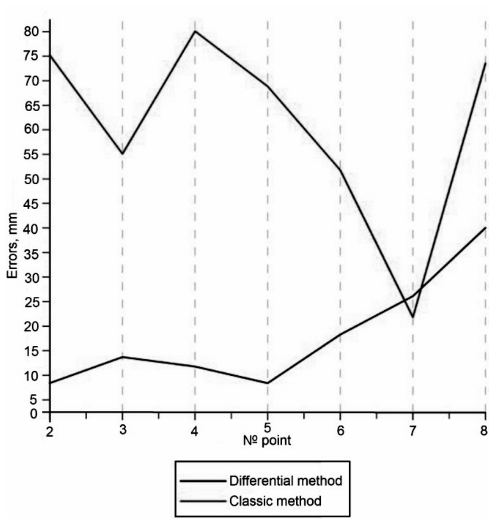

Fig. 6d

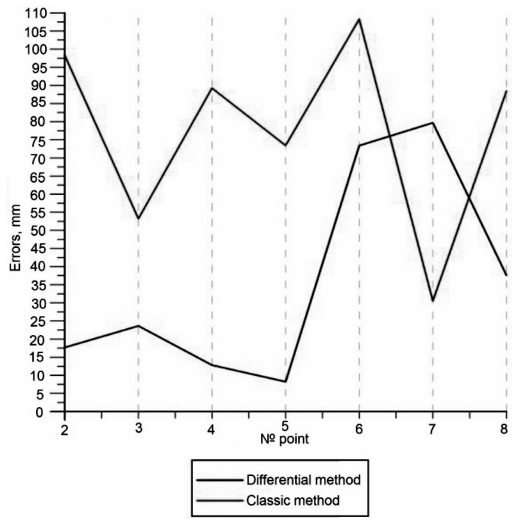

Fig. 6e

Fig. 6. Changing of determination of the set coordinate errors applying differential and classic parameter methods (Fig. 6a. Errors d_x ; Fig. 6b. Errors d_y ; Fig. 6c. Errors d_h ; Fig. 6d. Errors in the plan; Fig. 6e. Errors in the spatial)

Summarizing the results of processing the chosen network it is necessary to admit that average square errors determined by classic method is 60 % less than the errors determined by differential method. They are up to 20 % less. Thus, it confirms the advantages of differential method applied to get rid of systematic measuring errors.

The average and maximum errors of determination of the set coordinates in the whole are 10–50 % less than when differential method of balancing is applied comparing to classic one. It is necessary to admit that differential method does not have substantial divergences between the set errors of coordinates and the average square errors based on balancing results. Comparing the maximum values, it is evidently, that the errors of coordinates prevail the expected accuracy. But making analogical comparisons of the classic balancing method which considerable exceeds determination of coordinate errors which are above the expected accuracy of network balancing. This tendency is widely seen for the average and maximum values of accuracy parameters.

On the basis of conducted GNSS network measurements applying classic method in extreme conditions (partly limitation of visibility, relatively short intervals of observation) there are systematic errors of simultaneously processing measuring vectors. On the basis of the done researches, the results of processing of GNSS network measurements by differential method have been executed in extreme conditions (partly limitation of visibility of satellites and diminishing duration of vector measuring).

Conclusions

The differential method has been worked out theoretically. The efficiency of differential method is approved at networks with the ideal conditions of satellite visibility (open territory) and within limited visibility. The results of network processing are tested by two softwares (LGO, TBC) and they are practically the same.

The efficiency of differential balancing method comparing to classic parameter method used for networks with the ideal conditions of visibility is 10–20 %. The systematic errors are more in unsatisfactory conditions of satellite access. For such networks the efficiency of differential method comparing to classic parameter method is 10–50 %.

The worked out method should be applied for processing GNSS measurements which are executed in a few sessions at the networks set for geodynamic grounds and for monitoring large engineering building deformations.

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MODIFIED PARAMETER METHODS OF RESEARCHING GNSS NETWORKS WITH CORRELATIVE MEASUREMENTS AND SYSTEMATIC ERRORS

K. Tretyak, K. Smoliy

The hydroelectric power stations are mainly built in mountainous conditions and this fact considerably complicates doing the researches based on there deformations. One of the most effective methods of researching deformation is GNSS observations. Thus, the limit of signal access to the satellite in mountainous conditions and correlativeness of the simultaneous measuring display the increasing systematic errors. To decrease systematic error influence a modified parameter method has been worked out to balance GNSS measurements. The suggested method has been tested in network with the ideal signal access to satellite and the results accuracy is 10–20 % comparing with classic parameter method. The suggested method has been applied in network with the restricted signal access to satellite and the accuracy of the results is 10–50 %.Thus, the suggested method should be applied for balancing engineer-geodesic networks of hydroelectric power stations.

МОДИФІКОВАНИЙ ПАРАМЕТРИЧНИЙ МЕТОД ОПРАЦЮВАННЯ ГНСС МЕРЕЖ З КОРЕЛЬОВАНИМИ ВИМІРАМИ ТА СИСТЕМАТИЧНИМИ ПОХИБКАМИ

К. Третяк, К. Смолій

Гідроелектростанції переважно будуються в гірських умовах, що значно ускладнює виконання досліджень за їх деформаціями. Одним з найефективніших методів дослідження деформацій є ГНСС-спостереження. Однак в зв’язку з обмеженістю доступу до сигналу супутника в гірських умовах та корельованістю одночасних вимірів прояв систематичних похибок посилюється. Для зменшення впливу систематичних похибок ми розробили модифікований параметричний метод урівноваження ГНСС вимірів. Запропонований метод апробовано на мережі з ідеальними умовами доступу до сигналу супутника. Достовірність отриманих результатів становить 10–20 % порівняно з класичним параметричним методом. Також дослідження запропонованого методу проведено для мережі зі складними умовами доступу до сигналу супутника, достовірність результатів становить 10–50 %. Отже, запропонований диференційний метод потрібно застосовувати для урівноваження інженерно-геодезичних мереж ГЕС.

МОДИФИЦИРОВАННЫЙ ПАРАМЕТРИЧЕСКИЙ МЕТОД ОБРАБОТКИ ГНСС СЕТЕЙ С КОРЕЛИРОВАННЫМИ ИЗМЕРЕНИЯМИ И СИСТЕМАТИЧЕСКИМИ ПОГРЕШНОСТЯМИ

К. Третяк, Е. Смолий

Гидроэлектростанции преимущественно строятся в горных условиях, что значительно затрудняет выполнение исследований по их деформациям. Одним из наиболее эффективных методов исследования деформаций является ГНСС наблюдение. Однако в связи с ограниченностью доступа к сигналу спутника в горных условиях и корелированностью одновременных измерений проявление систематических погрешностей увеличивается. Для уменьшения влияния систематических погрешностей нами разработан модифицированный параметрический метод уравновешивания ГНСС измерений. Предлагаемый метод апробирован на сети с идеальными условиями доступа к сигналу спутника. Достоверность полученных результатов составляет 10–20 % по сравнению с классическим параметрическим способом. Также исследование предложенного метода проведено для сети со сложными условиями доступа к сигналу спутника, достоверность результатов составляет 10–50 %. Таким образом, предложенный дифференциальный метод нужно применять для уравновешивания инженерно-геодезических сетей ГЭС.