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Қ. И. Сәтпаев атындағы Қазақ ұлттық техникалық зерттеу университеті

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ИЗВЕСТИЯ

НАЦИОНАЛЬНОЙ АКАДЕМИИ НАУК
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Қазақстан Республикасы Ұлттық ғылым академиясы "ҚР ҰҒА Хабарлары. Геология және техникалық ғылымдар сериясы" ғылыми журналының Web of Science-тің жаңаланған нұсқасы Emerging Sources Citation Index-те индекстелуге қабылданғанын хабарлайды. Бұл индекстелу барысында Clarivate Analytics компаниясы журналды одан әрі the Science Citation Index Expanded, the Social Sciences Citation Index және the Arts & Humanities Citation Index-ке қабылдау мәселесін қарастыруда. Webof Science зерттеушілер, авторлар, баспашылар мен мекемелерге контент тереңдігі мен сапасын ұсынады. ҚР ҰҒА Хабарлары. Геология және техникалық ғылымдар сериясы Emerging Sources Citation Index-ке енуі біздің қоғамдастық үшін ең өзекті және беделді геология және техникалық ғылымдар бойынша контентке адалдығымызды білдіреді.

НАН РК сообщает, что научный журнал «Известия НАН РК. Серия геологии и технических наук» был принят для индексирования в Emerging Sources Citation Index, обновленной версии Web of Science. Содержание в этом индексировании находится в стадии рассмотрения компанией Clarivate Analytics для дальнейшего принятия журнала в the Science Citation Index Expanded, the Social Sciences Citation Index и the Arts & Humanities Citation Index. Web of Science предлагает качество и глубину контента для исследователей, авторов, издателей и учреждений. Включение Известия НАН РК. Серия геологии и технических наук в Emerging Sources Citation Index демонстрирует нашу приверженность к наиболее актуальному и влиятельному контенту по геологии и техническим наукам для нашего сообщества.

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RESEARCH OF SYSTEMATIC ERRORS ACCORDING TO THE RESULTS OF PROCESSING SATELLITE OBSERVATIONS BY SOFTWARE COMPLEXES

Abstract. Nowadays, the processing of results of static satellite observations is performed by well-known software complexes.

In order to study and analyze the issues of increasing the accuracy of observations, the full-scale satellite GNSS-measurements were performed at the points of the state geodetic network of the Northern region of Ukraine and the processing of their results was carried out using the OCTAVA and GrafNav/GrafNet software complexes commonly used in the geodetic practice.

As a result of the mathematical processing of observations by the mentioned software processing complexes, the influence of residual systematic errors in the differences of coordinate determinations has been noted. Various criteria have been used to further detect and process them, which made it possible to carry out statistical studies comparing the coordinate definitions of rover points using software systems. This work is devoted to these issues.

The article investigates the differences between geodesic latitudes and heights, which contain systematic errors and mean square errors of the unit of weight for each of the coordinates. It is also stated that there is no correlation between deviations in the plan and the height of coordinate definitions differences depending on the distance to the base station. On the basis of performed statistical researches the method of determination of accuracy of the results processing of GNSS-observations by software complexes on the basis of the method of double non-uniform measurements has been developed.

The methodology is relevant, it is tested based on the results of full-scale GNSS-observations in Chernihiv region and aims at detecting, taking into account and minimizing the residual systematic errors, and will contribute to increasing the accuracy of coordinate support for satellite observations.

Key words: mean square error; systematic error; double homogeneous measurements; software complexes.

Introduction. The dynamics of the development of modern geodetic technologies today is at such a level that scientific research on a given issue should not have inertia. In our opinion, this is relevant in the first place to researches connected with the issues of increasing the accuracy of satellite GNSS-observations, since the impact of residual systematic errors must be detected [1], taken into account and, if possible, minimized. These impacts have been investigated on the basis of the results of full-scale satellite-based GNSS-measurements at the points of the state geodetic network. The processing of their results has been carried out with the use of software complexes commonly used in geodetic practice, which made it possible to investigate the presence of systematic errors in the differences of coordinates of the same rover points.

Detection and accounting of systematic errors are considered in a number of papers. For example, [2] describes the process of diagnosing systematic errors that affect the measurement of angles performed by the tacheometer. The diagnosis consists in detecting and identifying the specific components of the instrument errors to exclude them from angular measurements.

Different schools of measurement error theory are compared in the work [3], in particular, different approaches to accounting systematic error in electronic distance measurement (EDM) in the work of Chinese scientists are studies and a new theory of measurement errors is suggested, according to which any error is a bias and obeys the random distribution. The paper refers to the incomprehension of the traditional theory of measurements, proposes a new interpretation of the concept of measurements uncertainty, proposes a unified system of measurement concepts in all disciplines, including geodesy, geomatics, metrology, instrumentation.

The analysis of the latest researches and publications on the issue. Scientists and specialists from universities in Chernihiv, Kyiv and Lviv conducted a GNSS-campaign to investigate the precision of coordinate support in conducting geodetic and land-cadastral works in the Northern region of Ukraine. The research was based on a network of three active permanent GNSS-stations: CNIV-Chernihiv, PRYL-Pryluky, KORP-Korop and rover points.

During the preparation for experimental studies, the reconnaissance of the points of the State geodetic network, most of which were laid down in the 1960s - 1980s, was carried out. Of the 55 surveyed points in the region, 24 points of the first, second and third grades were found.

The conditions of experimental research envisaged the use of the points of the State geodetic network, which are located in an open area with an angle of closure of the horizon of no more than 5 degrees. According to this criterion, 4 points were rejected. Two points could not be reached because of bad weather. Therefore, 16 points of the State geodetic network have been involved in the experimental research [4].

Observations at 16 rover points were performed by six two-frequency GNSS-receivers of the geodetic class LEICA GX1230GG with high-precision antennas AX 1202 OO. The duration of observations at the rover points was at least 2 hours.

Receivers and antennas were located at the reference stations: CNIV – NOVATEL OEMV3 receiver with antenna NOV702GG; KORP – TRIMBLE 400SSI receiver with antenna TRM29659; PRYL – NOVATEL OEMV3 receiver with antenna NOV702GG. Observations at stations CNYV and KORP lasted for 24 hours and at the PRYL station –18 hours.

For the analysis of the results of observations, there were used: the results of the first and second coordinate solutions for the point; a diagram of satellites radiolabeling and types of received data; change of DOP factors; multi-radiance at the frequency L1 (L2) for the point; the noise level of code observations at the frequency L1 (L2) for the point; noise level of phase observations at the frequency L1 (L2) for the point.

To process the results of satellite GNSS-measurements various software tools were used, such as: BERNESE [5], GrafNav / GrafNet [6], OCTAVA [7], GAMIT-GLOBK [8].

The coordinates of the KORP and PRYL stations were determined with respect to the CNVI station using the software complex OCTAVA and BERNESE (Switzerland). The coordinates of 16 rover points were defined for the CNVI station using the software complexes OCTAVA and GrafNav / GrafNet software [4].

The analysis of the results of the initial processing of observations at the reference stations showed satisfactory results, and on the rover – the presence of high-level multi-radiance of signals from the GPS/GLONASS satellites and a large number of omissions in the observations at three points. Therefore, we had to reject these results of observations and use data from 13 points in the further processing.

The processing of GNSS data using GrafNav / GrafNet software products is discussed in the works [9-11], with the help of VERNESE – in the works [12-14].

Statement of the problem. The main aim of this article is to study the results of coordinate definitions performed at the rover points using the OCTAVA and GrafNav / GrafNet software complexes.

The research included the determination of the presence or absence of a systematic error in the differences of coordinates of the same rover points, defined using the software complexes OCTAVA and GrafNav / GrafNet, and the calculation of the mean square error (MSE) of the unit of weight for each coordinate.

Results. In the table 1 the names of the rover points used during the GNSS-campaign [6], the coordinates of the CNIV (Chernihiv) base station, the coordinates of the rover points and the distance between them and the base station have been listed.

Table 1 – Coordinates of points and distance of rover points from the CNIV (Chernihiv) base station

№	Name	*X*, m	*Y*, m	*Z*, m	*S*, km
0	CNIV	3397785	2066991	4969812	0
1	BRZN1	3357092	2148092	4963070	90.99
2	BRZN2	3378190	2148723	4948588	86.69
3	BRZN3	3388021	2131603	4949257	68.50
4	CNIV1	3408549	2061735	4964649	13.04
5	CNIV2	3400925	2055021	4972617	12.69
6	CNIV3	3394207	2068124	4971772	4.23
7	KORP2	3358758	2154856	4959069	96.74
8	KOZL1	3458464	2090416	4818201	83.03
9	KOZL2	3450879	2091820	4922895	75.08
10	KOZL3	3459671	2069474	4926158	75.77
11	KORO2	3337328	2164478	4969250	114.71
12	PRYL1	3435179	2170656	4899859	130.53
13	PRYL2	3434959	2165806	4902145	125.40

The distance from the base station to the rover point was determined by the formula

$$S = \sqrt{(X_{CNIV} - X_R)^2 + (Y_{CNIV} - Y_R)^2 + (Z_{CNIV} - Z_R)^2} \,. \quad (1)$$

Accuracy of determination of the planned position in the static with the help of the receiver LEICA GX1230GG is m_{PL} = 5 mm + 1 mm/km, and the height m_H = 10 mm + 1 mm/km [15]. Since the distan-ces from the base station to the rover points (see Table 1) were in the range from 4 km to 130 km, it is clear that the accuracy of the planned high-altitude coordinates of the rover points will be different.

At the same time, the coordinates of the rover point determined using the software complex OCTAVA and the software GrafNav/GrafNet will be considered equivalent to each other. In this way, it is necessary to perform processing of double non-uniform measurements.

Let's write the formula of the residual systematic error θ [16]

$$\theta = \frac{\sum_{i=1}^{n} p_i d_i}{\sum_{i=1}^{n} p_i}, \quad (2)$$

where p_i – weight of coordinate definitions, d_i – the differences in the coordinates of the rover points obtained using the OCTAVA software complex and the software GrafNav / GrafNet.

Then, the MSE of the unit of weight is determined by the formula (3)

$$\mu = \sqrt{\frac{\sum_{i=1}^{n} p_i d_i^{\,2}}{2n}}, \quad (3)$$

where n – number of rover points equal to 13.

The presence of residual systematic errors in the differences in coordinates is estimated by the criterion [16]

$$|\theta| \le 0{,}2\mu . \tag{4}$$

This criterion does not depend on the law of the distribution of differences *di* and does not require knowledge of the confidence probability, the value of which is necessary to determine the Student's coefficient, or how it is necessary for the implementation of other criteria [17-20].

If inequality (4) is performed, then the residual systematic error in the differences of coordinates is considered significant. Then the differences of coordinates d_i', free from systematic error, are determined by the formula:

$$d_i' = d_i - \theta , \tag{5}$$

and the MSE of the unit of weight is determined by the formula (6)

$$\mu' = \sqrt{\frac{\sum_{i=1}^{n} p_i (d_i')^2}{2(n-1)}} . \tag{6}$$

Control of the definition d_i' is

$$\sum_{i=1}^{n} p_i d_i' = 0 . \tag{7}$$

When calculating the weights of coordinate definitions p_i the following approach has been used. The precision of the point's planned position m_{PL} depends on the accuracy of the definition m_X and m_Y, and is described by the formula [17]

$$m_{PL} = \sqrt{m_X^2 + m_Y^2} . \tag{8}$$

The known value for LEICA GX1230GG receiver is m_{PL} = 5 mm + 1 mm/km [6], while m_X and m_Y remain unknown. Therefore, in determining the weights p_X and p_Y of measurements, the dependence has been used

$$p_i = \frac{c}{D_i} , \tag{9}$$

where the values of the constant c can be different for each of the coordinate axes, taking into account their independence, D_i – distances from the base station to the rover point on the coordinate axis.

Taking into account the significant distances between the base station and the rover points, and for the purpose of visualizing the values of latitude and longitude differences determined using the OCTAVA software complex and the GrafNav / GrafNet software, the differences and angular distances between the points have been calculated linearly in the form of arcs of meridians and parallels on the surface of a general-Earth ellipsoid for GPS-definitions.

Directions along the meridian of the base station to the north and along its parallel to the east have been selected as coordinate axes.

To determine the arcs of meridians and parallels, in the beginning the first eccentricity of the reference ellipsoid has been calculated using the known formula [21].

$$e^2 = \frac{a^2 - b^2}{a^2} , \tag{10}$$

where a – big and b – small semi-axes of the reference ellipsoid.

The radius of curvature in the Meridian M_i for the mean value of the latitude B_{m_i} of the base station and the rover point i has been determined [21, 22]

$$M_i = \frac{a(1-e^2)}{\sqrt{(1-e^2\sin^2 B_{m_i})^3}}, \tag{11}$$

and the radius of the curvature in the Prime Vertical N_i for the rover point i

$$N_i = \frac{a}{\sqrt{(1-e^2\sin^2 B_{m_i})}}. \tag{12}$$

The length of the meridian arc for the latitude difference ΔB°, taken in degrees ΔB° with $\rho^\circ = 57{,}29578^\circ$ is calculated by the formula

$$D_{M_i} = M_i \frac{\Delta B_i^\circ}{\rho^\circ}. \tag{13}$$

The length of the arc of parallel in the latitude B_i, taken in degrees ΔL°, for the rover point is calculated by the formula

$$D_{P_i} = N_i \cos B_i \frac{\Delta L_i^\circ}{\rho^\circ}. \tag{14}$$

The values of semi-axes of the reference ellipsoid for WGS-84 with accuracy up to meters are accepted a = 6 378 137 m, b = 6 356 752 m [21].

Table 2 shows the values of the lengths of arcs of meridians and parallels for the rover points relative to the base station CNIV (Chernihiv), calculated for latitudes and longitudes obtained with the help of GrafNav / GrafNet software. The value of latitudes and longitudes of the points is taken from the work [4].

Table 2 – Determination of the lengths of arcs of meridians and parallels for the rover points relative to the base station CNIV (Chernihiv)

№	B_i^o	M_i, m	N_i, m	D_M, km	L_i^o	D_P, km	S_i, km
CNIV	51.51893923	–	–		31.313601267	–	–
1	51.422055527	6 374 572	6 391 242	10.78	32.613835585	90.35	90.99
2	51.213524898	6 374 458	6 391 204	33.98	32.458711530	79.75	86.69
3	51.223206956	6 374 463	6 391 206	32.90	32.176401375	60.08	68.50
4	51.444486627	6 374 584	6 391 246	8.28	31.168558684	10.08	13.04
5	51.559429634	6 374 647	6 391 267	4.50	31.142512118	11.87	12.70
6	51.547258895	6 374 640	6 391 265	3.15	31.354362172	2.83	4.23
7	51.364139623	6 374 540	6 391 232	17.22	32.682744068	95.20	96.74
8	50.779713015	6 374 220	6 391 125	82.24	31.150220748	11.43	83.03
9	50.846517010	6 374 257	6 391 137	74.81	31.222997234	6.34	75.08
10	50.892885364	6 374 282	6 391 146	69.65	30.886632417	29.84	75.77
11	51.511080326	6 374 621	6 391 259	0.87	32.966068854	114.71	114.71
12	50.519590855	6 374 078	6 391 077	111.18	32.288387392	68.40	130.53
13	50.551914346	6 374 096	6 391 083	107.58	32.232194287	64.43	125.40

To control the calculations, the distances on the ellipsoid from the rover points to the base station have been calculated, which coincided with the ones shown in table. 1. The indicated distances have been calculated according to the formula:

$$S_i = \sqrt{D_{M_i}^2 + D_{P_i}^2}. \tag{15}$$

Further, according to the latitudes and longitudes of the rover points determined using the OCTAVA software complex and the GrafNav/GrafNet software [4], their differences have been calculated firstly at an angle and next translated linearly as small arcs of meridians and parallels by formulas (13) and (14). The values of the radii of curvature of the meridians and the first vertices for the corresponding rover points have been taken from table 2.

After preparatory calculations, studies have been carried out to detect residual systematic errors in the geodetic coordinates' differences.

By values of arcs of the meridians D_{M_i} for the rover points relative to the base station from table 3 the weights p_i of the rover points have been calculated according to the formula (9) (table 4). The latitude differences ΔB is linearly taken from table 3. It has been found (see table 4) that the residual systematic error is $\theta = +2.3$ mm. By criterion (4), it is significant ($|\theta| = 2.3$ mm; 0.2μ = 1.4 mm). Therefore, it has been removed from latitude differences by formula (5) and the MSE of the unit of weight has been calculated by the formula (6), which received $\mu' = 6.1$ mm.

Table 3 – Latitudes and longitudes of rover points identified using the OCTAVA software complex and GrafNav/GrafNet software and their differences

№	$(B_i^{OC})^o$	$(B_i^{GN})^o$	ΔB, m	$(L_i^{OC})^o$	$(L_i^{GN})^o$	ΔL, m
1	51.422055506	51.422055527	-0.0023	32.613834873	32.613835585	-0.0495
2	51.213524891	51.213524898	-0.0008	32.458711464	32.458711530	-0.0046
3	51.223207071	51.223206956	0.0128	32.176401276	32.176401375	-0.0069
4	51.444486643	51.444486627	0.0018	31.168558551	31.168558684	-0.0092
5	51.559429692	51.559429634	0.0065	31.142512154	31.142512118	0.0025
6	51.547258942	51.547258895	0.0052	31.354362278	31.354362172	0.0074
7	51.364139676	51.364139623	0.0059	32.682744036	32.682744068	-0.0022
8	50.779713056	50.779713015	0.0046	31.150220519	31.150220748	-0.0162
9	50.846517209	50.846517010	0.0221	31.222997250	31.222997234	0.0011
10	50.892885403	50.892885364	0.0043	30.886632350	30.886632417	-0.0047
11	51.511080330	51.511080326	0.0004	32.966068758	32.966068854	-0.0067
12	50.519590874	50.519590855	0.0021	32.288387166	32.288387392	-0.0160
13	50.551914377	50.551914346	0.0034	32.232194284	32.232194287	-0.0002

Table 4 – Definition of the systematic error and the MSE of the unit of weight of different latitudes, identified using the OCTAVA software complex and GrafNav/GrafNet software

№	D_M, km	p	ΔB, mm	$p\Delta B$, mm	$p\Delta B^2$, mm^2	$\Delta B'$, mm	$p\Delta B'$, mm	$p(\Delta B')^2$, mm^2
1	10.78	3.71	-2.3	-8.53	19.63	-4.58	-16.98	77.69
2	33.98	1.18	-0.8	-0.94	0.75	-3.08	-3.62	11.14
3	32.90	1.22	12.8	15.56	199.20	10.52	12.80	134.66
4	8.28	4.83	1.8	8.70	15.65	-0.48	-2.30	1.09
5	4.50	8.89	6.5	57.78	375.56	4.22	37.55	158.61
6	3.15	12.70	5.2	66.03	343.37	2.92	37.13	108.58
7	17.22	2.32	5.9	13.70	80.86	3.62	8.42	30.51
8	82.24	0.49	4.6	2.24	10.29	2.32	1.13	2.63
9	74.81	0.53	22.1	11.82	261.15	19.82	10.60	210.13
10	69.65	0.57	4.3	2.47	10.62	2.02	1.16	2.35
11	0.87	45.98	0.4	18.39	7.36	-1.88	-86.24	161.78
12	111.18	0.36	2.1	0.76	1.59	-0.18	-0.06	0.01
13	107.58	0.37	3.4	1.26	4.30	1.12	0.42	0.47
Σ		83.15	66	189.23	1330.31		0	899.66
$c = 40$; $\theta = +2.28$ mm; $\|\theta\| = 2.28$ mm; 0.2μ = 1.43 mm ($\mu = 7.15$ mm;); $\mu' = 6.12$ mm.								

Table 5 shows the results of calculations of systematic error and the MSE of the unit of weight of the longitudinal differences of the rover points determined using the OCTAVA software complex and the GrafNav/GrafNtet software. As can be seen from Table 5, inequality (4) is not satisfied. Therefore, the systematic error $\theta = –0{,}58$ mm is not significant. The mean square error of the unit of weight of longitudes differences equals $\mu = 12.8$ mm.

Table 5 – Definition of systematic error and the MSE of the unit of weight of the longitudinal differences determined using the OCTAVA software complex and the GrafNav/GrafNet software

№	D_P, km	p	ΔL, mm	$p\Delta L$, mm	$p\Delta L^2$, mm^2
1	90.35	0.55	-49.5	-27.39	1355.98
2	79.75	0.63	-4.6	-2.88	13.27
3	60.08	0.83	-6.9	-5.74	39.62
4	10.08	4.96	-9.2	-45.63	419.84
5	11.87	4.21	2.5	10.53	26.33
6	2.83	17.67	7.4	130.74	967.49
7	95.2	0.53	-2.2	-1.16	2.54
8	11.43	4.37	-16.2	-70.87	1148.03
9	6.34	7.89	1.1	8.68	9.54
10	29.84	1.68	-4.7	-7.88	37.01
11	114.71	0.44	-6.7	-2.92	19.57
12	68.4	0.73	-16.0	-11.70	187.13
13	64.43	0.78	-0.2	-0.16	0.03
Σ		45.26	-105.2	-26.38	4226.39
$c = 50$; $u = -0.58$ mm; $\lvert u \rvert = 0.58$ mm; $0.2\mu = 2.55$ mm; $\mu = 12.75$ mm.					

To determine the scales of the differences of geodetic heights of the rover points determined using the OCTAVA software complex and the GrafNav/GrafNet software, the formula has been used

$$p_i = \frac{c}{m_{H_i}^2}, \tag{16}$$

where $m_{H_i} = 10mm + 1mm \cdot S_i(km)$ – the MSE of defining heights by the LEICA GX1230GG receiver.

Table 6 – Definition of the systematic error and the MSE of the unit of weight differences of the geodetic heights determined using the OCTAVA software complex and the GrafNav/GrafNet software

№	Sм, km	m_H, mm	p	ΔH, mm	$p\Delta H$, mm	$p\Delta H^2$, mm^2	$\Delta H'$, mm	$p\Delta H'$, mm	$p(\Delta H')^2$, mm^2
1	90.99	100.99	0.87	-30	-26.06	781.84	-25.63	-22.27	570.81
2	86.69	96.69	0.95	-2	-1.90	3.79	2.37	2.24	5.31
3	68.5	78.5	1.44	-26	-37.38	971.94	-21.63	-31.10	672.89
4	13.04	23.04	16.69	1	16.69	16.69	5.37	89.57	480.68
5	12.69	22.69	17.21	1	-189.30	2082.32	-6.63	-114.16	757.26
6	4.23	14.23	43.76	-2	-87.51	175.02	2.37	103.55	245.05
7	96.74	106.74	0.78	-11	-8.55	94.09	-6.63	-5.16	34.22
8	83.03	93.03	1.02	2	2.05	4.09	6.37	6.52	41.49
9	75.08	85.08	1.22	-12	-14.69	176.25	-7.63	-9.34	71.32
10	75.77	85.77	1.20	-16	-19.27	308.32	-11.63	-14.01	163.00
11	114.71	124.71	0.57	-10	-5.70	56.97	-5.63	-3.21	18.08
12	130.53	140.53	0.45	-2	-0.90	1.79	2.37	1.06	2.51
13	125.4	135.4	0.48	-12	-5.80	69.59	-7.63	-3.69	28.16
Σ			86.64	-131	-378.32	4742.73		0	3090.78
$c = 8860$; $\theta = -4.37$ mm; $\lvert u \rvert = 4.37$ mm; $0.2\mu = 2.7$ mm ($\mu = 13.51$ mm;); $\mu' = 11.35$mm.									

The results of calculations are given in table 6. The differences of the geodetic heights of the rover points determined using the OCTAVA software complex and the GrafNav/GrafNet software have a residual systematic component $\theta = -4.37$ mm, which by criterion (4) is significant ($|\theta| = 4.37$ mm; $0.2\mu = 2.7$ mm). Therefore, the differences in geodetic heights have been deprived (released) of the systematic component and calculated the MSE of the unit of weight, which was $\mu' = 11.35$ mm.

The general deviations of the planned coordinates Δ_i have been calculated by the formula (15), where: $\Delta_i = S_i$, $D_{M_i} = \Delta B_i$, $D_{P_i} = \Delta L_i$ (table 7). Values ΔB and ΔL are taken from table 4 and table 5 for the corresponding rover points.

Table 7 – The value of the total deviation of the planned coordinates of the rover points

№	1	2	3	4	5	6	7	8	9	10	11	12	13
Δ_i, mm	49.6	4.7	14.5	9.4	7.0	9.0	6.3	16.8	22.1	6.4	6.7	16.1	3.4

Using the values of total deviations and values of distances of rover points from the base station, the graph is built, as shown in figure 1.

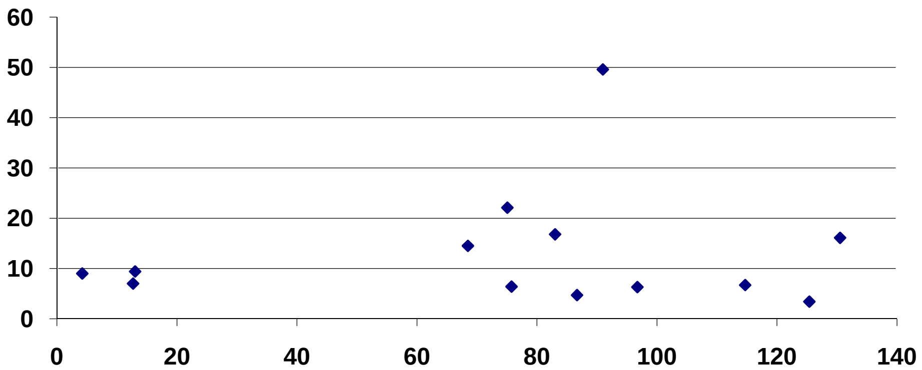

Figure 1 – Distribution of general deviation of planned coordinates depending on the distance of rover points from the base station CNIV

From the graph it is clear that the magnitudes of deviations practically do not correlate with distance. A similar graph is constructed for deviations in the values of the geodetic heights of the rover points calculated using the software complexes OCTAVA and GrafNav / GrafNet, which is depicted in figure 2. Here too, there is no correlation between deviations in height and distance of rover points from the base station

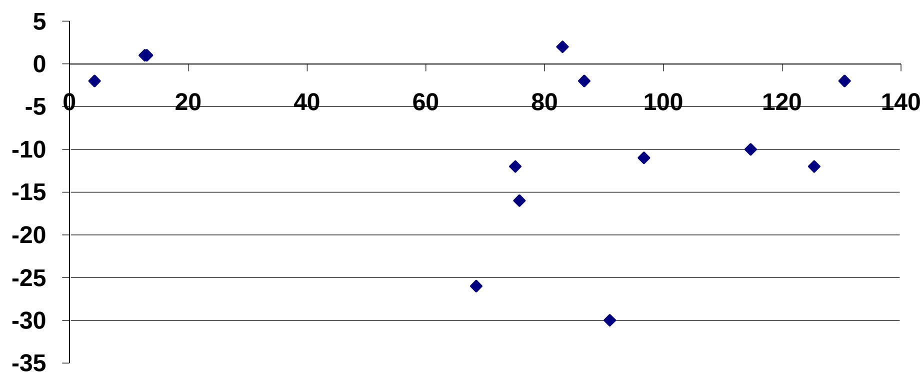

Figure 2 – Distribution of deviations in the values of the geodetic heights of the rover points calculated using the software complexes OCTAVA and GrafNav / GrafNet depending on the distance to the base station CNIV

The next step is to determine the average values of the heights of the rover points and to calculate their accuracy.

The average values of geodetic heights of rover points obtained using the software complexes OCTAVA and GrafNav / GrafNet, are calculated by the formula [17, 19]

$$H_i = \frac{H_i^{OC} + H_i^{GN}}{2}. \qquad (13)$$

The weights of the average geodetic heights calculated using the OCTAVA or GrafNav / GrafNet software complex are equal to $\sqrt{2p_i}$. Therefore, the mean square error of geodetic heights, calculated using any of these software complexes, are determined by the formula

$$m_{H_i} = \frac{\mu'}{\sqrt{2p_i}}. \qquad (14)$$

The values of the average heights of the rover points and the accuracy of their calculation by the indicated software products are given in the table 8.

Table 8 – Calculation of average values of heights of rover points and their accuracy

№	H_i^{OC} , m	H_i^{GN} , m	H_i , m	$\sqrt{2p_i}$	m_{H_i} , mm	S_i , km
1	141.275	141.305	141.2900	1.31	8.7	90.99
2	165.005	165.007	165.0060	1.38	8.2	86.69
3	158.081	158.107	158.0940	1.70	6.7	68.50
4	170.570	170.569	170.5695	5.78	2.0	13.04
5	179.595	179.606	179.6005	5.87	1.9	12.70
6	175.780	175.782	175.7810	9.36	1.2	4.23
7	167.016	167.027	167.0215	1.25	9.1	96.74
8	148.970	148.968	148.9690	1.43	7.9	83.03
9	146.143	146.155	146.1490	1.56	7.3	75.08
10	155.991	156.007	155.9990	1.55	7.3	75.77
11	152.992	153.002	152.9970	1.07	10.6	114.71
12	156.347	156.349	156.3480	0.95	11.9	130.53
13	157.457	157.469	157.4630	0.98	11.6	125.40

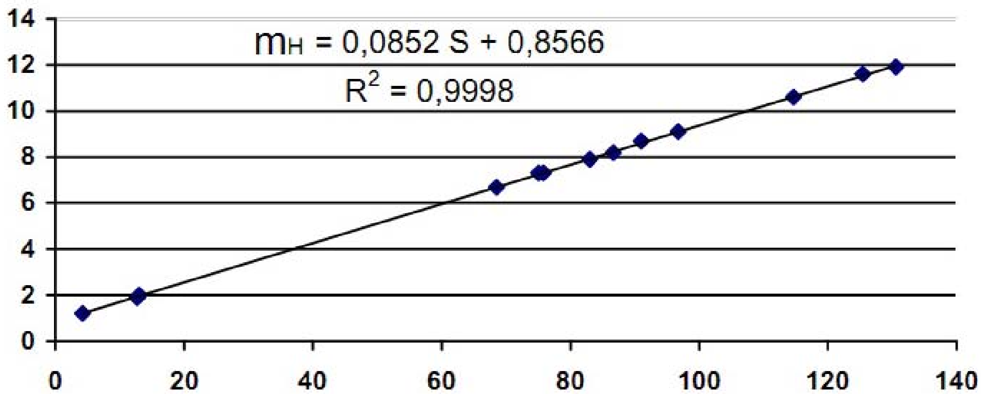

Figure 3 – The graph of dependency of the MSE of the geodesic heights of the rover points calculated using the software complexes OCTAVA or GrafNav / GrafNet, depending on the distance to the base station CNIV (Chernihiv)

Figure 3 shows the graph of dependency of the MSE of the geodesic heights of the rover points calculated using the software complexes OCTAVA or GrafNav / GrafNet, depending on the distance, constructed according to the data of the Table 8. The line of trend of the MSE of geodetic heights is given, with which it is possible to predict the accuracy of calculating the geodetic heights of the rover points using the indicated software products at intermediate rover points, depending on the distance from the base station CNIV (Chernihiv). The accuracy of the approximation is high and is $R^2 = 0.9998$.

The average values B_i of the latitudes of the rover points (table 9) have been defined, calculated using the software complexes OCTAVA and GrafNav / GrafNet, with a correction $-0.5\theta_B^{\circ}$ for the syste-matic error $\theta_B = +2.28$ mm (see table 4), which is determined at an angle measure in particles of a degree taking into account the formula (9)

$$\theta_B^{\circ} = \frac{\theta_B}{M_i}\rho^{\circ}, \tag{15}$$

Table 9 – Calculation of the mean values of latitudes of rover points and their accuracy

№	$(B_i^{OC})^o$	$(B_i^{GN})^o$	B_i	$\sqrt{2p_i}$	m_{Bi}, mm	D_{M_i}, km
1	51.422055506	51.422055527	51.4220555165	2.72	2.25	10.78
2	51.213524891	51.213524898	51.2135248945	1.54	3.98	33.98
3	51.223207071	51.223206956	51.2232070135	1.56	3.92	32.90
4	51.444486643	51.444486627	51.4444866350	3.11	1.97	8.28
5	51.559429692	51.559429634	51.5594296630	4.22	1.45	4.50
6	51.547258942	51.547258895	51.5472589185	5.04	1.21	3.15
7	51.364139676	51.364139623	51.3641396495	2.15	2.84	17.22
8	50.779713056	50.779713015	50.7797130355	0.99	6.18	82.24
9	50.846517209	50.846517010	50.8465171095	1.03	5.94	74.81
10	50.892885403	50.892885364	50.8928853835	1.07	5.73	69.65
11	51.511080330	51.511080326	51.5110803280	9.59	0.64	0.87
12	50.519590874	50.519590855	50.5195908645	0.85	7.21	111.18
13	50.551914377	50.551914346	50.5519143615	0.86	7.11	107.58
$0.5\theta_B^{\circ} = (+1.02 \cdot 10^{-10})^{\circ}$.						

The MSE of the latitudinal position of the rover points calculated using the software complexes OCTAVA or GrafNav/GrafNet, is executed using a formula similar to formula (14). These values are linearly determined m_{B_s} in the table 9.

Figure 4 shows the graph of the dependence of the MSE of the geodesic latitudes of the rover points linearly, calculated using the software complexes OCTAVA or GrafNav / GrafNet depending on the distance in the meridional direction relative to the station CNIV (Chernihiv), constructed according to the data of the table 9.

A trend line has been developed, which allows predicting the accuracy of calculating the geodetic latitudes of the rover points using the indicated software products at intermediate rover points, depending on the distance from the base station CNIV (Chernihiv) along the meridian of the point. The accuracy of the approximation is $R^2 = 1$.

The average values L_i\ of the longitudes of the rover points have been determined, calculated using the software complexes OCTAVA and GrafNav / GrafNet (table 10), the longitudinal values of the mean square error m_{Li} are calculated using the formula:

$$m_{L_i} = \frac{\mu}{\sqrt{2p_i}}, \tag{16}$$

where $\mu = 12.75$ mm and weights p_i, the values of which are given in the table 5.

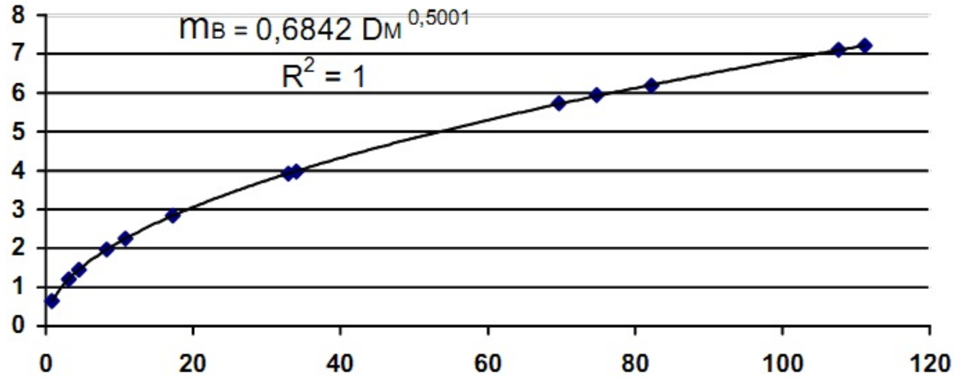

Figure 4 – The graph of the dependence of the MSE of the geodesic latitudes of the rover points linearly, calculated using the software complexes OCTAVA or GrafNav / GrafNet depending on the distance in the meridional direction relative to the station CNIV (Chernihiv)

Table 10 – Calculation of mean values of longitudes of rover points and their accuracy

№	$(L_i^{OC})^o$	$(L_i^{GN})^o$	L_i	$\sqrt{2p_i}$	m_{Li}, mm	D_{P_i}, km
1	32.613834873	32.613835585	32.6138352290	1.05	12.2	90.35
2	32.458711464	32.458711530	32.4587114970	1.12	11.4	79.75
3	32.176401276	32.176401375	32.1764013255	1.29	9.9	60.08
4	31.168558551	31.168558684	31.1685586175	3.15	4.0	10.08
5	31.142512154	31.142512118	31.1425121360	2.90	4.4	11.87
6	31.354362278	31.354362172	31.3543622250	5.94	2.1	2.83
7	32.682744036	32.682744068	32.6827440520	1.41	12.4	95.20
8	31.150220519	31.150220748	31.1502206335	2.96	4.3	11.43
9	31.222997250	31.222997234	31.2229972420	3.97	3.2	6.34
10	30.886632350	30.886632417	30.8866323835	1.41	7.0	29.84
11	32.966068758	32.966068854	32.9660688060	0.94	13.6	114.71
12	32.288387166	32.288387392	32.2883872790	1.21	10.6	68.40
13	32.232194284	32.232194287	32.2321942855	1.25	10.2	64.43

Figure 5 shows the graph of dependence of the MSE of the geodetic longitudes of the rover points in the linear measure, calculated using the software complex OCTAVA or the GrafNav/GrafNet software depending on the distance in the parallel direction with respect to the meridian of the station CNIV (Chernihiv), constructed according to the data of the table 9.

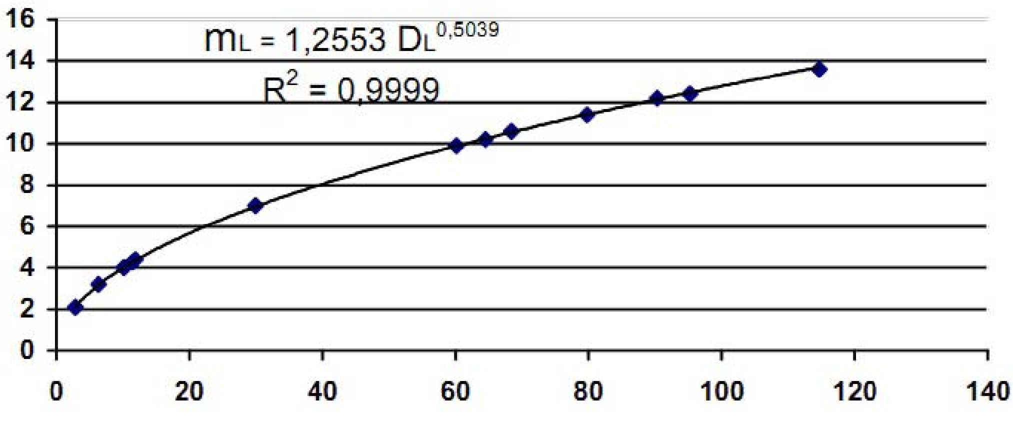

Figure 5 – The graph of dependence of the MSE of the geodetic longitudes of the rover points in the linear measure, calculated using the software complex OCTAVA or the GrafNav / GrafNet software depending on the distance in the parallel direction with respect to the meridian of the station CNIV (Chernihiv)

A trend line has been made that predicts (forecasts) the accuracy of calculating the geodetic longitudes of the rover points, depending on the distance from the meridian of the CNIV base station along the parallel of the rover point. The accuracy of the approximation is $R^2 = 0.9999$.

Using the values of the MSE of the position of points in latitudinal and longitudinal directions, it is possible to construct ellipses of errors of the planned position of the rover points. Figure 6 provides the ellipse of errors of the planned position of the point BRZN3. For intermediate points, it is possible to use the equations of the trend lines, and calculate the lengths of the meridians and parallels by the formulas (13) and (14).

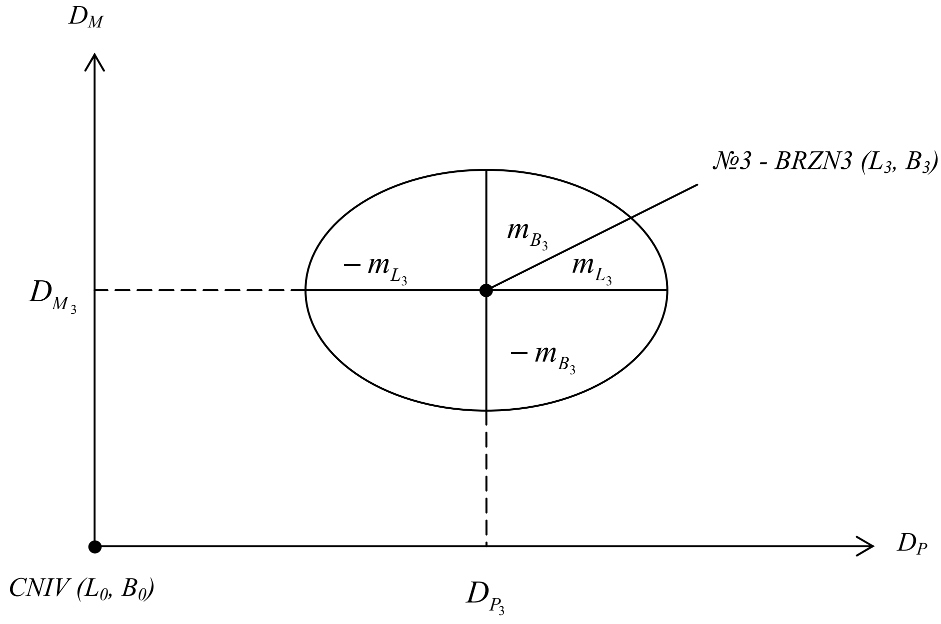

Figure 6 – The ellipse of errors of the planned position of the point BRZN3

Conclusions. According to the results of statistical research of the comparison of coordinate definitions of the rover points using the software complexes OCTAVA and GrafNav / GrafNet, the following conclusions can be drawn:

- the differences between the geodesic latitudes and heights contain systematic errors, which are respectively linearly equal to + 2.3 mm and - 4.4 mm;
- the MSE of the unit of weight for each of the coordinates is for geodetic latitudes, longitudes and heights of 6.1 mm, 12.8 mm and 11.4 mm respectively;
- the greatest differences in geodetic coordinates are determined: in latitude - 22 mm; in longitude - 50 mm; in height - 30 mm;
- it was established that the correlation between the deviations in the plan and in heights of the differences in coordinate definitions, depending on the distance to the base station, is absent;
- a method for determining the accuracy of the processing of GNSS observations by software complexes based on the method of double non-uniform measurements is developed. The method has been tested according to the results of full-scale GNSS-observations in Chernihiv region.

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БАҒДАРЛАМАЛЫҚ ҚАМТАМАСЫЗДАНДЫРУ КЕШЕНІ АРҚЫЛЫ СПУТНИКТІК БАҚЫЛАУДЫ ӨҢДЕУ НӘТИЖЕЛЕРІ БОЙЫНША ЖҮЙЕЛІ ҚАТЕЛЕРДІ ЗЕРТТЕУ

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ИССЛЕДОВАНИЕ СИСТЕМАТИЧЕСКИХ ПОГРЕШНОСТЕЙ ПО РЕЗУЛЬТАТАМ ОБРАБОТКИ СПУТНИКОВЫХ НАБЛЮДЕНИЙ ПРОГРАММНЫМИ КОМПЛЕКСАМИ

Аннотация. На сегодня обработка результатов статических спутниковых наблюдений выполняется известными программными комплексами.

С целью исследования и анализа вопросов повышения точности наблюдений выполнены натурные спутниковые ГНСС-измерения на пунктах государственной геодезической сети Северного региона Украины и проведена обработка их результатов с применением распространённых в геодезической практике программных комплексов OCTAVA и GrafNav / GrafNet.

По результатам математической обработки наблюдений упомянутыми программными комплексами выявлено влияние остаточных систематических погрешностей в разницах координатных определений. Для их дальнейшего выявления и обработки были применены разные критерии, которые дали возможность провести статистические исследования сравнения координатных определений роверных пунктов с использованием программных комплексов. Этим вопросам посвящена данная работа.

В статье исследованы разницы геодезических широт и высот, которые содержат систематические погрешности и средние квадратические погрешности единицы веса по каждой из координат. Установлено также отсутствие корреляции между отклонениями в плане и по высоте разниц координатных определений в зависимости от расстояния до базовой станции. На основе проведённых статистических исследований разработана методика определения точности обработки результатов ГНСС-наблюдений программными комплексами, базируясь на способе двойных неравноточных измерений.

Методика является актуальной, она прошла апробацию по результатам натурных ГНСС-наблюдений в Черниговской области (Украина) и направлена на выявление, учёт и минимизацию остаточных систематических погрешностей и будет способствовать повышению точности координатного обеспечения при спутниковых наблюдениях.

Ключевые слова: средняя квадратическая погрешность; систематическая погрешность; двойные неравноточные измерения; программные комплексы OCTAVA, GrafNav / GrafNet, BERNESE.

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