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INVESTIGATION OF THE ACCURACY OF GNSS-VECTOR MEASUREMENTS DURING THE DEFORMATION MONITORING OF ENGINEERING STRUCTURES: CASE STUDY IN TESTED NETWORK

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Purpose. The aim of the investigation is optimization monitoring of spatial displacements by GNSS and selection of minimal intervals of GNSS observations with given accuracy parameters. **Methodology**. For simulate the monitoring process on a real object tested network GNSS vectors with different lengths were installed. The network consisted of 4 points where two-frequency GNSS receivers were installed. At one of the points for deformation simulation, a specially designed device was installed which allowed to change the GNSS antenna position with high accuracy. The reference stations SULP and NTEH as well as the JAHT station, which was installed on the pillar of the 2nd academic building of the Lviv Polytechnic National University, was chosen as a geodetic reference point. Continuous observations were conducted in static mode from January 25 to February 8, 2017 inclusive. During 15 days of observations, the antenna was displaced in a horizontal plane by means of a deformation simulation device. In total, 4 displacements were made during the investigation period. To detect model deformations, single vectors with 1, 3 and 6 hours observation intervals were used. These results were compared with the results of network adjustment. **Results** The observations data were processed in the software Leica Geo Office 8.2. According to the results of the observations, the accuracy of the detection of antenna spatial displacements for the various lengths of the vectors and the duration of the GNSS observations were calculated. Experimental studies carried out for vectors up to 2 km show that to achieve the accuracy of the deformation determination at a level of 3 mm in the horizontal plane and 5 mm in height that there was enough 1 hour interval observations with the data sampling rate 1 s. **Practical significance.** The obtained results in the future can be used as recommendations in the design and construction of automated systems for monitoring complex engineering structures.

Key words: GNSS station, satellite observation, monitoring, deformation.

Introduction

In recent years, engineers increasingly use satellite technology to monitor engineering structures. The automated monitoring systems installed at 4 hydroelectric power plants in Ukraine (Dnister HPP, Kaniv HPP, Dnipro hydroelectric power station and Central Dniprovska HPP) have become widely used. The use of automated monitoring systems is not limited only to HPP and HPPS – there are other complex engineering structures (bridges, tall buildings, air transitions, overpasses) that require constant geodetic supervision.

At present, there are many examples of successful useage of automated systems that are installed on various objects and continuously conduct geodetic monitoring. For example, [Currie, 2013] has shown the main and most practical methods of deformation monitoring, with achieved accuracy in real time in New Zealand. Modern GNSS receivers are used for spatial definitions, which are able to determine in real time coordinates with an accuracy of 10–20 mm, and with static observations with a duration of 30–120 minutes, get coordinates with an accuracy of 5 mm and better. In [Chrzanowski et al., 2001], it has been shown that the use of a 1 hour interval of satellite observation performed by automated monitoring systems can detect deformations larger than 10 mm.

Another interesting example is the Pacoima (USA) automated dam monitoring system, which was deployed in 1995 [Hudnut et al., 1998]. It consists of 6 stations – 2 stations directly on the dam, 1 station is installed near the fixed rock massif and 3 more stations are used from the network of reference stations within a radius of 2.5 km. The stations operate continuously, and accumulate data at intervals of 30 seconds, and through communication channels send data to the processing centre. After processing daily RINEX files with precise ephemeris, the authors achieved precision of 4–6 mm in the horizontal coordinates and 12 mm in height.

In [Srbinoski et al., 2010], the results of the observation of the dam of Mavrovo (Bulgaria), performed by traditional linear-angular (microtriangulation, trilateration) and satellite methods are given. Satellite observations were conducted in the mode of fast statics for a 10 minute duration with a 1-second simple rate. The difference between the results obtained by these methods did not exceed 5 mm, which indicate high accuracy and reliability of satellite monitoring methods for deformation [Kaftan et al., 2013].

Similar comparisons between satellite and terrestrial observations were obtained at [Kalkan et al., 2010]. For the monitoring of the Atatürk Dam (Turkey), 8 hours of satellite observation at intervals of 5 seconds were used for 3 years. It has reached the accuracy of detecting deformations of several mm's, and after comparing the results to terrestrial observations, the difference did not exceed 1 cm.

In [Yodis, 2015] for one month employees of the company JAVAD tested the automated monitoring system at the hydroelectric power station. According to the results of tests using GNSS-equipment the accuracy of 1–2 mm in horizontal coordinates and 2–4 mm in height were reached. The preliminary results of the deformation monitoring in automatic mode show that use of hourly intervals of GNSS observations can detect displacement within a few millimeters. The main conditions for ensuring such accuracy are the lack of multipath and obstructions in the frequency band of satellite measurements that are performed at reference and controlled points, as well as the correct placement of these points on the object.

The systems of Leica GeoSystems (Leica GeoMoS), Topcon (DC3) and Trimble (Trimble 4D Control 3.0) are applied in different directions: construction, exploitation, environmental protection and mining. The difference between these systems is the number of modules and software implementation of each of the manufacturers. An example of the implemented project is the Leica GeoMoS monitoring system for bridge construction in Moscow (2010). The accuracy of the monitoring is 1–2 mm and 2–3 mm at a discreteness of 15 minutes and 1 s respectively. Also, the system worked during the construction of Olympic facilities in Sochi. At a 2-hour interval, an accuracy of 0.6 mm ±1 mm / km was obtained. The Trimble 4DC system was used in Zurich (Switzerland) during the construction of an underground line. The discreteness of the work was 30 minutes, and the accuracy of 1mm ± 1 mm / km.

As we see from the foregoing, in order to obtain more precision, they prefer static observation over kinematics, and the duration of observations on different objects is not the same. Another feature of automated monitoring systems is, as a rule, the absence of long vectors (more than 5 km), which reduces the duration of observations without significant loss of accuracy.

The automated satellite monitoring system using the GLONASS/GPS [Kosmicheskaya GES, 2013] was developed for monitoring the displacement of control points at the Nizhnekamsk hydroelectric power station (Russia), which provides determination of displacements with an accuracy of 1–3 mm for a 6-hour cycle. It should be noted that just a 6 hour duration of the session of static satellite observations is actually considered optimal for determining coordinates with millimeter precision, which meets the requirements for high precision monitoring of objects of this type. A similar technique was widely used to install automated systems by the Institute of Geodesy at the National University "Lviv Polytechnic" for monitoring a number of Ukrainian power plants: Kaniv HPP (May, October 2007, 2010); Kremenchug HPP (2007); Dneprodzerzhinsk HPP (May, October 2007); Dnipro HPP (2005, 2010); Dniester HPPS (2003, 2004, 2005, 2006, 2007, 2009, 2011, 2012, 2013, 2014, 2015, 2016) [Bisovetsky et al., 2011] [Lompas et al., 2016] [Tretyak et al., 2017]. It should also be noted that during the investigated period, for the given objects the accuracy of the definition of horizontal displacement was 2 mm, and the vertical – 3 mm. However, using 6 hours monitoring sessions or more reduced monitoring efficiency. Therefore the selection of optimal observation intervals is an important criterion for the design of such systems.

Purpose

The aim of the investigation is optimization monitoring of spatial displacements by GNSS and selection minimal intervals of GNSS observations with given accuracy parameters. Also, we compared results of processing singles GNSS vectors and results after network adjusting.

Methodology

To conduct the experiment, to simulate the monitoring process on a real object, a tested network with different vectors lengths was installed. 3 stations were selected as a geodesic basis (Fig. 1) with 2 reference stations (SULP and NTEH) and JAHT station, which was installed on the pillar on the top of 2nd university academic building (Fig. 2).

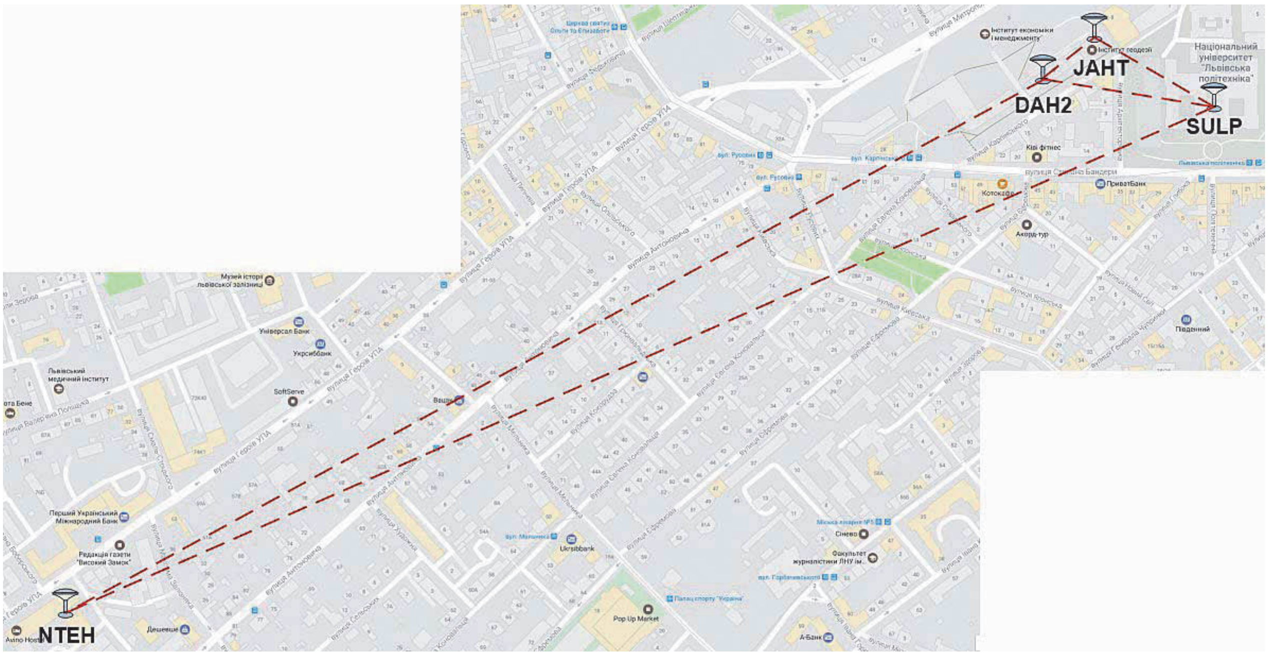


Fig. 1. Tested Network location

SULP NTEH JAHT

Fig. 2. Reference stations for monitoring

A specially designed device for deformations simulation (DDS) was installed at the station DAH2 (2^{nd} academic building of the Lviv Polytechnic National University). This device allowed to change the GNSS antenna position with high accuracy (Fig. 3).

The device consists of two carriages moving in mutually perpendicular directions. In addition, the left carriage can also move in vertically. Using micrometric screws, the carriage can be displaced at certain distances with high accuracy (up to 0.01 mm). GNSS antenna Trimble ZEPHYR GEODETIC Model 2 with dual-frequency receiver Trimble R7 was installed on the device for deformations simulation. The following parameters were set on all receivers: cut-off angle – 10°, simple rate – 1 sec. The reference station SULP was located 190 meters from the device for deformations simulation, the reference station NTEH was 1400 meters away, and JAHT was 30 meters away.

Continuous observations were conducted in static mode from January 25 to February 8, 2017. During 15 days of observations, the GNSS-antenna was displaced in a horizontal plane. During this period 4 displacements were made. The schedule and the magnitude of the displacements are given in

Table 1. The carriage moved along the azimuth 279° 09' 09.7", for correct analysis of the displacement magnitude, it was calculated for North and East directions (ΔN and ΔE).

Fig. 3. Device for deformations simulation at the station DAH2

Table 1

Schedule of carried displacements using deformation modeling device

	Date	UTC	Counting on a differential carriage micrometer	Magnitude of the displacements (mm)	ΔN (mm)	ΔE (mm)
1	25.01.2017 р.	18:00	55.0			
				15	-2.38	+14.81
2	01.02.2017 р.	12:30	70.0			
				10	+1.59	-9.87
3	03.02.2017 р.	11:32	65.0			
				5	+0.79	-4.94
4	06.02.2017 р.	09:00	60.0			
				5	+0.79	-4.94
5	08.02.2017 р.	09:25	55.0			

To detect model deformations, measured single vectors SULP-DAH2, NTEH-DAH2, JAHT-DAH2 with 1, 3 and 6 hours observation intervals were used.

Results

The observations were processed in the software Leica Geo Office 8.2. In some automated monitoring systems, in particular those installed at the Ukrainian hydroelectric power plants, information on possible deformations is obtained on the measurement of single vectors. Therefore, one of the main tasks was to establish the feasibility of using such an approach for monitoring deformations and comparing them to the results obtained after network adjusting. The intervals of observation for single vectors NTEH-DAH2, SULP-DAH2 and JAHT-DAH2 were 6, 3 and 1 hour. The lengths of the vectors were 1400 m, 190 m and 30 m, respectively. Fig. 4–6 shows the displacements of the GNSS antenna in the horizontal plane, in height, as well as in the north N and east E directions for 6 hour, 3 hour and 1 hour time intervals. As we can see on the Fig. 4–6 the biggest displacements were made along W-E direction and as result the scale of vertical axis is different for different component.

The main numerical characteristics are summarized in Table 2, which contains information on the number of observed epochs (Num), the mean deviation (Avg), standart deviation (SD), the minimum and maximum deviations (Min and Max), which allow to sum up the scope of deviation. All values in Table 2 are in millimeters. Displacements in the horizontal plane are denoted d, the displacement in the north and east directions are denoted n and e respectively, and the displacement in height – u.

As can be seen on the Figs. (4–6) and Table 2, the standard deviation in the horizontal plane varies from 1–1.5 mm for a 6 hour interval to 2 mm for 1 hour. A similar situation is observed for the North and East components. Such a high level of horizontal precision meets the requirements for majority of automated monitoring systems, for which this criterion is 3–5 mm. As for the high-altitude component the standard deviation ranges from 1.5–2 mm for a 6 hour interval to almost 5 mm for a 1 hour interval.

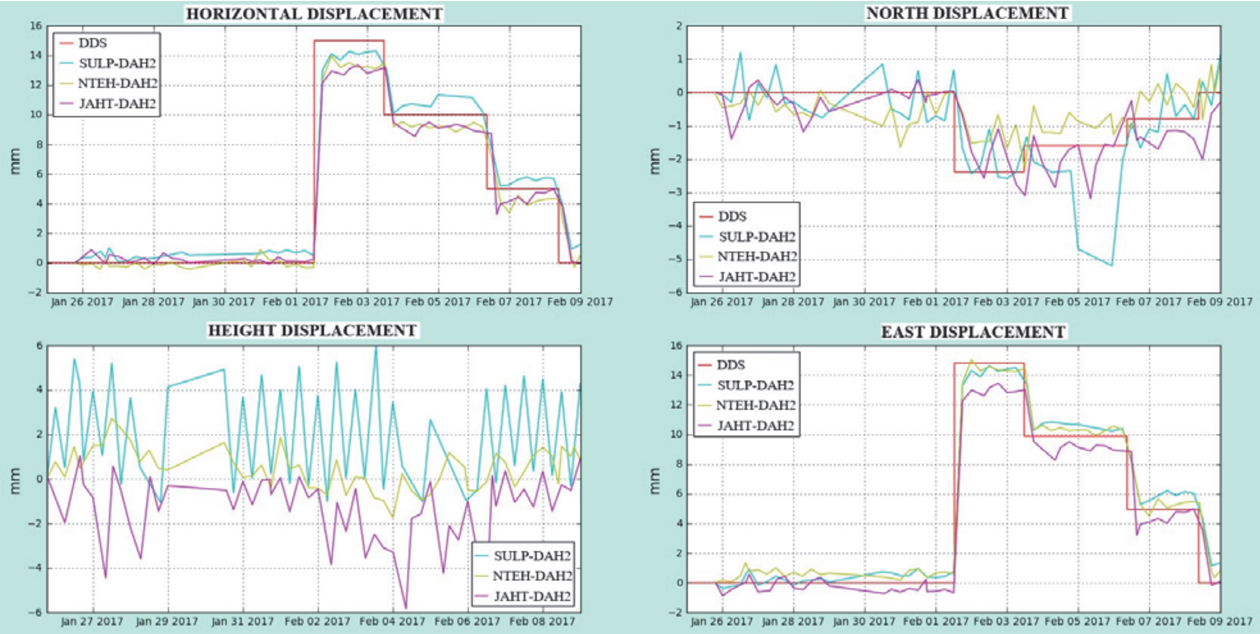


Fig. 4. Results of vectors measurement by 6 – hour interval

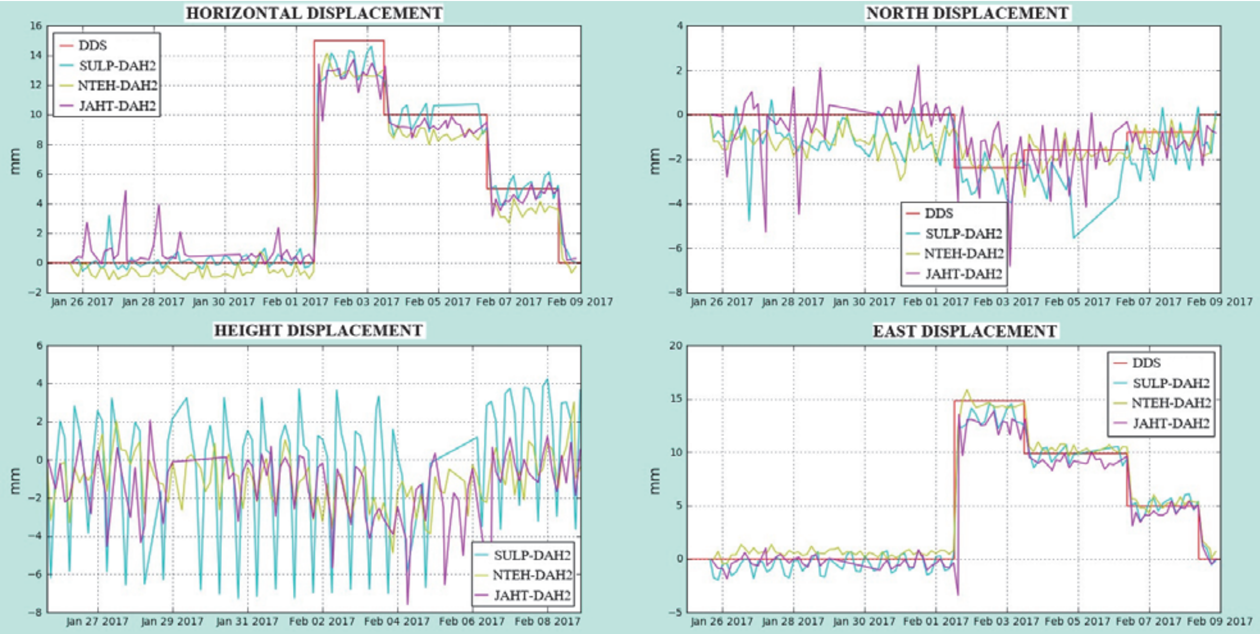


Fig. 5. Results of vectors measurement by 3 – hour interval

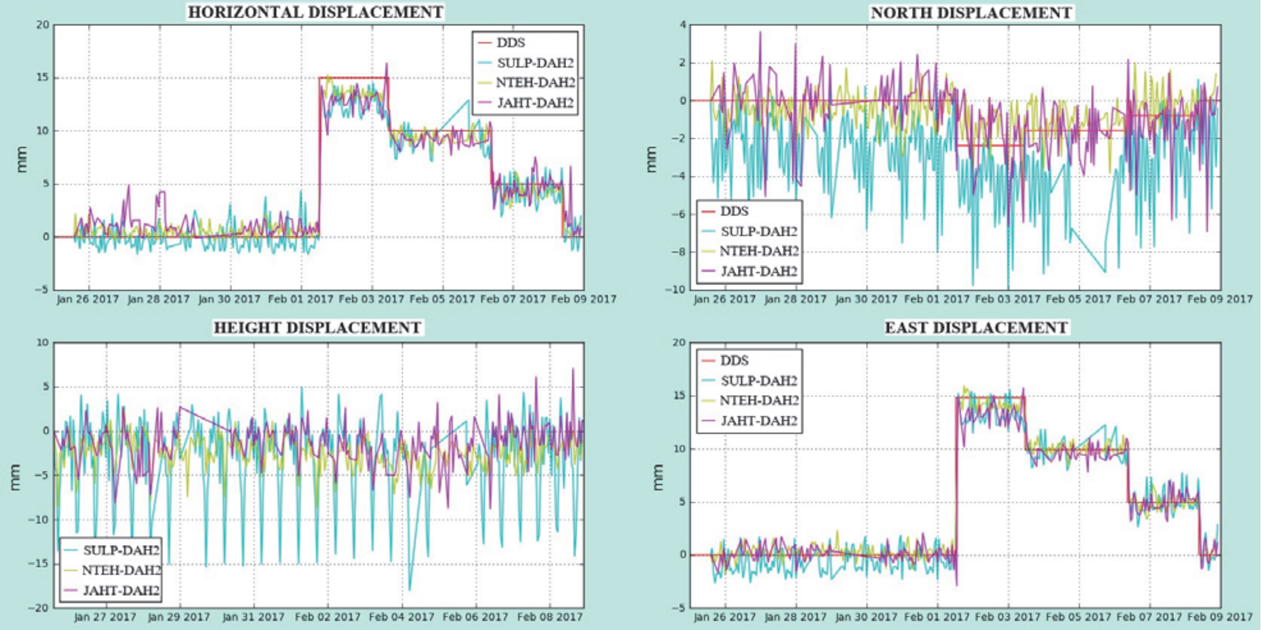


Fig. 6. Results of vectors measurement by 1 – hour interval

Table 2

Basic statistical characteristics of displacements by individual vectors

		SULP-DAH2					NTEH-DAH2					JAHT-DAH2				
		Num	Avg	SD	Min	Max	Num	Avg	SD	Min	Max	Num	Avg	SD	Min	Max
Interval 6h	d	49	0.5	**1.0**	-2.0	3.9	56	-0.3	**1.2**	-2.6	4.3	54	-0.2	**1.3**	-2.8	3.8
	n	49	-0.2	**0.9**	-3.6	1.4	56	0.2	**0.7**	-1.6	1.8	54	-0.3	**0.6**	-2.0	1.7
	e	49	0.6	**1.0**	-1.5	4.4	56	0.7	**1.1**	-1.3	5.4	54	-0.4	**1.2**	-2.5	3.9
	u	49	2.1	**2.3**	-1.1	6.0	56	0.5	**0.9**	-1.7	2.7	54	-1.3	**1.6**	-5.8	1.0
Interval 3h	d	100	-0.2	**1.0**	-2.9	3.2	113	-1.0	**0.8**	-0.6	3.1	102	-0.4	**1.8**	-10.5	4.9
	n	100	-1.0	**0.9**	-4.8	1.2	113	-0.7	**0.8**	-0.1	1.4	102	-0.2	**1.3**	-5.3	2.8
	e	100	-0.5	**1.0**	-2.6	2.5	113	0.4	**0.7**	0.7	4.7	102	-0.9	**2.0**	-18.2	3.2
	u	100	-0.4	**3.5**	-7.2	4.3	113	-1.1	**1.4**	-0.1	3.0	102	-1.5	**1.8**	-7.6	2.1
Interval 1h	d	297	-0.7	**1.5**	-9.3	4.3	331	-0.1	**1.0**	-8.1	2.3	238	0.0	**1.7**	-10.5	6.7
	n	297	-2.4	**2.0**	-8.0	1.9	331	0.1	**1.1**	-3.4	2.8	238	-0.1	**1.5**	-6.9	3.6
	e	297	-0.6	**1.3**	-8.0	3.8	331	0.1	**0.8**	-7.3	2.7	238	-0.2	**1.6**	-17.7	5.7
	u	297	-3.0	**4.7**	-18.0	5.0	331	-2.5	**1.8**	-8.7	2.3	238	-1.2	**2.3**	-8.8	7.0

In addition, it should be noted that in our case the accuracy was not heavily dependent on the length of the vector – sometimes we received inferior accuracy from the shortest vector JAHT-DAH (30 m) than from the longest vector NTEH-DAH (1400 m). This is especially raises concerns to the altitude component. Also, from Figs (4–6) and Table 2 it follows that the use of the 6 hour observation interval does not yield significant advantages in accuracy above the 1 hour interval. This suggests the possibility of using shorter observation intervals for satellite-based automated monitoring systems. Although, using 1 hour intervals gives a worse accuracy (about 1 mm in horizontal and 2 mm in height) compared 6 hours, but significantly increases the efficiency of the monitoring system. To confirm this predicate, histograms of error distribution for each vector were constructed at different intervals of observations (Figs. 7–9). In fig. 7 to 9 other colors highlighted the area (±3 mm in horizontal and ±5 mm in height), which satisfy the accuracy requirements of most modern automated monitoring systems for engineering structures, in particular systems installed at the Ukrainian hydroelectric power plants. This accuracy was stated by PJSC "Ukrhydroenergo" in the competition for the implementation of part of the project "Rehabilitation of hydroelectric power stations" at the Dnister HPP, Kaniv HPP, Dnipro hydroelectric power station and Central Dniprovska HPP [Mizhnarodna spivpratsya, 2013].

As we see from histograms, most of deviations describe the normal distribution law, and with the exception of a few percent, they are within ±3 mm in the horizontal plane. As predicted the height component was worse (deviations fluctuate within ±5 mm), but as seen from the graphs and histograms, deviations are jump-like. Such behavior of the height component and the possibility of removing the "saw" from results requires additional research.

To investigate the feasibility of using the adjustment procedure during the monitoring process, a comparison of the measurement results obtained from single vectors was made before and after adjustment were performed. For this purpose, the network was adjusted in the Leica Geo Office 8.2. Figure 10 shows graphs of deviations for adjusted data. The main statistical characteristics of deviations received after adjustment are presented in Table 3.

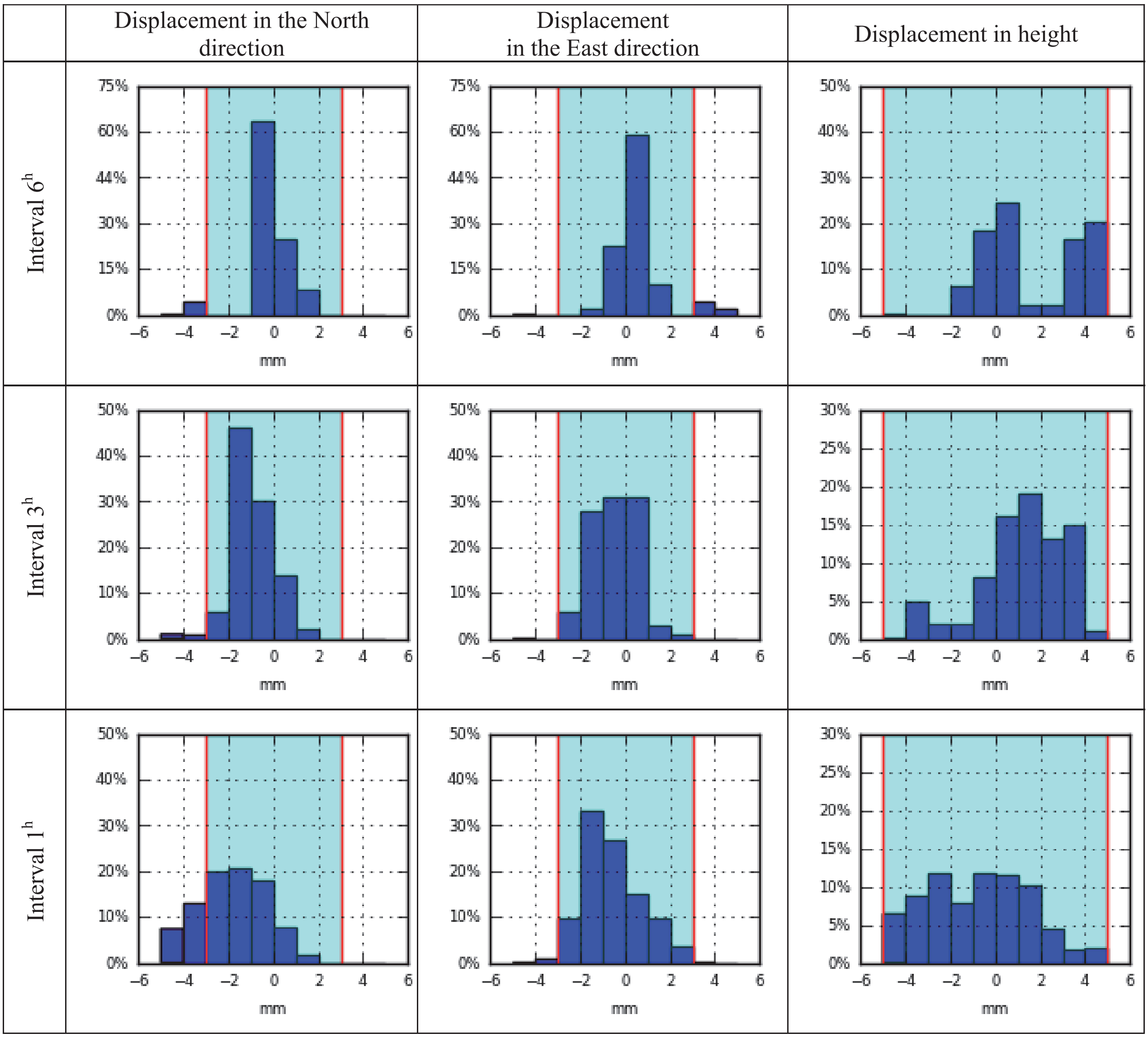


Fig. 7. Histogram of the errors distribution for the SULP-DAH vector

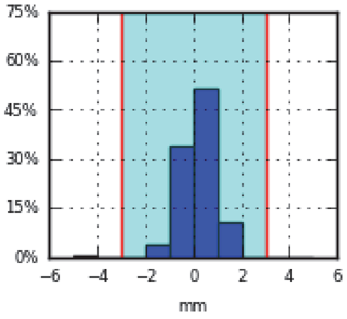
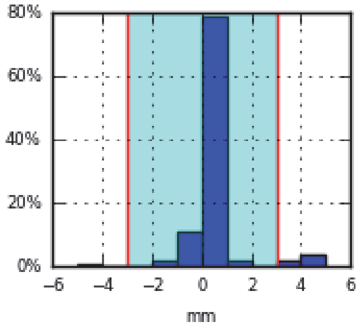
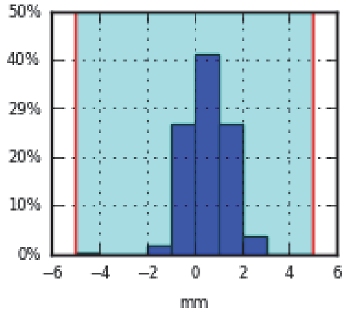
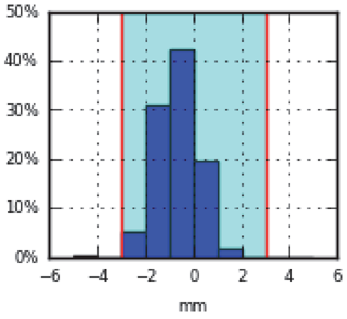
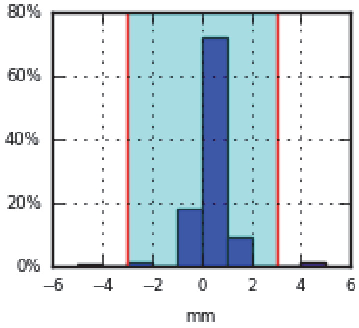
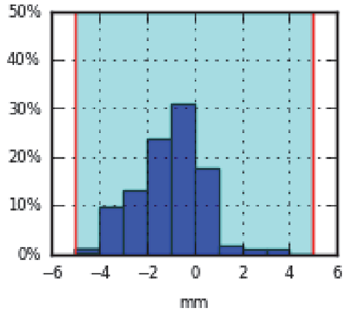
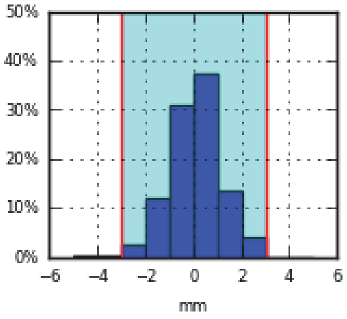
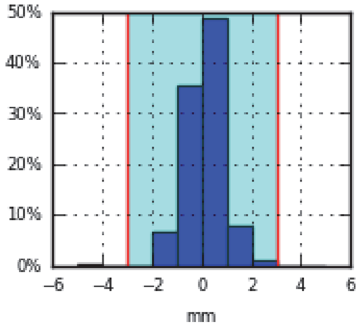
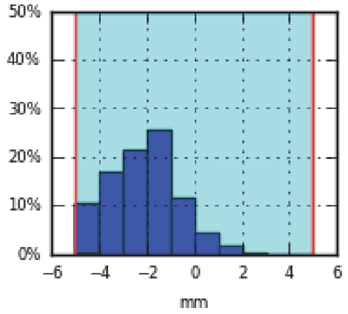
	Displacement in the North direction	Displacement in the East direction	Displacement in height
Interval 6^h			
Interval 3^h			
Interval 1^h			

Fig. 8. Histogram of the errors distribution for the NTEH-DAH vector

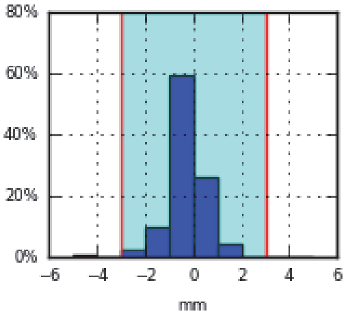
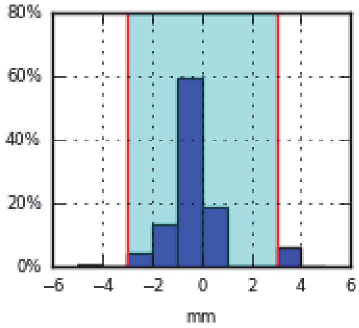
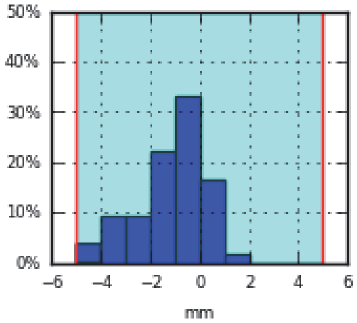
	Displacement in the North direction	Displacement in the East direction	Displacement in height
Interval 6^h			

Fig. 9. Histogram of the errors distribution for the JAHT-DAH vector

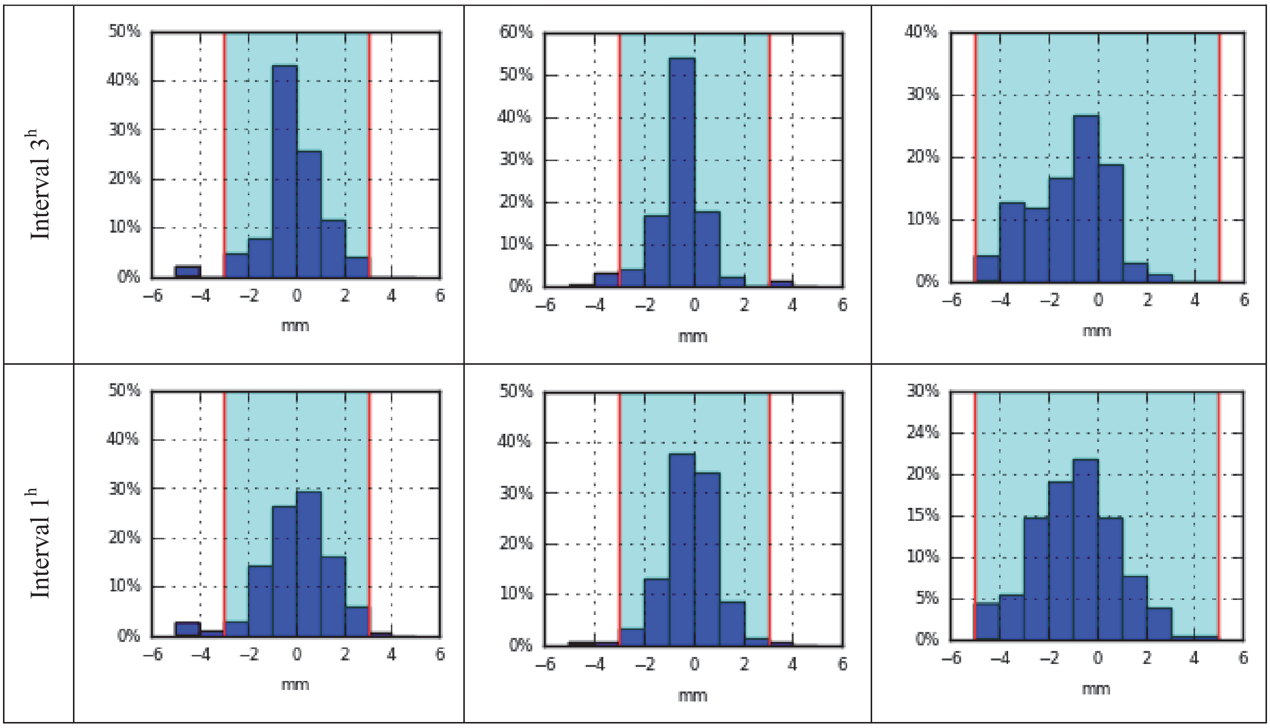


Fig. 9. Histogram of the errors distribution for the JAHT-DAH vector (cont.)

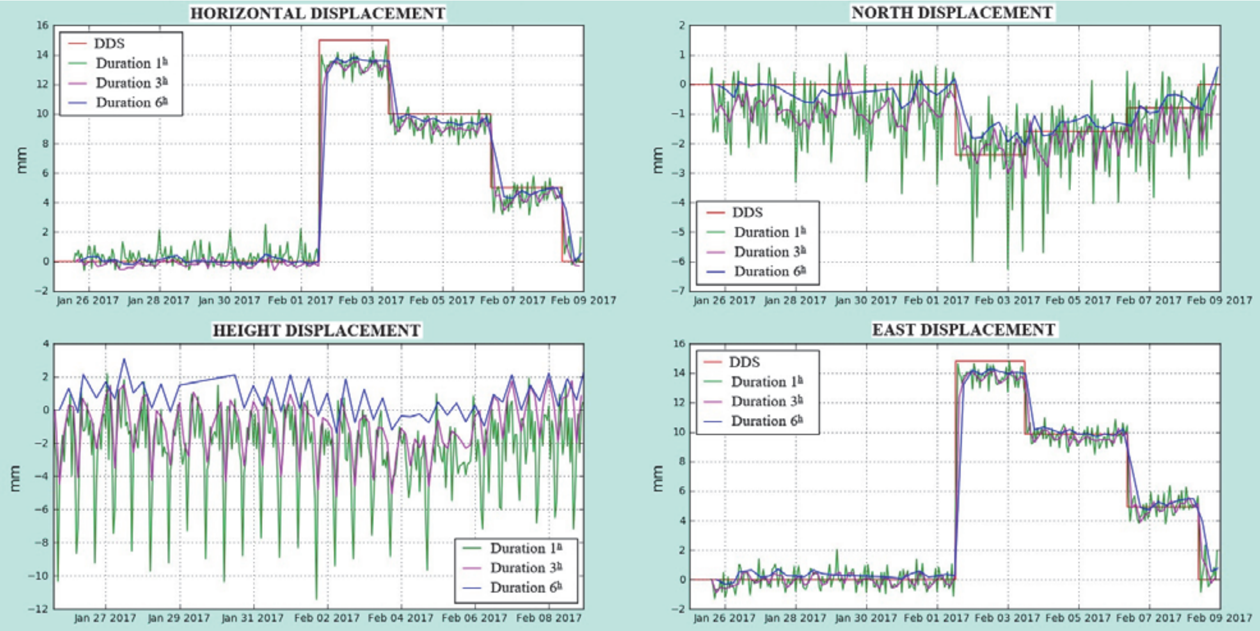


Fig. 10. Deviations from adjusted data

Table 3

Basic statistical characteristics of deviations after adjustment

	Interval 6^h					Interval 3^h					Interval 1^h				
	Num	Avg	SD	Min	Max	Num	Avg	SD	Min	Max	Num	Avg	SD	Min	Max
d	53	-0.1	**1.0**	-2.3	3.6	115	-0.5	**0.7**	-3.2	3.1	341	-0.3	**1.0**	-7.1	3.0
n	53	0.1	**0.5**	-0.9	1.4	115	-0.6	**0.6**	-1.9	1.4	341	-0.5	**1.0**	-4.1	2.0
e	53	0.3	**0.9**	-1.6	4.1	115	-0.2	**0.7**	-2.4	3.6	341	-0.1	**0.8**	-6.2	3.2
u	53	0.7	**1.1**	-1.4	3.1	115	-1.0	**1.7**	-5.2	1.9	341	-2.3	**2.4**	-11.4	2.2

Based on the results obtained after adjustment, an errors distribution histogram was constructed (Fig. 11). Similar to the case with single vectors, other color has area with errors ±3 mm in horizontal and ±5 mm in height.

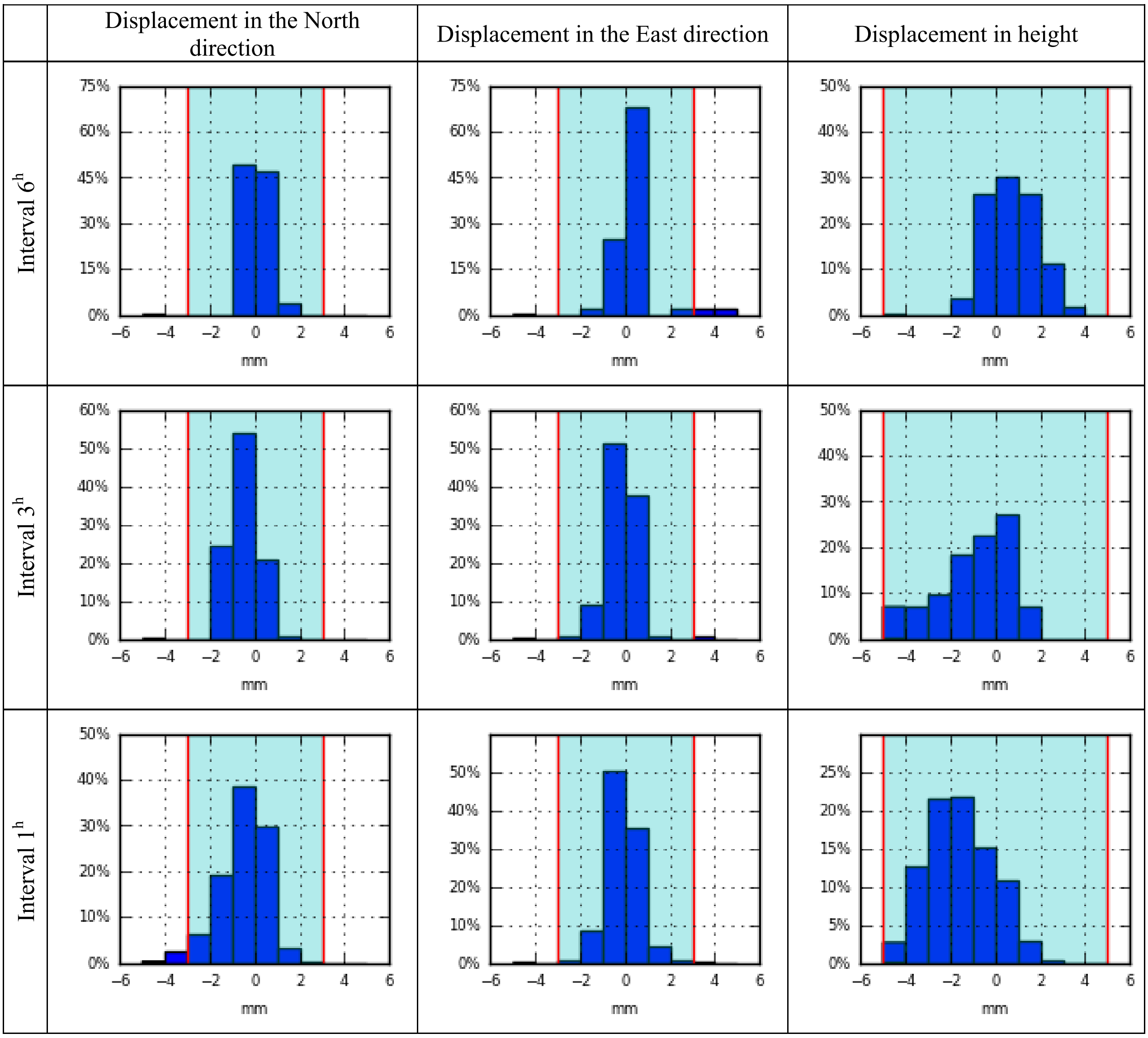


Fig. 11. Histogram distribution of errors received after adjustment

From Fig. 11 and Table 3 above, we can see a slight increase in accuracy for both horizontal and vertical components. The standard deviation in the horizontal coordinates is ≈1 mm regardless of duration. The standard deviation of height varies from 1 mm for a 6 hour interval to 2.5 mm for a 1 hour interval. In the analysis of histograms, we see that deviations also obey the normal distribution law and more than 95 % are within ±2–3 mm in horizontal and ±3–4 mm in height.

Scientific novelty and practical significance

The obtained results in the future can be used as recommendations in the design and construction of automated systems for monitoring complex engineering structures.

Conclusions

Most modern automated systems of deformation monitoring of complex engineering objects, including the system installed on the dams of Ukrainian hydroelectric plants, are oriented to the accuracy of determination of deformations at the level of 3–5 mm. In this case, 6 hour intervals of observations are used, which considerably reduces the efficiency of the system 's response to possible extraordinary events. According to the results of the performed research, the possibility of using 1 hour intervals instead of 6 hours without significant loss of accuracy has been proven, since the mean square deviation in the horizontal plane varies from 1–1.5 mm for the 6 hour observation interval, and up to 2 mm for a 1 hour interval. For the height component, the mean square deviation ranged from 1.5–2 mm for a 6 hour interval to almost 5 mm for 1 hour. The use of 1 hour intervals gives a slight deterioration in accuracy (about 1 mm in plan and 2 mm in height) compared to 6 hours, however it significantly increases the efficiency of the monitoring system.

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ДОСЛІДЖЕННЯ ТОЧНОСТІ ВИМІРЮВАННЯ ГНСС-ВЕКТОРІВ ПРИ МОНІТОРИНГУ ДЕФОРМАЦІЙ ІНЖЕНЕРНИХ СПОРУД

Мета. Метою дослідження є оптимізація моніторингу за допомогою ГНСС просторових зміщень на складних інженерних спорудах та мінімізація інтервалів ГНСС-спостережень за заданих параметрів точності. **Методика**. Для проведення експерименту розгорнуто тестову знімальну мережу з різними довжинами векторів, яка імітує моніторинг на реальному об’єкті. Мережа складалася з 4 пунктів, на яких встановлено двочастотні ГНСС-приймачі. На одному з пунктів для моделювання деформацій встановлено спеціально розроблений пристрій, який давав змогу проводити зміщення антени та фіксувати їх з високою точністю. Як геодезичну основу вибрано референцні станції SULP та NTEH, а також та станцію JAHT, яку встановлено на пілоні 2-го навчального корпусу Національного університету “Львівська політехніка”. Безперервні спостереження проводилися у статичному режимі з 25 січня по 8 лютого 2017 року включно. Протягом 15 днів спостережень проводились зміщення антени в горизонтальній площині за допомогою пристрою для моделювання деформацій. Всього за досліджуваний період проведено 4 зміщення. Для виявлення модельних деформацій використовувались виміряні поодинокі вектори від опорних станцій SULP, NTEH, JAHT з інтервалами спостережень 1, 3 та 6 годин, а також результати врівноважування мережі з цих векторів. **Результати.** Дані спостережень опрацьовано у програмному пакеті Leica Geo Office 8.2. За результатами виконаних спостережень обчислено точність виявлення просторових зміщень антени для різних довжин векторів та тривалостей ГНСС-спостережень. Проведені експериментальні дослідження для векторів до 2 км показують, що для досягнення точності визначення деформацій на рівні 3 мм в горизонтальній площині та 5 мм по висоті достатньо 1 годинного інтервалу спостережень при дискретності запису даних 1 с. **Практична значущість**. Отримані результати у подальшому можна використати як рекомендації під час проектування та побудови автоматизованих систем моніторингу складних інженерних споруд.

Ключові слова: ГНСС-станція, супутникові спостереження, моніторинг, деформації.

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