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DETERMINATION OF VERTICAL DISPLACEMENTS OF INFRASTRUCTURE OBJECTS BASED ON THE RADAR INTERFEROMETRY DATA

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Abstract. The aim of this paper is to determine the current capabilities of the radar interferometry methods and the expediency of their use for observations of the infrastructure vertical deformations on the example of the educational building of Ivano-Frankivsk National Technical University of Oil and Gas. Based on the obtained radar information, we were able to process an array of data for a short period using the method of Persistent Scatterers Interferometry (PS) (interferometry of constant reflectors of the radar signal). As a result, we determined the average velocity values of the vertical displacements of the university area. In order to establish the reliability of the results obtained by radar interferometry, the values of the structure displacements were measured according to the permanent station FRKV data, which operates in the IFNTUOG educational building №5. The results, based on both GNSS and radar interferometry methods, correlate and confirm the absence of significant deformation shifts of the construction.

Keywords: radar interferometry, PS method, GNSS, infrastructure object, vertical deformations of the construction.

Introduction

In order to avoid catastrophic construction deformations, subsidence and displacements of structures are usually observed by the ground-based geodetic methods (high-precision geometric leveling, trigonometric leveling, hydro-, micro-leveling) and remote sensing methods (photogrammetric survey methods, GNSS). None of these methods is universal and has both positive and negative features. Therefore, for technical monitoring it is advisable to combine different geodetic and geotechnical methods of observation, appropriate in each case.

Involvement of the modern satellite services for infrastructure observations allows not only monitoring the condition of roads, bridges, buildings and other important objects, but also can be an effective tool in combating illegal natural resources extraction and preventing emergencies.

Significant advantages of the space observations over other types of technical control are globality, exterritoriality, durability, efficiency, continuity and comprehensiveness, which determine its leading place in solving engineering and geodetic problems (Astashkin, 1991; Kanashchenkova, 2006; Frodella et al., 2016).

One of the methods of determining the deformation processes of the Earth's surface, as well as structures, is the technology of radar interferometry (InSAR – Interferometric Synthetic Aperture Radar) (Hanssen, 2001). It is considered as a modern form of remote sensing data analysis that allows us to determine the dynamics of different objects (landslides, geodynamic displacements, deformations of the structures or of the Earth's surface, etc.).

Over the last decade, radar interferometry has become widely used not only due to its high technical performance and ability to operate regardless of weather conditions, but also because of its ability to accumulate results, analyze them and predict critical deformations a few days in advance (Pakshyn et al., 2019).

Ukrainian regulations that establish obligatory performance of geodetic monitoring of buildings construction and operation (DBN B.1.3.-2:2010 (Ministry of Regional

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Development of Ukraine, 2010)), as well as the accuracy level of the geodetic measurements during these processes (DSTU B.V.2.1-30:2014 (Ministry of Regional Development, Construction and Housing of Ukraine, 2014), do not involve the use of radar interferometry techniques. Although they have obvious benefits over traditional methods, especially in efficiency requiring much less labour remuneration, resulting in their own lower cost.

Therefore, the purpose of the research is to clarify the possibility of using radar interferometric methods for geodetic monitoring. During the exploitation of buildings and engineering structures it is necessary to conduct high-precision monitoring of their deformations. In the process of research, it is important to determine the speed and direction of deformations. Therefore, it is required to choose the optimal monitoring method.

1. Analysis of recent studies and publications regarding the solution to this problem

As it is demonstrated in the works of scientists Ferretti et al. (2007), Costantini (Costantini et al., 2009), the differential processing of data from more than 30 radar images allows to determine the vertical displacements of the Earth's surface with centimeter accuracy. This fact provides wide prospects for the use of radar systems for a deeper study of the displacement processes of the Earth's surface and monitoring the condition of human made objects over large areas. The obvious advantages of this approach are: 1) reduction of labour intensity; 2) obtaining a comprehensive picture of man-made impact, covering the entire research area.

The paper (Fanti et al., 2013) improved the methods of processing interferometric data, as well as highlighted ways to reduce the impact of systematic errors.

The paper (Feoktistov et al., 2015) presents the main characteristics of the small baseline subset algorithm (Small BASeline, SBAS) and the results of the comprehensive experimental studies on the example of the territory of Chiba Prefecture (Japan).

However, the analysis of literature sources revealed that the use of the radar interferometry methods for observations of structures deformations has not been studied enough. Therefore, it is appropriate to perform further research to develop a methodology based on the generalized available knowledge and experience of experts, which will confirm the possibility and consider the prospects of using radar data to monitor vertical displacements of infrastructure objects.

1.1. Problem statement

The problem of the study is to conduct a comparative analysis of the results of the processed radar interferometry data (Persistent Scatterers Interferometry Method) with data obtained from the permanent station, to estimate the reliability of infrastructure objects.

Figure 1. Territory of Ivano-Frankivsk National Technical University of Oil and Gas

1.2. Statement of the main material

To determine the deformations of the construction, the educational building No. 5 of Ivano-Frankivsk National Technical University of Oil and Gas (IFNTUOG) (Figure 1), which is over 50 years old, was selected. From experience, we know that the greatest building subsidence is occurring during the first five years of exploitation.

Therefore, we can assume that in the absence of seismic activity and landslides in this part of the terrain surface, taking into account the service time of the building, the indicators of the vertical deformations will be insignificant. At the next stage, it is necessary to conduct an analysis of the soils types under the building, and then calculate the values of deformation using remote sensing methods.

The sequence of rocks on the territory of the university is presented in Figure 2.

Apparently, the quaternary deposits are loam and gravel-pebble deposits of sand. The thickness of the rocks reaches 12 m. In the range of depths of 12–68 m argillite clay occurs, 68–105 m – clay with sandstone; in the range of 105–140 m – gypsum lies, 140–200 m – clay with sandstone. It can be argued, that the building chosen for research is built on stable and reliable soils and rocks. Determination of the vertical displacements of the infrastructure objects of the IFNTUOG territory for the period from April 1, 2019 to October 22, 2020 was carried out according to the data of the space radar survey.

The method of interferometric processing called Persistent Scatterers Interferometry (PS) was used for our research (Berardino et al., 2002). 72 radar images from the Sentinel-1 spacecraft for the territory of Ivano-Frankivsk were chosen as the incoming data for processing.

For the PS method, the interferometric processing cycle is performed in ENVI SARscape for each pair of

	Age	Breeds	Lithological section	Depth of stratum, m	Bottom depthof stratum, m
1		Loam		2	2
2	Q	Gravel-pebble deposits		10	12
3	N	Argiline clay		56	68
4		Clay with sandstone		37	105
5		Gypsum		35	140
6		Clay with sandstone		60	200

Figure 2. Lithological-stratigraphic column for a well near the IFNTUOG educational building No. 5

images of the interferometric series (general parameters are shown in Figure 3). Pairs of images are selected by the program automatically from the given series of images on the basis of the set parameters before the beginning of calculations (Figure 4).

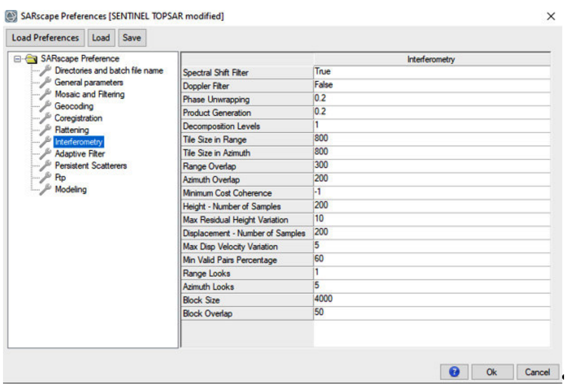

Figure 3. ENVI SARscape software settings

The specified parameters determine pairs of images which meet the criteria, depending on the limitations on

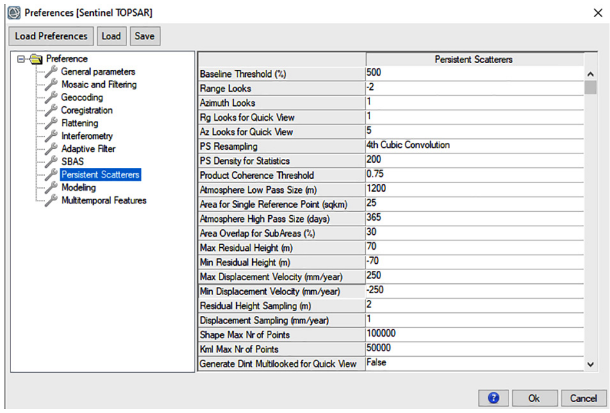

Figure 4. ENVI SARscape software settings for the PS method

the choice of interferometric pairs for further automated processing. For the PS method, the number of interferometric pairs was 71.

The specified parameters determine pairs of images which meet the criteria, depending on the limitations on the choice of interferometric pairs for further automated processing. For the PS method, the number of interferometric pairs was 71. It is necessary to perform a complex element-by-element phase multiplication for each pair of images of the interferometric series.

The main source file of this procedure is a differential interferogram, which is the result of subtracting the synthesized phase of the terrain from the complex interferogram.

The differential interferogram contains a component of deformations of the Earth's surface that occurred during the period between surveys; a component of phase noise and a component of influence of atmospheric conditions when taking each of the pictures of the chosen series (Figures 5–11).

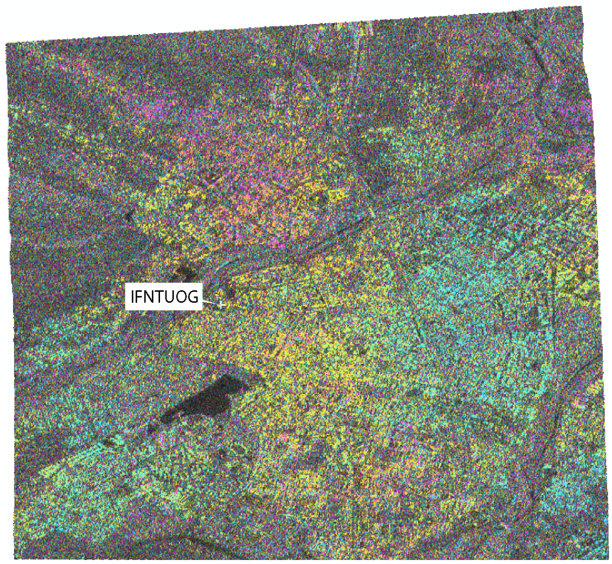

Figure 5. Filtered differential interferogram for the period 01.04.2019 – 09.11.2019

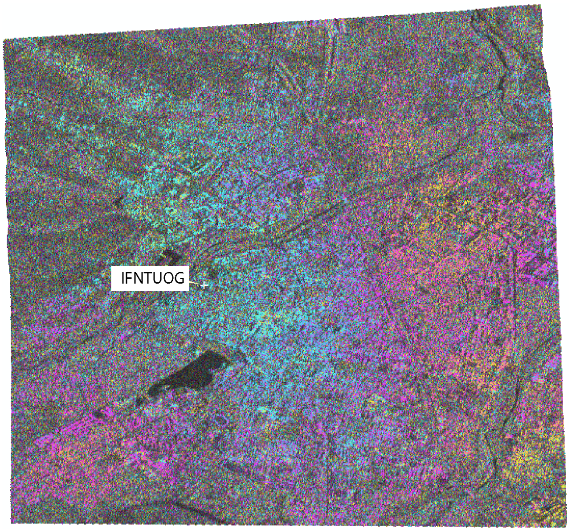

Figure 6. Filtered differential interferogram for the period 06.07.2019 – 09.11.2019

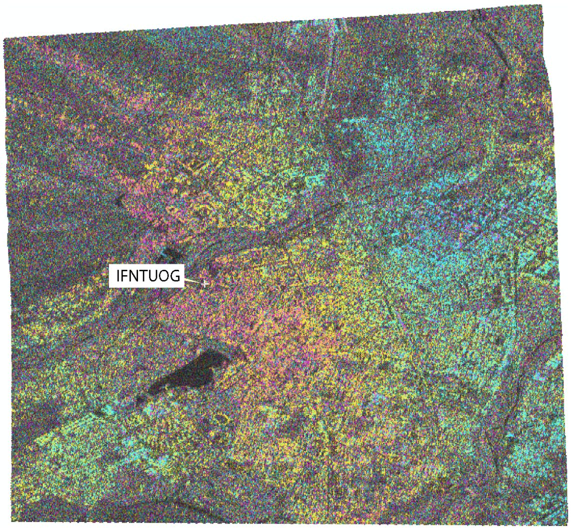

Figure 9. Filtered differential interferogram for the period 01.04.2020 – 09.11.2019

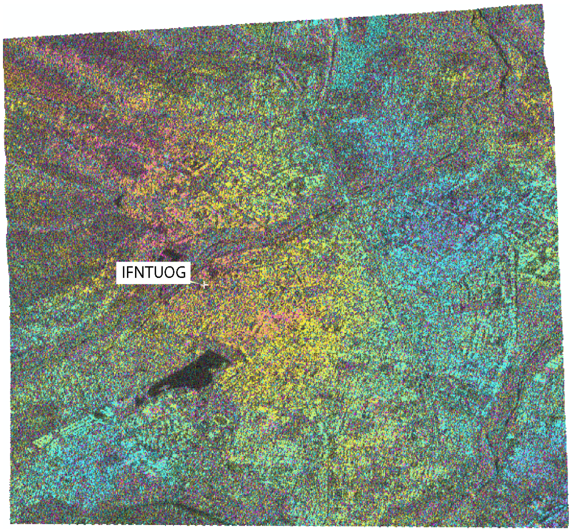

Figure 7. Filtered differential interferogram for the period 04.10.2019 – 09.11.2019

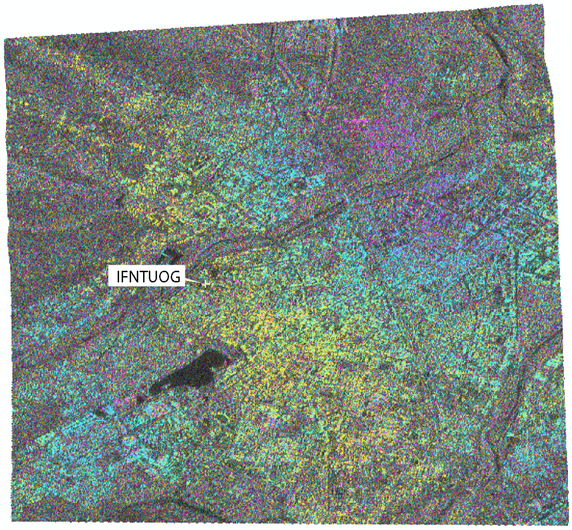

Figure 10. Filtered differential interferogram for the period 06.07.2020 – 09.11.2019

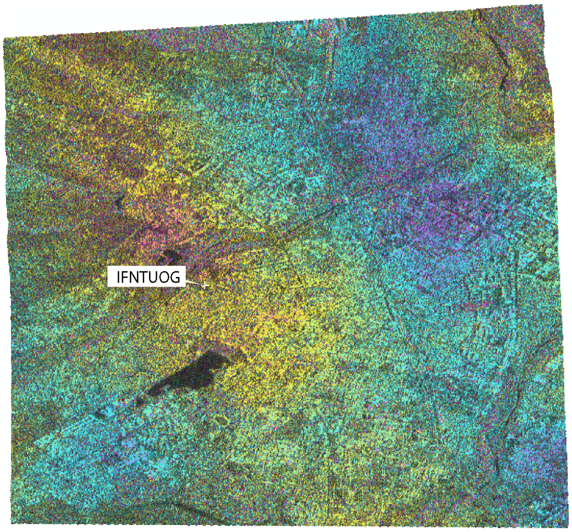

Figure 8. Filtered differential interferogram for the period 03.11.2019 – 09.11.2019

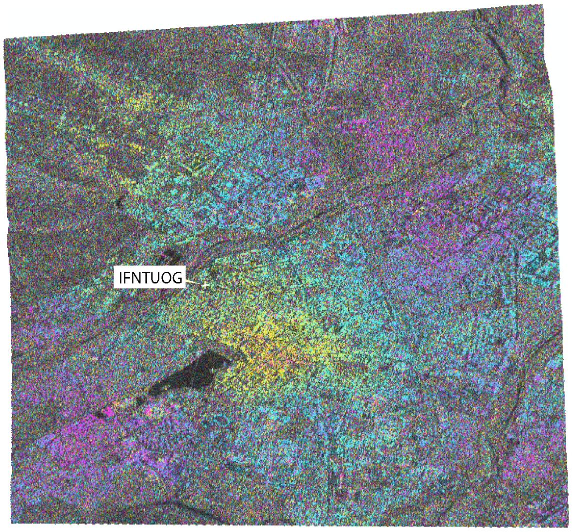

Figure 11. Filtered differential interferogram for the period 04.10.2020 – 09.11.2019

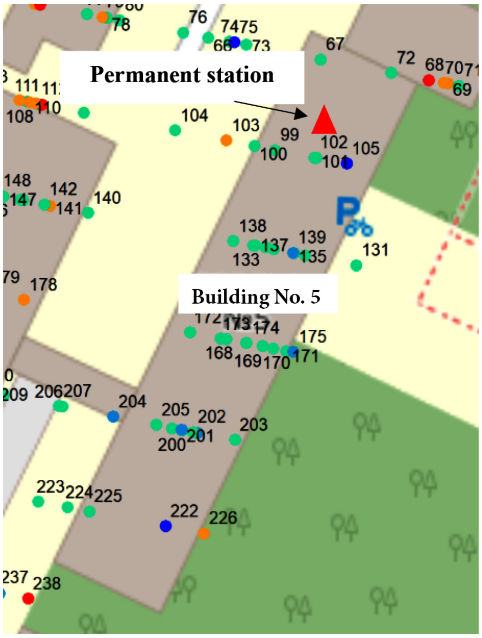

Figure 12. Placement of the permanent stable radar reflectors on the building (Ivano-Frankivsk, building No. 5 IFNTUOG)

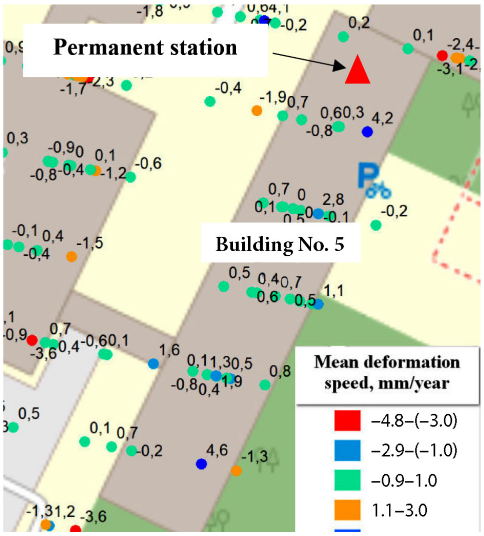

Figure 13. Average annual velocity of the vertical displacements of the building (Ivano-Frankivsk, building No. 5 IFNTUOG)

The result of data processing is a vector file containing points that characterize the dynamics of deformation of the structure. Figure 12 shows the placement of the permanent stable reflectors of the radar signal on the IFNTUOG building. At these points, the algorithm found constant stable reflectors of the radar signal, which are the main elements in the method of processing radar data. The average speed of vertical displacements during the study period (01.04.2019–22.10.2020) was up to +4 mm/year (Figure 13).

To establish the accuracy of the results, a comparative analysis of the research results obtained by radar interferometry and the results of permanent station FRKV data processing (Table 1) was done. FRKV is a part of the network of permanent stations System Solution. Measurements of the FRKV permanent station were obtained in the period from March 26, 2020 to October 10, 2020 in the WGS-84 coordinate system. Taking into consideration Table 1 data, the changes of the permanent station height in accordance with the date of observation is graphically represented in Figure 14.

Table 1. FRKV permanent station data

Data / Year 2020	X, m	Y, m	H, m
26.03	48 – 55′ 47,03005″ N	24 – 41′ 40,33301″ E	305,7597
01.04	48 – 55′ 47,03008″ N	24 – 41′ 40,33292″ E	305,7634
07.04	48 – 55′ 47,03004″ N	24 – 41′ 40,33310″ E	305,7625
13.04	48 – 55′ 47,03005″ N	24 – 41′ 40,33312″ E	305,7587
19.04	48 – 55′ 47,03013″ N	24 – 41′ 40,33293″ E	305,7596
25.04	48 – 55′ 47,03008″ N	24 – 41′ 40,33307″ E	305,7616
01.05	48 – 55′ 47,03003″ N	24 – 41′ 40,33307″ E	305,7608
07.05	48 – 55′ 47,02999″ N	24 – 41′ 40,33305″ E	305,7599
13.05	48 – 55′ 47,03000″ N	24 – 41′ 40,33308″ E	305,7589
19.05	48 – 55′ 47,02997″ N	24 – 41′ 40,33309″ E	305,7602
25.05	48 – 55′ 47,03003″ N	24 – 41′ 40,33300″ E	305,7591
31.05	48 – 55′ 47,02993″ N	24 – 41′ 40,33301″ E	305,7599
06.06	48 – 55′ 47,03002″ N	24 – 41′ 40,33300″ E	305,76
12.06	48 – 55′ 47,02998″ N	24 – 41′ 40,33297″ E	305,7603
18.06	48 – 55′ 47,03003″ N	24 – 41′ 40,33316″ E	305,7585
24.06	48 – 55′ 47,03002″ N	24 – 41′ 40,33307″ E	305,7616
30.06	48 – 55′ 47,03001″ N	24 – 41′ 40,33306″ E	305,7625
06.07	48 – 55′ 47,03017″ N	24 – 41′ 40,33310″ E	305,7618
12.07	48 – 55′ 47,03003″ N	24 – 41′ 40,33306″ E	305,7613
18.07	48 – 55′ 47,03003″ N	24 – 41′ 40,33307″ E	305,7593
24.07	48 – 55′ 47,03003″ N	24 – 41′ 40,33303″ E	305,761
30.07	48 – 55′ 47,03004″ N	24 – 41′ 40,33302″ E	305,7609
05.08	48 – 55′ 47,03003″ N	24 – 41′ 40,33301″ E	305,7607
11.08	48 – 55′ 47,03003″ N	24 – 41′ 40,33302″ E	305,7607
17.08	48 – 55′ 47,03002″ N	24 – 41′ 40,33301″ E	305,7602
23.08	48 – 55′ 47,03003″ N	24 – 41′ 40,33302″ E	305,7608
29.08	48 – 55′ 47,03003″ N	24 – 41′ 40,33303″ E	305,7604
04.09	48 – 55′ 47,03003″ N	24 – 41′ 40,33304″ E	305,7602
10.09	48 – 55′ 47,03003″ N	24 – 41′ 40,33301″ E	305,7607
16.09	48 – 55′ 47,03003″ N	24 – 41′ 40,33302″ E	305,7602
22.09	48 – 55′ 47,03003″ N	24 – 41′ 40,33304″ E	305,7602
28.09	48 – 55′ 47,03003″ N	24 – 41′ 40,33302″ E	305,7605
04.10	48 – 55′ 47,03003″ N	24 – 41′ 40,33302″ E	305,76
10.10	48 – 55′ 47,03001″ N	24 – 41′ 40,33303″ E	305,7601

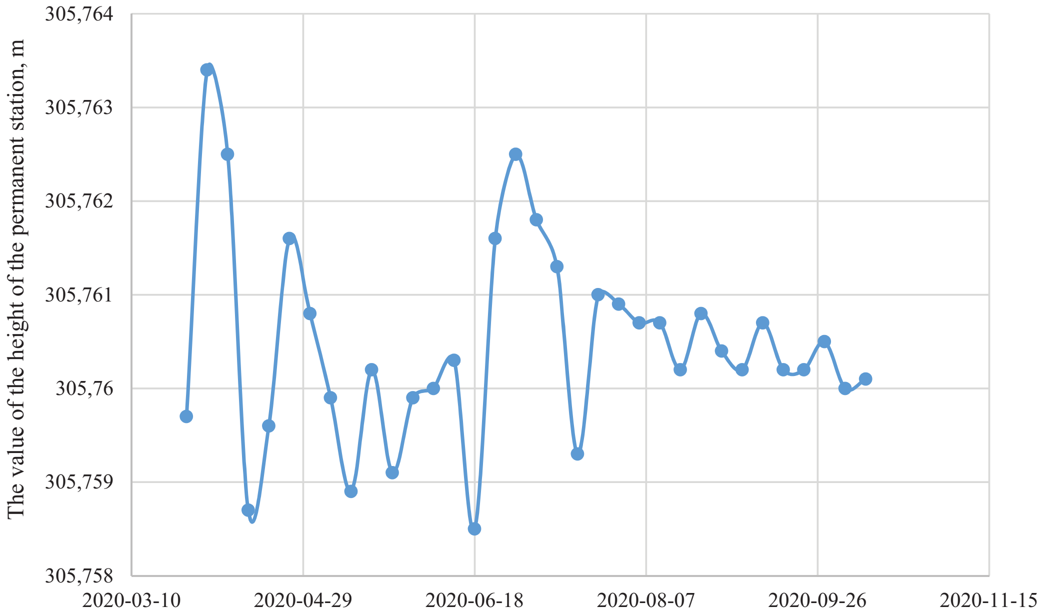

Figure 14. Graph of the change of the FRKV permanent station height

Based on the research, it was found that the change of the maximum and minimum values in the height of the permanent station in the period from 26.03.2020 to 10.10.2020, was 4.9 mm according to GNSS (Figure 14).

According to radar interferometry, the average annual speed of the vertical displacements of the points, situated closer to the receiver antenna, is from –0.8 mm/year to +4.2 mm/year.

While analyzing the interferometric time series in the radar measurement No. 102 (the closest radar measurement to the permanent station), namely 35 values of the vertical displacements in the period from 23.03.2020 to 22.10.2020, it appeared that the majority of them (30 values) are in the range of –8… +1 mm (Figure 15). Assuming that the accuracy of the vertical displacement determining in the radar measurement by the PS method is in the range of 4–6 mm, we conclude that the radar measurement is stable. During the specified period (from 26.03.2020 to 22.10.2020) it was investigated that the dynamics of the vertical displacements in the radar dimension No. 102 is insignificant and comparable with the calculation error of the

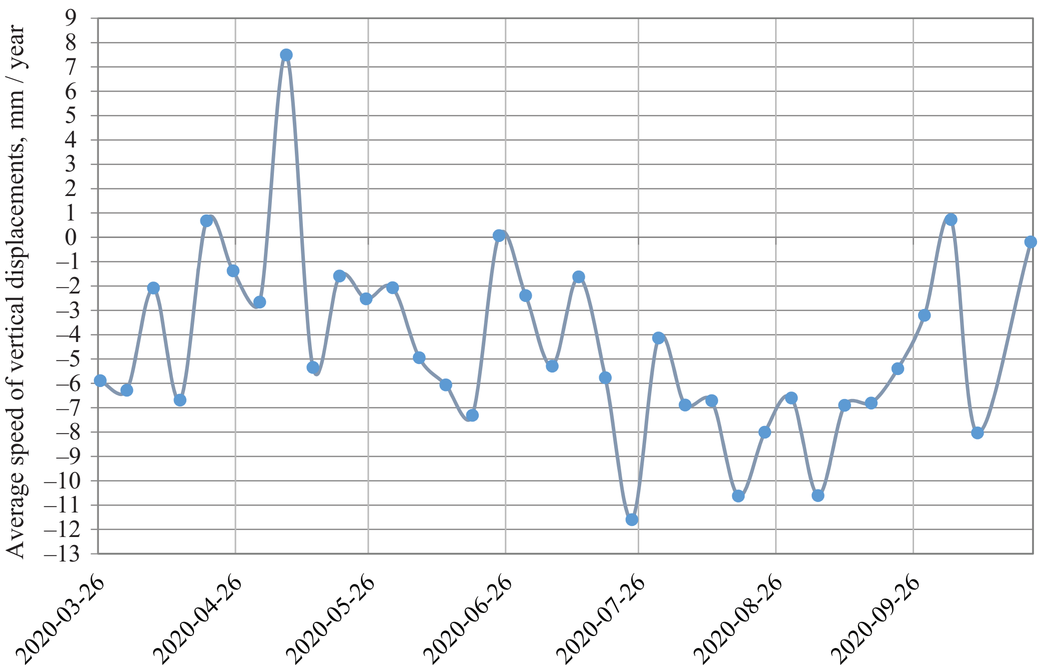

Figure 15. Dynamics of the vertical displacements at the point No. 102 for the period 26.03.2020 – 22.10.2020

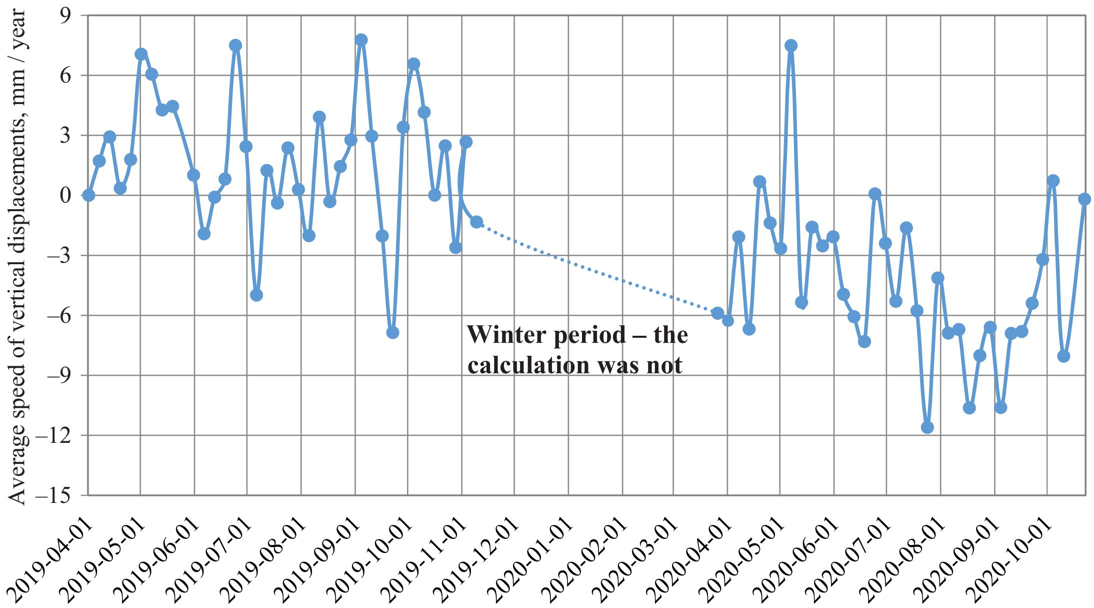

Figure 16. Dynamics of the vertical displacements at the point No. 102 for the period 01.04.2019 – 22.10.2020

vertical displacements by the interferometric method PS.

In addition, the statement is confirmed by the dynamics of the vertical displacements over a longer period of time (two years), namely in the period from 01.04.2019 to 22.10.2020, where the average speed of the vertical displacement is 0.6 mm/year (Figure 16).

Conclusions

1. It should be noted, the present research of the infrastructure object reliability confirmed the absence of significant values of the deformation displacements, as the construction is built on the reliable soils.

2. Evaluation of the infrastructure objects reliability has shown that the results of the processed data by radar interferometry correlate with the data obtained by the GNSS method. Since in the period from 26.03.2020 to 10.10.2020, the change in the height of the permanent station was 4.9 mm according to GNSS, whereas the vertical displacement of the points closest to the receiver antenna was generally from –0.8 mm to +4.2 mm according to radar interferometry.

3. The expediency of using radar survey data to determine the vertical displacements of infrastructure objects was also confirmed. During the research period from 01.04.2019 to 22.10.2020, the average speed of the vertical displacements of the IFNTUOG territory was in the range from –4 to +4 mm/year according to the satellite radar survey.

Disclosure statement

The authors declare no conflict of interest.

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