Assessment of Usefulness of Radar Interferometer for Measuring Displacements and Deformations of Dams

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ABSTRACT:

Dams are interesting engineering structures, which have extraordinary importance for water management and also for people living in the surrounding area. For early detection of potential risks dams are subjected to permanent controlling. Geodetic measurements of displacement and deformation are the integral part of safety control. Currently, the complete automation of measurements is tended, as well as increasing their frequency. Despite the increasing simplifying of measurement process (the use of robotic total station or GNSS receivers) determination of absolute displacements requires the long-term process of measuring and computing. In order to provide the continuous monitoring of objects such as dams, relative methods (inclinometers, extensometers, etc.) can be applied. However, they do not provide the complete image of dam displacements .Quite recently, a new technology, ground-based microwave interferometry has appeared. It was developed for quasi-continuous measurement of object displacement with accuracy of ±0.1 mm. An important feature of this system is the possibility of remote control of measurement and unnecessary access to the measured object in order to mount the sensors or measuring signals. During each data acquisition, which lasts a few minutes, the entire structure, which is within the radar range, is observed. Hence, we are not dealing with discrete (limited to points) measurement, but we obtain the continuous displacement map for the entire area of interest. Measurement can be performed regardless of weather conditions. However, like any novel technology, the radar interferometry must be tested for its reliability and accuracy, with reference to the methods currently used. The purpose of this study is to test the accuracy of IBIS-L (an interferometric radar) on the specially prepared test field and the test building which is the Poland's largest reinforced concrete dam in Solina. Thanks to the automatic system of sensors it is possible to compare results obtained from the inclinometers and feeler gauges with the IBIS-L results. Analysis of differences will enable verification of its usefulness in geodetic monitoring of displacements and deformations of the dam in Solina.

1. INTRODUCTION

Water reservoirs, similarly to chimneys, towers, bridges, or skyscrapers, are the structures that require special supervision of their work and technical condition. History knows many cases where the lack of concern about the state building construction ended in disaster. In the XIX and XX century more than 300 major accidents and disasters of dams have happened. Most of them are summarized in Table 1.

Year	Name of dam	Country	Number of victims
1802	Puentes	Spain	680
1872	South-Fork	USA	approx. 2500
1889	Jonston	USA	approx. 4000
1916	Brela Disna	Czech Rep.	approx. 60
1923	Gleno	Italy	approx. 60
1959	Malpasset	France	421
1963	Vaiont	Italy	2100
1976	Pereira	Colombia	70
1993	Qinghai	China	223

Table 1. The largest disasters of dams (Bryś & Przewłocki, 1998)

With the beginning of new century the security problem has not disappeared. A well-known example is the break of the dam in western Hungary. On October 4, 2010 the rupture induced the leakage of a toxic by-product formed during the production cycle at a nearby Ajka aluminum steelworks. The leakage covered over 1017 hectares, resulting in 9 dead and 150 wounded people. It should be noted that the reservoir had not have any monitoring system and any earlier detection of threats was not possible.

Currently, around the world there operates more than 45 000 large dams, which are not being monitored. They can be a major threat for millions of people living in surrounding areas.

One of the fundamental methods of measuring displacements and deformations of a dam is a classic measurement of points representing the structure using total stations or GPS receivers (Rueger, 2006). These measurements usually take place from 2 to 4 times per year and provide information about the absolute movements. An additional information about relative movements is provided by various sensors (pendulums, extensometers, feeler gauges, etc.). Measurements with their use are made once a week.

Currently implemented monitoring systems automatically perform the measurement process. The first stage of automation is the use of electronic sensors of relative movements, which continuously record the observations and send them directly to the database system. The second stage is to automate the process of determining the absolute displacements. With the development of robotic total stations and GNSS receivers fully autonomous systems are available. They provide the quasi-

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continuous information about the movements of selected points (Duffy et al., 2001; Wilkins et al., 2003). However, these systems also have disadvantages:

- operation range,
- discrete measurements (in points),
- number of GNSS receivers equals to the number of observed points.

Recently, a new ground-based radar interferometry technology has appeared (IDS, 2007a). It combines the advantages of relative and absolute measurement and is devoid of the above mentioned drawbacks.

2. GROUND-BASED RADAR INTERFEROMETRY

Radar interferometry technology has gained in popularity thanks to its use in satellite remote sensing techniques. During the observation of the land surface using satellite radar interferometry the intensity of reflection and the phase of the reflected wave are recorded. Apart from possibility of preparing the land use maps, it is possible to obtain information about the shape of the land and small deformations taking place between consecutive imaging of the same area.

With time, this technology was transferred to the surface of the earth, where it serves to study deformation of various types of engineering structures such as towers or bridges and for monitoring landslides, slopes, dikes, dams and buildings (Bernardini et al., 2007).

One of the devices, which applies the discussed technology is the IBIS radar (Image by Interferometric Survey), developed and manufactured by Italian company IDS and Department of Electronics and Telecommunication of the Florence University. In order to satisfy the largest possible range of needs two versions of this system are available:

- IBIS-S – for observation of structures in one dimension (bridges, chimneys and skyscrapers) that require the high sampling frequency,
- IBIS-L – used to the quasi-continuous observations of small movements of objects that require the representation in two dimensions (dams, landslides, volcanoes, glaciers, avalanches, etc.).

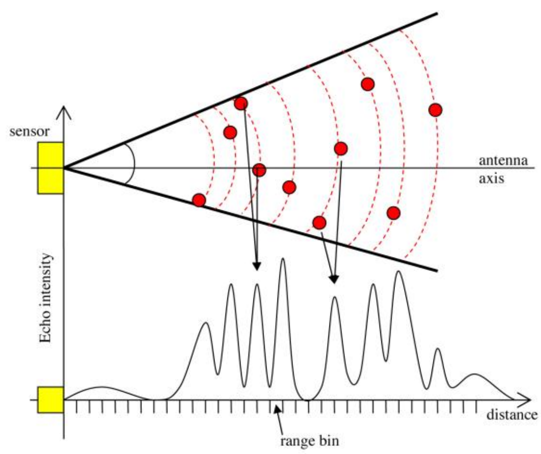

Figure 1. Range profile (IDS, 2007b)

For the positioning of measured objects and the determination of displacement it is necessary to use three radar techniques (Alba et al., 2008). Thanks to the stepped-frequency continuous wave modulation (SF-CW) the measurement of land situation along the line of sight is possible. It is used to detect the surface of objects located at different distances from the device. However, it should be noticed that the distance measurement is not continuous but carried out in intervals, which size (resolution) depends on the wave frequency and in the case of IBIS-L is equal 0.5 m. A sample profile of the radar interferometer presents Figure 1.

For the monitoring of dams the positioning along the line of sight only is not sufficient. In order to obtain a position in the transverse direction, the SAR technique (Synthetic Aperture Radar) is used. With the ability of stepped change of the device position on a 2-metres long rail during a single pass (measurement series) radar performs a few hundred acquisitions. Each measurement allows the "look" at the object at a different angle so that it is possible to precisely determine the transverse position of the measured objects. In the performed test the angular resolution is 14.5' (0.25°), which gives 0.77 m based on the distance of 200 m.

The main objective of the IBIS-L system measurements is not the terrain mapping but displacement determination of selected object points. This is possible by using the interferometry technique (Figure 2), which by comparison of the reflected electromagnetic wave phase allows to determine changes in the position of an object with an accuracy of up to ±0.1 mm. Displacement along the direction of wave propagation is determined by the formula (1):

$$dp = \frac{\lambda}{4 \cdot \pi} \cdot \Delta\varphi \qquad (1)$$

where dp = measured displacement
λ = wavelength
$\Delta\varphi$ = carrier wave phase shift

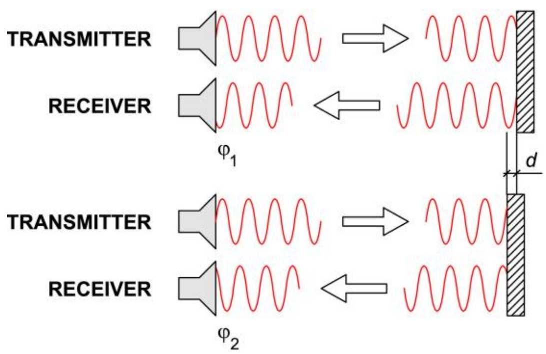

Figure 2. The principle of interferometric measurement

The information about the radial displacement enables calculation of the displacement in an appropriate coordinate system, using the simple trigonometric functions.

3. DETERMINATION OF IBIS-L ACCURACY ON FIELD TEST

Any attempt to implement a new measurement tool for the surveying practice should be preceded by many experiences in order to determine its accuracy and usefulness. This necessity relates also to the implementation of the IBIS-L for measuring displacements and deformations of such critical structures as dams. In the related literature some tests of IBIS-L can be found, however, the measuring samples are not too large. Moreover, in most cases tests were performed on the operating objects and therefore, testing of the measurements repeatability was not possible.

Figure 3. Location of the test base

The experiment aimed to determine the actual accuracy of the set consisting of radar and the target (a microwave reflector). In order to perform the test a 140-metres long measurement base was established (Figure 3). The interferometer was placed on three foundation blocks, in accordance to the rules given in the stabilization manual (Figure 4).

Figure 4. IBIS-L set on the foundation blocks

The tested object (microwave reflector) was placed on a mobile platform consisting of a trolley placed on a rail which was set on two surveying tripods (Figure 5). The trolley movement was precisely monitored using the electronic slide caliper DIGI-MET manufactured by Preisser (Figure 6). The accuracy of measurement equals ±0.01 mm – ten times greater than in the case of IBIS-L.

Figure 5. Test platform with microwave reflector attached

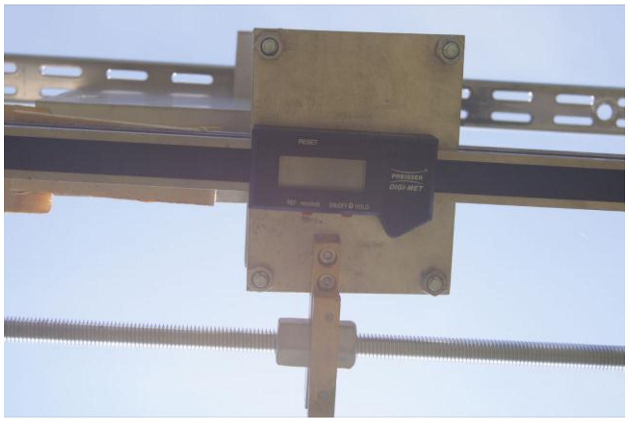

Figure 6. Electronic slide caliper DIGI-MET

The experience was based on measurement the displacement of reflector moving along the line of sight of radar interferometer. Movements of range 0÷11 mm with the step of 1 mm were recorded. Additionally, the first seven measurements were performed twice to verify repeatability of the obtained results.

Post-processing of measurements was carried out in the IBIS Data Viewer software, version 03.04.012. Using the graphical presentation of all measured objects in the form of map (Figure 7), one pixel representing the measured reflector, situated opposite the radar at a distance of 140 m, was identified. The value of coherence was 0.72 and thermal SNR – 71.3 dB.

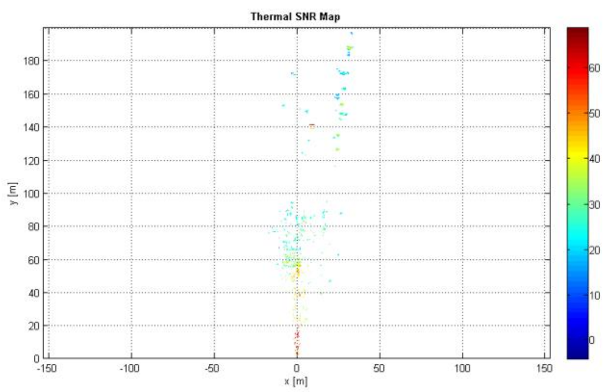

Figure 7. Thermal SNR map

Using the analysis functions of the built-in programme, displacements of the analyzed point were generated and presented together with caliper readouts in Figure 8.

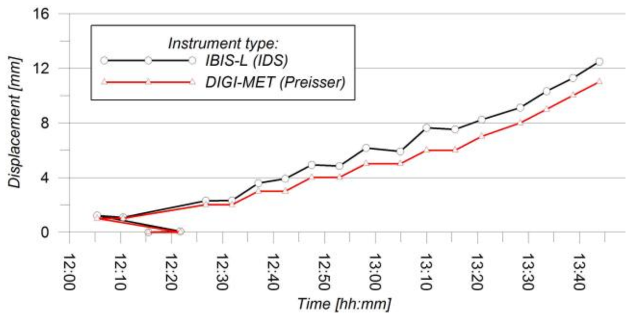

Figure 8. Comparison of displacement measurement results and calibration system IBIS

Two measurements carried out for the seven positions of the reflector enable to determine the internal consistency of the received values of displacement, disturbed only with a radar measurement errors and the residual influence of the atmosphere. Table 2 contains a summary of the results.

Number	First meas.	Second meas.	Δ
	mm	mm	mm
1	0.00	0.07	0.07
2	1.21	1.08	-0.13
3	2.31	2.32	0.01
4	3.60	3.92	0.32
5	4.93	4.85	-0.08
6	6.17	5.91	-0.26
7	7.64	7.53	-0.11

Table 2. Summary of measurements made twice

To determine the average error of single measurement the following formula was used:

$$\sigma_m = \pm\sqrt{\frac{\sum \Delta^2}{2 \cdot n}} = \pm 0.12mm \qquad (2)$$

where σ_m = mean squared error of single measurement
Δ = difference between the measurements
n = number of positions

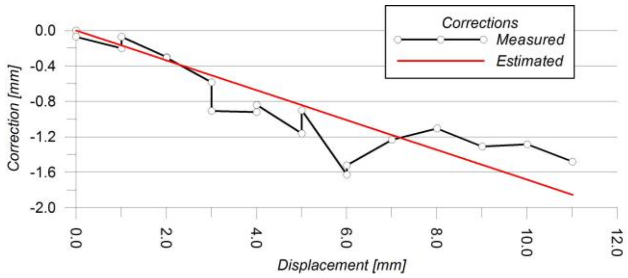

Figure 9. Graph of differences of displacements as a function of displacement

Experimentally determined value of the single measurement error is close to the value specified by the manufacturer, which is ±0.1 mm. However, the most important thing is to analyze the differences between the values determined by the IBIS-L system and a model system which was the electronic measuring caliper DIGI-MET. In order to compare the obtained differences are summarized and presented in a graph (Figure 9).

Analysis of the graph allow to state the presence of a significant systematic error. In order of determine its value the Least Square Method and model (2) were applied.

$$dp_{DIGI-MET} - dp_{IBIS-L} + v = a \cdot dp_{IBIS-L} \qquad (2)$$

where $dp_{DIGI-MET}$ = the displacement value from the DIGI-MET sensor
dp_{IBIS-L} = the displacement value from the IBIS-L
v = random error component
a = systematic error component

Estimated value of the systematic component a = -0.168 with the mean error σ_a = ±0.011. It should be noted that it is 17% of the designated value of displacement, which is the significant value.

4. SYSTEM INSTALLATION AND MEASUREMENT OF THE SOLINA DAM

After the artificially prepared tests, the experiment should have been performed in natural measuring conditions of the interferometric radar. For this test the highest hydrotechnical structure in Poland – heavy concrete dam in Solina (Figure 10) – was selected. The dam project was developed in 1921 in the Department of Hydraulic Engineering at Technical University of Lviv. Preparations for construction began in 1937, but they were interrupted by the beginning of World War II. Construction was restarted in 1960 and lasted for the next 8 years. In 1968 the structure was put into use.

Basic technical data of dam are the following:

- height: 81.8 m,
- length: 664.8 m,
- crown width: 8.8 m,
- cubature: approx. 760 000 m^3,
- mass: about 2 mln tons.

Figure 10. Heavy concrete dam in Solina

Dam's axis in the horizontal projection is not a straight line. The shape of axis was determined by the complicated geological conditions and the profile of a riverbed. The cross section has a shape similar to a triangle. The whole structure was divided into 43 sections, each of 15 metres width. Dilatations between them are sealed with rubber bands. Excess of water is drained by two steep drainage channels. Inside the building the galleries are situated on 4 levels.

Based on field interview and detailed map of the dam and surrounding area the possible positions of the radar interferometer were designed (Figure 11). During selecting the positions the existing concrete blocks and access to electrical installation were considered. An important factor affecting the location of anchor bolts was ability of equipment transport, which is critical during installation of the IBIS-L system.

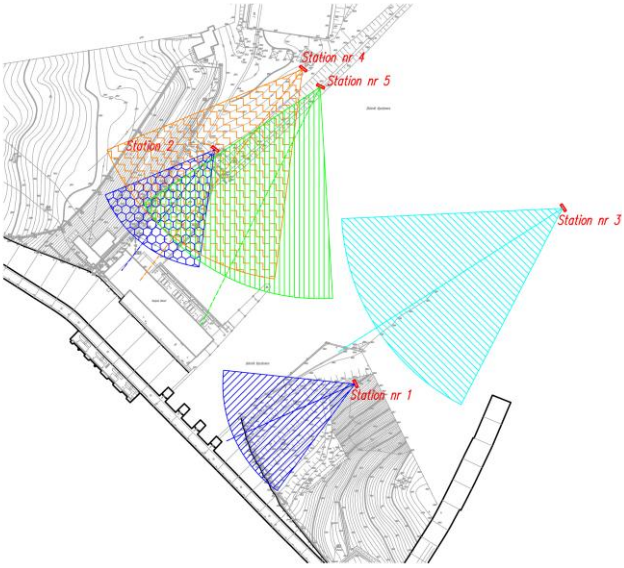

Figure 11. The preliminary project of the radar position layout

Finally, the stabilization of two measuring positions (numbers 2 and 5 on Figure 11) was done. The first position was placed possibly close to the dam, focusing on the observation of its middle sections. For the purpose of stabilization a concrete foundation was built. In this foundation the bolts supporting the radar rail were embedded (Figure 12).

Figure 12. Anchoring of bolts

The second position is located about 220 metres from the face of dam (Figure 13). In order to accelerate the process of stabilization the existing concrete block was used to ensure sufficient stability of the position in time.

Figure 13. IBIS-L system installed at the second position

A few days after bolts stabilization the first test measurement was performed. In order to analyze and eliminate the impact of atmospheric refraction the 24-hours measurement was assumed. The interval between consecutive measurements lasted 5 minutes. During this time 231 measurements were recorded. Based on the thermal SNR map a set of points is selected for the analysis of measured displacement (Figure 14). The selected points were spread out regularly to represent the dam crown from overfalls to the dam vertex (in horizontal plane). For the purpose of calculation the factor, which corrects the effect of temperature, a set of points was selected. These points were located on the building of power plant and other items not related directly to the dam.

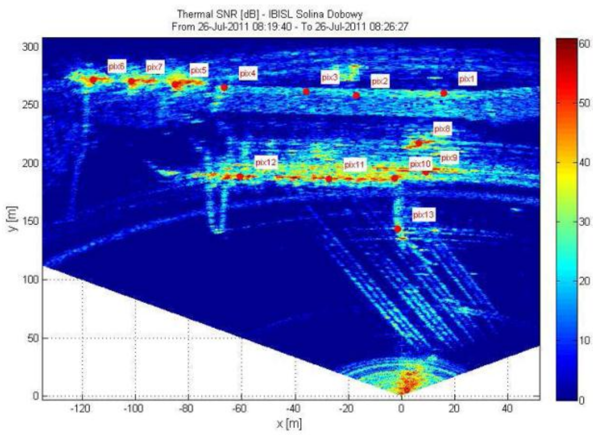

Figure 14. Thermal SNR from second station map

Post-processing began from generating the graph of movements without the prior elimination of atmospheric effects using control points (Figure 15). It is easy to notice that all the points show movement in 4 mm range. Shapes of the displacement graphs are approximately the same for each point, and differ only in scale. Therefore, the presence of systematic error caused by the atmosphere influence may be assumed.

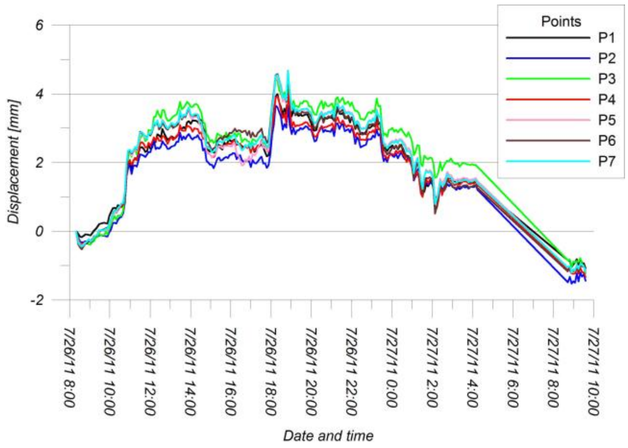

Figure 15. Graph of displacement without environmental correction

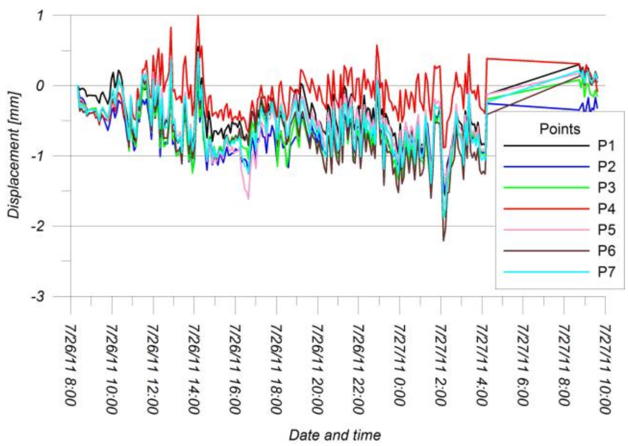

Figure 16. Graph of displacement including environmental correction

The atmospheric correction coefficients were analyzed for six different points located in front of the dam face. These values differ significantly from each other. It may be caused by complicated weather conditions, such as fog lifting or rain. Finally, one point, where the microwave reflector was installed, was selected. This reflector is used mostly for dynamic measurements with the IBIS-S system. The graph of displacements including the correction parameters is shown in Figure 16. To better illustrate the difference between the displacements before and after entering the necessary adjustments, the graph for the central point P1 of the dam is presented (Figure 17).

During analyzing the displacement graph (Figure 17) small movements of up to 1.5 mm may be noticed. They are much larger than the actual movements of the dam recorded with pendulums (Figure 18). These values have no correlation with changes of water level or thermal deformation. As mentioned earlier, during the measurement fog or rain were appearing frequently. In such conditions the proper correction of measurements with the use of checkpoints was impossible.

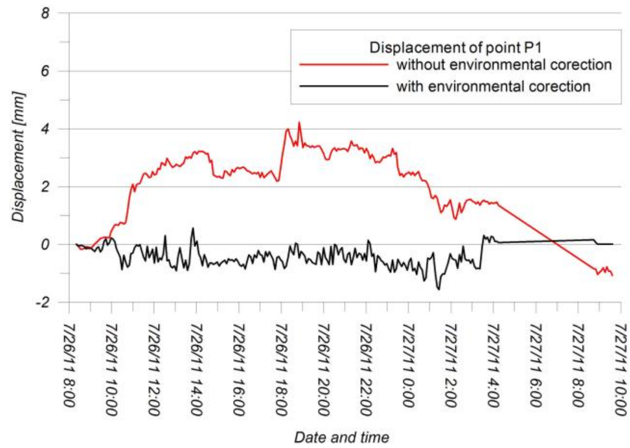

Figure 17. Displacement of the central point P1

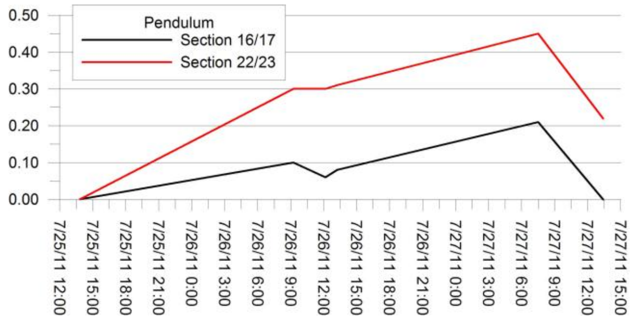

Figure 18. Displacements of dam read out from pendulums

5. RESULTS AND DISCUSSION

IBIS-L system seems to be an ideal tool for monitoring of such objects as dams. It can work 24 hours a day with a small time interval between consecutive measurements (about 5 minutes). Measurement is made not only to the signaled points, but to the entire area illuminated by the radar beam. These are the certain advantages that places this technology higher than the classical methods based on the use of total stations and GNSS receivers. The ±0.1 mm accuracy ensured by the manufacturer has been verified and validated during the test of measurement repeatability. However, the comparison with displacements measured by the device of much higher accuracy showed the presence of 17% systematic error of the measured displacement. Further research is needed to check the presence of error and its dependence on time or displacement value.

The research of usefulness of the IBIS radar interferometer to measure the dam in Solina was encountered by adverse weather conditions which showed the weakness of the method. Theoretically, the proper selection of control points should eliminate any influence of the atmosphere, but if there are zones of highly differing weather conditions (e.g. low fog), the final result will be less accurate. The solution to this situation could be the radar installation on a much greater height, but in this case it was impossible. The authors see a necessity to carry out further research on the accuracy of the interferometer operating in other conditions.

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