Tomasz OWERKO
AGH UNIVERSITY OF SCIENCE AND TECHNOLOGY,
DEPARTMENT OF ENGINEERING SURVEYING AND CIVIL ENGINEERING, Cracow, Poland

Eliminating the problem of one-dimensionality of radar interferometry techniques for long-span slender bridge structures

Abstract

Ground-based radar interferometry have been proved as a very useful tool for vibration monitoring and bridge load testing in recent years. However, if we try to apply this technique to monitoring long, slender bridges it appears that radar interferometry has some disadvantages due to its one dimensional nature. This publication presents a new solution to that problem. It has been tested and implemented for ATR sensors of modern total stations. Data have been processed with proper signal processing algorithms and as a result full compatibility between the proposed solution and radar interferometry has been proved.

Keywords: signal processing, radar interferometry, ATR, vibration monitoring.

1. Introduction

Slender bridge structures are frequently characterized by a high sensitivity to mechanical excitation and, consequently, a probable occurrence of the excitation which is close to the natural frequency, especially in the low frequency range. One of the reasons is the tendency of the excessive load and excessive speed of vehicles. Such situations obviously increase the dynamic load of a bridge structure [1]. Therefore, there is an actual danger that the natural frequencies will have a value very close to the frequency of the factors causing these vibrations (e.g. pedestrian or vehicular traffic, aerodynamic excitation). Thus, there is a real need for close monitoring of these frequencies so that the use of such structures was safe [2, 3] and comfortable [4]. In road transport, the tendency to exceed the permissible axle load is permanent, and the cases of the issuance of a permit for an oversize passage are frequent as well. This results in shorter life of bridges. As a consequence, the assessment of the technical condition of bridge structures becomes a necessity. Such an assessment cannot be based solely on visual inspection of the structure, but it should be based on appropriate measurements and respective algorithms.

The author's calculations and implementation of the algorithms as well as the preformed signal processing presented in this publication were carried out in the Matlab programming language. From the hardware and sensors point of view, the proposed solution was based on Leica total stations and was verified against IBIS-S radar interferometer unit.

2. Surveying monitoring techniques

There are numerous methods which allow recording the dynamic behavior of a span and other structural elements of a bridge structure. The most popular include:

a) Real-time GNSS systems. Thanks to the uniform time system, they allow for the identification of a spatial model of objects of any size. Unfortunately, the accuracy of the determined parameters depends on external factors (satellite visibility, signal multipath, number of satellites). However, the major drawback of this method is a worse accuracy of determining the elevation coordinates, compared to the horizontal coordinates. It should also be noted that such devices will work well only for long spans characterized by a high amplitude and low frequency of vibrations [5].
b) The system of accelerometers is a verified and proven method, which has no restrictions on the higher frequencies. It should be remembered that this is a discrete method (one unit will enable the measurement of only one point). Before the measurement, it is important to take into account the potential distribution of vibration modes so that the accelerometers are not located on the wave nodes [6].
c) The classical surveying method - geometric and trigonometric leveling - may be useful to measure the static deflection of spans. However, due to the low record rate, its use in the standard form has limited possibilities in dynamic tests [7].

In recent years, ground-based radar interferometry has gained great popularity in the monitoring of engineering structures. Its use for the observation of bridges is characterized by the possibilities to monitor the behavior of the whole bridge span simultaneously (often along with the pylon) with frequencies allowing to record the vibrations of engineering objects in the band of (0…50) Hz, which is hazardous for the structure. Taking into consideration that the recording frequency of this radar system reaches 200 Hz, it allows making measurements without the risk of the occurrence of unwanted aliasing. Radar systems also enable the recording of vibrations with evenly distributed sampling, which facilitates the use of popular, numerically effective algorithms, such as the FFT, which assume a uniform time interval between samples [8].

The drawbacks which should be taken into account when working with radar systems is an ambiguous identification of the span elements (difficulty with the correct interpretation of the radar profile) and a one-dimensional nature of the system operation. However, probably the biggest problem associated with the operation of radar units, is the one-dimensional nature of the acquired data. In the publication [9], the authors present how poor geometry adversely affects the accuracy of the obtained measurement.

3. The essence of the solution - technological aspects

The author is a co-inventor of the utility model of the integrated EDM reflector, allowing for a measurement with the radar and automated optoelectronic systems (e.g. of the Leica ATR type) to the same point, filed with the Patent Office of the Republic of Poland under number W.122987 (Fig. 1).

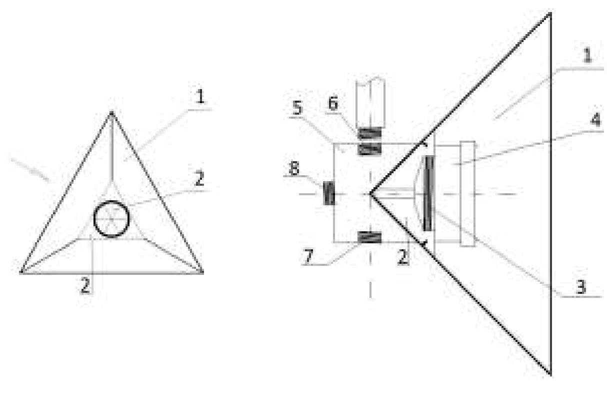


Fig. 1. The patented solution of a radar reflector (UP RP W.122987)
(1 – microwave reflector, 2 – EDM reflector, 3,5-8 – mount points)

Interferometric radar systems measure changes in distance between the radar unit and the selected point of the radar profile (hereinafter referred to a range bin) along the line of sight. Consequently, if there are vertical displacements in the area of our interest, the optimal location of the radar unit would be its setting right under the bridge. Such a solution is preferred for overpasses, if we can afford to record only a limited number of points on the analyzed span. Naturally, such a solution is not possible for bridges, due to the water obstacle. Since a radar records displacements for the line of sight (radial component of displacement) for long and low bridge spans, the measurement accuracy of vertical component will decrease. In addition, for the lines of sight other than the vertical ones, the horizontal movements of the span, exemplified by expansion joints, will be recorded as a change in the Rbin distance to the radar, and so they will distort the correct interpretation of vertical vibrations and displacements of the span.

The use of the patented solution (Fig. 1) resulted in the movements of the points also being recorded with the ATR systems, which are built in contemporary electronic total stations and allow tracking the position of a reflector in motion [10]. In the total station which was used during the tests, the ATR system sampling rate of the vertical angle was nominally 10 Hz.

It should be noted, that the presented algorithm of data acquisition, which uses a method to eliminate length measurement while tracking the position of a target, instead of representing the mechanical vibrations by changing the vertical angle, must be implemented personally. This allows for a full use of the qualities of the ATR system, which samples relatively evenly (as for the sensors of the TC class instruments), and enables the recording of vibrations in the plane vertical to the longitudinal axis of the bridge span. From the technological standpoint, it is worth noting that this solution is especially recommended for the devices which are not equipped with the technology to measure the distance based on the WFD (Wave Form Digitizer Technology) [11]. In this way, for the ratio of the height of a bridge structure to the distance to the observed point, which is so unfavorable for the radar, the system based on the proposed solution works very well, if only the amplitude of the vibration exceeds the minimum value of the record of changes to the ATR system. From the point of view of bridge structures, this system is not applicable only for the short, stiff spans, for example for prestressed bridges. Therefore, the only limitation of the system is the resolution of the CCD of the ATR system.

Regarding the implementation, the solution can be deployed in two ways, taking into account the architecture of the GeCom protocol [12]:

a) communication with the total station is carried out through ASCII request. The command is sent by a selected communication interface (serial port, USB or TCP/IP), then it is interpreted thanks to the number referred to a specific request - according to the RPC (Remote Procedure Call) technology. Additionally, each request contains a set of input parameters of the function, resulting in specific replies of the software controlling instrument modes. Such a use of the function may be implemented in any language that supports serial communication or TCP/IP, for example in Matlab.
   As an example of the RPC sent to the serial port of the instrument, let us consider TMC_GetAngle1 - returning a complete angle measurement (Table 1).

Tab. 1. RCP Request formats example

The method of implantation	Form of the request
C/C++ (declaration)	TMC_GetAngle (TMC_ANGLE &Angle, TMC_INCLINE_PRG Mode),
VBA (declaration)	VB_TMC_GetAngle1(Angle As TMC_ANGLE, ByVal Mode As Long),
ASCII	Request: %R1Q,2003:Mode [long] Reply: %R1P,0,0:RC,Hz[double], V [double], AngleAccuracy [double], AngleTime [long], CrossIncline [double],LengthIncline [double], AccuracyIncline[double], InclineTime[long], FaceDef[long]

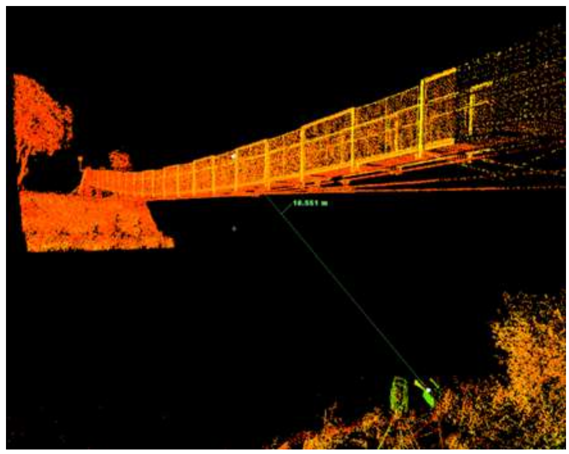
b) The second way is to use Dynamic-Link Libraries for the supported languages: C++ or VBA (Visual Basic for Applications). From a purely programming perspective, this method is easier, as long as we decide to use the environment which is supported. In the case of the implementation in the Matlab language, DLL used for the C/C++ language can be easily integrated with the code and therefore DLL approach is supported. The limitations of this solution have been described in the documentation [13].

Regardless of the choice of the implementation technique, the algorithm remains unchanged. Regarding the device, it is based on tracking the position of the reflector in the vertical plane. The use of the patented reflector ensures that both measuring systems take measurements of exactly the same point and therefore they can be directly compared.

4. The test verifying the assumptions and evaluation of the results. Algorithmic aspects

Figure 2 illustrates an object on which the tests were performed - pedestrian footbridge located in Myślenice.

a)



b)

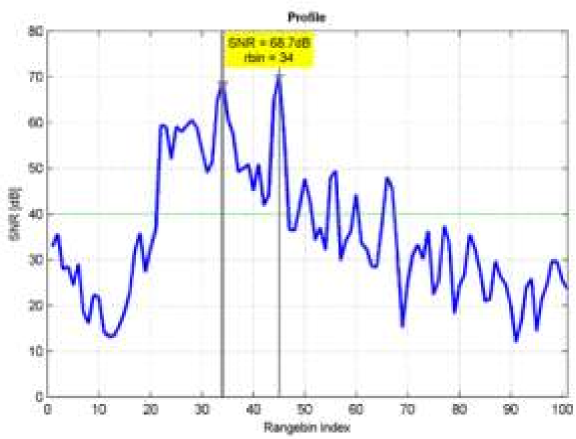


Fig. 2. Scenario measured by a laser scanner a) and radar profiles of the scenario including footbridge b)

The elements of the radar profile are identified by comparing the distance between the radar unit and those elements of the measured object which can give a good reflection of the radar waves. In the case of bridge structures, these are usually crossbeams, anchorage of the cable-stayed system or elements of the pylons. If we are interested in measuring a point whose Signal to Noise Ratio (SNR) is not high, we are forced to mark this point by using a radar reflector. On the recorded radar profile illustrated in Fig. 2, only two points have the SNR greater than 65 dB: the point marked with the radar reflector (Rbin 34) and one of the crossbeams on the line of sight, for which the radar antenna gain was close to maximum (Rbin 45).

The location of the test structure allowed performing a series of tests involving the excitation of vibrations of the bridge structure, and then recording the structural responses, starting from the beginning of the excitation and finishing with a complete, free damping. The test was carried out for one and two pedestrians. In both cases, the footbridge was excited by a pedestrian walking through it, and then after a complete damping, by running. Free damping occurred for the empty structure, after the person inducing the vibrations left the footbridge. The plot (Fig. 3) presents an example of the time series recorded during the test, in this case – damping after the excitation by two people running.

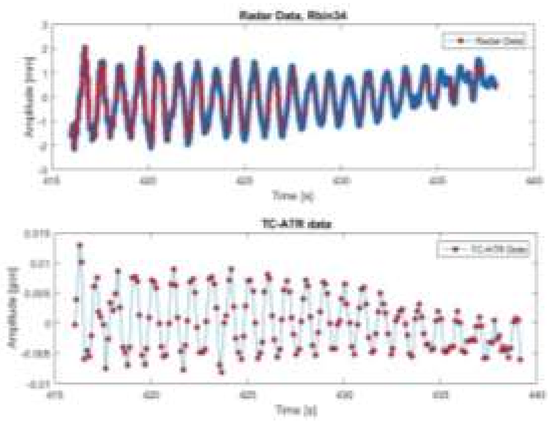


Fig. 3. Time series recorded using the radar system (top) and the developed solution based on Automatic Target Recognition system (bottom). Note that the blue line is not a signal estimation and signals are after normalization process

Prior to the analysis, time series are subjected to transformation by the formula (1):

$$D_{st} = D - mean(D) \qquad (1)$$

where: D_{st} - the analyzed time series, D - raw data.

Fast data analysis allows making interesting observations at the very beginning. Although the two systems are characterized by very different sampling rates, a similar spectral resolution should be expected in both results, if the Discrete Fourier Transform was applied in the calculations. This is due to the fact that the ratio of the sampling rate F_s to the number of samples N is similar and amounts to 0.0455 Hz for the radar system and 0.0433 Hz for a system that was developed. It should be emphasized, that at this stage no techniques which would artificially increase the spectral resolution were used, such as adding zeros, which are well known in the literature regarding digital signal processing [14]. First of all, let us examine how the vibration energy is scattered in the individual frequencies, and thus, what the power spectral density is. To do this, we can use Lomb-Scargle power spectral density estimation.

The plot presented in Fig. 4 illustrates the power spectral density estimation of the two obtained signals. As we can see, for both of them their maximum is circa (1.01…1.03) Hz, which means that both measuring systems record the frequencies of 1 Hz as the main range of the transfer of the energy of mechanical vibrations of the analyzed footbridge - this is marked with green frames. The scale of the vertical axis presents the ratio of the signal power to the given frequency. In this case, the advantage of the radar system is evident, for which the ratio of the power to the frequency reaches 11 dBW/Hz, whereas for the ATR-based system, this value is –34 dBW/Hz (red frame). Moreover, the plot demonstrates that the points recorded by the radar system and by the proposed ATR-based system, are in a uniform time system. In practice, it is easy to achieve by using the GPS-based time systems.

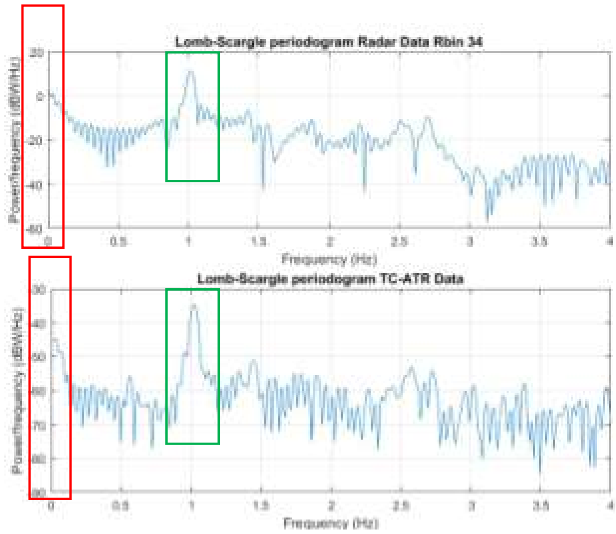


Fig. 4. The Lomb-Scargle power spectral density (PSD) estimate of a signal from the radar and developed TC/ATR system

Basing on the calculations of the recorded time series, it can be stated that the radar system sampled the mechanical signal of the oscillating span at 6 ms. Non-uniformity of the sampling was at the level of ca. ±0.03 ms, which gives the relative value of 0.5%. This value gives the possibility to use the assumption of regular sampling and, consequently, to use the efficient numerical algorithms such as Power Spectral Density (PSD) estimation using Welch's overlapped segment averaging estimator. For the test signal x_n sampled at the frequency f_s, the periodogram is a nonparametric estimate of the power spectral density (PSD) of a stationary random process, and takes the form (2):

$$\hat{P}(f) = \frac{\Delta t}{N}\left|\sum_{n=0}^{N-1} x_n e^{-i2\pi f n}\right|^2 \quad -\frac{1}{2\Delta t} < f \le \frac{1}{2\Delta t} \qquad (2)$$

where: Δt - sampling interval, N - sample size.

The total station sampled changes in the reflector position in the horizontal plane at 125 ms. In this case, the non-uniformity of the sampling is at the level of ±25 ms, which gives a relative value of 20% (they reach 30%, taking into account the selected fragments of the time series). For the analysis of such signals, appropriate algorithms must be used. As it appears from the publications [15, 16, 17, 18, 19], it is clear that the standard algorithm of the Fast Fourier Transform is not suitable for the data spectral analysis, which are unevenly spaced. This can be seen in Fig. 5. The standard algorithm of the Fast Fourier Transform was applied to the both time series, and it did not produce fully consistent results (Fig. 5, red arrows).

It can already be concluded that the two measuring systems equally identify the main range of the energy of mechanical vibrations. Taking into account the results of the Fast Fourier Transform, attention is drawn to two facts. Firstly, the identification of the main frequency is not the same - the difference is not large, but still it exists. Taking into account the resolution of the DFT, it is one band away. This is due to the unequal signal sampling by the ATR system. Secondly, because the sampling rate of the measuring system based on the TC-ATR around 4 Hz is in the Nyquist plot of frequency of this system, the green frame reduces the region without spectral band replication. Consequently, for a value of about 7 Hz, we can see the added DTFT image of the dominant frequency (red frame). In Figure 5, there are no added DTFT image for the radar signal, since its sampling frequency was significantly higher, to be precise was more than 149 Hz.

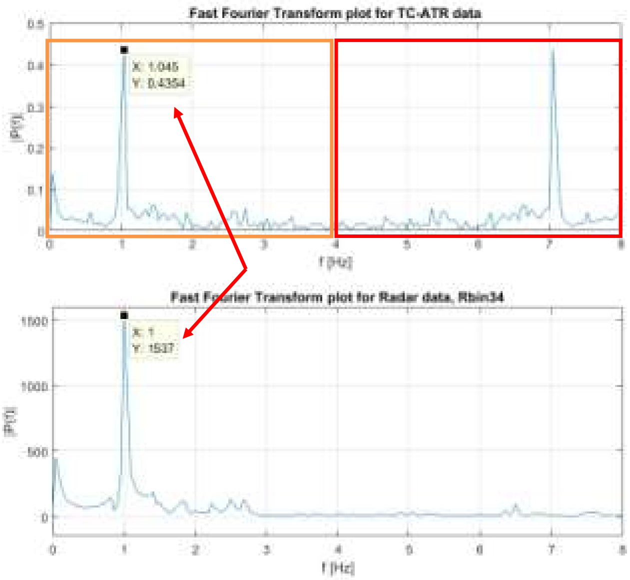


Fig. 5. FFT of time series: TC data (top) and Radar (bottom)

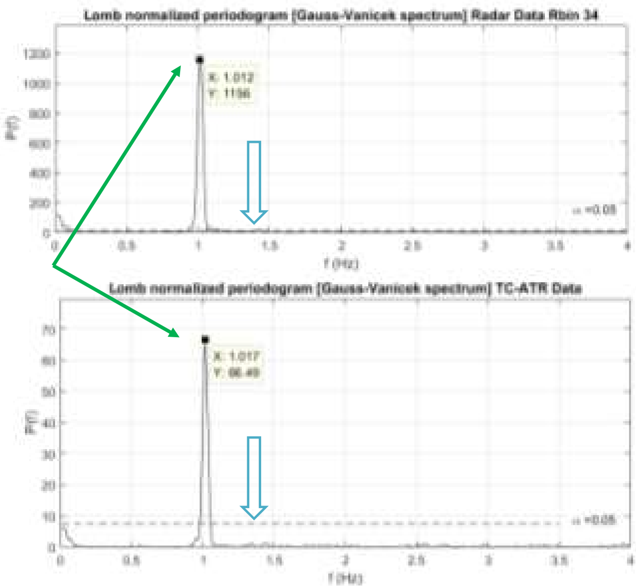


Fig. 6. Gauss-Vanicek spectrum plot: TC data (bottom) and Radar (top)

Accordingly, the data were analyzed using the algorithm resistant to unequal sampling. Generally speaking, the algorithms of this family are called the least-squares spectral analysis (LSSA). Their major advantage over the well-known implementation of the Discrete Fourier Transform using the FFT algorithm is that FFT increases random noise of a long period in the time series in these places where the lack of data occurs. In other words, the algorithms from the LSSA group are not sensitive to uneven sampling. Figure 6 illustrates the periodogram of the spectrum obtained using the spectral analysis with the Lomb-Scargle algorithm (Lomb, 1976) (3):

$$P_{LS}(f) = \frac{1}{2\sigma^2}\left\{\frac{\left[\sum_{k=1}^{N}((x_k-\bar{x})\cos(2\pi f(t_k-t))\right]^2}{\sum_{k=1}^{N}\cos^2(2\pi f(t_k-t))} + \frac{\left[\sum_{k=1}^{N}((x_k-\bar{x})\sin(2\pi f(t_k-t))\right]^2}{\sum_{k=1}^{N}\sin^2(2\pi f(t_k-t))}\right\} \quad (3)$$

where:
$\bar{x}$ – the mean value from the data, σ – standard deviation.

The vertical scale is in the linear form. The attention should be paid to two facts:

a) first of all, in both cases, the identified frequency of the normal mode of vibrations was significantly above the significance level (blue arrows). For clarity, only the significance level $\alpha = 0.05$ was marked in the figure, however, it occurs despite the fact that both systems have a different sensitivity to the amount of vibration energy transmitted by the identified basic frequency of the natural mode of vibration of the tested span - which was proven in Figure 4 (red rectangles),
b) secondly, the value of the identified basic frequency differs only by 0.005 Hz, which proves the conformity of the methods - taking into account the fact that exactly the same point at the same time was observed.

5. Conclusions

The designed measuring system based on the automatic targeting is fully efficient and identifies the frequencies according to the radar system IBIS-S. It can be used in several cases:

a) there are reasonable grounds to believe that, based on the structure of the bridge, the radar system will record the horizontal displacements of the span as a one-dimensional system. In this case, the proposed system can verify such a hypothesis experimentally;
b) uniform accuracy is required to acquire information about the spectrum of the vibration of the whole span structure, for example, to record the mechanical wave propagation along the span. The proposed system can be used as a supplement for the information provided by the radar system for the more distant targets;
c) the test structure is characterized by a high amplitude of vibration, but obscured horizon makes it impossible to use satellite systems;
d) we examine an oscillating structure with a limited clear visibility. In this case, the radar spectrum will prevent the identification of the point which is of interest to us, and therefore, what is left, is the use of accelerometers or the proposed system - exemplified by truss structures of bridge spans or hoist towers.

The author would like to thank to Mr Mateusz Seta for his independent implementation of measuring system in the Borland Delphi language and assistance during measurements.

This publication was prepared with the financial support from the statutory research fund number 11.11.150.005 of the Department of Engineering Surveying and Civil Engineering, Faculty of Mining Surveying and Environmental Engineering of AGH University of Science and Technology in Krakow.

6. References

[1] GDDKiA: https://www.gddkia.gov.pl, Access: 24.04.2016.
[2] Gazzola F., Pavani R.: Blow-up oscillating solutions to some nonlinear fourth order differential equations describing oscillations of suspension bridges, IABMAS12, 6th Int. Conf. on Bridge Maintenance, Safety, Management, Resilience and Sustainability, 3089-3093, Stresa 2012, Biondini & Frangopol (Editors), Taylor & Francis Group, London 2012.
[3] Ammann O.H., von Kármán T., Woodruff G.B.: The failure of the Tacoma Narrows Bridge, Federal Works Agency 1941.
[4] Dallard P., Fitzpatrick T., Flint A., Low A., Smith R.R., Willford M., Roche M.: London Millennium Bridge: Pedestrian-Induced Lateral Vibration, J. of Bridge Engineering, Trans. ASCE, 6, 412-417, 2001.
[5] Gikas,V., Daskalakis S.: Comparative testing and analysis of RTS vs. GPS for structural monitoring using calibration measurements upon sinusoidal excitation. XXIII FIG symposium on deformation measurement and analysis. Lisbon, Portugal 2008.
[6] Li X.: Integration of GPS, accelerometers and optical fibre sensors for structural deformation monitoring, 17th Int. Tech. Meeting of the Satellite Division of the U.S. Institute of Navigation, Long Beach, California 2004.
[7] Kovačič B., Kapović Z: Precision and results reliability analysis of different instruments for investigating vertical micro-displacement of structures. Survey review - Dir. Overseas Surv., 38, 2005.

[8] Owerko T.: Beat frequency detection of bridges using ground-based radar interferometry. Pomiary, Automatyka, Kontrola, ISSN 0032-4140, 2014 vol. 60 nr 11.
[9] Gocał J., Ortyl Ł., Owerko T., Kuras P., Kocierz R., Ćwiąkała P., Puniach E., Sukta O., Bałut A.: Determination of displacement and vibrations of engineering structures using ground-based radar interferometry. Wydawnictwa AGH, 2013.
[10] Kirschner H., Stempfhuber W.: The Kinematic Potential of Modern Tracking Total Stations - A State of the Art Report on the Leica TPS1200+, 1st International Conf. on Machine Control & Guidance, 2008.
[11] Marr H., Zogg H.M.: WFD – Wave Form Digitizer Technology White Paper Leica Geosystems AG, Heinrich-Wild-Strasse CH-9435 Heerbrugg, 2014.
[12] Leica FlexLine GeoCOM Reference Manual Version 1.30, Leica Geosystems AG, Heinrich-Wild-Strasse CH-9435 Heerbrugg.
[13] Mathworks: http://www.mathworks.com/help/matlab/matlab_external/limitations-to-shared-library-support.html, Access: 24.04.2016.
[14] Zieliński T.P.: Od teorii do cyfrowego przetwarzania sygnałów, Wydział EAIiE, AGH w Krakowie, 2002.
[15] Press, William H. and George B. Rybicki: Fast Algorithm for Spectral Analysis of Unevenly Sampled Data. Astrophysical Journal. Vol. 338, 1989.
[16] Lomb, Nicholas R.: Least-Squares Frequency Analysis of Unequally Spaced Data. Astrophysics and Space Science. Vol. 39, 1976.
[17] Scargle J. D., Jeffrey D.: Studies in Astronomical Time Series Analysis. II. Statistical Aspects of Spectral Analysis of Unevenly Spaced Data. Astrophysical Journal. Vol. 263, 1982.
[18] Press H., Teukolsky S.A., Vetterling W.T., Flannery B.P.: Numerical Recipes: The Art of Scientific Computing, Third Edition (2007) Cambridge University Press, ISBN-10: 0521880688.
[19] Horne, James H. and Sallie L. Baliunas. :A Prescription for Period Analysis of Unevenly Sampled Time Series." Astrophysical Journal. Vol. 302, 1986.

Received: 09.12.2015 *Paper reviewed* *Accepted: 03.02.2016*

Tomasz OWERKO, PhD

An assistant professor at the Department of Engineering Surveying and Civil Engineering of AGH University of Science and Technology, Poland. His research includes the design and development of algorithms related to modern technologies such as radar interferometry techniques, GNSS, TLS and HDS in deformation and structural monitoring, as well as application of IT in Engineering Surveying and Civil Engineering.

e-mail: owerko@agh.edu.pl