Electrical, Control and Communication Engineering
ISSN 2255-9159 (online)
ISSN 2255-9140 (print)
2022, vol. 18, no. 1, pp. 11–17
https://doi.org/10.2478/ecce-2022-0002
https://content.sciendo.com

GPR Application for Non-Rigid Road Pavement Condition Assessment

Dmitry O. Batrakov (*V. N. Karazin Kharkiv National University, Kharkiv, Ukraine*),
Mariya S. Antyufeyeva* (*V. N. Karazin Kharkiv National University, Kharkiv, Ukraine*),
Angelika G. Batrakova (*Kharkiv National Automobile and Highway University, Kharkiv*, *Ukraine*)

***Abstract* – The main aim of the article is to demonstrate the effectiveness of the use of ground penetrating radars to assess various objects using the example of assessing the current state of highways. The article uses the software developed by the authors and the corresponding mathematical models. The analysis of the results obtained is based on mathematical models that have proven their effectiveness and is time-tested. It should be emphasised that the main problem in assessing roads with non-rigid pavement is associated with a change in the main parameters of the layers – thickness and dielectric constant. Previously, we proposed a scheme for the layer-by-layer determination of the values of the relative permittivity and then - the subsequent determination of the thickness of each layer, starting from the top layer and ending with the base. The paper presents the results of experiments actually carried out by the authors with various GPRs, which not only have different values of the central frequency, but also have significant design differences. In addition, the results of processing real data using the software developed by the authors are presented. As a result, an improved method of signal calibration has been proposed, which makes it possible to increase the reliability of assessing the thickness of road surfaces, as well as other objects.**

***Keywords* – asphalt, dielectric materials, ground penetrating radar, impulse testing, nondestructive testing, ultra-wideband technology.**

I. Introduction

Ultra-wideband (UWB) ground penetrating radars (GPRs) are widely used as an effective means for non-destructive testing and remote sensing of natural environments and technical structures [1], [2]. The progress in the use of georadars is based on the solution of two main problems. The first problem is associated with the development of technologies and the improvement of the georadars themselves [3], [4]. The second problem involves the development of methods and computer tools for processing the results obtained [5], [6]. The increasingly intensive use of georadars for solving many important problems in various branches of science has led to the appearance of a significant number of publications. We will consider only issues that are associated with the use of ultra-wideband georadars to the problems of assessing the current state of highways with non-rigid surfaces. We will also touch upon the problems of predicting the degradation of the state of such roads. This is primarily due to the fact that for a road engineer, the associated task of optimizing the allocation of resources for the repair and maintenance of such roads is of great importance. Unfortunately, these problems do not have an unambiguous and relatively simple solution. Therefore, in this article, we will focus on the previously proposed solutions for improving the methods and computational algorithms for signal processing. In this case, we will use the simplest model of a lossless environment. In the presence of losses, one can use the approach proposed in [7]. We also note that basically the existing methods of processing radarograms are based on visual processing by the operator [8], [9]. First of all, the disadvantages are associated with the low productivity of the operator and, as a consequence, with the high cost of such work. Also, with such a processing scheme, the probability of operator errors is high, for example, due to an incorrect estimate of the propagation speed of the GPR signal, which depends on the value of the relative permittivity. It is also important that if the relative permittivity of the upper layer can be determined relatively accurately, then for the lower layers errors will accumulate and may eventually lead to incorrect results. Therefore, in this article, the main attention is paid to improving the algorithms previously developed by the authors for the layer-by-layer determination of the values of the dielectric constant.

Thus, the key feature of this formulation of the problem is also the use of the procedure for calibrating the signal emitted by the GPR by measuring the reflection from a sheet of metal located on the surface of the probed medium [10]. Due to the fact that the properties of a real metal can differ significantly from the properties of an ideally conducting metal, such a task also requires careful verification and, if necessary, adjustments of this procedure. Another problem is the limited sheet size. From the point of view of the theory of electromagnetism, this leads to the presence of repeated reflections, which can also lead to distorted results. Another problem is the lack of rigorous methods of the theory of diffraction, which would allow for efficient numerical simulation of this process. Therefore, in this article, the authors have proposed a combined technology. It consists in carrying out laboratory and field experiments, the subsequent processing of the results and the development of

* Corresponding author.
E-mail: antyufeyeva@karazin.ua

practical recommendations that allow increasing, first of all, the reliability of the resulting estimates. We also emphasise that the effectiveness of the proposed approach essentially depends on the parameters and design features of the GPRs used. First of all, this applies to the values of the centre frequency and some other design features. Therefore, this article focuses primarily on the proposed new signal calibration procedure and the corresponding methods for interpreting the data obtained.

The scientific novelty of the article lies in the proposed new technology for assessing the current state of roads with non-rigid pavement and its practical implementation.

II. Problem Statement and Solution

Above, we have formulated the main goal of this article. It consists in increasing the efficiency of the GPR application for the tasks of assessing road surfaces taking into account the antenna units used and data processing methods. Once again, we note the importance of the problems that are associated with the peculiarities of technologies for registration and processing of the received initial data. The importance of these tasks is due to the high cost of not only the construction of the road network, but also the cost of their maintenance and repair. Therefore, further, we will first of all focus on the most important aspects of the identified problems.

We will start by setting the problem in general terms and then consider specific results. In the general statement, the probing problem can be divided into two basic parts.

The first part is an assessment of the parameters of asphalt concrete layers. First of all, this refers to the determination of the values of the relative permittivity and further recalculation of the obtained values into other parameters. This is primarily the thickness and density of the layers [11].

The second task is the detection, identification and positioning of subsurface defects. The term “identification” will denote the determination of the nature of defects, and positioning is the determination of the direction of primarily dangerous subsurface cracks [12] and delamination [11].

To solve the first problem, various approaches were previously proposed. However, as mentioned above, these approaches were mainly based on the visualization of images by radargrams of subsequent processing of the resulting images. In some cases, it was suggested to apply different filtering methods. However, this approach has significant drawbacks. They are primarily associated with the presence of a relationship between various parameters. For example, the value of the relative permittivity is associated with the speed of propagation of electromagnetic waves in the medium [13]. Without taking into account such a connection, it is impossible to speak about the reliability of the estimates obtained. We have already spoken about this above. Now we note that the speed of propagation of electromagnetic waves depends from the point of view of physics also on the degree of compaction of the layer material. It also depends on the ratio of the various components in the mixture. This is due to the fact that bitumen, crushed stone and other components in the composition of the mixture have different values of the relative permittivity. In certain situations, air or even water may be present between the layers [14].

We also note that the previously proposed approaches based on methods for solving inverse scattering problems in different formulations [15] are, to a certain extent, an alternative to the layer-by-layer reconstruction method proposed in [16]. To solve the formulated problems, it is necessary to involve the appropriate physical and mathematical models. On the one hand, these models should take into account all the features of the problem under consideration, and, on the other hand, provide a set of simplifications that allow you to get a quick and effective solution. Experimental studies, in particular, have shown that even at the central GPR frequency up to 1.6 GHz, the roughness of the outer boundary and inner boundaries between the layers can be neglected [5], [16]. The simplest model in this case is a plane-layered medium. Such a medium can contain heterogeneities, for example, subsurface cracks, drainage pipes, and some others. Earlier, we proposed data processing models containing the following stages [17]:

- registration of the so-called direct antenna coupling signal, in other words, the signal that entered the receiving antenna bypassing the medium under study;
- registration of a signal that was reflected from a sheet of metal; further, this signal would be used as a model of the probing UWB pulse;
- travel over the structure under study and recording GPR data sets. These datasets would then be used to obtain processing results.

This article is also based on the analysis of two GPR samples. The first sample is Odyag-1 (TRF-1) with a central frequency of about 900 MHz. The second is Odyag-4.2 with a central frequency of approximately 1.5–1.6 GHz. View of the devices is shown in Figs. 1 and 2. The first GPR has a scheme with full frequency independent electromagnetic decoupling, as described in the patent [4].

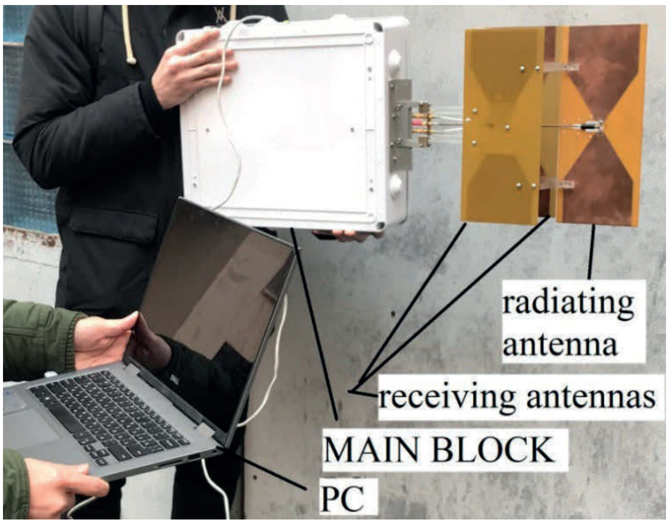

Fig. 1. GPR TRF-1.

We have already said that we have previously proposed a scheme for processing sounding data. This scheme is based on the layer-by-layer determination of the values of the relative permittivity with the subsequent determination of the thickness of the corresponding layer. The physical basis of this scheme is formed by the well-known Fresnel formulas [13]. The use of such a processing scheme assumes the division of the original sounding signal into two mutually orthogonal parts (components). In this case, for the component that is parallel to the plane of polarization of the original signal, we will use the notation $\|$. Then, for the field component that is orthogonal to the plane of polarization of the probe pulse, we will use the notation $\perp$. In this case, the vector of the magnetic field strength is determined by the equation (1) [13]:

$$\mathbf{H} = \sqrt{\frac{\varepsilon}{\mu}} \cdot \mathbf{s} \times \mathbf{E}, \tag{1}$$

where $\mathbf{s}$ is a unit vector in the direction of wave propagation, **H**, **E** are the values of the strengths of the magnetic and electric fields, respectively.

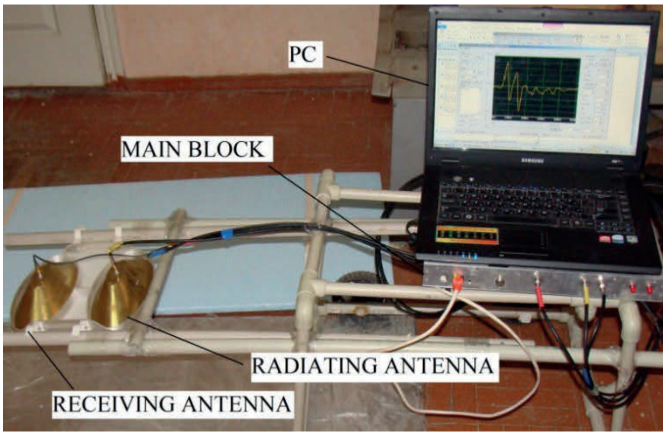

Fig. 2. GPR Odyag-4.2.

For further progress, it is necessary to concretize the model in more detail. Most often for processing in this case, the division of the plane wave incident on the structure under study is used [1], [2]. In a general case, this model also allows one to consider the phenomenon of depolarization. Obviously, this phenomenon does not occur in a homogeneous flat-layered medium; such a phenomenon arises only in the presence of inhomogeneities. This is a convenient indicator of the presence, including of subsurface inhomogeneities. Therefore, we now write [13] in the form:

$$T_{\|} = \frac{2\cdot\cos\theta_i}{\frac{n_2}{n_1}\cdot\cos\theta_i + \sqrt{1-\left(\frac{n_1}{n_2}\sin\theta_i\right)^2}} A_{\|}, \tag{2}$$

$$T_{\perp} = \frac{2\cdot\cos\theta_i}{\cos\theta_i + \frac{n_2}{n_1}\cdot\sqrt{1-\left(\frac{n_1}{n_2}\sin\theta_i\right)^2}} A_{\perp}, \tag{3}$$

$$R_{\|} = \frac{\frac{n_2}{n_1}\cdot\cos\theta_i - \sqrt{1-\left(\frac{n_1}{n_2}\sin\theta_i\right)^2}}{\frac{n_2}{n_1}\cdot\cos\theta_i + n_1\cdot\sqrt{1-\left(\frac{n_1}{n_2}\sin\theta_i\right)^2}} A_{\|}, \tag{4}$$

$$R_{\perp} = \frac{\cos\theta_i - \frac{n_2}{n_1}\cdot\sqrt{1-\left(\frac{n_1}{n_2}\sin\theta_i\right)^2}}{\cos\theta_i + \frac{n_2}{n_1}\cdot\sqrt{1-\left(\frac{n_1}{n_2}\sin\theta_i\right)^2}} A_{\perp}. \tag{5}$$

The main idea of such an approach is based on the application of two integral transforms to the analysis of impulse signals. These transforms are: Hilbert transform [17] and the related concept of an analytical signal, as well as another integral transform proposed in [18].

The Hilbert transform is based on the procedure for calculating the so-called orthogonal signal complement $s(t)$:

$$s_{\text{ort}}(t) = \int_{-\infty}^{\infty} \frac{s(t)}{\pi\cdot(t-\tau)} \mathrm{d}\tau. \tag{6}$$

From (6) it follows that the Hilbert transform is essentially the result of the convolution of the signal $s(t)$ and function $h(t) = 1/(\pi\cdot t)$. Note also that, in fact, the Hilbert transform is the impulse response of the linear filter at the output of which the orthogonal complement is formed. Therefore, a filter with a corresponding impulse response of the form $h(t) = 1/(\pi\cdot t)$ is usually called a Hilbert filter. It is customary to write the Hilbert transform in the frequency domain in the following form (7):

$$s_{\text{ort}}(\omega) = H(\omega)\cdot S(\omega). \tag{7}$$

The properties of the Hilbert transform analysis shows that in fact the Hilbert transform performs the functions of an ideal phase shifter. Another feature of the Hilbert transform is that it removes the DC component of the signal. The second transformation, which was proposed in [18] and then modified in [17], is based on a single signal integration procedure with a variable upper limit. The purpose of this transformation is to locate the zeros of the corresponding function. The basis of this approach is based on the assumption that in the case of an ideal signal representing a Gaussian function, the resulting function will be described by an expression of the form:

$$S(t) = \exp\left(-\frac{t^2}{2}\right). \tag{8}$$

On the other hand, it is obvious that in this case the first derivative of such a signal is represented by the formula:

$$S'(t) = -t\exp\left(\frac{t^2}{2}\right). \tag{9}$$

For clarity, Fig. 3 shows the three graphs. The first graph is a graph of a signal that was virtually created using the GeoVizy software. The second graph is the Hilbert transform from the synthesized signal. Finally, the third signal is the result of a single integration with a variable upper limit [17]. As mentioned above, the second and third signals differ in that one signal (Hilbert transform) has a maximum at the maximum of the original signal, and the second transform has a zero value at the same point. In this way, more reliable signal processing is achieved. The value of the integral transformation with a variable upper limit is calculated by the formula:

$$S(t) = A_1 \cdot \exp\left(-M \cdot \frac{t^2}{2}\right), \quad (10)$$

where: $A_1 = 1$, and the M parameter provides a maximum at 1.7 ns on the graph.

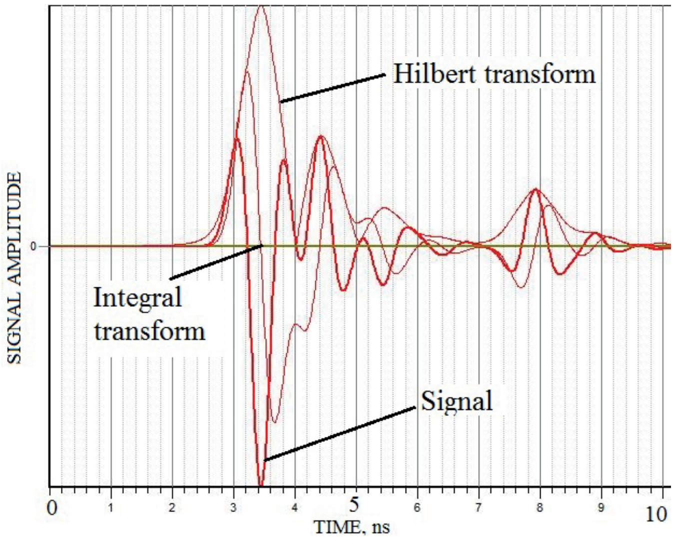

Fig. 3. Signal diagrams in a model experiment (synthesized data).

The modelled structure (construction) consists of three layers and a semi-infinite substrate. The thickness values of the layers from top to bottom are 6, 10 and 20 cm. The substrate is semi-infinite. The values of the relative permittivity in this simulation are equal to: 6.8; 2.5; 3.3; 2.4. Fig. 4 demonstrates the results of processing the obtained data.

It can be seen that the values of the relative dielectric constant of the two upper layers are precisely matched, and of the two lower layers – with very high accuracy. The values of the layer thicknesses are also determined with high accuracy, which allows us to tell about the efficiency of the numerical simulation procedure. Fig. 4 also shows some results of the analysis of experimental data obtained with the Odyag-4.2 GPR. The structure under study consists of three layers. The first layer of asphalt concrete is 5–6 cm thick. The second layer is sand approximately 10 cm thick, and the third layer consists of loam approximately 20 cm thick. We emphasise once again that we have previously proposed a method for the layer-by-layer determination of the relative permittivity and the subsequent restoration of the values of the layer thickness, starting from the upper layer. In this case, the GeoVizy software operates in a semi-automatic mode. The results of the initial processing step are shown in Fig. 5.

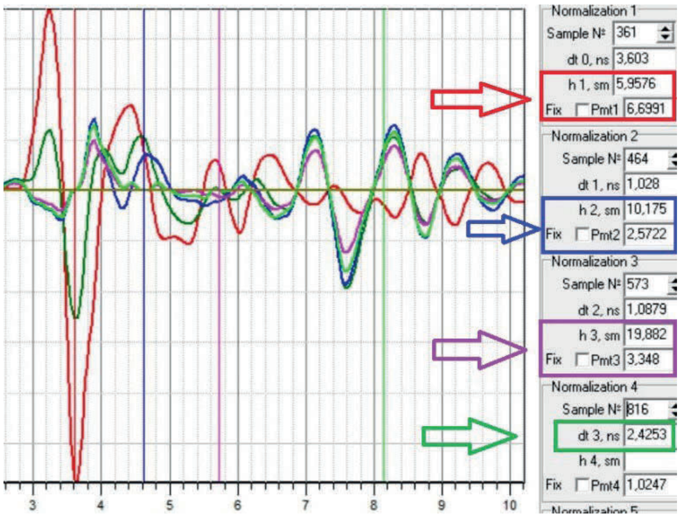

Fig. 4. Processing results of Fig. 3 signals.

First, we note that the processes of layer-by-layer determination of the relative permittivity are associated with the subsequent determination of the thickness values. This is another advantage of the proposed method. In other words, the values of the relative permittivity determined using the proposed method make it possible to estimate some other parameters, for example, the density associated with the destruction of the layer material.

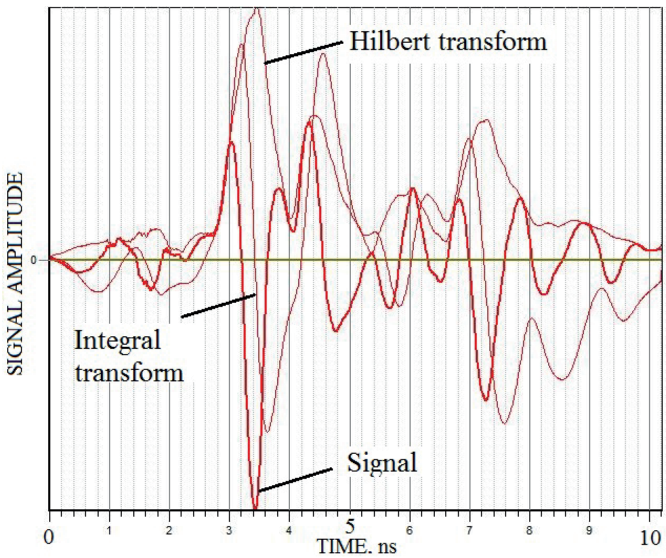

Fig. 5. Results using GPR Odyag-4.2 (experimental datasets).

Note that an additional result of this article is the application of a new calibration procedure. This procedure is used to determine the shape and parameters of the probing pulse. It involves measuring the reflection from a sheet of metal that is placed on the surface of the test medium. As our experiments with various designs of GPR have shown, when using a rectangular sheet of metal, reflection from the boundaries of the metal can occur several times. Moreover, reflections from different boundaries can overlap and further increase their mutual influence. As a result, incorrect reflections can occur, which can be superimposed on reflections from layer boundaries. To reduce the influence of this phenomenon, we proposed the option of using a sheet of metal with a star-shaped edge.

Also note that not only the calibration procedure, but also the actual process of sensing road structures using the UWB GPR has a complex character. This is primarily due to the imperfection of the models used. Attempts to apply numerical methods, such as the finite difference time domain method (FDTD) and others, not only require a significant amount of computer time, but also do not provide a sufficient degree of reliability of the results obtained. In this sense, the approach we propose is optimal for solving the problems of non-destructive testing of non-rigid road pavements.

Fig. 6 demonstrates the original view of the graphs of the signal reflected from the metal and the signal reflected from the investigated road. A laboratory design was used to obtain these data. It was created to test the accuracy and reliability of the estimates. The graph also shows the so-called jitter effect caused by a slight instability of the GPR parameters. To correct this and other effects that hinder the correct processing in the GeoVizy software, signal shift functions are provided. The corresponding result is shown in Fig. 7.

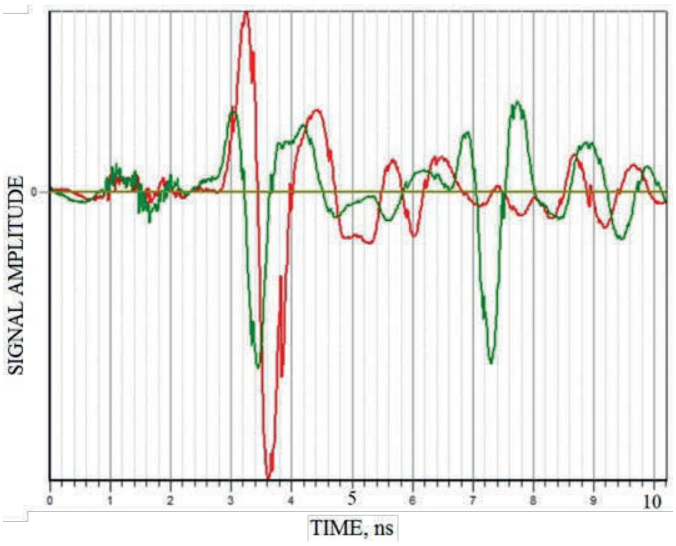

Fig. 6. Graphs of signals with noise and distortion.

Let us emphasise again that the results presented in Figs. 4–7 were obtained in semi-automatic processing mode. The use of this mode prompts the operator only to select the signal evaluation criterion – by the maximum or by the minimum value. Further, the operator is required to indicate the signal numbers from 3 to 7. The first two signals reflected from the metal and reflected from the structure are generated automatically. All other actions of the GeoVizy software are performed independently.

Finally, Fig. 8 shows the results of data processing using the Odyag-4.2 GPR.

The results of processing the sounding data in the semi-automatic mode indicate the high efficiency of the proposed approach to the analysis of the processing of the obtained data.

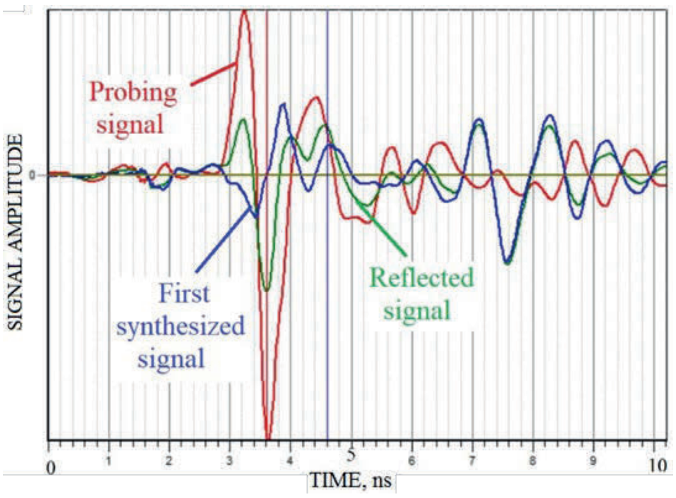

Fig. 7. First stage processing results.

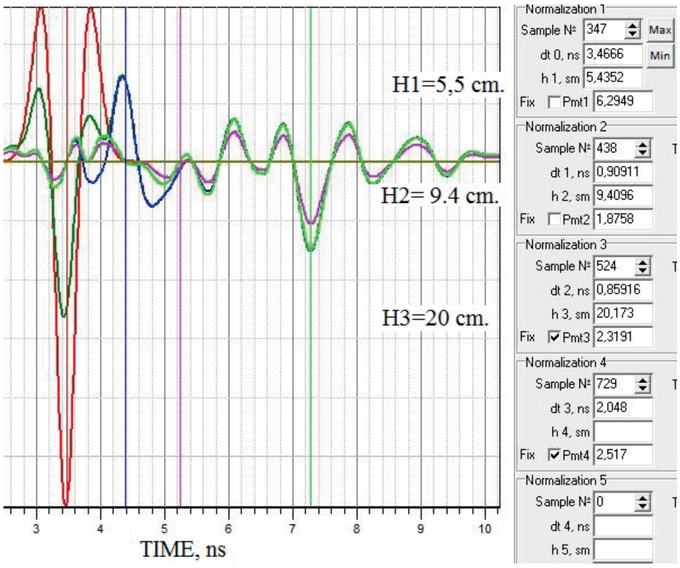

Fig. 8. Results of processing the data obtained in the laboratory using the Odyag-4.2 GPR.

All thickness values determined in semi-automatic mode correspond to the actual data. Small deviations are most likely caused by the presence of uneven boundaries. We also emphasise once again that certain values of the dielectric constant can be an important indicator of the state of the pavement layers. They can be used by the road engineer both in a stand-alone data system for the process of assessing the current state of the pavement, and for calculating the cost of maintenance and repair activity.

III. Conclusion

1. The analysis of the capabilities of two modern GPRs, namely, Odyag-1 (TRF-1) and Odyag-4.2, carried out in the article, is based on the use of modern signal processing methods. These are the Hilbert transform and the single integration procedure with a variable upper limit. As a result, methods for processing pulsed UWB GPR signals have been proposed, which take into account the design features of ground penetrating radars, and are also focused primarily on increasing the reliability of processing results.

The review of the literature carried out in the work showed the high potential of using modern pulsed georadar. It consists not only in solving important practical problems of assessing the current state of non-rigid pavement structures. Another direction of using GPR can be the assessment of the current state of other important critical infrastructure facilities, such as bridges and other building structures.

2. In terms of the practical implementation of pulsed GPR for solving urgent problems of non-destructive testing of road pavements, it is also necessary to note the high efficiency of the proposed methods and software. This efficiency is based on the low cost of using the UWB GPR and the relatively high reliability of the results obtained. It should also be noted that a combined approach is also possible, which involves the use of a coring procedure, as well as the use of other means of assessing the condition of the road pavement. One such popular tool is the falling weight deflectometer (FWD). FWD is a testing device used by civil engineers to evaluate the physical properties of pavement in highways, local roads, airport pavements, harbour areas, and railway tracks.
3. Thus, it can be argued that the formulation of the problem proposed in the article, together with the results of theoretical analysis and numerical modelling, first of all, increased the reliability of the process of non-destructive testing of highways using modern UWB GPRs. We also considered the details of the proposed computational algorithms only in the most general form, without detailing. Unfortunately, we were not able to fully reflect all the features of the process of obtaining primary sounding data and all processing details. However, we hope to pay more attention to these issues in our subsequent publications.

Acknowledgement

The authors are grateful to the Ministry of Education and Science of Ukraine for supporting the research on the topics:

- ID:64094 25.08.2016 (299-1), Methods for analysis and diagnostics of plane-layered media with inhomogeneities and optimal synthesis of equipment for non-destructive testing of the state of complex objects.

- State Registration No. 0119U001301, Development and improvement of methods, models, algorithms and means of GPR diagnostics of the technical and operational state of transport structures.

The authors are also grateful to anonymous reviewers for a number of useful recommendations, which were considered by the authors.

References

[1] J. D. Taylor, *Introduction to Ultra-Wideband Radar Systems*. CRC Press, 1994.

[2] D. J. Daniels, *Ground Penetrating Radar*. The Institution of Electrical Engineers, London, UK, 2004.

[3] A. Benedetto, F. Tosti, L. B. Ciampoli, and F. D'Amico, "An overview of ground-penetrating radar signal processing techniques for road inspections," *Signal Processing*, vol. 132, pp. 201–209, Mar. 2017. https://doi.org/10.1016/j.sigpro.2016.05.016

[4] Yu. A. Kopylov, S. A. Masalov, and G. P. Pochanin, "Method for decoupling between transmitting and receiving modules of antenna system," Patent UA 81652, Jan. 25, 2008.

[5] N. P. Zhuck and D. O. Batrakov, "Determination of electrophysical properties of a layered structure with a stastistically rough surface via an inversion method," *Physical Review B*., vol. 51, no. 23, pp. 17073–17080, June 1995. https://journals.aps.org/prb/abstract/10.1103/PhysRevB.51.17073

[6] D. O. Batrakov, "Quality and efficiency of information monitoring at radio wave testing of inhomogeneous dielectric layers by using a multifrequency method," *Russian Journal of Nondestructive Testing*, vol. 8, pp. 68–76, 1998.

[7] D. O. Batrakov, M. S. Antyufeyeva, A. V. Antyufeyev and A. G. Batrakova, "Remote sensing of plane-layered media with losses using UWB signals," in *2017 XI International Conference on Antenna Theory and Techniques (ICATT)*, Kyiv, Ukraine, May 2017, pp. 370–373. https://doi.org/10.1109/ICATT.2017.7972666

[8] X. N. Nieto, M. Solla, V. Marecos and H. Lorenzo, "Applications of the GPR method for road inspection," in *Non-Destructive Evaluation of Structures and Infrastructure* (Structures and Infrastructures Series), vol. 11, B. Riveiro and M. Solla, Eds. London: CRC Press, 2016. https://doi.org/10.1201/b19024

[9] M. Solla, X. Núñez-Nieto, M. Varela-González, J. Martínez-Sánchez and P. Arias, "GPR for road inspection: Georeferencing and efficient approach to data processing and visualization," in *Proceedings of the 15th International Conference on Ground Penetrating Radar*, Brussels, Belgium, Dec. 2014, pp. 913–918. https://doi.org/10.1109/ICGPR.2014.6970559

[10] R. L. Lytton, "System dentification and analysis of subsurface radar signals", U.S. Patent US5384715A, Jan. 24, 1995. https://patents.google.com/patent/US5384715/en

[11] Z. Dong *et al.*, "Rapid detection methods for asphalt pavement thicknesses and defects by a vehicle-mounted ground penetrating radar (GPR) System," *Sensors*, vol. 16, no. 12, Art. no. 2067, Dec. 2016. https://doi.org/10.3390/s16122067

[12] D. O. Batrakov, M. S. Antyufeyeva, A. V. Antyufeyev and A. G. Batrakova, "GPR data processing for evaluation of the subsurface cracks in road pavements," in *2017 9th International Workshop on Advanced Ground Penetrating Radar (IWAGPR)*, Edinburgh, UK, Jul. 2017, pp. 1–6. https://doi.org/10.1109/IWAGPR.2017.7996072

[13] M. Born and E. Wolf, *Principles of optics*. Pergamon press, 1968.

[14] L. Krysiński and J. Sudyka, "Typology of reflections in the assessment of the interlayer bonding condition of the bituminous pavement by the use of an impulse high-frequency ground-penetrating radar," *Nondestructive Testing and Evaluation*, vol. 27, no. 3, pp. 219–227, May 2012. https://doi.org/10.1080/10589759.2012.674525

[15] N. P. Zhuck, D. O. Batrakov, "Inverse scattering problem in the polarization parameters domain for isotropic layered media: Solution via Newton-Kantorovick iterative technique," *Journal of Electromagnetic Waves and Applications*, vol. 8, no. 6, pp. 759–777, Apr. 1994. https://doi.org/10.1163/156939394X00551

[16] D. O. Batrakov, M. S. Antyufeyeva, O. V. Antyufeyev and A. G. Batrakova, "GPR application for the road pavements surveys," in *2017 IEEE Microwaves, Radar and Remote Sensing Symposium (MRRS)*, Kiev, Ukraine, Oct. 2017, pp. 81–84. https://doi.org/10.1109/MRRS.2017.8075033

[17] D. O. Batrakov, A. G. Batrakova and M.S. Antyufeyeva, "Combined GPR data analysis technique for diagnostics of structures with thin near-surface layers," *Diagnostyka*, vol. 19, no. 3, pp. 11–20, 2018. https://doi.org/10.29354/diag/91489

[18] L. Y. Astanin, M. V. Kipke and V. V. Kostyleva, "The structural features of ultrawideband signals," in *2008 4th International Conference on Ultrawideband and Ultrashort Impulse Signals*, Sevastopol, Ukraine, Sep. 2008, pp. 180–182. https://doi.org/10.1109/UWBUS.2008.4669402

[19] J. Sudyka and L. Krysiński, "Radar technique application in structural analysis and identification of interlayer bonding," *International Journal of Pavement Research and Technology*, vol. 4, no. 3, pp. 176–184, 2011. http://www.ijprt.org.tw/mailweb/files/sample/V4N3_176-184.pdf

[20] M. Shokrabadi and A. Joshaghani, "Ground penetrating radar (GPR) applications in concrete pavements," *International Journal of Pavement Engineering*, July 2021. https://doi.org/10.1080/10298436.2021.1954182

Dmitry O. Batrakov received his Dr. sc. ing. degree in radiophysics in 1995; the position of full professor – in 2002, and IEEE senior member in 2005. His main scientific interests include inverse scattering problems for multilayered penetrable objects, and signal processing in remote and subsurface sensing; theory of diffraction, wave propagation, and polarimetric methods relating to the wave scattering problems; application of ultra wideband GPR signals to assess the current state of the non-rigid roads pavements and other technical objects.
E-mail: batrakov@karazin.ua
ORCID iD: http://orcid.org/0000-0002-6726-8162

Mariya S. Antyufeyeva graduated with honours from the Faculty of Radiophysics of V. N. Karazin Kharkiv National University in 1999, and received the PhD degree in radiophysics in 2010. Currently, she is an Associate Professor and Senior Scientific Researcher at the Department of Theoretical Radiophysics of School of Radiophysics, Biomedical Electronics and Computer Systems (Faculty of Radiophysics) of V. N. Karazin Kharkiv National University. Research interests include electromagnetics in time domain, signal processing, inverse problem in electromagnetics, ultra-wideband and ultrashort impulse signals, GPR, electromagnetic fields in a cavity resonator, temporary dispersive media with positive and negative refractive index, metamaterials. She is a member of IEEE and EUMA.
E-mail: antyufeyeva@karazin.ua
ORCID iD: https://orcid.org/0000-0002-6654-4794

Angelika G. Batrakova received her Dr. sc. ing. degree in technical sciences in 2014, and a position of professor degree in 2019. Her main research interests include pavement mechanics, pavement design and calculation methods; methods of non-destructive diagnostics, assessment and prediction of the condition of road pavements, including the use of ground penetrating radars.
E-mail: agbatr@ukr.net
ORCID iD: https://orcid.org/0000-0002-4067-4371