Proceedings of the 11th International Conference "Reliability and Statistics in Transportation and Communication" (RelStat'11), 19–22 October 2011, Riga, Latvia, p. 275-283. ISBN 978-9984-818-46-7
Transport and Telecommunication Institute, Lomonosova 1, LV-1019, Riga, Latvia

USING OF RADAR MONITORING FOR ROAD COVERAGE QUALITY ESTIMATION

Alexander Krainyukov, Valery Kutev

Transport and Telecommunications Institute
Lomonosova str. 1, Riga, LV-1019, Latvia
Ph.:+371 67100634. Fax: +371 67100660
E-mail: Aleksandrs.Krainukovs@tsi.lv, Valerijs.Kutev@tsi.lv

This work deals with problems of flexible pavement structure quality estimation with help of ground-penetrating radars (GPR). Forward and inverse problems of flexible pavement structure GPR probing are discussed. Iterative procedure to solve the inverse problem in frequency domain is used on the base of aim function minimization by using the genetic algorithm. The results of reconstruction of electro-physical characteristics for model of flexible pavement structure are presented.

Keywords: radar probing, inverse problem, genetic algorithm, reconstruction of electro-physical characteristics

1. Introduction

For optimisation of exploitation, upkeep and reconstruction of road cover certain information is crucial, such as condition of its internal layers and the processes taking place within them.

Basic flexible pavement structure is shown on Figure 1. A typical flexible pavement structure consists of the surface course, the underlying base and subbase courses [1].

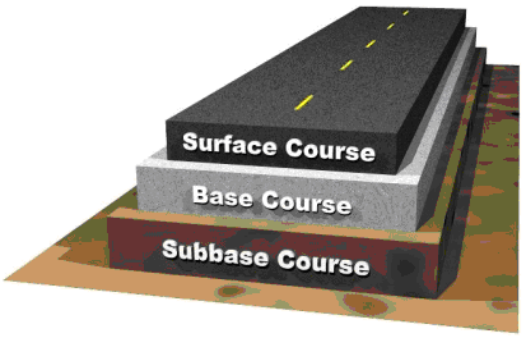

Figure 1. Basic flexible pavement structure

The surface course is the layer in contact with traffic loads and normally contains the highest quality materials. This top structural layer of material is sometimes subdivided into two layers: wearing course and intermediate/binder course. First of them is the layer in direct contact with traffic loads, and second layer provides the bulk of the HMA structure. The base course is immediately beneath the surface course. It provides additional load distribution and contributes to drainage and frost resistance. The subbase course is between the base course and the subgrade. It functions primarily as structural support.

To improve road safety it is necessary to constantly monitor the condition of the inner layers of the road structure. Nowadays to research the inner structure of flexible pavement Ground - penetrating radar (GPR) is widely used [2, 3]. In spite of substantial achievements in research and development of GPR there are some problems to improve the interpretation of radar probing data. Flexible pavement is a complex multi-layered construction, various layers of which consist of materials of different durability. It is well-known that in different times of the year and in different environmental conditions the preservation of road cover depends not only on usage but also on different climate-related factors. This is why it is necessary to constantly monitor the condition of the inner layers of the road structure, in order to act in time in response to the changes the state of its layers.

Traditional GPR has not sufficient time resolution and therefore do not provide the required effectiveness of flexible pavement structure monitoring. It is necessary to perform reconstruction of electro-physical parameters of roadway coverage with detection and identification of inner zones and objects. Reconstruction of electro-physical characteristics of the pavement structure is in essence identification of electro-physical parameters of the layers, which can be achieved by solving the inverse problem of flexible pavement structure monitoring which is in general ill-posed and not unique. To overcome these difficulties the comparison method may be used in which the results of the radar forward problem solution for an assumed subsurface structure with limited area of electro-physical parameters changing are comparing with data of radar probing. In this way a solution of the inverse problem can be found both in the time and the frequency domain.

2. Frequency Model for GPR Probing of Flexible Pavement Structure

A typical GPR has three main components: a transmitter and a receiver are directly connected to their antennas, and a control unit with a display [3,4]. The transmitting antenna radiates a short high-frequency electromagnetic (EM) pulse into the inspected medium, where it is refracted, diffracted and reflected primarily as it encounters changes in dielectric permittivity and electric conductivity. Waves that are reflected back by the probed medium induce signals in the receiving antenna, and are recorded as digitised signals for display and further analysis.

The GPR antennas are usually located above the roadway coverage at a low height H and are parallel to each other. The boundary of the air – the top layer of roadway coverage in the near field (H<<λ, where λ is the signal wavelength in air), and therefore has an influences on the characteristics of antennas. In this case the received signal consists of the following components: the direct signal, the lateral signal and the signal reflected from the internal boundaries of roadway coverage [5,6]. According to that, the signal forming channel in frequency domain may be presented as it is shown on Figure 2, where

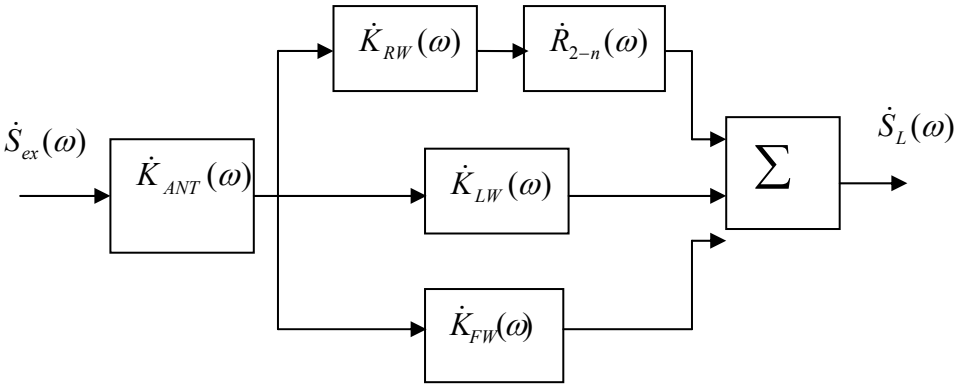

Figure 2. Signal forming channel for subsurface GPR probing of flexible pavement in frequency domain

the following denotations are used:

- $\dot{K}_{FW}(\omega)$ is a complex transfer function of direct signal,
- $\dot{K}_{LW}(\omega)$ is a complex transfer function of lateral signal,
- $\dot{K}_{RW}(\omega)$ is a complex transfer function of the signal reflected from the subsurface ideal reflector, located at a depth equal to the thickness of the first layer of roadway coverage,
- $\dot{R}_{2-n}(\omega)$ is a reflection coefficient of 2-n layers of the roadway coverage,
- $\dot{K}_{ANT}(\omega)$ is complex transfer function of the antenna system,
- $\dot{S}_{ex}(\omega)$ is the signal spectrum, which is used for impact excitation of the transmitting antenna,
- $\dot{S}_{L}(\omega)$ is the spectrum of the signal across the load resistance of the receiving antenna.

As a result, complex transfer function of signal forming channel for subsurface radar probing may be represented in the following way:

$$\dot{K}_{RAD}(\omega) = \dot{S}_L(\omega)/\dot{S}_{ex}(\omega) = \dot{K}_{ANT}(\omega)\cdot\left(\dot{K}_{FW}(\omega) + \dot{K}_{LW}(\omega) + \dot{K}_{RW}(\omega)\dot{R}_{2-n}(\omega)\right). \quad (1)$$

It depends on the conditions of the subsurface radar probing, as well as on the geometry of the antennas location.

Then complex transfer function of the antenna system $\dot{K}_{ANT}(\omega)$ for linear vibrators may be presented as [5]

$$\dot{K}_{ANT}(\omega) = -j\frac{30k_0\dot{L}^2_{eff}(\omega)R_L}{[R_L + \dot{Z}_{in}(\omega)]^2}, \quad (2)$$

where $j = \sqrt{-1}$ is image unity; $k_0 = \omega/c$ is the wave number for free space; $\omega = 2\pi f$ is the angular frequency of monochromatic wave with liner frequency f; $\dot{Z}_{in}(\omega)$ is input impedance of radar antennas; R_L is load resistor of the receiving antenna; $\dot{L}_{eff}(\omega)$ is effective antennas length, which is expressed as

$$\dot{L}_{eff}(\omega) = \frac{2}{\dot{k}_L}\cdot\frac{1-\cos\dot{k}_L l}{\sin\dot{k}_L l}. \quad (3)$$

l is half length of linear antenna; $\dot{k}_L$ is complex wave number of wave propagation in antenna which is expressed in the following way [7]:

$$\dot{k}_L = k_0\left\{1 + \frac{2}{\ln\frac{2H}{a}}\left[\frac{1}{(2k_0\dot{n}H)^2} - \frac{K_1(2k_0\dot{n}H)}{2k_0\dot{n}H} + j\left(\frac{\pi I_1(2k_0\dot{n}H)}{4k_0\dot{n}H} - \sum_{i=1}^{\infty}\frac{(2k_0\dot{n}H)^{(2i-1)}}{(2i-1)!\cdot(2i+1)!}\right)\right]\right\}^{\frac{1}{2}} \quad (4)$$

and depends on antennas diameter a, antennas high H over upper boundary of inspected medium, and complex refraction coefficient $\dot{n} = \sqrt{\dot{\varepsilon}_2(\omega)}$ for complex permittivity $\dot{\varepsilon}_2$ of inspected medium (surface course of the pavement structure). In (4) $K_1(.)$ and $I_1(.)$ are a modified Bessel functions of the first order.

In accordance to [3], complex transfer function of direct signal is expressed as

$$\dot{K}_{FW}(\omega) = \frac{2\cos\theta_1}{\cos\theta_1 - \sqrt{\dot{\varepsilon}_2(\omega) - \sin^2\theta_1}}\cdot\frac{e^{-jk_0R_1}}{R_1}, \quad (5)$$

where $\theta_1 = arctg(d/2H)$ is angle of incidence on the boundary of the air – the top layer of the pavement; d is distance between the antennas and $R_1 = \sqrt{d^2 + (2H)^2}$.

Lateral wave occurs when a spherical wave is refracted at the critical angle of incidence θ_{cr}. Complex transfer function of lateral signal $\dot{K}_{LW}(\omega)$ is expressed as [6]:

$$\dot{K}_{LW}(\omega) = \frac{j2\dot{\varepsilon}_2(\omega)}{k_0\cdot(\dot{\varepsilon}_2(\omega)-1)\sqrt{d}\cdot L^{3/2}}\cdot e^{-jk_0\left(L+\sqrt{\dot{\varepsilon}_2(\omega)}L_0\right)}, \quad (6)$$

where $L_0 = \frac{2h_2}{\cos\theta_{cr.tr}}$ is length of the propagation path of lateral signal in the top layer of roadway coverage; h_2 is thickness of the top layer of the pavement; $L = d - 2\cdot h_2\cdot tg\theta_{cr.tr.}$ – is length of the

propagation path of lateral signal along the boundary of the air – the top layer of roadway coverage; $\theta_{cr.tr.} = arctg\left(\mathrm{Re}\left(\dot{tg}(\dot{\theta}_{cr})\right)\right) = arctg\left(\mathrm{Re}\left(\frac{1}{\sqrt{\dot{\varepsilon}_2(\omega)-1}}\right)\right)$ is the true value of the critical angle of incidence θ_{cr}.

Complex transfer function of $\dot{K}_{RW}(\omega)$ describes the reflection from a subsurface target if a height of antennas location H over upper medium boundary is sufficient small ($H \approx 0$). When the roadway coverage probing $\dot{K}_{RW}(\omega)$ is expressed as [4]:

$$\dot{K}_{RW}(\omega) = \frac{2\sqrt{\dot{\varepsilon}_2(\omega)}\cos\theta_2}{\sqrt{1-\dot{\varepsilon}_2(\omega)\sin^2\theta_2}+\sqrt{\dot{\varepsilon}_2(\omega)}\cos\theta_2}\cdot\frac{e^{-jk_0\sqrt{\dot{\varepsilon}_2(\omega)}R_2}}{R_2} \quad \text{for } \theta_2 \le \theta_{cr} \tag{7}$$

and

$$\dot{K}_{RW}(\omega) = \frac{2\sqrt{\dot{\varepsilon}_2(\omega)}\cos\theta_2}{-j\sqrt{1-\dot{\varepsilon}_2(\omega)\sin^2\theta_2}+\sqrt{\dot{\varepsilon}_2(\omega)}\cos\theta_2}\cdot\frac{e^{-jk_0\sqrt{\dot{\varepsilon}_2(\omega)}R_2}}{R_2} \quad \text{for } \theta_2 > \theta_{cr}, \tag{8}$$

where $\theta_2 = arctg(d/2h_2)$ is an angle of incidence on the boundary of air – surface course of the pavement, and $R_2 = \sqrt{d^2+(2h_2)^2}$ is length of the propagation path for signal reflected from surface course of the pavement.

The model of roadway coverage may be conceived as homogeneous horizontal layers. Therefore reflection coefficient $\dot{R}_{2-n}(\omega)$ in (2) is expressed as a complex reflection coefficient for oblique incidence of plane wave on the upper boundary of the second layer of the pavement structure model. Calculation of $\dot{R}_{2-n}(\omega)$ is performed by using the expressions (9-12):

$$\dot{R}_{2,n}(\omega) = \frac{\dot{R}_{2,3}(\omega)+\dot{R}_{3,n}(\omega)\cdot\exp(-j2k_0\sqrt{\dot{\varepsilon}_3(\omega)}h_3/\cos\theta_{3ucm})}{1+\dot{R}_{2,3}(\omega)\cdot\dot{R}_{3,n}(\omega)\cdot\exp(-j2k_0\sqrt{\dot{\varepsilon}_3(\omega)}h_3/\cos\theta_{3ucm})}, \tag{9}$$

$$\dot{R}_{i,k}(\omega) = \frac{\dot{R}_{i,i+1}(\omega)+\dot{R}_{i+1,k}(\omega)\cdot\exp(-j2k_0\sqrt{\dot{\varepsilon}_{i+1}(\omega)}h_{i+1}/\cos\theta_{i+1ucm})}{1+\dot{R}_{i,i+1}(\omega)\cdot\dot{R}_{i+1,k}(\omega)\cdot\exp(-j2k_0\sqrt{\dot{\varepsilon}_{i+1}(\omega)}h_{i+1}/\cos\theta_{i+1ucm})}, \text{ for } k \ne i, k \ne i+1, \tag{10}$$

$$\dot{R}_{i,i+1}(\omega) = \frac{\sqrt{\dot{\varepsilon}_i(\omega)}\cos\theta_i-\sqrt{\dot{\varepsilon}_{i+1}(\omega)-\dot{\varepsilon}_i(\omega)\sin^2\theta_i}}{\sqrt{\dot{\varepsilon}_i(\omega)}\cos\theta_i+\sqrt{\dot{\varepsilon}_{i+1}(\omega)-\dot{\varepsilon}_i(\omega)\sin^2\theta_i}}, \tag{11}$$

$$\sin\theta_i = \frac{\dot{\varepsilon}_{i-1}(\omega)}{\dot{\varepsilon}_i(\omega)}\sin\theta_{i-1}, \tag{12}$$

where $\dot{\varepsilon}_i(\omega)$ – the relative complex permittivity of (i-1)-th layer; θ_i – is angle of incidence on the boundary of (i-1)-th layer – i-th layer of roadway coverage; h_i – the thickness of (i-1)-th layer.

The electro-physical parameters of the modelled pavement structure are presented in Table 1.

Table 1. Electro-physical parameters of partial model media

№	Partial medium of model	Electro-physical parameters of partial model medium		
		$\dot{\varepsilon}'$	σ, s/m	h, m
1	Air	1	0	∞
2	Dense grated HMA	2,9	$5*10^{-9}$	0,06
3	Coarse-grained asphalt 2 marks	3,6	$5*10^{-8}$	0,08
4	Coarse asphalt 2 marks	5,0	$5*10^{-6}$	0,12
5	Crushed stone	7,0	$5*10^{-4}$	0,33
6	Sand	9,0	$5*10^{-3}$	0,65
7	Loam	15,0	$5*10^{-2}$	∞

The electro-physical parameters of the pavement structure has been modelled taking into account that the roadway coverage layers are composed of such materials as asphalt, concrete, crushed stone, crushed slag, sand and others. The number of the layers can vary but the electro-physical characteristics of some layers can be very similar or even equal. The five-layered model of the pavement structure has been used in our investigations. Electro-physical parameters of the model partial layers as well as the parameters of two semi-infinite spaces: upper space – air, and low space – subgrade.

3. Forward Modelling of Flexible Pavement Structure GPR Probing

Forward problem of the flexible pavement structure GPR probing was solving numerically with the using of the frequency model described above. Calculations were carried out under the following conditions:

- distance between the antennas ……...……..1 m;
- antennas high over upper boundary.....5 m;
- half length of linear antennas.....0,25 m, 0,50 m, 0,75 m;
- diameter of antennas.....0,0025 m;
- load resistor of the receiving antenna..... 425 Om.

The probing signal was generated by the shock excitation of the transmitting antenna by triangular video pulse duration of which was equal to 2 ns, and its was equal to 100 V.

Complex transfer function $\dot{K}_{RAD}(\omega, \vec{P})$ is calculated according to equations (1)-(12) for vector $\vec{P}$, components of which are corresponded data presented in Table 1.

The spectrum of receiving signal is computed in the following form:

$$\dot{S}_L(\omega) = \dot{K}_{RAD}(\omega) \cdot \dot{S}_{ex}(\omega), \tag{13}$$

where

$$\dot{S}_{ex}(\omega) = \int_{-\infty}^{\infty} u_{ex}(t) \cdot e^{-j\omega t} dt \tag{14}$$

is spectrum of excitation signal $u_{ex}(t)$.

To obtain time shape of the received signal inverse Fourier transform in form was performed:

$$u_L(t) = \frac{1}{2\pi} \int_{-\infty}^{\infty} \dot{S}_L(\omega) e^{j\omega t} d\omega. \tag{15}$$

Frequency dependence complex transfer function of signal forming channel for the flexible pavement structure GPR probing are shown on Figure 3 for three half length of linear antennas, which are equal 0,25 m, 0,50 m, and 0,75 m.

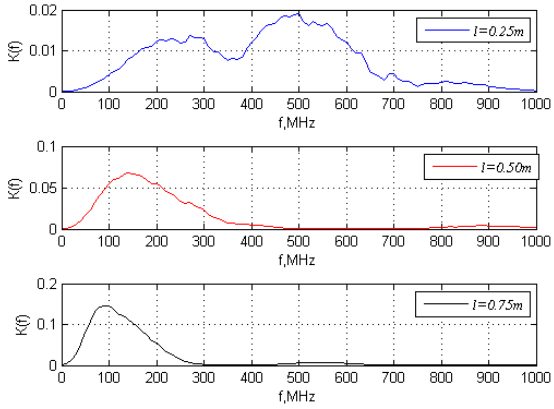

Figure 3. Transfer functions of signal forming channel for different half lengths of used linear antennas

This dependence shows that the increasing of antennas length gave the same effect both on antennas broadband and on the total level of the complex transfer function $\dot{K}_{RAD}(\omega, \vec{P})$ module.

The corresponding Frequency dependences of effective antennas length $\dot{L}_{eff}(\omega)$ are shown on Figure 4. It is shown as the half length of linear antennas decreases the characteristic $\dot{L}_{eff}(\omega)$ becomes more narrowband, frequency of the first peak decreases and the value of all the peaks is increased.

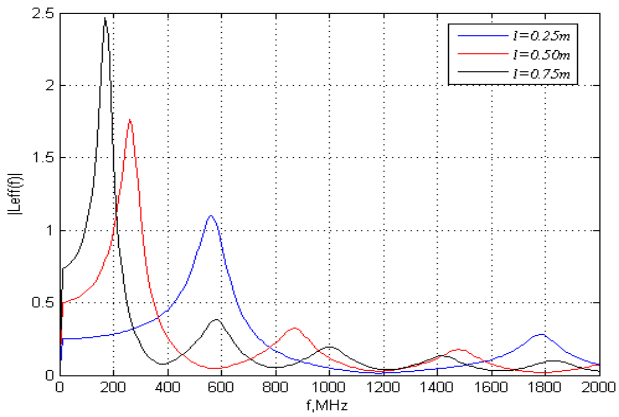

Figure 4. Frequency dependence of effective antennas length

Signals on output of receiving antenna and their spectrum modules for antennas half lengths, which are 0,25 m, 0,50 m, and 0,75 m are shown on Figure 5a,b.

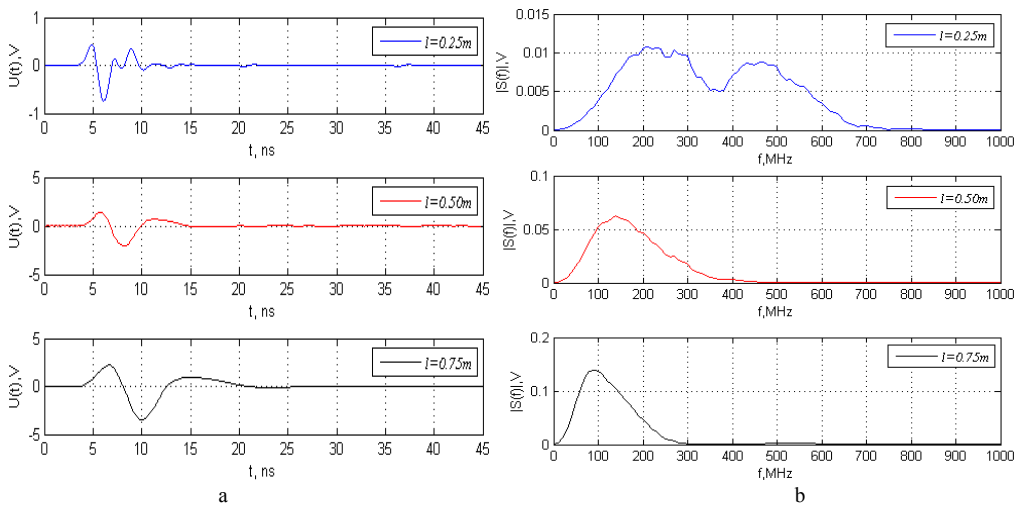

Figure 5. Characteristics of the signals on output of receiving antenna in the time (a) and frequency (b) domain

The modules of the received signal spectral densities are practically the same as the corresponding dependence of the complex transfer function of signal forming channel $\dot{K}_{RAD}(\omega,\vec{P})$, that are shown on Figure 2. It is seen that with decreasing length of the antenna resolution is getting worse, so determine the time delay of the signals reflected from the boundaries of the layers is impossible. Therefore, it is impossible to determine the thickness of each layer of roadway coverage, using amplitudes of the received signals.

The received signal and its components are shown on Figure 6 for the half length of used linear antenna l=0,25 m. Figure 6 shows that levels of the lateral signal and direct signal are comparable to the level of the signal reflected from the bottom of the first layer of roadway coverage. Since the duration of the forward and lateral signals more double passing time of reflected signal through the top layer of roadway coverage, the initial part of the received signal is the result of interference of the three signals. The reflected signal consists of the signals reflected from the entire boundary between the layers of roadway coverage. The signals reflected from the lower layers have significantly lower levels. When l=0,50 m or l=0,75 m the relative level of signals reflected from the lower layers are even smaller [6]. This eliminates the possibility to determine the thickness of the layers of roadway coverage by analysing the received signals.

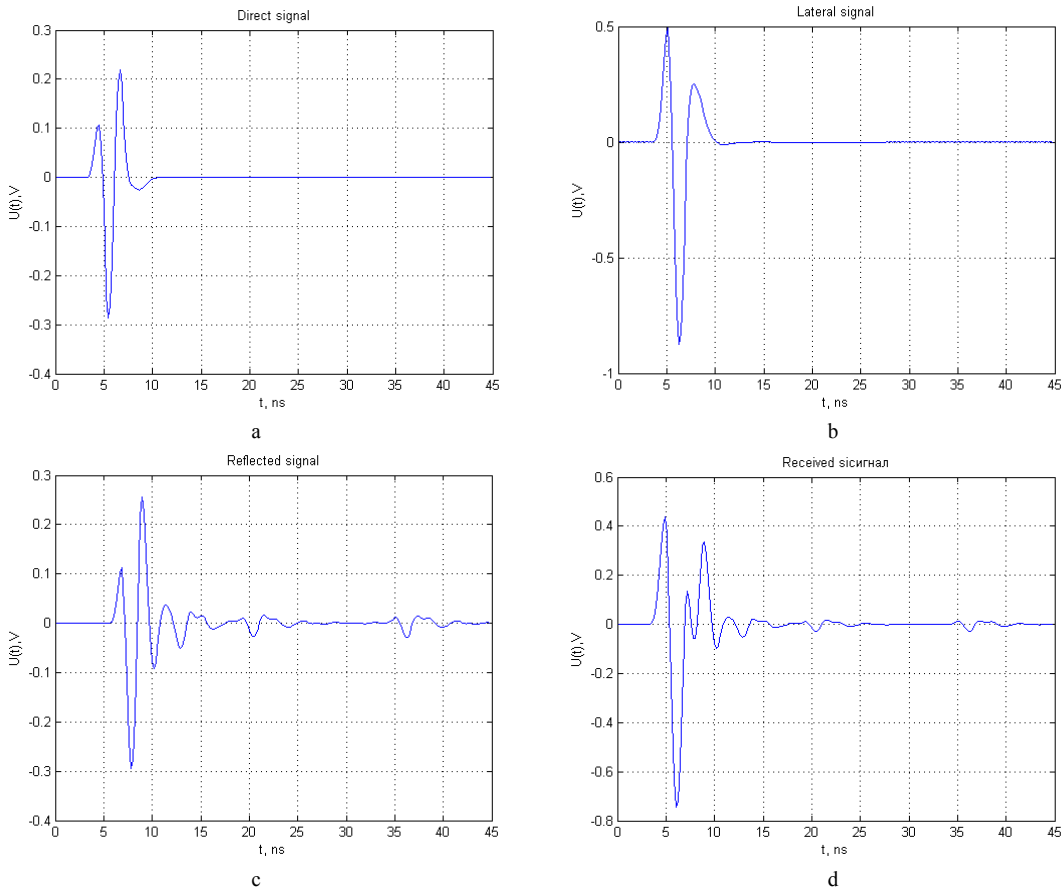

Figure 5. Received signal and its components:
a – direct signal; b – lateral signal; c – reflected signal; d – total signal received by GPR antenna

4. Inverse Problem of Flexible Pavement Structure GPR Probing

In [8] we investigated the inverse problem of roadway coverage radar probing in the frequency domain using vector $\vec{P}=\{p_1,p_2,...,p_n\}$, in which components p_i were electro-physical parameters of layers for n-layered model of probed media. Electro-physical parameters of each layer are as follows: thickness *h*, conductivity σ and the real part of relative complex permittivity ε' of the layer's materials.

The solution of the inverse problem of radar probing has been received in the frequency domain by the method of comparison in which used the aim function Φ in the following form:

$$\Phi = \frac{1}{n_{\max}} \sum_{i=0}^{n_{\max}} \left| B_e\left(\omega_i, \vec{P}\right) - B_t\left(\omega_i, \vec{P}_M\right) \right|^2 , \tag{16}$$

where n_{max} is number of the spectral component with frequency f_{max}; $B_e\left(\omega_i, \vec{P}\right)$ is value of function of parameter vector $\vec{P}$ for angular frequency ω_i,which is derived from the reflected signal; $B_t\left(\omega_i, \vec{P}_M\right)$ is value of the model function of parameter vector $\vec{P}_M$ for angular frequency ω_i which is derived from the solving of forward problem of GPR probing. To calculate $B_t\left(\omega_i, \vec{P}_M\right)$ the vector of parameters $\vec{P}_M$ was limited by the set of allowed values of parameters $\vec{P}_{POS}$. The solution of the inverse problem was the vector of parameters $\vec{P}_M$ which corresponded to the global minimum of the aim function Φ. The complex spectral density $\dot{S}_e\left(\omega_i, \vec{P}\right)$ as well as module of spectral density $\left|\dot{S}_e\left(\omega_i, \vec{P}\right)\right|$ was used in [3] as function of parameters B_e. Iterative procedure was used for finding of the aim function Φ global minimum with help of the genetic algorithm (GA).

In this work we used a more complex model of the pavement and for finding of the forward problem solution we took into account the geometric dimensions of used antennas as well as its mutual location. For the chosen model of flexible pavement structure the solution of the inverse problem of GPR probing was carried out by using the generic algorithm with the same characteristics as in [8].

We used the search ranges of medium parameters as it is shown in Table 2.

Table 2. Range of electro-physical parameters of partial model medium

№	Partial medium of model	The search ranges of electro-physical parameters					
		$\dot{\varepsilon}'$		σ, S/m		h, m	
		min	max	min	max	min	max
1	Dense grated HMA	2,5	3,3	10^{-9}	10^{-8}	0,045	0,075
2	Coarse-grained asphalt 2 marks	3,3	4,0	10^{-8}	10^{-7}	0,06	0,1
3	Coarse asphalt 2 marks	4,0	6,0	10^{-6}	10^{-5}	0,09	0,12
4	Crushed stone	6,0	8,0	10^{-4}	10^{-3}	0,24	0,41
5	Sand	8,0	10,0	10^{-3}	10^{-2}	0,48	0,81
6	Loam	10,0	20,0	10^{-2}	10^{-1}	-	-

It had been found that the search range parameter affects the error recovery parameters of pavement. Therefore we refined the search range in the first stage, when the K value was low. This allowed us to narrow the search range adaptively, and for each electro-physical parameter differently. In the second stage value K was set by large, therefore the threshold α was reduced, and then searched the parameters of the $\vec{P}_M$ vector.

To obtain statistical assessment about 100 solutions of the inverse problem for two different models of flexible pavement structure were used.

In Table 3 are presented the relative errors of reconstruction of electro-physical parameters of flexible pavement structure (Table 1) for half length of used linear antennas equal l=0.25 m.

Table 3. Relative errors of reconstruction of electro-physical parameters

№	Partial medium of model	Relative errors,%		
		$\delta_{\dot{\varepsilon}'}$	δ_σ	δ_h
1	Dense grated HMA	<1,0	15-20	<1,0
2	Coarse-grained asphalt 2 marks	<2,0	15-20	<1,0
3	Coarse asphalt 2 marks	<3,0	15-20	<2,0
4	Crushed stone	<3,0	15-20	<2,0
5	Sand	<2,0	15-20	<2,0
6	Loam	<2,0	15-20	-

Statistical assessment of reconstruction of electro-physical parameters of modelling flexible pavement structure were obtained also for the half length of used linear antennas l=0,50 m, and l=0,75 m. By increasing the half length of used linear antennas do not increase of the error values.

5. Conclusions

The following verities are proved in this research:

- the inverse problem of flexible pavement structure GPR probing may be solved by taking into account the influence of GPR antenna system characteristics as well as the influence of probed medium;
- the reconstruction of electro-physical parameters for flexible pavement structure is possible with high accuracy for linear antennas with half length 0,25 m, 0,50 m, and 0,75 m;
- using an adaptive algorithm of search ranges parameters is possible to reduce the error reconstruction of parameters and the duration of the inverse problem solving.

References

1. *Pavement Types Module – Pavement Interactive*. http://pavementinteractive.org/index.php?title=HMA_Pavement
2. Rexford M. Morey. *Ground Penetrating Radar for Evaluating Subsurface Conditions for Transportation Facilities (Synthesis of Highway Practice)*. Washington D.C.: National Academy Press, 1998, p. 37.
3. *Ground penetrating radar: theory and applications / Editor Harry M. Jol.* Elsevier Science, 2009. 524 p.
4. *Problems of subsurface radiolocation. Collective monograph / Ed. by A. Yu. Grinev*. M.: Radiotehnika, 2005. 416 p. (In Russian)
5. Krainyukov, A. V., Kutev, V. A. Modeling of the reflected signals formation in problem of layered terrestrial covers radar probing, *Scientific Papers of Riga Aviation University*. Riga: RAU, 1995, pp. 17–23. (In Russian)
6. Brekhovskikh, L.M. *Waves in Layered Media*. M.: Science, 1973. 344 p.
7. King, R.W.P. and G.S. Smith. *Antennas in Material Fundaments, Theory, and Applications*. The MIT Press, 1981. 675 p.
8. Krainyukov, A., Kutev, V., Opolchenov, D. Reconstruction of the Roadway Inner Structure Electro-physical Characteristics. *Proceedings of the 10th International Conference "Reliability and Statistics in Transportation and Communication" (RelStat'10), 20–23 October 2010, Riga, Latvia*. Riga: Transport and Telecommunication Institute, 2010, p. 55.