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RECONSTRUCTION OF THE ROADWAY INNER STRUCTURE ELECTRO-PHYSICAL CHARACTERISTICS

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This work has focused on the development of approach to the inverse problem of roadway coverage radar subsurface probing solution. Iterative procedure to solve the inverse problem in frequency domain is used on base of aim function minimization. Genetic algorithm is used for search of global minimum of aim function.

To improve accuracy of the electro-physical characteristics reconstruction with the use of genetic algorithm it is necessary correctly to choose the values of arguments for aim function and parameters of genetic algorithm. We propose value of threshold in aim functional was set with the use of middle power of spectral constituents, used for the calculation of aim function.

Reconstruction of parameters for model roadway coverage is executed with the use of two different kinds of aim functions. Statistical estimations of the reconstruction accuracy under various conditions are done.

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

1. Introduction

Roadway structure 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.

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: the appearance of potholes, changes in dampness of the soil, changes in the ability of the soil to filter water, etc. Timely identification of these processes allows one to make an informed decision about the necessary actions. 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.

In present time to research the inner structure of objects, of both artificial and natural origin, subsurface radar probing methods are widely used [1,2]. The latter allows one to ascertain the thickness of the inner layers of the road structure, the degree and quality of compactness of various road components, as well as to identify areas of excessive dampness, potholes and sources of water penetration. Determining pavement thickness, detected voids beneath pavement and measuring the moisture content in pavement layers are examples of such using. However, traditional methods of interpretation of the results of the subsurface radar probing of roadways do not provide the required precision and effectiveness of the road monitoring. Transportation departments need better methods for measuring near-surface and subsurface conditions of their transportation facilities [2]. It is possible to increase the precision of diagnosis and identification of inner zones and objects based on the results of radar subsurface probing through reconstruction of the geometrical and electro-physical characteristics, which leads to the necessity to solve the inverse problem of radar subsurface probing. Reconstruction of electro-physical characteristics of the road structure is in essence identification of electro-physical parameters of the layers of the road structure, which can be achieved by solving the inverse structure problem of subsurface radar probing.

In [3,4] we will look at the specifics of solving the inverse structure problem of subsurface radar probing in the frequency domain with through using a generic algorithm for search of global minimum of aim function.. Block diagram of iterative procedure to solve radar inverse problem is shown on Figure 1.

The initial stage of the iterative procedure is concerned with calculating of module spectral density $\left|\dot{S}_e\left(\omega_i,\vec{P}\right)\right|$ for reflected signal $U_{ref}(t)$. Further, in order to solve the inverse problem of subsurface radar probing, we introduce vector of parameters:

$$\vec{P} = \{p_1, p_2, ..., p_n\} \in \vec{P}_{POS}, \tag{1}$$

where $\vec{P}_{POS}$ – is a set of possible (allowed) values for parameters of probed area. The set of allowed values for parameters is determined on the basis of pre-existing hypotheses about internal structure of probed medium.

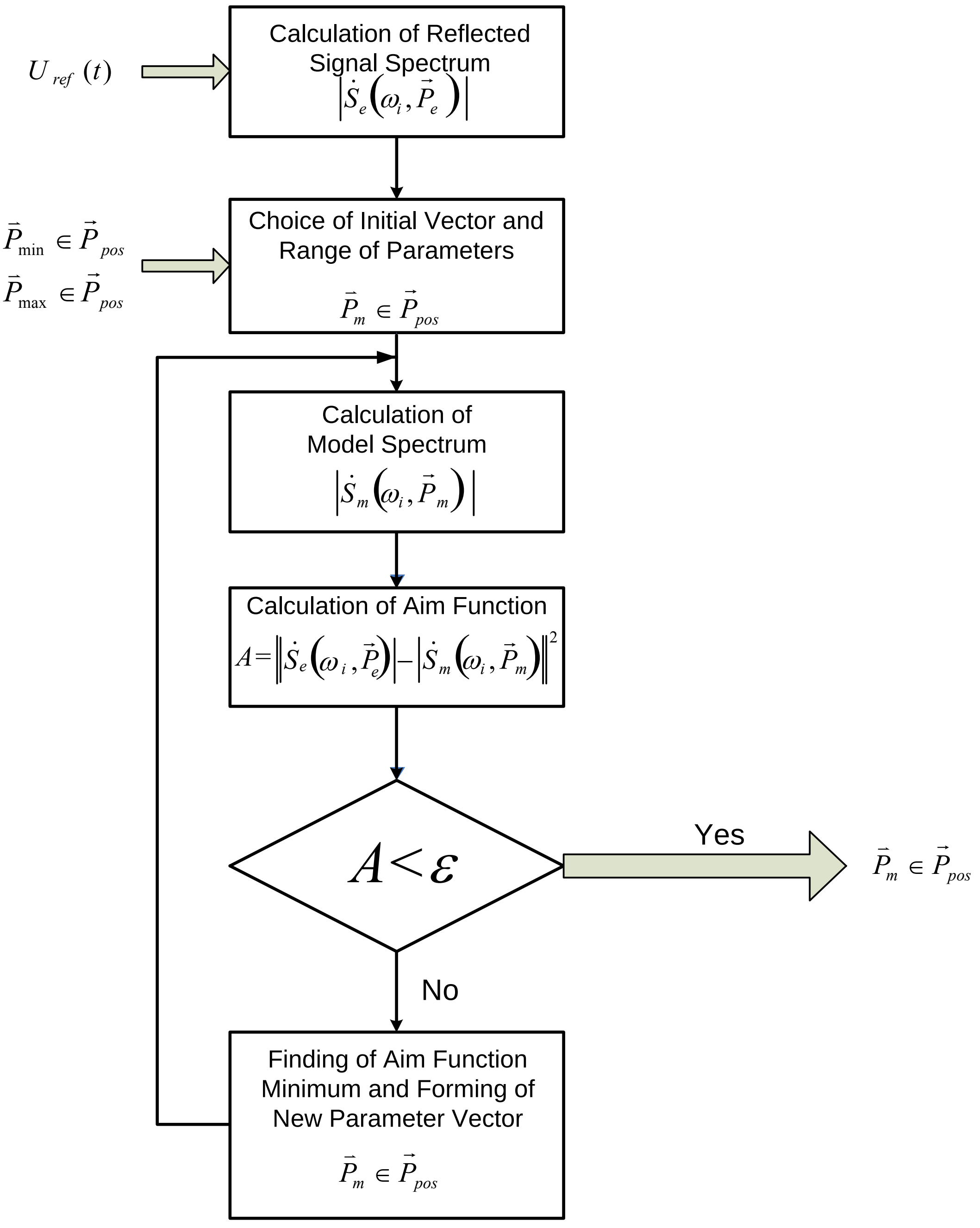

Figure 1. Block diagram of iterative procedure to solve radar inverse problem in frequency domain

Calculating of theoretical spectral density $\dot{S}_T(\omega_i, \vec{P})$ equates to the solving of the direct problem of subsurface radar probing. To calculate $\dot{S}_T(\omega_i, \vec{P})$ we chose the starting vector of parameters $\vec{P}_M$ belonging to the set of allowed values of parameters $\vec{P}_{POS}$.

The choice of the starting vector of parameters is also determined on the basis of pre-existing hypotheses about the object of probing.

Values of the modules of experimental and theoretical spectral densities are used to calculate aim function Φ_1:

$$\Phi_1 = \left\| \left|\dot{S}_e\left(\omega_i, \vec{P}\right)\right| - \left|\dot{S}_T\left(\omega_i, \vec{P}_M\right)\right| \right\|^2 = \frac{1}{n_{\max}} \sum_{i=0}^{n_{\max}} \left\| \left|\dot{S}_Э\left(\omega_i, \vec{P}\right)\right| - \left|\dot{S}_T\left(\omega_i, \vec{P}_M^j\right)\right| \right\|^2, \quad (2)$$

where n_{max} – index of the spectral component with frequency f_{max}.

If the value of the aim function Φ_1 is not more than the value of a threshold α, then solving the inverse structure problem is finished. The solution (pseudo-solution) is the vector of parameters $\vec{P}_M$. If the value of the aim function Φ_1 is greater than the value of α, then taking into account the current values of the vector $\vec{P}_M$ we formulate a new vector of parameters $\vec{P}_M$, which is used to calculate new values of the aim function Φ_1. This means, that finding a solution to the inverse problem in the form of the vector $\vec{P}_M$ is performed by iteration with the sequential improvement of accuracy of the parameters $\vec{P}_M$.

It has been suggested [4] that the value of α is set as follows:

$$\alpha = \frac{P_{av}}{K}, \quad (3)$$

where P_{av} – the averaged mean power of those spectral components $\dot{S}_e\left(\omega_i, \vec{P}\right)$, which are used for calculating of aim function Φ_1, and K – dimensionless coefficient, set by the user.

In [3,4] we researched the effect of the conditions of solving the inverse problem and parameters of generic algorithm on the error of restoration of electro-physical parameters of the modelled three-layered medium. The value of the electro-physical parameters of the layers of the two-layered medium being modelled (layer thickness h, electrical conductivity σ and the relative dielectric permittivity ε) corresponded to the electro-physical parameters of the materials of the layers road structure. It was determined that the error of restoration of electro-physical parameters can reach up to 10% and the results of restoration depends significantly on the assumptions about the parameters of the modelled two-layered medium. Optimal values of the coefficient K from the point of view of restoration of the parameters of the road surface and iteration of the algorithm lie within range from 1000 to 3000.

When solving the inverse problem of sub-layer probing it is very important to rationally select the original inputs, which are determined by various informational characteristics, scope of their existence and their quantities.

In aim function (2), used in [3,4], informational characteristic used was the spectral density of the reflected signal is in the form of its modular values ($\left|\dot{S}_e\left(\omega_i, \vec{P}\right)\right|$ and $\left|\dot{S}_T\left(\omega_i, \vec{P}_M\right)\right|$). However, this informational characteristic can also be used in the form of complex values. In this case the expression for calculation of aim function Φ_2 is as follows:

$$\Phi_2 = \left\| \dot{S}_e\left(\omega_i, \vec{P}\right) - \dot{S}_T\left(\omega_i, \vec{P}_M\right) \right\|^2 = \frac{1}{n_{\max}} \sum_{i=0}^{n_{\max}} \left| \dot{S}_e\left(\omega_i, \vec{P}\right) - \dot{S}\ \left(\omega_i, \vec{P}_M^j\right) \right|^2, \quad (4)$$

and the algorithm of solving the inverse structural problem of subsurface probing stays the same (Fig. 1).

Irrespective of the form of the informational characteristic aim functions Φ_1 and Φ_2 greatly depend on the parameters of the probing medium and frequency range, in which the inverse structure problem of subsurface probing is being solved. Apart from the global minimum aim functions Φ_1 and Φ_2 have numerous false local minimums, which give possible incorrect solutions to the inverse problem.

In this work we research the effect of electro-physical parameters of the three-layer modelled medium on the behaviour of aim functions Φ_1 and Φ_2.For the chosen model of the probed medium, probing signal and aim functions Φ_1 and Φ_2, we solve the inverse problem using GA, according to the block diagram of iterative procedure shown on Figure 1.

2. Analysis of Aim Functions For the Inverse Problem of Roadway Coverage Radar Subsurface Probing

2.1. Models of the roadway coverage and of the probe signal

The model of roadway coverage may be conceived as homogeneous horizontal layers: first layer-pavement and second layer -base, which are placed between two semi-infinite spaces: upper-air and lower-sub grade. Electro-physical parameters of partial model media are presented in Table 1.

Table 1. Electro-physical parameters of partial model media

Partial medium ofmodel	Electro-physical parameters of partial model medium		
	ε'	σ	h ,m
Air	1	0	∞
First layer (pavement)	2.6	0.0015	0.3
Second layer (base)	7.0	0.001	0.4
Lower semi-infinite space (sub grade)	15.0	0.05	∞

Used model of probe signal was the same as in [3]. Model of probe signal and module of spectral density of model probe signal are presented on Figure 2 and Figure 3.

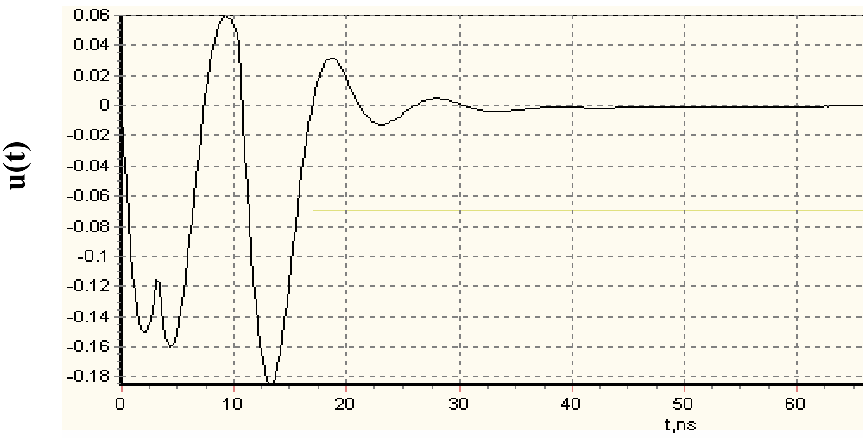

Figure 2. Model of probe signal on output of receiving antenna.

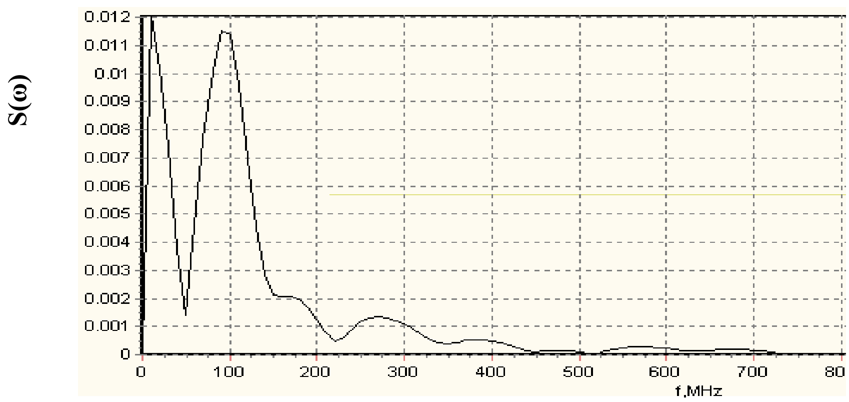

Figure 3. Module of spectral density for model probe signal

Calculation of theoretical spectral density is performed by multiplying of the spectrum of the probe signal and the theoretical coefficient of reflection of the medium $\dot{R}_T\left(\omega_i, \vec{P}_M\right)$, which is described by the vector $\vec{P}_M$:

$$\dot{S}_T\left(\omega_i, \vec{P}\right) = \dot{S}\ \left(\omega_i\right) \cdot \dot{R}_T\left(\omega_i, \vec{P}_M\right) \tag{5}$$

Calculation of $\dot{R}_T\left(\omega_i, \vec{P}_M\right)$ is performed by using the following expressions:

$$\dot{R}_{1,n} = \frac{R_{1,2} + R_{2,n}\exp(j4\pi h_2 / \lambda\sqrt{\dot{\varepsilon}_2})}{1 + R_{1,2}R_{2,n}\exp(j4\pi h_2 / \lambda\sqrt{\dot{\varepsilon}_2})}$$

$$\dot{R}_{i,k} = \frac{R_{i,i+1} + R_{i+1,k}\exp(j4\pi h_{i+1} / \lambda\sqrt{\dot{\varepsilon}_{i+1}})}{1 + R_{i,i+1}R_{i+1,k}\exp(j4\pi h_{i+1} / \lambda\sqrt{\dot{\varepsilon}_{i+1}})}, \tag{6}$$

where: $\dot{R}_{i,i+1} = \left(\sqrt{\dot{\varepsilon}_i} - \sqrt{\dot{\varepsilon}_{i+1}}\right) / \left(\sqrt{\dot{\varepsilon}_i} + \sqrt{\dot{\varepsilon}_{i+1}}\right), k \neq i, k \neq i+1,$ k and i - index of a model layer; n – number of model layers, λ - wavelength of probe signal in air.
Note: λ and $\sqrt{\dot{\varepsilon}}$ – is calculated for each of the frequencies from the interval $f \in \left[f_1, f_2, ..., f_{\max}\right]$.

2.2. Influence of electro-physical parameters of the medium on aim functions

Aim functions Φ_1 and Φ_2 of the inverse problem of radar subsurface probing being solved are functions of parameter vector $\vec{p}$ and used frequency spectrum of reflected signal which has maximal frequency f_{max}. For the studied model of the probed medium the number of arguments of aim functions Φ_1 and Φ_2 equals 9, i.e. 8 electro physical parameters of the model medium (Table 1) and maximal frequency f_{max}

In order to demonstrate the dependency of the aim functions on electro physical parameters in three-dimensional form we selected two partial arguments for calculations of them.

To calculate the value of the theoretical spectral density $\dot{S}_T\left(\omega_i, \vec{P}\right)$ we were changing the values of two of the electro physical parameters of one of the layers of the medium while keeping the remaining 6 constant and equal to the modelled ones. The range of changes of the chosen parameters was symmetrical to the modelled values and equal to them.

2.2.1. Dependence of aim functions on dielectric permittivity and thickness of the layers

Dependencies of aim functions Φ_1 and Φ_2 on dielectric permittivity ε' of the layers and their thickness *h* are shown on Figures 4 and 5.

In the upper part of each figure there is a three-dimensional view of the dependence of the aim function on two parameters calculated for f_{max} = 300 MHz, and in the bottom part – the level of the functions depends on two parameters for three values of maximal frequency f_{max} =100, 300 and 500 MHz. For the minimal level the threshold value α was used. In all of the diagrams for aim functions the value α was used, calculated using K = 2000.

The areas of aim functions Φ_1 and Φ_2 with values less than α, are shown in the centre of the diagrams and highlighted in white. The geometric form of these areas allows us to judge the degree of the effect of each parameter on the aim function.

The geometric forms of the white areas show on Figure 4 and Figure 5 are ellipses, but of different sizes. Comparative analysis of these areas allows us to make the following:

- dielectric permittivity and thickness of layers heavily affect the values of aim functions Φ_1 and Φ_2;
- calculation of the aim functions for $f_{\max} > 300$ MHz increases the size and compression of the ellipses, which means that in order to calculate aim functions it is crucial, that $f_{\max}$ is less than 300 MHz;

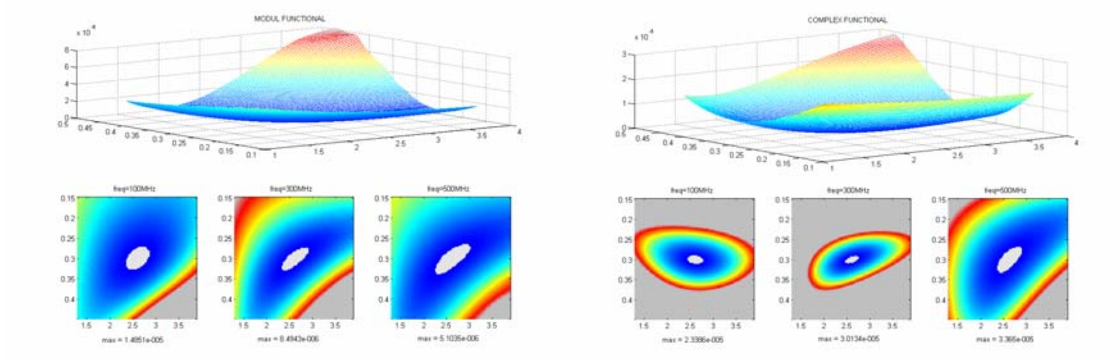

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Figure 4. Influence of dielectric permittivity $\varepsilon_1^{'}$ and thickness h_1 of the first layer (pavement) on the aim functions Φ_1(a) and Φ_2(b)

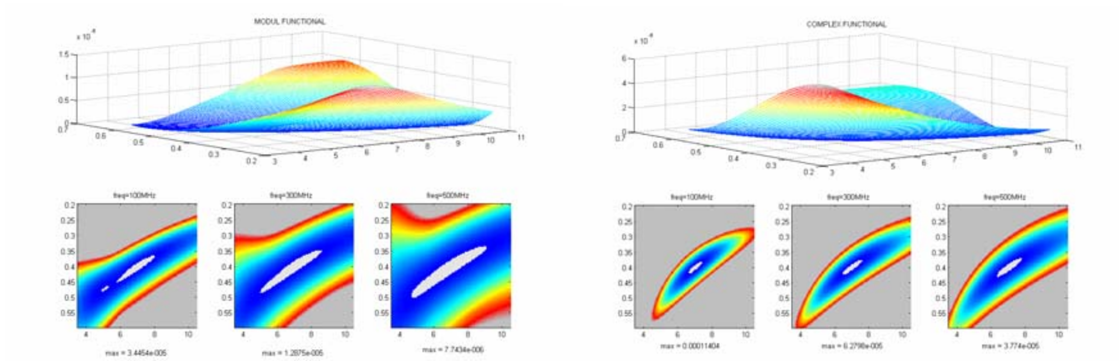

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Figure 5. Influence of dielectric permittivity $\varepsilon_2^{'}$ and thickness h_2 of the second layer (base) on the aim functions Φ_1(a) and Φ_2(b)

- aim function Φ_2 with a complex spectral density is more informative, because areas taking values less than α are smaller in size, i.e. corresponding ranges of h_1 and $\varepsilon_1^{'}$ on the diagrams for Φ_2 are less than those for Φ_1;
- values of aim functions Φ_1 and Φ_2 less than α, are obtainable under multidirectional changes of dielectric permittivity and thickness of the layers against the modelled values of the parameters of the layers, which can lead to errors of reconstruction of parameters of the probed medium.

2.2.2. Dependencies of aim functions on the electrical conductivity of the layers

Dependencies of aim functions Φ_1 and Φ_2 on the electrical conductivity of the layers σ and on two other parameters are shown in the Figure 6 to Figure 9. Conditions of calculations, representations and values of f_{max} are the same as those shown in the Figure 4 and Figure 5.

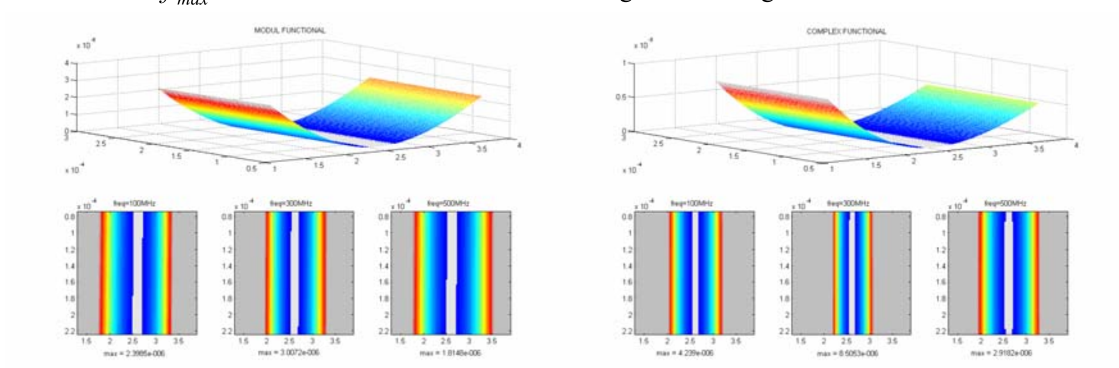

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Figure 6. Influence of dielectric permittivity $\varepsilon_1^{'}$ and electrical conductivity σ_1 of the first layer (pavement) on the aim functions Φ_1(a) and Φ_2(b)

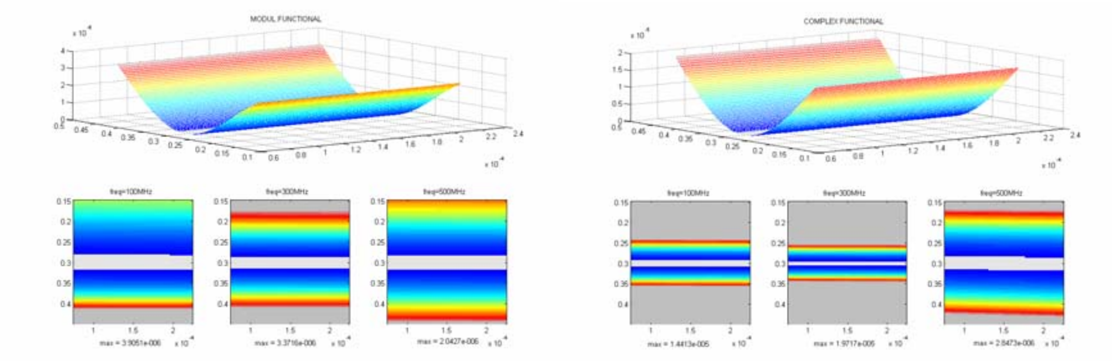

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Figure 7. Influence of electrical conductivity σ_1 and thickness h_1 of the first layer (pavement) on the aim functions Φ_1(a) and Φ_2(b)

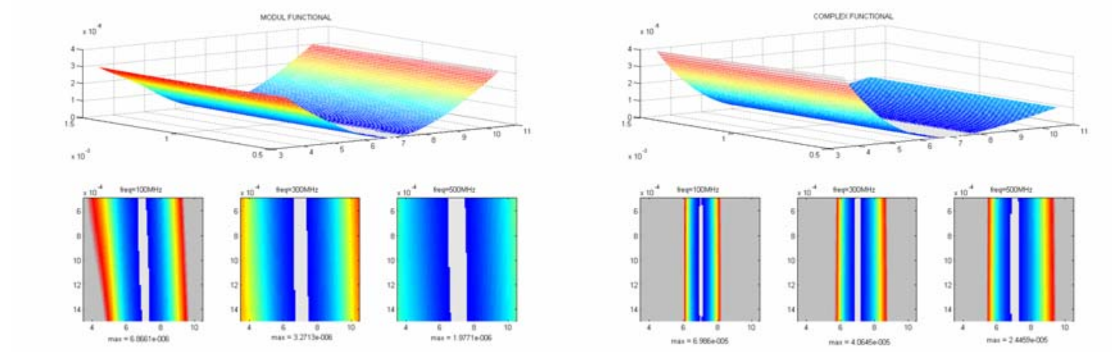

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Figure 8. Influence of dielectric permittivity $\varepsilon_2^{'}$ and electrical conductivity σ_2 of the second layer (base) on the aim functions Φ_1(a) and Φ_2(b)

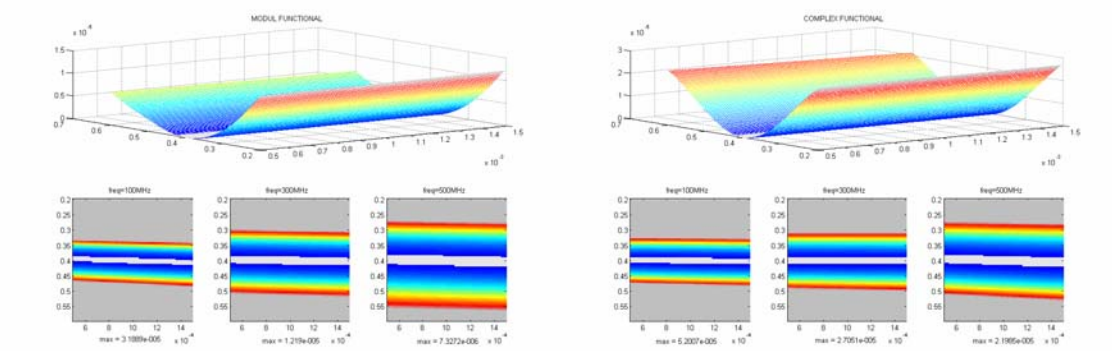

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Figure 9. Influence of electrical conductivity σ_2 and thickness h_2 of the second layer (base) on the aim functions Φ_1(a) and Φ_2(b)

The geometrical form of the white areas is close to a rectangle, the length of which is equal to the range of changes of electrical conductivity of the layer, and the width depends on the second electro-physical parameter of the layer or the width of the frequency range (value f_{max}). This means that the influence of the electrical conductivity of the layers on the values of the aim functions is negligible.

2.2.3. Influence of the parameters of lower semi-infinite space **(sub grade)** *on the aim functions*

On Figure 10 we have shown the influence of dielectric permittivity $\varepsilon_3^{'}$ and electrical conductivity σ_3 of lower semi-infinite space (sub grade) on the aim functions Φ_1 and Φ_2. The affect of these parameters is quite significant: the shape of the areas corresponding to the minimal values of the aim functions (less than α) is close to a circle and their sizes are minimal compared to the similar areas in previous figures. Therefore, the aim functions Φ_1 and Φ_2 are very sensitive to changes in ε_3' and σ_3, particularly the function Φ_2. The increase of f_{max} leads to increase of these areas, hence for the solution of the inverse problem it is crucial that f_{max} does not exceed 300 MHz.

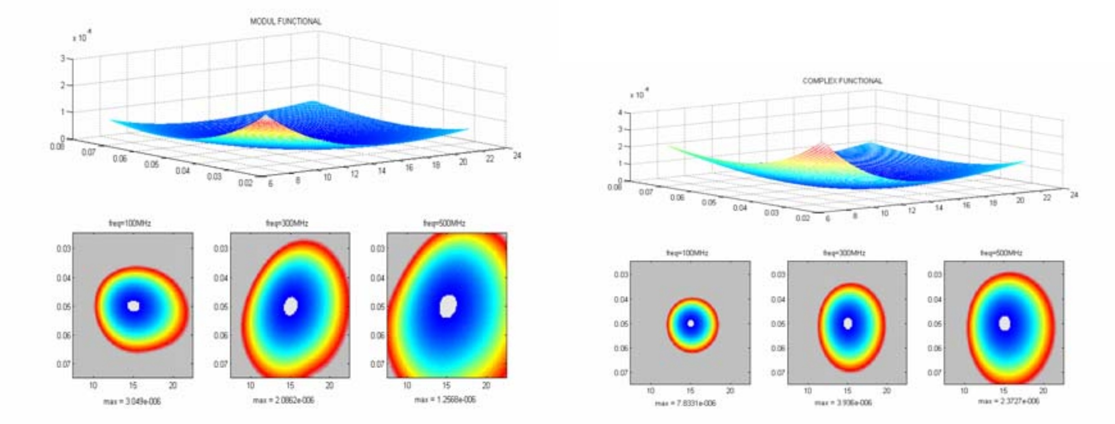

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Figure 10. Influence of dielectric permittivity ε_3' and electrical conductivity σ_3 of lower semi-infinite space (sub grade) on the aim functions Φ_1(a) and Φ_2(b)

3. Results of Roadway Coverage Parameters Reconstruction with Using Aim Functions Φ_1 and Φ_2

For the chosen model of roadway coverage, probing signal and the aim functions Φ_1 and Φ_2 the solution of the inverse structural problem was carried out using generic algorithm (GA). In order to find the global minimal values generic algorithm was used with the same parameters as in [3-5].

The solution of the above problem – vector $\vec{P}_M$ was used to access the relative error of reconstruction of each of the parameters of the modelled medium . At the same time the mean number of repetitions, necessary to finish the generic algorithm, was accessed.

In order to define the optimal conditions for the generic algorithm (GA) used to solve the inverse problem of radar `subsurface probing we researched how these values are influenced by the following factors:

- coefficient K, defining the threshold of the acceptable solution α;
- frequency range of used reflected signal spectrum, limited by its maximal frequency f_{max}.

To obtain statistical assessment about 100 solutions of the inverse problem for two layer model of roadway structure were used.

3.1. Influence of value coefficient K on the errors of roadway model parameters reconstruction

The value of K in our calculations was changed within the range of 100 to 5000 with fixed $f_{max} = 500$ MHz.

Influence of value K on first layer (pavement) parameters reconstruction On Figures 11 and 12 we show dependencies of the relative error (upper figures) and relative root-mean-square (SMR) error (lower figures) of the results of reconstruction of electro-physical parameters of the first layer (pavement) on value coefficient K.

When using the aim function Φ_2 the relative errors of reconstruction ε_1 and h_1 are less than when using aim function Φ_1, and are, in fact, close to 0 (this is clearly illustrated on Figure 4). When $K \geq 1000$ ε_1 and h_1 slightly decrease.

Dependencies of relative RMS error for the first layer parameters show that the increase of K will result in a smaller range of possible values of ε_1 and h_1 (Fig. 4).

Dependencies of relative RMS error for the first layer parameters show that the increase of K will result in a smaller range of possible values of ε_1 and h_1 (Fig. 4).). The range of possible values of σ_1 remains unchanged with the increase of ***K*** (Fig. 6 and Fig. 7); therefore the values of relative RMS error for σ_1 are stable and significant. For this reason dependencies of σ_1 have a chaotic character.

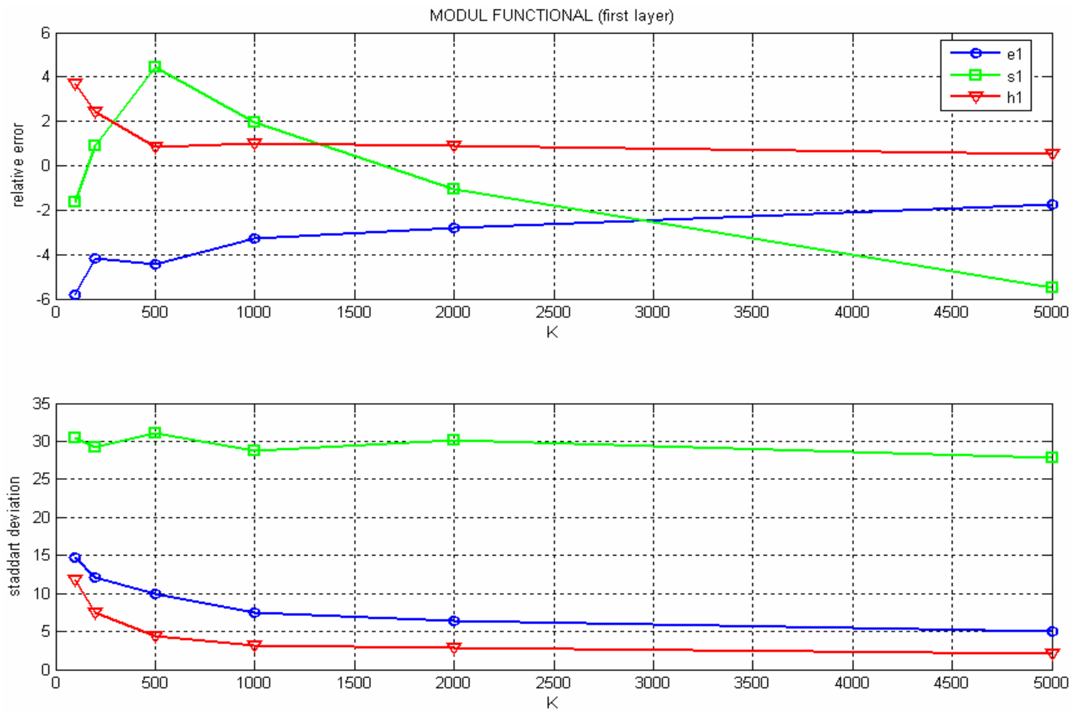


Figure 11. Influence of value K on accuracy reconstruction of first layer (pavement) parameters for using aim function Φ_1

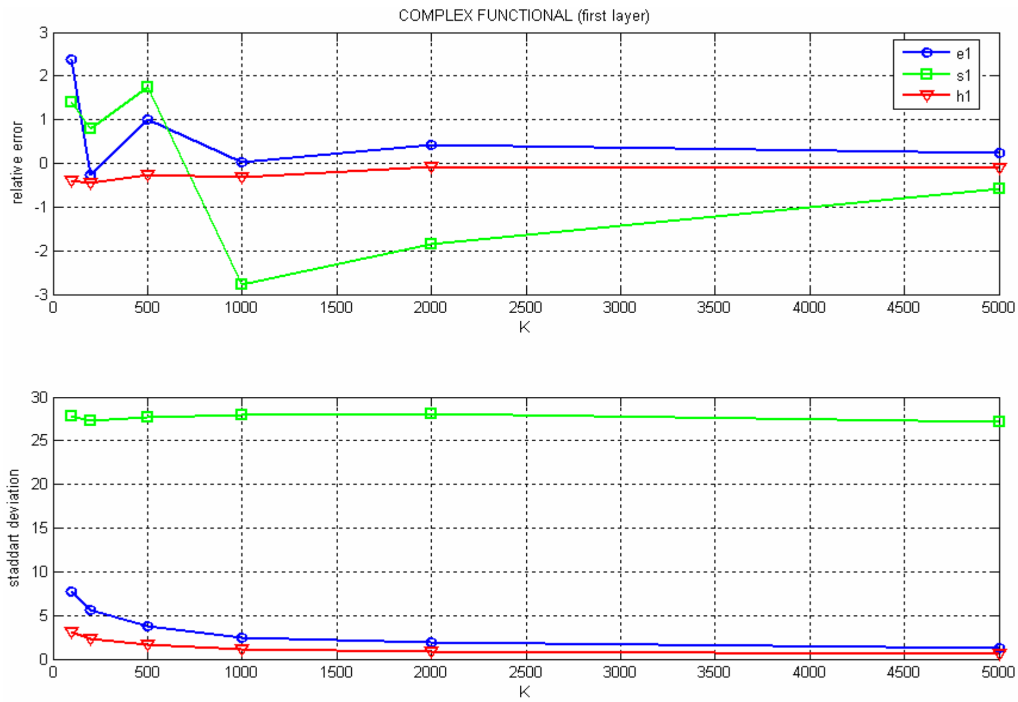
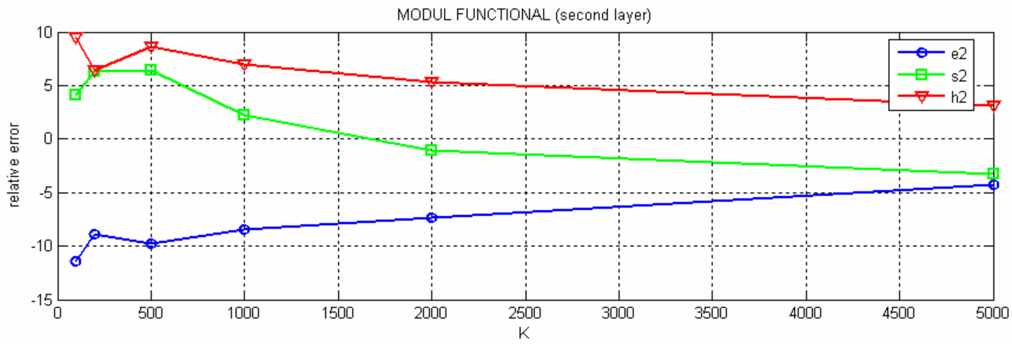


Figure 12. Influence of value K on accuracy reconstruction of first layer (base) parameters for using aim function Φ_2

Influence of value K on second layer (base) parameters reconstruction (Fig. 13). Influence of value K on of relative RMS errors of second layer parameters reconstruction is similar to those of the first layer's. The difference is in higher values of relative RMS errors for ε_2 and h_2, as it is shown on Figure 4 and Figure 5. Correspondingly the values of ε_2 and h_2 are higher although they decrease with the increase of K when using the aim function Φ_1 (Fig. 13,a). When using the aim function Φ_2 ε_2 and h_2 are less than 1% already when $K = 1000$ (Fig. 13,b). Dependence of σ_2 has also a chaotic character as for σ_2 RMS error is independent of K (Fig. 8 and Fig. 9).



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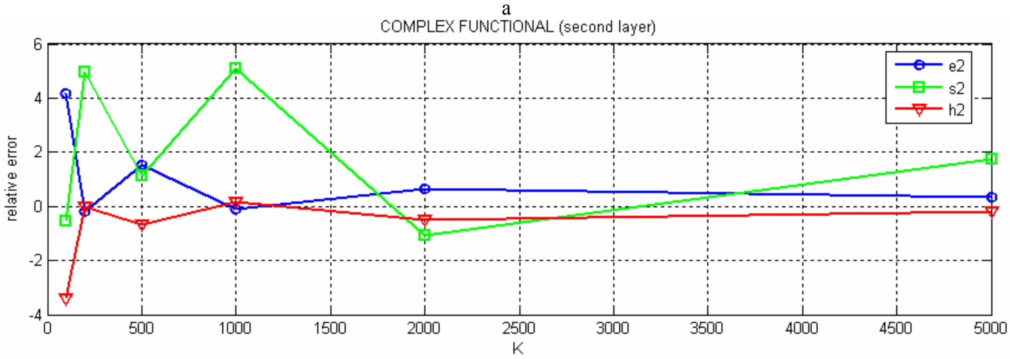

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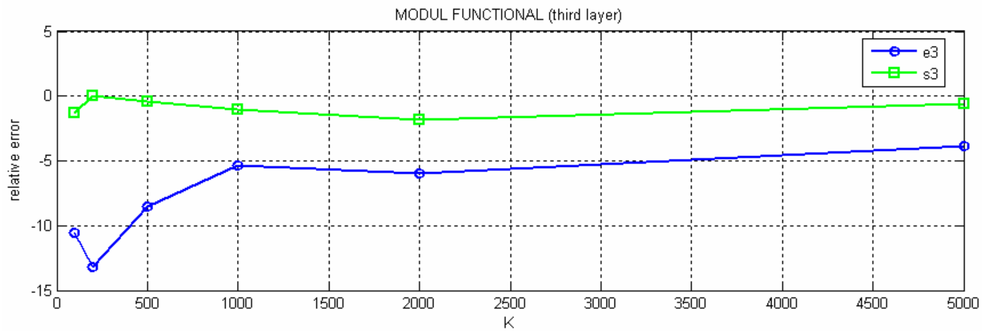
Figure 13. Influence of value K on accuracy reconstruction of second layer (base) parameters for using aim function Φ_1 (a) and aim function Φ_2 (b)

Influence of value K on lower semi-infinite space (sub grade) parameters reconstruction (Fig. 14). Increase of value K leads to decrease of RMS errors for ε_3 and h_3 and therefore to decrease of relative errors of these parameters reconstruction.



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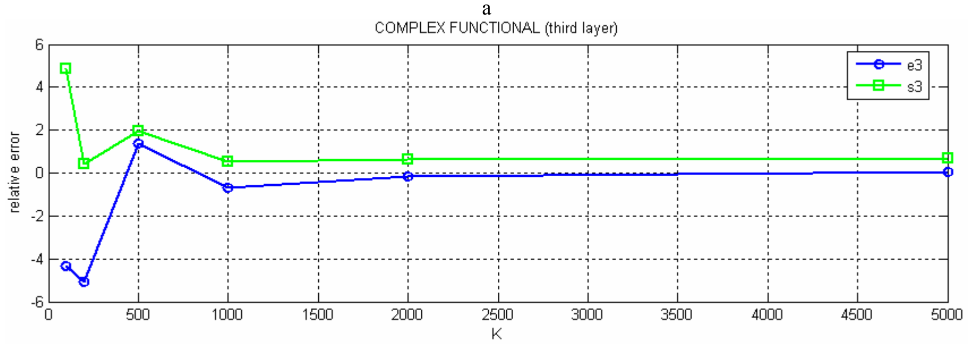

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Figure 14. Influence of value K on accuracy reconstruction of lower semi-infinite space (sub grade) parameters for using aim function Φ_1 (a) and aim function Φ_2 (b)

When $K > 1000$ the relative errors hardly change. Using the aim function Φ_2 allows to obtain ε_3 and h_3 with relative error less than 1% already when $K = 1000$ (Fig. 14,b).

3.2. Influence of Frequency Range on the Error of Parameter Reconstruction of the Modelled Medium

Solving of a subsurface radar probing inverse problem in a frequency area can be performed with different number of spectral components, i.e. in frequency ranges of a different width as well as differently positioned on the frequency axe. The aim of choosing of the optimal frequency range is minimizing the relative error determination of medium electro-physical parameters: dielectric permittivity ε, electrical conductivity σ and the layer thickness *h* for all layers of roadway structure.

In this work solving of the inverse problem was carried out in the frequency range $[f_1 \dots f_{\max}]$, where f_1 – is the frequency of the first spectral component, equal to 10 MHz, and value of $f_{\max}$ was changing in range from 50 MHz to 500 MHz .Influence of $f_{\max}$ on the solution of the inverse problem was researched with two values of *K*: *K* = 1000 and 2000. Both aim functions Φ_1 and Φ_2 were used in our experiments. Analysis of results shows that using aim function Φ_2 allowed to achieve lower relative error of parameter reconstruction compared to the results obtained using aim function Φ_1 .Figure 15 illustrates influence of $f_{\max}$ on the relative error of pavement (first layer) and base (second layer) parameters reconstruction when aim function Φ_2 is used. From this figure one can see:

- relative error of parameter reconstruction h_1, $\varepsilon_1^{'}$ (Fig. 15,a), h_2 and $\varepsilon_2^{'}$ (Fig. 15,б) is less than 1% when $f_{\max} > 100$ MHz and is independent of K;
- relative error of parameter reconstruction σ_1 and σ_2 has a complex dependence on $f_{\max}$.

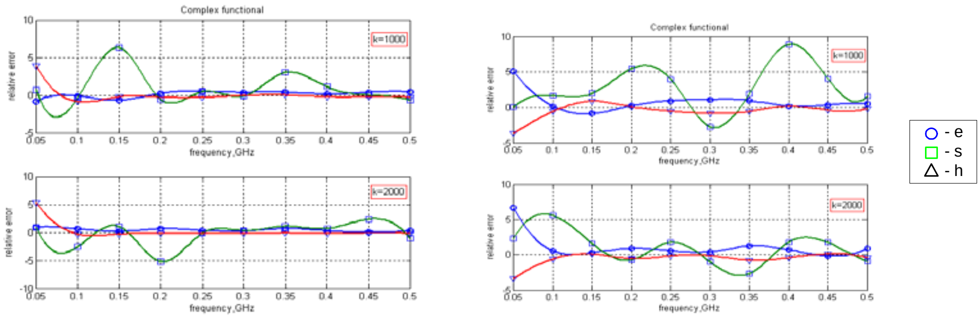

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Figure 15. Influence of $f_{\max}$ on the relative error of the first layer parameter reconstruction (a) and the second layer parameter reconstruction (b) using Φ_2

The similar character of the dependencies shown in the Figure 15 can be explained by the fact that the electro-physical parameters of the first (pavement) and second (base) layers have an identical affect on Φ_2, where as an increase of $f_{\max}$ does not change the size of the areas around the global minimum, values of which are less of *α* (Figures 4,b and 5,b). When aim function Φ_2 is using then relative errors of σ_3 and $\varepsilon_3^{'}$ determination are approximately 1%. Note that when $K = 2000$ the values of the above variables can be obtained when used maximal frequency of reflected signal is in range $100\,MHz \le f_{\max} \le 450\,MHz$.

4. Conclusions

We have researched the influence of electro-physical parameters of a two-layered model and chosen initial conditions on the aim functions used. The main results are as follows:

- using complex spectral density $\dot{S}(\omega)$ as an informational characteristic increases sensitivity of an aim functions to changes in parameters of the probed medium.
- using an aim function Φ_2 with a complex spectral density of reflected signal allows for regeneration of ε' and h of the layers with error less than 1%, which is not possible to achieve using an aim function Φ_1 with a module of spectral density;
- for solving of the inverse problem it is not necessary to use the energy (power) of all spectral components of the reflected signal, but instead only use a selection of those.

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