DEVELOPMENT OF AN NEW EFFICIENT NUMERICAL APPROACH FOR OBJECT RECOGNITION

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ABSTRACT

Based on the conception of scattered field's analytical continuation [1], a new approach of remote exploration of buried bodies by means of reflected pulse is presented in this article. The ways to simplify the experimental evaluations are presented. The results of some software simulations of soil properties reconstruction are presented. It consists of several parts: first one is determination soil's electrodynamic characteristics (like permittivity and dielectric loss tangent dependence on frequency) in order to find the best EM monitoring pulse, for deep penetration of its frequency contents waves. Second part is dedicated to buried objects image reconstruction by reflected pulse field. The next objectives of this paper are creation of the program package for determination of shape and position of metallic and/or dielectric bodies embedded within a dielectric media, determination of dielectric parameters of the body suppose. The main goal is construction of a high-speed device for measurement and recording amplitude and phase information of the electromagnetic pulse wave over boundary of two medium, connected to the computer will realize the detection process using developed software.

1. INTRODUCTION

Remote determination of shape and position of latent bodies is important in vast number of applications in different branches of science and technology - applied electrodynamics, tomography, medicine, archeology, military engineering etc. Application of different methods is necessary for verification of the observed results. Often when a direct contact to the body is undesirable, dangerous, or impossible at all such methods represent the only reliable way of investigation.

Most of the currently existing EM methods allowing object's shape recognition deal only with bodies with sizes significantly larger than wavelength. One of the advantages of the proposed method is that it can be used even when the wavelength is comparable to the body's sizes.

This paper consist of two main parts: first one dedicated to soil electrodynamic characteristics determination (like permittivity and dielectric loss tangent) on the frequency in order to find the best EM monitoring pulse, for deep penetration of its frequency content waves. It is well known fact that ε' and ε'' both depend on such characteristics of soil as humidity, temperature, chemical composition, etc. and waves with different frequencies penetrate deep differently into it. Thus maximum information from examined area can be obtained only when emitted electromagnetic impulse is formed in frequency range given soil is most transparent to.

Second part is dedicated to buried objects image reconstruction by means of reflected field. Results are presented for holographic/photographical method of immersed body visualization. All researches are directed to create software package for high resolution image recognition devices.

2. PROBLEM STATEMENT AND MODEL DESCRIPTION

A general model of proposed experiment is presented on Fig.1. An emitter antenna is pointed to the area, the latent body is supposed to be in, and a grid of EM sensors, capable of registering reflected EM field's amplitudes and phases in the wide frequency range is placed nearby. Generally, during experiment, we have to deal with completely unknown characteristics soil. In order to choose the best shape and time delay of the monitoring pulse, which could reach dipper into the soil?

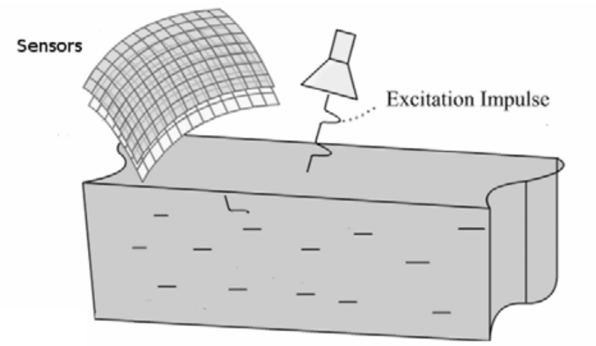


Figure 1 Problem statement

Proposed method enables us to build required characteristics with adequate accuracy without needs for laboratory experiments. If we have plane interface of two homogeneous mediums, this problem has rigorous solution - Fresnel's formulas [2], were from it could be obtain exact values for desired quantity:

$$r_{\perp} \equiv \frac{R_{\perp}}{\mathrm{E}_{\perp}} = \frac{n_1 \cos\varphi - n_2 \cos\psi}{n_1 \cos\varphi + n_2 \cos\psi} \quad (1)$$

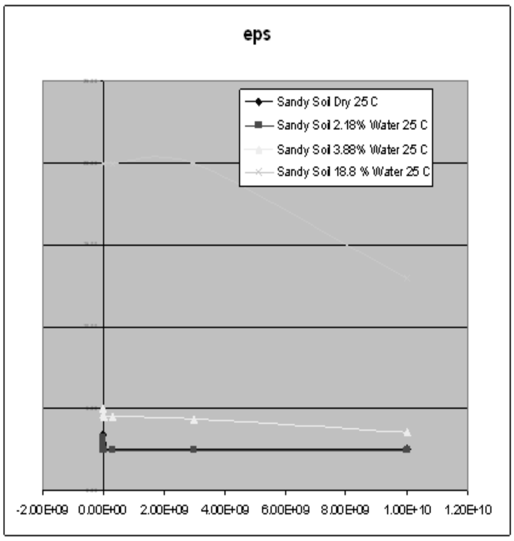
Where, $n_1 = \sqrt{\varepsilon_1}$, $n_2 = \sqrt{\varepsilon_2}$

Considering for the first media (air), $\varepsilon_1' = 1$ and $\varepsilon_1'' = 0$, we obtain:

$$\varepsilon_2 = \left(\frac{\cos\varphi}{\cos\psi}\right)^2 \cdot \left(\frac{1-r_\perp}{1+r_\perp}\right)^2 \qquad (2)$$

In our case: initially we know, that soil is not homogeneous, interface is not plane. So, it could be supposed, that we could determine just average properties of the earth. Below it will be shown, that comparative analysis of incident and reflected field's Fourier frequency components (amplitudes and the phase's delays) contains information about soil characteristics.

3. SOIL CHARACTERISTIC CONSIDERATION



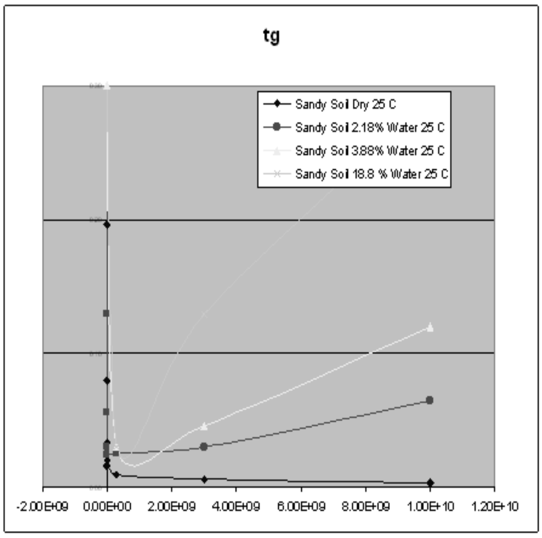


Figure 2 Typical soil characteristic

For computer simulation of impulse incidence on examined surface we use its direct and inverse Fourier transform. For each of Fourier transform components we calculate both reflected and immersed part, and through using obtained data we build required dependencies.

As it is well known complex permittivity consists of two parts $\varepsilon = \varepsilon' + i\varepsilon''$, where ε'-determines the permittivity and ε''-corresponds to absorption (We consider nonmagnetic media). Loss tangent is determined as $tg\Delta = \frac{\varepsilon''}{\varepsilon'}$. Generally, both $\boldsymbol{\varepsilon'}$

and ε'' depend on frequency, but in some cases, using computer simulation, one of these parameters can be considered as a fixed one. Anyway, we examine all of three possible cases: ε' is fixed and ε'' depends on frequency, ε'' is fixed and ε' depends on frequency, and when both parameters do depend on frequency.

In Fig. 2, as an example, represents typical experimental results dependencies of ε' and dielectric loss tangent on frequency [3]. The absorption of soil depends on humidity and it increases when the soil is more wet. On the right image we can see absorption minimums for presented type of soil which can be clearly observed in same frequency range. That means that the soil with such characteristics should be more or less transparent for EM waves with frequency between roughly 100 and 300 MHz. In other cases it must be differently. So, for image reconstruction in every new place it is an important task is to know which frequencies propagates dipper in order to choose the EM pulse with best frequency content waves.

Let's say, ε' does not depend on frequency and ε'' dependency for the given soil is unknown. We can give that dependency virtually any shape and test how good can our computer model reconstruct it. For simplicity we've chosen the dependency to be of a Gaussian shape Fig.3.

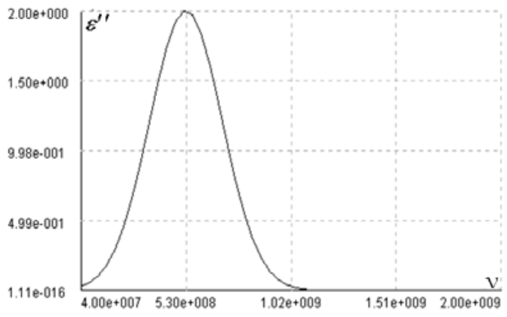


Figure 3 ε'' dependence on frequency

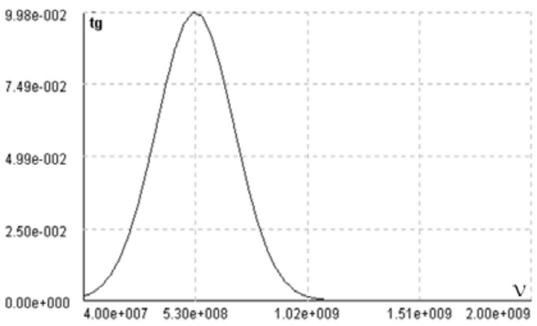


Figure 4 Loss tg dependence on frequency

With fixed ε' and given ε'' dependence on frequency, we can automatically get (Fig.4.). Performing calculations according to Fresnel's equation for diffraction we obtain following dependencies [2]

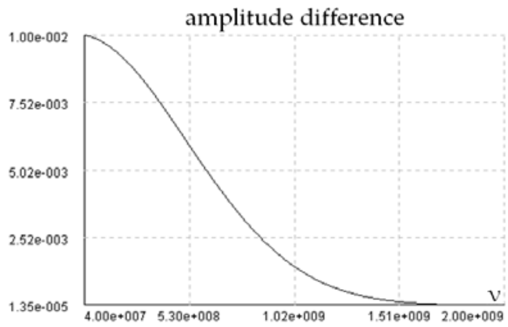


Figure 5 Amplitude difference dependence

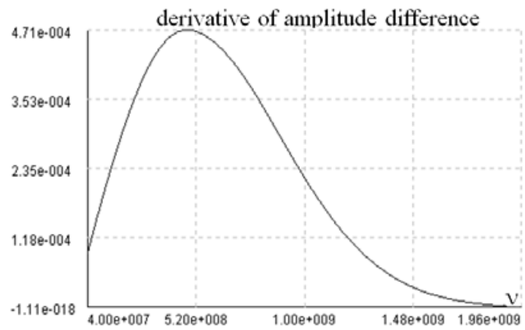


Figure 6 Derivative of amplitude difference dependence on frequency

As it appears on Fig. 8 both the initial dependency and the obtained one for phase difference has extremum in same frequency interval. The same comes out for the derivative of amplitude difference (Fig.6), which also has an extremum in same interval. Performing same calculations with ε'' fixed we obtain same type of result.

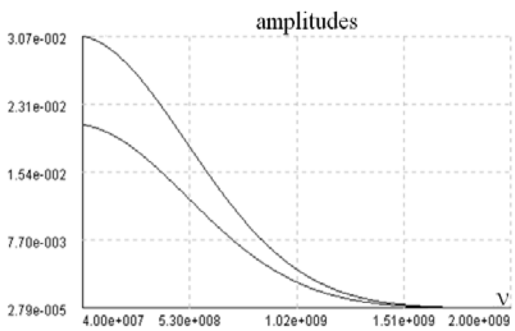


Figure 7 Amplitudes dependence on frequency

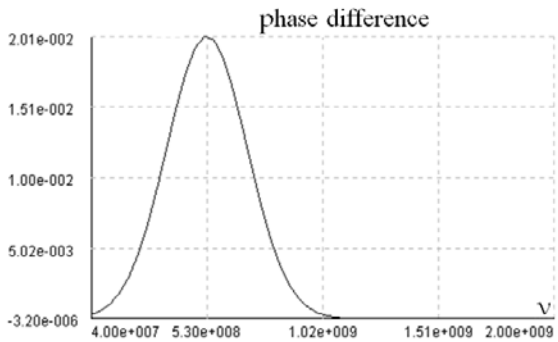


Figure. 8 Phase difference dependence on frequency

also be predicted for initial dependencies the same way. Thus, we've reached the goal of predicting in what frequency interval given soil will be transparent.

4. HOLOGRAPHIC METHOD

Let’s consider a simplified problem: a certain dielectric body is buried on certain distance in the Earth. Our task is to reconstruct its shape by means of above-earth reflected field observation. Traditional measurement equipment represents a spherical segment uniformly filled with EM field sensors (fig. 9). However, unlike numerical evaluations, only a finite number of sensors are available per unit area in real experiments. Thus, we have to assume that the reflected (and total) fields change smoothly from sensor to sensor, that it the reliable field description is obtained.

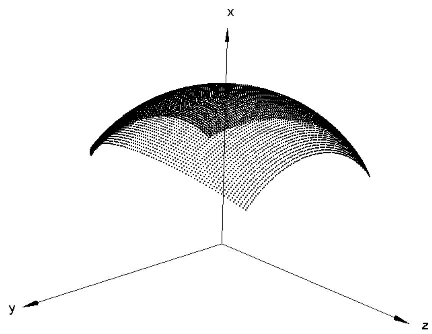


Figure 9 Spherical-sensors-segment

Another problem consists in that the EM response from the Earth, automatically accounted, can interfere with the response from the structure of interest. This happens because the earth doesn't have a strictly uniform structure and its EM properties (permittivity and conductivity) significantly change from point to point, and depend on the environmental conditions (temperature, humidity…). However, there always exists a special range of frequencies, where the effect of these heterogeneities is negligible, and the earth becomes nearly "transparent". For example, the humid, damp ground is most easily penetrated by frequencies from 100 MHz to 300 MHz within which damps is minimal. Now, taking into the account that the object of interest usually has completely different EM characteristics it is possible to use the ground-"transparent" frequencies to investigate the pure object-response. In order to increase solution accuracy and create criterions for stability and convergence observation we radiate the area of interest by a periodical EM impulse that carries the majority of ground - “transparent” frequencies spectrum (fig. 10). The pulse-delay time is limited by the condition that all the reflected waves must reach the corresponding sensors before the next cycle. For this purpose we need to have a pulse generator with a rather flexible, adjustable spectrum.

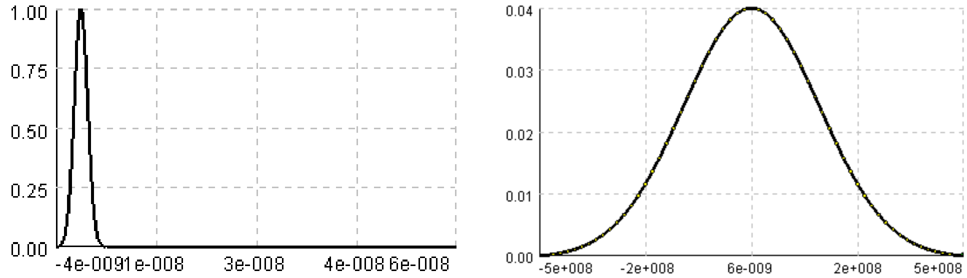


Figure 10 a , b Impulse time dependence (left) and spectrum (right)

After we measure the reflected wavefields on the remote sensor-surface we use a direct Fourier transform to obtain the responses for each of the spectral frequencies.

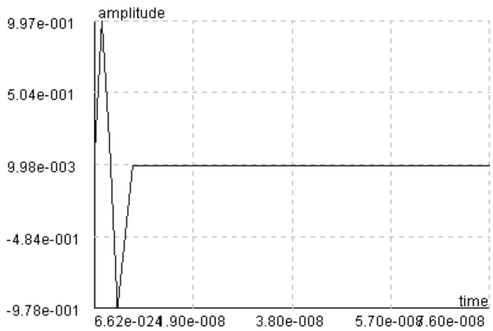


Figure 10c Impulse time dependence

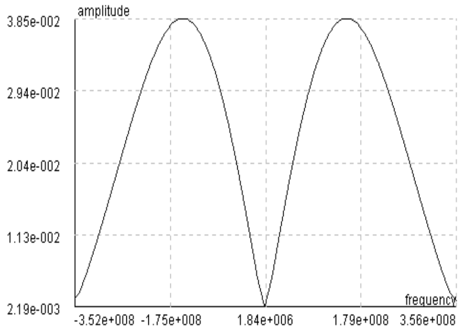


Figure 10d   Impulse spectrum

This data is consequently used in the slightly updated Method of Auxiliary Sources (MAS) in order to reconstruct the immersed object surface: a layer of auxiliary EM field sources is placed on the certain distance above the sensors. These sources are later used to describe the field reflected from the dielectric body. In order to determine their amplitudes (i.e. current distribution along the auxiliary surface) we’re required to put the boundary conditions on the wavefields across the sensor surface.

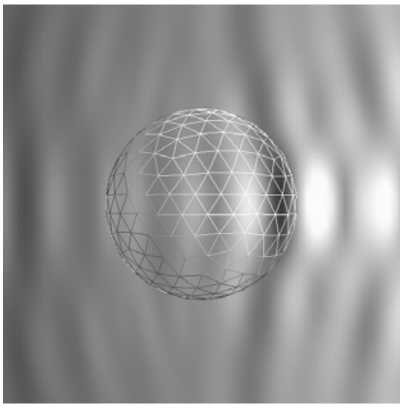


Figure 11 Single response-based sphere Element Reconstruction (black).

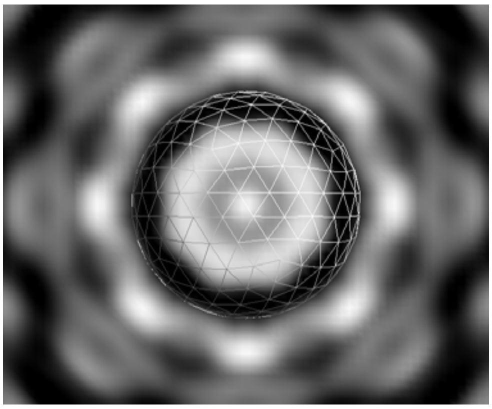


Figure 12 Reconstructed surface of a dielectric sphere (8 measurements)

(According traditional MAS, these boundary conditions arise from Maxwell equations and imply the continuity of tangential EM field components across the boundary) After that, knowing auxiliary sources amplitudes, we analytically continue the scattered field back to its singularities.

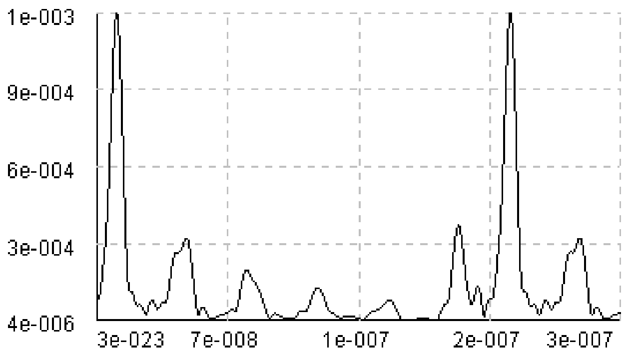


Figure 13 Impulse response from a sphere. 1st through 6th order reflections are visible.

For this purpose we just change the wavefield propagation direction for the auxiliary sources ("holographic" method) $\vec{k} \rightarrow -\vec{k}$ and add it to the incident wavefield. Lately [5], it has been proved, that the resulting "total" fields have minimums right in the vicinity of the object's boundary.

For experimental evaluations it is crucial, that the spherical layer segment of auxiliary sources best describes the fields only inside its corresponding spherical sector. That means, that in order to increase solution accuracy and improve the approach itself we have to make a series of overlapping measurements from different locations, once we encounter the part of the surface of interest. As an illustration, consider fig. 11 and fig. 12. First one presents the reconstructed fields from a single irradiation, while fig. 12 shows the combined result of 8 consequent measurements, conducted from different locations [5] (actually, in this case we first solved the direct scattering problem, and used those results to numerically recover the unknown surface). Note that the areas of minimal value of total reconstructed field correspond to the sphere surface (black area enclosing the triangulated surface). The actual (measured) responses from a sphere are shown on fig. 13 - ***dt*** is the time delay between two peaks, corresponding to first- and second-order reflections. Having found the surface geometry we can use these data to calculate already the dielectric parameters of the immersed body.

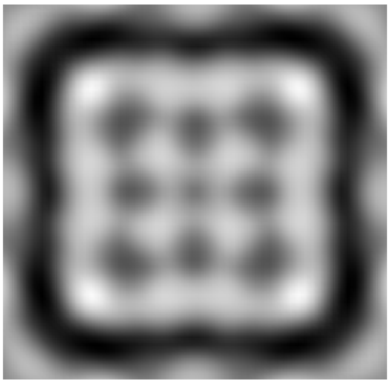


Figure 14 Surface reconstruction of a dielectric parallelepiped.

Fig. 14 represents the results of simulation of a rectangular box, with its contours perfectly visible. There are also some local minimums inside the box, but we focus only on the global ones.

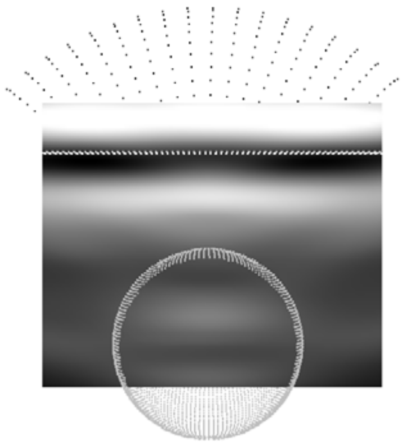


Figure 15 Surface reconstruction of a buried sphere. Sensors, earth and actual sphere surface are presented.
Global field minimum corresponds to earth boundary. Second order minimum – is that of the sphere upper cap.

Fig. 15 represents a part of a real-life scenario, when a buried spherical object is irradiated from above. Besides the actual surface of the body, there is another area of least-field-values just above it. It corresponds to Earth surface boundary, which represents a boundary of two media (earth-air). Anyway, this fact doesn't affect the precision of calculation of the surface of the object of interest.

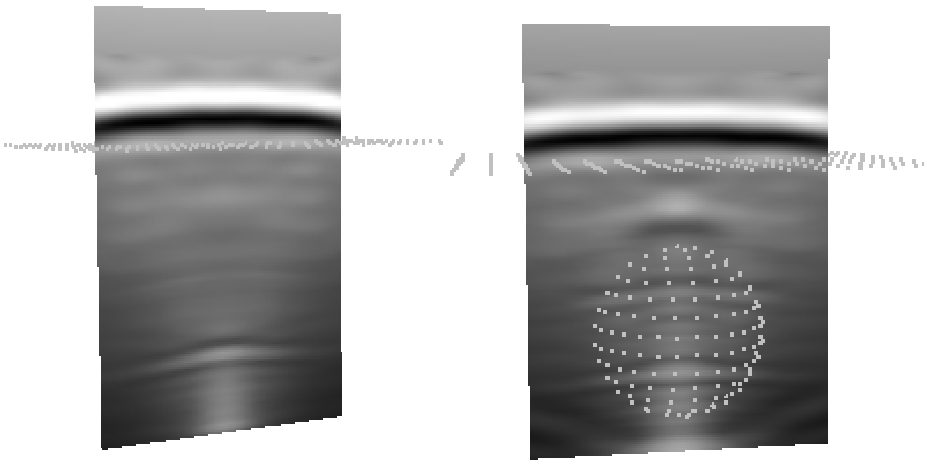


Figure 16 Field continuation without sphere (left) and spherical surface reconstruction (right)

Fig. 16 represents a part of a real-life scenario, when a spherical object, buried in the dry and sandy soil, is irradiated from above. Besides the actual surface of the body, there is other area of least-field-values just above it. It corresponds to Earth surface boundary, which represents a boundary of two media (earth-air). Anyway, this fact doesn't affect the precision of calculation of the surface of the object of interest. Fig. 17 also represents an investigation of immersed body [6]. First peak corresponds to reflection from ground. Second one corresponds to the reflection from the body itself. The amplitude lessens due to the absorption and dissipation.

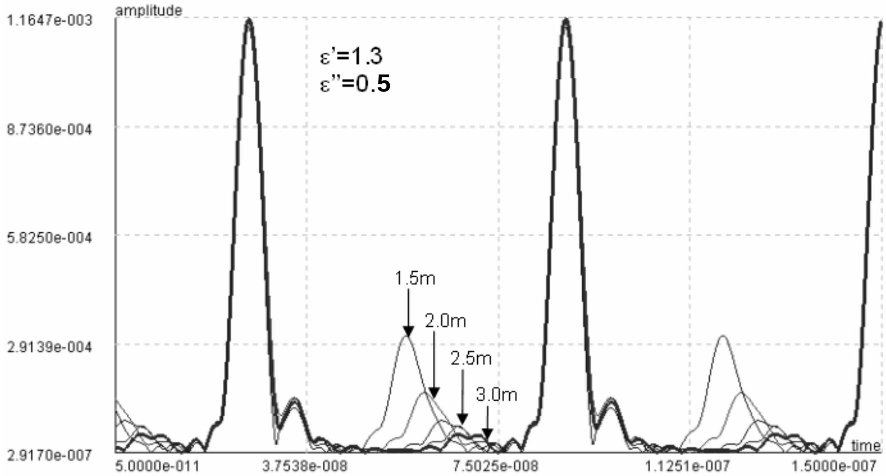


Figure 17 Investigation of body immersion
Impulse reflected from ground with different immersion depth

In real life situations, in order to reduce the total number of expensive sensors, we have checked the possibilities to reduce their total number on the segment surface. in the area between sensors.

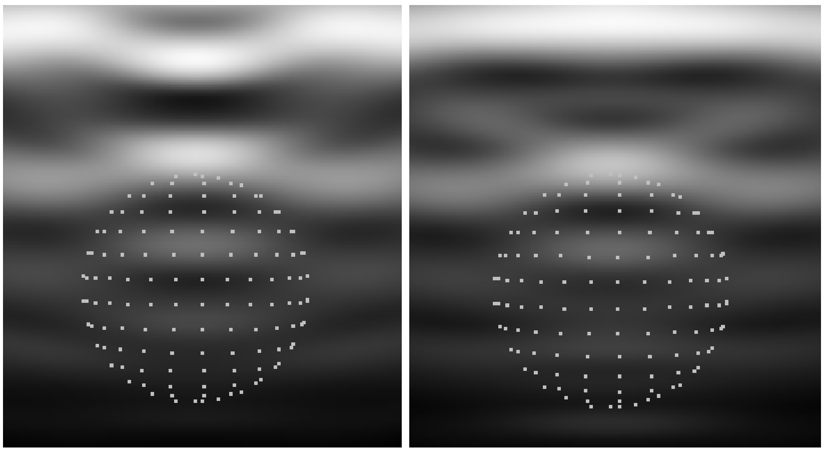


Figure 18 On the first picture the 11x11 sensor segment was used, while the second one corresponds to the interpolated data over 3x3-sensor segment.

The drawback is that we need to perform a certain number of interpolation procedures. The results are presented at Fig. 18. You may notice, that the difference in reconstructed surfaces in nearly negligible in cases of 11x11-precise and 3x3-interpolated evaluations. This makes it possible for us to test our numerical simulations and theoretical ideas in future with a satisfactory precision.

5. PHOTOGRAPHIC METHOD

Consider photographic method. The idea of this approach is to getting the brilliant image on screen just for desired plane of section we need to separate out. This one is very similar what is doing our eye or in photographic instrumentation. Let us assume that we have wave field in some section, coming from several sources, located on different distance from selected section (Fig. 19). Now if in this section would be lens with different focal distance **F**, on the projection plane on the right side of the lens we are getting brilliant image just of the sources or, generally, reradiated points of the object, located on the determinable space versus focal length of the lens.

Below, as examples, there is illustration of the foreside's idea. In Fig. 19 there are 3 sources, located in the same flat layer on the distance -6 and one source on the distance -4. We measure the field, radiated by these 4 sources on the lens surface.

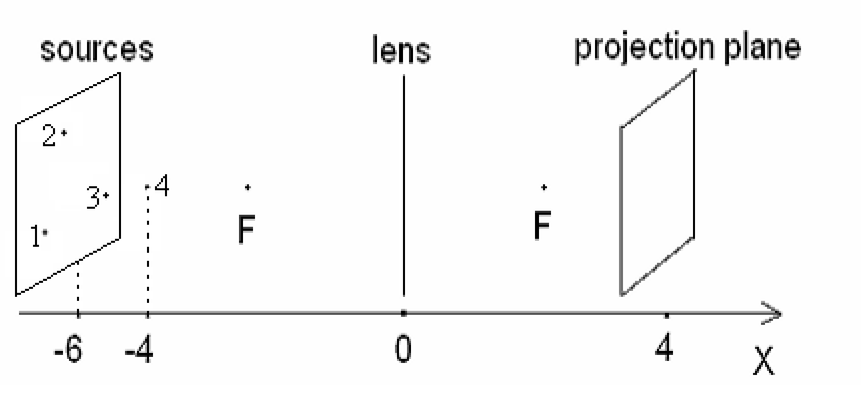
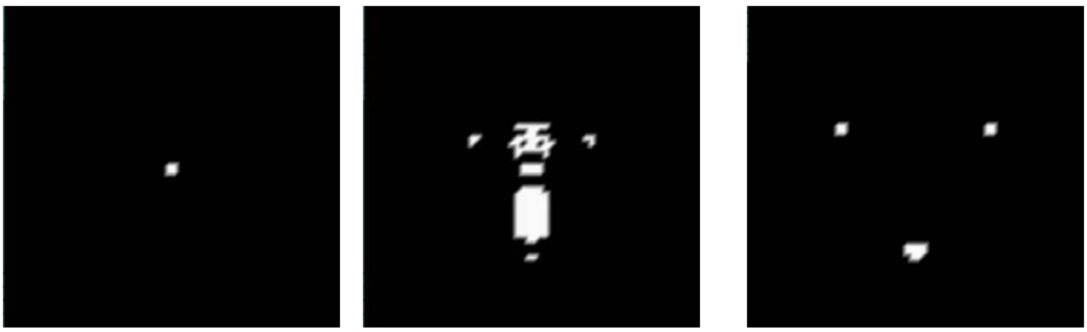


Figure 19 Photographic method

Then, by means of phases shifting and executing by imagined (fictitious) lens with variable focal distance, we are trying to get image of the sources on the project plane. In other words, each measured value in the lens plane we multiply on the phase shift which in real case make the lens and using analytical continuation we reconstruct field on the projection plane. (Fig.19)

So, we have 4 sources located in different distances and depending on the focal distance we get different image on the projection plane fig. 20. The first one a) the lens is in-focus image on 4 m. and corresponds to the just one source, located on distance 4m. As we can see there is just brilliant image of one source located on 4m and no images of 3 another sources, located deeply on distance 6m. The second one is in-focus image on 5 m. as an intermediate case. The image on the projection plane is as a washed picture of all sources and finally in c) is the brilliant image just three sources and no image of that one source, located closer to the lens.

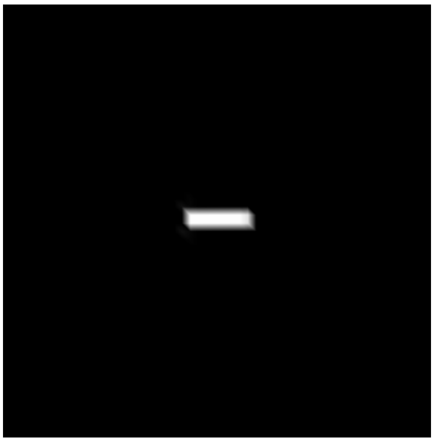


a) Scanning distance = - 4m   b) Scanning distance = - 5m   c) Scanning distance= -6m

Figure 20 4 sources image reconstruction using photographic method

Here it could be mention that distances between the sources are order of field's wavelength values and that is why around the images there is interference pattern. In case of higher frequency this images could be better. But the main advantage of the photographic image method is that in case of the additional nosy field from the source located outside of the interest area could be ignored completely!

Now we consider the comparison between holographic and photographic method. Fig. 21 represents one and two sources reconstruction case using photographic method (wave number k=20, distance between sources 0.6m)



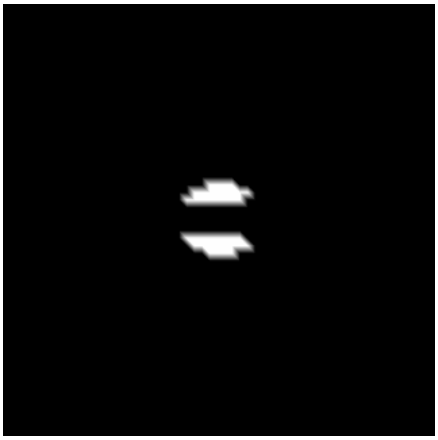
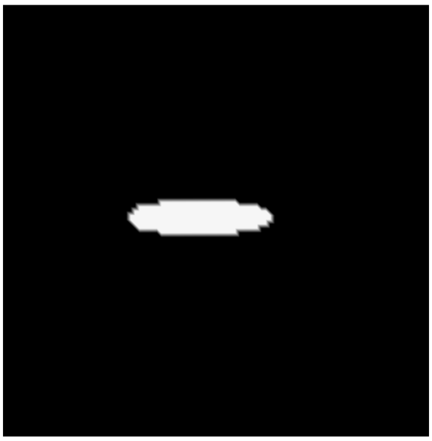


Figure 21 One and two source image reconstruction using photographic method

Fig. 22. shows the same for holographic method as we see photographic method gives better quality of reconstructed image.



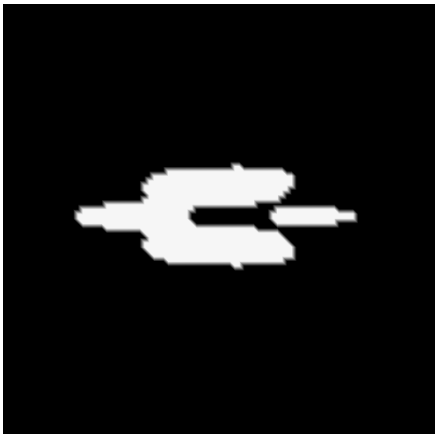


Figure 22 One and two source image reconstruction using holographic method

6. BURIED OBJECTS VISUALIZATION USING HOLOGRAPHIC+PHOTOGRAPHIC METHOD

Experiment scheme is presented on Fig. 23. It is quite similar to the previous one, except for the presence of buried body. Our goal is by means of analyzing reflected signal visualize any object in the examined area.

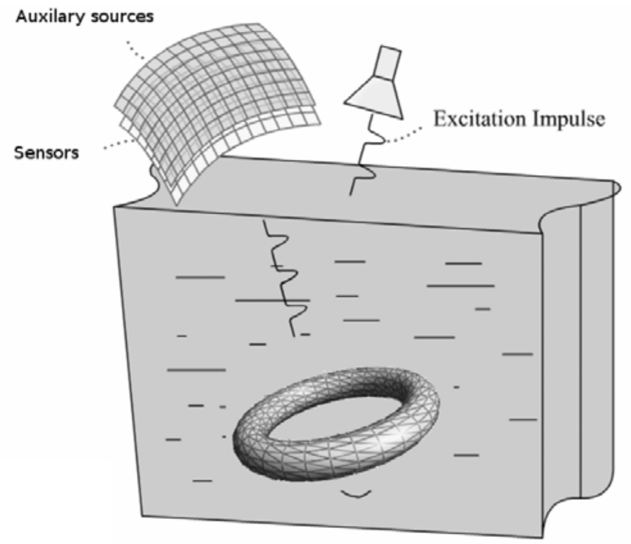


Figure 23 Experiment scheme

Now when we know the frequency range the given soil is more or less transparent to, we can form the sounding impulse the way it would penetrate deep enough into the earth. There are several methods of visualization which can be applied here. The best results were obtained using so called: holographic - photographical method with developed ideas, presented in [5, 6].

It is based on the MAS (Method of Auxiliary Sources [1]) and the same principle, an image is being formed in the human's eye. The key idea of proposed method is following: after the reflected signal is being measured, first we are using holographic method to build the analytical continuation of the wave field, and then we place an imaginary lens parallel to the grid's plane surface. Being able to build the analytical continuation of field in the selected area, and changing lens parameters (focal distance) we are able to get a series of images that represent corresponding slices of examined area. Obtained results with different lens focal distance for a buried torus are presented on the following sequence of images (Fig. 24, a-f).

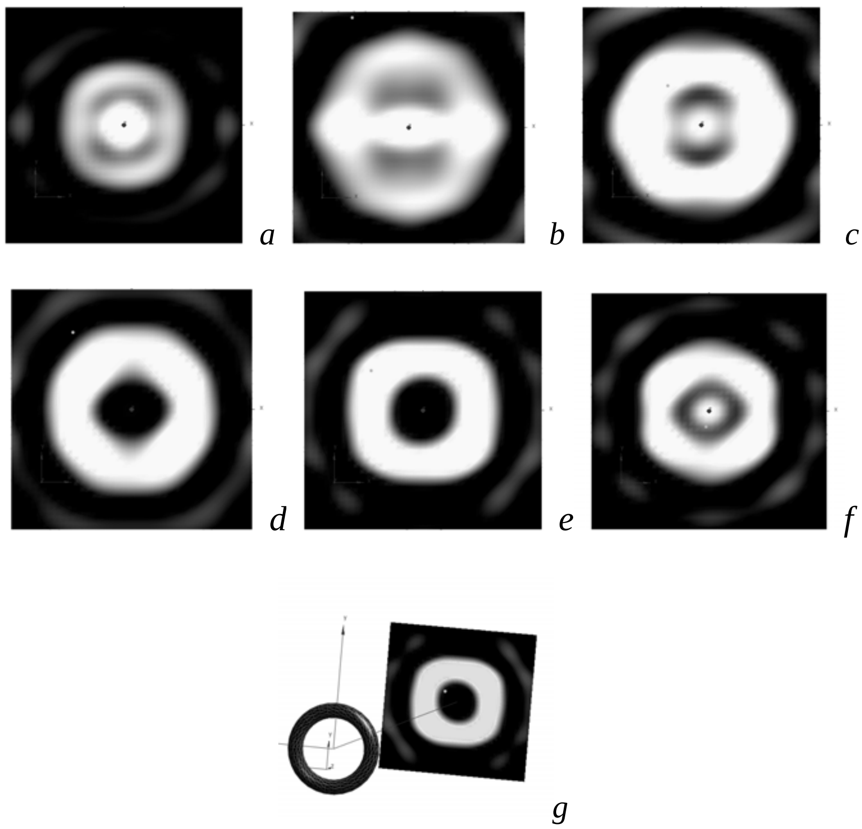
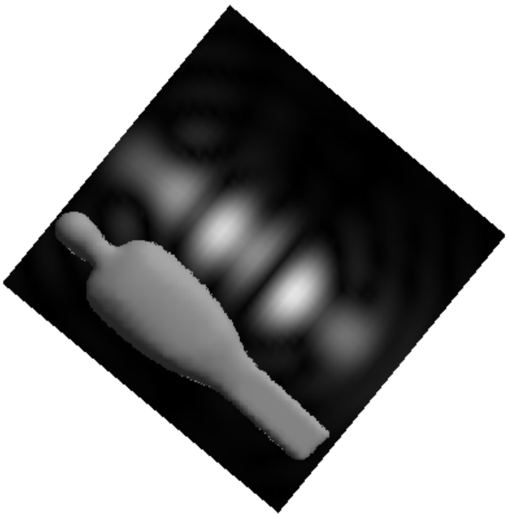
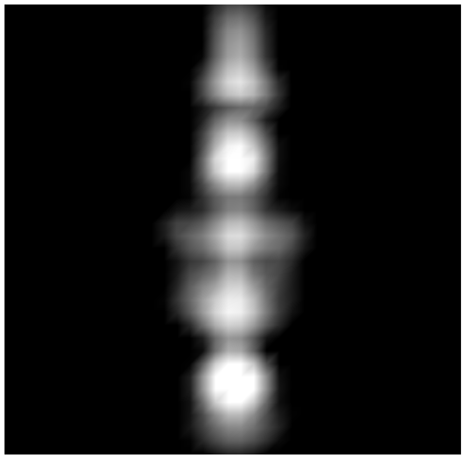


Figure 24 Torus shape reconstruction

Fig. 24,g shows how the shape of the latent object (torus) conforms to the obtained image. The focal distance for the image with highest gradient distribution corresponds to the buried body position (Fig. 24, e), and the image itself conforms to the buried body shape. Fig. 25 represents human body surface reconstruction. a) Corresponds



a)



b)

Figure 25 Human body reconstructions

a) Reconstruction with one frequency
b) Reconstruction with three frequencies

to the reconstruction with one frequency and b) corresponds to the reconstruction with three frequency image superposition. As we can see the images are overturned.

As it appeared during the simulation process, in case of metallic body, electric currents induced on its surface, and as a result an obtained image of the object have sharp, clear-cut just that parts where are induced high current. This problem could be arise in case of using plane-linear polarized pulse. This can be avoided if two impulses with perpendicular polarization are used and both obtained images are merged. Generally, it is better to use circular polarized pulse.

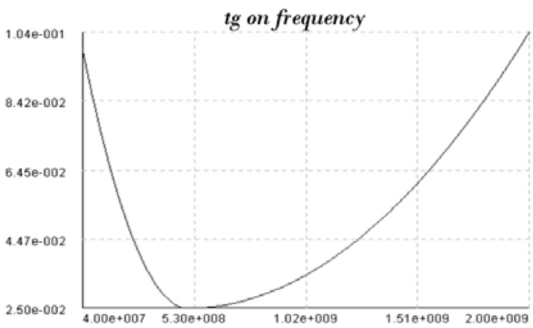


Figure 26 Loss tg dependence on frequency

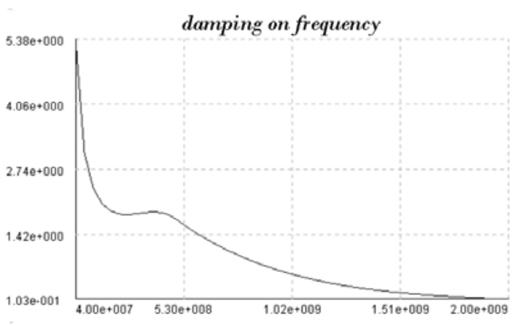


Figure 27 Damping dependence on frequency

Speaking about a buried body's shape visualization it is also very important to consider the damping of signal.

As a result of numerical experiment for the know in literature dependency of loss tg on frequency for wet sandy soil (Fig. 26), we obtain the dependency of damping on frequency.

As it can be seen from Fig. 27, waves with low frequencies penetrate easily into the soil but the resolution is very low due to the big wavelength, an extremum can also be observed near 500 MHz. Sounding at that frequency gives an adequate resolution and field penetrates deep enough into the soil, it damps ***e*** times at the depth of 2 meters.

a) $\nu_1 = 1.3Ghz$

b) $\nu_1 = 1.3Ghz, \varphi_1 = 0$
$\nu_2 = 1.13Ghz, \varphi_2 = 4.3$

c) $\nu_1 = 1.3Ghz, \varphi_1 = 0$
$\nu_2 = 1.13Ghz, \varphi_2 = 4.3$
$\nu_3 = 0.88Ghz, \varphi_3 = 4.5$

Figure 28
Torus surface reconstruction
a) One frequency case
b) Two frequencies case
c) Three frequencies case

Fig. 28 represents torus surface reconstruction using superposition several frequencies. Case a) corresponds to one frequency and as we can see image quality is not good we see extra fields near torus surface. If we use two frequencies with phase difference showed on the Fig. 28 b) we get image with better quality but there are field values inside of torus, and when we consider three frequency case when their phases are in relation shoved on the Fig. 28 c) we get the best quality of reconstructed image the frequencies are chosen not arbitrarily they are in relation as in visible light base colors (red, green, blue) this relation is 0.69:0.85:1.

During real experiment we must consider sensor characteristic because it changes measuring impulse. Reflected impulse contains also the noise and we have to except it from measured impulse [7].

CONCLUSION

A new approach of remote exploration of buried bodies by means of pulse irradiation is presented. The way to overcome losses and heterogeneities of the earth layers are discussed. The results of some software simulations of surface reconstruction are presented. Further investigation directions are outlined.

There are presented results for the holographic/photographical method of immersed body visualization. In the future, creation of an image recognition system for existing software package is planned.

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