Modeling of the reflected signal of a ground penetrating radar

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Abstract. The objective of this paper is the simplified model of the reflected signal during subsurface sounding. Physical processes which influence the propagation of the electromagnetic wave are examined in the article. The process of accounting for reflecting local objects situated in the path of the sounding signal propagation is explained in the article. The proposed model is implemented in MatLab software.

1. Introduction
Subsurface radiolocation is a developing technical field with many practical applications. The emission of ultra-wideband (UWB) pulses and the reception of electromagnetic waves (EMW), which are reflected from the boundaries of media and the probed objects with different electrophysical properties, are the essence of the subsurface radar sounding method. Modeling the physical properties of the medium under study and the signal reflected from it is useful both in the development of ground penetrating radars (GPR) and in the further processing of experimental data. Preparatory modeling helps in the development of a GPR. For example, it helps choosing the speed of the locator moving over the surface under study, the type of initial pulse and parameters that characterize its energy. Subsurface sounding allows exploring various optically opaque media without using of damaging effects. For example, such media can be ice and earth covers, reinforced ferroconcrete and various anthropogenic road covers. A GPR is often used for geological research to determine the holes, rock boundaries, etc. The search for buried local objects such as mines and unexploded ordnance, cables, pipes and so on are determined by sounding of the medium in which these objects are located. A GPR can also be used for research in the ecology, for example, to determine the thickness of oil films that occur when it spills on the surface of water [1–3].

Despite the wide variety of tasks of the subsurface radiolocation, as a rule, all of them can be divided into 2 large groups. The first group includes geological, hydrogeological and engineering-geological tasks, and the second - the search for local objects as well as the examination of engineering structures and violations of the standard situation.

2. Physical processes arising by ground penetrating sounding
Waves whose lengths are in the meter range are used for ground penetrating radar studies. The propagation of these waves in media obeys the laws of geometric optics (Fermat's principle, Snell's law, Huygens–Fresnel principle). In this case at large distances from the source the wave is considered flat and at small distances – spherical [3–5].

The propagation of electromagnetic waves (EMW) during subsurface sounding differs significantly from the propagation in a free medium. First of all, this is due to the large attenuation of the signals
arriving at the input of the receiver, so receiver work is done with small signals. The magnetic and dielectric constants of the medium are those indicators on which the propagation velocity of an electromagnetic wave depends. The magnetic permeability $\mu$ is approximately equal to 1 and does not depend on the field frequency for most media. Then the wave propagation velocity $V$ is equal to [6]:

$$V = \frac{c}{\sqrt{\mu_r \varepsilon_r}} = \frac{c}{\sqrt{\mu_0 \varepsilon_0}}$$

where $c = 1/\sqrt{\mu_0 \varepsilon_0}$, $c$ is the velocity of light, $\mu_0$ and $\varepsilon_0$ are the magnetic and dielectric permittivities in vacuum. EMW velocity is one of the main characteristics of the medium in radar research.

The propagation of electromagnetic waves in the ground is determined by such physical processes as reflection, refraction, diffraction and attenuation. Let us consider each of these physical phenomena.

2.1. Reflection
Let us consider the reflection from the interface between two layers of a material. It is directly determined by the dielectric permittivity of these layers. In general, the dielectric constant ($\varepsilon$) consists of two parts (real ($\varepsilon'$) and imaginary ($\varepsilon''$)):

$$\varepsilon = \varepsilon' - j\varepsilon''$$

The imaginary part is associated with the final conductivity of the dielectric, and the real part is associated with the polarization of the dielectric when a field is applied to it. Reflection coefficients can be calculated by the formula (1) [4,7]:

$$K_{rfl} = \frac{\sqrt{\varepsilon'_1 - \varepsilon'_2}}{\sqrt{\varepsilon'_1 + \varepsilon'_2}}$$

2.2. Refraction
Refraction, like reflection, is determined by the dielectric constant of two adjacent layers. Refraction is quantified by the refractive coefficient, or, as it is also called, the coefficient of passage through the boundary:

$$K_{rfr} = 1 - K_{rfl} = \frac{2\sqrt{\varepsilon'_2}}{\sqrt{\varepsilon'_1} + \sqrt{\varepsilon'_2}}$$

Double passage introduces a total attenuation equal to:

$$1 - K^2_{rfl}$$

An EMW can pass through the same boundary twice, for example, when reflected from the boundary located at a farther distance from the surface [4].

2.3. Diffraction
The mathematical description of diffraction is very difficult. Diffraction arises if the size of the reflecting object is less than the predominant wavelength of the irradiating signal. According to the Huygens principle, each point of the wave front represents a secondary source of waves. As a result, the entire investigated object can be considered a secondary source of electromagnetic waves. For the subsurface radio location this phenomenon is extremely important because finding of local objects means to search secondary radiation sources in the image obtained using a GPR. This makes it possible not only to determine the presence but also the depth of the object as well as the speed of propagation of electromagnetic waves in the medium above the target [4, 5].

2.4. Attenuation
The term attenuation means a general decrease in the amplitude of the emitted GPR signal when the signal passes through the medium to the reflecting boundary and backward. The decrease in amplitude is due to the following factors [4]:

- refraction and reflection at intermediate boundaries;
• losses due to the final conductivity of the medium;
• geometric divergence of the wave front.

At a large distance from the source the wave front can be considered flat, and the influence of the last factor can be neglected. The geometric discrepancy significantly affects only at small distances from the source when the wave can be considered spherical. Then the amplitude decreases inversely with the distance from the source (radius of the sphere $R$) $^4,5$:

$$K_{div} = \frac{1}{R}.$$  

In calculating the decrease in amplitude due to the divergence of the spherical front, the distance from the source $R$ is taken as the doubled depth of the reflecting surface $(2h)$.

The amplitude of the signal reflected from the boundary at a depth of $h$ (in meters) $^4,7$:

$$A_H = A_0 K_{rfl} \prod_{k=1}^{n} \left(1 - K_{i rfl}^2\right) e^{-\frac{\tilde{A} h}{2h}},$$

where $A_0$ is the amplitude of the emitted signal at a distance of 1 m from the source, the product $\prod_{k=1}^{n} \left(1 - K_{i rfl}^2\right)$ takes into account the passage through the intermediate boundaries; $K_{rfl}$ - the reflection coefficient from the border at a depth of $h$; $\tilde{A}$ is the specific attenuation expressed in dB / m.

3. Reflection from local objects
Reflection from objects located in the ground can be characterized by the value of the radar cross section (RCS, $\sigma$).

For modeling we take a simplified model of the reflector taking into account the fact that the effective scattering surface of the object is described by the formula $^8$:

$$\sigma = 4\pi D^2 \frac{I_2}{I_1},$$  

where $D$ is the distance to the target, $I_2$ is the intensity of the reflected signal, $I_1$ is the intensity of the incident radiation at the object.

From the formula (2) we can conclude that the formula for calculating the RCS consists of two factors, the first $(4\pi D^2)$ – related to the range to the target, the second $(I_2/I_1)$ - makes sense of the reflection coefficient.

For calculations within the framework of the proposed model, it is necessary to bring the value of the RCS of the object to the dimensionless values accepted in the model, this value is the ratio of the signals incident on the object and reflected by the object ($K_{obj} = I_2/I_1$). This ratio for a given RCS and a known depth can be obtained as:

$$K_{obj} = \frac{4\pi D^2}{\sigma}.$$  

In the framework of the proposed model for calculating the pulse response of the medium at the site of the object, the reflection coefficient $K_{rfl}$ is replaced by $K_{obj}$. Note that the proposed model at this stage involves modeling objects with dimensions not exceeding the first Fresnel zone.

4. Modelling
Let us consider the algorithm of the program, which is presented in the figure 1.
The input of the initial data includes the input of data on the propagation medium, namely, the layers and their dielectric permittivities, the input of data on local objects if it is necessary, and choosing of the probe signal. In the simulation, two types of signals were used: a Gaussian monocycle and a short radio pulse.

By forming a calculation step is meant a transition to dimensionless numerical quantities convenient for calculation.

Let us consider in detail the calculation of the pulse response of the propagation medium. First, you need to create a distribution medium model. It is an array of permittivities located at appropriate depths. Next, the reflection coefficients are calculated by the formula (1). To take into account the presence of local reflectors, we replace the reflection coefficients corresponding to their location calculated by formula (1) by reflection coefficients calculated by formula (3) because the reflection coefficient from point objects is determined by their RCS. Then we find the attenuation coefficients and by multiplying the matrices of reflection and attenuation coefficients we directly calculate the pulse response of the medium by the formula (4) [5]:

$$g(k) = K_{ref} \cdot K_{att} = \frac{K_{ref} \cdot e^{\exp(-\frac{\mathcal{A}2\rho}{2h})}}{2h}.$$  \hspace{1cm} (4)

The reflected signal is the result of the passage of the probe signal through the filter in the form of a propagation medium. Therefore, to calculate the reflected signal, we use the convolution of the pulse response of the medium and the probe signal. The resulting reflected signal is formed by summing the reflected signals at each depth according to the formula (5) [5]:

$$S_{x,t} = \sum_{\varphi} S_{x,h}. \hspace{1cm} (5)$$

By depth is meant the radius of a sphere centered at the location of the GPR.

Transformation of the result means the transition from array elements to meters and seconds.

At the end of the program, graphs of the propagation medium and the signal reflected from it are output.
5. Results
Let us consider the simulation results. Figure 2 shows the structure of the modeled section. The white indicates dry sand with a permittivity of $\varepsilon=5$, the black – wet sand $\varepsilon=23$ and the gray – clay $\varepsilon=10$.

The signal at the input of a subsurface locator receiver in the section under consideration with a length of 10 meters is shown in figure 3. The amplitude of the reflected signal is shown by the brightness on a linear scale. The figure shows that the greatest reflection occurs from the border of media with the maximum difference in permittivity (dry and wet sands). The signal reflected from the border of wet sand and clay has a strong attenuation due to the weakening of the signal when passing through the first section of media and the layer of wet sand.

![Figure 2. Modeling area.](image)

Let us also consider the results of modeling the reflection from a point reflecting object buried in dry sand at a depth of 1.5 meters. The simulation was performed for two signals with a central frequency of 900 MHz (figure 4) and 450 MHz (figure 5). The figures show that due to the signal attenuation the size of the diffraction hyperbola is significantly smaller at a higher frequency. This completely coincides with the theoretical data and measurement results described in the literature.
Figure 3. Model of received signal from underground area. Using 900 MHz.

Figure 4. Model of received signal from local object. Using 900 MHz.
6. Conclusion
The considered algorithm for modeling the subsurface locator signal takes into account the main processes that affect the detection depth. The model of the reflected signal of a subsurface locator has low requirements for computing resources. The results of modeling both for reflections from the interface of heterogeneous soils and for reflections from point objects are in good agreement with the results of measurements presented in scientific articles.

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