SIMULATION OF SUBSURFACE ELECTROMAGNETIC WAVE PROPAGATION AND SCATTERING

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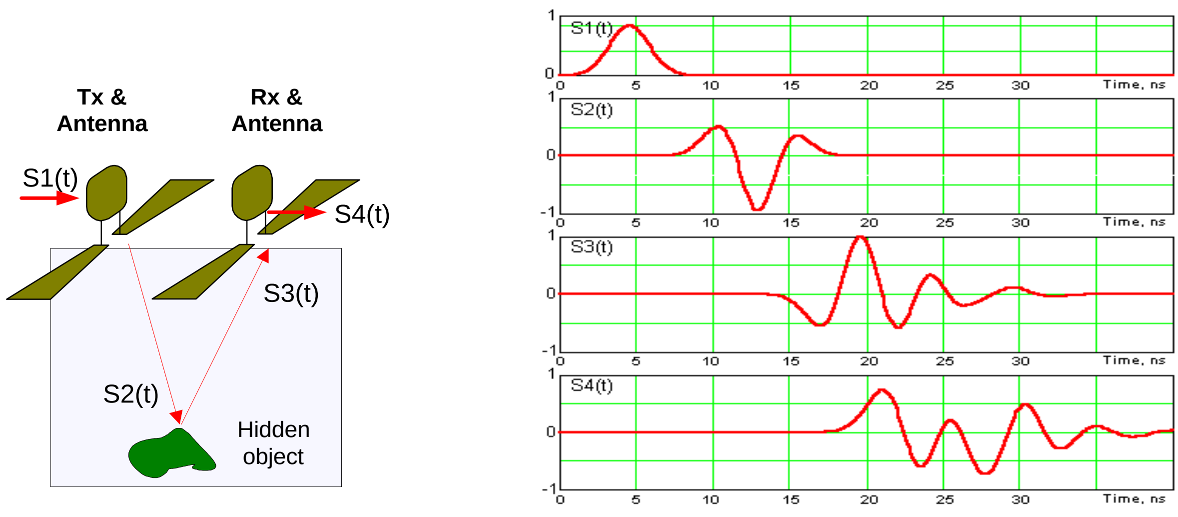
INTRODUCTION

A subsurface radar technique is used for a microwave non-invasive probing in opaque regions in soils, rocks, fresh water, brick, concrete etc. There is an inherent complexity of a subsurface radar survey some. Unavoidable features of a radar functioning, numerous wave propagation and scattering events complicate seriously a radar data processing and an interpretation [3]. Such electromagnetic events in subsurface radar involve:

1) dispersion effects caused namely by internal water in matter in a used microwave band [1],
2) various wave propagation phenomena like a multipath propagation [1], lateral waves [1,4] etc.,
3) strong diffraction events forced by comparability of magnitude of used wave-lengths and dimensions of subsurface finite-size objects should be detected by radar [3],
4) subsurface clutters and a statistical heterogeneity common for internal regions and a surface roughness,
5) inherent physical properties of a ultra-wide band (UWB) radiation and reception by transient antennas [2] as well as a UWB scattering by finite-sized targets including the effect of near-field range.

A basic arrangement of subsurface radar is shown in Fig. 1a with the simulated characteristic waveforms *S1…4(t)* in Fig. 1b for all specific points in a radar radio channel [2]. Two dipole antennas under a double passing excitation [2] form this radar radio channel. A waveform *S1(t)* is an excitation signal for a transmitting (Tx) antenna that produced a signal *S2(t)*, which is differ to *S1(t)* and illuminates a subsurface target. Due to scattering this target generates an echo pulse signal *S3(t)* that reaches a receiving antenna (Rx). Signal *S3(t)* embodies the specific features of a target like additional ringing signal in its waveform. Finally the resulting signal in an antenna load has a waveform *S4(t)* that is quite different from an original waveform *S1(t)*. The presented data in Fig. 1b obtained by simulation in time-domain (TD) illustrate an inherent complexity of signal transformation in subsurface radar especially due to influence of the near-filed effects. There are the two main research approaches in time-domain and in frequency-domain (FD that can be applied for investigation of the all effects on subsurface radar. Deterministic and statistical simulations should be employed for these goals also. This submission will present the applications of some TD and FD techniques developed for simulation of subsurface radar returns and making easy an interpretation of real field radar data.



a) b)

Fig. 1. (a) Subsurface radar arrangement in bistatic mode with transmitting (Tx) and receiving (Rx) antennas to detect a hidden object inside medium. (b) Characteristic waveform in a radar radio channel in accordance to (a).

SIMULATION IN FREQUENCY-DOMAIN

A FD simulation of subsurface radar is preferable in some cases due to the following reasons. A FD technique is very advanced now and some of its approaches may be employed here like the T and S wave matrixes. Numerically effective technique such as the Fast Fourier Transform (FFT) can be used for an appropriate computing. Some aspects of considered branch of electromagnetics like as the frequency dispersion effect are easier for its treatment in FD. Let consider a FD simulation of a subsurface radar sounding in a typical problem involves a radar non-invasive testing of a limestone wall to estimate its internal volumetric water content.

Frequency Dispersion Effect

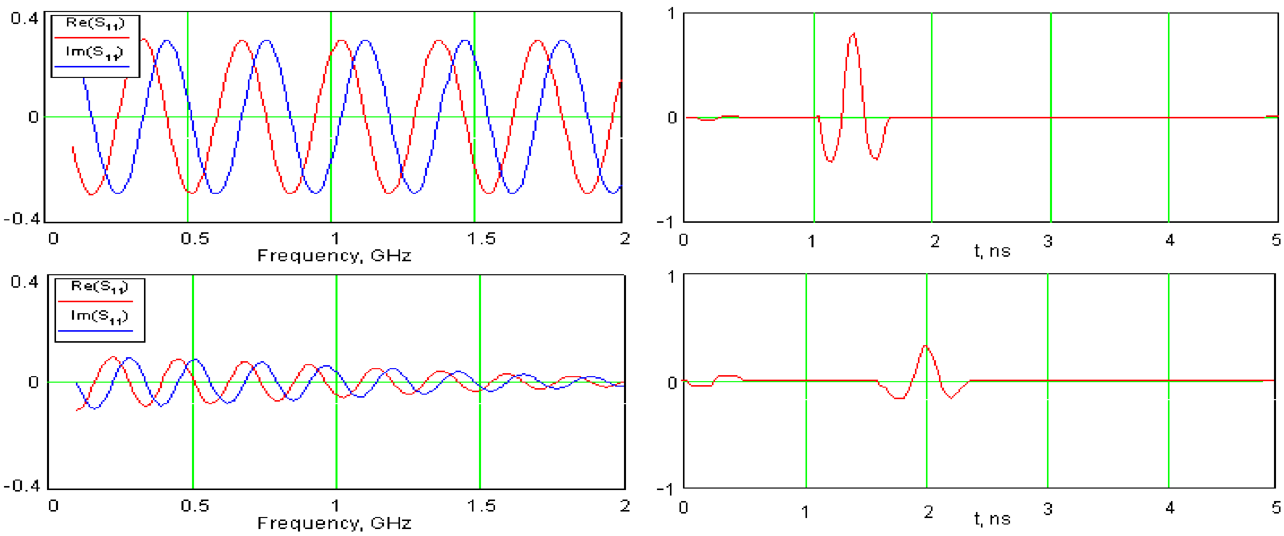
An internal water inside sounding matter is a most disturbance factor due to the strong dispersion in the 100 MHz –10 GHz microwave frequency range caused by a resonance adsorption of electromagnetic energy in water [1]. Fig. 2 illustrates how both the real and image parts of dielectric constant are changing versus frequency and humidity levels that based on the Debay's model [1] and binary model of wetted medium formed by dry matter and water inside it.

2-D Simulation of Layered Medium

Using a simple waveform similar to *S2(t)* in Fig. 1b with 0.5-ns duration of main signal lobe and a T-matrix technique to present a layer one is able computing both the frequency and the time responses of a single-layered medium formed by a limestone wall of 25-cm thickness. Fig. 3a corresponds to a dry wall while Fig. 3b shows a case with 5% volumetric water content. Dispersion phenomena such as a stretching in time with corresponding spectrum transformation, a time delay due to velocity modification and a signal attenuation caused by growing of the image part of dielectric constant are clear visible in Fig. 3.

a) b)

Fig. 2. Real (a) and image (b) parts of dielectric constant of limestone with volumetric water content 0…30%.



a) b)

Fig. 3. Frequency (a) and time (b) responses of one layered medium formed by a limestone wall of 25-cm thickness in dry state (the upper pair of figures) and with 5 per cents internal humidity (the lower figures).

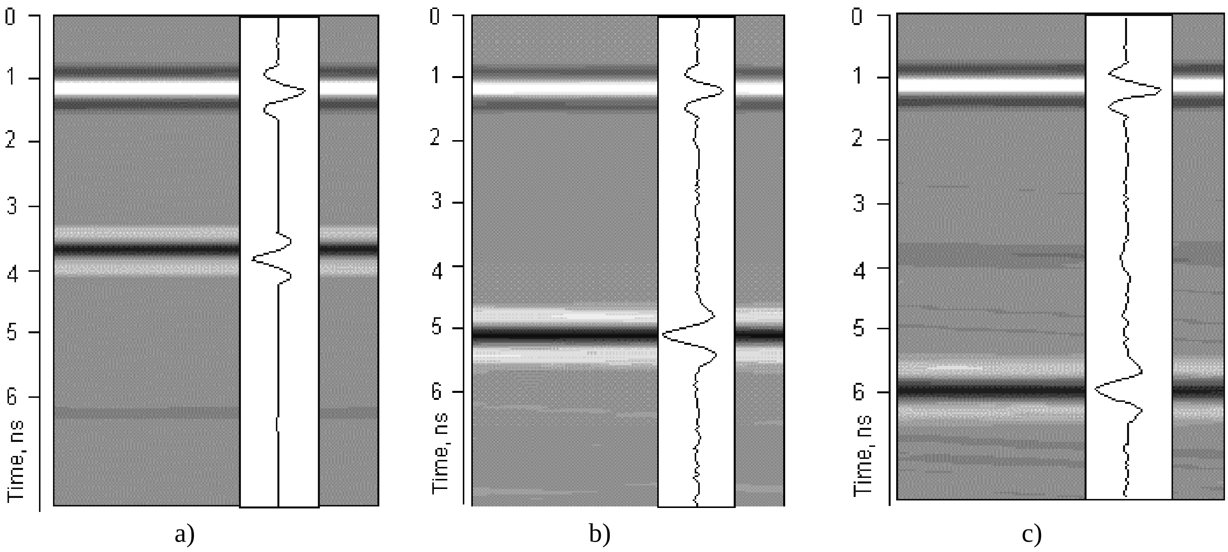


Fig. 4. Simulated radargram for 40-cm limestone wall for operation conditions and radar setting: (a) dry matter, w/o automatic gain control (AGC); (b) 5% humidity, linear AGC ranged 10 dB; (d) 10% humidity, linear 10 dB AGC.

Data above in Fig. 4 illustrate a simulated radar cross-section of a 40-cm limestone wall with different magnitudes of volumetric water content resulted in a signal stretching in time and a signal amplitude attenuation. The upper part of each radargram contains a direct-coupling signal between the Tx and Rx antennas also. The second reflection from a backside of wall is visible in Fig. 4a as well as the random disturbances are observed in Fig. 4c that is modeled by developed simulation stochastic technique. Note those presented in Fig. 4 synthetic radargrams describe a simple case of subsurface scatterer, i.e. a layered medium with infinite horizontal borders. The more complex by their shape targets are treated in the next section by a TD technique.

SIMULATIONS IN TIME-DOMAIN

This approach allows specifying some principal features of subsurface sounding that are difficult for their analysis by a FD technique. A time-domain physical-optics (TD-PO) model is involved in the presented research too.

Time-Domain Physical-Optics Model

In order to simulate TD wave scattering phenomena, a modified Huygen's principal to build a TD-PO model is used. In accordance to a bistatic setup of radar's antennas (Fig. 1a) the Tx and Rx antennas are located on the border of the dielectric half-spaces with quite different electrical features. Only those components of diffracted waves are valuable for this analysis that reached the Rx antenna after scattering by a subsurface target. For simplicity, a waveform of receiving signal *Rx(t)* can be expressed as a linear sum of delayed and weighted *N* copies of a waveform of signal *Tx(t)* radiated by the Tx antenna, i.e.

$$Rx(t) = \sum_{i=1}^{N} a_i \cdot Tx(t - t_i) \qquad (1)$$

The retarded time t_i in (1) is determined by a time-delay along an *i*-ray trajectory. A factor a_i is product of pattern functions of the both antennas as well as reflection factor and pattern function of elementary sections (the Huygen's element) on a scattering surface. For verification of diffraction TD-PO model (1) let consider its application to ascertain relation of physical optics and rays optics applied to solve subsurface diffraction problems. A test medium with the two layers with various dielectric constants ε1 < ε2 is shown in Fig. 5a. There is possibility also to install the receiving antenna on the both sides of medium with ε2. The result of numerical simulation using (1) in the left part of Fig. 5a demonstrates an outstanding fact that among possible variety of ray trajectories only those ones form a radar image that corresponds directly to the Snails law of geometrical optics.

Due to low directivity features of a transient antenna [2], the synthetic-aperture technique is employed to locate and image a spatial position of a hidden subsurface object with acceptable spatial resolution. This technique is implemented by continues moving or step-by-step replacement of a bistatic pair of Tx-Rx antennas along a transect line laid over a medium under radar survey. The left parts of Fig. 5 b,c,d show an original geometry of a task and the right ones are simulated radar images that include a direct coupling component in the upper part also. As seen in Fig. 5 the edge effect due to finite size of a subsurface target causes strong diffraction events.

SUMMARY

A simulation of radar returns is useful to study physical nature of problems as well as to recognize a subsurface object by comparison of a real radar image and simulated one. Moreover the proposed TD-PO model of subsurface scattering illustrates remarkably a connection between geometrical and physical optics. The presented FD and TD models are quite simple that other approaches implemented by labour numerical approaches. The developed simulation techniques give a clear physical meaning and can be employed without tremendous programming efforts rather by using of mathematical software like Matlab, Mathcad etc. The last fact is very important for academic goals too. An numerically effective simulator of subsurface radar scenes involved principal radar subsystems, targets and features of operational environment is in advance now that based on a optimal combining both the TD and the FD techniques.

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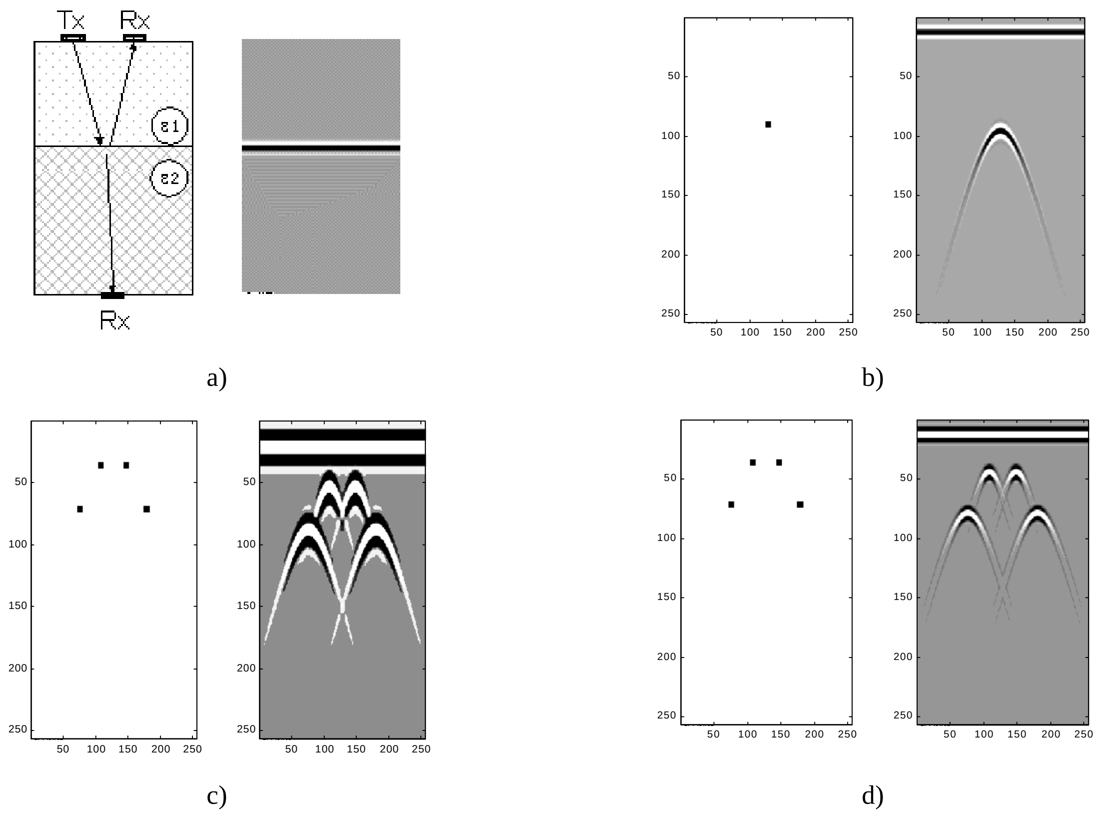

Fig. 3. (a) Numerical TD-PO simulation to install a relation between wave scattering model based on the Huygen’s principal of physical optics and ray-based geometrical optics model. Computer TD-PO simulation of the radar imaging: (b) quasi-point scattering object, four-poit discrete target in low-(c) and high (d) frequency bands.