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Time-Domain Physical-Optics Simulation Technique for Electromagnetic Imaging by Subsurface Radar

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Abstract – **This paper presents a 2-D scalar numerical time-domain (TD) model based on physical optics (PO) for simulation of electromagnetic phenomena. This TD-PO model should be applied for detection and location of objects hidden in opaque media by subsurface TD radar system. The proposed approach allows considering of basic physical principles, governing electromagnetic radiation and scattering and reception, to form electromagnetic image of subsurface region by simulation of radar returns based on TD- PO model. The TD-PO model is very preferable due to its high numerical efficiency and clear physical meaning.**

I. INTRODUCTION

Detection and localization as well as discrimination of the objects hidden in opaque media (soils, rocks, ice, brick, concrete, vegetation etc.) by subsurface radar or ground-penetrating radar (GPR) are important for worldwide scientific and engineering practice as valuable technology of remote sensing and noninvasive control [1]. Key features of operation of impulse subsurface radar to simulate it will be considered in this paper. In general, operation of the subsurface radar is based on registration and processing of electromagnetic fields scattered by internal heterogeneity of a medium under investigation. Practical opportunities of subsurface radar to study real problems is often limited due to complexity of interpretation of scattered fields to restore original problem's geometry by processing the radar data registered.

In spite of the large amount of works on direct/inverse subsurface electromagnetic scattering, the authors were not able to locate any research where consideration of problem was preferable for own field GPR practice entirely. What is matter? Of course, there are many interest papers on GPR problems like [1,2,7]. But complex theoretical models characterize those studies for particular cases that demands high level of mathematical experience and tremendous computing efforts like for FDTD approaches. At the same time, there are also other simple simulation methods based on geometrical optics with unavoidable restrictions to apply directly for finite-sized and near-range targets where plane-wave model is incorrect etc.

This paper is devoted to obtain simple effective time-domain (TD) physical-optics (PO) model with clear physical picture of electromagnetic events and some opportunities to estimate problem qualitatively from parametric point of view. There are the three subsets of parameters specifying the three key components of problem, i.e. (1)-transmitting (Tx) and receiving (Rx) antennas installed near the border between two half-spaces, (2)-subsurface medium and (3)-hidden objects should be detected (Fig. 1).

The problem will be considered here in TD that is more preferable and adequate due to its inherent physics in contrast to frequency-domain (FD) because the transformation of signal waveform of transient nature is key moment of TD radar operation. Moreover, transient mode of impulse radars can be considered in FD as so called ultra-wide operation as result of using of electromagnetic signals with their total bandwidth compared to the middle value of frequency in signal's spectrum [5].

A general geometry of problem is presented in Fig. 1 where antennas of radar bistatic set-up are located on the interface between the upper air-filled medium and the lower opaque one with an object hidden in it. A 2-D scalar problem is chosen in this paper for simplicity reason of the following consideration as well as a homogenous non-disperse medium is involved in research and characterized by dielectric constant ε and wave attenuation factor Γ with dB/m unit of measure, for example. Conductivity of subsurface medium is not under investigation here.

Among the three key problem's components aforementioned radar antennas behavior and electromagnetic image of hidden subsurface object produced by scattering of sounding electromagnetic wave will be under investigation later in this paper.

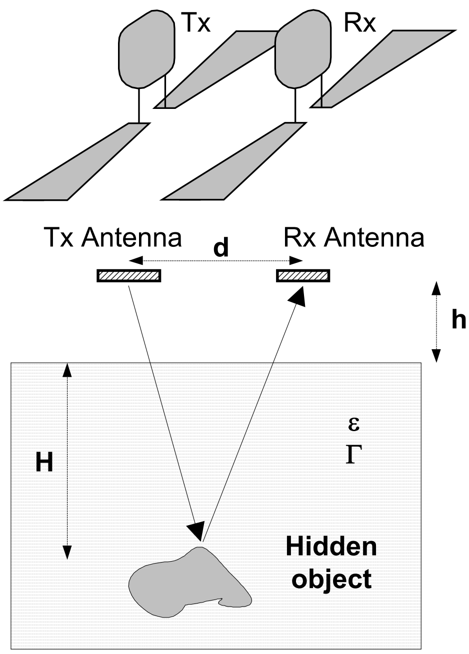


Fig.1. A basic geometry of problem to simulate subsurface radar imaging with bistatic setup of transmitting (Tx) and receiving (Rx) antennas located with the based distance d and the height h over surface to locate subsurface hidden object at the depth H.

II. ANTENNA TIME-DOMAIN MODEL

Let consider firstly a TD model of impulse antennas, operating in the free air-filled space. The authors studied this problem before [4-6]. The results of these studies can be applied for subsurface radar imaging after some adaptation discussed below. The main theses of such TD theory of impulse antennas valuable for considered matter are listed shortly below.

1. Key features of impulse antennas are determined by signal's waveform transformation like shown schematically in Fig. 2.
2. Transmitting and receiving antennas demonstrate various features and classical principal of a antenna's reciprocity is not applicable in this case at all [5-6].
3. Principal aspects of subsurface radar antennas involve radar operation in the near-field region with specific signal waveforms and antennas' behavior.
4. Antenna's directivity features in the far-field region can be considered by an energy pattern presentation [4] due to transient nature of electromagnetic events.
5. Practical application of high-quality impulse antennas for radars is implemented by its balanced integration with active electronics components (Fig. 2).
6. Antennas' location on/over surfaces of medium like ground, brick, concrete etc. in process of radar survey causes modification of the antennas' properties.

In general, consideration and analysis of the items No. 6 is complex task due to common heterogeneity of subsurface media and stochastic presence clutters there, but the two key features may be considered that are principal for subsurface radar operation.

Firstly, there is a slow-wave factor ξ to describe some decelerating of propagation of current exciting wave along antenna. It gives antenna low-frequency properties in contrast to air-medium operation of same antenna. To estimate slow-wave factor ξ, a electromagnetic model applied to a strip line of the width W spaced at the height h over lower half-space with dielectric constant ε can be used. Fig. 3a demonstrates a range of values for dependence of slow-wave factor ξ versus problem's geometry.

Secondly, antennas' energy pattern becomes asymmetrical one with some focusing of pattern directed towards the lower half-space. The last can be illustrated by non-central shape of antennas energy pattern in the azimuth (Fig. 3b) and in the elevation (Fig. 3c) coordinate planes. Note that some waveform transformation of antennas' signals takes place also as well as transmitting and receiving antennas have different patterns [6].

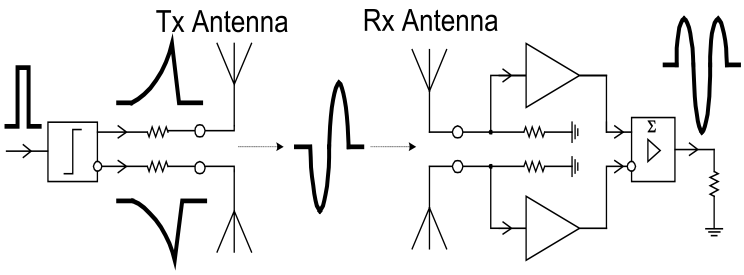


Fig.2. Schema of transformations of signal's waveform in a wireless link with same impulse antennas operating in the far-range and principal electronics of transmitter and receiver to implement a concept of active balanced antennas [6].

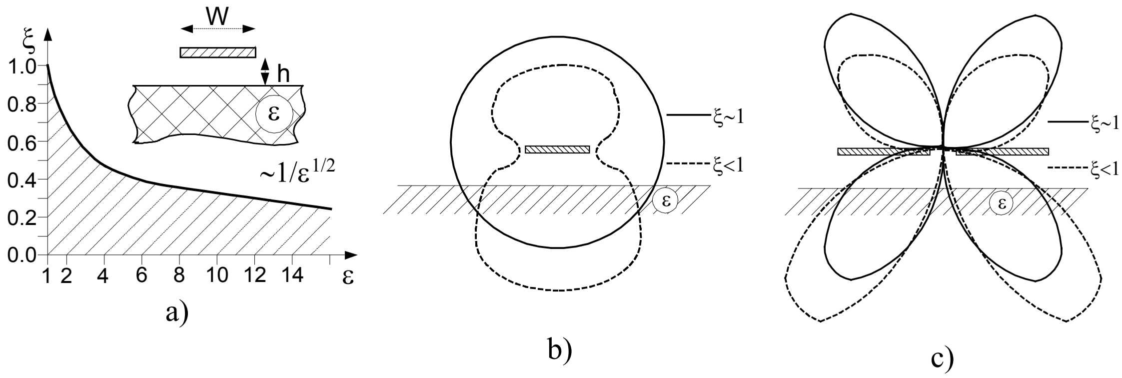


Fig. 3. Estimation of performances of impulse antenna formed by a strip line located on/over surface of border between two dielectric half-spaces, i.e. the air-filled upper and the opaque lower ones. (a) range of values of slow wave factor ξ versus dielectric constant ε and transverse geometry of antenna {W, h}, (b) antenna energy pattern in the azimuth plane, (c) antenna energy pattern in the elevation plane.

III. SCATTERING AND PROPAGATION BY TD-PO MODEL

In order to simulate TD wave scattering phenomena, a modified Huygen's principal to build TD-PO model is used in this study. In accordance of bistatic setup of radar's antennas (Fig. 1), let consider a source-point Tx with transmitting antenna and a probe-point Rx with receiving antennas located on the border of two dielectric half-spaces as seen in Fig. 4. There is also target in subsurface region that diffuses electromagnetic waves illuminated it by the source Tx. Only those components of diffracted waves presented by the corresponding rays in Fig. 4a are valuable for this analysis that reached probe-point Rx. Therefore, the waveform of resulting signal *Rx(t)* in point Rx can be expressed as a linear sum of delayed and weighted *N* copies of waveform of signal *Tx(t)* radiated by source-point Tx, i.e.

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

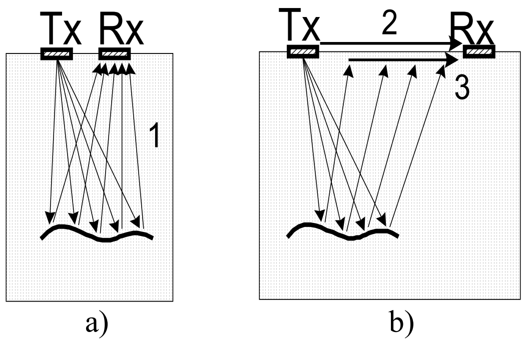


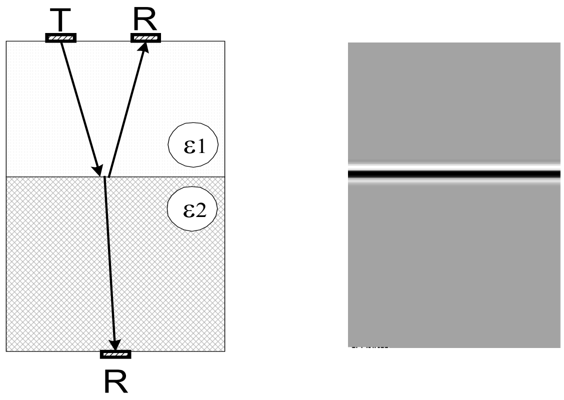
Fig. 4. General conception of bistatic operation of radar's antennas to locate subsurface object where: 1- diffracted waves, 2 – direct coupling waves, 3 – lateral waves.

The retarded time factor τ_i in (1) is determined by time delay along *i*-ray trajectory. The factor a_i is product of pattern functions of the both antennas as well as reflection factor and pattern function of elementary section (the Huygen's element) on scattering surface. This approach is similar by some features to a TD focusing technique discussed in [3].

Note that variety of possible ray trajectories in Fig. 4 can be divided into three principal groups. The first group is a set of reflected ray trajectories due to the classic Huygen's principal. The second one is described by direct coupling between Tx and Rx antennas and the third group consists of ray trajectories interpreted like lateral waves [8].

Let us consider, for instance, application of the presented model on the base of (1) to ascertain relation of physical optics and rays optics applied to solve subsurface diffraction problems. A test medium with two layers of various dielectric constants $\varepsilon 1 < \varepsilon 2$ is shown in Fig. 5a. There is possibility also to install the receiving antenna on the both sides of medium with $\varepsilon 2$. A common set-up of subsurface radar corresponds to a case when both the Tx and Rx antennas are located on the same side. If the Tx and Rx antennas spaced on the different sides, an offset gather like transmission tomography is employed.

Numerical simulation using (1) with non-principal assumption $a_i \equiv 1$demonstrates in Fig. 5b 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.



a) b)

Fig. 5. 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: (a) problem's geometry, (b) results of TD-PO simulations.

IV. Some simulation results on radar imaging

Due to low directivity features of impulse antennas considered before in Section II, the synthetic-aperture technique [3] is used to locate and image a spatial position of hidden subsurface object with acceptable spatial resolution. This technique is implemented by continues moving or step-by-step replacement of bistatic pair of Tx-Rx antennas along transect line laid over medium under investigation.

Results presented below in Fig. 6 were being computed with a Matlab simulator for several basic geometrical structures of subsurface finite-sized objects as radar targets.

The left side of each pictures in Fig. 6 shows an original geometry of problems under investigation. The right side of corresponding pictures is their simulated radar images that include direct coupling component in the upper part of each image also. As seen in Fig. 6 the edge effect due to finite size of subsurface target causes a strong diffraction events. The given results of computer simulation in Fig. 6 demonstrate significant regularities of subsurface radar imaging to collect a set of radar imaging that can be used to form their electronic library. This collection is very useful for operator interpration based on human recognition and discrimination by visual data comparions [1] as well as by computer-based methods of pattern recognition.

V. DISCUSSIONS AND CONCLUSIONS

The TD models of antennas presented above as well as TD-PO model of radar image are rather simple than other models [1,2,7] applied to simulate subsurface radar's returns. A simulation of radar returns is useful to study physical nature of problems as well as to recognize a subsurface object by comparison of real radar image and simulated one. Moreover the proposed TD-PO model of subsurface scattering illustrates remarkably connection of geometrical optics and physical optics too.

Other kinds of antennas including dipole, V-shaped dipole, bow-tie, TEM-horn antenna and antennas with shielding etc. can be considered like strip dipole antenna analyzed before as well as antennas' operation with some gap between plane of antenna aperture and the border between two dielectric half-spaces. Note that in accordance of discussed before in Section II, a bow-tie antenna located over dielectric media demonstrated disperse features due to variable value of slow wave factor along antenna.

At the same time, other important aspects of problem may be involved in studies on the basis of discussed before models with evident physical meanings. These aspects include disperse and multi-modes features of wave propagation in subsurface regions, presence of clutter located stochastically etc. Investigations of antenna arrays, some aspects of TD focusing, transmission and diffraction tomography techniques are also important for radar imaging technique.

The presented studies have also some academic importance due to clear physics and simple formal representation to learn the transient electromagnetic phenomena and radar imaging considered traditionally as complex subject for such goals. Notice that universal mathematical software like Matlab, Maple etc. was being used for computing of discussed TD-PO models and presenting their results without tremendous programming and computing efforts.

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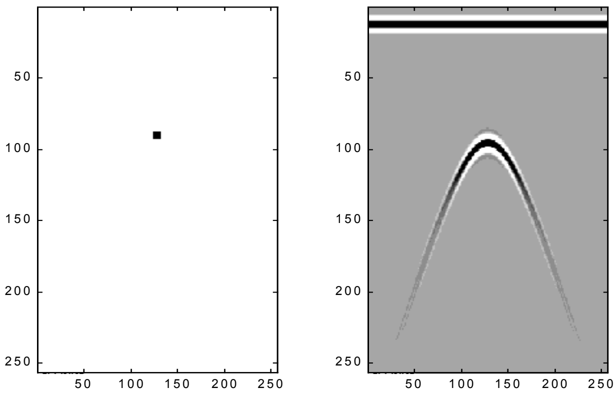
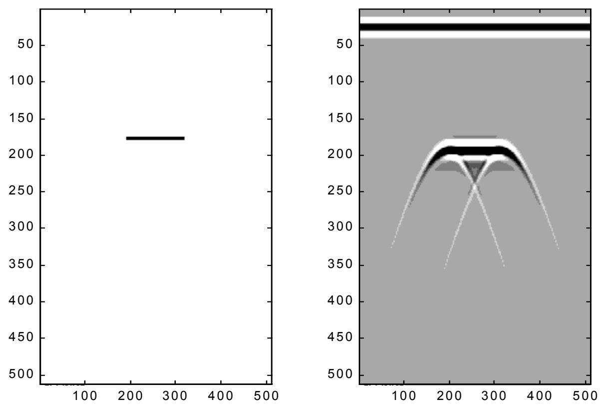
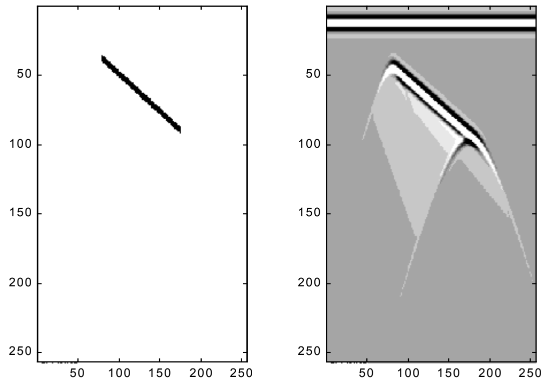


a)

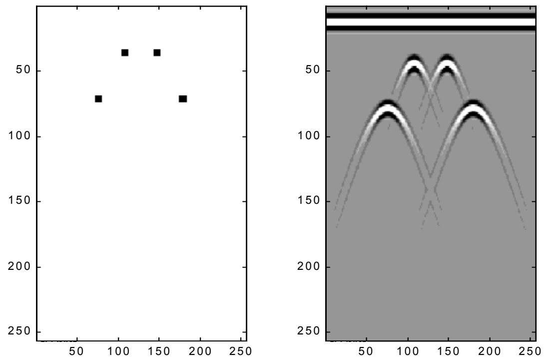


b)

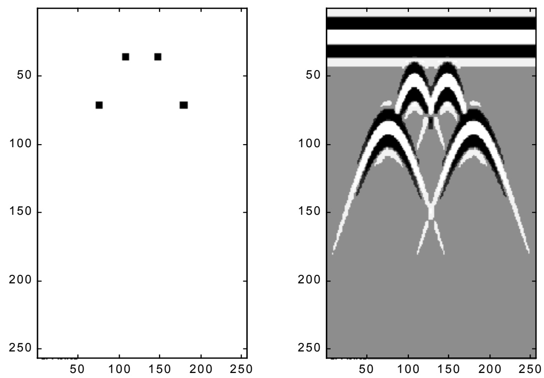
Fig. 6. Computer TD-PO simulation of the radar imaging: (a) quasi-point scattering object, (b) horizontal segment. (*to be continued)*



c)



d)



e)

Fig. 6. (*continued*) Computer TD-PO simulation of the radar imaging for subsurface hidden targets: (c) inclined segment, (d) four-poit discrete target in high-freqency band of sounding radar impulse signal, (e) four-poit discrete target in low-frequency band.