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Agent-based model simulation for ground penetration radar based on Netlogo platform

Hamid Bezzout, Hanan El Faylali
Laboratory of Electronic Systems Information Processing Mechanics and Energetics, Department of Physics and Computer Science, Faculty of Sciences, Ibn Tofail University, Kenitra, Morocco

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ABSTRACT

Ground penetrating radar is used to detect magnetic materials underground by transmitting an electromagnetic wave into the material and receive the reflected pulse. In this paper, we develop a new agent-based model to simulate and evaluate the behavior of the ground penetrating radar based on Maxwell's equations. This model contains several agents that represent the electric field, the magnetic field, the transmitted wave, the simulated medium, and the object to be detected. The implementation of this model is performed in Netlogo plaform because of its simplicity of coding and robustness of simulation. In order to validate our model, we have simulated the effect of the medium characterized by a dielectric constant and a conductance on the transmitted wave to evaluate the behavior of ground penetrating radar. The results obtained are compared with the literrature. Findings demonstrate that the transmitted pulse in the form of Gaussian pulse is reflected when it interacts with the object to detect. Thus, the ground penetrating radar can be efficiently simulated on Netlogo platform.

Corresponding Author:

Hamid Bezzout
Laboratory of Electronic Systems Information Processing Mechanics and Energetics
Department of Physics and Computer Science, Faculty of Sciences, Ibn Tofail University
P.O. Box 242, Kenitra, Morocco
Email: hamid.bezzout@uit.ac.ma

1. INTRODUCTION

Ground penetrating radar (GPR) is a geophysical technique used to survey the underground subsurfaces that can investigate pipes, metals asphalts and so on. Among the advantages of GPR is its resolution compared to other non-destructive testing techniques [1]. There are several applications of GPR like civil engineering; while some applications are about the identification of masonry texture and geometrical reconstruction that is implemented for seismic purpose [2], others in hydrology use the application of GPR technique to measure the soil water content based on the measurement of dielectric permittivity of soil [3]. A processing technique for GPR based on frequency domain is developped in [4].

The process of this survey technique is mainly based on the behavior of electromagnetic waves in different mediums including propagation and reflection. In addition, Maxwell's equations serve as a mathematical model to describe the behavior of these waves. Various numerical methods can be used to solve this mathematical model, like finite difference time domain (FDTD) method and transmission line matrix (TLM) method. Different research papers have been published about the use the FDTD method to solve electromagnetic problems ranging from the modeling of Graphene on the Drude dispersion [5], to the measurement of the permittivity of human tissue [6]. In addition, a suitable FDTD scheme has been developed for the two-dimensional Lorentz model [7]. FDTD is used to model GPR in interaction with anisotropic and dispersive media [8]. On the other hand, several researchers use the TLM method to describe and analyze the behavior of electromagnetic waves, in Lorentz medium [9] by adapting the auxiliary differential equation for TLM method, and the use of the Debye medium through the use of exponential time difference scheme [10]. A high-order discontinuous Galerkin time domain method is used in two dimensional problem to solve Maxwell's equations using a perfectly matched layer (PML) absorbing boundary conditions to absorb the wave in boundaries [11].

Agent based modeling technique is a reliable and efficient method to simulate the behavior of complex phenomena [12]. In agent-based simulation, each agent acts as an autonomous entity interacting with its environment and with other agents. It is used in various domains like transportation [13] and construction [14]. Bezzout and Faylali [15] investigate the propagation of electromagnetic waves in air and dielectric medium. This approach can be used in medical science to model and simulate blood flow in brain aneurysm by by hybridization of the multi-agent model and Laticce boltzman method [16]. The researches use Lattice Boltzman method to simulate the blood flow in cerbral aneurysm by using different architecture to accelerate the aforementioned method [17], [18].

In this paper, a new agent based model to simulate the process of Ground penetrating Radar in front of medium that characterize ground layers is performed. This model contains four agents; in the first, the excitation wave agent which represents the transmitter of GPR permits to act as Gaussian pulse or sine modulated Gaussian pulse, the Electrical field agent, the magnetic field agent, the lossless media agent, and the lossy media agent. The implementation of this model is investigated based of the Netlogo platform. Firstly, a set of governing equations are introduced to model the GPR's process. Then, a model design and the algorithm of interaction and updating agent state are introduced, based on the well-defined equations. The model is validated through the in-two part; the first concerns the propagation of incident wave in lossless media, and the second performs the propagation in the reinforced concrete wall as lossy media with simulation in final step of propagation to determine the distance between the interface air / concrete wall and the metallic object to detect. To the best of our knowledge, there are no reported results to use agent based modelling for GPR process. We choose FDTD method to compare our result because it is largerly used in electromagnetic domain and commonly used method for time dependent problems. A good agreement was obtaind between our approach and FDTD method.

2. RESEARCH METHOD

2.1. Governing equations

As shown in Figure 1, GPR is made up of different elements; a transmission component that ensures the transmission of a short duration pulse in the nanosecond range, which provides a resolution to detect objects of a couple of centimeters [19], a reception component which receives the wave reflected through the detected object, a data storage component, and a data processing component.

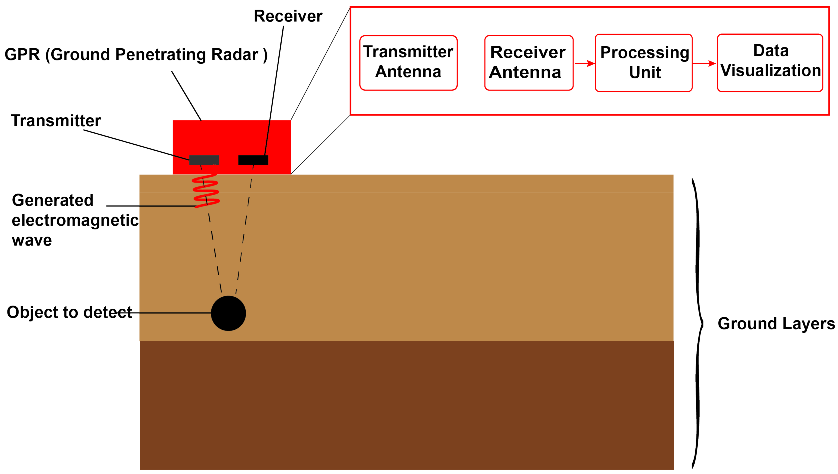


Figure 1. Operation principle and structural blocks of GPR

The electromagnetic (EM) wave transmitted in the ground through the transmission component penetrates different types of materials. When it is in contact with two dielectric materials, part of the EM wave is reflected and the other part is transmitted through the second material. The speed of EM waves differs from one material to another. It depends on the dielectric characteristics of the material: relative permittivity (ϵ), magnetic permeability (μ) and the magnetic conductivity (σ) [20] that describes the environmental parameters.

To model the various electromagnetic phenomena and to describe the relationship between the electric and magnetic fields with their sources and the interactions with the neighboring environment, we use Maxwell's equations:

$$\frac{\partial \overline{E}(t)}{\partial t} = \frac{1}{\epsilon_0 \epsilon_r}(\nabla \times \overline{H}) \tag{1}$$

$$\frac{\partial \overline{H}(t)}{\partial t} = -\frac{1}{\mu_0 \mu_r}(\nabla \times \overline{E}) \tag{2}$$

where, ϵ_0, μ_0 are respectively the permittivity and permeability of the vacuum, ϵ_r, μ_r are respectively the permittivity and relative permeability of the dielectric medium. These parameters are the characteristics of the modeled medium. According to (1) and (2), we can develop the writing of these three-dimensional equations:

$$\frac{\partial \overline{H}_x(t)}{\partial t} = -\frac{1}{\mu_0 \mu_r}\left(\frac{\partial \overline{E}_z}{\partial y} - \frac{\partial \overline{E}_y}{\partial z}\right) \tag{3}$$

$$\frac{\partial \overline{H}_y(t)}{\partial t} = -\frac{1}{\mu_0 \mu_r}\left(\frac{\partial \overline{E}_x}{\partial z} - \frac{\partial \overline{E}_z}{\partial x}\right) \tag{4}$$

$$\frac{\partial \overline{H}_x(t)}{\partial t} = -\frac{1}{\mu_0 \mu_r}\left(\frac{\partial \overline{E}_y}{\partial x} - \frac{\partial \overline{E}_x}{\partial y}\right) \tag{5}$$

$$\frac{\partial \overline{E}_x(t)}{\partial t} = \frac{1}{\epsilon_0 \epsilon_r}\left(\frac{\partial \overline{H}_z}{\partial y} - \frac{\partial \overline{H}_y}{\partial z}\right) \tag{6}$$

$$\frac{\partial \overline{E}_y(t)}{\partial t} = \frac{1}{\epsilon_0 \epsilon_r}\left(\frac{\partial \overline{H}_x}{\partial z} - \frac{\partial \overline{H}_z}{\partial x}\right) \tag{7}$$

$$\frac{\partial \overline{E}_z(t)}{\partial t} = \frac{1}{\epsilon_0 \epsilon_r}\left(\frac{\partial \overline{H}_y}{\partial x} - \frac{\partial \overline{H}_x}{\partial y}\right) \tag{8}$$

to simplify our study, we perform a transformation of the 3D equations to a one-dimensional problem. We select the orientation of the electric and magnetic fields in the plane (x, y). Thus, the direction of propagation of the electromagnetic wave is along the z direction. In this paper, the model of GPR is composed of different layers containing dielectric materials that will be considered as a one-dimensional problem. Therefore, the partial derivatives with respect to x, and y will be zero :$\frac{\partial \overline{H})}{\partial x} = \frac{\partial \overline{E}}{\partial x} = 0$, $\frac{\partial \overline{H}}{\partial y} = \frac{\partial \overline{E}}{\partial y} = 0$. As a result, the (3) to (8) can be transformed into 1D where, $(\Delta x = \Delta y = 0)$.

$$\frac{\partial \overline{H}_x(t)}{\partial t} = \frac{1}{\mu_0 \mu_r}\left(\frac{\partial \overline{E}_y}{\partial z}\right) \tag{9}$$

$$\frac{\partial \overline{H}_y(t)}{\partial t} = -\frac{1}{\mu_0 \mu_r}\left(\frac{\partial \overline{E}_x}{\partial z}\right) \tag{10}$$

$$\frac{\partial \overline{E}_x(t)}{\partial t} = -\frac{1}{\epsilon_0 \epsilon_r}\left(\frac{\partial \overline{H}_y}{\partial z}\right) \tag{11}$$

$$\frac{\partial \overline{E}_y(t)}{\partial t} = \frac{1}{\epsilon_0 \epsilon_r}\left(\frac{\partial \overline{H}_x}{\partial z}\right) \tag{12}$$

The E_x/H_y mode is represented by (10) and (11), the E_y/H_x mode is also represented by the (9) and (12). Both modes propagate independently in the dielectric medium and have the same behaviour regarding the medium of propagation. Obviously, it is necessary to use only one mode to minimize the computing time. In the present paper, we adopt the E_x/H_y mode, we obtain:

$$\frac{\partial \overline{E}_x(t)}{\partial t} = -\frac{1}{\epsilon_0 \epsilon_r}\left(\frac{\partial \overline{H}_y}{\partial z}\right) \tag{13}$$

$$\frac{\partial \overline{H}_y(t)}{\partial t} = -\frac{1}{\mu_0 \mu_r}\left(\frac{\partial \overline{E}_x}{\partial z}\right) \tag{14}$$

by the application of the finite difference scheme to (13) and (14), we obtain (15) and (16).

$$\overline{E}_x|_k^{n+1} = \overline{E}_x|_k^{n} - \frac{\triangle t}{\epsilon_0 \epsilon_r \triangle z}(\overline{H}_y|_k^{n+1/2} - \overline{H}_y|_{k-1}^{n+1/2}) \tag{15}$$

$$\overline{H}_y|_k^{n+1/2} = \overline{H}_y|_k^{n-1/2} - \frac{\triangle t}{\mu_0 \triangle z}(\overline{E}_x|_{k+1}^{n} - \overline{E}_x|_k^{n}) \tag{16}$$

2.1.1. Modeling of propagation in a lossy medium

The model developed in the previous section concerns only the vacuum medium, which is far from the real GPR model. Hence, to be close to the reality of the GPR radar, it is modeled through a lossy medium. In other words, the energy generated by the transmitting antenna is attenuated when it comes into contact with the lossy medium. This loss in the medium is introduced by adding a conductivity term that is associated with the electric field in Maxwell's equations as shown in (17):

$$\frac{\partial \overline{E}_x(t)}{\partial t} + \frac{\sigma}{\epsilon_0 \epsilon_r}\overline{E}_x(t) = -\frac{1}{\epsilon_0 \epsilon_r}\left(\frac{\partial \overline{H}_y}{\partial z}\right) \tag{17}$$

where σ is the electrical conductivity of the medium. By applying the finite difference scheme for (17) as previously explained, we obtain:

$$\overline{E}_x|_k^{n+1} = A.\overline{E}_x|_k^{n} - \frac{B}{\triangle z}(\overline{H}_y|_k^{n+1/2} - \overline{H}_y|_{k-1}^{n+1/2}) \tag{18}$$

where $A = \frac{2\epsilon_0\epsilon_r - \sigma\Delta t}{2\epsilon_0\epsilon_r + \sigma\Delta t}$ and $B = \frac{2\Delta t}{2\epsilon_0\epsilon_r + \sigma\Delta t}$. The (15) is found by replacing the value of the conductivity with $\sigma = 0$ in (18).

Therefore, inserting the material conductivity in the model has no effect on the magnetic field. The final equations are:

$$\overline{E}_x|_k^{n+1} = A.\overline{E}_x|_k^{n} - \frac{B}{\triangle z}(\overline{H}_y|_k^{n+1/2} - \overline{H}_y|_{k-1}^{n+1/2}) \tag{19}$$

$$\overline{H}_y|_k^{n+1/2} = \overline{H}_y|_k^{n-1/2} - C.(\overline{E}_x|_{k+1}^{n} - \overline{E}_x|_k^{n}) \tag{20}$$

where $C = \frac{\triangle t}{\mu_0 \mu_r \triangle z}$. So, the (19) computes the electric field E_x from the magnetic field H_y, and the (20) allows to compute the magnetic field H_y from the electric field E_x.

2.2. Developed model and simulation approach

Ground penetrating radar process is complex due to the propagation and reflection phenomena related to the electromagnetic waves. Therefore, it is very important to use a good approach to model this process. To the best of our knowledge, agent based modeling is the appropriate one for complex problems.

There are different technological solutions for agent-based modeling such as Repast [21], MASON [22], and Netlogo [23]. In Netlogo, each agent is characterized by attributes and actions to do. The multi-agent environment Netlogo [24] has different types of agents such as ”turtles” which are characterized by mobility in the environment and allows to make actions in the environment and towards other agents. Also, the

”patches” agents are stationary in the environment which allows to contain turtles agents to perform actions in the environment as well. The ”link” agent is used to link two agents of type ”turtle”. The super-agent ”observer” enables actions to be taken on all the agents mentioned above, such as observing the state of each agent in the case of movement, and connecting to other platforms or entities for visualizing the data of the established model [23].

In the multi-agents systems modeling, the process of ground penetrating radar is developed with all agents contained in this model and their characteristics. The specified agents of ground penetrating model as an agent-based model is represented in Figure 2 with their characteristics.

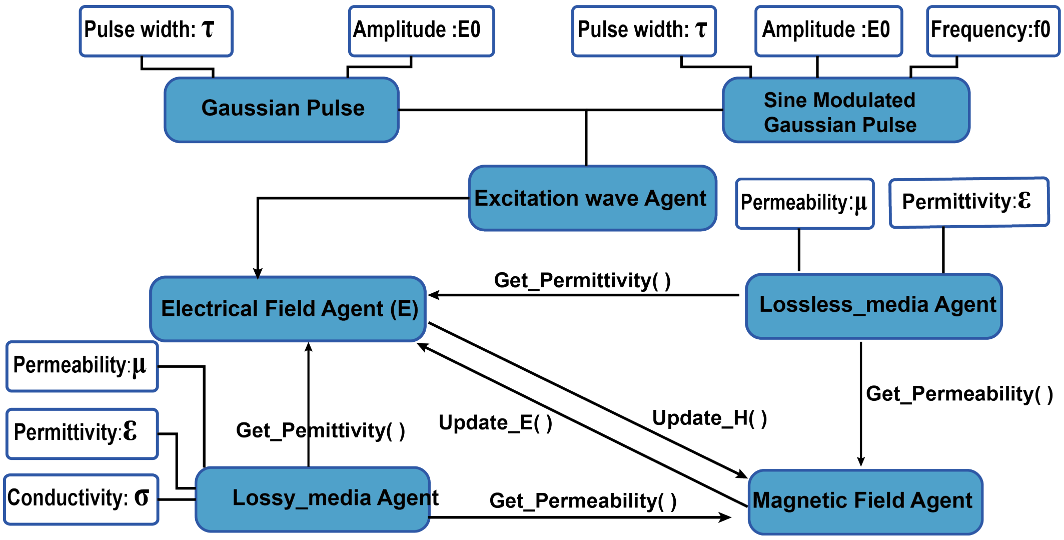


Figure 2. Distribution of agents in the world, and their characteristics

The selected platform to implement the GPR multi-agent model is the Netlogo platform because it is able to integrate a variety of tools necessary for visualization and programming. Netlogo is structured in three tabs: visualization tab, information and model description tab, and code tab that allows to implement algorithms using the governing equations of the GPR model. The agent electrical field (E) as shown in Figure 3 updates its state using the Algorithm 1, and the agent Magnetic field updates its state using the algorithm described in Algorithm 2.

Algorithm 1 : algorithm of updating state of Electrical field (E) agent

Input : *excitation* E_x, H_y *of preceding step*
Ouptut : E_x
Initialize : *n, i*
For *n = 0,time* ***do***
  For *i = 0, spaceGrid* ***do***
    Perform updating rule in equation (19)
  end for
end for

Algorithm 2 : algorithm of updating the Magnetic field (H) agent

Input : E_x *from preceding step ,A, B*
Ouptut : H_y
Initialize : *n, i*
For *n = 0,time* ***do***
  For *i = 0, spaceGrid* ***do***
    Perform updating rule in equation (20)
  end for
end for

Figure 3. Algorithms for updating electrical field and magnetic field agents

While preparing our multi-agent model, the solution of the initial step is calculated through the input parameters, the initial conditions and the boundary conditions of the electric field Ex and the magnetic field Hy. Then the solution of the electric field Ex and the magnetic field Hy are calculated through the two algorithms: Algorithm 1 and Algorithm 2 .

In addition, the type of excitation in the model, the parameters of the dielectric medium and other necessary parameters are adjusted through sliders, choosers, switches and inputs in the Netlogo interface. These components are used to modify different parameters in our model. Regarding the outputs, we have called a python extension to visualize our model. The diagram in Figure 4 describes this process.

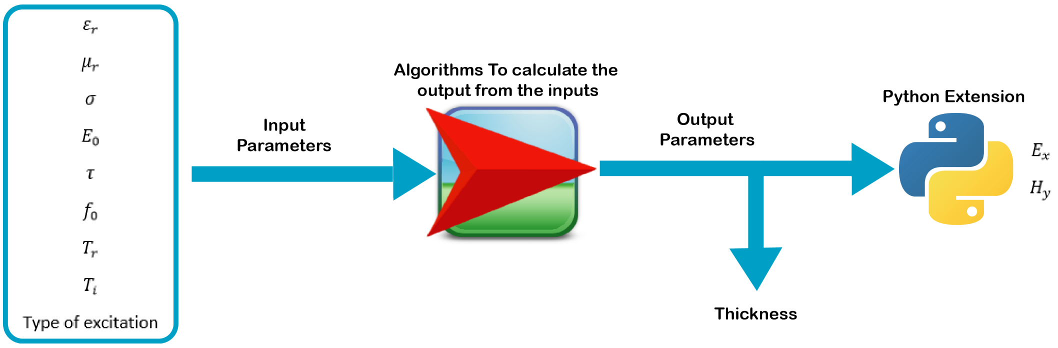


Figure 4. Input/output diagram of the process to calculate electrical field and thickness from different parameters of the GPR

3. RESULTS AND DISCUSSION

3.1. Model validation

In order to prove the usability and performance of our multi-agent model, we have used data reported in [25] to validate the model against literature results. We have focused on two case studies while the first study examine the effect of lossless medium on the electromagnetic wave, the other case involves the effect of the lossy medium on the electromagnetic wave, which then allows to simulate the real model of detecting metal object by a ground penetrating radar. The incident electromagnetic wave or the excitation wave considered in this model has the form of a Gaussian centered on t_0 represented by (21):

$$E_x(t) = e^{-\left(\frac{t-t_0}{\tau}\right)^2} \tag{21}$$

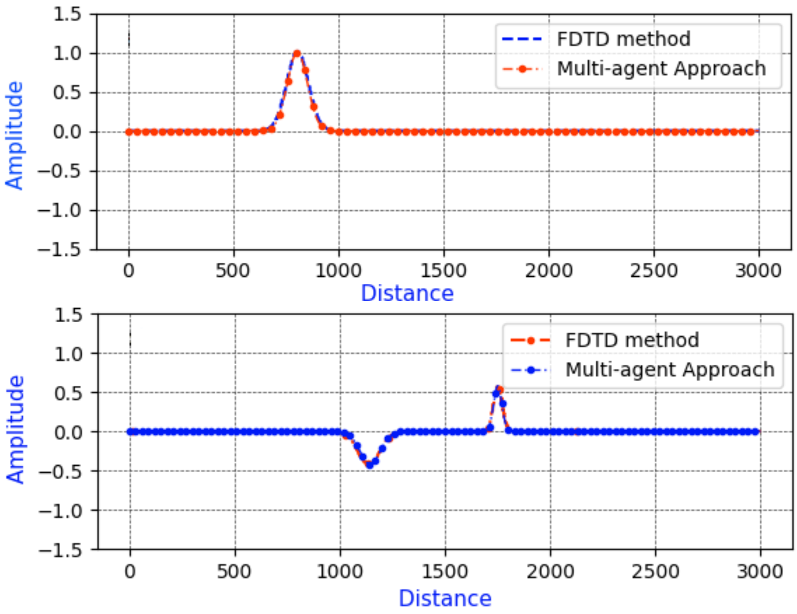
where, $\tau = 1.7fs$, $t_0 = 4.2fs$, this form of excitation can simulate a transmitter of ground penetrating radar.

3.2. Multi-agent model for propagation through lossless medium

Figure 5 shows the propagation of the electromagnetic wave. At first, the wave propagates through air until it reaches the dry sand medium at a distance of 4.71 meters as shown in Figure 5(a). Then, a part of it is transmitted into the dielectric medium and the other part is reflected into the air medium. As shown in Figure 5(b) the magnitude of the electric field of the incident wave is reduced after hitting the dry sand medium and it changes polarity. From the difference between the time of incident wave and the time of reflected wave, we can find out the distance crossed from transmitter to the second medium (dry sand).

3.3. Multi-agent simulation for Reinforced concrete wall

In this part, we propose a multi-agent model of ground penetrating radar close to reality by introducing media providing the real characteristics of the object to be detected (buried rebar) as well as the real characteristics of the concrete wall. We implement our multi-agent model in the Netlogo platform based on the algorithms defined in the previous section. Figure 6 shows the configuration of the model in the Netlogo platform.



(b)

Figure 5. Simulation of electromagnetic wave: (a) incident wave and (b) reflected and transmitted wave

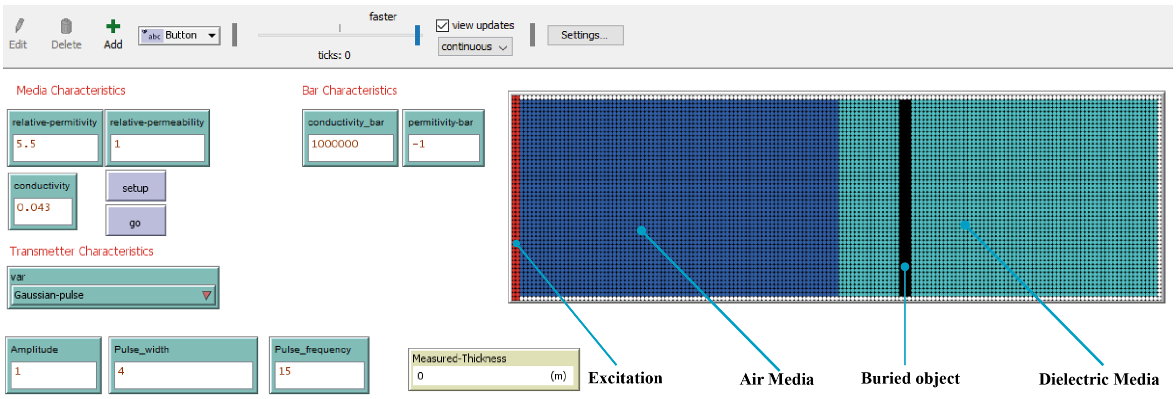


Figure 6. Initial configuration of Netlogo platform

This model contains a concrete wall with a thickness of 1 m characterized by $\epsilon_r = 5.5$ and $\sigma = 0.0043 S/m$, a buried object with a thickness of 10 cm materialized by $\epsilon_r = 5.5$ et $\sigma = 10^6$, and the source of the wave which is a radar transmitter located in the air medium. Figure 7 shows that the magnitude of the electrical field decreases in the case of lossy medium ($\sigma = 0.0043 S/m$), which indicates a loss of energy in the medium where the conductivity is not equal to zero.

Initially in Figure 8, we simulate the propagation of the electromagnetic wave in a concrete wall with a thickness of 1 m; Figure 8(a) shows the incident pulse modeling the transmitter of GPR after the propagation of this pulse in the air medium. Once it reaches the interface between air medium and concrete wall, we observe that a part of the wave is reflected in the air and the other part is transmitted in the concrete wall showing the behavior visualized in Figure 8(b). After the crossing of the air/concrete wall interface, the wave keeps on propagating along the wall, but this time the amplitude of the transmitted wave decreases (Figure 9). That is normal due to the fact that the wall has the characteristics of a dielectric medium with losses ($\epsilon_r = 5.5$, $\sigma = 0.0043 S/m$).

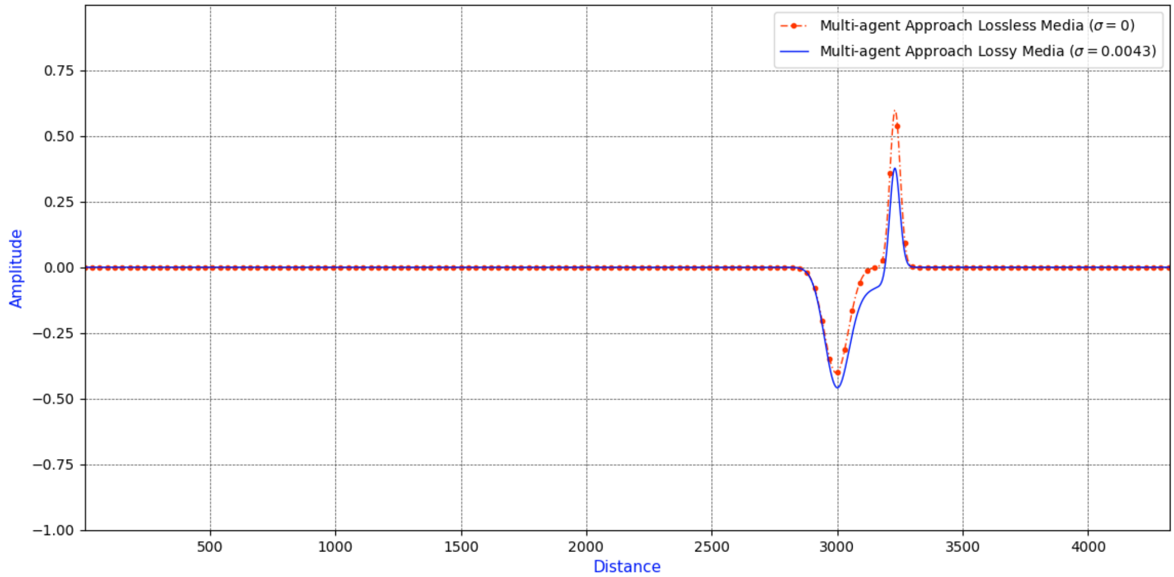


Figure 7. Initial configuration of Netlogo platform

According to the results presented in figures Figure 8 and Figure 9, when comparing the performance of our multi-agent model with the numerical FDTD method, we achieve a very good correlation between the two approaches, which allows us to say that our model is validated against the results obtained in the literature. After the validation of our multi-agent model, a steel bar is incorporated to simulate the real behavior of object detection through GPR. The bar is characterized by the metallic properties of a dielectric medium with a very high electrical conductivity ($\sigma = 10^6 S/m$), which allows the electric field to be zero in the bar. Owing to the impurity of the metal and in order to represent the reality of the material, a negative permittivity $\epsilon_r = -1$ is defined.

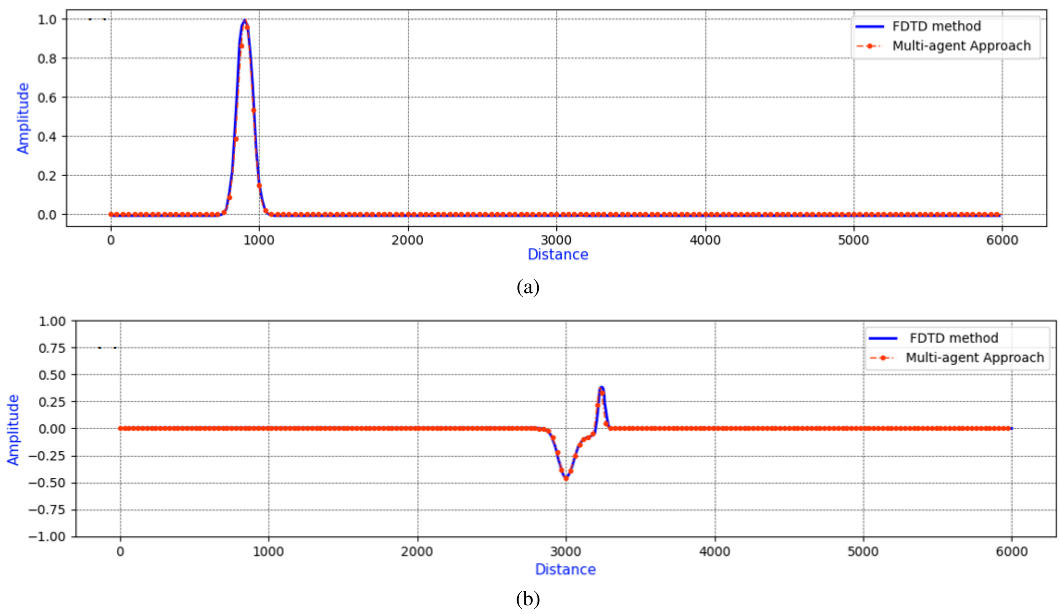


Figure 8. Propagation of the Gaussian electromagnetic wave in the concrete wall, (a) incident electric field in the air medium and (b) reflection on air-concrete wall interface (air-dielectric)

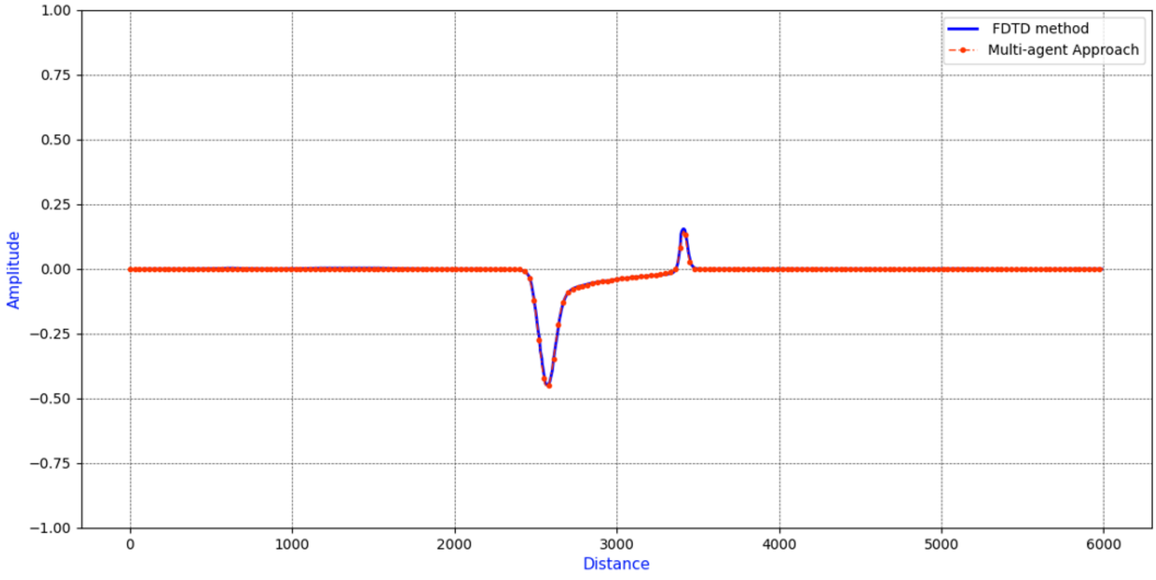


Figure 9. Transmitted electromagnetic wave in the dielectric medium (concrete wall), and reflected wave in the air medium

The multi-agent model implemented in the Netlogo platform Figure 10 allows to visualize the model configuration with the necessary properties of each medium ,as well as integrating input parameters such as permittivity, conductivity, permeability of the medium that is the metal bar or the concrete wall. The output parameters that must be determined are the behavior of the electric field in the different media, and the depth of the steel bar with respect to the wave source (transmitter of the Radar).

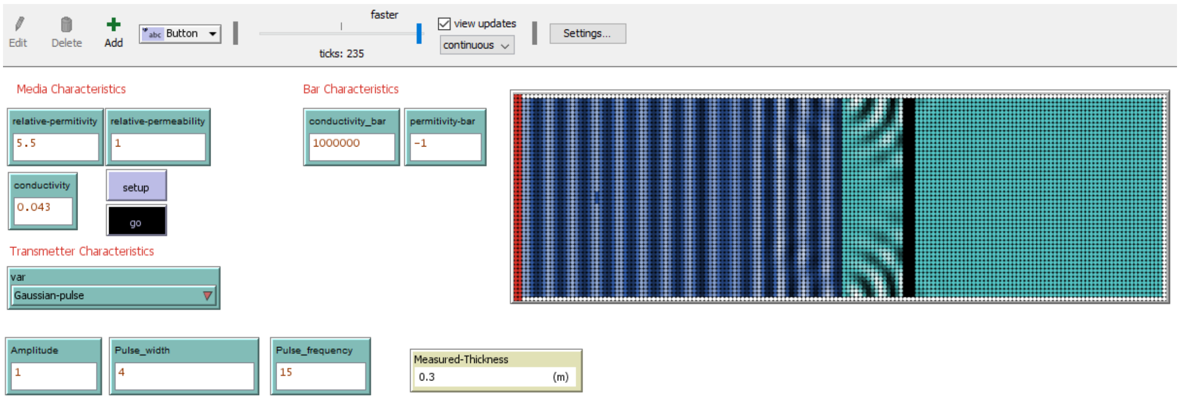
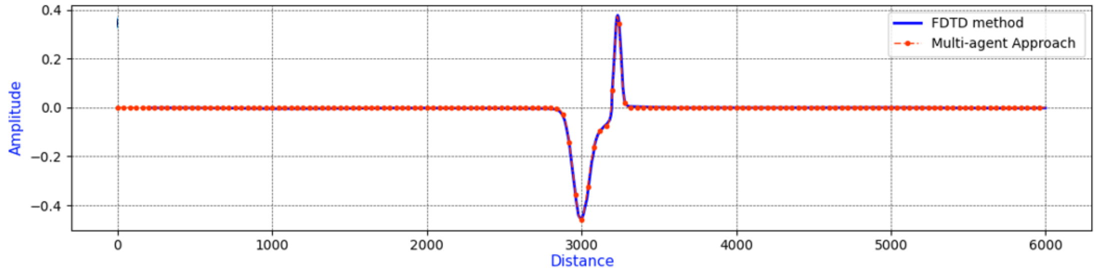
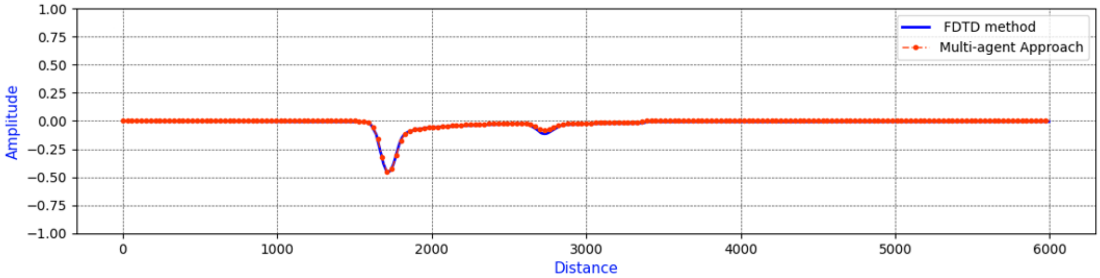


Figure 10. Simulation of the ground penetrating radar in Netlogo platform

From the behavior of the electromagnetic waves (Figure 11), we notice that a part of the wave is reflected at first in the interface air/concrete wall (Figure 11(a)); afterwards, the wave meets the metal object (steel bar) inducing the total reflection of the wave (Figure 11(b)). After measuring the difference between the two instants of the reflected pulses, we can determine the thickness of the concrete wall cover in relation to the steel bar. The Netlogo platform allows to encompass all the configuration and parameters such as measurement, or determination of the thickness, and visualization of wave's behavior in a single interface. Figure 11 shows that the measured thickness is 0.3 m which confirms the initial configuration of our problem. This work has different limitations for example it has considered only of one dimensional wave propagation problem with limited types of media (air media, lossless and lossy media). Also, the frequency domain scenarios are not included.



(a)



(b)

Figure 11. The behavior of the electromagnetic waves of (a) reflected wave at the interface air/concrete wall Réflexion de l'onde de forme Gaussien à l'interface air/mur béton and (b) total reflection of transmitted wave which reaching the metal object

4. CONCLUSION

The main purpose of this work is to examine closely and minutely the feasibility of using multi-agent approach to model the behavior of ground penetrating radar. Hence, the model is implemented in Netlogo platform to simulate this system. After describing the theoretical aspect of GPR and adapting à multi-agent model to it, the model is validated through the FDTD method in the case of studying the behavior of electromagnetic waves inside the air media, the concrete wall, and steel bar or object to detect. Different input parameters are examined; permittivity, permeability, conductivity of media, and the excitation pulse. The output parameter obtained is the behavior of electrical field and the thickness measured to detect the object. The simulation results show that the incident wave is reflected partially in the interface of air and concrete wall, and completely in front of the steel bar due to the high conductivity of metals. Based on the two time steps of two reflected pulses, the first one in the concrete wall, and the second one through the metal object; the thickness is calculated. Based on the findins of this paper, the proposed multi-agent with adjustable Graphical user interface in Netlogo platform can easily show the behavior of electrical field and calculate the distance between the transmitter and object. This model allows also to change the type of excitation which can help us to model dispersive media in the future. Future work involves the use of other types of media, including dispersive and nonlinear media, as well as increasing dimensionality of problems (2D and 3D) and the incorporation of frequency domain to enhance the analysis.

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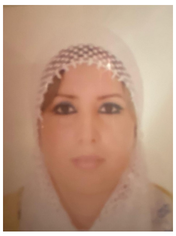
BIOGRAPHIES OF AUTHORS

Hamid Bezzout is currently a Professor of Mechanical Engineering in the Preparatory Classes for higher Schools (CPGE) and a member of the Laboratory of Electronic Systems, Information Processing, Mechanics and Energetics at the Ibn Tofail University. In 2014, he received his State Engineer Degree in Industrial Engineering from the National School of Applied Sciences (ENSA), Morocco. His research interests include essentially: Multi-Agents Systems, Machine Learning Approaches, Electromagnetic waves, Ground Radar Design, Radon transport. He can be contacted at emails: hamid.bezzout@uit.ac.ma or hamid.bezzout@gmail.com.



Hanan El Faylali is currently a full professor at Sciences faculty, Ibn Tofail University of Kenitra, Morocco and performing research activities in physics department of Ibn Tofail University. She obtained his National Doctorate degree in telecommunication and computer sciences from Sciences Faculty, Abdelmalek Essaadi of Tetouan, Morocco in 2012. Hanan's main research activities concern modelization and simulation of wave propagation, optical control of microwave circuits, time-domain modeling of antennas, TLM analysis of nonlinear materials and other electromagnetic or electronic structures. She can be contacted at emails: hanan.elfaylali@uit.ac.ma or wh_elfaylali@yahoo.fr.