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Characterisation of a ground penetrating radar antenna in lossless homogeneous and lossy heterogeneous environments

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ABSTRACT

Directly measuring the radiation characteristics of Ground Penetrating Radar (GPR) antennas in environments typically encountered in GPR surveys, presents many practical difficulties. However it is very important to understand how energy is being transmitted and received by the antenna, especially for areas of research such as antenna design, signal processing, and inversion methodologies. To overcome the difficulties of experimental measurements, we used an advanced modelling toolset to simulate detailed three-dimensional Finite-Difference Time-Domain (FDTD) models of GPR antennas in realistic environments. A semi-empirical soil model was utilised, which relates the relative permittivity of the soil to the bulk density, sand particle density, sand fraction, clay fraction and volumetric fraction of water. The radiated energy from the antenna was studied in lossless homogeneous dielectrics as well as, for the first time, in lossy heterogeneous environments. Significant variations in the magnitude and pattern shape were observed between the lossless homogeneous and lossy heterogeneous environments. Also, despite clear differences in time domain responses from simulations that included only an infinitesimal dipole source model and those that used the full antenna model, there were strong similarities in the radiated energy distributions.

1. Introduction

The diversity of Ground Penetrating Radar (GPR) usage means there are a variety of different GPR systems and antennas. Understanding how energy is transmitted and received by a particular GPR antenna can be beneficial for antenna design and usage, and can improve signal processing techniques like migration and inversion. For example, to achieve accurate amplitude migration of GPR data knowledge of the radiation pattern of the antenna is generally required [1]. The radiation characteristics of any antenna are usually investigated by analysing parameters such as impedance, field pattern shape, and directivity in free space. Crucially, however, for GPR antennas these characteristics must be studied in the different environments that can be encountered in GPR surveys. This is because a complex series of interactions occur between the antenna and the environment, which change how the antenna behaves.

Radiation pattern measurements in free space of simple antennas, as well as for more widely used commercial GPR antennas, have been made [2–4]. There have also been laboratory measurements of radiation patterns of simple antennas over homogeneous materials obtained directly with another antenna [5], and indirectly through the recording of responses from a simple target [4,6]. Received energy patterns were measured from a commercial GPR antenna in a series of oil-in-water emulsions which represented lossy homogeneous environments [7]. However, measuring antenna radiation patterns in lossy heterogeneous environments that are realistic for GPR presents many practical difficulties. This has prompted researchers to develop numerical simulations of GPR antenna radiation patterns.

Simple and more complex antennas have been modelled in free space, and simple antennas have been modelled in realistic environments, but there have been very limited studies that combine realistic GPR antenna models with realistic environments. Models of antennas over layered media have been developed for an off-ground horn antenna using linear transfer functions [8] and for an antenna operating in the near-field using equivalent sets of infinitesimal electric dipoles [9]. The energy distribution of a shielded dipole antenna over various lossless half-spaces was studied by [10], and similarly [7] used an FDTD antenna model to compare simulated and measured data.

This paper presents an investigation of the radiation characteristics of a high-frequency GPR antenna in lossless homogeneous and, for the first time, in lossy heterogeneous environments using detailed FDTD models. An advanced simulation

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toolset allowed a detailed model of a GPR antenna to be used in heterogeneous environments that simulate realistic soils. Section 2 describes the development of the FDTD models of the antenna and the soil. The results of the simulations in lossless dielectrics and lossy heterogeneous environments are presented in Section 3. Different values of dielectric constant, and different types and distributions of realistic soil properties are compared. Principal electric and magnetic field patterns are analysed at a range of observation distances from the antenna using a total energy metric.

2. Finite-Difference Time-Domain simulations

All of the simulations conducted for this research used gprMax (http://www.gprmax.com) which is an electromagnetic wave simulator based on the Finite-Difference Time-Domain (FDTD) method. gprMax was originally developed in 1996 [11] and over the past 20 years has been one of the most widely used simulation tools in the GPR community. It has been successfully used for a diverse range of applications in academia and industry [12–17], and has been cited more than 200 times since 2005 [18]. gprMax has recently undergone significant modernisations to the code and also added a number of new advanced features including an unsplit implementation of higher order perfectly matched layers (PMLs) using a recursive integration approach; uniaxially anisotropic materials; dispersive media using multiple Debye, Drude or Lorenz expressions; improved soil modelling using a semi-empirical formulation for dielectric properties and fractals for geometric characteristics; rough surface generation; and the ability to embed complex transducers and targets [19].

2.1. Antenna model

The simulations included a model of a GPR antenna that is representative of a Geophysical Survey Systems, Inc. (GSSI) 1.5 GHz antenna, which is a high-frequency, ground-coupled antenna. The antenna model includes all of the main features and geometry of the real antenna. Details of the antenna model development and initial validation can be found in [20]. A spatial discretisation of $\Delta x = \Delta y = \Delta z =$ 1 mm was chosen as a good compromise between accuracy and computational resources. The Courant Friedrichs Lewy (CFL) condition was enforced which resulted in a time-step of $\Delta t = 1.926$ ps.

2.2. Lossy heterogeneous soil models

gprMax was used to build lossy heterogeneous environments that represent soils with more realistic dielectric and geometrical properties. A semi-empirical model, initially suggested by [21], was used to describe the dielectric properties of the soil. The model relates the relative permittivity of the soil to bulk density, sand particle density, sand fraction, clay fraction and water volumetric fraction. Using this approach, a more realistic soil with a stochastic distribution of the aforementioned parameters can be modelled. The real and imaginary parts of this semi-empirical model can be approximated using a multi-pole Debye function plus a conductive term. This dispersive behaviour has been implemented in gprMax by using a recursive convolution method to express dispersive properties as apparent current density sources [22]. Fig. 1 shows the FDTD mesh of the antenna model on a heterogeneous soil model with a stochastic distribution of realistic dielectric and geometrical properties. The size of each simulation was approximately 385 million cells (28 GB RAM), which required up to 10 h to run (depending on the necessary length of time window) on a 4 GHz Intel Core i7 CPU.

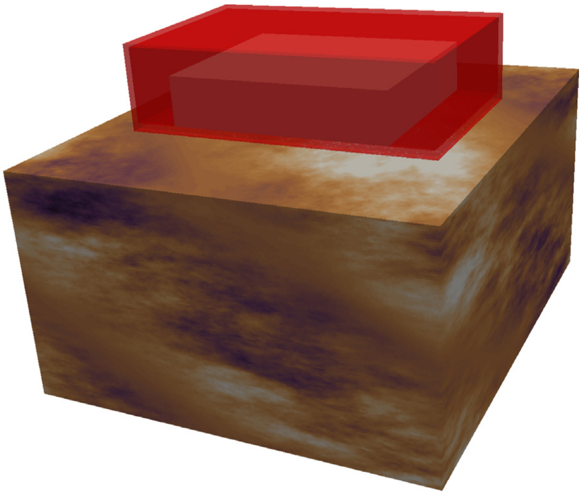

Fig. 1. Antenna (representative of a GSSI 1.5 GHz antenna) and heterogeneous soil model with a stochastic distribution of the volumetric water fraction.

3. Simulated radiation patterns

Traditionally antenna patterns are plotted at a specific single frequency, however these are of limited use in analysing the overall performance of an ultra-wideband (UWB) GPR antenna, e.g. peaks and troughs present in a pattern at a single frequency can interfere constructively and destructively with those present at another frequency. Therefore, a measure of the total energy given by Eq. (1), adapted from [10], was used:

$$\Psi(r,\theta) = \sum_{t=0}^{T} E(r,\theta)^2 \qquad (1)$$

Ψ is the total energy at a specific radius (r) and angle (θ); the summation is made over the duration of the time-domain response; and E is the electric field value at a specific radius (r) and angle (θ).

A total of six different environments were investigated:

- Lossless dielectric, relative permittivity $\epsilon_r = 5$.
- Lossless dielectric, relative permittivity $\epsilon_r = 20$.
- Lossy heterogeneous environment with soil properties – sand fraction $S=0.5$, clay fraction $C=0.5$, bulk density $\rho_b = 2$ g/cm^3, and sand particle density $\rho_s = 2.66$ g/cm^3 – and fractal dimension $D=1.5$.
- Lossy heterogeneous environment with soil properties – sand fraction $S=0.5$, clay fraction $C=0.5$, bulk density $\rho_b = 2$ g/cm^3, and sand particle density $\rho_s = 2.66$ g/cm^3 – and fractal dimension $D=2$.
- Lossy heterogeneous environment with soil properties – sand fraction $S=0.9$, clay fraction $C=0.1$, bulk density $\rho_b = 2$ g/cm^3, and sand particle density $\rho_s = 2.66$ g/cm^3 – and fractal dimension $D=2$.
- Lossy heterogeneous environment with soil properties – sand fraction $S=0.1$, clay fraction $C=0.9$, bulk density $\rho_b = 2$ g/cm^3, and sand particle density $\rho_s = 2.66$ g/cm^3 – and fractal dimension $D=2$.

The fractal dimension is a value for characterising fractal patterns or sets by quantifying their complexity.

All the heterogeneous environments had a volumetric water content range of 0.001–0.25, with 50 different materials created in the model to simulate this range. The heterogeneous environments were simulated using a semi-empirical model, initially suggested by [21], to describe the dielectric properties of the soil.