Optimising models of commercial GPR antennas

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***Abstract*—This paper presents three-dimensional (3D) numerical models of commercially used Ground-Penetrating Radar (GPR) antennas from Geophysical Survey Systems, Inc. (GSSI) and Mala Geoscience. GprMax, an electromagnetic simulator based on the Finite-Difference Time-Domain (FDTD) technique, is used along with ParaView (an open-source visualisation application) to create and visualise the models. An implementation of Taguchi's method is used to optimise unknown parameters in the models. Comparisons of real and modelled antenna free-space responses (crosstalk) have shown excellent agreement. Accurate antenna models of real GPR antennas allow the direct comparison of modelled and real GPR signals, providing an investigative tool for future research in areas such as material property and geometry information from GPR wavelets, and optimisation of antenna designs.**

***Index Terms*—antennas, commercial, FDTD modelling, GPR, near-field, optimisation, subsurface, Taguchi**

I. Introduction

Ground-Penetrating Radar (GPR) is used for a wide range of different applications in areas like geophysics and engineering. Despite its growth over the past decade or so, the interpretation of GPR data by practitioners is still largely experience-based, recognising specific patterns and associating them with specific features. There is, therefore, a continual need for the systematic study of GPR signals at a macroscopic level, and this requires the development of accurate GPR models. The knowledge and understanding gained from these types of studies can be used to develop better techniques for object detection (shape, orientation and size), layer identification, material property determination, and antenna design.

Utility detection and the Non-Destructive Testing (NDT) of infrastructure are the primary applications for GPR, which is typically used to locate and identify features such as reinforcement, ducts, pipes, voids, and cracks within the concrete. These are often shallow, closely-separated sub-surface targets that require the use of high-frequency antennas to provide adequate resolution. The responses from these types of target have a fast arrival times and are often lost in the direct wave between transmitter and receiver. In these situations the only way to be able to make a direct comparison between real and modelled data, is to ensure the model includes a description of the real GPR antenna. Currently, however, most GPR simulations represent the antenna as a theoretical source such as a Hertzian dipole. This is simple to implement and computationally cheap, but is not useful for analysing real responses. This is clearly demonstrated in Fig. 1, which shows an A-scan of two pipes buried one above the other in sand. It is evident that the Hertzian source model does not compare well with the real response for this type of target and environment. Therefore, a GPR simulation should include accurate models of the ground/structure, objects/targets, and the GPR antennas.

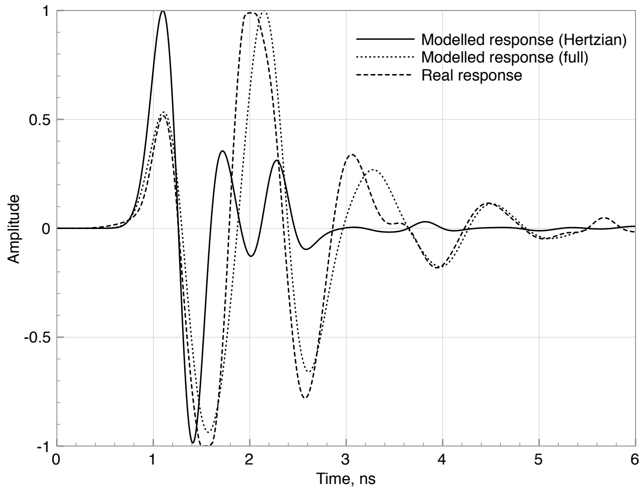


Fig. 1. Real and modelled A-scans of buried pipes

This paper begins with an overview of the process and tools used to create antenna models, then focuses on the optimisation of the many unknown parameters in the models, before finally presenting initial model validation results. Section II describes the computational tools, methods and resources required to create the antenna models. Section III presents details of the antenna models, including geometric, material, and electrical characteristics. In the following Section IV an implementation of Taguchi's optimisation method is used to find values for the unknown parameters in the models. Initial validation of the models using cross-corellation of free-space responses is then shown in Section V.

II. Computational tools and resources

An accurate, and preferably fast, electromagnetic (EM) solver is an important tool for any GPR simulation. GprMax3D is part of a suite of EM wave simulators [1] based on the Finite-Difference Time-Domain (FDTD) method. GprMax has been used for a variety of different GPR simulations by a number of researchers [2]–[4]. It includes features such as: Perfectly Matched Layer (PML) boundaries, user-specified excitation, and frequency dependent materials. Additionally, for antenna modelling, good visualisation software is required to create models that include the fine geometrical and elec-

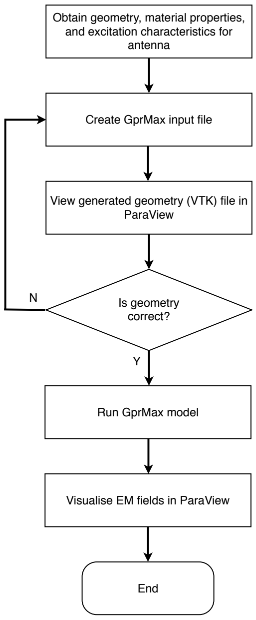


Fig. 2. Process of developing a basic antenna model

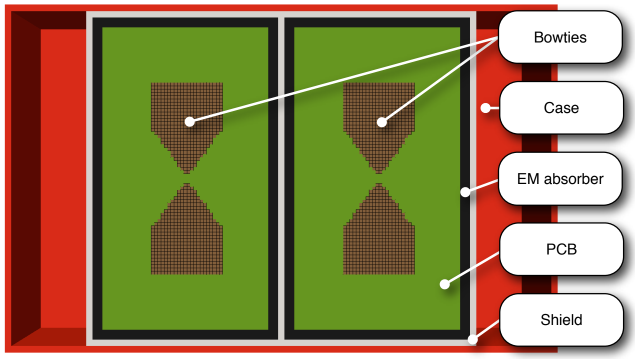


Fig. 3. FDTD meshed model geometry of a GSSI 1.5GHz antenna

trical features of real GPR antennas. ParaView [5] is an open-source parallel application that utilises the Visualisation Toolkit (VTK) format to enable visualisation of scientific data. GprMax3D and ParaView were the primary pieces of software used in the development of the antenna models. Fig. 2 shows the process used to create an antenna model. Although the software tools were developed primarily for research use, the computational resources required can be satisfied by most current high-end workstations. A typical free-space antenna model based on a 1 mm uniform mesh (9 million cells) used approximately 600 MB of RAM. To compute a single 6 ns trace from this type of model required 25 mins runtime on 8 CPUs. Due to the number of simulations necessary for this research, GprMax3D models were run on a Beowulf cluster at The University of Edinburgh. This enabled multiple A-scan traces to be run in parallel and then combined to produce B-scan radargrams. It also enabled the iterative optimisation techniques discussed in Section IV to be easily evaluated.

III. Antenna models

A range of the most commonly used antennas from leading GPR manufacturers — Geophysical Survey Systems, Inc. (GSSI), Mala Geoscience, and Utsi Electronics — have been studied. This paper focuses on models of a Mala 1.2 GHz antenna and GSSI 1.5 GHz (Model 5100) antenna. Both of these antennas are regarded as high-frequency, high-resolution antennas, and primarily used for the evaluation of structural features in concrete: location of rebar, conduits, and post-tensioned cables, as well as estimation of layer thickness on bridge decks and pavements. To create an accurate model of any GPR antenna it is essential to know the geometry, electrical characteristics, and material properties of the main antenna components. Many of these details are either commercially-sensitive or difficult to determine without specialist test equipment.

A. Main components and geometry

The geometry of the antennas was the simplest and most readily obtainable information to input into the models. The antenna enclosures were opened so that the dimensions of the main components could be taken. Both antennas use a bistatic configuration where the transmitter (Tx) and receiver (Rx) are housed in the same enclosure. The Tx and Rx antennas are bowties and their dimensions and electrical loading are critical to the directionality and efficiency of the antenna. The Mala antenna uses a classic bowtie shape with a flare angle of 85 degrees. The GSSI antenna uses bowties with a flare angle of 76 degrees but with additional rectangular patches added to the open ends of the bowties. In both antennas the bowties are printed onto a circuit board which forms one side of a metal box shield. Mala and GSSI use an open-cell carbon-loaded foam as a broadband absorber in the cavities behind the bowties. All the main geometrical features of the antennas are included in the models: Tx and Rx bowties, printed circuit board (PCB), EM cavity absorber, shielding box, the polypropylene case, and the High-Density Polyethylene (HDPE) skid plate. The Mala antenna model also includes surface mount technology (SMT) resistors which are used to load the bowties. Fig. 3 shows the components highlighted on a FDTD meshed geometry of the GSSI antenna. All models use a uniform mesh size of 1 mm which was chosen as a compromise between model accuracy, resolution of geometrical features, and computational resources.

B. Material properties

The electrical properties of the materials used in the antennas are another key consideration for the models. The metals and plastics have well defined values for permittivity and conductivity that can be easily input into the models. However the exact values for the permittivity and conductivity of the broadband absorber, which is critical to the performance of both antennas, were unknown. Initially assumptions were made using data from typical microwave absorbers [6], and latterly these parameters where found using the iterative optimisation technique discussed in Section IV. Table I lists the permittivity and conductivity values used in the models.

C. Excitation

The models are not intended to include circuit-level features and therefore do not include the electronic components used in the transmitter feed, and the receiver circuits. This avoids

TABLE I
MODELLED MATERIAL PERMITTIVITY AND CONDUCTIVITY VALUES

Material	Permittivity	Conductivity (S/m)
Copper	1	59.6E6
GSSI outer absorber	20	0.125
GSSI inner absorber	4	0.416
Mala absorber	6.4	0.202
PCB	3	0
Polypropylene	2.26	0
High-Density Polyethylene	2.35	0

the necessity to use a sub-millimetre mesh which would greatly increase the computational requirements. However the excitation of the antenna — pulse shape, frequency content, and feed method — is important. The shape and frequency content of the input pulses used by GSSI and Mala are unknown parameters. A Gaussian shaped pulse with a centre frequency close to manufacturers specification for the antenna was used a common choice in many GPR simulations [7]–[10].

The method used to feed the pulse to the bowtie is another important consideration because it effects the input impedance of the antenna. Two feed models were available and potentially applicable: a voltage source or a one-dimensional (1D) two-wire transmission line. The voltage source is a resistive source introduced over a one cell gap at the drive-point of the Tx bowtie. In the other feed model the impressed voltage is introduced at the gap by virtually attaching a 1D transmission line. It has been shown the geometry and the type of these simple feed models is critical to the overall antenna model performance [11]. Initially a resistive voltage source model has been used, but a study of the different effects of the two feed models on the input impedance of the modelled antennas is planned.

IV. TAGUCHI'S METHOD: OPTIMISING MODEL PARAMETERS

A number of the material properties and electrical characteristics of the antennas were not readily obtainable due to commercial-sensitivity or the lack of specialist test equipment. Initially assumptions were made for these unknowns but it was quickly apparent some sort of systematic refinement would be required. Traditional optimisation methods such as a full factorial study, or trial-and-error approach were considered too onerous because of the shear number of simulations needed to achieve an optimum or satisfactory result. Therefore different optimisation techniques were considered: genetic algorithm (GA), particle swarm optimisation (PSO), simulated annealing (SA), artificial neural network (ANN), and Taguchi's method. For this application a global method with a good convergence rate was desirable. Taguchi's method has both these characteristics, is simple to implement, and has been previously used in electromagnetics for the optimisation of antenna design [12]. Taguchi's method uses Orthogonal Arrays (OAs) to design simulations so that the optimal result can be found from the fewest runs. An iterative implementation of Taguchi's method [13] was used and is shown in Fig. 4. The fitness function used to assess the accuracy of each model was a cross-corellation of the free-space response (crosstalk) from each model with the measured free-space response from the corresponding real antenna. The OA selected for the optimisation contained 18 simulations per iteration. Table II shows the five parameters that were optimised and the initial ranges chosen for each parameter. If a full factorial study was conducted (allowing twenty possible values for each parameter) it would require $5^{20} \approx 95$ trillion simulations. Using Taguchi's method a converged result was typically achieved in ten iterations, therefore requiring a total of $18 \times 10 = 180$ simulations. Fig. 5 shows the convergence history for the optimisation of the free-space response of the GSSI antenna model.

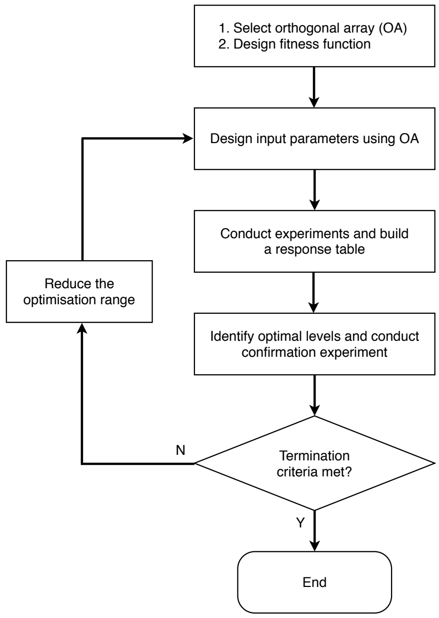


Fig. 4. Implementation of Taguchi's method

TABLE II
MODEL OPTIMISATION PARAMETER RANGES

Parameter	Range
Centre frequency of feed pulse	800 MHz - 2.5 GHz
Permittivity of EM absorber	4 - 20
Conductivity of EM absorber	0.05 - 1 S/m
Resistance of Tx voltage source	25 - 750 Ω
Resistance of Rx receiver sink	25 - 750 Ω

V. MODEL VALIDATION: FREE-SPACE RESPONSE

The initial phase of validating the accuracy of the antenna models was to compare the modelled free-space responses (crosstalk) to measured, real free-space responses. For this test each model domain contained the antenna surrounded by 50 cells of free-space and PML absorbing boundaries. The real free-space responses of the antennas were measured by placing each antenna in an open space, and recording the direct wave between the transmitter and receiver. Figs. 6 and 7 show the excellent correlation (96% and 97% respectively) between real and modelled responses (amplitudes have been normalised). All the main features in each antenna responses are well captured with good agreement for both amplitude and phase.

Further validation of the models at a laboratory scale is currently being undertaken. A technique using oil-in-water emulsions to simulate the electrical properties of concrete is being used [14], [15]. This allows the models to be tested

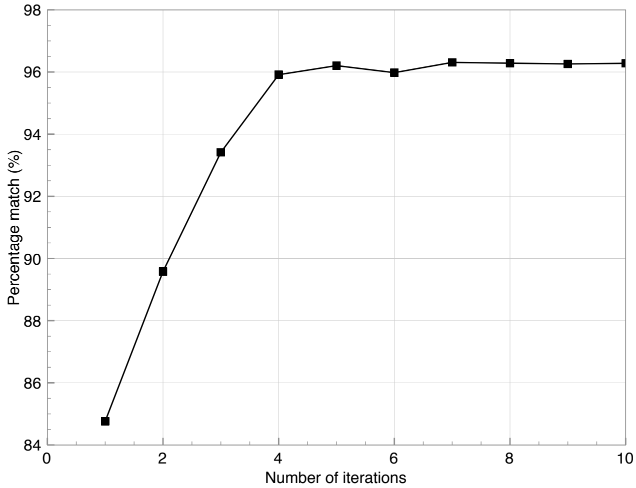


Fig. 5. Convergence history of optimisation of model free-space response using Taguchi's method

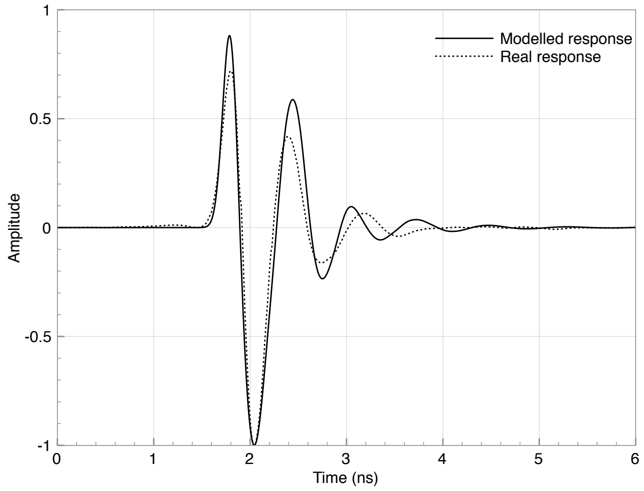


Fig. 6. Free-space response from GSSI 1.5GHz antenna

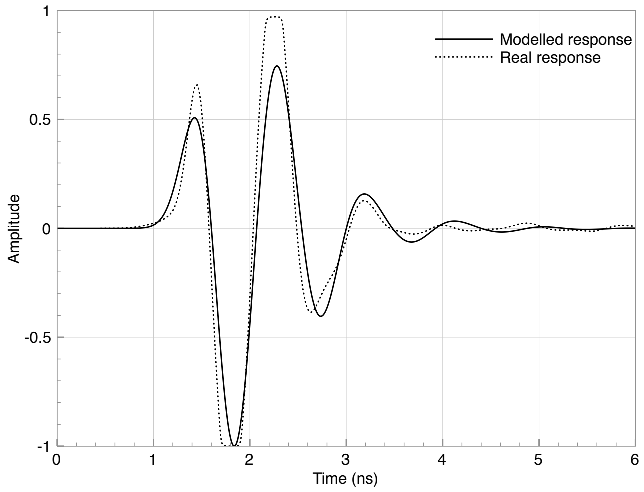
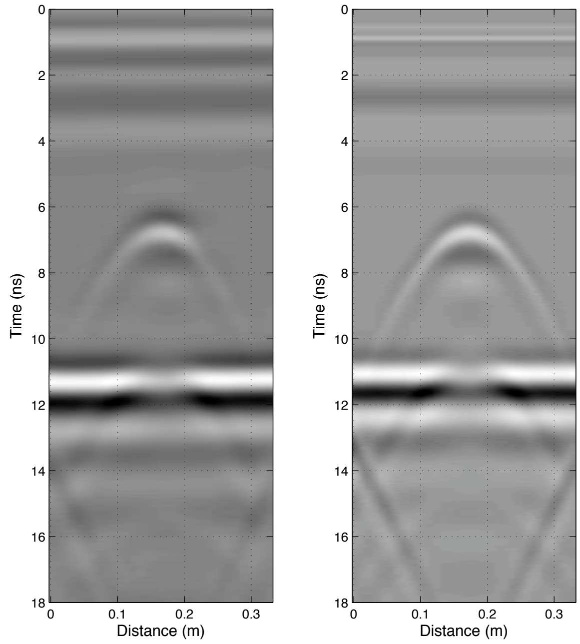


Fig. 7. Free-space response from Mala 1.2GHz antenna



(a) Real response (b) Modelled response

Fig. 8. Responses from a 12 mm rebar in distilled water (GSSI antenna)

against a known homogeneous medium that can have set permittivity and conductivity values. In addition, different types of target — rebars, pipes, metal and plastic boxes — can be easily placed at known locations in the emulsion. Experiments with distilled water and mineral oil (the two main constituents of the emulsion) were undertaken before the planned experiments using the emulsions. Fig. 8(a) shows the real B-scan and Fig. 8(b) shows the modelled B-scan from a 12 mm rebar submerged in distilled water. The model compares well with the real response from the GSSI 1.5 GHz antenna.

VI. Conclusions

A toolset has been put together that allows the creation, visualisation, and validation of detailed 3D GPR antenna models. GprMax is an EM simulator based on the FDTD method, and is used along with ParaView, a parallel visualisation application, for this process. Models of commonly used commercial antennas from GSSI (1.5 GHz) and Mala (1.2 GHz) have been created using these tools. Taguchi's optimisation method has been successfully used to estimate parameters in the model that are not readily obtainable due to commercial-sensistivity. A numerical antenna model will never exactly replicate the real system, but initial validation of the models using a cross-corellation of real and modelled free-space responses has shown excellent agreement. Accurate models of realistic GPR antennas will permit investigation into areas such as the correlation of ground/structure material properties, and target/scatterer geometry with the wavelets that compose the actual GPR signal.

Further validation of the models at both a laboratory level, using emulsions to simulate concrete, and with field data are currently being carried out. It is also proposed to study the input impedance of the modelled antennas.

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