Development of electromagnetic simulators for Ground Penetrating Radar

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***Abstract*—This paper presents two electromagnetic simulators based on the Finite-Difference Time Domain (FDTD) technique and Boundary Element Method (BEM), for Ground Penetrating Radar applications. The first simulator is the new open-source version of the software gprMax, which employs Yee's algorithm to solve Maxwell's equations by using the FDTD method and includes advanced features allowing the accurate analysis of realistic scenarios. Additionally, E^{2}GPR is a freeware package conceived to ease the use of gprMax: it assists in the creation, modification and analysis of two-dimensional models and can be used to plot results. The second simulator is TWiNS-II: this is free software for the analysis of multiple thin wires in the presence of two media, implementing the Galerkin-Bubnov Indirect BEM; calculations can be undertaken in the frequency or time domain. These tools have been developed by Members of the COST Action TU1208 "Civil Engineering Applications of Ground Penetrating Radar."**

Keywords—Ground-Penetrating Radar; Finite-Difference Time Domain; Boundary Element Method

I. INTRODUCTION

Founded in 1971, COST (European COoperation in Science and Technology) is the first and widest European framework for the transnational coordination of research activities. It operates through Actions, science and technology networks with a duration of four years.

The main objective of the COST Action TU1208 "Civil Engineering Applications of Ground Penetrating Radar" [1] is to exchange and increase knowledge and experience on Ground-Penetrating Radar (GPR) techniques in civil engineering, while promoting in Europe a wider use of this technique. Research activities carried out in TU1208 include all aspects of the GPR technology and methodology: design, realization and testing of radar systems and antennas; development and testing of surveying procedures for the monitoring and inspection of structures; integration of GPR with other non-destructive testing approaches; advancement of electromagnetic-modelling, inversion and data-processing techniques for radargram analysis and interpretation.

GPR radargrams often have no resemblance to the subsurface or structures over which the profiles were recorded. Various factors, including the innate design of the survey equipment and the complexity of electromagnetic propagation in composite scenarios, can disguise complex structures recorded on reflection profiles. Electromagnetic simulators can help to understand how target structures get translated into radargrams. They can show the limitations of GPR technique, highlight its capabilities, and support the user in understanding where and in what environment GPR can be effectively used. Furthermore, electromagnetic modelling can aid the choice of the most proper GPR equipment for a survey, facilitate the interpretation of complex datasets and be used for the design of new antennas. Electromagnetic simulators can be employed to produce synthetic radargrams with the purposes of testing new data-processing, imaging and inversion algorithms, or assess the effectiveness of existing ones. A fast and accurate forward solver can also be used as part of an inverse solver.

This paper presents two electromagnetic simulators, based on the Finite-Difference Time Domain (FDTD) technique and Boundary Element Method (BEM). In Section II, the new open-source version of the software gprMax is presented, which implements FDTD and includes advanced features for the analysis of realistic scenarios. E^{2}GPR is a freeware package conceived to ease the use of gprMax. In Section III, TWiNS-II is introduced: this is free software for the analysis of a thin-wire configuration in the presence of two media and implements the Galerkin-Bubnov Indirect BEM.

II. GPRMAX AND E^{2}GPR

The open source software gprMax [2] employs Yee's algorithm to solve Maxwell's equations using the FDTD method. It was originally developed in 1996. Recently, the software has been rewritten in Python, with performance-critical parts implemented in Cython, and released under the GNU General Public License. In the process of rewriting the software, several changes have been made to improve its efficiency, speed, and usability. For instance, the Perfectly Matched Layer boundary conditions have been improved. Moreover, all geometrical and physical properties defining the scenario can now be parameterised.

New advanced features have been added to the simulator:

- A library of antennas that can be included in the models.

- It is possible to build heterogeneous media using fractals, as well as objects with rough surfaces.
- Anisotropic media can be defined. This allows materials such as wood and fibre-reinforced concrete, which are often inspected with GPR, to be accurately modelled.
- Media with arbitrary frequency-dispersive properties can be defined. This paves the way to the use of gprMax in new areas, such as the modelling of human tissues.
- Optimisation of parameters based on Taguchi's method can be performed. This feature can be useful to optimise material properties based on experimental data or to design new antennas.

E^2GPR [3] stands for 'Edit your geometry, Execute GprMax and Plot the Results!'. This freeware tool is conceived to ease the use of gprMax. The main purposes of E^2GPR are to:

- Assist in the creation, modification and analysis of two-dimensional (2D) gprMax models, through Computer-Aided Design.
- Facilitate parallel and/or distributed computing with gprMax, on multicore machines or networks of computers.
- Automatically plot radargrams generated by gprMax.

gprMax is command-line driven and does not feature a Graphical User Interface (GUI). This implies that, for complicated scenarios, creating or modifying a model can be a not straightforward work. Moreover, the geometry of a model cannot be checked in real time, while editing it. E^2GPR helps overcoming these limitations and assists the user in the creation of gprMax 2D models. It is written in HTML and JavaScript, hence it runs on any device. A new scenario can be created from scratch, or an existing input file can be loaded and modified. Electromagnetic properties of different media can be defined. Basic shapes are available and arbitrary shapes can be hand-drawn by using any pointing device. Objects can be copied and pasted, deleted, shifted and resized. It is possible to load a background picture and draw the model by tracing it. For the shift of transmitting and receiving antennas, a fixed step can be defined or an arbitrary path can be hand-drawn, to move the antennas on irregular curved and rough interfaces.

In the new gprMax, the FDTD loops (which are the most computationally intensive parts of the code) have been parallelised by using OpenMP: all CPU cores available on a machine can be exploited to perform calculations. A Message Passing Interface has been employed to implement a task farm, which can be utilised to distribute a series of models to different cores as independent tasks. This is very useful when a B-Scan is required: each A-Scan composing the B-Scan can be task-farmed as an independent model. E^2GPR facilitates the use of this feature (the user can set all parameters through an intuitive GUI) and allows monitoring how the calculation is advancing, through reader-friendly progress bars.

Finally, E^2GPR includes a plotter. This script automatically plots A- and B-Scans generated by gprMax, to offer a first and easy view of the results.

III. TWINS-II

TWiNS-II is free software for electromagnetic simulation of thin-wire configurations in the presence of two media. It is the improved version of the previously developed tool TWiNS [4] and implements the Galerkin-Bubnov Indirect Boundary Element Method. The package contains two applications called TD-TWiNS-II and FD-TWiNS-II, which can be used to undertake the analysis in the frequency or time domain, respectively. The software is focused primarily on calculation, but a rudimentary graphical representation is integrated in the package. A wide range of options exists, to export results for further processing with other tools, if specialized graphical representation or further calculation is required: the authors of the package feel that this approach simplifies its usage and allows a greater degree of flexibility for the final user.

The time-domain application TD-TWiNS-II is focused on the assessment of current distributions along thin wire structures. The configuration that can be analyzed is a set of parallel thin wires placed in free space above a perfect ground, or above a dielectric lossless half-space. The wire array resides in a plane parallel to the interface. The formulation is based on the space-time Hallen integral equation approach. Within this basic geometry, the user is allowed to arbitrarily change the number, size and position of wires, their excitation characteristics and the dielectric constant of the half-space.

The frequency-domain application FD-TWiNS-II is used for the frequency analysis of the same wire configuration as in the time domain counterpart. The formulation is based on the Pocklington integro-differential equation approach. In addition to features provided by TD-TWiNS-II, the FD-TWiNS-II accounts for the effects of losses in the ground.

IV. CONCLUSIONS

In this paper, two electromagnetic simulators based on the Finite-Difference Time Domain (FDTD) technique and on the Boundary Element Method (BEM) were presented: (i) the open source software gprMax, implementing FDTD, and the additional freeware tool E^2GPR; (ii) the TWiNS-II free package, implementing BEM, for the simulation of thin wires in the presence of two media.

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