An extension module to embed commercially sensitive antenna models in gprMax

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***Abstract*—Models of antennas have been included in numerical simulations of ground penetrating radar (GPR) intermittently over the past 20 years with varying degrees of realism. Those antenna models that have been published have been mainly of antennas used in academia or for research purposes, and not regularly used commercial antennas. This is, of course, understandable as GPR manufacturers have a great deal invested in their intellectual property (IP) and want to protect it. However, there is a desire to find a solution to this problem, namely, to enable models of commercial antennas to be used in simulations whilst safeguarding the IP of the manufacturer. We present a framework that allows manufacturers to build encrypted modules containing models of their antennas that can be used with 3D gprMax models. All the properties of the antenna model such as the geometry, materials, and excitation, remain completely invisible to the user. The antenna module communicates with the main finite-difference time-domain grid by exchanging only electric and magnetic field values at boundaries around a volume enclosing the antenna. The initial development of this framework has been in done in cooperation with Sensors & Software Inc. using an experimental dipole antenna model. The finalised toolset will offer the potential of a step change in the quality of data from numerical models of GPR systems.**

I. INTRODUCTION

Simulations of ground penetrating radar (GPR) that have included models of the actual antenna details have been mainly of antennas used in academia or for research purposes [1]–[10]. There has been very limited published work of GPR simulations with models of commercial antennas [11]–[13]. In fact, many simulations have used a theoretical Hertzian dipole source to represent a real GPR antenna where only far-field behaviour or travel-time information was of interest, or where computational resources were limited. However, computing power is increasing dramatically and becoming more accessible – multi-core CPUs and gigabytes of RAM are now standard features on desktop and laptop machines, and many businesses and universities now have their own high-performance computing (HPC) systems. These computational advances have particularly benefitted volume-based numerical techniques such as the finite-difference time-domain (FDTD) method, and allowed larger and more complex problems to be investigated. This, coupled with the desire to investigate quantitative information from GPR, means detailed 3D FDTD models of realistic GPR antennas need to be created and used. Developing such models of commercial antennas presents a challenge because GPR manufacturers have a great deal invested in their intellectual property (IP) and naturally want to protect it.

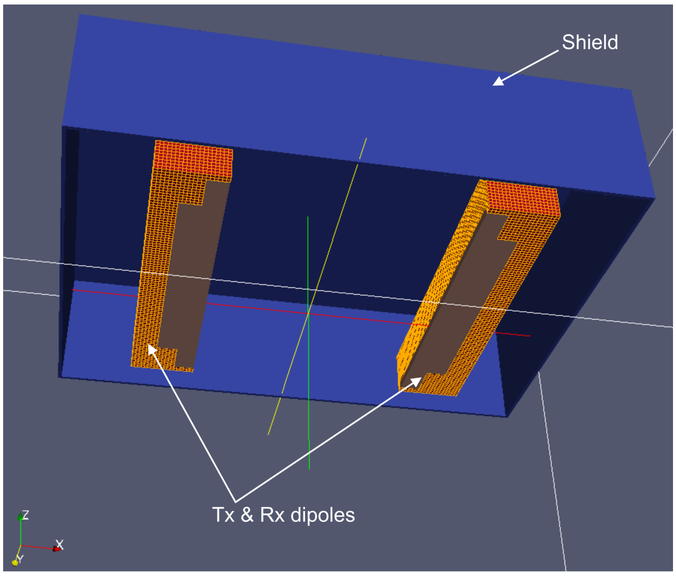

Fig. 1. Detailed model of a high-frequency antenna created using gprMax3D [11].

gprMax (http://www.gprmax.com) is a set of freely-available electromagnetic wave simulation tools [14] based on the FDTD method. Over the past 18 years gprMax 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 [15]–[18], and has been cited nearly 200 times since 2005 [19]. It contains many powerful and flexible features for modelling antennas, such as the example shown in Fig. 1. These features include: Perfectly Matched Layer (PML) absorbing boundary conditions; user-definable materials; user-specifiable excitation functions; simulation of thin wires; voltage sources and 1D transmission line models for feeding antennas.

The first part of the paper outlines the general redesign of gprMax which was undertaken as part of the development of the antenna modelling framework. Then in the second part of the paper the structure and operation of the commercial antenna modelling framework is described.

II. GPRMAX CODE REDESIGN

gprMax offers a cross-platform 3D FDTD code that was originally written using the C programming language, with the computationally intensive parts – the 3D FDTD solver loops – parallelised using OpenMP [20]. To facilitate the implementation of new advanced features and to lay the foundation for future developments, it was decided that gprMax should be rewritten in an object-orientated language. Python [21] is an interpreted language that is object-oriented and features dynamic typing and automatic memory management. It is also intended to be a highly readable and extensible. However, the ease and flexibility of Python comes at a cost of speed when compared to statically typed languages such as C. This loss of speed can be mitigated by utilising Cython [22] – a superset of Python that generates efficient C source code that can be compiled into extension modules. Therefore the new version of gprMax has been written using a combination of Python, NumPy, and Cython with OpenMP, which keeps the benefits of Python with most of the speed of C.

gprMax has retained a simple text-based input file where users specify all the parameters for a simulation, e.g. model size, discretization, time window, geometry, materials, excitation. The input file has now been made scriptable by permitting blocks of Python code to be specified, which are executed when the file is read into gprMax. Listing 1 demonstrates an example of this benefit by including repetitive geometry commands scripted directly in the input file using simple Python loops.

Listing 1. Python scripting in an input file

```
#python:
for x in range(0, 8)
    print(’#cylinder: z 0.000 0.100 {} 0.050
        0.005 pec’.format(0.020 + x * 0.020))
#end_python:
```

Alongside improvements to the input file there is a new output file format – HDF5 [23] – to manage the larger and more complex data sets that are being generated. HDF5 is a robust, portable and extensible format with a number of free readers available. In addition, the Visualization Toolkit (VTK) [24] is being used for improved handling and viewing of the detailed 3D FDTD geometry meshes. The VTK is an open-source system for 3D computer graphics, image processing and visualisation. It also has a number of free readers available including Paraview (http://www.paraview.org).

III. ANTENNA FRAMEWORK

The redesign of gprMax using Python provided a route to develop a framework for modelling commercial GPR antennas. The main objectives of the framework were to:

1) Allow GPR manufacturers to easily create and test 3D models of their own antennas using gprMax.
2) Protect the IP of the manufacturer, i.e. ensure details of their antennas would not be accesible to either the end-users or developers of gprMax.
3) Enable the antenna models to be easily included in 3D simulations by end-users of gprMax.

The tools that are required for the commercial antenna modelling framework are the new version of gprMax, and a source code template Cython module.

The new 3D version of gprMax includes all the functionality present in the previous version for building antenna models as well as new features that are useful for antenna modelling such as: an unsplit implementation of higher order perfectly matched layers (PMLs) using a recursive integration approach; uniaxially anisotropic materials; and dispersive media using multiple Debye and Drude expressions. Once the manufacturer has developed their 3D antenna model in gprMax there is a new command which allows the key model data to be encrypted and saved to file. The encryption process has been implemented using the PyCrypto [25] module and the Advanced Encryption Standard (AES) symmetric-key algorithm. The data is encrypted using an AES key that is set by, and private to, the manufacturer. The manufacturer then inserts the same key into a provided source code template module that they compile. This compiled Cython extension module will be able to read the encrypted antenna data and will communicate with the main 3D FDTD grid in gprMax. By compiling the extension module the manufacturers key remains private. The extension module only communicates essential data with gprMax – it supplies its sub-domain extent to the main grid and the output values from the antenna receiver as they are calculated. Electric and magnetic field values are exchanged between the antenna extension module and the main grid at the boundaries of the antenna model. By limiting data communication in this way, the geometry, materials, and excitation used in the antenna model are not accessible, which helps protect the IP of the manufacturer. The encrypted data file and the compiled extension module can then be safely distributed to end-users of gprMax.

The following list summarises the key steps to building the extension module for modelling commercial antennas:

1) The manufacturer goes through a phase of developing and testing their 3D antenna model using gprMax.
2) The finalised model data is encrypted with the manufacturer’s own private key and saved to file.
3) The manufacturer inserts their private key into a Cython extension module (from a code template) which is the compiled. This module will be able to read the encrypted data and will communicate with the main 3D FDTD grid in gprMax.
4) The encrypted data file and the Cython module can be then be used directly with gprMax to include the 3D antenna model in any simulation.

Listing 2 demonstrates the simplicity of including the antenna model in a simulation – with two commands a model of the Sensors & Software Inc. experimental dipole antenna can be used.

Listing 2. Inserting a commercial antenna model into an input file

```
#python:
import from gprMax3D.lib_sensoft import
    antenna_dipole
antenna_dipole(0.050, 0.050, 0.050, resolution='1
    mm')
#end_python:
```

The model uses a 1mm 3D FDTD mesh. Currently, the main FDTD model must use the same spatial resolution as the antenna model. This is not a significant restriction as models featuring high-frequency GPR antennas are usually for near-surface investigations, so do not need to be physically large. The user can specify the coordinates of where the antenna should be located in the main model, and can script the movement of the antenna, e.g. to collect B-scan data. The output from the receiver part of the antenna is communicated from the extension module and saved in the gprMax output file.

IV. CONCLUSION

The ability to include accurate models of commercial GPR antennas in simulations is a significant step forward for advanced numerical modelling of GPR. For example, it offers a faster route for data processing and inversion algorithms to be developed from a numerical model and then put into practical application. It should also strengthen links between numerical modelling, manufacturers and practitioners.

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