SUBGRIDDED FDTD SIMULATION OF ELECTROMAGNETIC FIELDS IN INHOMOGENEOUS EARTH MEDIA FOR GEOPHYSICAL PROBING APPLICATIONS

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ABSTRACT

We describe a finite-difference time-domain(FDTD) algorithm to simulate propagation/diffusion of electromagnetic fields in inhomogeneous earth media. The algorithm employs a cylindrical grid to conform to usual measurement apparatus geometries of well logging tools for oil and gas exploration. The grid is made very compact around the measurement apparatus by using a cylindrical perfectly matched layer (PML). In order to avoid the disparate cell sizes inherent to a cylindrical grid, a subgridding algorithm is employed in the radial coordinate. This FDTD scheme is validated against numerical mode matching (NMM) results and used to simulate logging tools in complex geophysical environments.

INTRODUCTION

Energy prospection techniques rely heavily on the ability to model the interaction of electromagnetic fields with complex geophysical environments [1]. The modeling of the measurement-while-drilling (MWD) or wire-line logging tools in general non-symmetric three-dimensional (3-D) environments, with all important details of the tool geometry (such as grooves, pipes, and mandrels), included is a very challenging problem. A powerful numerical approach able to treat such general problems is the finite-difference time-domain (FDTD) method. FDTD provides unparalleled flexibility and high scalability for simulation in parallel computers [2-3].

In this work, we describe a FDTD technique to model logging tools in a wide range of frequencies (from tens of kHz to tens of MHz). The surrounding geophysical formation is allowed to have an arbitrary spatial distribution of permittivity and conductivity. Low frequency responses are extracted from the time-domain data from the early time response of ramp sinusoids excitations. The FDTD is compared against the numerical mode matching (NMM) method and it used to estimate the resistivity/conductivity profile of various geophysical formations.

FDTD MODELS

The present FDTD technique consists of a 3-D staggered-grid scheme developed in cylindrical coordinates to better conform to the vast majority of tool geometries. In order to simulate unbounded domain problems, a cylindrical perfectly matched layer (PML) absorbing boundary condition (ABC) is used [3]. This makes the 3-D FDTD grid considerably more compact both in the radial and the axial directions, and reduce the overall memory requirements for a problem of given physical size. Contrary to previously developed ABCs, the PML is also applicable to arbitrary media (e.g., inhomogeneous, dispersive, and/or anisotropic) [4].

Because FDTD is a matrix-free technique, it does not require any storage other than the necessary to store the fields and describe the parameters of the formation. Hence, the memory requirements are considerably reduced in comparison to similar-size finite-difference simulations in the frequency domain. Moreover, despite being computationally intensive, the FDTD technique has a low ($O(N^{1.33})$ in 3-D, where N is the number of unknowns) computational complexity both in terms of memory and CPU time cost. Contrary to frequency-domain techniques however, the FDTD technique requires a time integration procedure. Still, because geophysical problems usually have a low-Q (i.e., deal predominantly with diffusion or induction problems), a relatively small integration time is needed to reach convergence.

Despite of that, the time integration is a major factor for the overall CPU time cost of the method. In order to reduce the integration time, we adopt a two-pronged strategy here. (a) We implement a mesh refinement scheme tailored to the cylindrical grid properties, to merge highly elongated cells in the direction of the shortest dimension (usually the azimuth direction), and reduce the cell aspect ratio and the total number of unknowns. This also allows for the use of a larger time step, as dictated by the Courant condition. (b) We implement techniques for fast extraction of the frequency domain data from very early-time simulation results.

Typically, mesh refinements for time-domain simulations are prone to late time unconditional instabilities. The reasons for these instabilities are subtle and normally connected with inconsistencies on the definition of spatial grid operators representing the derivatives in the coarse-to-fine transition region [5]. Therefore, care must be exercised when defining discrete derivative operators on the cylindrical coarse/fine transition to ensure that the resultant schemes are stable [4].

RESULTS

In the following, we show results of the PML-FDTD simulation of well-logging tools consisting of transmitter and receiver loop antennas inside a borehole surrounded by a geophysical formation. Both measuring-while-drilling (MWD) tools and induction tools are considered.

Fig. 1 illustrates the robustness of the PML-FDTD method by considering the response from a MWD tool at 2 [MHz] on a three-layer formation with conductivities σ = 5.0, 0.0005, and 1.0 [S/m], respectively, obtained by the PML-FDTD and the NMM. The position of the transmitter loop antenna is 0 [in] and the receiver loop antennas are located at 24 [in] and 30 [in] inches, respectively. The antennas are located around a metallic mandrel of radius equal to 4 [in], and both loop antenna radii are 4.5 [in]. The measurement tool is located in a borehole of radius 5 [in]. Notice the extremely large conductivity contrast of 10^4 between adjacent beds (close to the maximum dynamic range of the usual measurement tools).

Deviated drilling has become a very efficient means to explore large areas at reduced cost. In deviated drilling, the study of the effect of dipping beds in the tool response is of paramount importance. Fig. 2 illustrates the effect of different dip angles in the response (amplitude ratio) for the MWD tool using the PML-FDTD method.

Fig. 3 shows another comparison, now for an induction-logging tool at 32 [KHz]. We consider a vertical borehole in a formation with three axial layers. Each of these axial layers has 4 radial zones: (a) a metal tube at the center with radius of 0.55 [in]; (b) a fiberglass mandrel from 0.55 [in] to 1.8125 [in] (with resistivity $\rho = 10^8$ [$\Omega \cdot m$] and ϵ_r=1.0); (c) the borehole itself with radius 5 [in] (filled with a mud with resistivity of 2000 [$\Omega \cdot m$]); and (d) the formation. The same formation conductivities are considered as before: 1.0, 0.01, and 1.0 [S/m]. The tool itself consists of a transmitter loop antennas with 200 turns at 0 [in] and a receiver composite loop antenna consisting of -47 turns at 78.035 [in], 104 turns at 69.00 [in], -47 turns at 59.95 [in]. The coil diameter is 2.695 [in] and the mandrel (or pipe) diameter 1.1 [in]. Shown in this figure is the voltage amplitude measured at the receiver antenna.

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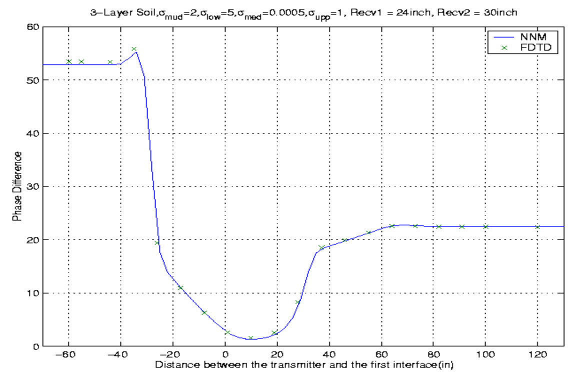

Figure 1: MWD tool response at 2MHz (amplitude ratio) for a high-contrast three-layered formation: PML-FDTD vs. NMM results.

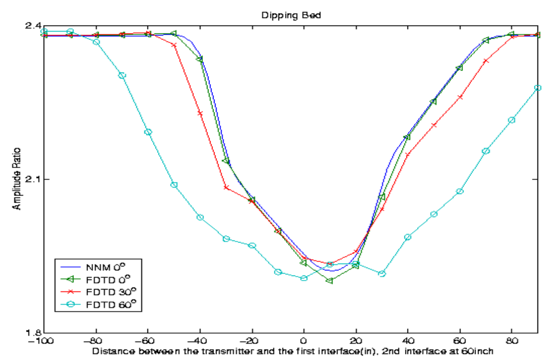

Figure 2: MWD tool response of a three-layer formation for different dipping angles.

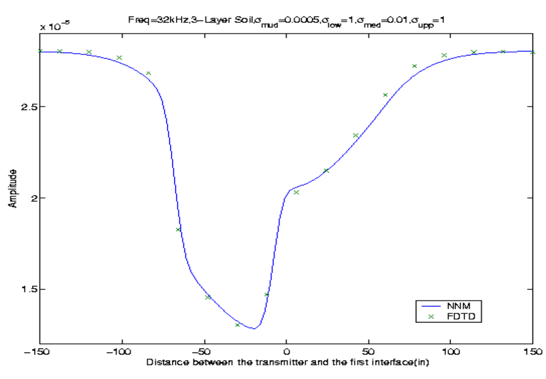

Figure 3: Induction tool response at 32KHz (voltage amplitude): PML-FDTD vs. NMM results.