Fast Simulation of 2.5D LWD Resistivity Tools

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Abstract. As a first step towards the fast inversion of geophysical data, in this work we focus on the rapid simulations of 2.5D logging-while-drilling (LWD) borehole resistivity measurements. Given a commercial logging instrument configuration, we calibrate the FE method offline with respect to (i) the element sizes via non-uniform tensor product grids; (ii) the arbitrary polynomial order of approximation on each element; and (iii) the interpolation of certain Fourier modes. This leads to the design of proper FE discretizations to simulate measurements acquired in an arbitrary 2D formation.Numerical results show that we accurately simulate on a sequential computer any field component at a rate faster than one second per logging position.

Introduction

We are developing a Finite Element (FE) method with arbitrary high-order, mixed finite element approx-imations of H^1-conforming and $\mathbf{H}$(curl)-conforming discretizations suitable for the efficient inversion of borehole resistivity measurements. In this work, we focus on the fast simulation of 2.5-dimensional (2.5D) resistivity logging-while-drilling (LWD) measurements as a first step towards their inversion [Zhou (2015); Dupuis and Denichou (2015)]. In the 2.5D formulation [Shen and Sun (2008)], the prob-lem dimensionality of the forward modelling is reduced under the assumption that material properties are homogeneous in one spatial direction.

LWD logging instruments record post-processed quantities of the magnetic field $\mathbf{H}$, implicitly defined as the solution of the reduced wave equation:

$$\nabla \times (\hat{\sigma}^{-1} \nabla \times \mathbf{H}) + j\omega\mu \, \mathbf{H} = -\mathbf{M}^{\mathbf{imp}}, \quad (1)$$

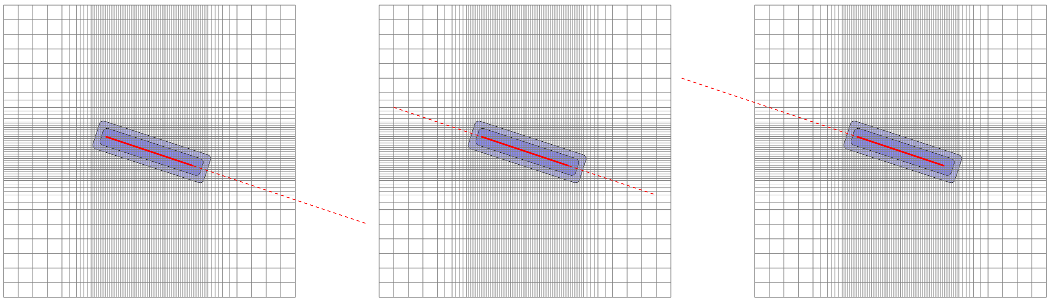
over an unbounded, anisotropic medium, satisfying the Sommerfeld radiation condition [Rothwell and Cloud (2010)]. In the above, $\mathbf{H}$ is the magnetic field, j is the imaginary unit, μ is the free-space magnetic permeability tensor, $\hat{\sigma} := (\sigma + j\omega\varepsilon)$, σ is the piecewise-constant conductivity tensor of the medium, ($\rho = \sigma^{-1}$ is the resistivity tensor of the medium), $\varepsilon = \varepsilon_0 \approx 8.85 \times 10^{-12}$ F/m is the constant per-mittivity of the medium, $\omega = 2\pi f$ is the angular frequency and f is the frequency of operation of the resistivity tool. Finally, $\mathbf{M}^{\mathbf{imp}}$ is the time-harmonic directed magnetic dipole source excited by the tri-axial transmitter coils mounted on the logging tool.

At every tool position, we solve a 2.5D direct problem associated to Eq. (1) using a FE method. Sub-sequently, we post-process the solution in order to evaluate the so-called *apparent resistivity* of the formation by means of the *attenuation* and the *phase difference* (*phase shift*). For example, for a specific LWD logging tool with two receivers $\mathscr{R}_{\mathbf{x}_1}$ and $\mathscr{R}_{\mathbf{x}_2}$, attenuation and phase differences for the co-axial component ($\mathbf{H}_{zz}$) are obtained by taking the real and the imaginary part, respectively, of the following (nonlinear) *quantity of interest (QoI)*

$$q_{zz}(\mathbf{H}) = \log \frac{\mathbf{H}_{zz}(\mathscr{R}_{\mathbf{x}_1})}{\mathbf{H}_{zz}(\mathscr{R}_{\mathbf{x}_2})} = \log \mathbf{H}_{zz}(\mathscr{R}_{\mathbf{x}_1}) - \log \mathbf{H}_{zz}(\mathscr{R}_{\mathbf{x}_2}). \quad (2)$$

The 2.5D FE method

In order to limit the computational time of the 2.5D simulations, our FE software incorporates the fol-lowing features:



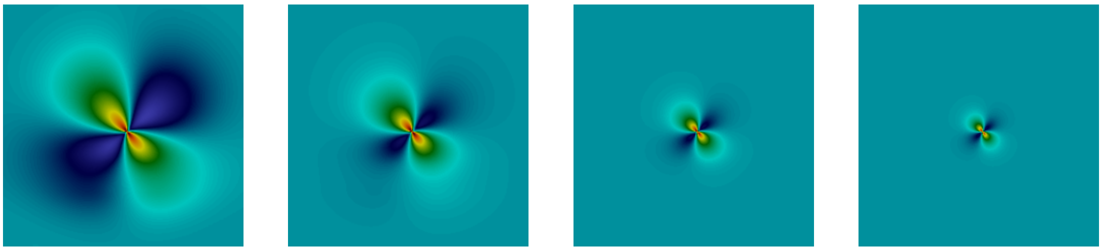
(a) Left trajectory section **(b)** Central trajectory section **(c)** Right trajectory section

Figure 1: Computational grids associated to three different sections of a logging trajectory. At every element, the darker the blue color is, the higher the polynomial order of approximation.

1. In terms of element sizes, we employ non-uniform tensor product grids composed of quadrilateral elements (Fig. 1), with finer element size around the area where measurements take place. However, in terms of the polynomial order of approximation, we employ non-tensor product adaptive grids with higher number of unknowns in the proximity of the logging instrument.

2. The well trajectory is optimally subdivided into sections (see Fig. 1) so the total computational time is minimized. Within each section, we use a single computational grid in order to factorize the system of linear equations only once.

3. We employ different grids for different Fourier modes (see Fig. 2). Since we only need accurate results at the receivers, some modes are simulated via FE, while the remaining ones are interpolated in the logarithmic scale, saving up to 58% of the total computational time (see Fig. 3 and reference [Rodríguez-Rozas and Pardo (2016)]).



(a) Fourier mode 0 **(b)** Fourier mode 3 **(c)** Fourier mode 6 **(d)** Fourier mode 10

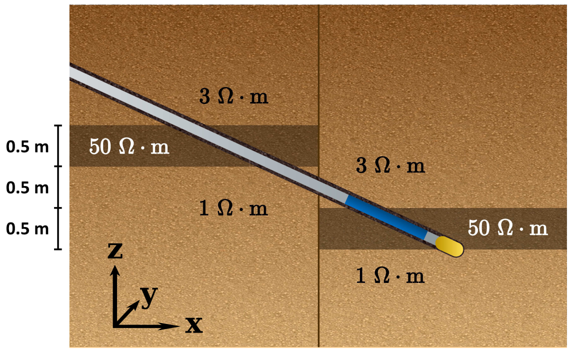
Figure 2: Real part of the $\mathbf{H}_{zz}$ solution corresponding to different Fourier modes showing that the higher the Fourier mode, the smaller the support of the electromagnetic (EM) fields.

4. The parallel software can execute each Fourier mode and each trajectory section in a different core. This leads to a perfect parallel scalability that permits a drastic reduction of the total computational time.

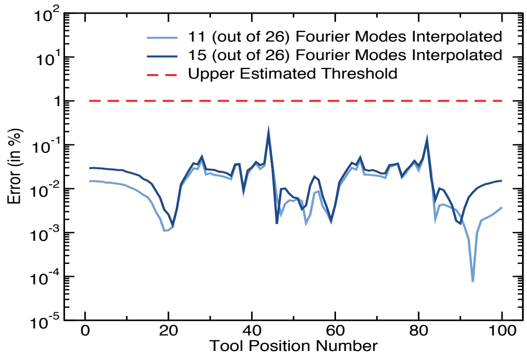
Additionally, we compute derivatives of the measurements with respect to the material properties. Such derivatives are needed for inversion. Since recorded measurements are given by nonlinear combinations of the magnetic field at various receiver positions, computation of the derivatives require the solution of several adjoint problems (as many as the number of receivers).

Numerical results

Figure 4 shows the simulated attenuation and phase apparent resistivities of the co-axial component of an LWD commercial instrument operating at 2 MHz and at 400 KHz. We observe a good agreement



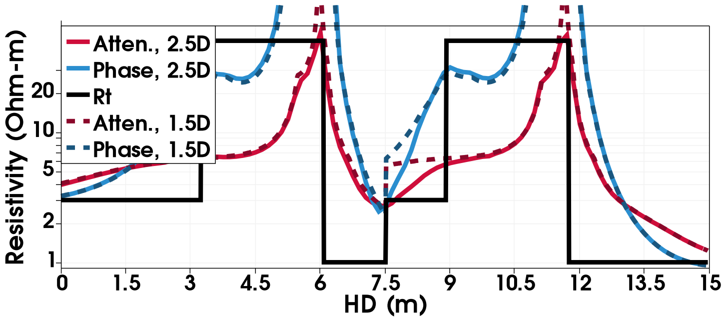
(**a**) Model problem. Dip angle=80°.



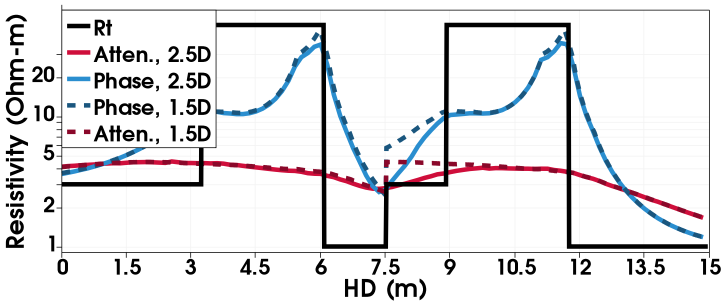
(**b**) Numerical errors

Figure 3: Error due to second-order interpolation of multiple Fourier modes (see panel b) on a model problem with a geological fault (see panel a).

between 1.5D and 2.5D simulations, except on the proximity of the geological fault, as physically expected. Each 2.5D curve composed of 100 logging positions is computed in approximately 62 seconds using a MacBook Pro laptop equipped with a 3 GHz Intel I7 processor, i.e., in less than 1 second per logging position.



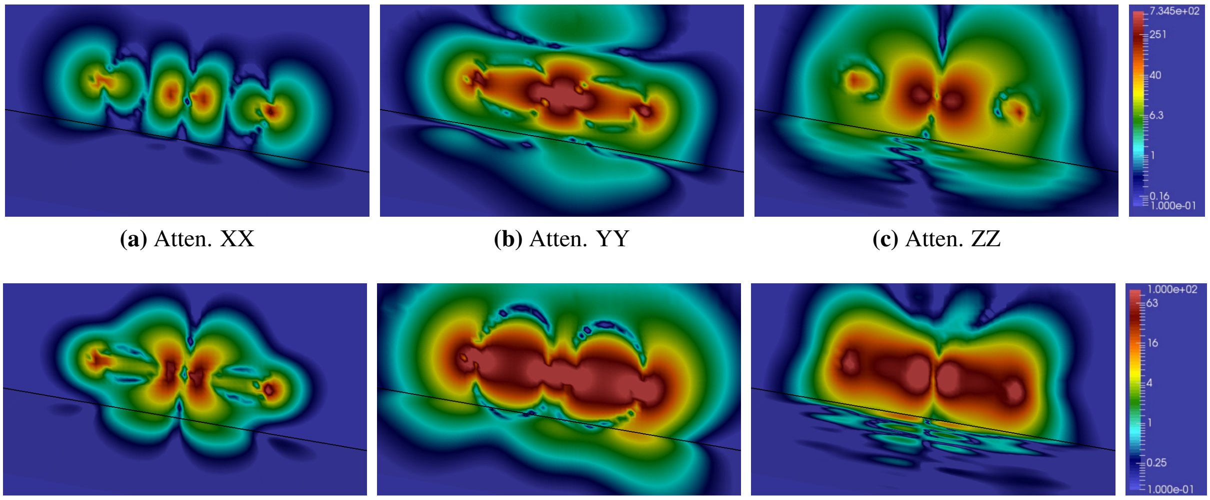
(**a**) Log at 2 MHz



(**b**) Log at 400 KHz

Figure 4: LWD resistivity logs corresponding to the model problem of Fig. 3(a).

Figure 5 shows various tri-axial sensitivity functions corresponding to the first logging position of the above example. In there, we observe that each component exhibits a rather different sensitivity. For example, the zz-component of the attenuation is more sensitive to variations in the resistivity on the proximity of the receiver than those possibly occurring around the transmitters. For the case of deep and extra-deep azimuthal resistivity measurements, similar results are obtained (details are omitted here to fit into the page limit) by using a proper change of coordinates (stretching of the domain).



(a) Atten. XX **(b)** Atten. YY **(c)** Atten. ZZ

(d) Phase XX **(e)** Phase YY **(f)** Phase ZZ

Figure 5: View of various 3D sensitivity functions at 2 MHz for different components of attenuation and phase with respect to the logarithm of the resistivity of the formation, expressed in absolute value using logarithmic scale. We display these functions along two planes intersecting at the black line, which is parallel to the logging trajectory: (i) A vertical plane $y = 0$ cutting the logging trajectory, and (ii) a plane parallel to the tool trajectory located 0.32 m below it and pointing in the y-direction.

Conclusions and future work

We are developing a library for the rapid simulation of 1D, 2D, 2.5D, 2.75D and 3D borehole measurements. Preliminary 2.5D simulations on LWD and other logging instruments illustrate the flexibility and high performance of the library. In particular, we simulate 2.5D LWD resistivity measurements on a laptop using below one second per logging position. Moreover, the developed FE technology allows us to easily compute the corresponding derivatives (sensitivity functions) employed by gradient based inversion methods, which are necessary for the accurate interpretation of the acquired measurements.

As future work, the 2.5D software will be executed on a 128-core machine, where we expect to compute all components of the electromagnetic fields and their derivatives at a rate below 0.1 seconds per logging position. We shall also combine it with the rapid 1.5D inversion library [Pardo and Torres-Verdín (2015); Bakr et al. (2016)] of borehole co- and tri-axial resistivity measurements acquired in geological formations where 1.5D methods alone are insufficient to provide accurate results.

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