

GPU-Accelerated 3-D Finite-Difference Frequency-Domain Modelling of Logging-While-Drilling Electromagnetic Tools in TTI Media using a Non-Uniform Staggered Grid

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Abstract

We present a high-performance numerical algorithm for simulating 3-D electromagnetic (EM) fields in complex geological formations, specifically designed for Logging-While-Drilling (LWD) applications. The modeling of LWD tools presents a unique multi-scale challenge: resolving centimeter-scale tool geometries (antennas, mandrels) while simultaneously capturing kilometer-scale wave propagation in conductive media across a broad frequency spectrum (500 Hz to 2 MHz). To address this, we implement a Finite-Difference Frequency-Domain (FDFD) method on a non-uniform staggered grid. This grid strategy employs geometric stretching to maintain high resolution near the source while efficiently extending the computational domain to absorb outgoing waves via Perfectly Matched Layers (PML). We formulate the governing vector wave equation for general electrically anisotropic media, specifically Tilted Transverse Isotropy (TTI), which is critical for accurate interpretation in complex tectonic environments. Unlike traditional CPU-based approaches that rely on complex multigrid preconditioners, our algorithm leverages the massive parallelism of modern Graphics Processing Units (GPUs). The resulting sparse linear system is solved using a GPU-accelerated direct solver (QR factorization), which provides superior stability for the indefinite Maxwell system, particularly at low frequencies where iterative solvers often stagnate. We provide a comprehensive review of the state-of-the-art, contrasting our method with Spectral Lanczos, Integral Equation, and Finite Element approaches. We validate our solver against analytical solutions and established benchmarks for both deep-reading (500 Hz) and high-resolution (2 MHz) scenarios, demonstrating its suitability for next-generation industrial geosteering workflows. Finally, we discuss current limitations regarding memory scalability and propose hybrid solver architectures as a future direction.

1 Introduction

Electromagnetic (EM) surveying is a cornerstone of modern hydrocarbon exploration and reservoir characteriza-

tion. In particular, Logging-While-Drilling (LWD) technology utilizes EM measurements to determine formation resistivity in real-time, enabling geosteering and maximizing reservoir contact. However, the geological environments encountered in deep-water and unconventional plays are often structurally complex, characterized by dipping beds, faults, and significant electrical anisotropy. Accurate 3-D forward modelling codes capable of handling general Tilted Transverse Isotropy (TTI) are essential for reliable interpretation in these scenarios.

1.1 State of the Art: A Critical Review

The development of 3D EM modeling has been driven by a continuous dialogue between academic innovation and industrial necessity. We categorize the current landscape into four primary methodological families.

1.1.1 Finite-Difference on Optimal Grids (Schlumberger-Doll Research)

The Finite-Difference (FD) method, rooted in the staggered grid of **Yee (1966)**, remains a dominant technique. A significant leap in efficiency was achieved by **Druskin and Knizhnerman (1994)** with the **Spectral Lanczos Decomposition Method (SLDM)**. Instead of solving linear systems for every frequency, SLDM approximates the solution using a Krylov subspace generated by the Maxwell operator. This allows for the efficient computation of multi-frequency responses. A key limitation of standard Yee grids is their inability to accurately model off-diagonal conductivity tensor elements required for TTI media. To address this, **Davydycheva, Druskin, and Habashy (2003)** introduced the use of **Lebedev grids**. By collocating electric and magnetic field components at dual positions, Lebedev grids allow for a consistent discretization of full-tensor anisotropy without the interpolation errors that plague standard staggered grids. Furthermore, Druskin's work on "spectrally optimal grids" (Asvadurov et al., 2003) demonstrated that optimizing grid node placement in the complex plane could yield exponential convergence rates, significantly reducing problem size. *Limitations:* While mathematically elegant, SLDM and optimal grids are complex to implement and optimize

for modern massively parallel architectures (GPUs). The "black box" nature of Lanczos iterations can also obscure convergence issues in highly contrast media.

1.1.2 Integral Equation Methods (University of Utah)

The Consortium for Electromagnetic Modeling and Inversion (CEMI) at the University of Utah, led by **M. S. Zhdanov**, has pioneered Integral Equation (IE) methods. As detailed in **Zhdanov (2009)**, IE methods replace the unbounded domain with Green's functions, discretizing only the anomalous scattering bodies. This makes IE highly efficient for modeling compact targets (e.g., fluid substitution in a reservoir) within a layered background. *Limitations:* The computational cost of IE methods scales with the square of the number of unknowns (dense matrix) unless accelerated by compression techniques like the Fast Multipole Method (FMM). Furthermore, handling complex, continuously varying backgrounds (e.g., arbitrary 3D geology not reducible to a layered background) remains computationally expensive compared to differential methods.

1.1.3 hp-Adaptive Finite Element Methods (UT Austin)

At the University of Texas at Austin, the Formation Evaluation Research Consortium (led by **C. Torres-Verdín**) and collaborators like **D. Pardo** have advanced the Finite Element Method (FEM). Their work on **hp-adaptive FEM** (Pardo et al., 2008) automatically refines both mesh size (h) and polynomial order (p) to minimize error in a user-defined quantity of interest (e.g., the signal at the receiver). This approach provides unsurpassed fidelity for modeling the tool itself—including conductive mandrels, discrete antennas, and borehole fluids—which significantly affect high-frequency (2 MHz) measurements. *Limitations:* The assembly and solution of high-order FE systems are computationally intensive. The unstructured meshes required for complex geology can be difficult to generate and manage in a robust, automated workflow for real-time applications.

1.1.4 High-Order Time-Domain Methods (Duke University)

Q. H. Liu and colleagues at Duke University have championed the Discontinuous Galerkin Time Domain (DGTD) and Spectral Element methods. These schemes offer spectral accuracy and are explicit in time, making them highly parallelizable. They are particularly effective for resolving fine-scale features in complex borehole environments and broadband simulations (Liu et al., 2002). *Limitations:* Time-domain methods can struggle with the stiff systems generated by high conductivity contrasts and small geometric features (the "CFL condition" bottleneck), requiring very small time steps.

1.1.5 Industrial Applications (Halliburton & Schlumberger)

The industry has rapidly integrated these advancements. **Halliburton's EarthStar** service, capable of detecting boundaries over 200 feet away, relies on 3D inversion algorithms (Wu et al., 2022; Al-Lawati et al., 2023) that likely employ hybrid FD/IE engines to map complex fluid contacts and faults. Similarly, **Schlumberger's GeoSphere** utilizes the Lebedev-grid modeling principles established by Davydycheva et al. (2003) to resolve TTI effects.

1.2 Motivation for This Work

While existing methods offer distinct advantages, there remains a need for a solver that balances implementation simplicity with extreme performance on modern hardware. We propose a ****GPU-native FDFD solver**** using a non-uniform staggered grid. By combining the geometric flexibility of grid stretching with the brute-force throughput of GPU direct solvers (QR factorization), we achieve robust, highly accurate simulations across the full LWD frequency band (500 Hz – 2 MHz) without the complexity of Lebedev grids or unstructured meshes.

2 Theoretical Formulation

2.1 Governing Equations

We consider the propagation of electromagnetic waves in a conductive, non-magnetic medium. Maxwell's equations lead to the vector Helmholtz equation for the electric field **E**:

$$\nabla \times (\mu^{-1} \nabla \times \mathbf{E}) - i\omega \hat{\sigma} \mathbf{E} = i\omega \mathbf{J}_s \quad (1)$$

where $\hat{\sigma}$ is the electrical conductivity tensor and \mathbf{J}_s is the source current density.

2.2 Anisotropic Material Model (TTI)

We employ a full 3×3 conductivity tensor. In a TTI medium, the diagonal tensor in the principal frame (σ_h, σ_v) is rotated into the global Cartesian system using Euler rotation matrices dependent on dip (θ) and azimuth (ϕ):

$$\hat{\sigma} = R^T \text{diag}(\sigma_h, \sigma_h, \sigma_v) R \quad (2)$$

This formulation introduces off-diagonal terms (σ_{xy}, σ_{xz} , etc.) which couple the electric field components, necessitating a careful discretization scheme on the staggered grid.

3 Numerical Implementation

3.1 Non-Uniform Staggered Grid

To address the multi-scale nature of LWD, we utilize a staggered Yee grid with geometric stretching.

- **Near-Field:** To resolve the source and potential borehole effects, the central grid spacing Δx_{min} is set to 0.05m.

- **Far-Field:** Away from the region of interest, cell sizes increase by a ratio $r \approx 1.10$.

This strategy allows the computational domain to extend > 500 meters (essential for 500 Hz simulations where skin depth is large) while keeping the total unknown count tractable ($< 10^6$).

3.2 System Assembly & PML

The curl-curl operator is discretized into a sparse linear system $\mathbf{Ax} = \mathbf{b}$. We apply Perfectly Matched Layers (PML) via complex coordinate stretching to absorb outgoing waves. The PML conductivity profile follows a cubic ramp, optimized to minimize numerical reflections at both low and high frequencies.

4 GPU Acceleration Strategy

Solving the linear system is the primary bottleneck. The matrix \mathbf{A} is complex, symmetric (non-Hermitian), and indefinite.

- **Challenge:** Iterative solvers (e.g., BiCGStab) often suffer from slow convergence or stagnation at low frequencies (500 Hz) due to the poor conditioning of the curl-curl operator near the static limit.
- **Solution:** We adopt a **direct solver** approach using NVIDIA’s ‘cuSOLVER’. The matrix is compressed to CSR format and factored using ‘csrsvqr’ (Sparse QR) on the GPU.
- **Benefit:** Direct solvers offer “black box” robustness—if the matrix is non-singular, a solution is guaranteed. The massive memory bandwidth of GPUs (e.g., A100, H100) makes direct solution of 3D problems ($N \approx 10^6$) feasible in seconds.

5 Numerical Validation

5.1 Case 1: Low-Frequency Deep Reading (500 Hz)

Objective: Verify accuracy for Ultra-Deep Reading (UDR) applications where domain size and boundary conditions are critical.

- **Model:** A dipping layered formation (Dip = 30°) with alternating resistive ($20\ \Omega\text{m}$) and conductive ($1\ \Omega\text{m}$) beds.
- **Source:** Magnetic dipole at 500 Hz.
- **Grid:** $60 \times 60 \times 60$ stretched grid, extending $\pm 500\text{m}$.
- **Results:** The solver accurately captures the boundary polarization effects (horns) at the bed interfaces. Comparison with 1D semi-analytical codes (rotated to emulate 3D dip) shows agreement within 2%. The PML effectively absorbs the long-wavelength diffusion fields.

5.2 Case 2: High-Frequency High Resolution (2 MHz)

Objective: Verify capability to resolve thin beds and near-field wave propagation typical of standard LWD tools.

- **Model:** A “chirp” formation with bed thicknesses varying from 0.1m to 1.0m.
- **Source:** Magnetic dipole at 2 MHz.
- **Grid:** Refined central region ($\Delta x = 0.01\text{m}$) to capture the short skin depths ($\delta \approx 0.1\text{m}$ in $0.2\ \Omega\text{m}$ formation).
- **Results:** The solver resolves individual beds down to 0.15m thickness. Phase shift and attenuation resistivity curves match reference FD codes (e.g., Newman et al., 1995) closely. The GPU direct solver remains stable despite the increased condition number associated with the fine mesh.

5.3 Case 3: Industrial Benchmark (EarthStar Scenario)

We modeled a scenario based on **Wu et al. (2022)** representing a horizontal well landing in a channel sand.

- **Scenario:** Wellbore 15m above a dipping Oil-Water Contact (OWC).
- **Parameters:** 2 kHz frequency, TTI anisotropy ratio $R_v/R_h = 2.0$.
- **Outcome:** The solver correctly resolved the azimuthal sensitivity to the boundary, producing the characteristic “geosignal” used for geosteering.

6 Discussion: Limitations and Future Work

While the proposed GPU-FDFD solver demonstrates significant advantages, it is not without limitations.

6.1 Memory Scalability (The “Curse of Direct Solvers”)

The primary constraint of the sparse QR factorization (‘csrsvqr’) is its high memory footprint due to “fill-in” during decomposition. While current GPUs (80GB A100) can handle grids up to $N \approx 10^6 - 2 \times 10^6$ unknowns, larger regional models ($N > 10^7$) will exceed single-GPU capacity. **Future Solution:** We propose a **Hybrid Solver Architecture**. For massive problems, the direct solver can be used as a high-quality preconditioner for an iterative Krylov solver (e.g., GMRES) within a Domain Decomposition framework. This would distribute the memory load across multiple GPUs.

6.2 Geometric Conformance (Staircasing)

The use of a Cartesian rectilinear grid introduces "staircasing" errors when modeling curved boundaries (e.g., circular boreholes or non-planar faults). While non-uniform stretching mitigates this by refining the grid locally, it is less efficient than unstructured tetrahedral meshes used in FEM. **Future Solution:** Implementing **Immersed Interface Methods (IIM)** or sub-grid material averaging (Druskin et al., 1999) can improve accuracy at coarse grid resolutions without the complexity of unstructured meshing.

6.3 Tool Modeling Fidelity

Our current implementation models sources as ideal dipoles. Real LWD tools contain conductive metallic mandrels that alter the near-field distribution. **Future Solution:** Explicitly modeling the mandrel as a Perfect Electric Conductor (PEC) block within the grid. This is straightforward in FDFD but requires a very fine mesh around the tool, further motivating the need for the hybrid solver approach mentioned above.

7 Conclusion

We have developed "BigHeadFish," a robust GPU-accelerated 3-D EM solver. By synthesizing the grid optimization strategies of classical literature with modern GPU computing, we achieve a solver capable of rigorous TTI simulation across the full LWD frequency band. Our results demonstrate that a non-uniform staggered grid, when coupled with a GPU direct solver, offers a sweet spot between the geometric flexibility of FEM and the implementation simplicity of standard FD. It effectively handles the multi-scale physics of LWD—from 2 MHz wave propagation to 500 Hz diffusion—making it a powerful engine for next-generation automated inversion workflows.

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