BCAM Research Line I

MULTIPHYSICS, INVERSION, AND PETROLEUM

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BASQUE CENTER for APPLIED MATHEMATICS

Basque Center for Applied Mathematics (BCAM)

Promoting Technological Advances Through Mathematics

OVERVIEW

1. Motivation and Objectives: Joint Multiphysics Inversion
2. Simulation of Forward Problems
   - Parallel Self-Adaptive Goal-Oriented hp-Finite Element Method
   - Electromagnetic Applications
   - Sonic Applications
3. Inversion Library (Work in Progress)
   - h-Adaptive Newton's Method
   - Implementation
4. Conclusions and Future Work

MOTIVATION AND OBJECTIVES

Seismic Measurements

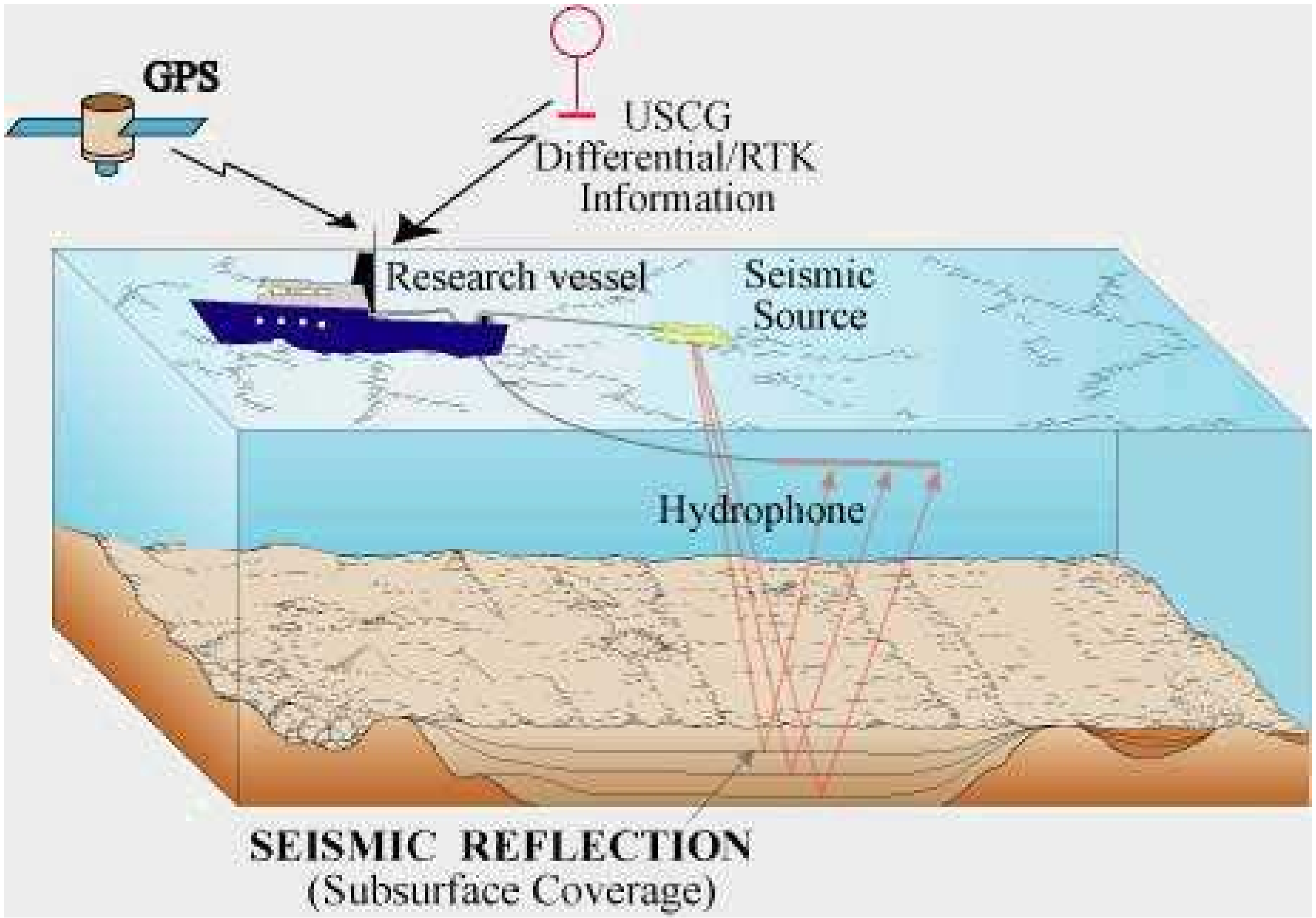


Figure from the USGS Science Center for Coastal and Marine Geology

MOTIVATION AND OBJECTIVES

Marine Controlled-Source Electromagnetics (CSEM)

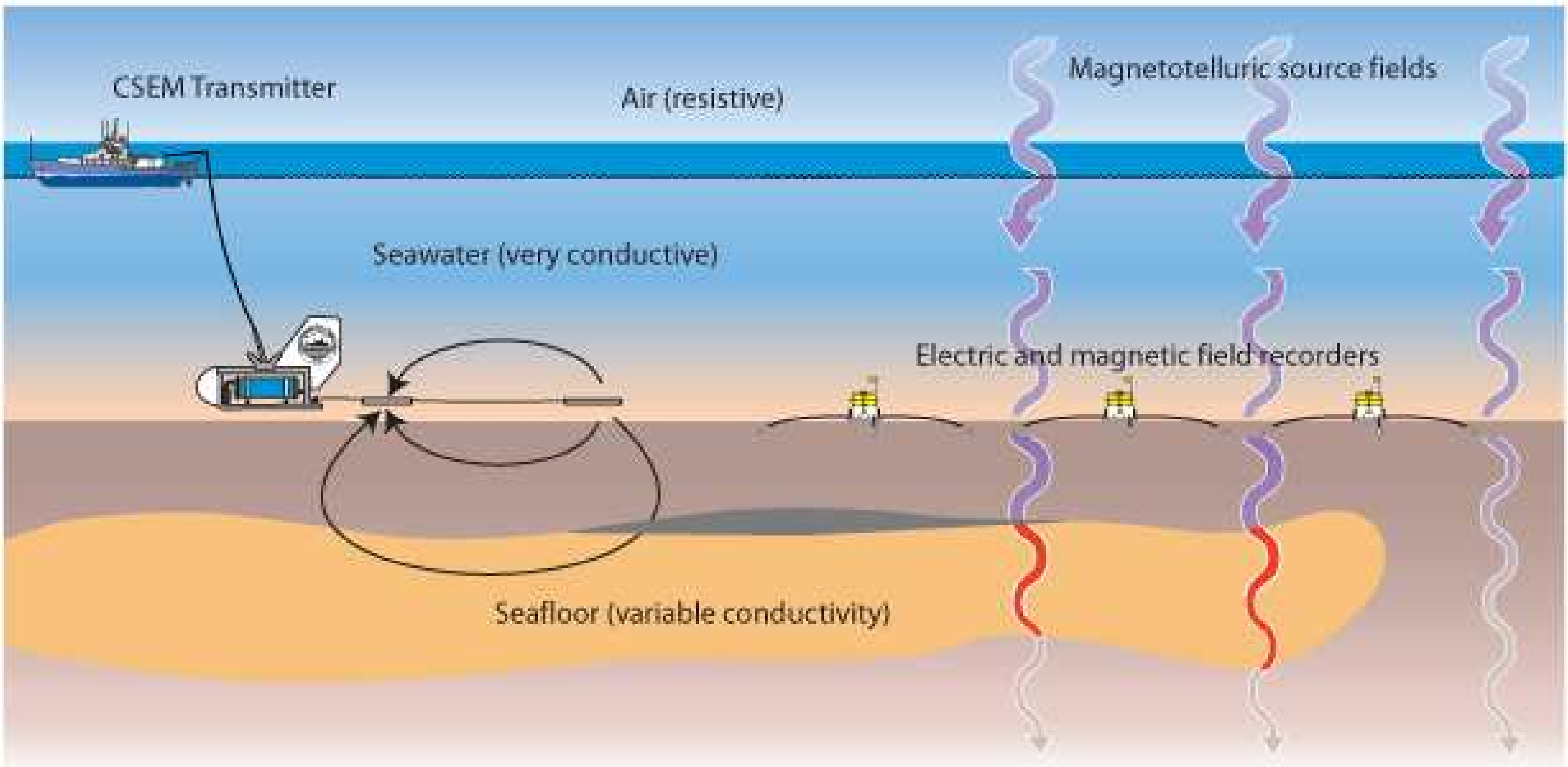
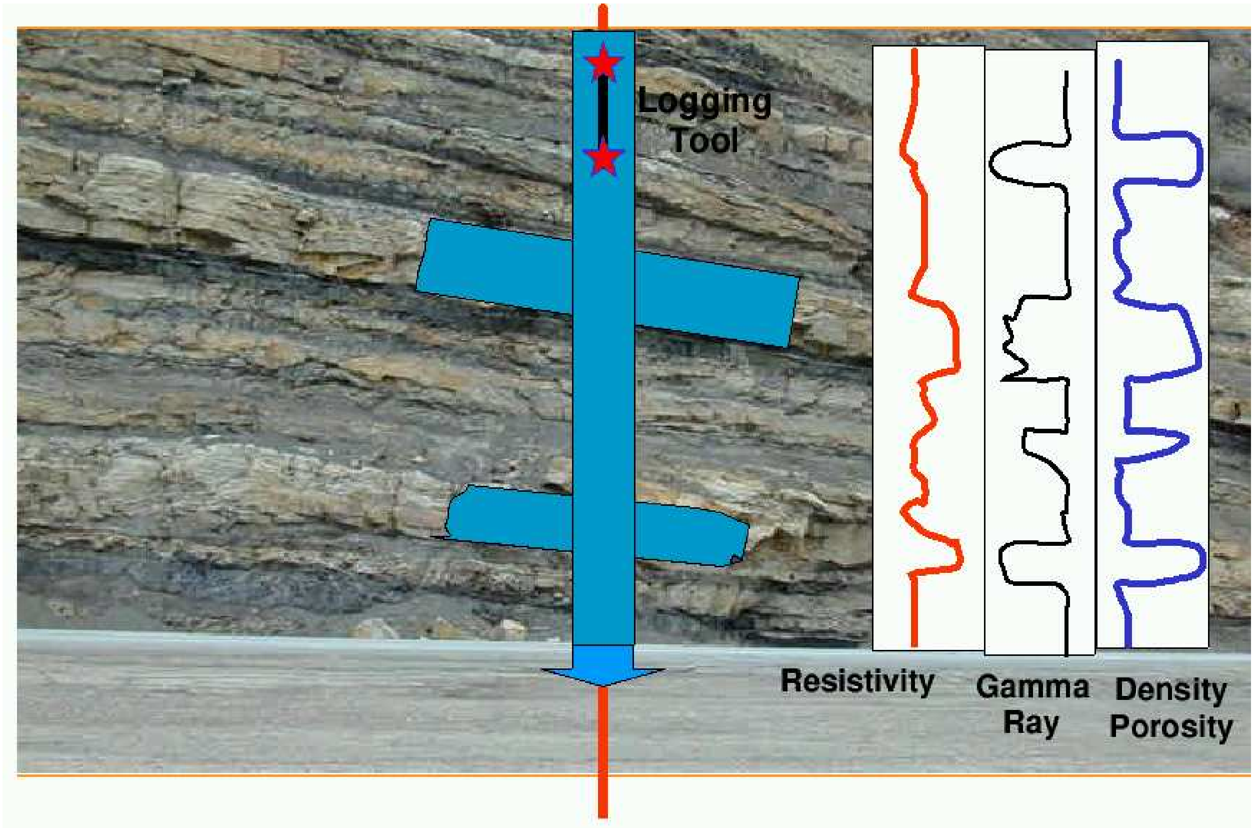


Figure from the UCSD Institute of Oceanography

MOTIVATION AND OBJECTIVES

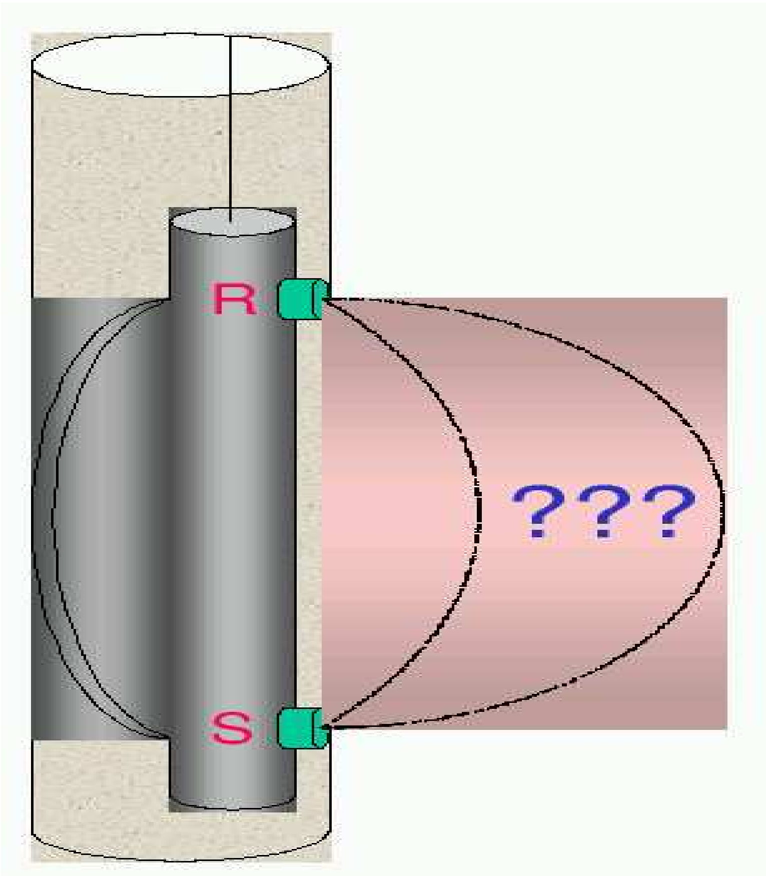
Multiphysics Logging Measurements



OBJECTIVES: To determine payzones (porosity), amount of oil/gas (saturation), and ability to extract oil/gas (permeability).

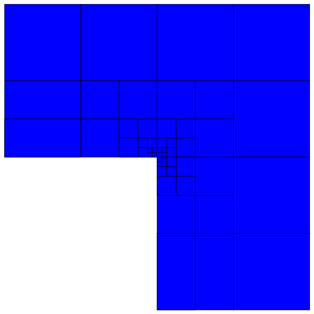
MOTIVATION AND OBJECTIVES

Main Objective: To Solve a Multiphysics Inverse Problem



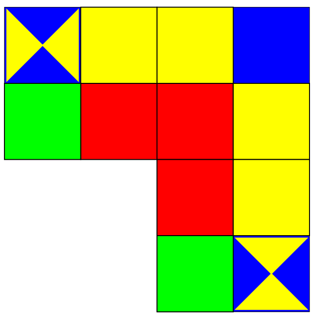
Given multi-frequency electromagnetic, acoustic, and nuclear measurements, the objective is to determine porosity, saturation, and permeability distributions in the reservoir.

SIMULATION OF FORWARD PROBLEMS (hp-FEM)



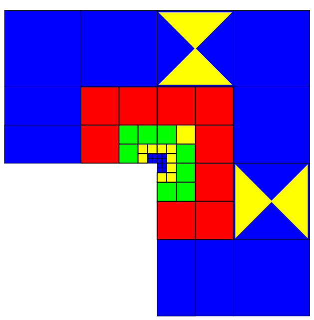
The h-Finite Element Method

1. Convergence limited by the polynomial degree, and large material contrasts.
2. Optimal h-grids do NOT converge exponentially in real applications.
3. They may "lock" (100% error).



The p-Finite Element Method

1. Exponential convergence feasible for analytical ("nice") solutions.
2. Optimal *p*-grids do NOT converge exponentially in real applications.
3. If initial *h*-grid is not adequate, the *p*-method will fail miserably.



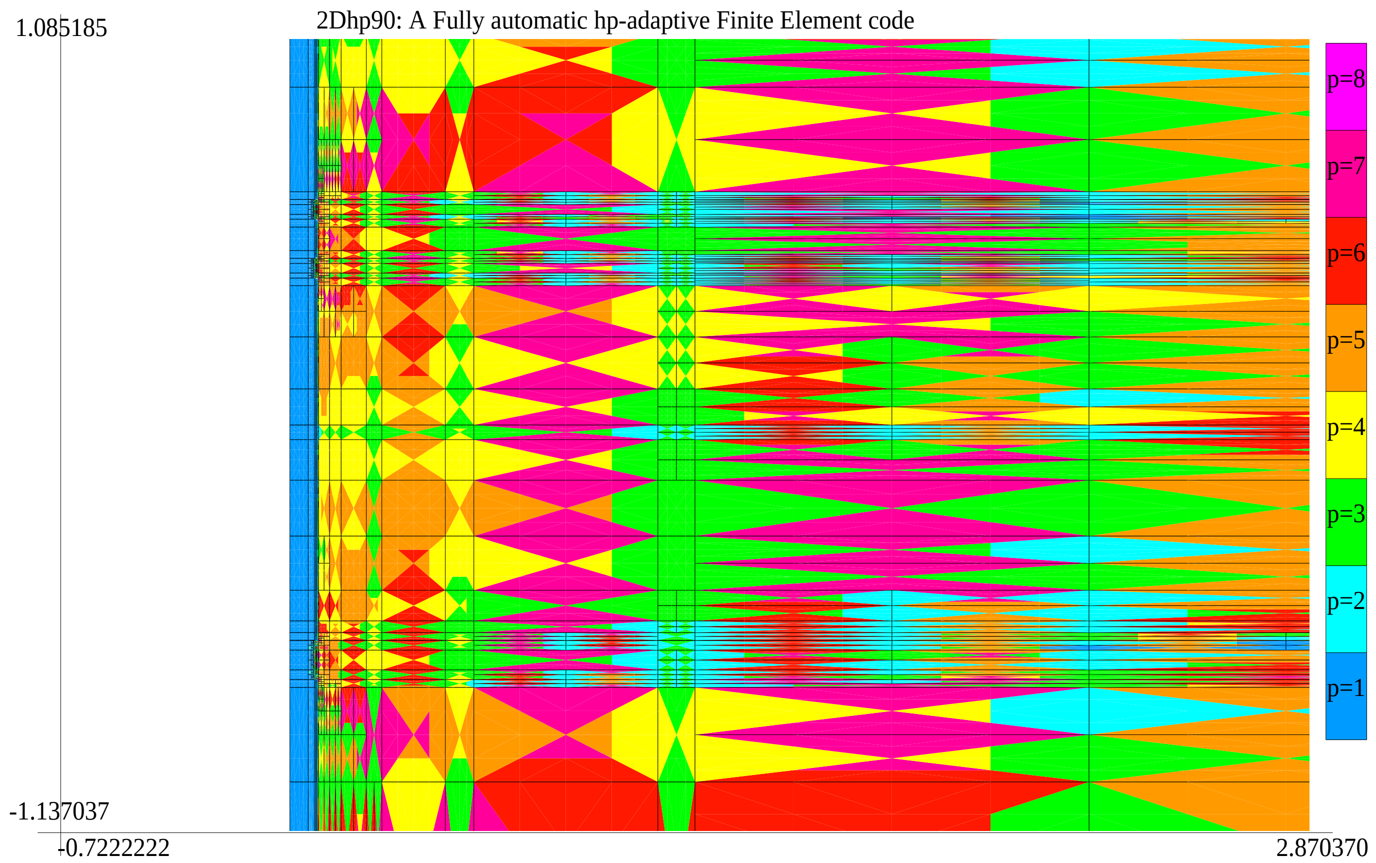
The hp-Finite Element Method

1. Exponential convergence feasible for ALL solutions.
2. Optimal *hp*-grids DO converge exponentially in real applications.
3. If initial *hp*-grid is not adequate, results will still be great.

SIMULATION OF FORWARD PROBLEMS (hp-FEM)

Axisymmetric Logging-While-Drilling (LWD) Simulation

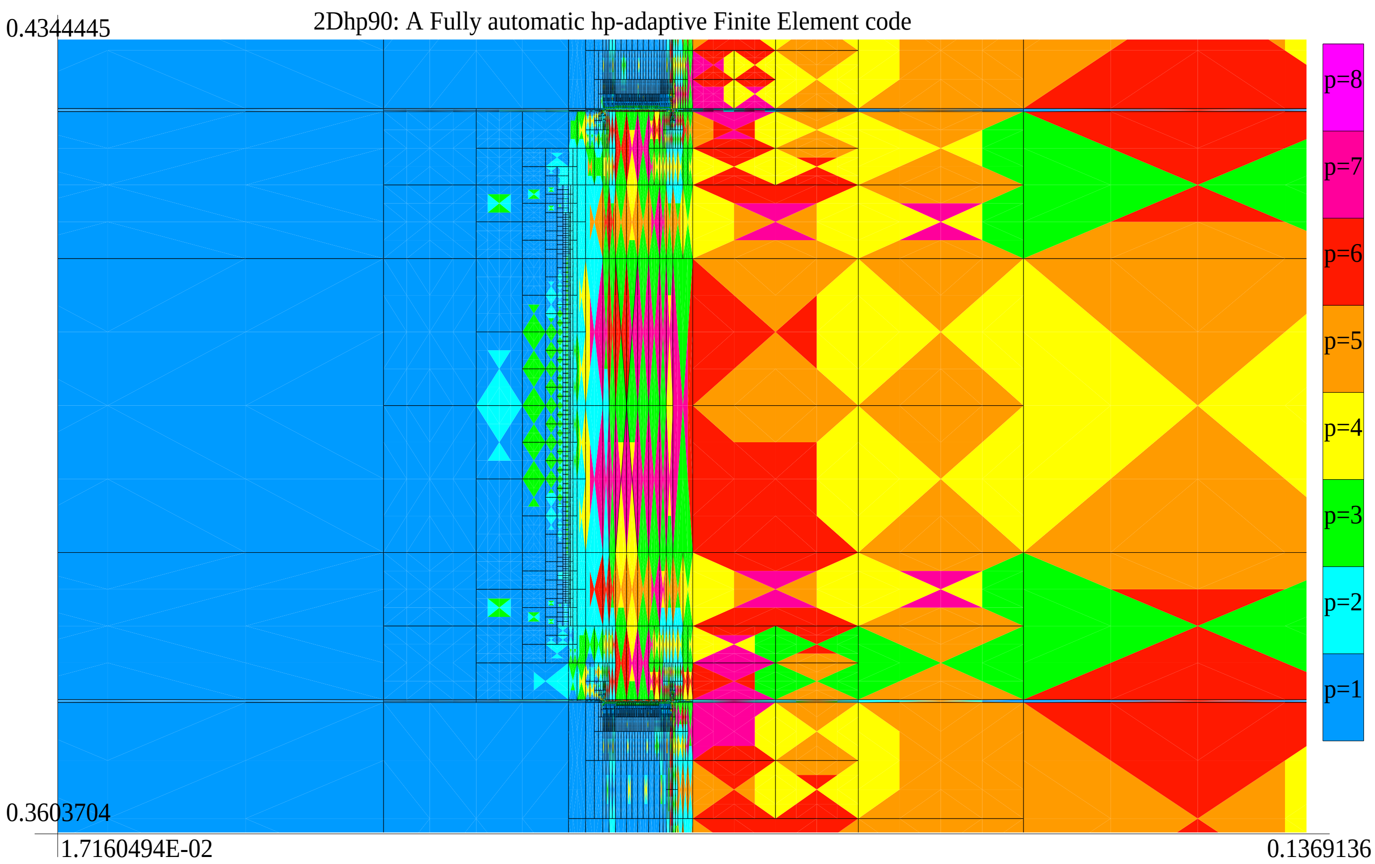
GOAL-ORIENTED HP-ADAPTIVITY (Quadrilateral Elements)



SIMULATION OF FORWARD PROBLEMS (hp-FEM)

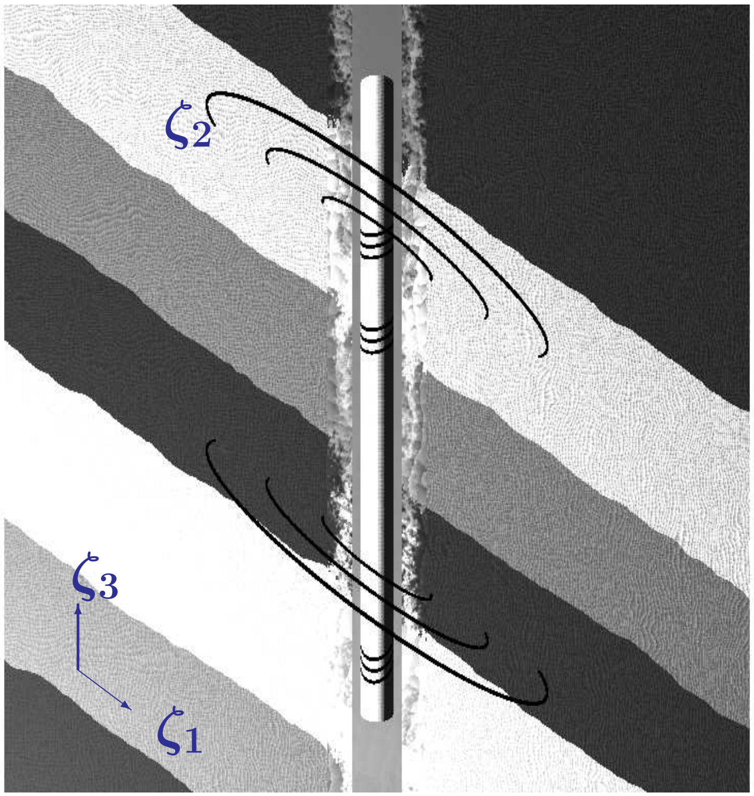
Axisymmetric Logging-While-Drilling (LWD) Simulation

GOAL-ORIENTED HP-ADAPTIVITY (ZOOM TOWARDS FIRST RECEIVER ANTENNA)



SIMULATION OF FORWARD PROBLEMS (hp-FEM)

Non-Orthogonal System of Coordinates



Material coefficients are constant with respect to the quasi-azimuthal direction ζ_2

Fourier Series Expansion in ζ_2

DC Problems: $-\nabla \sigma \nabla u = f$

$$u(\zeta_1, \zeta_2, \zeta_3) = \sum_{l=-\infty}^{l=\infty} u_l(\zeta_1, \zeta_3) e^{jl\zeta_2}$$

$$\sigma(\zeta_1, \zeta_2, \zeta_3) = \sum_{m=-\infty}^{m=\infty} \sigma_m(\zeta_1, \zeta_3) e^{jm\zeta_2}$$

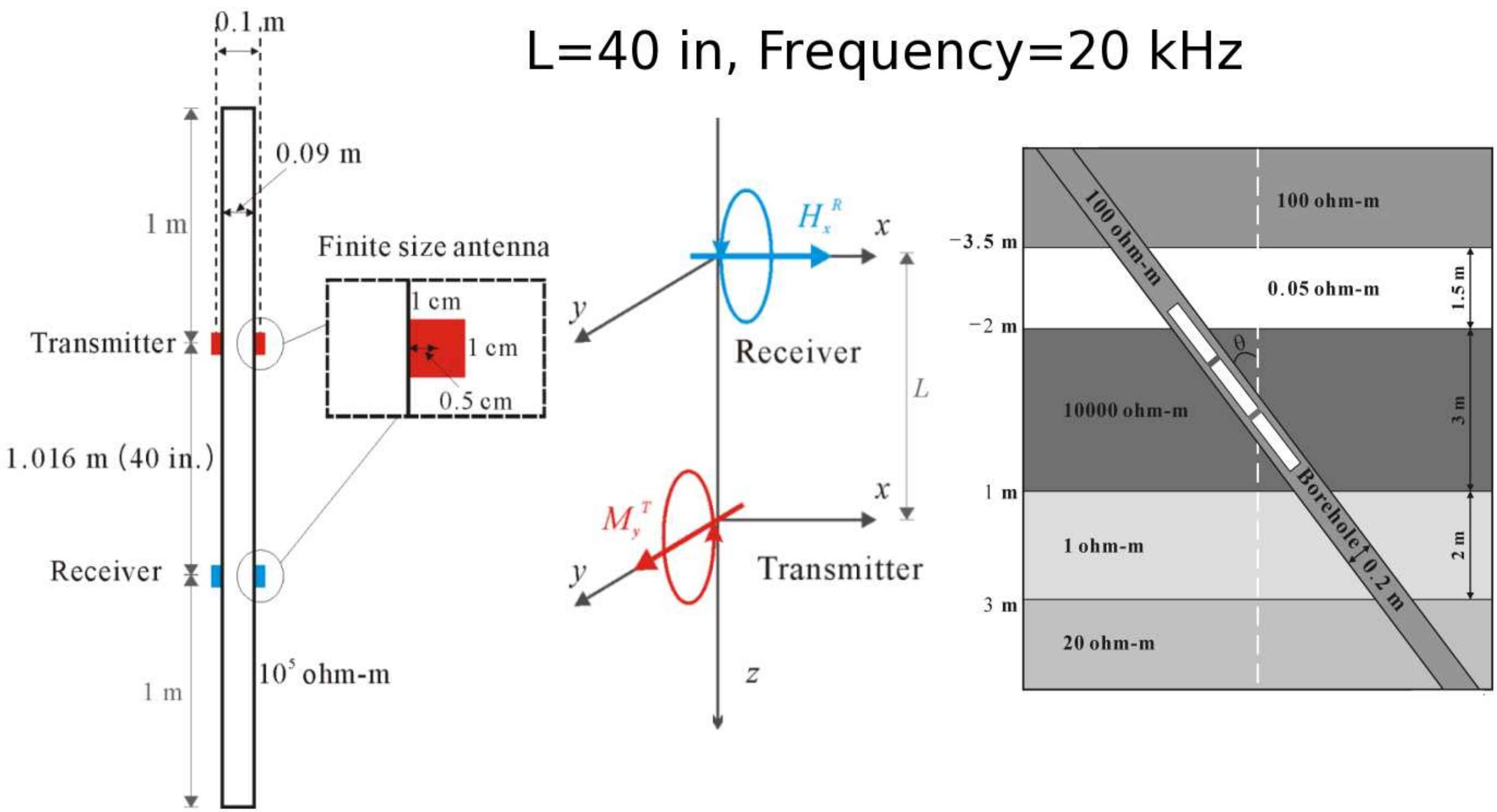
$$f(\zeta_1, \zeta_2, \zeta_3) = \sum_{n=-\infty}^{n=\infty} f_n(\zeta_1, \zeta_3) e^{jn\zeta_2}$$

Fourier modes $e^{jl\zeta_2}$ are orthogonal high-order basis functions that are (almost) invariant with respect to the gradient operator.

SIMULATION OF FORWARD PROBLEMS (hp-FEM)

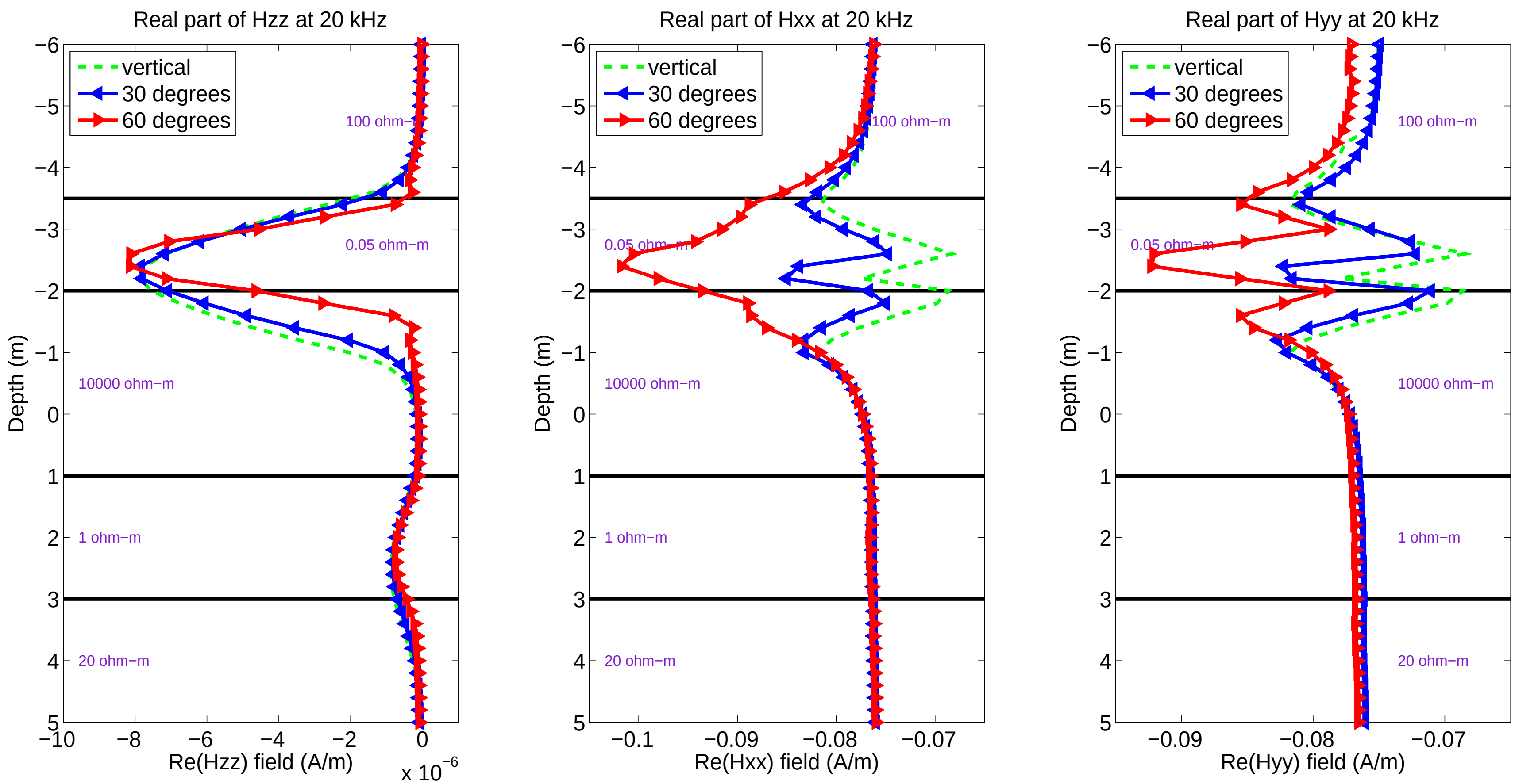
Tri-Axial Induction Tool

L=40 in, Frequency=20 kHz



SIMULATION OF FORWARD PROBLEMS (hp-FEM)

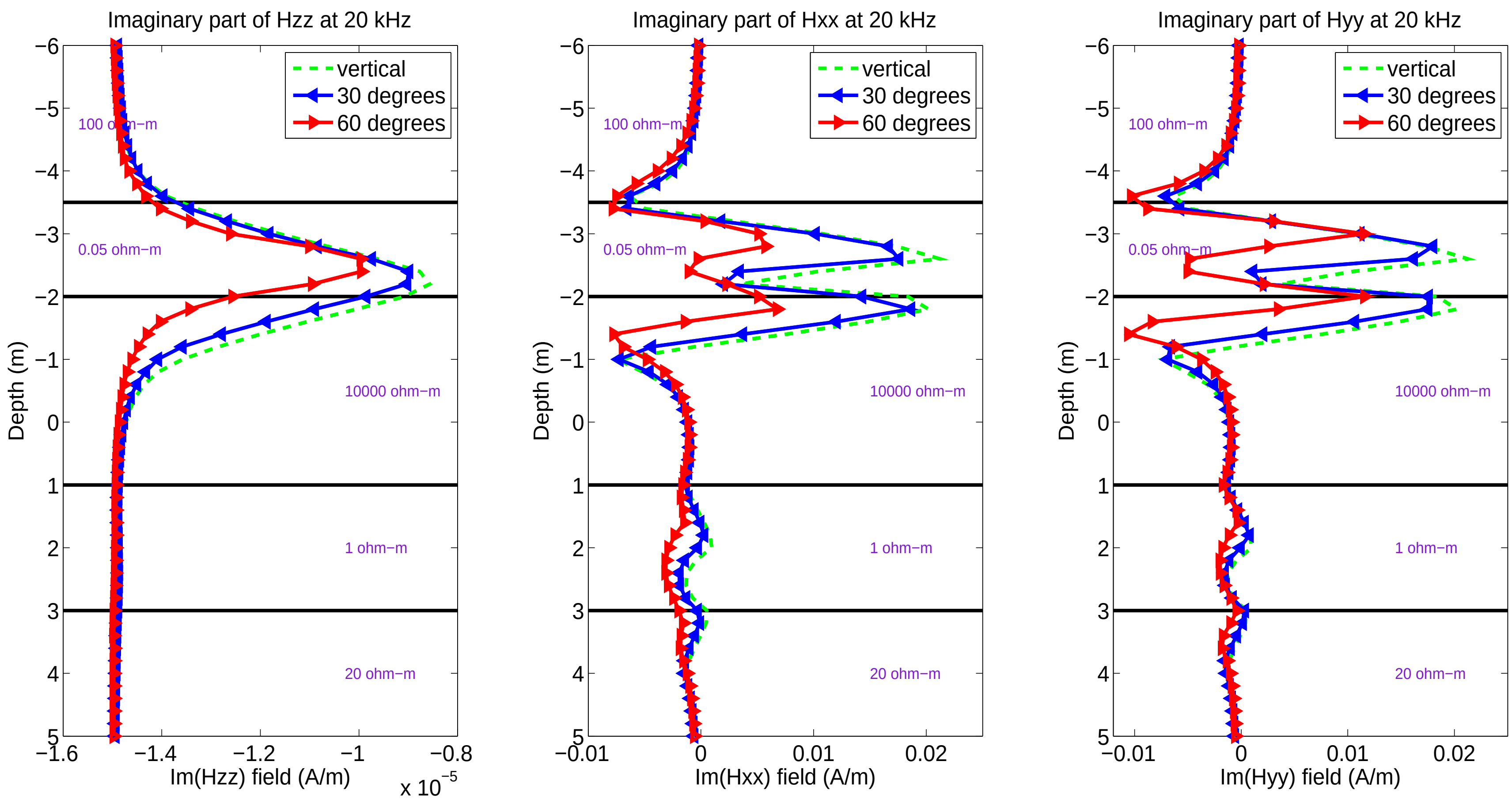
Tri-Axial Induction Tools in Deviated Wells (0, 30, and 60 degrees)



Triaxial tools are more sensitive to dip angle effects

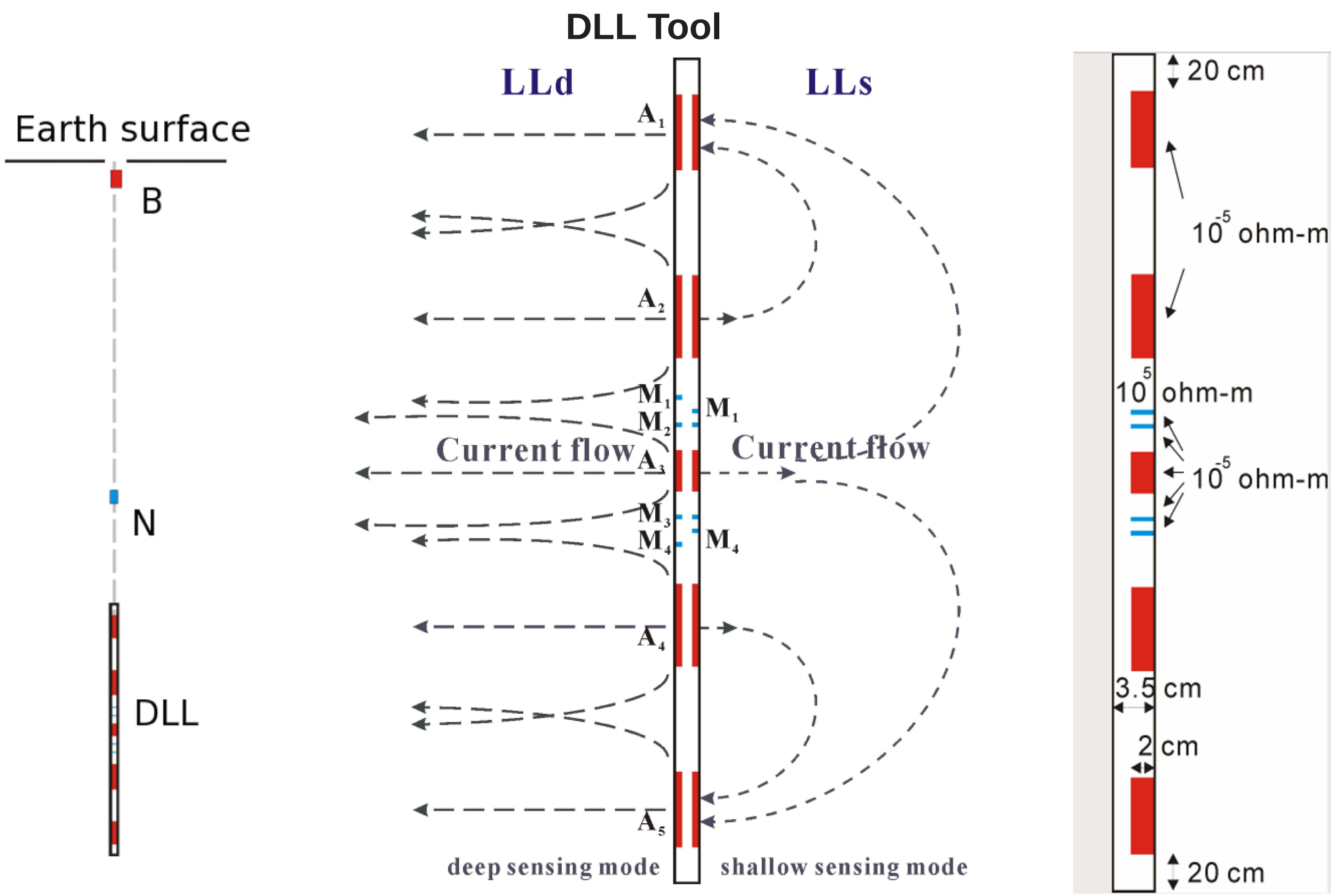
SIMULATION OF FORWARD PROBLEMS (hp-FEM)

Tri-Axial Induction Tools in Deviated Wells (0, 30, and 60 degrees)



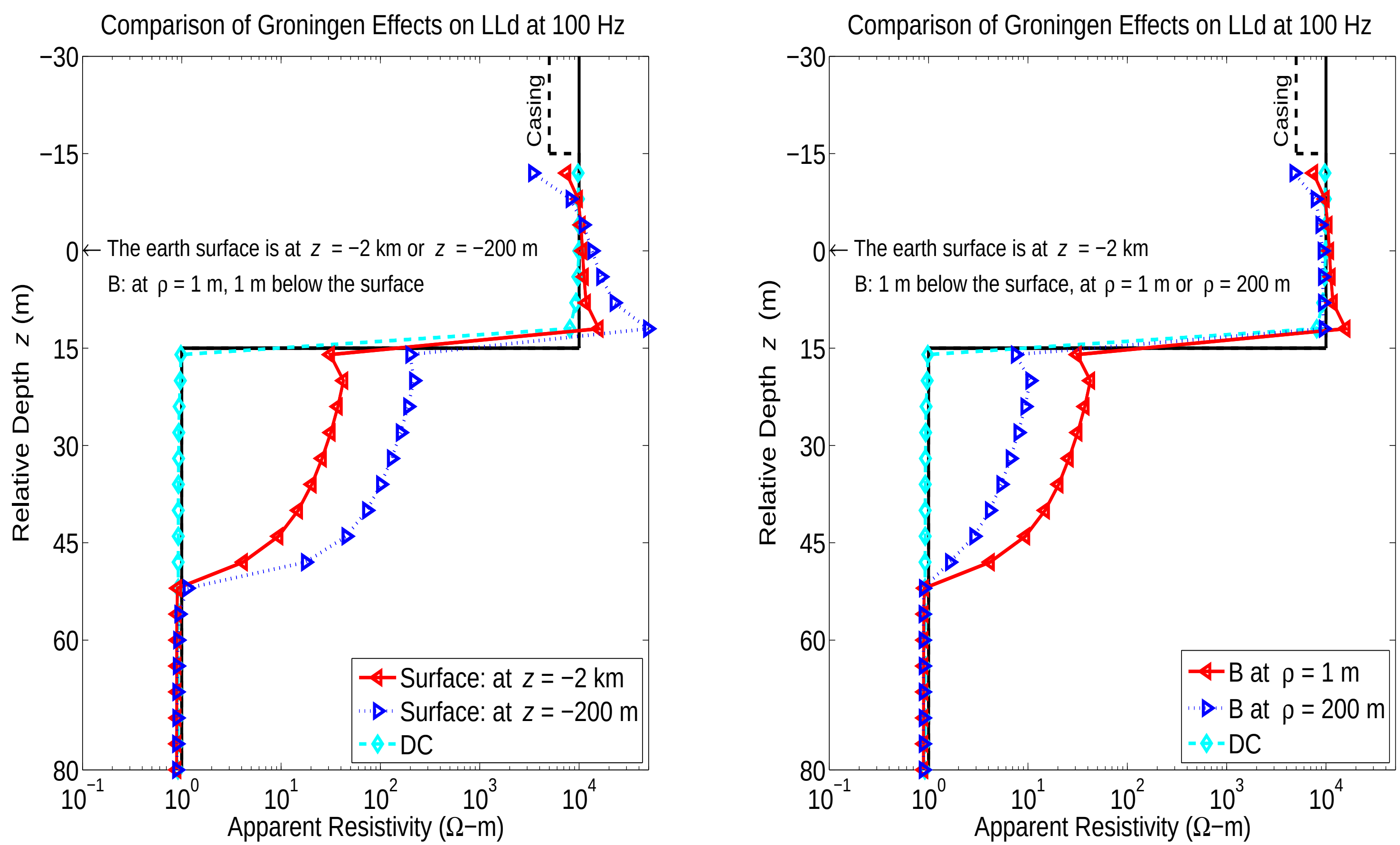
Triaxial tools are more sensitive to dip angle effects

SIMULATION OF FORWARD PROBLEMS (hp-FEM)



SIMULATION OF FORWARD PROBLEMS (hp-FEM)

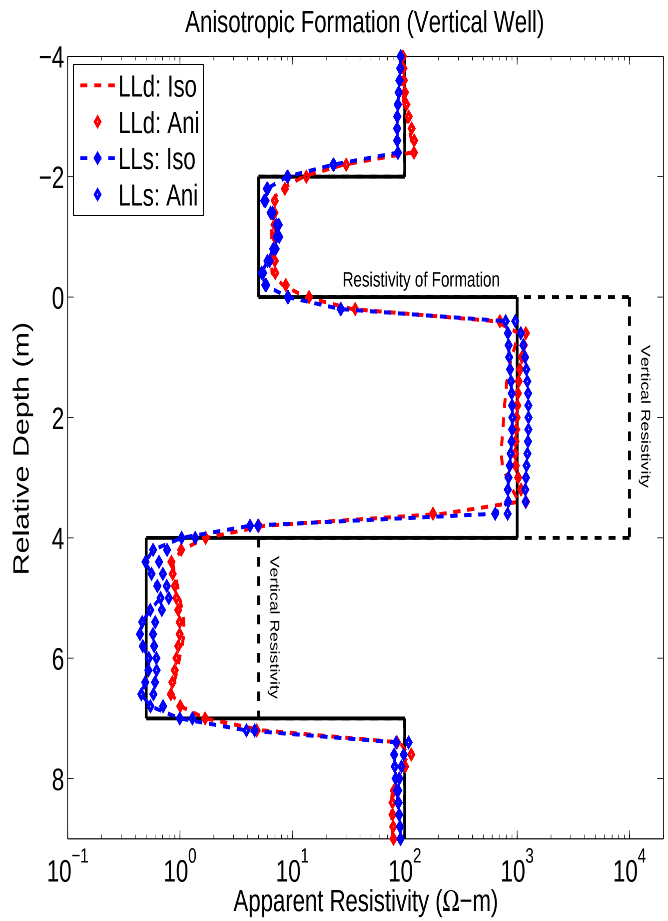
Groningen Effect

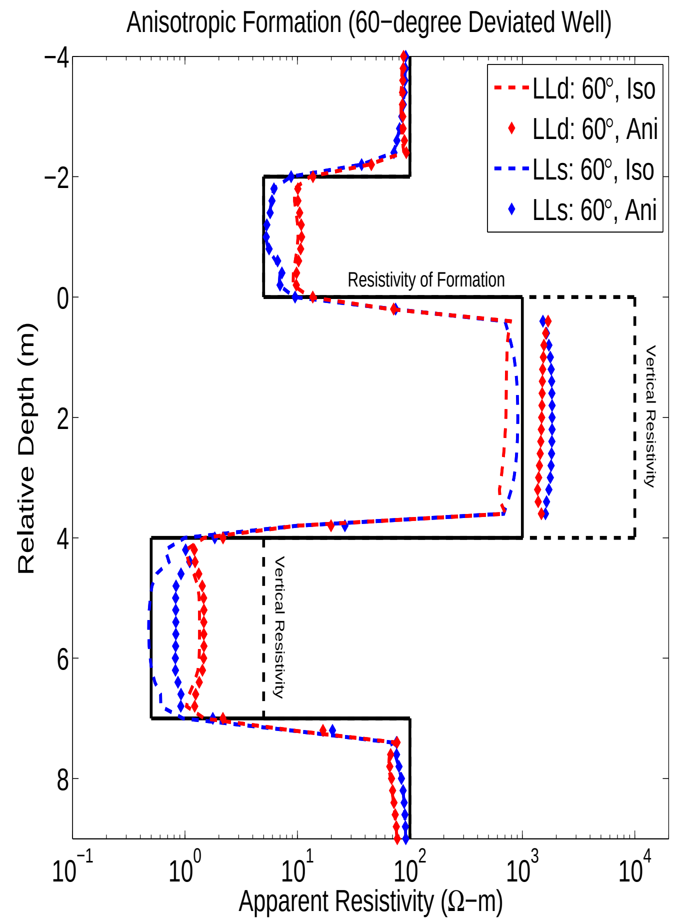


As we place the current return electrode B farther from the logging instrument, the Groningen effect diminishes

SIMULATION OF FORWARD PROBLEMS (hp-FEM)

DC DLL in Deviated Wells

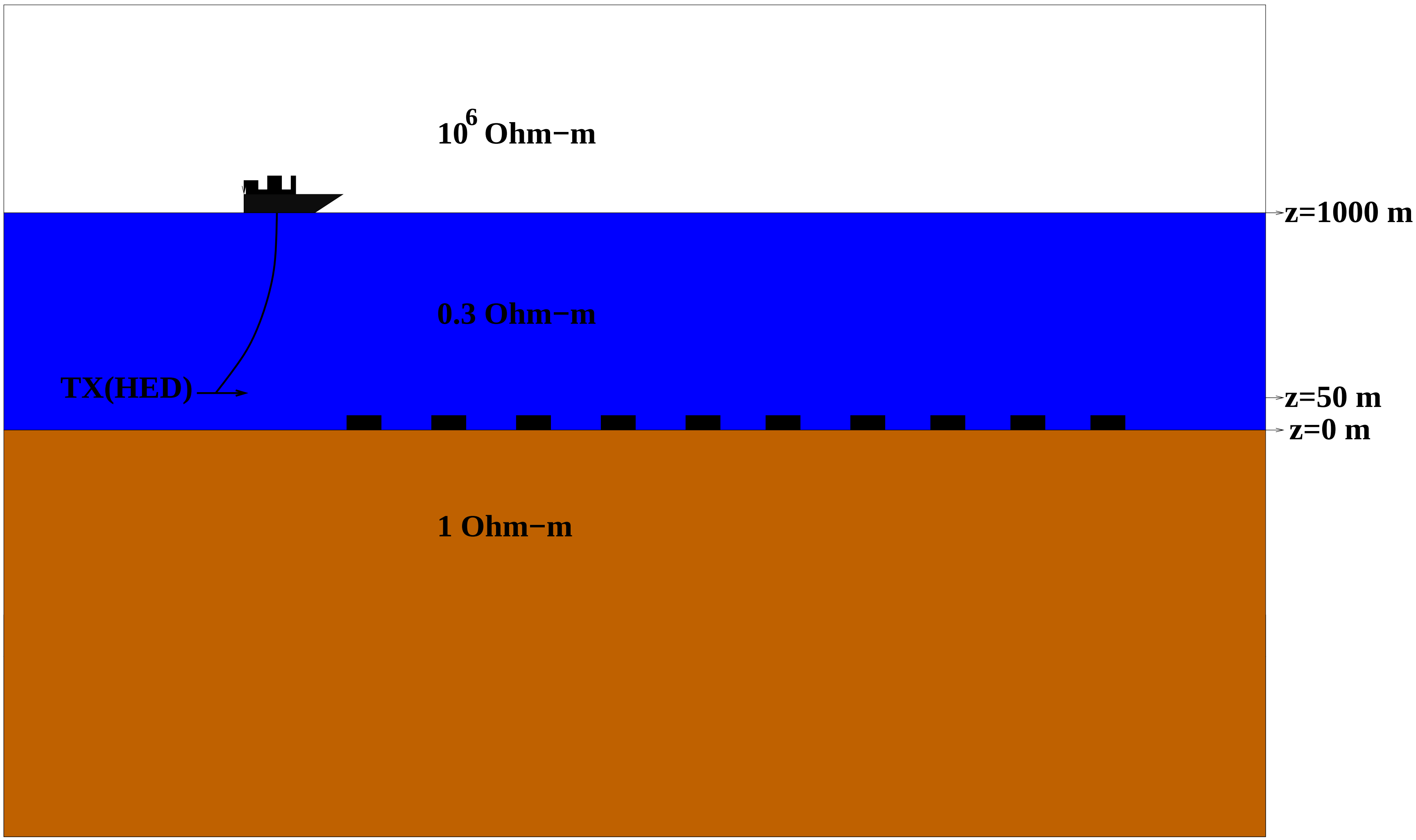




Anisotropy is better identified when using deviated wells

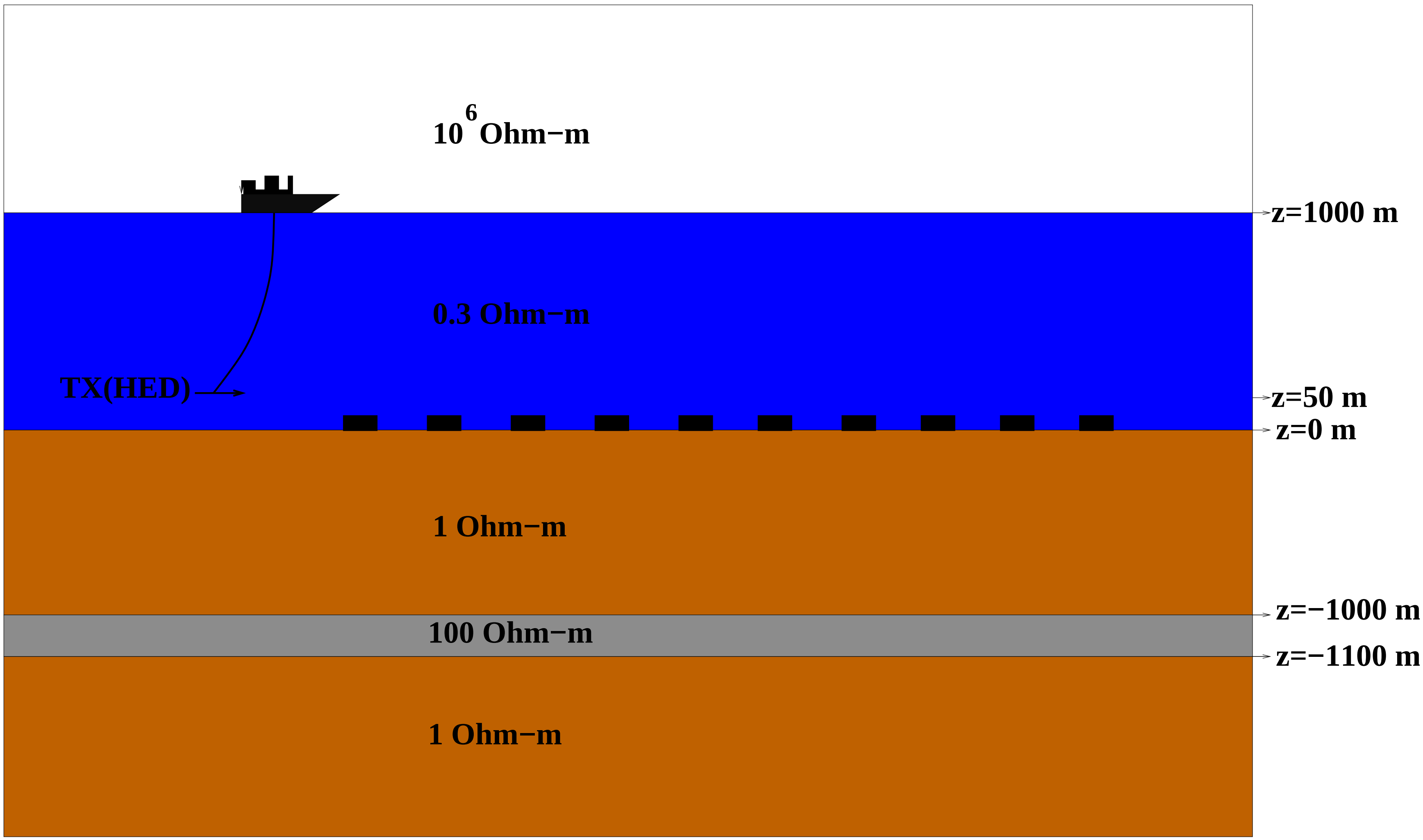
SIMULATION OF FORWARD PROBLEMS (hp-FEM)

NO OIL



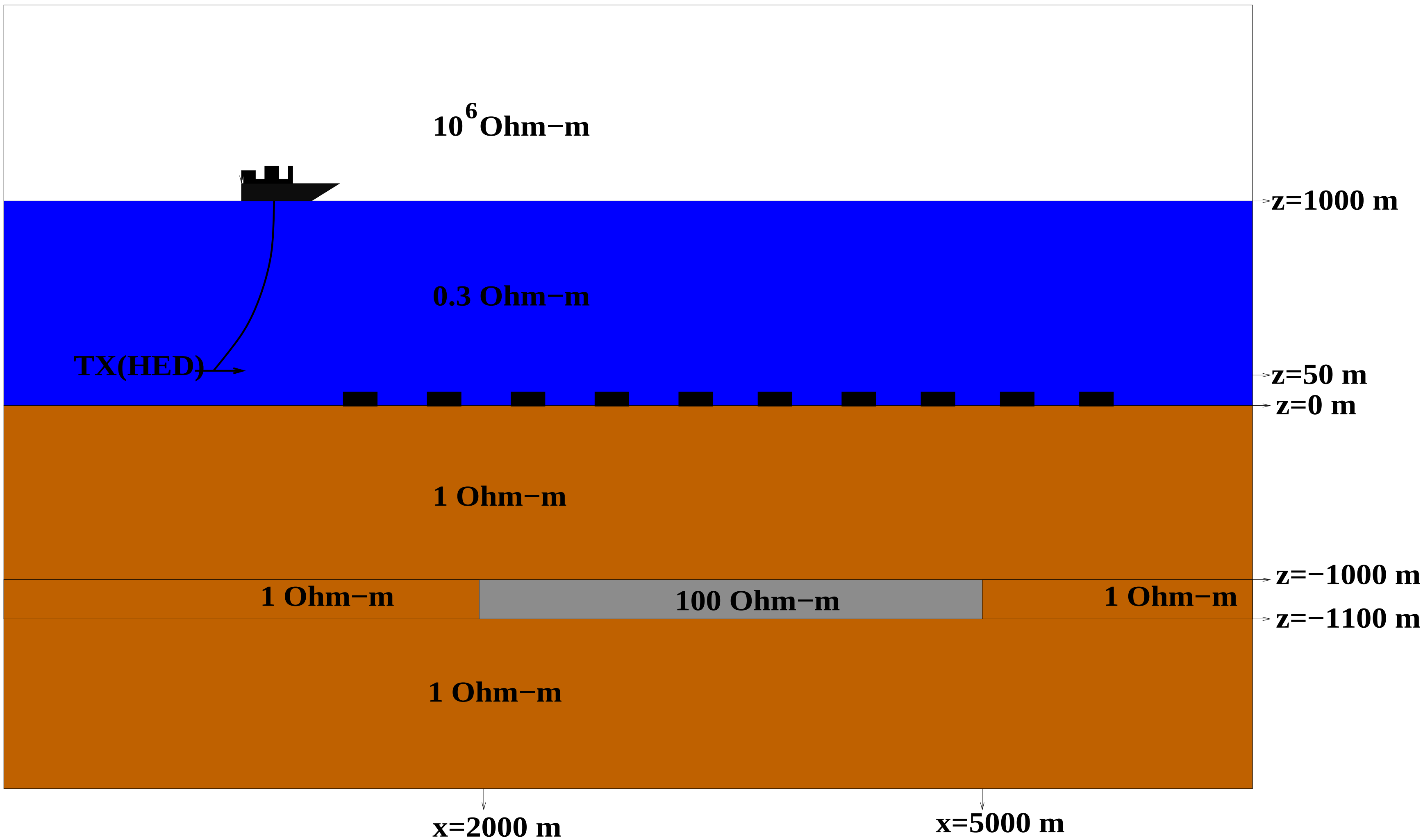
SIMULATION OF FORWARD PROBLEMS (hp-FEM)

INFINITE LAYER OF OIL



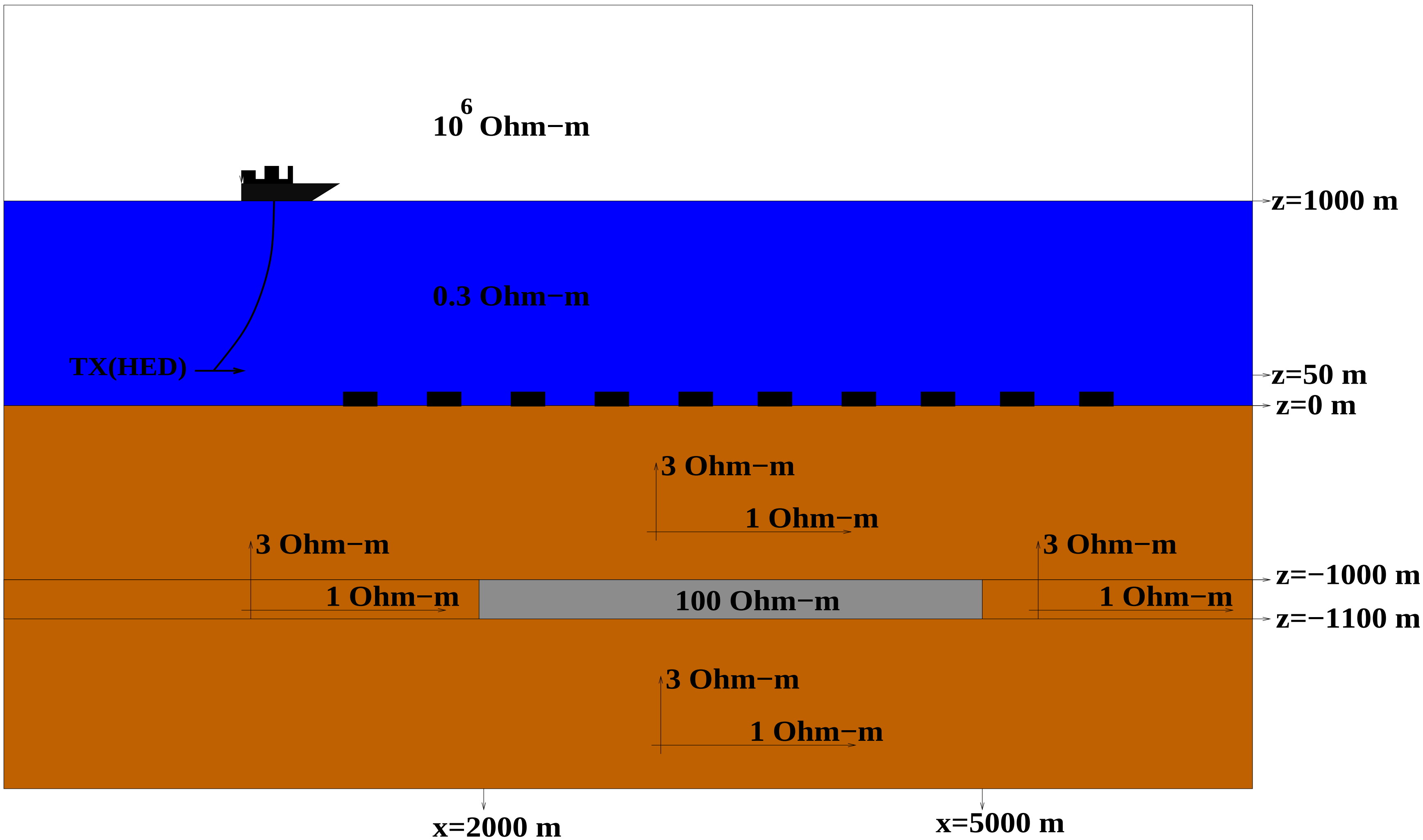
SIMULATION OF FORWARD PROBLEMS (hp-FEM)

FINITE LAYER OF OIL



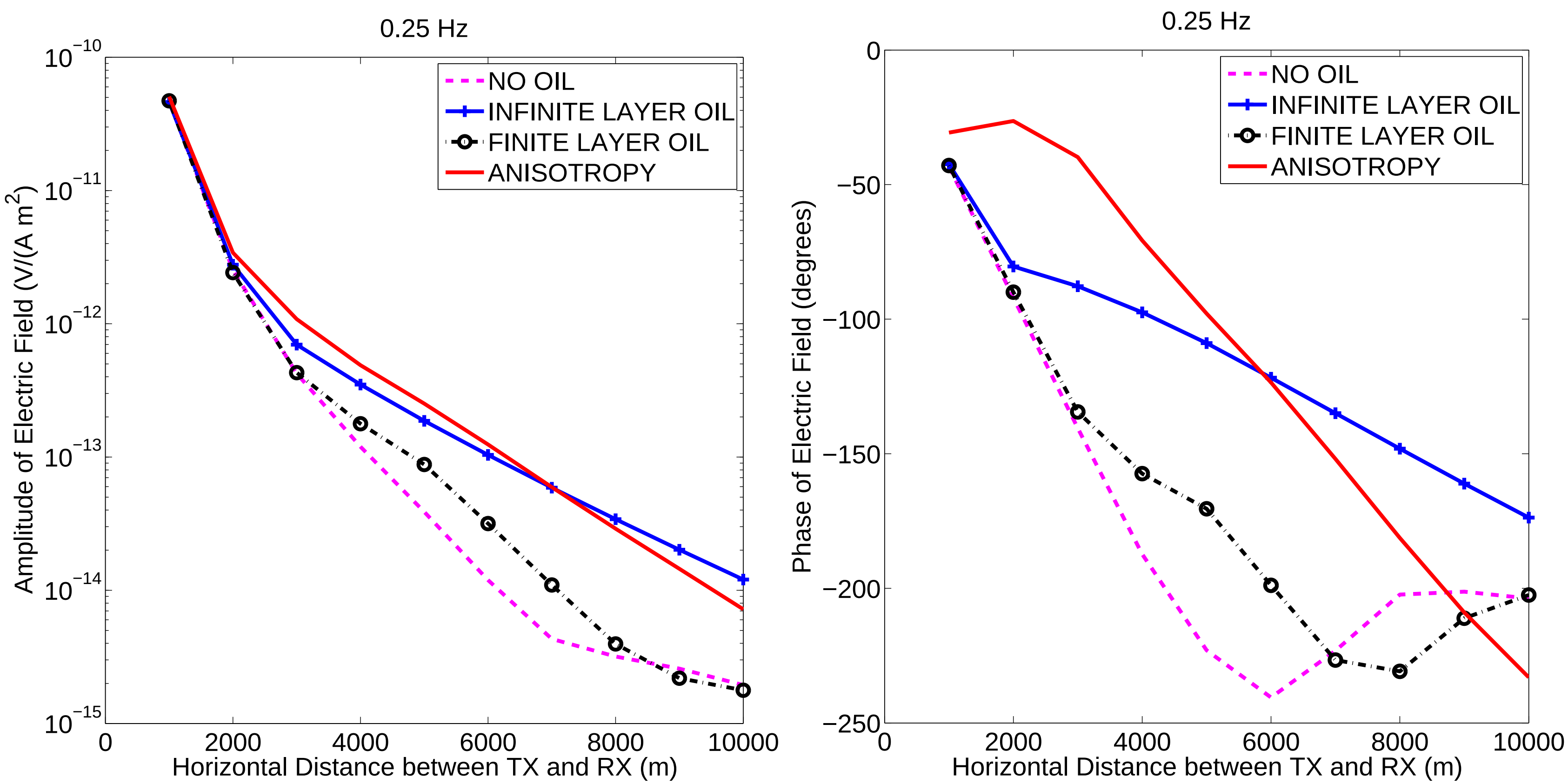
SIMULATION OF FORWARD PROBLEMS (hp-FEM)

FINITE LAYER OF OIL + ANISOTROPY



SIMULATION OF FORWARD PROBLEMS (hp-FEM)

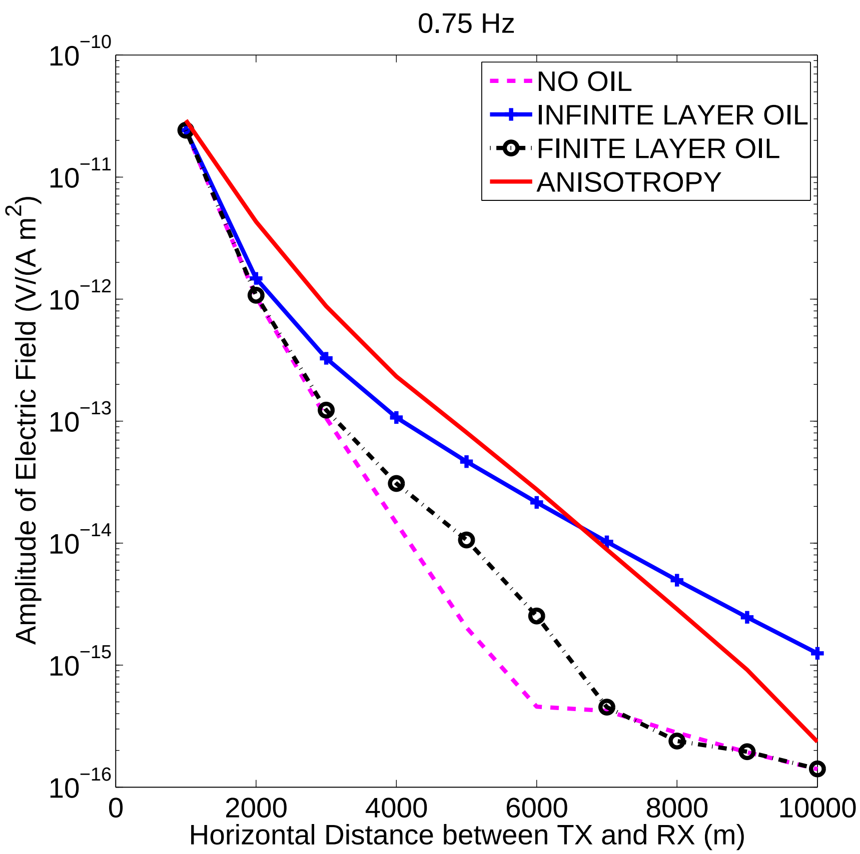
Comparison — 0.25 Hz —

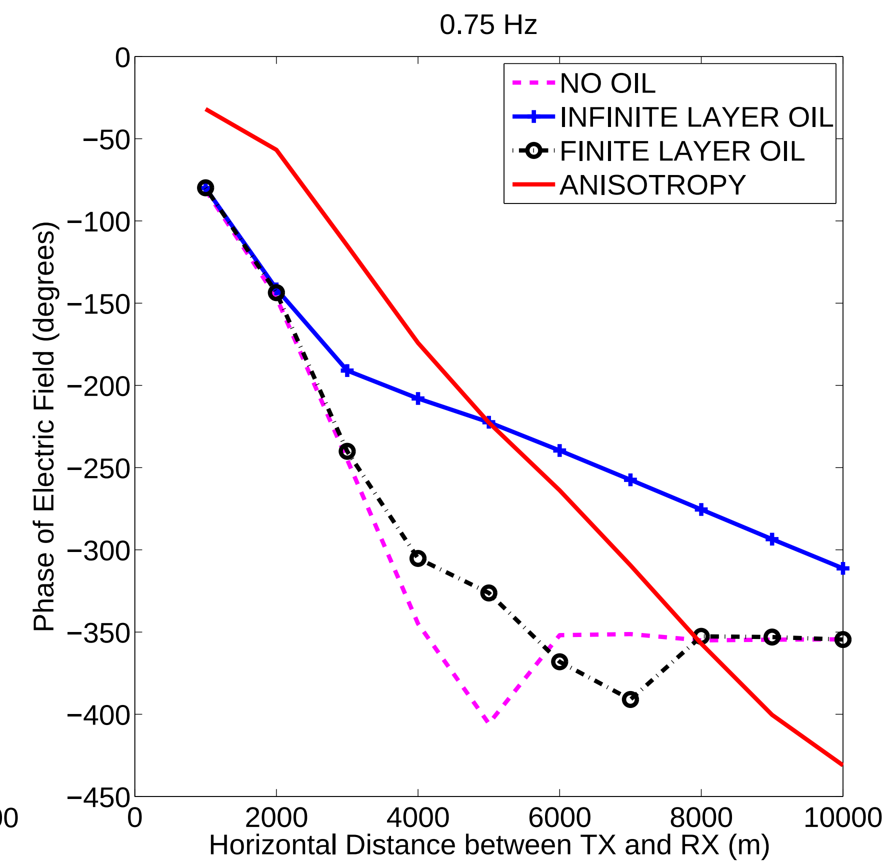


The finite layer of oil is clearly identified, and it is different from the solution for the infinite layer of oil. To consider anisotropy is essential.

SIMULATION OF FORWARD PROBLEMS (hp-FEM)

Comparison — 0.75 Hz —

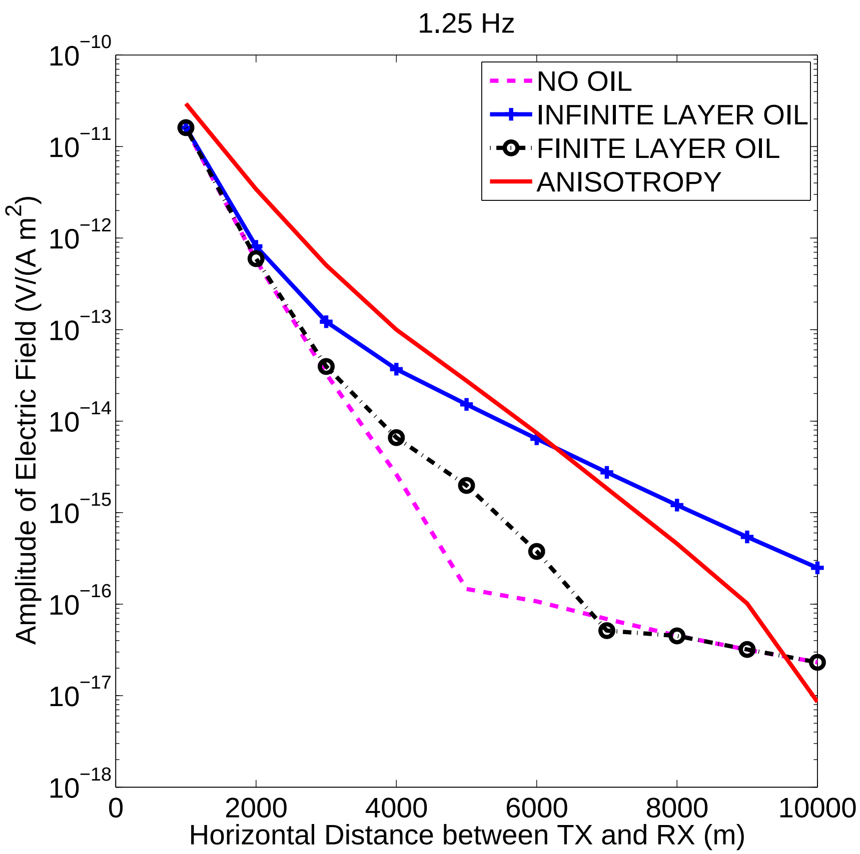


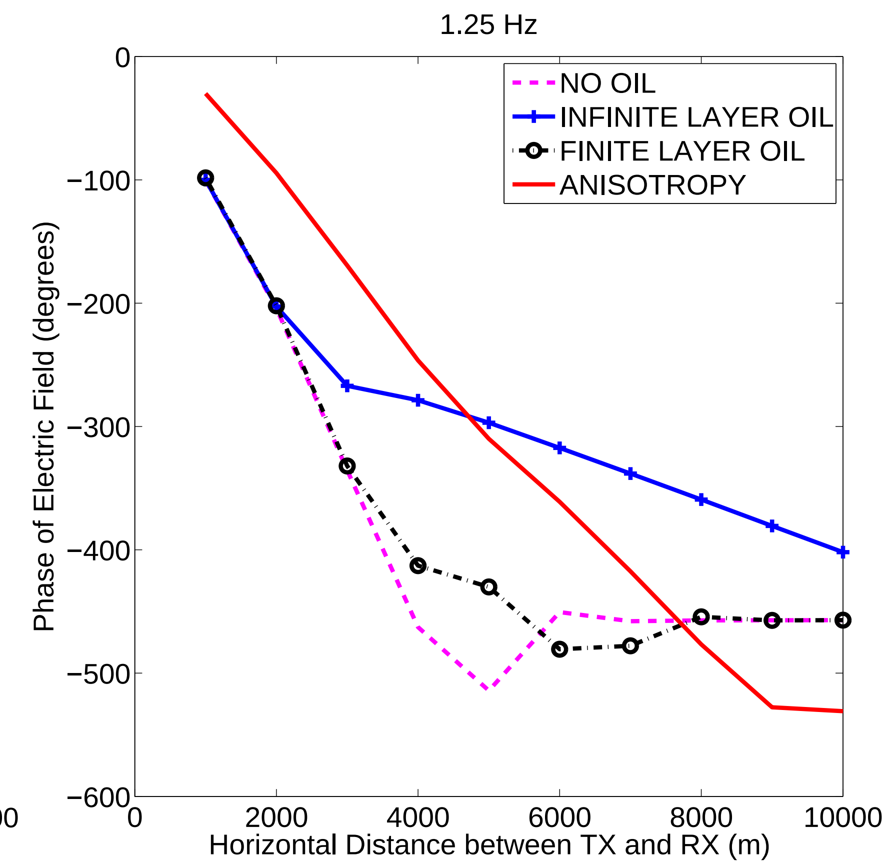


As we increase the frequency, the effect of oil becomes more localized.

SIMULATION OF FORWARD PROBLEMS (hp-FEM)

Comparison — 1.25 Hz —





As we increase the frequency, the effect of oil becomes more localized.

SIMULATION OF FORWARD PROBLEMS (hp-FEM)

Final hp-grid and solution

Monopole source, open borehole setting:

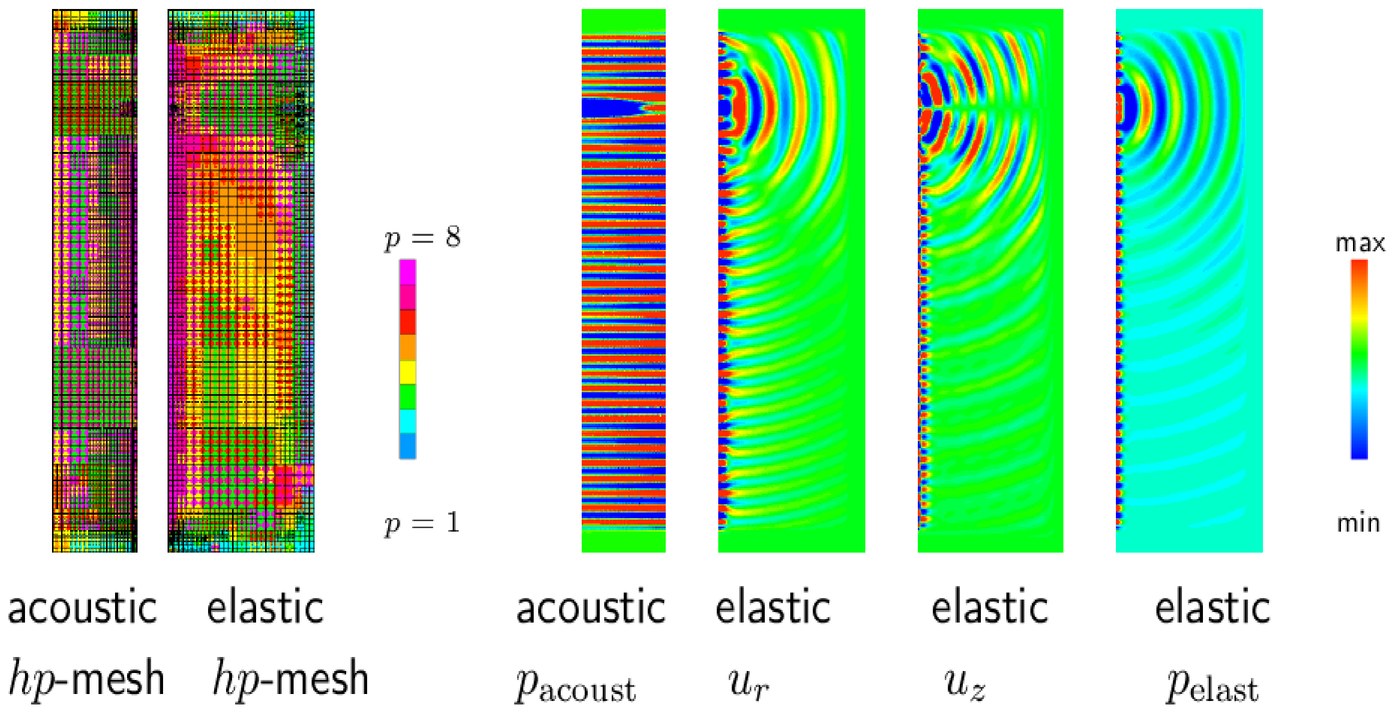


Figure: Frequency-domain solution at the center frequency of 8 kHz (acoustics subdomain scaled by a factor of 10 in radial direction; plotting ranges $[0.1\min, 0.1\max]$)

NEW LIBRARY FOR INVERSE PROBLEMS

Algorithms implemented within the inverse library

JOINT MULTI−PHYSICS INVERSION LIBRARY

CONSTRAINED OPTIMIZATION

1. KKT− Conditions
2. Penalization Method
3. Change of coordinates

SEARCH DIRECTIONS

1. Steepest Descent
2. Gauss−Newton
3. Newton−Raphson

STEP SIZE

1. Uniform step−size
2. Variable step−size
   (multiple algorithms)

The inverse library is composed of multiple algorithms for imposing constraints, and finding search directions and corresponding step sizes.

Jacobian and Hessian matrices are computed exactly by simply solving the dual (adjoint) formulation and performing additional integrations.

The inverse library is compatible with multi-physics problems.

INTEGRATED APPROACH TOWARD FORMATION EVALUATION

ONE software FOR ALL the formation evaluation