3D Subsurface Geophysical Imaging

Scientific Impacts and Opportunities in Computing

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PRESENTATION OVERVIEW

- Motivation for 3D Subsurface Imaging
  - The Marine Controlled Source Electromagnetic Method
  - CSEM Data Interpretation, Why 3D ?
  - Philosophy
- Large Scale Modeling Considerations
  - Parallelization over both the model and data space
  - Separation of inversion and simulation grids
- Field Example
  - Offshore Brazil
- Conclusions
  - Anticipated advances in 3D imaging/inversion technologies
- Acknowledgements

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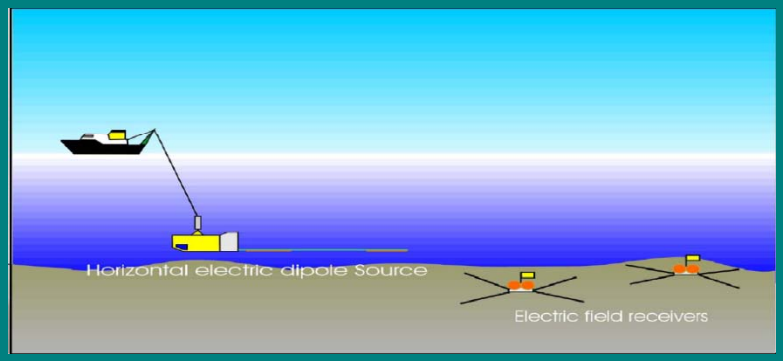
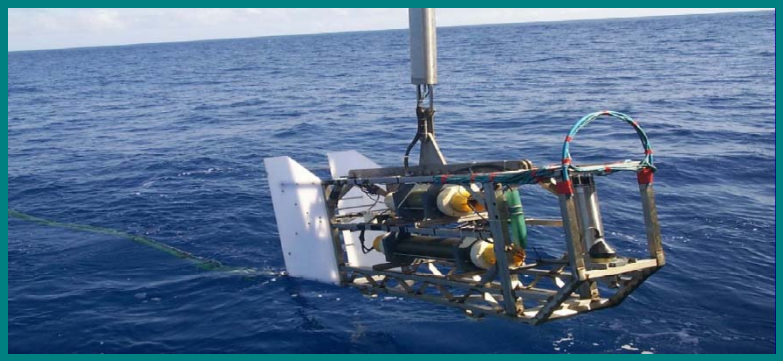
MOTIVATION: THE MARINE CSEM METHOD

- Deep-towed Electric Dipole transmitter
  - ~ 100 Amps
  - Water depth to 5 to 7 km
  - Alternating current 0.01 to 3 Hz
  - 'Flies' 50m above sea floor'
- Seafloor MT receivers
  - Measure orthogonal E & H
- The Geophysical Signature
  - Oil & gas reservoirs electrically resistive than background media
  - A non seismic indicator
  - Still requires seismic data to constrain interpretation





DATA INTERPRETATION

- Why 3D?
  - Data acquisition is 3D
    - » 2D interpretation often not appropriate
  - Prospective Oil & Gas Reservoirs & Targets Inherently 3D
    - » complex geology
- Philosophy on 3D Modeling & Inversion Methods
  - Interpretation must be as accurate as possible
    - » high stakes; offshore platforms & drilling - 100's millions of dollars
  - Treat large-scale nature of the interpretation problem
    - » High density CSEM data sets; millions of data points
    - » Large-scale imaging volumes; millions of image pixels
  - Avoid approximations
    - » Methods must be as accurate as possible & robust & reliable

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3D INVERSE MODELING

Minimize the cost functional:

$$\varphi = \{D(d_{obs} - d_p)\}^H \{D(d_{obs} - d_p)\} + \lambda\, \mathbf{m}\, \mathbf{W}^T \mathbf{W}\, \mathbf{m}.$$

$\mathbf{d}^{obs}$ and $\mathbf{d}^p$ are observed and predicted data

$\mathbf{D}$ = data covarance matrix

H = transpose-conjugation operator

$\mathbf{m}$ = electrical conductivity model parameters

$\mathbf{W} = \nabla^2$ operator; constructs a smooth model

λ = tradeoff parameter

LARGE-SCALE CONSIDERATIONS

- Require Large-Scale 3D Modeling and Imaging Solutions
  - 200 million field unknowns (fwd problem)
  - Imaging grids 400 nodes on a side
- Parallel Implementation
  - Two levels of parallelization
    - » Model Space (simulation and inversion mesh)
    - » Data Space (each transmitter-receiver set fwd calculation independent)
    - » Installed & tested on multiple distributed computing systems; 10 – 32,766 Processors
- Above procedure satisfactory except for very largest problems
  - To treat such problems requires a higher level of efficiency
- Optimal Grids
  - Separate inversion grid from the simulation/modeling grid
  - Potential for significant solution acceleration ~ order of magnitude

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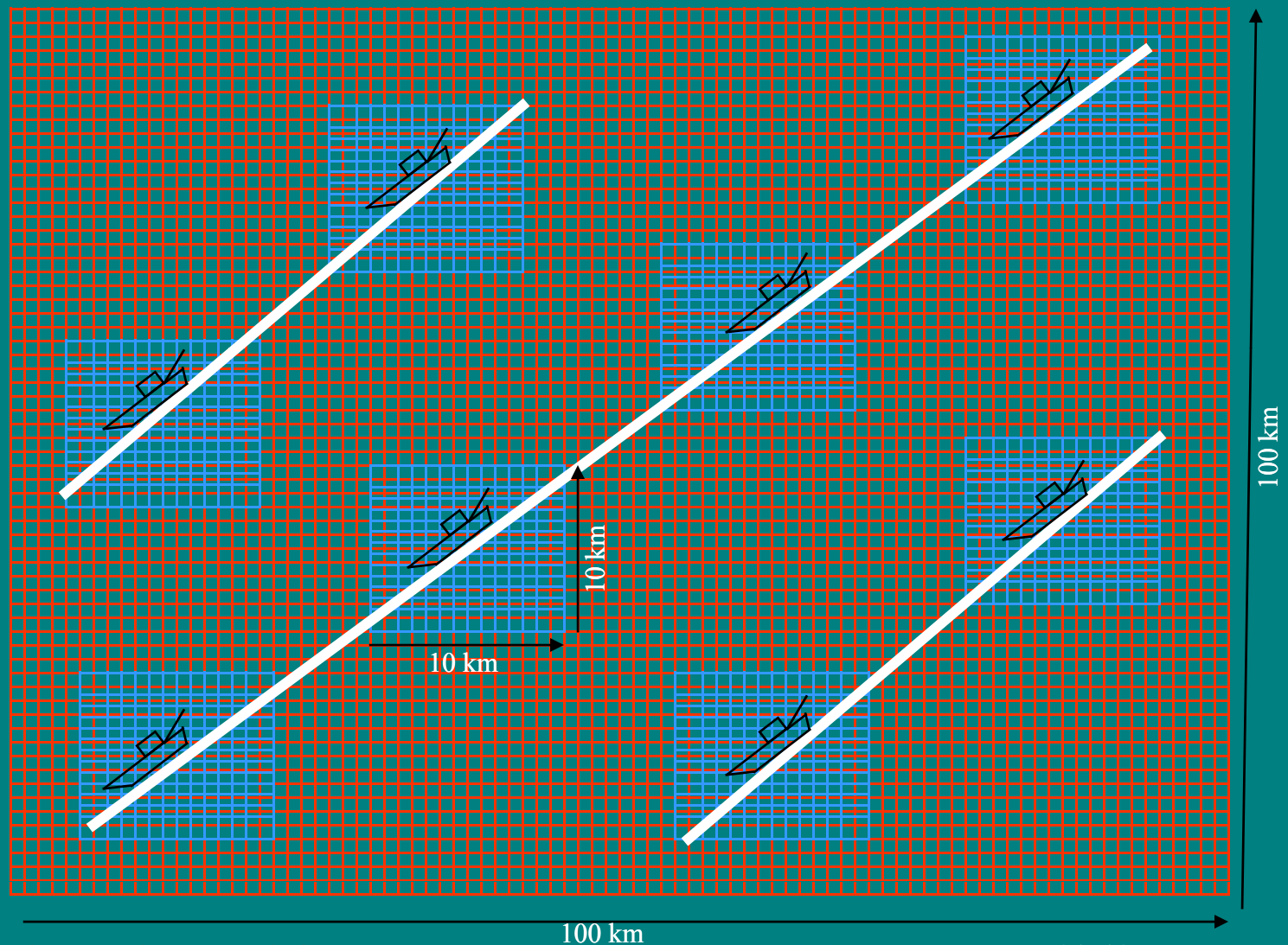
BASIC IDEA



Ω_m imaging grid Ω_s simulation grid — sail lines

GRID SEPERATION EFFICIENCIES

- Advantages
  - Taylor an optimal simulation grid Ω_s for each transmitter-receiver set
  - Inversion grid Ω_m covers basin-scale imaging volumes at fine resolution
  - Simulations grids much smaller, a subset of the imaging grid
  - Faster solution times follow from smaller simulation grids
- What's Required
  - A mapping of conductivity from Ω_m to Ω_s & Ω_s to Ω_m
    - » Conductivity on Ω_s edged based
    - » Conductivity on Ω_m cell based
  - An appropriate mixing law for the conductivity mappings

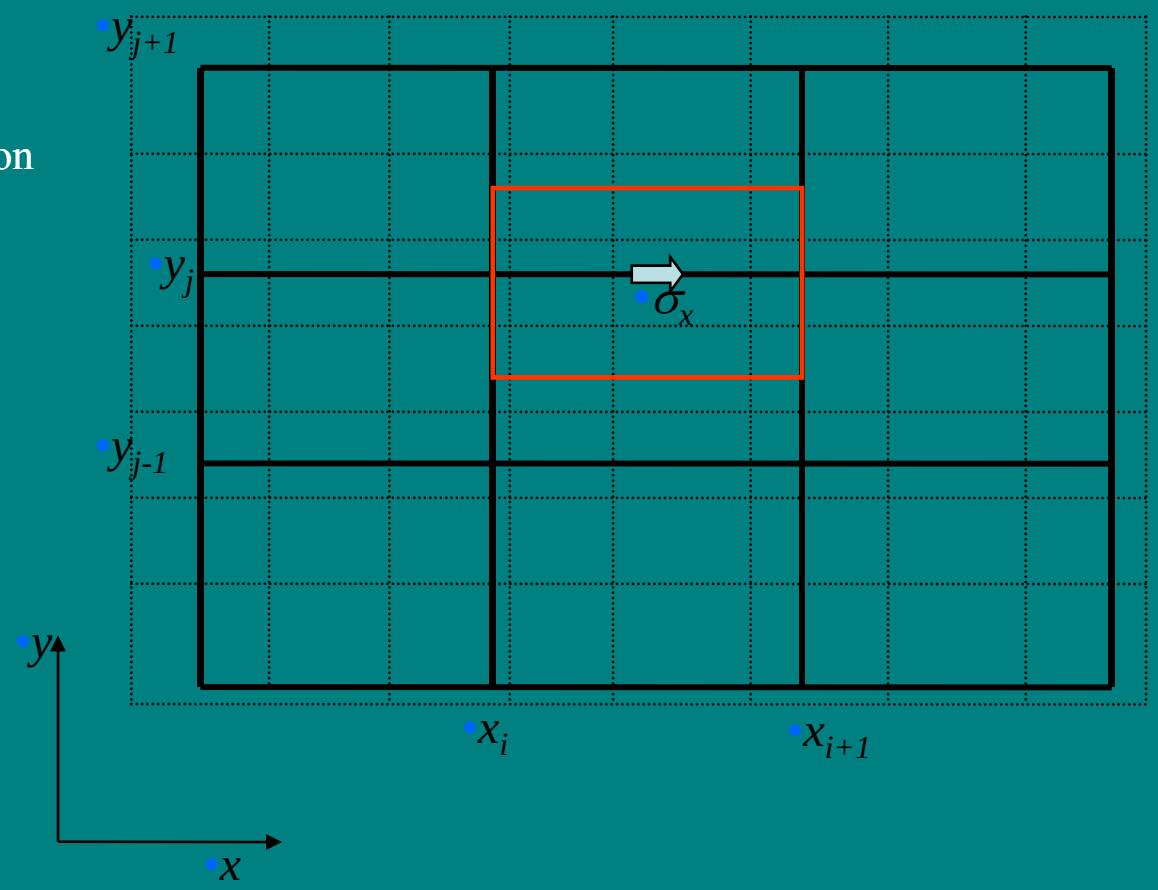
CONDUCTIVITY MAPPING (2D CASE)

$$\sigma_x = \left[\int_{x_i}^{x_{i+1}} \left(\int_{y_{j-1/2}}^{y_{j+1/2}} \sigma(x,y)dy \right)^{-1} dx \right]^{-1}$$

parallel-series circuit mixing law

Dashed grid model/inversion mesh

Solid grid simulation mesh

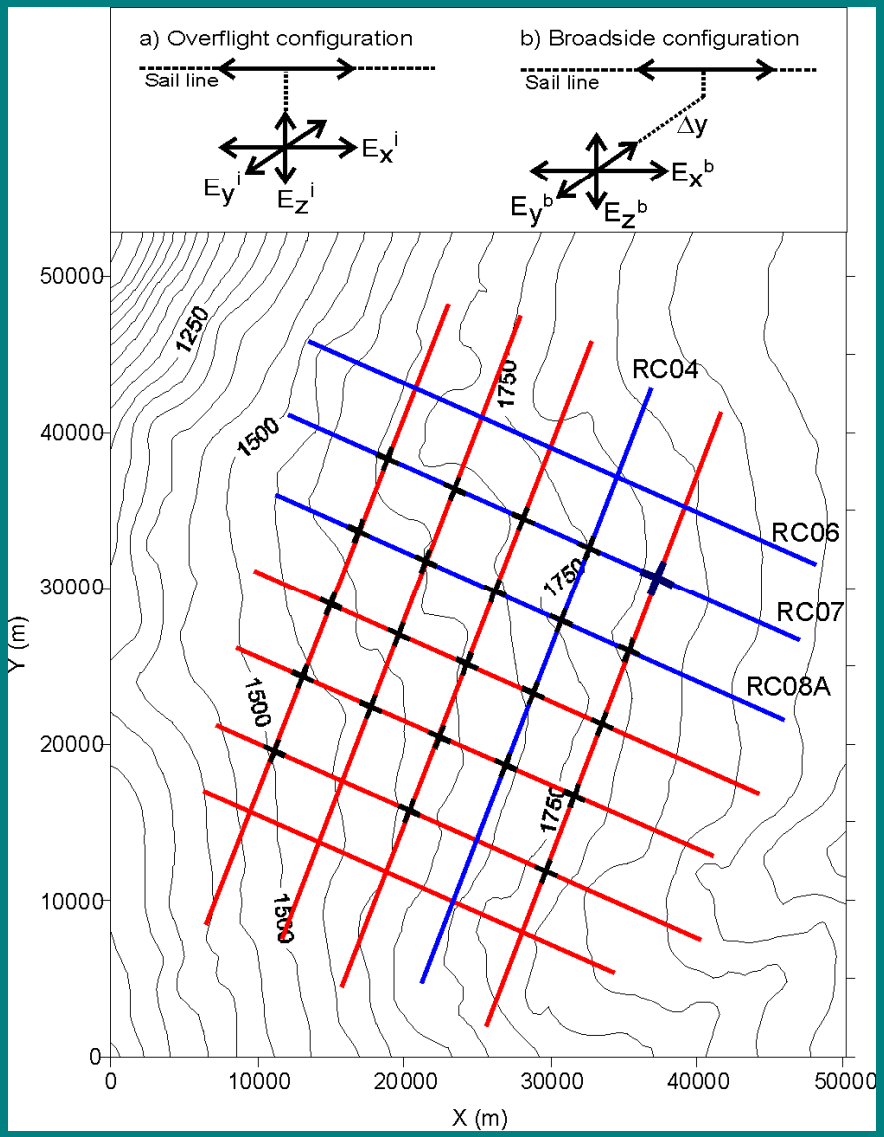


Red cell: conductivity region required to compute σ_x on the simulation mesh

FIELD EXAMPLE

- Offshore Brazil (Large Scale 3D Survey)
  - Joint Work with ExxonMobil Corporation
  - Data provided by ExxonMobil
  - Computational time on BG/L supercomputer provided by the IBM Corporation

OFF SHORE BRAZIL CSEM SURVEY



Logistics

23 sea bottom detectors

10 sail lines

3 transmitting frequencies

1.25, 0.75 and 0.25 Hz

Survey coverage ~900 km^2

Measurement Terminology

Over Flight: In Line & Vertical

Broadside: In Line, Vertical & Horizontal Perpendicular

OFF SHORE BRAZIL CSEM DATA
3D Image Processing Requirements

- 3D Data and Imaging Volumes
  - nearly 1 million data points, 207 effective transmitters
    (reciprocity processing significantly reduces number of transmitters)
  - more than 27 million modeling cells
    (a large subset to be updated within the inversion process)
- Image Processing Linux Clusters
  - 1024 tasks with Infinband fabric => several months of processing time
- Use Blue Gene (L) Super Computer for Faster Time to Solution
  - 32 766 processors/tasks used to image the data
  - each task has only 250 Mbytes memory
    (requires fine grained model decomposition over 512 tasks)
  - 64 data planes employed in the image processing
  - delivers imaging results in 24 hours compared to several months

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OFF SHORE BRAZIL DATA ANALYSIS

MESHING CONSIDERATIONS

Horizontal simulation mesh varies with frequency & sea water skin depth

- coarsest simulation mesh size employed: 250 m
- finest simulation mesh size employed: 125 m
- For each Tx simulation meshes truncated at ten skin depths horizontally

Identical vertical meshing for model and simulation mesh

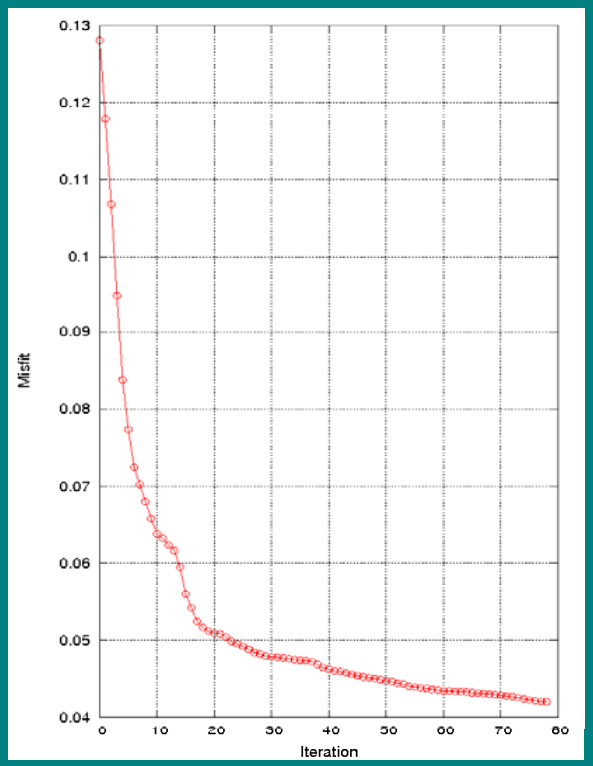
-honors bathymetry

Separate Grids

- leads to significant reduction in size of simulation problem
- results in much faster time to solution

Brazil Inversion Performance Measures

Solution Convergence

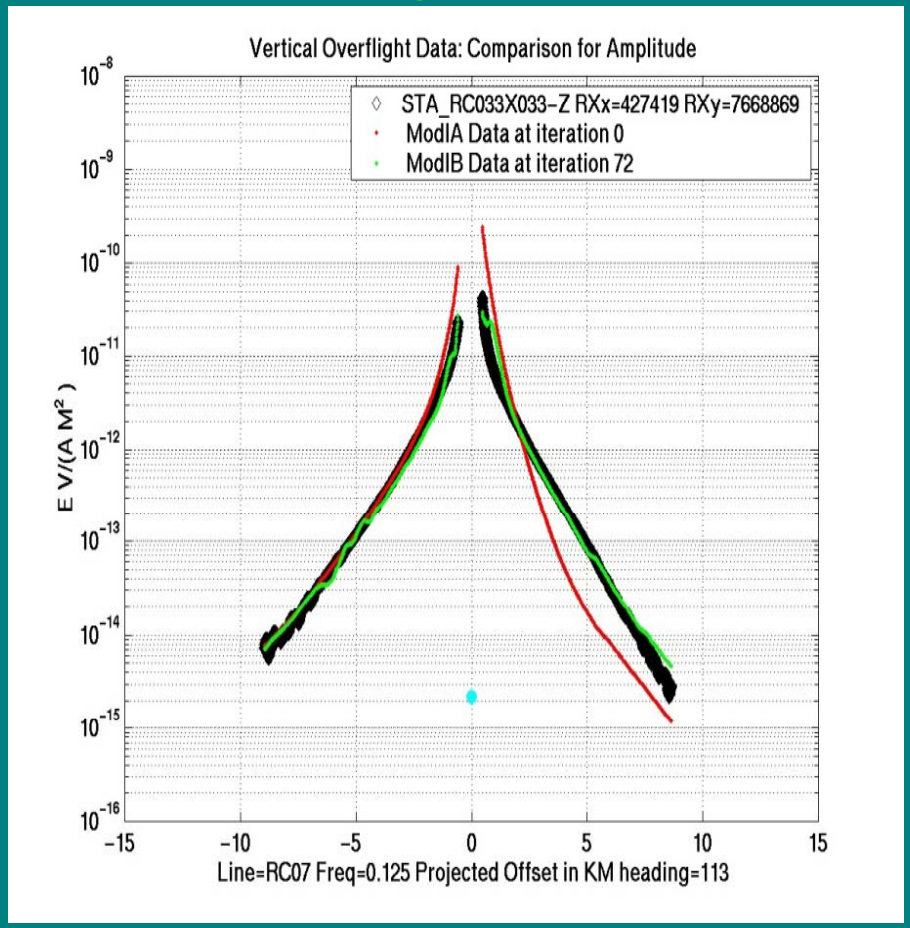


Computing Time Per Iteration
19 minuets/iteration

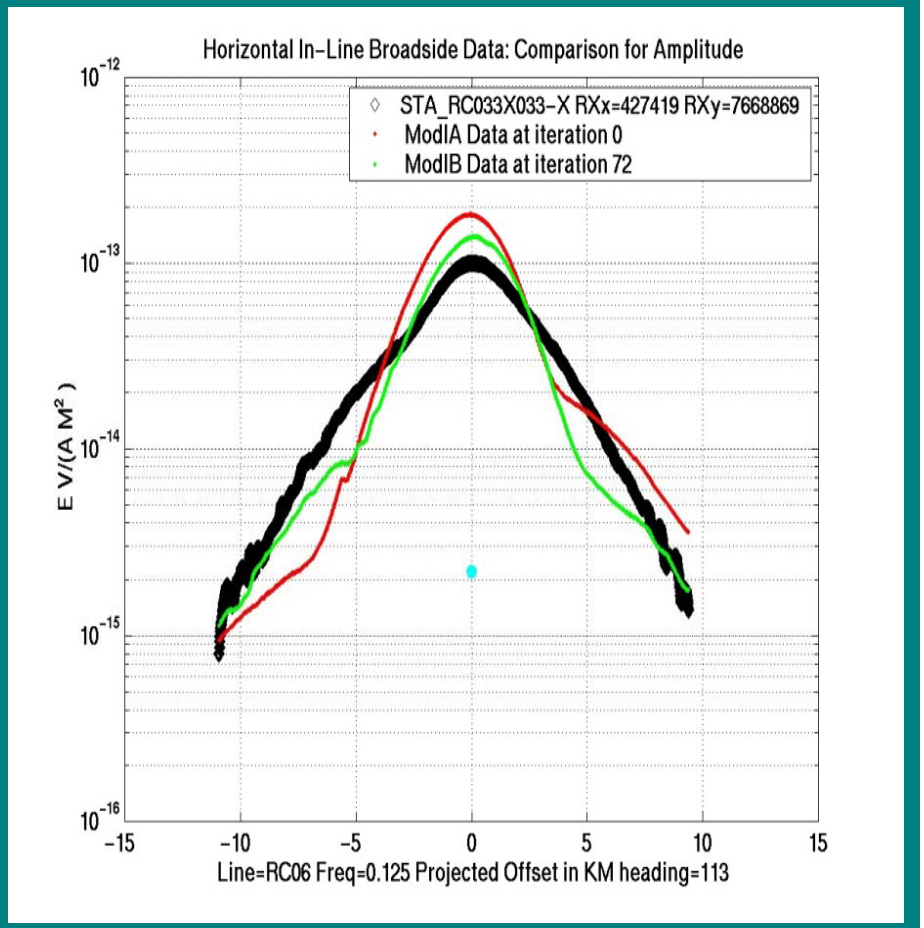
Misfit Reduction
Only 67%

DATA FITS

Overflight Profile



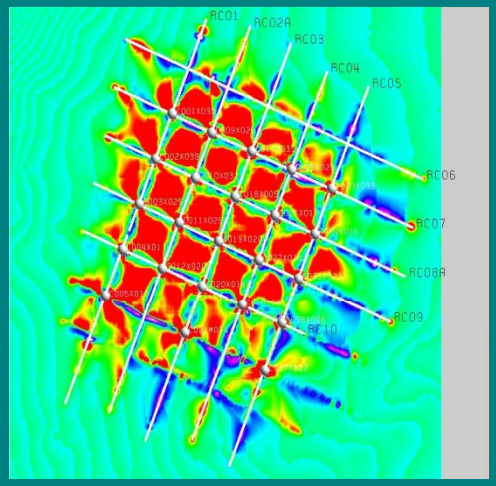
Broadside Profile



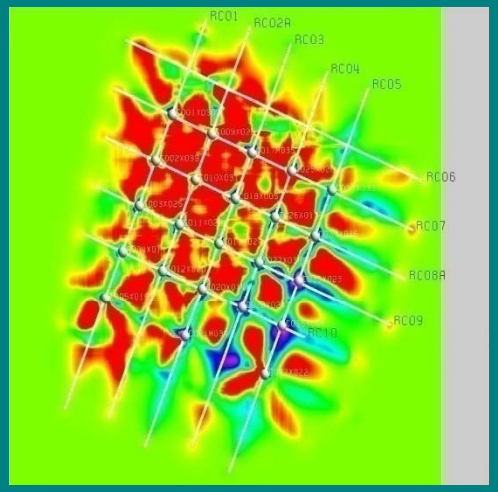
OFF SHORE BRAZIL

Integrated Resistivity Depth Sections

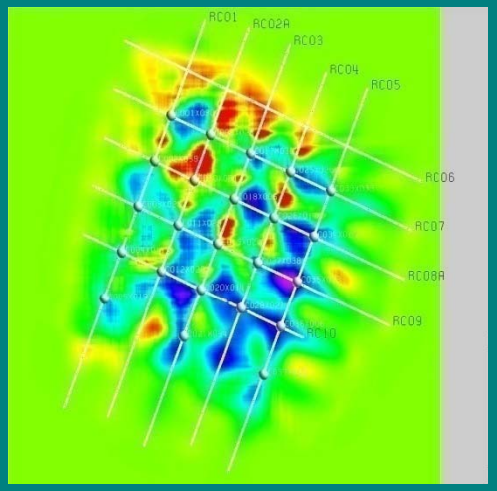
water bottom to 500 m below mud line

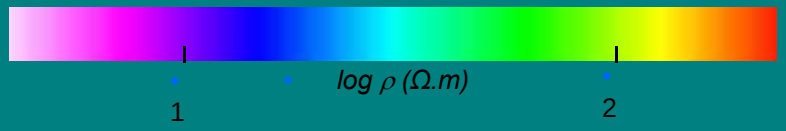


500 m to 1500 m below mud line



1500 m to 2500 m below mud line

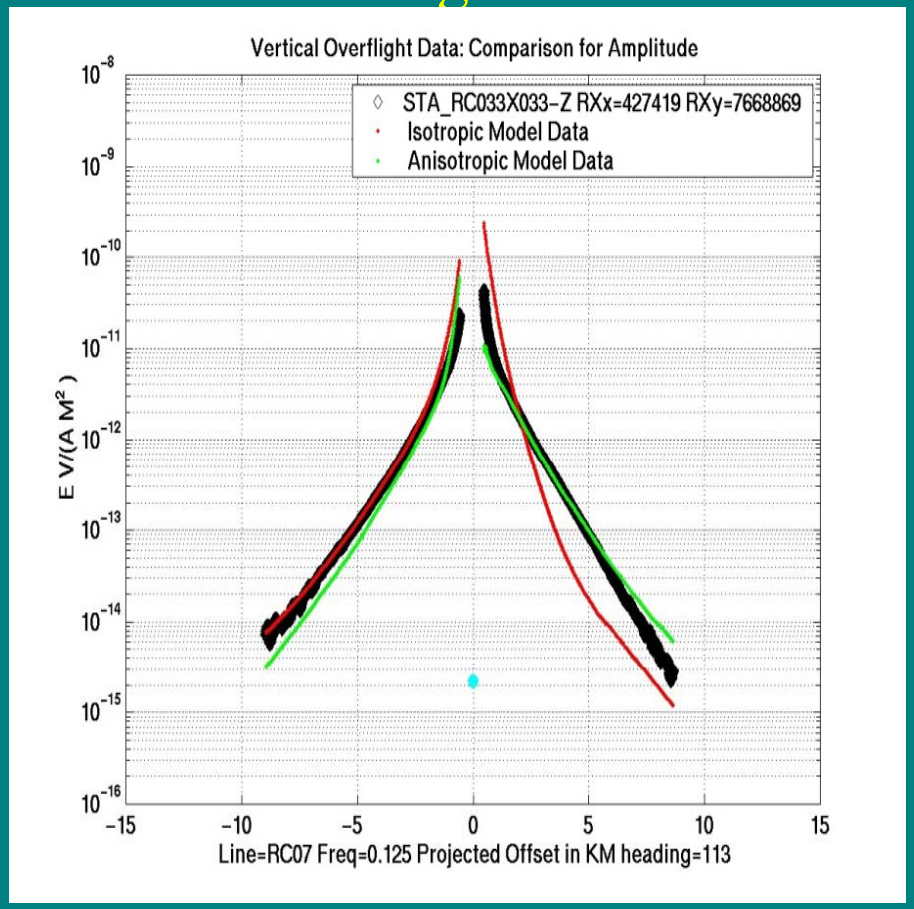




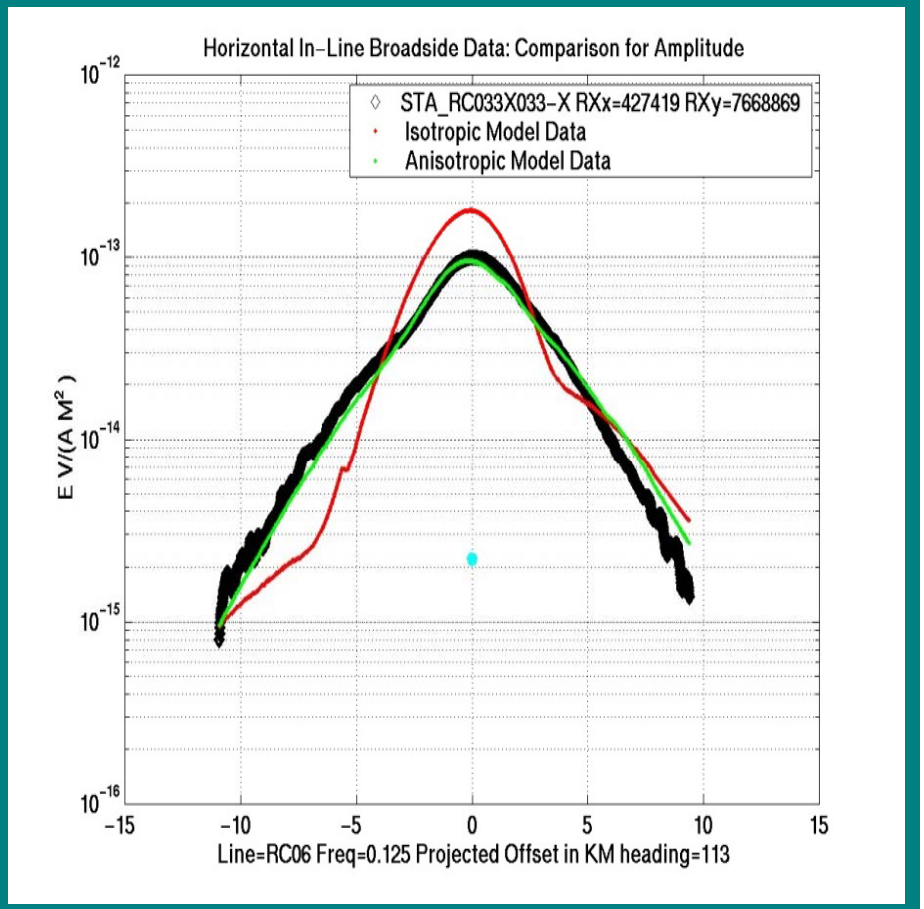
DATA FITS

Isotropic & VTI Anisotropic Starting Models

Overflight Profile



Broadside Profile



- VTI case: horizontal conductivity set to 3 times vertical conductivity

CONCLUSIONS

- Electrical Anisotropy
  - BG/L results show that electrical anisotropy in the Earth can be significant
    - » responses arising from background media can be larger than target reservoirs
  - BG/L results justify developing a 3D anisotropic imaging capability
    - » results delivered quickly has had important impact on future developments & productivity
- 3D CSEM Inverse Modeling
  - Parallelization in the model and data space allow for large-scale imaging
    - » necessary for multiple source & multiple frequency data
  - Separation of the simulation and inversion grids essential
    - » realistic basin-scale 3D imaging at very fine detail in an efficient manner
    - » provides a rigorous framework for developing a joint EM-seismic imaging scheme
- Anticipated Improvements in 3D Imaging/Inversion Technologies
  - Next 18 months
    - » Treat even larger data and imaging volumes (10x) with 100's thousands of processors
  - Next 3 to 5 years (Petaflop and Beyond)
    - » Multi-physics 3D imaging is coming (seismic and EM data volumes)
    - » Emerging Consensus: at least 100x more in computing resources required

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