U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Fracture Network and Fluid Flow Imaging for EGS Applications from Multi-Dimensional Electrical Resistivity Structure

April 23, 2013 ARRA funded R&D

Principal Investigator:
Philip E. Wannamaker
University of Utah
Energy & Geoscience Institute
423 Wakara Way, Ste 300
Salt Lake City, UT 84108
pewanna@egi.utah.edu

Track 2: Fluid Imaging

Relevance/Impact of Research

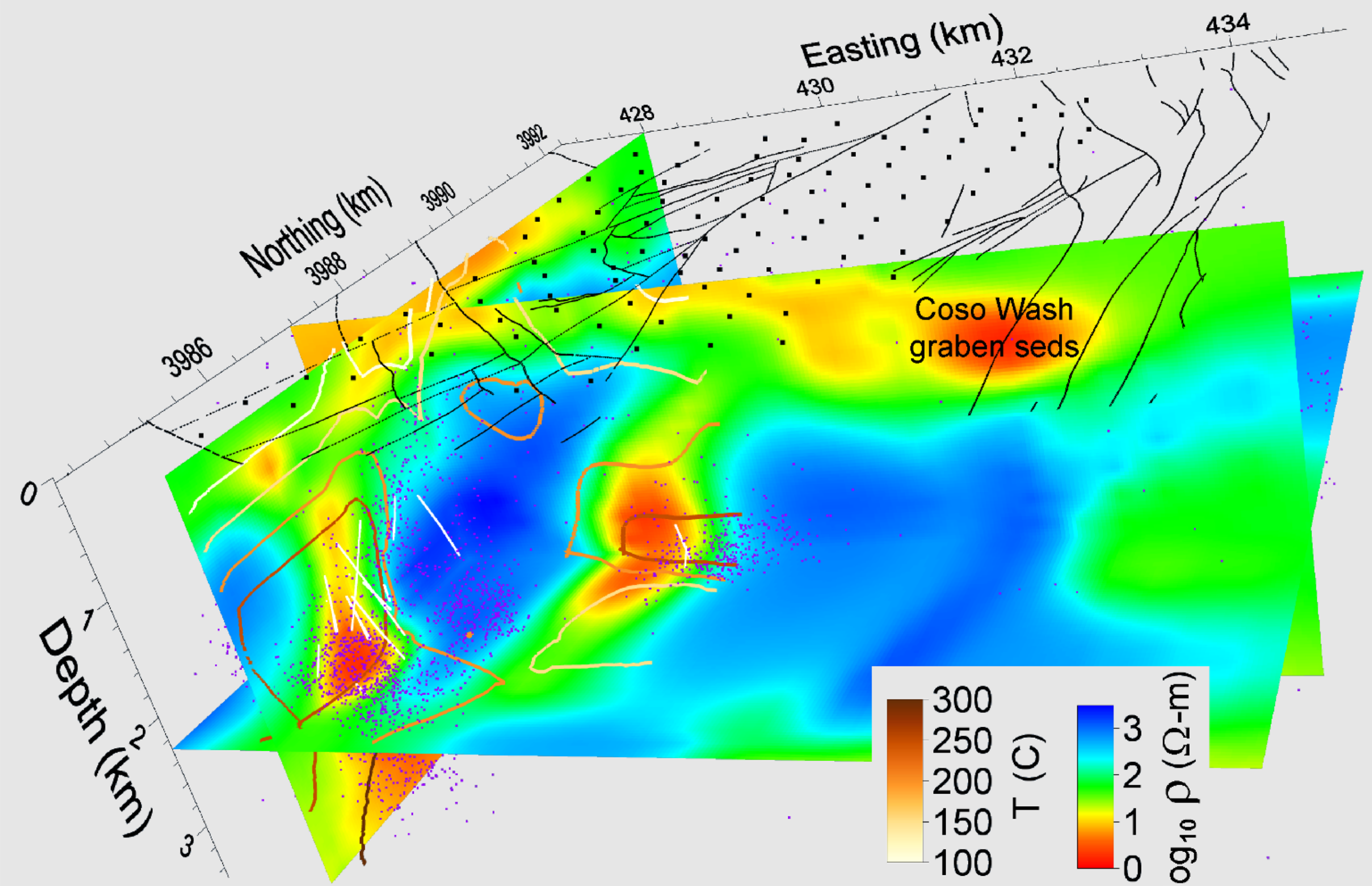
Project objectives:

- Barriers to Geothermal
  - Lack of available and reliable resource information
  - High exploration risks
  - Inadequate site selection/characterization, resource assessment
- Cost Reduction and Applications
  - Reduction of false structures and anomalies
  - Higher resolution below realistic receiver topologies
  - High physical property contrasts, conformal physics
- Innovative Aspects and Strengths
  - Accurate surface representation with non-rectilinear elements
  - Use of efficient direct solvers for stability and accuracy
  - Scalable parallelization on economical multi-core workstations

• Re GTO Goals: Electrical resistivity is one of the prime indicators of geothermal processes, but the imaging problem is ill-posed, inflexible in representations, and has been slow and costly.

Relevance/Impact of Research

Example Application of Inversion Development to date 1): Coso Geothermal Field



Coso 3-D Resistivity, Temperature, Seismicity, Well Production

V. Maris et al. (in prep.)

Relevance/Impact of Research

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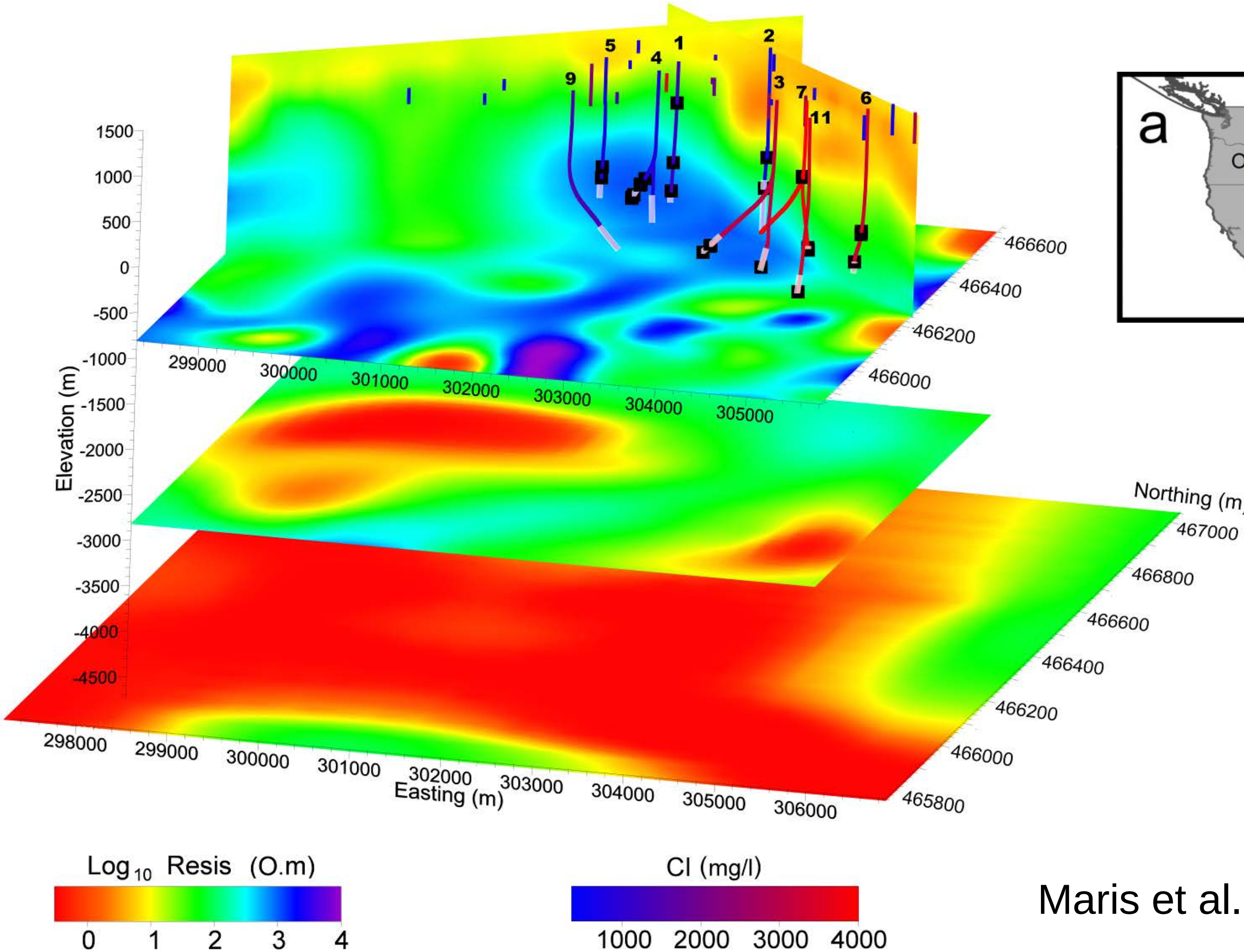
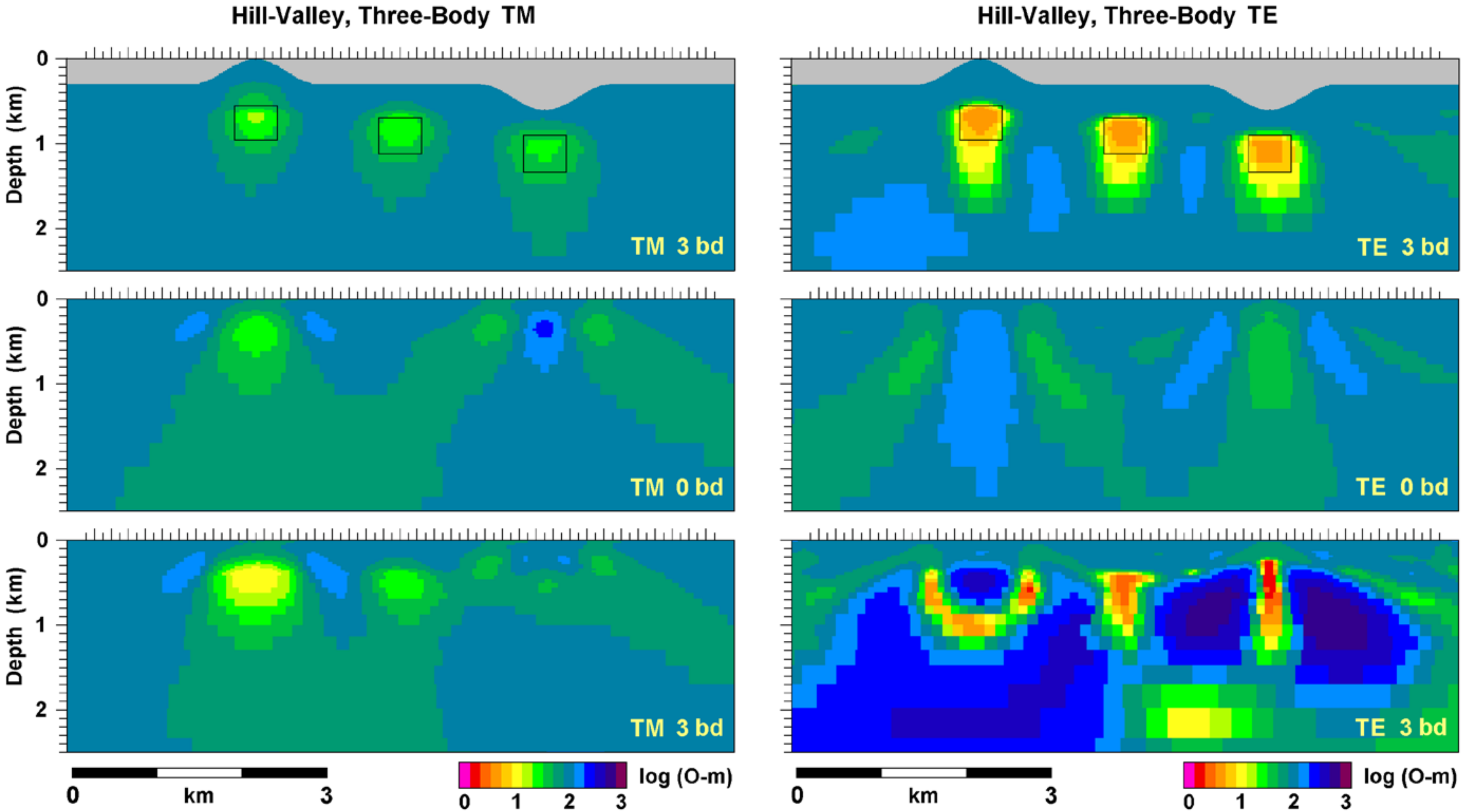
Example Application of Inversion Development to date 2): Raft R Geothermal Field



Maris et al., 2012, GRC

Influence of Topography/Errors When Ignored



Versatility and Efficiency in Imaging Fluid Flow via Electrical Resistivity

- 1), This is a focused tech dev effort. Create 3-D code for simulating EM responses at the surface of the earth with topographic variations. Evaluate two platform choices to determine the superior approach.

- 2), Incorporate the selected simulation code and the inversion parameter jacobians that follow from it into an existing inversion algorithm for imaging and monitoring and improve its efficiency.

$$\text{Objective:} \quad W_\lambda(m) = \{(d - F[m])^T C_d^{-1}(d - F[m])\} + \lambda\{(m - m_o)^T C_m^{-1}(m - m_o)\}$$

$$\text{NL Step:} \quad m_{k+1} - m_k = \{J_k^T C_d^{-1} J_k + \lambda C_m^{-1}\}^{-1}\{J_k^T C_d^{-1}(d_k - F[m_k]) - \lambda C_m^{-1}(m_k - m_o)\}$$

- 3), Parallelize the inversion code on new-generation, multi-core workstations to achieve fast calculations within a single, cost-efficient, symmetric multi-processing (SMP) box.

- 4), Apply the final algorithm to two important geothermal field MT data sets (Karaha, Coso EF, Cove Fort).

Scientific/Technical Approach

- Project Team:
  - P.I. Phil Wannamaker: Problem identification, solution concepts, test criteria, geophysical/geological integration, publication oversight

    EGI Post-doc Virginia Maris: Finite difference platform development, inverse step programming, MT data inversion, parallelization

Ph.D student Michal Kordy: Dept of Mathematics, quantitative EM geophysical research, statistics, finite element code development, SAGE student

Kordy: Deformable hexhedral elements for topo, implement divergence correction, parameter jacobians, parallelized direct solution.

- Maris: Gauss-Newton direct parameter step, great scalability on multi-core.
- Wannamaker: New multi-core sufficient for direct solvers, hex elements have good flexibility but preserve banded system matrices, need for div corr with E-fields.

Scientific/Technical Approach

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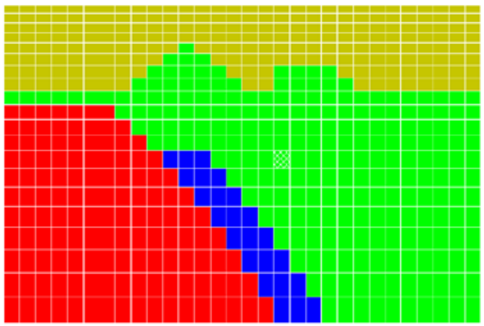
Electromagnetic Simulation and Inversion With Conformal Receiver Surfaces (Topography)

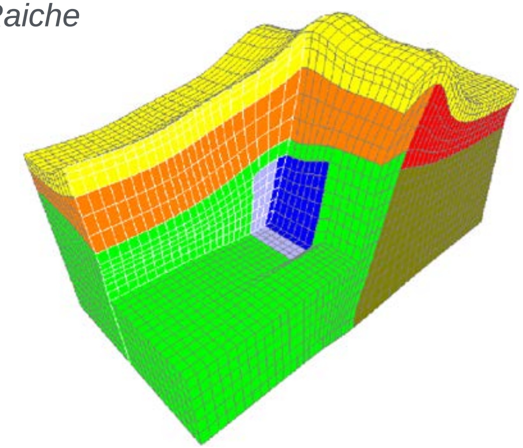
Madden et al., Newman et al., Siripunvaraporn et al., Sasaki



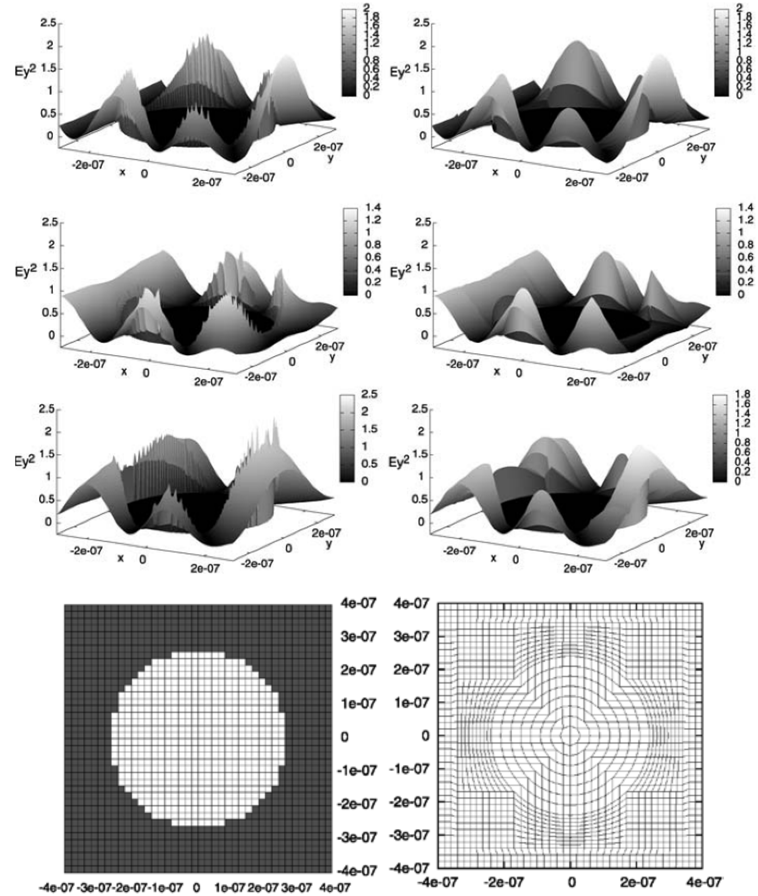
Finite Difference Topo Model

Graphics after Art Raiche

Sugeng et al., Nam et al.



Finite Element Cutout View



Liu et al., 2009

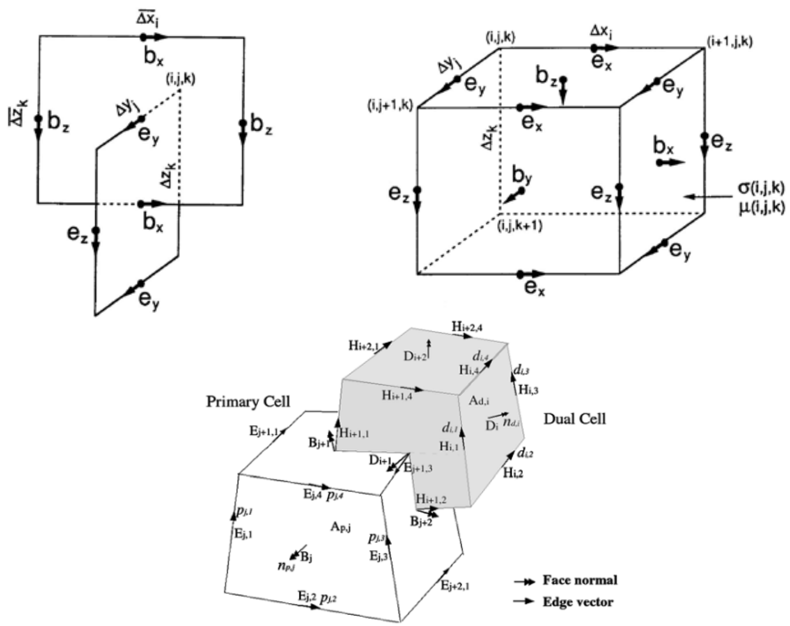
Numerical Approaches to Topographic Simulation

$$\oint H \cdot dl = \iint \sigma E \cdot ds$$

$$\oint E \cdot dl = \iint \mu\omega H \cdot ds$$

e.g.,

$$(E_{xt} - E_{xb})/\Delta z - (E_{zr} - E_{zl})/\Delta x = i\omega\mu H_{yc}$$



e.g., Liu et al. (2009)

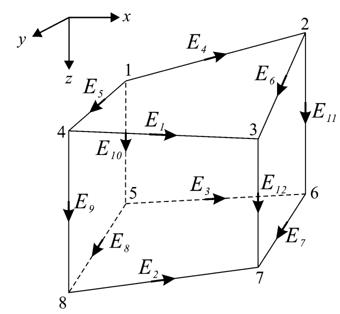
Finite Difference Staggered Grid

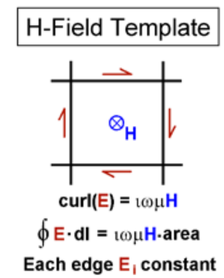
Generalize the circulations of ME's around the integration paths

$$\nabla \times E = -i\omega\mu H \qquad \nabla \times H = \hat{\sigma} E$$

$$\nabla \times \frac{1}{\mu} \nabla \times E - i\omega\hat{\sigma} E = J^{imp}$$

$$E = \sum_{i=1}^{n_e} x_i N_i \qquad H = \frac{-\nabla \times E}{i\omega}$$

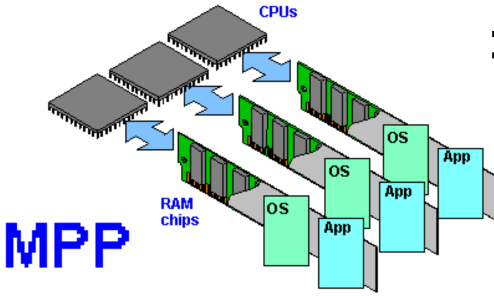




Finite Edge Element Deformable Grid

Shape functions already general for topography

Approach



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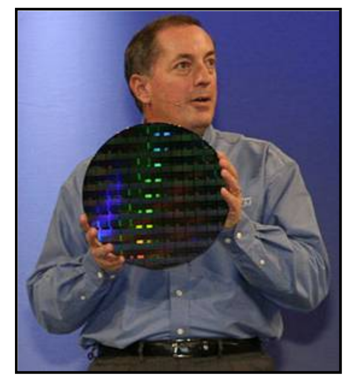

Intel CEO Paul Otellini holds 80-core chip wafer

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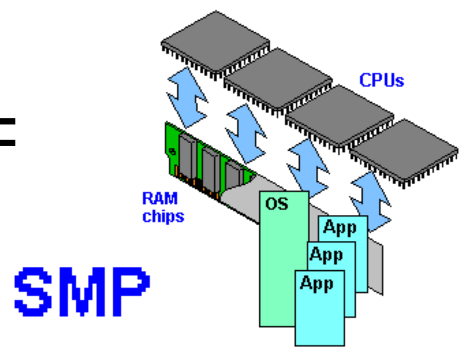

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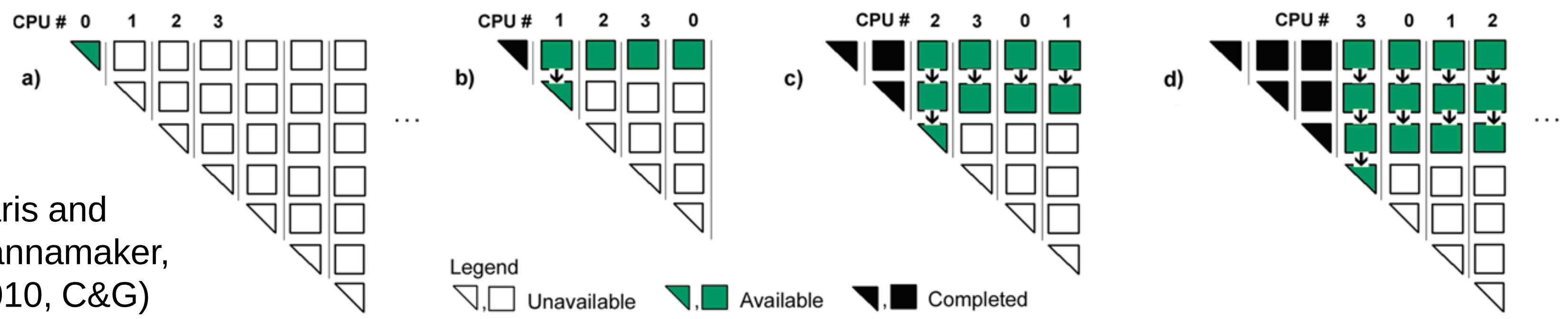
24-core, 0.5 TB RAM

Massively Parallel Processing

or <u>Symmetric Multiprocessing</u>

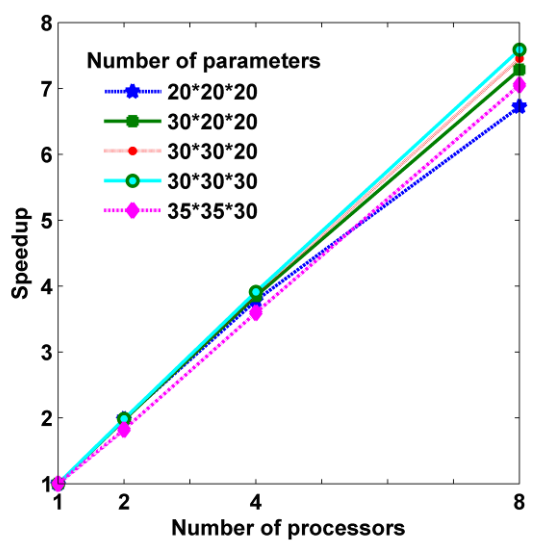
Parallelization of EM Inversion on Multi-core SMP Workstations

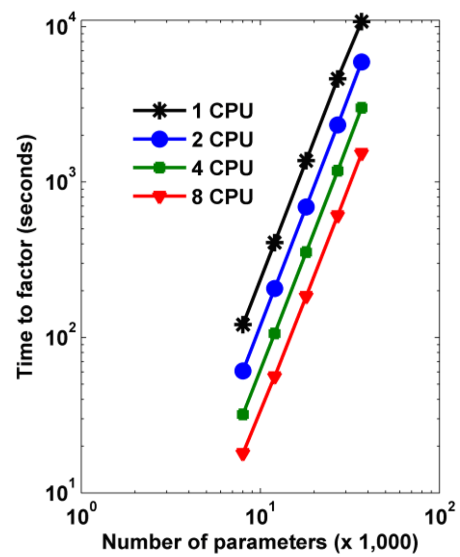
Asynchronous Block Factorization of Parameter Step Matrix

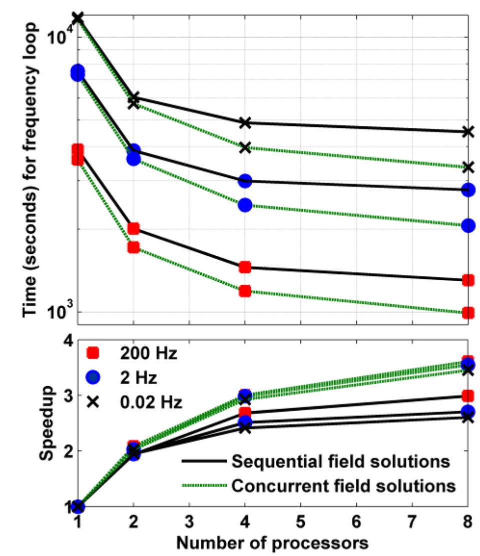


Maris and Wannamaker, (2010, C&G)

Scalability of Parallelization, Step and Forward/Jacobian







Accomplishments, Results and Progress

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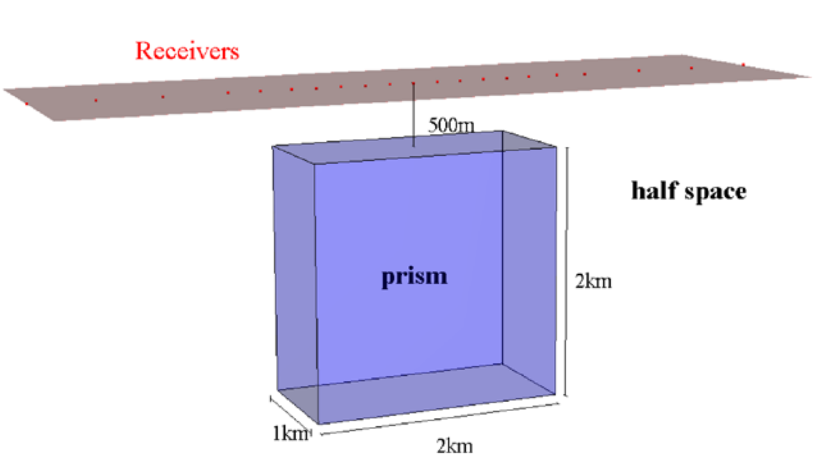
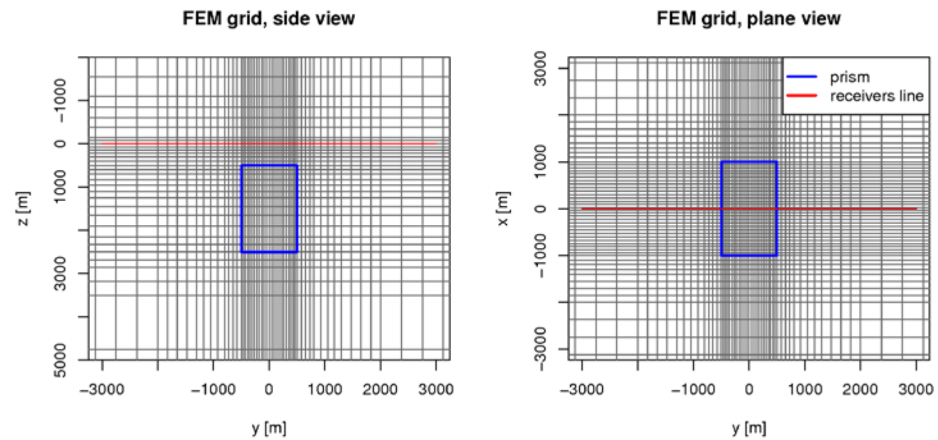
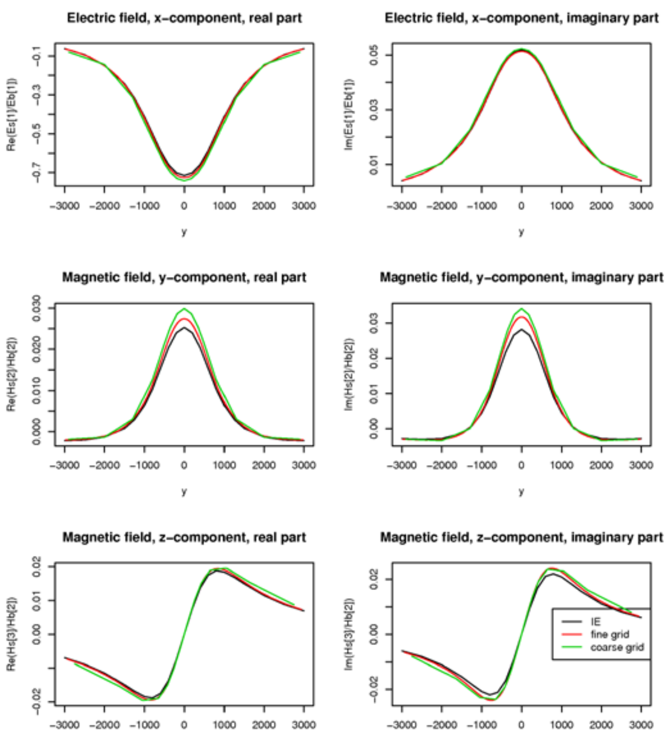
- We began with the edge-element Loki-3D platform (CSIRO); it solved for Lorentz vector potential but we could not get stable E.
- Research in deformable FD approaches incipient, deformable edge elements for E have seen much more investigation.
- Became convinced of advantages of direct (LDL^T) solvers given modern multi-core and experience with parameter step performance (immunity to large element aspect ratios, speed of solving many source vectors, excellent scalability, banded system matrix).
- Programmed flexible edge element E code, including divergence correction for parasitic curl-free errors: accuracy appears high.
- Acquired 24-core w/s with 0.5 TB RAM in November, 2012 ($14K usd). Excellent scalability in forward, 100's source vectors, parameter step.
- Parameter jacobians derived and programmed using 3D analog to reciprocity approach of deLugao and Wannamaker (1996) in 2D.
- Gauss-Newton step code merged and all parallelized on new workstation in March, 2013.

Results

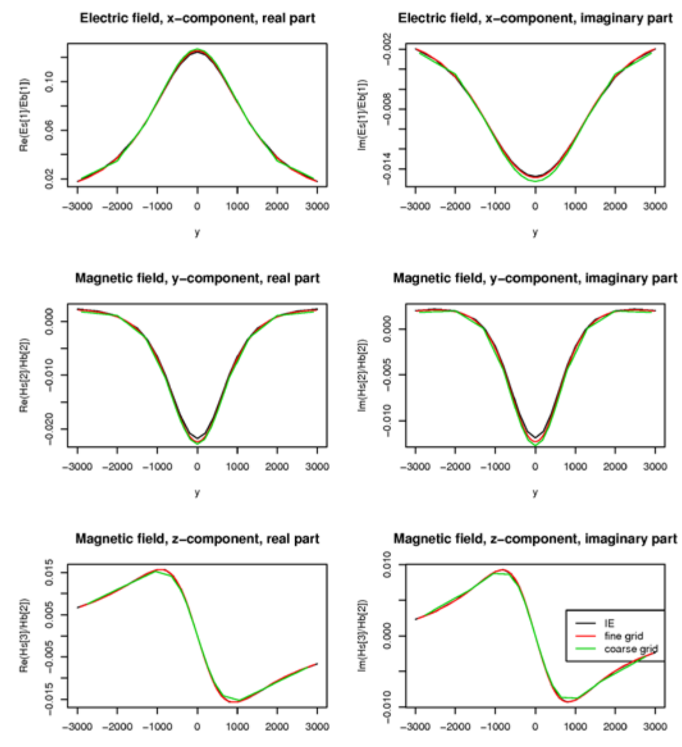
Numerical Checks: Prism in Half-Space





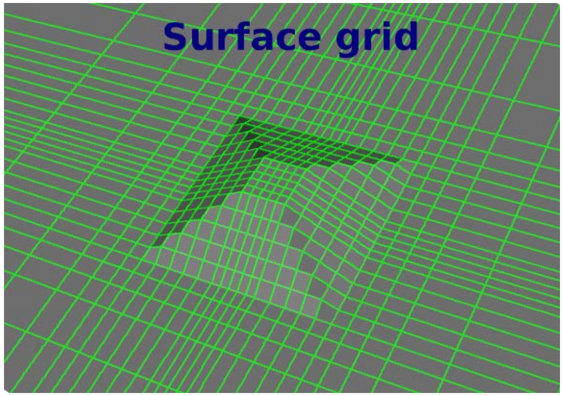


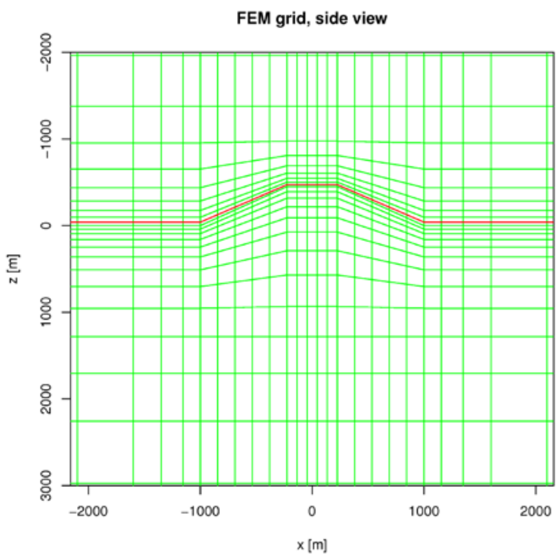
1 o-m prism in 100 o-m h.s.



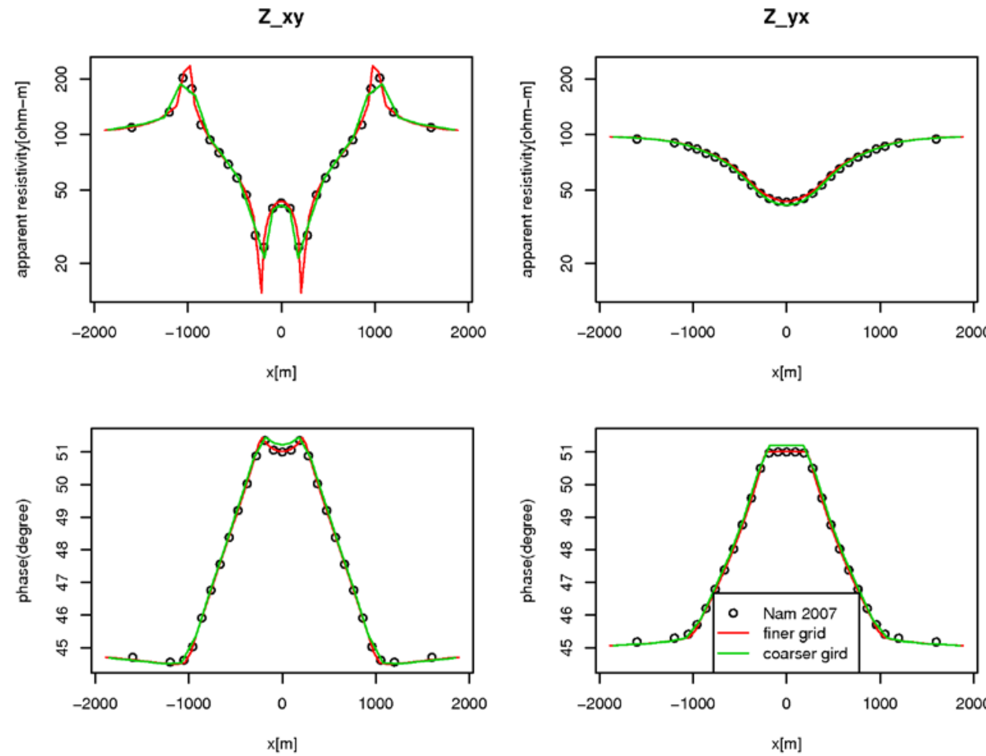
1000 o-m prism in 10 o-m h.s

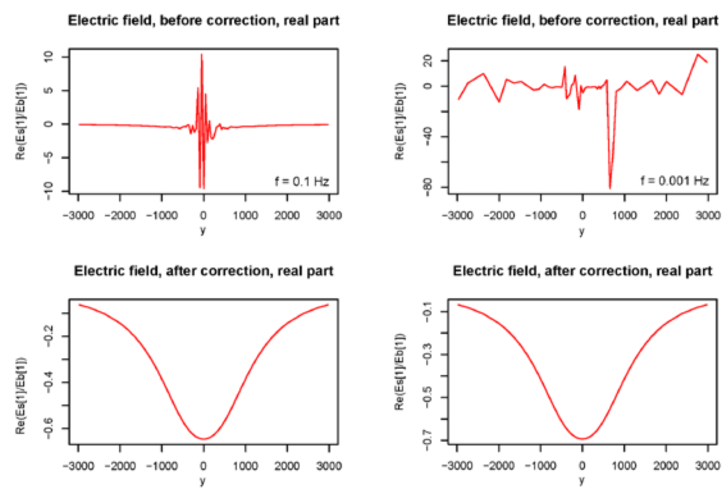
Results





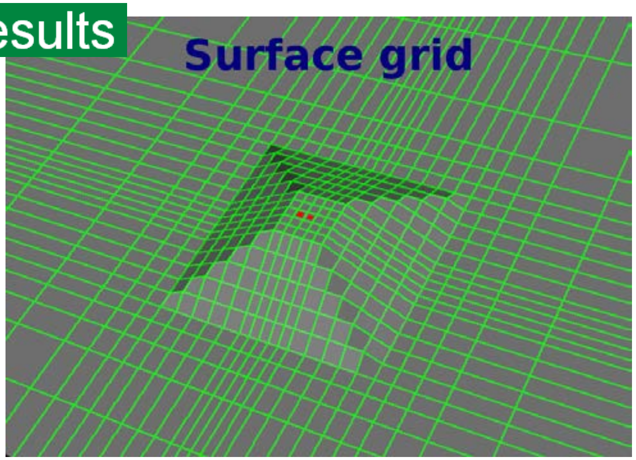
Topographic Test Model
(Coarse Discretization)
(after Nam et al., 2007)

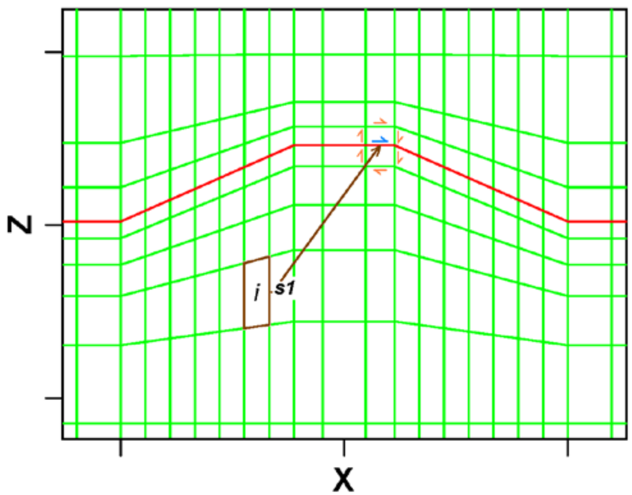




Divergence Correction, Prism Model

Results





$$\nabla \times \frac{1}{\mu}\nabla \times E' - i\omega\hat{\sigma}E' = i\omega E \quad \text{in region } j$$

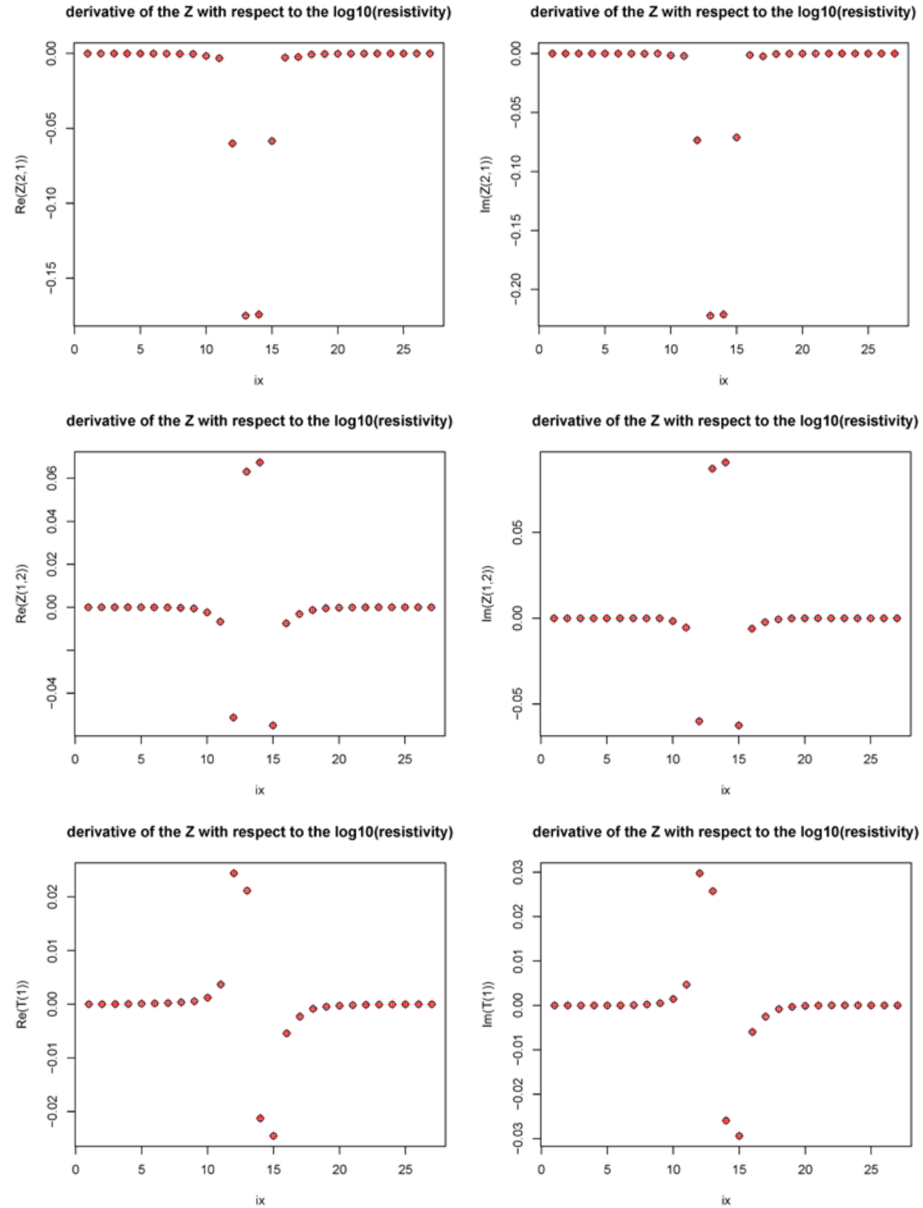
$$= 0 \quad \text{elsewhere}$$

$$H' = \frac{-\nabla \times E'}{i\omega}$$

3D parameter jacobians:

-diff. H.E. wrt region j, eq'n dual to Fwd

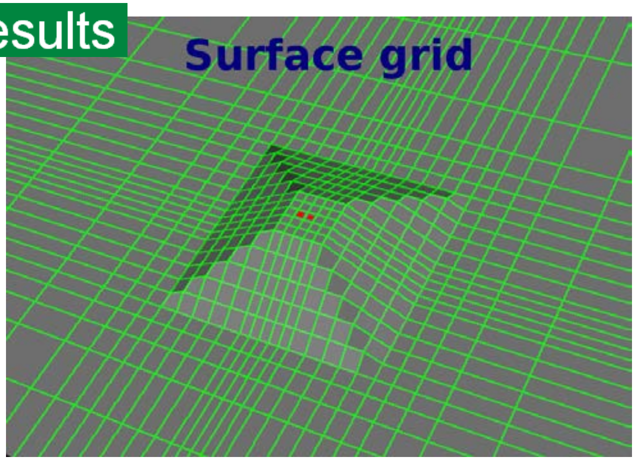
-invoke reciprocity to give 5Nrc sources

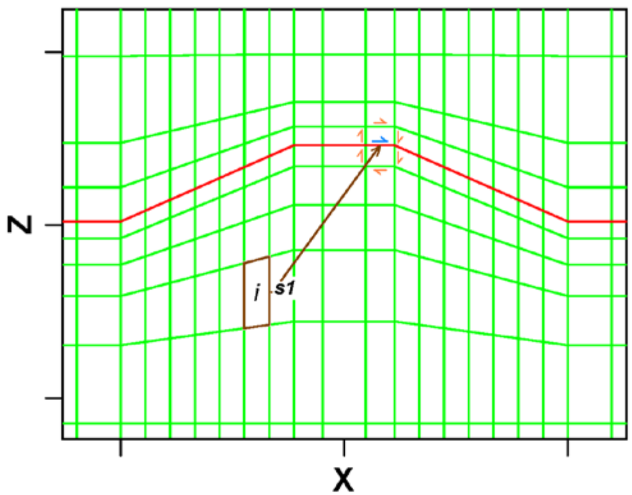


Zyx, Zxy and Tzx at 100 Hz

Circles = Recip, Pluses = FwDf

Results





$$\nabla \times \frac{1}{\mu}\nabla \times E' - i\omega\hat{\sigma}E' = i\omega E \quad \text{in region } j$$

$$H' = \frac{-\nabla \times E'}{i\omega} \qquad = 0 \quad \text{elsewhere}$$

<u>3D parameter jacobians:</u>

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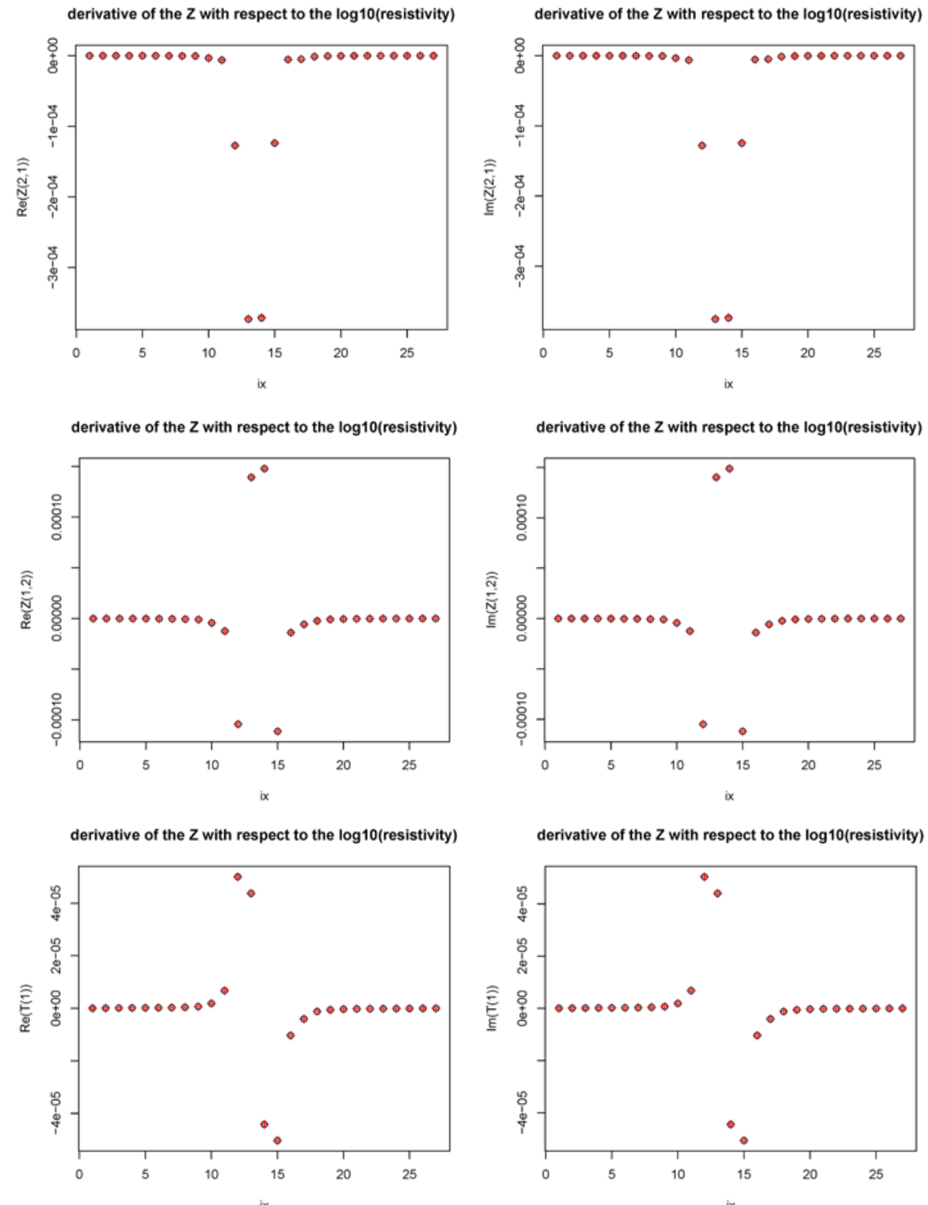
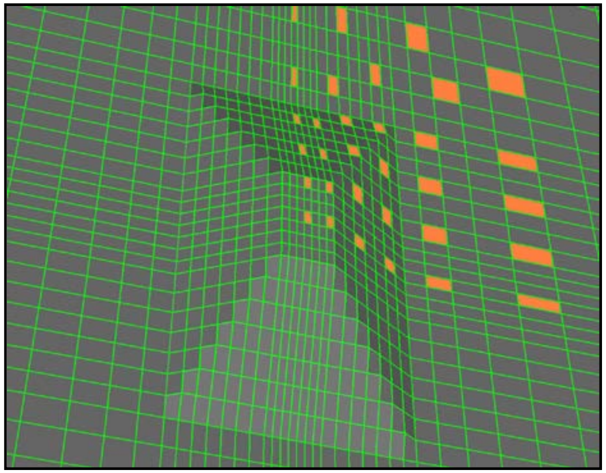


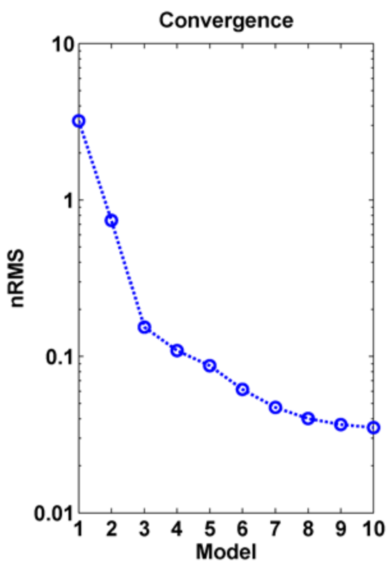
Zyx, Zxy and Tzx at 0.001 Hz

Circles = Recip, Pluses = FwDf

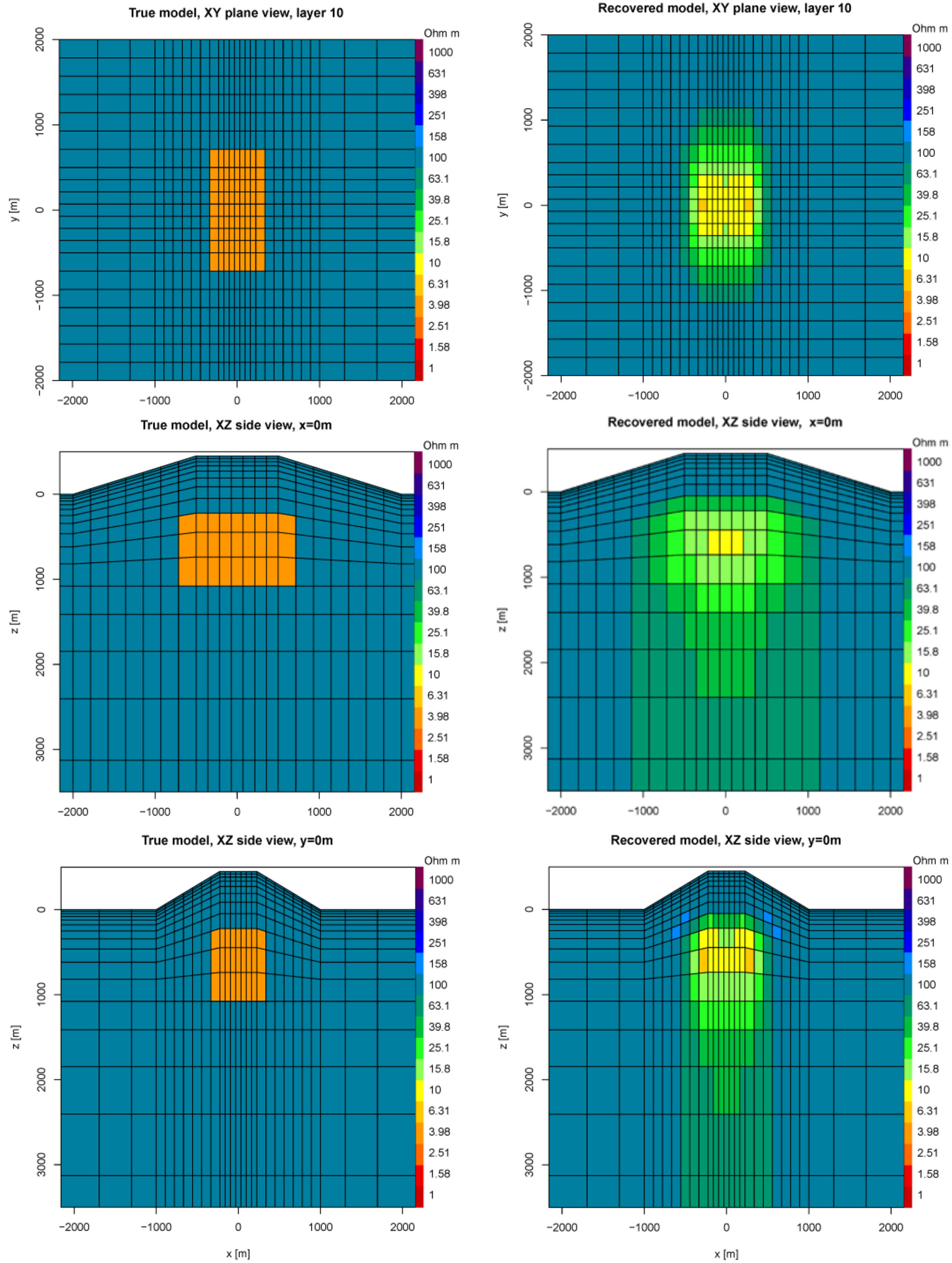
Results



Receiver distribution on hill
(one quadrant shown)

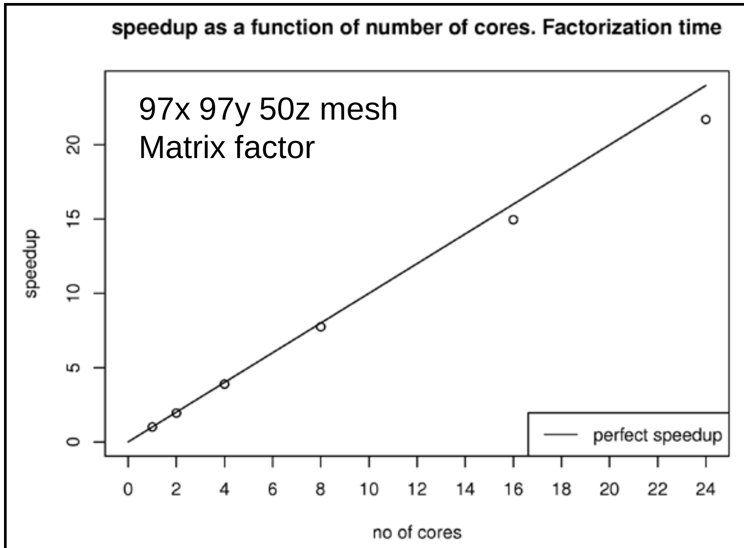


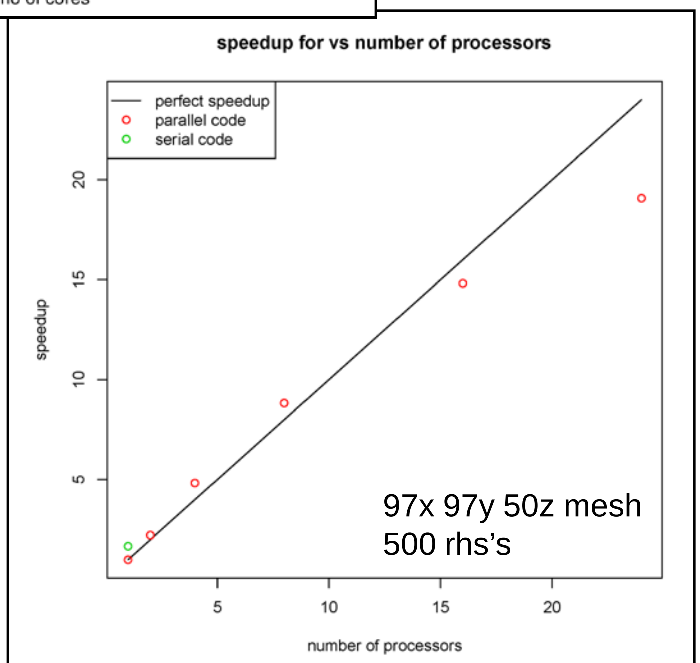
Model at iteration 5 shown
Starting guess of 50 ohm-m

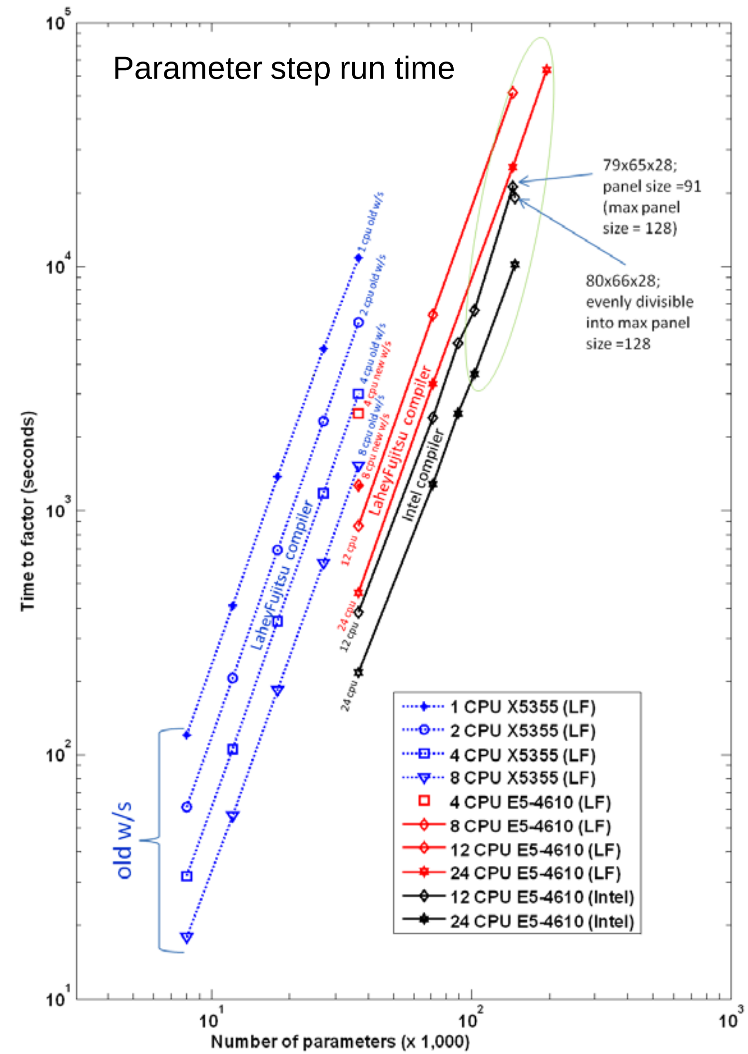


Results

Multi-core LDL^T factorization speedup







Future Directions

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Milestone or Go/No-Go	Status & Expected Completion Date
M1: FD or FE platform choice.	Neither EFD nor Loki attractive; decision to pursue edge E finite elements, June/12.
M2: New 24 core w/s, parameter step parallelization, compiler comp.	Done, November/12.
M3: Def'm edge E mesh and parameter jacobian programming.	Done, January/13.
M4: Merging of parameter step and fwd/jacobian codes, test model.	Done, March/13.
M5: Thorough testing on synthetic data for various topo configs.	Underway, May/13.
M6: Testing on two geothermal MT data sets (TerraGen, ENEL), writeup.	Subsequent to M5, September/13.

Summary Slide

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- Electrical resistivity a key geothermal indicator, esp. in concert with other information.
- Fully 3D analysis of EM data necessary, increasingly possible with mainstream computing.
- With modern multi-core, direct solutions are coming into their own.
- Direct solutions more stable w.r.t. mesh geometry, more efficient for many sources (~500 rhs's = 1 fwd problem in time).
- Multicore technology driven by large market forces and growing.

	FY2013	FY2014
Target/Milestone	To date, prototype 3D MT inversion using deformable mesh and direct solvers.	Project ends with FY13 (ARRA funded).
Results	Prototype completed, more thorough synth. evaluation underway, geothermal data prepped for testing.	

Project Management

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Timeline:

Planned Start Date	Planned End Date	Actual Start Date	Current End Date
January 8, 2010	January 31, 2013	March 21, 2010	September 30, 2013

Budget:

Federal Share	Cost Share	Planned Expenses to Date	Actual Expenses to Date	Value of Work Completed to Date	Funding needed to Complete Work
Ttl: $559,485	Ttl: $140,378	Ttl: $490,937 -M1 $190,050 -M2 $ 49,936 -M3 $124,839 -M4 $126,112 -M5 $ 72,738 -M6 $136,188	Ttl: $490,937 -M1 $190,050 -M2 $ 49,936 -M3 $124,839 -M4 $126,112 –M5 $ 0 -M6 $ 0	Ttl: $490,937 -M1 $190,050 -M2 $ 49,936 -M3 $124,839 -M4 $126,112 -M5 $ 0 -M6 $ 0	Ttl: $208,926 -M1 $ 0 -M2 $ 0 -M3 $ 0 -M4 $ 0 -M5 $ 72,738 -M6 $136,188

- Summary:
  - Fruitful mix of personnel with varying length and type of experience.
  - Should result in a leading technology in terms of accuracy and flexibility for geothermal MT data sets.
  - Pursues a computing technology that is experiencing strong growth.
  - Several available geothermal data sets warrant such analysis.