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

April 23, 2013    ARRA funded R&D
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

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

Maris et al., 2012, GRC
Relevance/Impact of Research

Influence of Topography/Errors When Ignored

Hill-Valley, Three-Body TM

Hill-Valley, Three-Body TE

Depth (km)

0
1
2
3

Depth (km)

0
1
2
3

0 km 3

0
1
2
3

log (O-m)

0 km 3

0
1
2
3

log (O-m)
Scientific/Technical Approach

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.

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).

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

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

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

\[ \oint H \cdot dl = \iint \sigma E \cdot ds \]
\[ \oint E \cdot dl = \iint \mu \omega H \cdot ds \]

\[ \frac{E_{xt} - E_{xb}}{\Delta z} - \frac{(E_{zt} - E_{zd})}{\Delta x} = i \omega \mu H \]

\[ \nabla \times E = -i \omega \mu H \quad \nabla \times H = \dot{\sigma} E \]
\[ \nabla \times \frac{1}{\mu} \nabla \times E - i \omega \dot{\sigma} E = J_{imp} \]
\[ E = \sum_{i=1}^{n_e} x_i N_i \quad H = \frac{-\nabla \times E}{i \omega} \]

Finite Edge Element
Deformable Grid

Generalize the circulations of ME's around the integration paths

Shape functions already general for topography
Massively Parallel Processing (MPP) or Symmetric Multiprocessing (SMP)

24-core, 0.5 TB RAM

Intel CEO Paul Otellini holds 80-core chip wafer
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
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 (LDLT$^T$) 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 m prism in 100 m h.s.

1000 m prism in 10 m h.s.
Topographic Test Model
(Coarse Discretization)
(after Nam et al., 2007)

Divergence Correction, Prism Model
3D parameter jacobians:
diff. H.E. wrt region j, eq'n dual to Fwd
invoke reciprocity to give 5Nrc sources

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

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

Zyx, Zxy and Tzx at 100 Hz
Circles = Recip, Pluses = Fwd
3D parameter jacobians:
-diff. H.E. wrt region j, eq’n dual to Fwd
-invoke reciprocity to give 5Nrc sources

\[ \nabla \times \frac{1}{\mu} \nabla \times E' - i\omega\sigma E' = i\omega E \quad \text{in region } j \]
\[ H' = \frac{-\nabla \times E'}{i\omega} = 0 \quad \text{elsewhere} \]

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
Multi-core LDLᵀ factorization speedup

**Results**

**speedup as a function of number of cores. Factorization time**

- 97x 97y 50z mesh
- Matrix factor

**Parameter step run time**

- 79x65x28; panel size = 91 (max panel size = 128)
- 80x60x28; evenly divisible into max panel size = 128

**speedup for vs number of processors**

- 97x 97y 50z mesh
- 500 rhs’s
### Future Directions

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

Summary Slide

<table>
<thead>
<tr>
<th>FY2013</th>
<th>FY2014</th>
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<tbody>
<tr>
<td>Target/Milestone</td>
<td>Project ends with FY13 (ARRA funded).</td>
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<tr>
<td>To date, prototype 3D MT inversion using deformable mesh and direct solvers.</td>
<td></td>
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<tr>
<td>Results</td>
<td></td>
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<tr>
<td>Prototype completed, more thorough synth. evaluation underway, geothermal data prepped for testing.</td>
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**Timeline:**

<table>
<thead>
<tr>
<th></th>
<th>Planned Start Date</th>
<th>Planned End Date</th>
<th>Actual Start Date</th>
<th>Current End Date</th>
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**Budget:**

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<tr>
<th>Federal Share</th>
<th>Cost Share</th>
<th>Planned Expenses to Date</th>
<th>Actual Expenses to Date</th>
<th>Value of Work Completed to Date</th>
<th>Funding needed to Complete Work</th>
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<tbody>
<tr>
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**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.