Deep Exploration Technologies Cooperative Research Centre

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OUTLINE

1. MT and Seismic (Conductivity vs Velocity)
2. A distraction: Seismic to electromagnetic coupling (and visa versa). (Is it real)
3. Cooperative Inversion: What are we trying to achieve – (could gradients be the key).
4. Properties that can be measured and sub-domains.
5. Seismic – Reflectivity → Spatial Attributes
6. Seismic - Attributes General (Dip Attributes, Streamlines, Direction of change, automatic conditioning of MT inversion)
7. Conclusion
Inputs → Output

Input
• MT → QC + Prepossessing absolutely critical.

• Seismic → Wide band acquisition + QC + True amplitude processing

Output
• Conductivity distribution,

• Acoustic impedance distribution,

• Derived parameters distribution (e.g. an attribute)
The output from cooperative inversion may be the *inputs* for:

1. *Full waveform seismic inversion*

2. Validation by *rigorous MT / Seismic Forward Modelling*

3. Or they may a *constraint on migrations* etc
Cubes of Parameters

Cooperative Processing/Inversion

Cycle 1

Synthetic Field Data

Cycle 2

Synthetic Field Data

Cycle 3

Field Data

Rigorous Forward Computation

Field Acquistion (e.g. Gravity, Seismic, MT)

QC field data
1. Basics EM and Seismic

1. Review Basics → EM and Seismic (conductivity?? and velocity??)

   1. EM - Basic equation and parameters
   2. Electrical conductivity from logging
   3. P-wave velocity from logging
   4. Acoustic impedance
The complete description

\[ \nabla \times E = -\frac{dB}{dt} \]

\[ \nabla \times H = J + \frac{dD}{dt} \]
Medium dependent parameters

\[ B = \mu H \]

\[ J = \sigma E \]

\[ D = \varepsilon E \]
The generic start point solution (Harris 2002)

\[(\nabla^2 + k^2)\Pi^{em} = -\delta(i)\delta(x)\delta(y)\delta(z) s^{em}\]

\[k^2 = \mu \varepsilon \omega^2 - i\mu \sigma \omega\]
Electrical Conductivity

Medium dependent parameter

\[ J = \sigma E \]

\[ I = \frac{V}{R} \]

\[ \rho = \frac{1}{\sigma} \alpha \text{Resistance} \]

Voltage \( V \) \( \rightarrow \) \( E \)

Current \( I \) \( \rightarrow \) \( J \)
What we call conductivity is strongly dependent on direction current is driven through the rock.

\[ \mathbf{J} = \sigma \mathbf{E} \quad (\sigma = \frac{1}{\rho}) \]
Seismic Basics

- Acoustic Impedance
  
  \[ Z = V \rho \]

- Reflection Coefficient
  
  \[ R = \frac{V_2 \rho_2 - V_1 \rho_1}{V_2 \rho_2 + V_1 \rho_1} \]
The Seismic Acquisitions challenge is to push frequency below 1 Hz. Why?

- Surface Seismic
- Sonic Logging
- Ultrasonic (Lab)

Measure for Years

SeaBed EM

Induction Logging

LWD (EM/Radar range)

MT

AMT

Radar

EM
2. Seismic to EM coupling

Anatomy of a seismoelectric conversion: Measurements and conceptual modeling in boreholes penetrating a sandy aquifer

J. C. Dupuis,1,2 K. E. Butler,1 A. W. Kepic,2 and B. D. Harris2

Received 17 July 2008; revised 25 June 2009; accepted 13 July 2009; published 3 October 2009.

[1] Conversions of compressional seismic waves to electric fields have been measured in two boreholes drilled in an unconfined sandy aquifer on the Gnangara Mound near Perth, Australia. The seismoelectric conversions at both field sites occurred in the vicinity of the water table at 13-m depth and yielded maximum amplitudes of 1 μV/m using a sledgehammer source on surface. Partially cemented layers, inferred from geological and geophysical logs, straddle the water table and may play a role in generating the conversion and influencing its amplitude distribution. The dense vertical sampling used in these borehole experiments reveals spatial and temporal polarity reversals of the interfacial signal which provide new evidence in support of the conceptual model for seismoelectric conversions at interfaces. We demonstrate that the growth rate of the source zone and its maximum vertical extent below the water table are encoded in the polarity of the interfacial signal. These experiments confirm that vertical seismoelectric profiling can be used to gain further insight into seismoelectric conversions and characteristics of interfaces that makes them amenable to detection.
Wire line logs

Do Seismic Wavefields Create EM wavefields

Why ??

Figures adapted from Dupuis, Butler, Kepic and Harris 2009 (JGR Vol 114 – B10306)
2. Of Course they do

But: How can we compute the EM Field ???
How big are they ???
Methods to fill out the Seed Volumes
- EM inversion (1D, 2D, 3D)
- Refraction tomography (Ocallaghans)
- Seismic Reflection processing 3.1
- Seismic Reflection Inversion (pre stack)
- Seismic Reflection Inversion (post stack)
- Dip Attributes
  - Gravity inversion
  - Surface wave Analysis etc

Joint Application / Inversion tools
- Cross Gradient
- 1D joint inversion
- Lithological constrained
- Statistical Constrained
- Cooperative inversion

Empty Cube
- Surveys
  - In-hole
  - EM and Seismic surveys

Seeds
- Density
- Conductivity
- Velocity

Final Model
- Density
- Conductivity
- Velocity

Rock type
- Lithology's

Petrophysics
- Wire line logging
- Chemistry
- Geology

Surface I
-hole
EM and Seismic surveys
Some Tools

- **Building/Perturbing Seed Models or conditioning inversion** (cube of conductivities, velocity and density).
  - EM derived conductivities (1D, 2D, 3D)
  - MT inversion (Graham)
  - LMO Cube
  - Refraction techniques
  - Full waveform tomography
  - Virtual source imaging (evolving quickly)
  - Surface wave analysis
  - Seismic Reflection Imaging (Milovan)
  - Diffraction Imaging (Roman)
  - Post and Pre-stack inversion (seismic)

**Attribute analysis**
Sub-domains

• Strategies for each sub-domain are different but interdependent.

1. Cover,
2. Weathering,
3. Host,
4. Mineralization.
We want the range of reasonable densities, conductivities and Velocities For each sub-domain.
Either know the value or at least know the range

Neither the value nor the confidence in each value are uniform throughout the volume.

**Example:**

*VSP velocity* → High certainty low coverage tight constraint around the bore hole

*Surface EM* – Low resolution high coverage
Each Cell Need a parameter and direction of change
Often the gradient is known for all parameters. However, the contrast may not be known.
Large Data Set (Barrick Gold) Reflectivity Vs Acoustic Impedance
How to deal with Gradients through

(i) How do vectors change at Boundaries
(ii) How do vectors change in Sub-volumes
Directional Attributes
5. Seismic – Reflectivity $\rightarrow$ Amplitude and Spatial Attributes

Adapted from Chopra and Marfurt 2005

GEOPHYSICS, VOL. 70, NO. 5 (SEPTEMBER-OCTOBER 2005); P. 3SO–28SO, 32 FIGS. 10.1190/1.2098670
More interactive INTERACTIVE EM SOFTWARE
See Andrew’s MCSEM web site
Examples of positive and negative curvature

Streamline – EM fields

1. EM fields - Streamlines (Pethick and Harris 2013)
Conclusions / Three key outcomes

1. **Computations of streamlines** representing direction of change of conductivity and direction perpendicular to horizons with strong reflection coefficient.

2. **MT constrained post stack inversion**. Here the MT inversion can help constrain the large scale Acoustic impedance model. The outcome must be viewed as a new type of MT constrained impedance attribute rather than explicit or accurate recovery of acoustic impedance.

3. **Automatic extraction of seismic structural constrains for MT inversion**
Importance of parallel computing for cooperative inversion workflow
Andrew Pethick, Curtin University
A Declining Industry?

Dedicated Geophysical Supercomputers in the Top500

Max GFlops

Number in Top 500

Overview

What is parallelisation

Overview parallelisation methods

Electromagnetic parallelisation case studies

Potential methods for parallelisation of joint inversion workflows
What is Parallelisation?
What is Parallelisation

“Parallelisation is the ability to perform two or more calculations simultaneously”
What is Parallelisation

Each sub problem is solved concurrently.
Parallelisation: Multi-threading

- A thread is a single piece of executable code scheduled to run on a processor
- Multi-threading is the ability to concurrently execute multiple pieces of code

Multi-threading produces faster execution speeds and enables true multi-tasking
Parallelisation: Multi-threading (Sequential batch)

Added First → Added Last

Task List

Dynamic Queue (Sequential Batch)

Input

Added First

Task 5

Task 6

Task 7

Added Last

Task N

Execute once core is available

Execution

Quad Core CPU

Task 1

Task 2

Task 3

Task 4

Output

(May not be sequential)

Task 1

Task 2

Task 3

Task 4

Task 5

Task 6

Task 7

Task N
Parallelisation

- Parallelisation can be integrated at two levels,
  - ‘Macro’ – On top of the compiled executable
  - ‘Micro’ – Within the code
Parallelisation

- **Macro Parallelisation**
  - Useful when only a compiled executable exists
  - Modernizing legacy code
    - Poorly documented
    - Overly complex
    - Unknown language
  - Simpler than using MPI

![Diagram showing the relationship between Macro, Wrapper, and Program]

- Requires compiled code
Parallelisation

- Micro Parallelisation
  - Requires source code and knowledge of code function
  - Good for when there are known computational dependencies
  - Difficult to implement effectively but more compatible with and better at scaling on supercomputers
Methods of Measuring Parallelization Effectiveness

- **CPU Time**
  - The total time each thread actively runs on the CPU core

- **Wall Time**
  - The total time taken from the start of the execution to the termination of the last thread.

- **Speedup**
  - The percentage increase in speed by parallelization

- **Efficiency**
  - How effective is the algorithm is distributing across multiple cores (i.e., does it scale well?)
Case Study 1
Marine Controlled Source EM
MCSEM: Computing The Fields

- Solving the Integral Equation method for computing EM Fields (Taken from Raiche, 1974)

Starting with Maxwell’s Equations

\[ \nabla \times E = -i \omega \mu H \]
\[ \nabla \times H = (\hat{\sigma} + i \omega \varepsilon) + J_0 \right) = \sigma E + J_0 \]

Solving for a geo-electrical conductivity distribution

\[ \sigma = \sigma_p + \sigma_p \]
MCSEM: Computing The Fields

The Integral equation method expresses each inhomogeneous cell by an equivalent scattered source.
MCSEM: Computing The Fields

- Solving the wave equation:

$$\nabla \times \mathbf{H} = \sigma_p \mathbf{E} + (\sigma - \sigma_p) \mathbf{E} + J_0 = \sigma_p \mathbf{E} + J_S + J_0$$

Inserting Faraday’s Law into

$$\nabla \times \nabla \mathbf{E} + i \omega \mu \sigma_p \mathbf{E} = i \omega \mu (J_S + J_0)$$

Yields

$$\nabla \times \nabla \mathbf{E} - \nabla \cdot \nabla (\nabla \cdot \mathbf{E}) = i \omega \mu (J_S + J_0) + \nabla \nabla \mathbf{E}$$

$$\nabla \times \nabla \mathbf{E} - k_p^2 \mathbf{E} = i \omega \mu (J_S + J_0) + \nabla \nabla (\nabla \cdot \mathbf{E})$$

$$k_p^2 = -i \omega \mu \sigma_p = -i \omega \mu \hat{\sigma}_p + \omega^2 \mu \varepsilon_p$$
Taking the divergence gives

\[ \nabla \cdot (\nabla \times H) = 0 = \nabla \cdot (\sigma_p E + J_S + J_0) \]

\[ \nabla \cdot (\sigma_p E) = -(J_S + J_0) \]

\[ \nabla \sigma_p \cdot E + \sigma_p \nabla \cdot E = -\nabla \cdot (J_S + J_0) \]

\[ \nabla \cdot E = -\frac{\nabla \sigma_p \cdot E}{\sigma_p} - \frac{\nabla \cdot (J_S + J_0)}{\sigma_p} \]

Plugging that back into wave eq. solution

\[ \nabla^2 E + k_p^2 E = i \omega \mu (J_S + J_0) - \nabla \left( \frac{\nabla \sigma_p \cdot E}{\sigma_p} \right) + \frac{\nabla \cdot (J_S + J_0)}{\sigma_p} \]

\[ \nabla^2 E + k_p^2 E + \nabla \left( \frac{\nabla \sigma_p \cdot E}{\sigma_p} \right) = i \omega \mu (J_S + J_0) - \nabla \frac{\nabla \cdot (J_S + J_0)}{\sigma_p} \]
MCSEM: Computing The Fields

(Finally, the tensor Green’s Function.)

- The tensor Green’s Function $G$ is a kernel function which solves inhomogeneous partial differential equations

$$E(r) = E_p(r) + \int G^E(r, r') \cdot \sigma_a(r')E(r')dv'$$

$G^E(r, r')$ relates the electric field at a radial position $r$ in layer 1 to a source element (scatterer) at $r'$ in layer $j$. 

MCSEM: Computing The Fields

- Notice that the IE solution needs to be computed independently for each
  - Source Location
  - Transmission Frequency
  - Conductivity distribution

\[ E(r) = E_P(r) + \int G^E(r, r') \cdot \sigma_{a}(r') E(r') dv' \]
MCSEM: Computing The Fields

• So how does this all fit in to parallelization?

• If a survey consisted of
  – 128 Source locations
  – 8 Transmission frequencies
  – 25 Receivers

• Then the tensor Green’s function would have to independently be solved 1024 times (128 sources x 8 frequencies)

• IE Fields computed with Marco (CSIRO’s P223 Project) (Xiong, 1992)

This means we can parallelize over source or transmission frequency but not receiver location!
MCSEM: Parallelisation

A ‘macro’ parallelisation method and software was developed to rapidly forward model electromagnetic fields generated during a MCSEM survey
MCSEM: Our Approach

• A grid computing based approach
MCSEM: Parallelising by Transmitter vs Freq.

\[
\text{Speedup} = \frac{t_{ws}}{t_{wn}}
\]

\[
\text{Efficiency} = \frac{\text{Speedup}}{N}
\]

Where,

- \(t_{ws}\) - Wall Time on a single CPU
- \(t_{wn}\) - Wall Time on a N CPU’s
- \(N\) - The total number of CPU’s utilised
Parallelisation reduces a 12hr task to a 3.2hrs on a single multi-core CPU!

A 375% Speedup
MCSEM: Scaling the Problem

- Real surveys can be composed of thousands of transmitters, hundreds of receiver locations in geo-electrical environments much more complex than a simple block.

Survey Complexity = nTrans. x nFreq.
MCSEM: Testing a Scaling Problem

- Utilising an empty computer lab with 16 Intel Core2 quad machines
  - Modelling performed using 64 cores
  - Surveys of increasing complexity were forward modelled
  - 16 computers running at 100% CPU for 24 hours creates a fair bit of heat and electricity.
  - ~57kW was used to run these ‘small’ experiments (@150W/hr per PC = 24x150x16=57600W or $17)

...the equivalent of running a 2400 Watt heater
MCSEM: Parallelising by Transmitter vs Freq.
Case Study 2
Airborne EM
AEM: Introduction

• An AEM survey was performed in Allanooka, North Perth Basin
• Consists of 93819 Source locations
AEM: The Experiment

- Using the same ‘macro parallelisation’ method described in case study 1
- Integrating the Airbeo 1D inversion routine (Chen and Raiche, 1998)
- Using a grid of 16 quad-code hyper-threaded Intel Core i7 computers
  - Despite only have 4 cores hyper-threading enables two threads to be executed on the same core
  - Hyper-threading is ~30% faster on a 4 core CPU
AEM: Testing the Parallelisation Method
AEM: Scaling the Problem
AEM: Resulting Inversion
Parallelisation integration into joint inversion workflows
Joint Inversion

• MT Inversion
  • ModEM (Egbert and Kelbert, 2000)
  • ModEM has a coarse grained parallelisation over source locations or geo-electrical models

• Seismic Inversion
  • 1D Model based post stack inversion within Hampson Russell
JI: Potential Workflow

Input Lithological Model

MT ModEM Inversion

Seis. Post Stack Inversion

Obtain Inversion Results

Combine and Sensitivities

Compare polar dip and conductivity gradient
JI: Implementing Macro-Parallelisation

JI Framework

Assess many inversions

Genetic Algorithm? Monte Carlo?

Parallelise along Initial Lithology

EARTH

MT INV SEIS INV

MT INV SEIS INV

MT INV SEIS INV

MT INV SEIS INV
Conclusions

- Parallelisation can be used to dramatically improve computational speed
- Parallelisation can be applied at ‘macro’ and/or ‘micro’ scales
- Electromagnetic problems are generally parallelised by source excitation, frequency, conductivity distribution or seed model
Conclusions

• Using Parallelisation, we are working towards a rapid joint MT Seismic inversion workflow
  ➢ Producing multi-seed model inversions
  ➢ Within a simple and semi-automated software framework
Useful References

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