Combined Electrical and Magnetic Resistivity Tomography (ERT/MMR)

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Outline

• Goals and motivation
• Project outline
• Experimental results
• Summary and conclusion
Goal and approach

- **Goal:** Enhance 3-dimensional resistivity resolution

- **Approach:** combine DC ERT with magnetometric resistivity (MMR) measurements
Motivation

• Need for enhanced information on subsurface EM properties

• ERT monitoring works, however installation in contaminated areas can be expensive

• Surface resistivity methods provide limited resolution

• Desire to increase resolution with fewer boreholes in contaminated areas

• Approach allows taking advantage of existing wells by using down hole magnetometer arrays
Advantages of approach over traditional ERT

• Uses existing wells at typical remediation sites

• Increases lateral resolution with a reduction in both cost and invasion of the subsurface

• Allows collection of MMR data sets without additional boreholes

• Provides integrated data sets
Project outline

• Year 1: Develop hardware and software, study resolution and inversion issues

• Year 2: Field testing and method enhancement

• Year 3: Full scale deployment -> transition to “production” method
**Principle behind method**

- DC current injection in subsurface will result in magnetic field

- Observing magnetic field (at surface/in boreholes) is equivalent to measuring electrical potential field at this location

- Use magnetic field observations in joint inversion with ERT data to obtain better subsurface image
After Jakowski, 1940
Theoretical development (2001-2002)

- MMR concept developed in late 1930’s
- Minimal use in marine environments using qualitative interpretation
- INEEL theoretical effort: Develop modeling and inverse codes (refer to papers)
Instrumentation and field tests (2002-2003)

- Develop instrumentation
- Design controlled field test site, collect and invert data
- Field area (Mud Lake, Idaho) consists of interbedded clay, silt, and sand lake deposits
Instrumentation

- **Power source:** 130 volts transmitted by a Zonge GDP32™ ERT system

- **Measurement:** 3-axis Bartington flux-gate magnetometer, and standard subsurface copper electrodes

- **Signal detection:** GDP32™
Data Collection

• 50% duty cycle current (8 Hz) is passed through the subsurface volume of interest via electrode pairs located at various depths

• The MMR system is then moved over the area of interest to collect the B-field data resulting from any resistivity contrasts

• B-field magnitude and phase are derived from synchronous detection methods
Field tests

• Data collection with no target (background data set)
• Data collection with cold rolled steel target (1 m square) at 25 cm depth
• Data collection with copper target (1 m square) at 25 cm depth
Background Data - Comparisons of Field and Model Data

- Transmitter depth 2.5 meters (shallowest depth with acceptable current flow (>0.1 amp))

- Following slides compare field data (bottom) and model MMR data (top) for horizontal dipoles.

- Three wells containing 13 electrodes each (wells 1, 3 and 4)

- Note important effect of surface wire geometry
Model Field

‘X’ Transmitter Total Field
MMR  nanoteslas/amp

Hx  Hy  Hz

nanoteslas/amp  -75  -50  -25  0  25  50  75
<table>
<thead>
<tr>
<th>Hx</th>
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<td>Model Field</td>
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Diagonal Transmitter Total Field MMR

nanoteslas/amp
‘Y’ Transmitter
nanoteslas/amp
Observation from background data

- Forward model predicts field data accurately
- Considering surface wire geometry is critical for correct modeling
Resolution enhancement

• Compare ERT only inversion to ERT + MMR data inversion

• Requires significant post-processing
ERT/MMR Data processing

• Pre-processing:
  – Reduce all data into proper frame of orientation
  – Subtract primary fields resulting from surface cable

• Post-processing:
  – Joint inversion of B field and E field data to obtain 3D subsurface resistivity model
Post-Processing efforts

• Multi-Phase Technologies of Sparks, NV
  – Develop a frequency domain forward model calculating surface and subsurface electromagnetic fields
  – Develop a DC approximation inversion code employing forward model

• University of Wisconsin
  – Testing of DC approximations against a full physics model
ERT vs ERT/MMR comparison

• Following two slides present inversions of field data for cold rolled steel plate data

• Slide 1: ERT alone - steel plate is not detected.

• Slide 2: ERT/MMR combined - although artifacts are present the steel plate is detected.
Data Misfit

- Number of data points (MMR+ERT) 1817
- Iteration# 15
- Old data error 1.657E+03
- New data error 1.653E+03
- Old Roughness 6.174E+02
- New Roughness 5.869E+02
- Roughness Factor 2.635E-01
Forward Modeling

\[ \nabla \cdot \hat{s} \nabla V = I - \nabla \cdot (\hat{s} A) \]

\( V \)  electrical potential in the earth

\( \hat{s} \)  anisotropic electrical conductivity tensor

\( A \)  magnetic vector potential of a small loop of moment 1 ampere-meter\(^2\).
Inversion

Use a 3-D finite-element mesh to approximate the electrical potentials within the region near the boreholes for either electrical or magnetic sources.

Occam’s Inversion:

Find the largest value of $\alpha$ for which minimizing the objective function

$$S(m) = (d_{\text{obs}} - g(m))^T C_D^{-1} (d_{\text{obs}} - g(m)) + \alpha \cdot (m - m_{\text{prior}})^T R (m - m_{\text{prior}})$$

such that $(d_{\text{obs}} - g(m))^T C_D^{-1} (d_{\text{obs}} - g(m)) = \chi^2$

Where $\alpha$ is the “roughness factor”
m is the estimate of the model parameters (log resistivity of a voxel),
$R$ is a matrix containing numerical difference operators,
$C_D$ the data covariance matrix,
$d_{\text{obs}}$ is a vector of data values,
g(m) is the forward solution (estimated voltage)
for a given model, m
$\chi^2$ is equal to the number of data points.
Cold Rolled Steel Plate ERT

Electrodes

4 m

NE

NW

SE

Tx & Control

Ohm-meters
Cold Rolled Steel Plate ERT & MMR
Summary

• Operational prototype system
  • integrated ERT/ three axis, synchronously detected, magnetic field measurement system
  • data pre-processing package
  • ERT/MMR inversion software

• Demonstrated to work in field
Future Work

• Continue field tests
  – Different target geometries
  – Infiltration tests

• Development of a multi channel MMR system
Acknowledgement

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