Idaho National Engineering and Environmental Laboratory

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

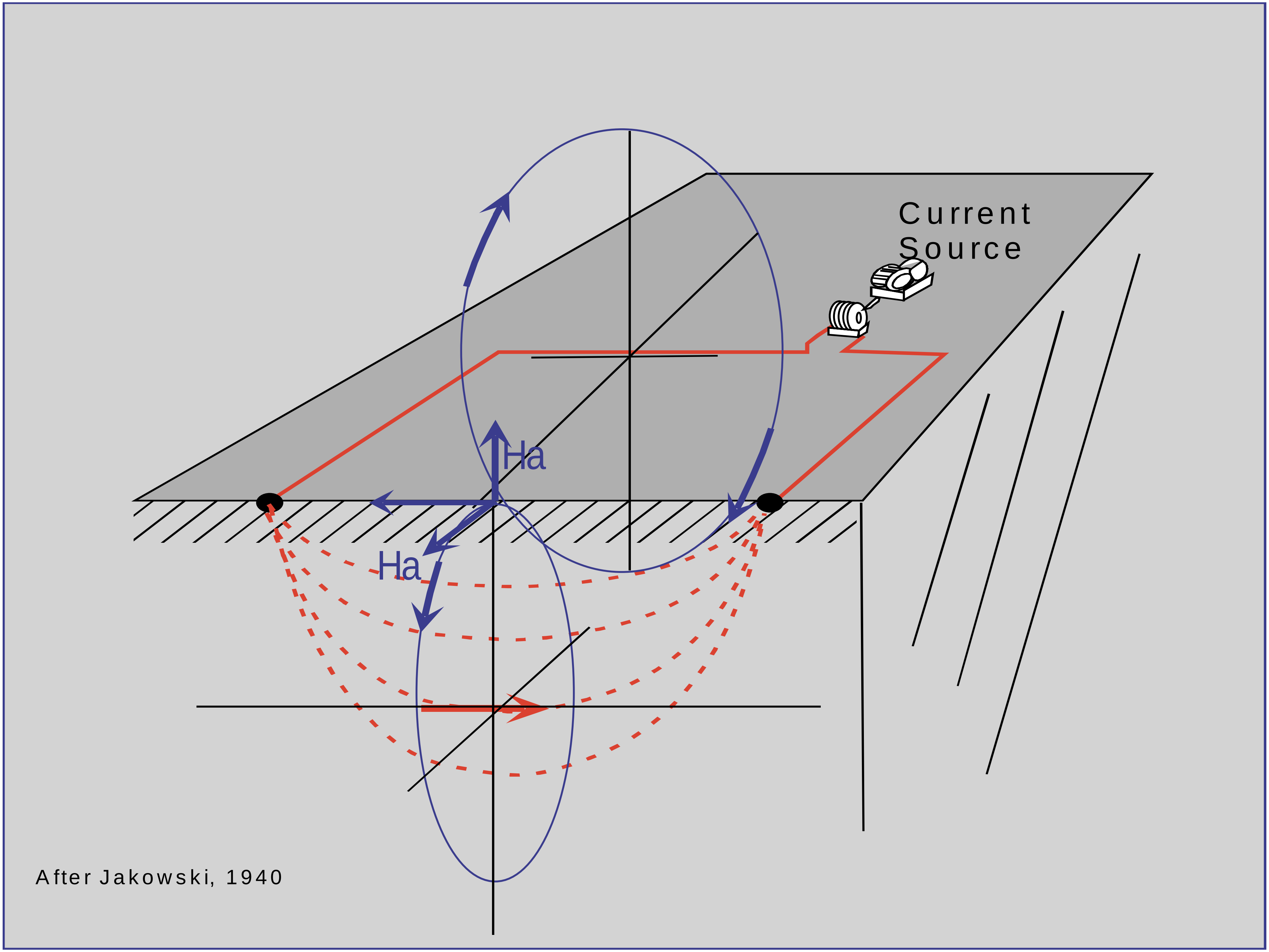
- *Uses existing wells at typical remediation sites*
- *Increases lateral resolution with a reduction in both cost and invasion of the subsurface*
- *Allows collection of MMR data sets without additional boreholes*
- *Provides integrated data sets*

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*


Current
Source
Ha
Ha
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)

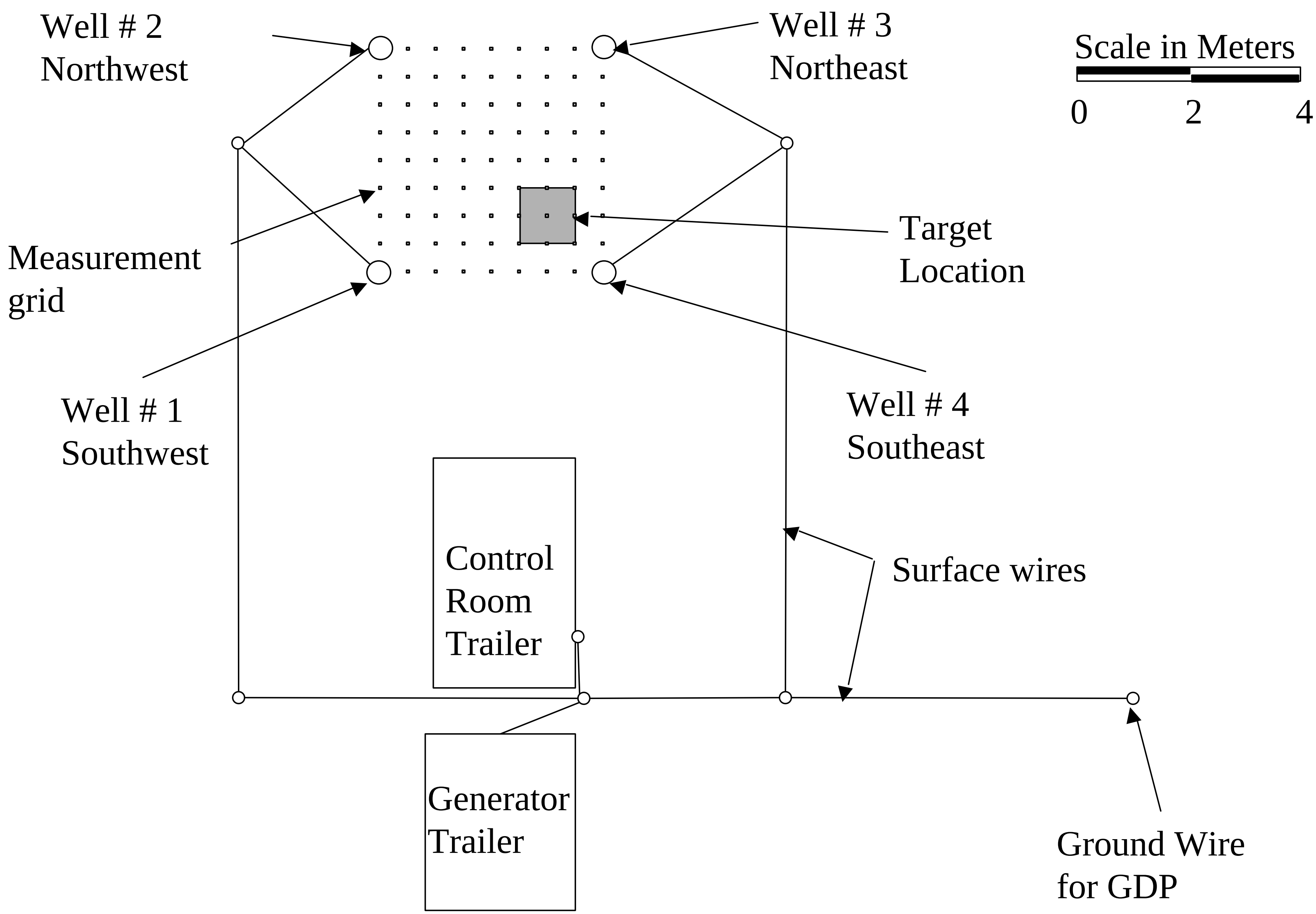
- *Develop instrumentation*
- *Design controlled field test site, collect and invert data*
- *Field area (Mud Lake, Idaho) consists of interbedded clay, silt, and sand lake deposits*

Instrumentation

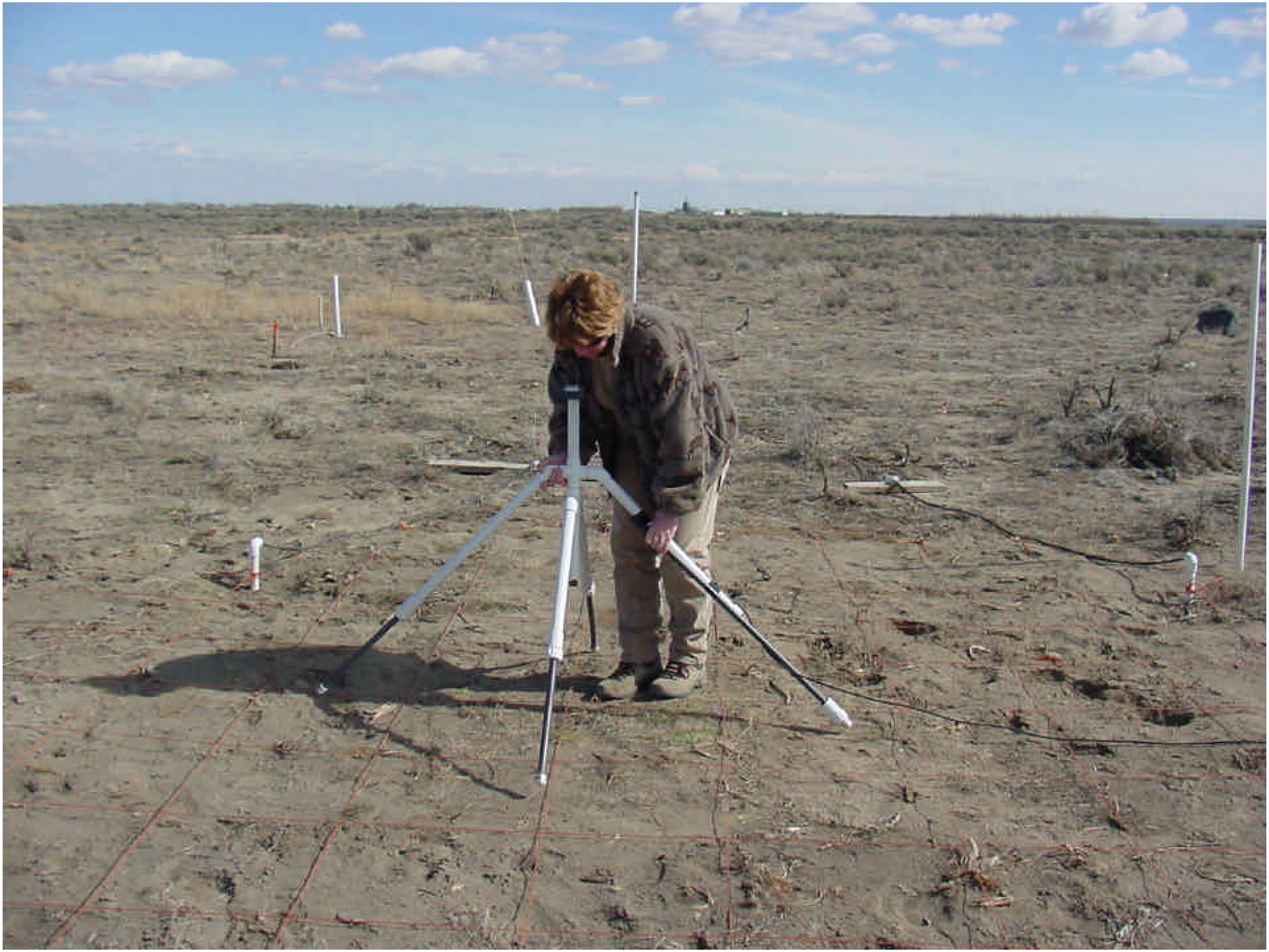
- ***Power source:*** *130 volts transmitted by a Zonge GDP32^{II} ERT system*
- ***Measurement:*** *3-axis Bartington flux-gate magnetometer, and standard subsurface copper electrodes*
- ***Signal detection:*** *GDP32^{II}*

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*



Well # 2
Northwest
Well # 3
Northeast
Scale in Meters
0
2
4
Measurement grid
Target Location
Well # 1
Southwest
Well # 4
Southeast
Control Room Trailer
Surface wires
Generator Trailer
Ground Wire for GDP

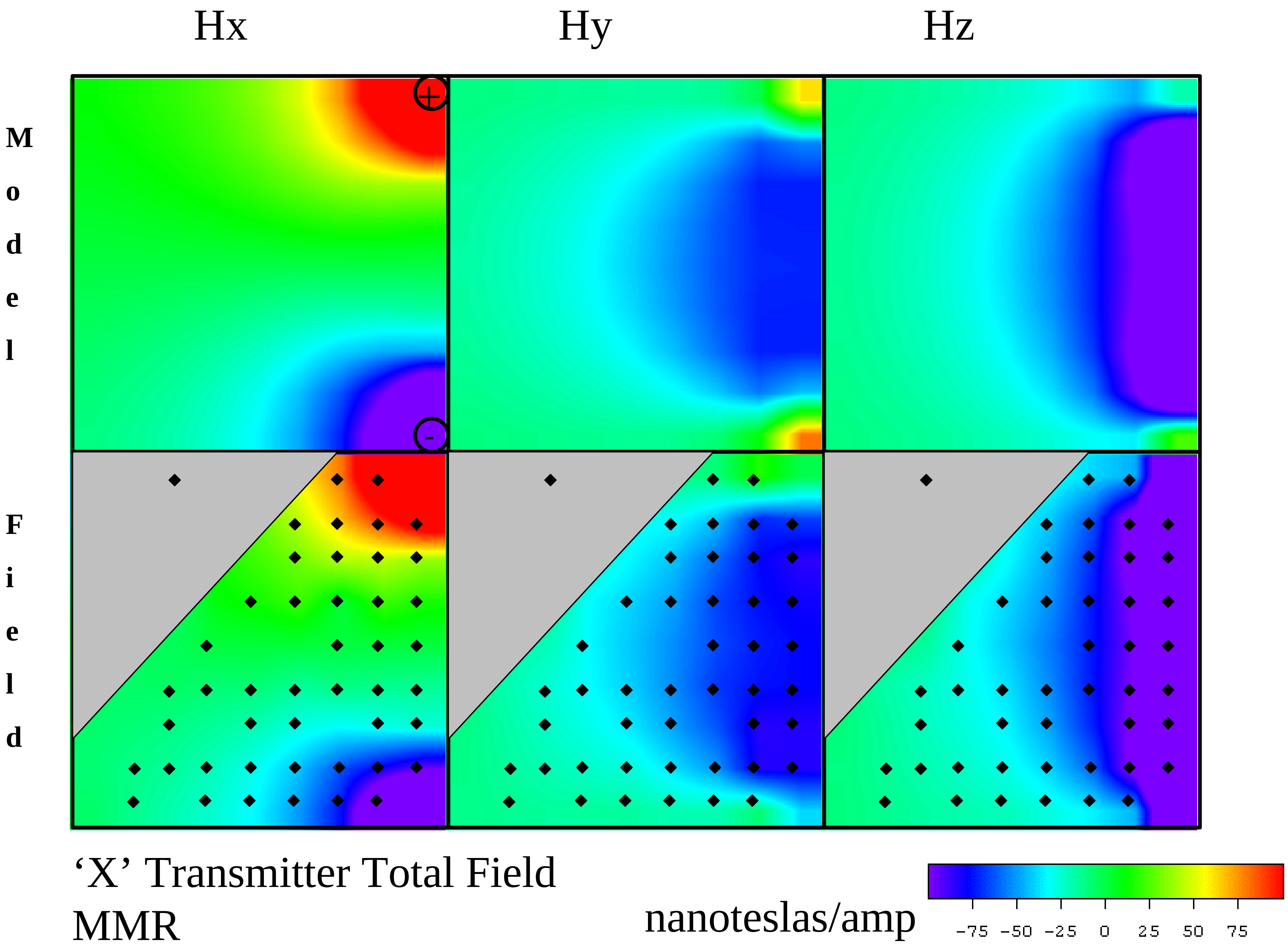


Field tests

- *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*

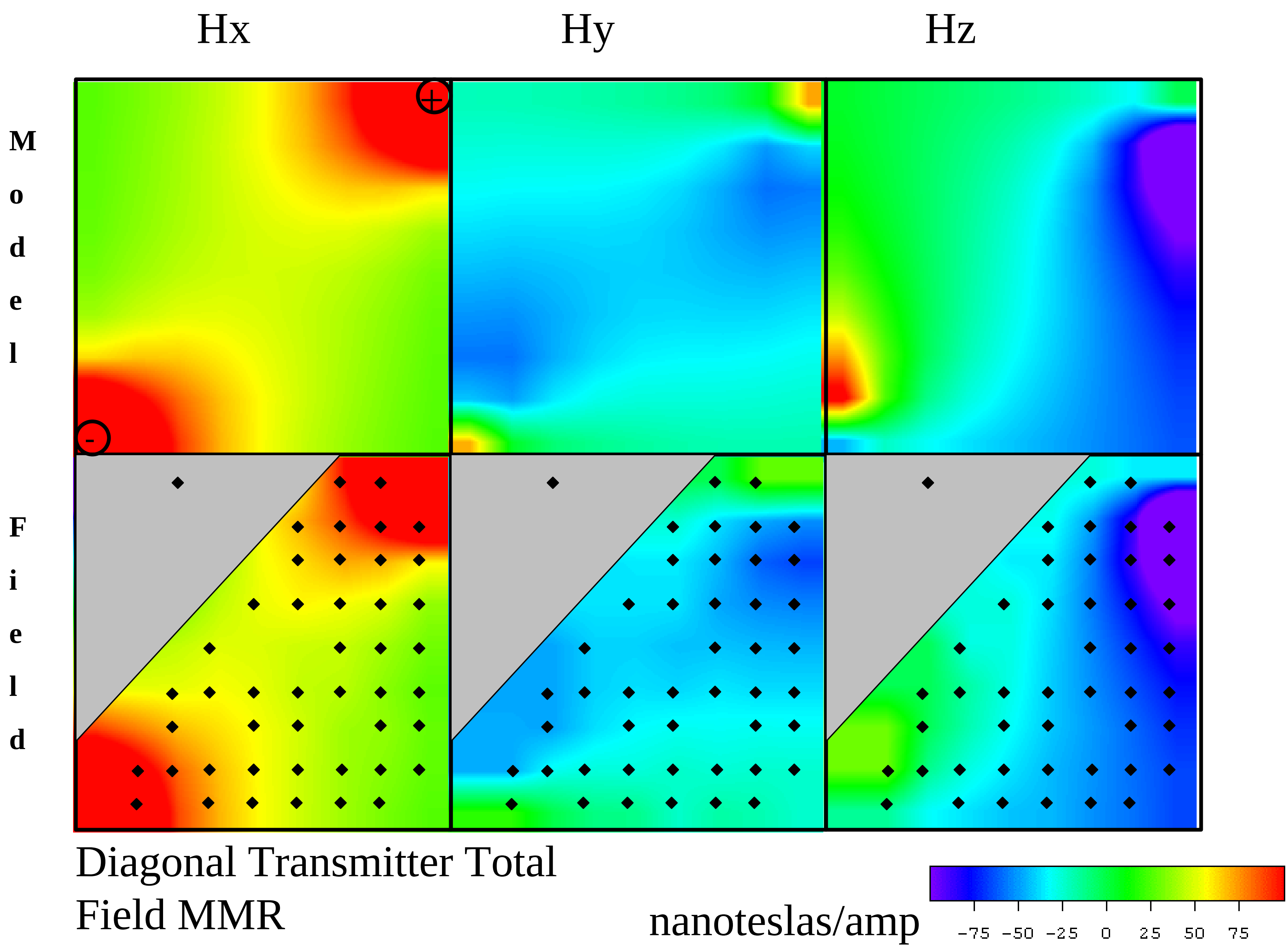
Background Data - Comparisons of Field and Model Data

- *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*

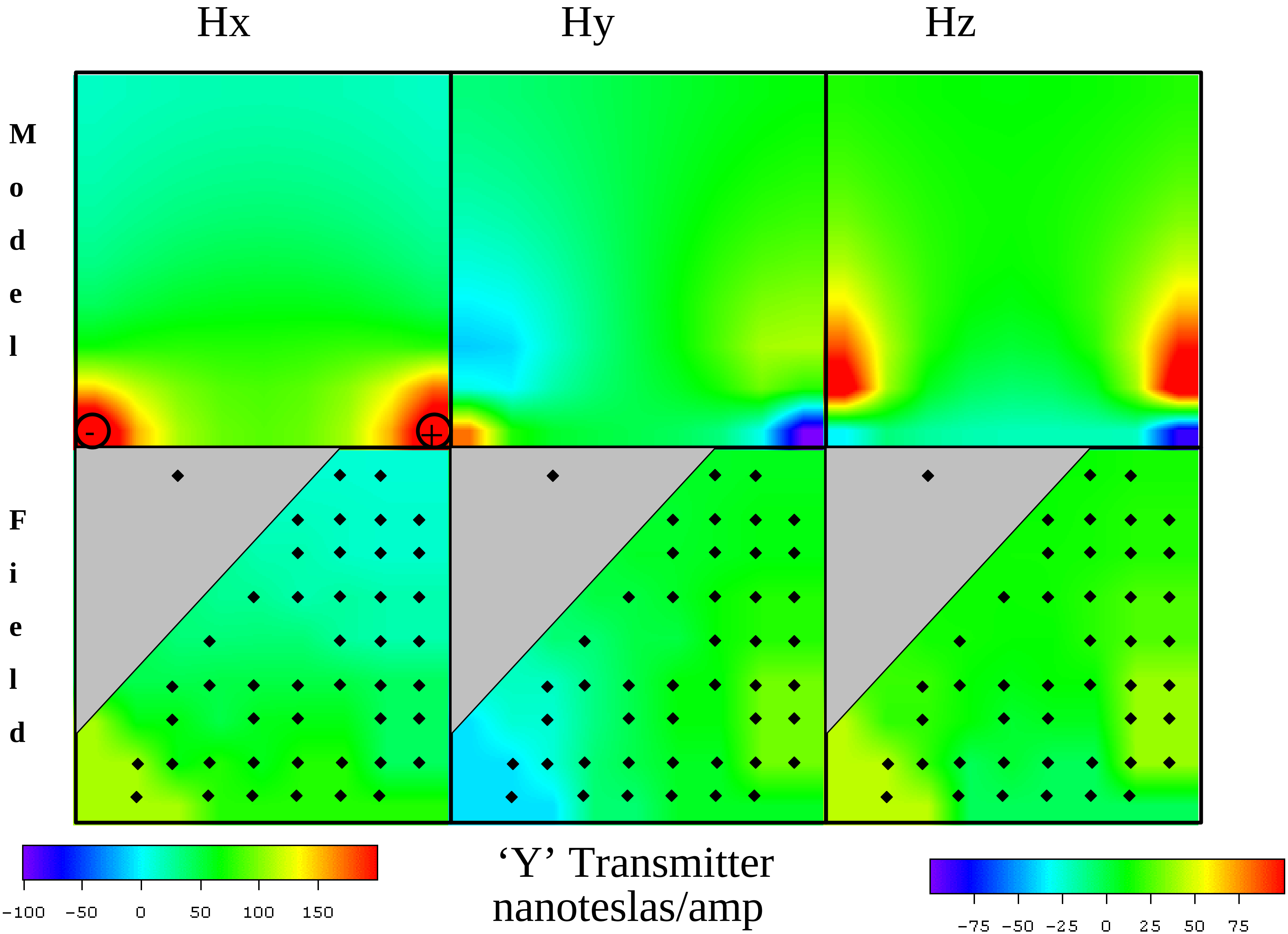


‘X’ Transmitter Total Field
MMR

nanoteslas/amp



Diagonal Transmitter Total
Field MMR



'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

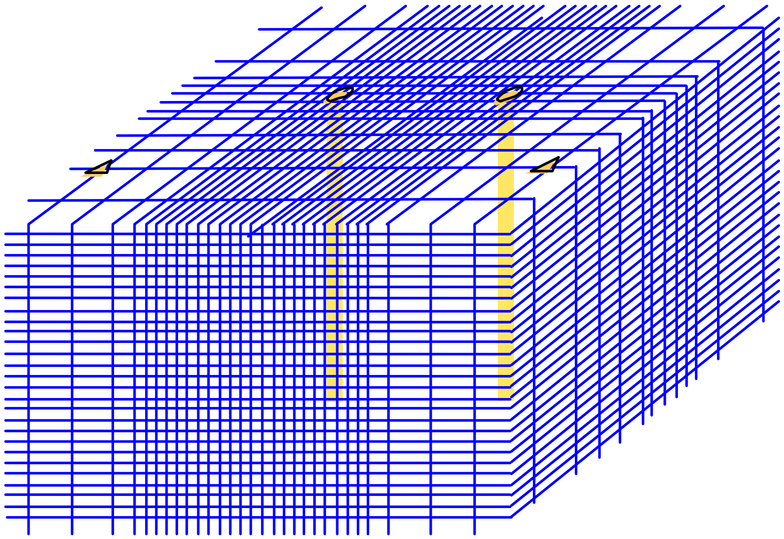
$$\nabla \bullet \hat{\mathbf{s}}\ \nabla V = I - \nabla \bullet \left(\hat{\mathbf{s}}\ \mathbf{A}\right)$$

V electrical potential in the earth

$\hat{\mathbf{s}}$ 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.

<u>Occam's Inversion :</u>

<u>Find the largest value of α for which minizing the objective function</u>

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

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

Where α **is the "roughness factor"**

m is the estimate of the model parameters (log resistivity of a voxel),

$\mathbf{R}$ **is a matrix containing numerical difference operators,**

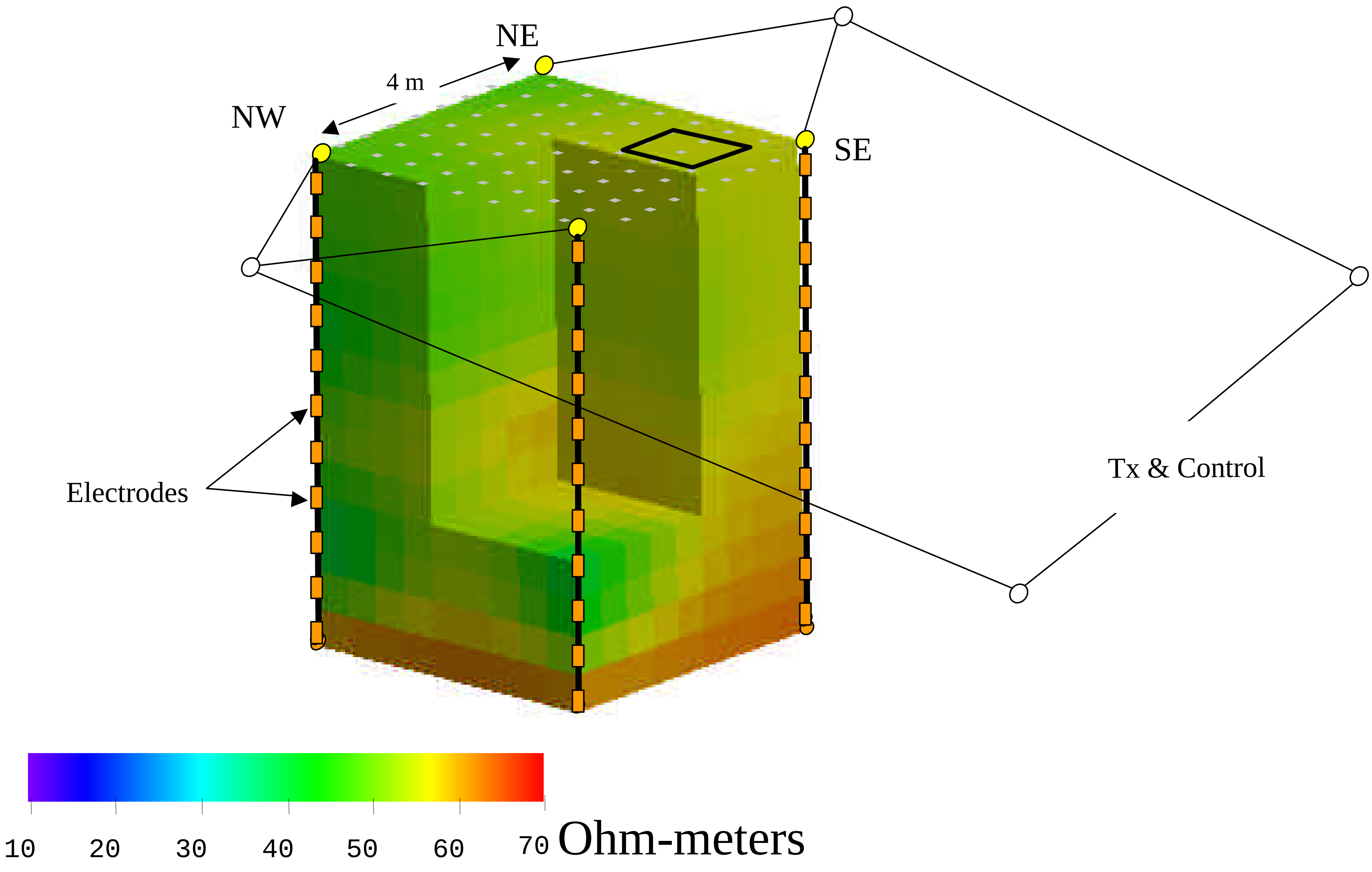
C_D **the data covariance matrix,**

d_{obs} **is a vector of data values,**

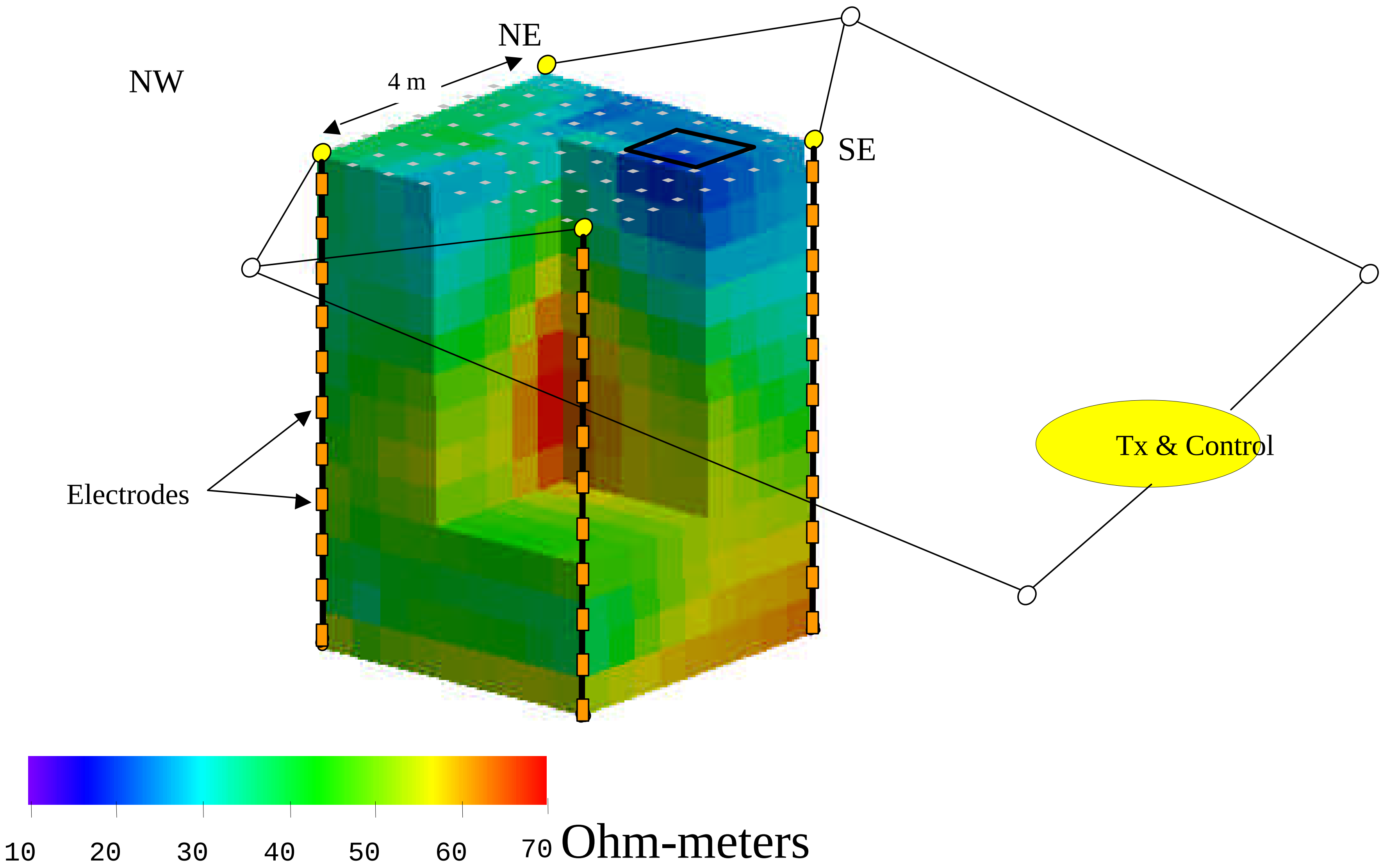
g(m) is the forward solution (estimated voltage) for a given model, m

χ^2 **is equal to the number of data points.**

Cold Rolled Steel Plate ERT



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*

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