High Frequency Electromagnetic Impedance Imaging for Vadose Zone Characterization

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Outline

- EMSP research objectives & tasks
- Electromagnetic Geophysical Methods
  - EM geophysical spectrum
  - The EM impedance technique
- Formulation of 3D inverse solution
- Hanford clastic dike survey
- 3D imaging results
- Future work
- Conclusions

EMSP Project Synopsis

- Study inductive EM systems for vadose zone site characterization
- Applications require rigorous 3D/2D forward and inverse modeling
- Inverse modeling uses measurements to produce an image of the subsurface electrical properties (conductivity)
- Variations in conductivity relate directly to subsurface saturation changes

EMSP Research Objectives

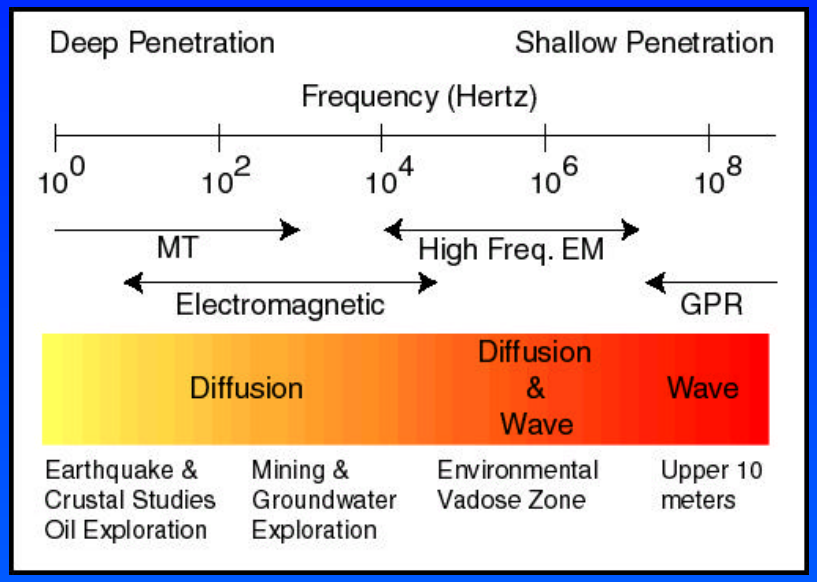
- Develop interpretation software to image the subsurface based on 2D/3D EM inversion methodology.
- Deploy a high frequency impedance system for field surveys at the Hanford Reservation.
- Interpret the resulting data sets for mapping transport pathways and contaminants within the vadose zone.

Project Tasks

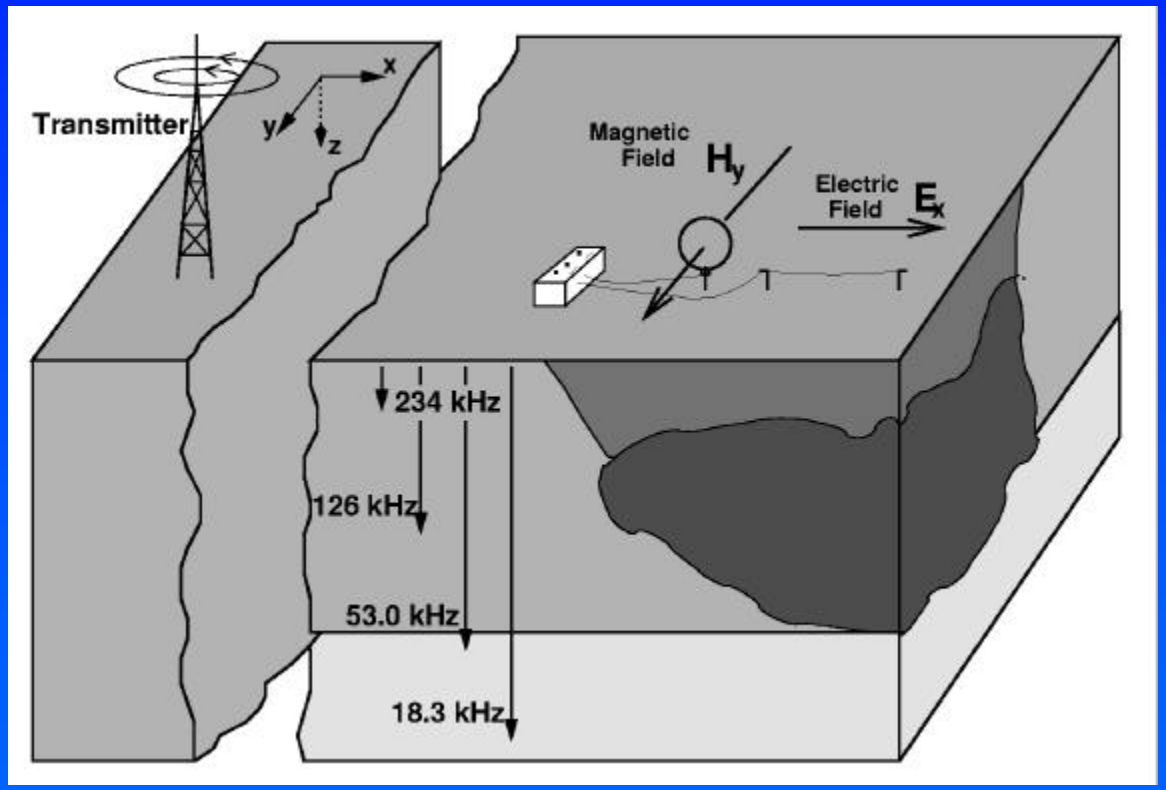
Task	**Completion**
Year 1	12 Months
Task 1.1 Field profile with *IMAGEM* system (10 Hz to 100 kHz) in California	
Task 1.2 System calibration and characterization	
Task 1.3 Acquire data at the Hanford Reservation with the *IMAGEM* system including processing of the data (clastic dike site)	
Year 2	12 Months
Task 2.1 Develop 3D inversion code to image data acquired with *IMAGEM* system	
Task 2.2 Analyze data acquired in year 1 using 3D inversion/imaging software	
Year 3	12 Months
Task 3.1 Acquire two new data set at Hanford for vadose zone characterization	
Task 3.2 Develop 2D inversion code for rapid imaging	
Task 3.3 Continue to improve 3D inversion code capabilities	
Task 3.4 Analyze new data sets using 2D/3D inversion codes	
Total	36 Months

Geophysical EM Spectrum

- HF Impedance systems occupy the frequency range between conventional EM systems and GPR
- Frequency Range 10 kHz to 10 MHz



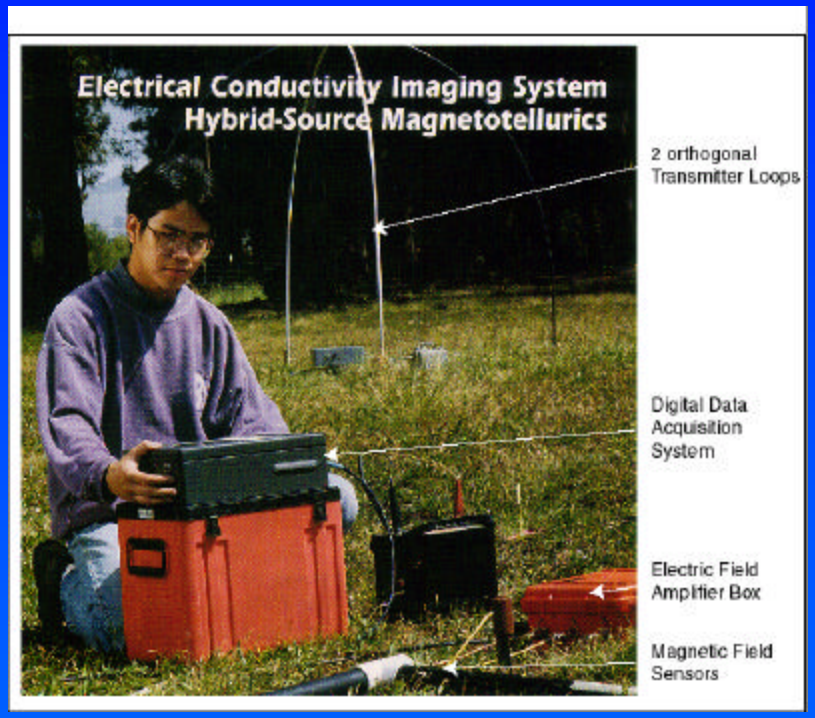
Electromagnetic Impedance Method



- Fixed Transmitter
- Impedance = E/H
  - eliminates need to monitor source waveform and current
- Depth of investigation depends on frequency
- In far field, plane wave assumption is valid
- Problem: Often one does not know when measurements are in the far field!

IMAGEM Impedance System

- Fixed Transmitter
- Roving E and H sensors
- Frequency Range (1 - 64 kHz)
- Power Consumption: 5W
- Running Time: 10Hr



Forward & Inverse Algorithms

The Forward Problem:

Solve the electric field vector equation

$$\tilde{N} \times \tilde{N} \times \mathbf{E} + (w^2 m_o s - \mathbf{i} w m_o s)\,\mathbf{E} = \mathbf{S}$$

where S depends on the source antenna

We also require the magnetic field

$$\mathbf{H} = -\tilde{N} \times \mathbf{E} / \mathbf{i} w m_o$$

Predicted Impedance $Z = \mathbf{E} / \mathbf{H}$

The Inverse Problem:

Minimize the cost functional j :

$$\varphi = \Sigma \{(Z_j^{obs} - Z_j^{p})/\varepsilon_j\}^2 + \lambda\, \mathbf{m}\, \mathbf{W}^T \mathbf{W}\, \mathbf{m}.$$

where

$\mathbf{Z}^{obs}$ and $\mathbf{Z}^{p}$: observed and predicted impedances

e = data weights (error estimates)

m = conductivity/dielectric model parameters.

W = $\tilde{N}^2$ operator; constructs a smooth model

λ = parameter to tradeoff between data misfit and model smoothness

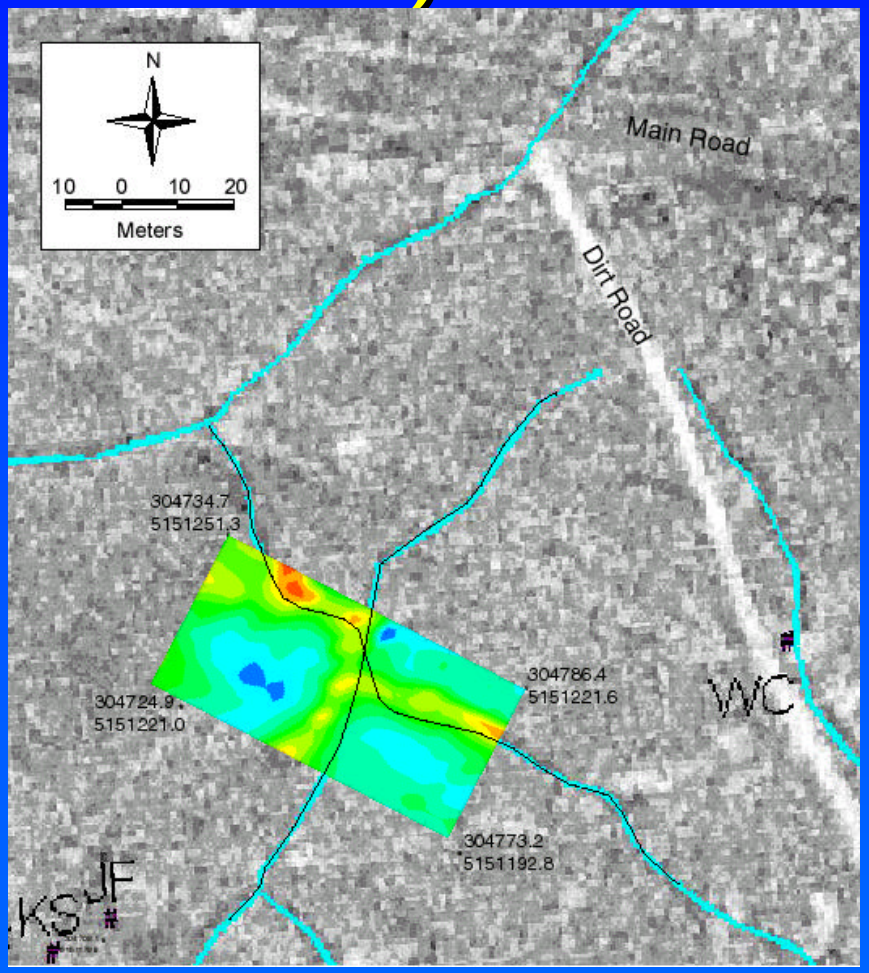
Three Dimensional Inversion

- Inversion scheme accounts for near, mid and far field effects: it incorporates the source antennas
- Solution of non-linear least square problem
  - Requires multiple solutions of the 3D Maxwell equations
  - A gradient type search is used in the minimization
  - Scheme requires an initial guess to launch inversion process and an estimate of the noise characteristics of the data
- Scheme is implemented on massively parallel computing platforms (Ascii-Red)

IMAGEM Survey Map (clastic dike site)

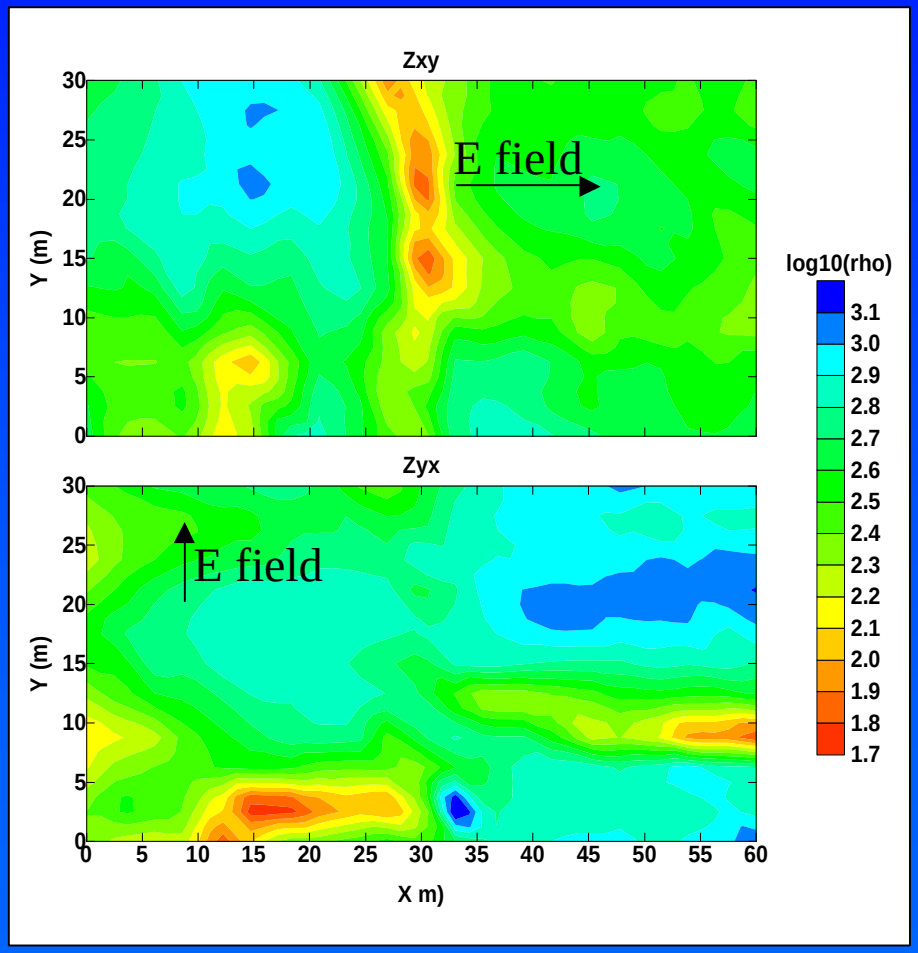
- 60 x 30m
- site spacing 3m
- 1.1 kHz - 66.2 kHz
- Survey time 3 days

- Subsurface structure indicated by resistivity differs from surface mapping



Dike Structure Apparent in Data

- $Z_{xy} = E_x/H_y$ shows ρ contrasts in X direction
- $Z_{yx} = E_y/H_x$ shows ρ contrasts in Y direction
- Dikes show up as low resistivity (red)

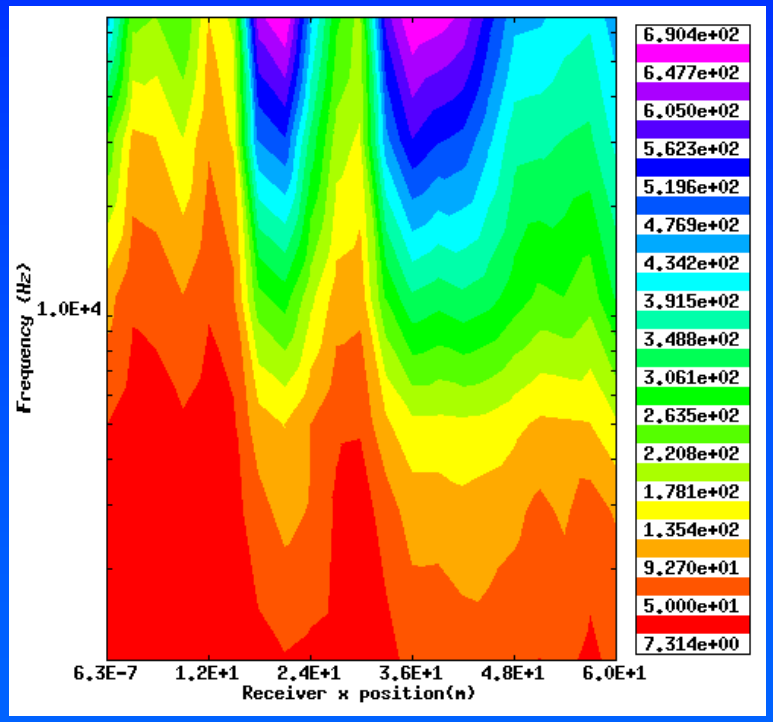


3D Zxy Data Fits

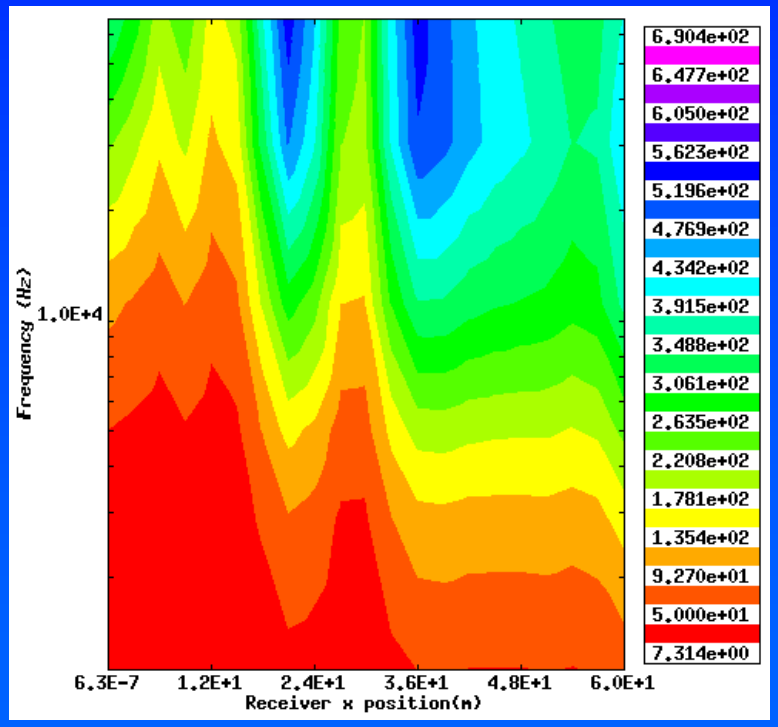
(Apparent Resistivity)

y=0m profile

Observed



Predicted



3D Zxy Data Fits

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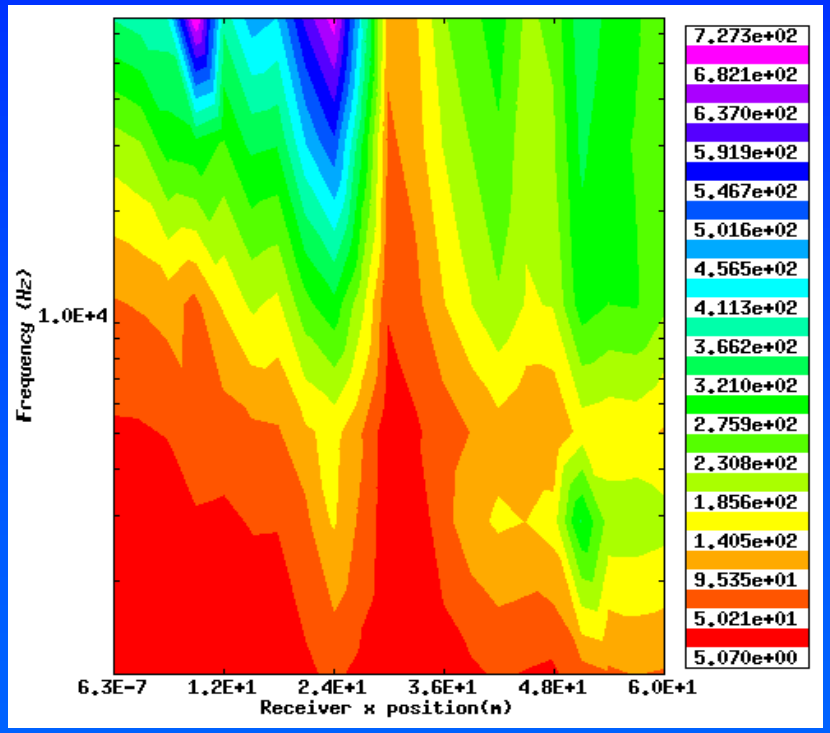
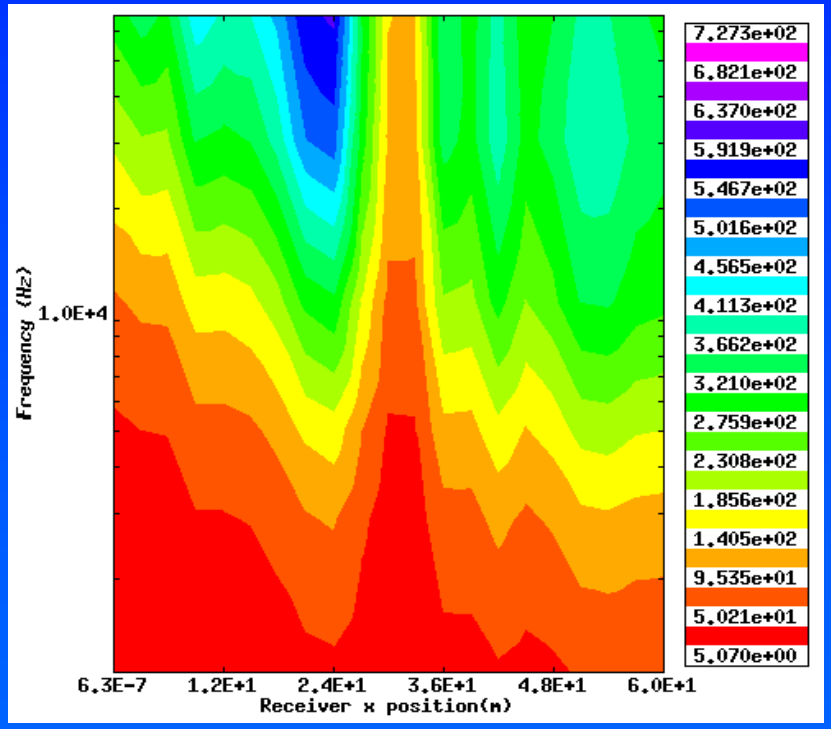


Predicted

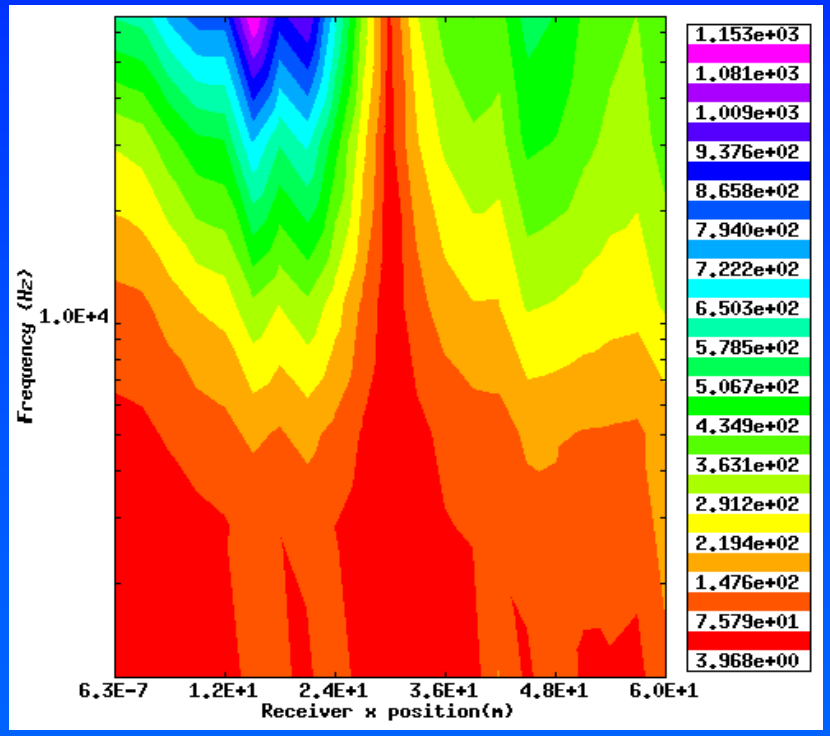


3D Zxy Data Fits

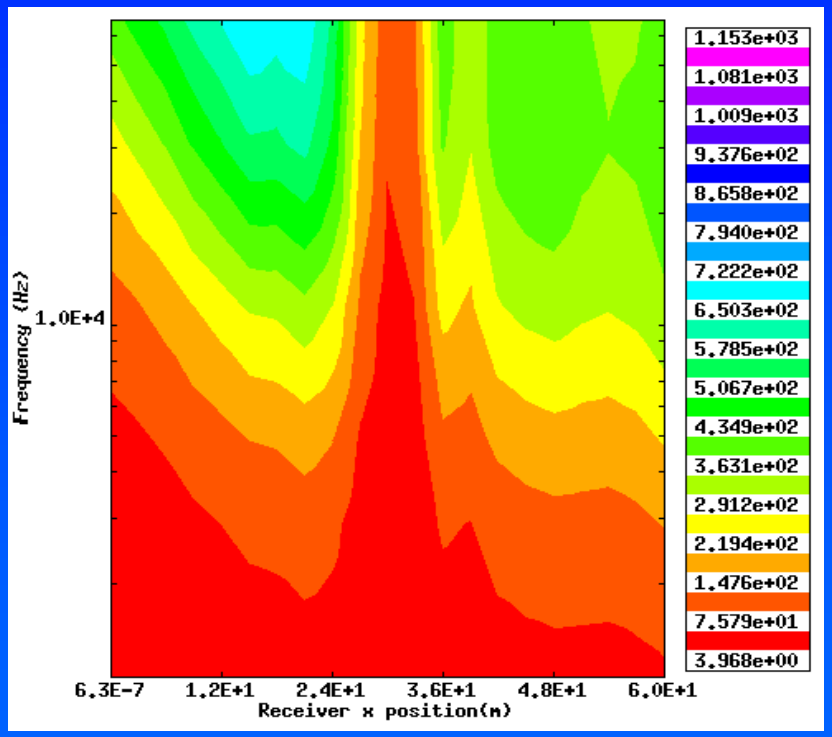
(Apparent Resistivity)

y=21m profile

Observed



Predicted

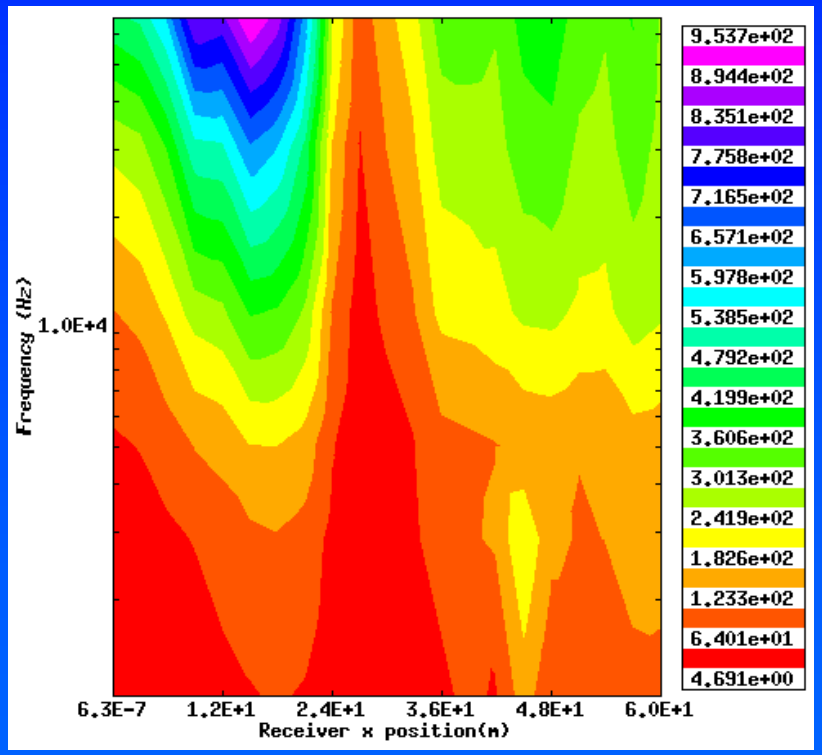


3D Zxy Data Fits

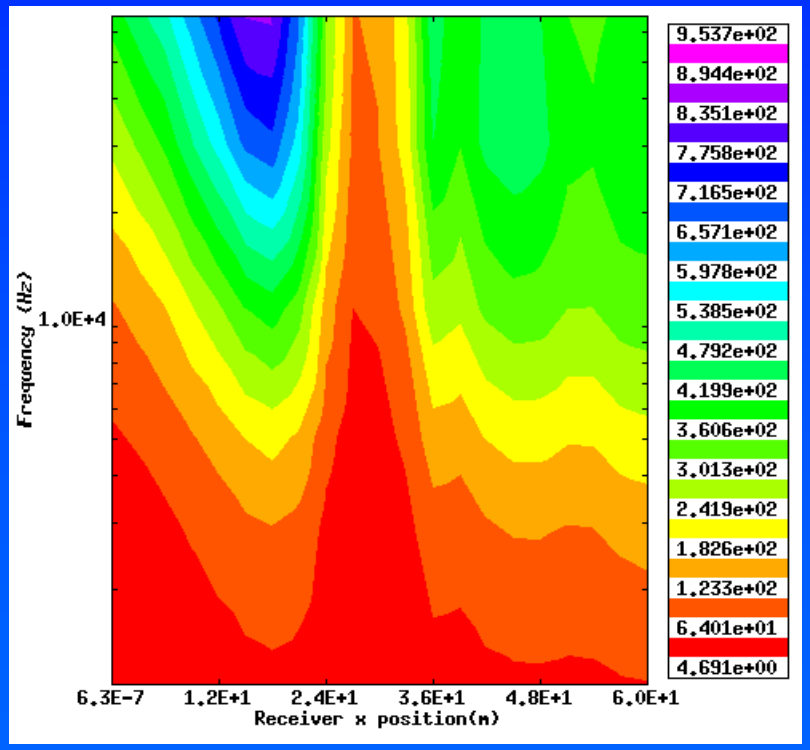
(Apparent Resistivity)

y=30m profile

Observed



Predicted



3D Zyx Data Fits

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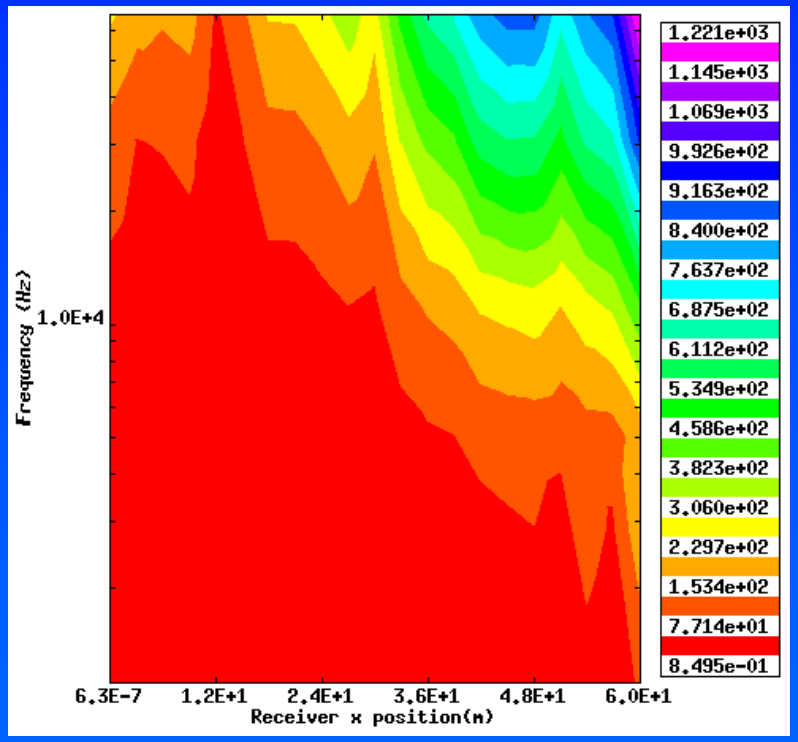
y=0m profile

Observed



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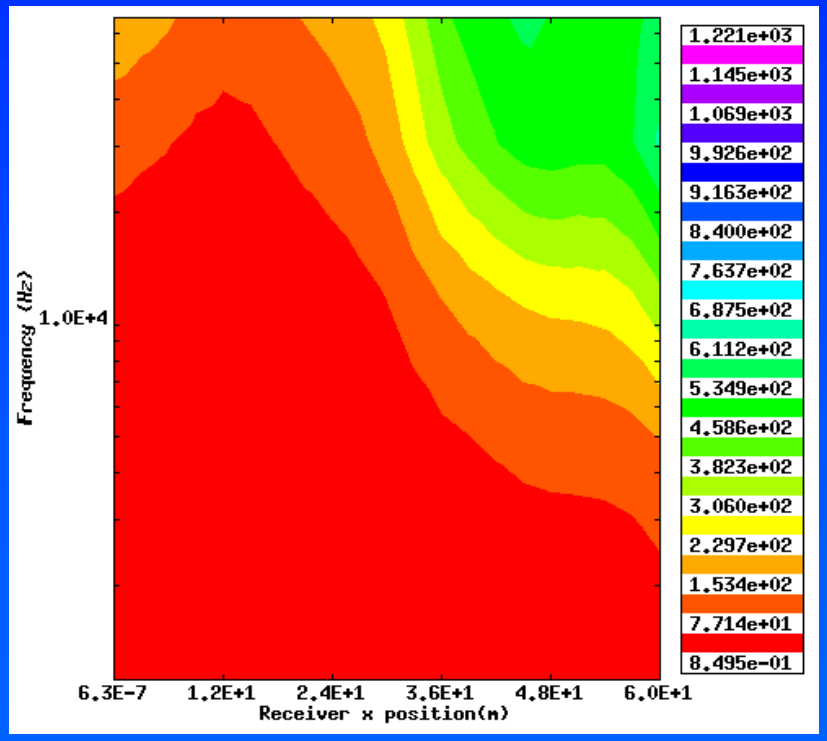

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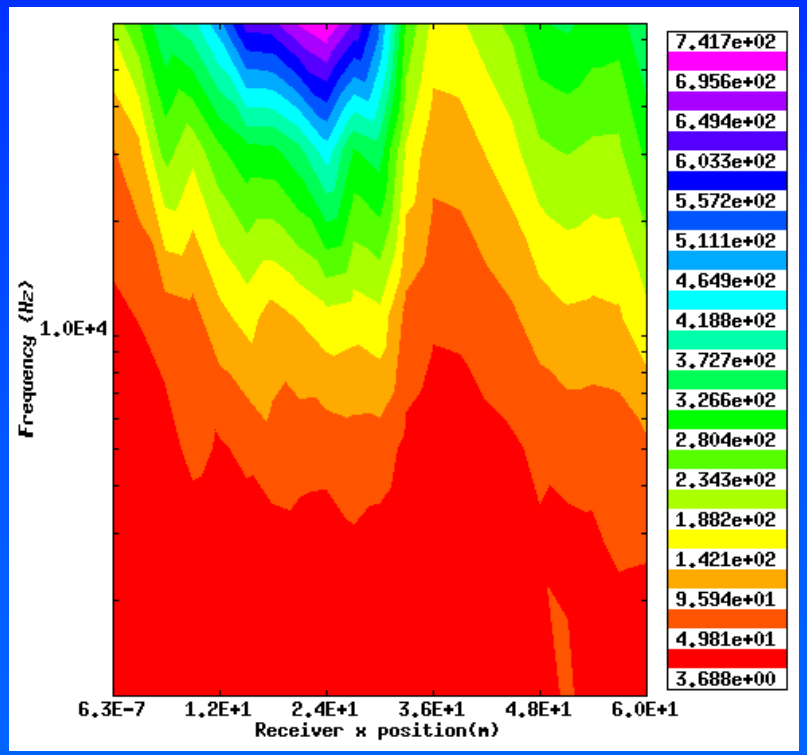
y=12m profile

Observed



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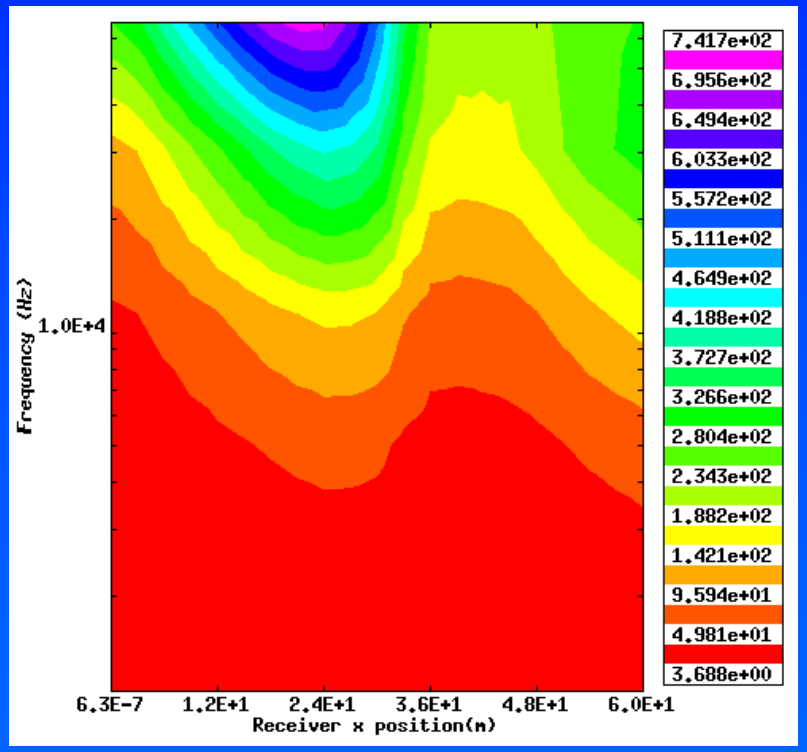

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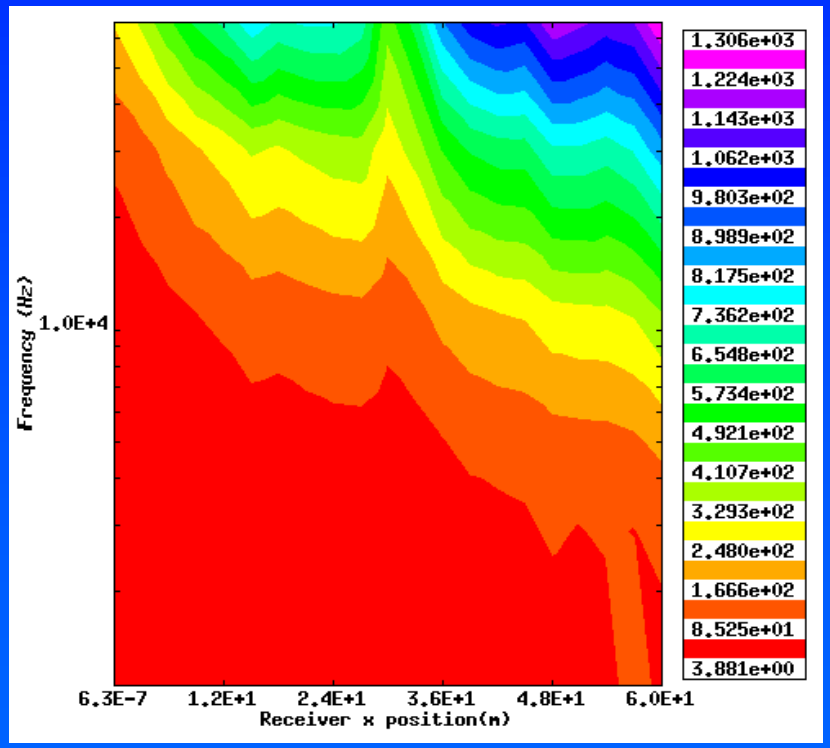

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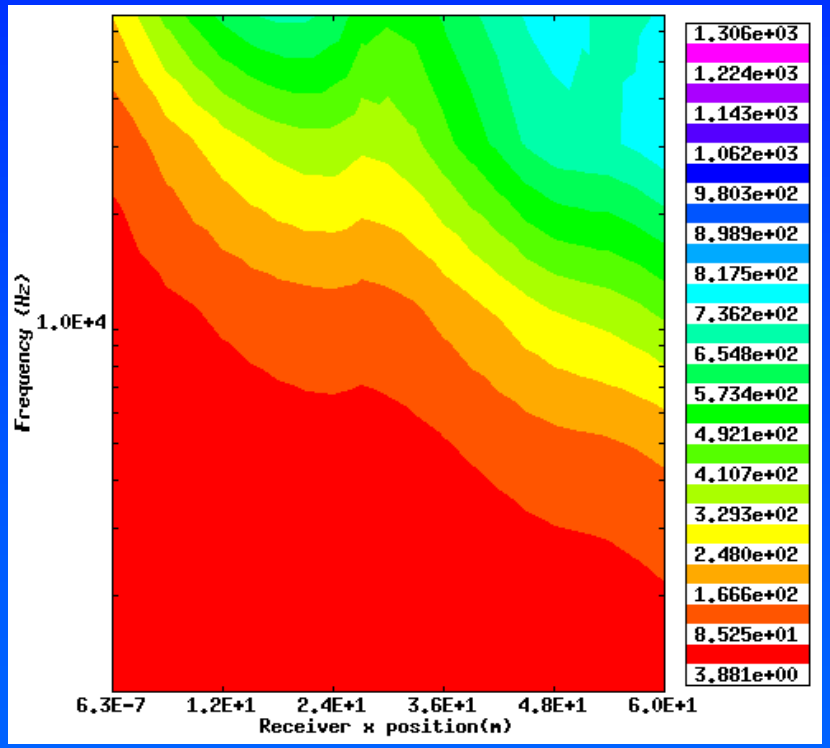

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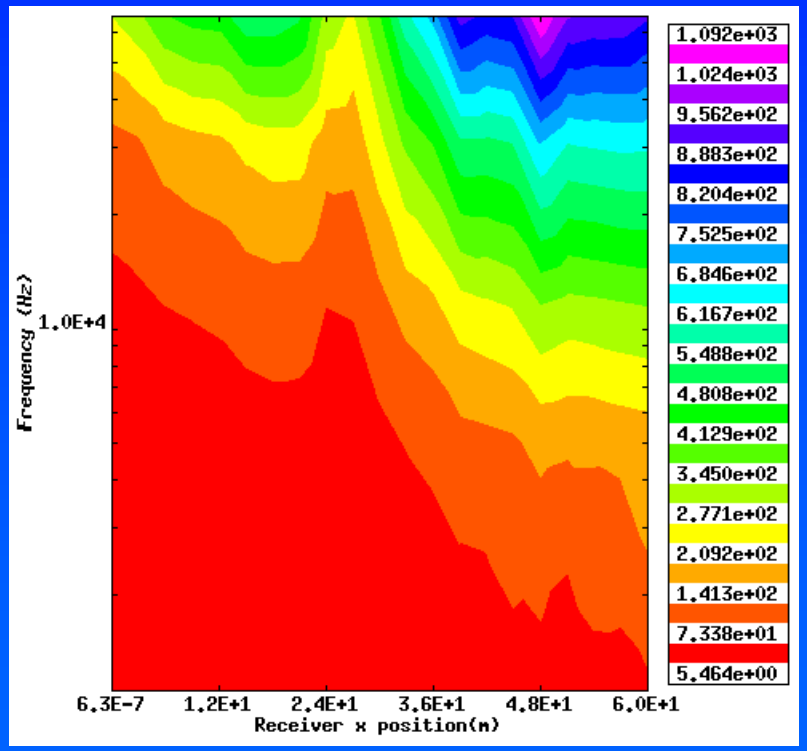

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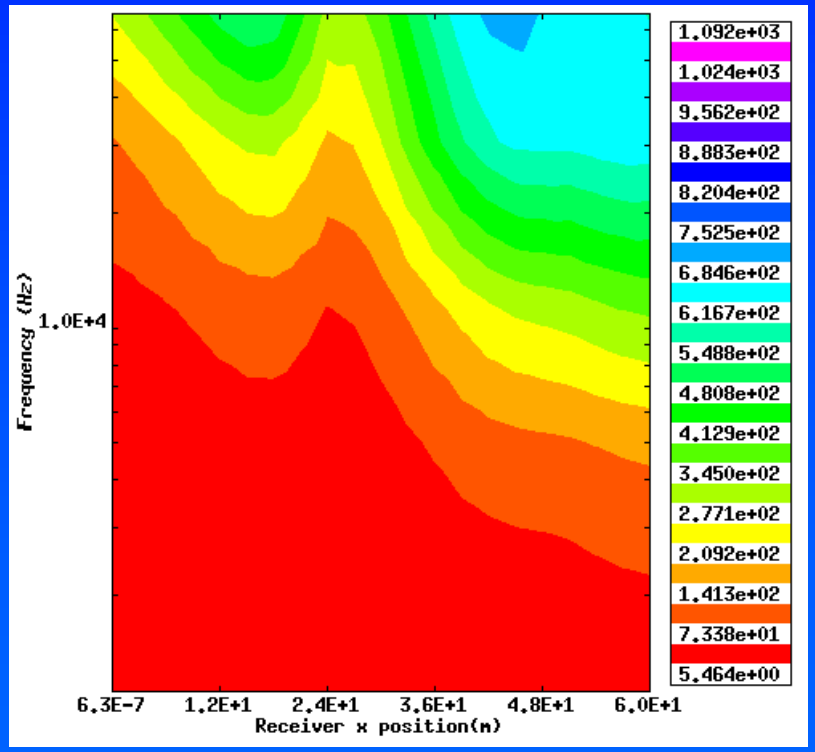

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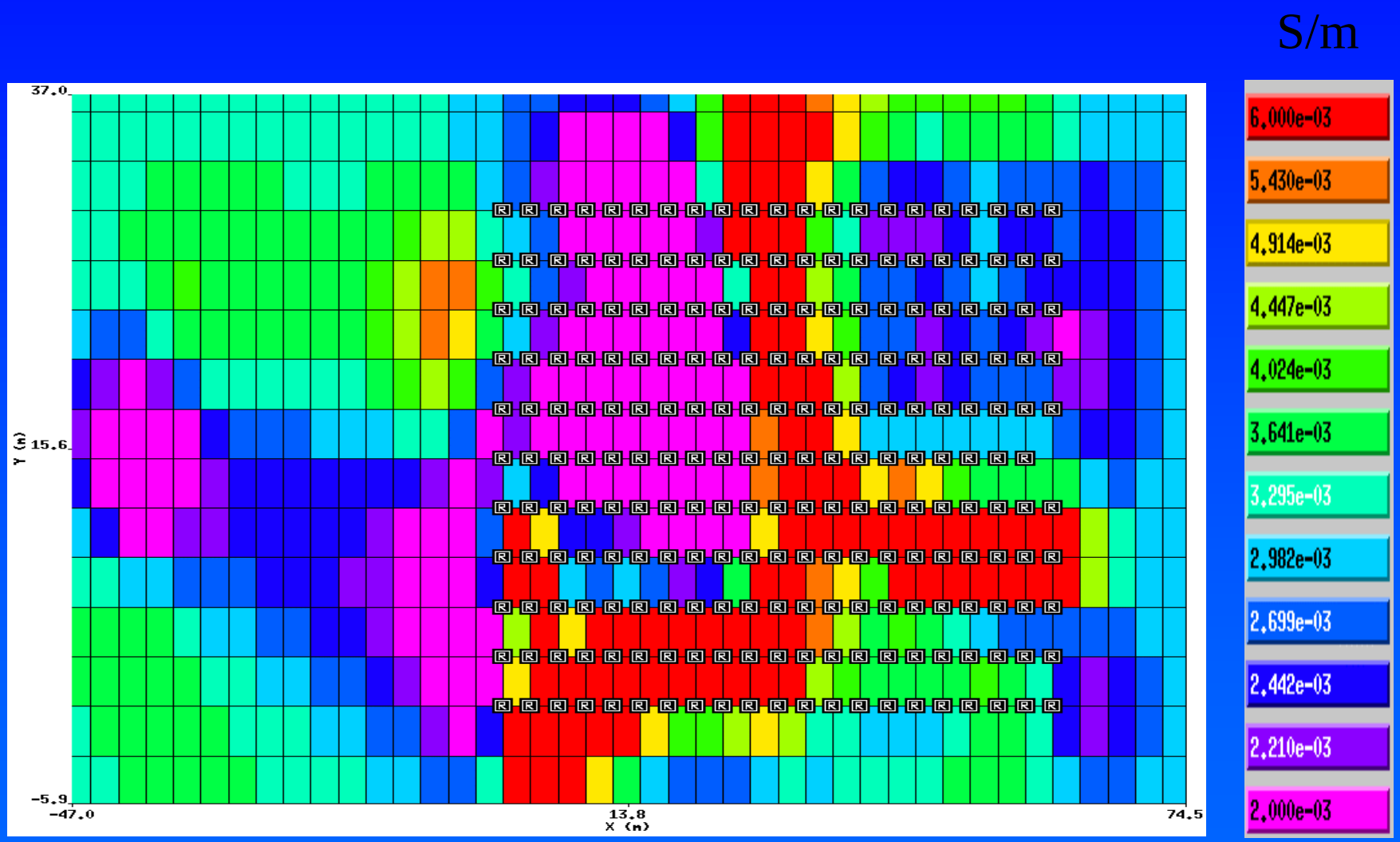
3D Conductivity Depth Maps

Z=1.5 m



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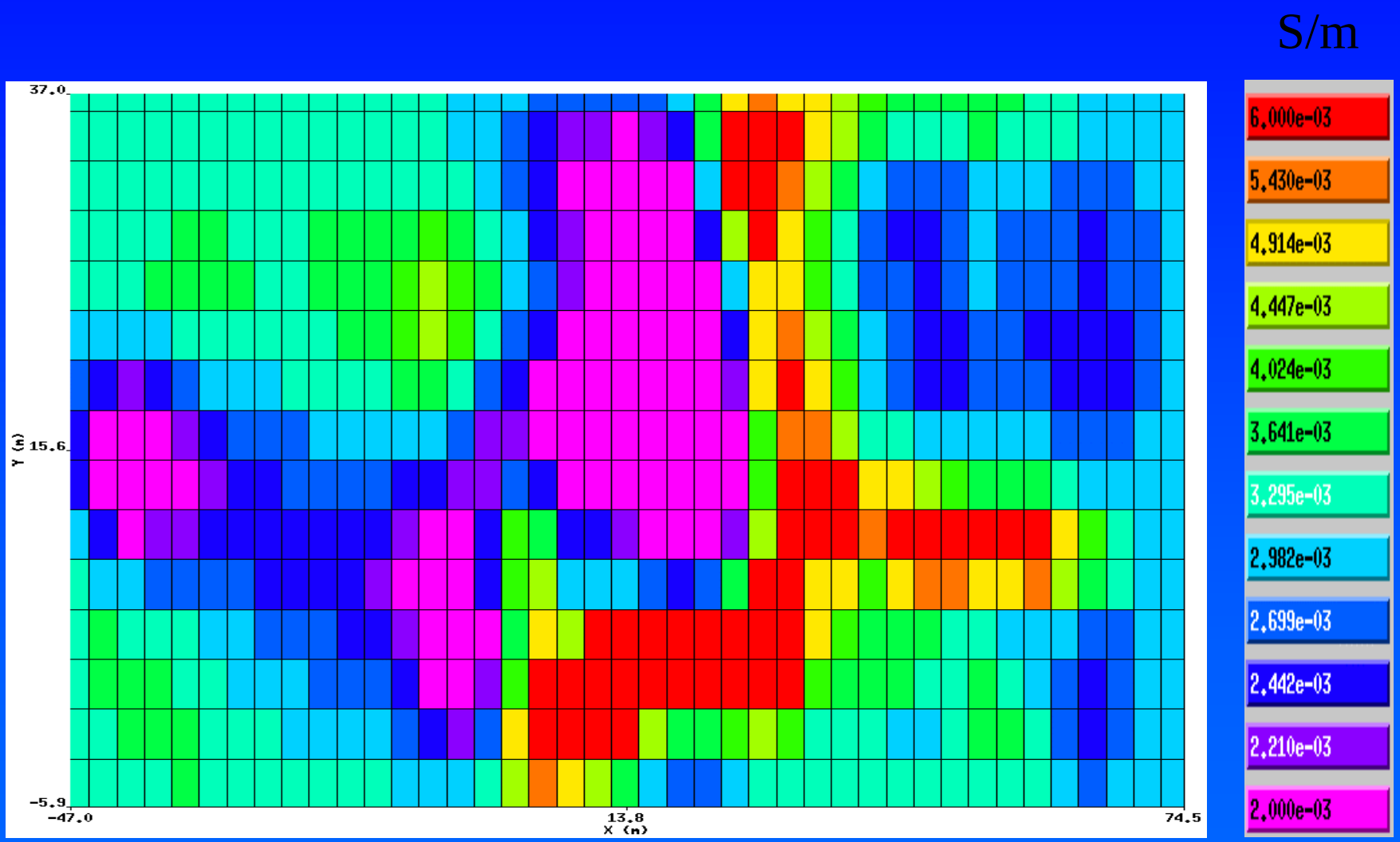
3D Conductivity Depth Maps

Z=4.5 m



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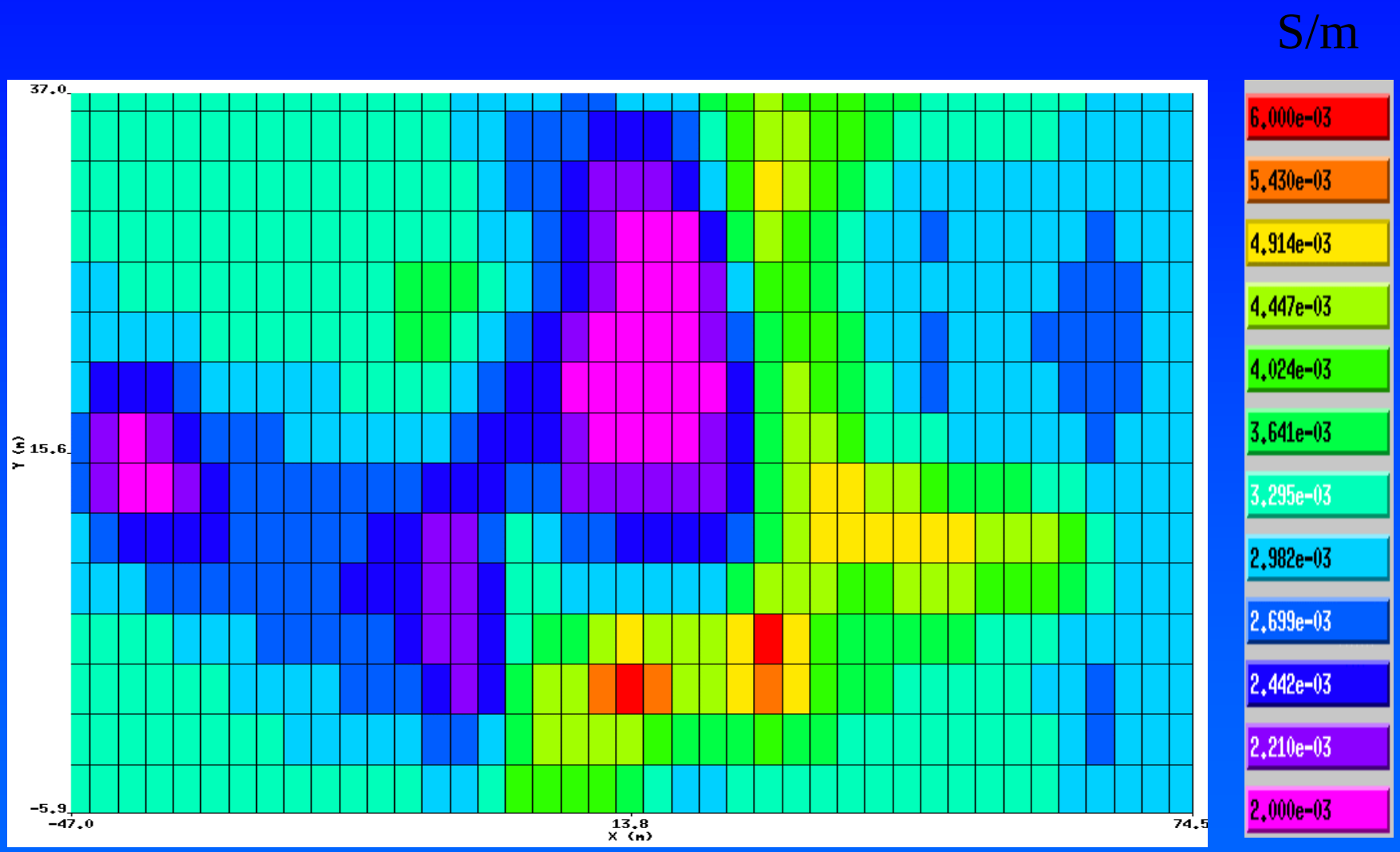
3D Conductivity Depth Maps

Z=7.5 m



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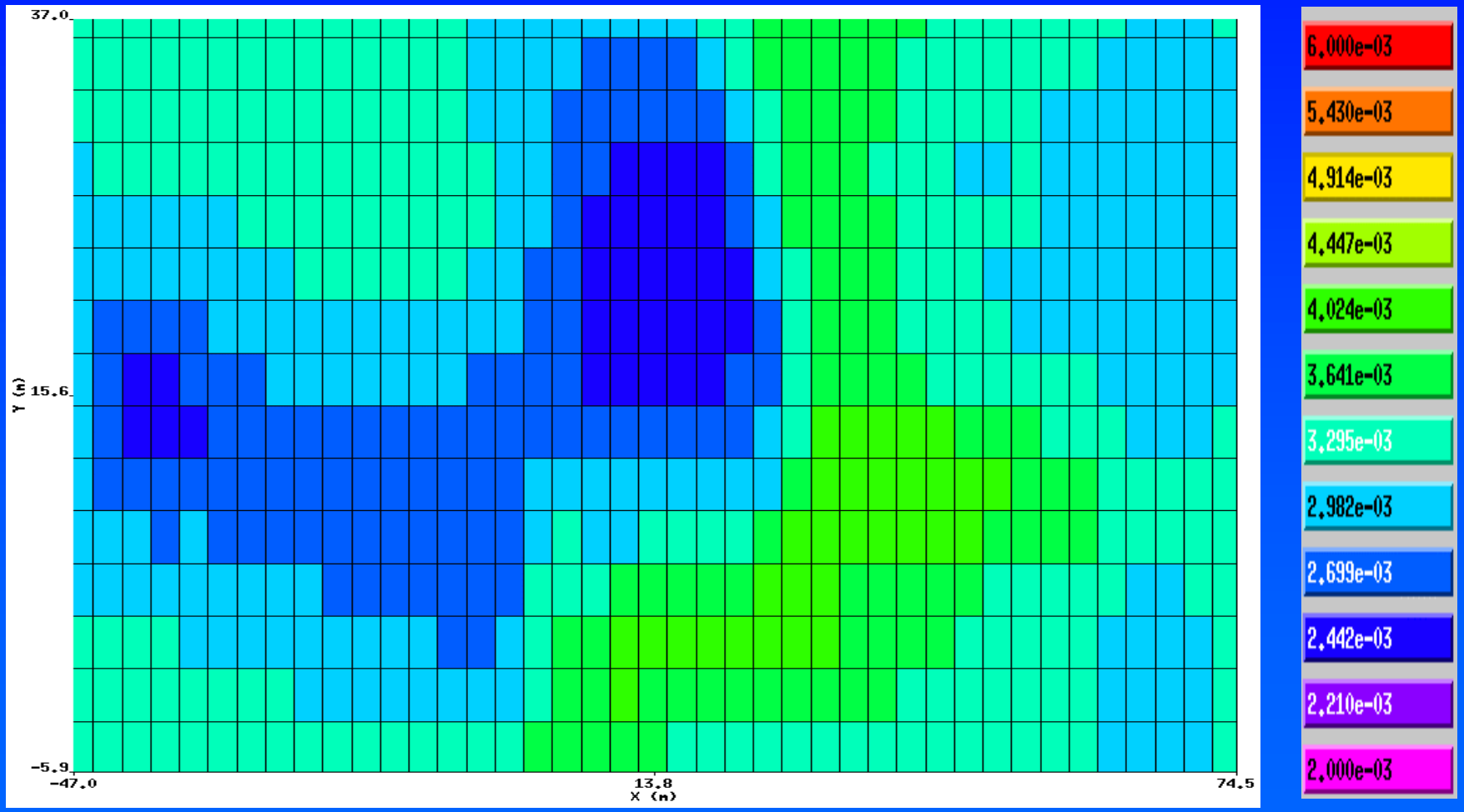
3D Conductivity Depth Maps

Z=10.5 m

S/m



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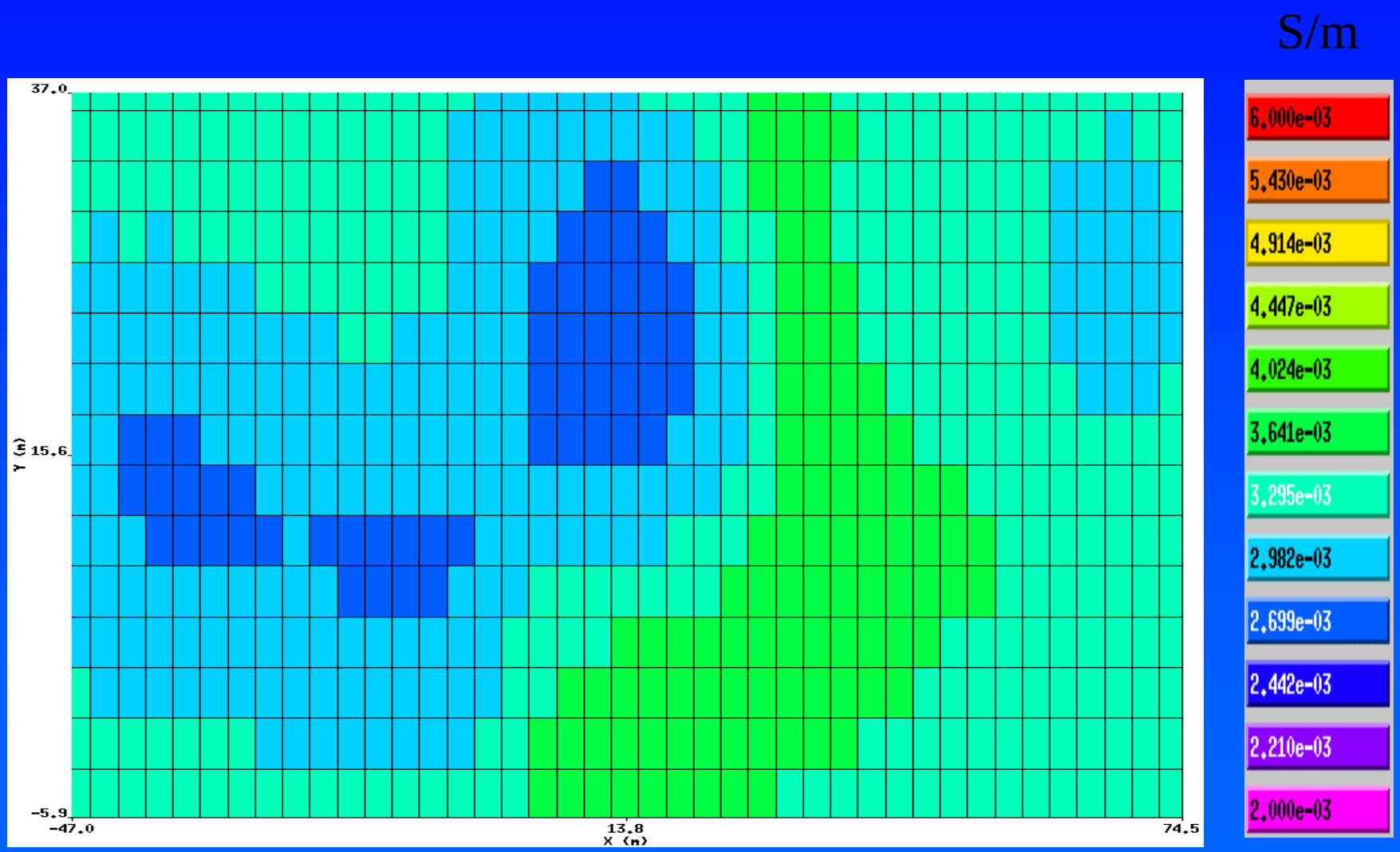
3D Conductivity Depth Maps

Z=13.5 m



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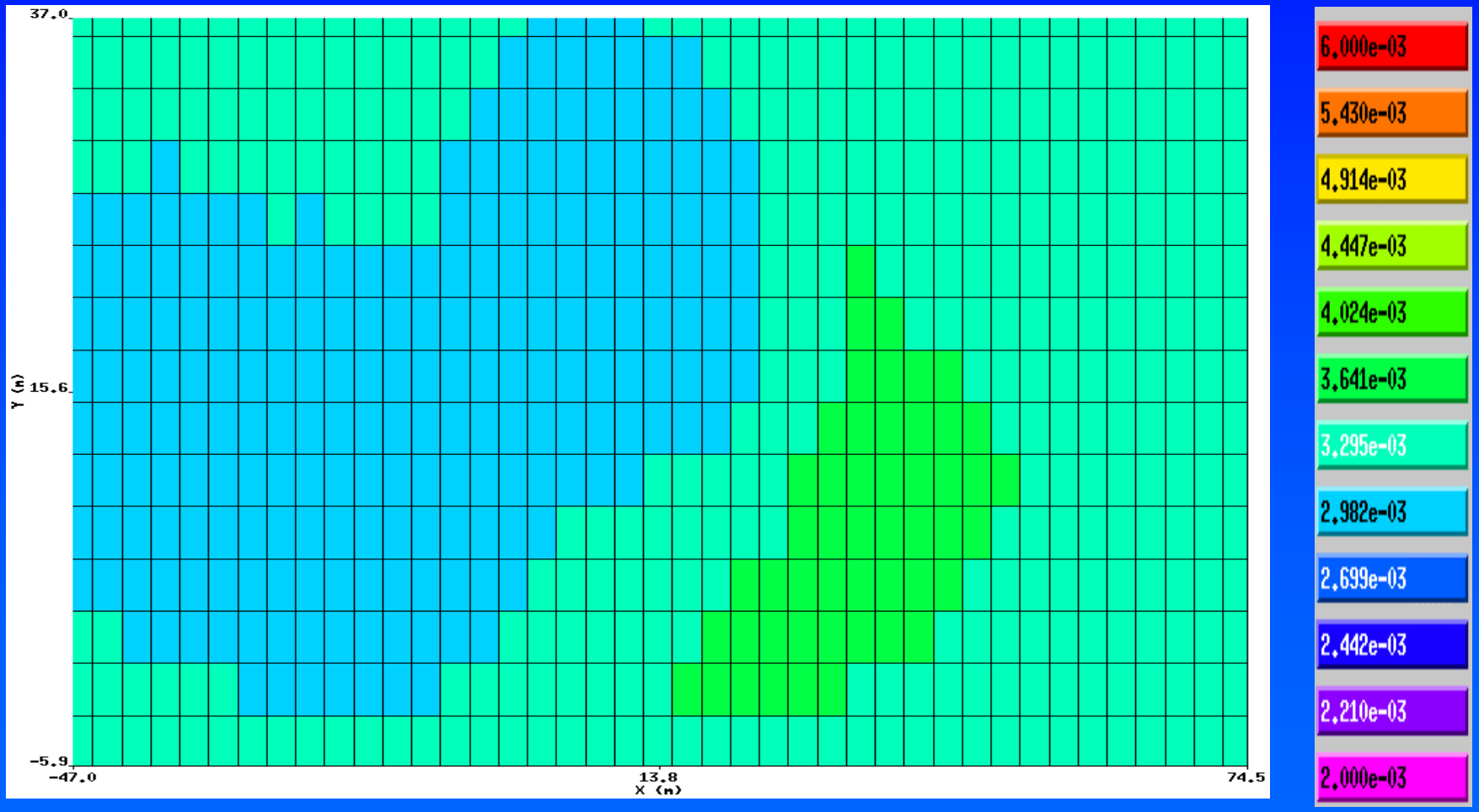
3D Conductivity Depth Maps

Z=16.5 m

S/m



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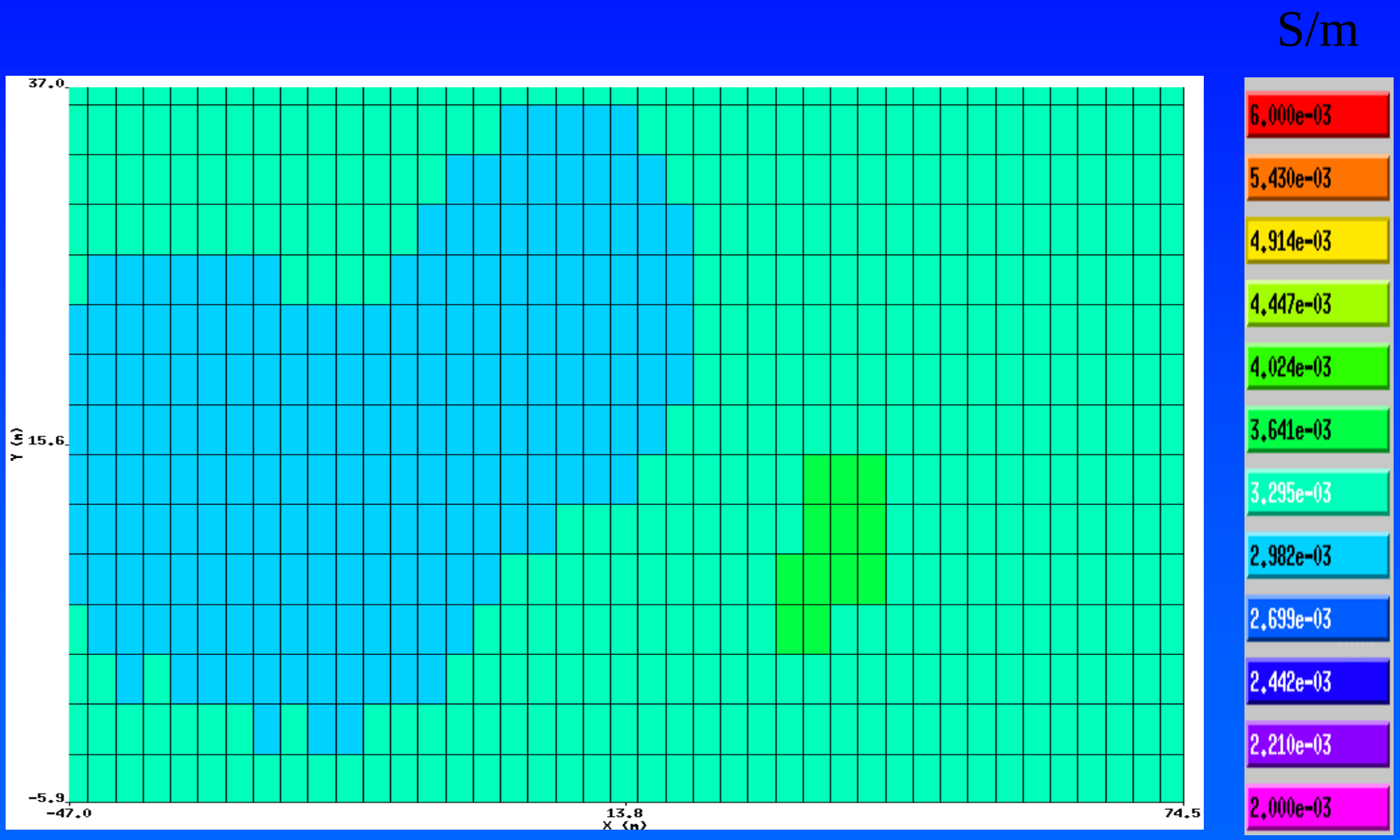
3D Conductivity Depth Maps

Z=19.5 m



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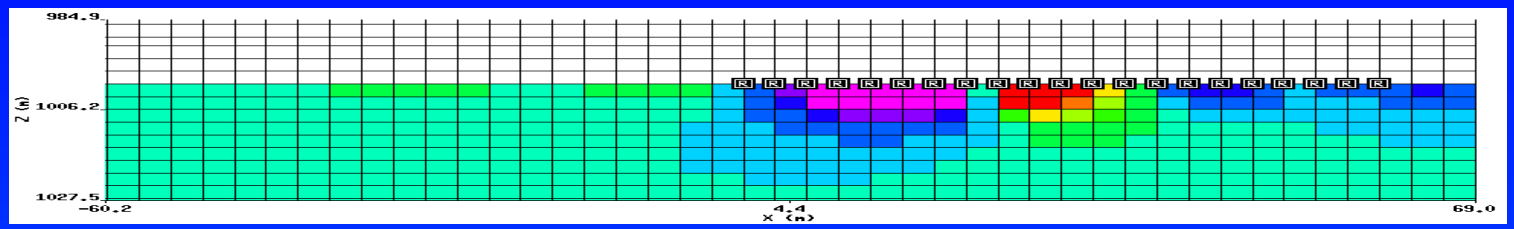
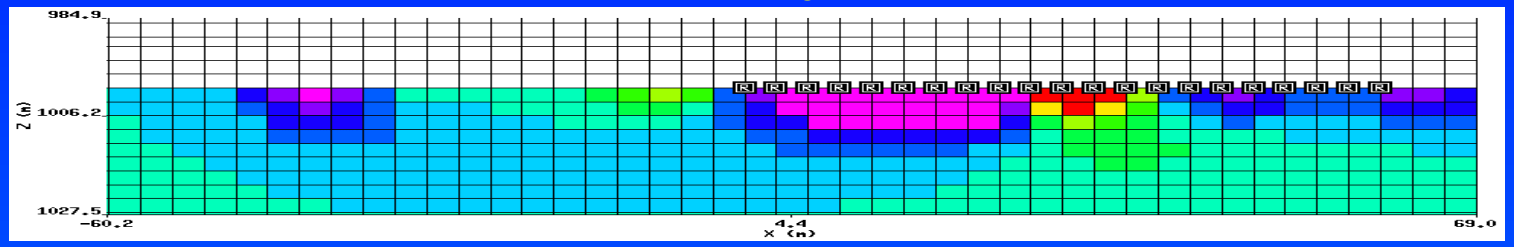
3D Conductivity Sections

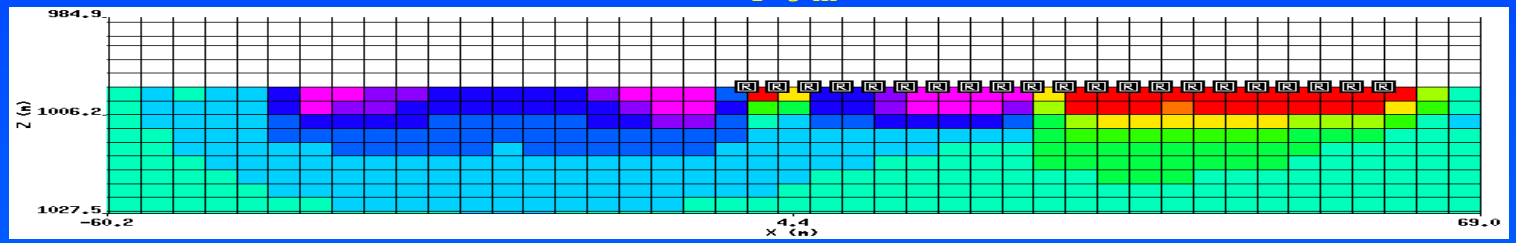
Y=30 m



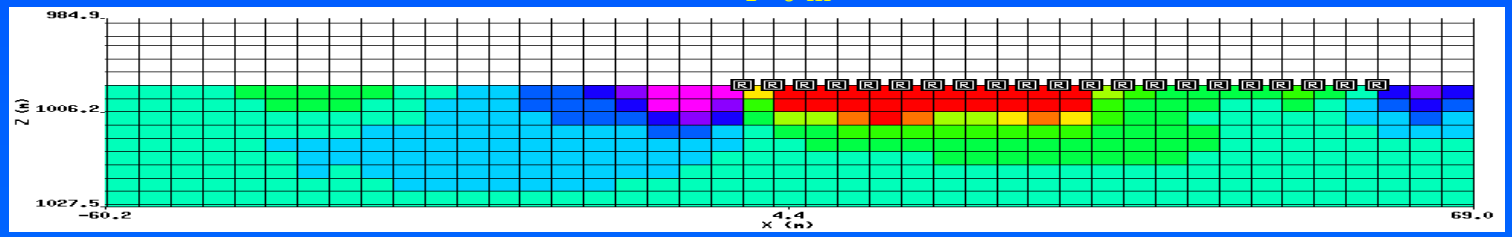
Y=18 m



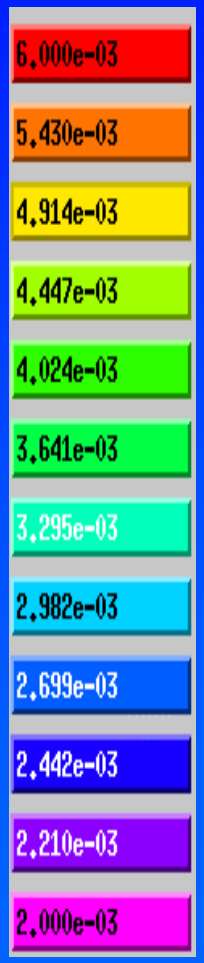
Y=9 m



Y=0 m



S/m



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Future Work

- Two new surveys at clastic dike sites (2001)
- Improve 3D inversion scheme convergence
- Improve image resolution at depth
  - incorporate a priori information into inversion scheme
  - use different types of geophysical data sets
- Implement rapid 2D inversion scheme
- Image new data sets using 3D/2D schemes

Conclusions

- The impedance method has potential for characterizing 3D transport pathways in the vadose zone.
- The method is sensitive to subsurface electrical conductivity variations
- Such variations often correlate with saturation changes in the subsurface