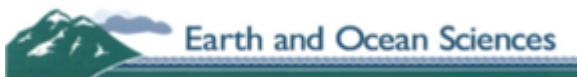




Parameterized inversion framework for proppant volume in a hydraulically fractured reservoir

Lindsey J. Heagy, Rowan Cockett & Douglas W. Oldenburg,
UBC Geophysical Inversion Facility,
University of British Columbia



SEG Denver
October 28, 2014

Hydraulic Fracturing Process

- Goal: to create pathways for hydrocarbons to flow

Section of the well isolated



Fluid pumped to fracture rock



Proppant pumped to keep
fractures open

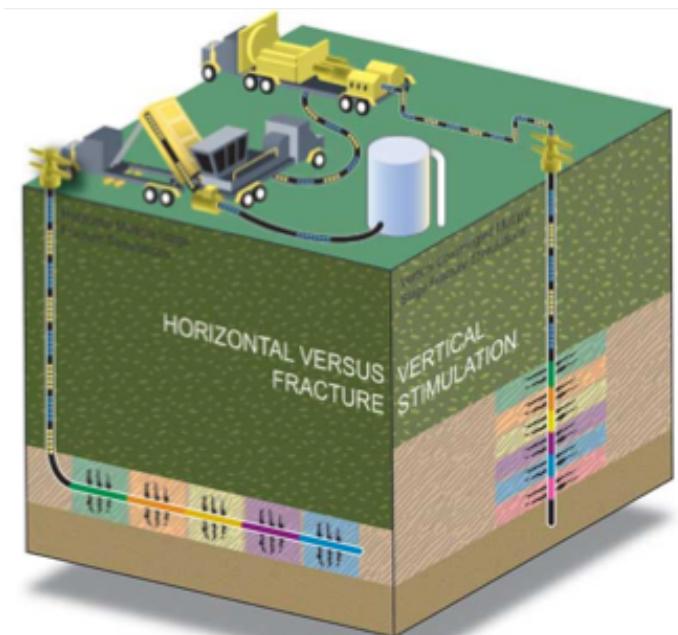


image: (National Energy Board, Canada, 2009)

Hydraulic Fracturing Process

- Goal: to create pathways for hydrocarbons to flow
- Fracture performance depends on:
 - completion parameters
 - reservoir properties
- Stimulated reservoir volume?

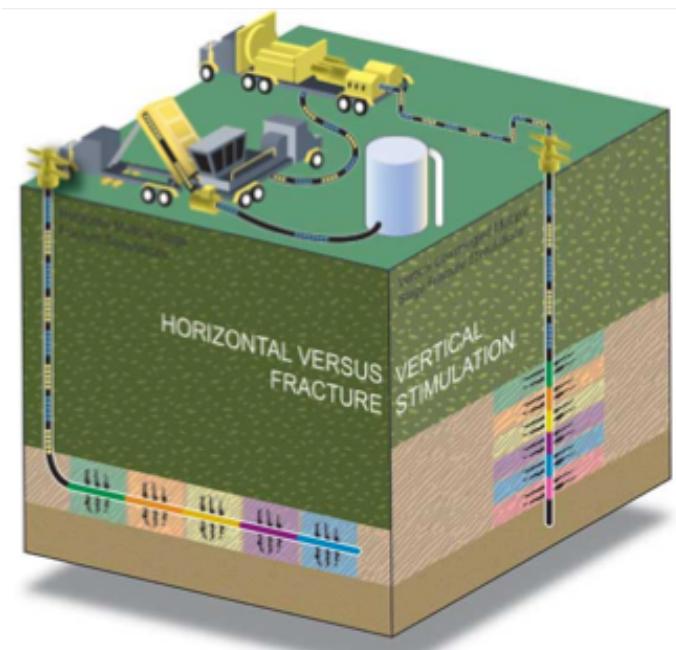
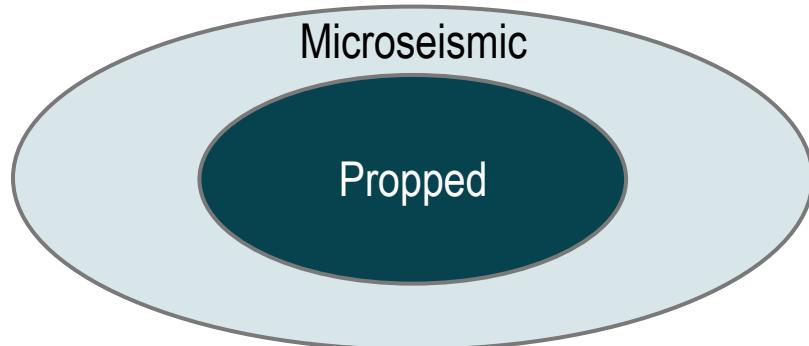


image: (National Energy Board, Canada, 2009)

Imaging the Propped Volume:

Requirements:

1. Physical Property
Contrast

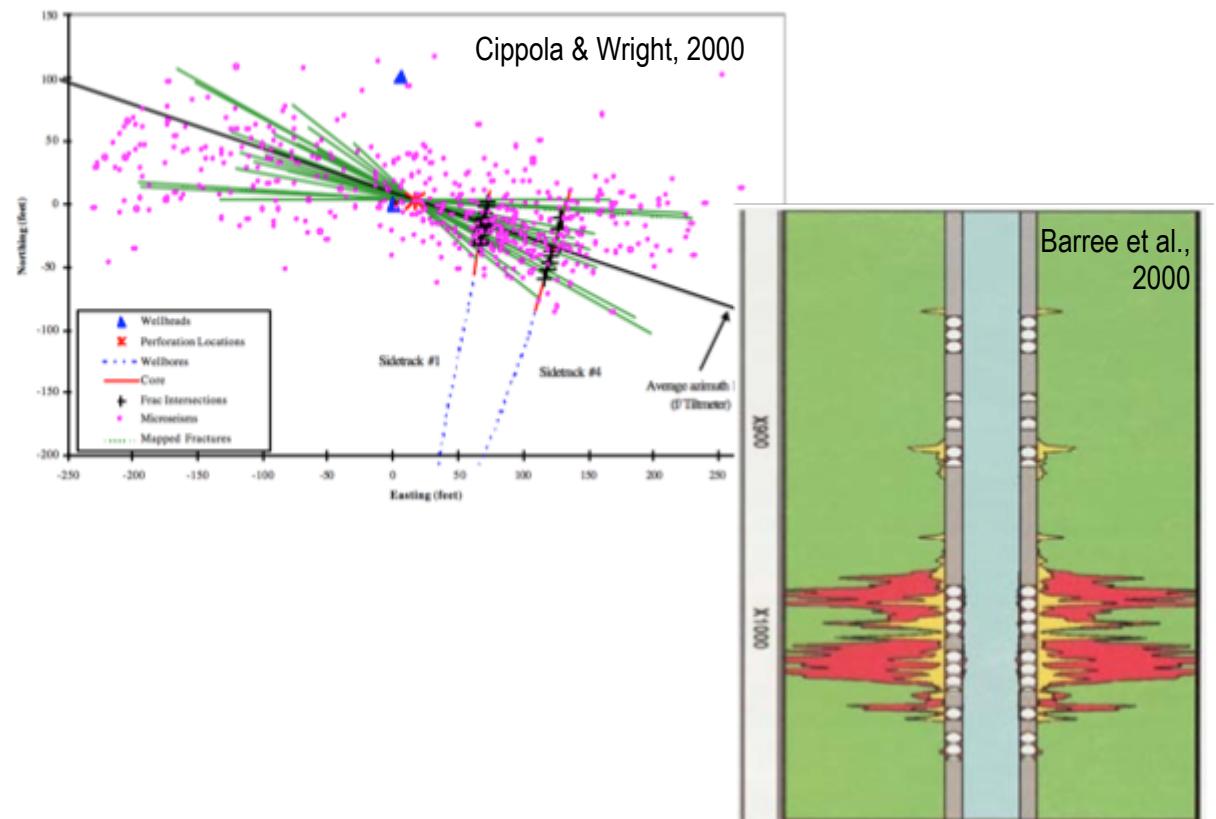
2. Survey Sensitive
to Contrast

3. Interpret / Invert
the data

1. Physical Property Contrast

Physical Property Contrast

- Current monitoring:
 - Near-Well
 - Logs
 - Tracers
 - Far-Well
 - Microseismic
 - Tiltmeters
 - Pressure
 - Fibre Optics



Imaging the Propped Volume:

Requirements:

1. Physical Property Contrast

Approach:

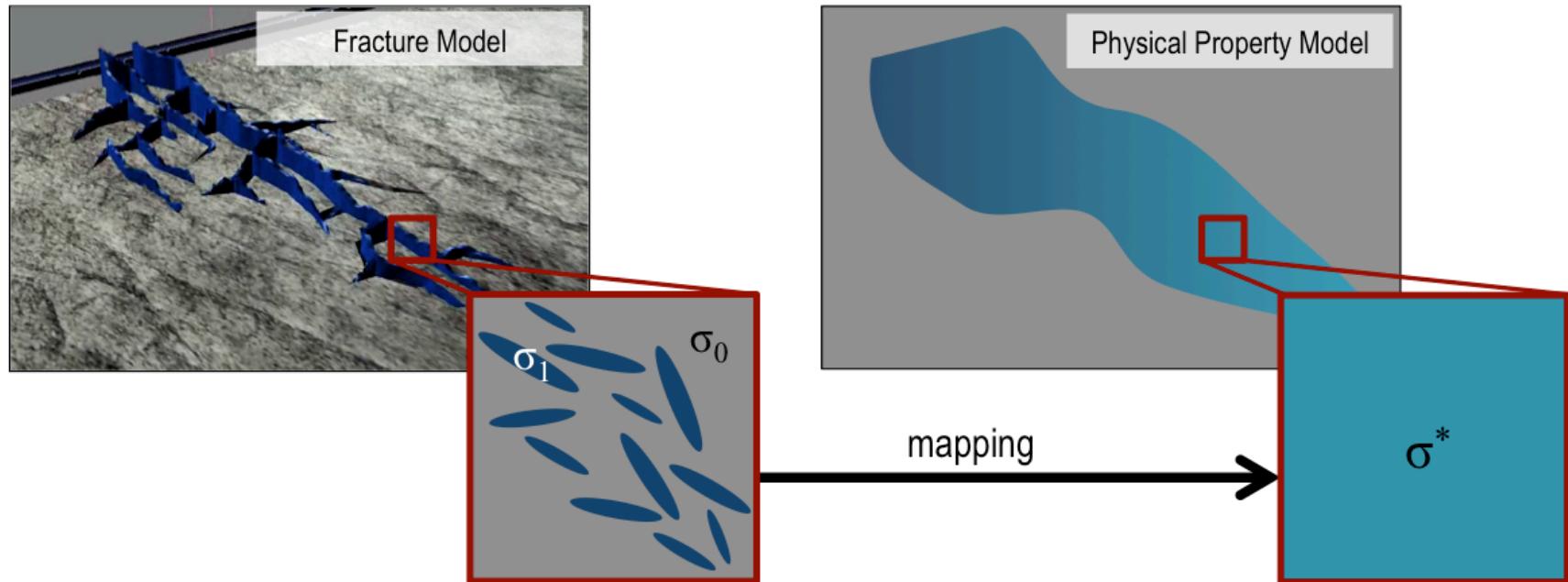
Electrically Conductive Proppant

2. Survey Sensitive to Contrast

3. Interpret / Invert the data

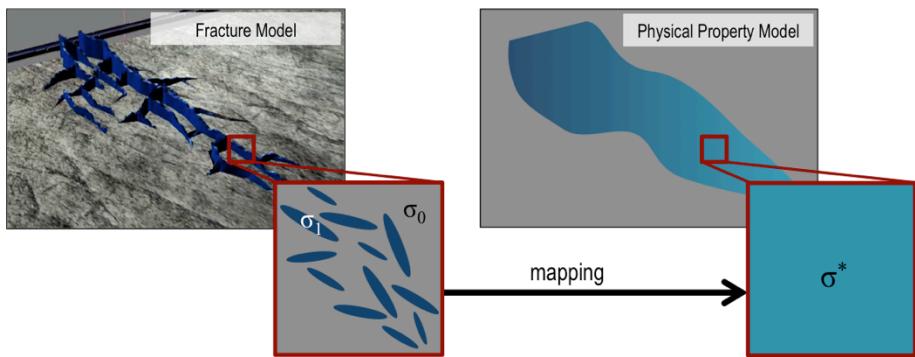
Electrical Conductivity Model

1. Physical Property Contrast



Electrical Conductivity Model

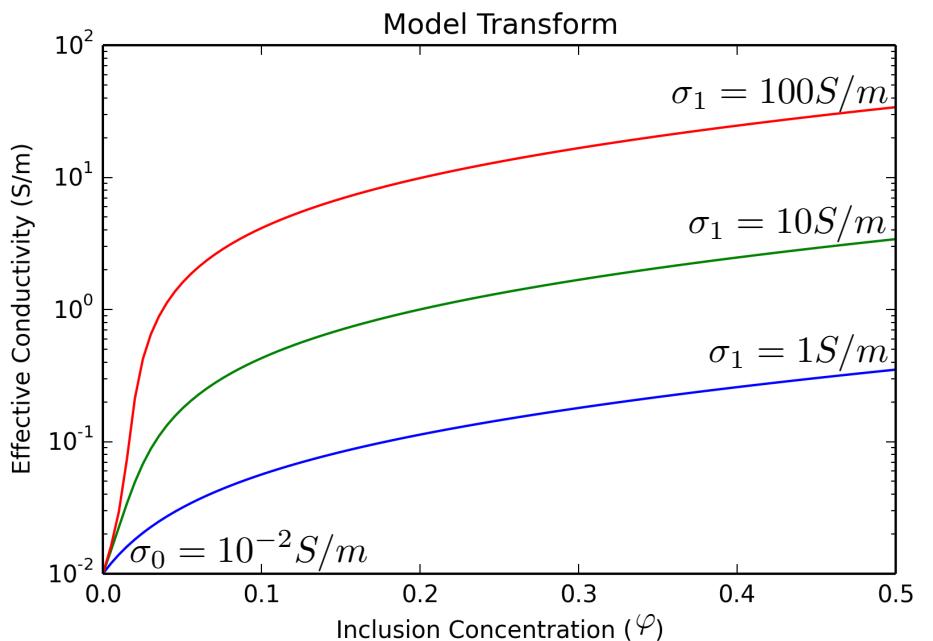
1. Physical Property Contrast



Mapping using Effective Medium Theory: $\sigma = f(\varphi)$

$$(1 - \varphi)(\sigma - \sigma_0)R^{(0)} + \varphi(\sigma - \sigma_1)R^{(1)} = 0$$

$$R^{(i)} = \frac{1}{3} \text{trace} \left(\left[1 + \mathbf{A} \frac{\sigma_i - \sigma}{\sigma} \right]^{-1} \right)$$



c.f. Torquato (2002),
Shafiro and Kachanov (2000),
Berryman and Hoversten (2013)

Imaging the Propped Volume:

Requirements:

1. Physical Property Contrast

Approach:

Electrically Conductive Proppant

2. Survey Sensitive to Contrast

Electromagnetic Survey

3. Interpret / Invert the data

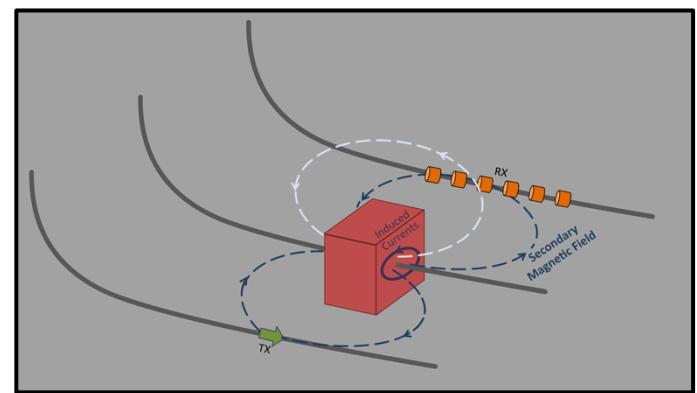
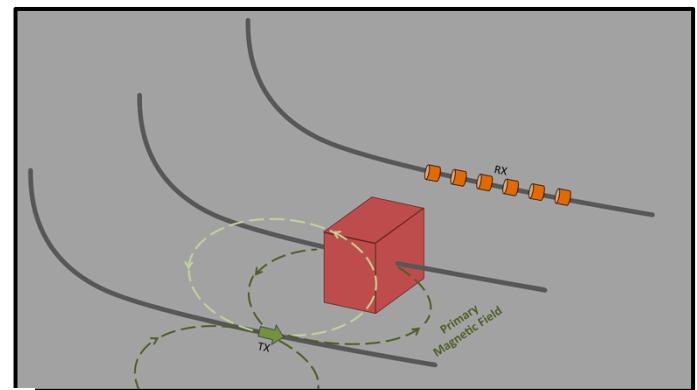
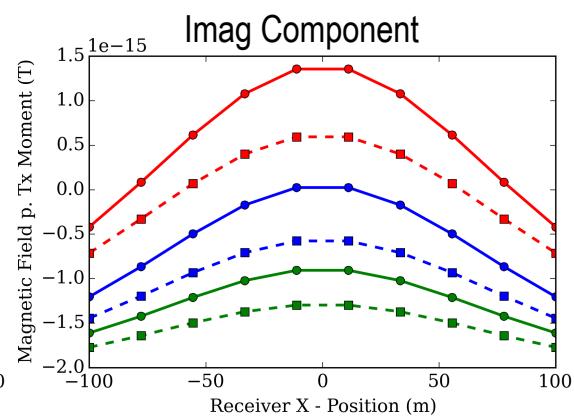
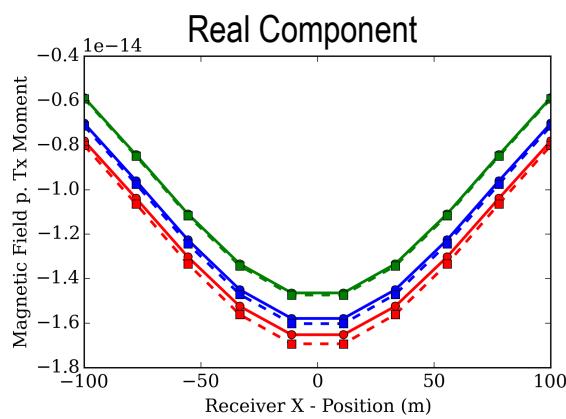
Survey & Data

2. Survey Sensitive to Contrast

$$\nabla \times \mathbf{E} + i\omega \mathbf{B} = 0$$

$$\nabla \times \mu^{-1} \mathbf{B} - \sigma(\varphi) \mathbf{E} = \mathbf{J}_s$$

- 300Hz, Frac
- - 300Hz, No Frac
- 500Hz, Frac
- - 500Hz, No Frac
- 700Hz, Frac
- - 700Hz, No Frac



Imaging the Propped Volume:

Requirements:

1. Physical Property Contrast

Approach:

Electrically Conductive Proppant

2. Survey Sensitive to Contrast

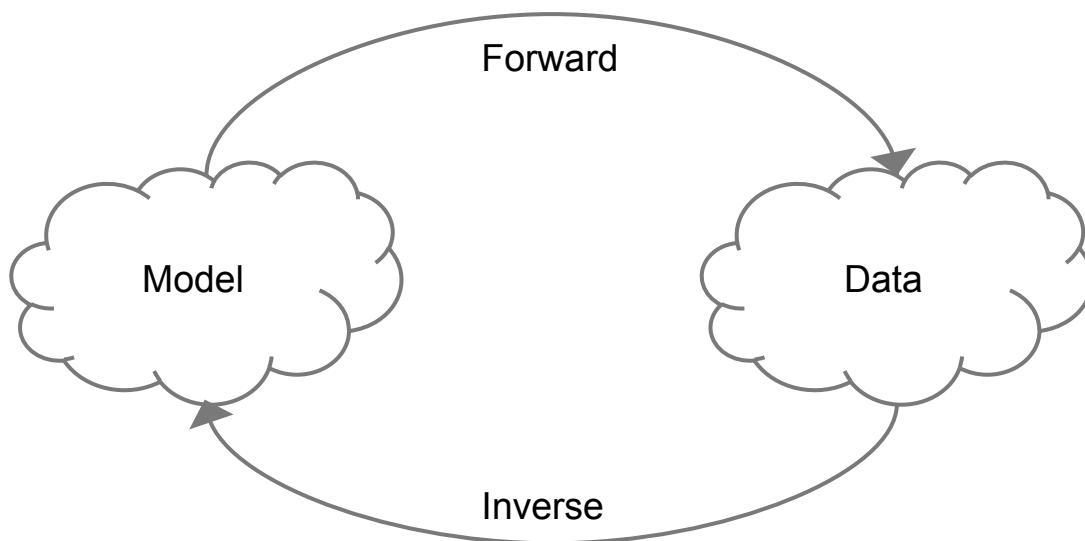
Electromagnetic Survey

3. Interpret / Invert the data

Invert for Proppant Distribution

Inverse Problem

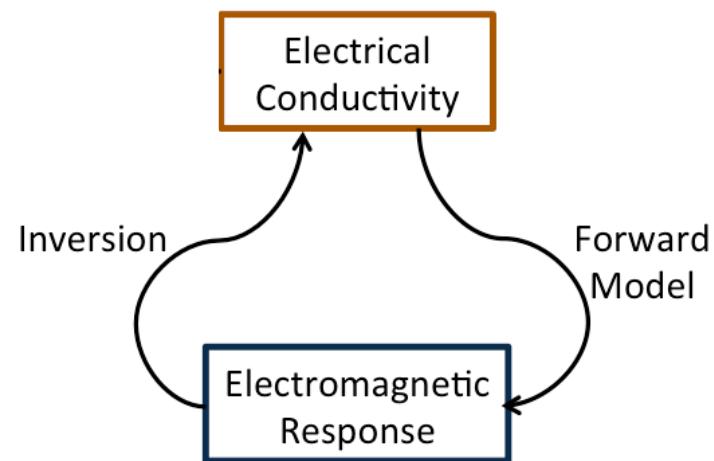
3. Interpret / Invert
the data



Inverse Problem

Typical Inversion

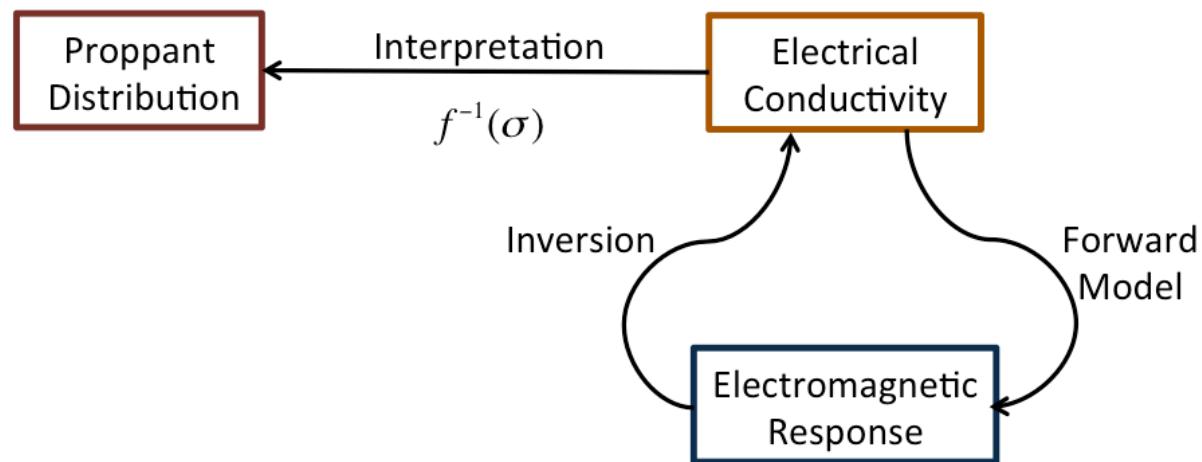
3. Interpret / Invert
the data



Inverse Problem

Typical Inversion

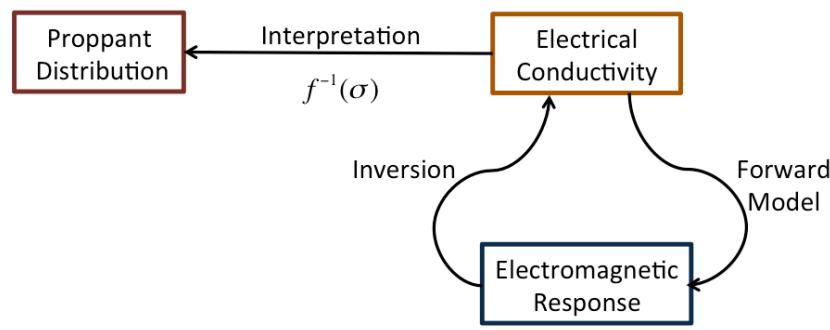
3. Interpret / Invert
the data



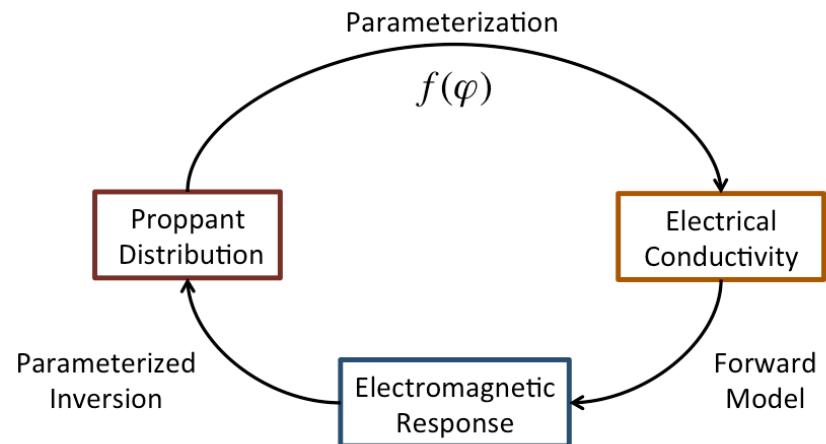
3. Interpret / Invert
the data

Two Inversion Approaches

Typical Inversion



Parameterized Inversion



3. Interpret / Invert
the data

What is the model?

Conductivity

$$m = \sigma$$

Log
Conductivity

$$m = \log(\sigma)$$

Proppant
Concentration

$$m = \varphi$$

Mapping

Physics

$$\nabla \times \mathbf{E} + i\omega \mathbf{B} = 0$$

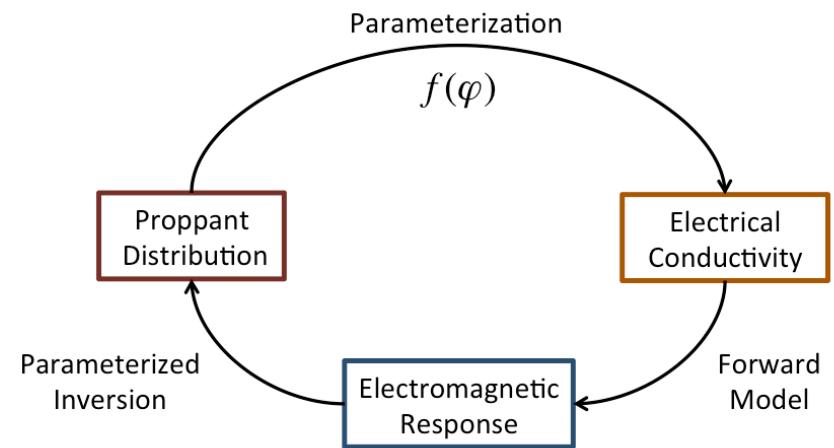
$$\nabla \times \mu^{-1} \mathbf{B} - \sigma \mathbf{E} = \mathbf{J}_s$$

3. Interpret / Invert
the data

Inversion through optimization

$$\varphi^* = \min_{\varphi} \phi_d + \beta \phi_m$$

↑
data misfit ↑
model regularization

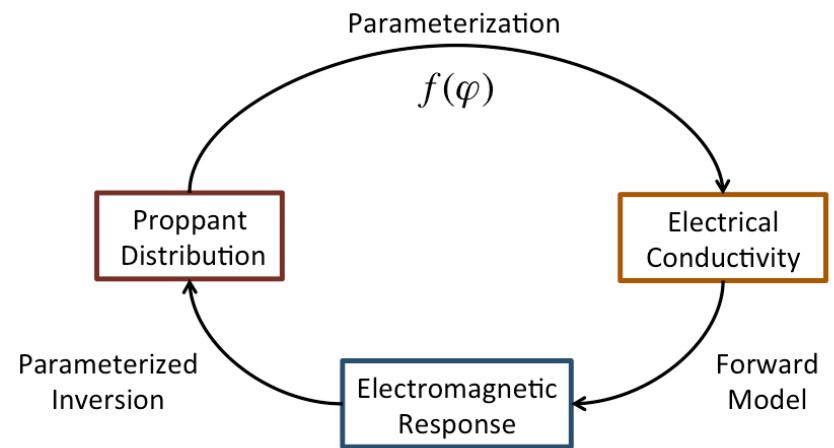


3. Interpret / Invert
the data

Data Misfit

- EM data:

$$\phi_{\text{EM}} = \frac{1}{2} \sum_{j=1}^N \left(\frac{d_j^{\text{obs}} - d_j^{\text{pred}}}{\varepsilon_j} \right)^2$$



3. Interpret / Invert
the data

Data Misfit

- EM data:

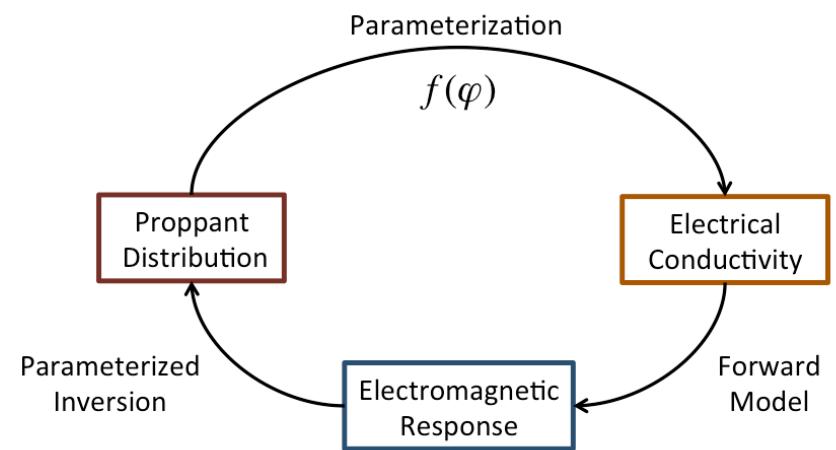
$$\phi_{EM} = \frac{1}{2} \sum_{j=1}^N \left(\frac{d_j^{obs} - d_j^{pred}}{\varepsilon_j} \right)^2$$

- Total Proppant Volume

$$\phi_V = \frac{1}{2} \left(\frac{\int \varphi dV - V_{prop}}{\varepsilon_V} \right)^2$$

Data Misfit:

$$\phi_d = \phi_{EM} + \beta_V \phi_V$$

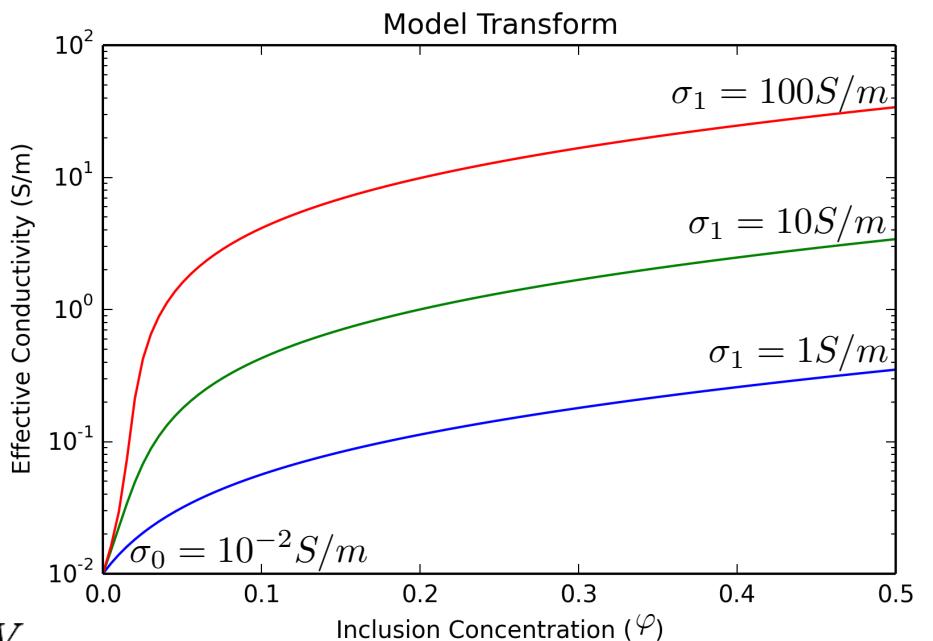


3. Interpret / Invert
the data

Model Regularization

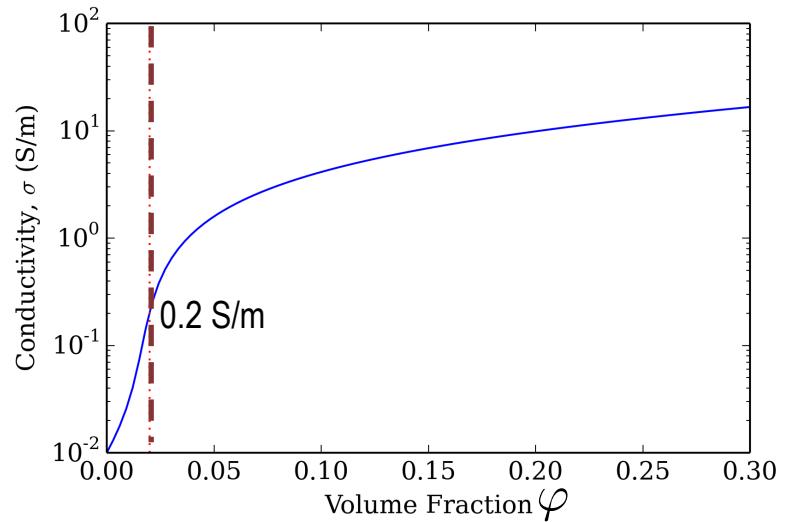
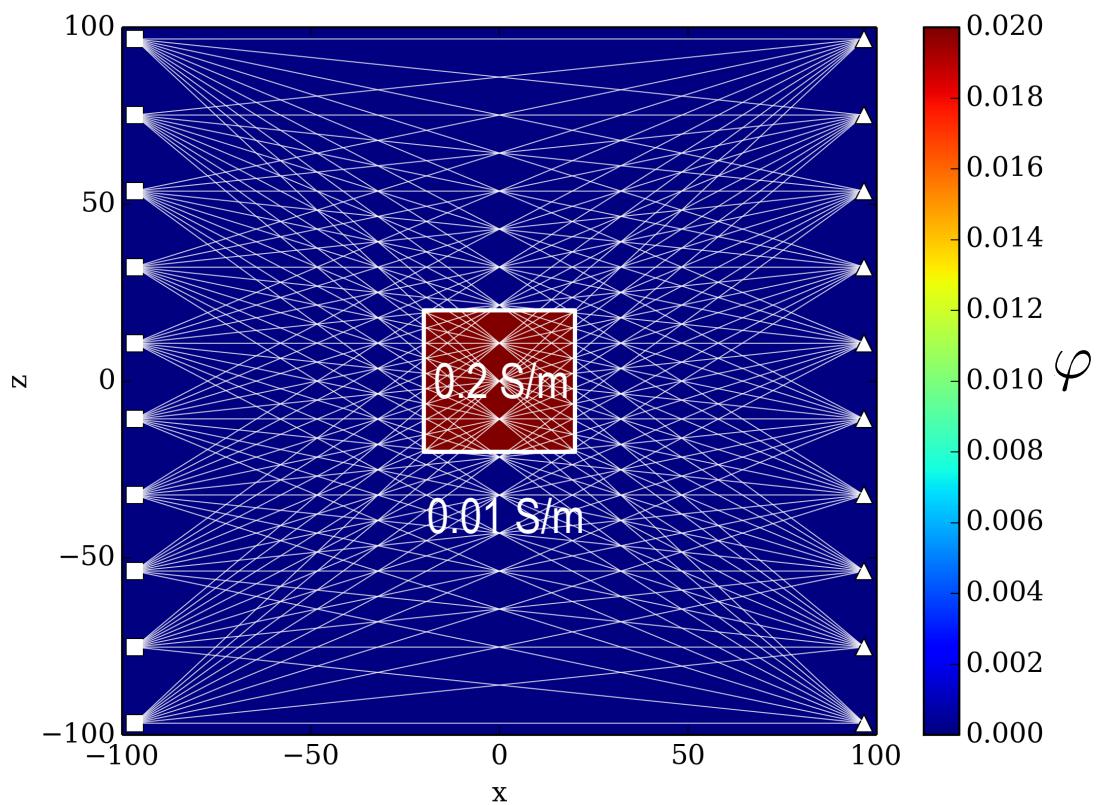
- Non-unique
- Tikhonov regularization
 - smoothness
 - smallness

$$\phi_m = \frac{\alpha_s}{2} \int (w_d(x, y, z)\varphi)^2 dV + \frac{\alpha_x}{2} \int \left(\frac{\partial \varphi}{\partial x} \right)^2 dV + \frac{\alpha_y}{2} \int \left(\frac{\partial \varphi}{\partial y} \right)^2 dV + \frac{\alpha_z}{2} \int \left(\frac{\partial \varphi}{\partial z} \right)^2 dV,$$

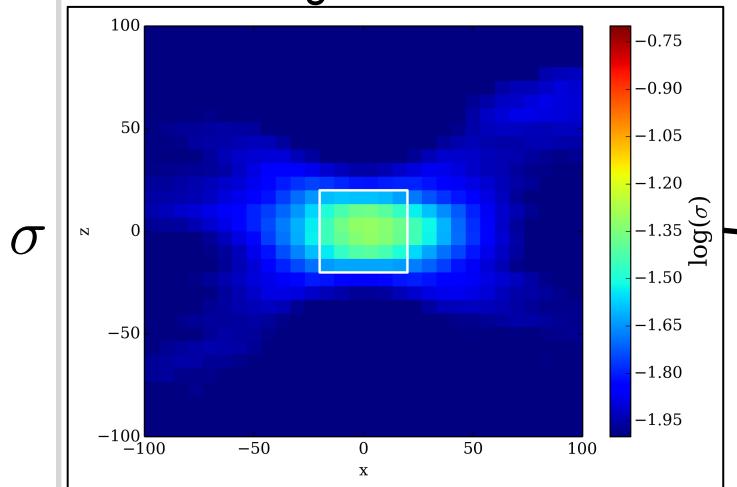


(does it work?)

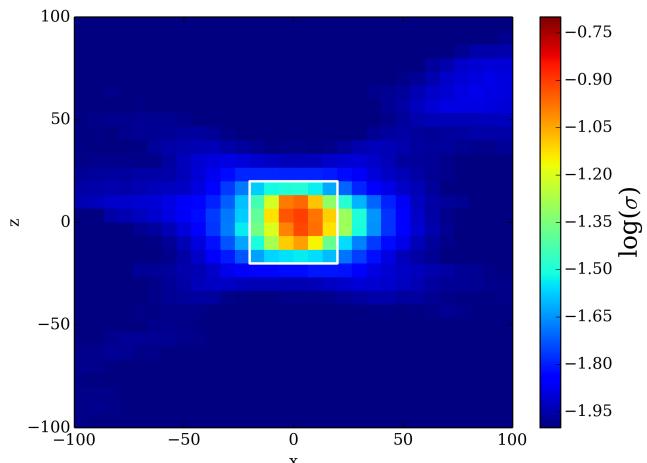
Linear Example 1



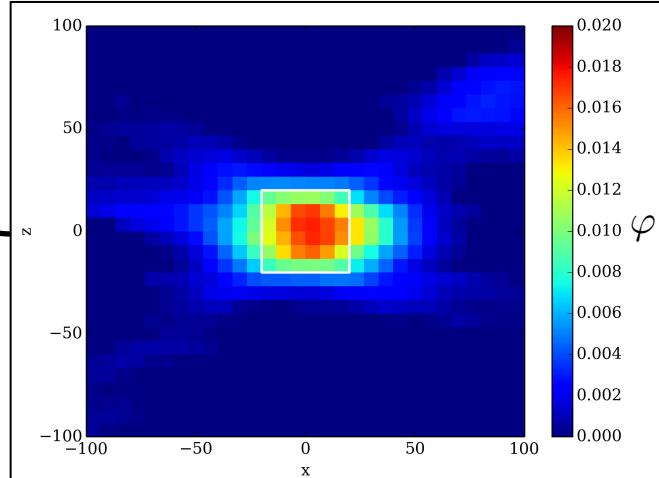
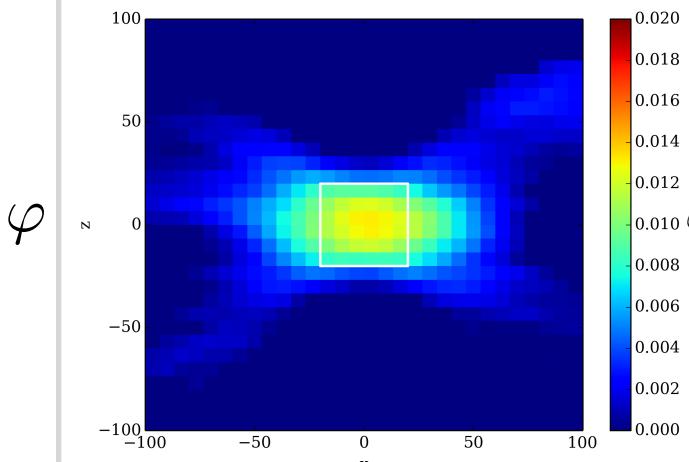
Inverting for σ



Inverting for φ , no Volume Term

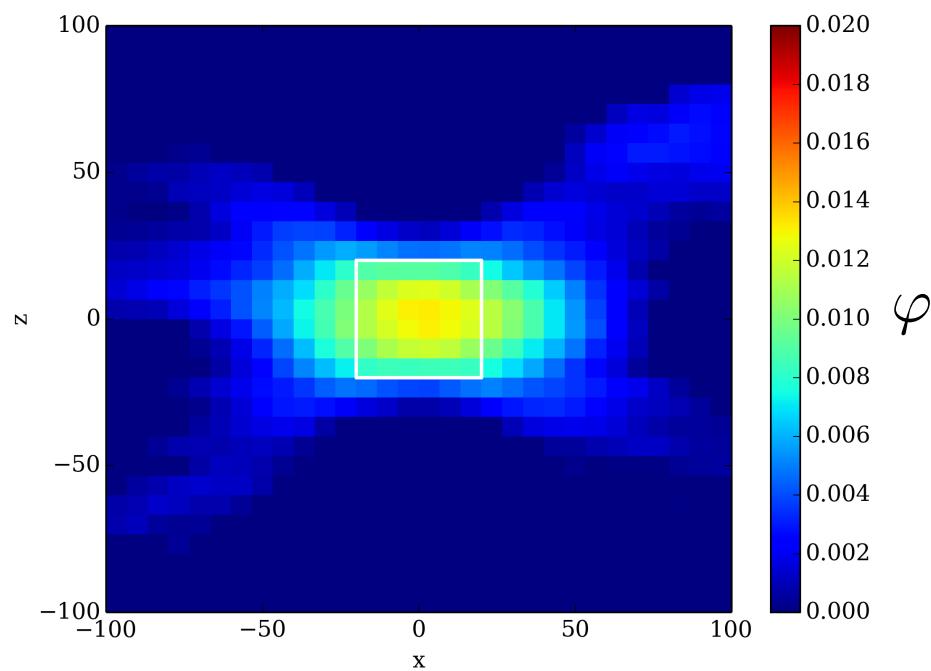


φ

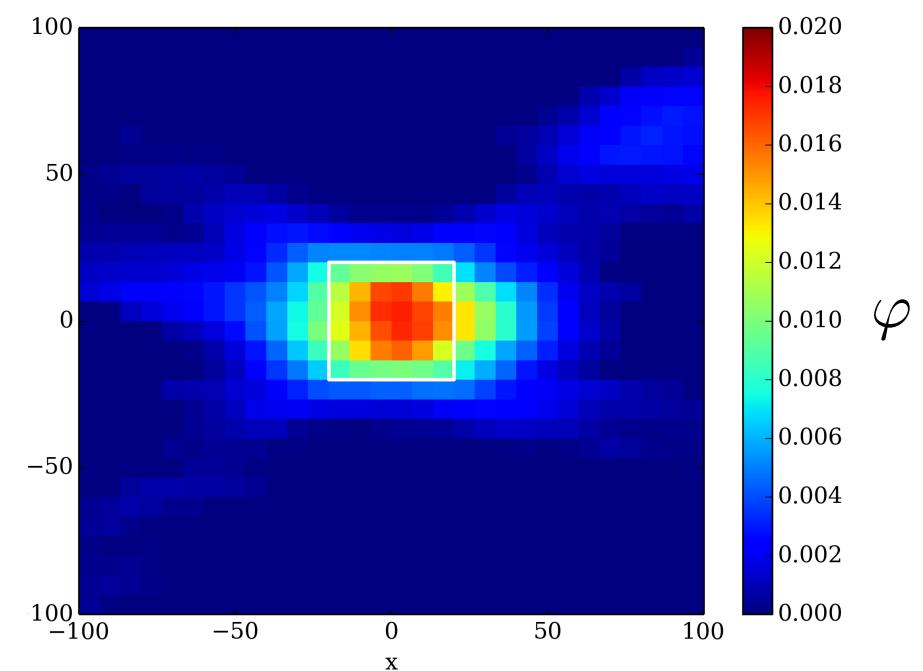


Linear Example 1

Inverting for σ

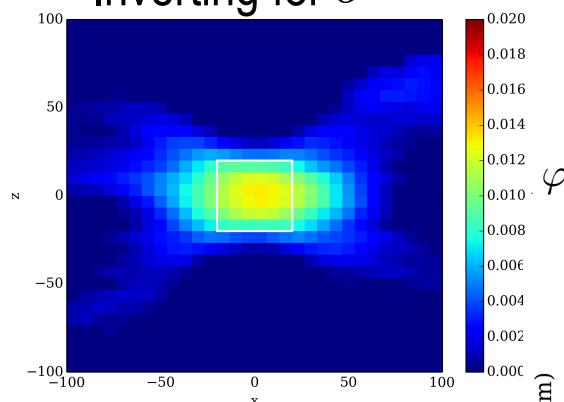


Inverting for φ , no Volume Term

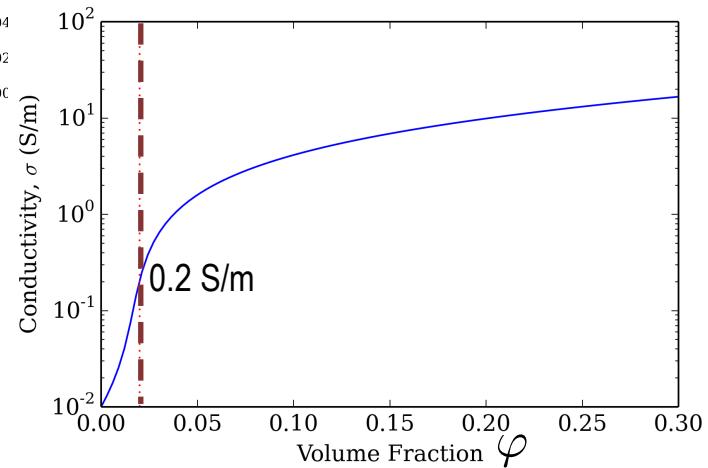


Linear Example 1

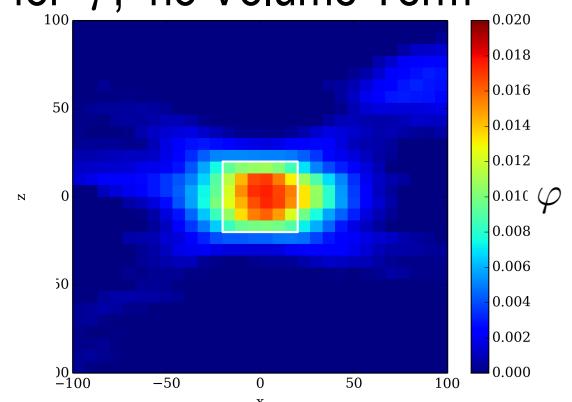
Inverting for σ



1.9 times true volume



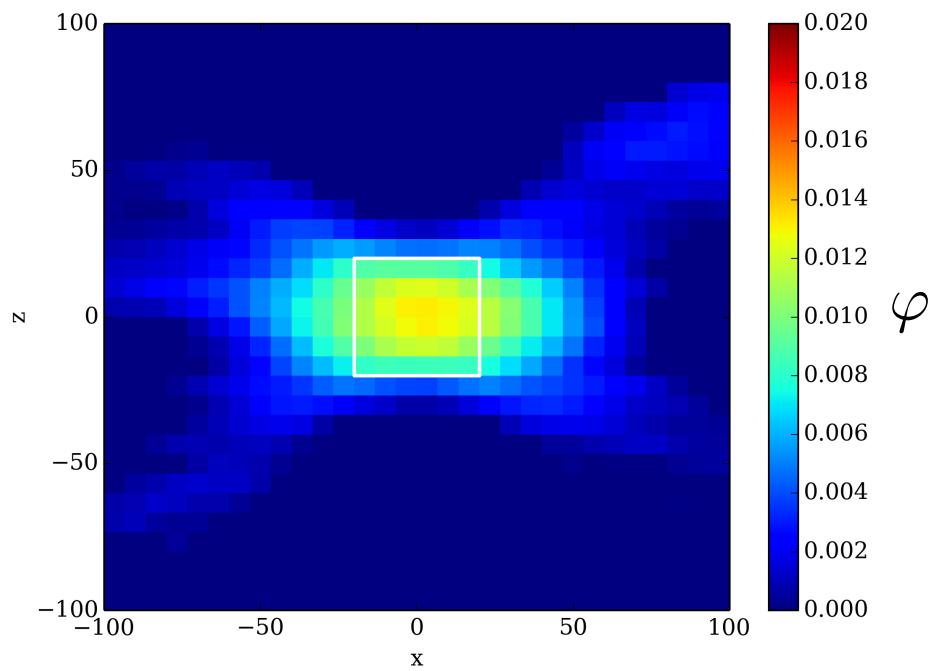
Inverting for φ , no Volume Term



1.7 times true volume

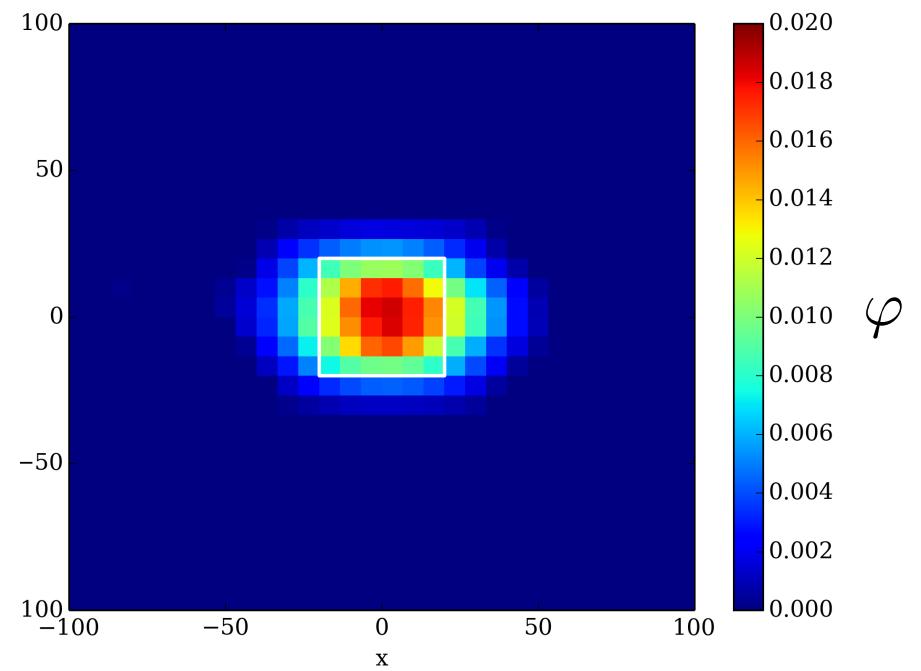
Linear Example 1

Inverting for σ



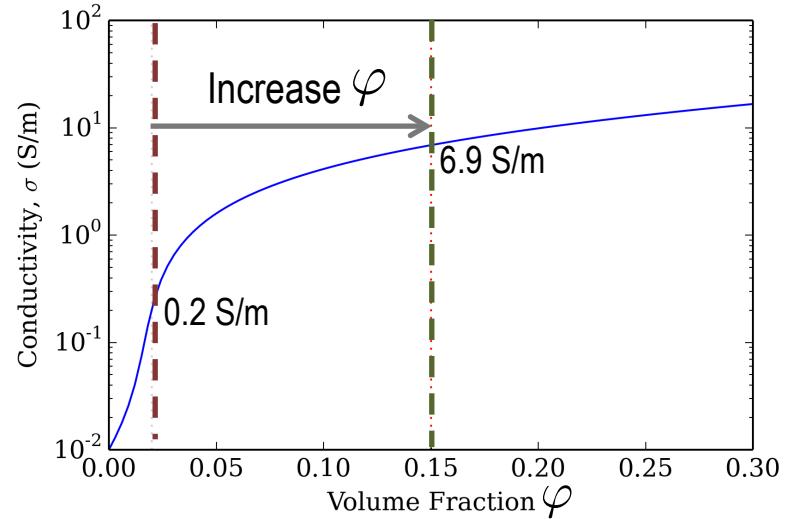
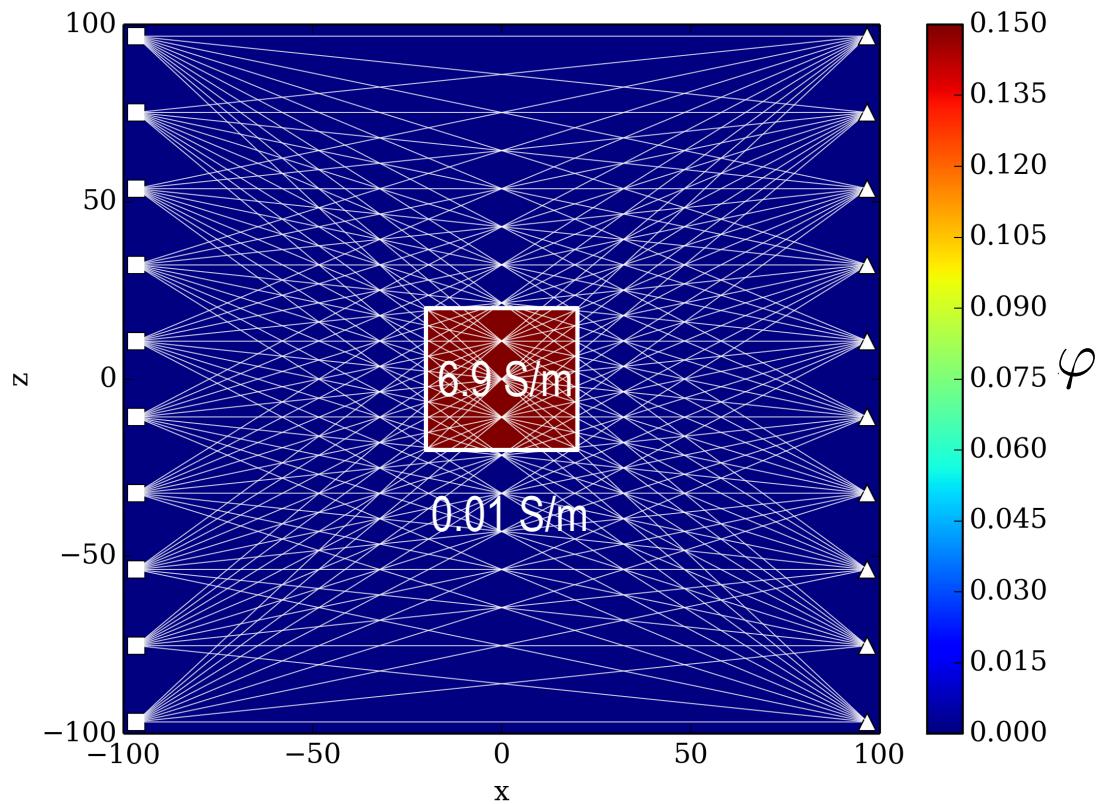
1.9 times true volume

Inverting for φ , with Volume Term



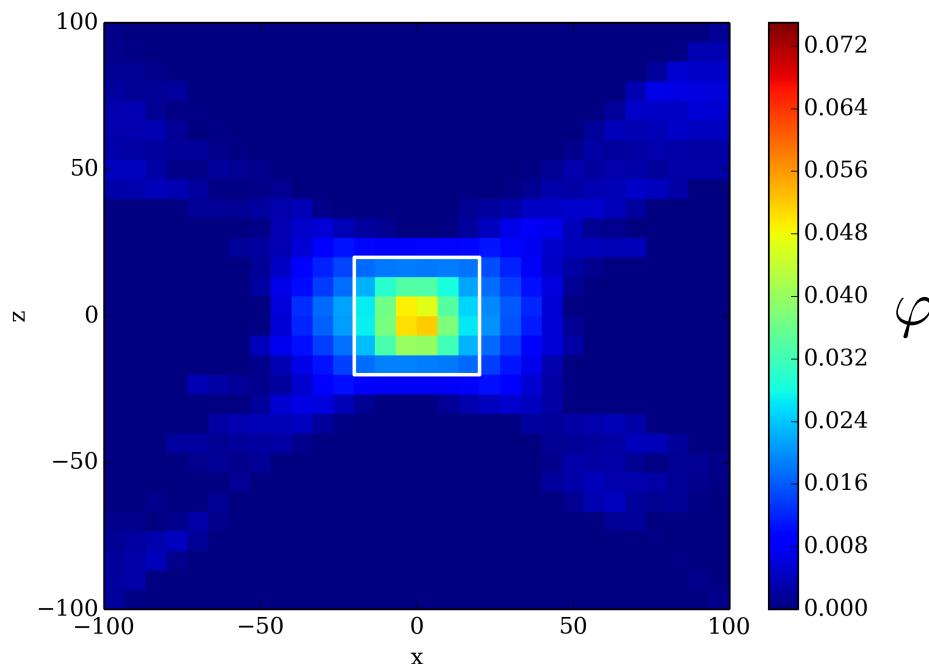
1.1 times true volume

Linear Example 2



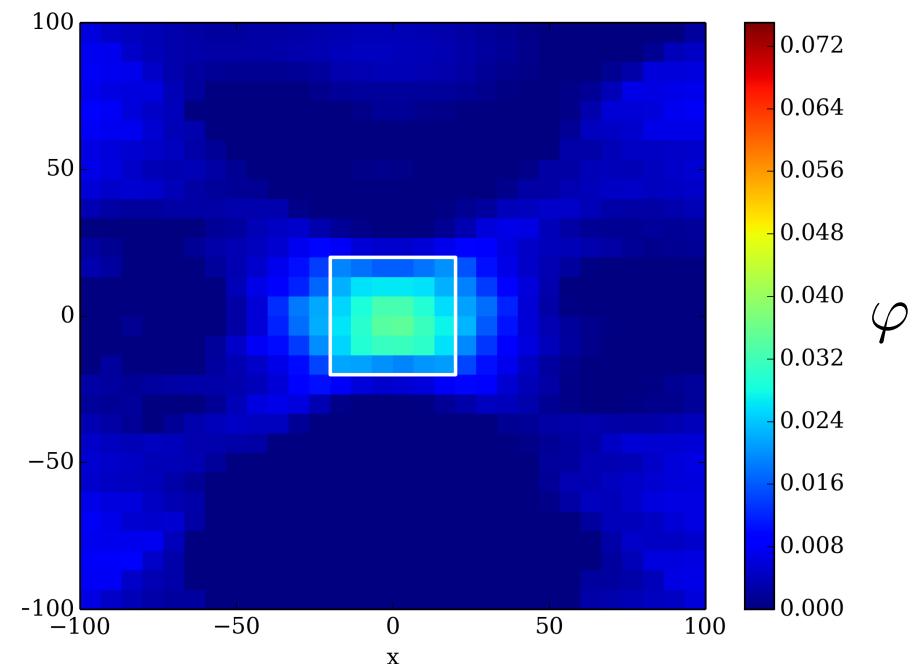
Linear Example 2

Inverting for σ



0.4 times true volume

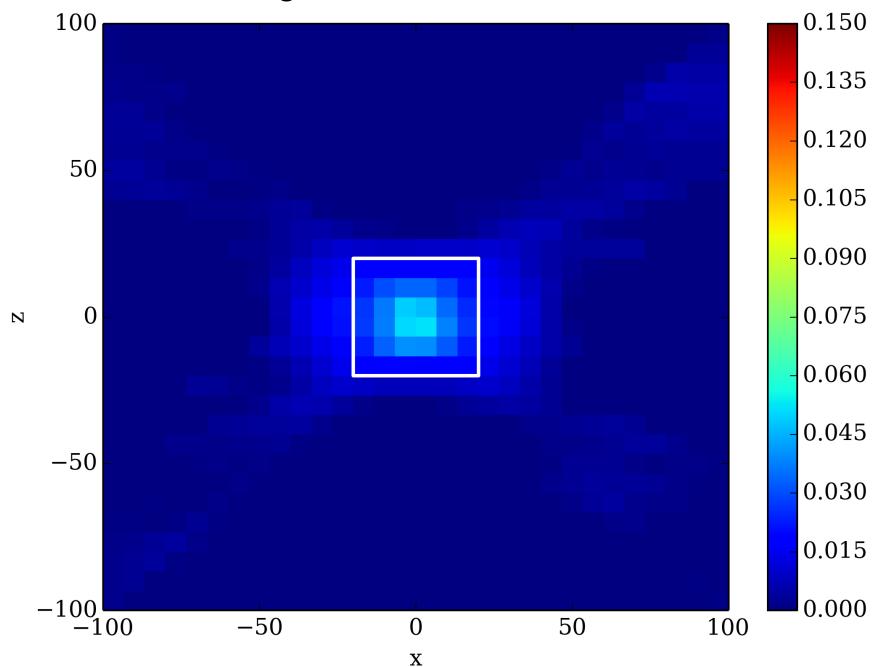
Inverting for φ , fixed Volume Term



0.6 times true volume

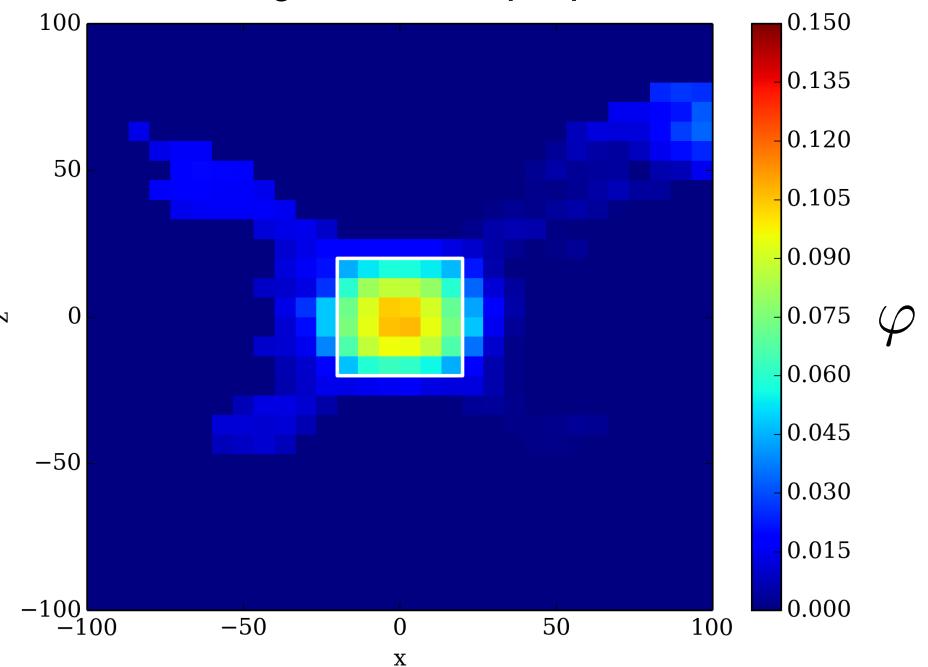
Linear Example 2

Inverting for σ



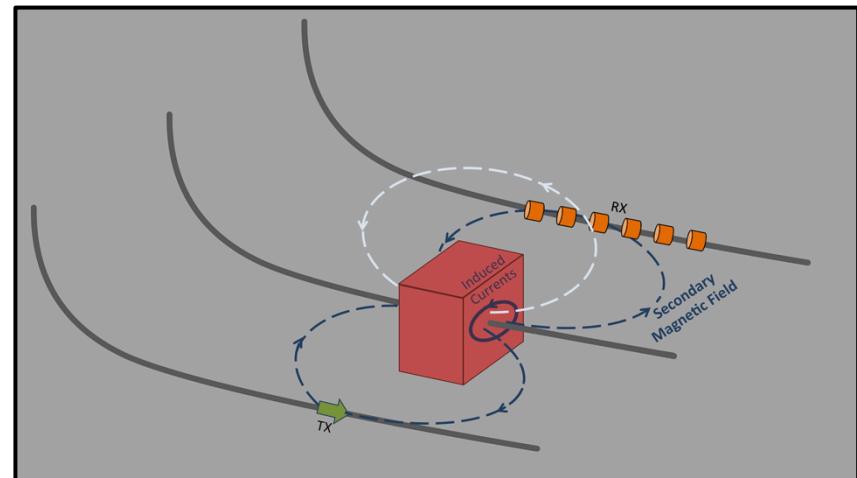
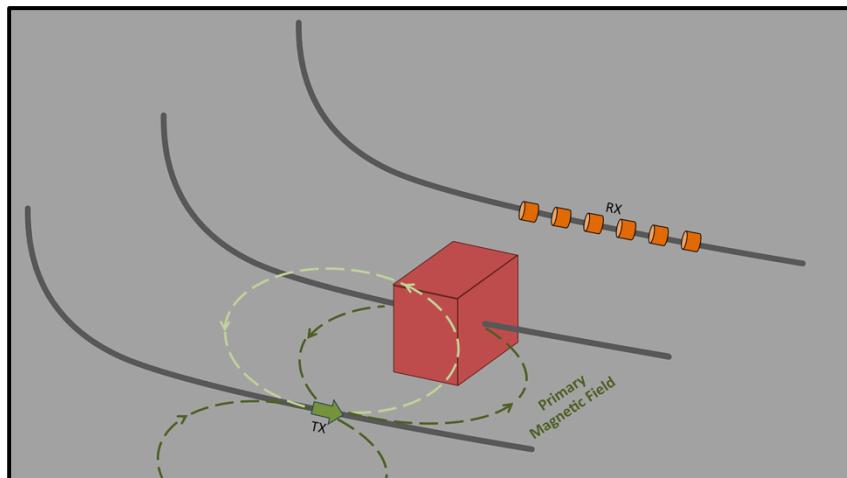
0.4 times true volume

Inverting for φ , ramp-up Volume Term

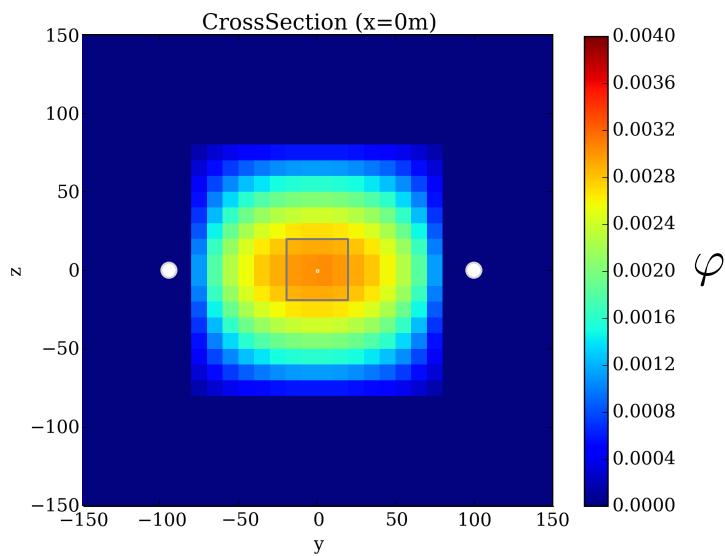


0.9 times true volume

Application to Electromagnetics



Application to Electromagnetics

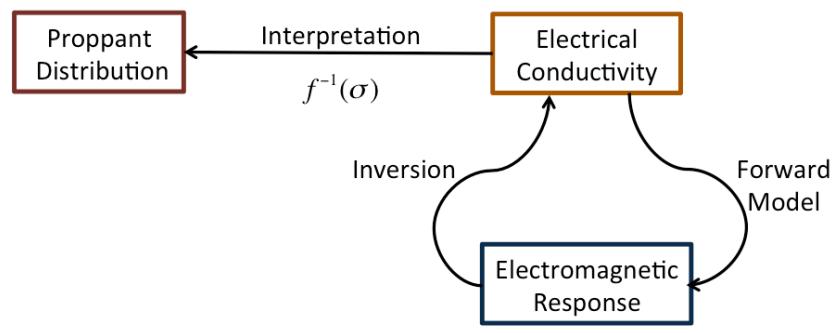


Where we are going?

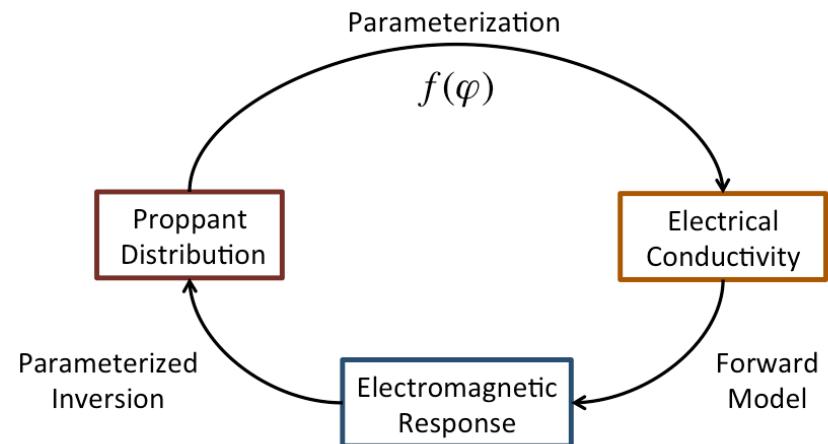
- 3D Cross-well EM inversion:
 - Non-Uniqueness
 - Parameter choices
- Volume Data Misfit
- Model Regularization:
 - compact norm
 - nesting parameterizations

Summary

Typical Inversion



Parameterized Inversion





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- SimPEG contributors
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- UBC GIF
- NSERC

Thank you!

References

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3. Interpret / Invert
the data

Sensitivity

Forward Simulation:

$$\mathcal{F}(\mathbf{E}, \sigma(\varphi)) = \nabla \times \mu^{-1} \nabla \times \mathbf{E} + \mathbf{i}\omega\sigma(\varphi)\mathbf{E} + \mathbf{i}\omega\mathbf{J}_s = \mathbf{0}$$

Sensitivity with respect to φ :

$$\frac{\partial \mathcal{F}}{\partial \mathbf{E}} \frac{\partial \mathbf{E}}{\partial \varphi} + \frac{\partial \mathcal{F}}{\partial \sigma} \frac{\partial \sigma}{\partial \varphi} = 0$$

$$\frac{\partial \mathbf{E}}{\partial \varphi} = - \left(\frac{\partial \mathcal{F}}{\partial \mathbf{E}} \right)^{-1} \frac{\partial \mathcal{F}}{\partial \sigma} \frac{\partial \sigma}{\partial \varphi}$$

3. Interpret / Invert
the data

Sensitivity

$$\frac{\partial \mathbf{E}}{\partial \varphi} = - \left(\frac{\partial \mathcal{F}}{\partial \mathbf{E}} \right)^{-1} \frac{\partial \mathcal{F}}{\partial \sigma} \frac{\partial \sigma}{\partial \varphi}$$

Sensitivity with respect to the physical property

Sensitivity of the physical property to the parameter of interest

Parameterizing the model changes the space in which we look for a solution.