Down-Hole Geophysical Testing for Rock Sockets

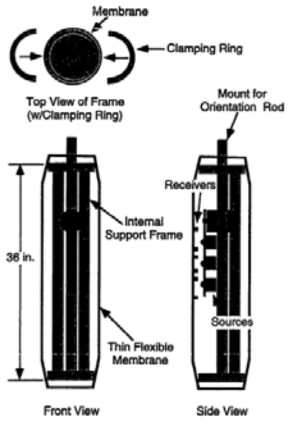
Dennis R. Hiltunen

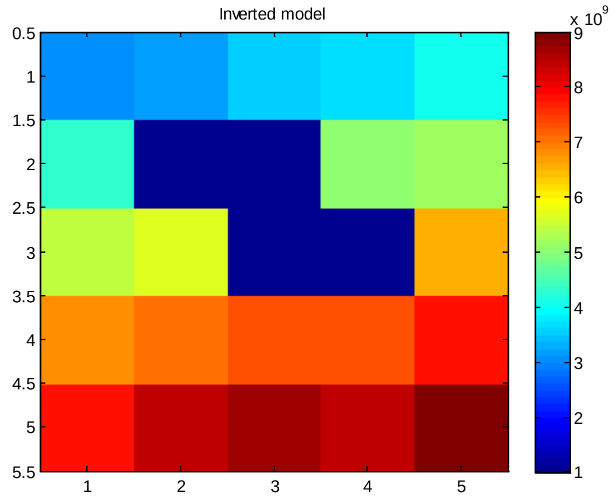
Pengxiang Jiang

University of Florida

FDOT Grip

August 9, 2013





Presentation Overview

- Motivation & Objectives
- Background
- Forward Model
- Inversion Scheme
- Synthetic Model Studies
- Conclusions & Future Work

Motivation

- Current practice in site investigation is often inadequate for karst terrane
- Foundation practice in Florida: heavily relies on single, large-diameter, non-redundant drilled shaft socketed into bedrock as foundation element to achieve bearing capacity
- Highly variable subsurface conditions can result in great uncertainty in design, and problems and disputes during construction
- Better characterization of the rock formations is desired for economic and reliable design solutions

Objectives

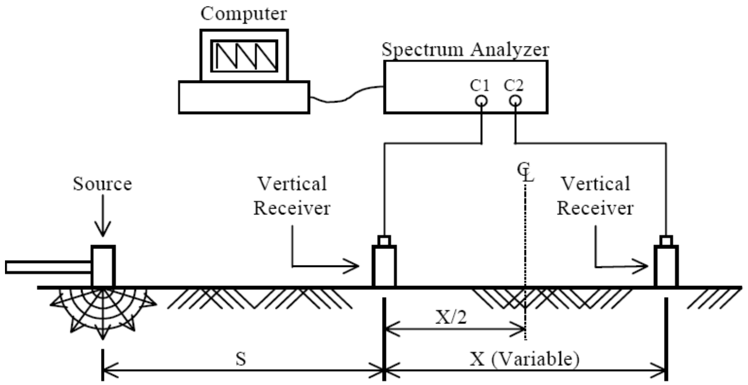
Develop a new borehole-based imaging technique via seismic full waveform inversion to characterize spatial variation of rock formations out to a distance of ~5 ft away from a borehole

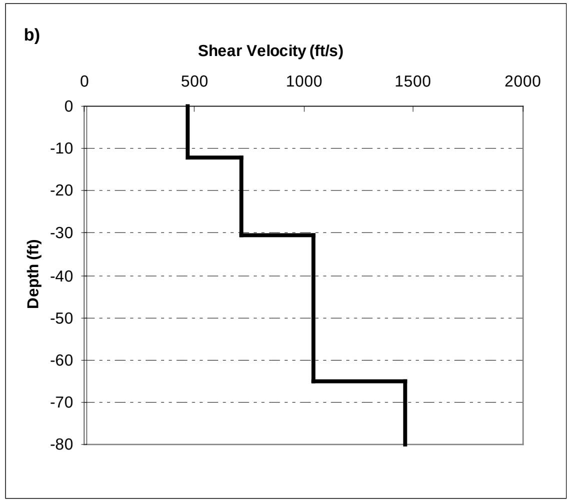
- Formulate and validate a forward model considering borehole geometry
- Develop an inversion scheme and test it via synthetic model studies
- Evaluate the feasibility of the proposed imaging technique in finding indications of isolated anomalies near a borehole

Background

Surface wave techniques:
SASW, MASW

- 1D variation in S-wave velocities vs. depth
- No lateral variation
- Poor resolution at depth
- Long array to achieve depth

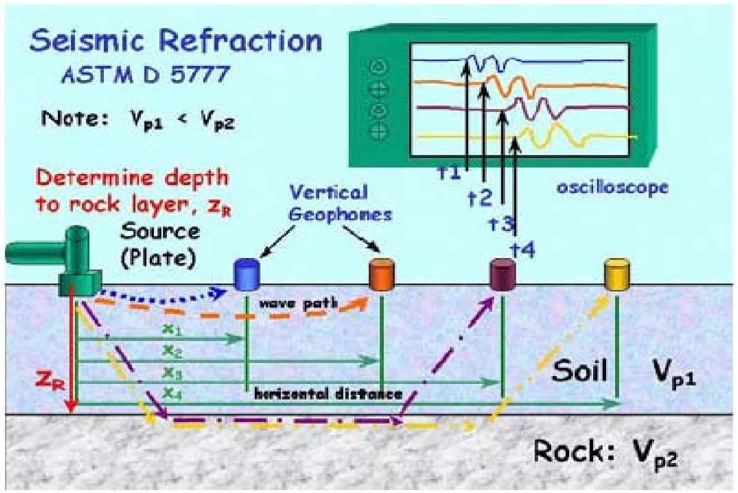


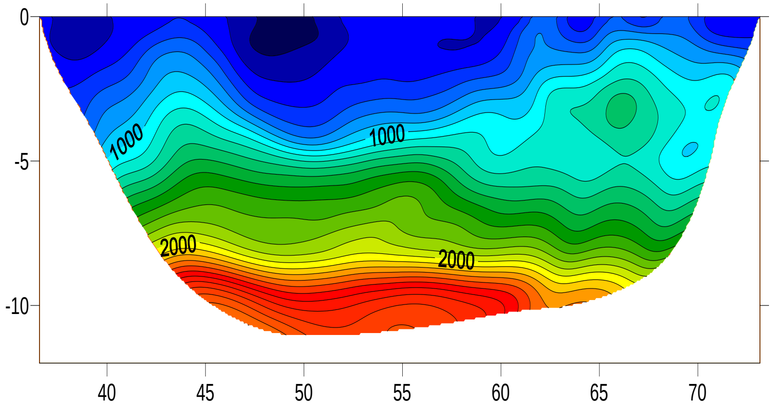


Background (cont'd)

Surface-based tomography: seismic refraction

- 2-D variation
- Can miss velocity reversals
- Poor resolution at depth
- Long array to achieve depth

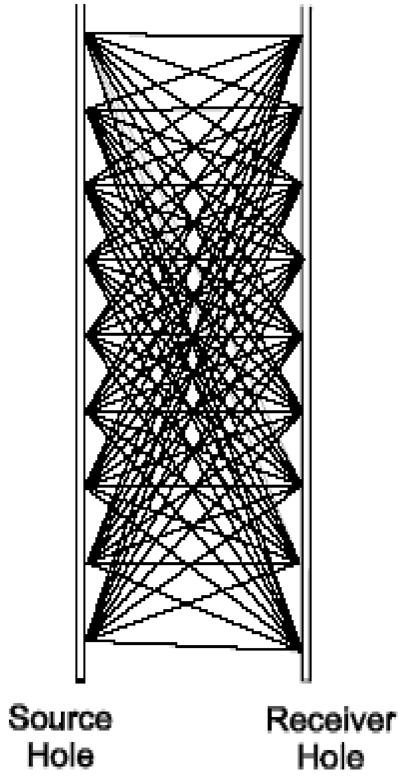


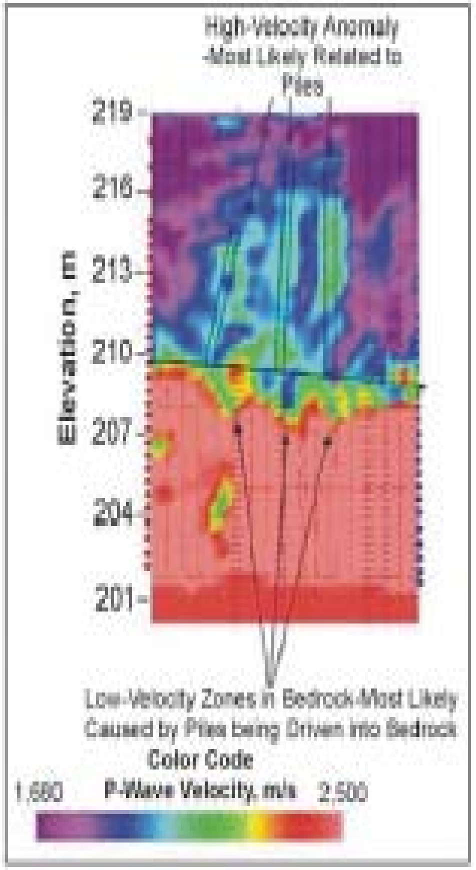


Background (cont'd)

Crosshole tomography

- 2-D variation
- Most effective
- Too costly: requires multiple boreholes

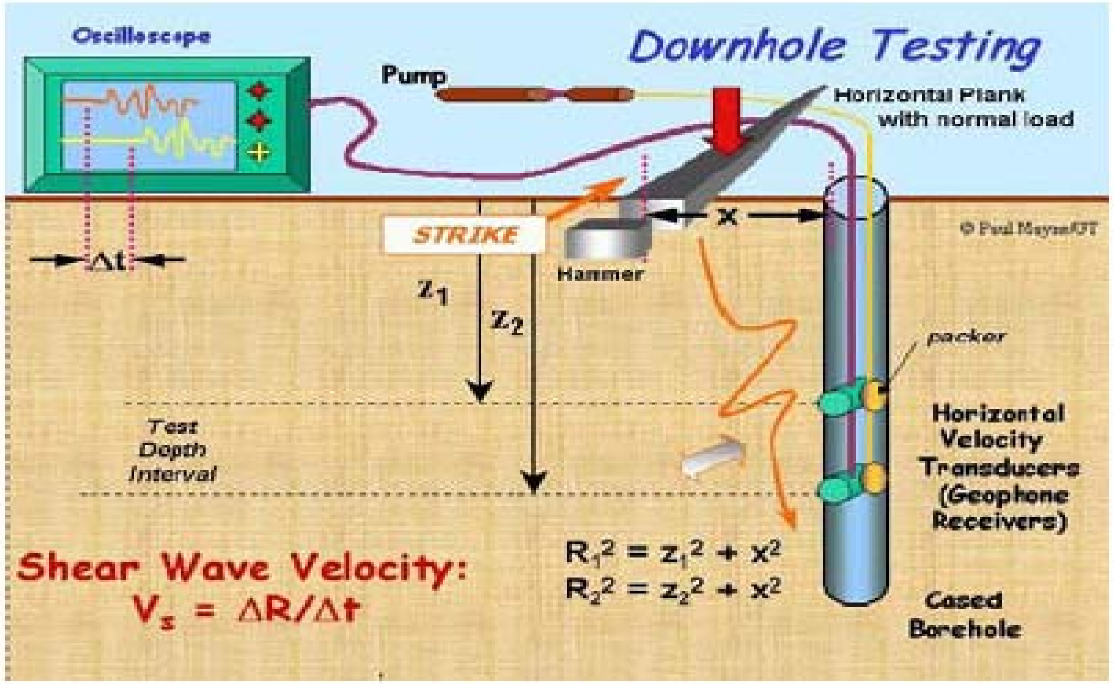




Background (cont'd)

Seismic downhole or seismic CPT

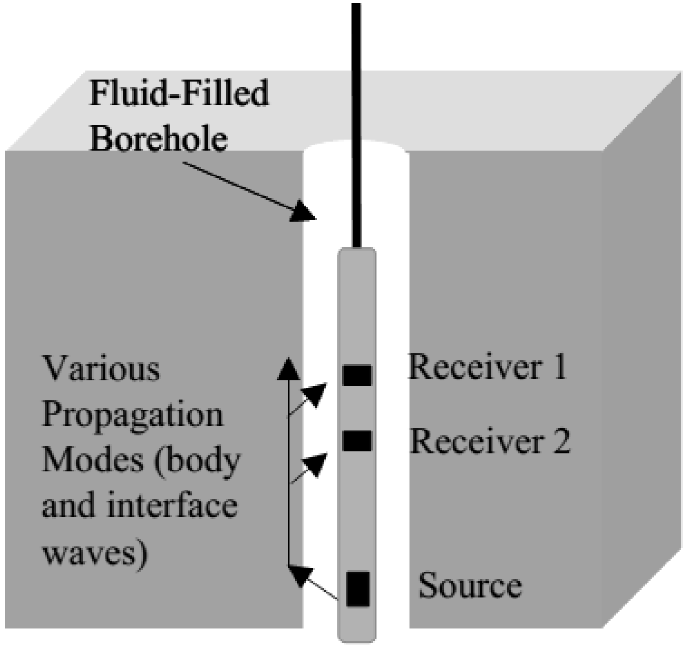
- 1-D variation in seismic velocities vs. depth
- No lateral variation around borehole

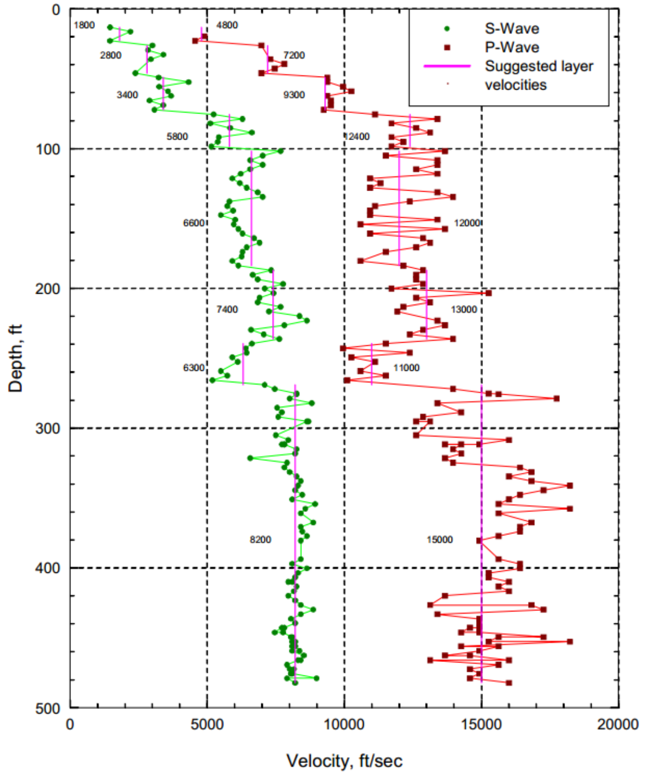


<u>**Background** (cont'd)</u>

Suspension P-S Logging

- 1-D variation in seismic velocities vs. depth
- No lateral variation around borehole

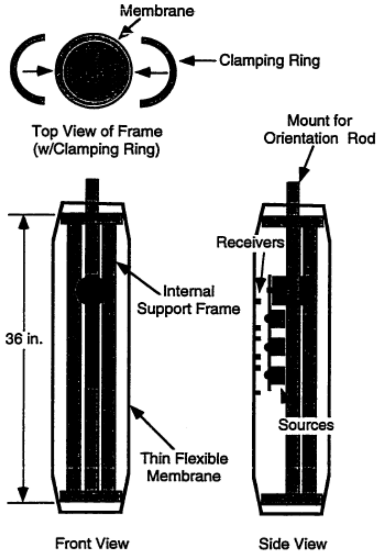


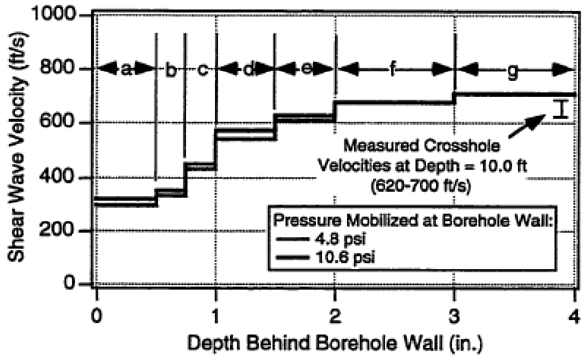


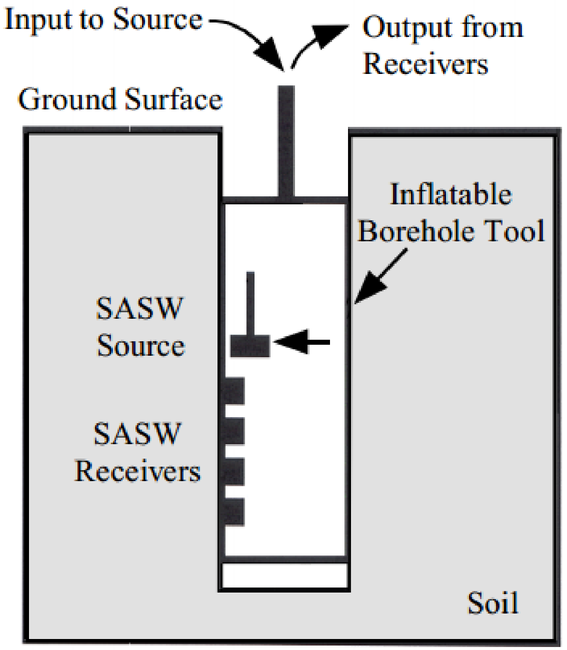
Recent efforts on inhole characterization

Borehole SASW (UT Austin)

- Mechanical borehole tool in dry holes
- 1-D lateral variation in S-wave velocities
- Only a few inches of penetration
- Geotechnical investigation



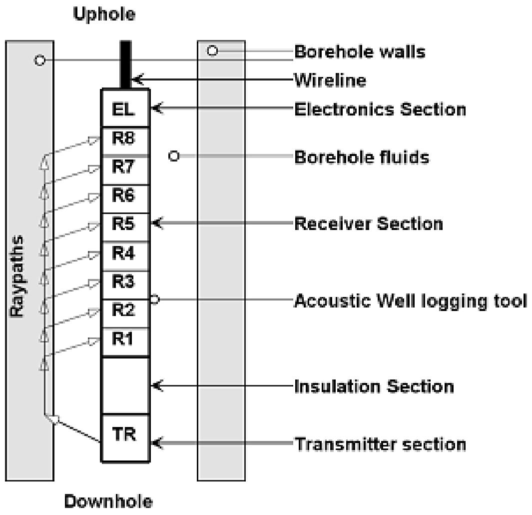


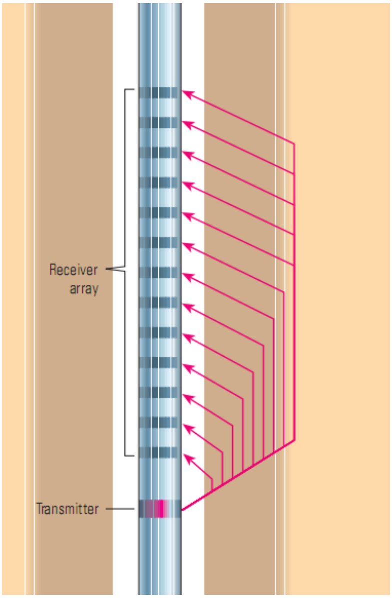


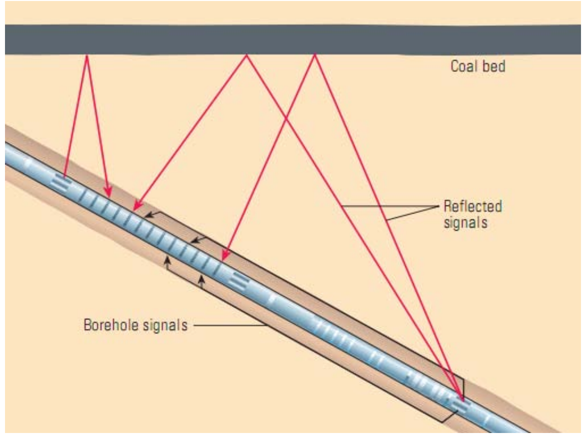
Recent efforts on inhole characterization (cont'd)

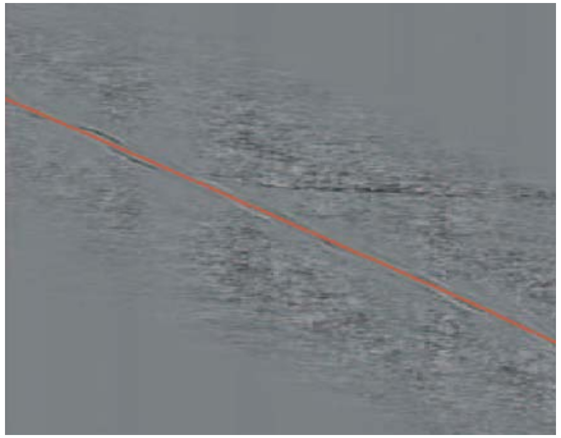
Sonic logging (Univ. of Calgary)

- Sonic logging tool in fluid-filled boreholes
- Refracted and reflected signals
- Migration-type of analysis
- No quantitative information
- Oil/Gas exploration







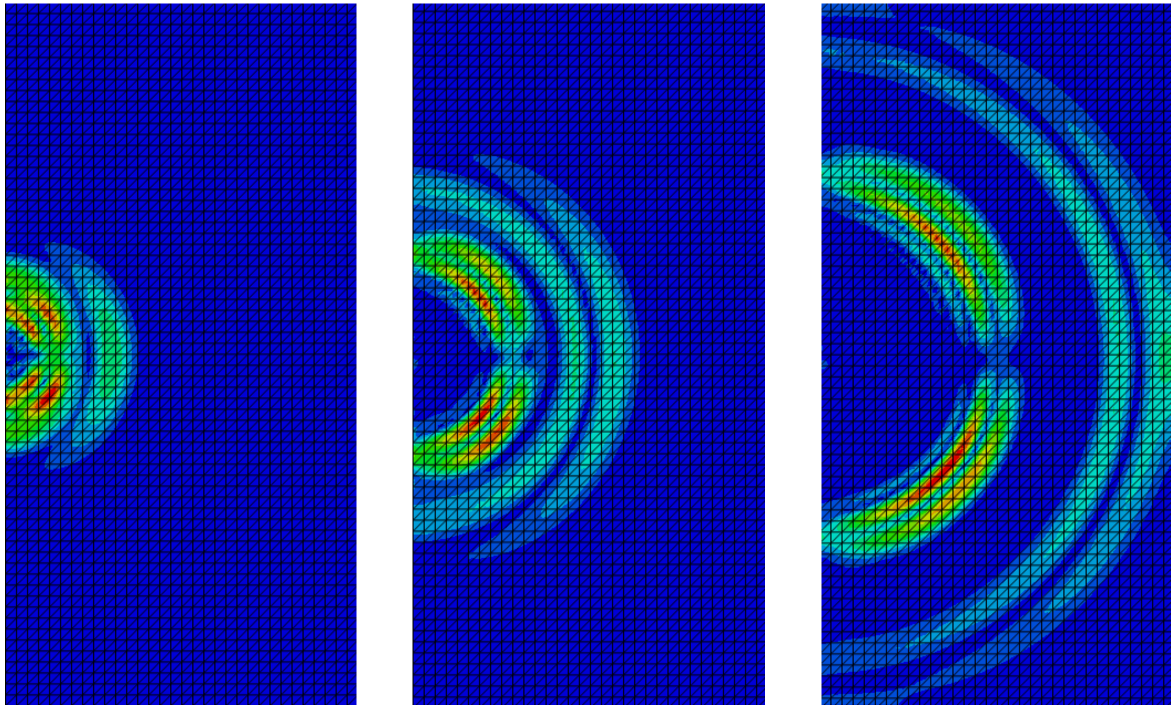


Proposed imaging technique
(overview of full waveform inversion)

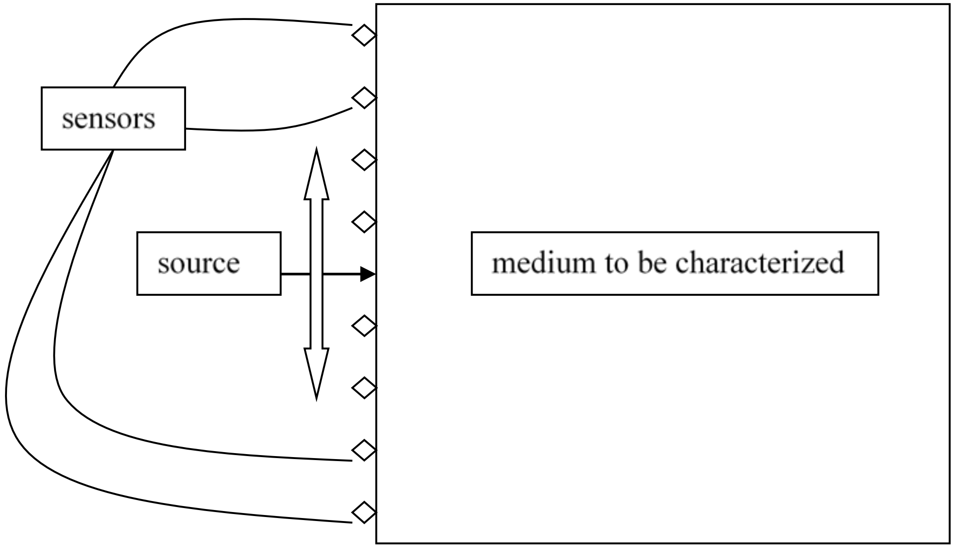
Make use of the entire seismic wavefield (amplitude and phase) to infer subsurface property

Require solving the elastic wave equations numerically (finite difference or finite element)

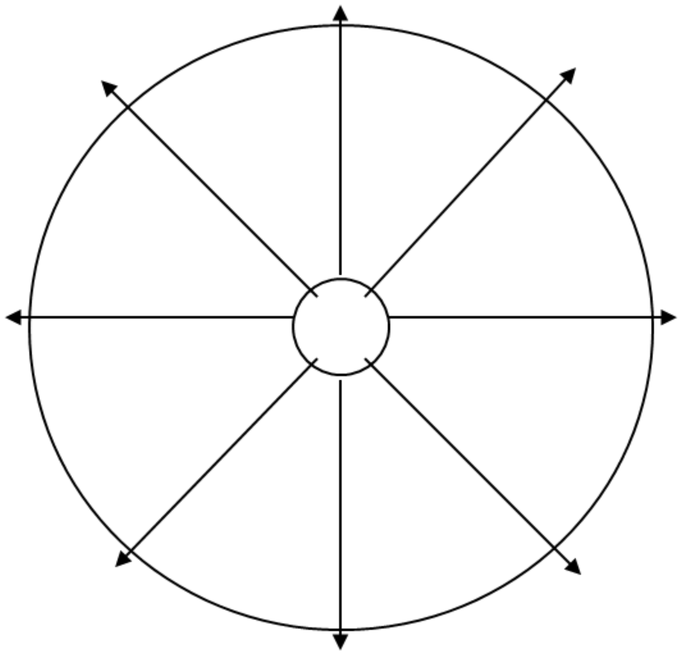
Automatically handle the multipathing, mode conversion, and other complex wavefield phenomena



Proposed imaging technique
(experimental design)



Multiple shots



Multiple planes

Proposed imaging technique (forward model)

Plane-strain, flat ground model cannot simulate borehole environment

Geometry-induced dispersion
Near-field effect

Finite element modeling using Abaqus

Axisymmetric forward model
Divided into 36 velocity cells
diameter=5cm, length=4m, width=2m

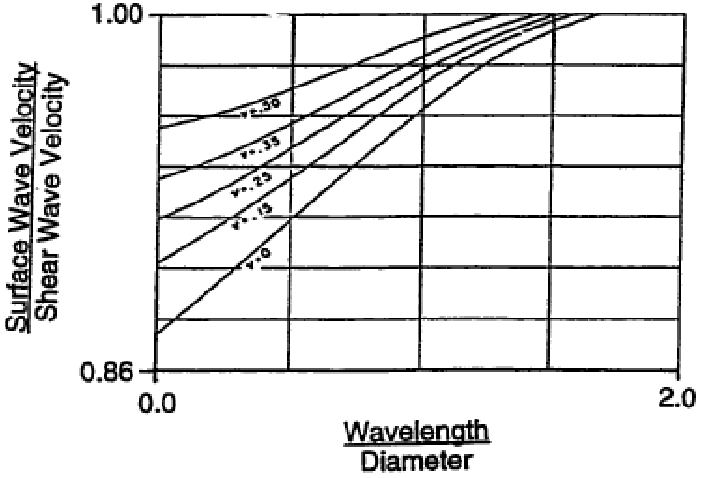
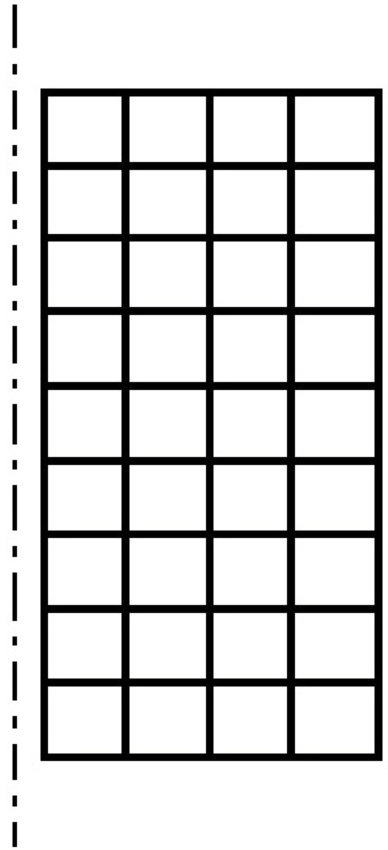
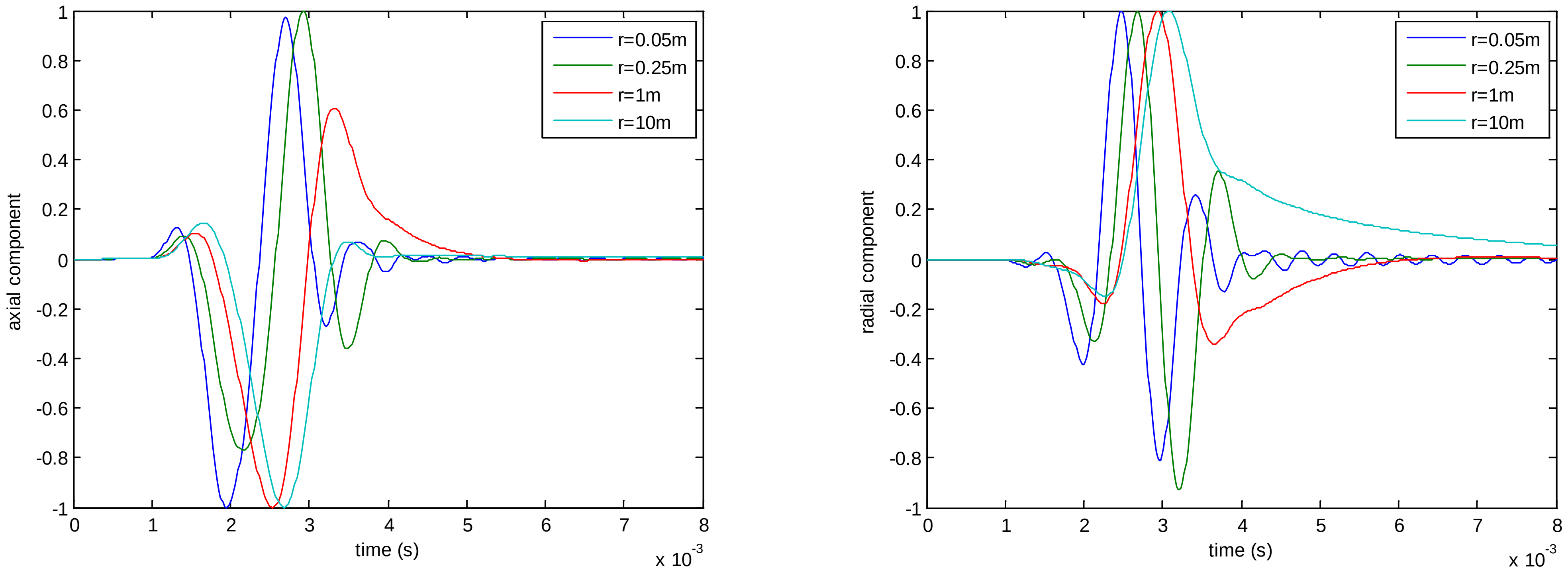


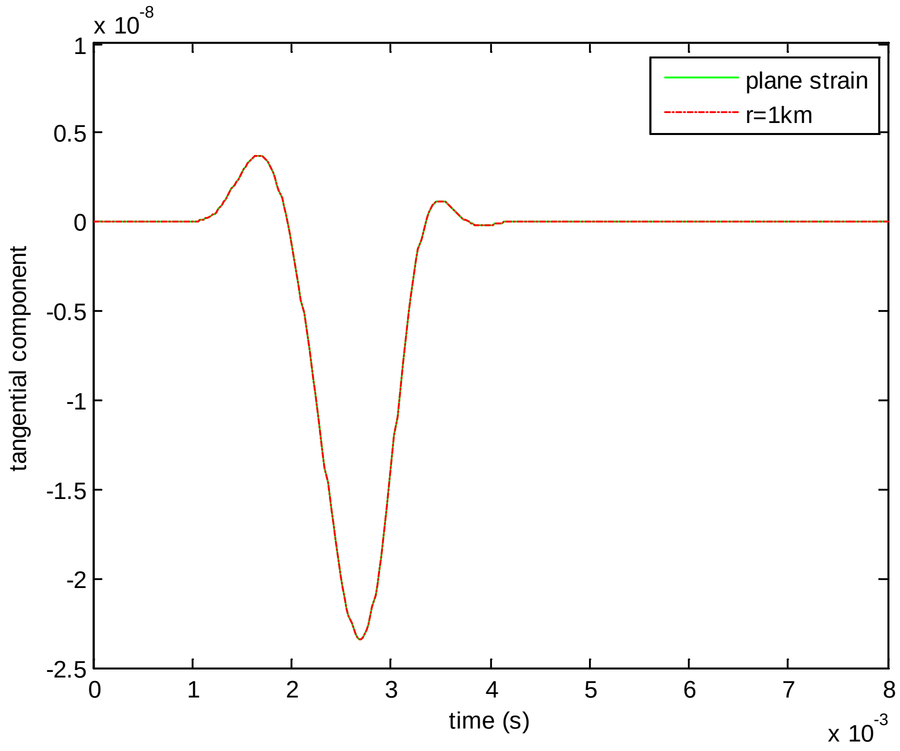
Figure 2.11. Geometry-Induced Dispersion of a Surface Wave Propagating Axially in an Uncased, Empty Cylindrical Cavity (Biot, 1952).

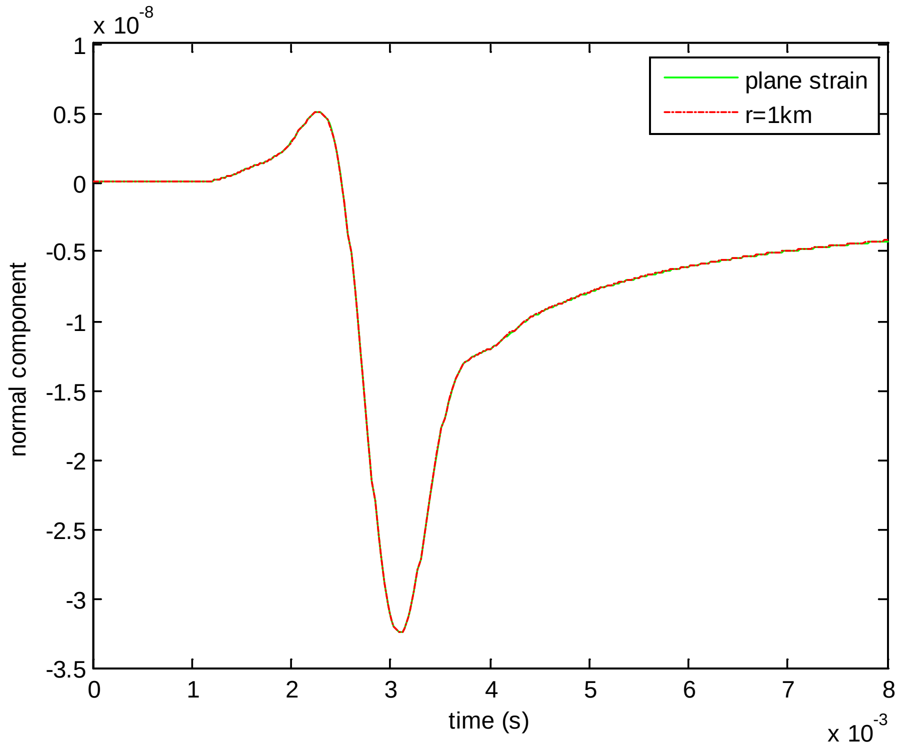


Proposed imaging technique (forward model)



Proposed imaging technique (forward model)



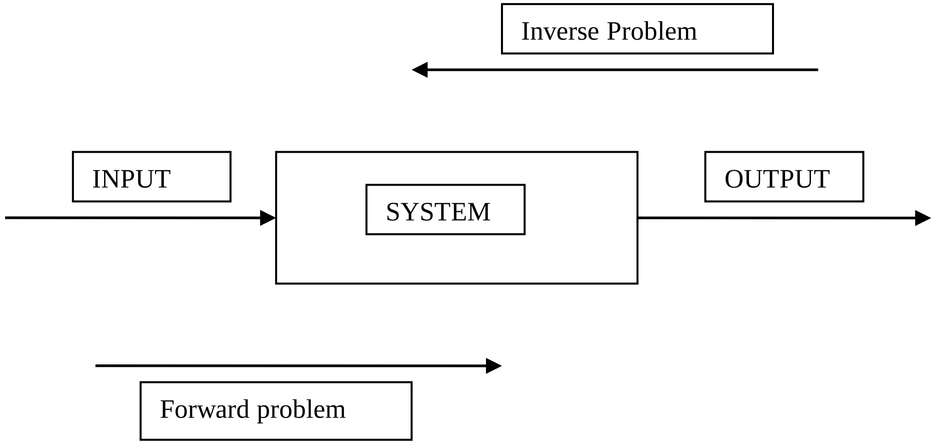


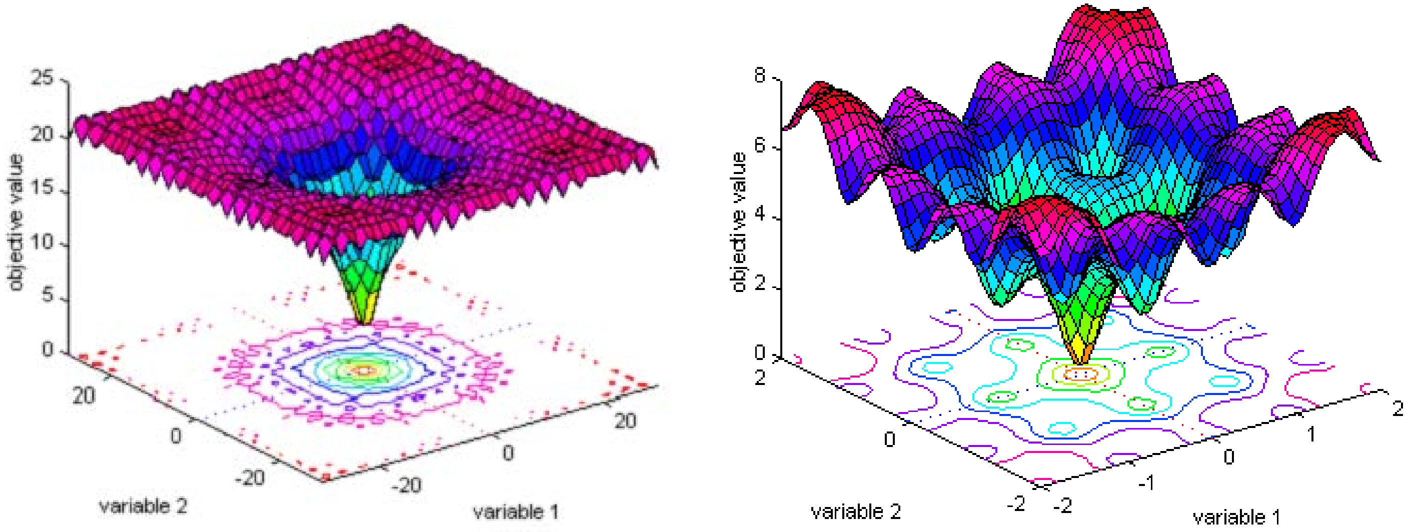
Proposed imaging technique (Inversion)

- Goal: determine unknown parameters from measurement by assuming a model that relates the two

- Ingredients: a forward model and an optimization technique

- Characteristics: highly nonlinear model-data relationship → multi-modal objective function ⟶ non-unique solution





Proposed imaging technique (Inversion)

- **Regularized Gauss-Newton Method**

  - Residual wave field: $\Delta \mathbf{d} = \mathbf{F}(\mathbf{m}) - \mathbf{d}$
  - Least-squares error: $\mathrm{E}(\mathbf{m}) = \frac{1}{2} \Delta \mathbf{d}^t \, \Delta \mathbf{d}$
  - Model updating: $\mathbf{m}^{n+1} = \mathbf{m}^n - \alpha^n [\mathbf{J}^t \mathbf{J} + \lambda_1 \mathbf{P}^t \mathbf{P} + \lambda_2 \mathbf{I}^t \mathbf{I}]^{-1} \mathbf{J}^t \Delta \mathbf{d},$
  - Gradient matrix J: $\mathbf{J} = \frac{\partial \, \mathbf{F}(\mathbf{m})}{\partial m_p}$
  - Step length:

$$\alpha^n \cong \frac{[\mathbf{J}^t g^n]^t [\mathbf{F}(\mathbf{m}^n) - \mathbf{d}]}{[\mathbf{J}^t g^n]^t [\mathbf{J}^t g^n]},$$

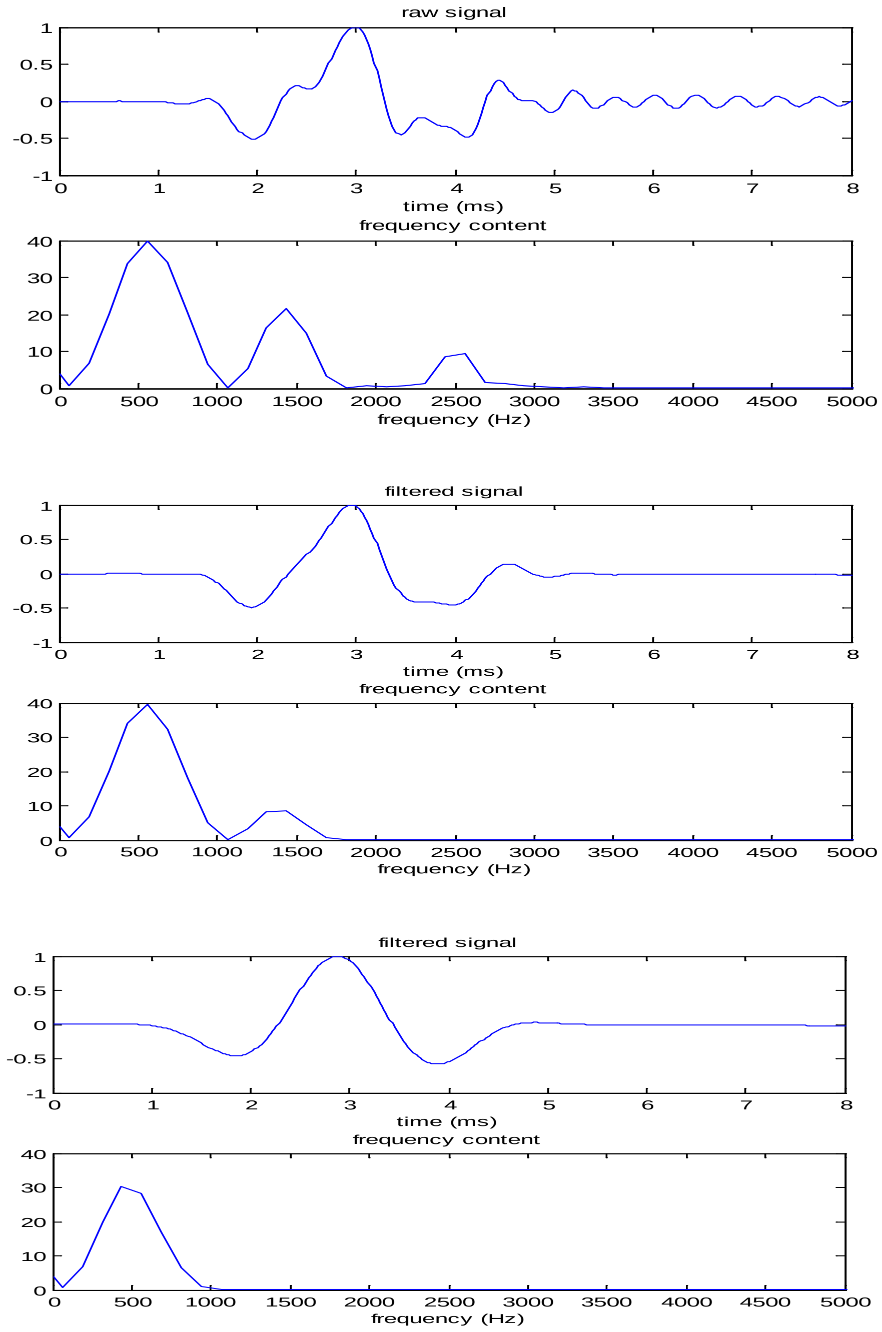
$$g^n = [\mathbf{J}^t \mathbf{J} + \lambda_1 \mathbf{P}^t \mathbf{P} + \lambda_2 \mathbf{I}^t \mathbf{I}]^{-1} \mathbf{J}^t [\mathbf{F}(\mathbf{m}^n) - \mathbf{d}].$$

Proposed imaging technique (Inversion)

Multiscale strategies

1) frequency filtering

2) temporal windowing

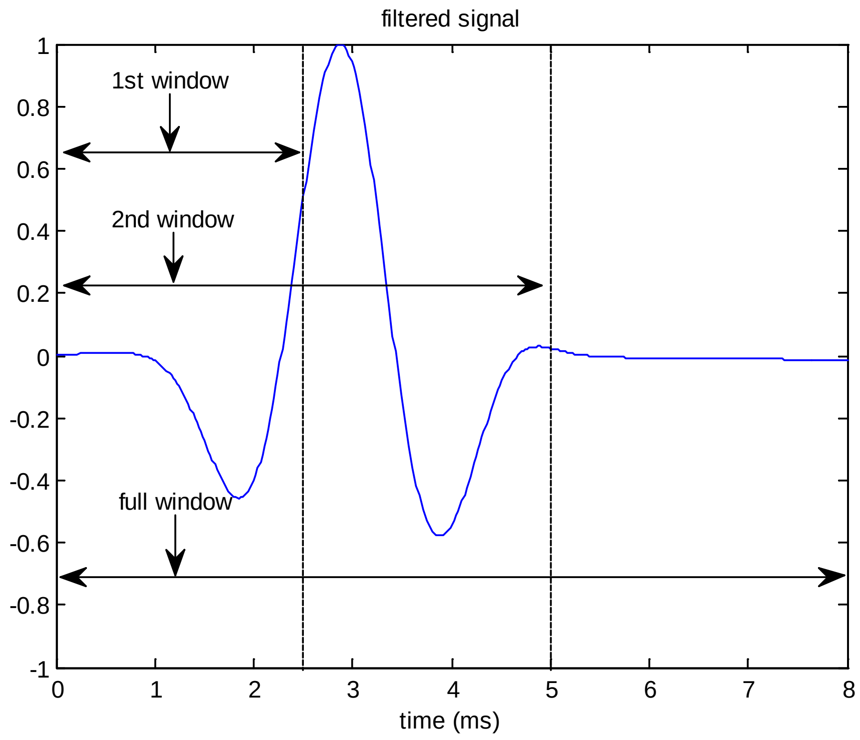


Proposed imaging technique (Inversion)

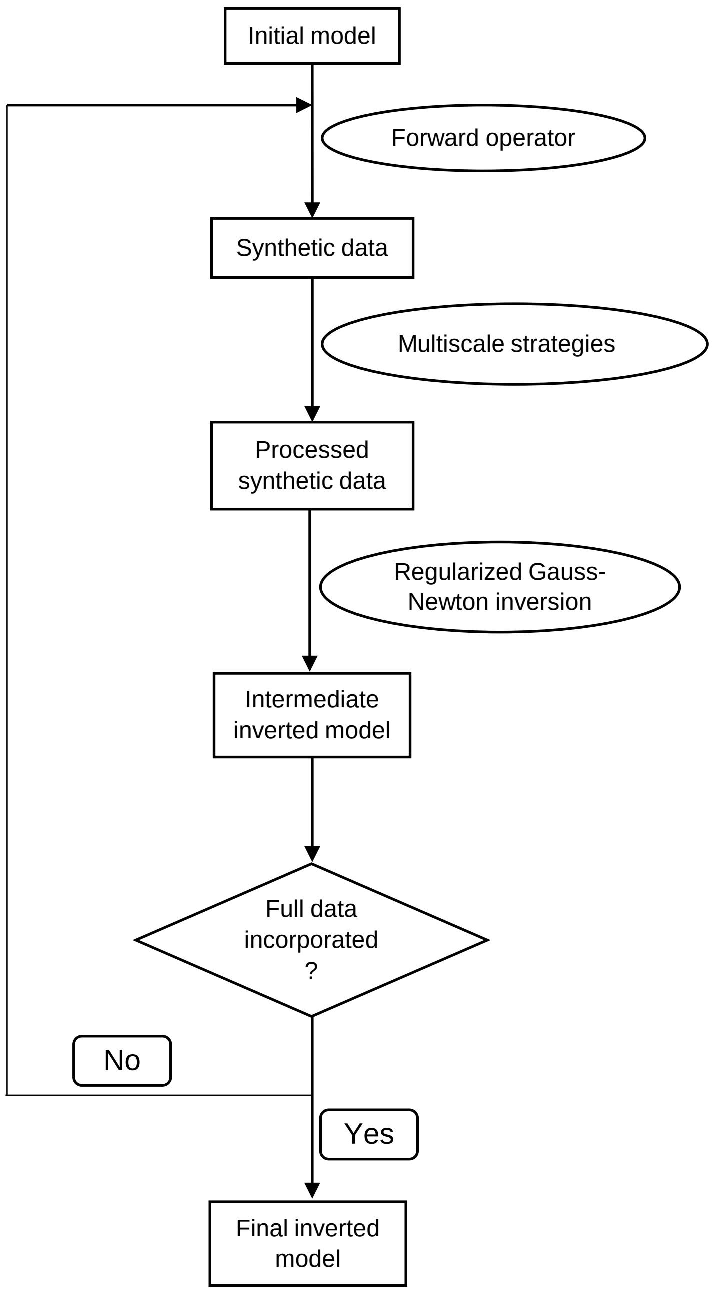
Multiscale strategies

1) frequency filtering

2) temporal windowing



Proposed imaging technique (Inversion)



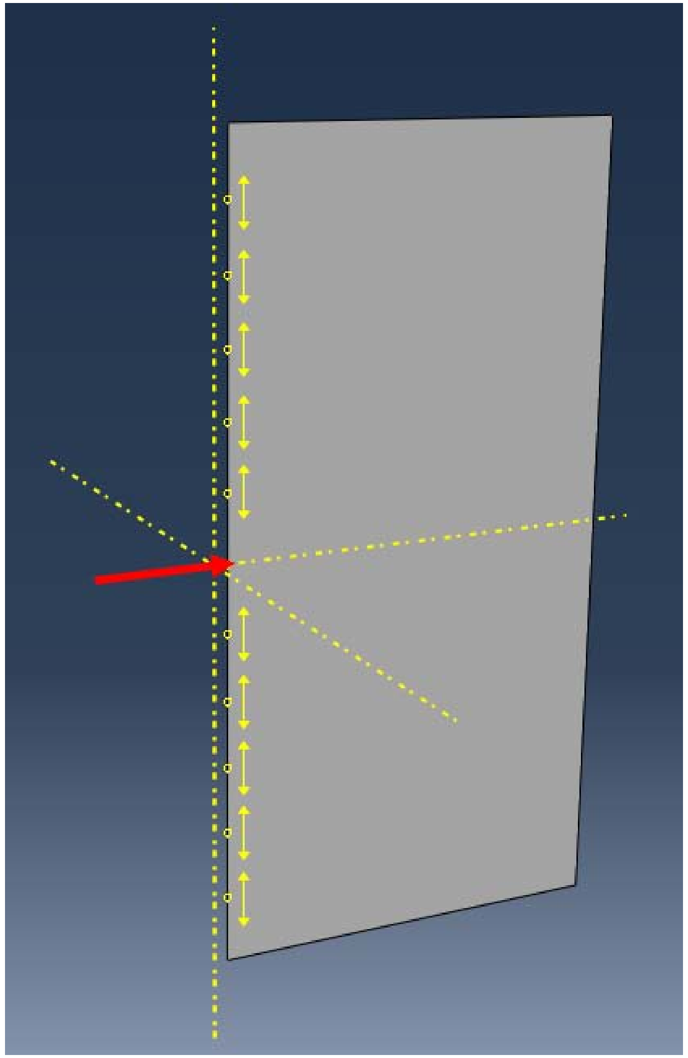
Synthetic model studies
(Axisymmetric model)

Schematic of synthetic experiment

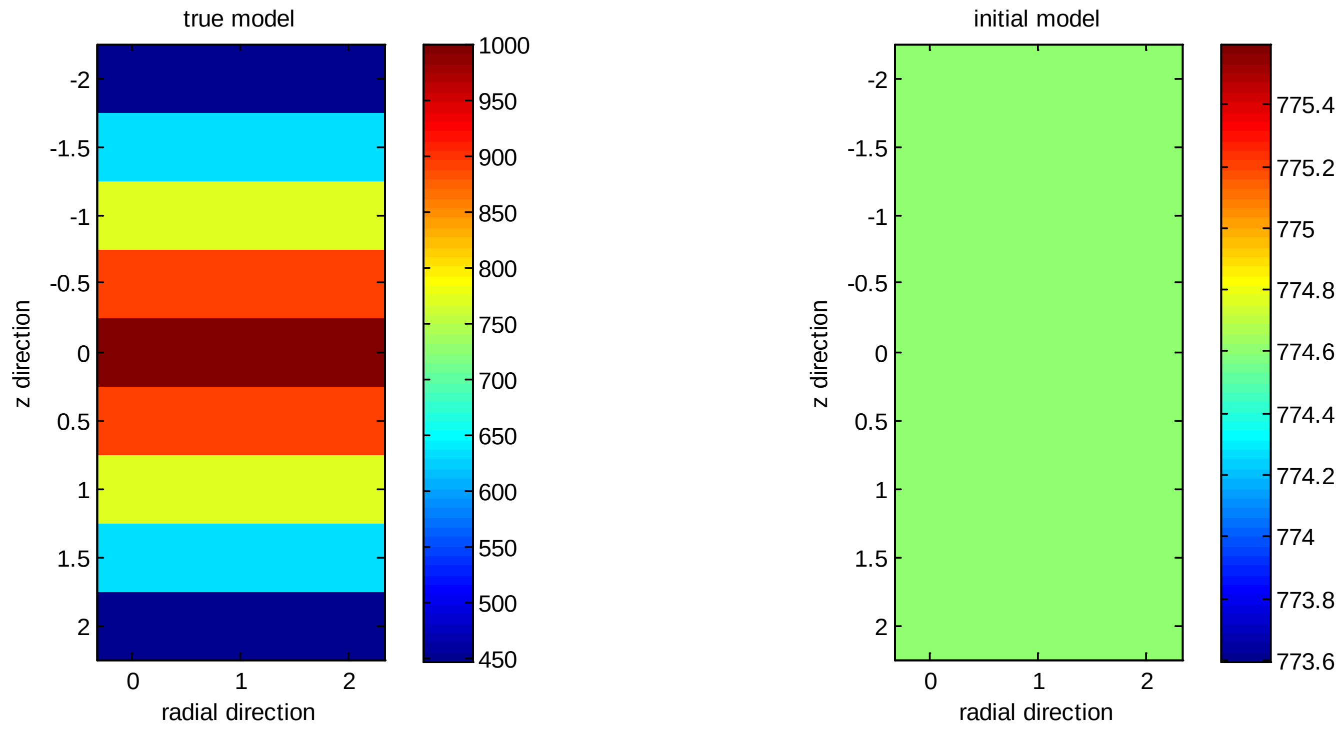
Forward model: axisymmetric borehole

Data: generated from the forward model

Inversion: regularized GN method coupled with multiscale strategies

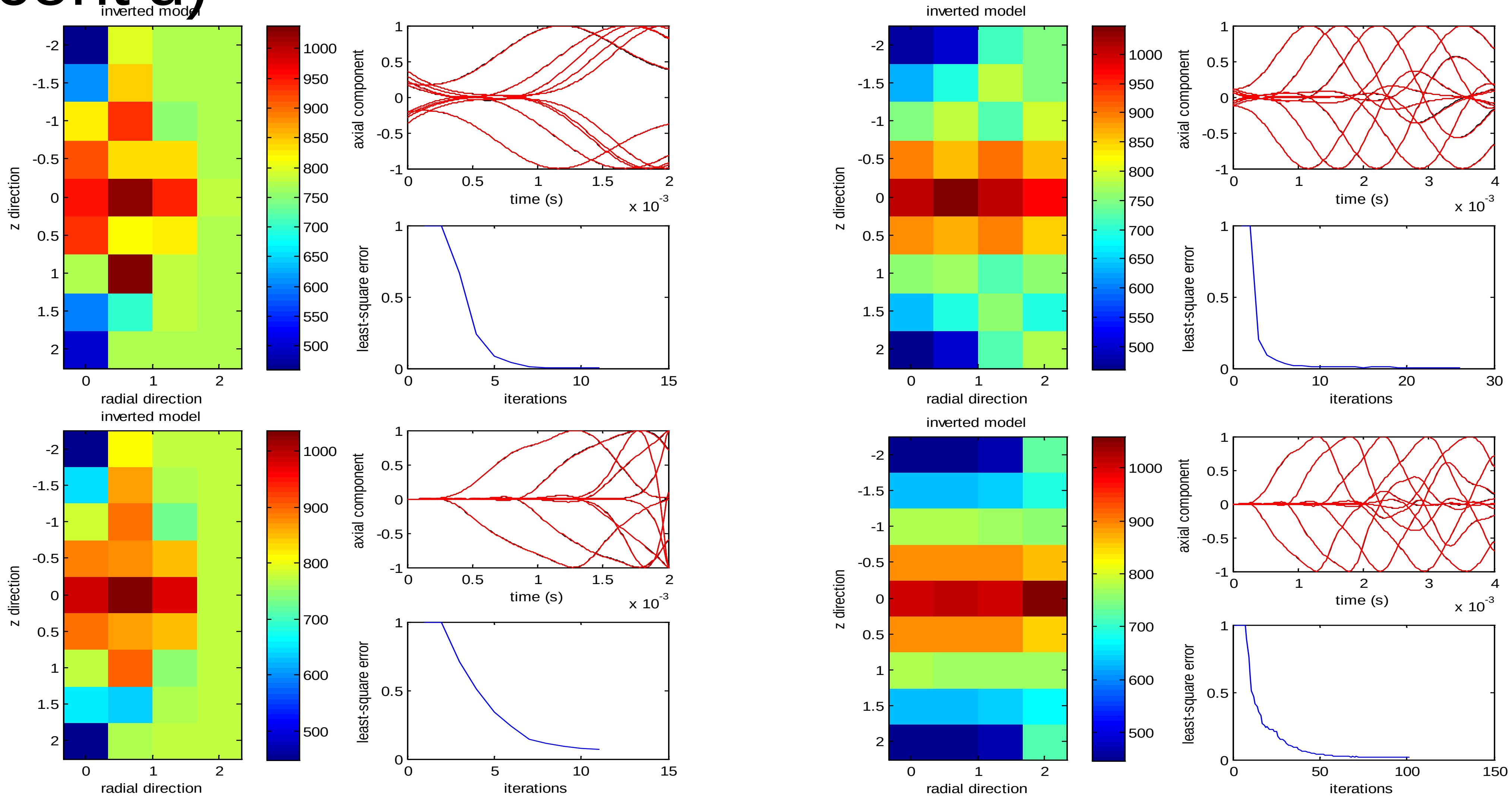


Synthetic model studies
(Axisymmetric model 1)

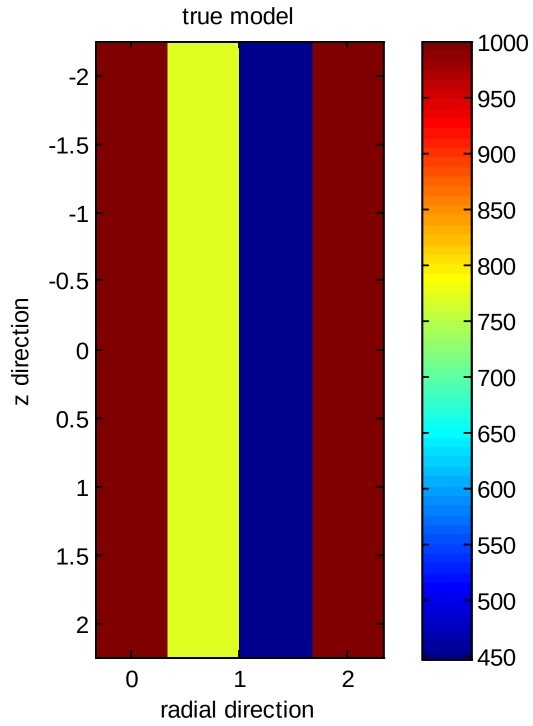


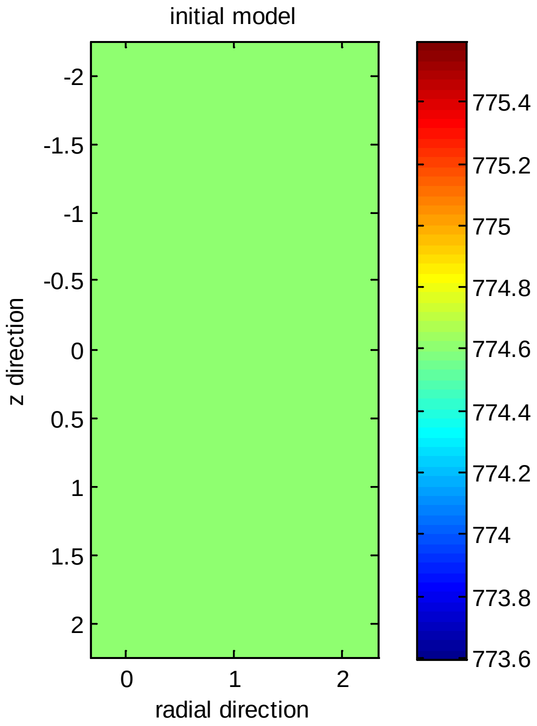
Synthetic model studies

(Axisymmetric model 1 – cont'd)

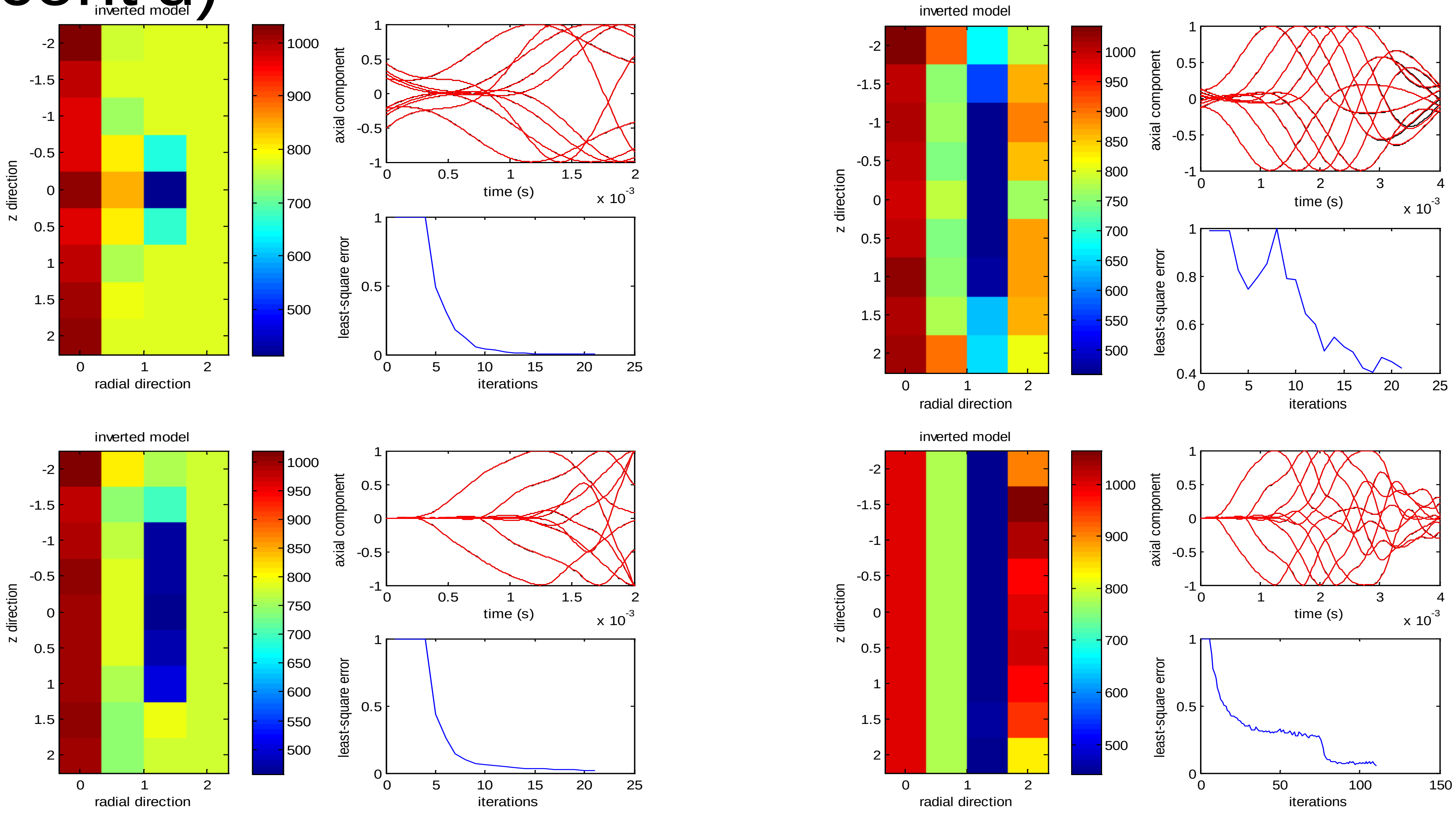


Synthetic model studies
(Axisymmetric model 2)





Synthetic model studies
(Axisymmetric model 2 – cont'd)



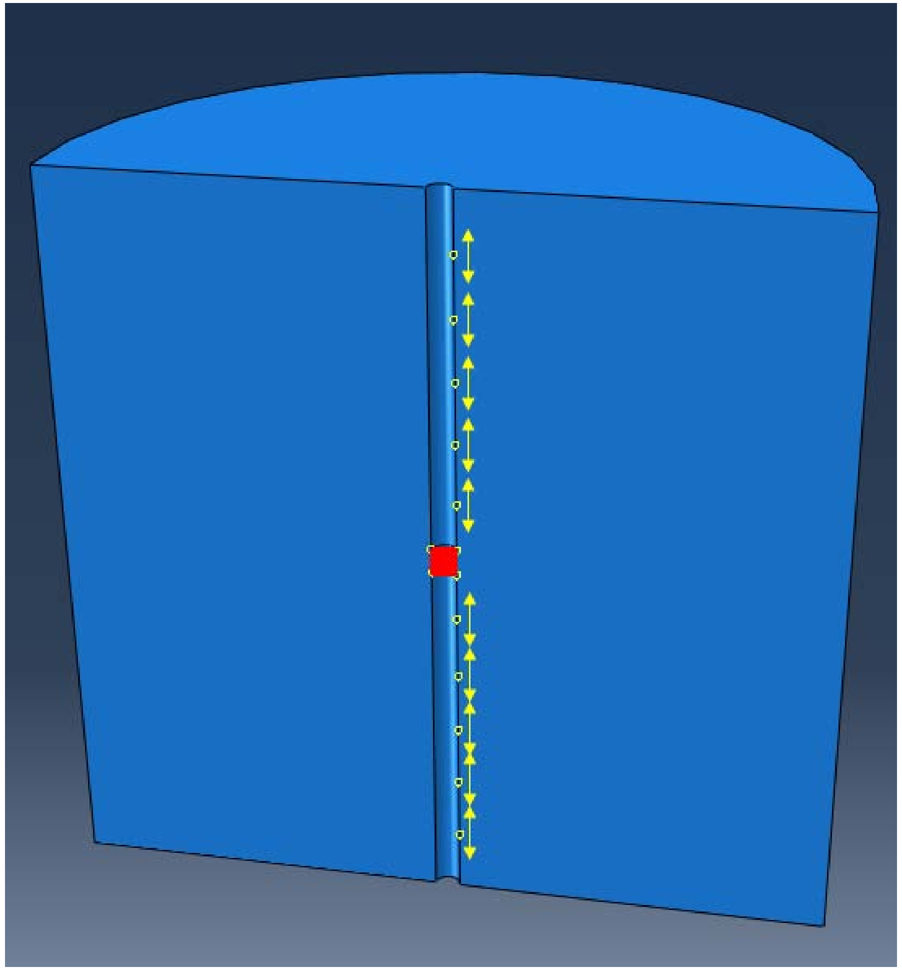
Synthetic model studies (3-D model)

Schematic of synthetic experiment

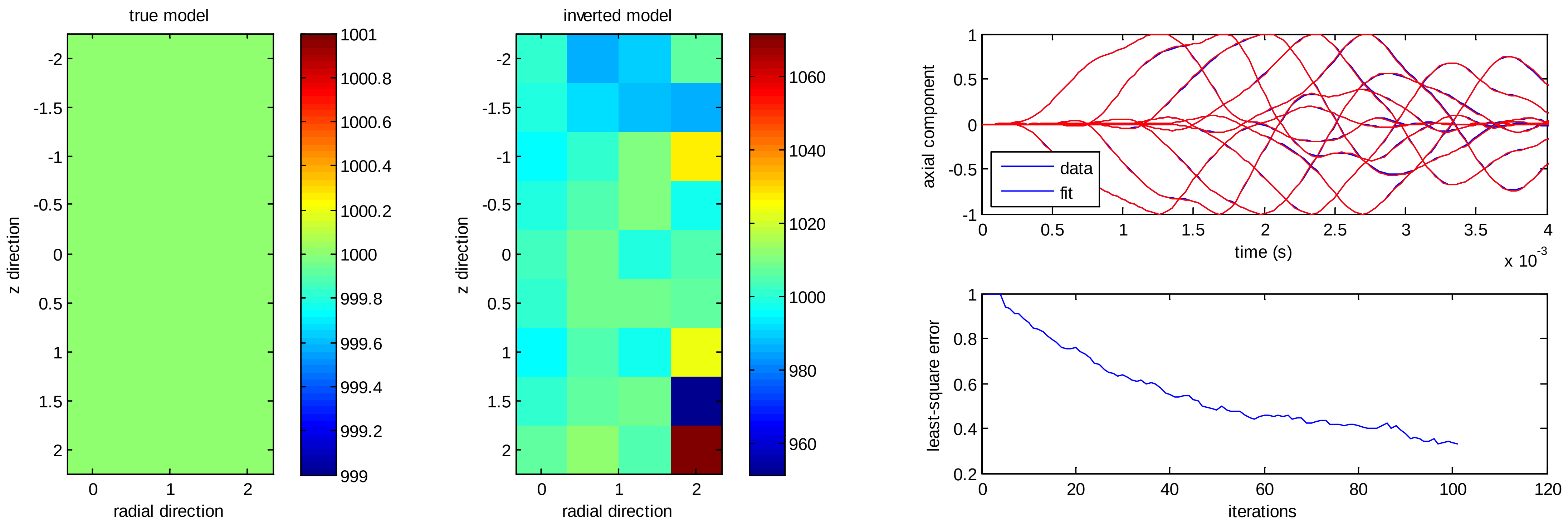
Forward model: axisymmetric borehole

Data: generated from 3-D model

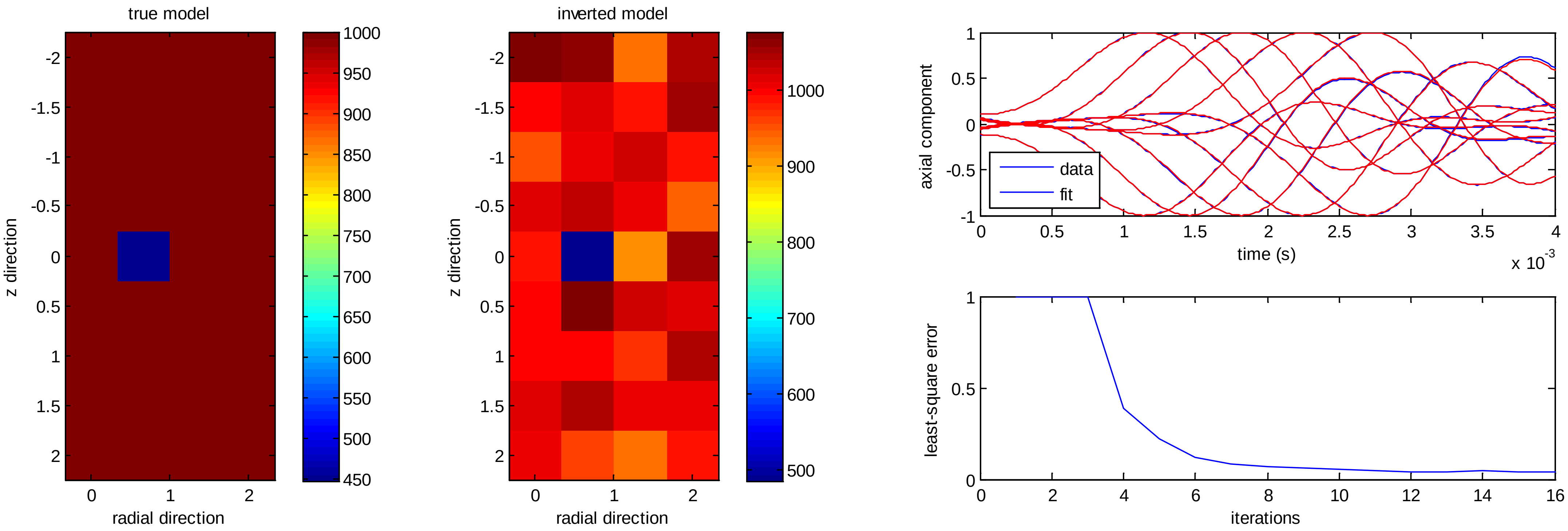
Inversion: regularized GN method coupled with multiscale strategies



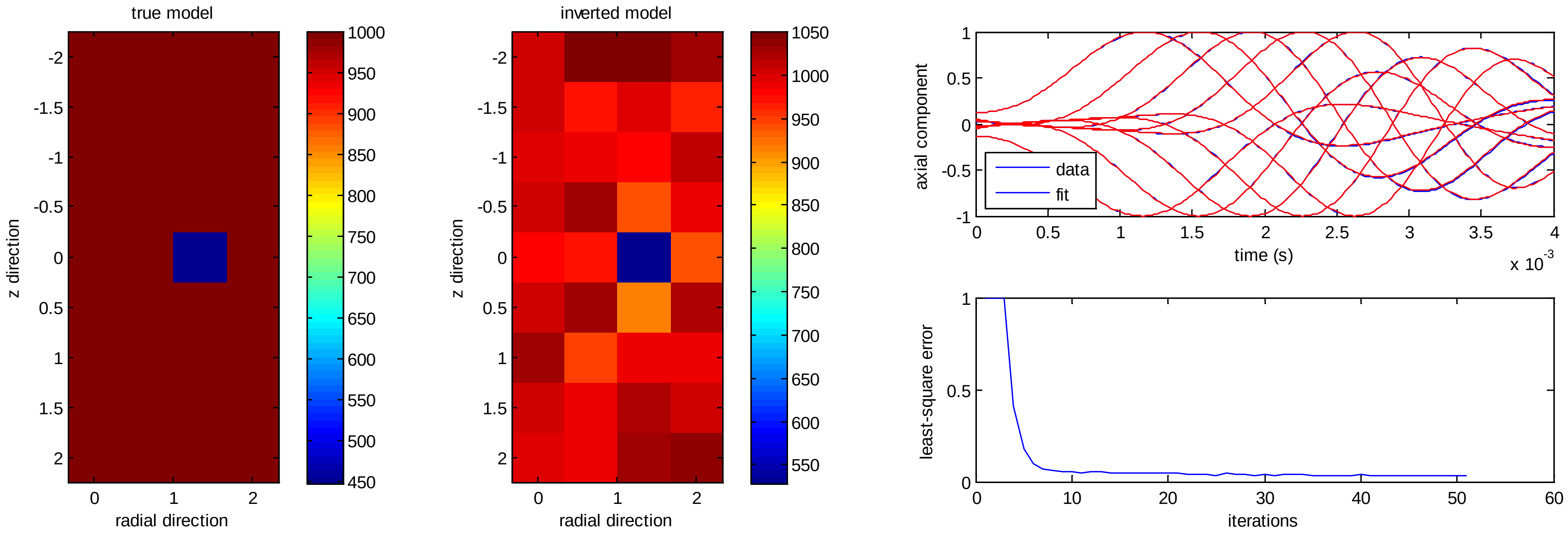
Synthetic model studies (3-D model 1)



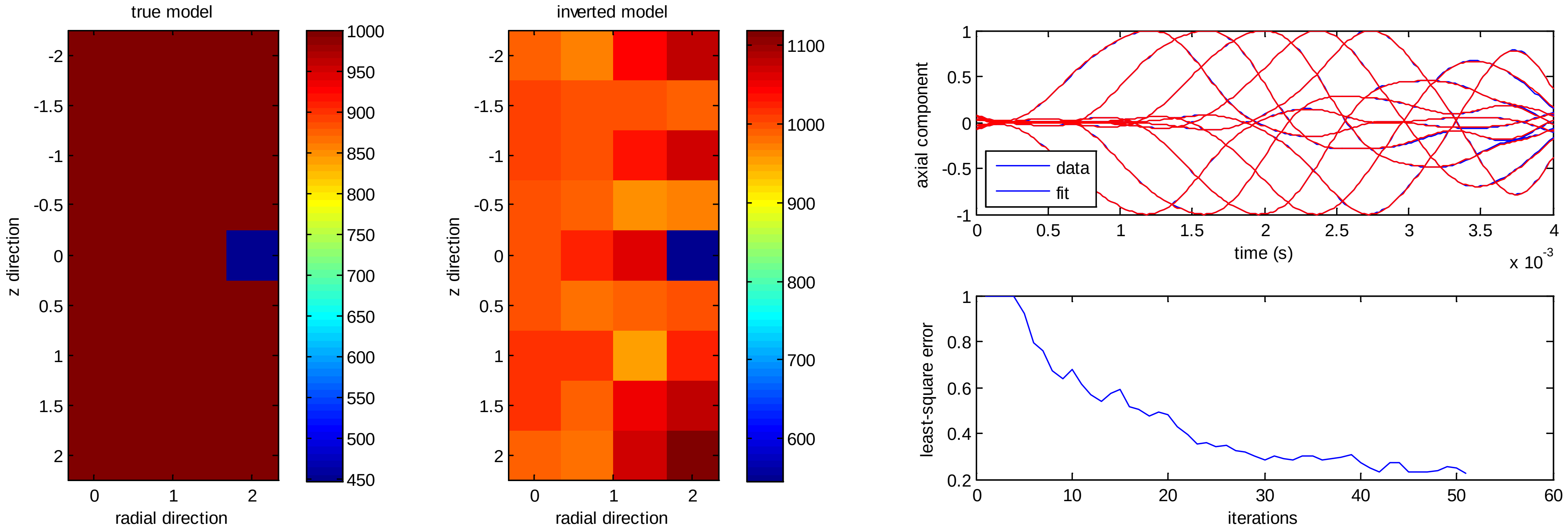
Synthetic model studies (3-D model 2)



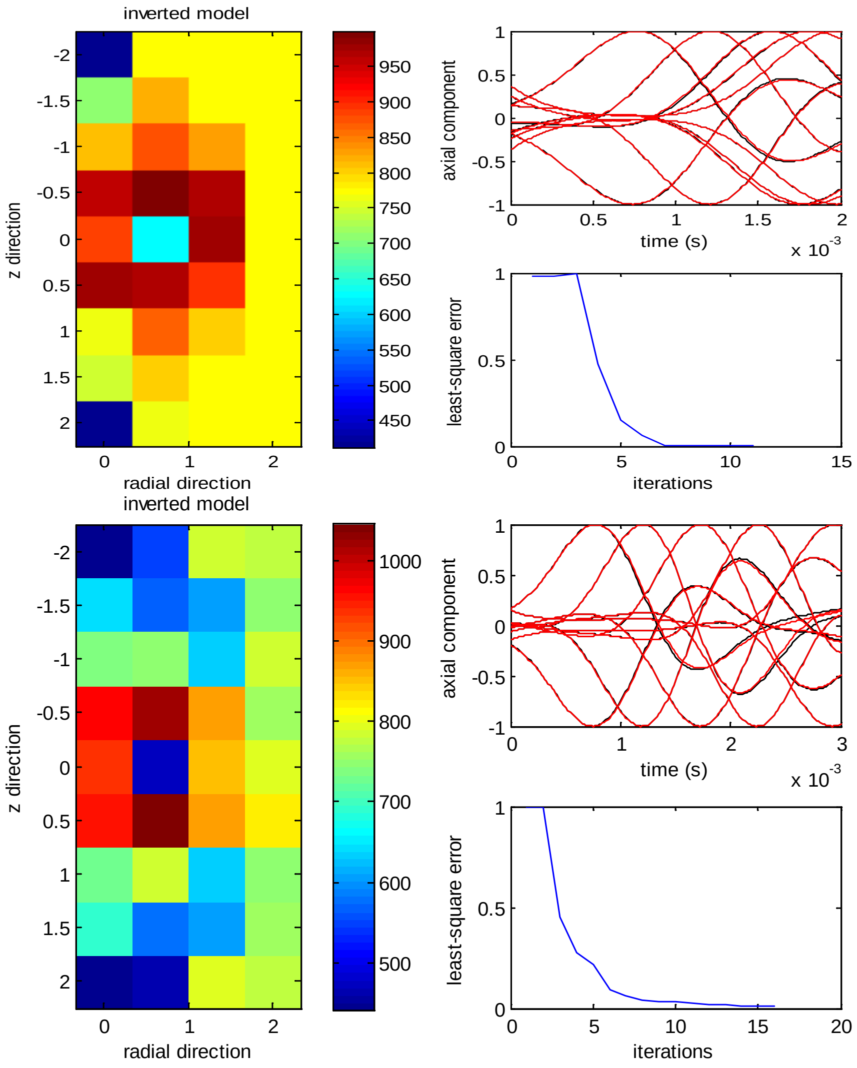
Synthetic model studies (3-D model 3)

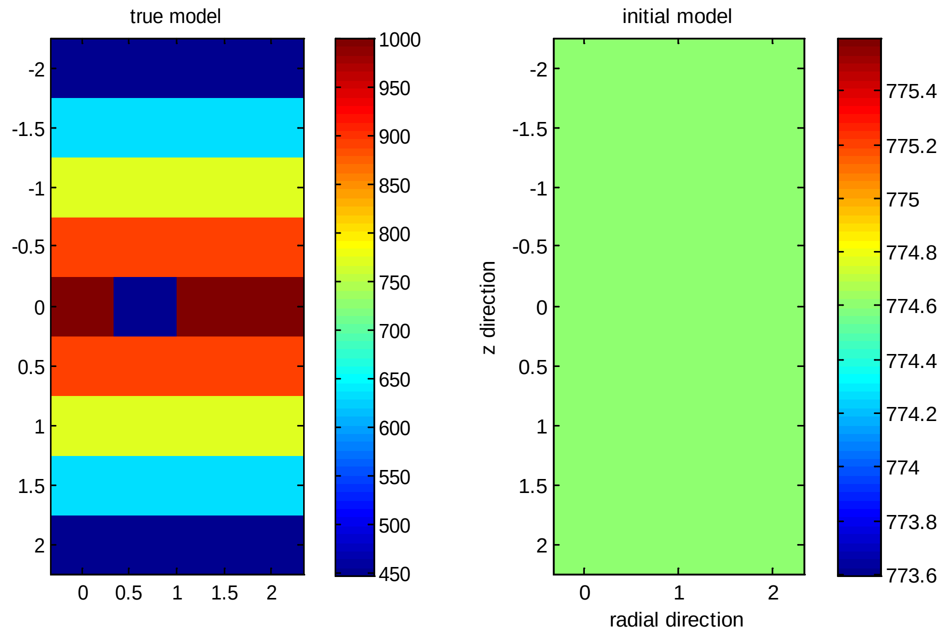


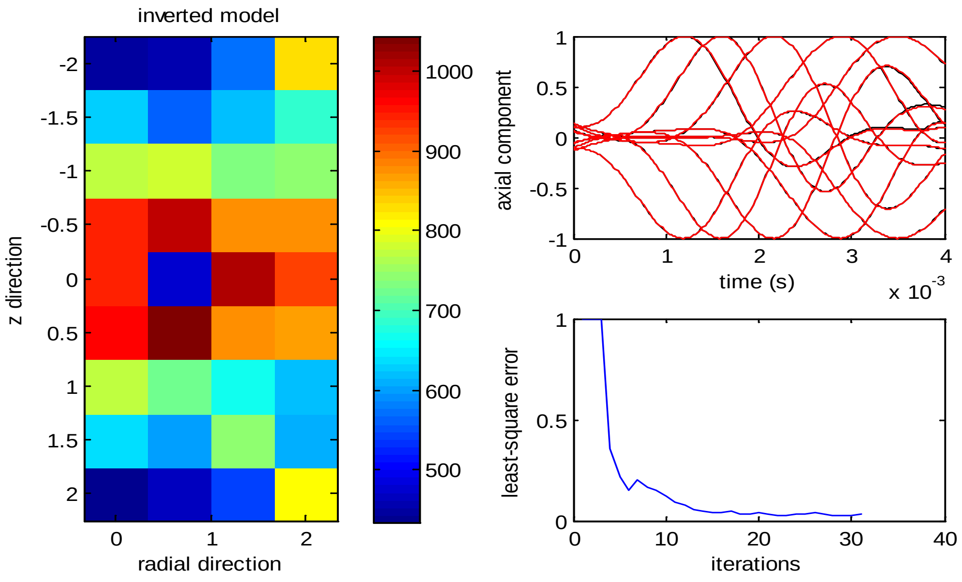
Synthetic model studies (3-D model 4)



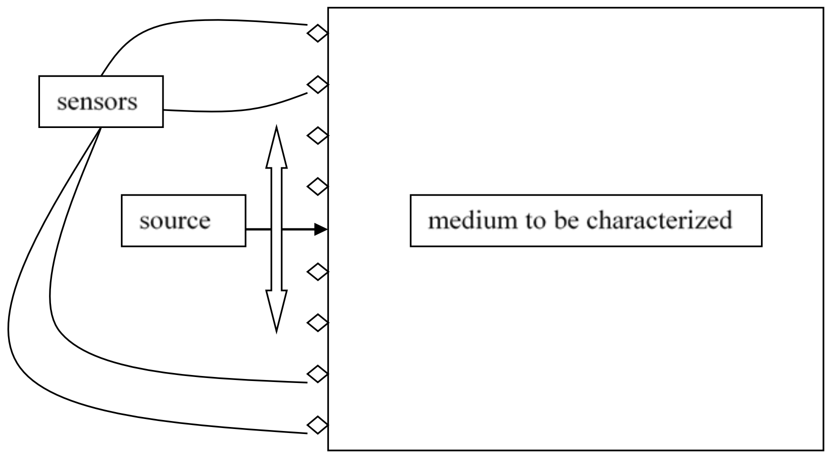
Synthetic model studies (3-D model 5)





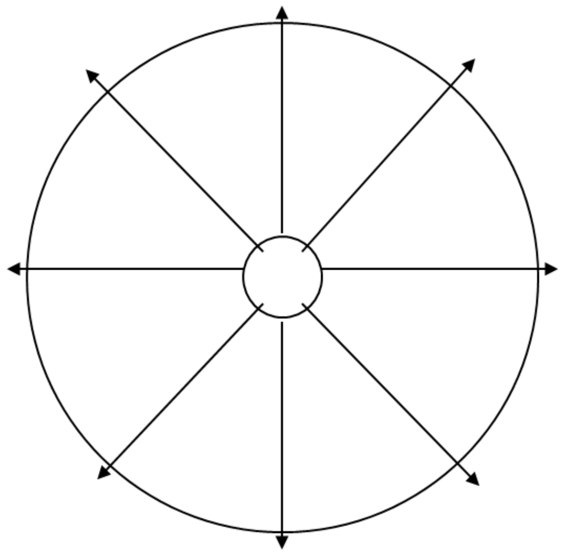


Synthetic model studies
(isolated anomaly)



Goal: use 2.5 D approximation to find indications of an isolated anomaly

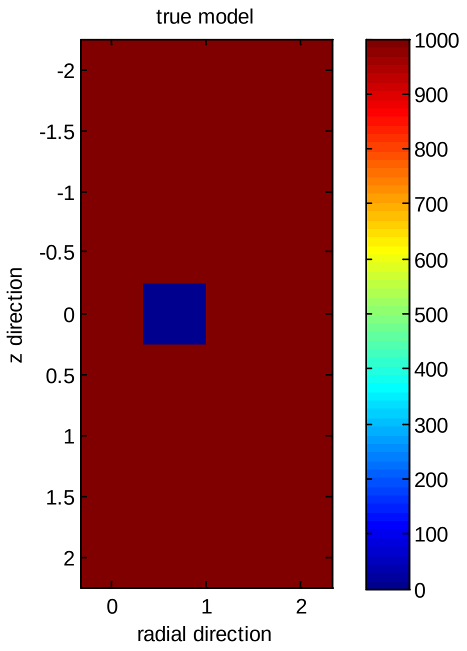
Forward model: axisymmetric borehole

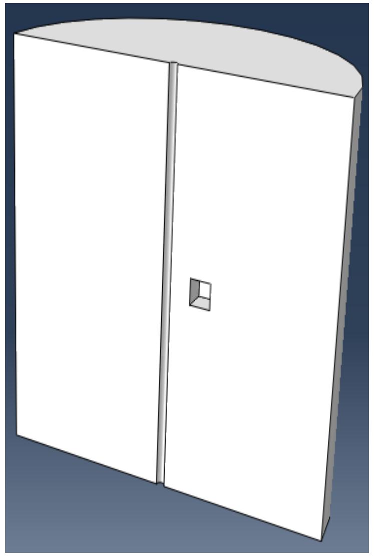


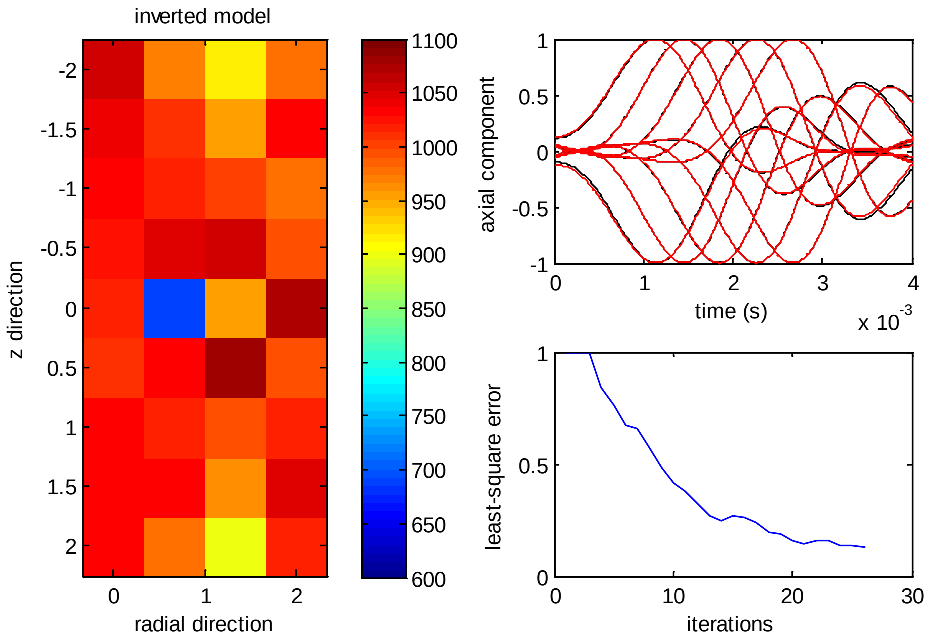
Data: generated from 3-D model with an isolated cavity

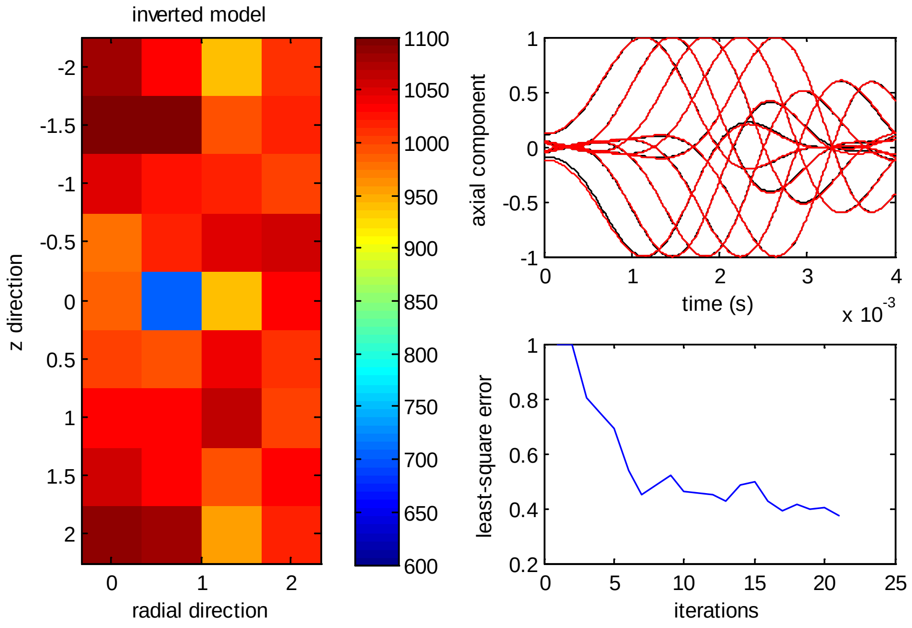
Inversion: regularized GN method coupled with multiscale strategies

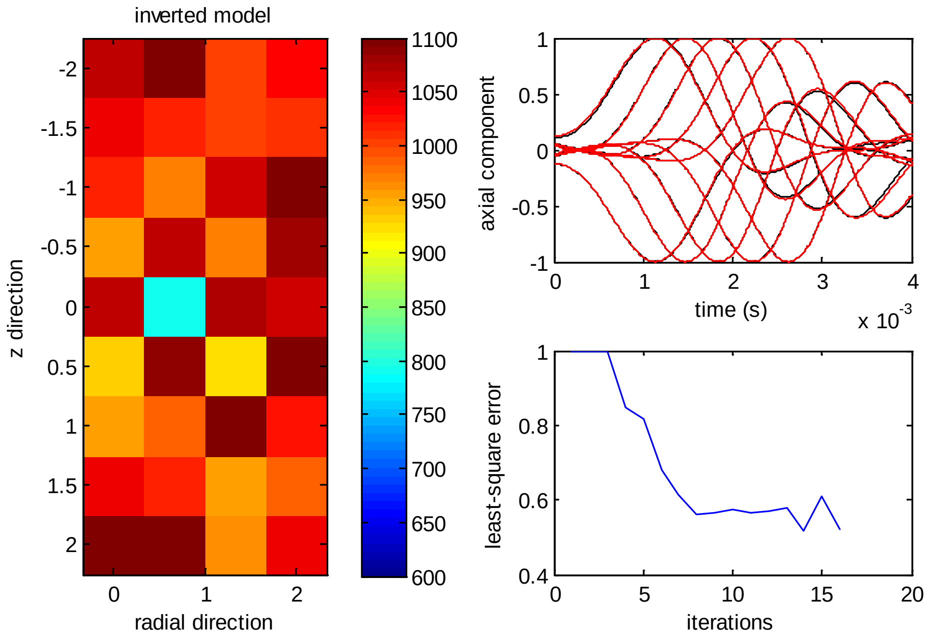
Model 1


true model
z direction
radial direction
-2
-1.5
-1
-0.5
0
0.5
1
1.5
2
0
1
2
1000
900
800
700
600
500
400
300
200
100
0

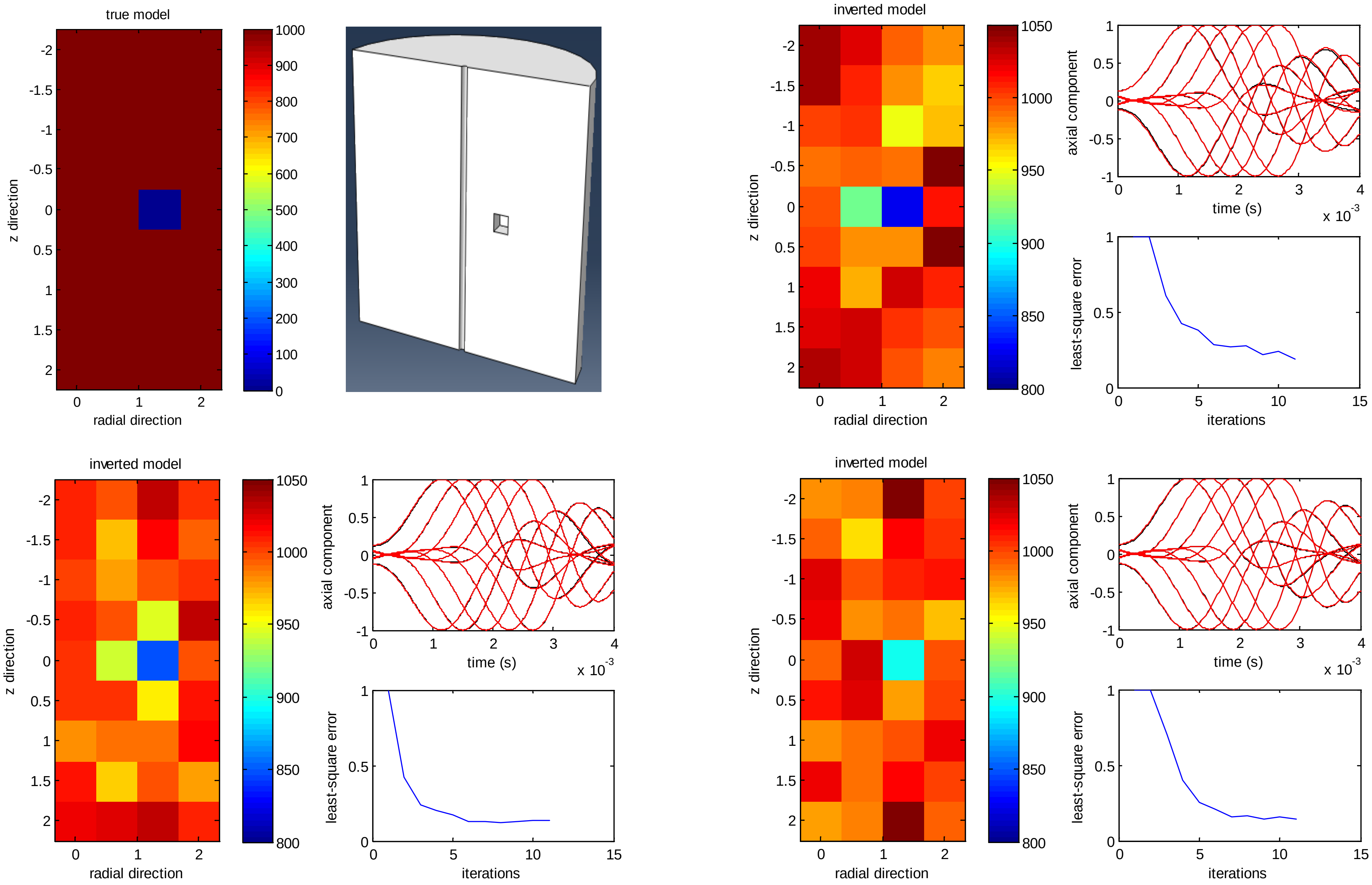



inverted model
z direction
radial direction
1100
1050
1000
950
900
850
800
750
700
650
600
axial component
time (s)
x 10^-3
least-square error
iterations

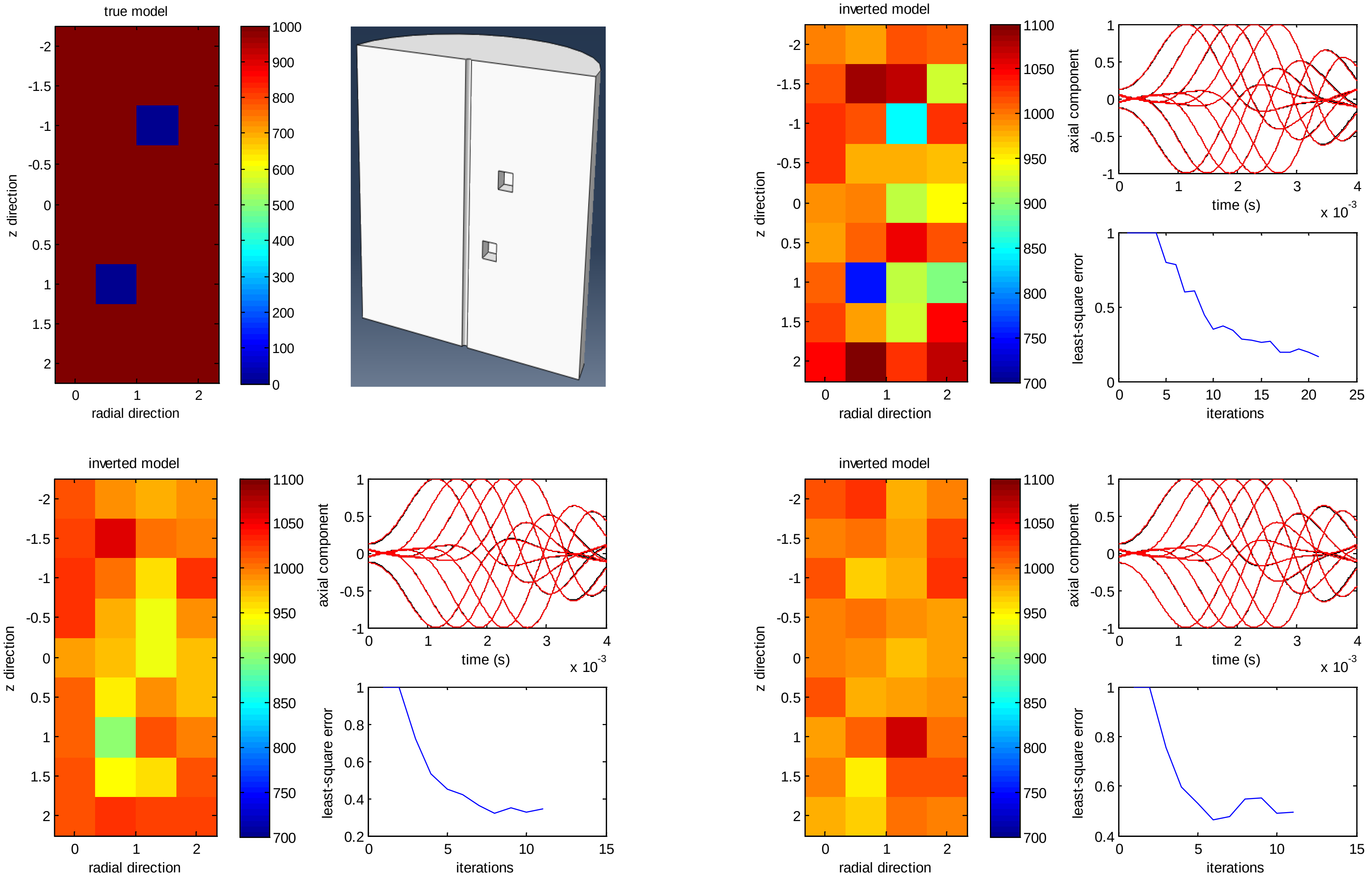

inverted model
z direction
radial direction
1100
1050
1000
950
900
850
800
750
700
650
600
axial component
time (s)
x 10^-3
least-square error
iterations


inverted model
z direction
radial direction
1100
1050
1000
950
900
850
800
750
700
650
600
axial component
time (s)
x 10^-3
least-square error
iterations

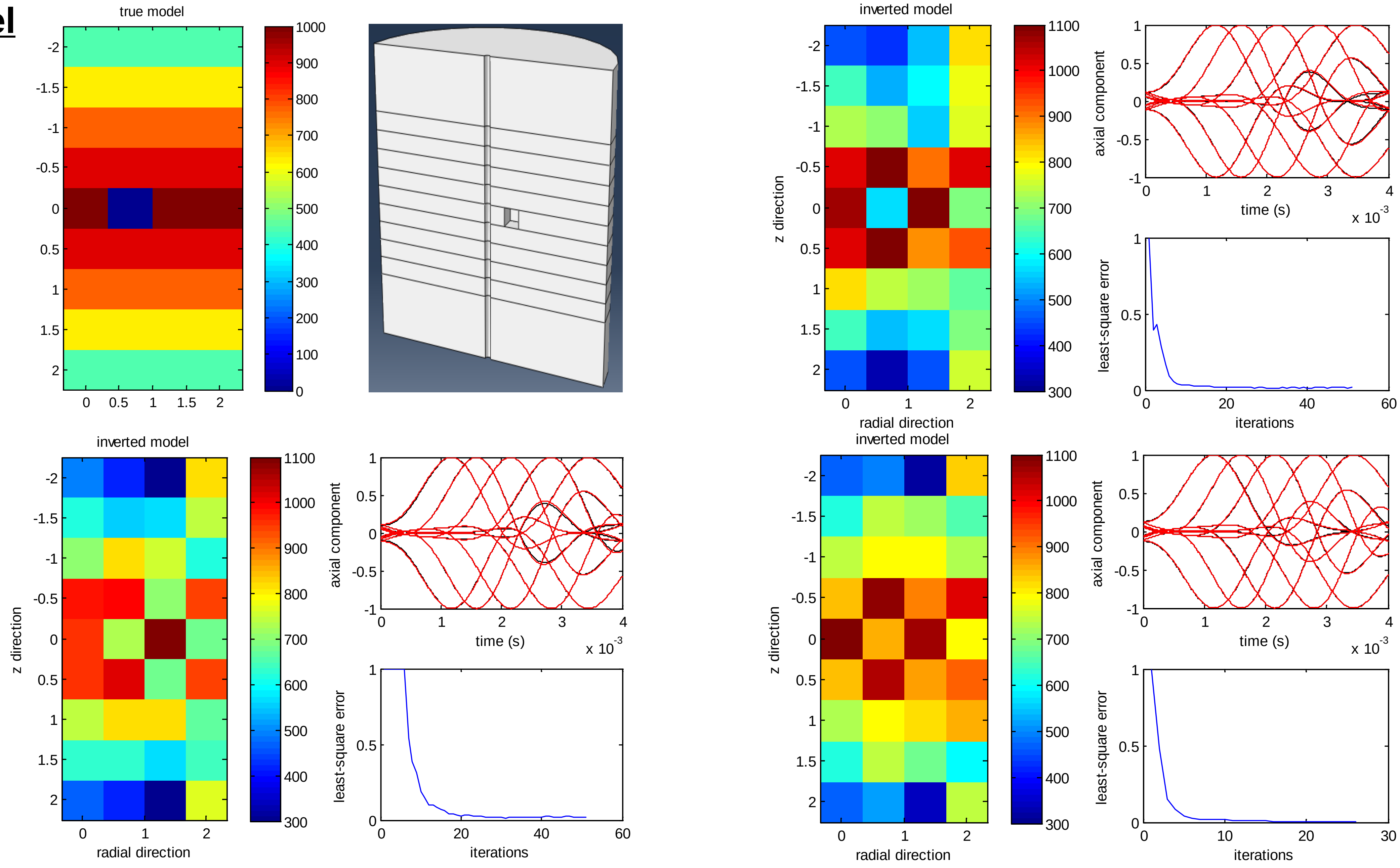
Model 2


true model
z direction
radial direction
inverted model
z direction
radial direction
axial component
time (s)
x 10^-3
least-square error
iterations
inverted model
z direction
radial direction
axial component
time (s)
x 10^-3
least-square error
iterations
inverted model
z direction
radial direction
axial component
time (s)
x 10^-3
least-square error
iterations

Model 3


true model
z direction
radial direction
inverted model
z direction
radial direction
axial component
time (s)
x 10^-3
least-square error
iterations
inverted model
z direction
radial direction
axial component
time (s)
x 10^-3
least-square error
iterations
inverted model
z direction
radial direction
axial component
time (s)
x 10^-3
least-square error
iterations

Model 4



true model
inverted model
inverted model
inverted model
z direction
radial direction
axial component
time (s)
x 10-3
least-square error
iterations

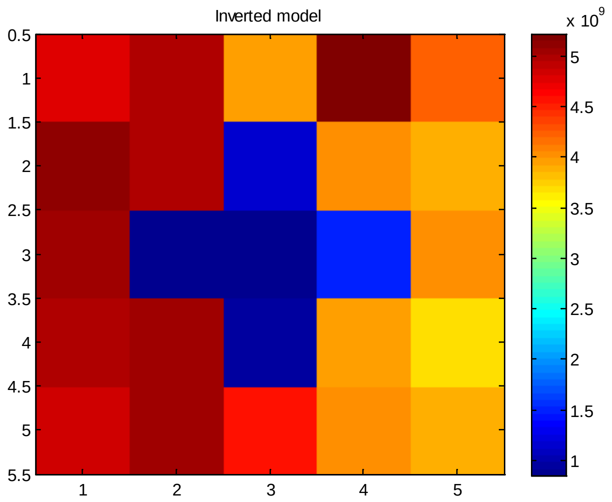
Conclusions

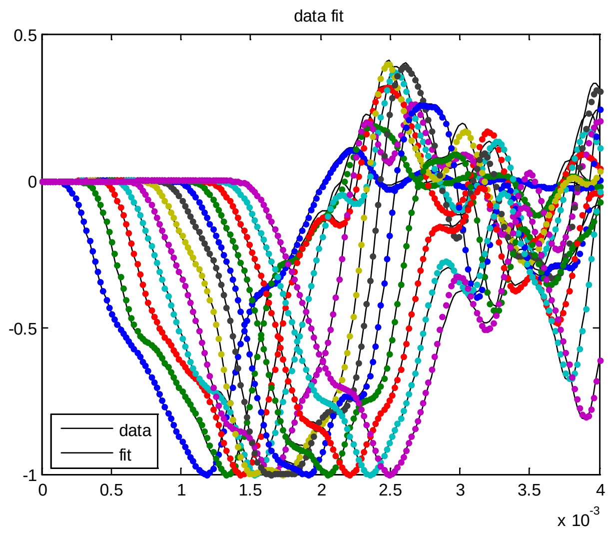
- The cylindrical geometry must be considered when modeling wave propagation inside a borehole (forward modeling)
- The Regularized Gauss-Newton method only works when coupled with multiscale strategies
- The inversion scheme is stable with respect to input data (axisymmetric and 3-D data)
- The proposed imaging technique appears capable of finding indications of an isolated anomaly in the vicinity of a borehole (radial distance and azimuth)

Future Work

- A inhole characterization tool that is able to generate and collect full waveforms inside a borehole needs to be developed
- The proposed imaging technique must be validated by small-scale physical modeling before it is intended for field applications
- The inversion scheme needs further development. For example, inversion of multiple shot gathers in parallel and multi-variable inversion (Vp, Vs, and density)
- Feasibility study of 3-D full waveform inversion within a borehole

THANK YOU!





UNIVERSITY OF FLORIDA

GATOR Engineering
at the University of Florida