Implementation of Down-Hole Geophysical Testing for Rock Sockets

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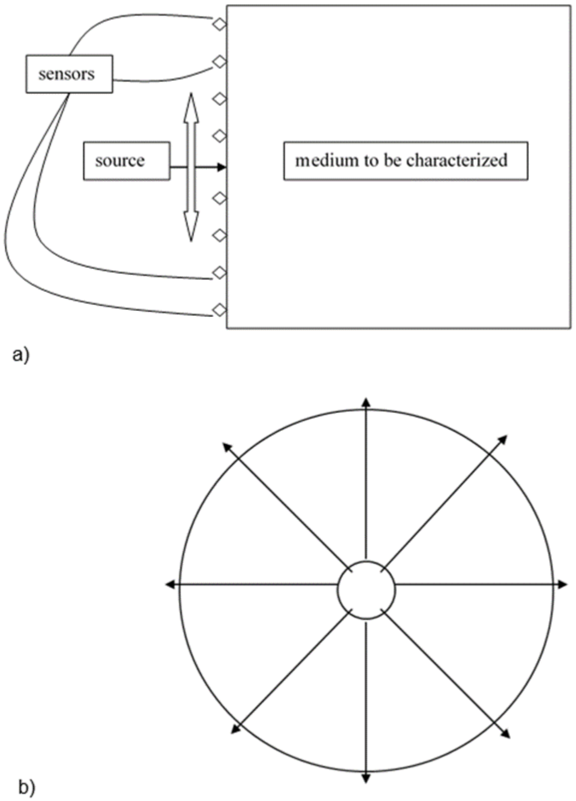
University of Florida

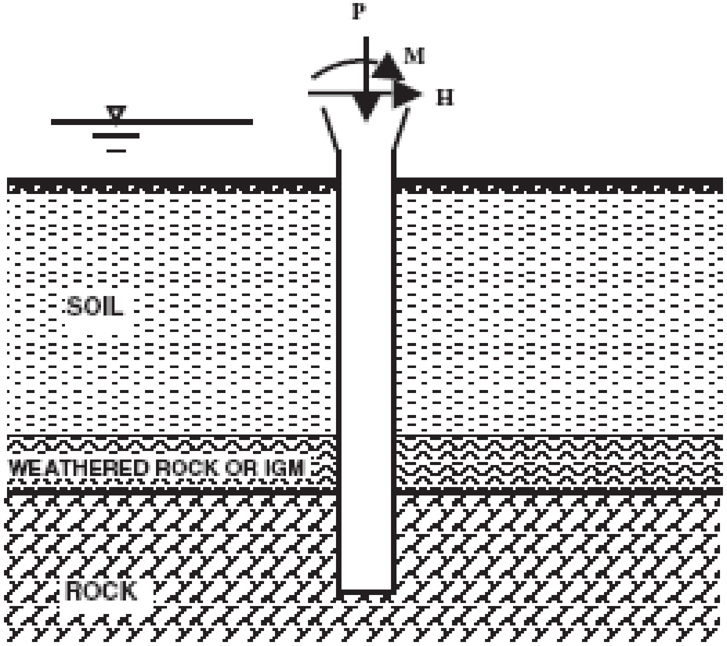
FDOT GRIP

August 21, 2015



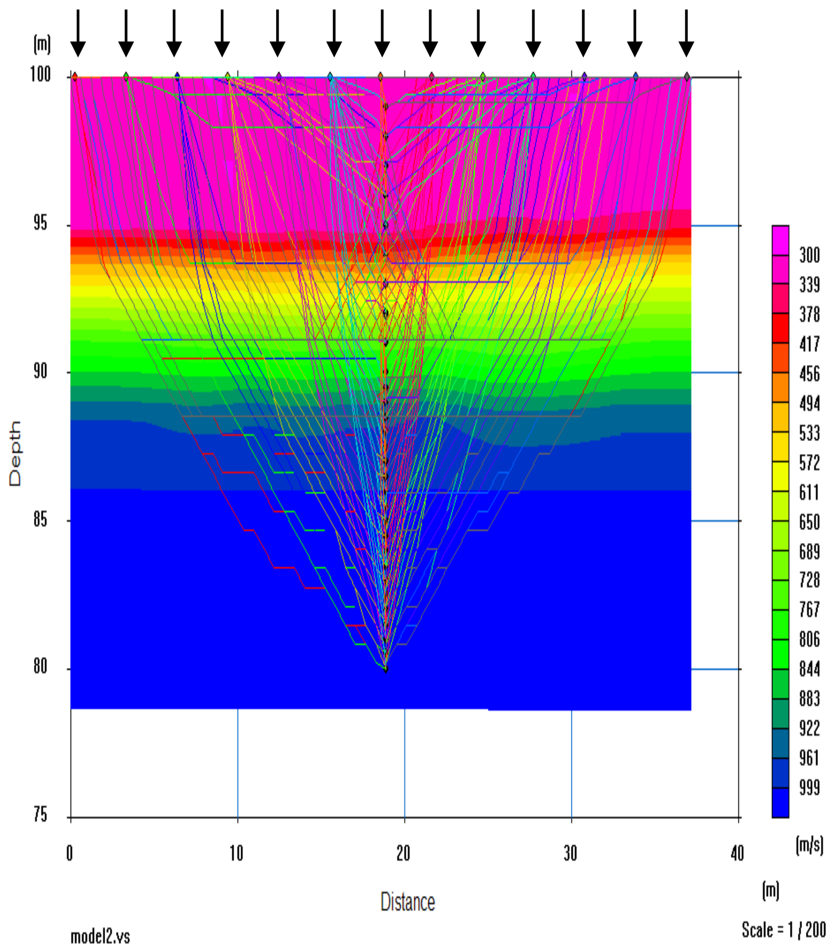
Geophysical Characterization of Rock Sockets

- Rock highly variable: extend characterization to ~5 ft laterally from borehole
- Develop geophysical technique to supplement boring cores and lab results
- Utilize only the one standard borehole
- Integrate with current boring, sampling, and testing tools



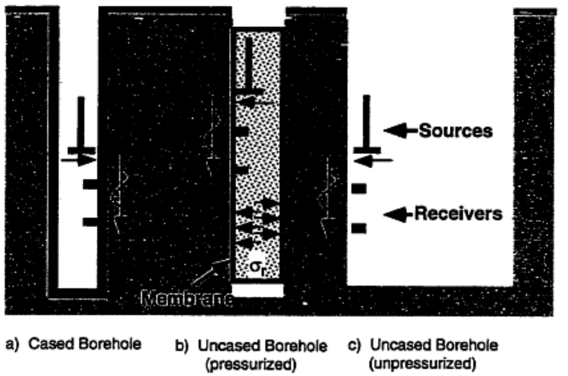
Surface/Borehole Travel Times

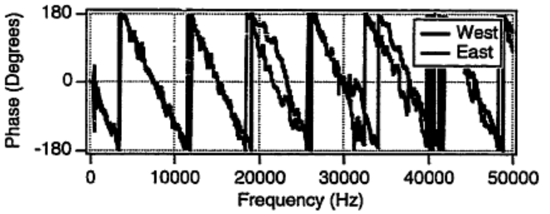
- Coupling of downhole and surface tomography
- Utilizes surface sources and surface and borehole receivers
- 2-D and 3-D variation
- Does not require long surface array
- Potentially good resolution at depth
- Can resolve low-velocity anomalies

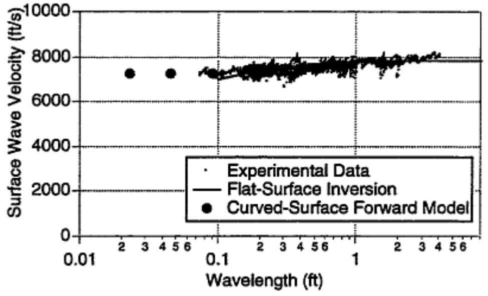


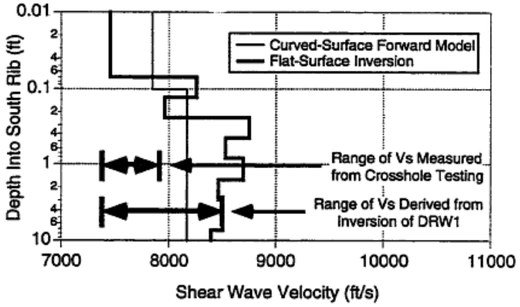
Kalinski (1998)

- University of Texas (Stokoe)
- SASW along axis of borehole (1-D)
- Concrete, rock, and soil
- Geometry-induced dispersion



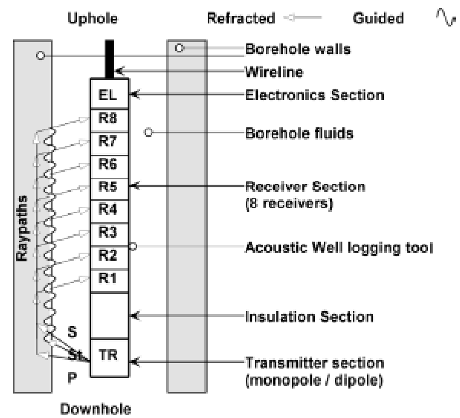


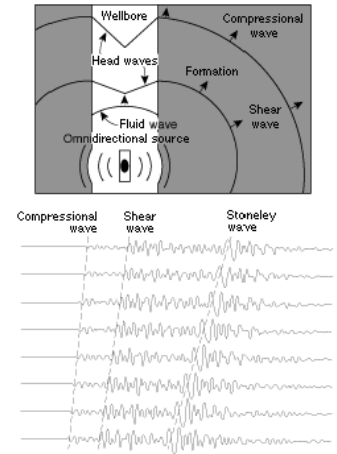


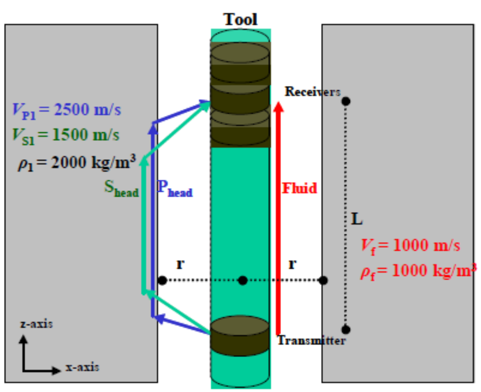


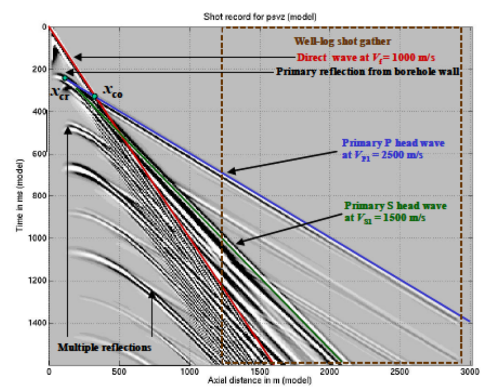
Chabot (2003)

- University of Calgary
- Sonic logging tool in fluid-filled borehole
- Seismic reflection-style processing
- Full waveform analysis of body waves (P and S)
- No surface waves



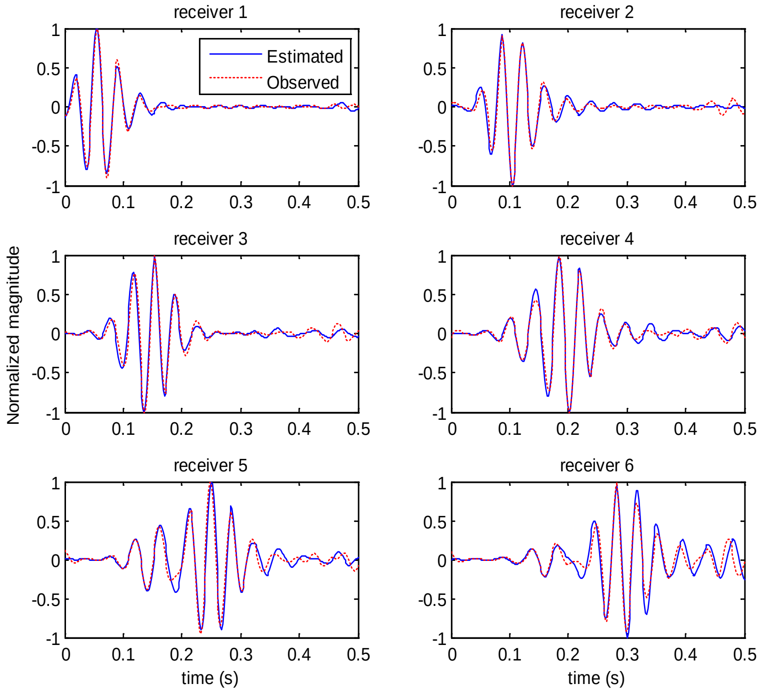




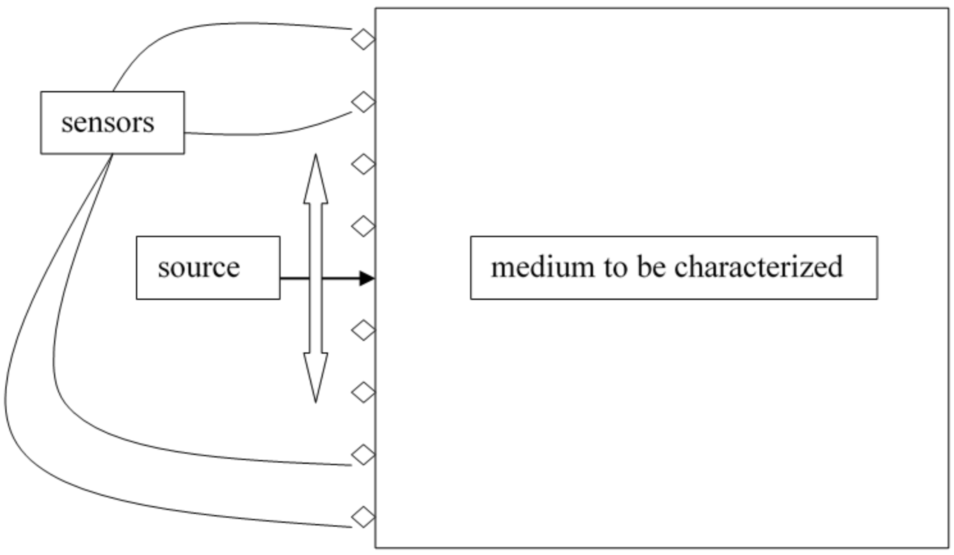


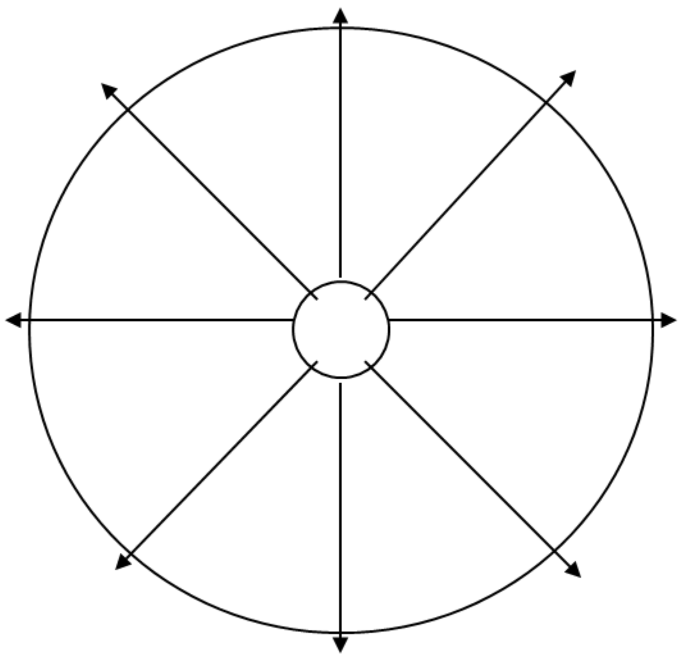
Full Waveform Inversion (FWI)

- Invert for model parameters by matching full waveforms
- Complex profiles create difficulties for traditional techniques (e.g, G, T, O'N, L)
- Studies have demonstrated improved resolution with FWI
- Advancements in wave propagation modeling, inversion algorithms, and computing have made this possible
- Have demonstrated for some challenging synthetic and field data sets



Borehole Tool Schematic

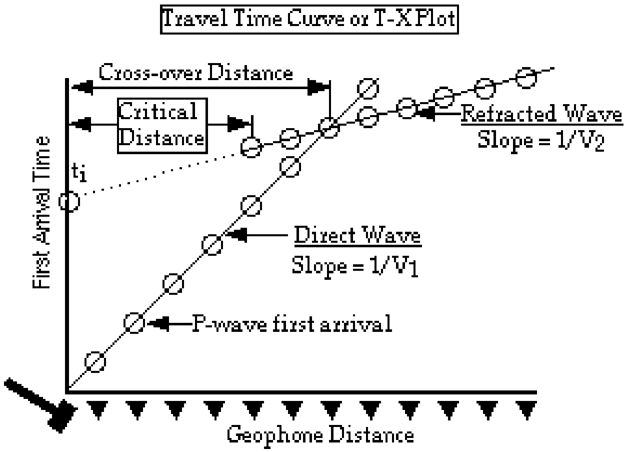


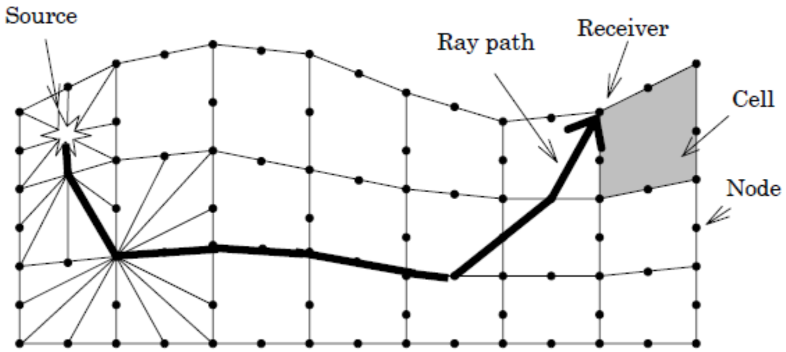


A joining of borehole instrumentation with full waveform inversion

Geophysics: Components

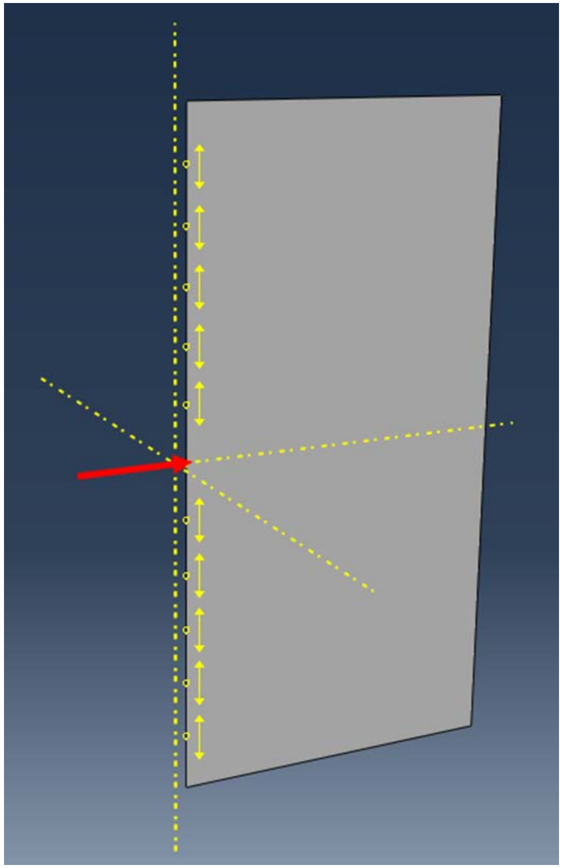
- **Measured data**: Boundary response to source energy
- **Forward model**: simulation of the experiment
- **Inversion algorithm**: back calculate the model parameters of interest





Inversion Schematic

ABAQUS 2.5D FEM



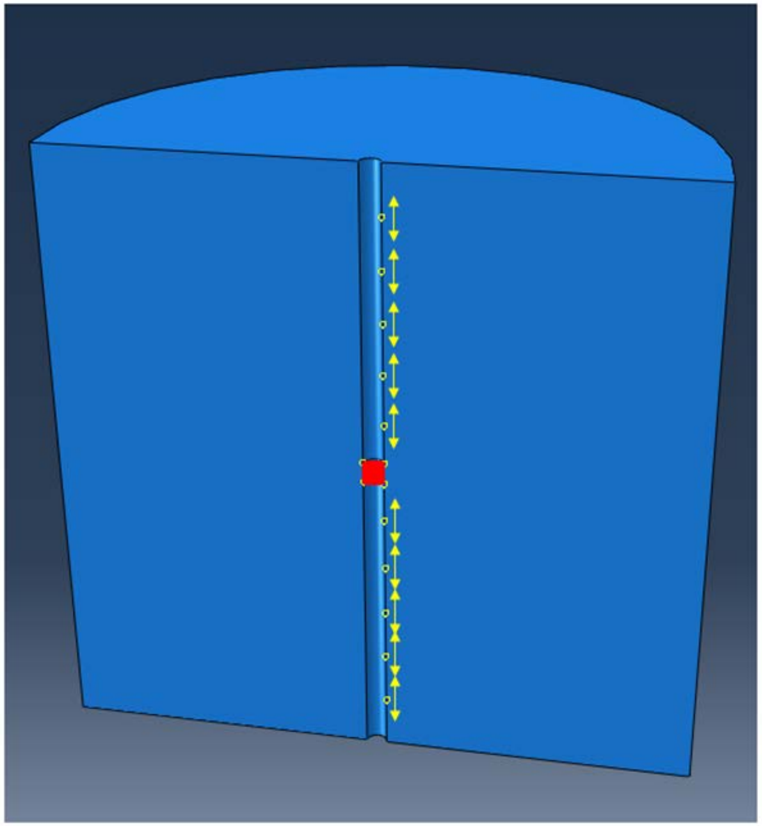
Regularized Gauss-Newton Method

- Residual wave field: $\Delta \mathbf{d} = \mathbf{F}(\mathbf{m}) - \mathbf{d}$
- Least-squares error: $E(\mathbf{m}) = \frac{1}{2} \Delta \mathbf{d}^t \Delta \mathbf{d}$
- 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: $\alpha^n \cong \frac{[\mathbf{J}^t g^n]^t [\mathbf{F}(\mathbf{m}^n) - \mathbf{d}]}{[\mathbf{J}^t g^n]^t [\mathbf{J}^t g^n]},$

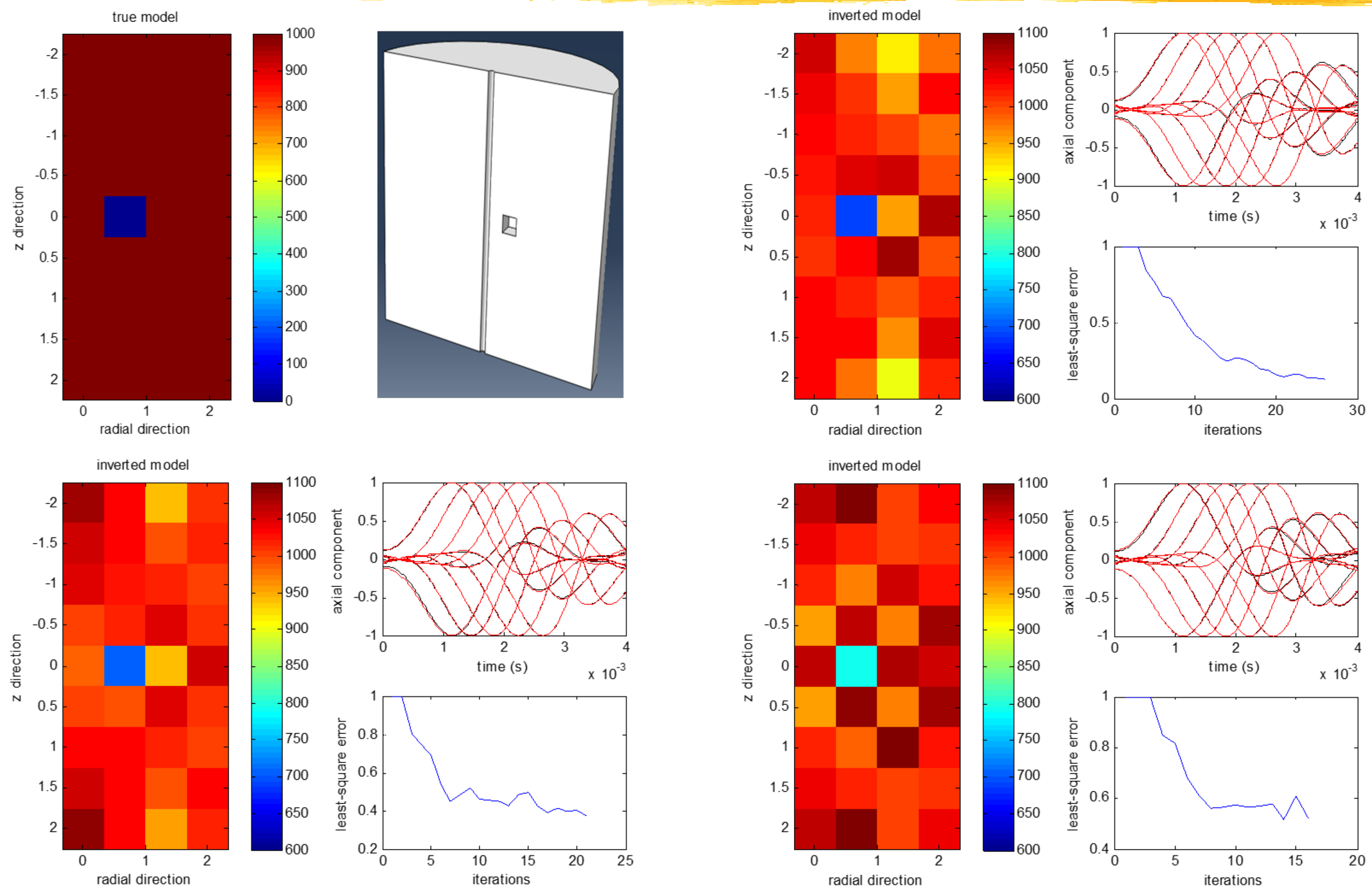
$$g^n = [\mathbf{J}^t \mathbf{J} + \lambda_1 \mathbf{P}^t \mathbf{P} + \lambda_2 \mathbf{I}^t \mathbf{I}]^{-1} \mathbf{J}^t [\mathbf{F}(\mathbf{m}^n) - \mathbf{d}].$$

Synthetic Models: Isolated Anomaly

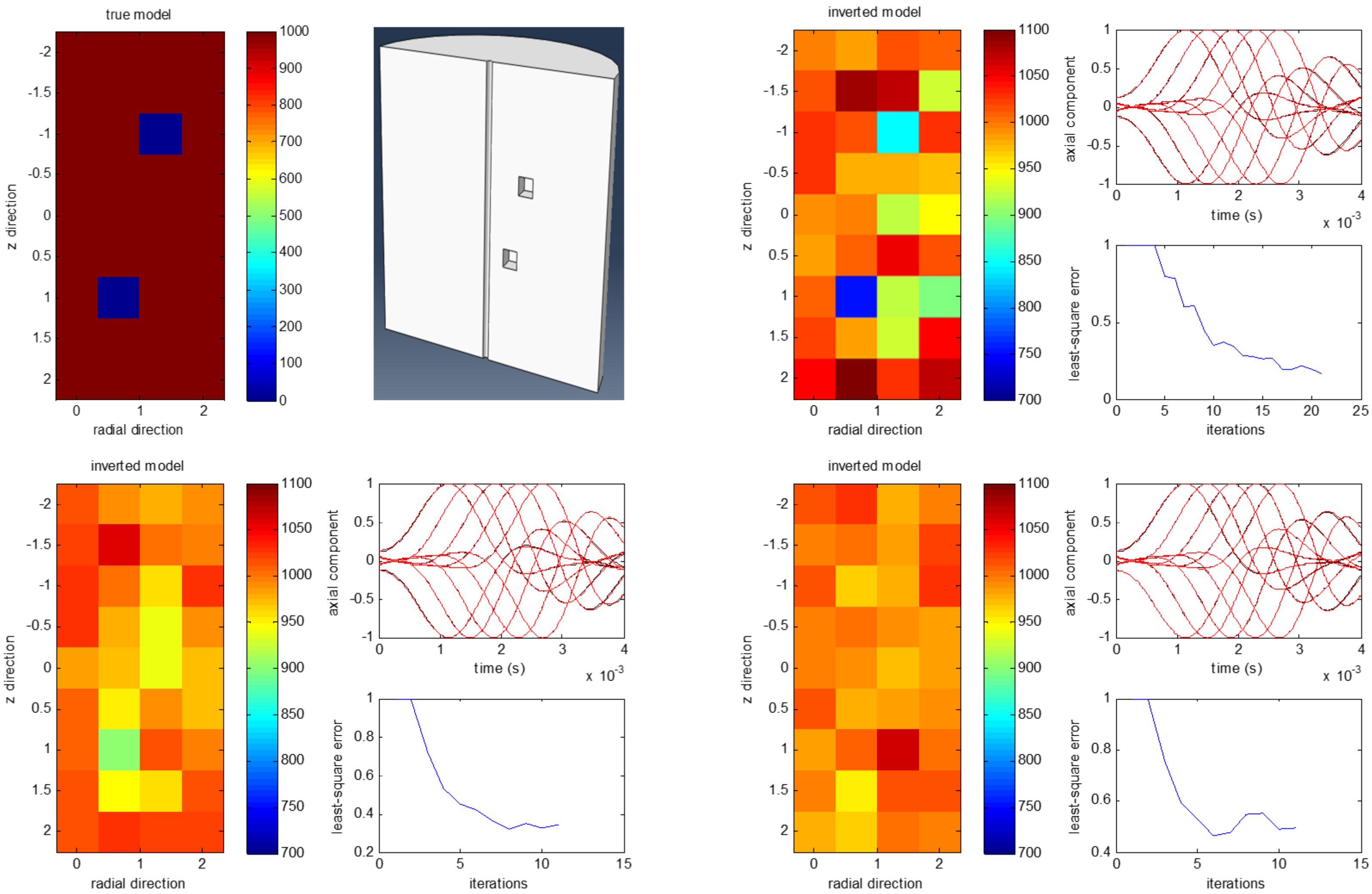
- **<u>Goal</u>: use 2.5D approximation to find indications of isolated anomalies in 3D space**
- **<u>Data</u>: generated from 3D model with isolated cavities**
- **<u>Forward model</u>: 2.5D axisymmetric borehole**
- **<u>Inversion</u>: regularized GN method coupled with multi-scale strategies**



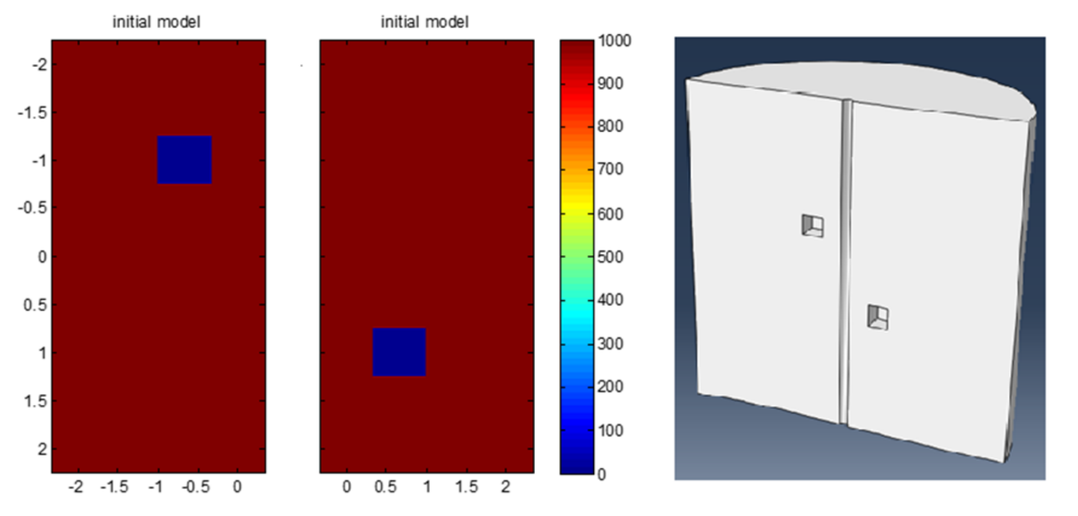
Isolated Anomaly in Homogeneous

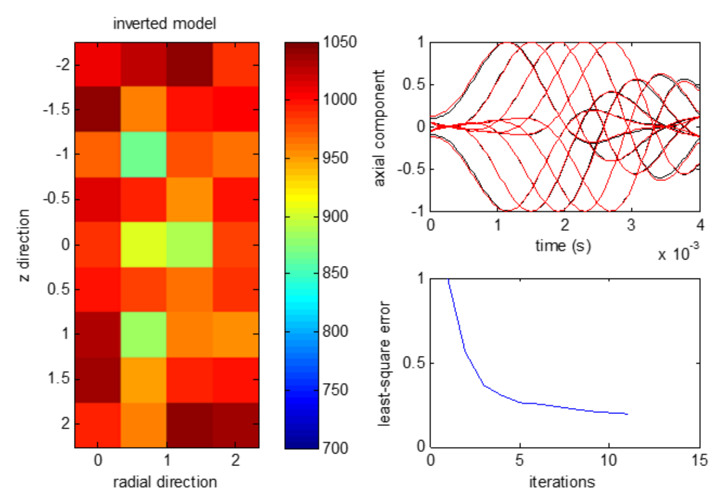


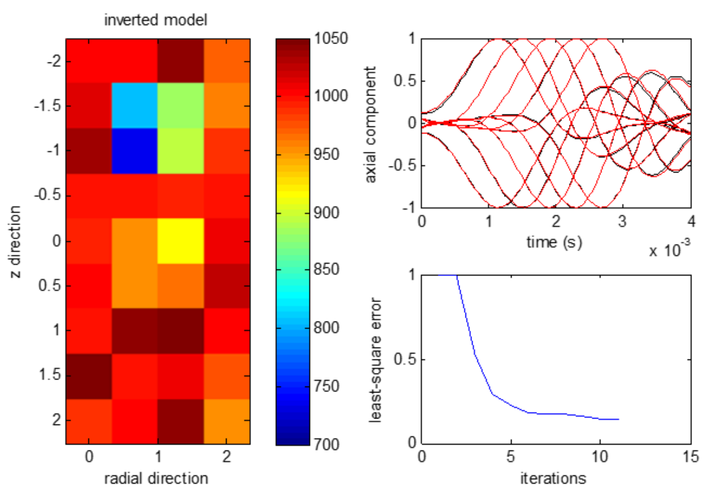
Two Anomalies Same Side

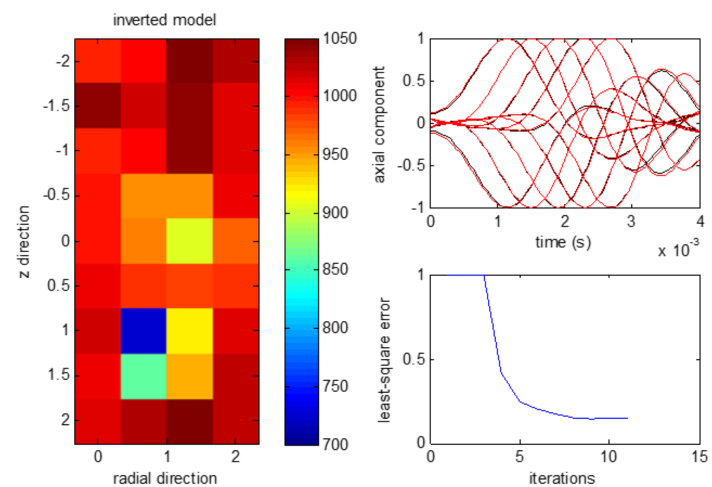


Two Anomalies Opposite Sides









Contributions

- **<u>Forward model</u>: The research investigated the problem of wave propagation inside a cylindrical borehole, and formulated an efficient forward model that is capable of generating synthetic seismograms.**
- **<u>Inversion</u>: The research established a robust nonlinear optimization technique, coupling ABAQUS with MATLAB, for solving general seismic inverse problems.**
- **<u>Borehole imagining</u>: The research made a first attempt to characterize spatial variations of rock sockets by imaging the S-wave velocity profiles using only one borehole.**

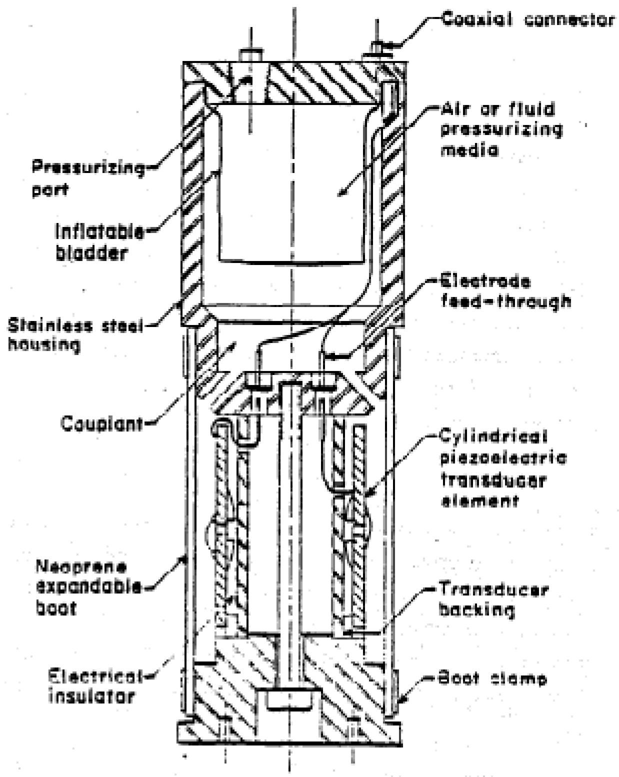
Future

- **An 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 via small-scale physical modeling followed by field applications.**
- **The inversion scheme needs further development. For example, inversion of multiple shot gathers in parallel and multi-variable inversion (Vp and Vs).**
- **3D full waveform inversion within a borehole.**

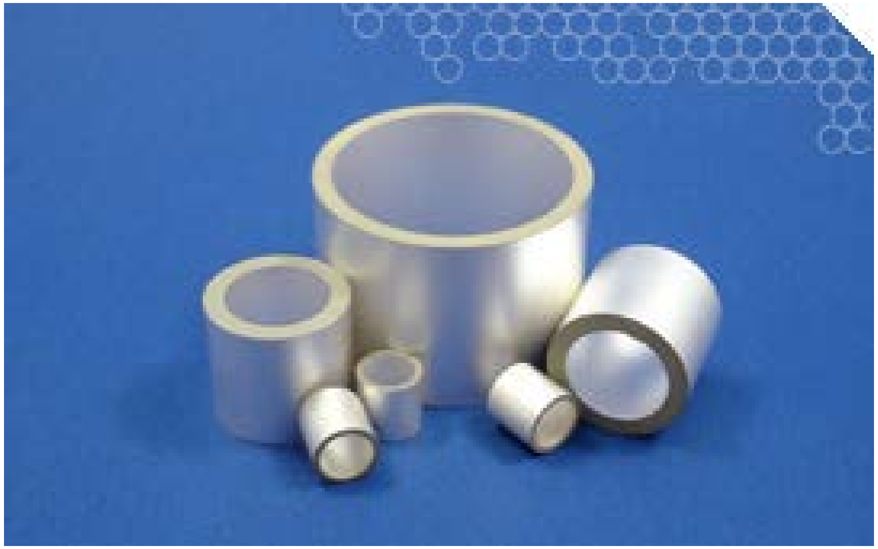
Workplan

- **Task 1: Borehole Instrument**
  - **Source for generating seismic (mechanical) waves**
  - **Receiver array for capturing the wavefield**
- **Task 2: Inversion Software**
  - **ABAQUS forward model**
  - **Stand-alone forward model for borehole geometry**
  - **Artificial neural network (ANN) trained by ABAQUS**
- **Task 3: Validation Experiments**
  - **Large laboratory block of synthetic limerock**
  - **Newberry and Kanapaha test sites**
- **Task 4: Report**

Piezoelectric Borehole Source



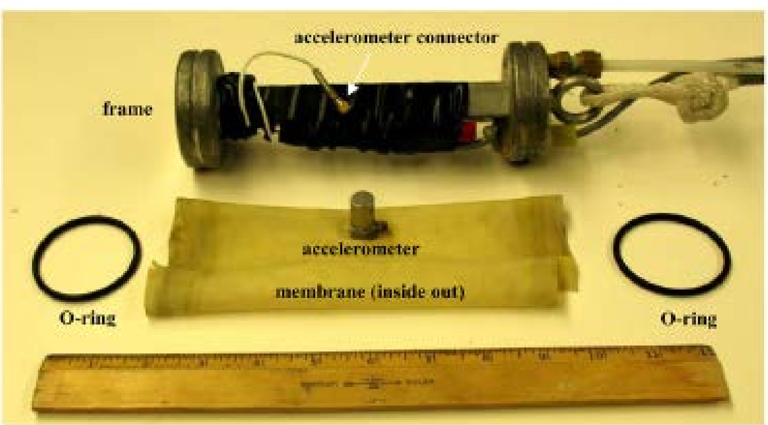
Thill (1978)



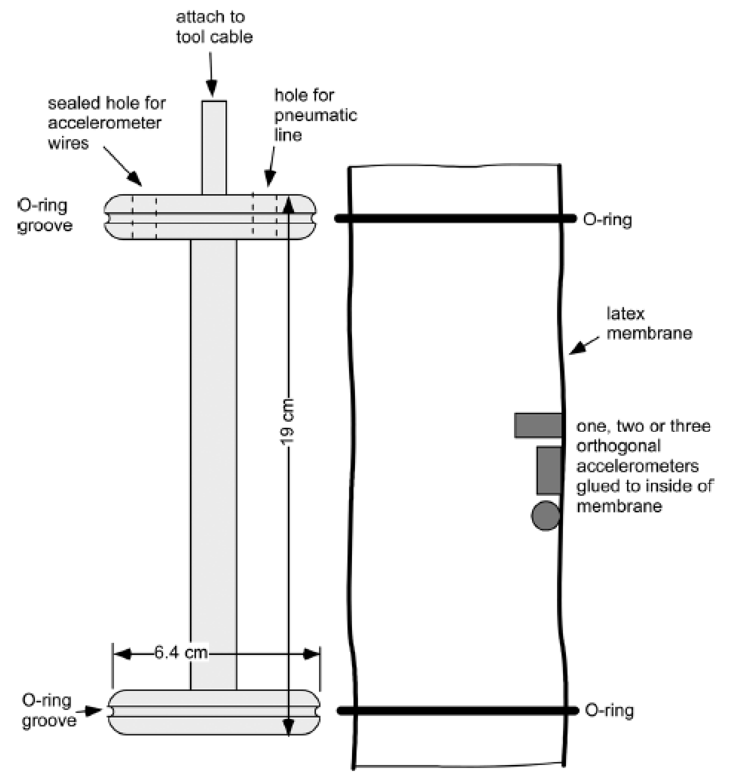
Piezoelectric Tube

Kalinski Borehole Receiver

a. assembled view



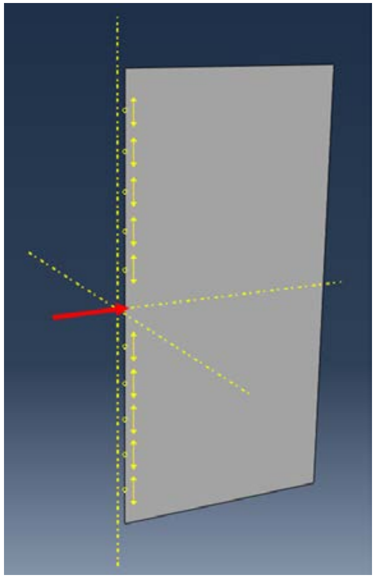
b. exploded view



a. support frame b. inflatable membrane

Inversion Software

- **ABAQUS 2.5D FEM and regularized Gauss-Newton method**
- **Improved FEM mesh and streamlined inversion code**
- **Open-source FEM: building model in OpenSEES**
- **Will also investigate borehole FD and ANN trained via FEM**



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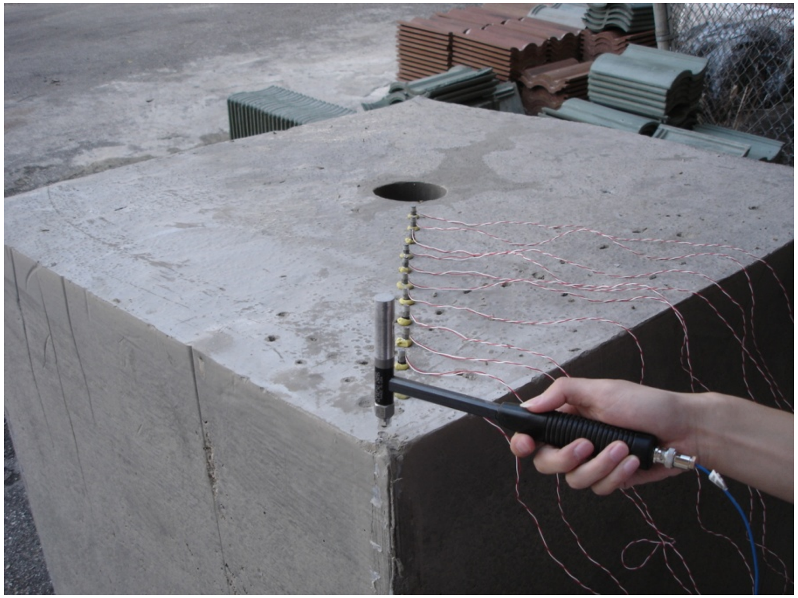
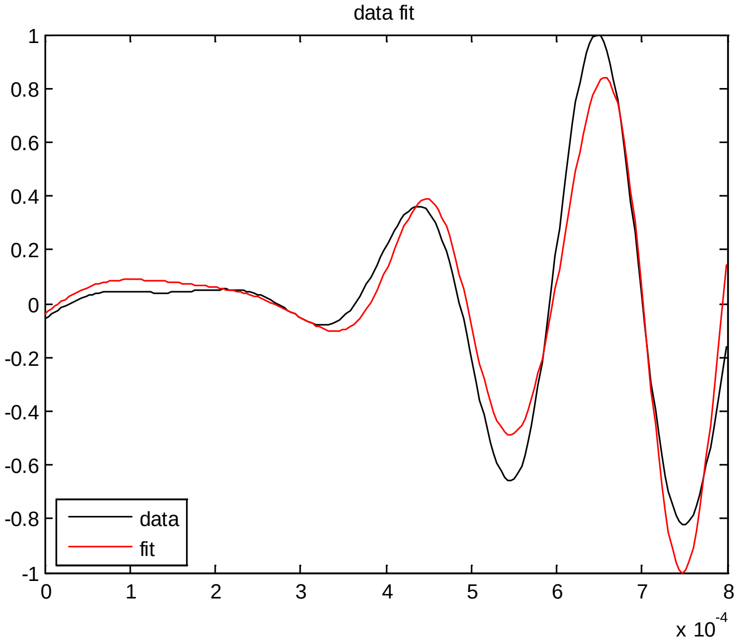
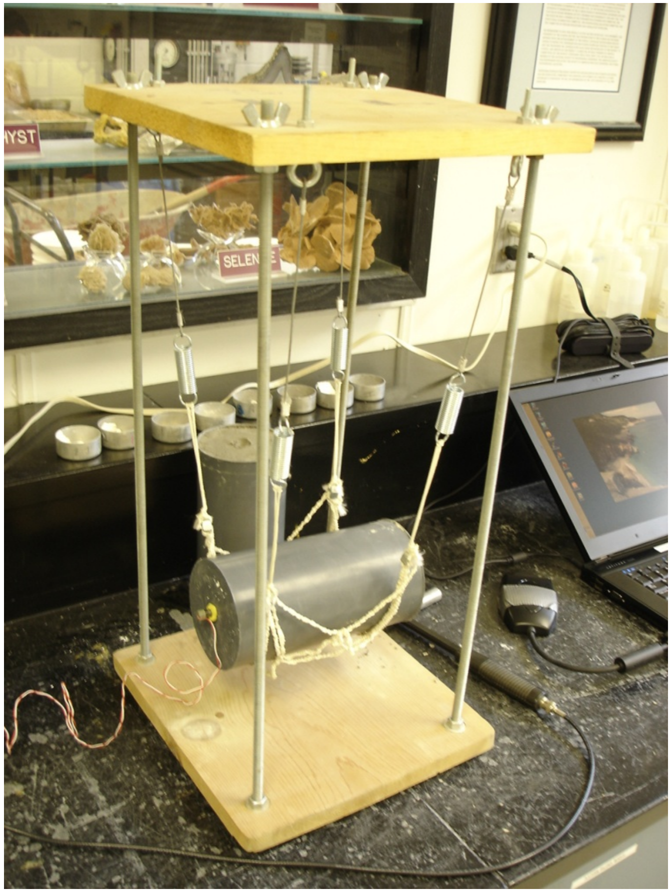
Synthetic Limerock Specimen





Synthetic Limerock Specimen

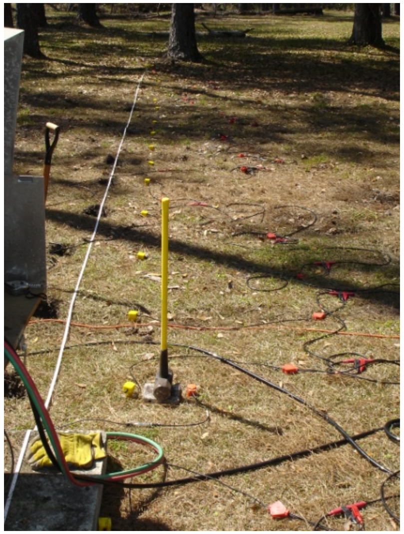
- **Preliminary results**
- **Vs = 935 m/s from FWI**
- **Free-free resonant column tests**
  - **Vp = 1500 m/s**
  - **Poisson's ratio = 0.2**
  - **Thus Vs = 890 m/s**

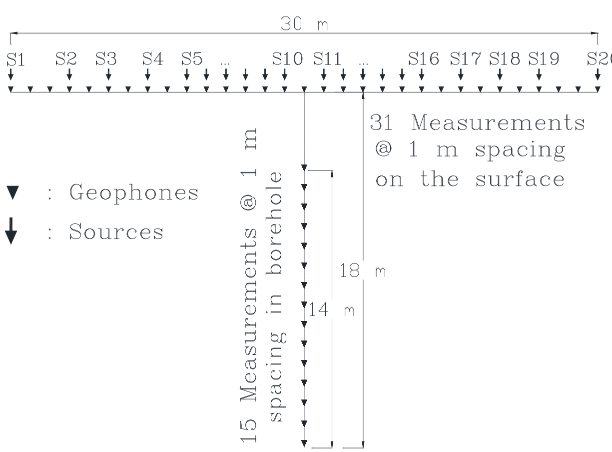


Thank You!

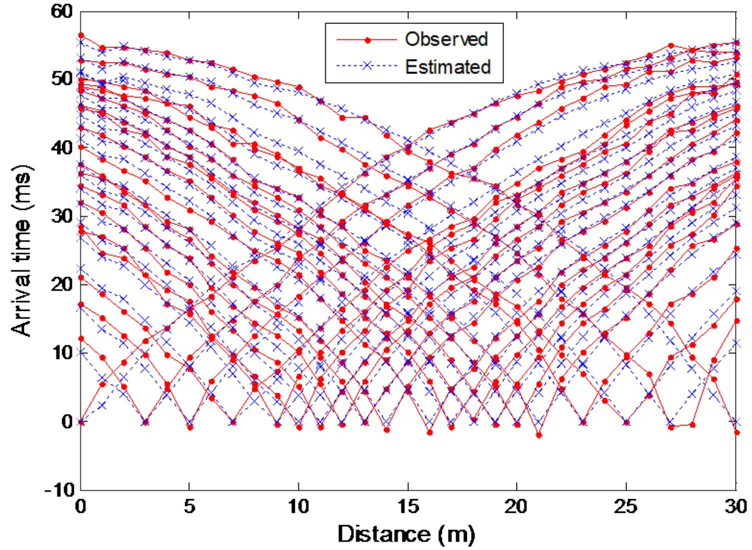
Ft. McCoy

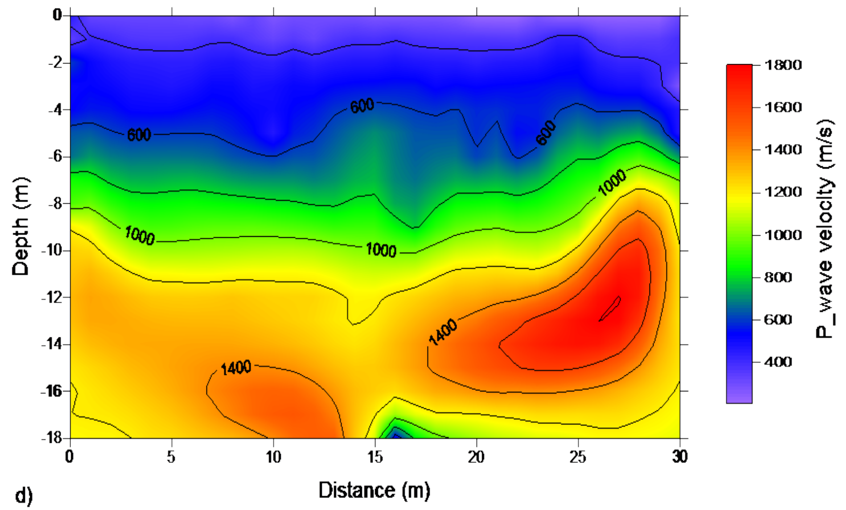
- Surface array: 31 geophones at 1-m spacing
- Borehole array: geophones 4-18 m at 1-m spacing
- Sledgehammer source: 1,2,3,4,5,6,8,10,12,15 m each side of well

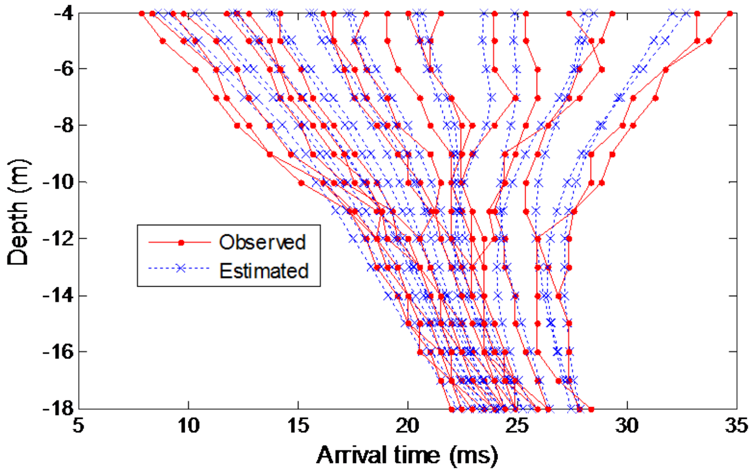


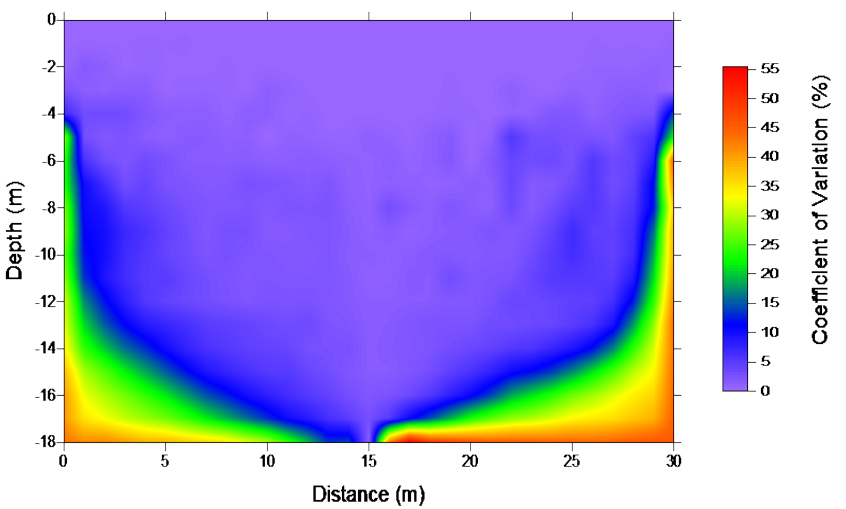


Ft. McCoy

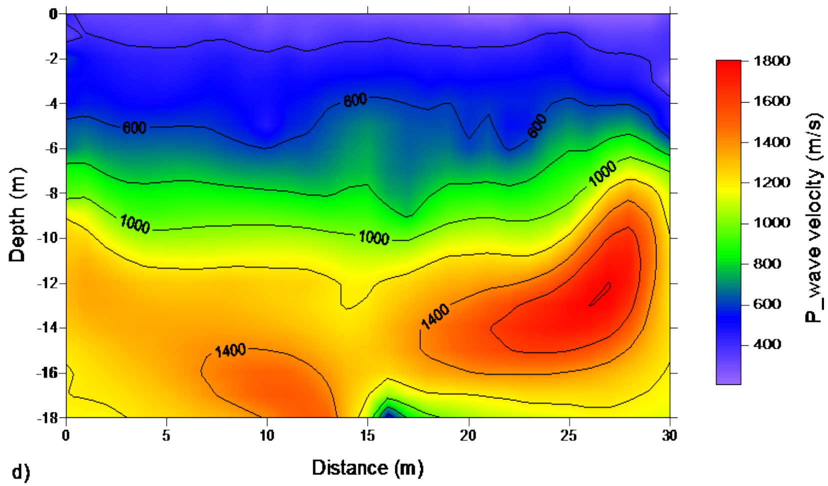

Observed
Estimated
Arrival time (ms)
Distance (m)

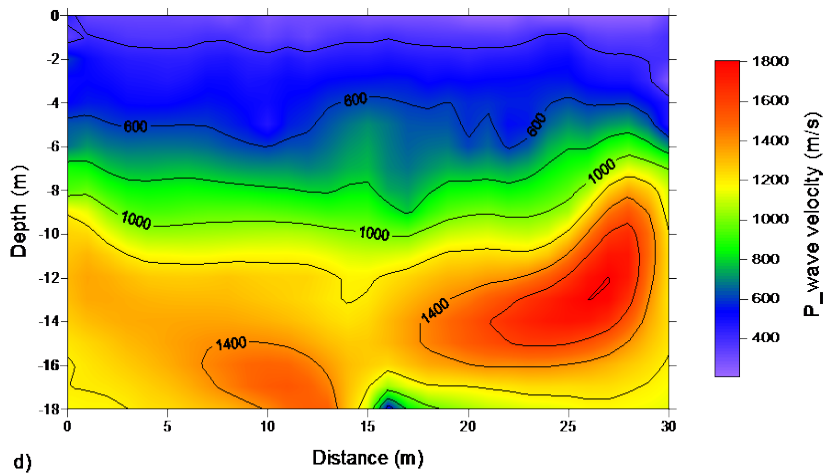

600
1000
1400
Depth (m)
Distance (m)
P_wave velocity (m/s)
d)

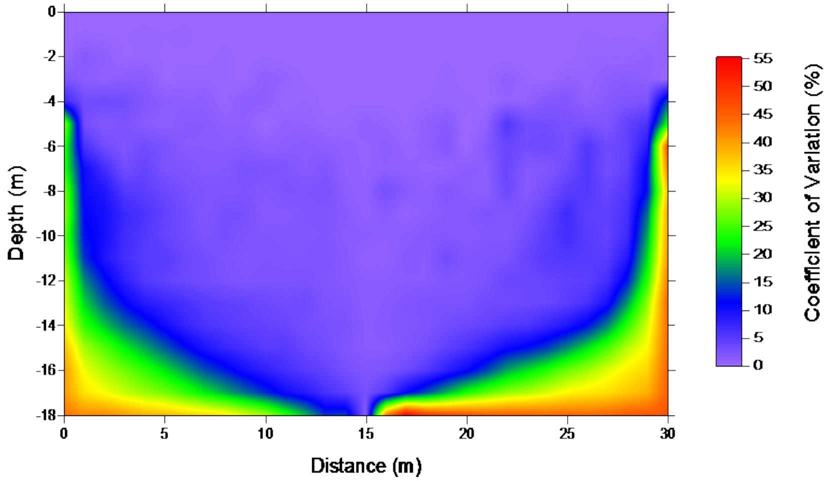

Observed
Estimated
Depth (m)
Arrival time (ms)

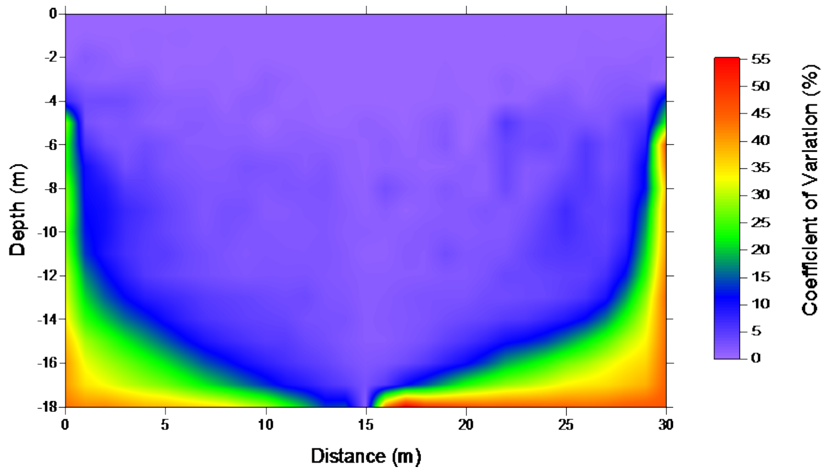

Depth (m)
Distance (m)
Coefficient of Variation (%)

Surface Only vs. Add Borehole

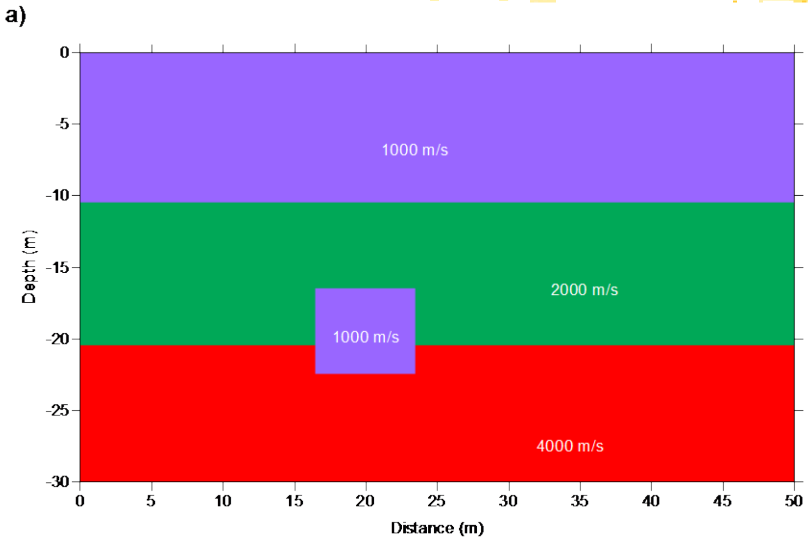


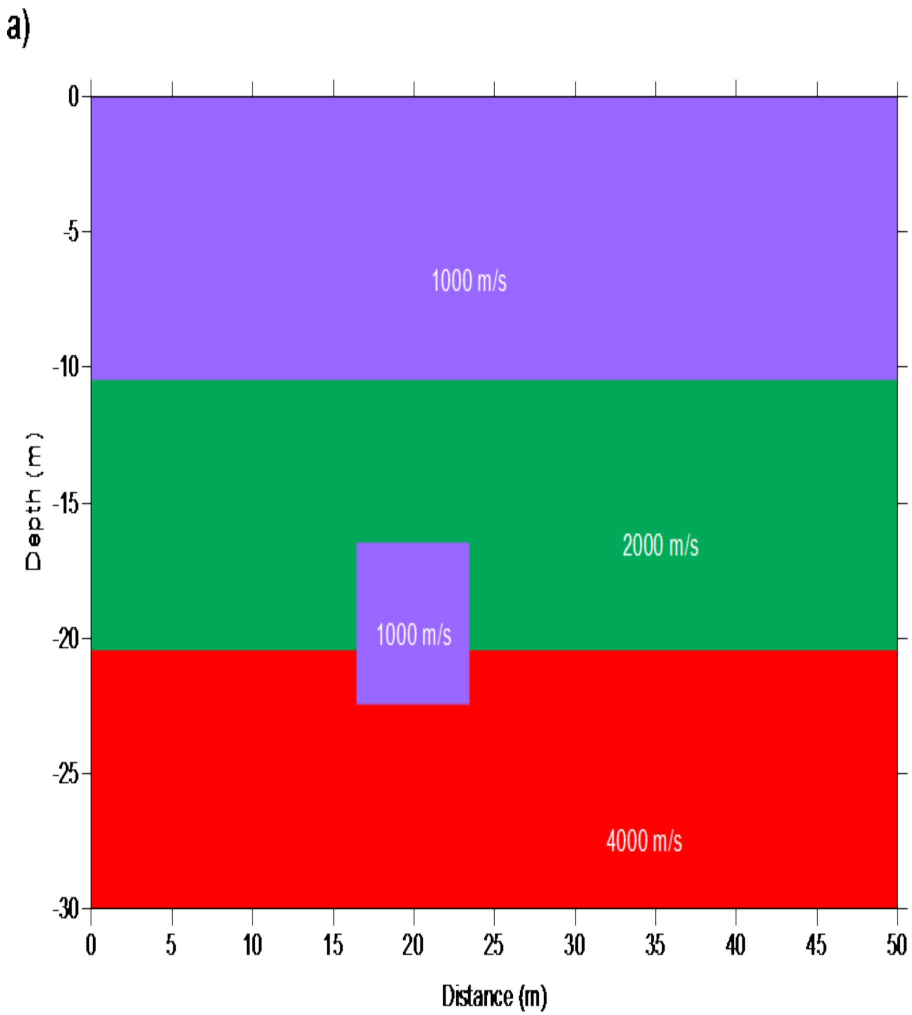






Synthetic Model with Anomaly

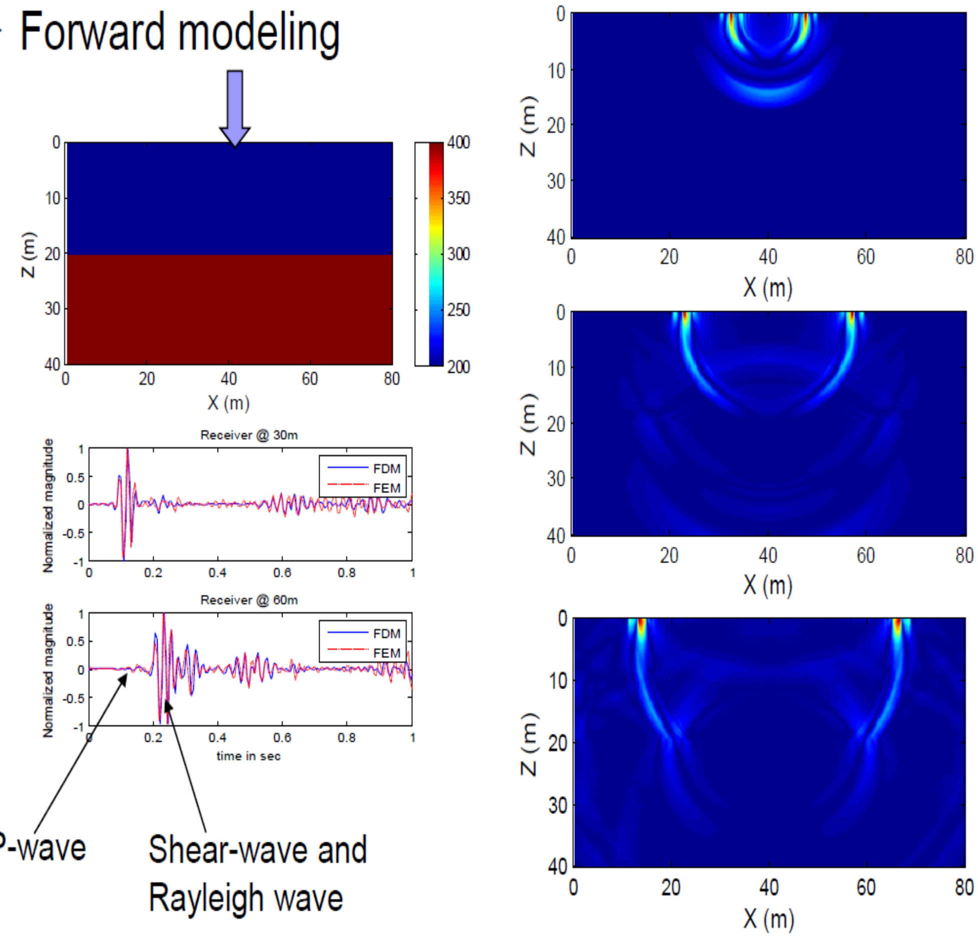




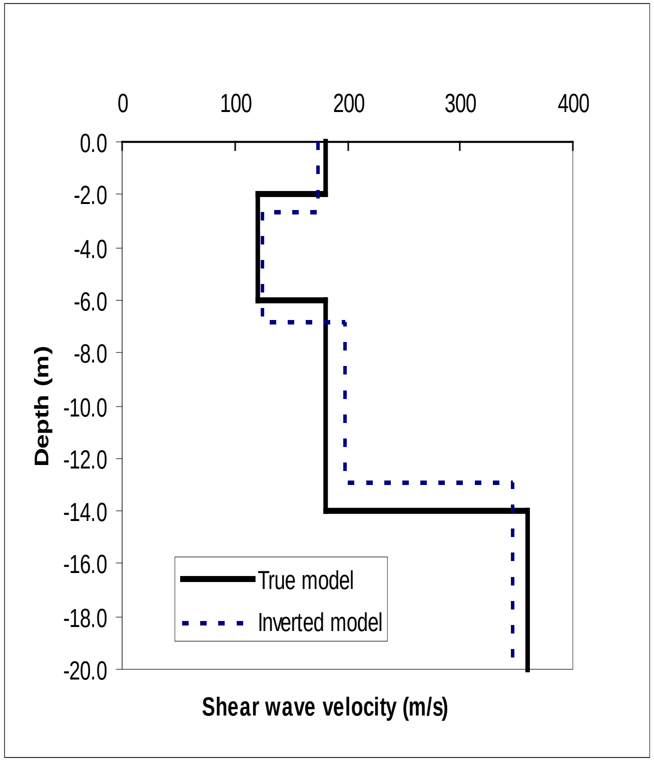
FWI Modeling

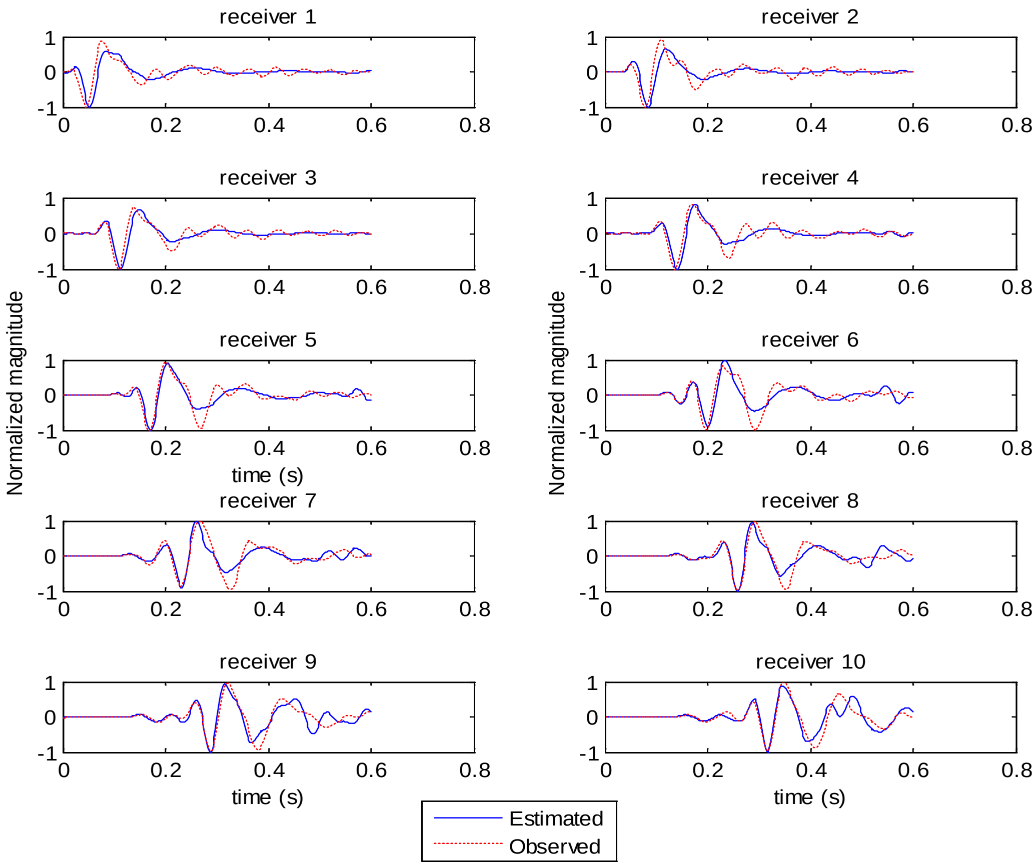
- Full waveforms via 2D, plane-strain finite difference (FD) solution:
- Or via commercial FEM solutions
- Absorbing boundaries
- Have used GA, SA, and Gauss-Newton inversion algorithms
- Solutions are feasible for MATLAB implement-tations on standard laptops

➢ Forward modeling



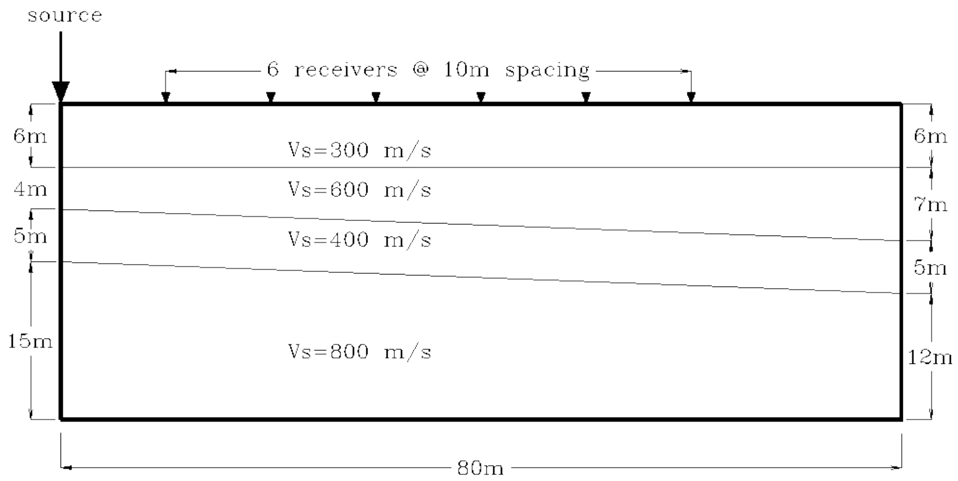
Tokimatsu 1D LVL: GA and SA

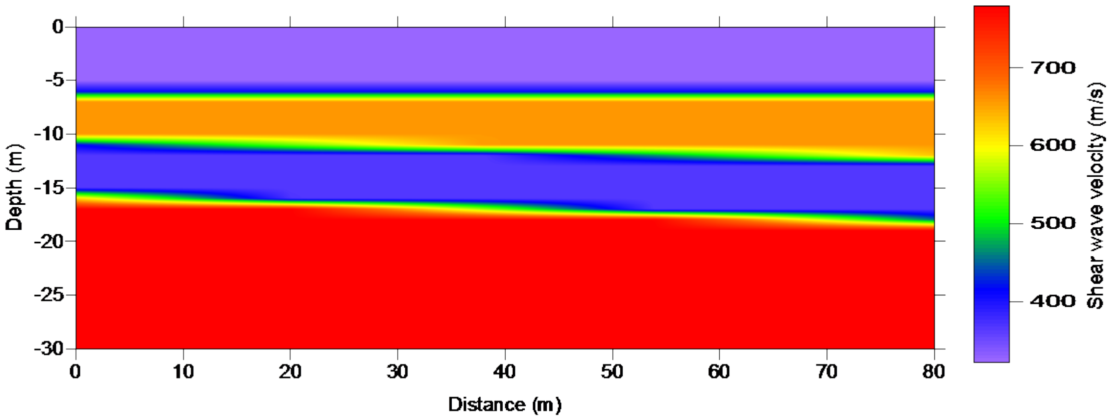




Algorithm parameters, parameter ranges, # of layers, uniform velocity

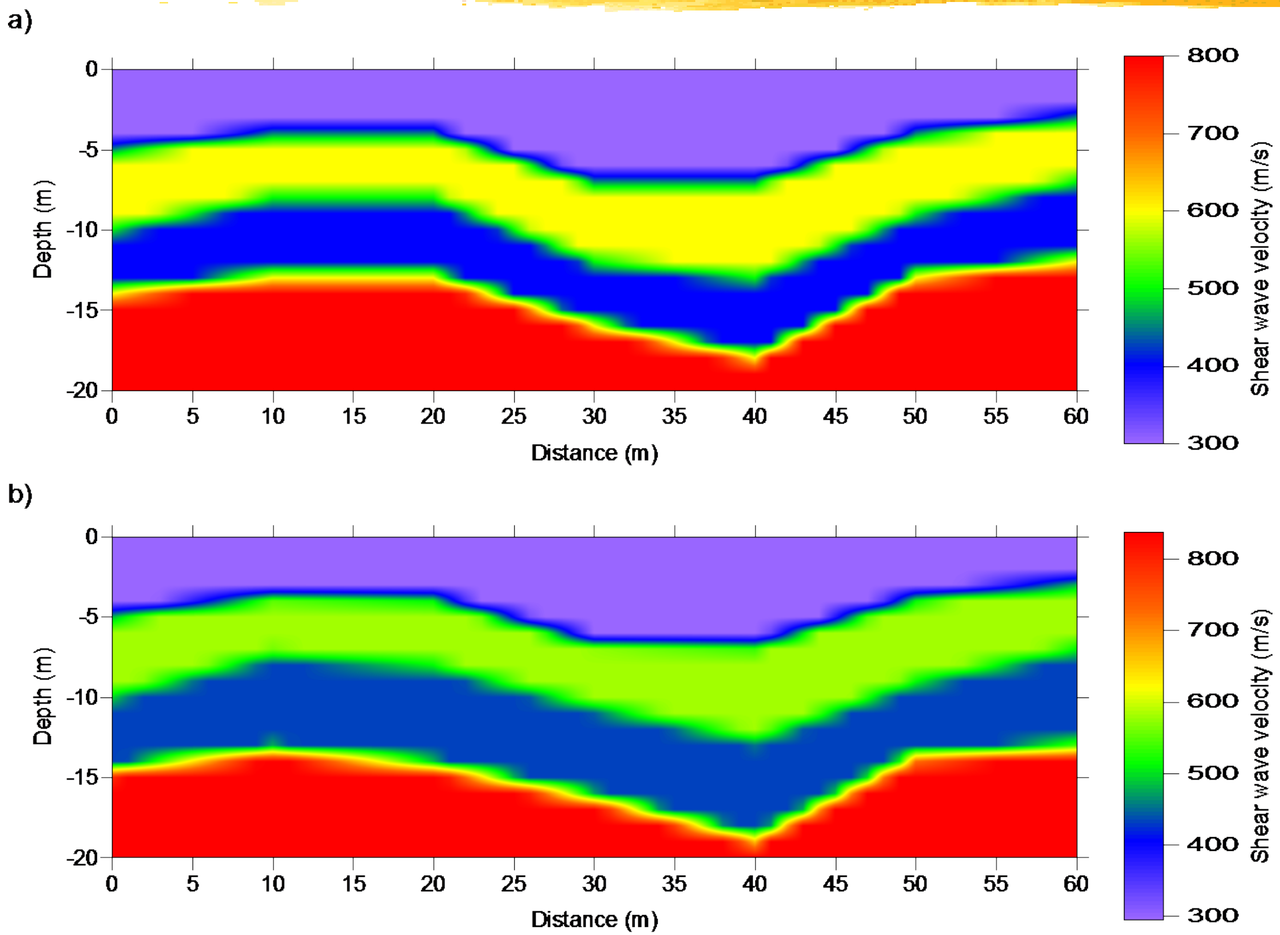
Tran Linear 2D HVL: Plaxis and SA





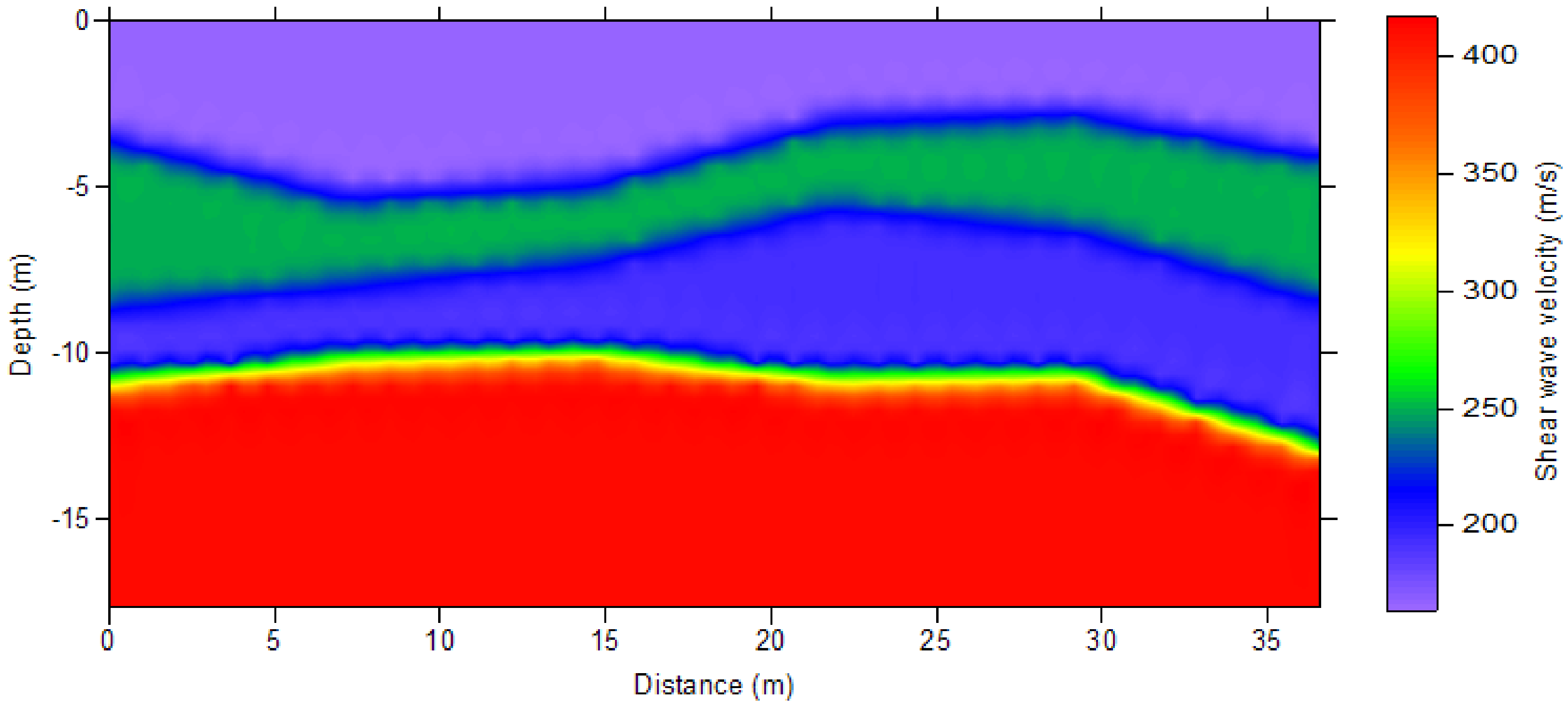
Algorithm parameters, parameter ranges, # of layers, uniform velocity

Tran Multi-Linear 2D LVL: FD & SA

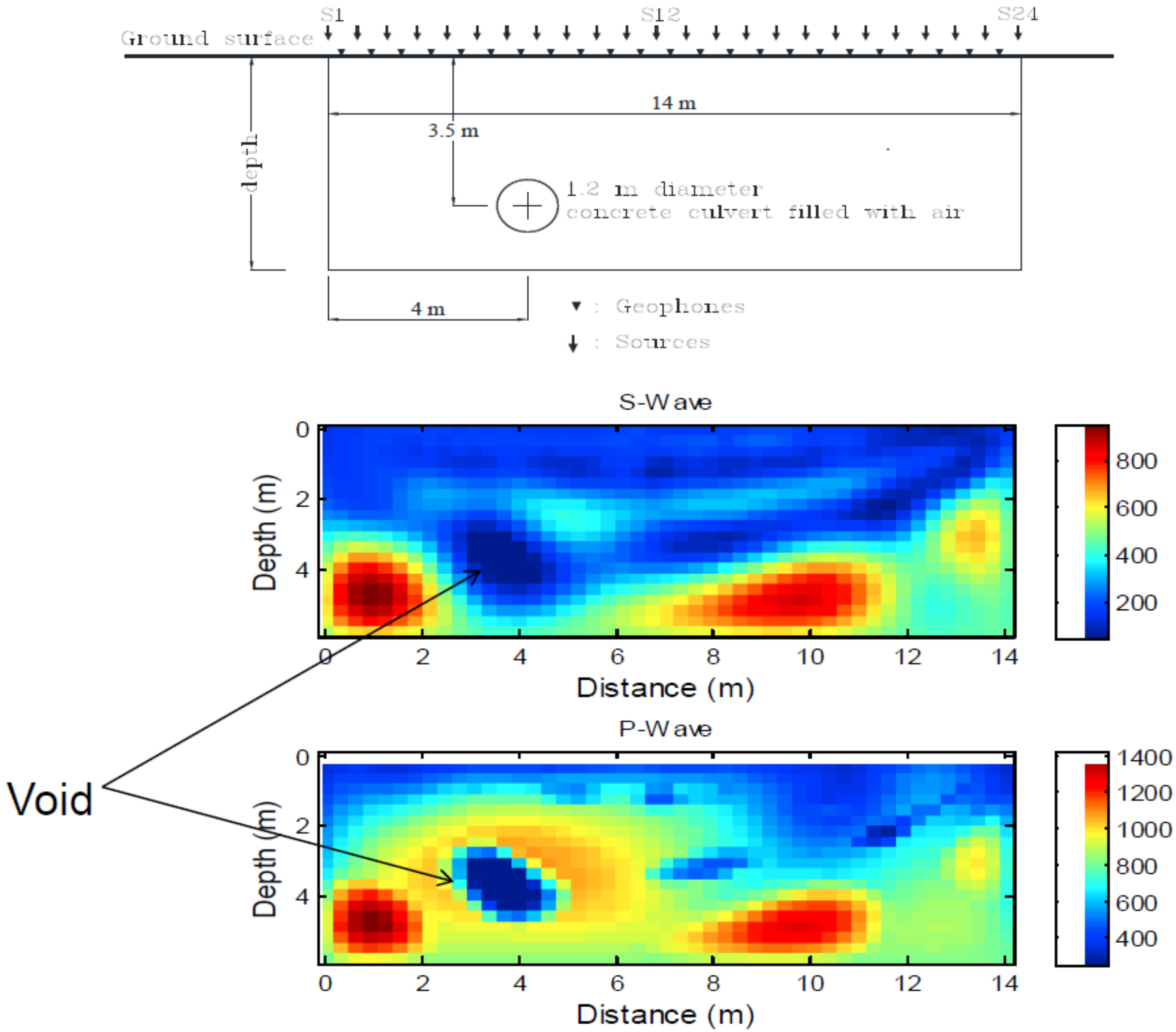


Algorithm parameters, parameter ranges, # of layers, uniform velocity

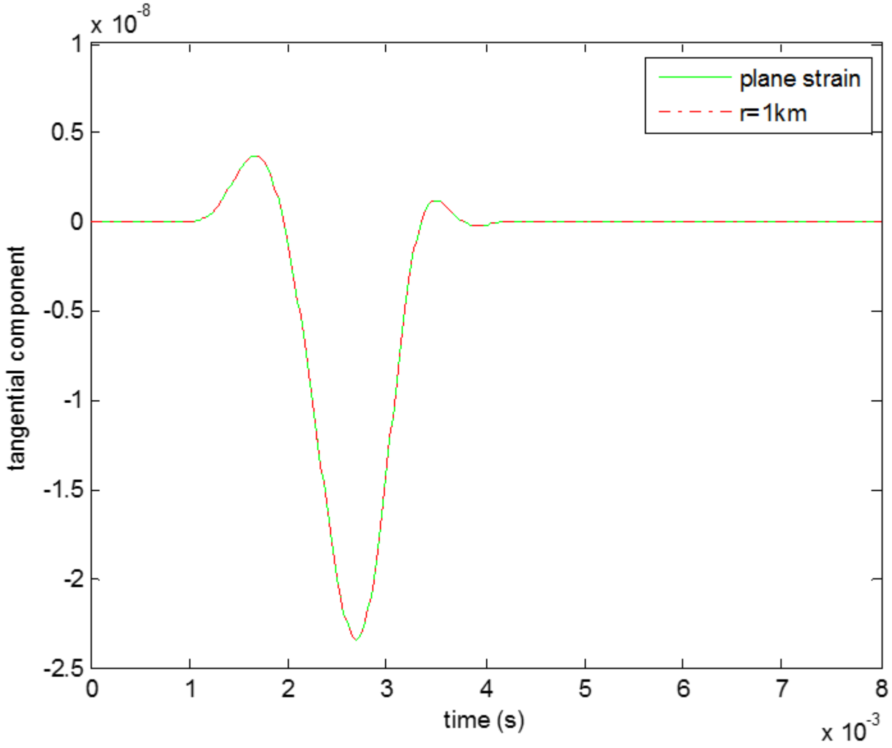
Full Waveform: Seg 2D at TAMU

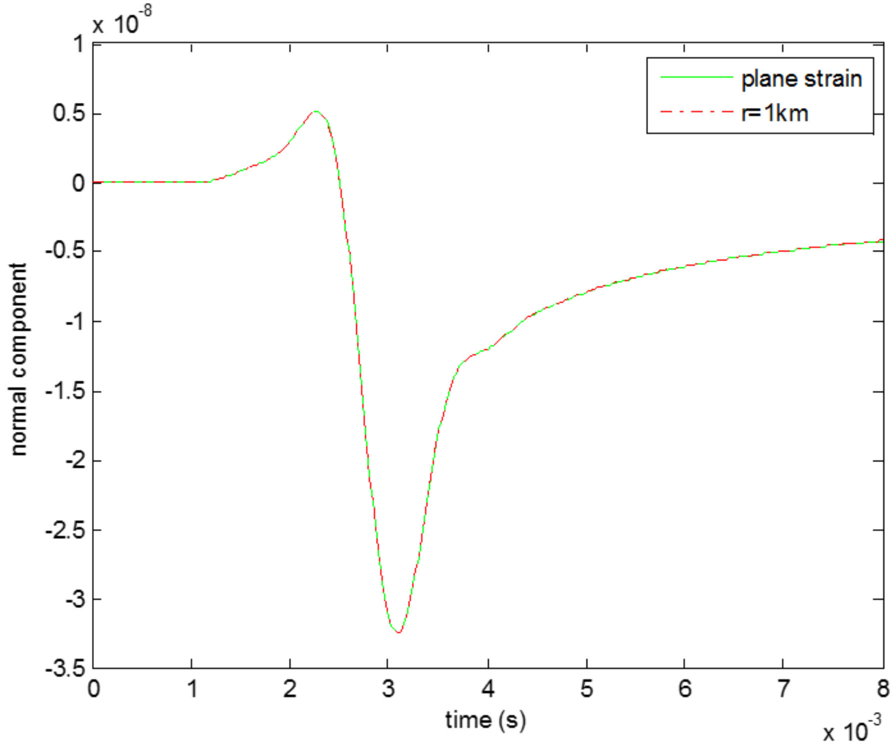


Tran Cell-By-Cell



Forward Model Validation





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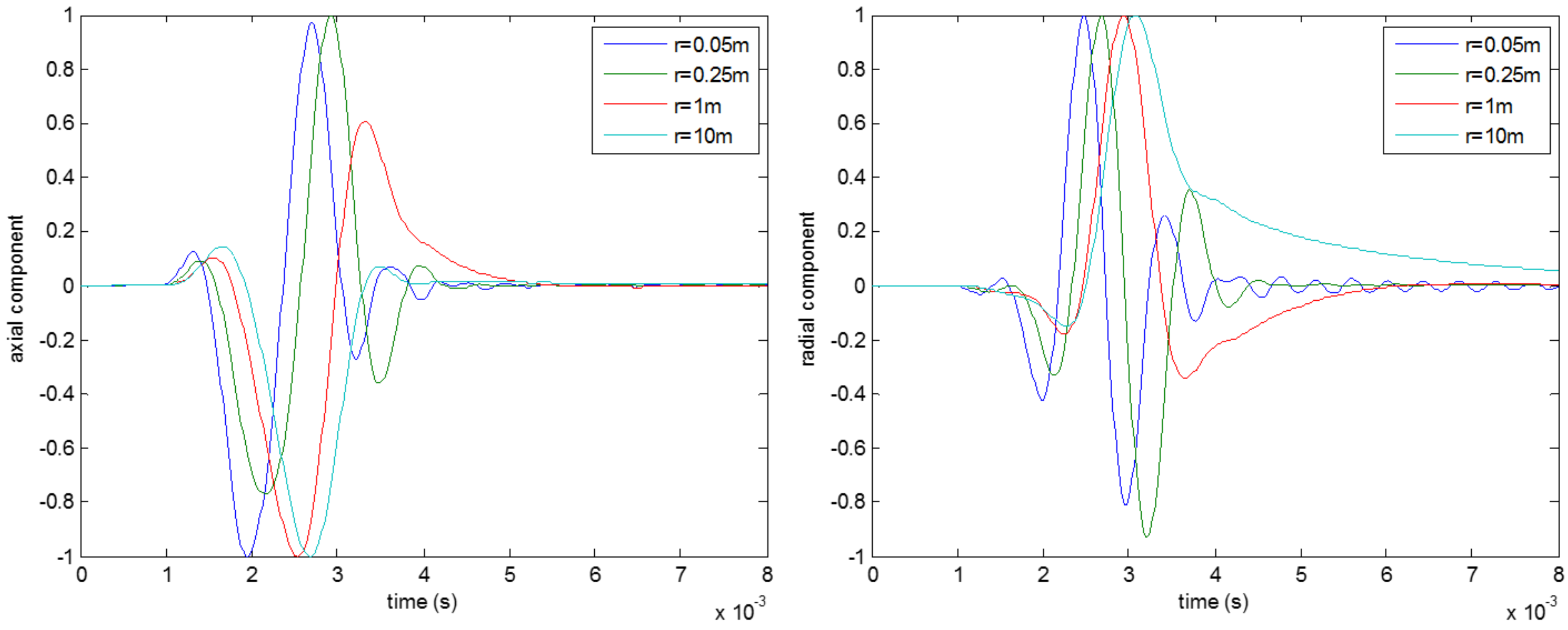
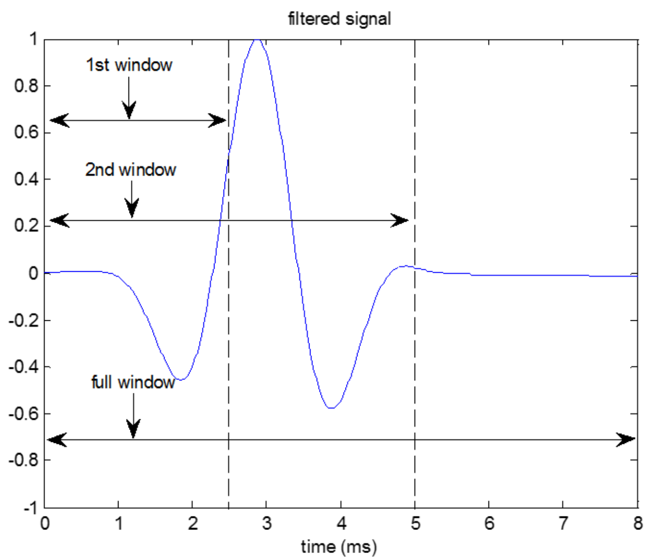
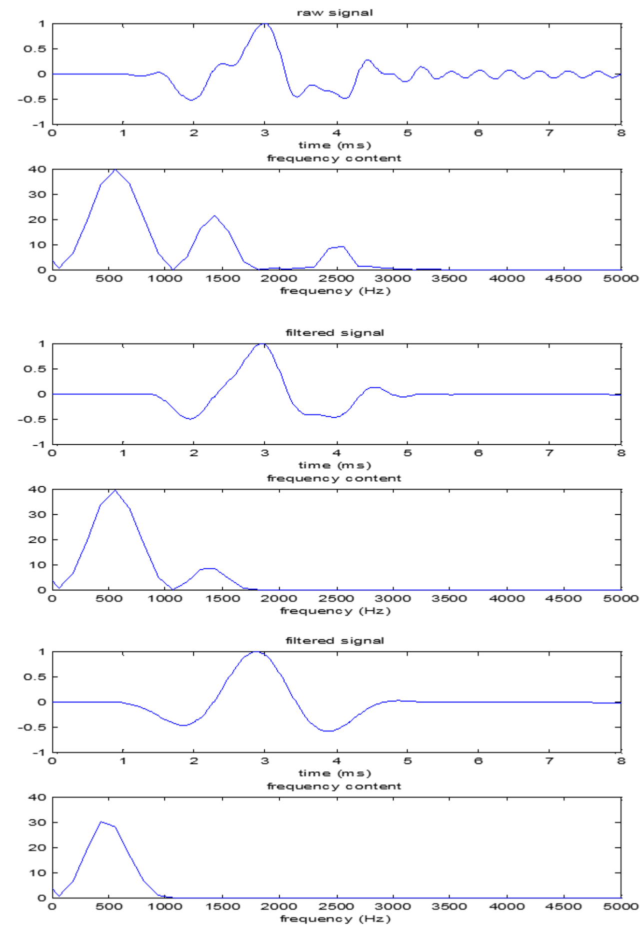


Multi-Scale Strategies

- **Utilized to reduce nonlinearity of the inverse problem**
- **Time windowing**

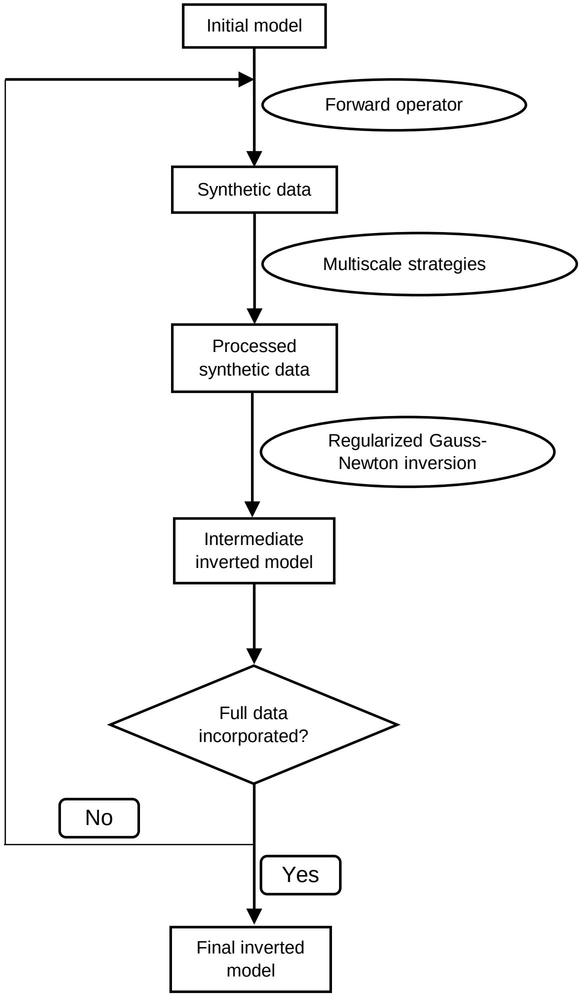


- **Frequency filtering**



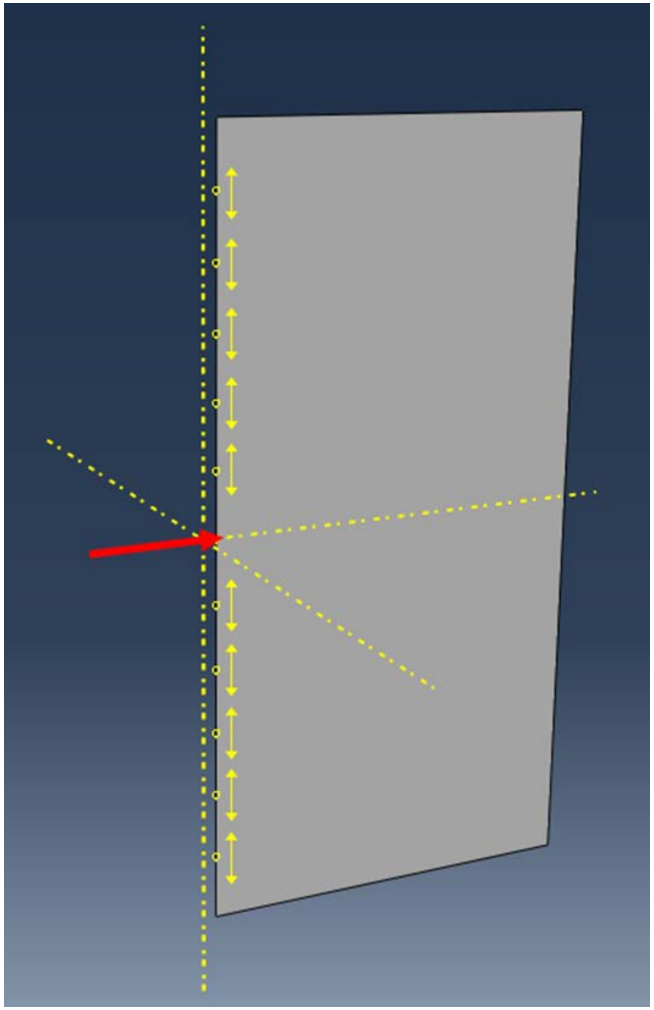
Inversion Flowchart

- Select an initial model and generate synthetic waveforms
- Process data and synthetics with multi-scale approach
- Invert data via regularized Gauss-Newton method
- Use the last updated model as initial model for the next update
- Repeat 2-4 until full data set is incorporated in the inversion
- Take the last updated model as an estimation for ground truth

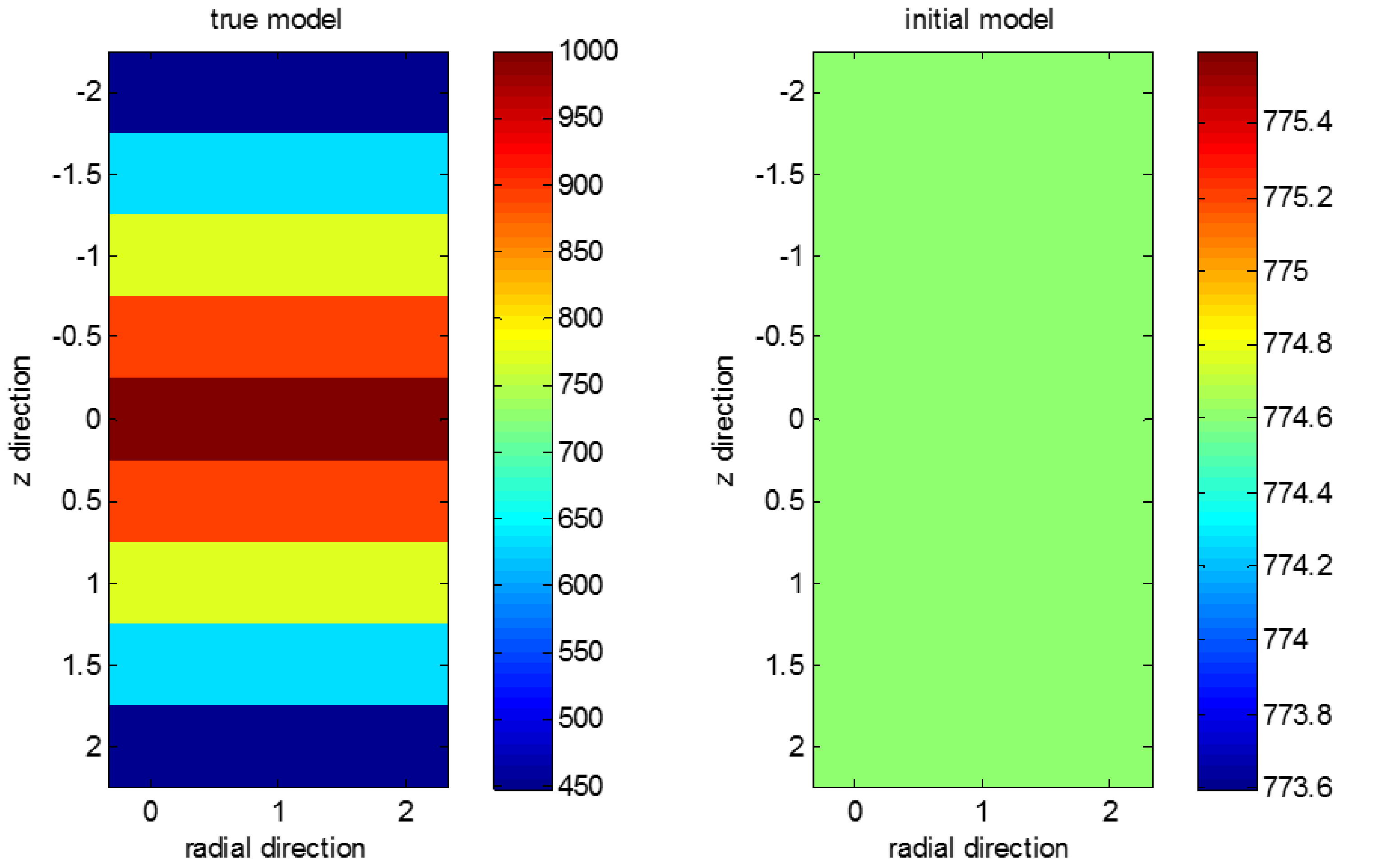


Synthetic Models: Inversion Strategy

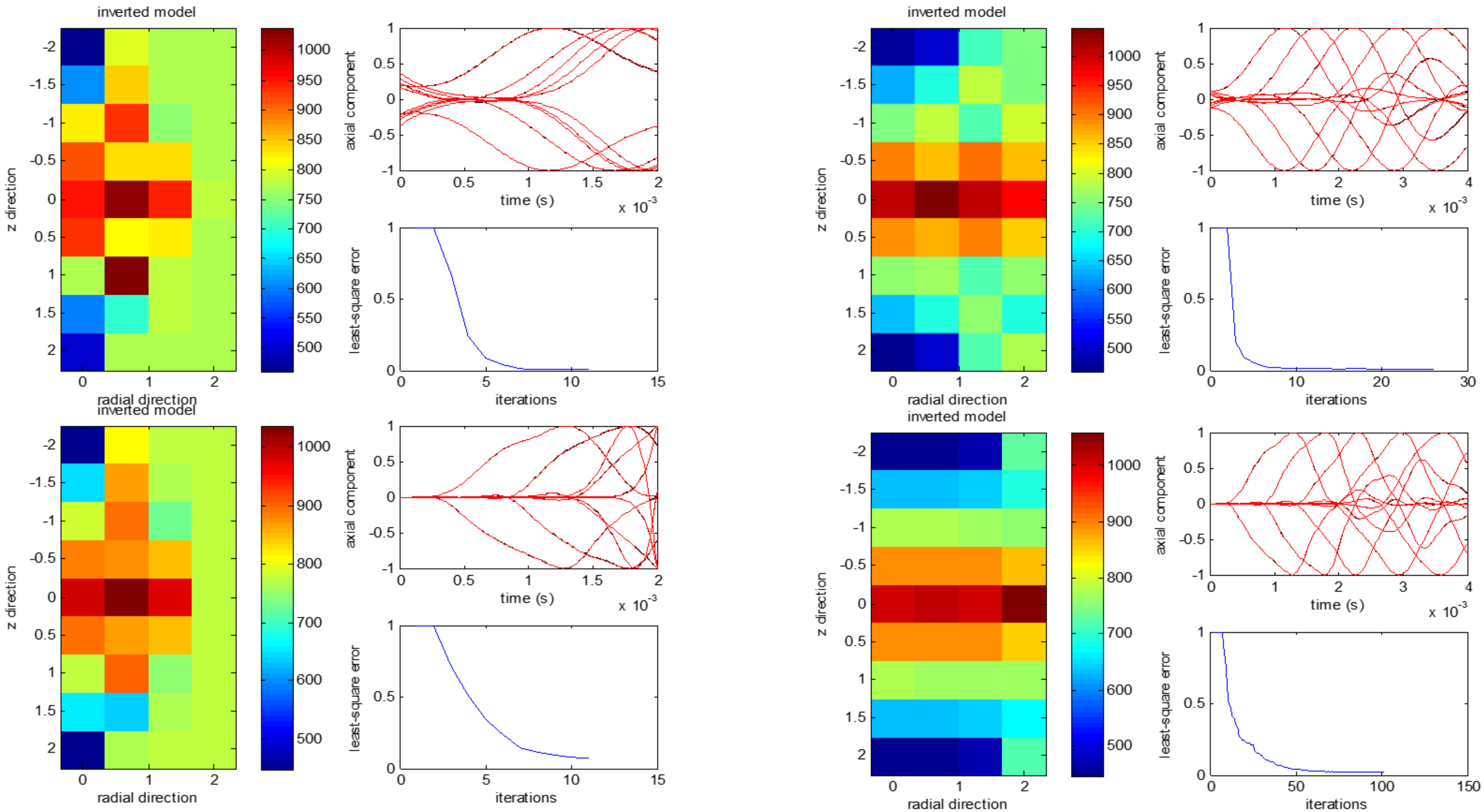
- **Goal**: test effectiveness of inversion strategy
- **Data**: generated from 2.5D model (perfect data)
- **Forward model**: 2.5D axisymmetric borehole
- **Inversion**: regularized GN method coupled with multi-scale strategies



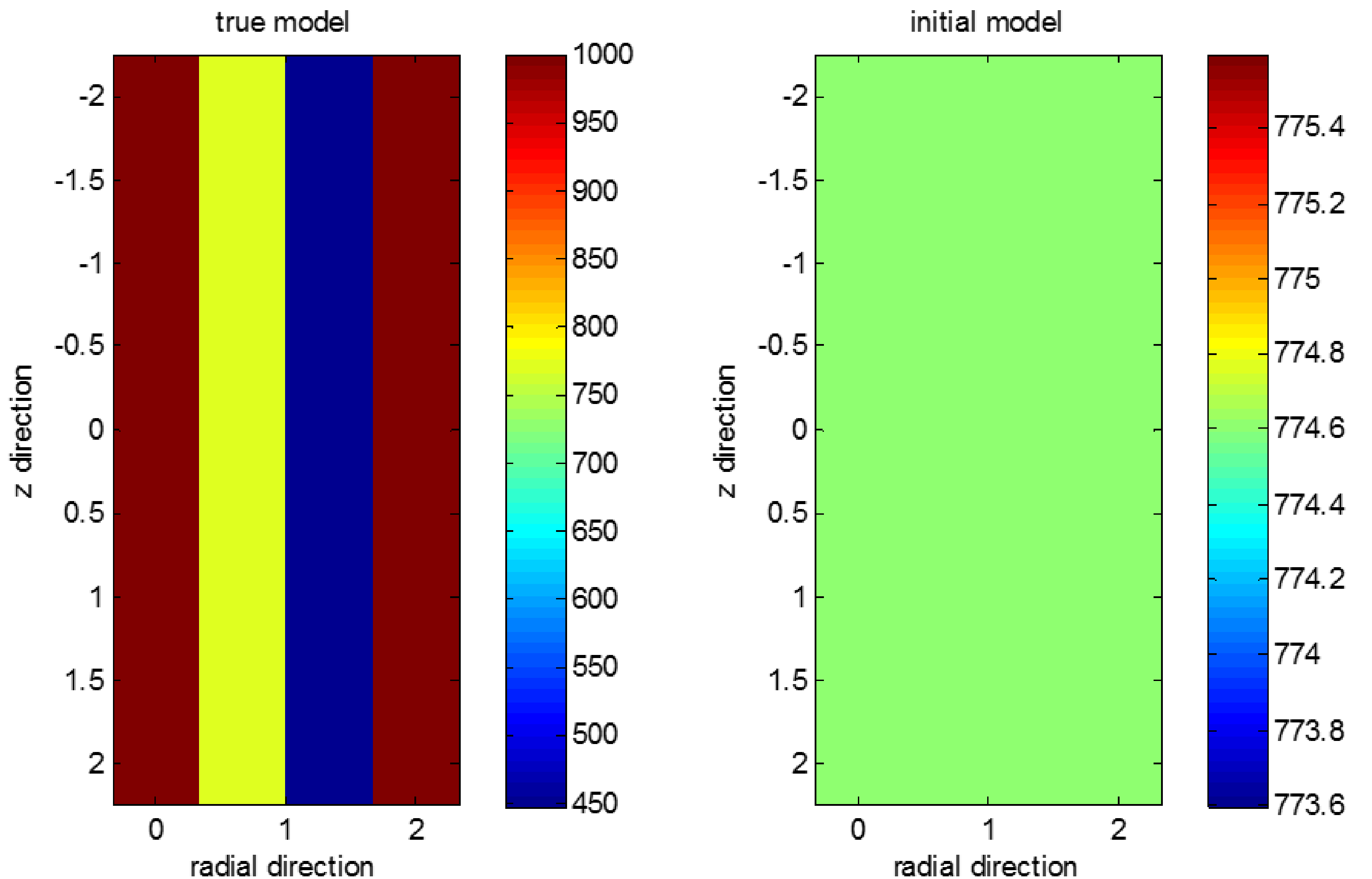
Horizontal Layers



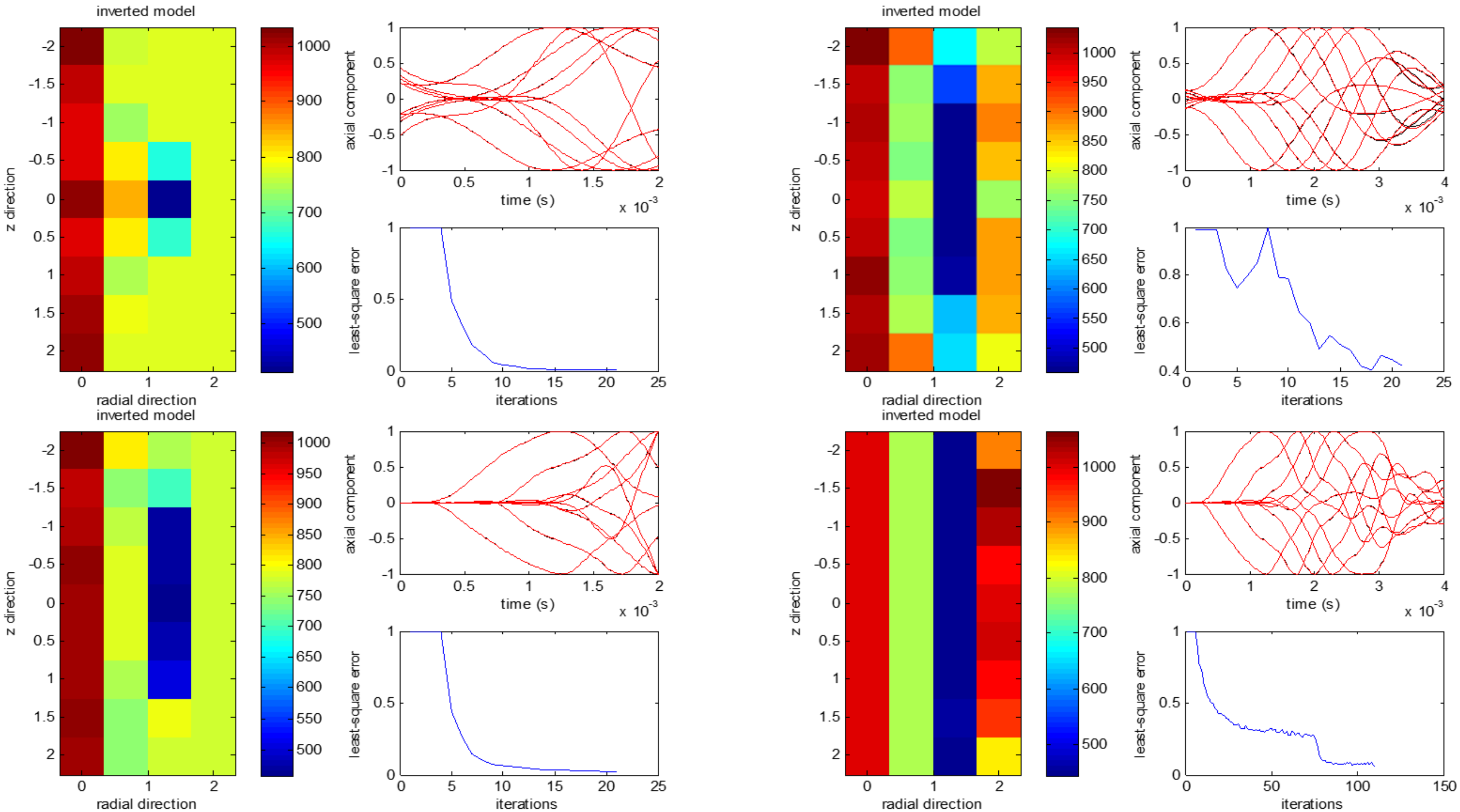
Horizontal Layers



Cylindrical Layers

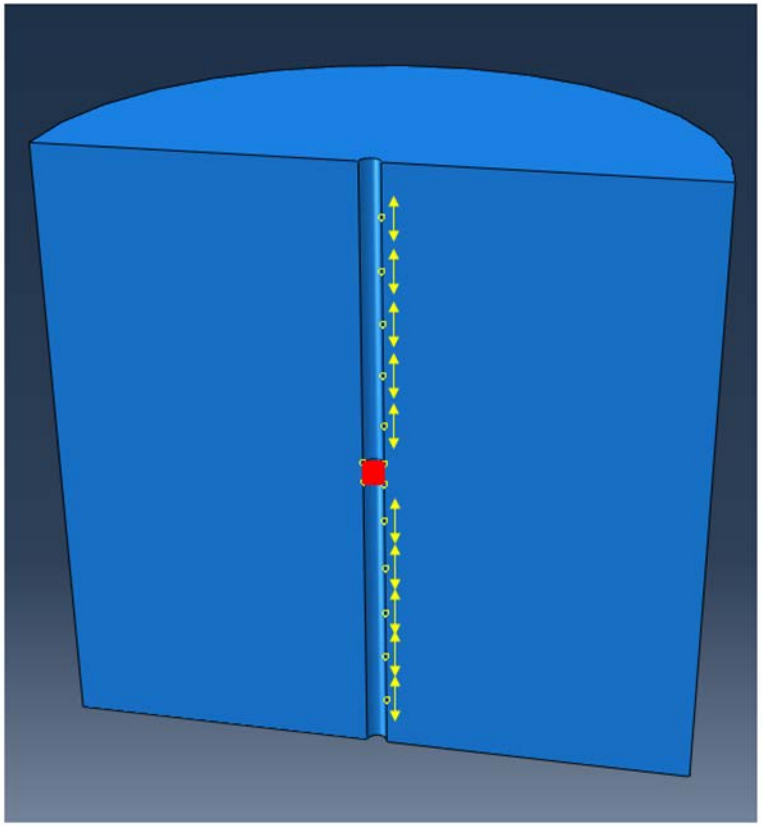


Cylindrical Layers

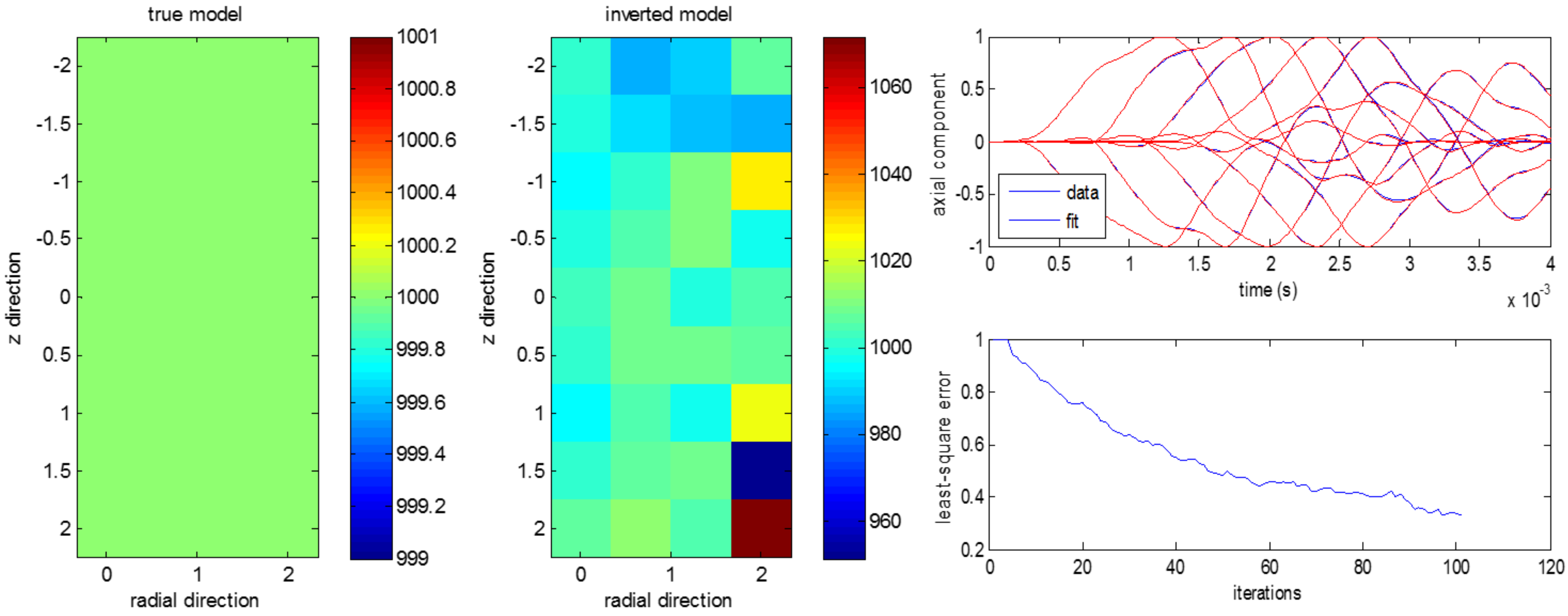


Synthetic Models: Compatibility

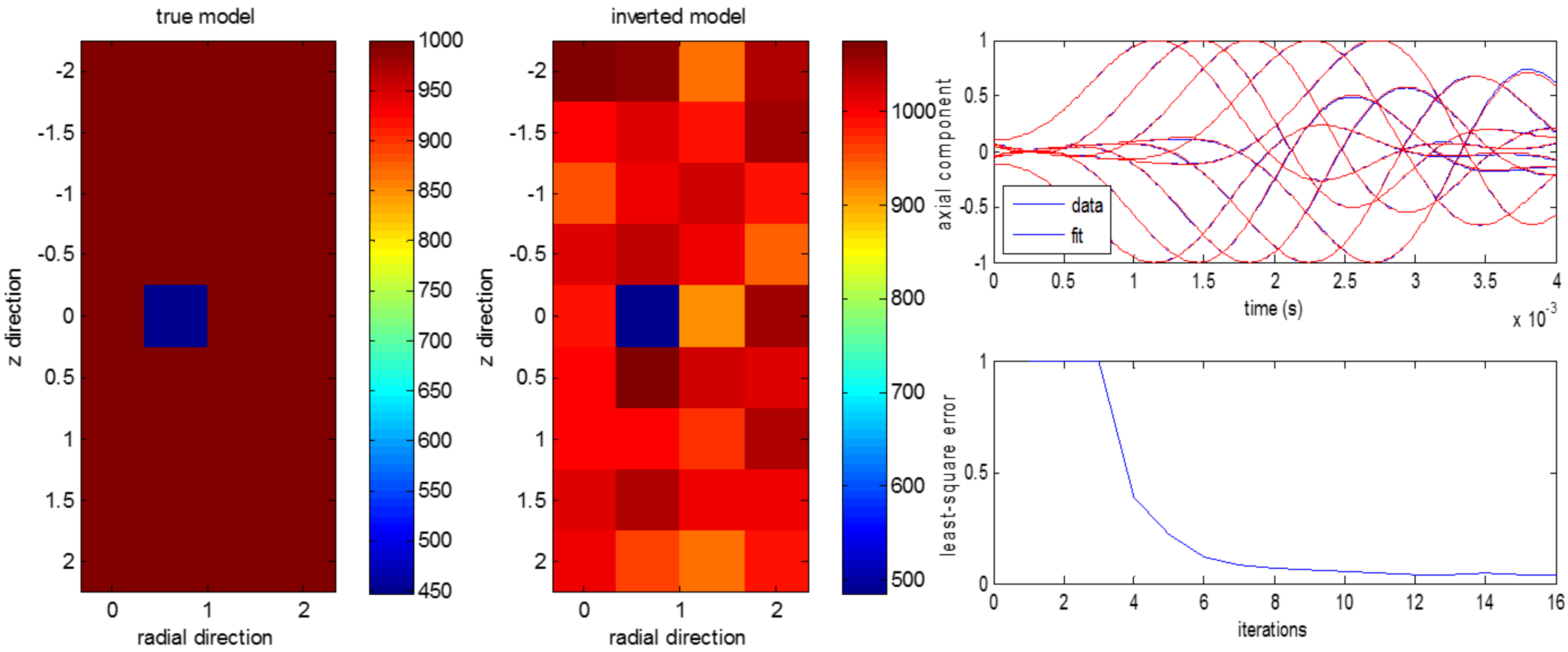
- **Goal**: use 2.5D approximation to image data from 3D space
- **Data**: generated from 3D ABAQUS model
- **Forward model**: 2.5D axisymmetric borehole
- **Inversion**: regularized GN method coupled with multi-scale strategies



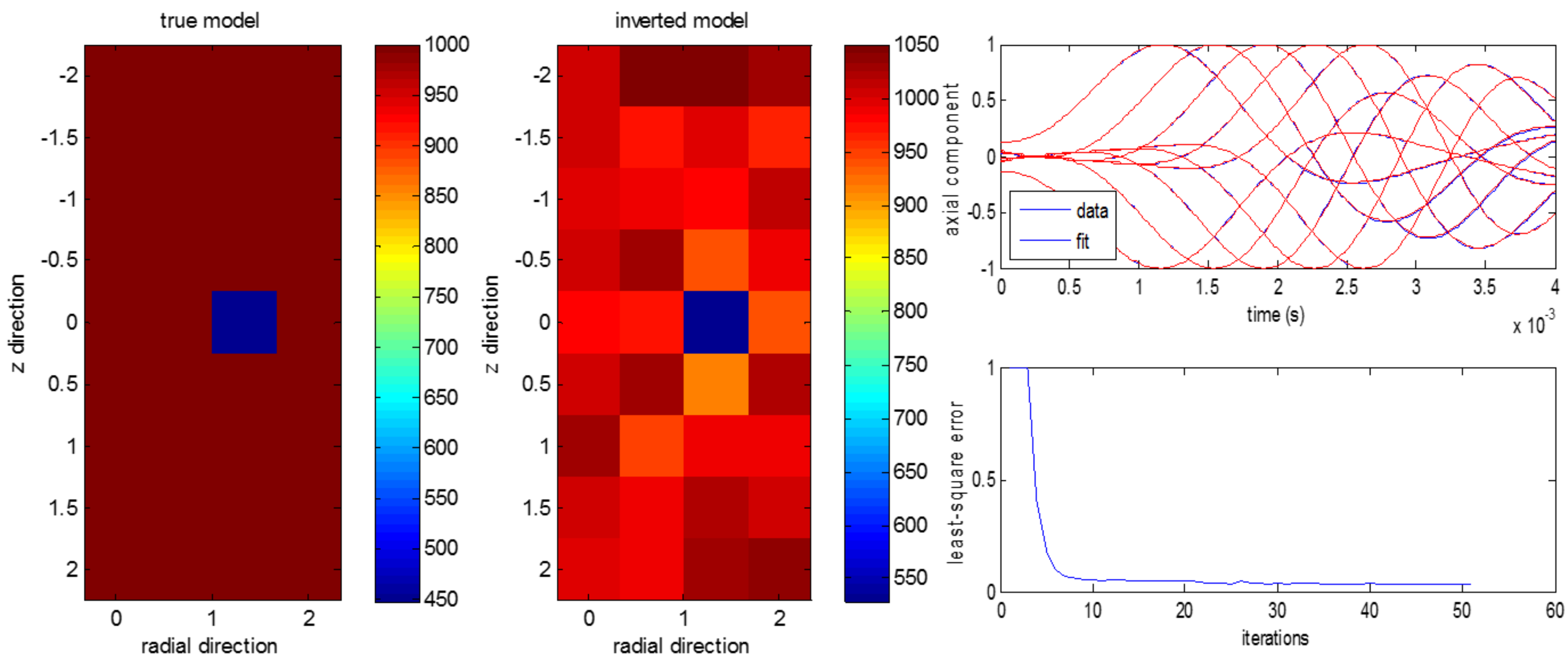
Homogeneous



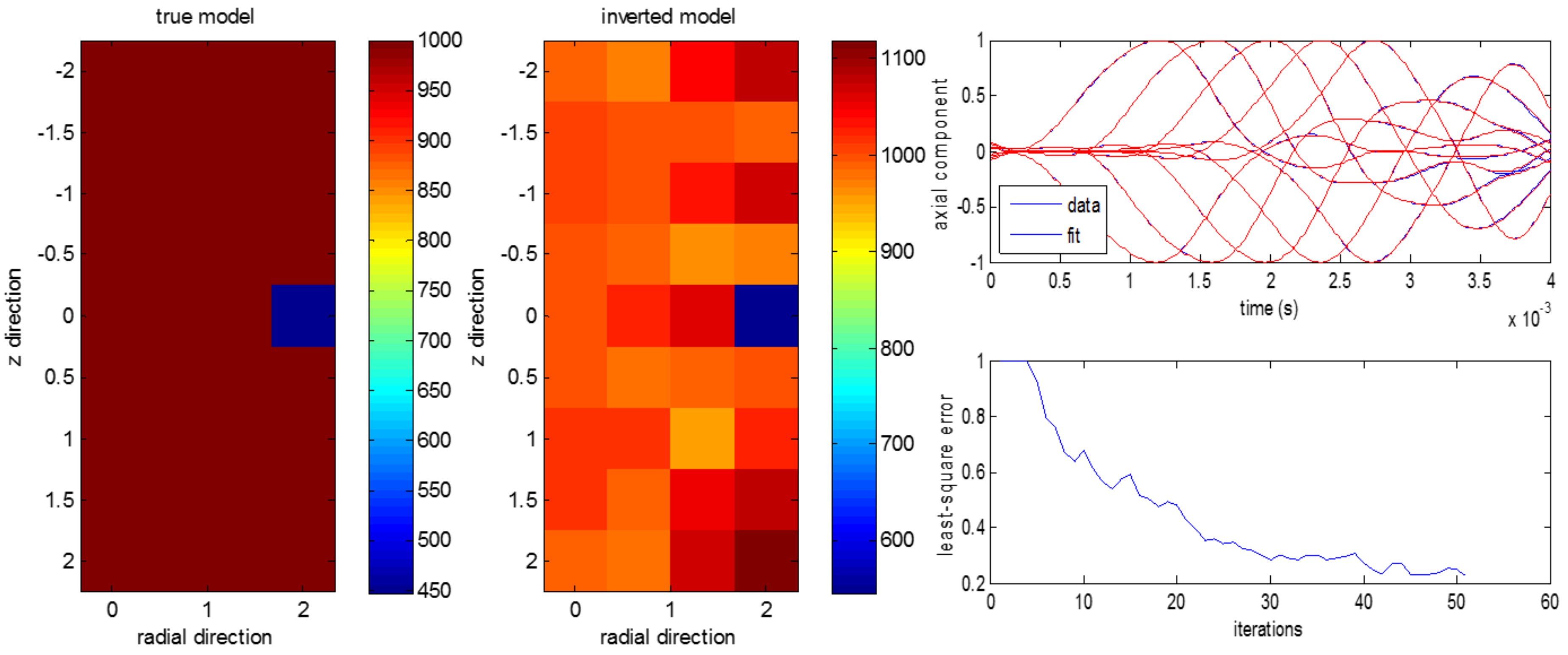
Ring Anomaly in Homogeneous



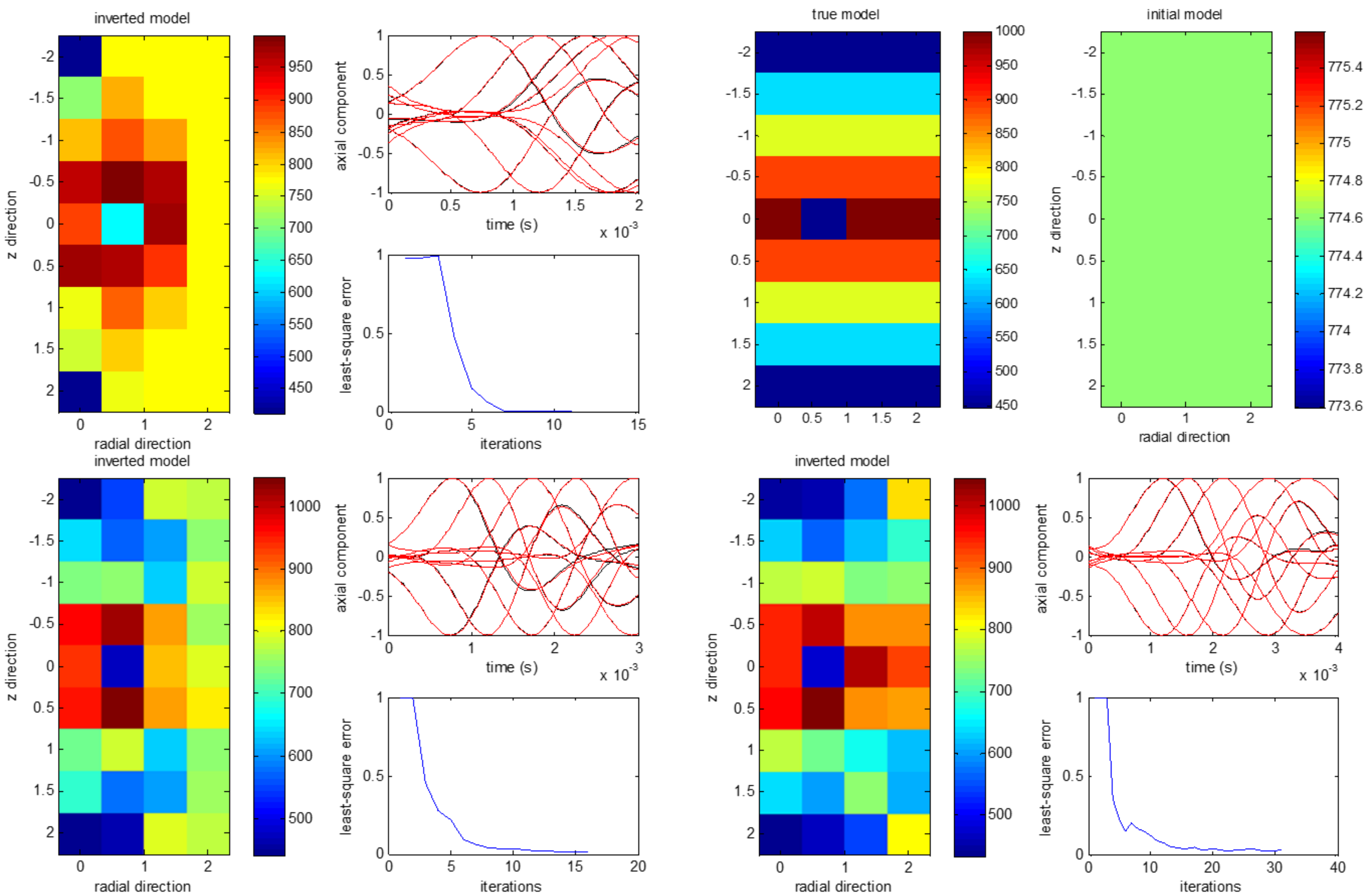
Ring Anomaly in Homogeneous



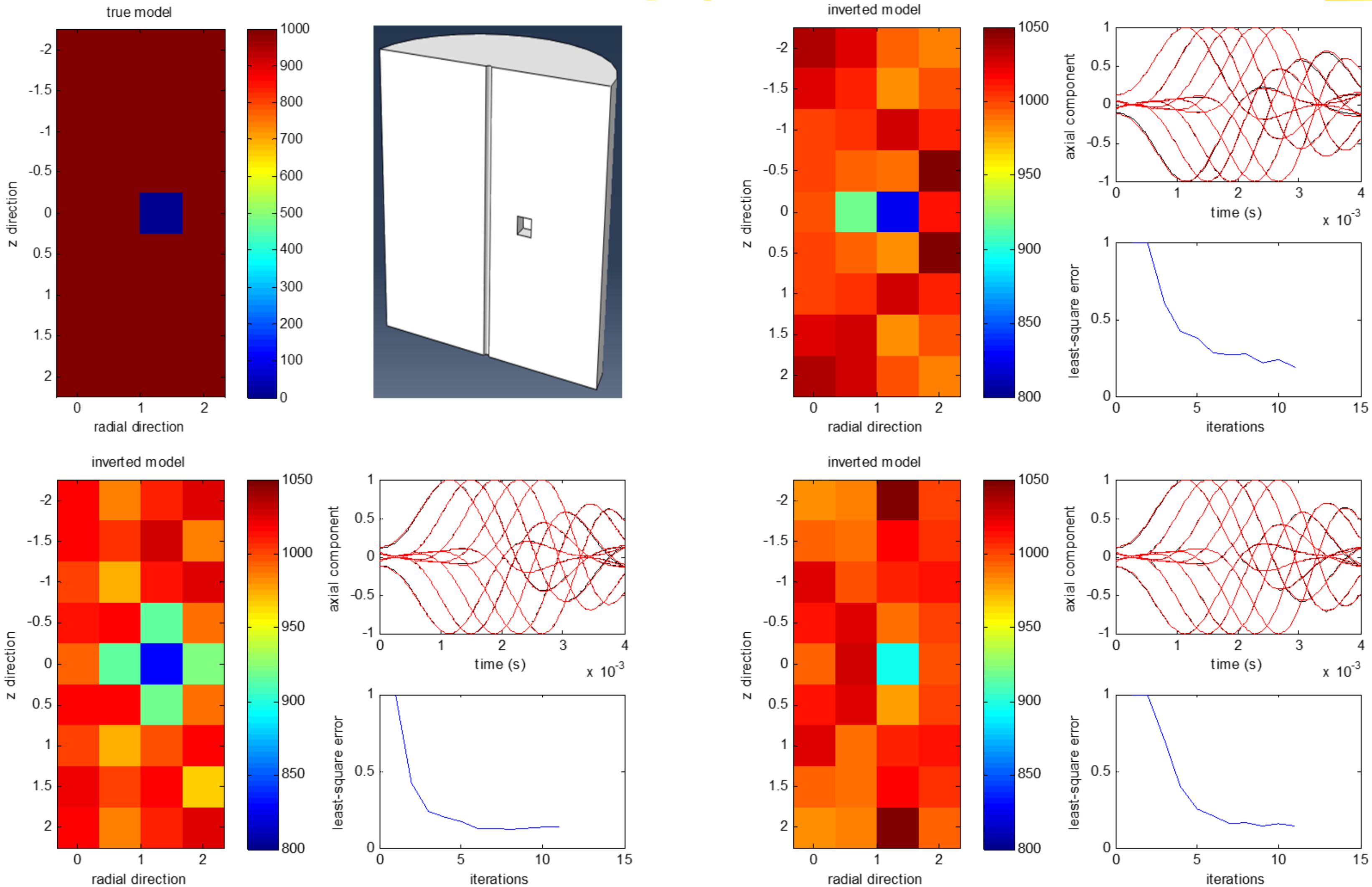
Ring Anomaly in Homogeneous



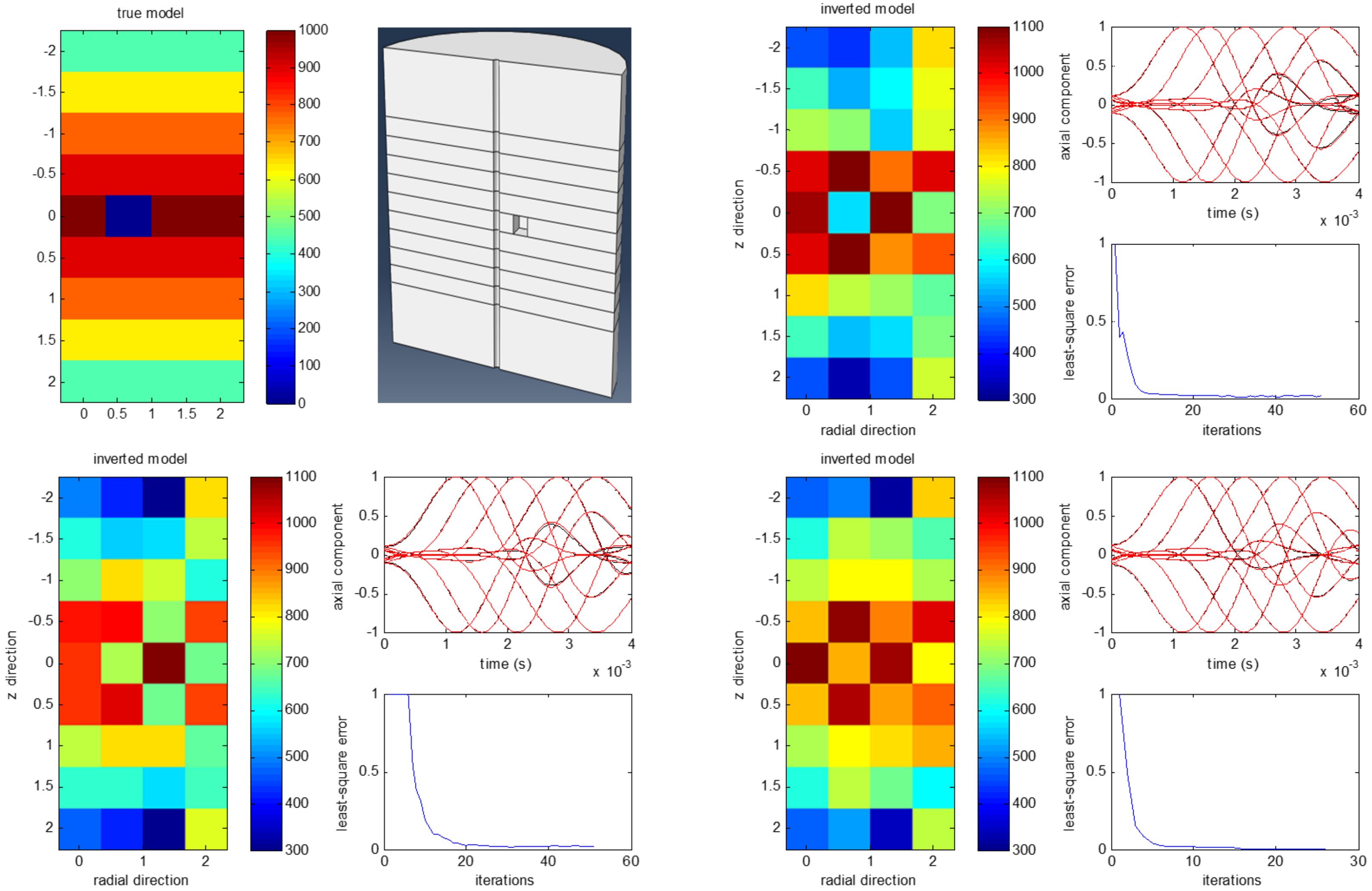
Ring Anomaly in Layered



Isolated Anomaly in Homogeneous



Isolated Anomaly in Layered



Conclusions

- **Forward model: Cylindrical geometry must be considered when modeling wave propagation inside a borehole**
- **Inversion: The regularized Gauss-Newton method must be coupled with multi-scale strategies**
- **Compatibility: The inversion scheme is stable with respect to input data (axisymmetric forward model vs. 3D data)**
- **Anomalies: The proposed imaging technique appears capable of finding indications of isolated anomalies in the vicinity of a borehole**