Implementation of Down-Hole Geophysical Testing for Rock Sockets

Dennis R. Hiltunen, Ph.D., P.E.
Jian Zou, Ph.D.

Geotechnical Research in Progress, July 14-15, 2016

Objectives

Primary objective: Develop a test method to characterize subsurface conditions in the vicinity of a drilled shaft's rock socket from within a single borehole

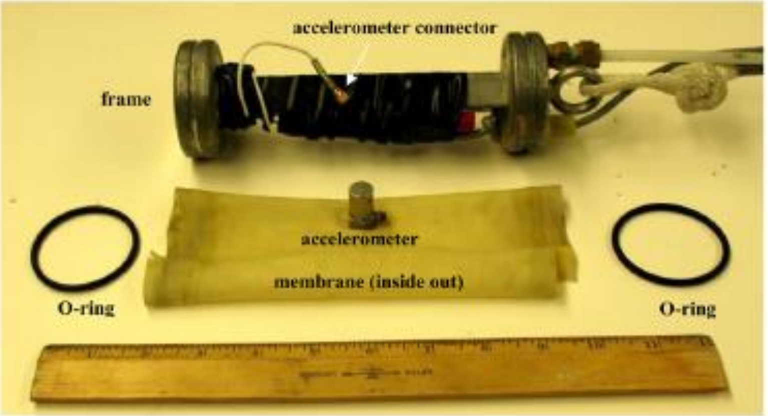
- Task 1: Borehole Instrument
- Task 2: Inversion Software
- Task 3: Validation Experiments
  - Large laboratory block of synthetic limerock
  - Newberry and Kanapaha test sites
- Task 4: Final Report

Task 1: Overview

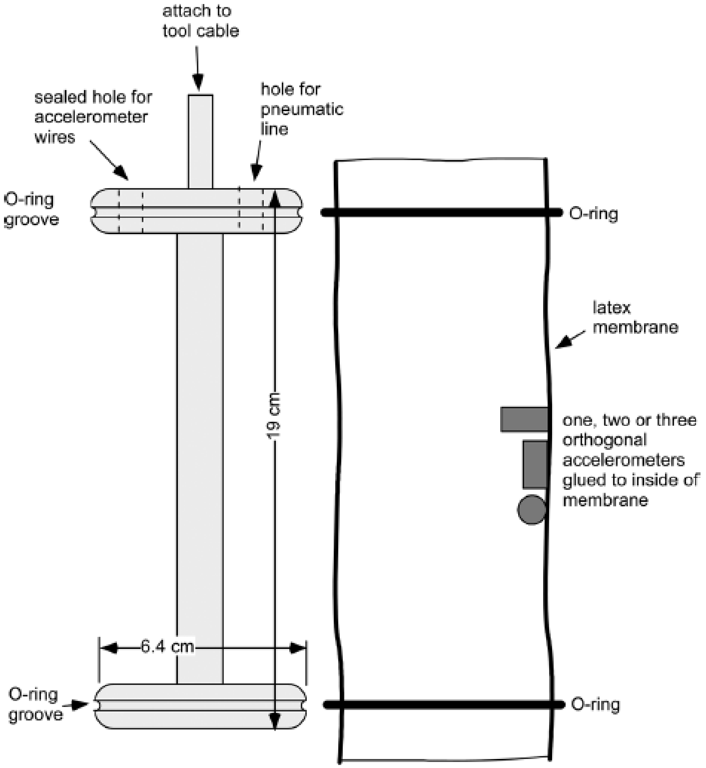
- Develop a prototype instrument for geophysical characterization of a zone of rock around the periphery of a single borehole, including two major components:
  - A source for generating seismic (mechanical) waves
  - A receiver array for capturing the wavefield
- A Kalinski-style membrane system (M. Kalinski at UK) created to couple the receiver array to the borehole wall
  - A cylindrical membrane constrained on each end, (like a triaxial test specimen) with the receivers attached inside
  - The membrane then inflated within the borehole to couple the receivers with the borehole wall

Kalinski Borehole Receiver

a. assembled view



b. exploded view



a. support frame b. inflatable membrane

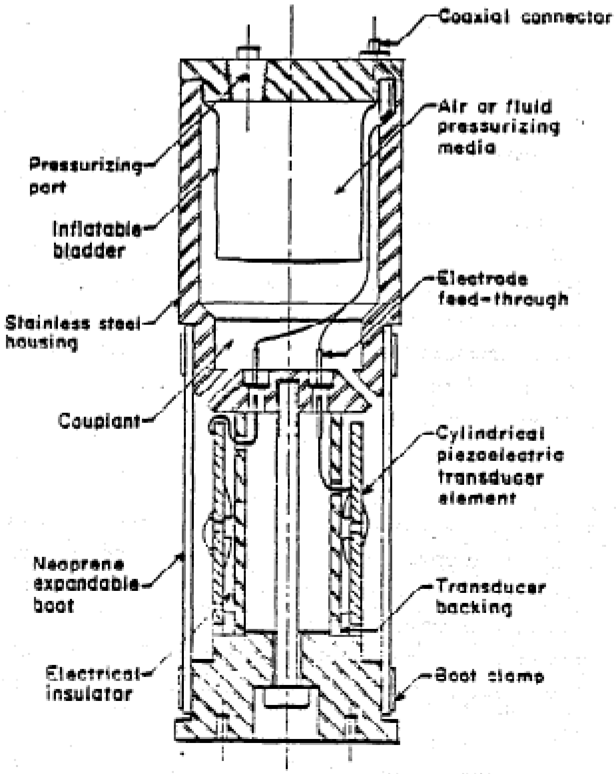
Borehole Receiver

- The receiver array will consist of 10 to 12 accelerometers in a line along the vertical sidewall of a borehole
- Both uniform and non-uniform spacing of the receivers will be considered

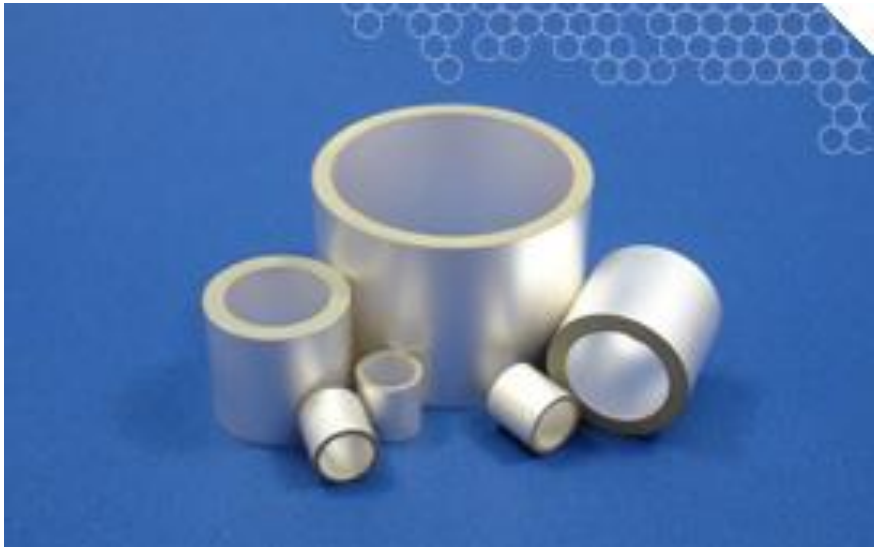
Borehole Source

- A source needed to generate a ring-type loading around the circumference of a borehole, which is consistent with the axisymmetric loading condition
- Piezoelectric cylinder source (high-frequency source good for rock characterization) selected to apply a uniformly-distributed ring loading within the borehole
- The source will be used to create wavefields from multiple shot locations along the length of a fixed receiver array to improve resolution

Piezoelectric Borehole Source

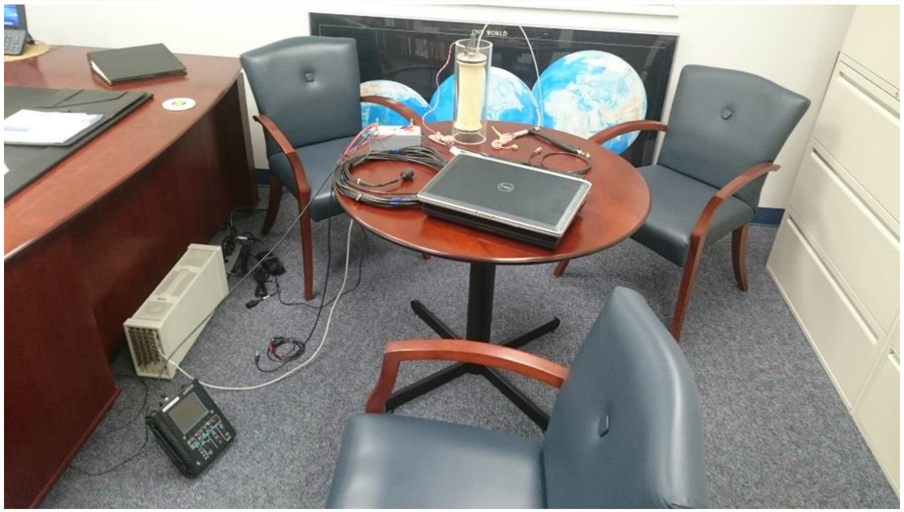


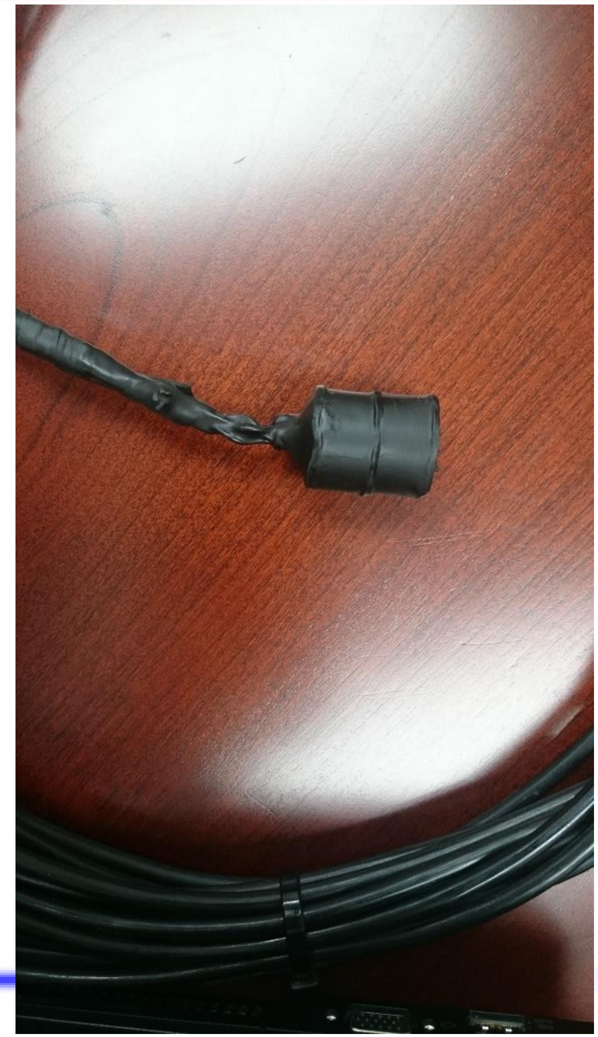
Thill (1978)



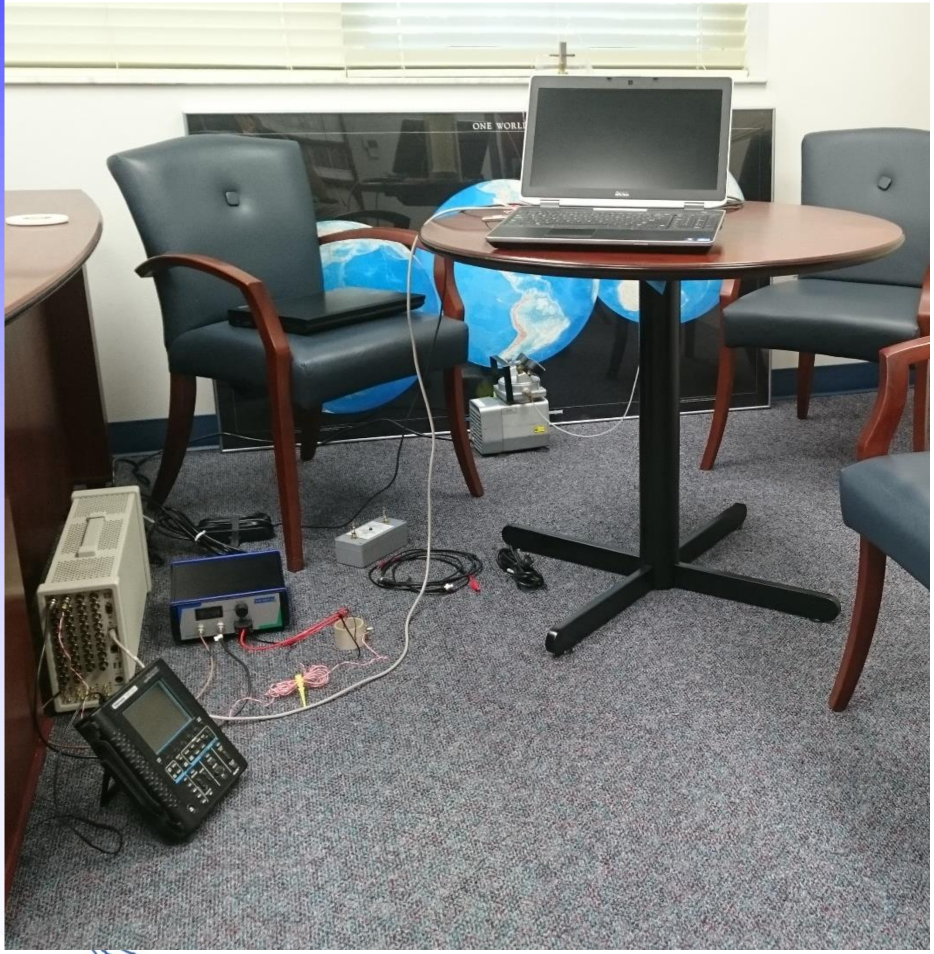
Piezoelectric Cylinders

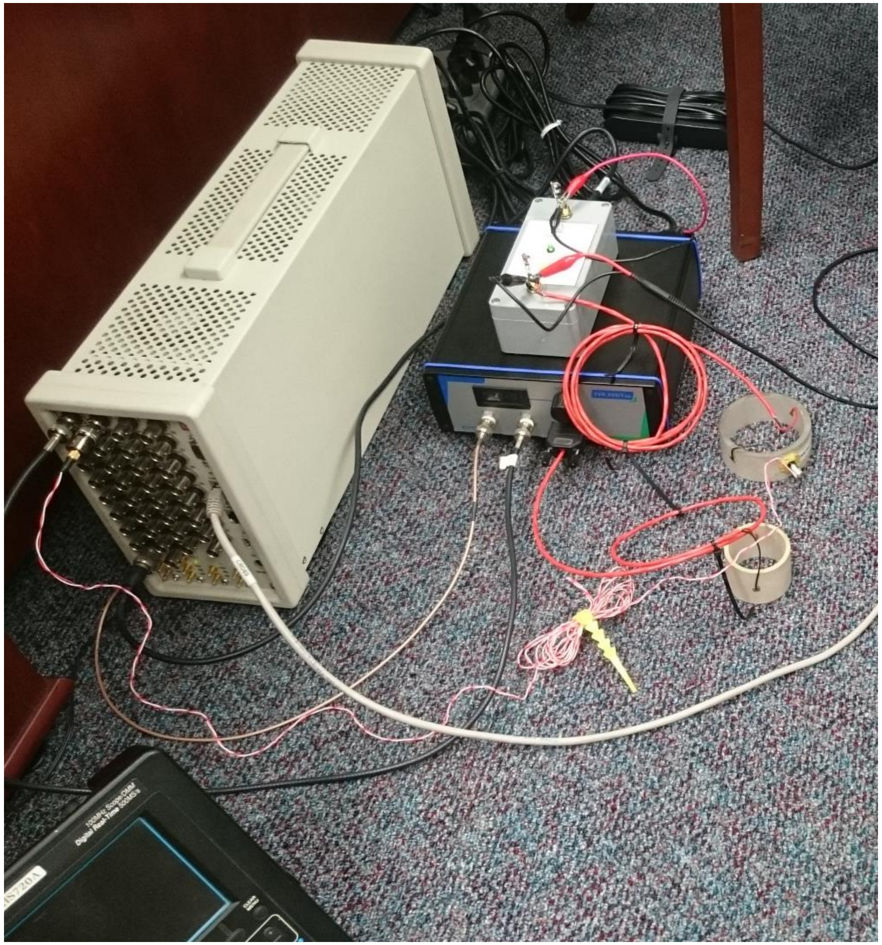
Cylinder and Amplifier: 1st Generation



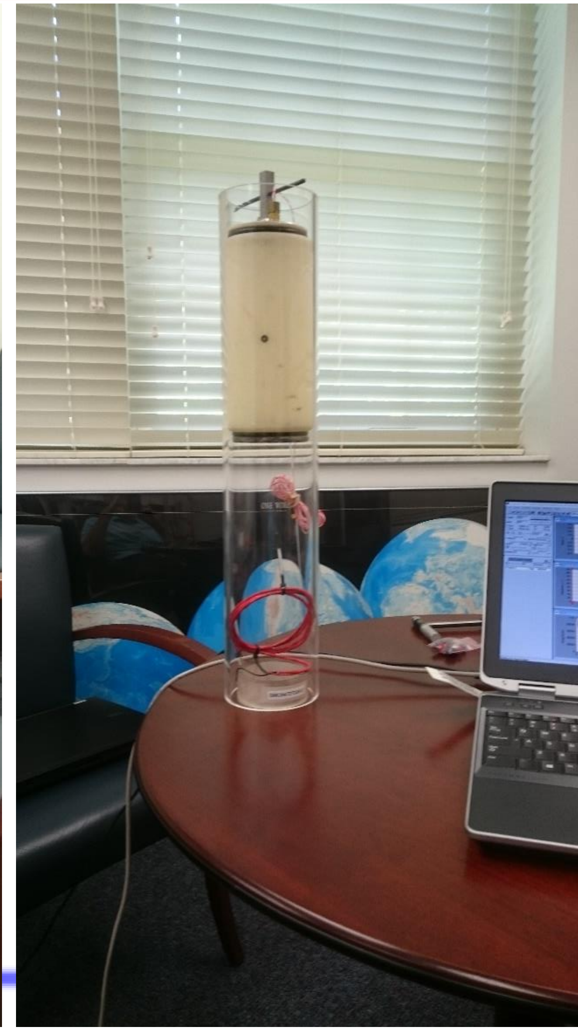


Cylinder and Amplifier: 2nd Generation





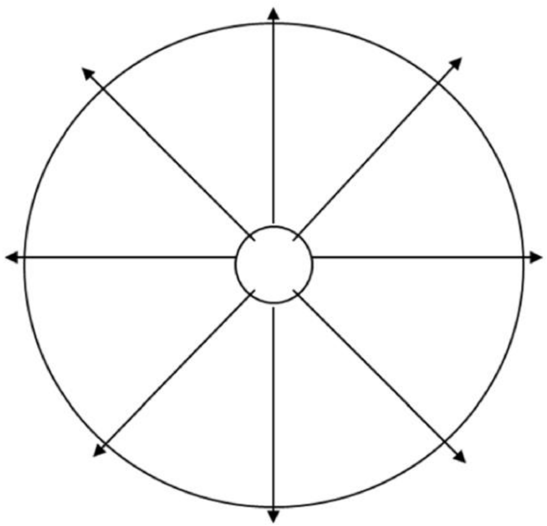
Combined Source/Receiver Concept



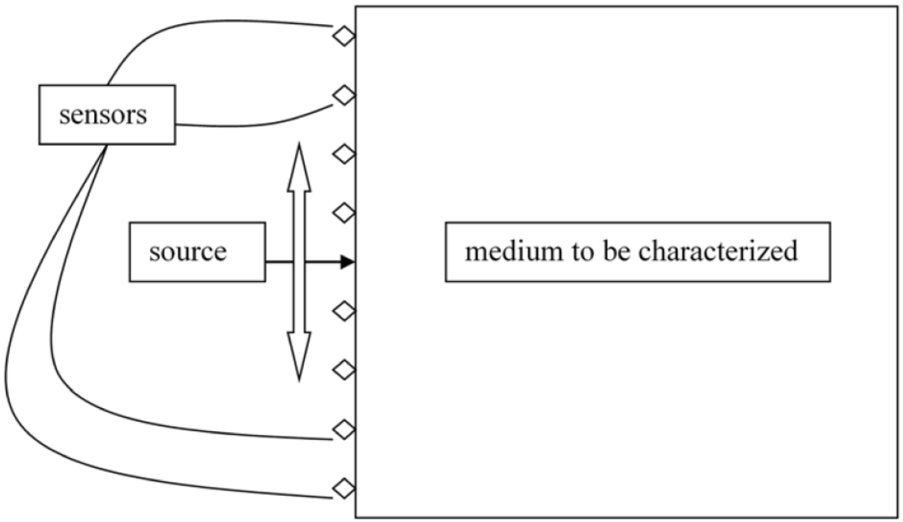
Task 2: Overview

- Develop an inversion software to create an image of the material adjacent to the borehole using measured (or synthetic) data

Plan View



Cross-Sectional View



Forward Model

- A forward model needed to predict motion versus time signatures occurred at each receiver position along the borehole sidewall (the so-called full waveforms)
- Finite element software package ABAQUS used in forward modeling
  - Axisymmetric forward model selected to predict the full waveforms
  - 3D forward model abandoned due to formidable computer time required for inversion

Inversion Scheme

- Full wave inversion (FWI) technology employed to create a 2D image along one radius from the borehole axis
  - The inversion conducted by minimizing least square error between the measured and predicted full waveforms based on a regularized Gauss-Newton method

- The nonlinear least square inversion scheme implemented in MATLAB

- The interface between ABAQUS (forward model) and MATLAB (inversion scheme) developed using Python script

Practical Strategies for FWI

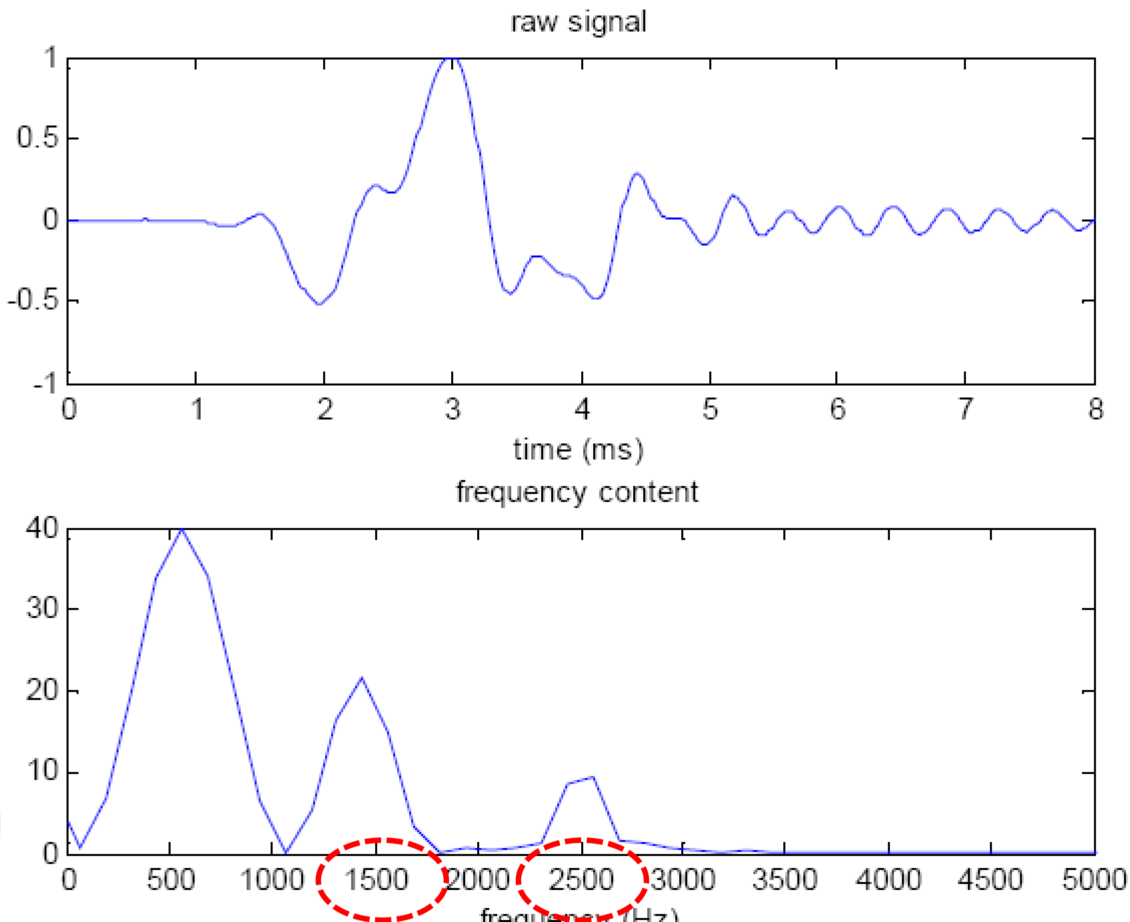
- Regularized Gauss-Newton method is one of the local optimization techniques

- Two practical strategies used to help improve the quality of initial models and to find the global minimum:
  - Frequency filtering
  - Time windowing

- Frequency filtering, also known as the multiscale approach, builds a background model by inverting the low-frequency components in the data, and then increases the resolution by gradually adding high-frequency components
  - Key idea: reducing nonlinearity in the data

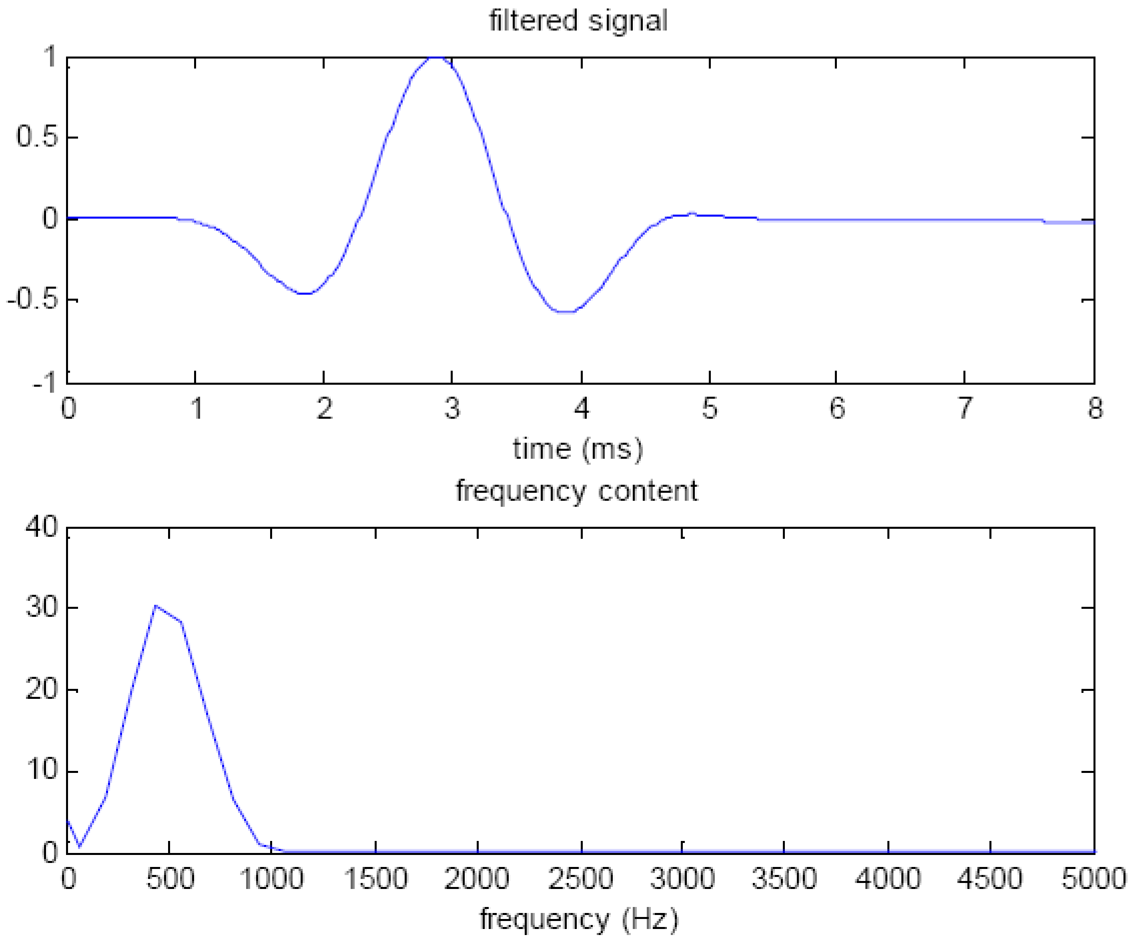
Frequency Filtering: Example

- Raw signal exhibited local "vibration"; three peaks existed in the frequency spectrum of the raw data



Frequency Filtering (Cont.)

- Time signal became smoother (more linear) after applying a low-pass filter; only lowest peak remained in the spectrum



Time Windowing

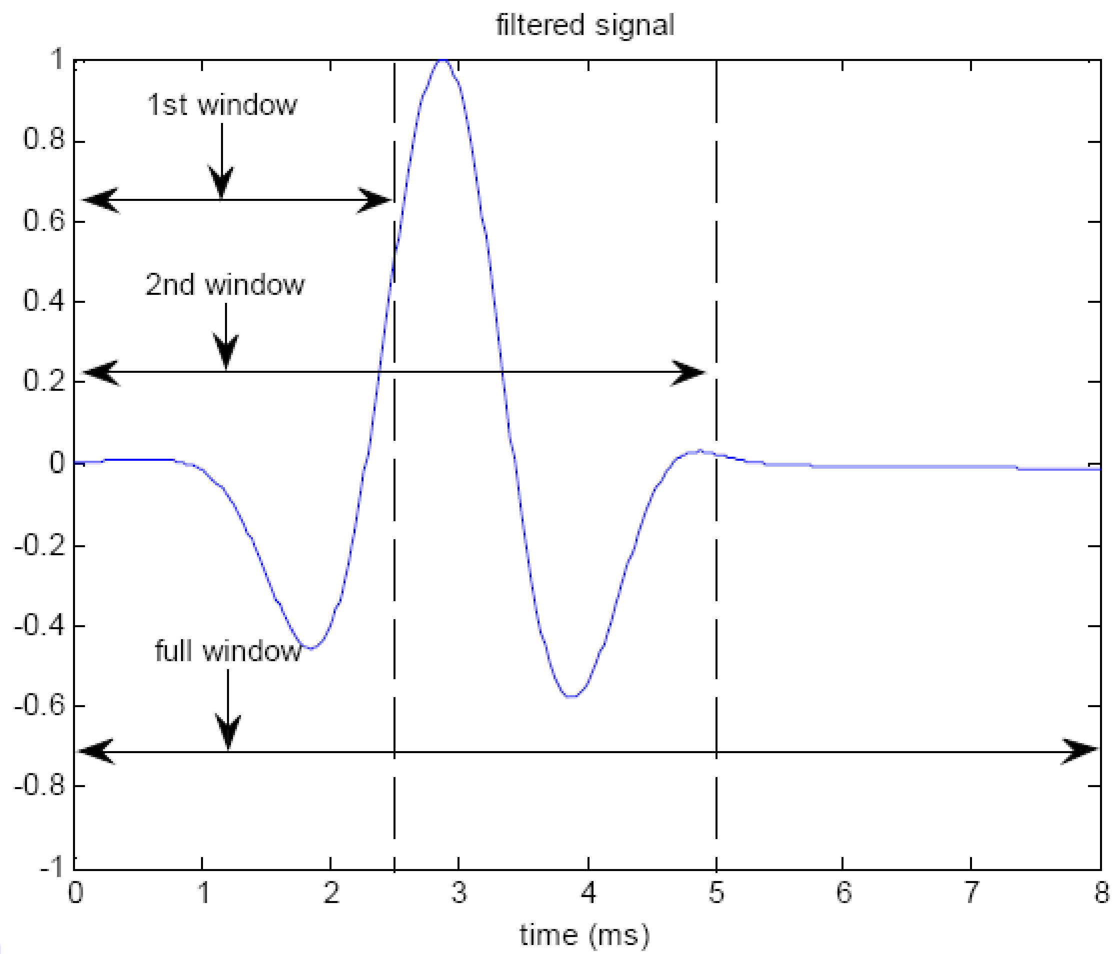
- Time windowing used to further reduce the nonlinearity: by starting inversion with a short time window at a low-frequency band; and then gradually increasing the time window and frequency bandwidth

- Using the filtered waveform in the prior example: (i) First window clipped at 2.5 ms; (ii) Second window at 5 ms; (iii) Full window corresponds to the entire length of the signal (8 ms)

  - Inversion started using the filtered data for the first window; After convergence, further inversion conducted using raw data

  - Then, the inversion continued with longer windows until full data set has been considered

Time Windowing (Cont.)

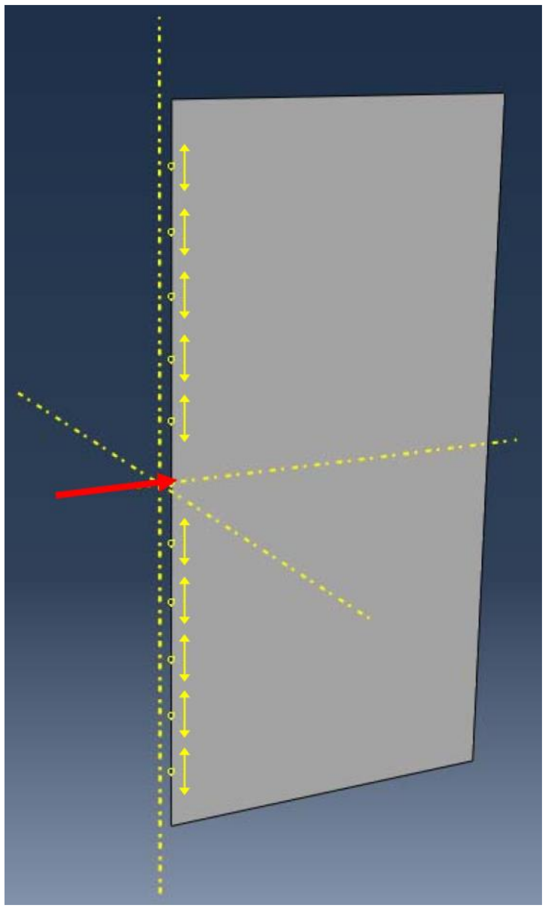


Example Simulations

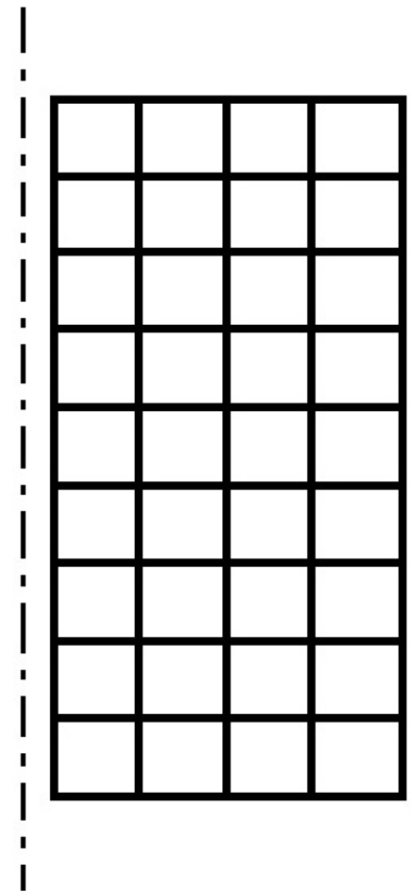
- Example simulations used to illustrate effectiveness of the analysis software, including
  - Case 1: multilayered system w/o anomaly
  - Case 2: multilayered system w/ one ring-type anomaly
  - Case 3: multilayered system w/ two ring-type anomalies

- Synthetic records created using axisymmetric forward models and treated as field data
  - Each forward model divided into 36 pixels (9 by 4), resulting in 36 parameters; Each represents one shear wave velocity
  - A shock loading excited at the center of borehole side wall
  - Synthetic records obtained at predefined locations of a 10-channel receiver array along the wall

Axisymmetric Forward Model

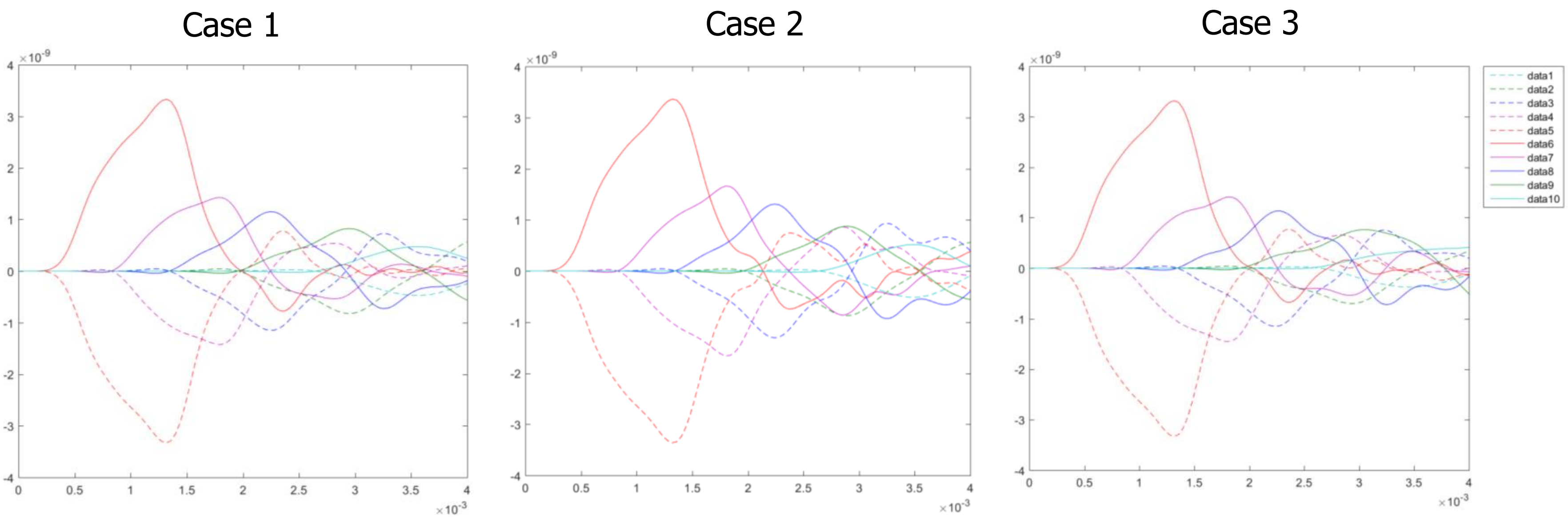


Schematic Loading and
Layout of Receivers



36-Pixel forward model

Synthetic Records



- Axial component of particle displacement obtained at each location of the 10-channel receiver array for all three cases
- Velocity profiles reconstructed by means of inversion

Inversion Procedure

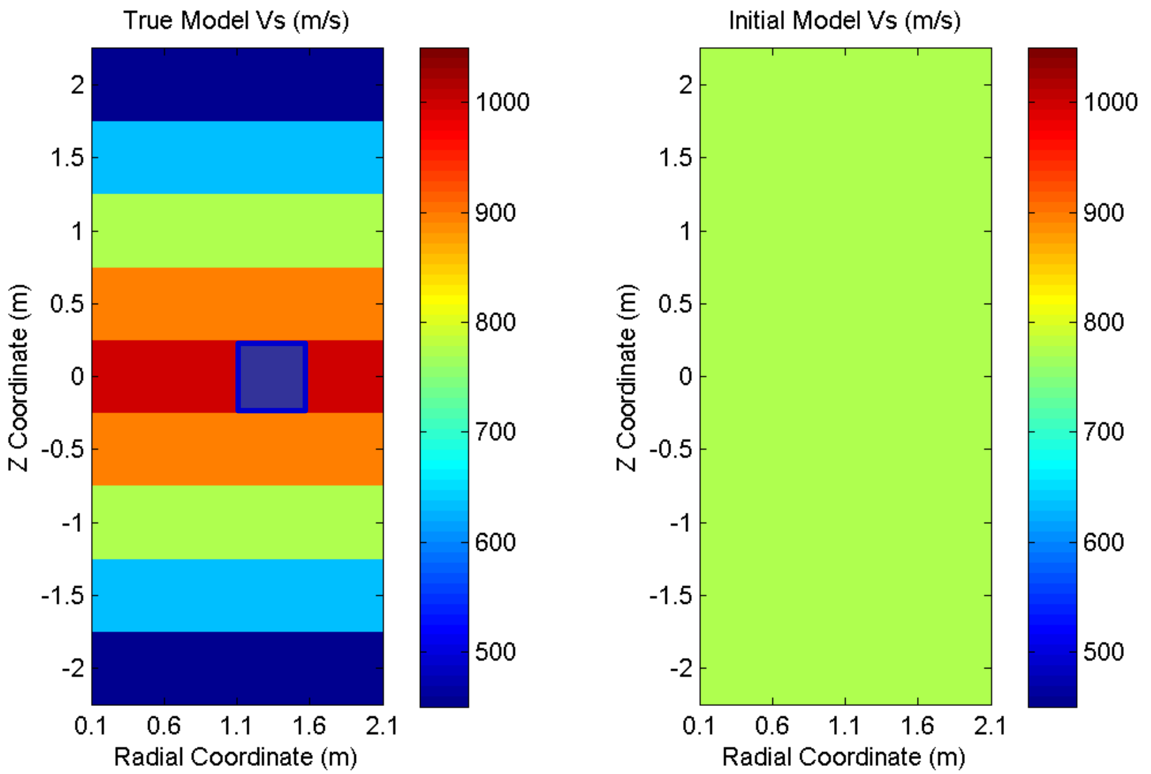
- Inversion conducted following four steps:
  - 1: 2-ms time window w/ a low-pass filter
  - 2: The same time window w/ no filter
  - 3: 4-ms time window w/ a low-pass filter
  - 4: The same time window w/ no filter

- For Step 1, initial velocity set to be 775 m/s throughout all 36 pixels; For the rest, the updated model obtained by end of the previous step was used as the initial model for the current step

- Convergence criterion set for each step using max. LSE (LSE_{max}); Also, max. iterations (k_{max}) specified to terminate the inversion as needed

Case 2: Multilayered Profile w/ One Anomaly

- The model comprised of nine layers with a varying velocity from 450 (the top) to 1000 (the middle) and back to 450 (the bottom).



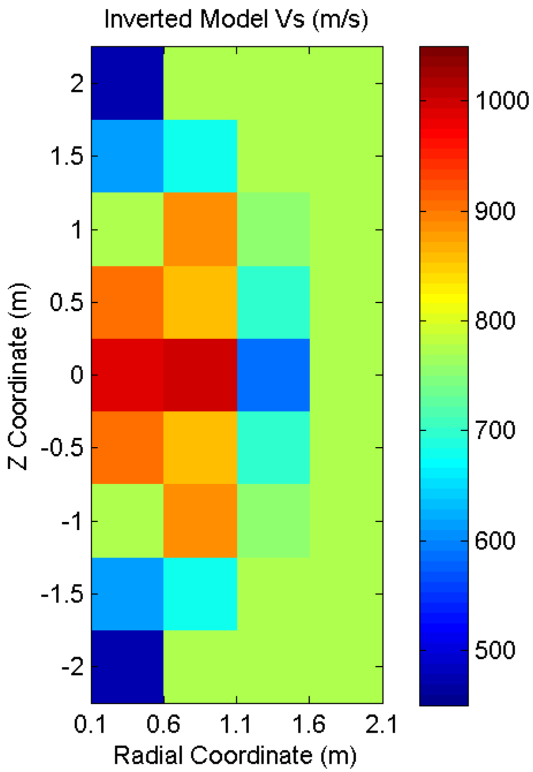
True Model

Initial Model for Step 1

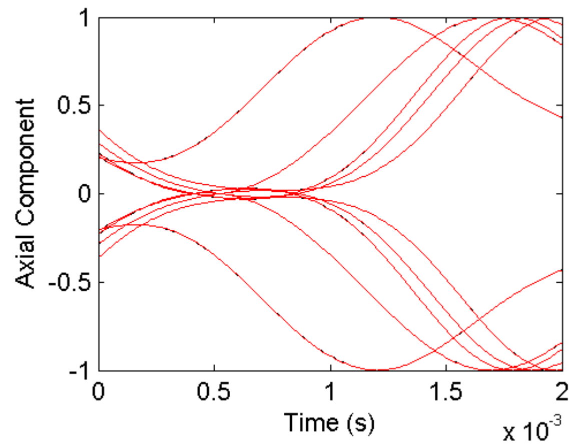
(V_s = 775 m/s)

Case 2 (Cont.)

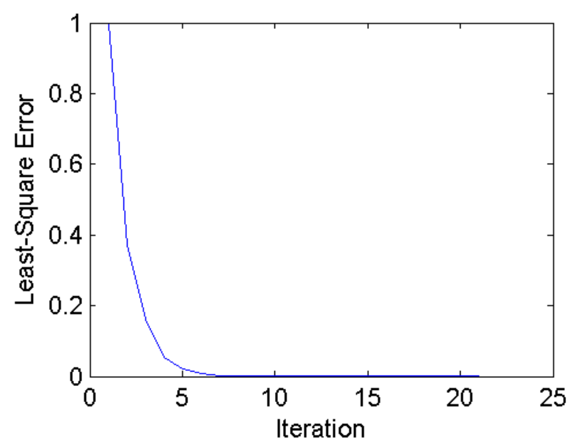
- Step 1: LSE < LSE_{max} (Converged at k = 20); k < k_{max}



Updated Model



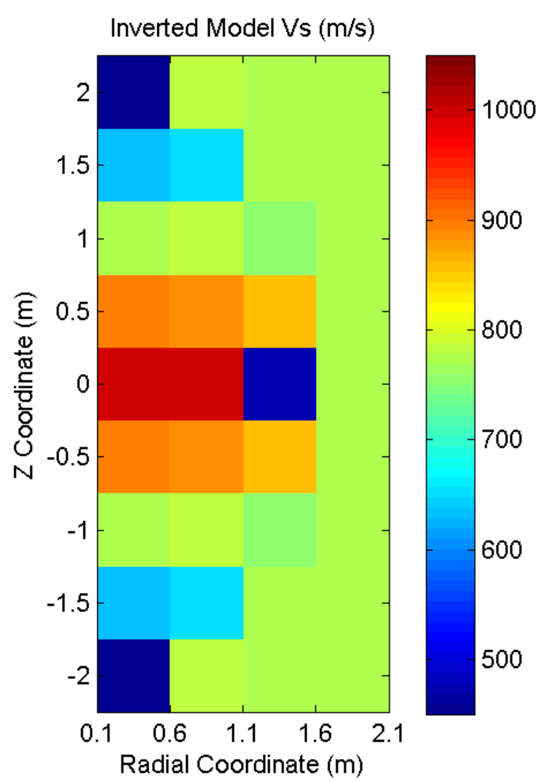
Filtered Waveforms in the 2-ms Time Window



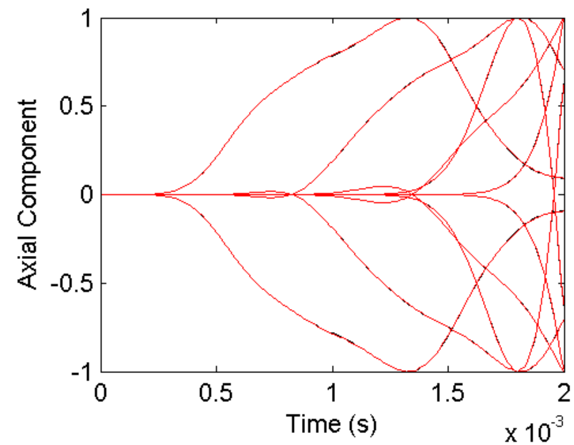
LSE Convergence Curve

Case 2 (Cont.)

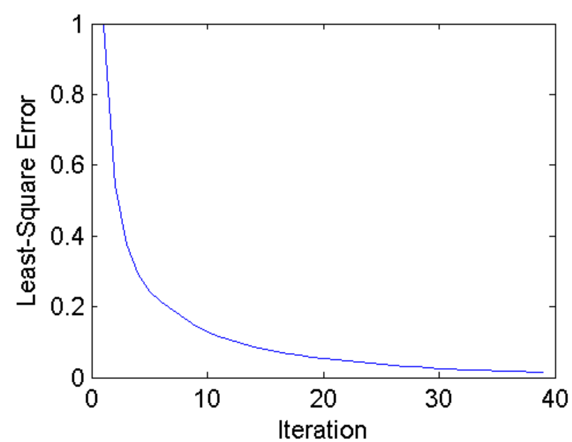
- Step 2: LSE < LSE_{max} (Converged at k = 38); k < k_{max}



Updated Model



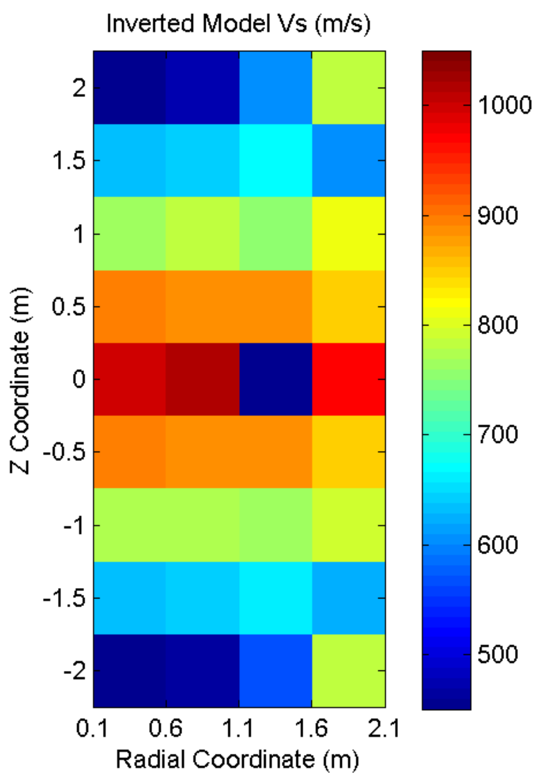
Raw Waveforms in the 2-ms Time Window



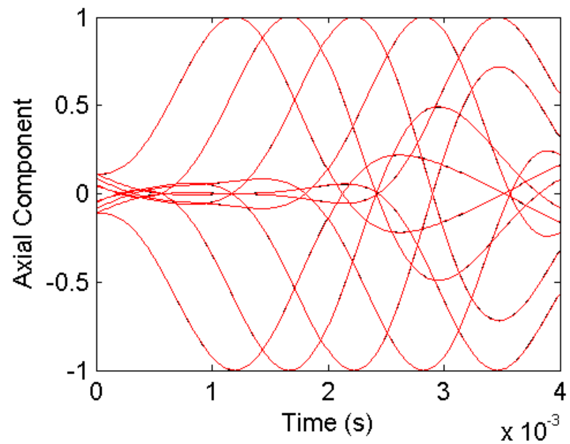
LSE Convergence Curve

Case 2 (Cont.)

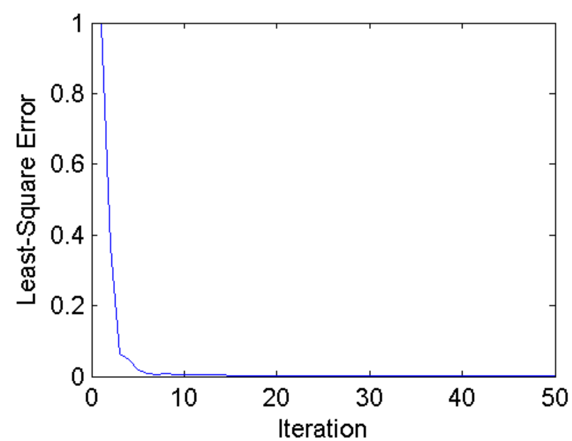
- Step 3: LSE < LSE_{max} (Converged at k = 49); k < k_{max}



Updated Model



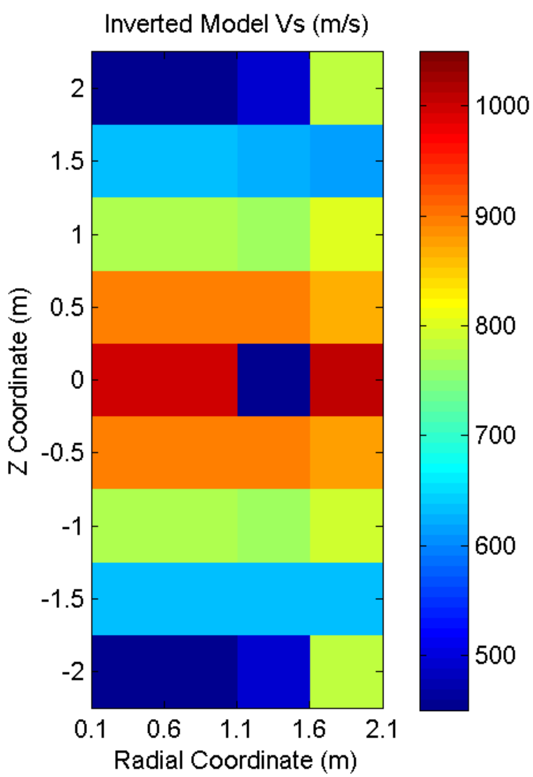
Filtered Waveforms in the 4-ms Time Window



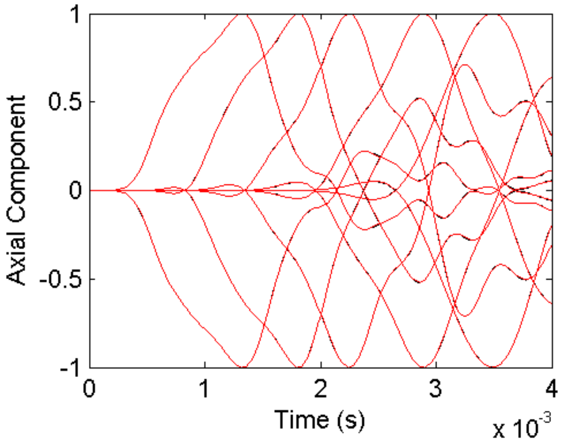
LSE Convergence Curve

Case 2 (Cont.)

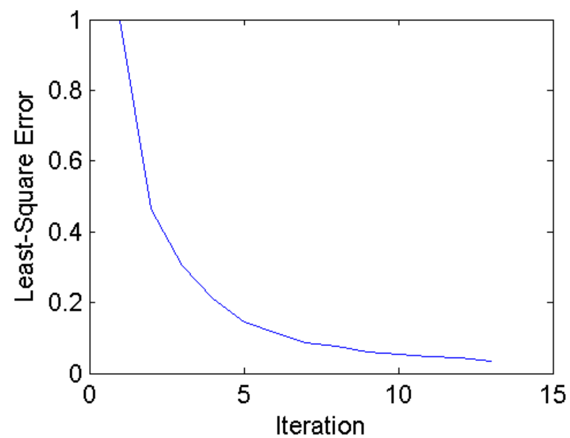
- Step 4: LSE < LSE_{max} (Converged at k = 12); k < k_{max}



Reconstructed Final Model



Raw Waveforms in the 4-ms Time Window

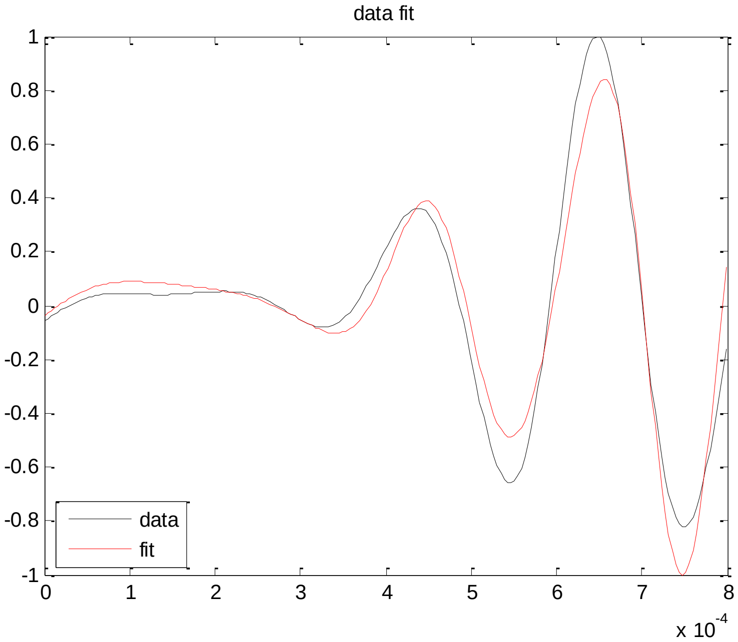


LSE Convergence Curve

Task 3: Overview

- Validation experiments: 1) Large laboratory block of synthetic limerock; and 2) Newberry and Kanapaha test sites

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

Concluding Remarks

- Development of piezoelectric borehole source is in progress
- Analysis software developed and imaging capability of the software clearly demonstrated through example simulations with synthetic records
- Work on validation experiments using large laboratory block of synthetic limerock is in progress
- The inverse procedure may be revised when field measurements (known to have noises) are used; A final version of the analysis software will be delivered along with the final report

Thank You!!!