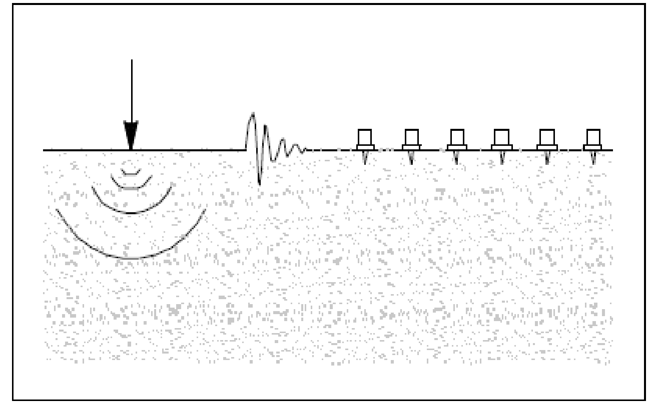
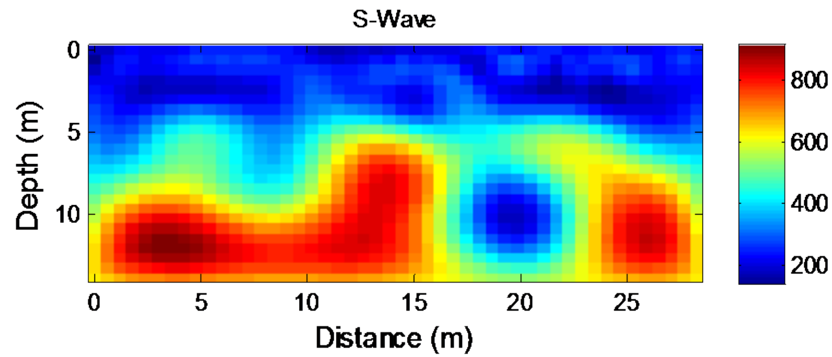
Detection of Sinkholes or Anomalies Using Full Seismic Wave Fields: Phase II

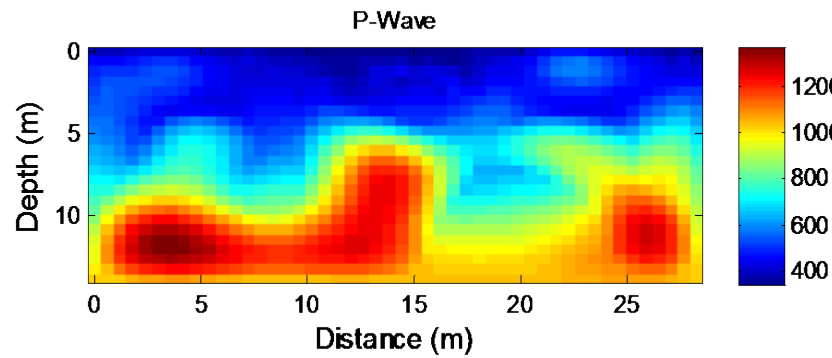
FDOT BDV31-977-29



GRIP Meeting 2015

Project Manager:
David Horhota, Ph.D., P.E.





Primary Researchers
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Outline of presentation

- Need and motivation
- Review of FWI technique
- Phase I results
- Goals of this project
- FWI Improvements
  - Computer time reduction
  - Data analysis automation
- Synthetic study
  - 3-D effects of offline voids
- GUI development
- Conclusion

Need of site investigation

- Problems and disputations during and after construction
- Structural damage/collapse
- Long-term affects on structures

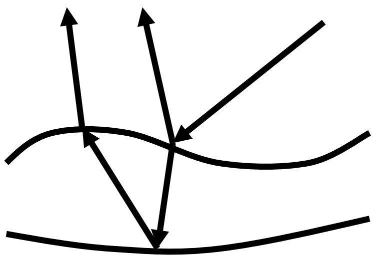
Goals of site investigation

- Soil/rock stratigraphy
- Embedded Sinkholes/Anomalies

Sinkhole claims cost $1.4 billion in Florida from 2006-2009 (FL Office of Insurance Regulation, 2010)

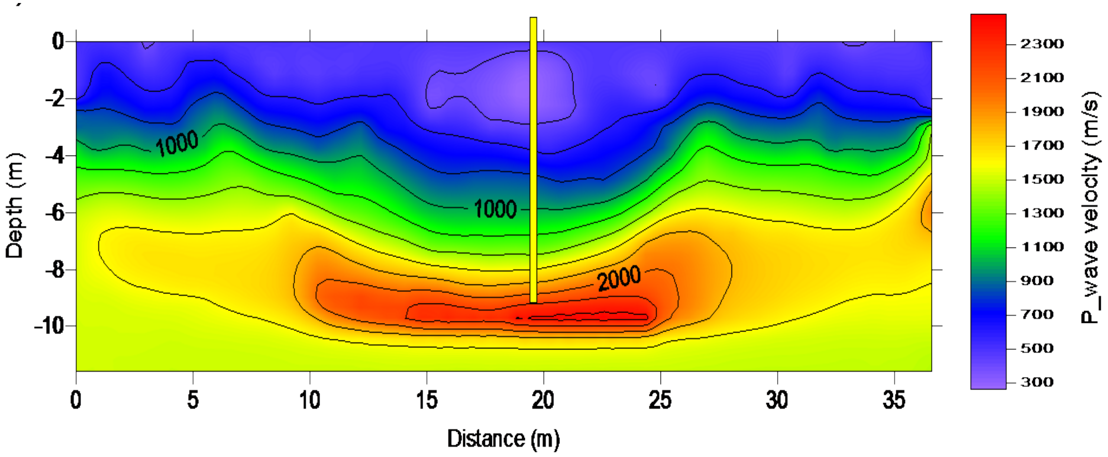
Seismic techniques

1) Imaging: localisation of interfaces (migration)



2) Material parameter (tomography)

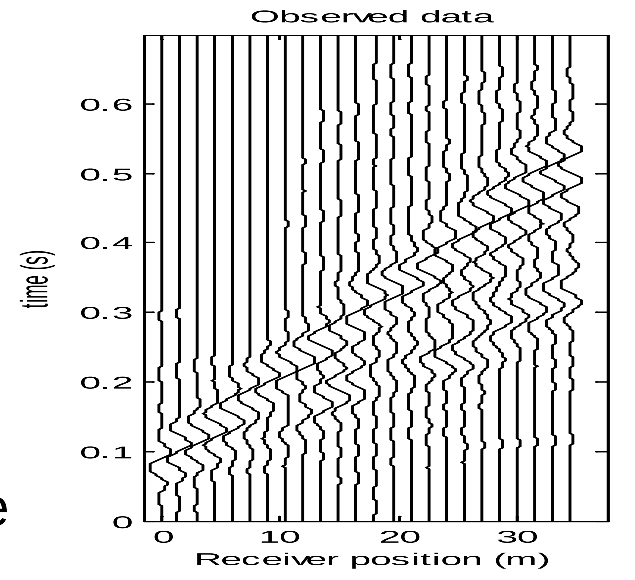
- P-wave velocity
- S-wave velocity
- Poisson's ratio
- Density
- Attenuation
- Anisotropy

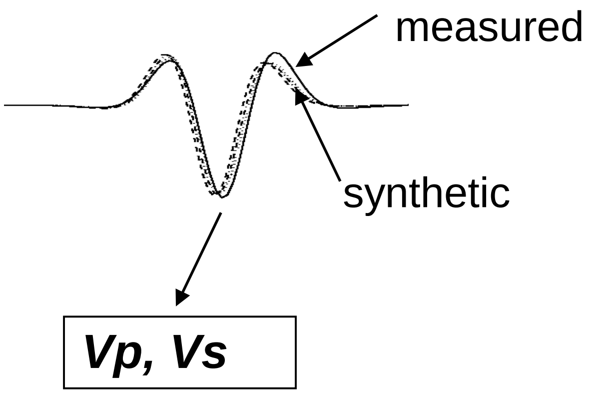


Full waveform inversion (FWI) motivation

- Most conventional seismic inverse methods analyse travel times of specific wave types only, e.g.
  - travel time tomography
  - inversion of surface wave dispersion
  - migration

- FWI is <u>wave-equation based</u> and has the potential to
  - use full information content (waveforms)
  - consider all elastic wave-phenomena
  - **infer multi-parameter images with high resolution**





Overview of FWI

Unknown engineering property: **m**

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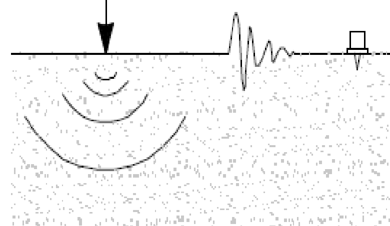
Dynamic testing



Dynamic response: **d**

Inverse problem

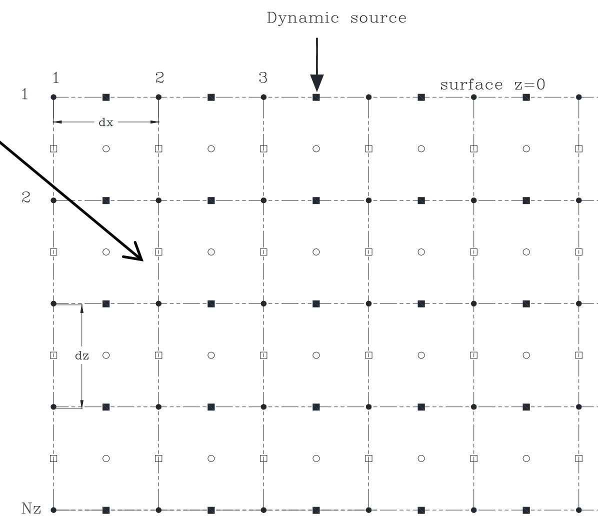
Inversion method:

1. Forward modeling **d** = f(**m**)

- 2-D elastic wave equations
- $\mathbf{d}_{est} = f(\mathbf{m}_{est})$

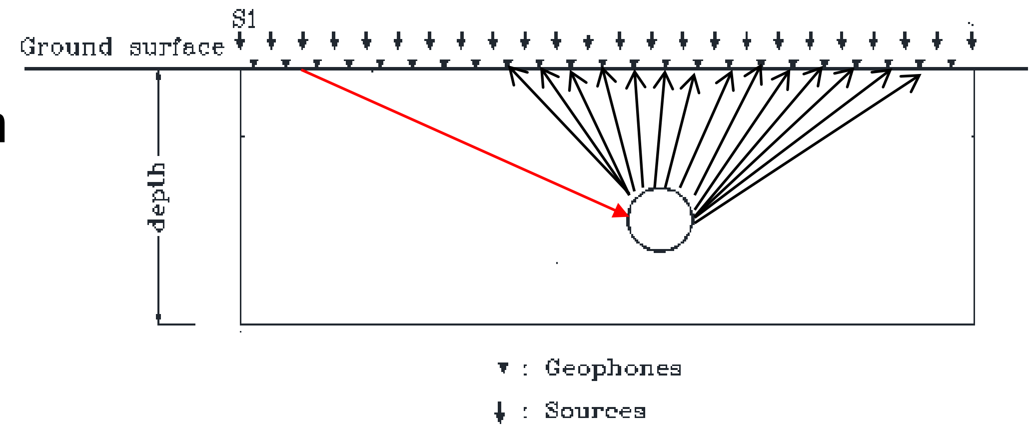
2. Model updating to get $\mathbf{d}_{est} \approx \mathbf{d}$

- Gauss-Newton method
- Converge when $\mathbf{d}_{est} - \mathbf{d} \sim 0$

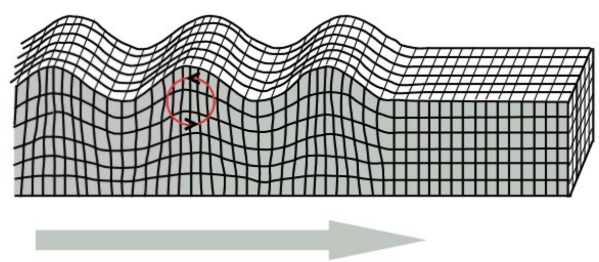


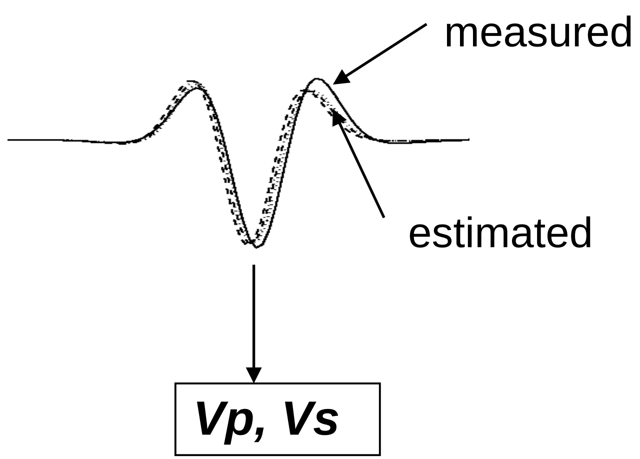
Data Acquisition and Analysis

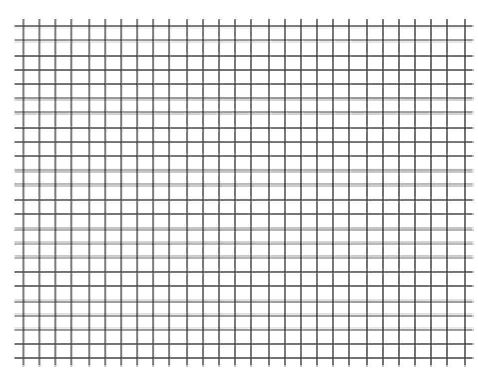
- Data Acquisition
  - Multiple geophones at 1 to 3 m spacing
  - Multiple sources (strikes of hammer) at 1 to 3 m spacing
- Analysis
  - Use all measured waveforms (Rayleigh, S and P waves)



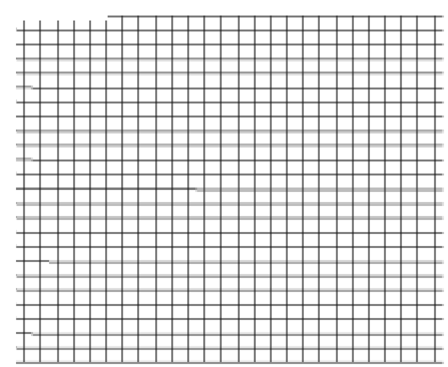
Rayleigh Wave





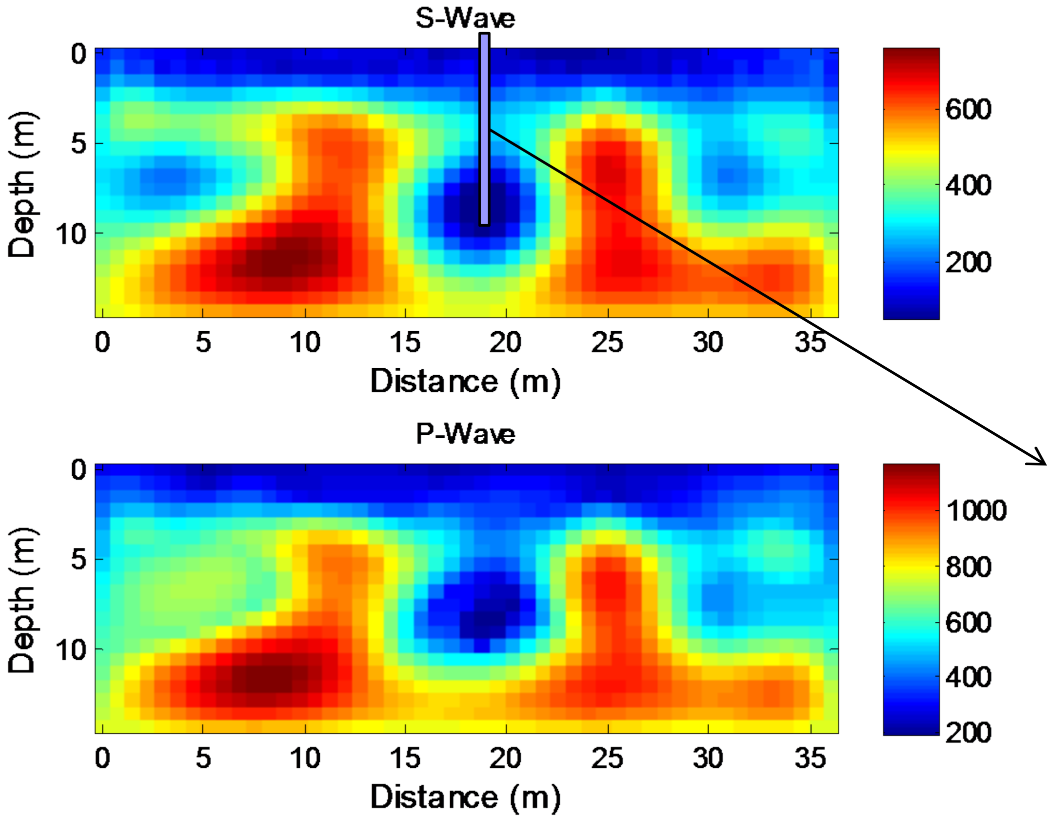


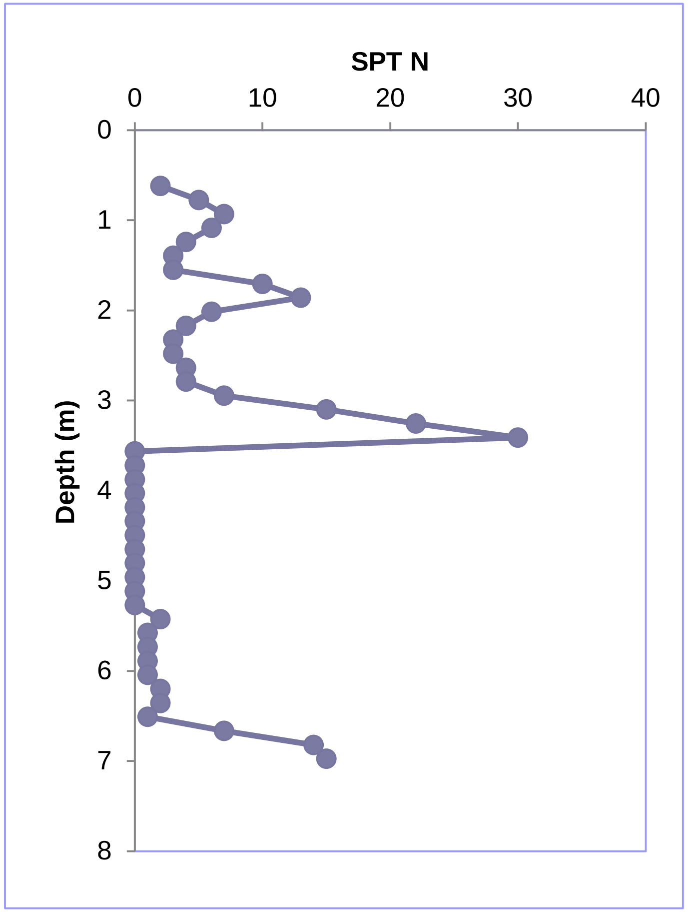
Compression wave



Shear wave

Phase I results





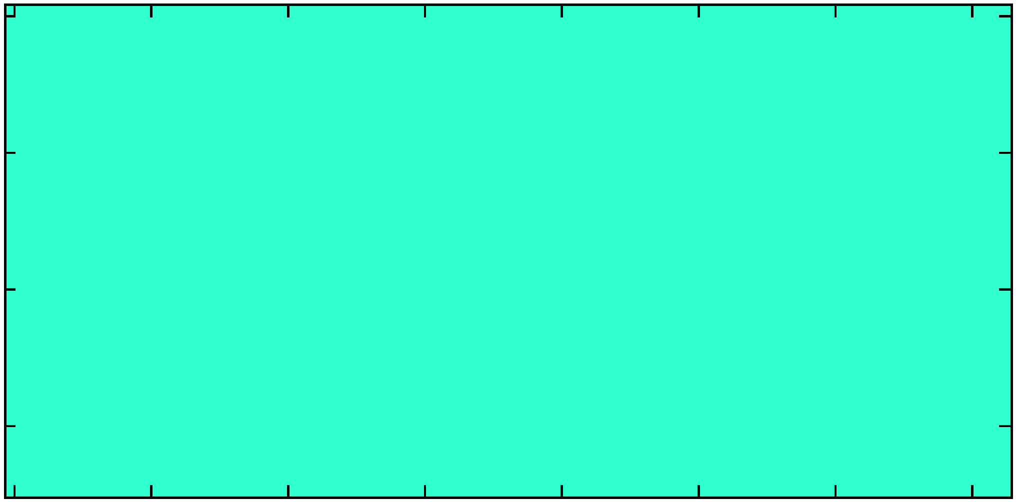
- Take 3 hours of computer time
- Need Matlab expertise for data analysis

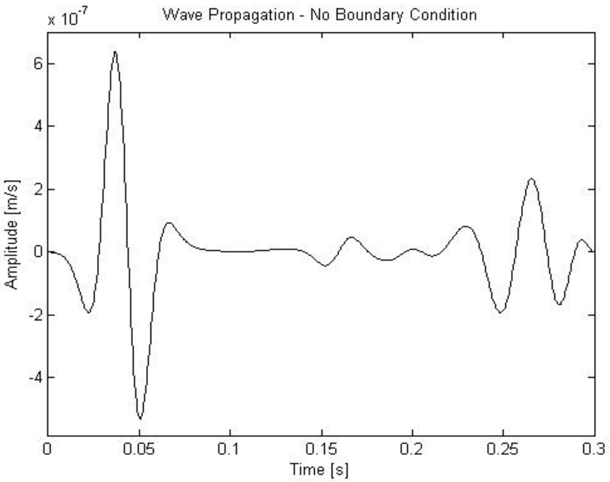
Goals of Phase II research

- Improve the FWI technique to allow for greater accuracy and reduced computational time for in-situ solution
- Investigate 3-D effect of off-line voids in 2-D waveform analysis
- Develop FWI software to allow users interacting through computer graphics

Forward Modelling

- Required to reduce reflections of waves off the boundary





- Free surface condition at top boundary
- Perfectly Matched Layer at all other boundaries

Perfectly Matched Layer (PML)

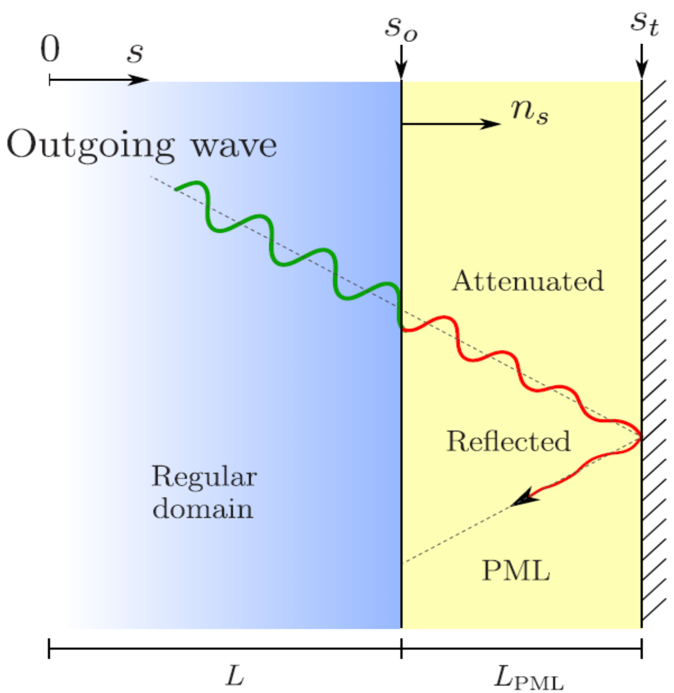
- Adds grid points (padding) to the necessary boundaries
- Padding gradually reduces the amplitude of the wave

$$\psi_x^n = b_x \psi_x^{n-1} + a_x (\partial_x)^{n+1/2}$$

$$\partial_{\tilde{x}} = \frac{1}{\kappa_x} \partial_x + \psi_x$$

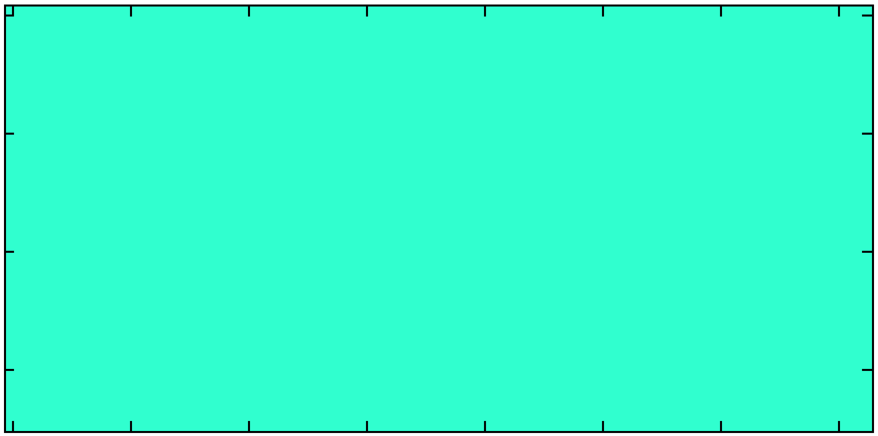
$$b_x = e^{-\left(\frac{d_x}{\kappa_x} + \alpha_x\right)\Delta t}$$

$$a_x = \frac{d_x}{\kappa_x (d_x + \kappa_x \alpha_x)} (b_x - 1)$$

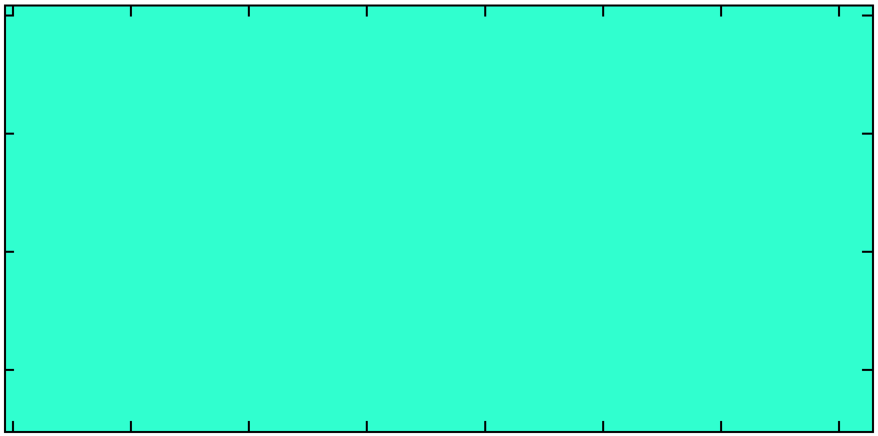


PML at boundary (Kallivokas, et al., 2013)

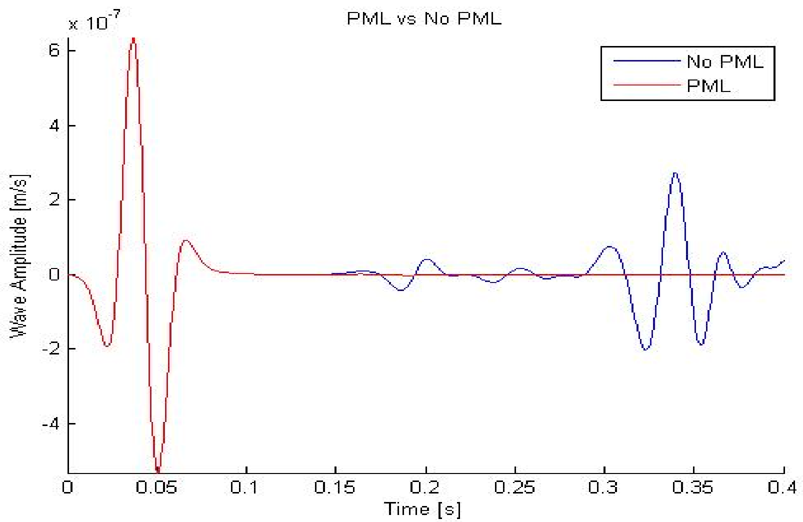
Perfectly Matched Layer (PML)



No PML



PML



- Benefits of PML
  - Reduce modeled domain
  - Improve convergence rate and accuracy of inversion

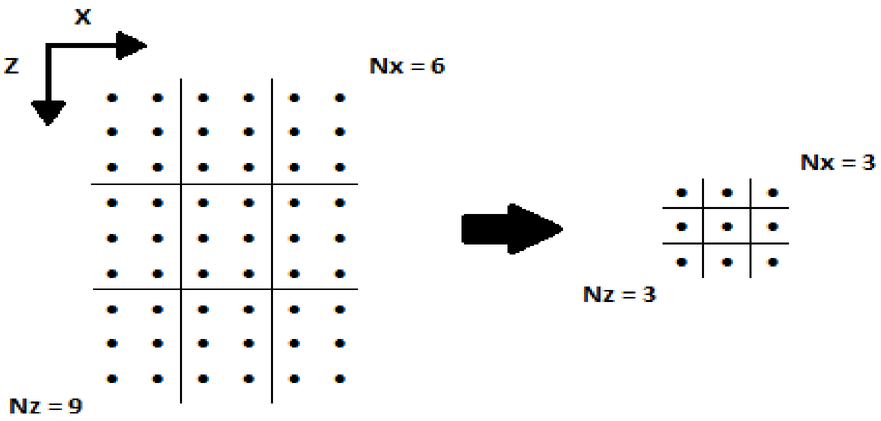
Other improvements

- Source signature estimation

$$\mathbf{F}(f,\mathbf{x},\mathbf{m}) = \mathbf{G}(f,\mathbf{x},\mathbf{m}) \cdot \mathbf{W}(f),$$

Frequency domain source estimation

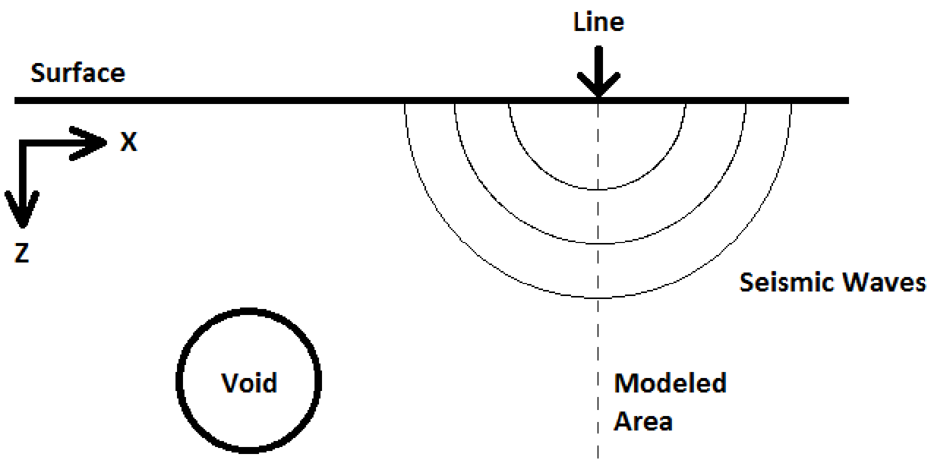
- Grid reduction
  - Merging cells into bigger inversion blocks for low-frequency analysis

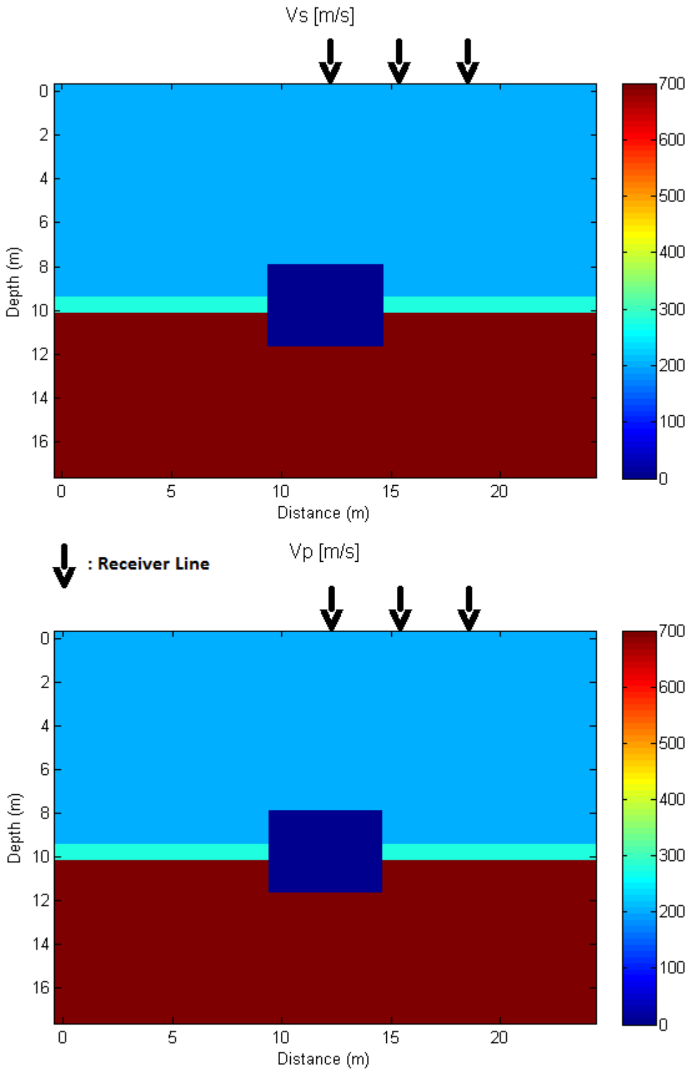


- Parallelization of computations

Synthetic Study

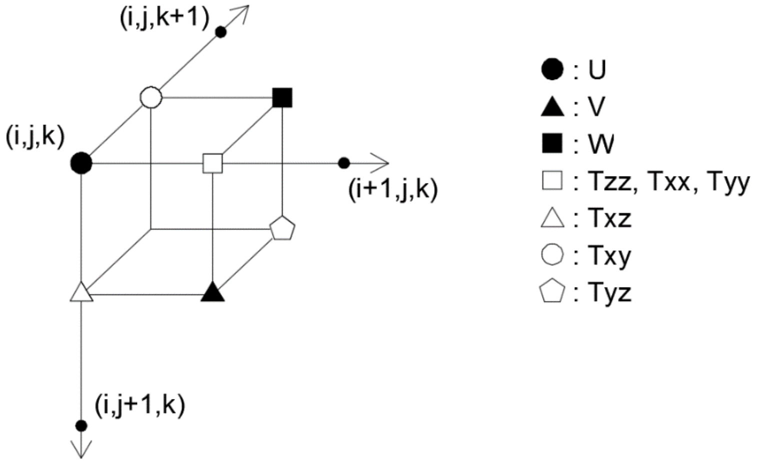
- Study the effects of off- line voids
- Generate data using 3D forward model





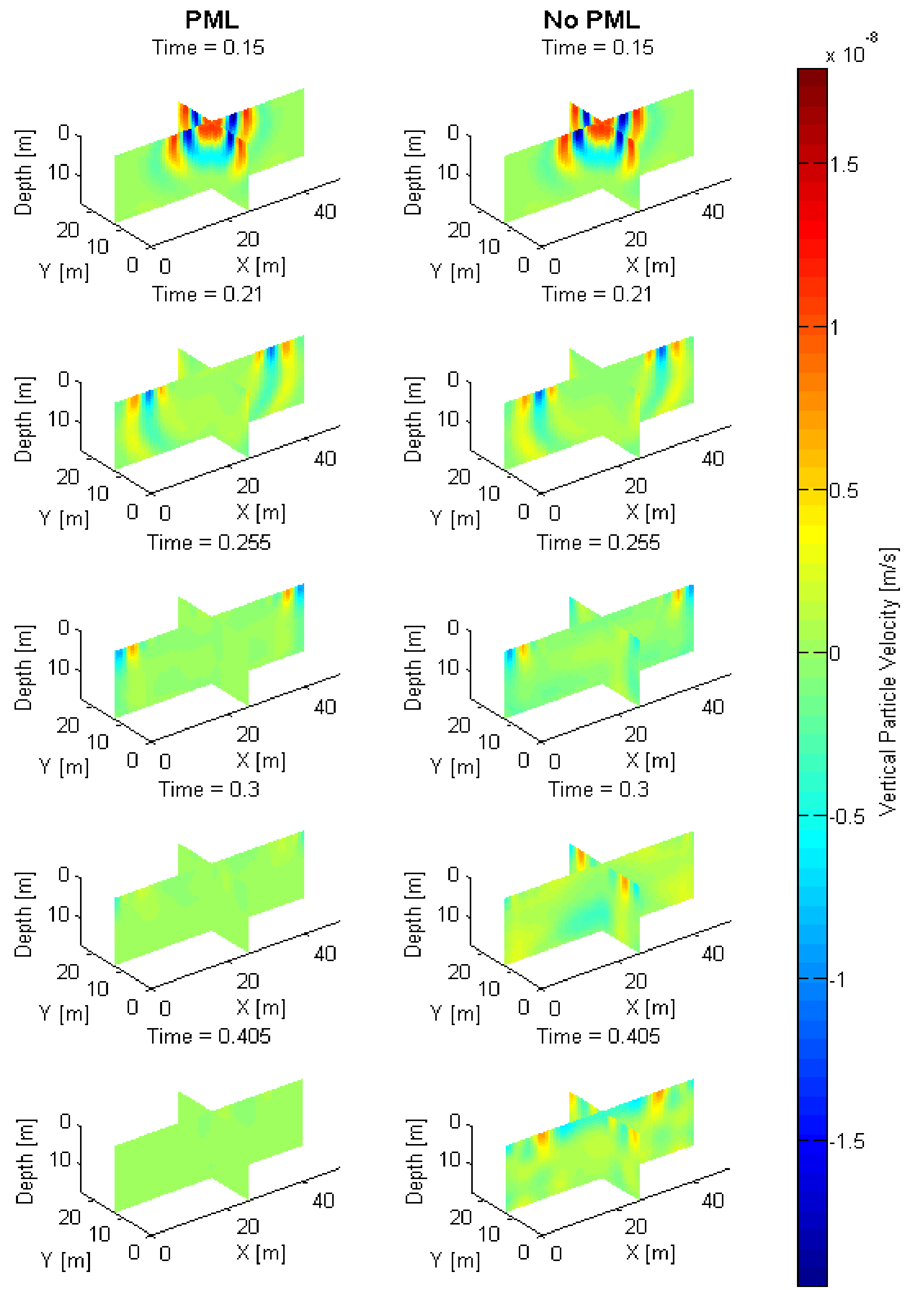
3-D Forward Model

- Similar to 2-D forward model with added dimension along the surface of the medium
- First order elastic wave equations converted into finite difference equations
- Free surface and PML boundary conditions



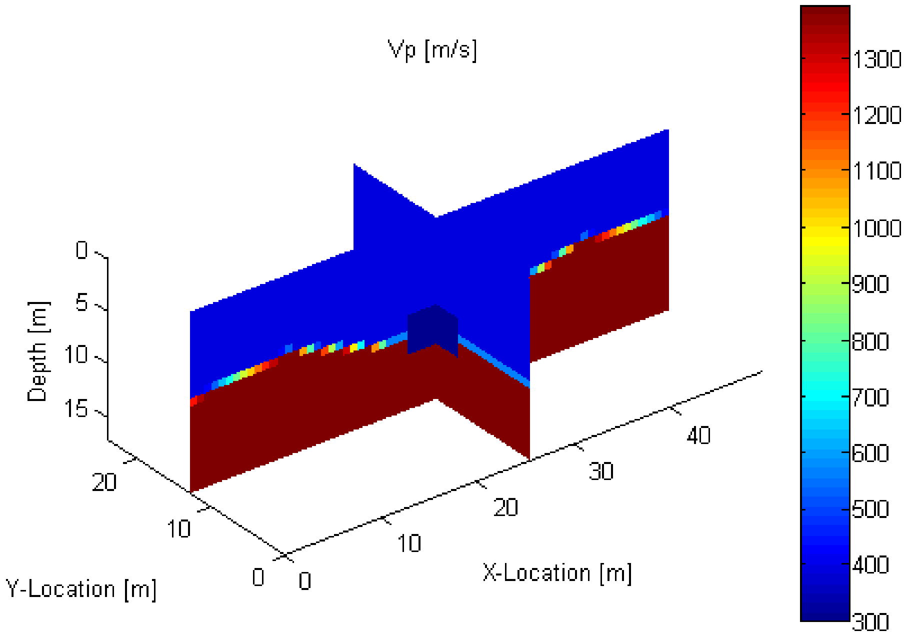
3D Staggered Grid

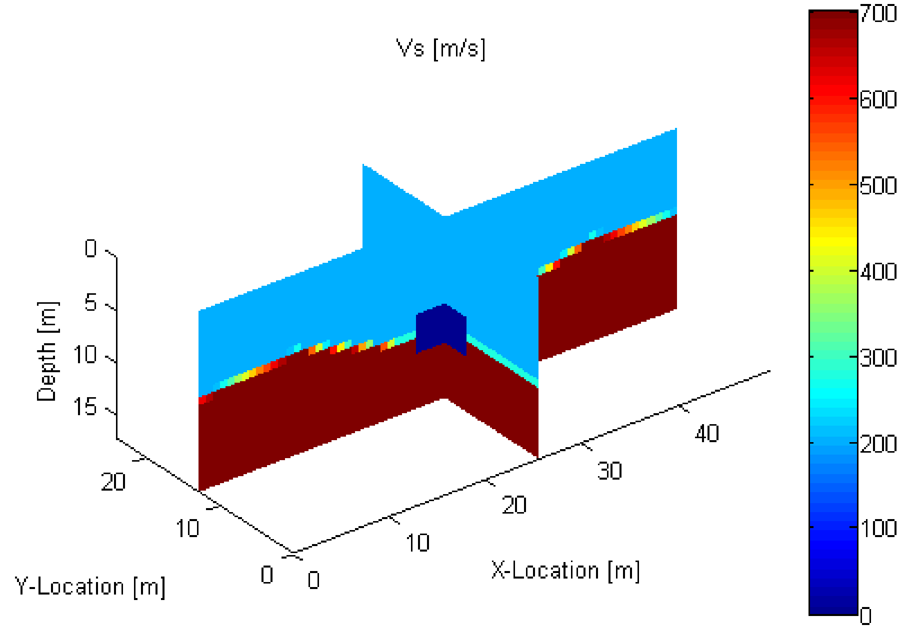
Example of 3-D Wave Propagation



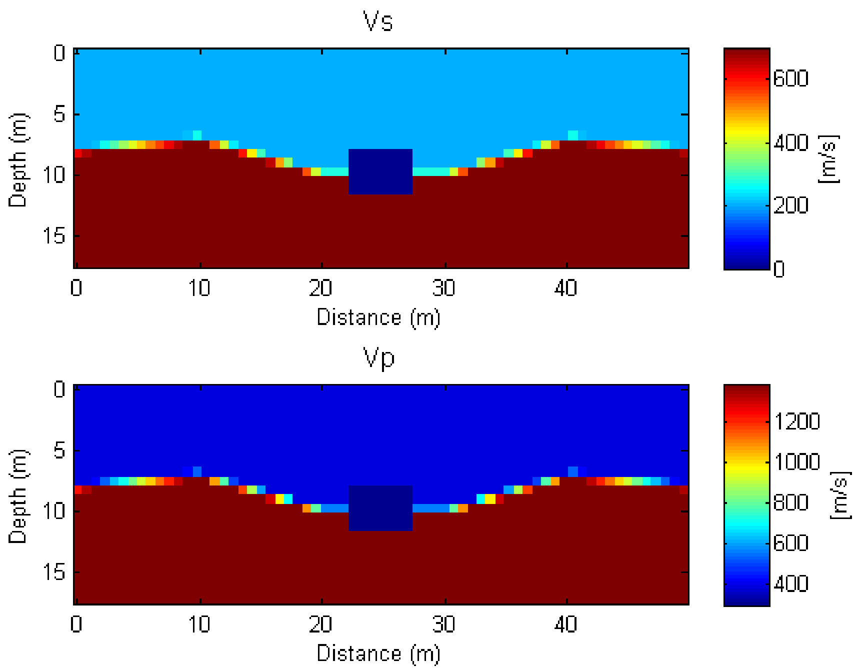
Model Implementation

- Dual layer model with a void of 5 x 5 x 3 m at center
- Receiver/shot arrays run along the x-axis

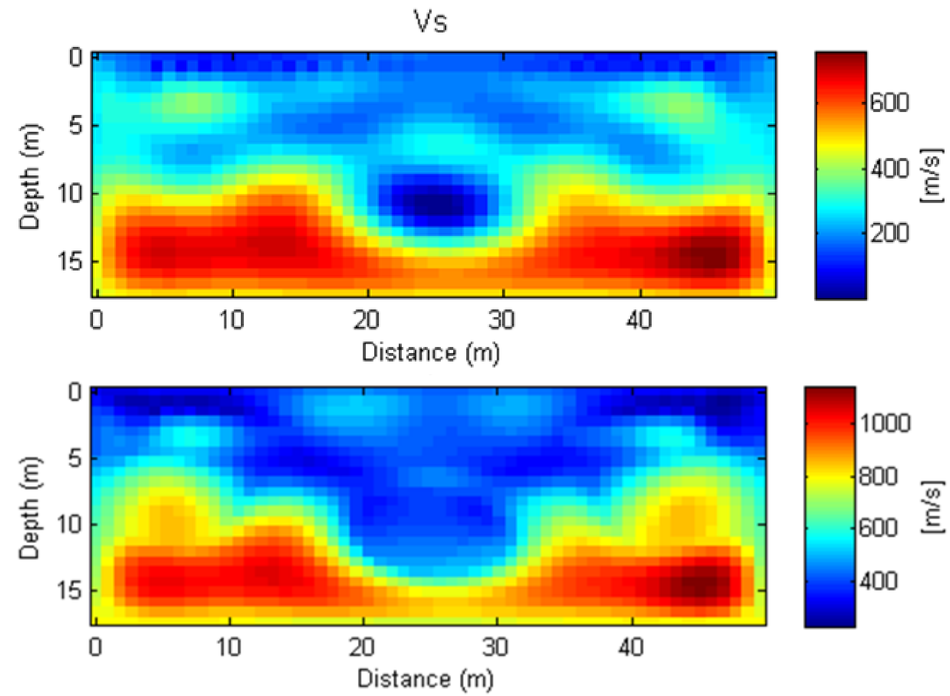




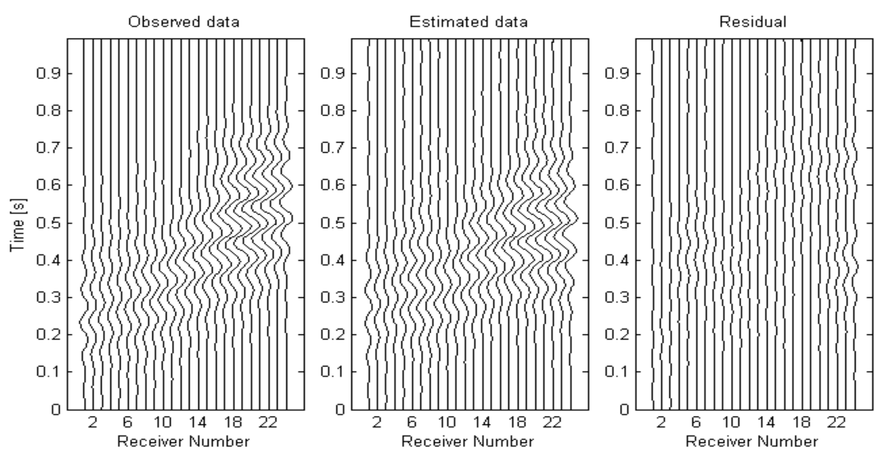
Line 1: Centered over void



True Model

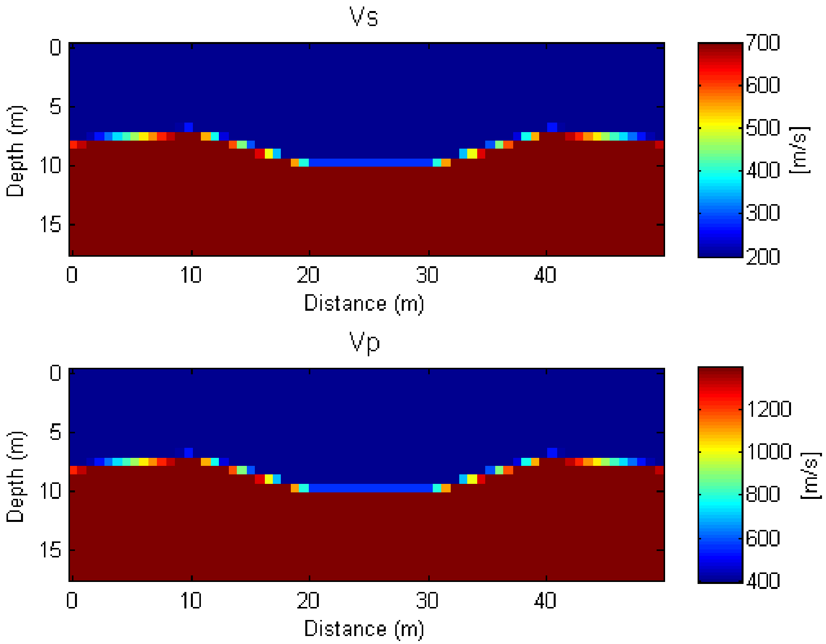


Inverted Model

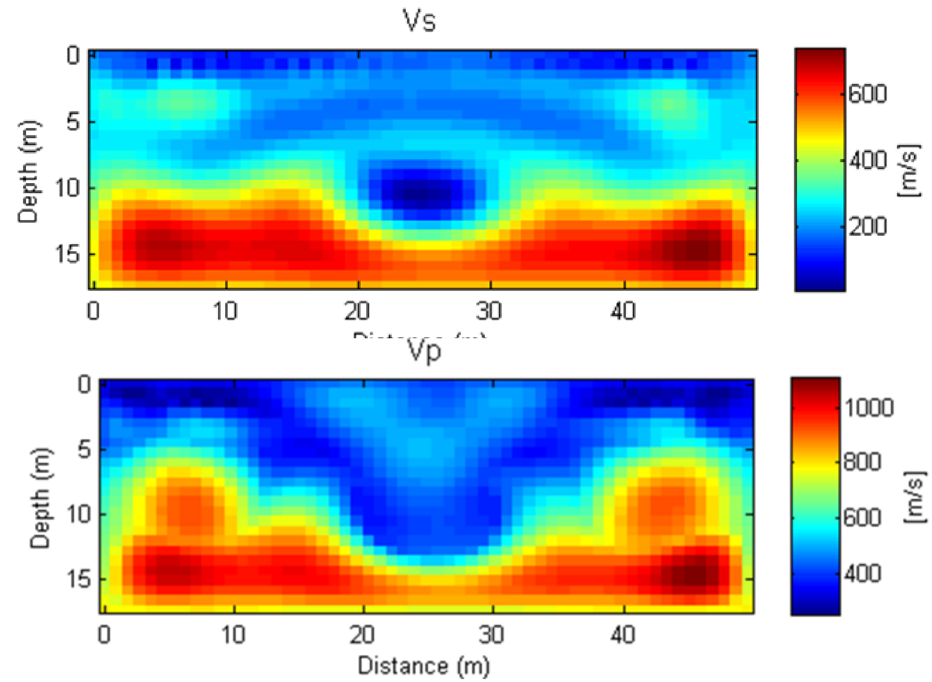


Wavefield comparison

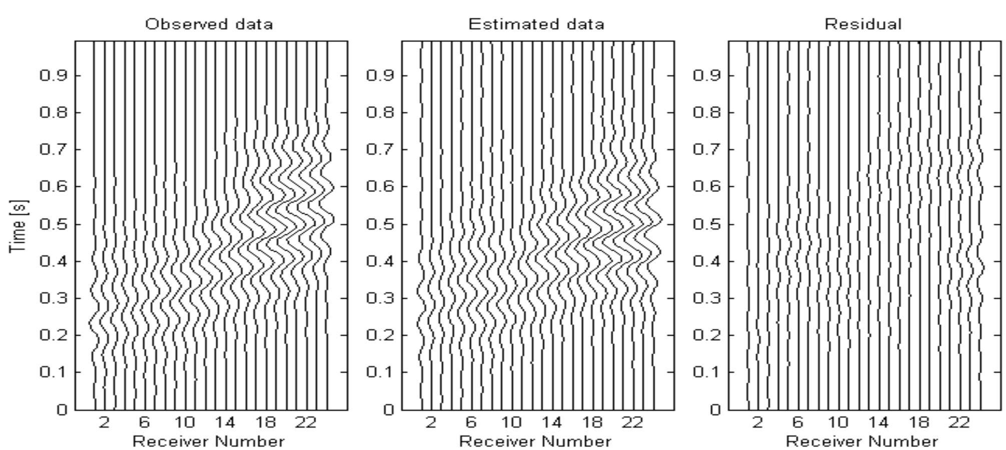
Line 2: At the edge of the void



True Model

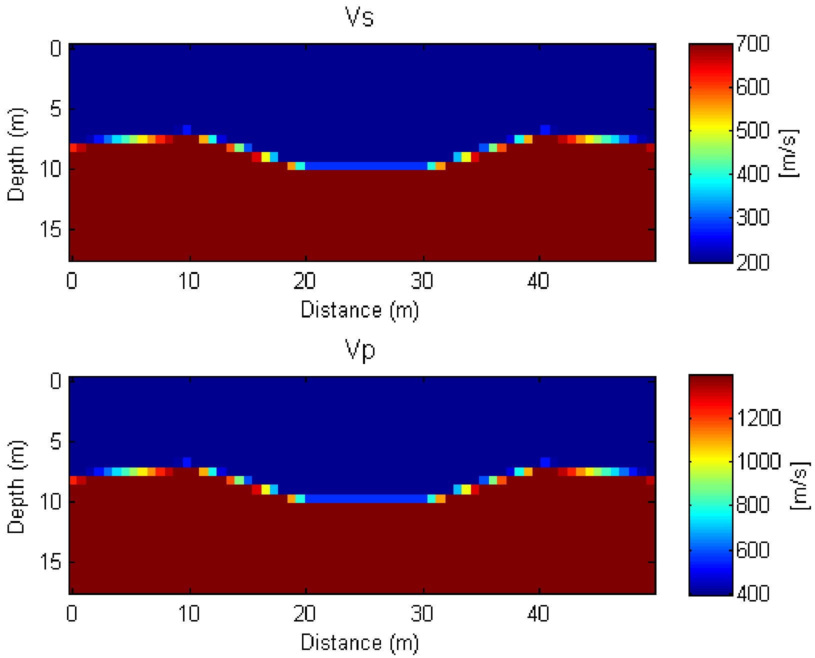


Inverted Model

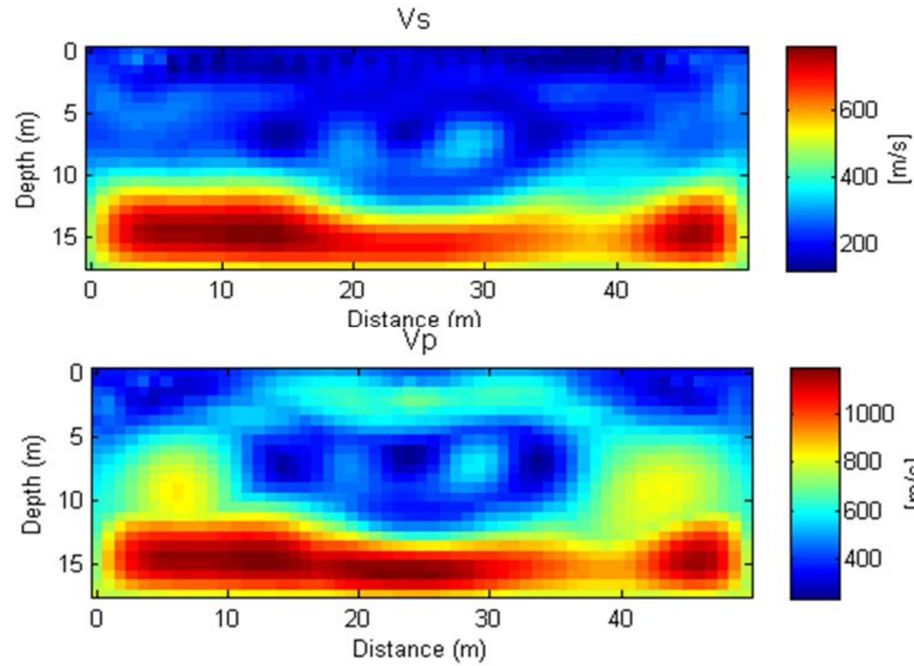


Wavefield comparison

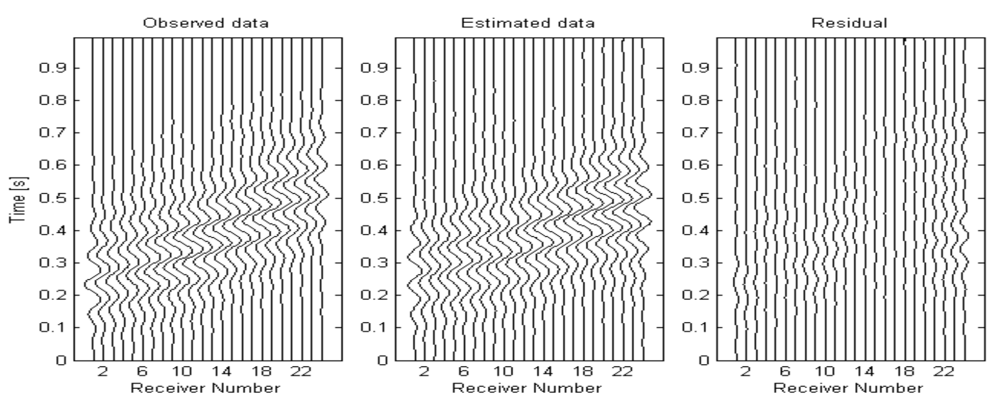
Line 3: One diameter from center of void



True Model



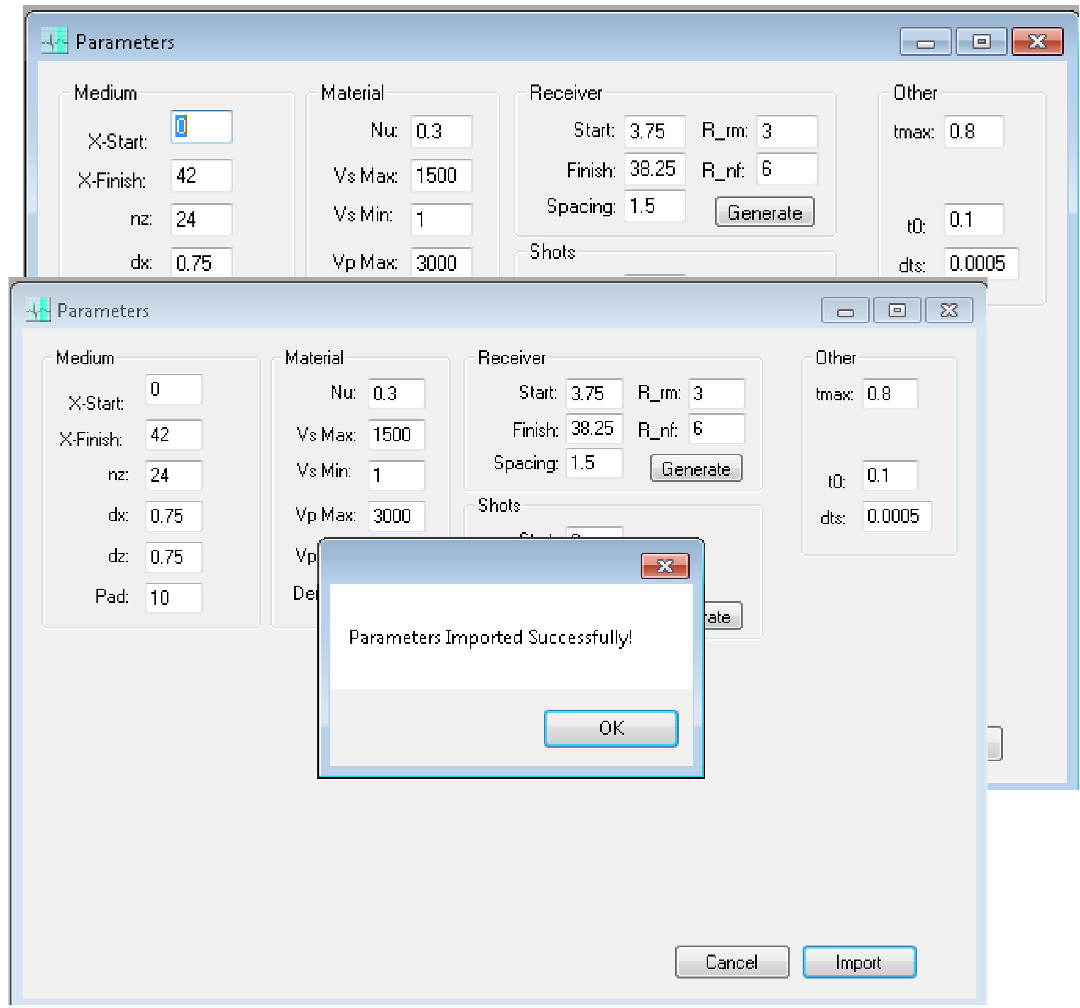
Inverted Model



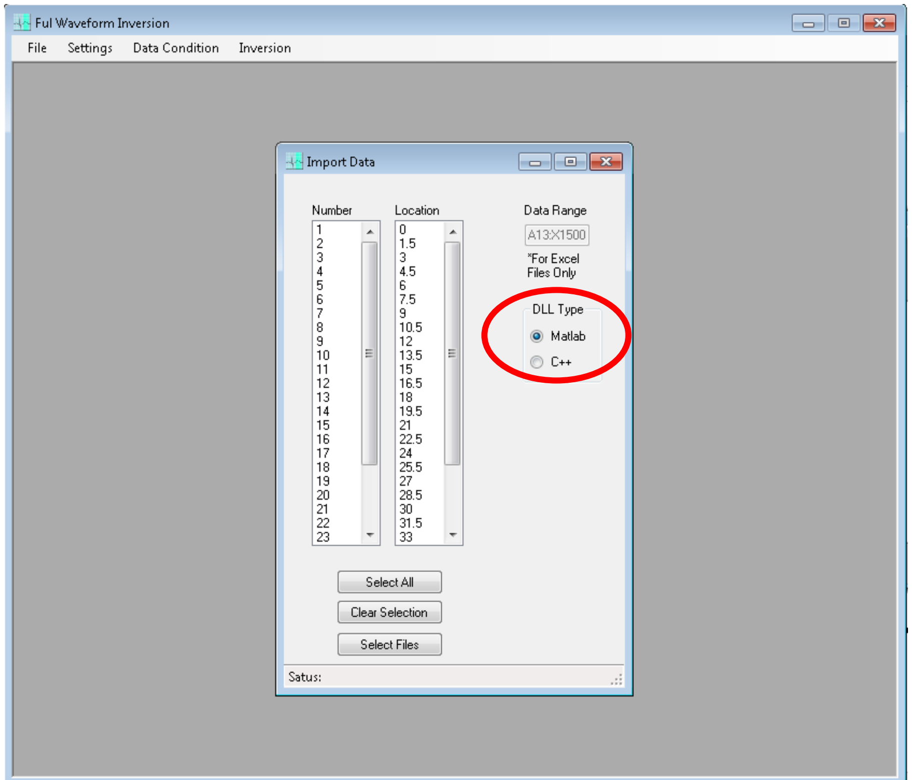
Wavefield comparison

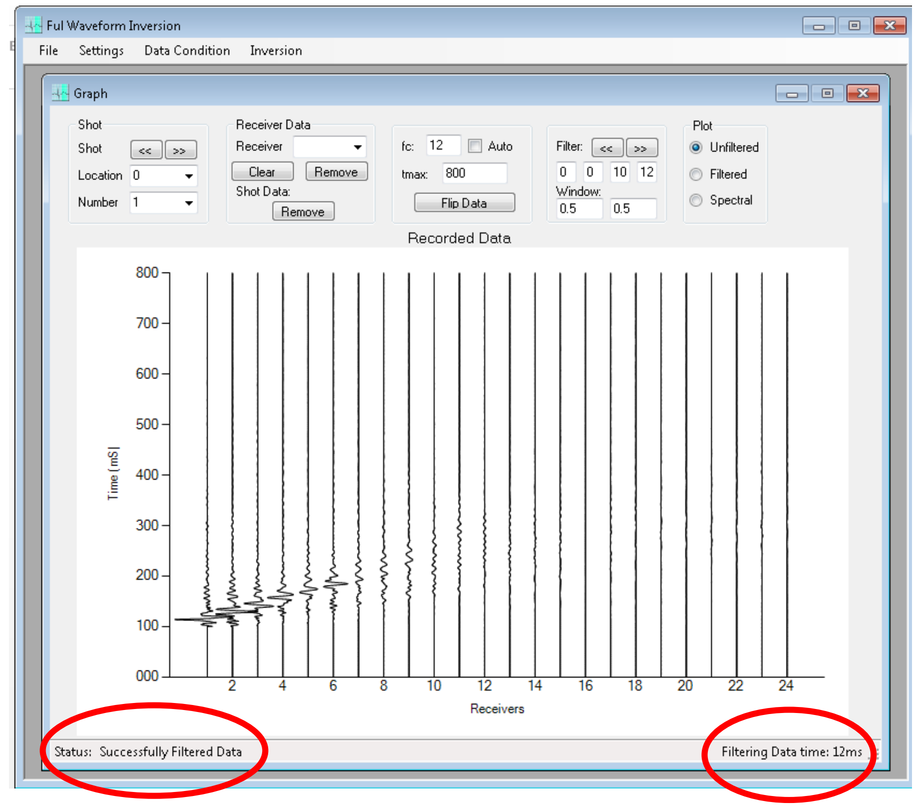
Graphical User Interface (GUI)

- Users can interact through computer graphics
- Allow technician to collect and analyze data
- Software GUI
  - Input parameters
  - Import and condition data
  - Generate an initial model
  - Invert imported data
  - View results
- Current version runs on C# (sharp) and Matlab dll
- Run time for 25 shots ≈ 70 mins
- 85% complete with version using C++ dll to reduce time



Import and condition data



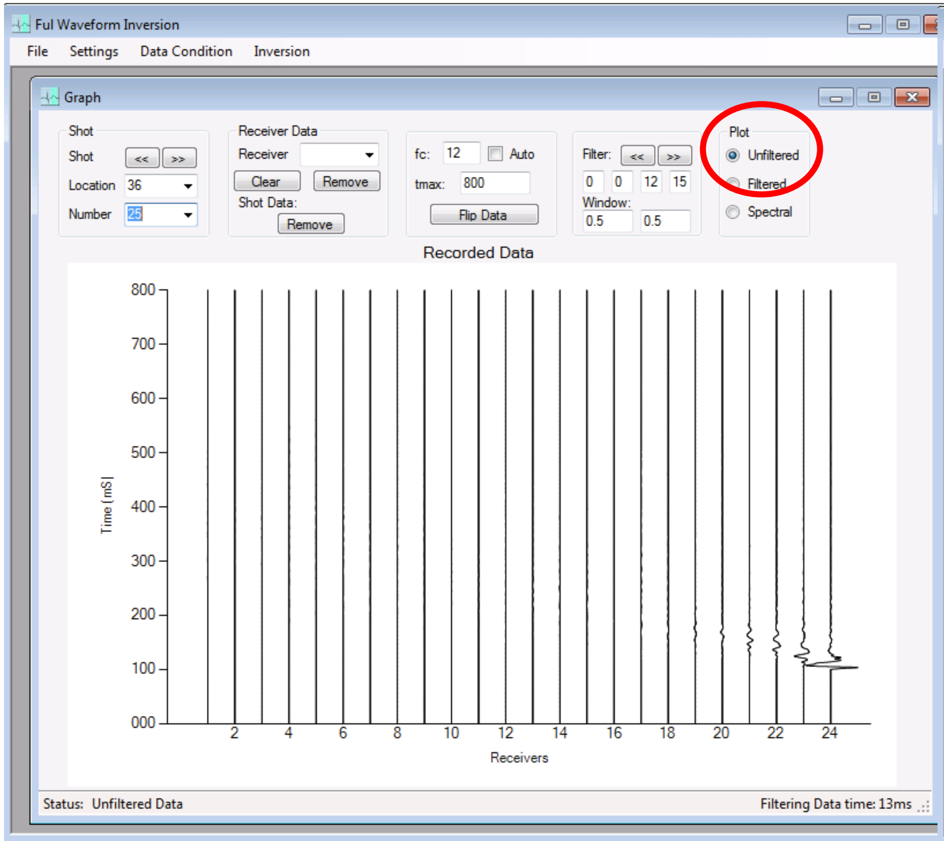


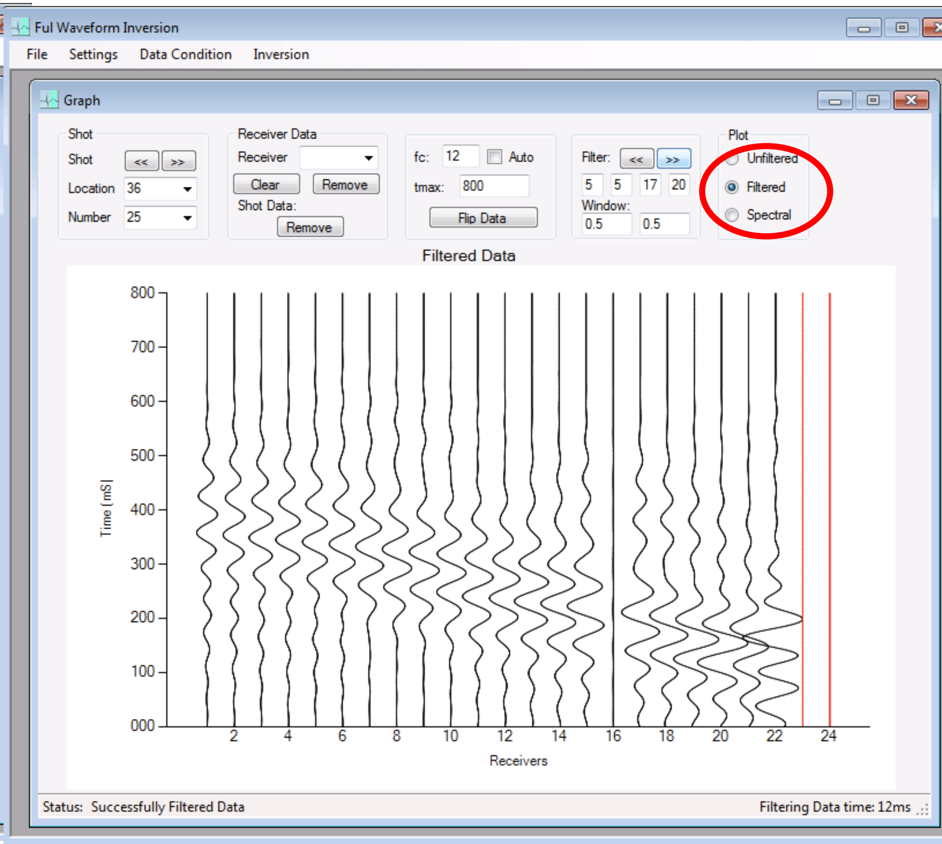
Import shot files

Condition data

Current version running on Matlab dll

Conditioned data

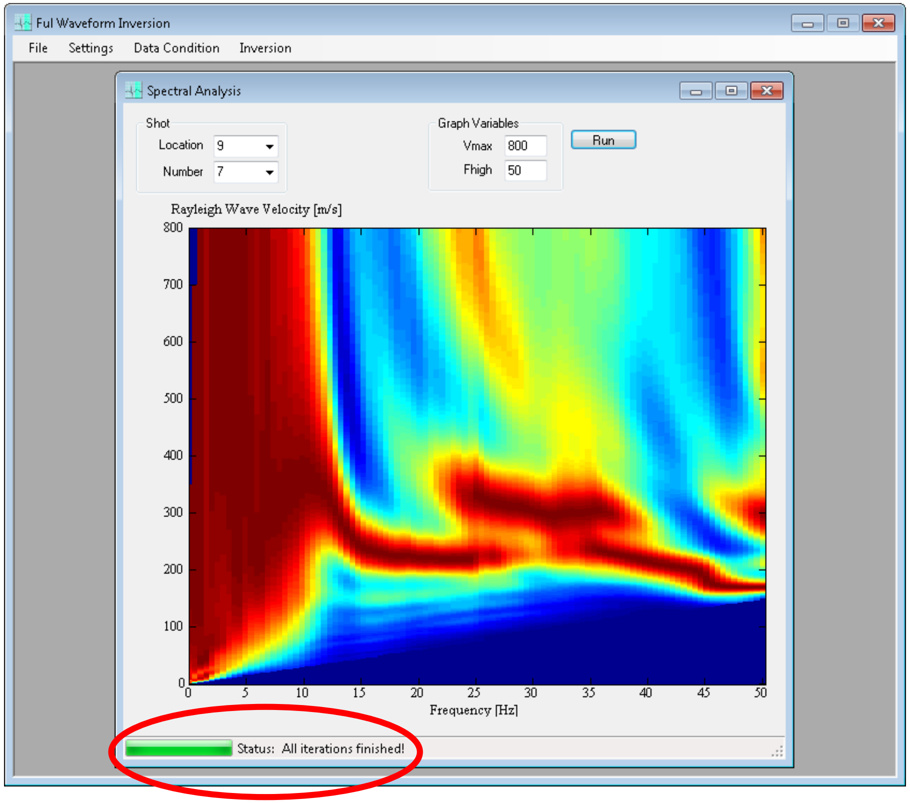




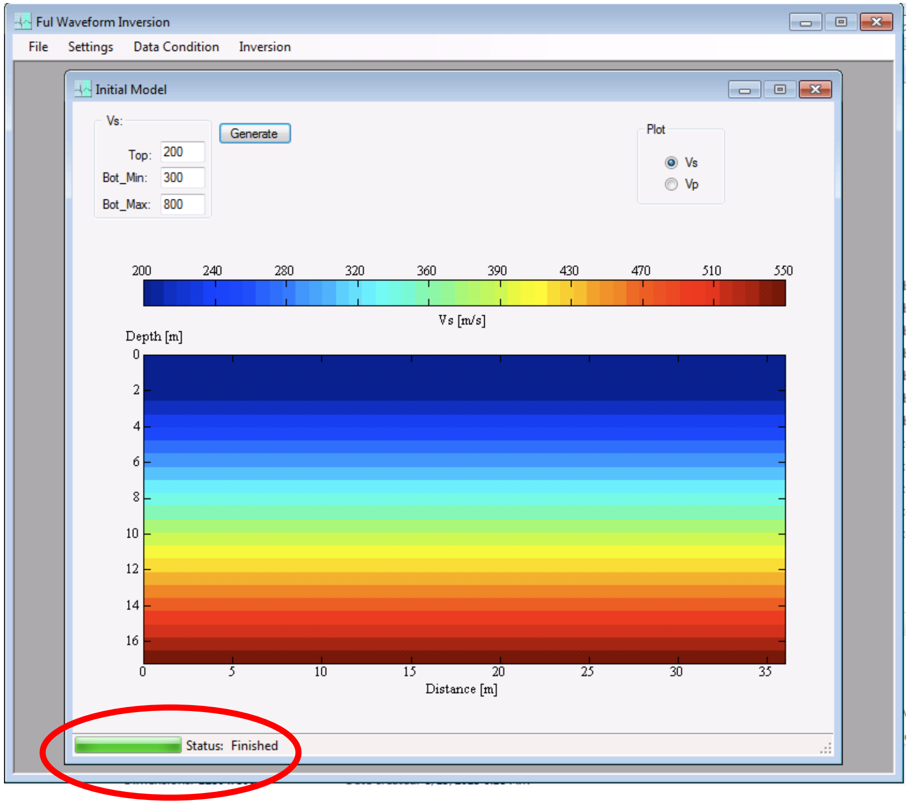
Unfiltered data

Filtered data
Receivers removed

Generate an initial model

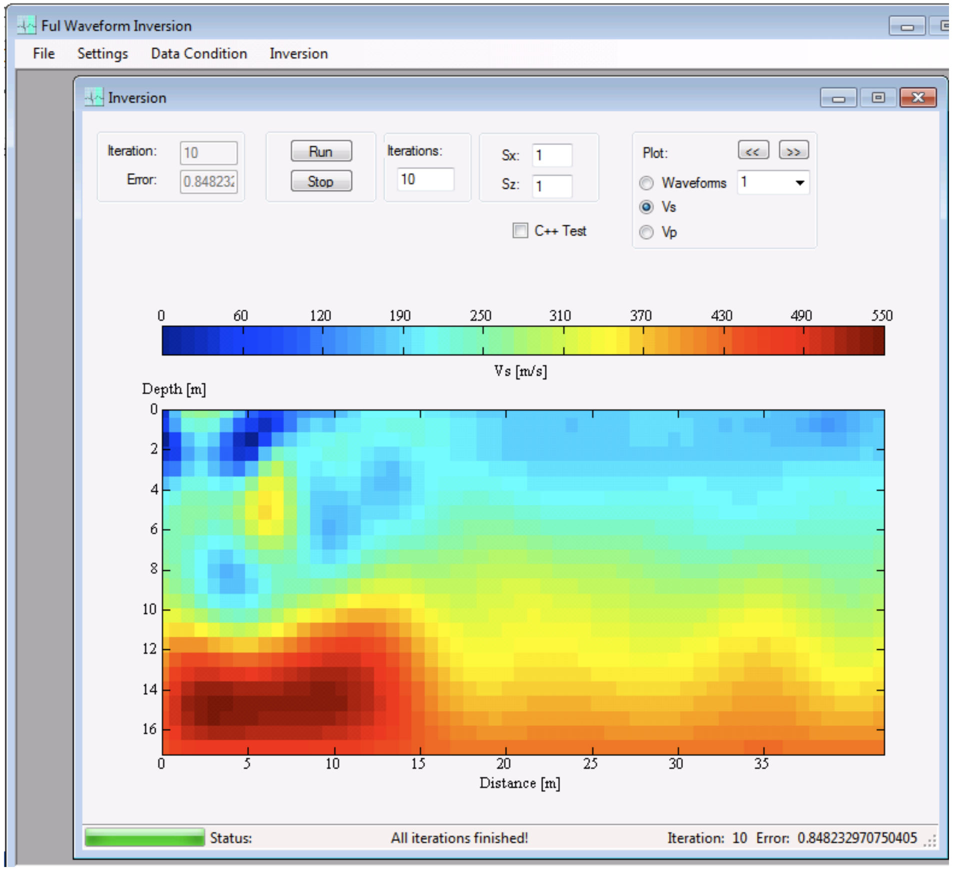


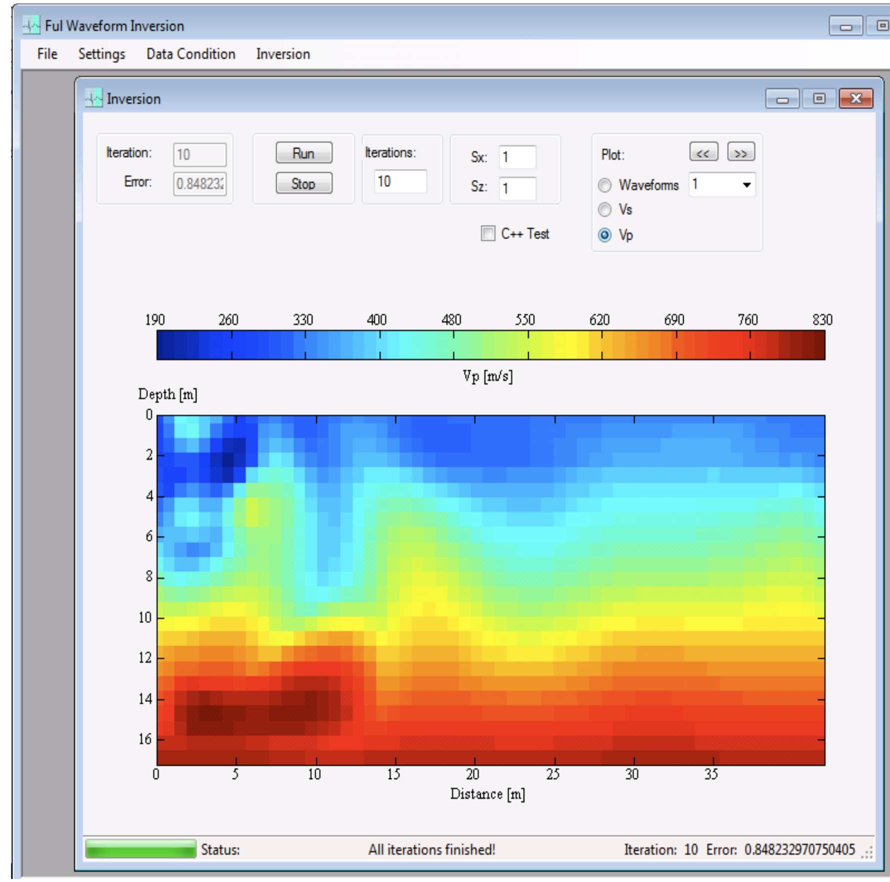
Spectral Imaging Page



Initial model of S-wave velocity

Analysis and results Kanapaha





Inversion Results

Conclusion

- A fast and nearly automatic algorithm of the full waveform inversion (FWI) has been developed for a field solution.
- Convolutional perfectly matched layers, parallelizing computations, temporal windowing, and grid reduction have been implemented to reduce required computer time. Visualized data conditioning, automated initial model, and automated analysis have also been implemented to reduce manual efforts during the analysis.
- The improved FWI algorithm can produce the field solution to obtain general information of the medium being tested within 30 minutes. More detailed information can be achieved by further analysis at higher frequencies after field testing.
- Synthetic study indicated that off line voids have minimal effect on results
- GUI software will free users from learning complex command languages, and allow them interacting through computer graphics.

Thank You!

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