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Linear Equivalent Sources and Stochastic Model Effects on Far-Field Moment Tensors



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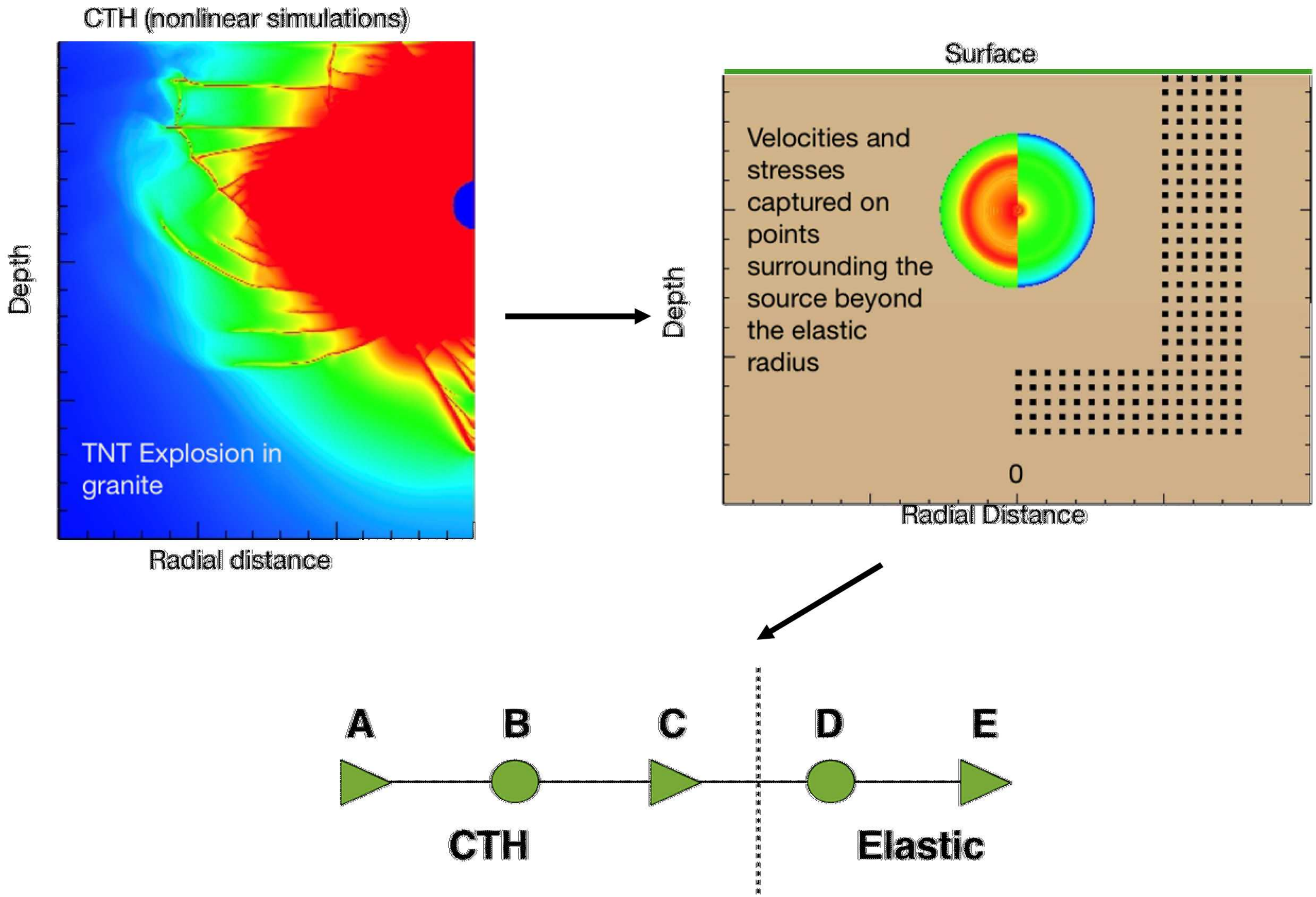
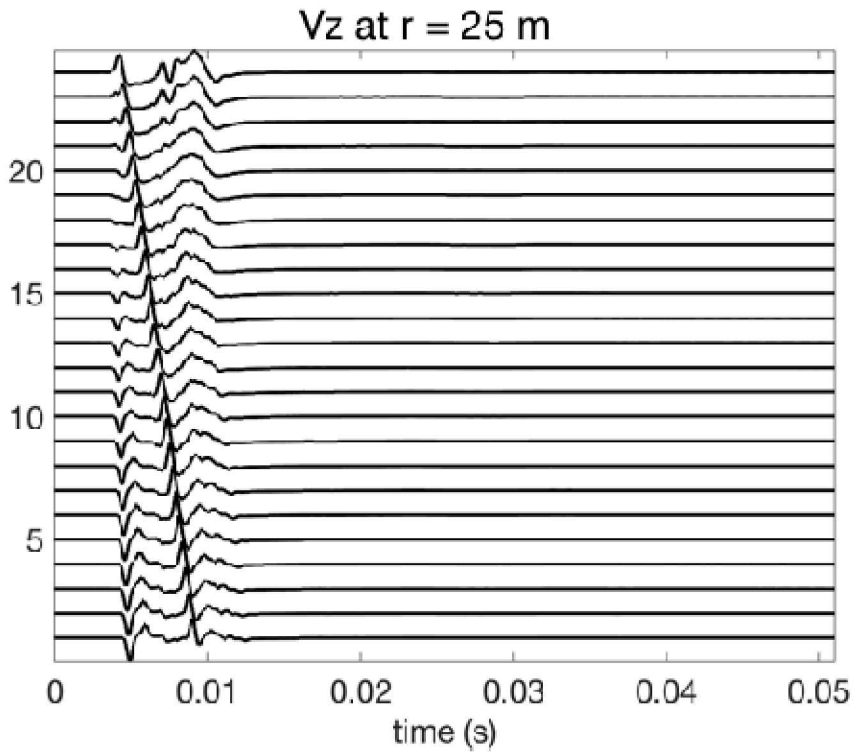
Nonlinear to Linear Modeling

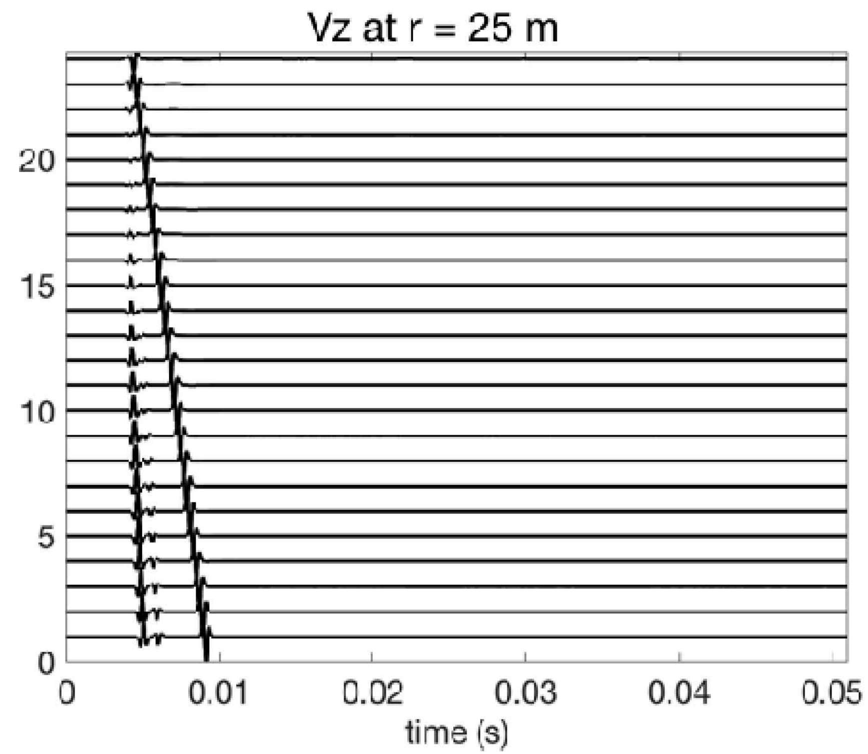


Nonlinear to Linear Modeling

Far-Field waveforms from nonlinear model, i.e., “observed” data

Purely linear Green’s Functions, convolved with 2000 Hz gaussian for visualization





Seismic source time function: Moment tensor

a) The model

$$u_k(\boldsymbol{x}', t') = \int_{-\infty}^{+\infty} \int_{V_0} G_{ki}(\boldsymbol{x}', t'; \boldsymbol{x}, t\ )\, M_i(\boldsymbol{x}, t) dx^3 dt$$

a) cast in frequency domain

$$u_k(f) = \sum_{i=1}^{N} G_{ki}(f) M_i(f)$$

N=number of components in the source (up to nine)

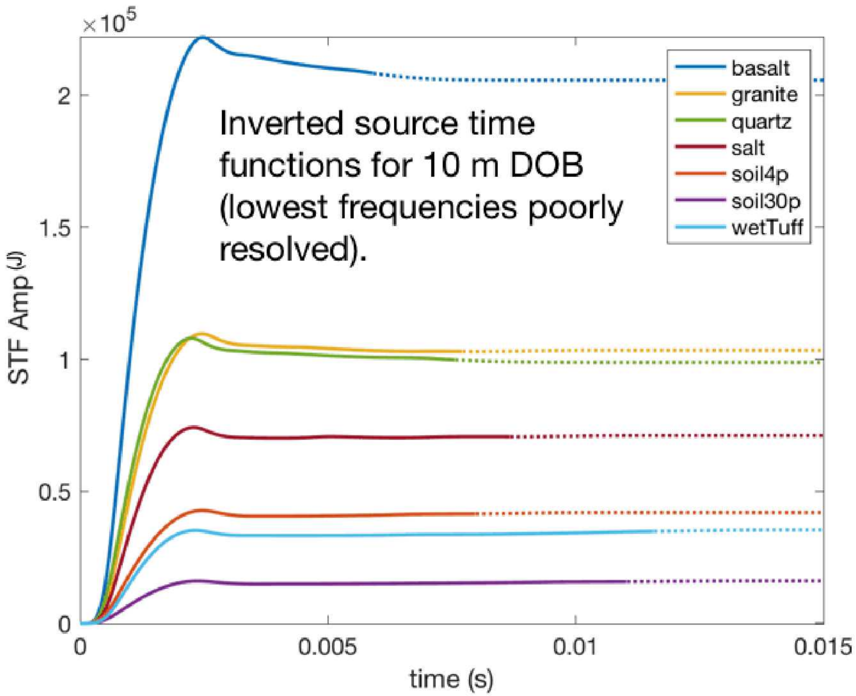
b) To solve, cast as a linear system of equations and invert

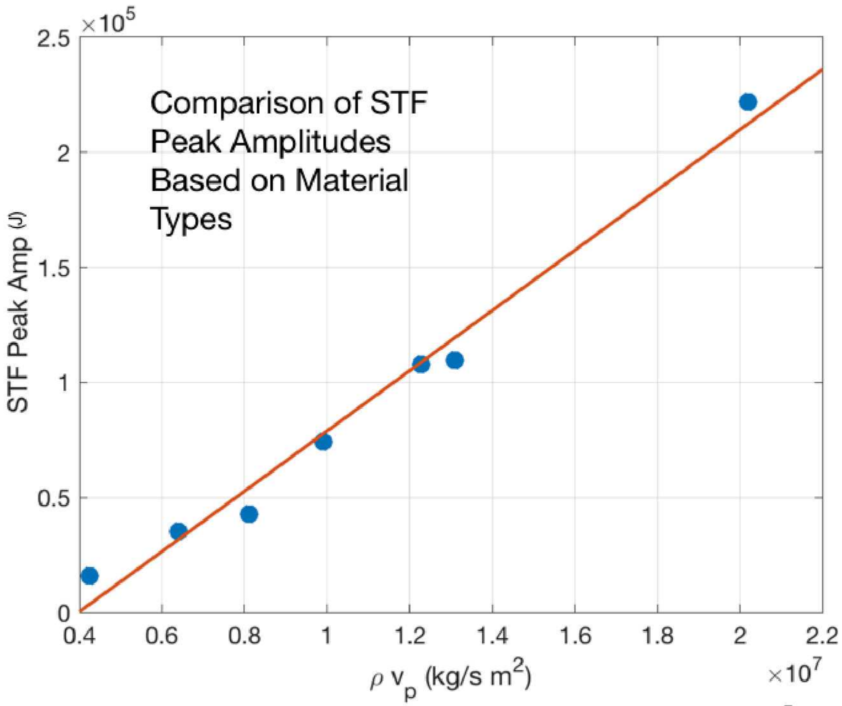
$$\mathbf{M} = \mathbf{G}^{+}\mathbf{u}$$

$\mathbf{G}^{+}$ = generalized inverse of G, may or may not include data/model weighting, regularization, of damping

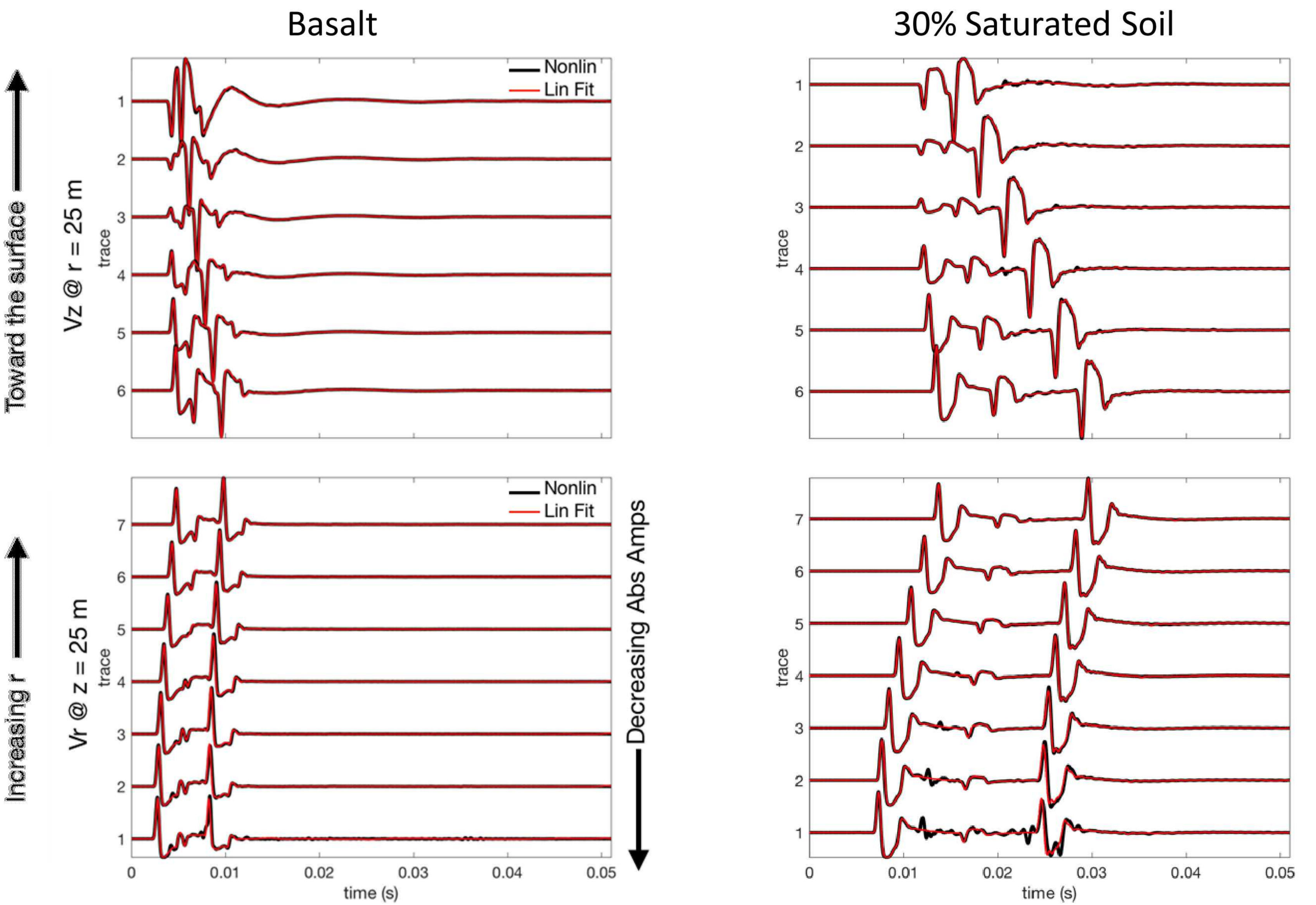
Results

- 2.5 kg TNT buried 10 m depth
- 7 homogeneous geomaterials
- 2D cylindrical simulations; isotropic-only inversions
- Receivers surround source to cover wide variety of take-off angles
- Utilized radial and vertical components of each receiver
- Used these STF's for 5 and 2.5 m DOB cases

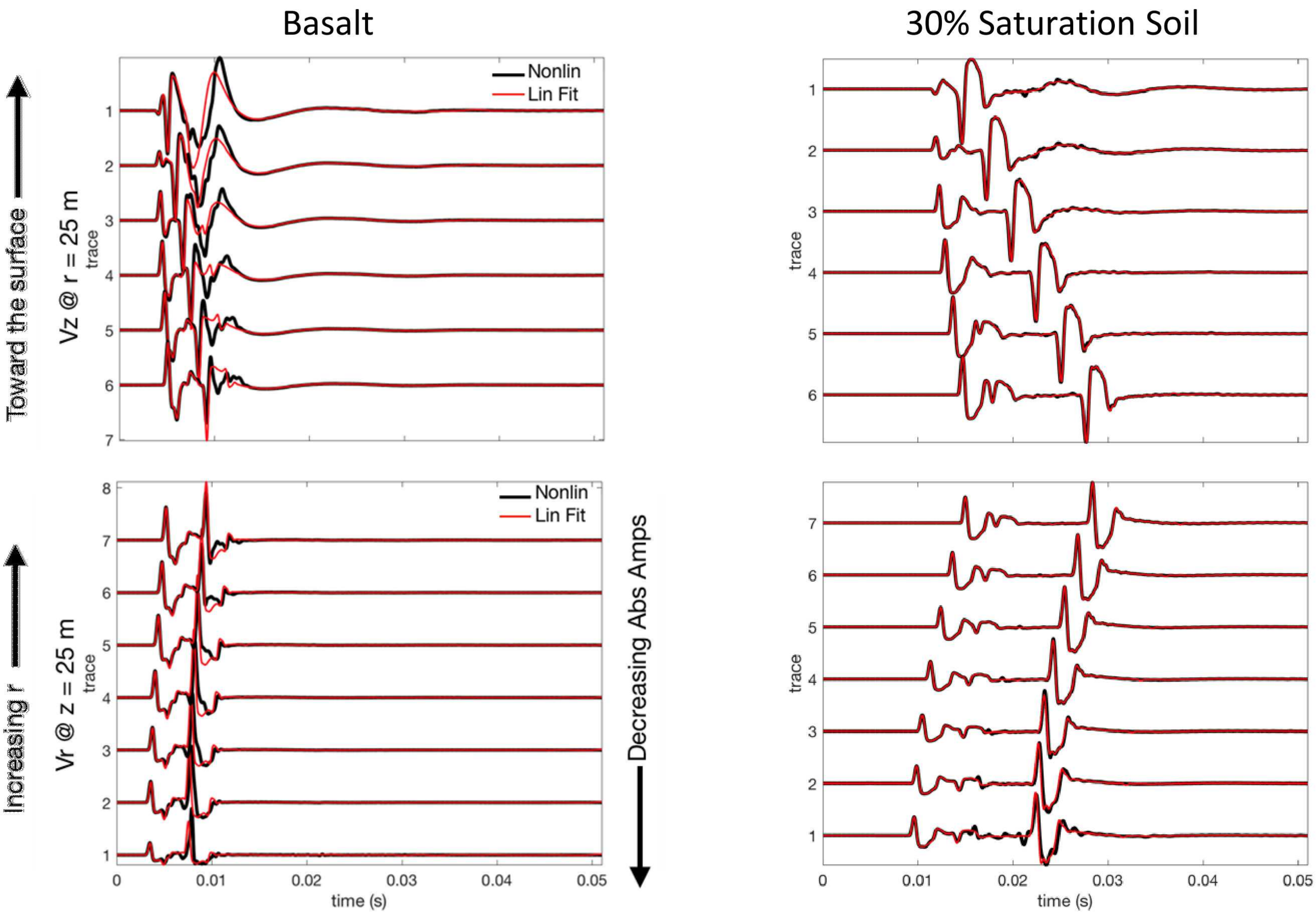




DOB 10 m, 2.5 kg TNT



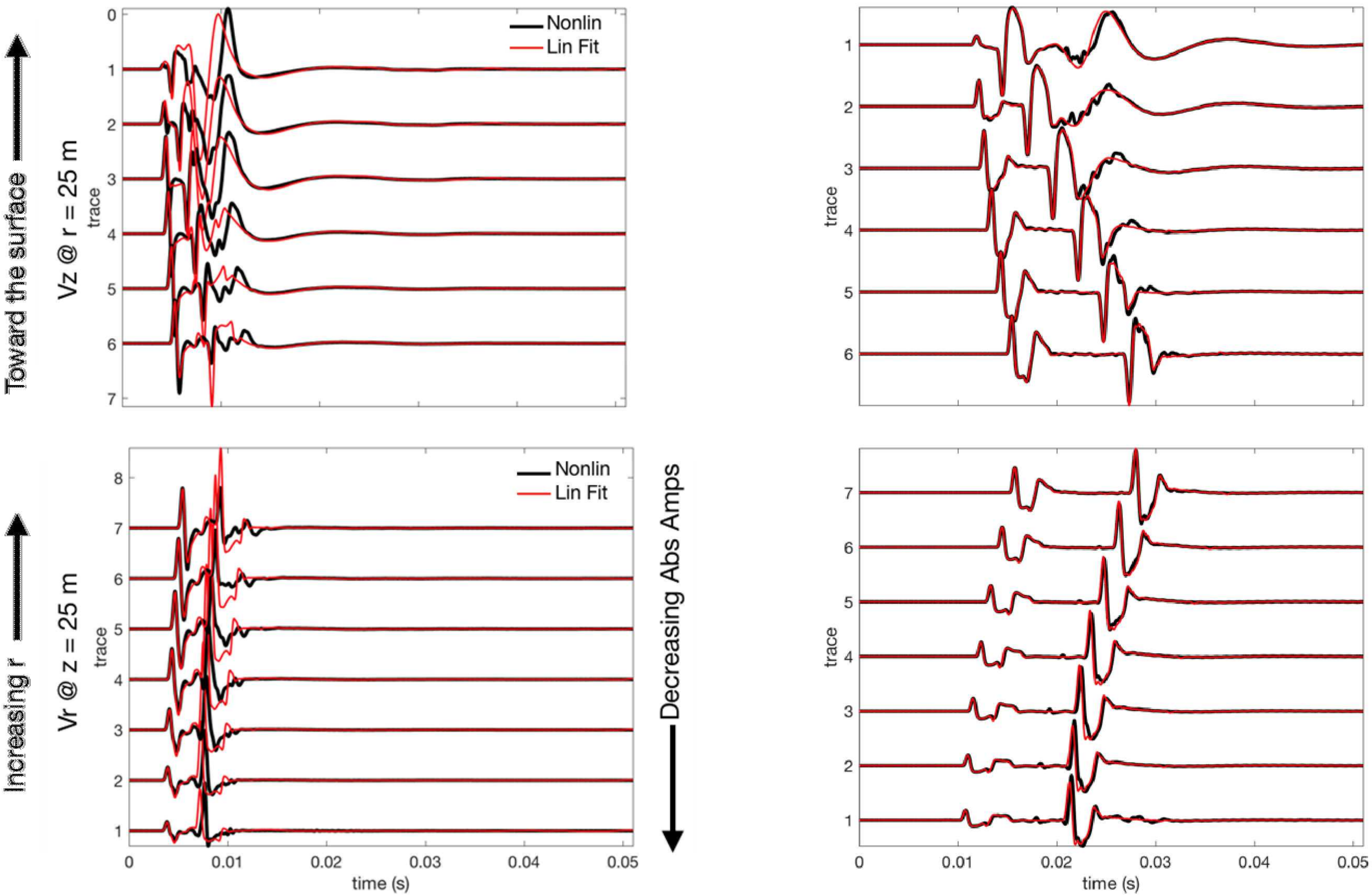
DOB 5 m, 2.5 kg TNT



DOB 2.5 m, 2.5 kg TNT

Basalt

30% Saturation Soil



How to deal with model with uncertain fine structure

$$\mathbf{M} = \mathbf{G}^{\dagger} \mathbf{u}$$

we need to know this!

- seismic tomography/refraction
- surface wave tomography
- etc.

geophys. inversions = smooth models
we generally know this

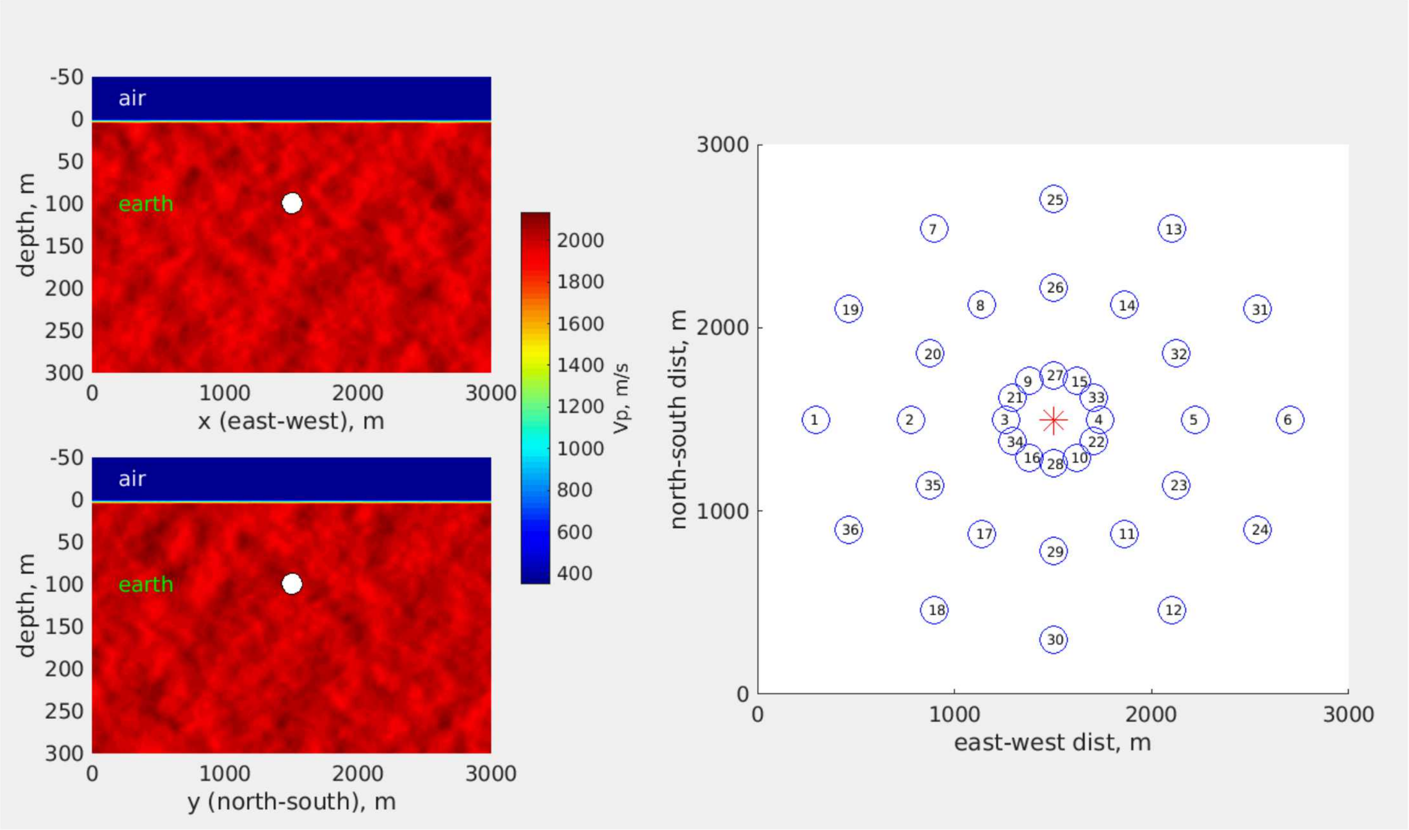
- well log
- geologic mapping

observations = NOT smooth!
we generally can only know the statistics of this

Explore this one

Numerical Experiments

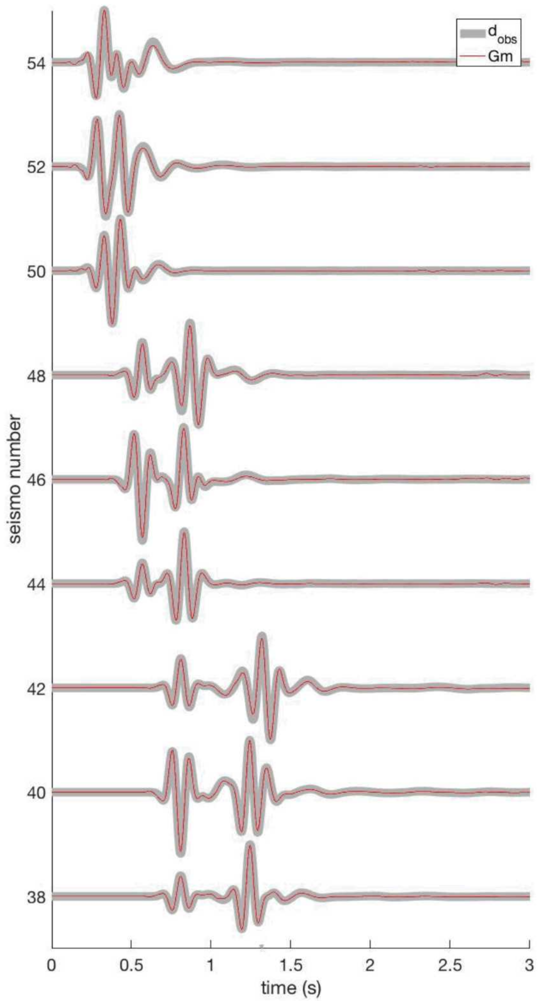
- Question: if we only know the “smooth” structure, how can we resolve the seismic source?
- Experiment
  - 1) generate a synthetic seismograms, using a heterogeneous model (von Karman):

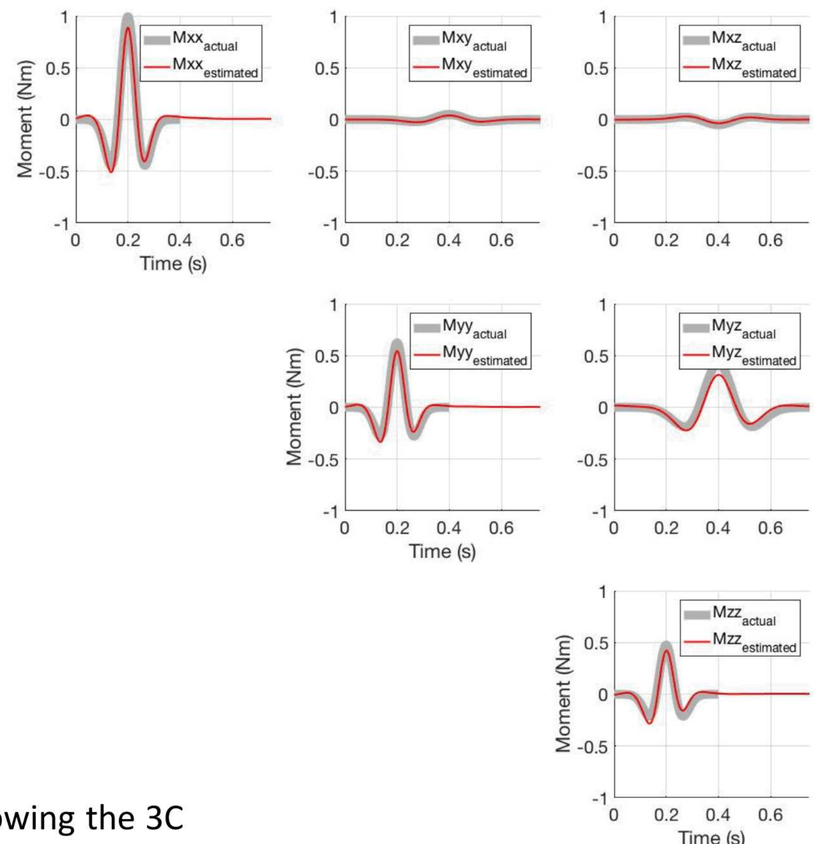


Numerical Experiments

- Experiment
  - 2) Invert data

Example with “perfect data”: i.e. same model to make the data and invert the data



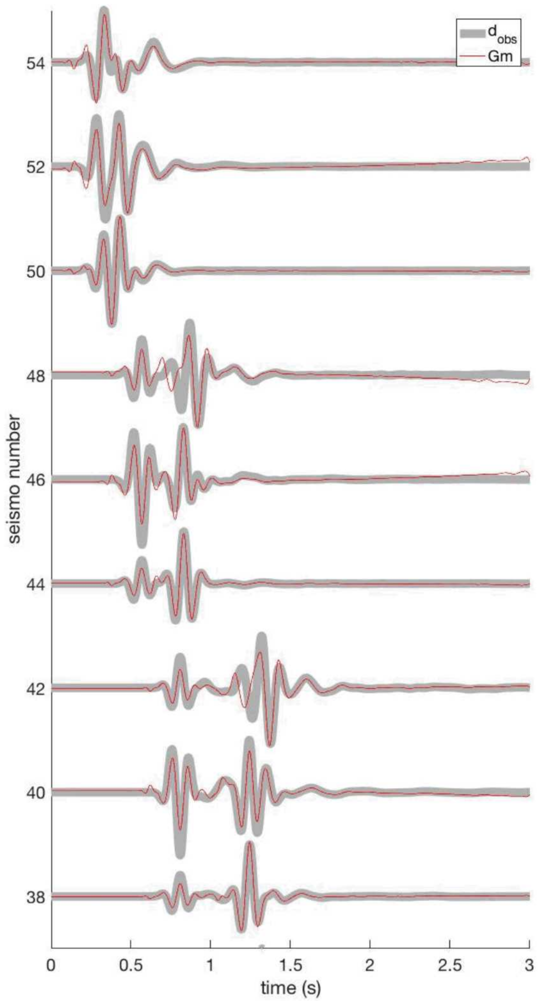


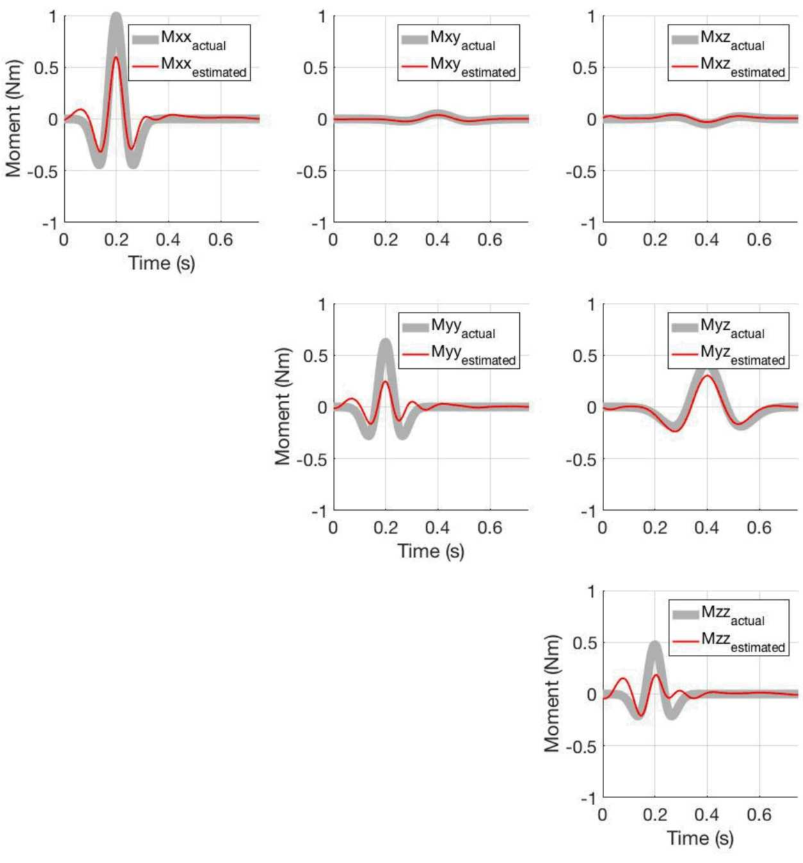
(only showing the 3C seismograms from three stations)

Numerical Experiments

- Experiment
  - 2) Invert data

Example with where the model to make the data not the same as that used to invert the data





Numerical Experiments

- Observation:
  - When we "only" know the smooth model, but can only guess at the heterogeneity spectrum, then the timing and amplitude of the recovered STFs is approximately correct. But the phase of the STFs and the predicted data are incorrect.
  - Three approaches:
    - 1) invert only the amplitude spectra
    - 2) Monte Carlo approach in full-spectral domain
    - 3) Combination of 1 and 2

$$\mathrm{u(f) = G(f)m(f)}$$

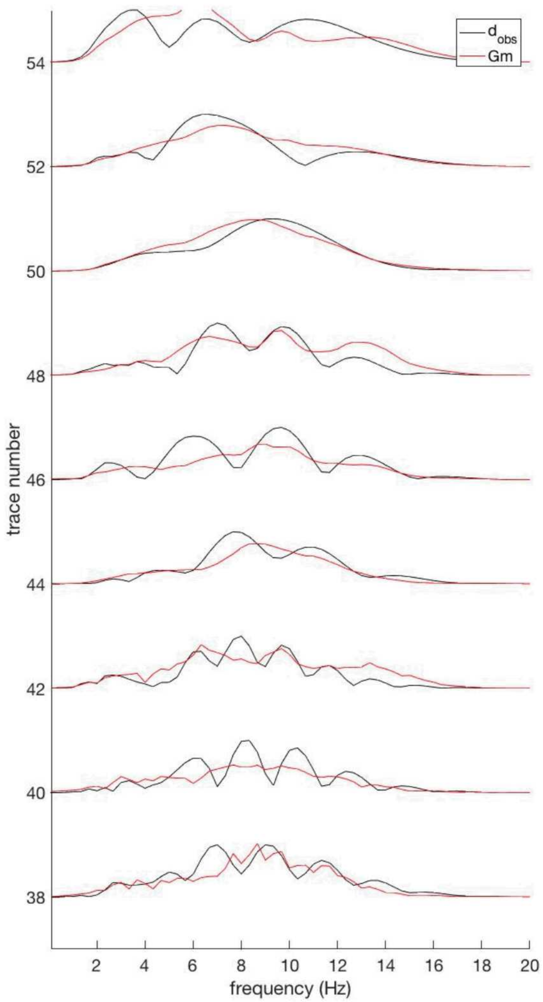
full spectrum inversion

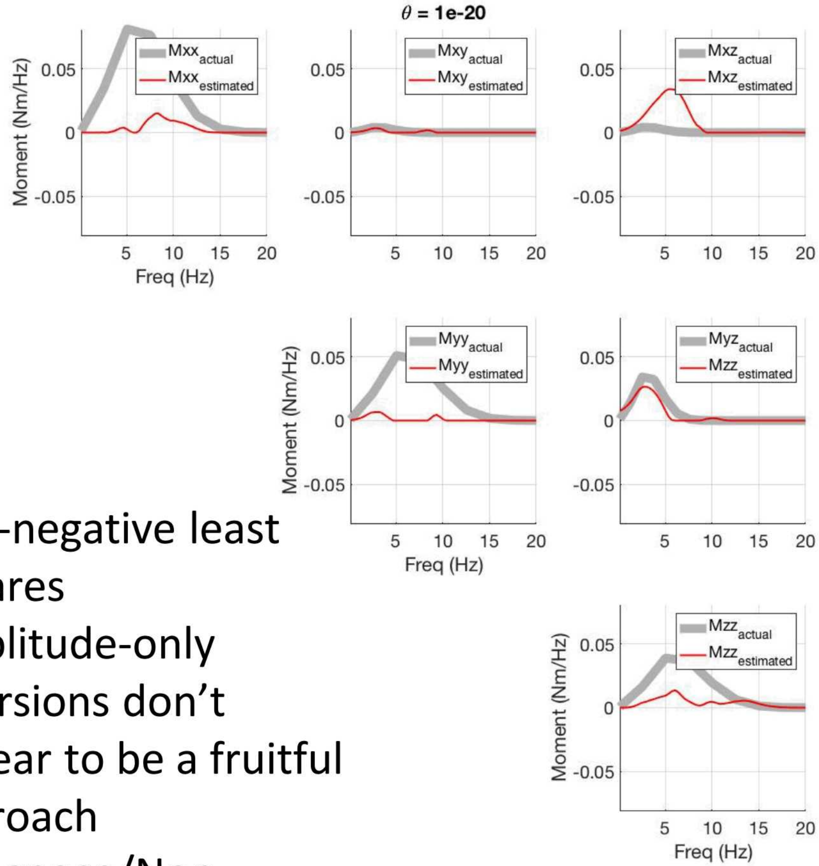
$$\mathrm{|u(f)| = |G(f)||m(f)|}$$

amplitude spectrum only inversion

Numerical Experiments

- 1) Amplitude spectra-only inversion: “perfect” data $|\mathrm{u}(\mathrm{f})| = |\mathrm{G}(\mathrm{f})||\mathrm{m}(\mathrm{f})|$

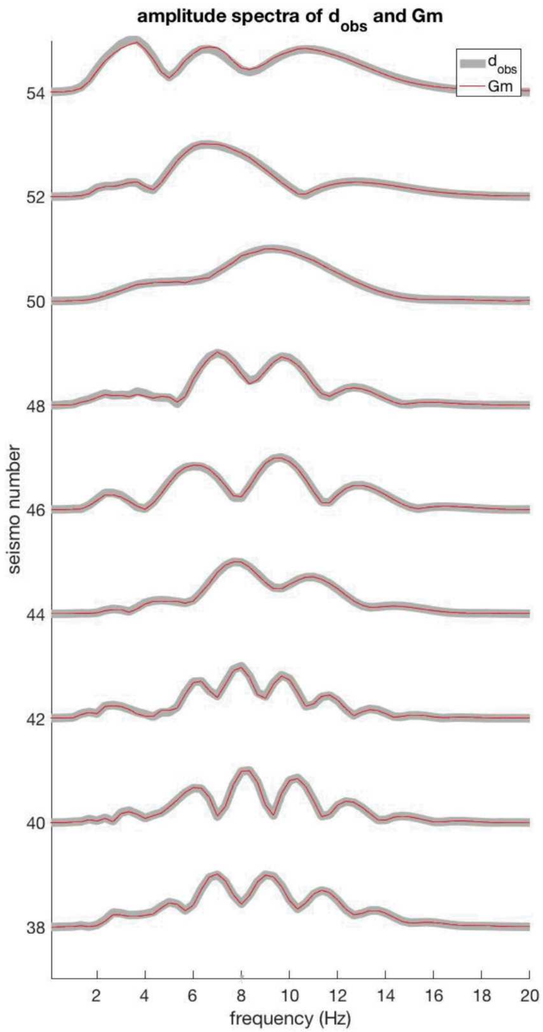


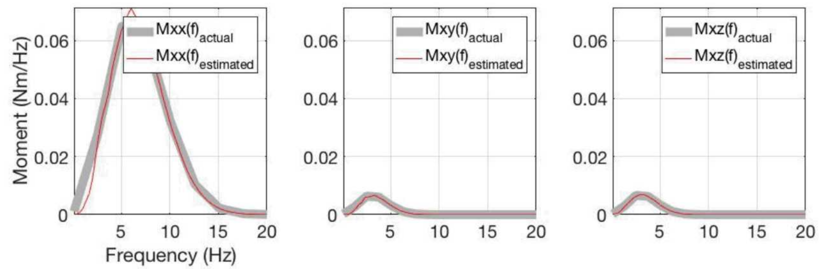


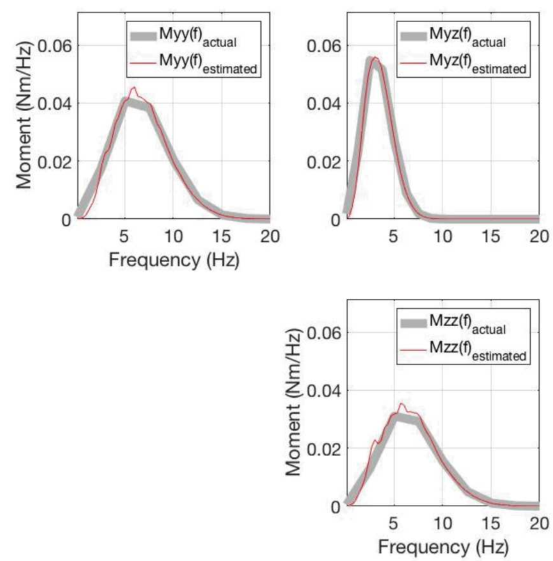
- Non-negative least squares
- Amplitude-only inversions don’t appear to be a fruitful approach
- Null space/Non-uniqueness?

Numerical Experiments

- 2) Invert full spectra, retain only amplitude spectra results



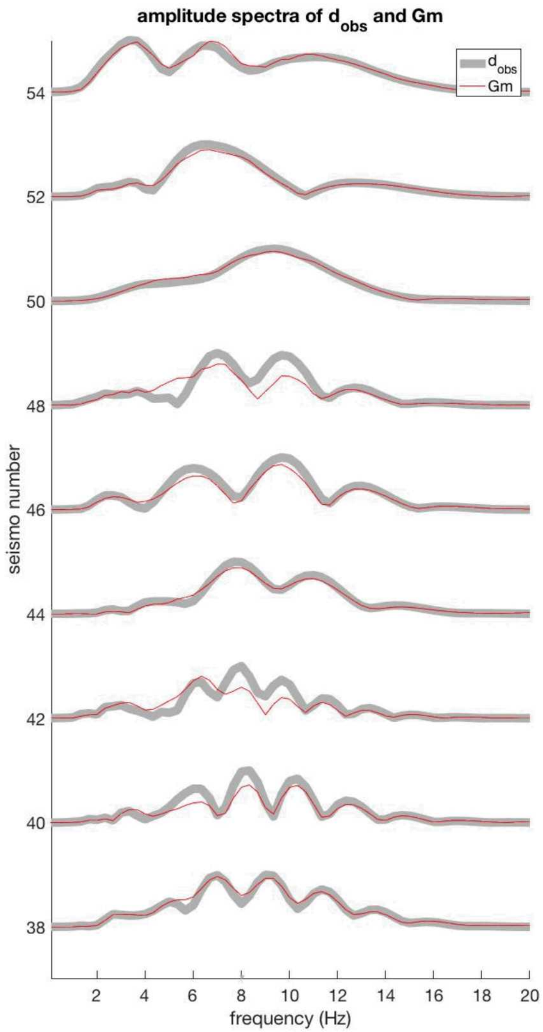


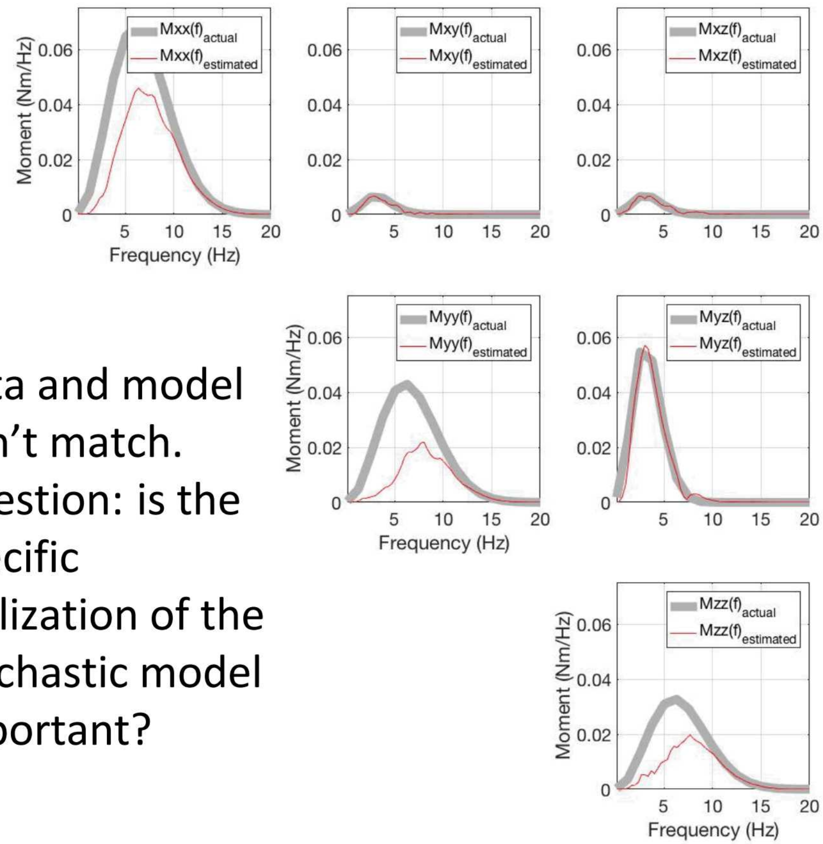


”perfect” data

Numerical Experiments

- 2) Invert full spectra, retain only amplitude spectra results



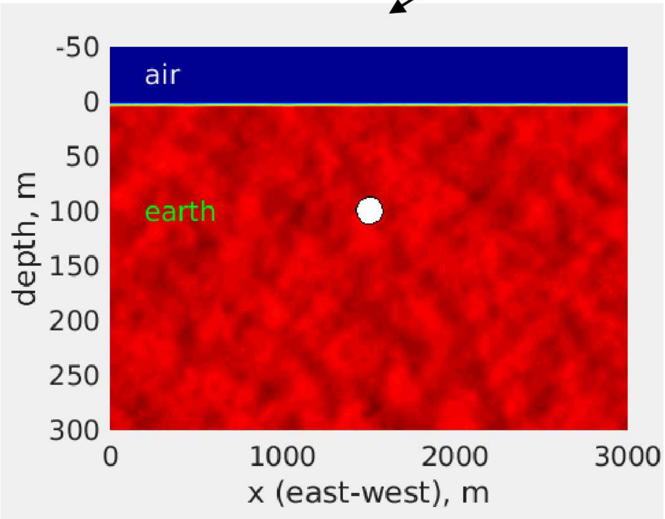


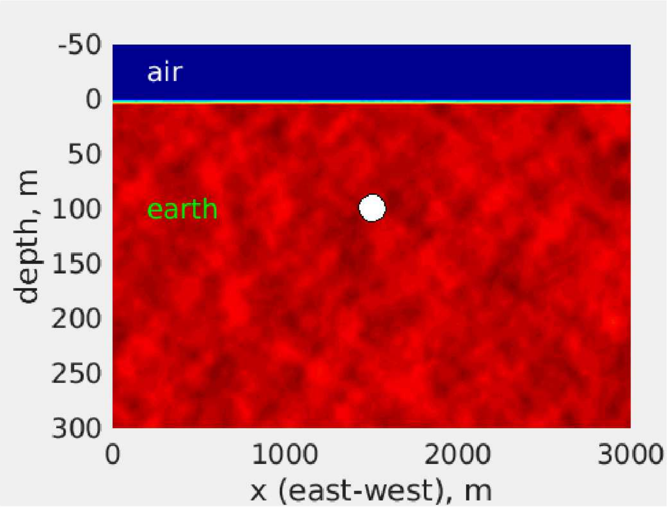
- Data and model don't match.
- Question: is the specific realization of the stochastic model important?

Numerical Experiments

- 3) Monte Carlo approach?
  - Smooth model is resolvable, but fine-scale model may not be.
  - Estimate the uncertainty in the fine-scale model using a Monte Carlo approach
    - use a suite of stochastic realizations: e.g. von Karman model (power spectral model, where phase is randomized)
    - relevant parameters are correlation length and Hurst exponent

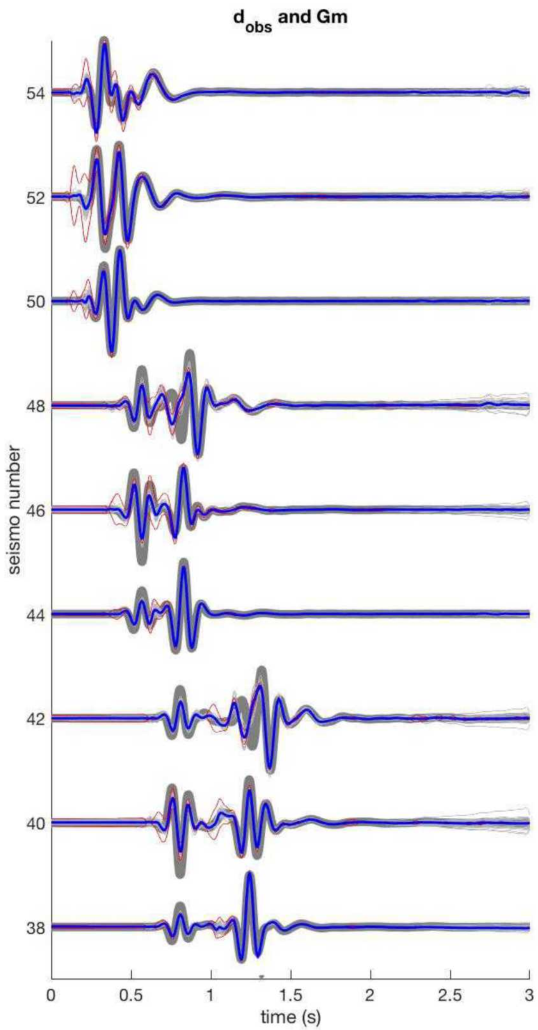
correlation length = 300m
Hurst exponent = 0.3
different seeds

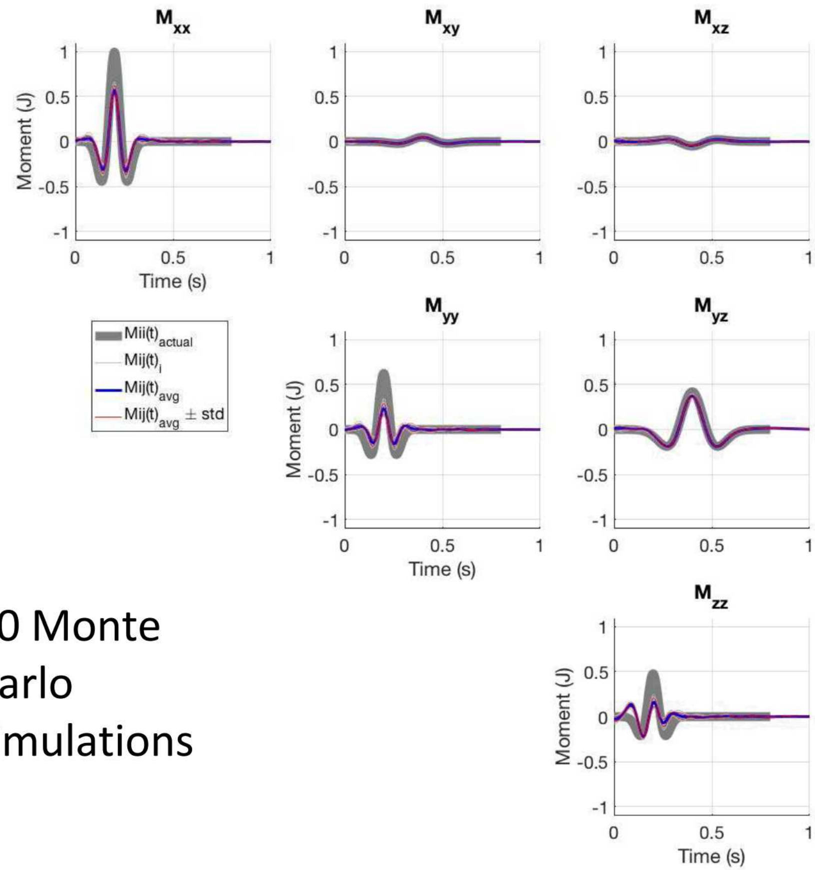




Numerical Experiments

- 3) Monte Carlo approach
  - full spectrum inversion, retain amplitude and phase

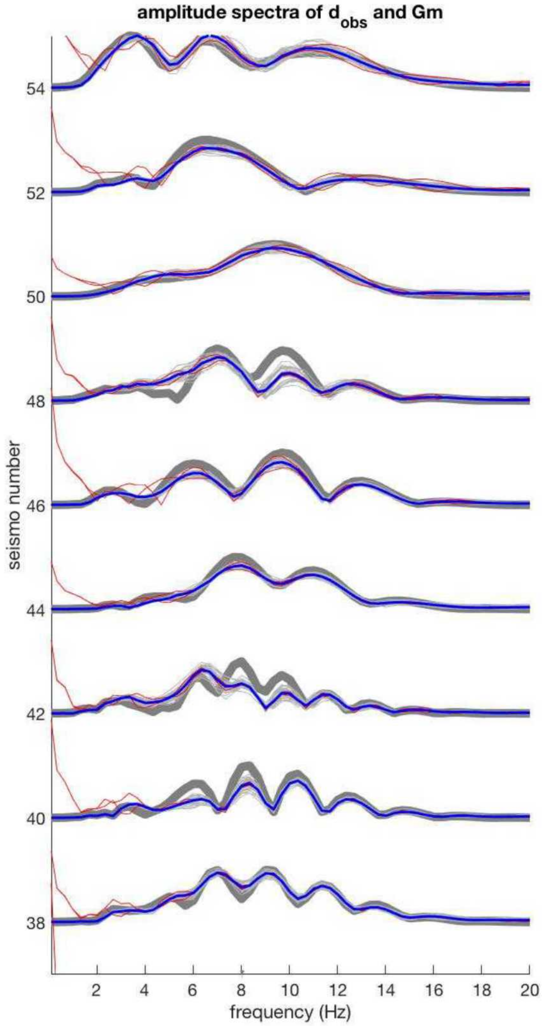


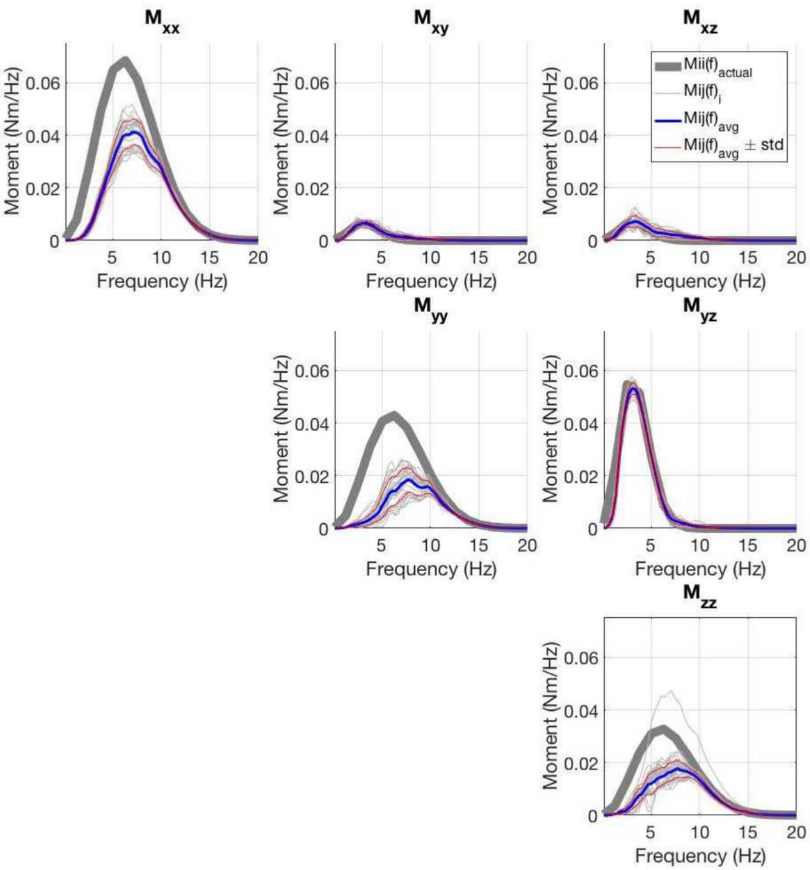


30 Monte Carlo simulations

Numerical Experiments

- 3) Monte Carlo approach
  - full spectrum inversion, retain amplitude only



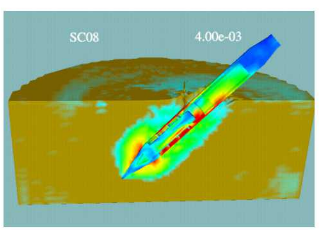


Zapotec for Near and Mid-Range Modeling Motivation

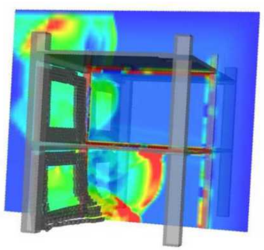
- Different length scales in this problem have different characteristics
  - Near source: intense pressures and energies, massive deformation, material phase change
  - Mid-range: high pressures and energies, significant deformation, no phase change but interaction with material discontinuities (e.g. rock joints)
  - Far-field: elastic response
- Previous work has already focused on linking near source and far-range responses using coupling between CTH and Parelasti
- To improve mid-range response, we are exploring the use of Zapotec for the source and mid-range modeling, and then couple it to Parelasti

Zapotec:
Coupling Between CTH and Sierra/SM

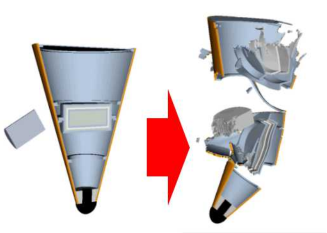
- Zapotec enables the analyst to use the best computational approach for different parts of multi-domain problems
- Key features:
  - Hex and shell finite elements supported in coupling (shells enable significant time savings for thin structures)
  - Material from failed elements in Sierra/SM can be incorporated into CTH domain to ensure conservation of mass and momentum
  - User-specified decoupling time enables computational savings in late-time results
- Sample use cases:



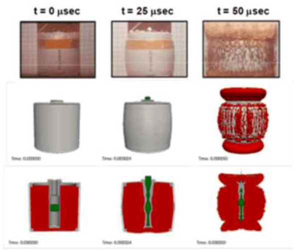
Penetration



Air Blast on Structures



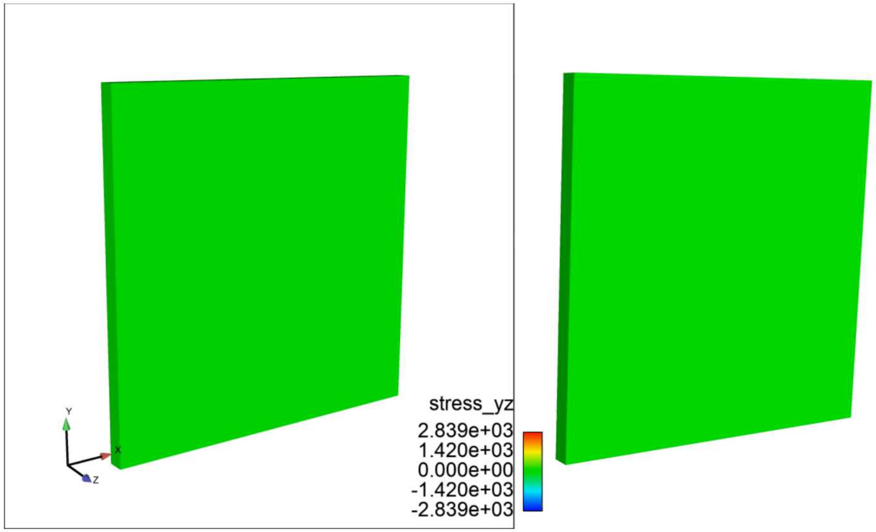
Hypervelocity Impact



Bomb Fragmentation

Computational Approaches

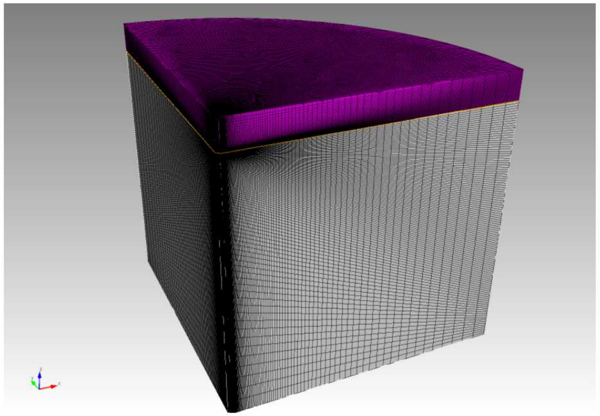
- For this work, we will still use CTH to model the source term, but after an appropriate distance use a finite element mesh in Sierra/SM to model mid-range structures
- Sierra/SM will utilize XFEM capabilities to include rock join effects
- Sierra/SM will then transfer to Paralasti for far distance solution
- Some challenges exist in matching material parameters across the coupling interface; this will be studied as the project continues



Sierra/SM Simulation of blast on plate; solid block on left, block with XFEM cohesive model on right

Testing Approach

- Currently underway is testing to confirm that swapping Zapotec out for CTH results in the same coupling to Paralasti
- Focus is on 5m depth of burial in Salt; suitable materials for this exist in both CTH and Zapotec
- After this test, both 2.5 and 10 m cases in salt will be considered and compared
- Other materials will be considered next



Initial finite element mesh for mid-range modelling

Summary

- Purely linear source models can match far-field waveforms from nonlinear sources
- These source-time functions resemble a Meuller-Murphy source function
- Amplitudes of the STF depend quasi-linearly on impedance of material
- Isotropic linear source models break down for strong materials near the free surface
- Material heterogeneity can introduce biases and errors into moment tensor inversions
- Inversions of only amplitude spectra have inferior performance relative to complete amplitude and phase inversions
- Monte Carlo simulations and inversions indicate biases especially in isotropic components, but off-diagonal components are less sensitive to random perturbations
- We will be pursuing better material models and modeling tools for near and mid-range distances