SAND2019-2643PE

Defense Nuclear Nonproliferation Research & Development

Nuclear Explosion Monitoring Program Review

NEM 2019

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

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Nonlinear to Linear End-to-End Modeling – LYNM Program

- Coauthors: Christian Poppeliers, Mehdi Eliassi, and Arne Gullerud (Sandia)
- Collaborators: Working with LLNL and LANL to obtain improved and calibrated nonlinear material models
- Overview and Goals
  - Develop and improve end-to-end modeling capabilities through numerical simulation and comparison with lab and field experiments
  - Focusing on how nonlinear, near-source properties affect far-field seismic waveforms and our ability to extract source information from those waveform relevant to the non-proliferation monitoring community
- FY19 Deliverable: Peer review journal article submitted end of FY
- Primary LYNM Science Questions: 21, 27, and 28
  - Addressing uncertainty in seismic modeling due to stochastic variability in the earth and the physics and code coupling requirements for end-to-end modeling

Nonlinear to Linear Modeling

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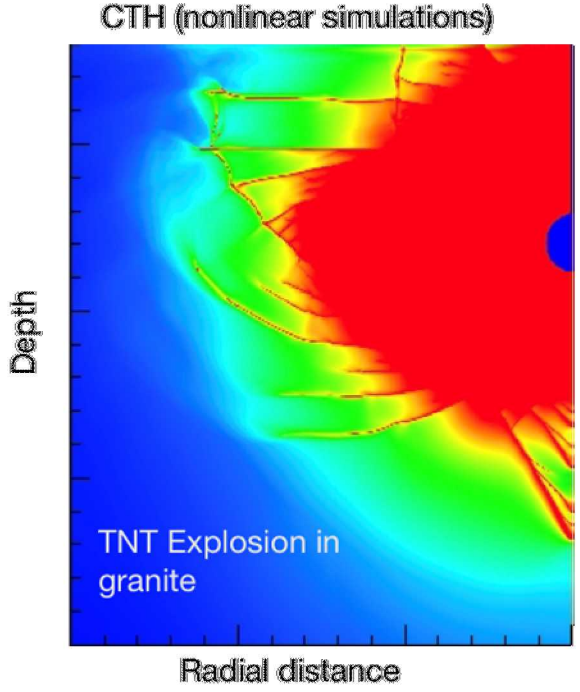
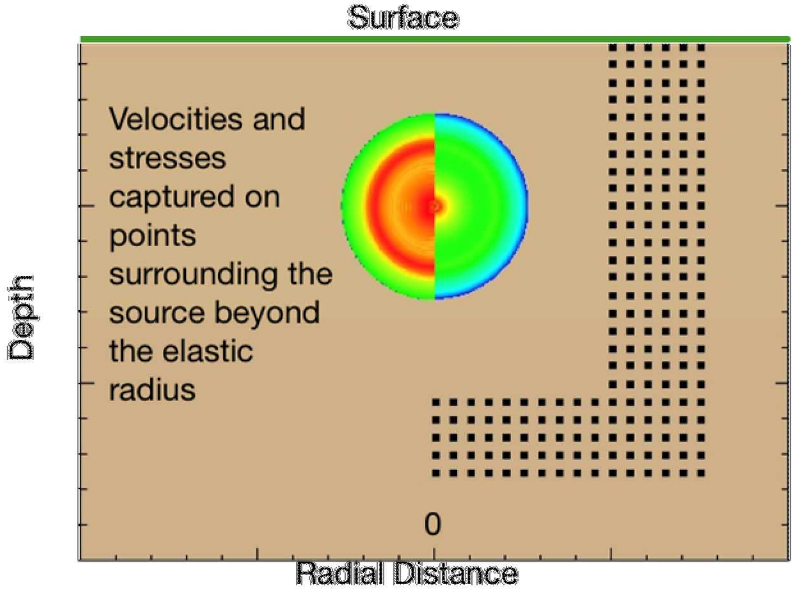
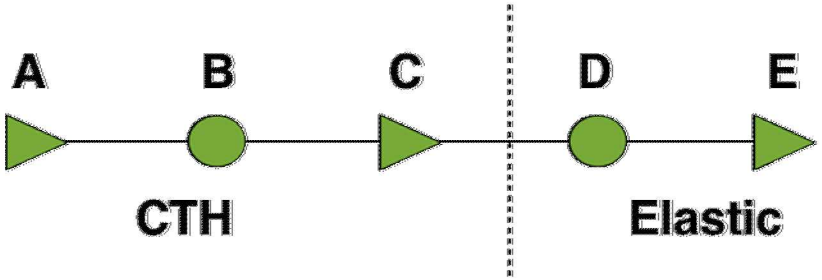
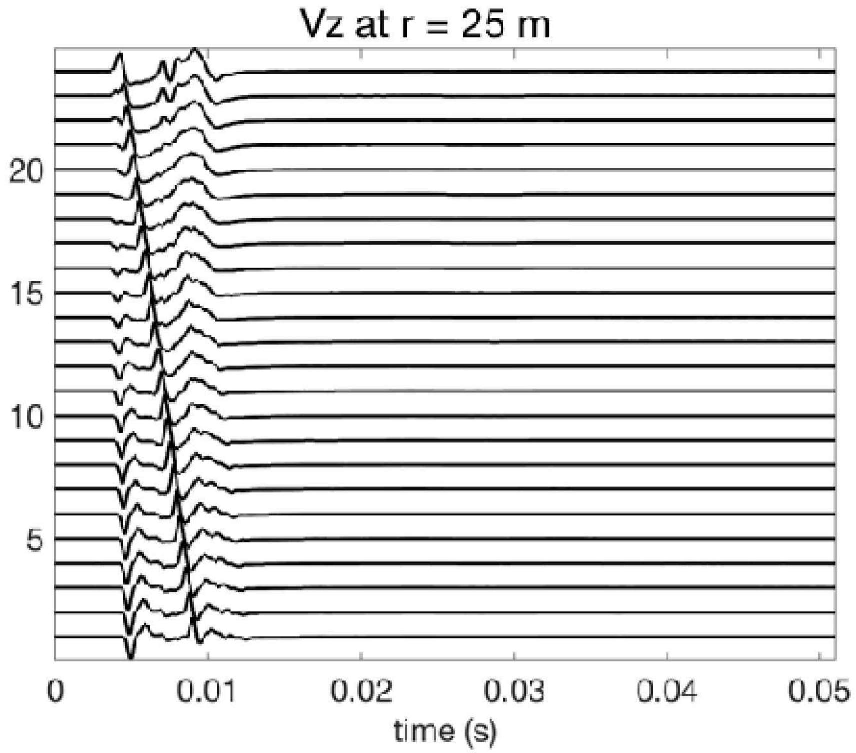






Far-Field waveforms from nonlinear model, i.e., “observed” data



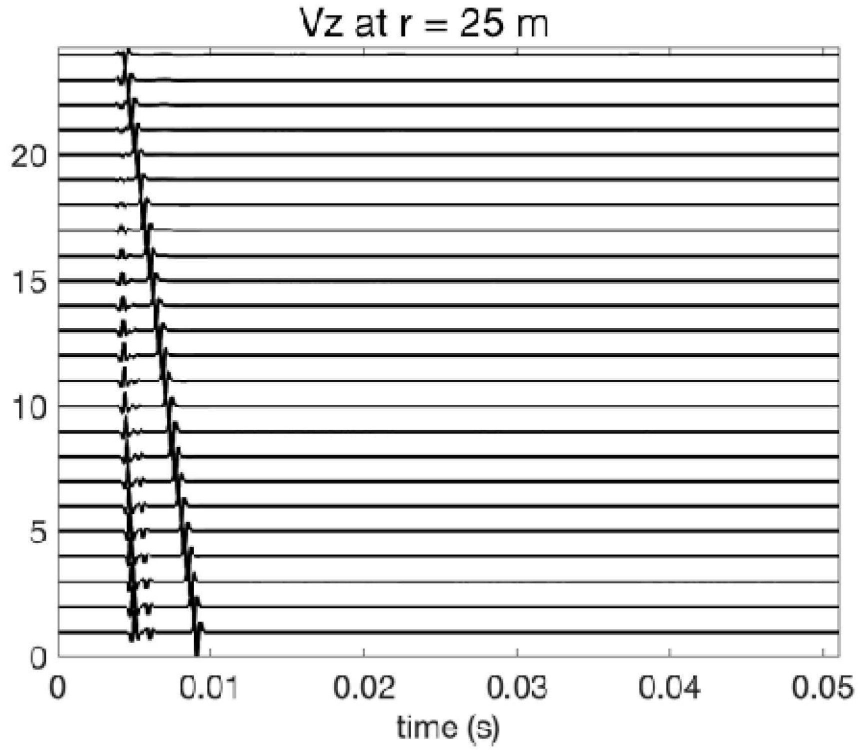
Linear Green's Functions and Source Inversion

- **Produce purely linear explosion (isotropic) Green's Functions using appropriate source depth**
- **Invert for Source Time Function (M) using nonlinear response as "observations" (u) and linear Green's function (G)**

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

$$\mathrm{M(f)} = \mathbf{G}(\boldsymbol{f})^{+}\mathbf{u}(\mathbf{f})$$

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



Nonlinear to Linear Modeling Method

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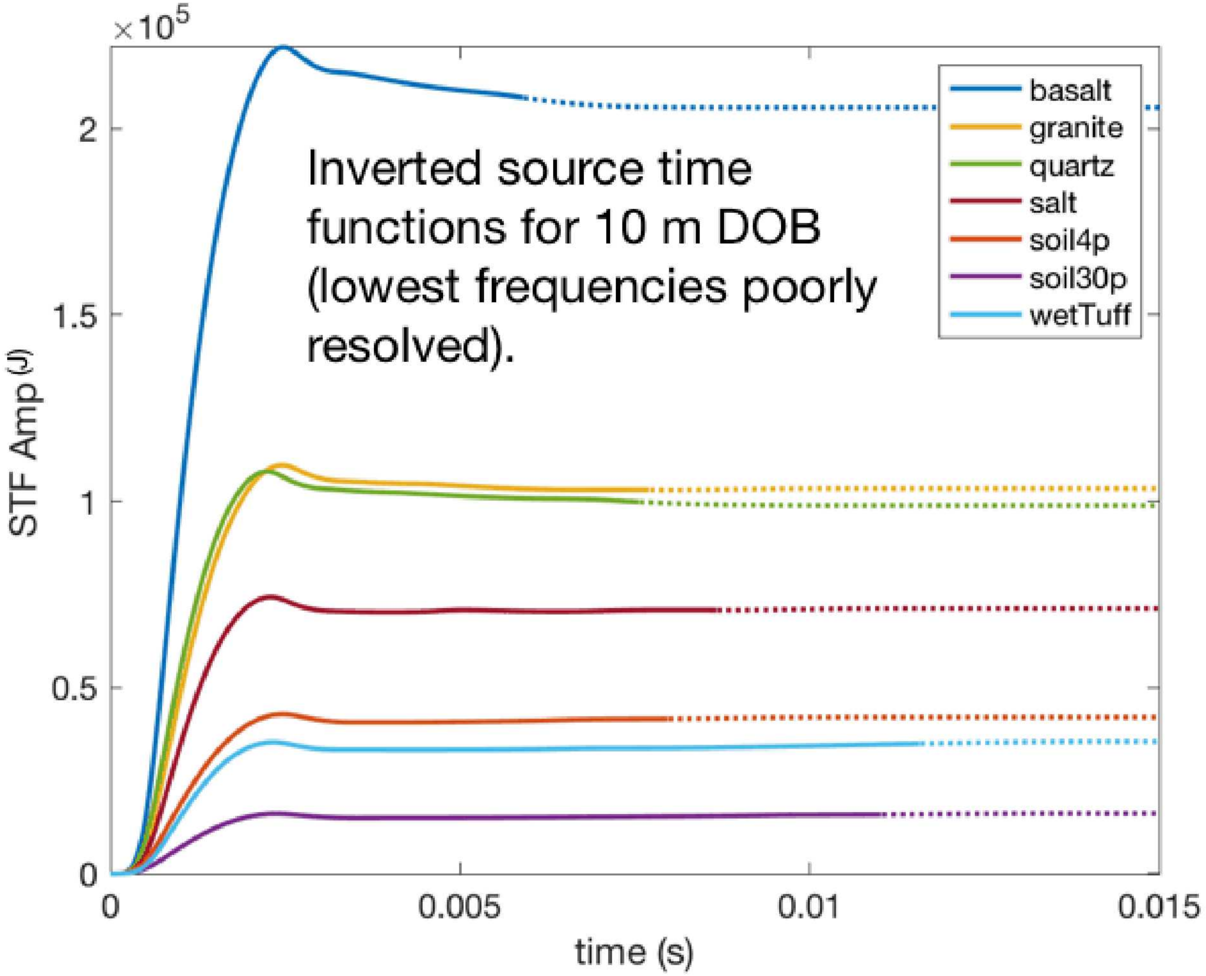
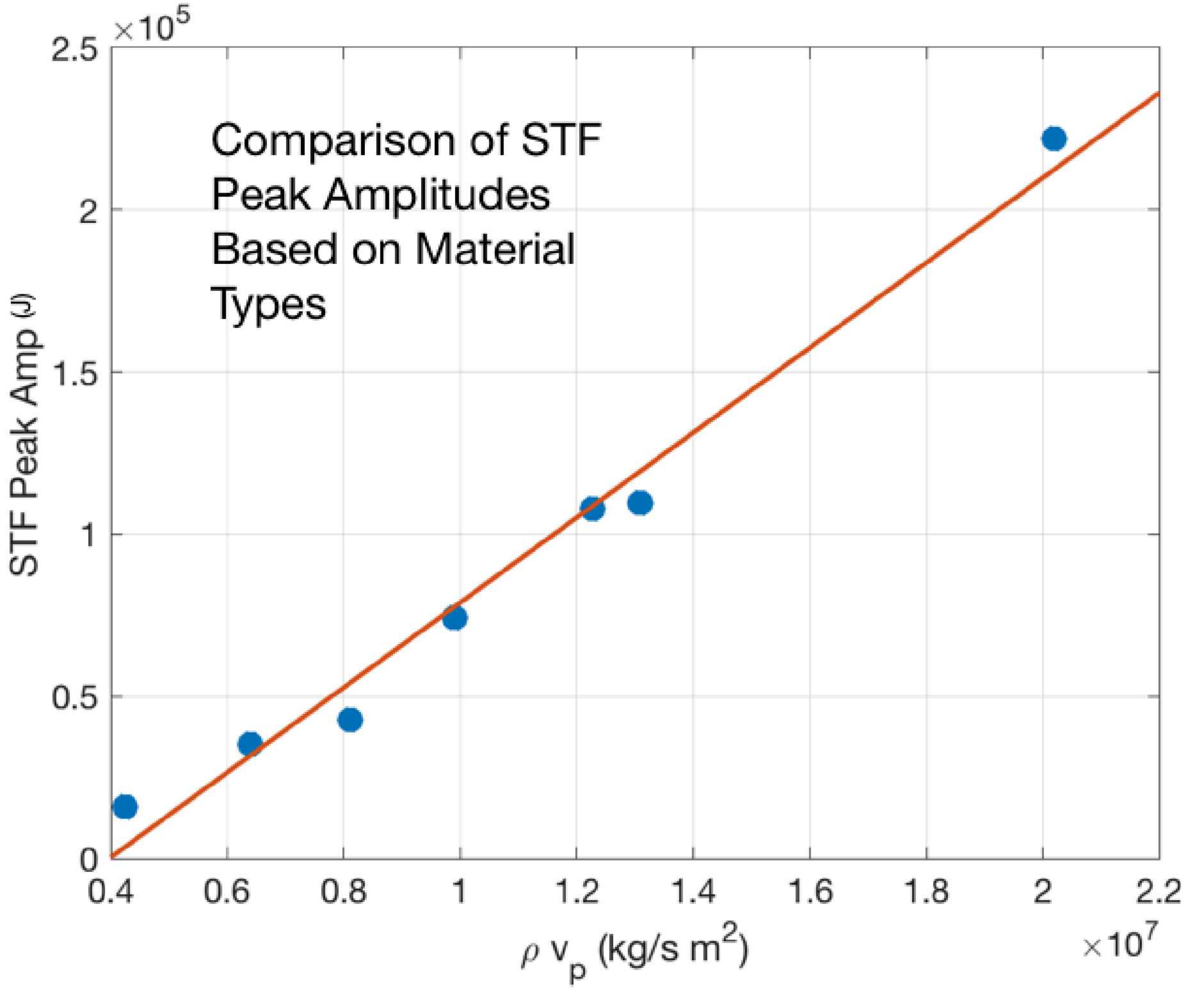
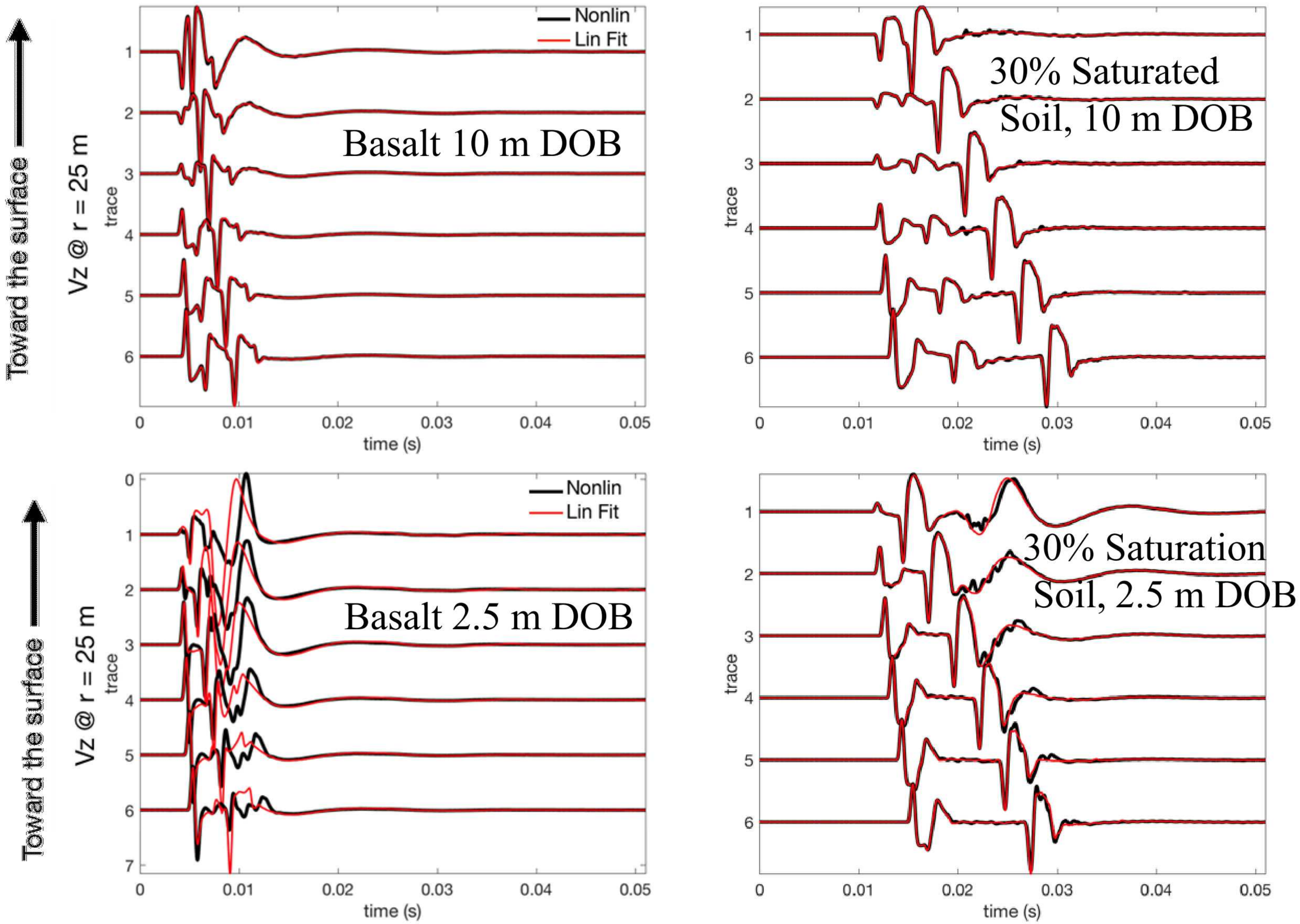
- 2.5 kg TNT buried 10 m depth used to invert for linear source time functions
- 7 homogeneous geomaterials tested with a range of strengths (basalt, granite, quartz, salt, 5% saturated soil, 30% saturated soil, and wet tuff)
- Nonlinear modeling currently uses uncalibrated material models, but in the process of obtaining calibrated models
- Nonlinear properties include physics capabilities of CTH including EOS, porosity crush, and strength models
- 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 the same source time functions from the 10 m depth case for 5 and 2.5 m depth of burial cases

Preliminary Results





How Well Does Purely Linear Source Model Fit Nonlinear Source Waveforms?



- Linear source models for all materials match nonlinear waveforms for 10 m DOB
- Linear explosion source model does not fit strong materials as well at 5 m DOB, but weak materials still are well fit
- At 2.5 m DOB even weak materials are not fit as well by linear explosion source model
- Nonlinear surface effects (spall) is not replicated by linear codes

How To Deal with Uncertain Fine Earth Structure

$$M(f) = \mathbf{G}(\mathbf{f})^{+}\mathbf{u}(\mathbf{f})$$

We need to know this!

- Seismic tomography/refraction
- Surface wave tomography
- etc.

Geophysical inversions are smooth models: We generally know this

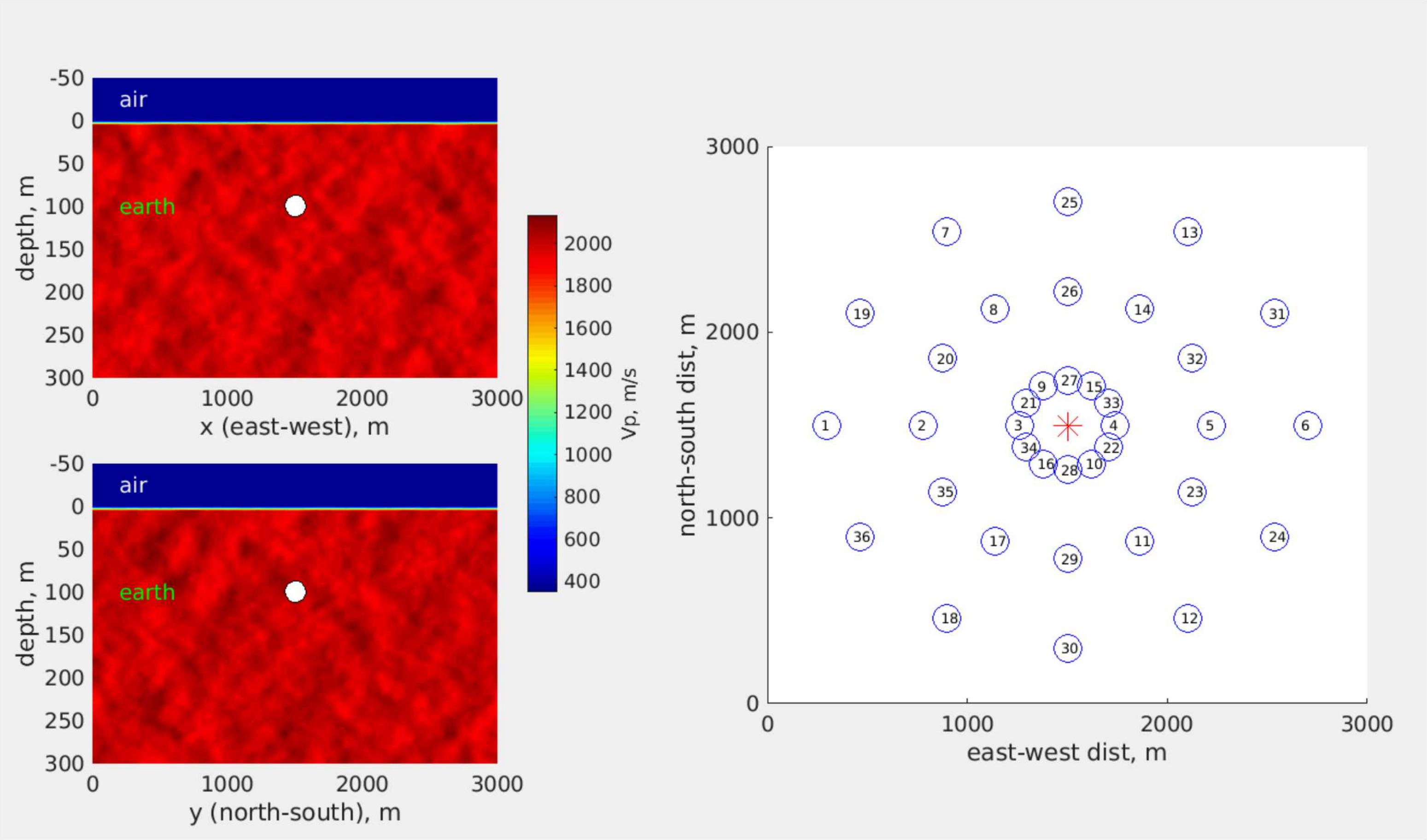
- Well log
- Geologic mapping

Observations = NOT smooth! We generally can only know the statistics of this

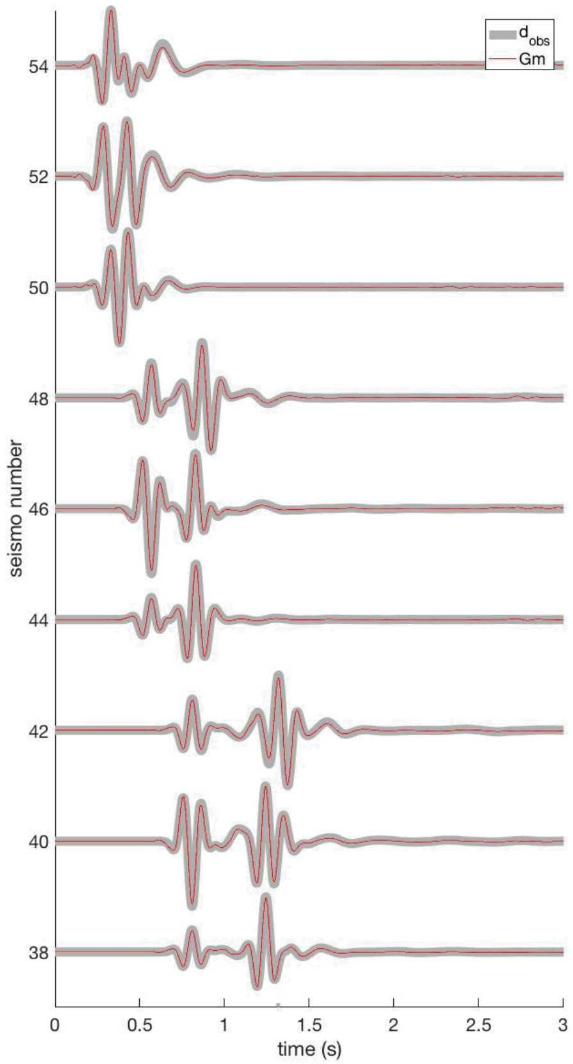
Explore this one

Numerical Experiments

- **Question: if we only know the "smooth" structure, how can we resolve the seismic source?**
- **Generate a synthetic seismograms, using a heterogeneous model (von Karman)**
- **Correlation length = 300m**
- **Hurst exponent = 0.3**
- **Different seeds**

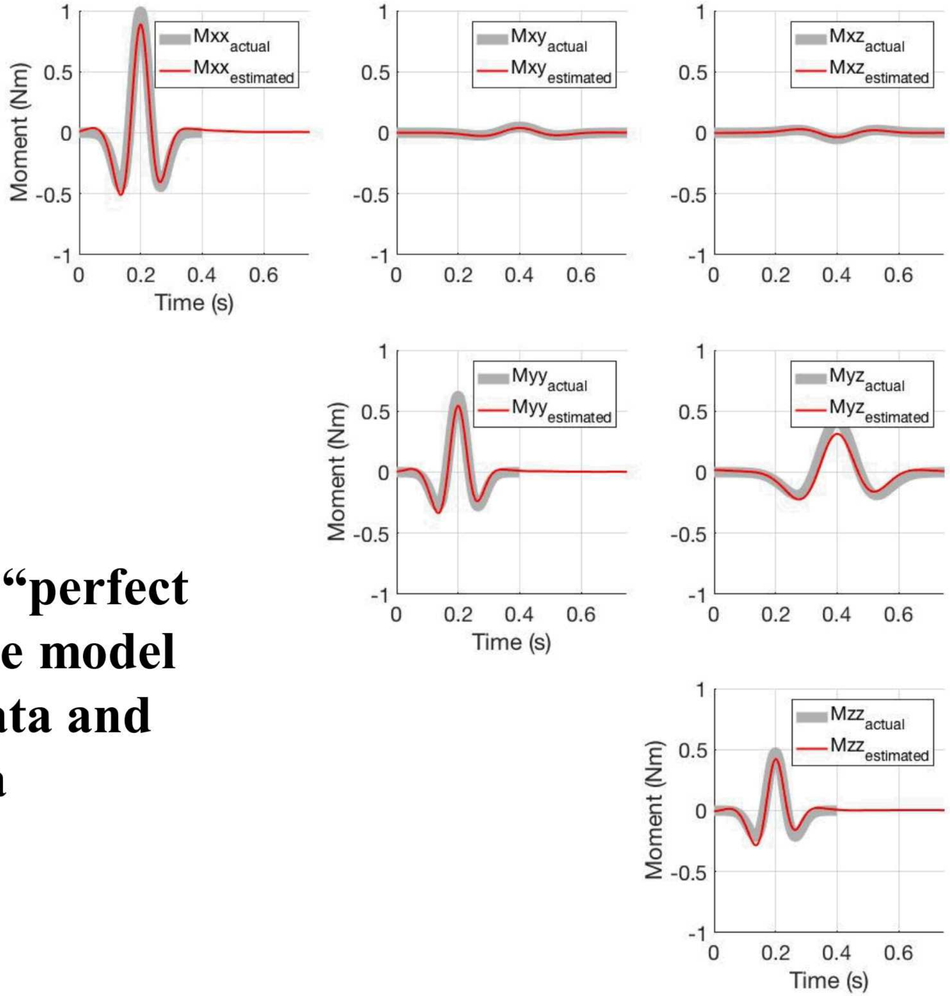


Numerical Experiment

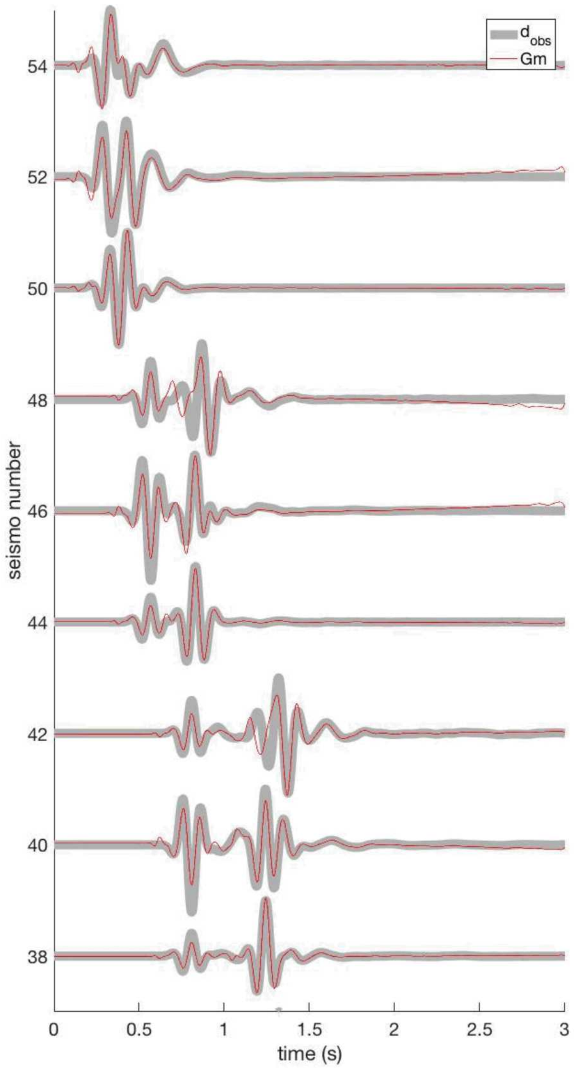


Example with "perfect data": i.e. same model to make the data and invert the data

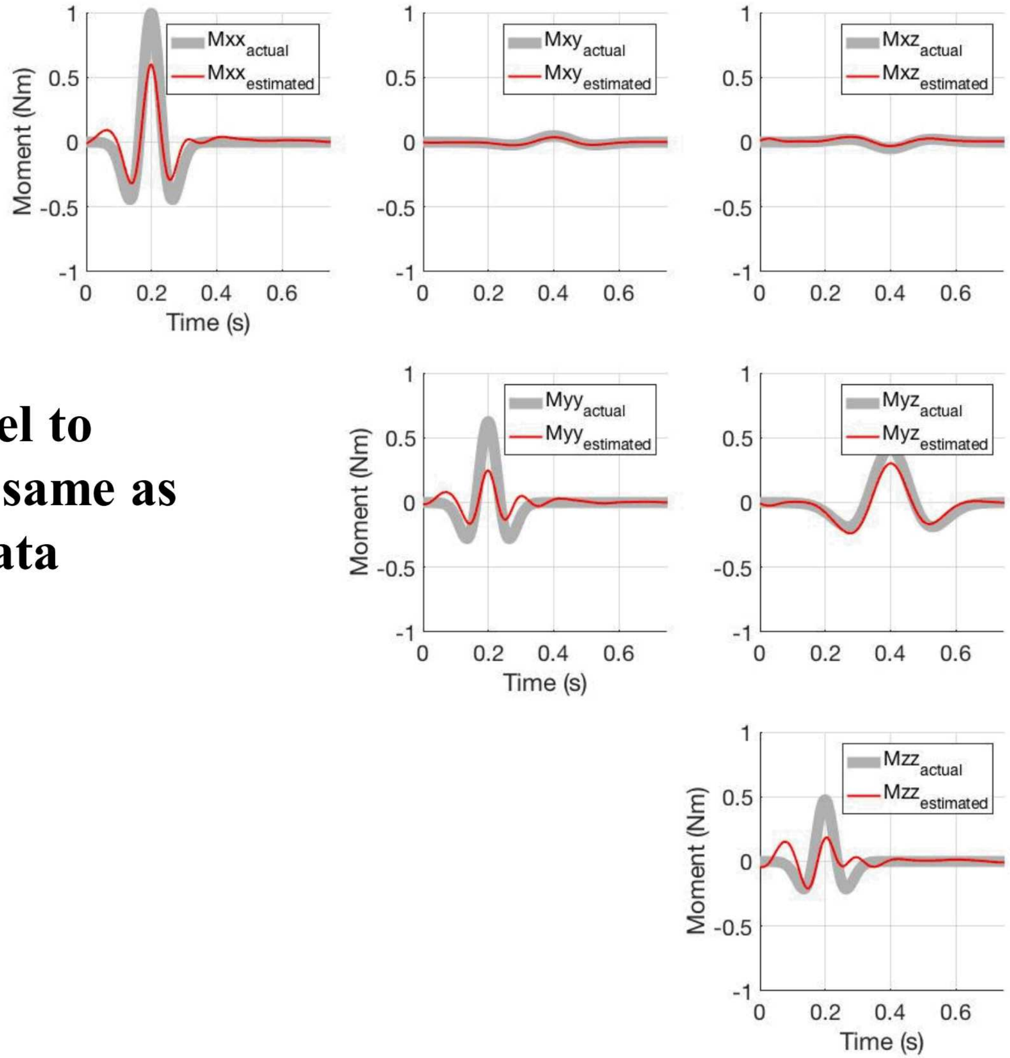
(only showing the 3C seismograms from three stations)



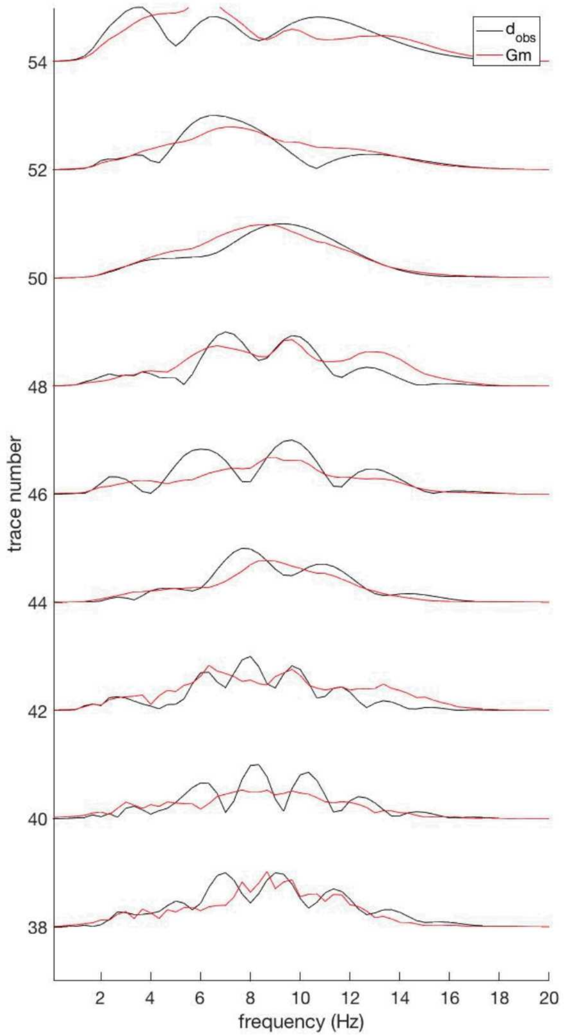
Numerical Experiment



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

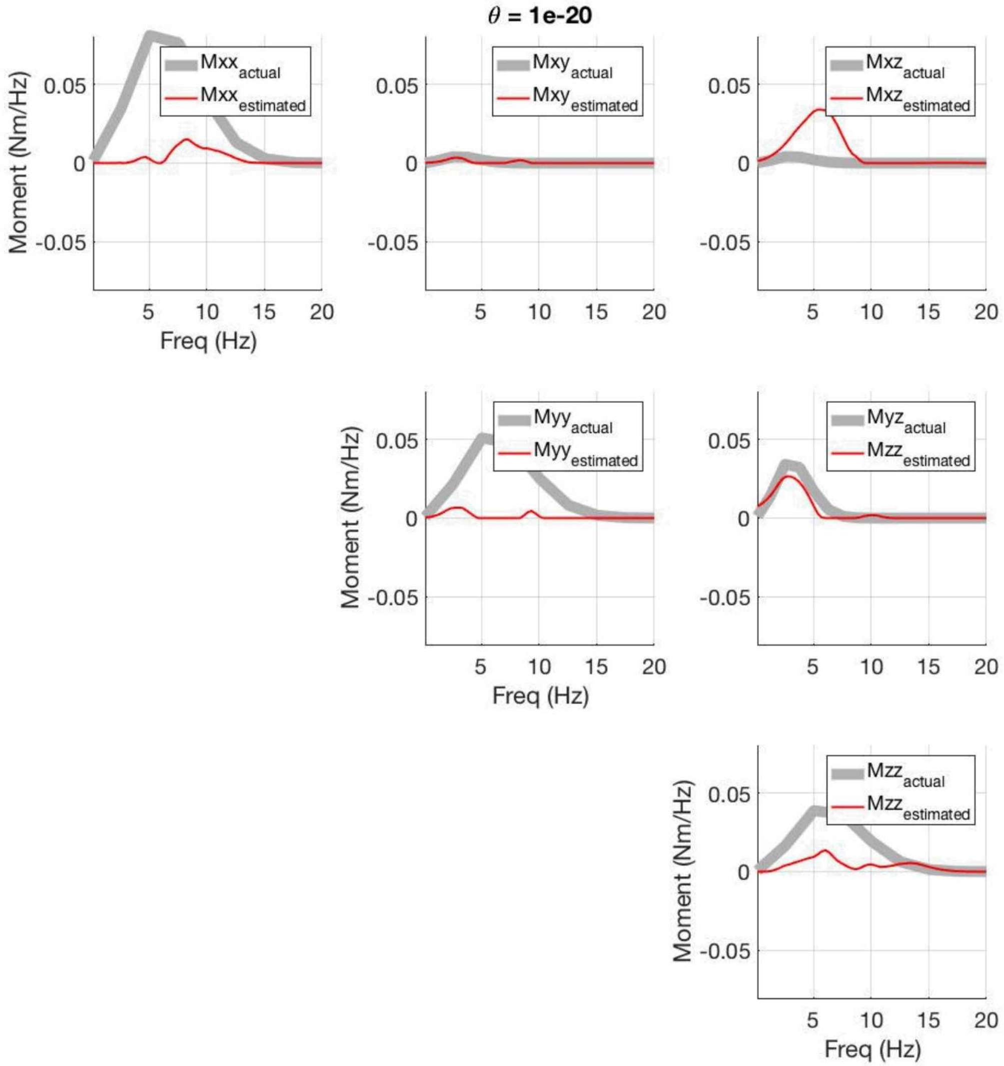


Amplitude Spectra-Only Inversion

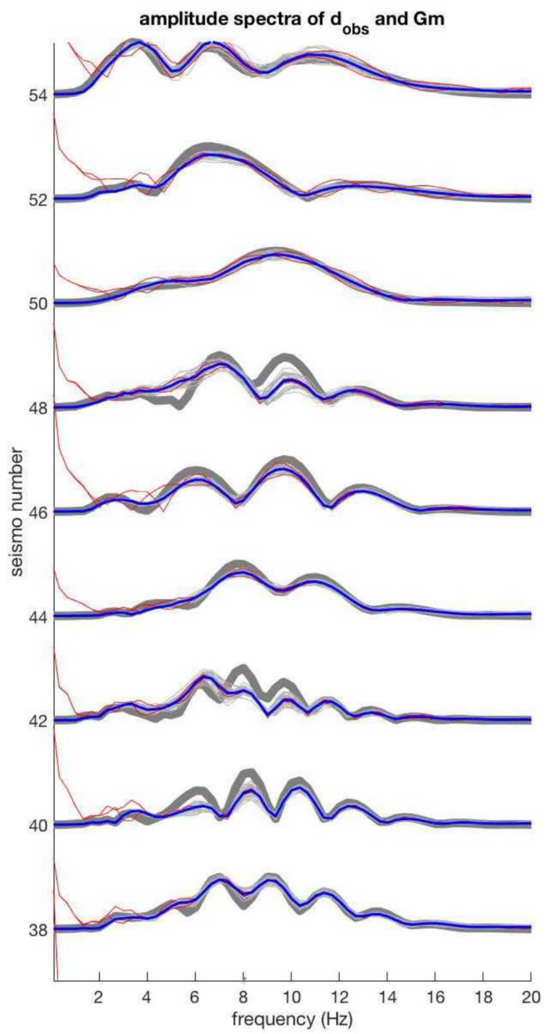


“Perfect” data

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

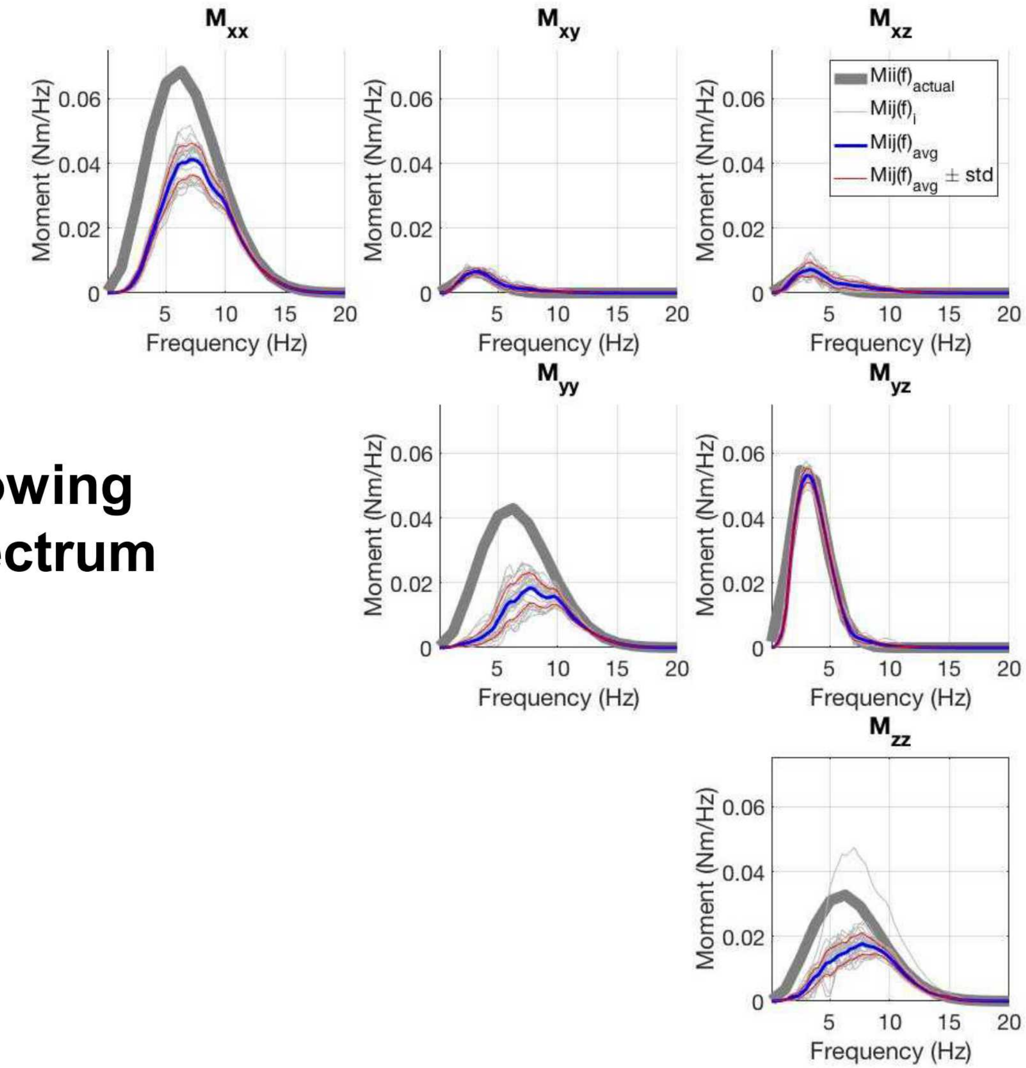


Monte Carlo Approach



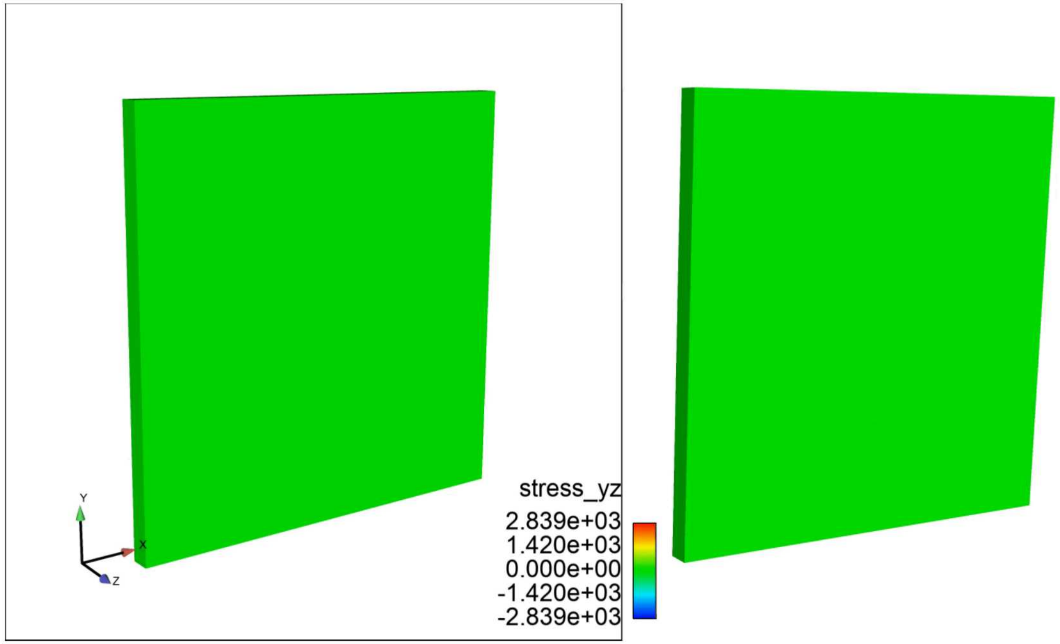
Full spectrum inversion, showing amplitude spectrum

30 Monte Carlo simulations



Near-Source Modeling Improvements

- **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**
- **Zapotec enables the analyst to use the best computational approach for different parts of multi-domain problems**



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

Summary

- Purely linear source models can match far-field waveforms from nonlinear sources and resemble Mueller-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 and explore more complex earth models