Defense Nuclear Nonproliferation Research & Development

Nuclear Explosion Monitoring Program Review

NEM 2019

Source modeling of SPE using acoustic and anisotropic simulators

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Sandia National Laboratories

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Source modeling of SPE using acoustic and anisotropic simulators (SPE Moving Media Acoustic)

The below content is required in each presentation.

Some slides may be extracted and used by NNSA to brief the ongoing portfolio. A consistent format will help that later effort.

- **Participating laboratories: Sandia National Laboratories, Lawrence Livermore National Laboratories**
- **Project overview, goals, technical approach, deliverables**
- **Description of capability improvement to be addressed by project success (relevant to the non-proliferation mission).**
- **Description of progress to date (results, findings, conclusions, ...)**
- **Where applicable, discussion of interaction with the nonproliferation, counter-proliferation, or counter-terrorism user community, user community interest, potential applications, and technology transfer opportunities and plans**
- **Technical challenges**
- **Future work for the remainder of the project Phase 1 modeling and inversion**

Goals of this Project

1. Incorporate three-dimensional atmospheric conditions to model the infrasonic wave field resulting from the SPE chemical explosions
2. Model the SPE infrasound data using first-order linear-equivalent source models
3. Determine the relative importance of assumed seismoacoustic sources
4. Investigate the impact of simplifying assumptions
5. Modeling and inversion using anisotropic assumptions

Technical Approach

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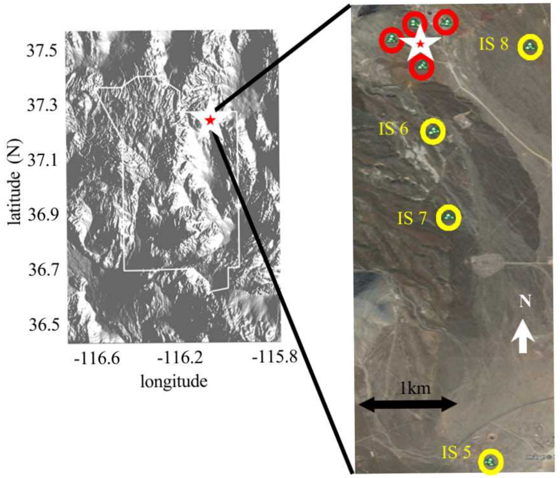
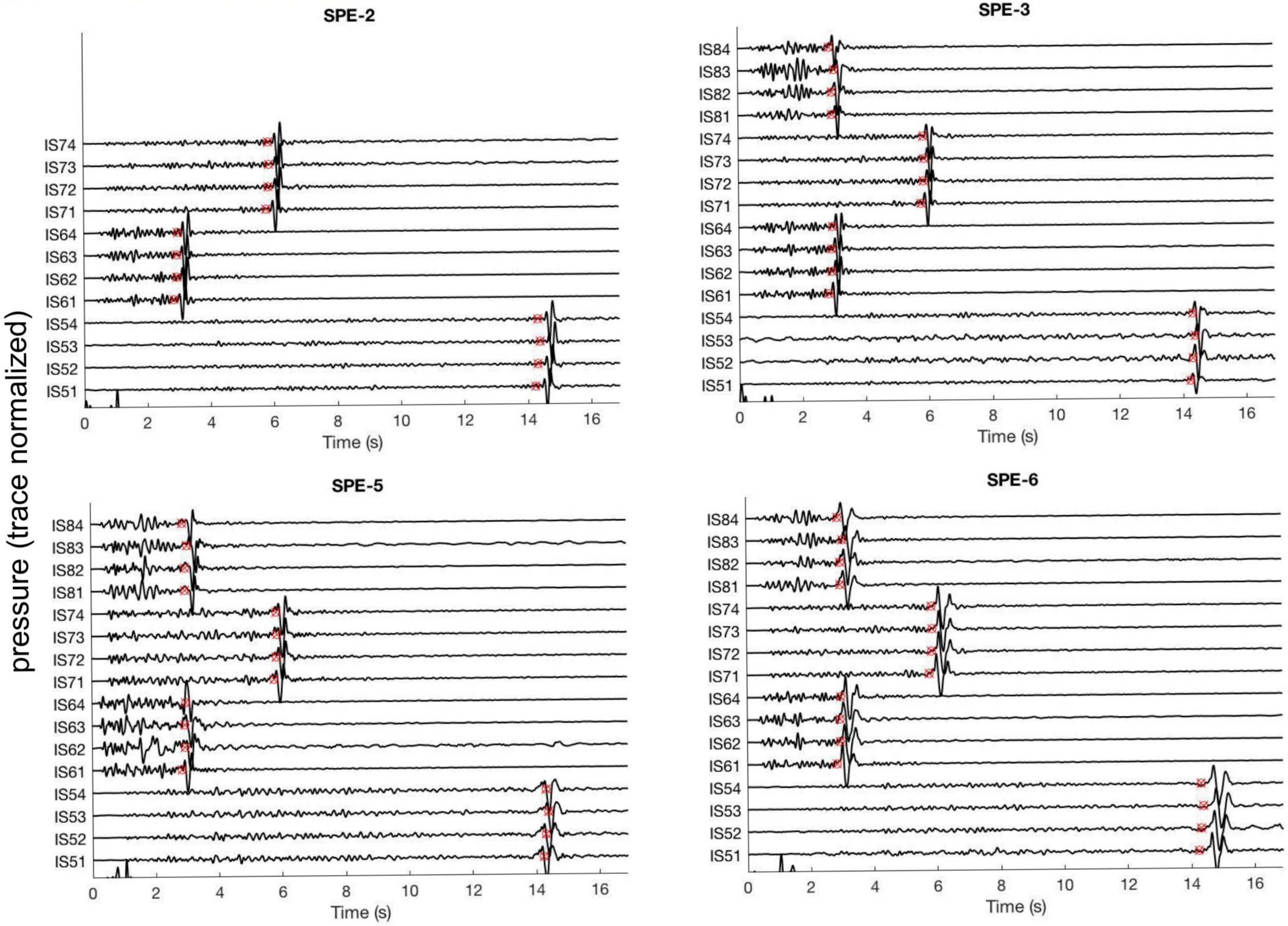
1. High resolution modeling of the acoustic wave field
    - three dimensional
    - incorporate regional and local weather observations
    - use wind and topography
    - allow for multiple source types

2. Least squares inversion of infrasound data for linear equivalent seismoacoustic source terms

3. Investigate the effects of simplifying assumptions in propagation model

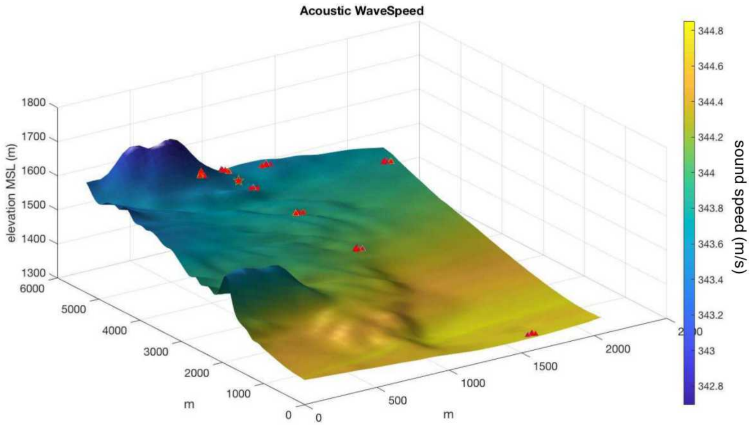
The Data

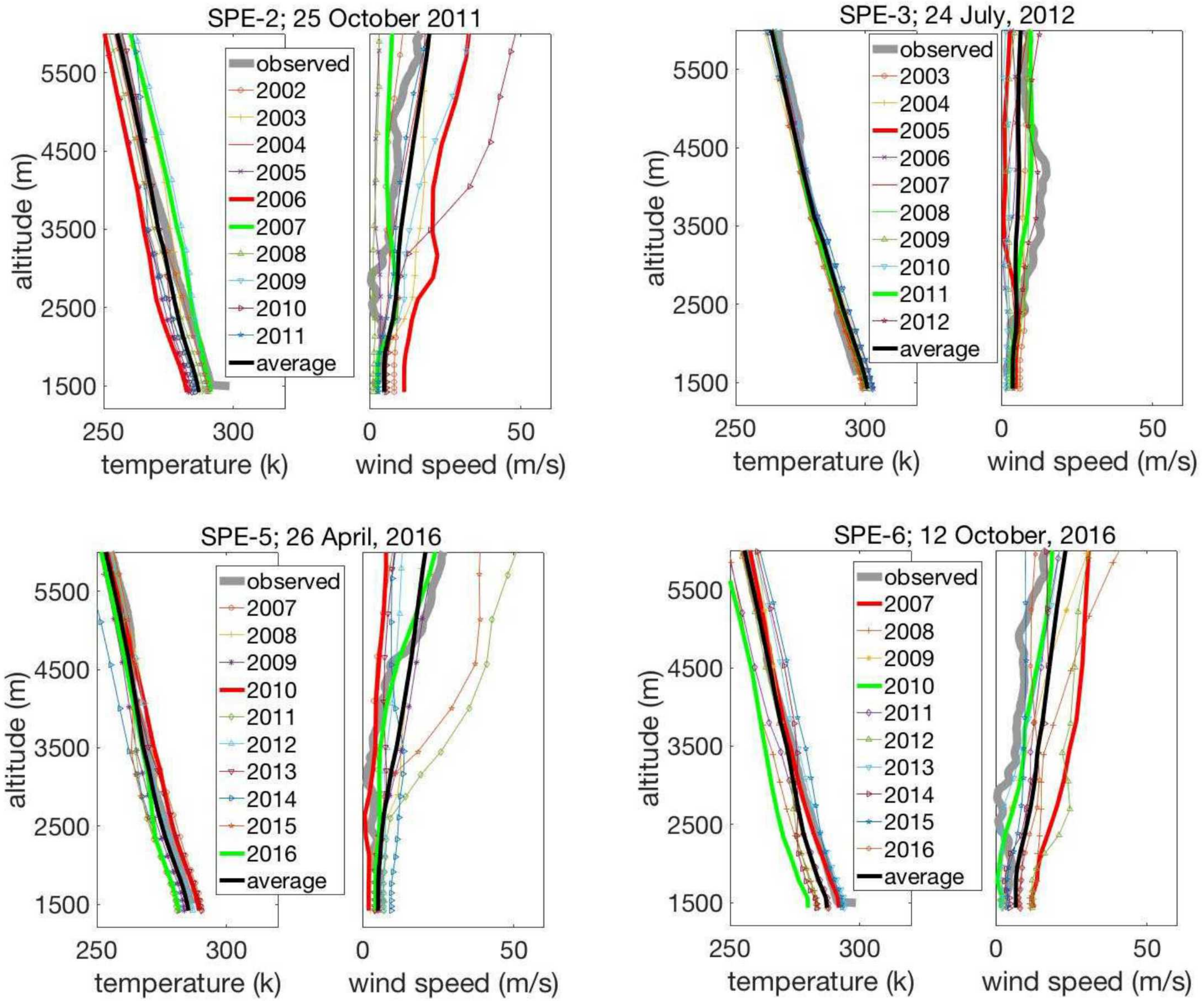

37.5
37.3
37.1
36.9
36.7
36.5
latitude (N)
-116.6
-116.2
-115.8
longitude
IS 8
IS 6
IS 7
IS 5
N
1km


SPE-2
SPE-3
SPE-5
SPE-6
pressure (trace normalized)
IS84
IS83
IS82
IS81
IS74
IS73
IS72
IS71
IS64
IS63
IS62
IS61
IS54
IS53
IS52
IS51
0
2
4
6
8
10
12
14
16
Time (s)

1) Incorporating Regional-Scale Weather Observations

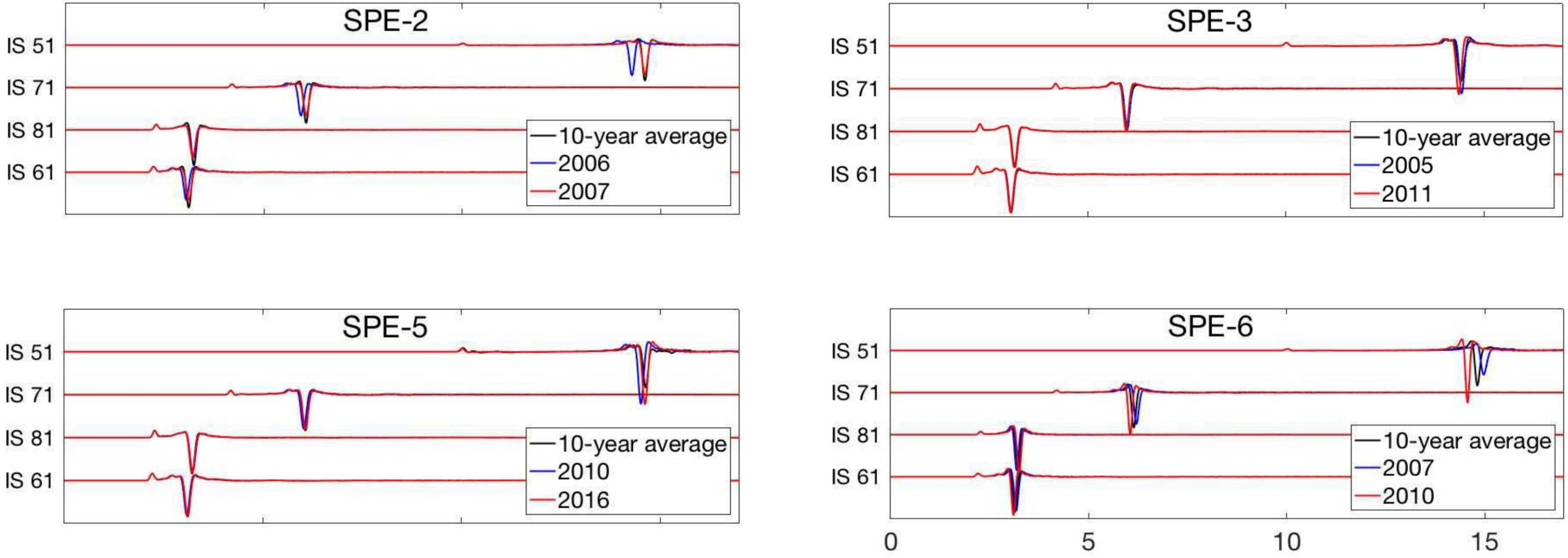
- Obtain regional-scaled weather data from National Center for Atmospheric Research (public)
  - date of experiment and the ten years prior
- Build 3D atmospheric models using Weather Research and Forecasting code
  - incorporates wind and topography
- Chose average and extrema
- Use Sandia-developed acoustic propagation code to simulate wave field





2) Acoustic Wave Modeling

- Modeled using Sandia-developed TDAAPS
- incorporates wind and topography
- average atmosphere and two extrema



3) relative importance of source model terms: inversion

- Invert infrasonic data for linear-equivalent seismoacoustic source terms, all three acoustic models

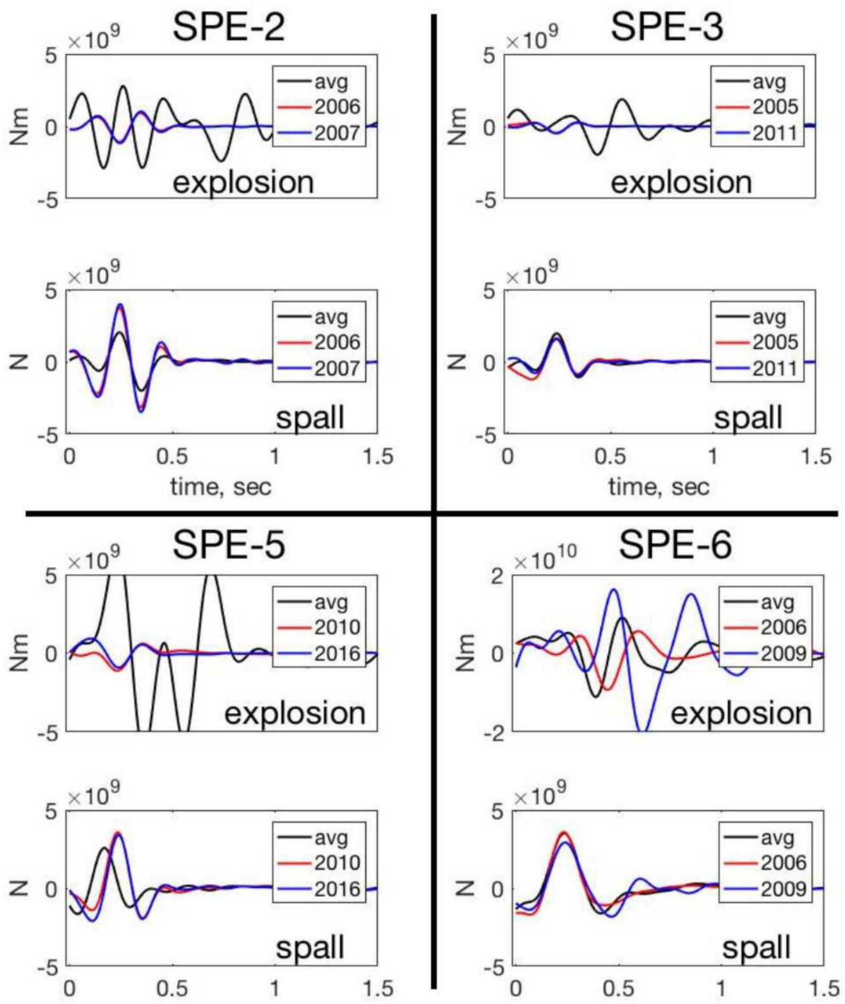
- In frequency domain:

$$u_j(f) = \sum_{i=1}^{N} G_{ij}(f) m(f)_i$$

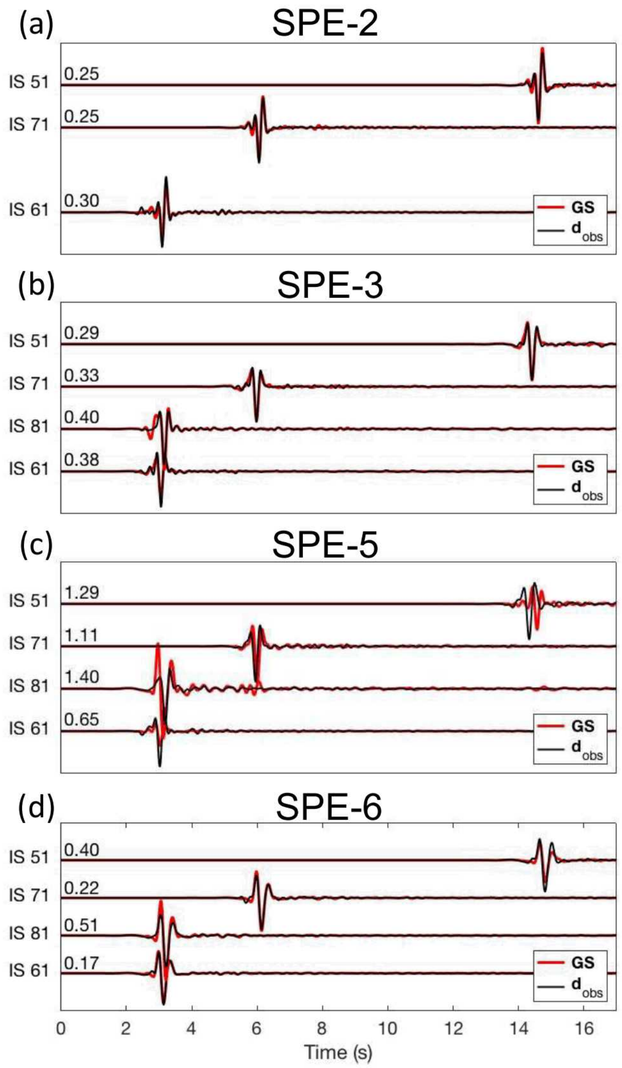
observed data — Green's functions — source terms

$$\mathrm{u} = \mathrm{Gm}$$

estimated source terms

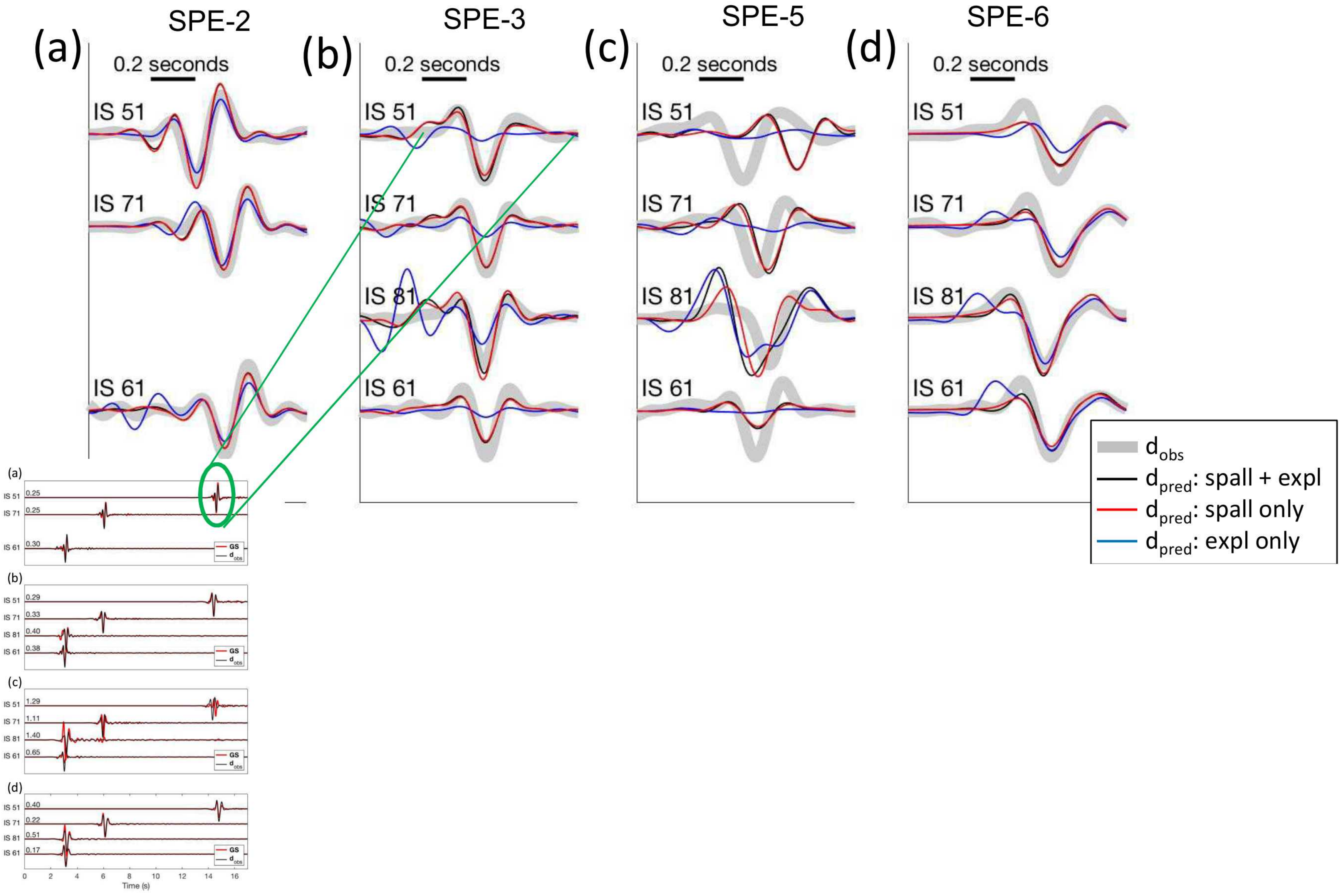


data fit



figures from Poppeliers et al. (2018), *Bull. Seis. Soc. Am.*, **109**(1) 463-475

3) relative importance of source model terms: inversion



- 98% of data can be explained using only a spall source model and the acoustic approximation seems to work
- Including a subsurface explosion term doesn't significantly improve fit to data
- Explosion-only source model
    - erratic, unstable STF estimate
    - the worst data fit

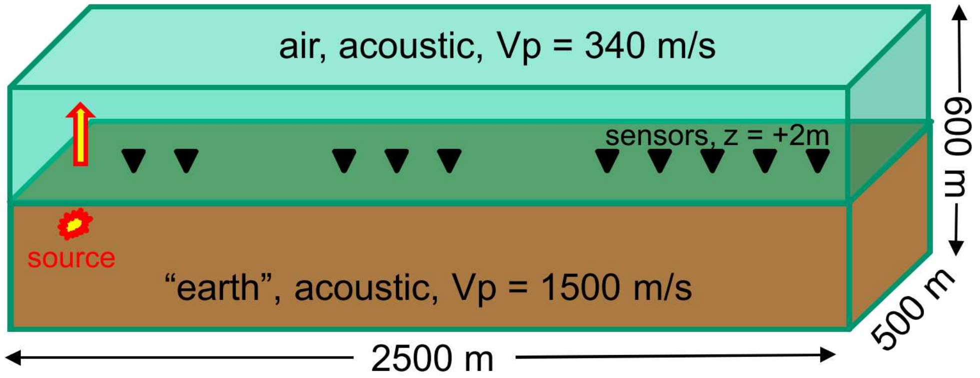
figures from Poppeliers et al. (2018), *Bull. Seis. Soc. Am.*, **109**(1) 463-475

4) investigate simplifying assumptions

Test by comparing waveforms and inversions from two simulation codes:

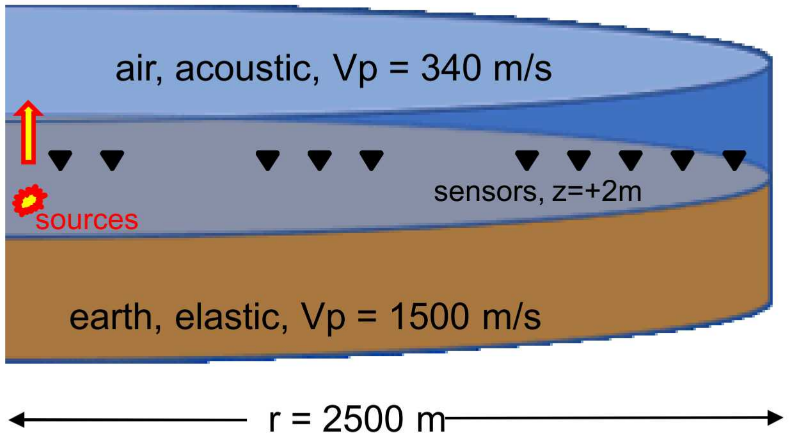
TDAAPS

- three dimensional
- acoustic throughout



axiElasti

- axially symmetric
- couples acoustic (air) with elastic (Earth)



Simulated wave field for each model: two source terms

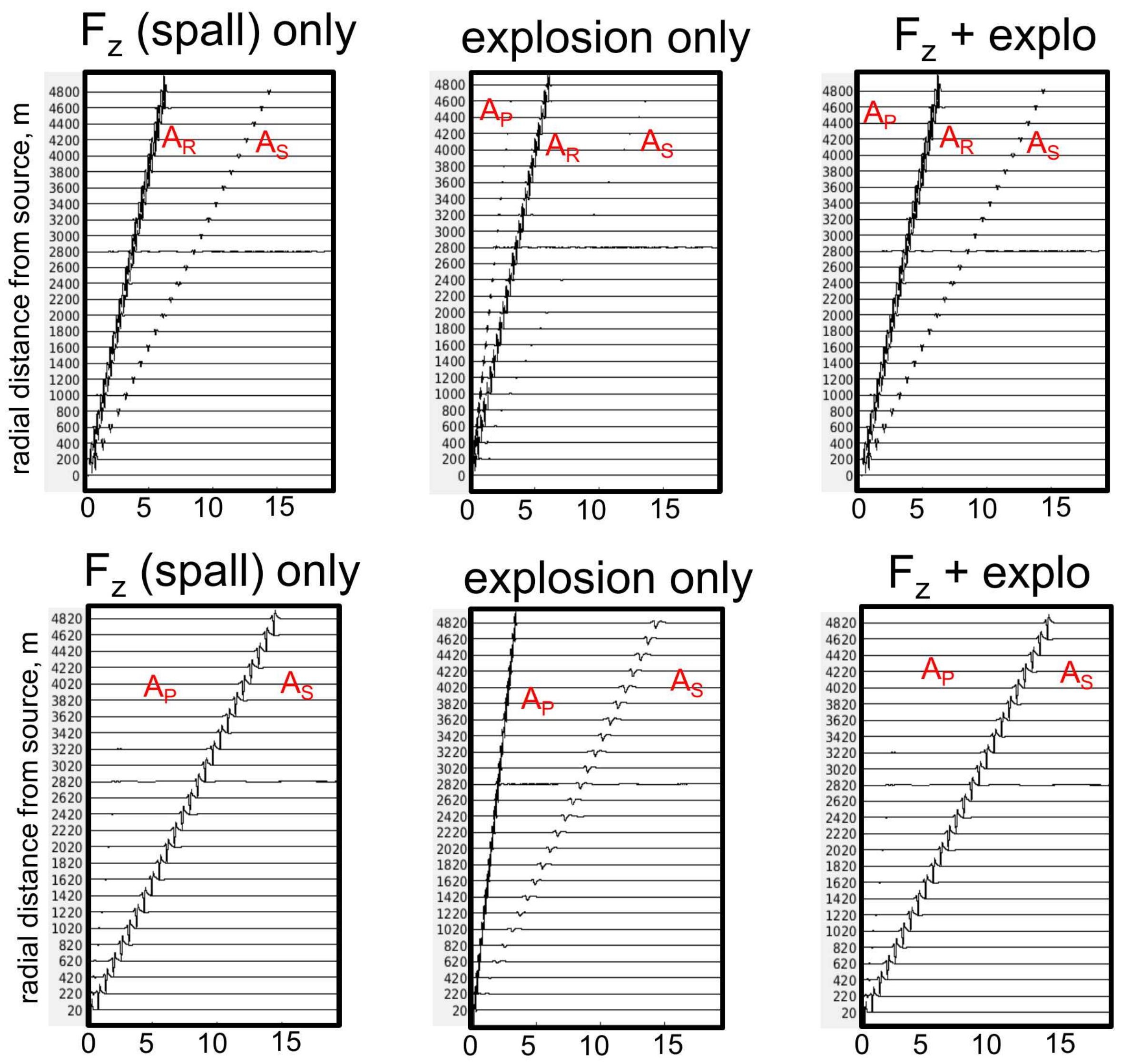
- isotropic explosion; z=-50 m
- spall is approximated by a vertical, upward-directed force; z=0 m
- unit amplitude for both
- all pressure receivers are located 2m above the ground surface (i.e. in air)

4) investigate simplifying assumptions

(displayed pressure traces formed by convolving the Greens functions with a 6Hz Gaussian)

axiElasti
(elastic + acoustic)

TDAAPS
(acoustic)



V_{Air} = 340 m/s
$V_{Raleigh}$ = 670 m/s
V_P = 1500 m/s

- TDAAPS (our current method) can not simulate surface waves
- Phase differences for spall-generated acoustic waves between two methods
  - due to elastic-to-acoustic coupling of P?
- phase and amplitude differences for explosion-generated acoustic waves
- spall source produces MUCH more far-field acoustic energy than explosion source

A_P: P to acoustic conversion at sensor
A_R: Rayleigh to acoustic conversion at sensor
A_S: Acoustic wave generated at source

4) investigate simplifying assumptions

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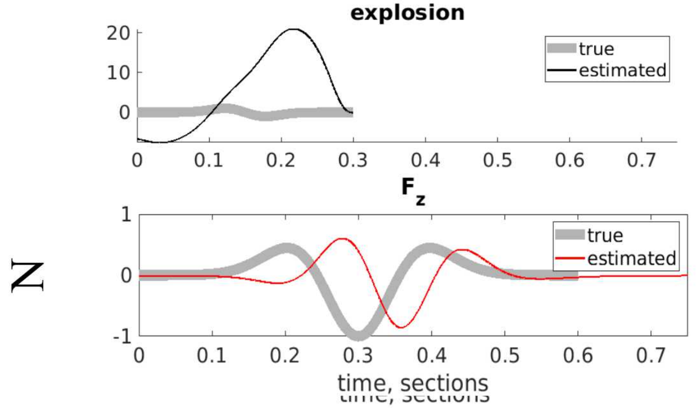
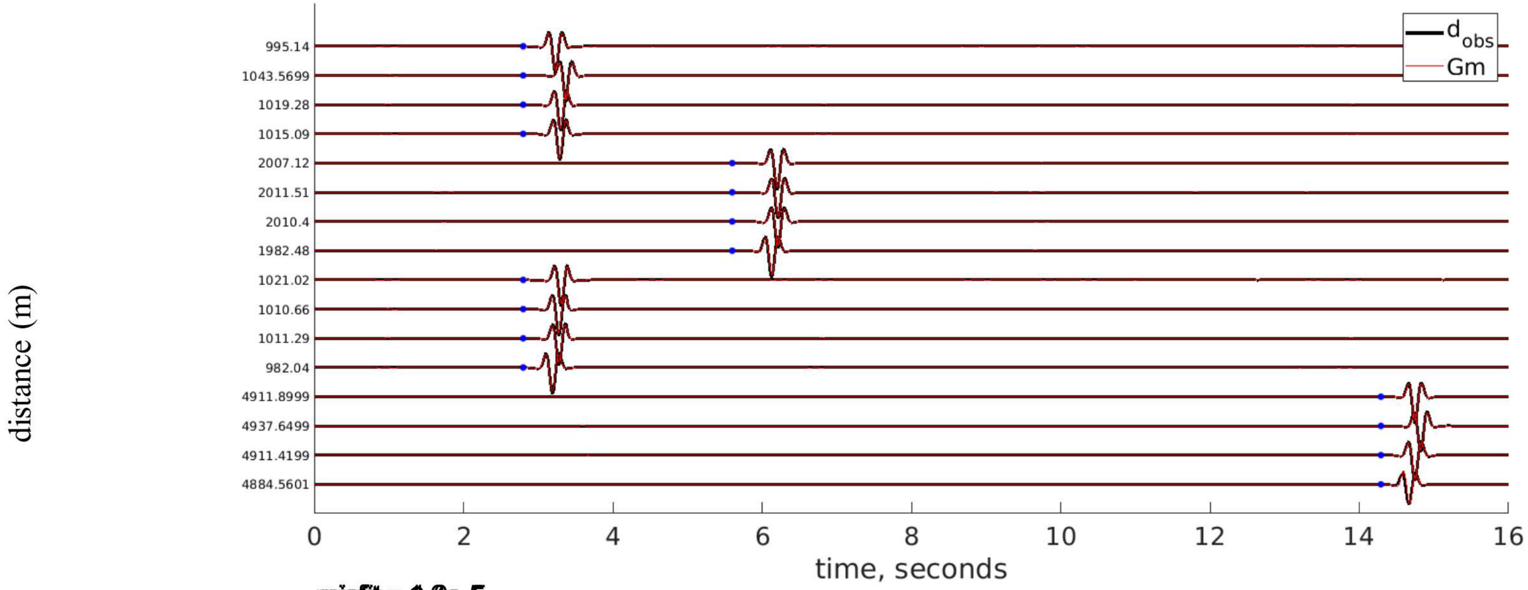
Case 3: F_z source model and mute A_P and A_R





misfit = 1.6e-5

For this test:

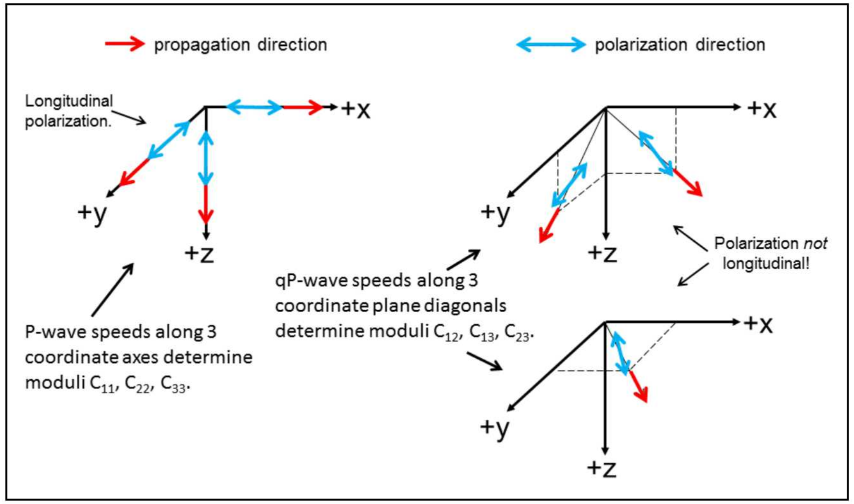
Data: acoustic-elastic
Greens functions: acoustic only

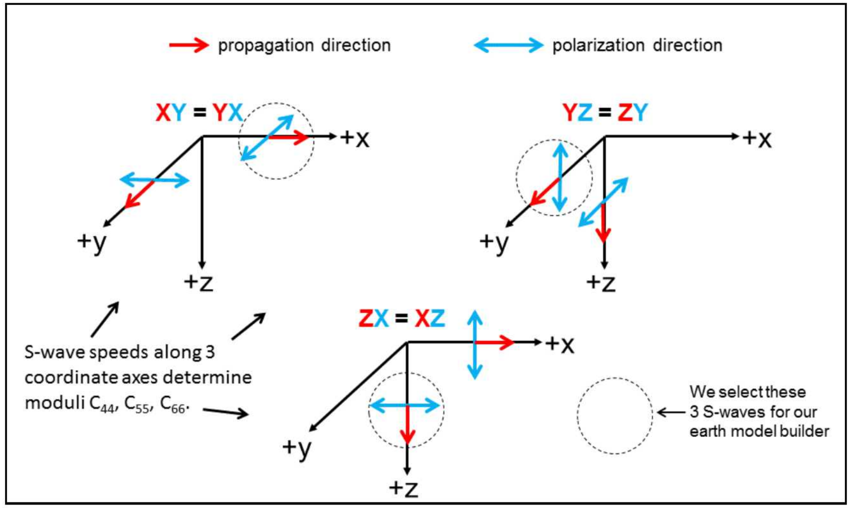
→The acoustoelastic data can be fit when using acoustic Greens functions!

- the estimated explosion term is widely inaccurate, regardless of source model,
- the dual-source data can be well fit using only the F_z source term
- the data fit is better when muting elastic effects

5) Anisotropic modeling and inversion

- Earth is anisotropic in terms of seismic velocities
- Create anisotropic models based on field observables
- Estimate Green's functions
- Invert as before





Standard TI and VF+TI Models

(after Schoenberg and Helbig, 1997)

	VTI	VF+TI	ISO
$c_P(\mathbf{n}=\mathbf{e}_1;\mathbf{p}=\mathbf{e}_1)$	3500	3320	3500
$c_P(\mathbf{n}=\mathbf{e}_2;\mathbf{p}=\mathbf{e}_2)$	3500	3472	3500
$c_P(\mathbf{n}=\mathbf{e}_3;\mathbf{p}=\mathbf{e}_3)$	2711	2697	3500
$c_S(\mathbf{n}=\mathbf{e}_1;\mathbf{p}=\mathbf{e}_2)$	1917	1635	1565
$c_S(\mathbf{n}=\mathbf{e}_2;\mathbf{p}=\mathbf{e}_3)$	1565	1565	1565
$c_S(\mathbf{n}=\mathbf{e}_3;\mathbf{p}=\mathbf{e}_1)$	1565	1400	1565
$c_P(\mathbf{n}=\mathbf{n}_{12};\mathbf{p}\perp\mathbf{e}_3)$	3500	3264	3500
$c_P(\mathbf{n}=\mathbf{n}_{23};\mathbf{p}\perp\mathbf{e}_1)$	3023	3001	3500
$c_P(\mathbf{n}=\mathbf{n}_{31};\mathbf{p}\perp\mathbf{e}_2)$	3023	2845	3500

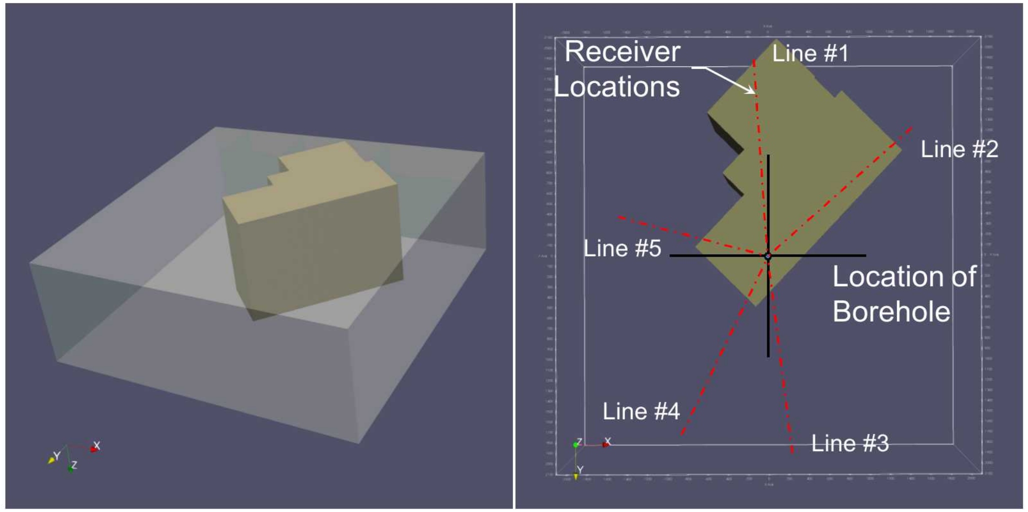
The wavespeeds

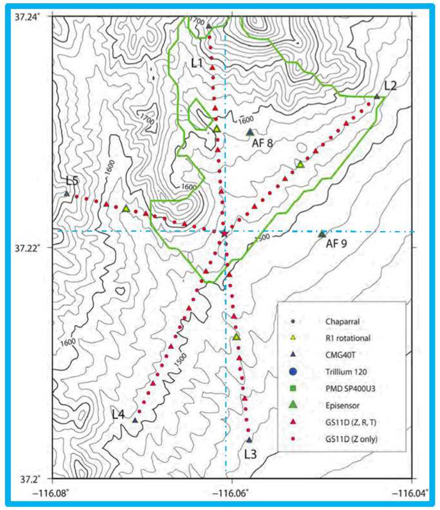
The density-normalized modulus tensor (m^2/s^2)

Mathematics!

$$A_{IJ}=\begin{bmatrix} 9 & 3.6 & 2.25 & 0 & 0 & 0 \\ 3.6 & 9.84 & 2.4 & 0 & 0 & 0 \\ 2.25 & 2.4 & 5.9375 & 0 & 0 & 0 \\ 0 & 0 & 0 & 2 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1.6 & 0 \\ 0 & 0 & 0 & 0 & 0 & 2.182 \end{bmatrix}.$$

5) Anisotropic modeling and inversion





Seismic model building:

- Based on 2D tomographic profiles
- No published anisotropy models of site
- 2101 x 2101 x 703 grid points at a 2 m grid point spacing
- Free-surface boundary along X-Y plane at z=0 m.
- Absorbing boundary conditions
- Source is wholly located within a granite inclusion, assumed to be surrounded by alluvium.

Inversion of seismic data using anisotropic forward model

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The inversion: linear assumption

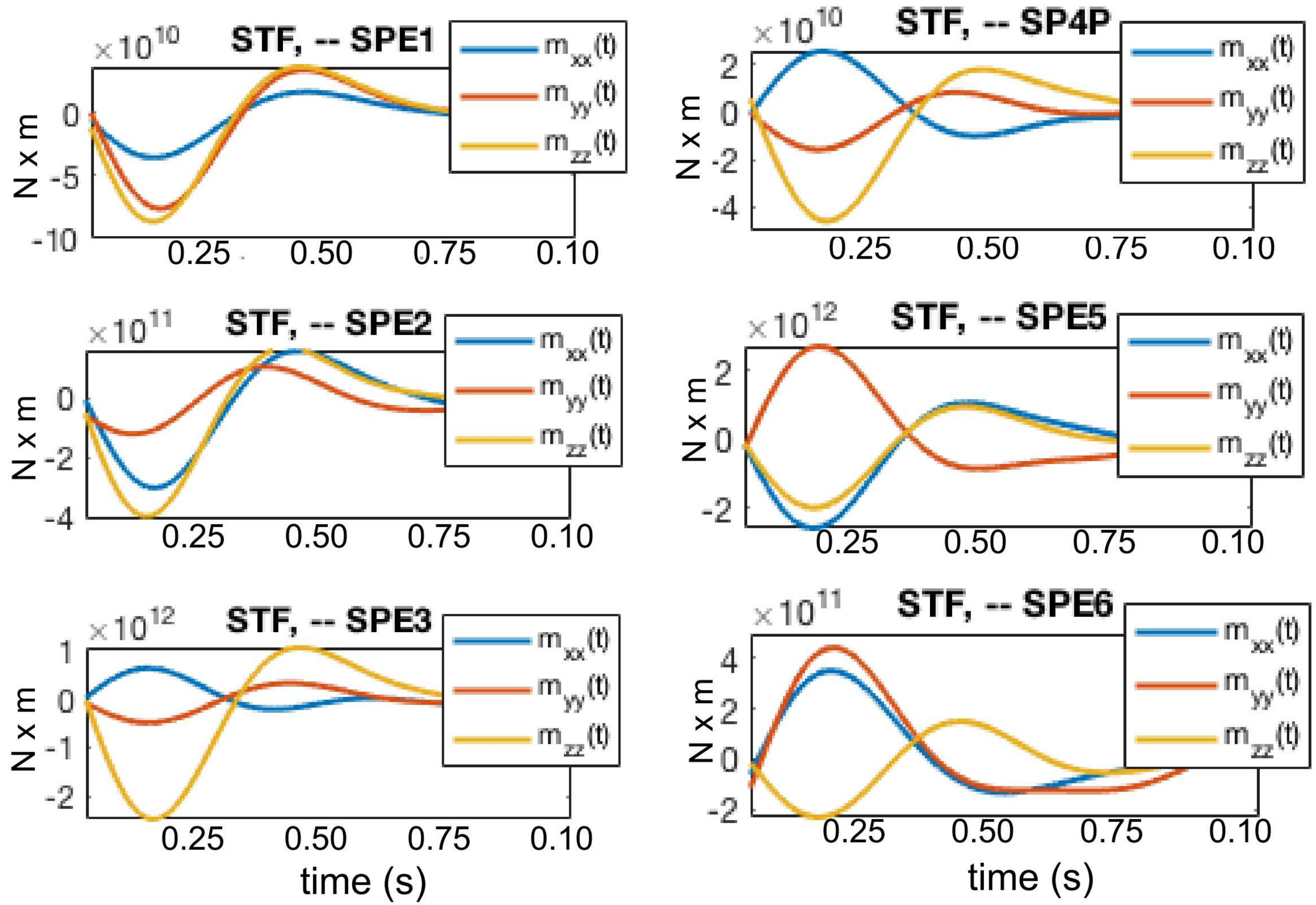
$$\mathrm{u} = \mathrm{Gm}$$

The model: explosion source but not necessarily isotropic

$$\begin{bmatrix} M_{xx}(t) & 0 & 0 \\ 0 & M_{yy}(t) & 0 \\ 0 & 0 & M_{zz}(t) \end{bmatrix}$$

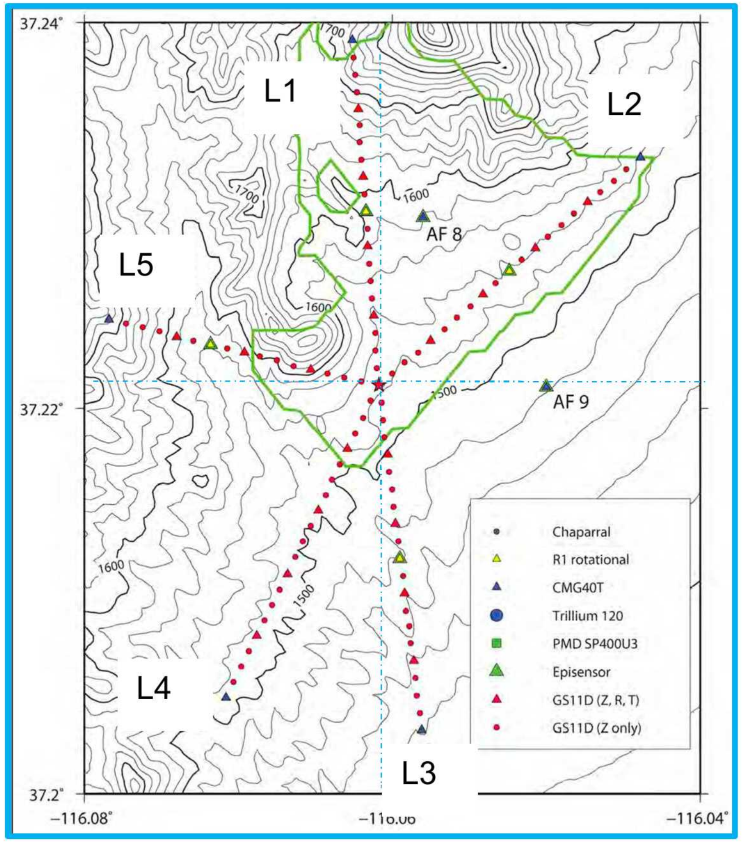
Inverted all seismograms simultaneously

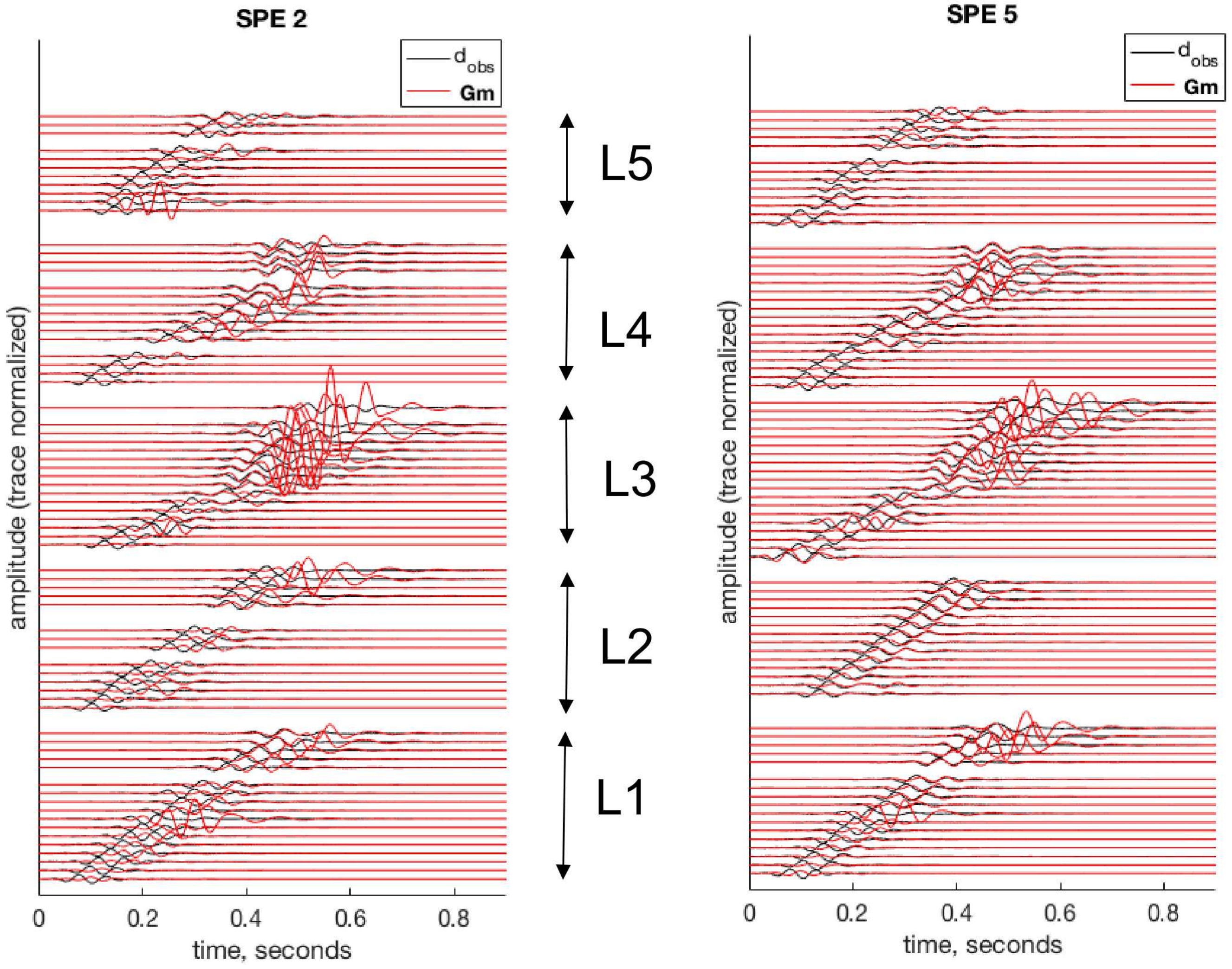
RESULTS



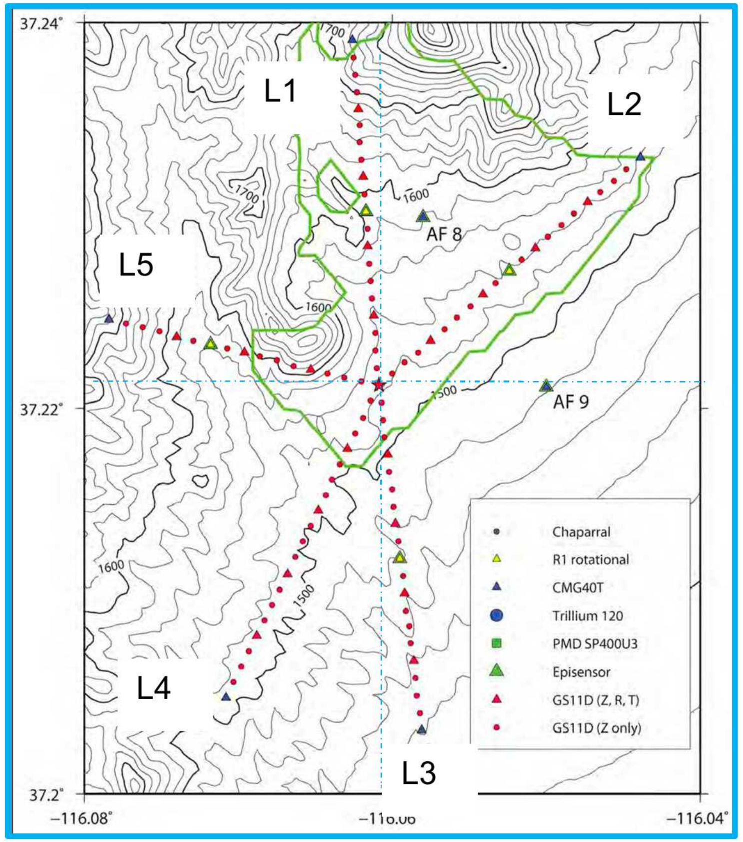
Inversion of seismic data using anisotropic forward model

FIT TO DATA (two examples)





Inversion of seismic data using anisotropic forward model



Results:

- The polarity of recovered source time functions should be the same but aren't
- The absolute amplitude of the estimated source time functions scale roughly with source energy
- The data fit is generally poor
  - SPE-5 is the best
  - SPE-4P is the worst
  - Line 2 is the best
  - Line 3 is the worst

Summary

- Progress to Date and Capability Improvements
  - Developed method to model the atmosphere using publically available, regional scale data
    - can forego on-site meteorological measurements
  - Verified that acoustic models are sufficient to analyze SPE infrasound data (seismoacoustic source)
    - simplified modeling can reduce analysis time
  - Spall source model describes ~98% of the infrasound data.
    - implies the need to link source energy to spall deformation
  - Demonstrable effects of seismic anisotropy on the analysis of the seismic source

- Application to nonproliferation mission
  - Simplifying assumptions of source and propagation model may be adequate to evaluate first-order source attributes of explosion-induced infrasound signals
  - Can reduces decision time for relevant stake holders

Summary

- Technical Challenges
  - Infrasound analysis
    - Incorporating elastic-acoustic coupling for full, three dimensional seismoacoustic wave field modeling
    - Incorporation of formal uncertainty estimates into forward models and inversion results
  - Anisotropic analysis
    - No published anisotropy models of SPE site
    - Improve velocity models to be fully three dimensional

- Future Work
  - Incorporate on-site atmospheric measurements for infrasound analysis
    - Verify that regional scaled atmospheric data is adequate for source inversions
  - Refine three dimensional velocity models for improved anisotropic analysis