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A comparison between predicted and observed atmospheric states and their effects on infrasonic source time function inversion at Source Physics Experiment 6

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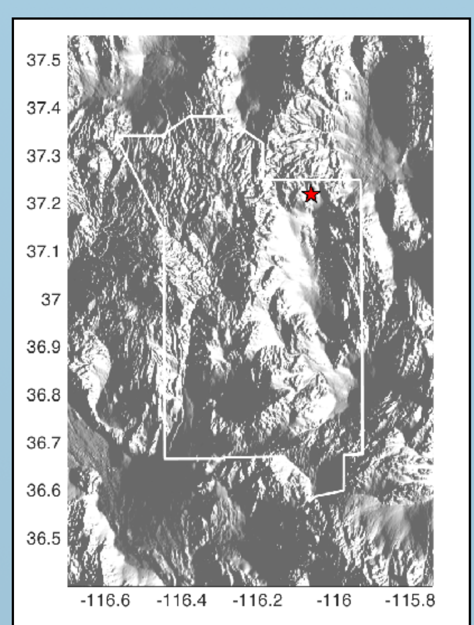
Abstract

The Source Physics Experiment (SPE) consists of a series of underground chemical explosions at the Nevada National Security Site (NNSS) designed to gain an improved understanding of the generation and propagation of physical signals in the near and far field. Characterizing the acoustic and infrasound source mechanism from underground explosions is of great importance to underground explosion monitoring. To this end we perform full waveform source inversion of infrasound data collected from the SPE-6 experiment at distances from ~300 m to ~6 km and frequencies up to 20 Hz. Our method requires estimating the state of the atmosphere at the time of each experiment, computing Green's functions through these atmospheric models, and subsequently inverting the observed data in the frequency domain to obtain a source time function. To estimate the state of the atmosphere at the time of the experiment, we utilize the Weather Research and Forecasting – Data Assimilation (WRF-DA) modeling system to derive a unified atmospheric state model by combining Global Energy and Water Cycle Experiment (GEWEX) Continental-scale International Project (GCIP) data and locally obtained sonde and surface weather observations collected at the time of the experiment. We synthesize Green's functions through these atmospheric models using Sandia's moving media acoustic propagation simulation suite (TDAAPS). These models include 3-D variations in topography, temperature, pressure, and wind. We compare inversion results using the atmospheric models derived from the unified weather models versus previous modeling results and discuss how these differences affect computed source waveforms with respect to observed waveforms at various distances.

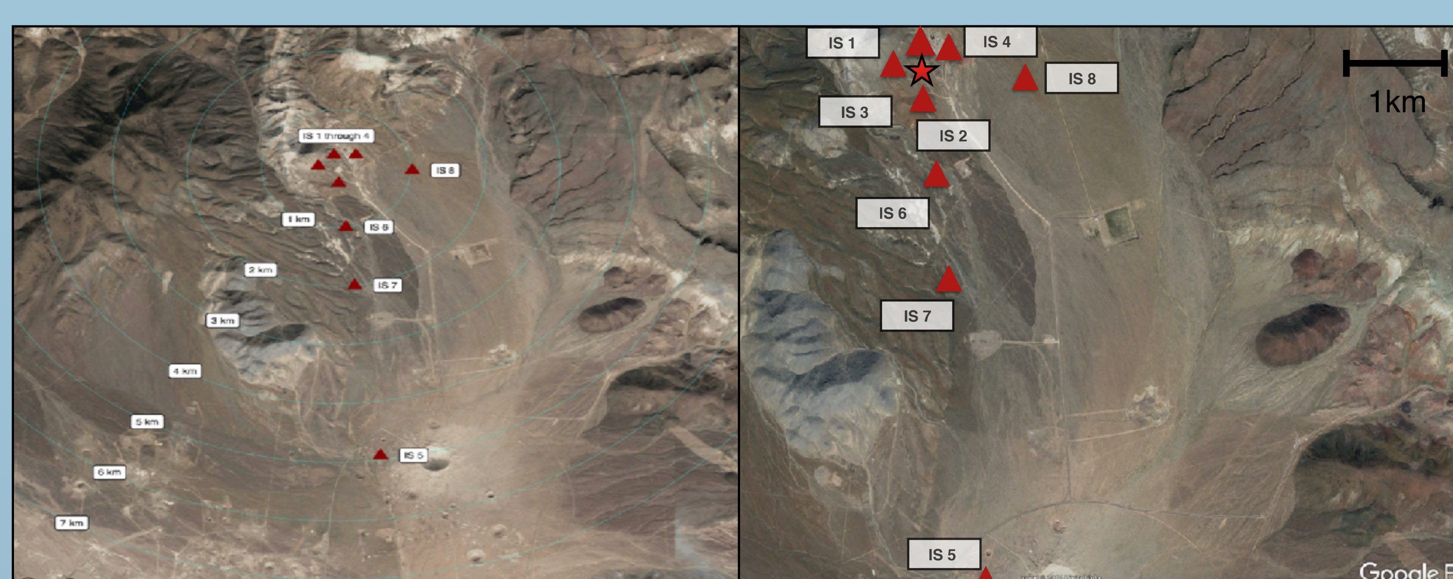
Experiment Design



Left: Overview map of the SPE experiment showing the outline of NNSS, with the location of the experiment indicated by the star.

Below Left: Far-field view of the eight infrasound array stations deployed during the SPE experiment. Infrasound sensors were placed 200m to 5 km from the experiment epicenter. Each array comprises 4 Hyperion sensors connected with four porous hoses approximately 30m apart. Circles denote distances between the various arrays and the experiment epicenter [*Figure: Preston et.al, 2016*].

Below Right: Expanded view of the local SPE experiment area. The surface location of the source is indicated by the star and the infrasound sensor arrays are indicated by triangles. Note the hill located to the NW of the source point and topography dropping off to the SE [*Figure: Google Earth*].



All SPE experiments to date are located at 37.2212°N, 116.0609° W. The SPE-6 source depth of burial was 31.4m, and had a yield of 2245 kg.

Method

Forward Model
Linearize the problem by naively assuming a "linear equivalent source":

$$\hat{u}(\vec{x},t) = \underbrace{-M_0 w(t)}_{\text{STF}} * \underbrace{g_{ij}\,\delta(\vec{x}-\vec{x}_0)}$$

$$g = \underbrace{\begin{pmatrix} M_{xx} & 0 & 0 \\ 0 & M_{yy} & 0 \\ 0 & 0 & M_{zz} \end{pmatrix}}_{\substack{\text{acoustic: isotropic explosion} \\ M_{xx}=M_{yy}=M_{zz}}} + \underbrace{\begin{pmatrix} F_x \\ F_y \\ F_z \end{pmatrix}}_{\text{vector force terms}}$$

Greens Function Calculation

- Obtain atmospheric conditions from the National Center for Atmospheric Research data archive (rda.ucar.edu) using the GCIP NCEP Eta model output
  - Use the WRF-DA (Weather Research and Forecasting - Data Assimilation) algorithm to predict the 3-D atmospheric conditions at the time of the experiment
  - To estimate the Greens functions through the atmosphere, we simulate an explosive source (isotropic moment tensor) by emplacing a delta function at the source location and then use Sandia's moving media acoustic full waveform simulation algorithm, TDAAPS (*Symons et al., 2005*)

Inversion Procedure

- Manually picked the acoustic arrival on the observed waveform data, which in all cases is within the seismic coda coupled to the infrasound sensor (see waveforms in right panel)
- Mute pre-arrival data in order to remove as much of the confounding seismic energy as possible
- Observed data are then resampled to match the time sampling of the synthetic Greens function; convert to the frequency domain
- Predicted data is given by:

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

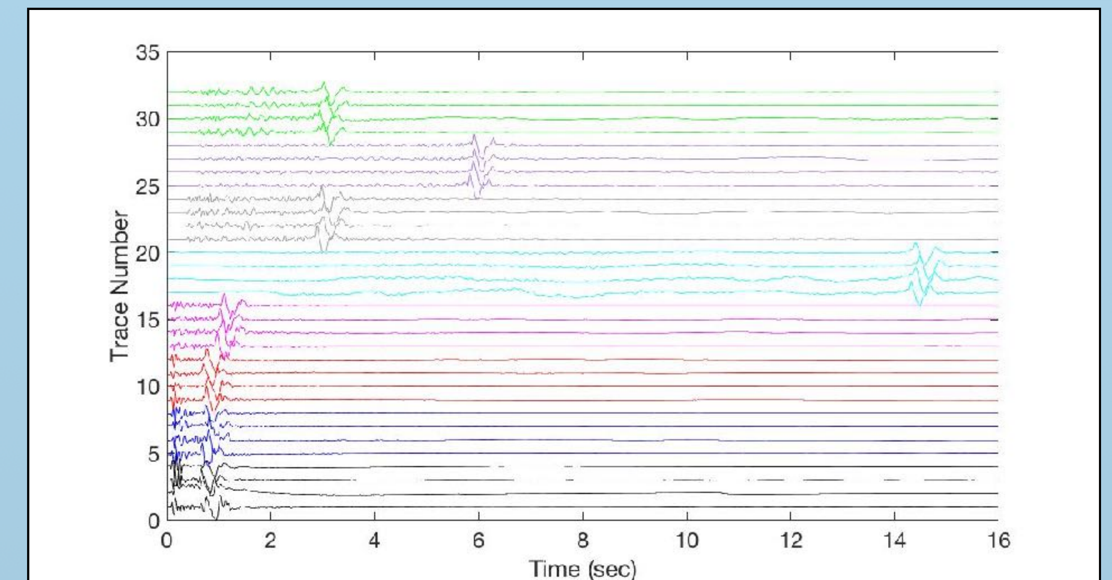
- Invert for the amplitude and phase spectrum of the source time function; can specify the number of source types
- Convert results to the time domain and convolve the estimated source time functions with the synthetic Greens functions to compare to the observed data

References

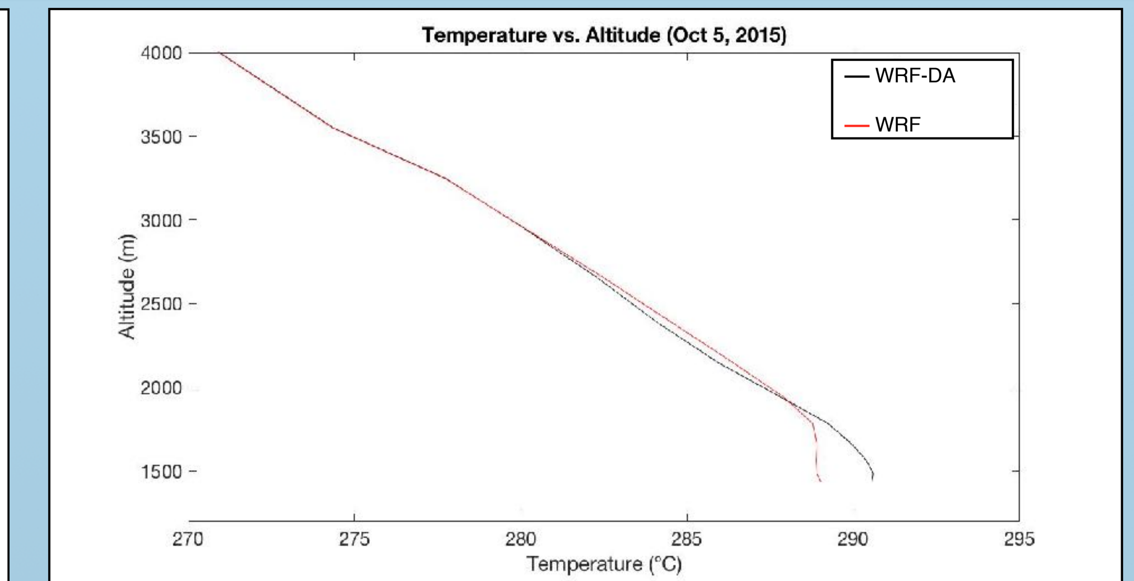
Preston, L, Bowman, D.C., Waxler, R., Whitaker, R., Jones, K.R., Albert, S., Aur, K.A., *The acoustic signature of underground chemical explosions during the Source Physics Experiment*, Poster Presentation, Vienna, Austria, 2016.

Symons, N.P., D.F. Aldridge, D.H. Marlin, S.L. Collier, D.K. Wilson, V.E. Ostashev, *Staggered-Grid Finite-Difference Acoustic Modeling with the TimeDomain Atmospheric Acoustic Propagation Suite (TDAAPS)*, Sandia National Laboratories,SAND2006-2540, 2005.

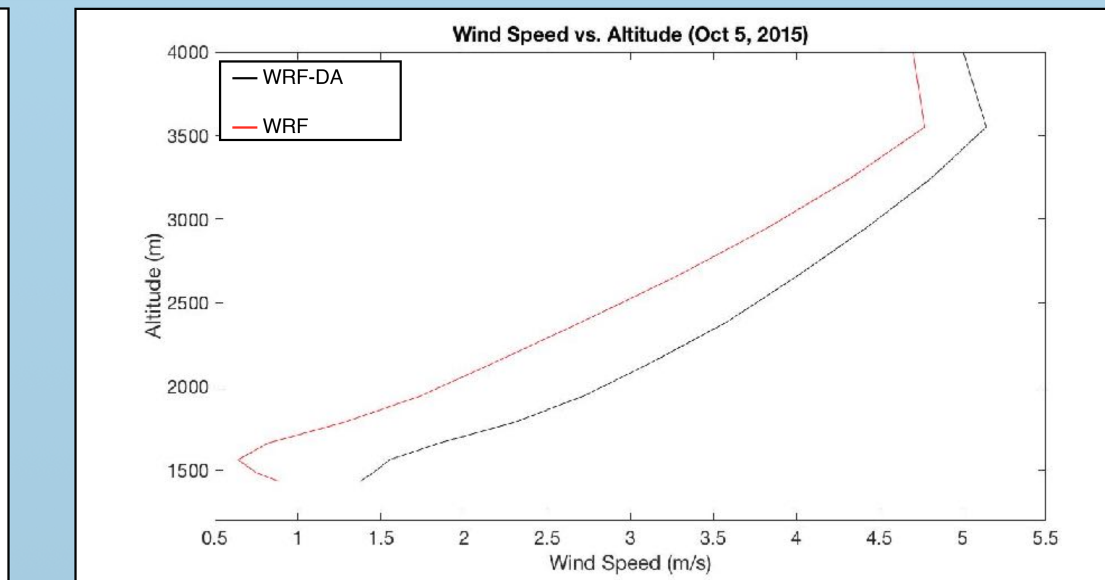
SPE-6 Observations



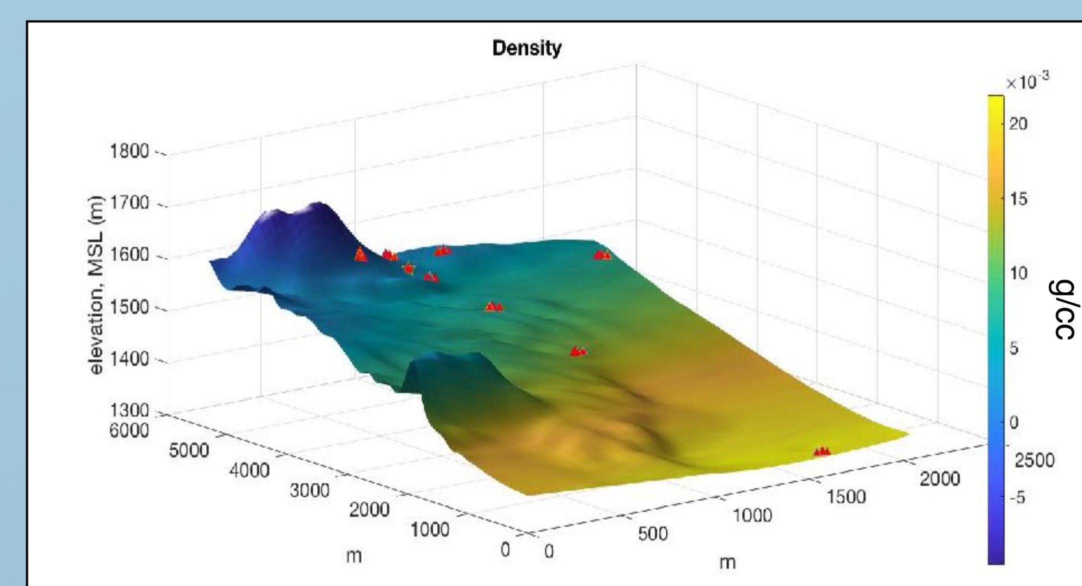
Observed acoustic waveforms as a function of array (varying colors correspond to arrays, array 1 (bottom), array 8 (top)); amplitudes are normalized to unity



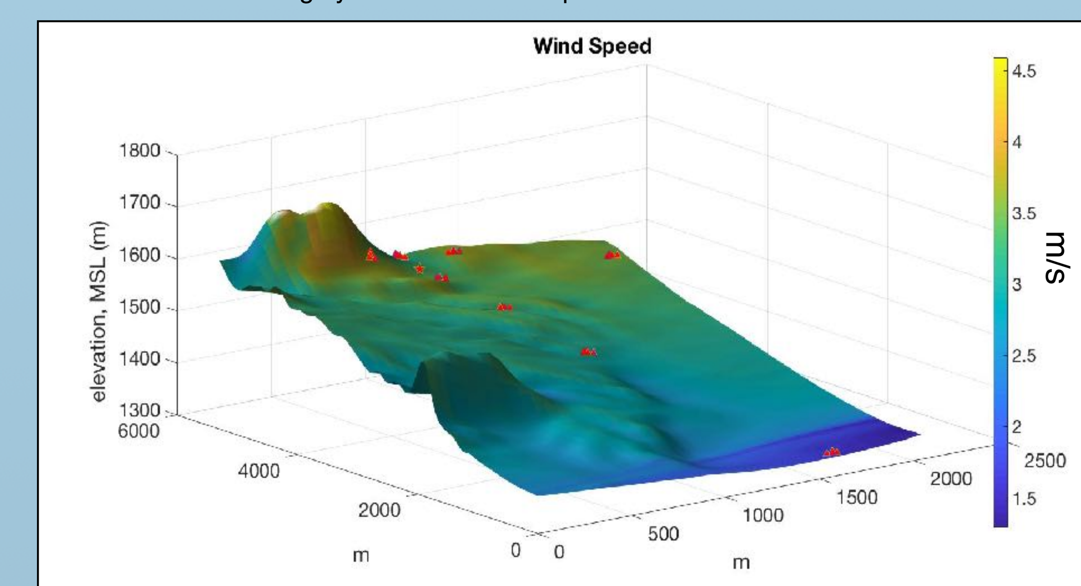
Weather observations from WRF-DA (black) vs. WRF (red) showing temperature as a function of altitude. WRF-DA incorporates local sonde observations into predictions whereas WRF utilizes regional, low resolution data. Sonde data were measured near the source location at roughly the time of the experiment.



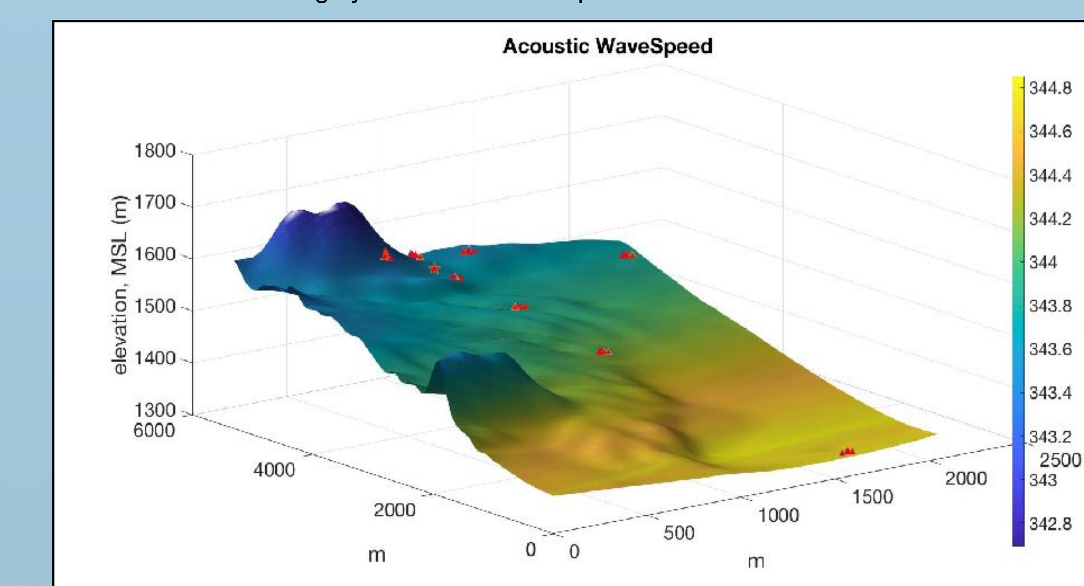
Weather observations from WRF-DA (black) vs. WRF (red) showing wind speed as a function of altitude. WRF-DA incorporates local sonde observations into predictions whereas WRF utilizes regional, low resolution data. Sonde data were measured near the source location at roughly the time of the experiment.



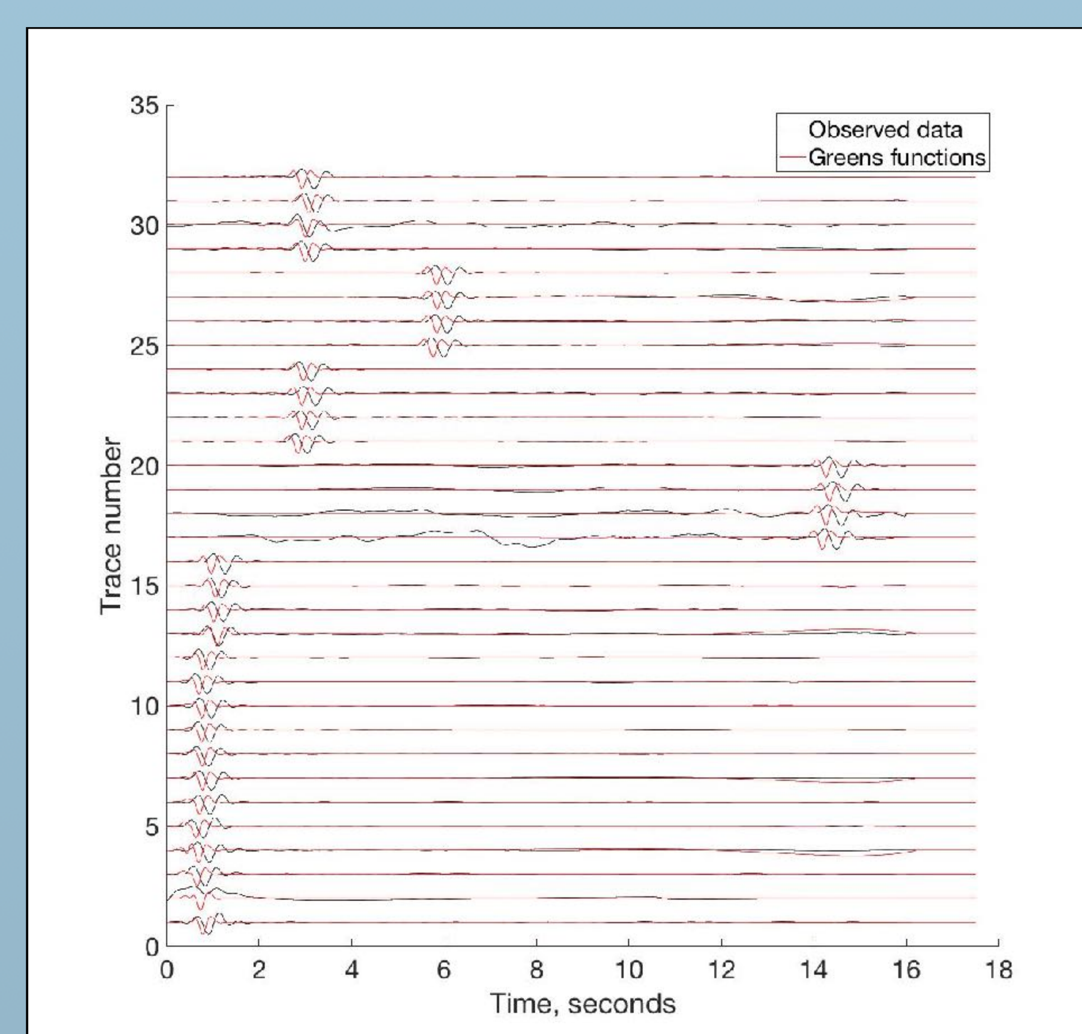
WRF-DA output displaying atmospheric density (g/cc). Red triangles denote acoustic sensors, while red star denotes



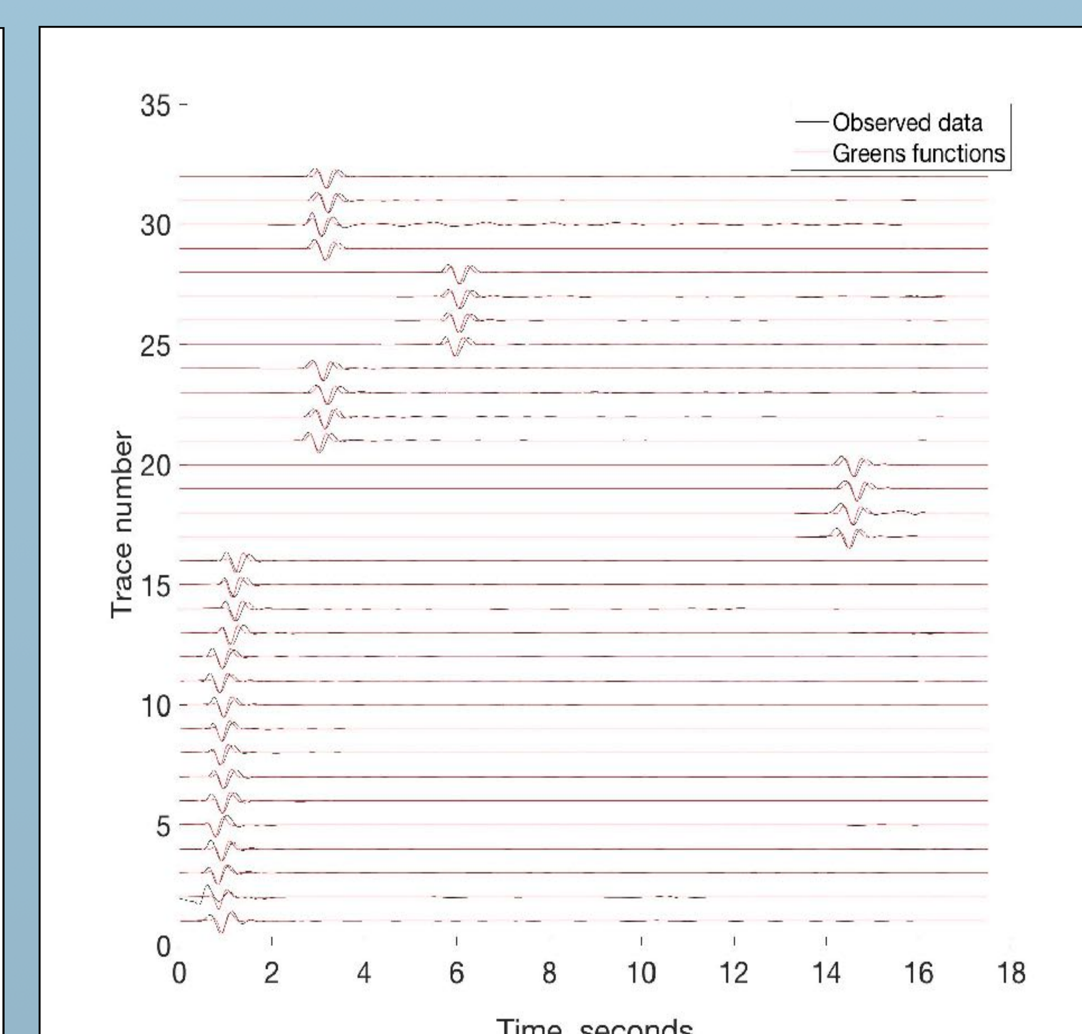
WRF-DA output displaying wind speed (m/s). Red triangles denote acoustic sensors, while red star denotes source location



WRF-DA output displaying acoustic wavespeed (m/s). Red triangles denote acoustic sensors, while red star denotes source location for SPE-6 experiment.



Red: Simulated Greens Functions constructed utilizing the atmospheric model shown above. Black: Observed acoustic data (filtered), seismic arrivals are not muted. Note that there is a slight timing misfit between the observed acoustic arrivals and the Greens



Red: Simulated Greens Functions constructed utilizing the atmospheric model shown above. The Greens functions are manually shifted to align first acoustic arrivals. Black: Observed acoustic data (filtered), seismic arrivals are muted.

Discussion

- Developed methodology to use WRF-DA to predict 3-D atmospheric state in order to generate Greens Functions corresponding to the experiment time
- Timing of synthetic acoustic arrivals are similar to observed acoustic arrivals
- STF inversion includes full moment tensor as well as force terms
- Apply this method to previous SPE experiments

Acknowledgements

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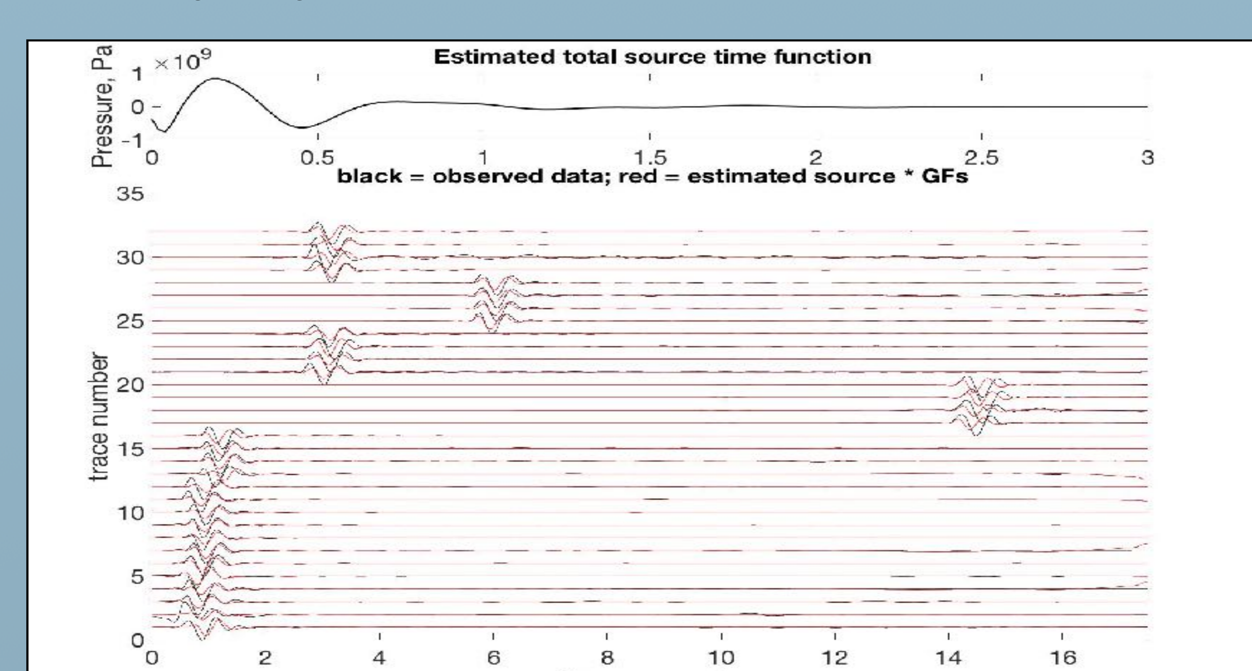
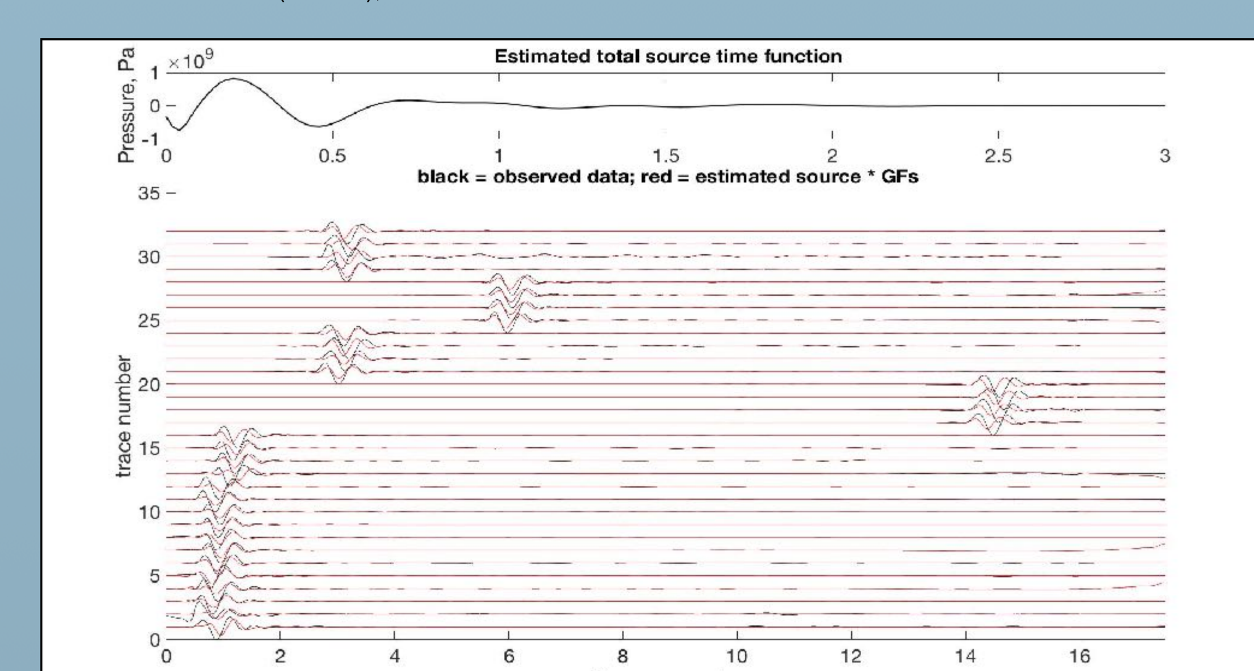
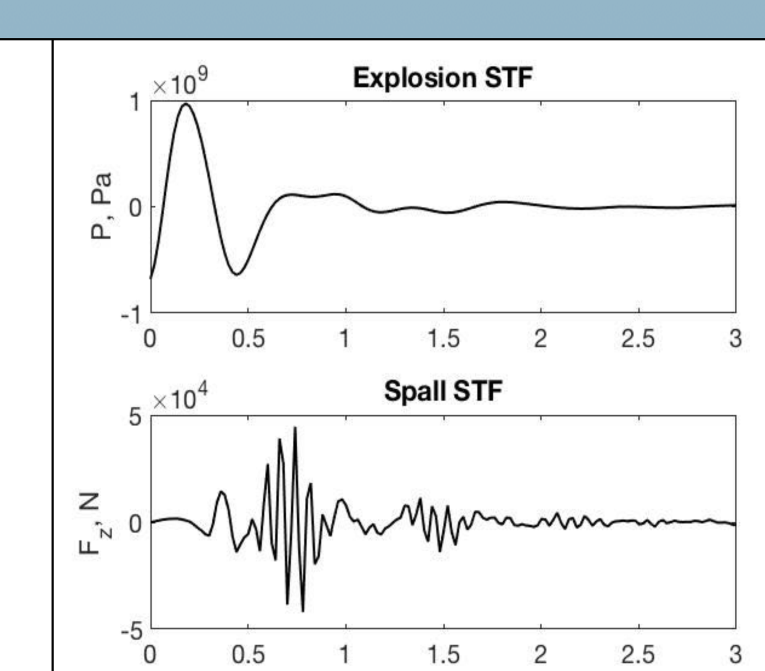


Top: Estimated source time function (STF) utilizing a single isotropic explosion model. Bottom: Black: Observed muted, filtered data, Red: Synthetic data constructed by convolving STF with simulated Greens Functions.





Left Top: Estimated source time function (STF) utilizing an isotropic explosion and a vertical force simulating spall. Left Bottom: Black: Observed muted, filtered data, Red: Synthetic data constructed by convolving STF with simulated Greens Functions. Right Top: Estimated explosion STF (unfiltered). Right Bottom: Estimated spall STF (unfiltered).