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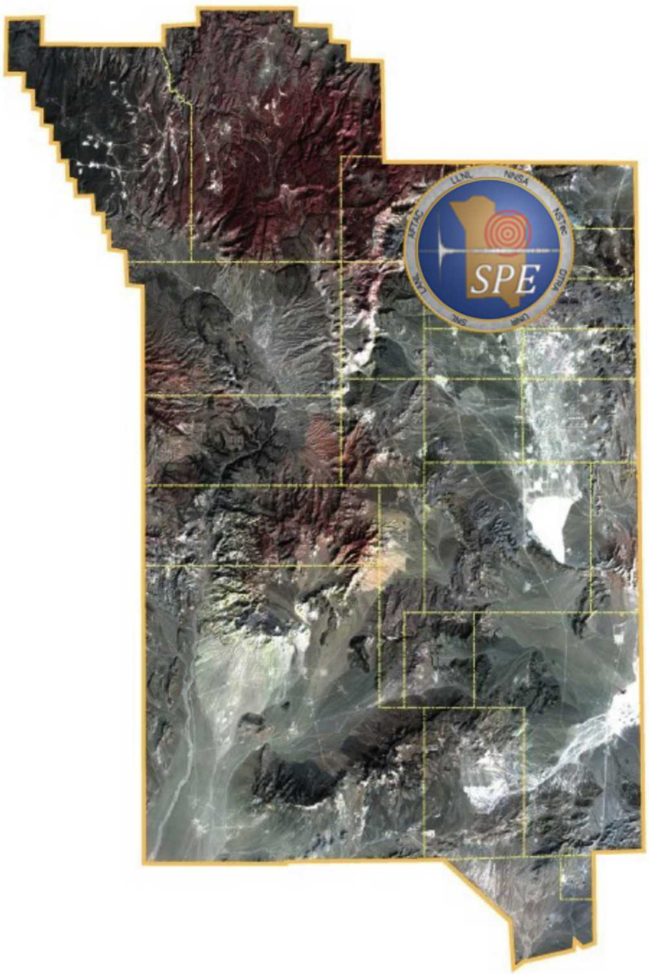
SAND2016-7051PE

The Source Physics Experiment at the



Coupling Near-Field to Infrasound

July 27, 2016

Kyle R. Jones [SNL]
Danny Bowman [SNL]
Leiph Preston [SNL]
Stephen Arrowsmith [SNL]
Rod Whitaker [LANL]
Artie Rodgers [LLNL]
Souheil Ezzedine [LLNL]
Roger Waxler [NCPA]

NNSA · NSTec · NCPA Atmospheric Acoustics · Lawrence Livermore National Laboratory · Los Alamos National Laboratory EST. 1943 · Sandia National Laboratories · NEVADA

Agenda

- Introduction
- Overall Motivation
- Infrasound at DPRK
- SPE Infrasound Observations
- SPE Infrasound Modeling
- DOB vs. Yield Tradeoff
- Pushing the Envelope
- Future Plans
- Conclusion

Motivation

- With nuclear tests conducted underground, infrasound can tell us something about DOB (too deep, no surface motion and no infrasound)
- Compared to EQs of same magnitude, UGTs have larger infrasound amplitudes and shorter durations
- Cost-effective measure
- By recording infrasound on tests such as SPE, we gain source knowledge necessary for event characterization and yield estimation at greater distances

Motivation (Contd.)

- Recordings close-in provide a way to "observe" the waveform before transmission through the atmosphere (know what we are starting with)
- Infrasound signal propagation is variable due to dynamic nature of the atmosphere and can be accounted for with atmospheric specifications (G2S and ECMWF)
- Infrasound is the primary IMS technology for atmospheric explosion detection

Infrasound From DPRK Testing

2013 & 2016 detected at I45RU and I30JP (Assink et al GRL 2016)

2013 test:

- Good SNR at I45
- Weak detection at I30

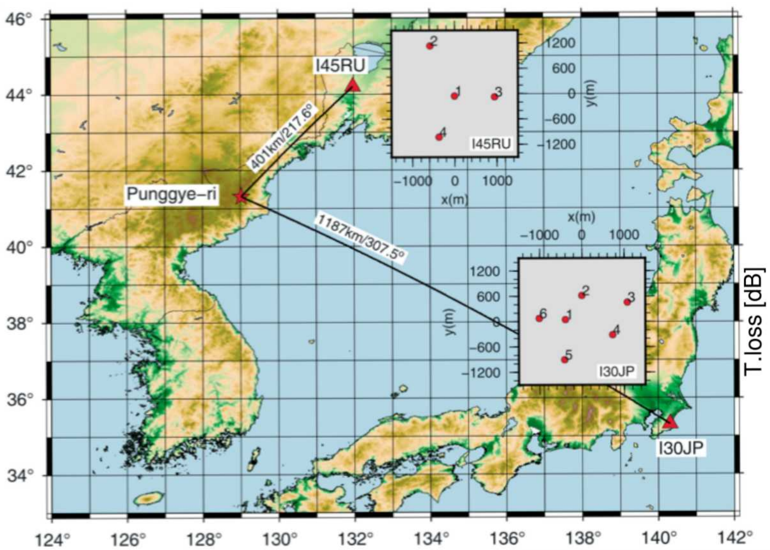
2016 test

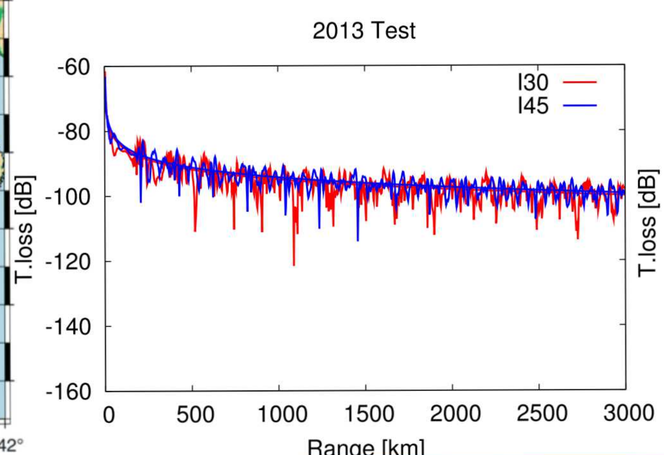
- Weak detections on both stations

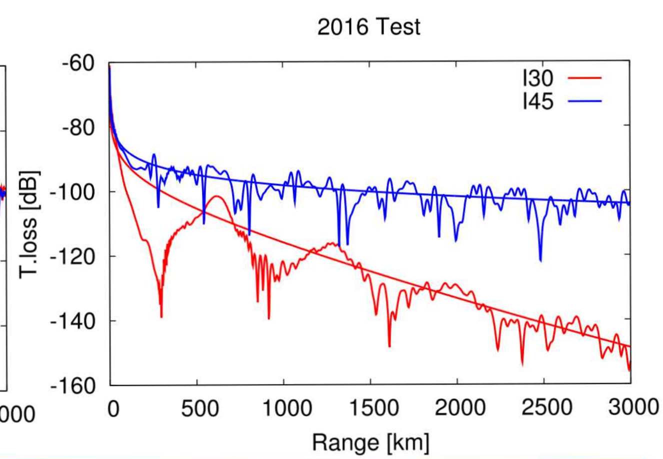
Depth estimate for the 2016 shot?

- Comparing seismic to acoustic signals

- The detections of the 2013 event were clearer, presumably due to shallower depth of the test and better atmospheric conditions for propagation and detection.

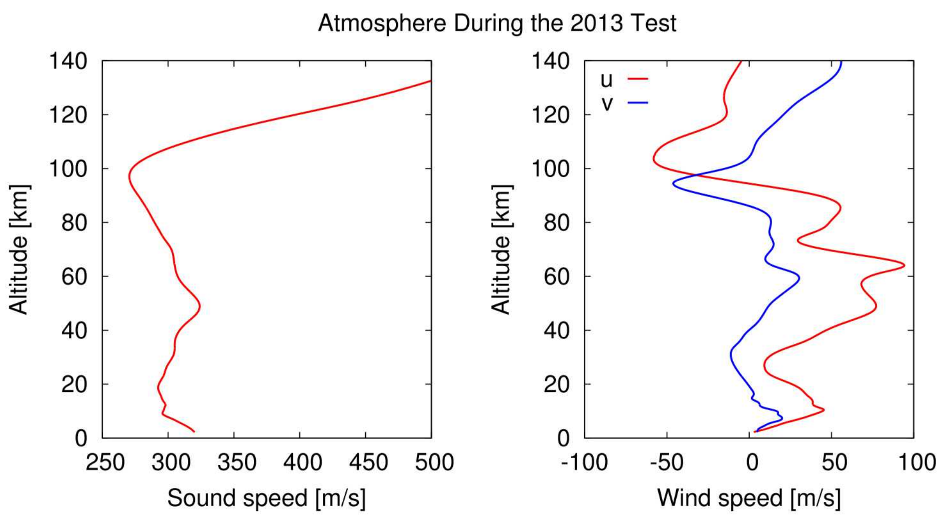


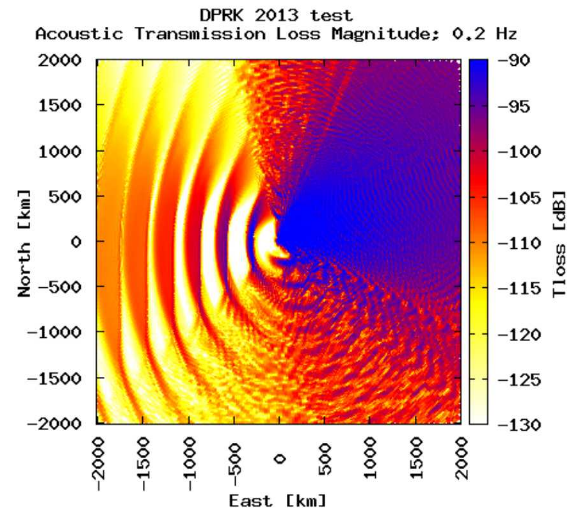


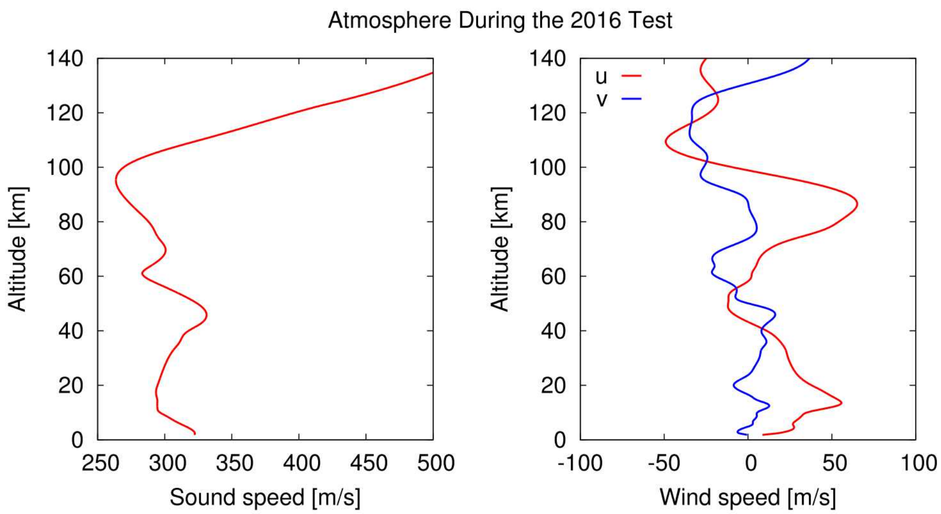


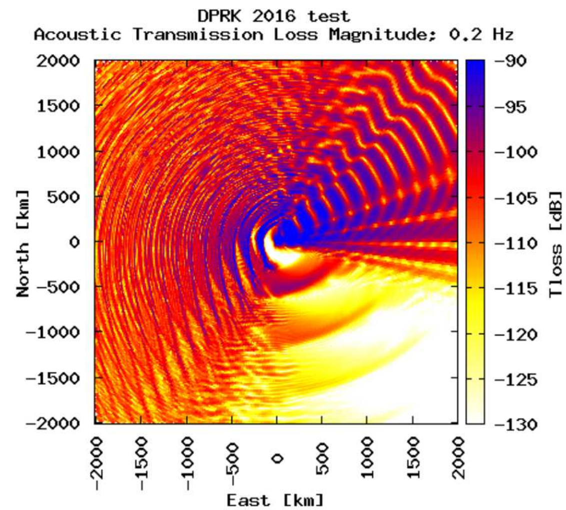
Assink Et. al 2016

Infrasound From DPRK Testing:
Propagation Modeling





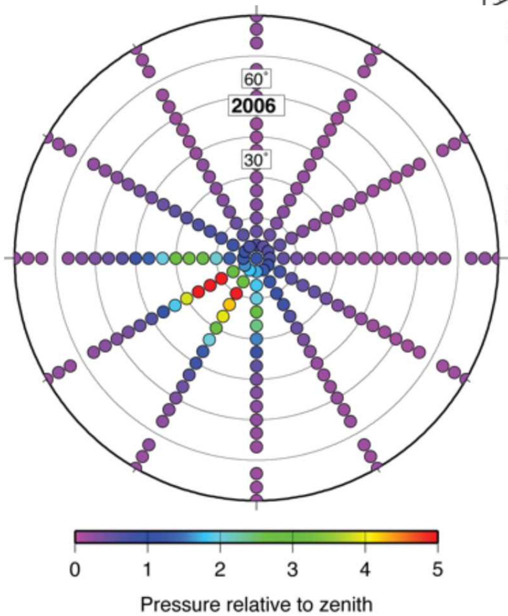


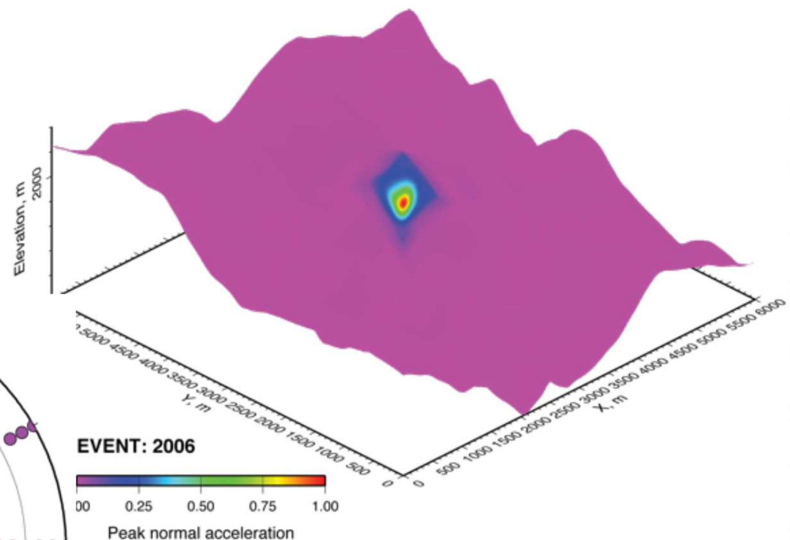


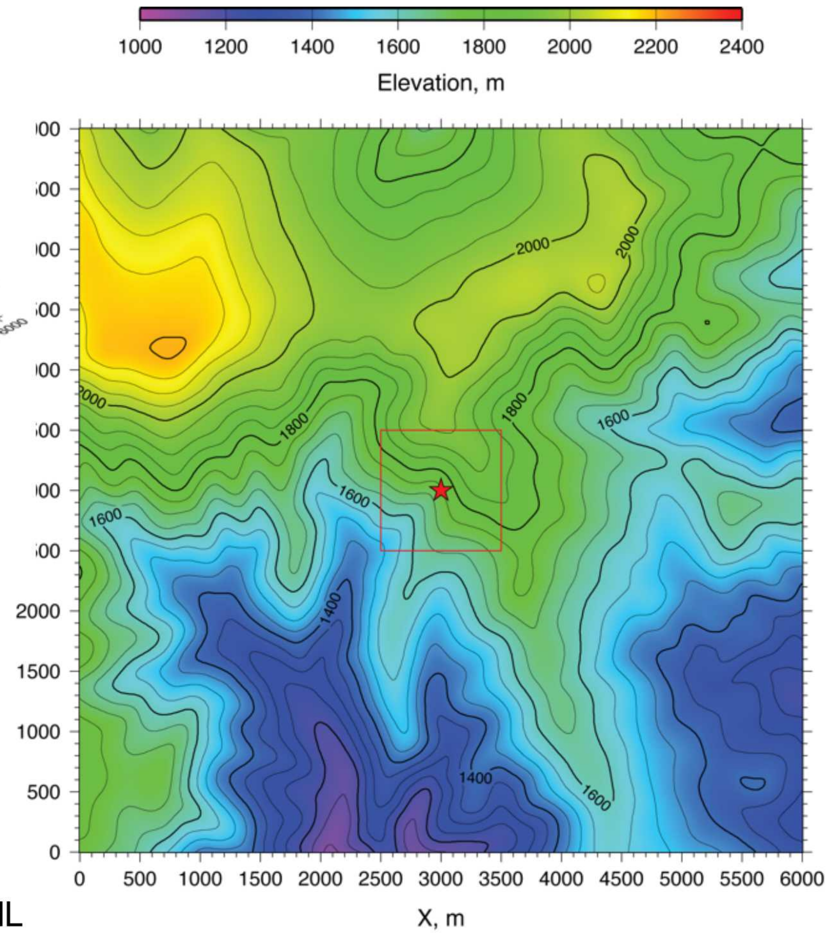
Infrasound From DPRK Testing:

Rayleigh Integral

- Modeling has been done with the infrasound to infer local topography at the site through directionality and the Rayleigh Integral





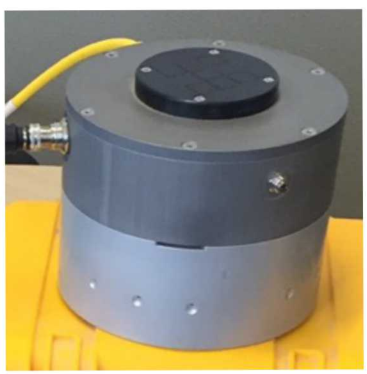


Images courtesy Artie Rodgers LLNL

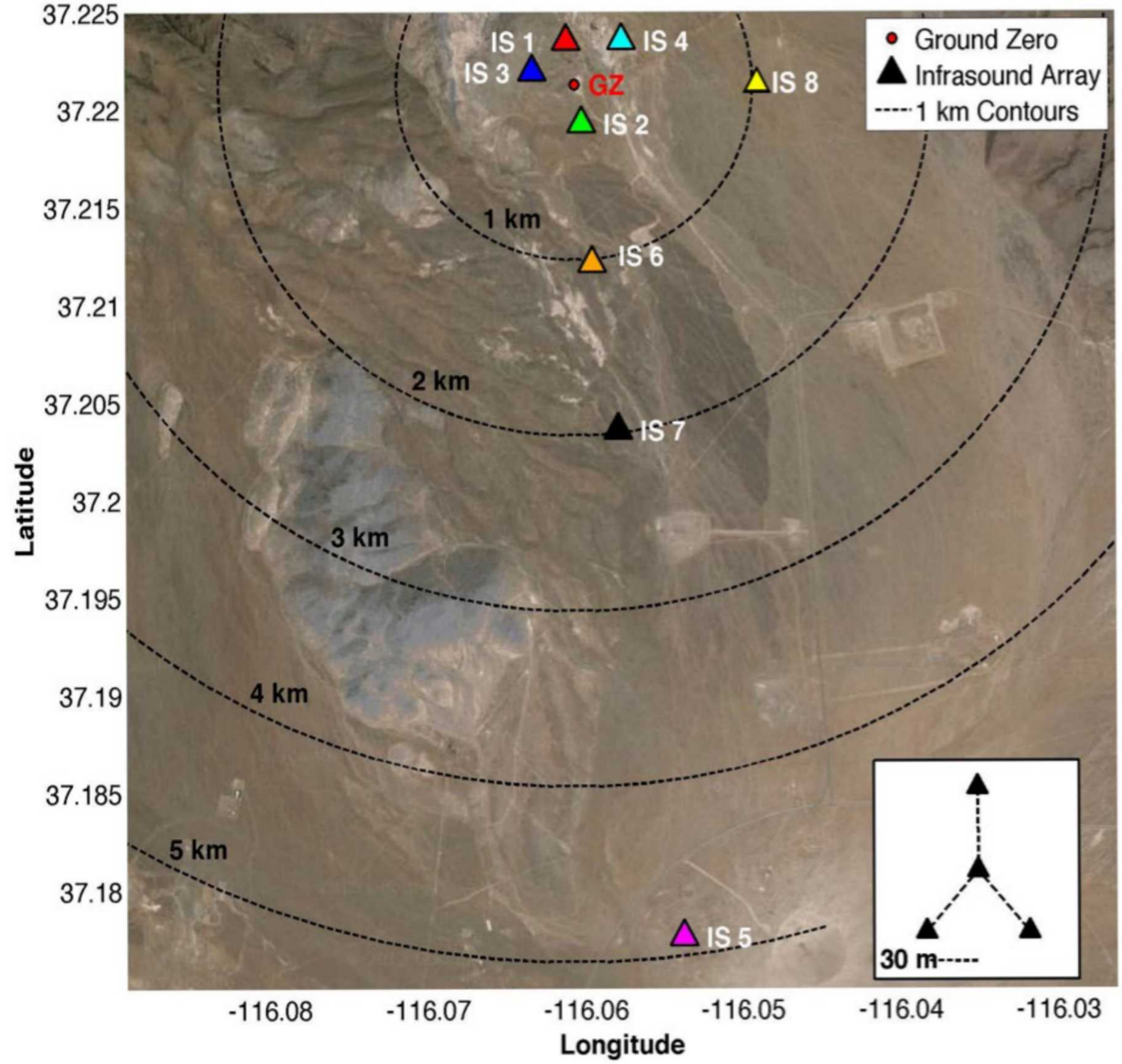
Map of SPE Infrasound Arrays

- 8 Infrasound Arrays
- 4 sensors per array
- Hyperion Sensors
- Flat from ~0.1 to ~40 Hz w/porous hoses
  - ~0.1 - 100 Hz without hoses
- 100 Pa Full Scale Range

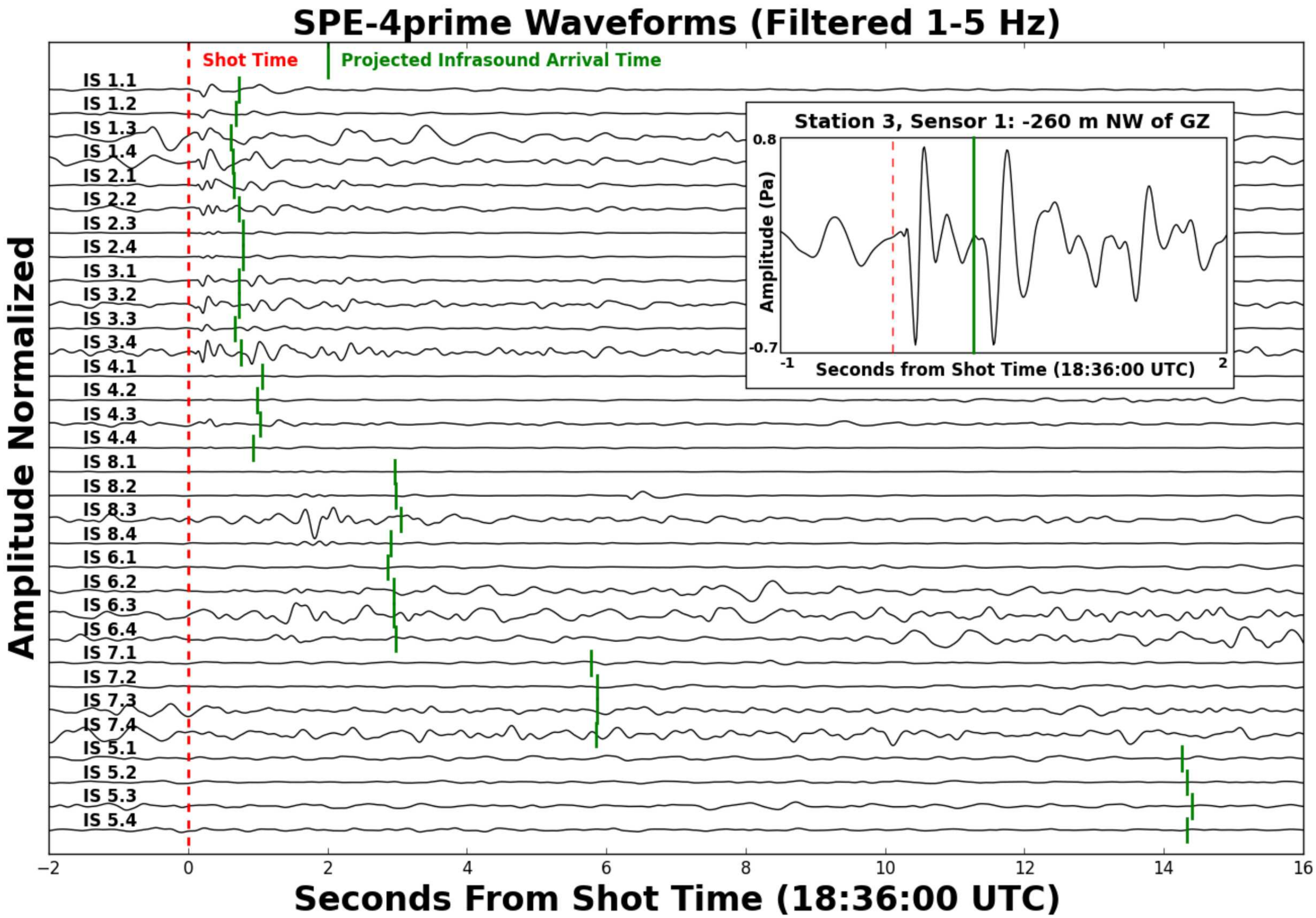
Standard Sensor



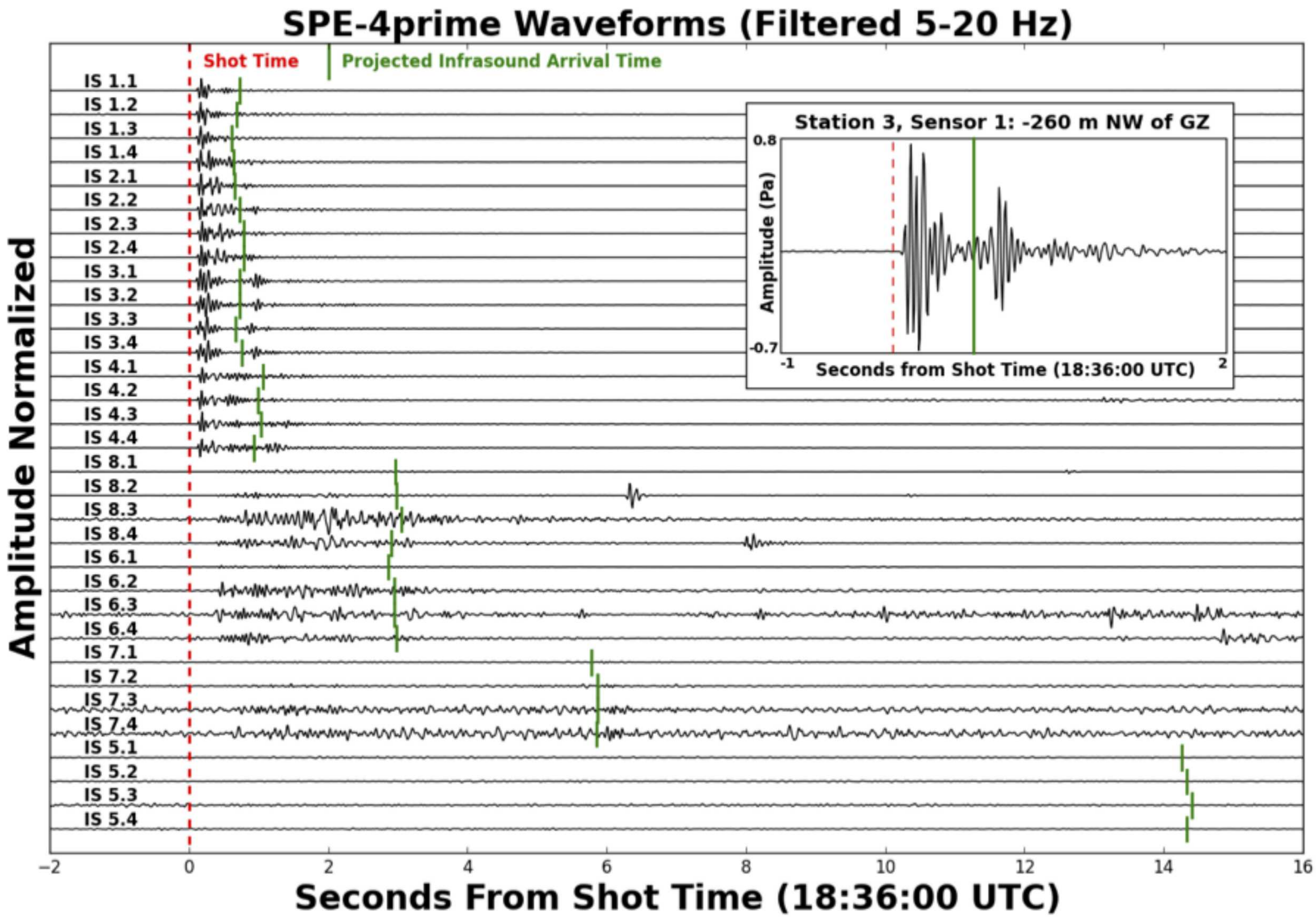
Seismically Decoupled



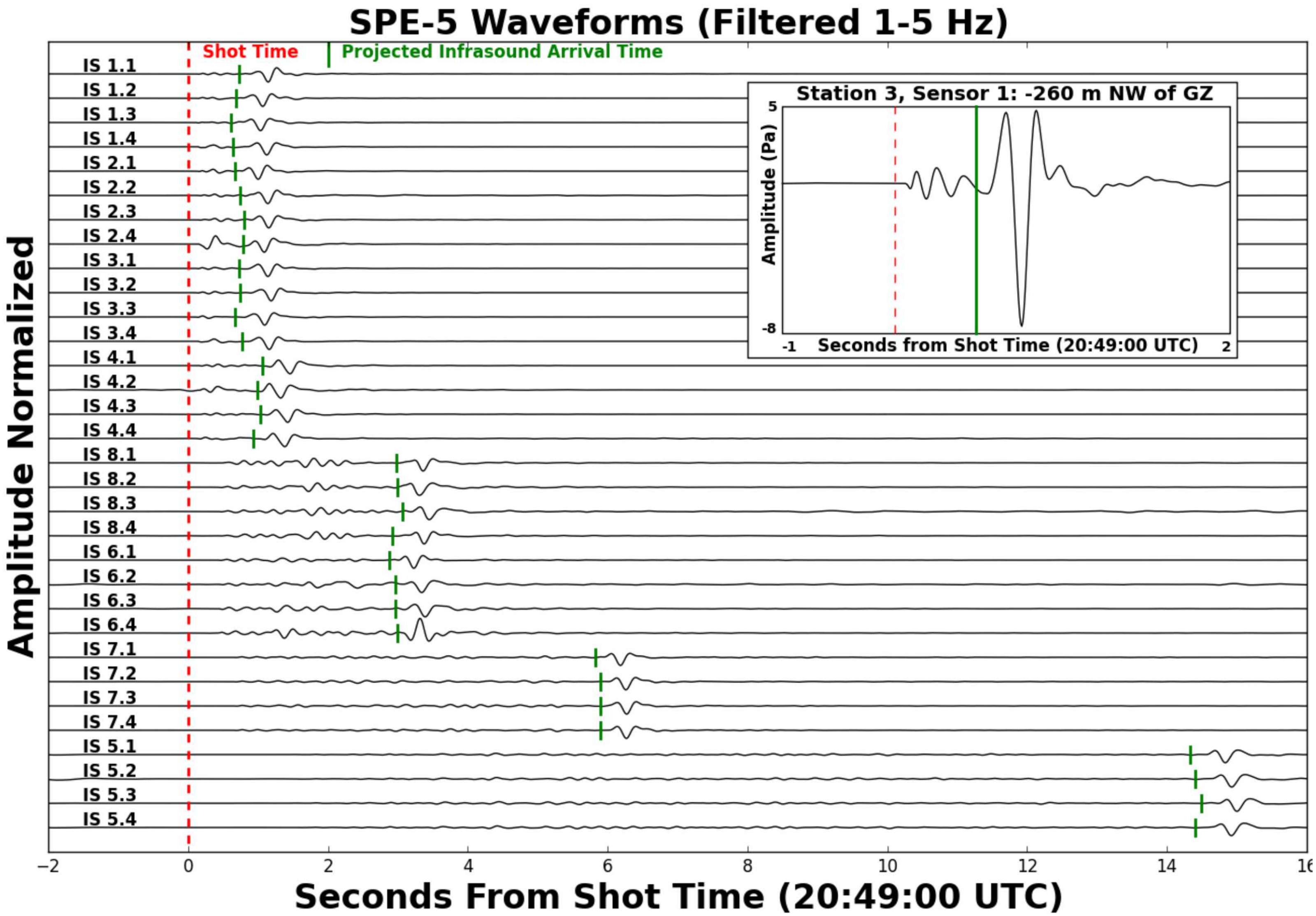
SPE Observations from SPE 4'



SPE Observations from SPE 4’

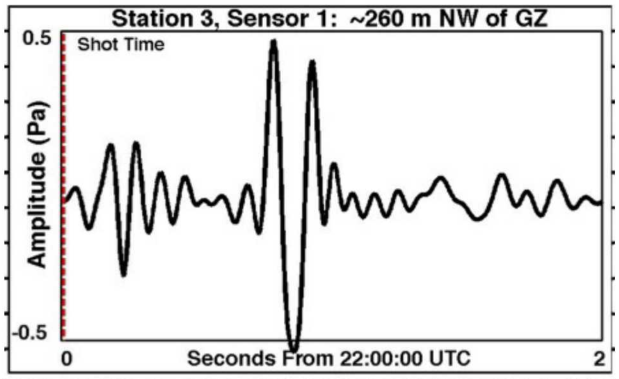


SPE Observations from SPE 5

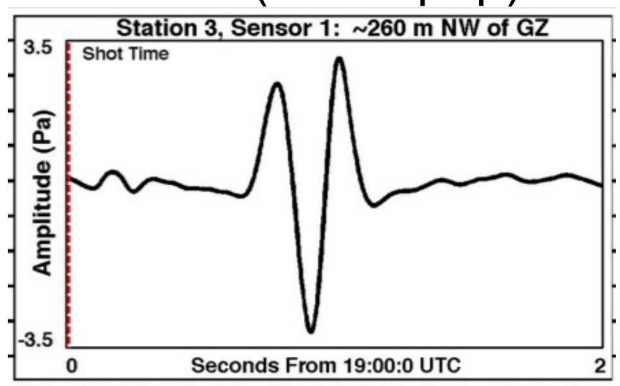


SPE Waveforms Comparisons 1 - 5

SPE 1 (1 Pa p2p)

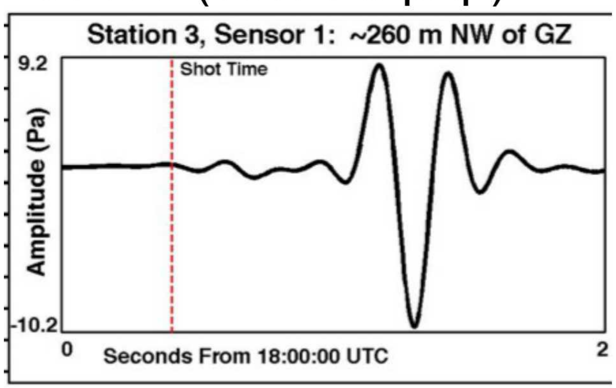


SPE 2 (24 Pa p2p)

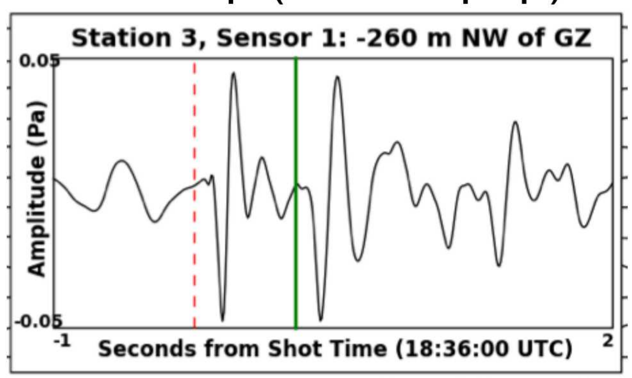


All filtered 1-5 Hz

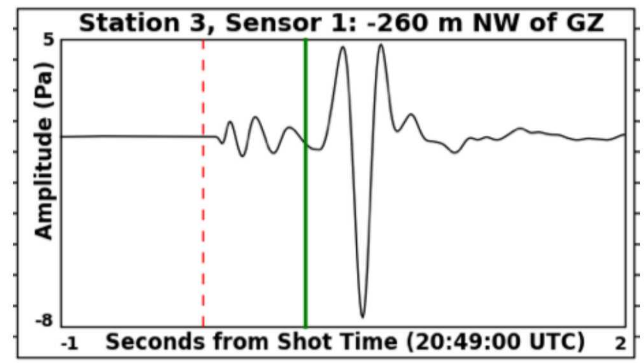
SPE 3 (19.4 Pa p2p)



SPE 4p (0.1 Pa p2p)



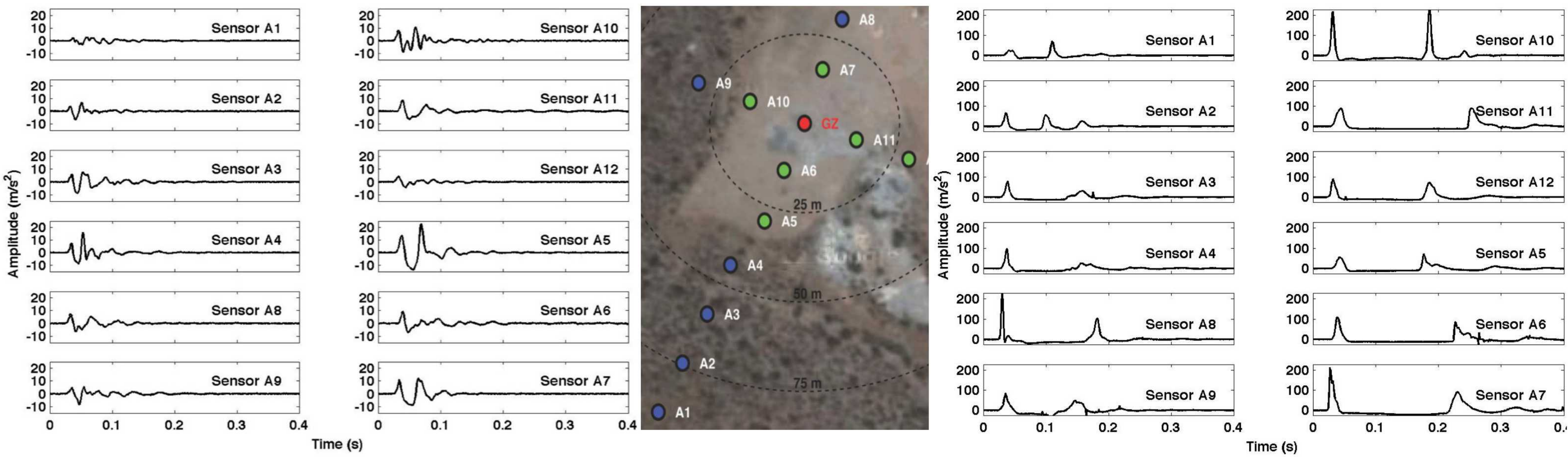
SPE 5 (12 Pa p2p)



SPE 4’ and 5 Surface Accelerations

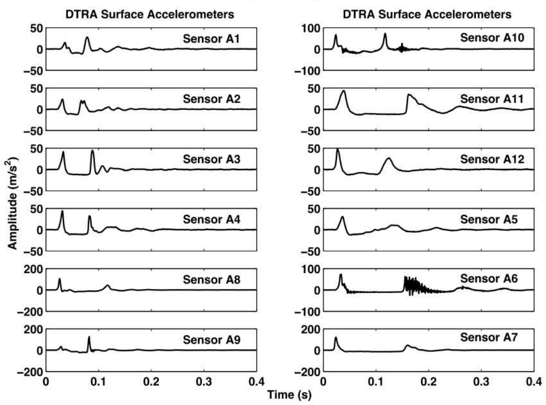
SPE 4’

SPE 5

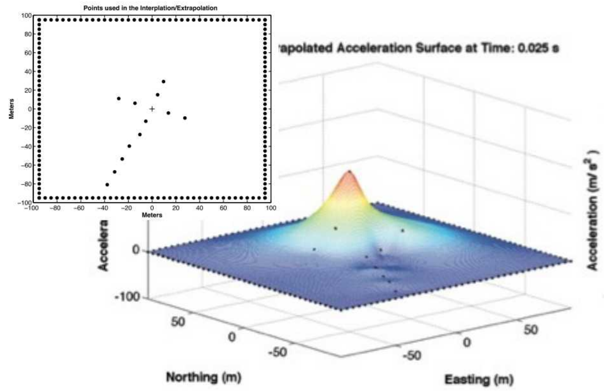


The Rayleigh Integral

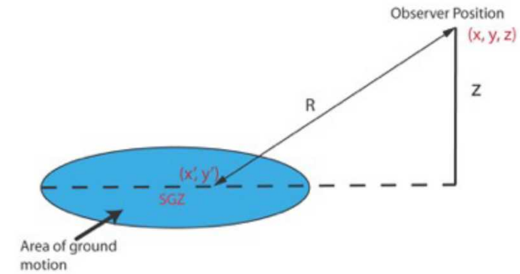
1) Use surface acceleromter data to get ground motion



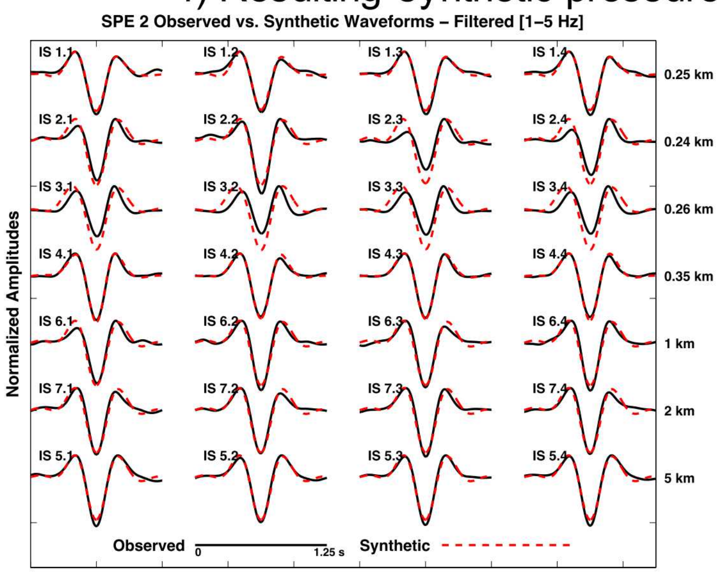
2) Extrapolate sparse data across entire grid and calculate pressures

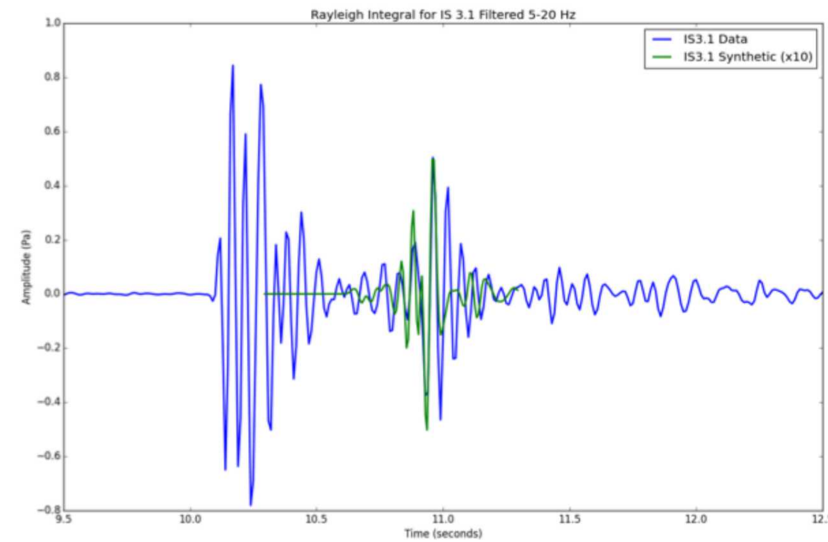


3) Integrate pressures at each point across over both area and time to create synthetic pressure waveforms



4) Resulting synthetic pressure waveform can be compared to observed data

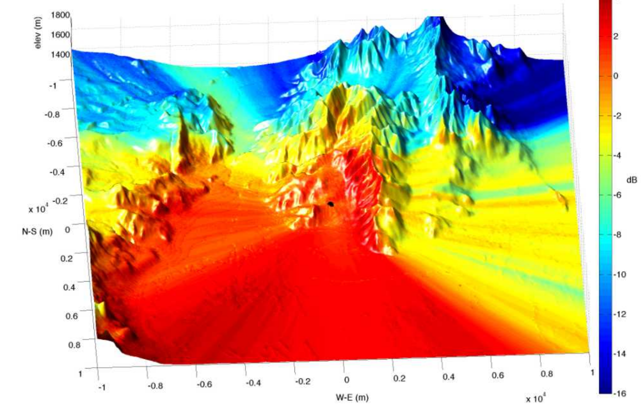




3-D Moving Media Acoustic Simulations

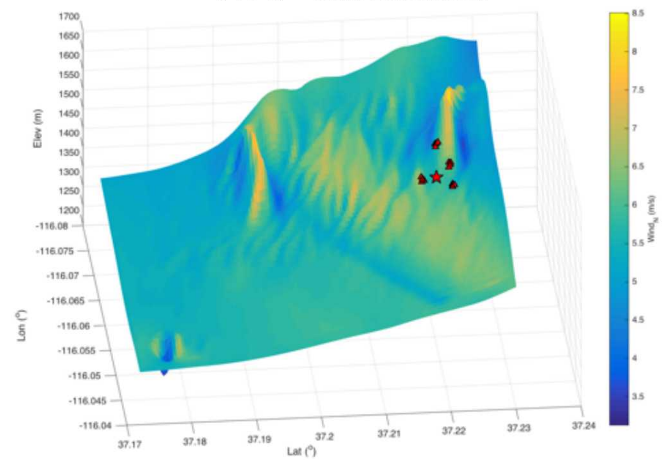
- 3-D Acoustic Simulations
  - Massively parallel finite-difference simulation code
  - Accommodates models with complex realistic 3-D geology, topography, underground voids, and atmospheric conditions including wind

Peak Pressure



- Weather Simulation
  - WRF (Weather Research and Forecasting) from National Centers for Atmospheric Research (20Km)
  - Historical 3-D atmospheric data over North America
  - Interpolates/predicts meteorological conditions (winds, temperature, etc.) to estimate atmospheric state

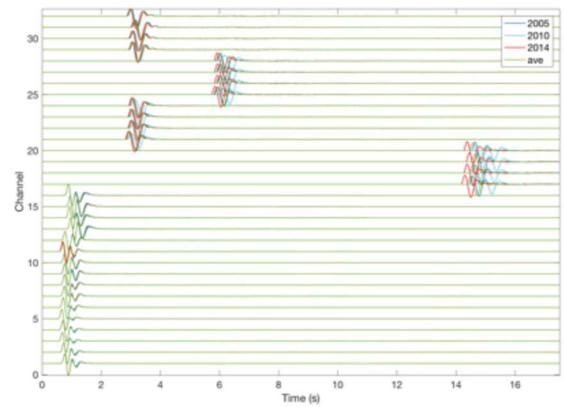
WRF Simulation

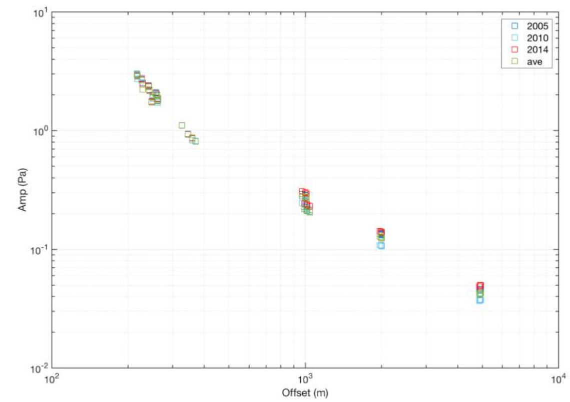


Predictions and Acoustic Source Inversion

- Predictions
  - Download past 10 years of weather data for site and estimated date/time of shot
  - Run WRF models for mean and extrema years
  - Perform acoustic simulations for these models to investigate signal variations due to weather
  - Use estimated source time function from source inversions

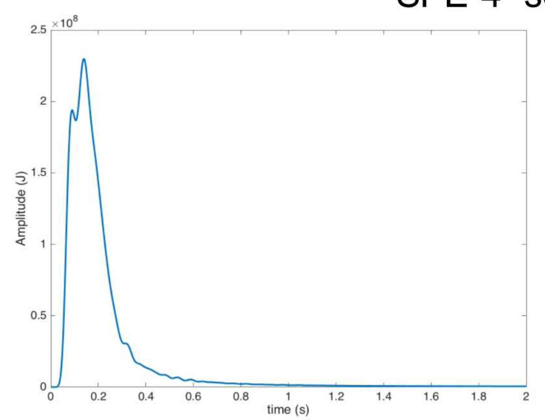
SPE-5 predictions

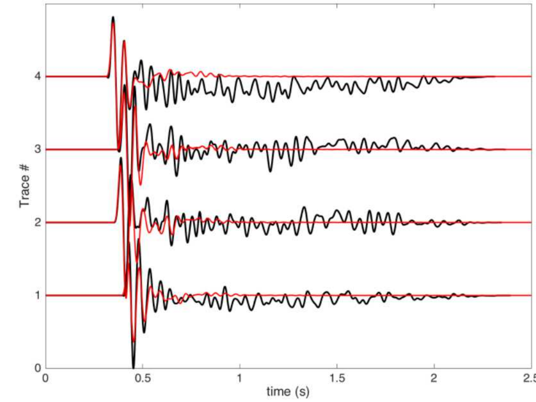




- Source Inversion
  - Collect observed weather data at time of shot
  - Run weather models over the infrasound array region
  - Perform acoustic simulations
  - Frequency domain inversion of synthetic and observed data spectra

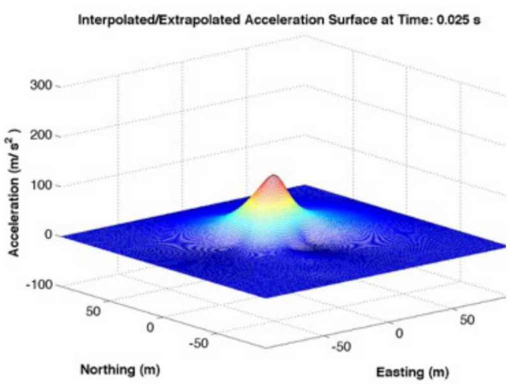
SPE-4' source inversion

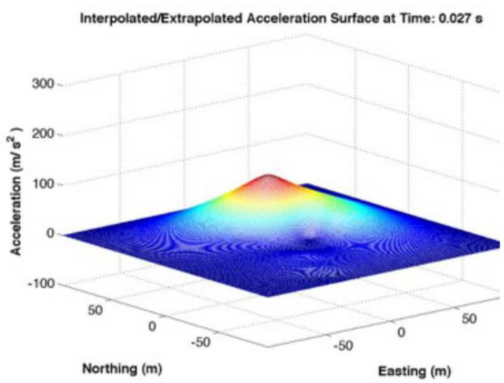


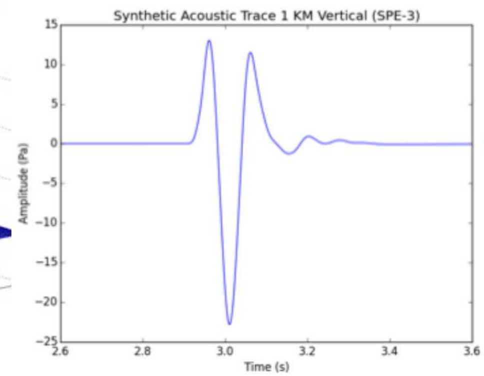


LLNL GEODYNE – L Modeling

SPE-3

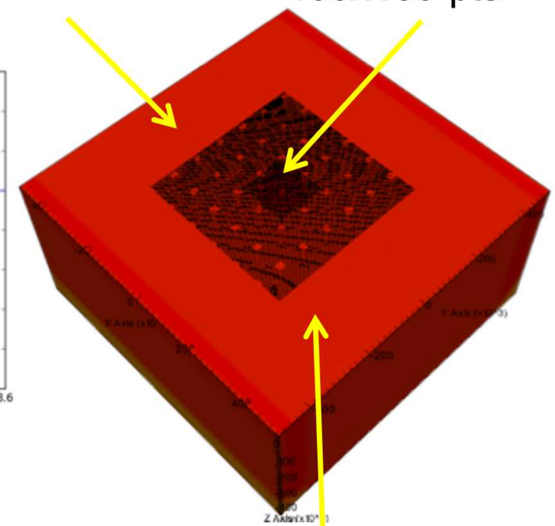






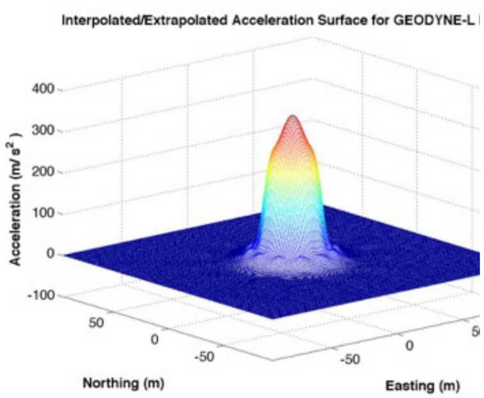
Domain
1km x 1km x 1/2km

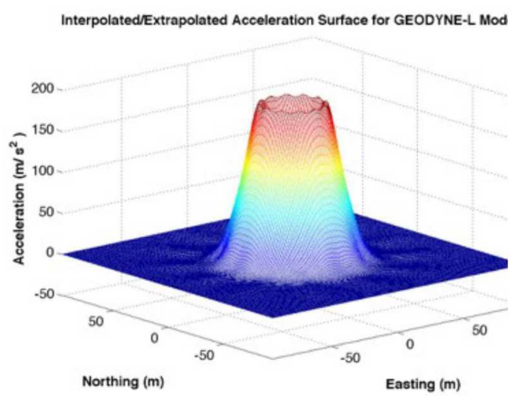
Rayleigh patch
500m x 500m
100x100 pts

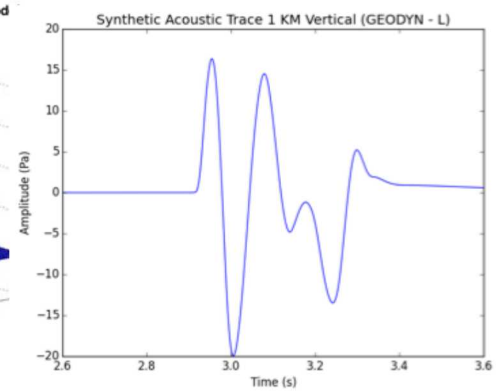


Source box
patch for far field
simulations

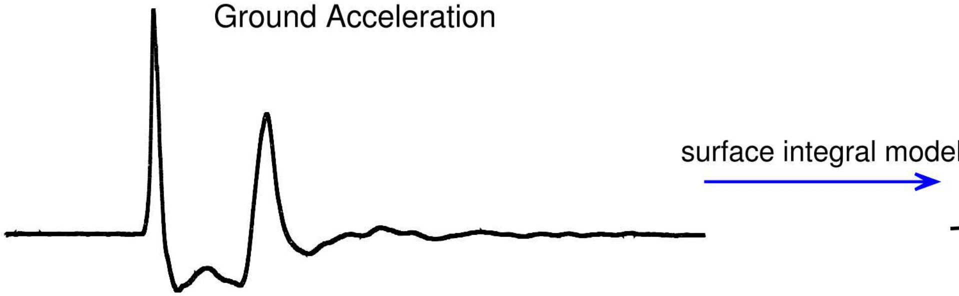
GEODYN-L

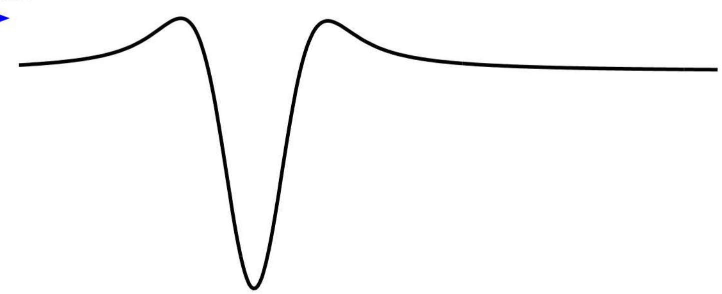






Seismic/Acoustic Data Fusion for Depth Determination





Ground motion estimation

- Depending on yield and depth

Nearfield acoustic source estimate

- From the ground motion estimate

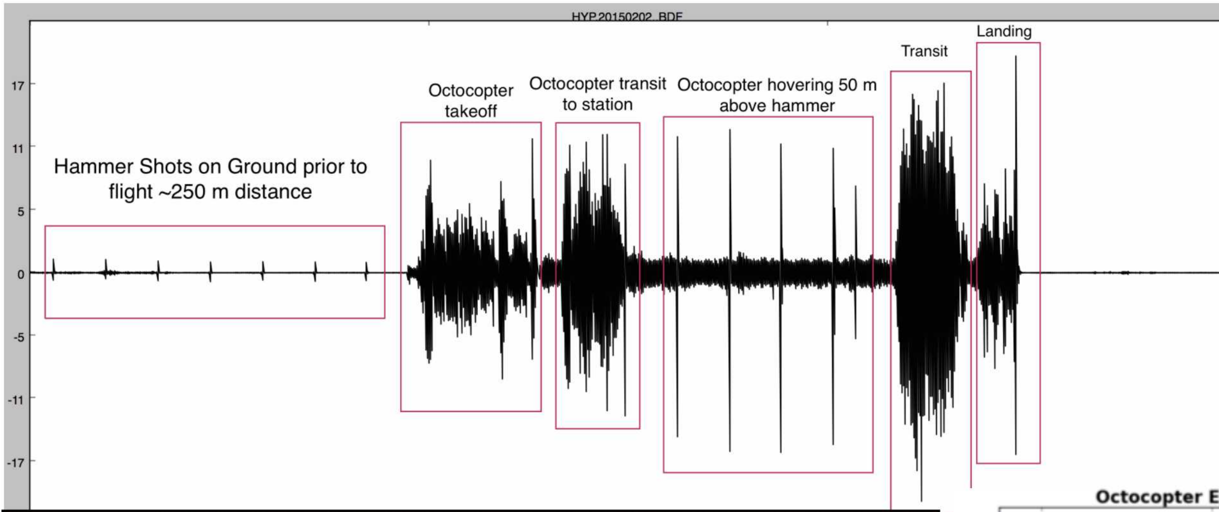
Propagate to the far field to constrain the ground motion model

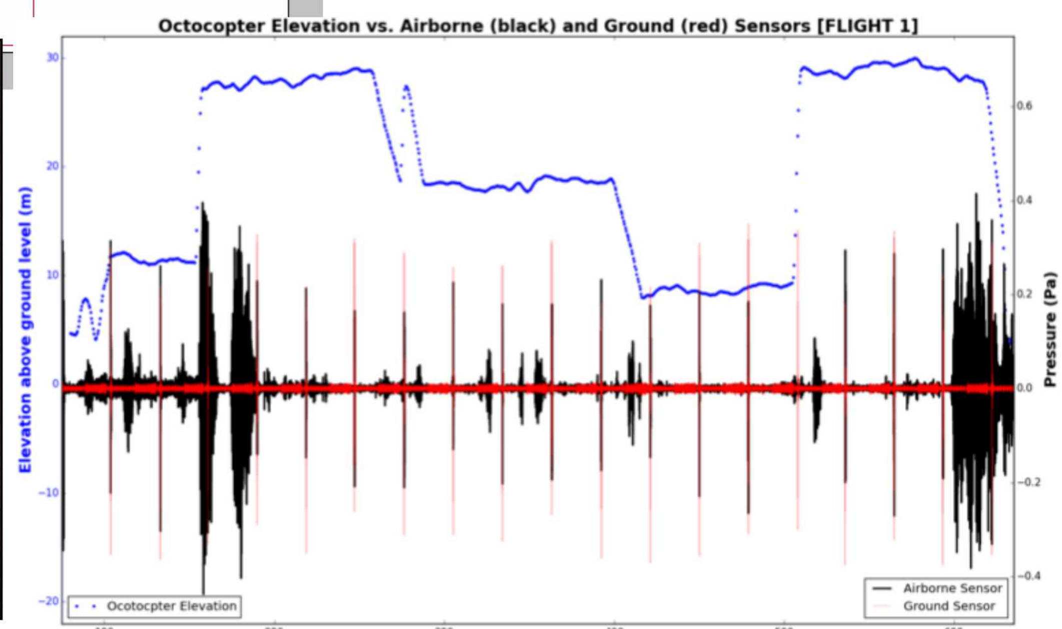
- Research needed to determine robust features
- Signal power (Waxler-Green)
  - Precise atmospheric data is not available
  - Use a mean (incoherent) transmission loss
- Peak frequency/dominant period

Possible issues:

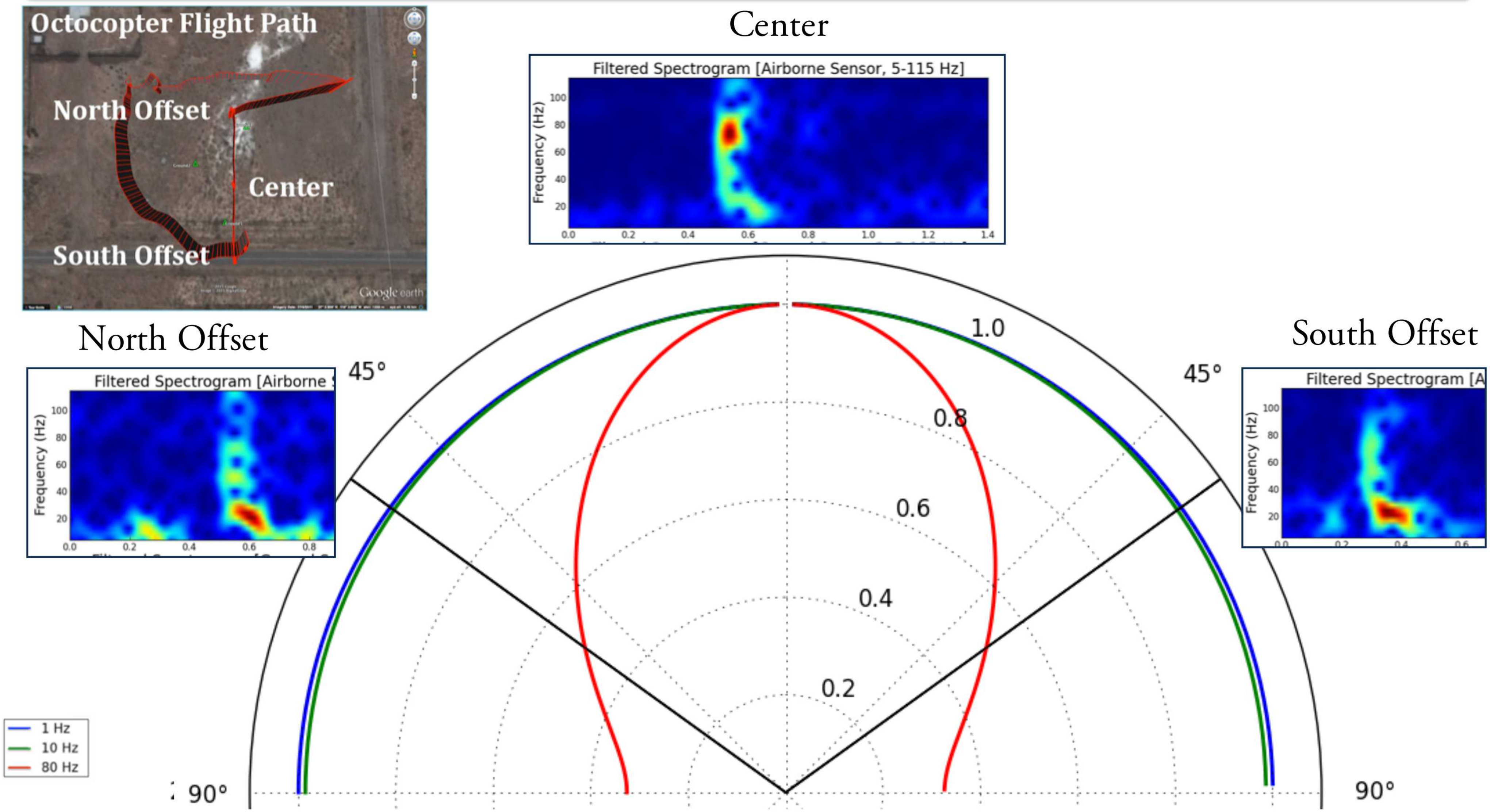
- Atmospheric variability means signal detection is uncertain
- SNR limits acoustic feature extraction

Octocopter Infrasound





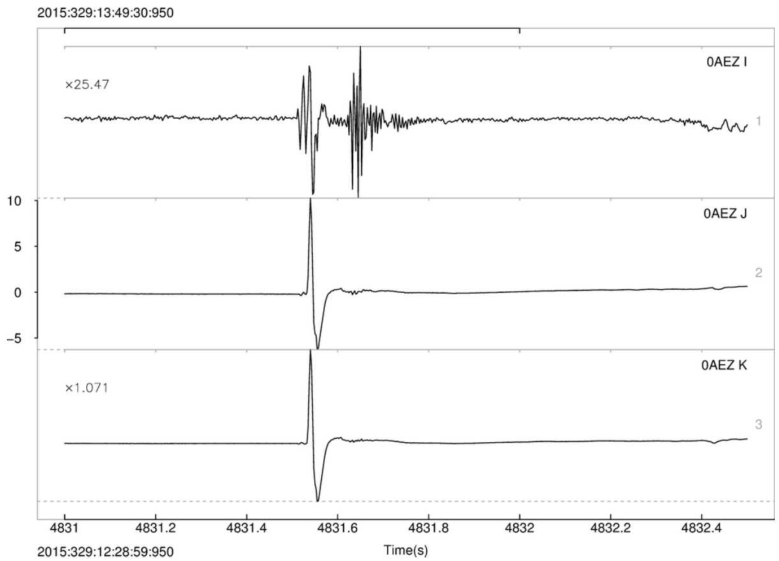
Octocopter Infrasound : Directivity

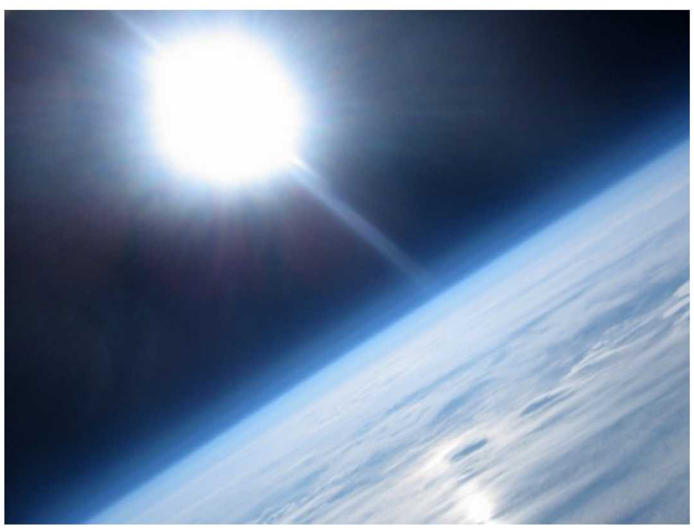


Tethered Infrasound Sensor

- Pressure waveforms at higher elevation angles should have larger amplitudes (from contained underground explosions) than along the ground
- Such data provide additional signals against which to compare models and to compare to other related measurements (such as on UGTs with similar SDOB)
- Models include boundary integral type methods, Rayleigh Intergral, as well as computational fluid dynamic (CFD) methods
- About 50 m elevation at range of 100m
  - Four tethers
  - 5 lb package of sensor and digitizer
- Plan to use Helikite aerostat for stability

Balloon-based High Altitude Infrasound





10-100x larger monitoring footprint

Improve inversion for source physics

Augment far field detection capability

Advantages:

- Extreme detection range (~150 km)
- 3D signal characterization
- No wind noise
- Virtually unexplored

Challenges:

- Station keeping
- Limited payload capacity
- Data recovery
- Pressure/sensitivity tradeoff

Conclusion

- Modelling infrasound signal generation from two underground explosions at the Source Physics Experiment using the Rayleigh integral, Geophys. J. Int. (February, 2015) 200 (2): 779-790 doi:10.1093/gji/ggu433
- Presentations at national and international conferences
  - SSA, AGU, CTBTO-ITW, CTBTO-SnT
- Successful infrasound data collection and analysis on all SPE events
  - 100% data return
  - Quick data analysis
- Close collaboration with both LANL, LLNL, Ole Miss-NCPA
  - Rayleigh Integral, Synthetic waveforms, propagation modeling, etc…
- Initial application to real-world, complex problems
  - DPRK, DOB vs. Yield
- Investigating other infrasound data collection platforms
  - Octocopter, tethered and free balloons
- Infrasound is a cost effective technology that can contribute complimentary information on underground tests in multi-technology analyses (data fusion)

Questions?

Backup

Rayleigh Integral using ground acceleration for Infrasound Excitation

$$p(x, y, z; t) = \rho_o \iint_S \dot{u}_p(x', y', t - R/c_o) dS$$

This is an exact solution – Blackstock's ***Fundamentals of Physical Acoustics***, Chapter 13

Limited by the spatial sampling of the area around ground zero and frequency content

Analysis for a uniform monochromatic piston vibration using asymptotic analysis shows near and far field behavior and Rayleigh distance behavior
Analysis for a nonuniform piston shows beam shaping

Diffraction analysis with Helmholtz/Kirchhoff Integral theorem also possible