SAND2017-11124PE

Borehole Accelerometers - SOA

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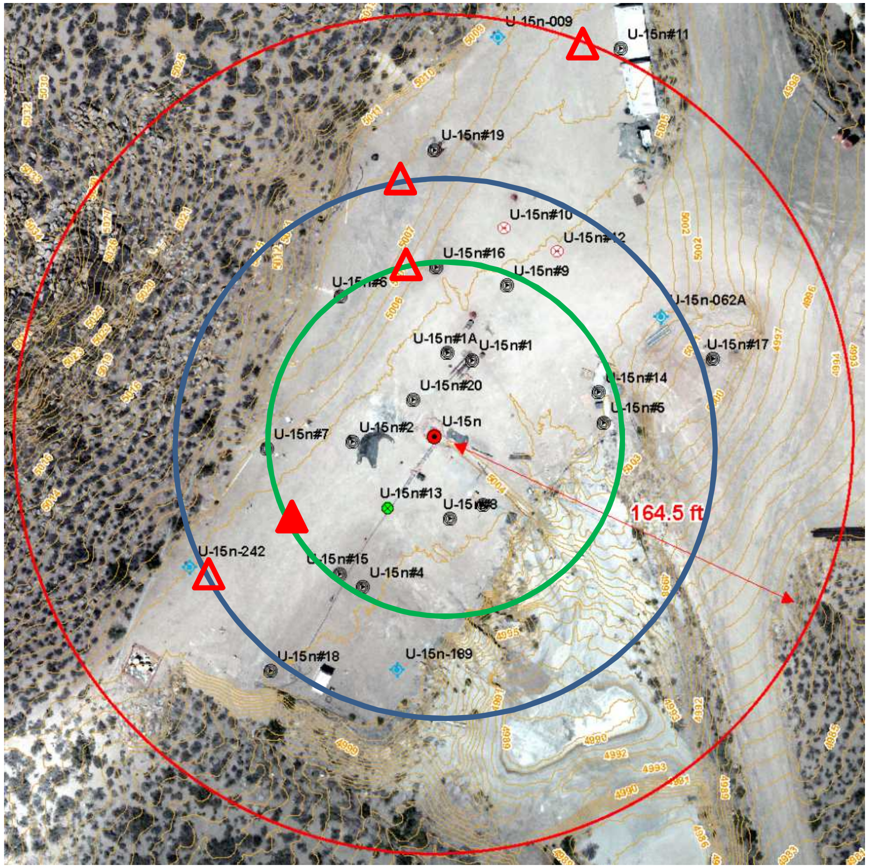
Phase I

- SPE-1: DTRA
- SPE-2: DTRA
- SPE-3: DTRA
- SPE-4’: DTRA
- SPE-5: DTRA + SNL
- SPE-6: SNL

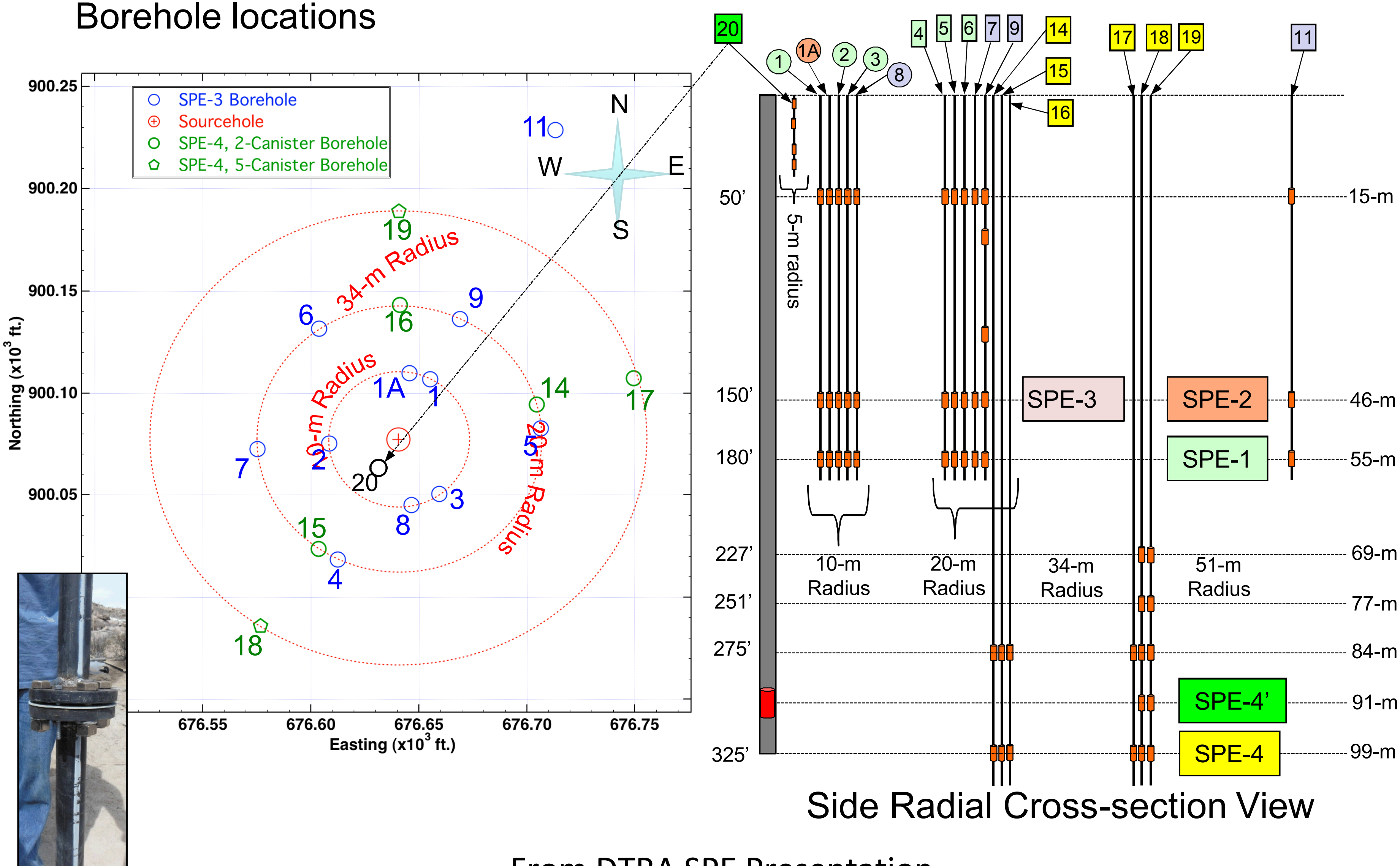


Phase I – SPE 1-2-3-4’

DTRA

Borehole Accelerometer Locations

Borehole locations

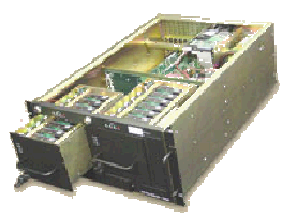


From DTRA SPE Presentation

Data Acquisition System

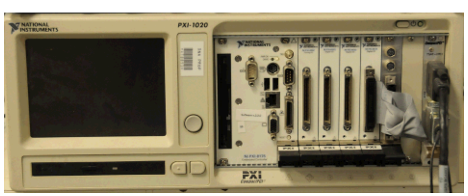
- All piezoresistive bridge type accelerometers
- SPE Core Data Acquisition System
  - 96 channels of Pacific 8656 auto balance amplifiers (10 racks)
  - 200 channels DTRA-RRS real time recording chassis
  - 1 Timing & Firing Sequencer

96 Channels ***Pacific 8656 Auto balance Amplifiers***



200 Channels ***DTRA-RRS Data Recorder***

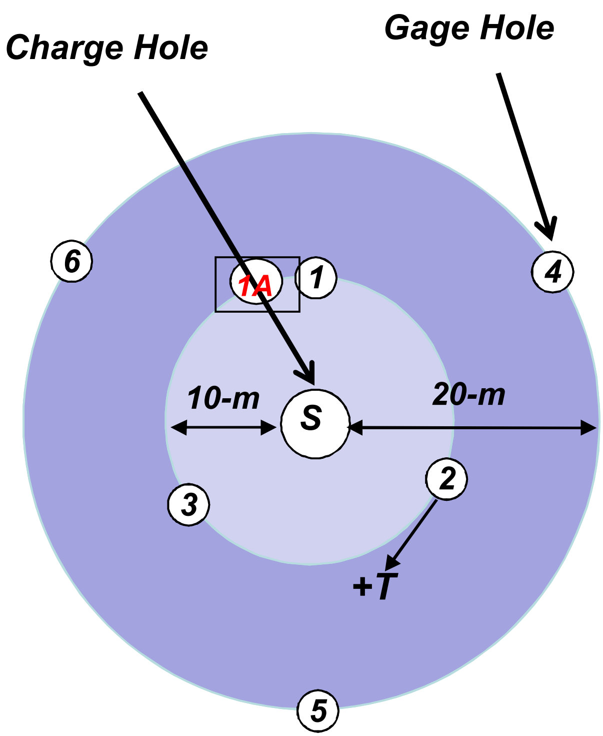
Redundant Recording



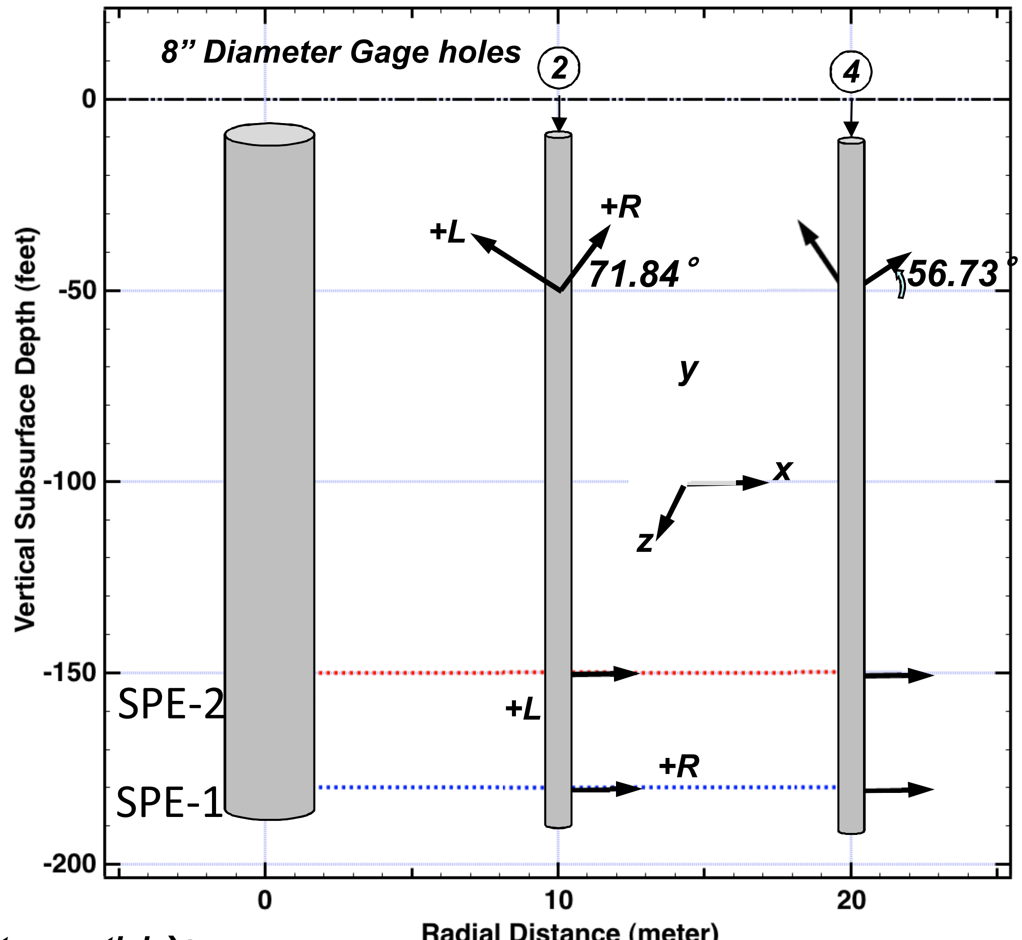
1 Unit ***DTRA-PES-2002 T&F System***

From DTRA SPE Presentation

SPE 1-2 Test Bed Layout



Top View



Side Radial Cross-section View

12-canisters with radial accels → +x, lateral →+y, tangential→+z
3-canisters with radial accels at 56.7° from +x
3-canisters with radial accels 71.8° from +x

From DTRA SPE Presentation

SPE 1-2 Assessment

- Some leak failures
- Questions arose regarding accelerometer orientation
- Original system used NPT threaded pipe flanges which may have rotated during installation

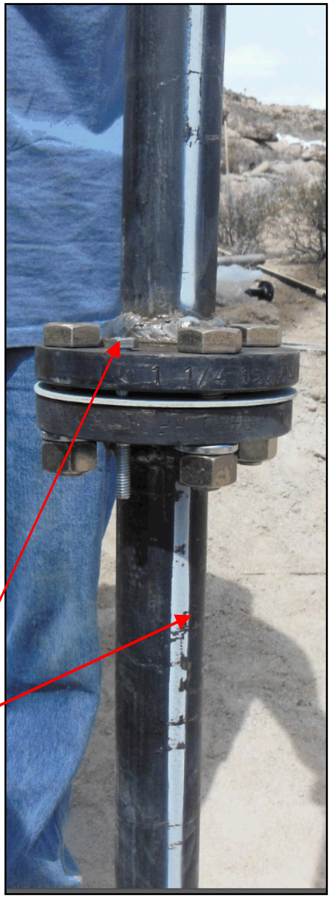
- Other possibilities include installation clocking mistake, wiring reversal, or real phenomena

SPE-3 Gage Canister Installation

- Installed new boreholes 7, 8, 9, and 11.
- Gage canisters designed to allow one orientation, verified with tap test
- GZ facing line scribed on pipes and canisters
- Waterproofed gauge canisters
- Connections made with flanges & alignment pin
- Final Azimuth relative to GZ confirmed with surveyors
- Azimuthal readings recorded from magnetic gages

Facing GZ

Verification of accelerometer orientation



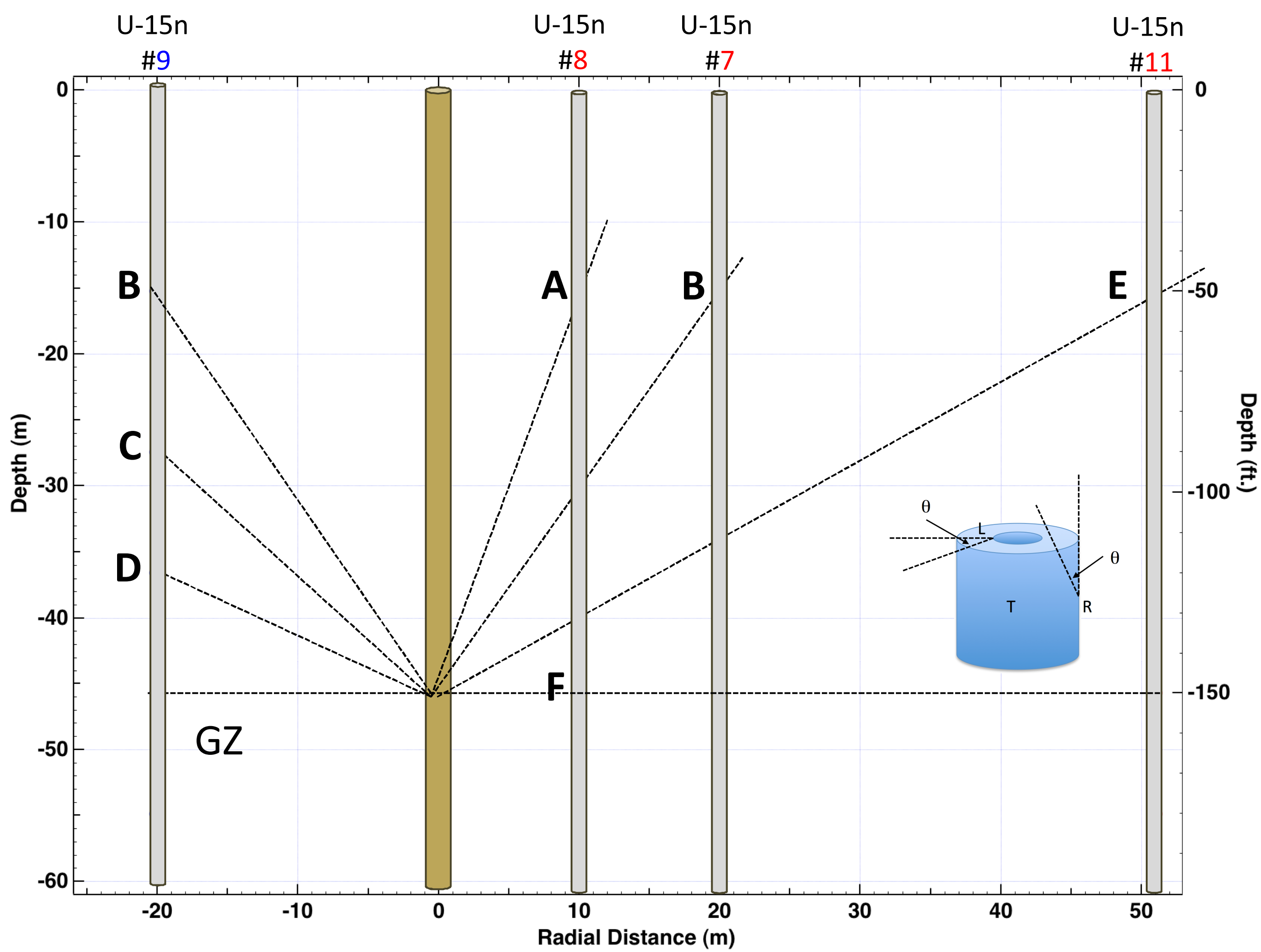
Connecting and aligning gage canisters.

Note Line facing GZ

Alignment pin

From DTRA SPE Presentation

SPE-3
Add-on Subsurface Gages



A. 10-m Radius, 50-ft. deep
θ = 71.8°
Need = 2

B. 20-m Radius, 50-ft. deep
θ = 56.7°
Need = 3

C. 20-m Radius, 90-ft. deep
θ = 42.4°
Need = 2

D. 20-m Radius, 120-ft. deep
θ = 24.6°
Need = 2

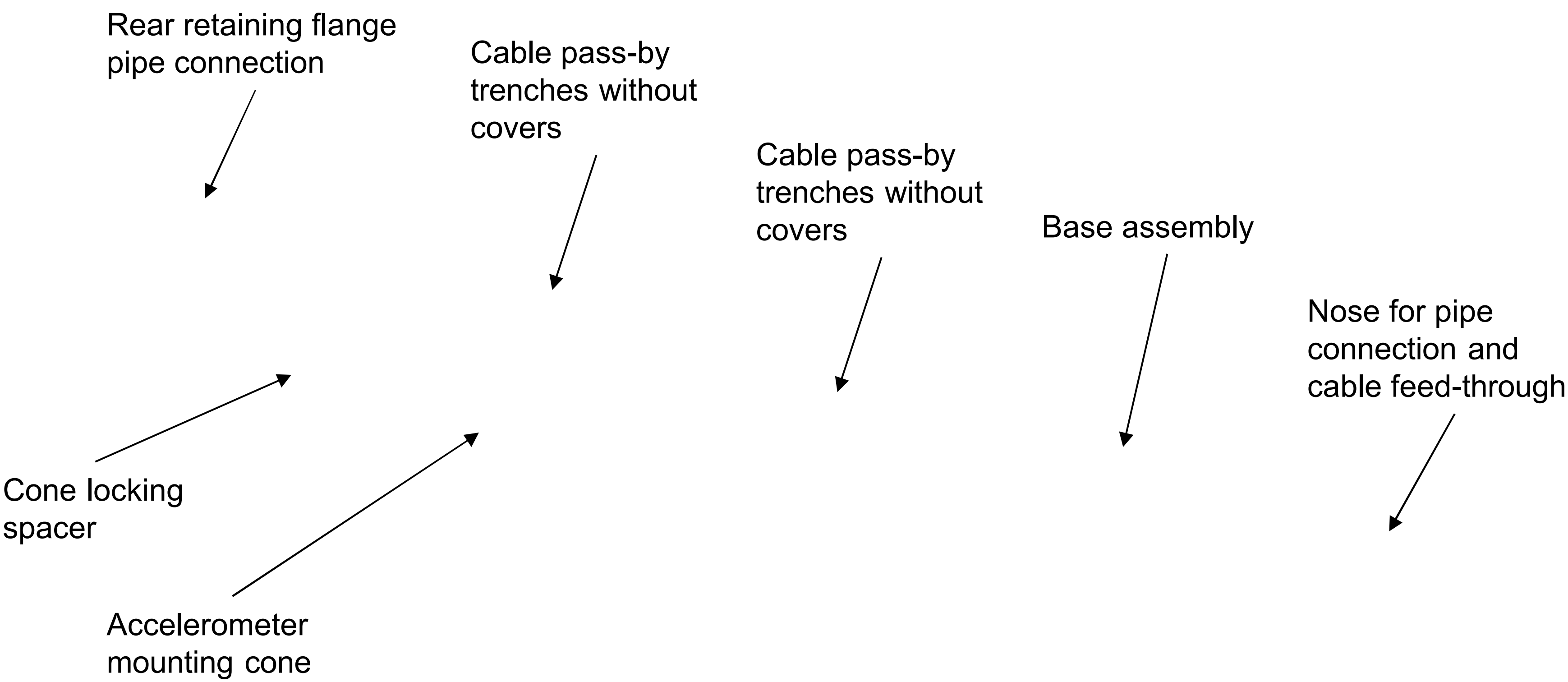
E. 51-m Radius, 50-ft. deep
θ = 30.9°
Need = 2

F. All Radius, ≥ 150-ft. deep
θ = 0°
Need = 13

From DTRA SPE Presentation

Gage Canister Components

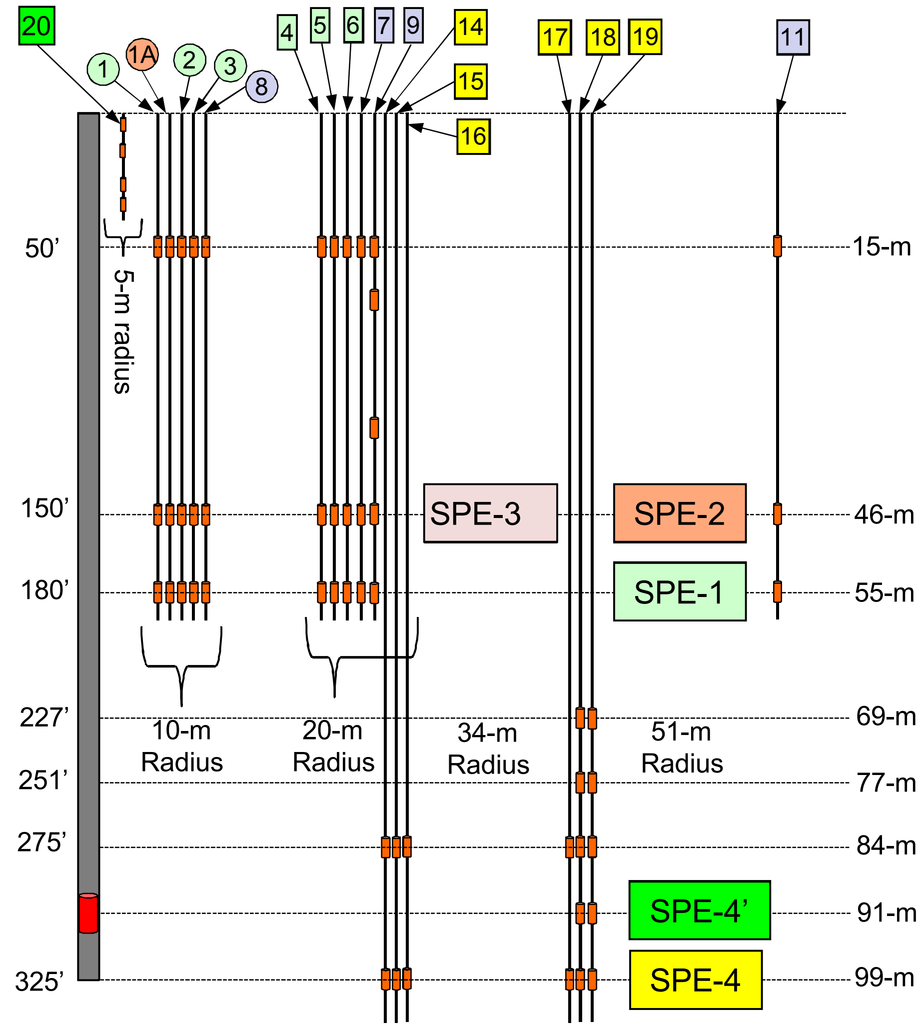
- Tandem gage canister in exploded view



From DTRA SPE Presentation

SPE-1-2-3-4’

- DTRA did a lot of good work and were kind enough to share their experience with SNL
- Initial alignment and leakage concerns addressed
- Some sensor failures over time
- No redundant sensors in L or T
- Some redundant sensors in R at different sensitivities

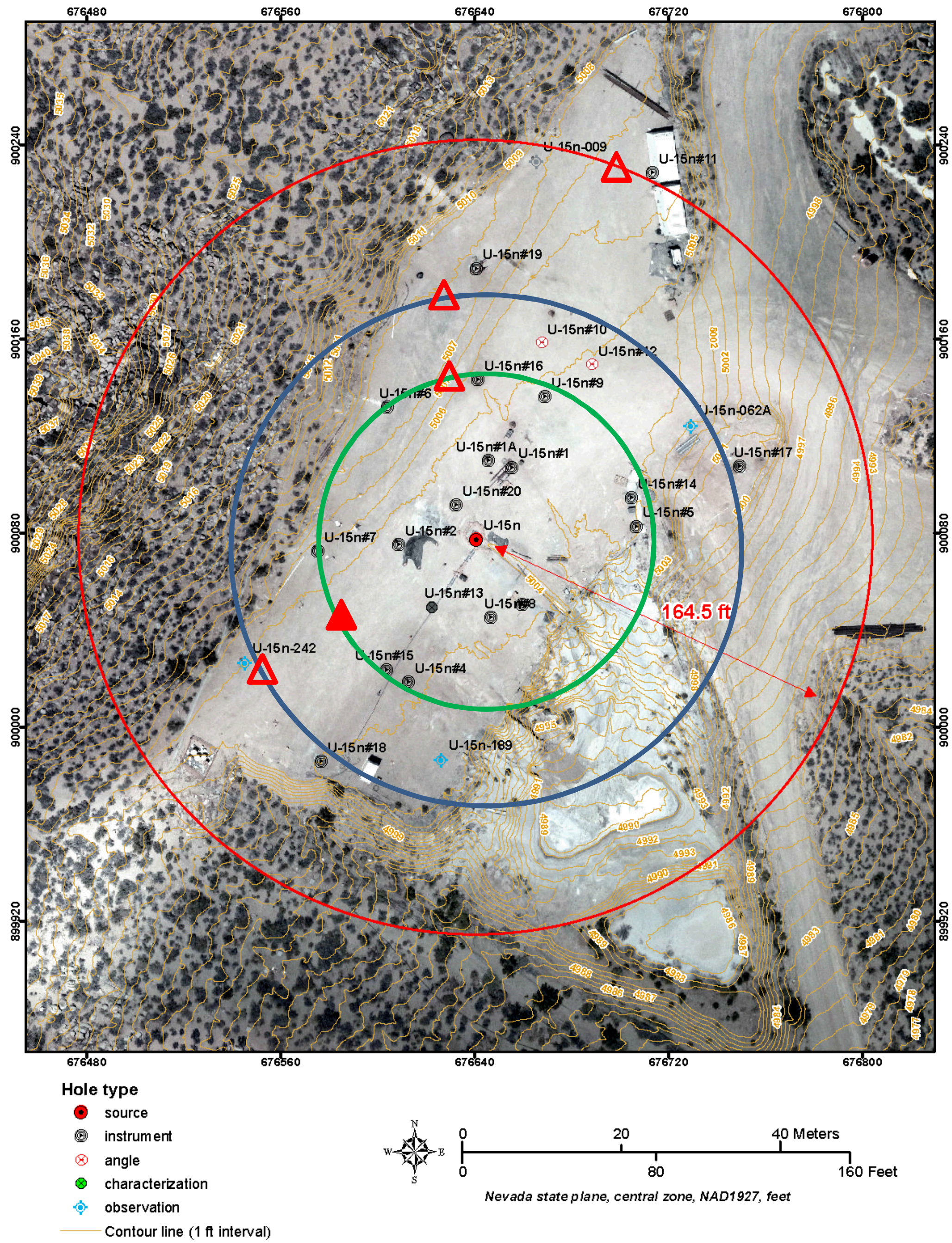


Side Radial Cross-section View

Phase I – SPE 5 SNL Design

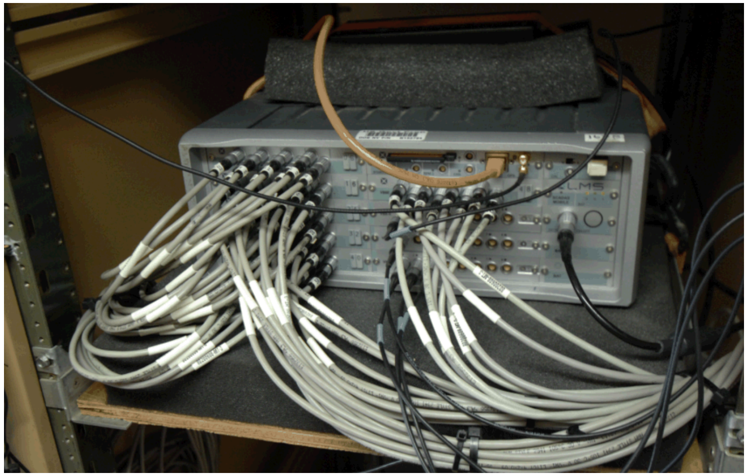
Prototype accelerometer package and new DAS V&V

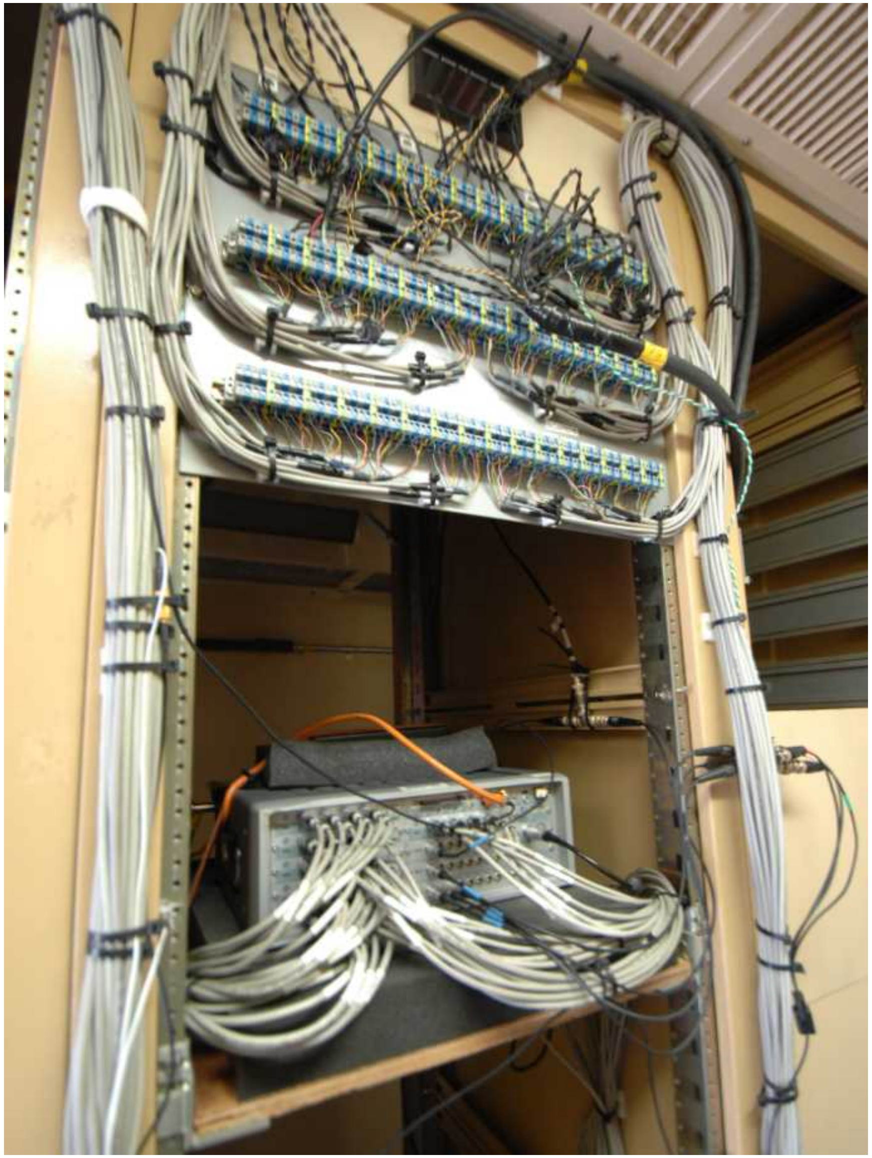
- R = 20m (Filled red triangle)
- 10” Borehole to ~262 ft
- 3 depths targeted (35m, 69m, 76m)
- Triaxial 2000g range accelerometers
- Redundant accelerometers at each depth
- Keyed Installation on size 1.5 rigid Sched-40 steel pipe
- Neat Cement Grout (~15lb/gal = 1.8 g/cm^3) with 25% fly ash to limit temperature



Digitizer

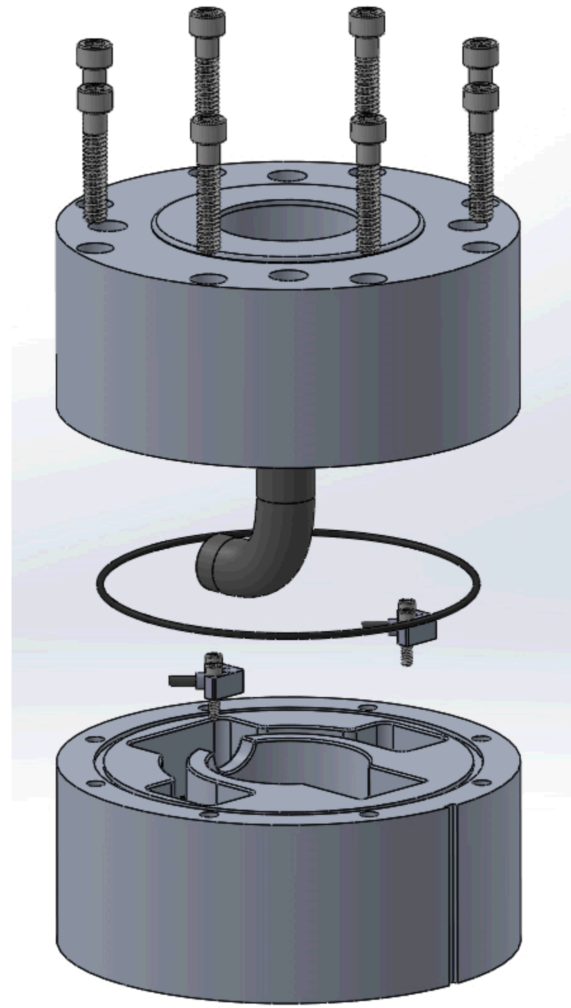
- LMS Scadas Recorder
- 51,200 Hz Sample Rate (19.5µs time resolution)
- 24-bit digitization
- Supports 6-wire bridge gauge interface (Max 10.25V excitation)
- 72-Channels
- Fiber optic connection to T&F trailer



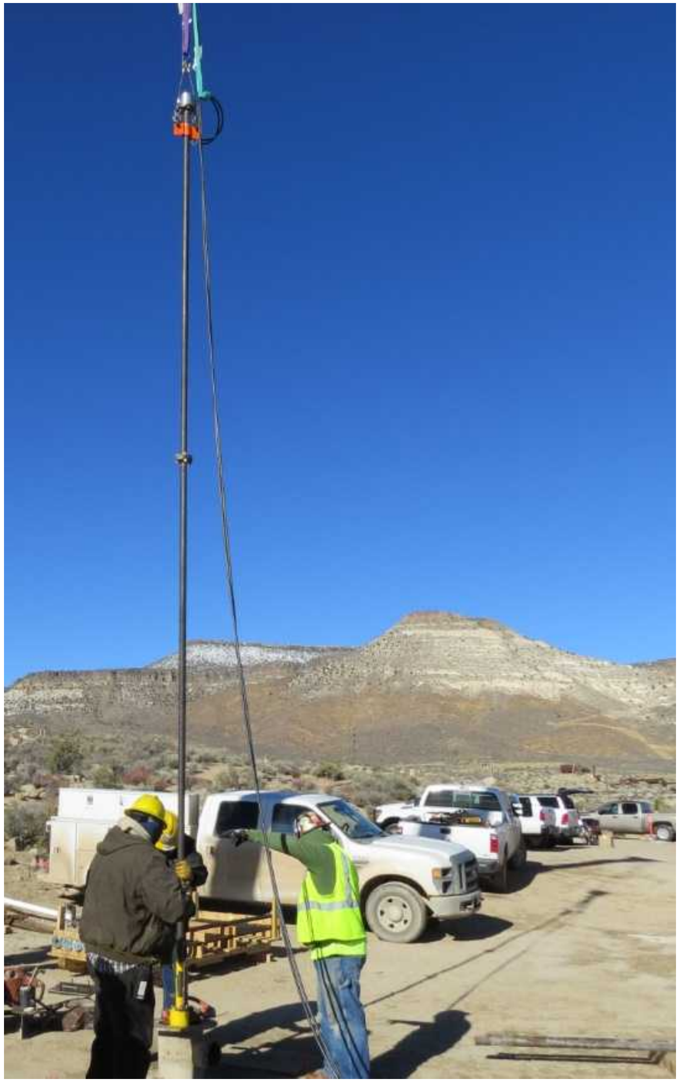


Package Assembly

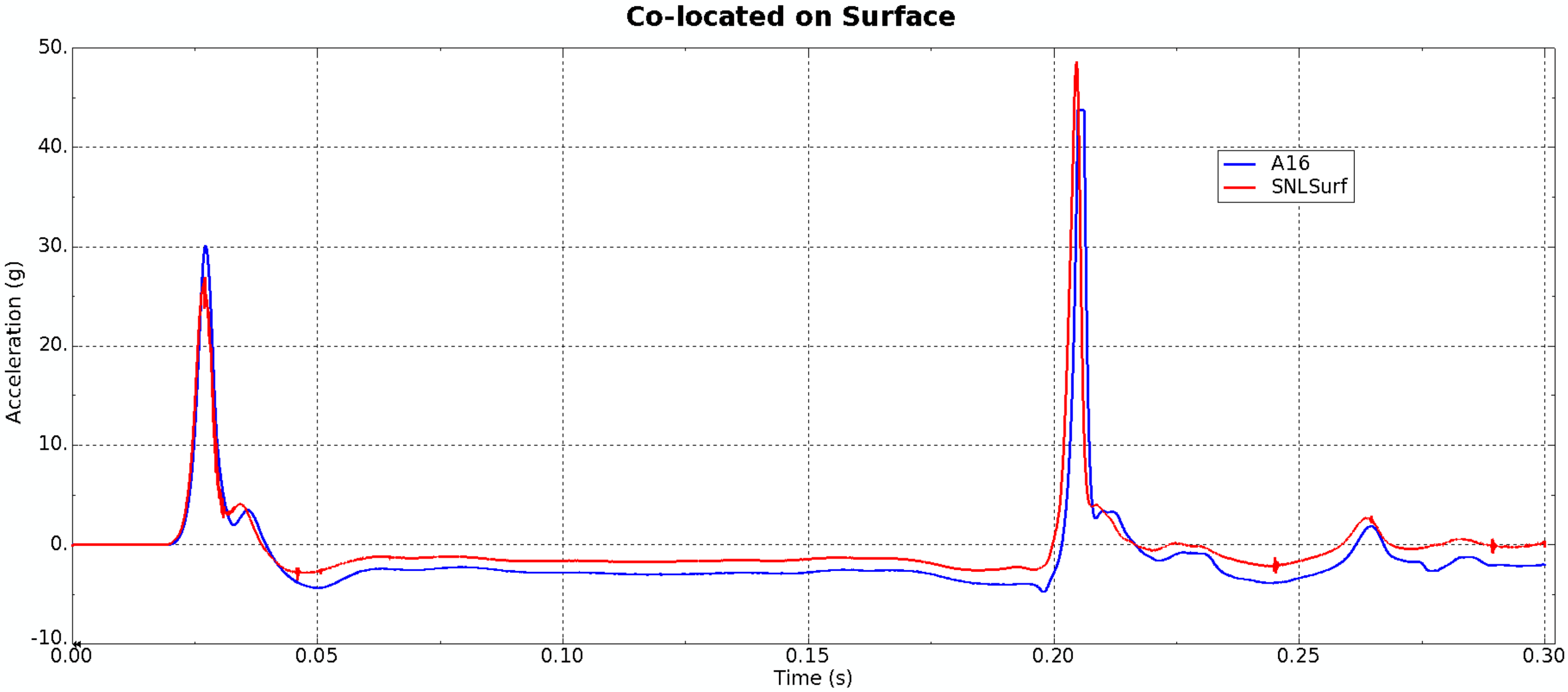
- 1.75” Diameter center through hole for cable running
- Flange interface for pipe string attachment
- 2 Triaxial, 2kg, DC-10kHz response redundant accelerometers wired separately
- Wires are soldered and protected with internal melt heat shrink tubing
- Body is 6061-T6 Aluminum
- After functionality verification, accelerometers and wires are potted in DP270 3M Clear Potting Compound for protection and stability



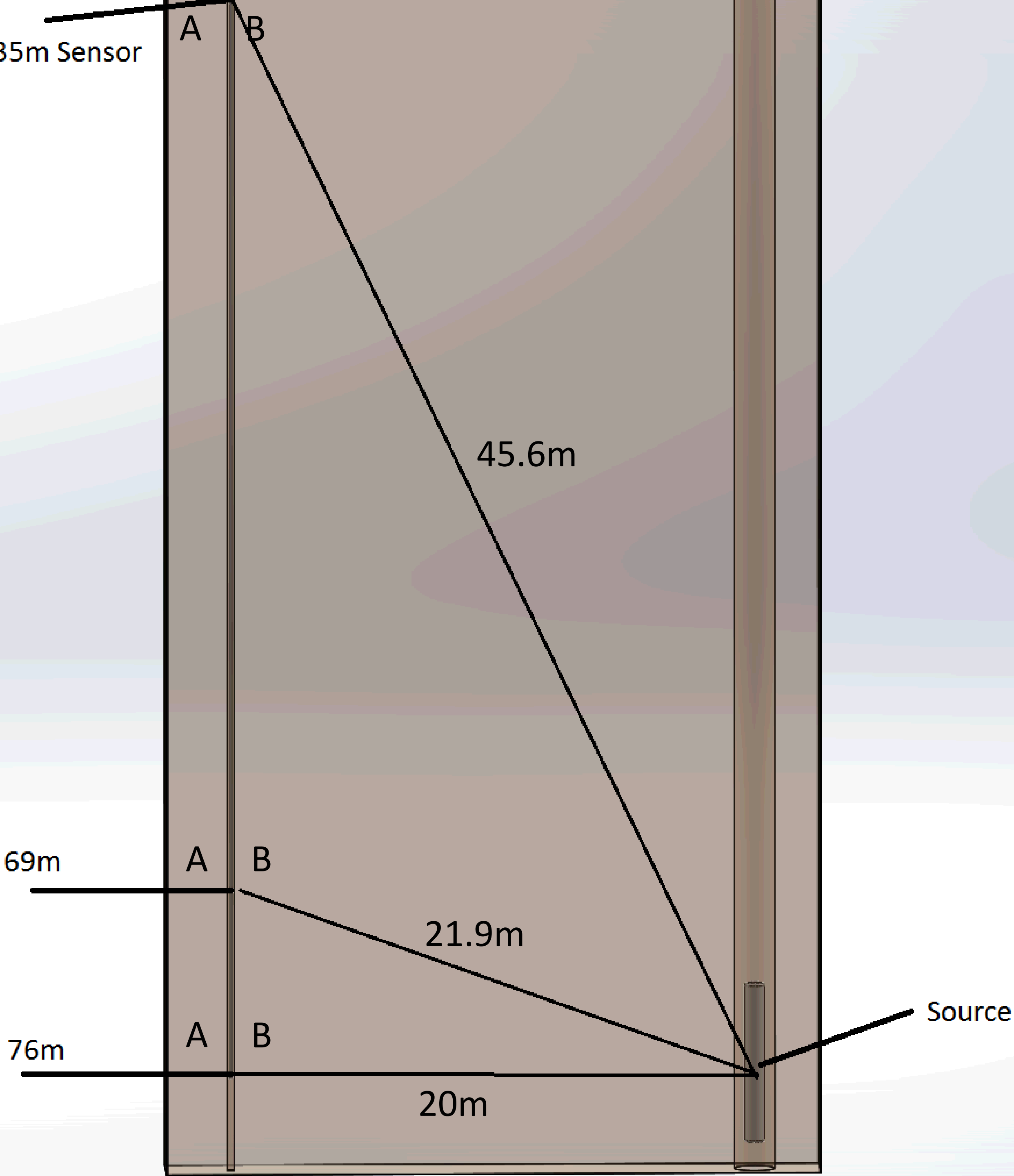
Field Installation



Direct Comparison to DTRA DAS



Plot from Dave Steedman (LANL)



$$Rate = \frac{D_{Path}}{t_{Arrival}}$$

Speed through path to 35m Sensor:
t = 8.594ms
R = 5308 m/s

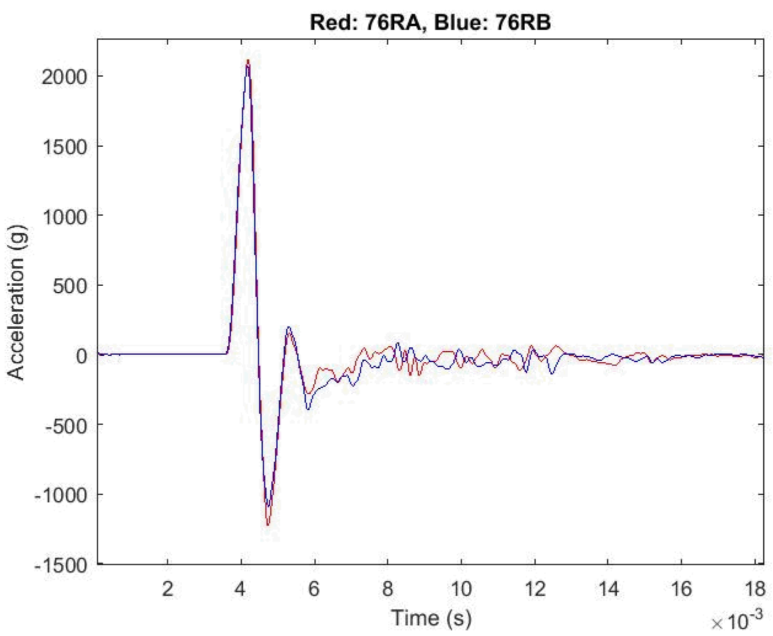
Speed through path to 69m Sensor:
t = 3.730ms
R = 5681 m/s

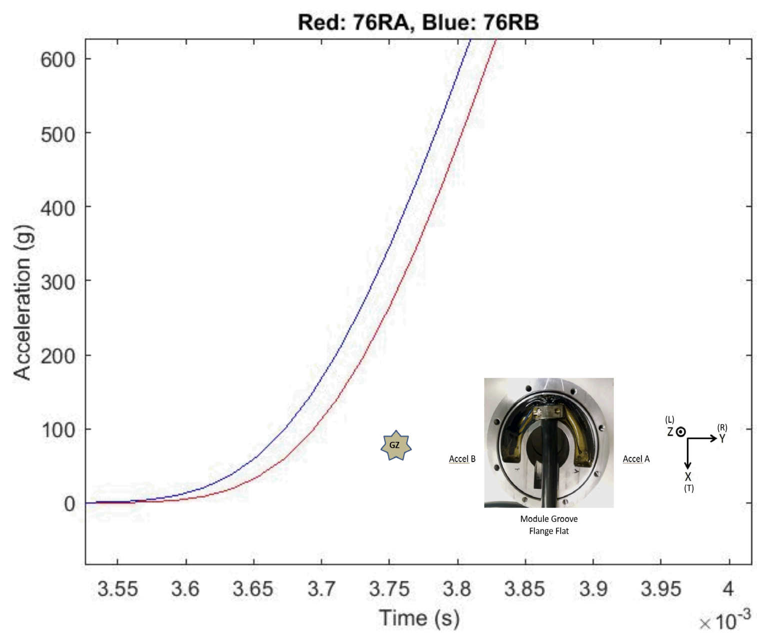
Speed through path to 76m Sensor:
t = 3.496ms
R = 5721 m/s

Note: Positions are nominal

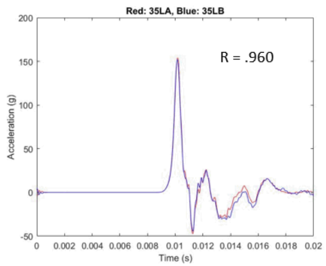
Arrivals

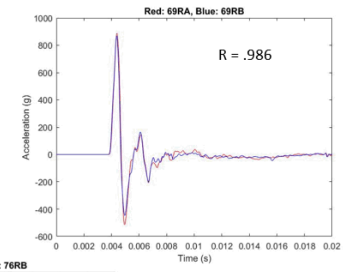
- Accelerations arrive in the expected order: (76m, 69m, 35m, Surface)
- Within the 69m and 76m canisters, the signal arrives first at the gauge closer to GZ (Gauge B)

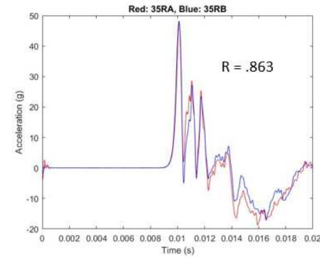


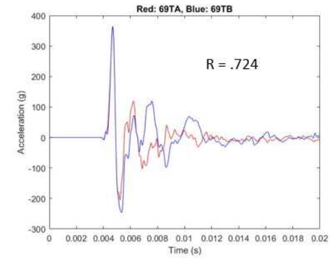


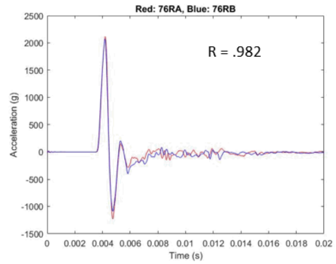
Comparison of Redundants

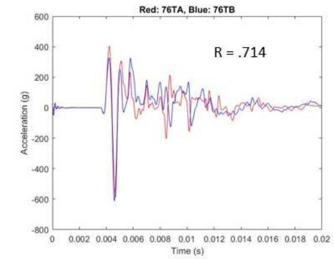


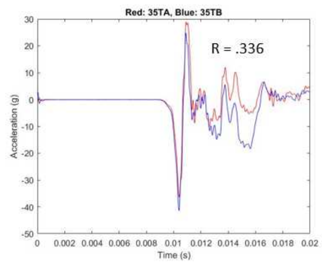


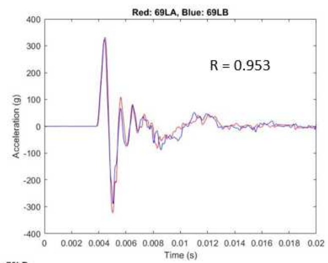


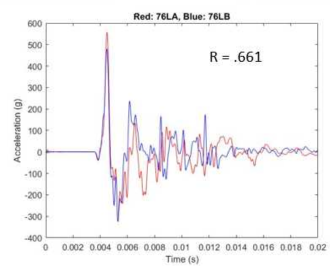






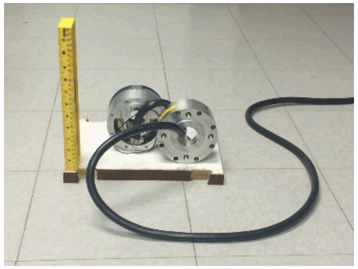




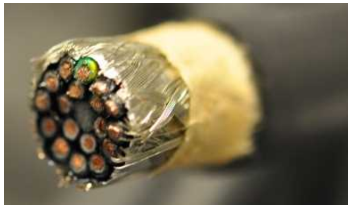


Possible causes of gauge disparities

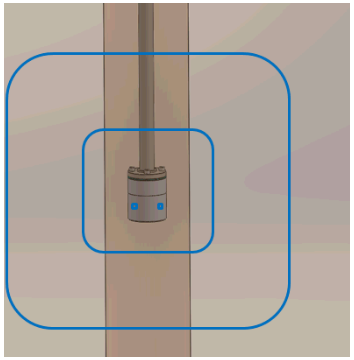
1) **Sensor Decoupling**: Late time failure of the accelerometer coupling to the canister housing



2) **Cable Noise**: Cross-talk and/or triboelectric and/or other noise picked up in the cable (confirmed)



3) **Local Vibrations**: Pitch/roll/yaw/ring vibrations of the canister detected by the diametrically opposed accelerometers (tested in SPE-6)



Phase I – SPE 6 Design

Primary Diagnostic

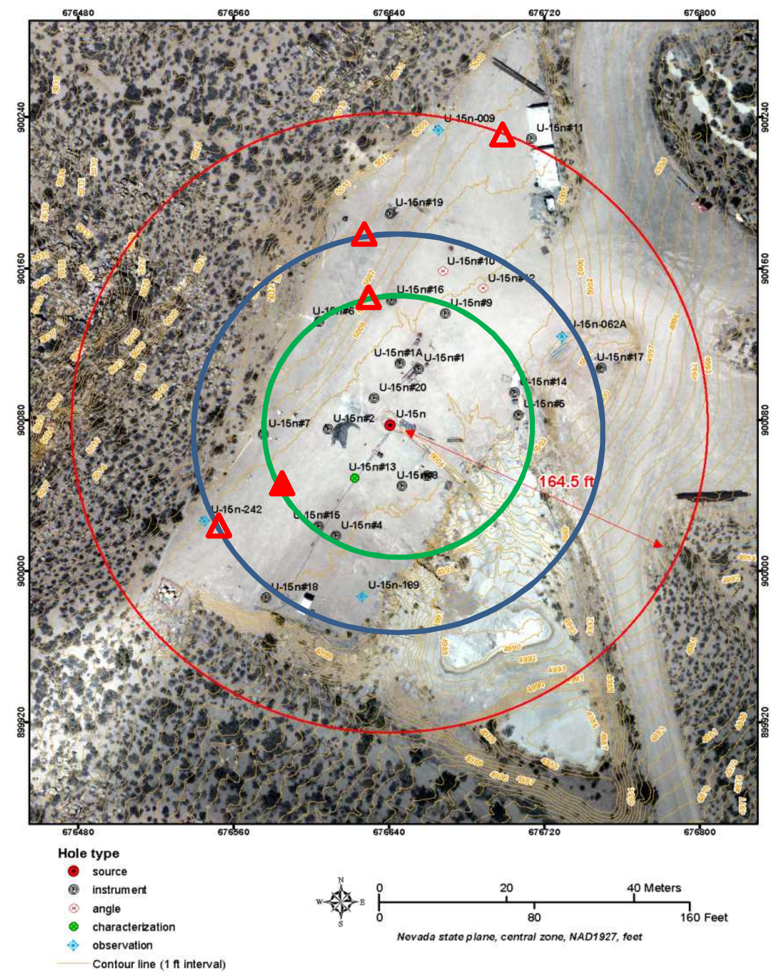
SPE-6 Peak Acceleration Predictions

- 2200kg Source
- Depth: 32.8m

20m Radius: 451g (1)

30m Radius: 162g (2)

51m Radius: 44g (1)

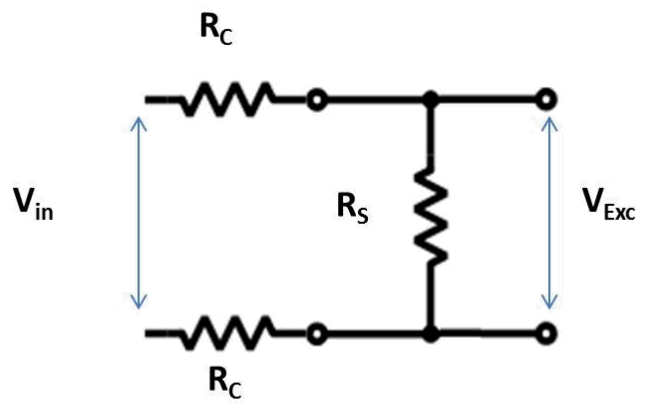


SPE-6 vs. SPE-5 System

- Uniaxial accelerometers mounted triaxially
- Double o-ring sealing
- Same or very similar accelerometers to the previously installed DTRA systems
- Individually shielded twisted pair cables
- 6-wire interface instead of 4-wire
- Redundant accelerometers mounted directly to one-another
- Local vibrations tested in 20m canister

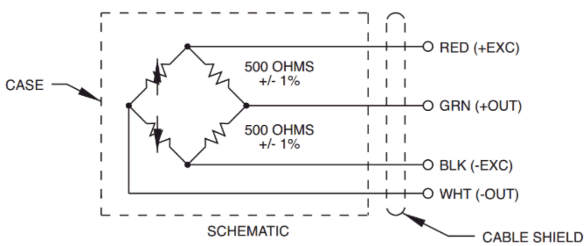
4-wire vs. 6-wire

4-wire

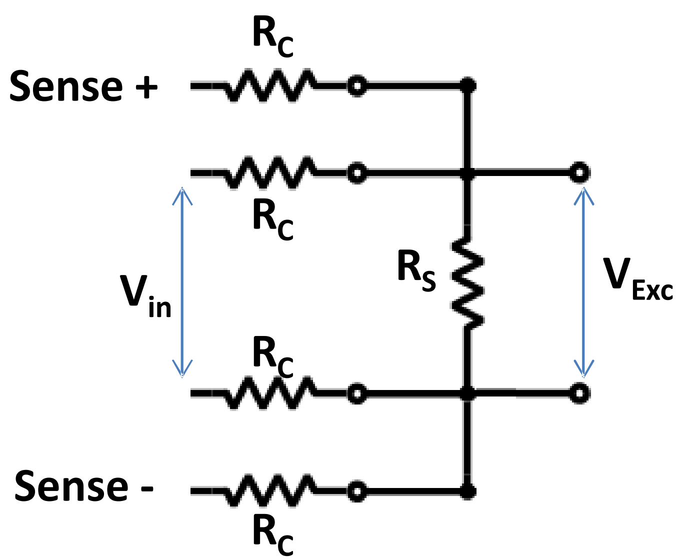


$$\frac{V_{in}}{2 * R_C + R_S} = \frac{V_{Exc}}{R_S}$$

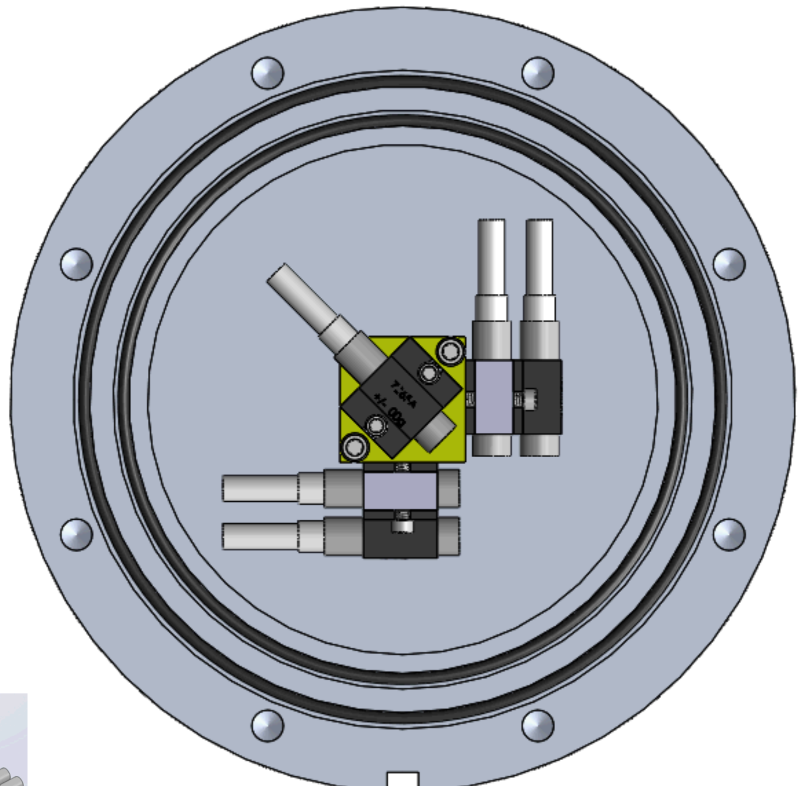
$$V_{Exc} = \frac{V_{in} R_S}{2R_C + R_S}$$



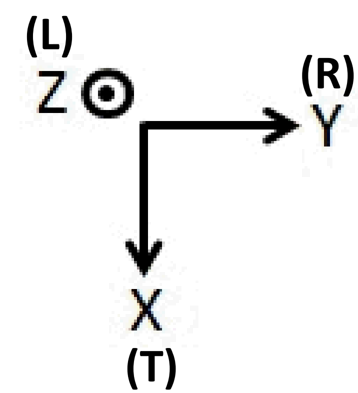
6-wire

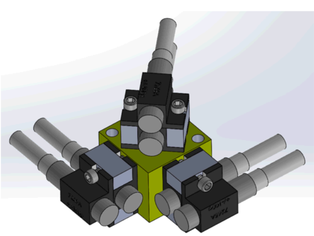


Accelerometer Axes

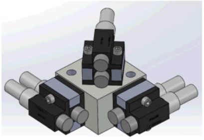


Module Groove
Flange Flat

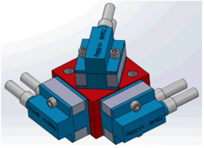




+/- 100g



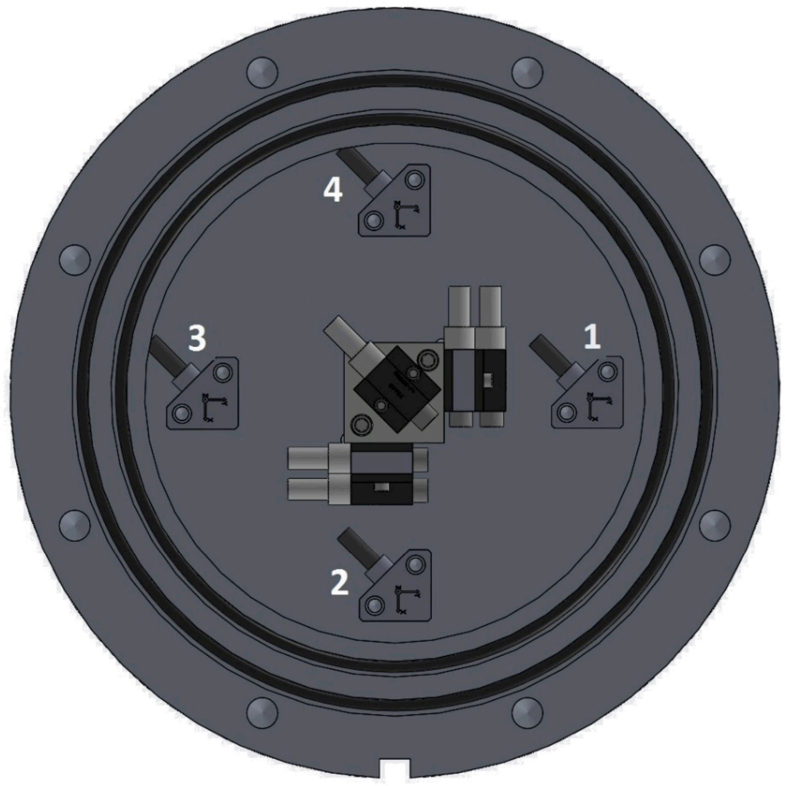
+/- 2000g

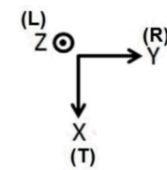


+/- 500g

SNL 20m Installation

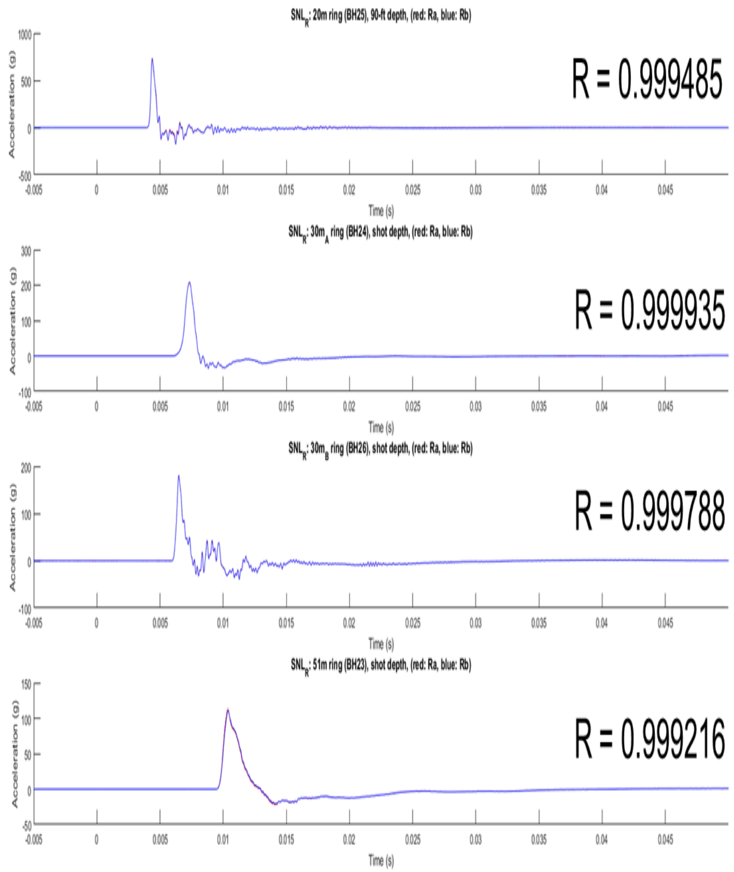
Sensor Depth: 27.31m





Radial – Velocity estimation from TOA

Time of Arrival



Velocity to 20m Node: ~5236m/s

Velocity to 30mA Node: ~4987m/s

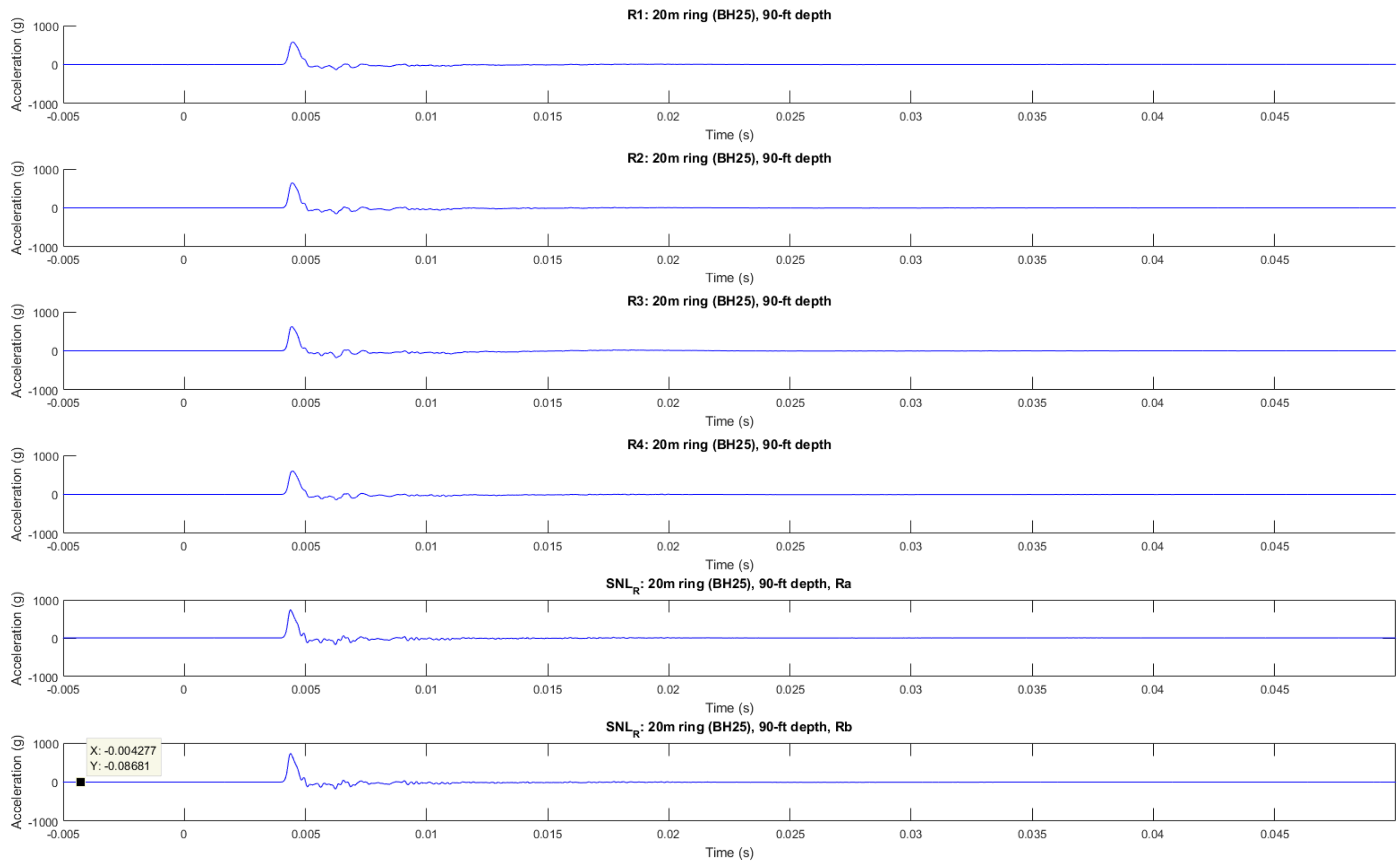
Velocity to 30mB Node: ~5069m/s

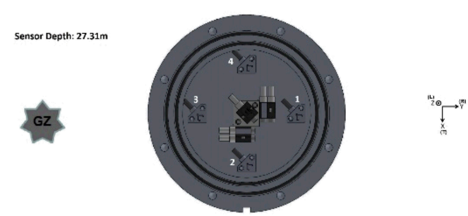
Velocity to 51m Node: ~5384m/s

Literature P-Wave Velocity of Granite: 4500 – 6000 m/s

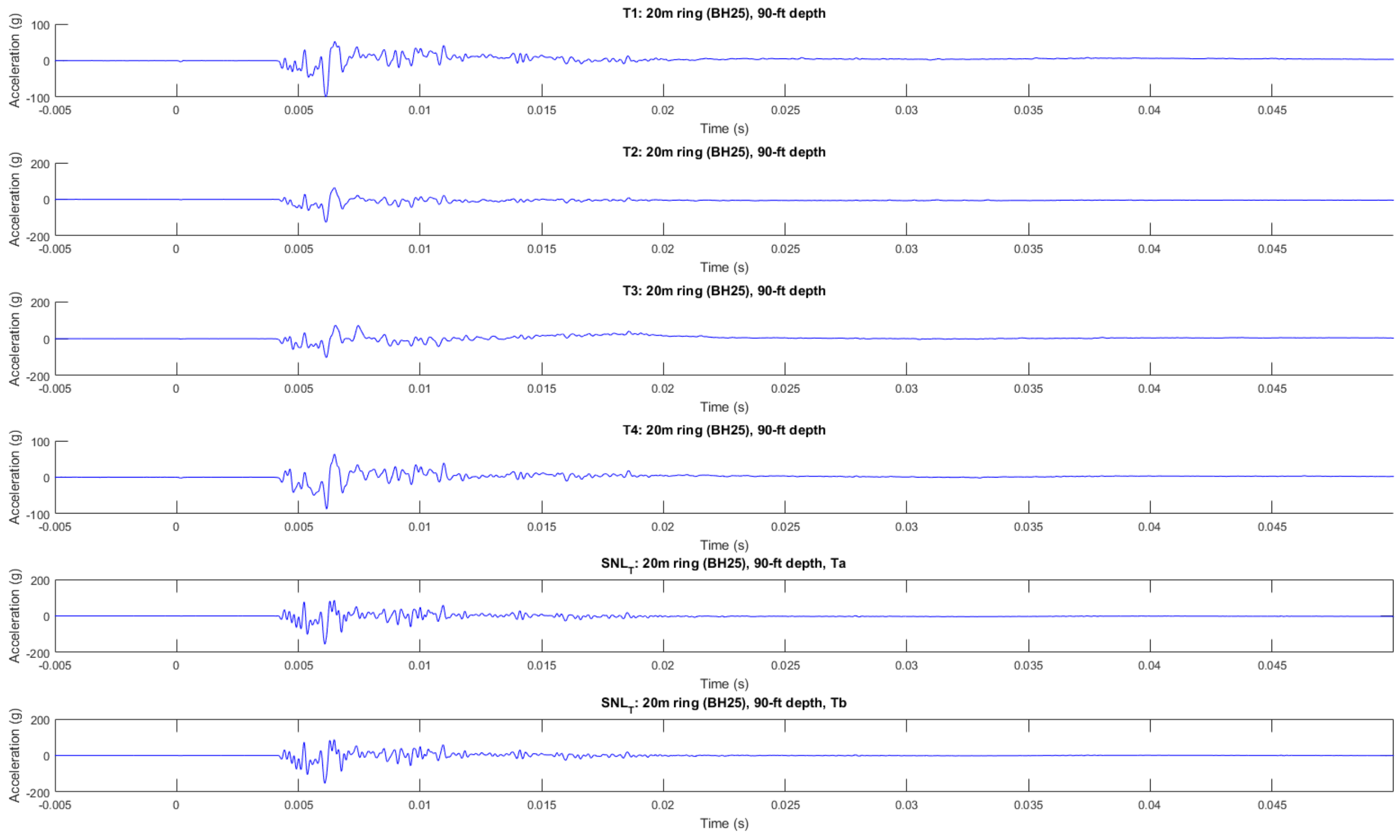
Elements of 3D Seismology
Christopher Liner

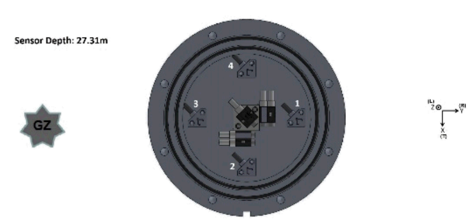
20m (6 independent radial gauges)



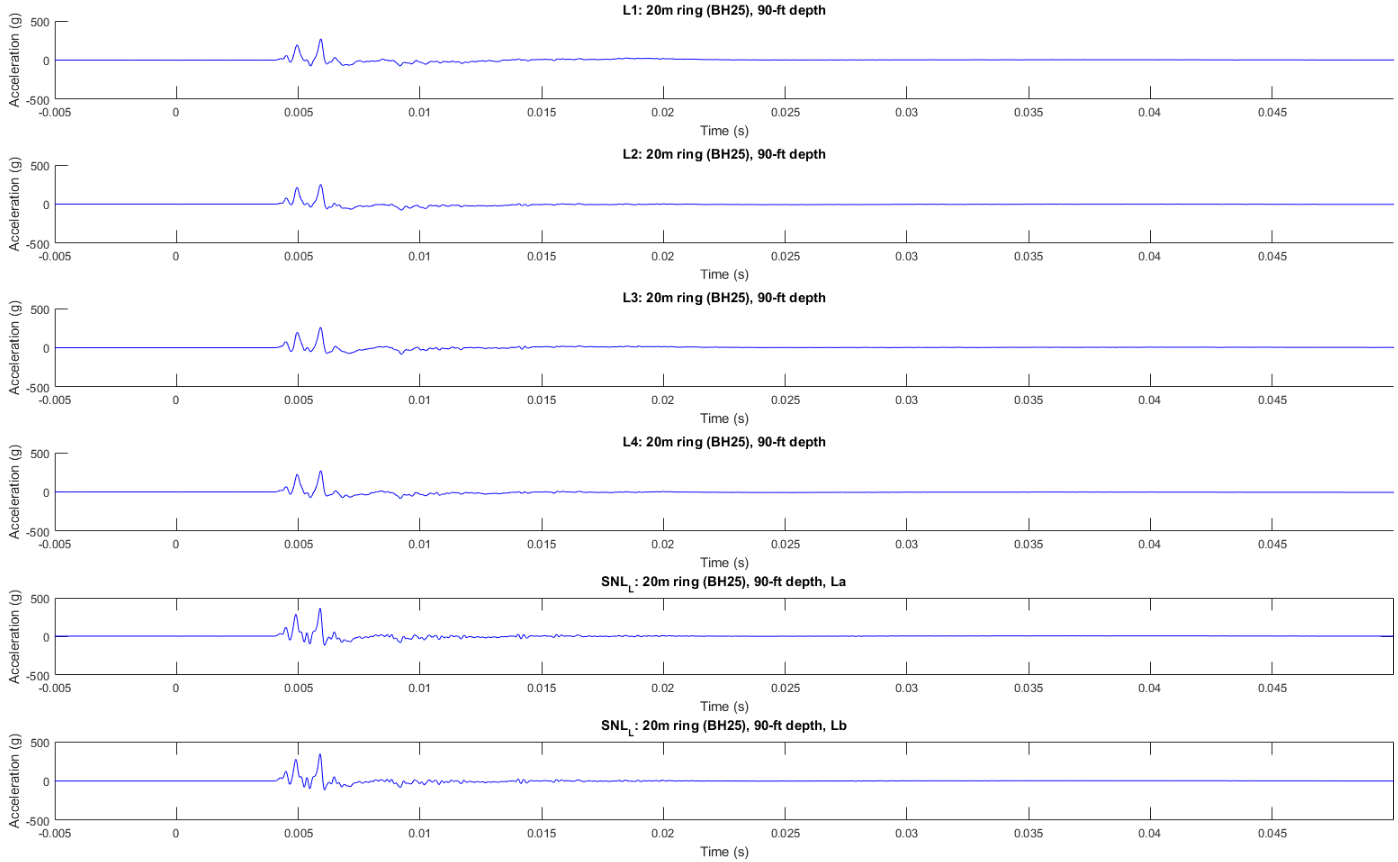


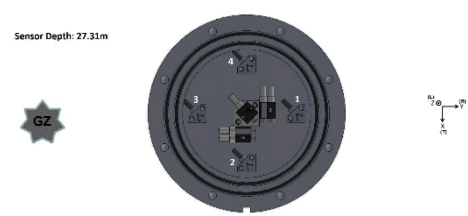
20m (6 independent transverse gauges)



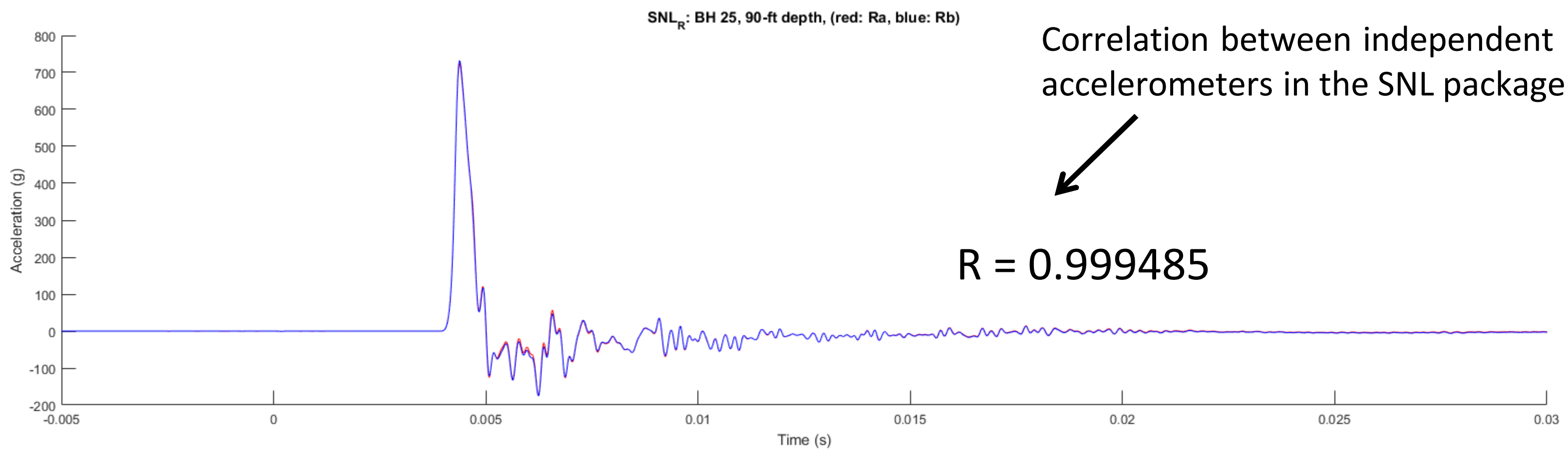


20m (6 independent lateral gauges)



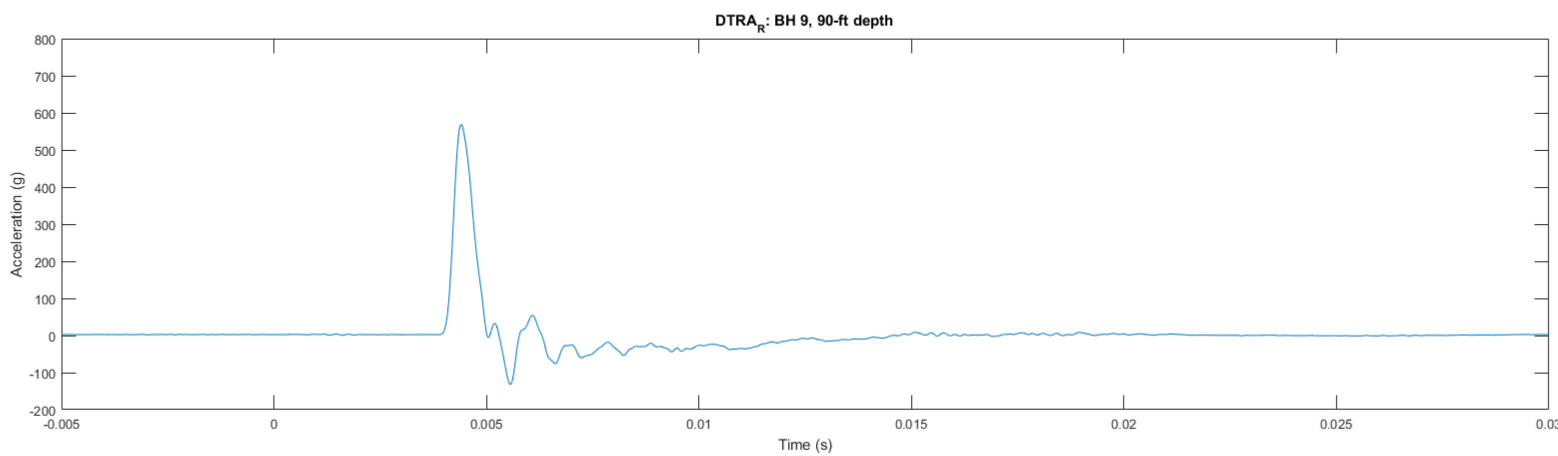


SNL and DTRA Comparison (Radial)



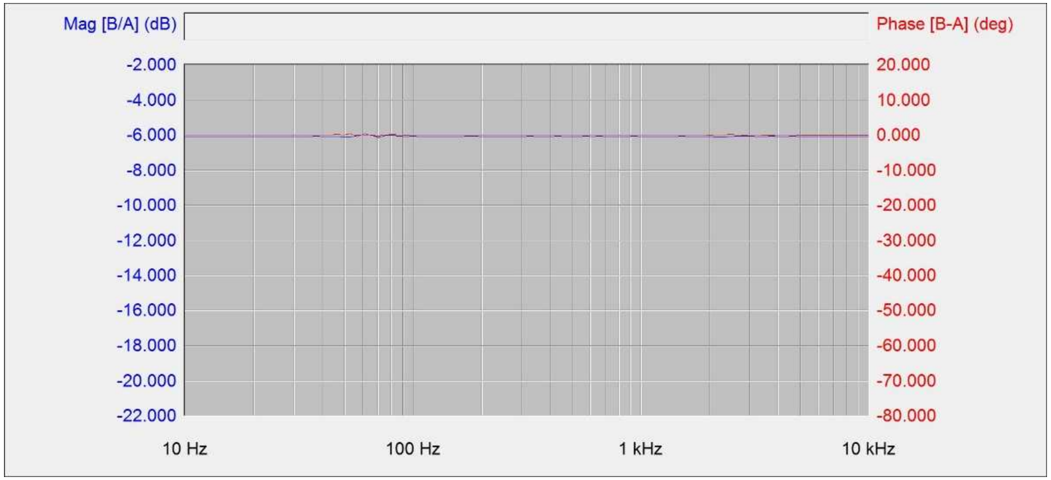
Correlation between independent accelerometers in the SNL package

R = 0.999485

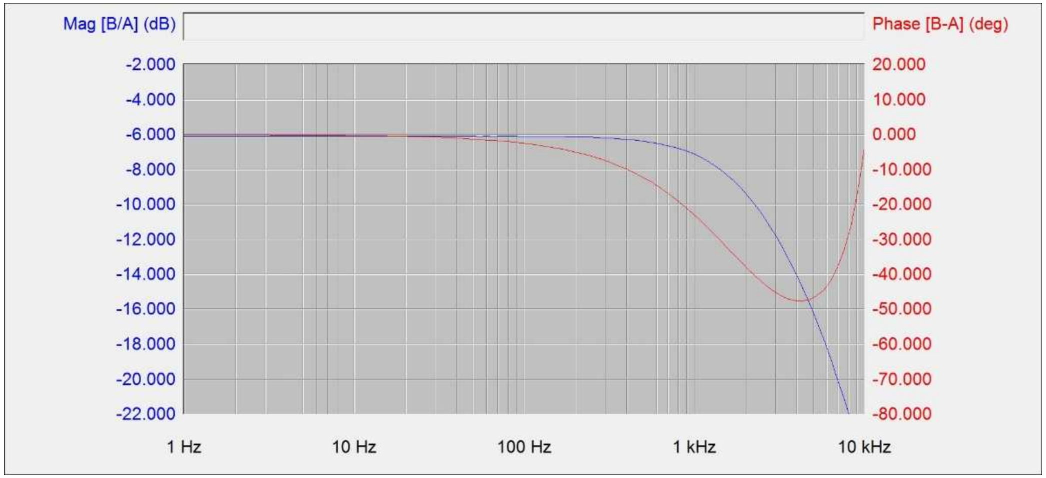


Spectrum Analyzer Results

SNL BH#25 (90 ft depth)



DTRA BH#9 (90 ft depth)



Data collected with an AP Instruments model 300 frequency response analyzer

Phase I Summary

- Borehole acceleration data was collected for all 6 Phase I experiments with improvements made throughout the series.
- SPE-1 & SPE-2 (DTRA): NPT flanged pipe sections. No redundant sensors in in T or L axes. Rotational alignment questions arose from inverted data.
- SPE-3 & SPE-4’ (DTRA): Welded pipe flanges, alignment pin, no redundant sensors in T or L axes. Some sensor failures.
- SPE-5: Last DTRA experiment. Sandia installed prototype canisters for design vetting. Redundant sensors in all axes. Comparison of LMS to DTRA DAS with a co-located surface sensor. Lessons learned from DTRA were incorporated in SNL design but late disagreement between redundant sensors suggested a new issue. Since DTRA systems had no redundant sensors, direct comparison was not possible. Triboelectric/cross-talk cable contamination confirmed from bulk twist cable, local vibrations tested on SPE-6.
- SPE-6 (SNL): 6-wire shielded twisted pair installation, welded pipe flanges, direct mounting of redundant sensors rather than diametrically opposed, additional diametrically opposed sensors show local vibrations but waveform shapes are similar. Frequency response questions arose from comparison to DTRA data. Spectrum analyzer showed that DTRA installations have a more narrow frequency response due to cable filtration. Velocity correlation vs acceleration correlation questions will be addressed in the laboratory with Laser Doppler Vibrometer testing.
- All Phase I accelerometers are piezoresistive bridge type which have high output impedance. Phase II installations will use significantly longer cables so we will use low output impedance IEPE sensors to reduce cable filtration and noise susceptibility.