Paulsson, Inc. (PI)

Björn Paulsson, Mike Wylie, Ruiqing He,
Ali Nekourouh, Jacob Shaw, Raul Pech, Alexis Saucerman, Rob Ramirez,
Gavin Markowitz, Cesar Inda, Steve Phillips, Panaya Srisook – The Team

Development of an Optical Based Single Well Seismic System (OSWS) for Improved CCUS, UGS+H2, EGS & EEOR Characterization and Subsurface Monitoring (SC0018613)

DOE 2022 Resource Sustainability Project Review Meeting
October 25, 2022

Single Well Seismic Project – DE-SC0018613

Survey and Monitoring Markets (>$2T) for Single Well Seismic Technology and Fiber Optic Seismic Vector Sensors (FOSVS)

- Carbon Capture Usage and Storage (CCUS)
  - >14,000 wells to be drilled before 2050
- Underground Gas Storage (UGS: NG, NG+H2, H2)
  - >$750 Billion market by 2026
- Enhanced Geothermal Systems (EGS)
  - EGS Potential: 2,300GW = 2X Current Electric Produc.
- Cleaner Enhanced Oil & Gas Recovery (CEOR)
  - We currently leave 65% behind in known location
- Nuclear Energy – generate and store Green H2
- Wind Energy Installations (WEI – OWCal) – store Green H2

Single Well Seismic Presentation

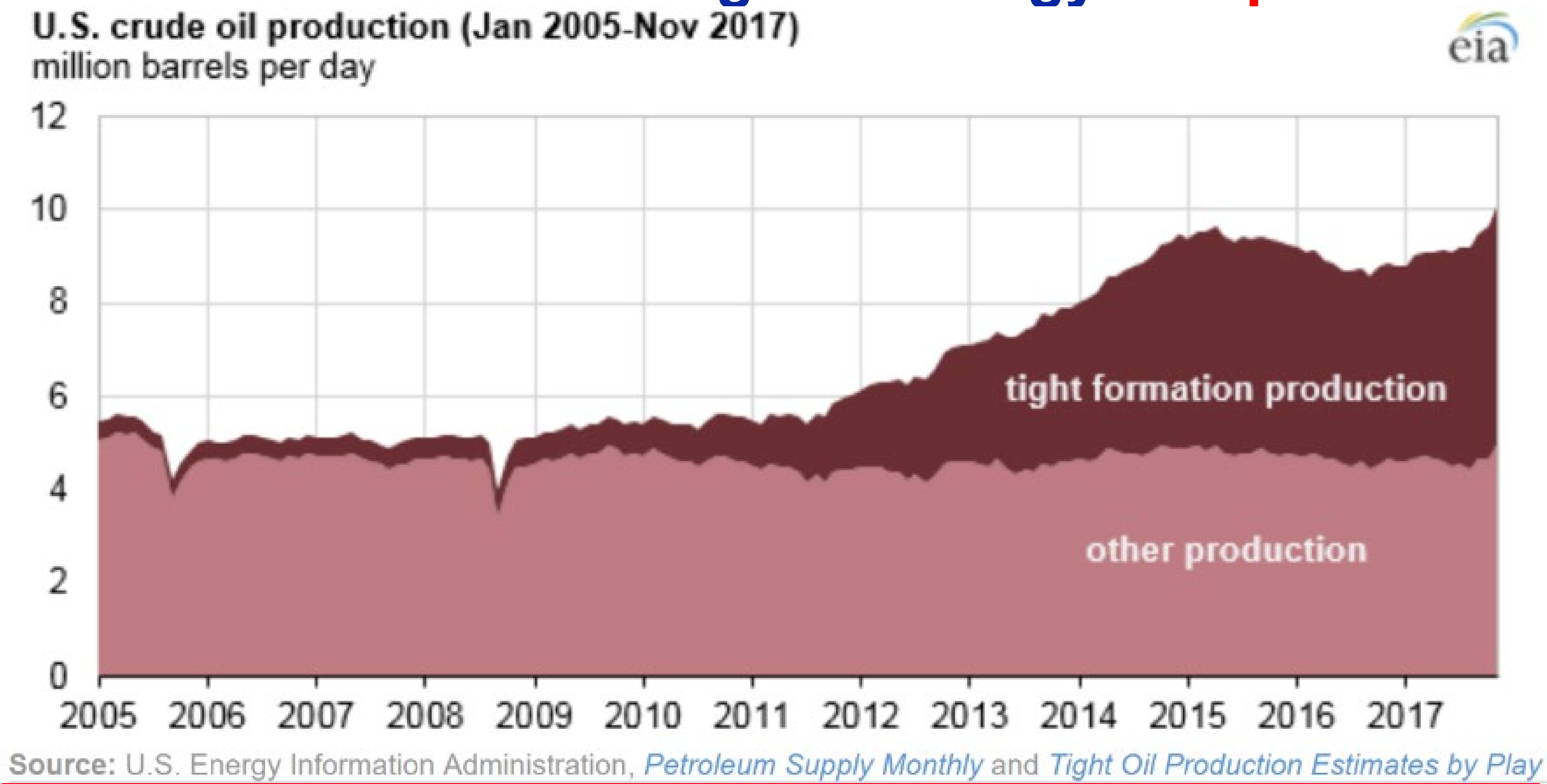
- Optical Sensors
  - Optical Accelerometers: DE-FE0024360
- Borehole Seismic Sources: DE-SC0018613
- Applications & Examples

Strengths of Fiber Optic Seismic Vector Sensors (FOSVS)

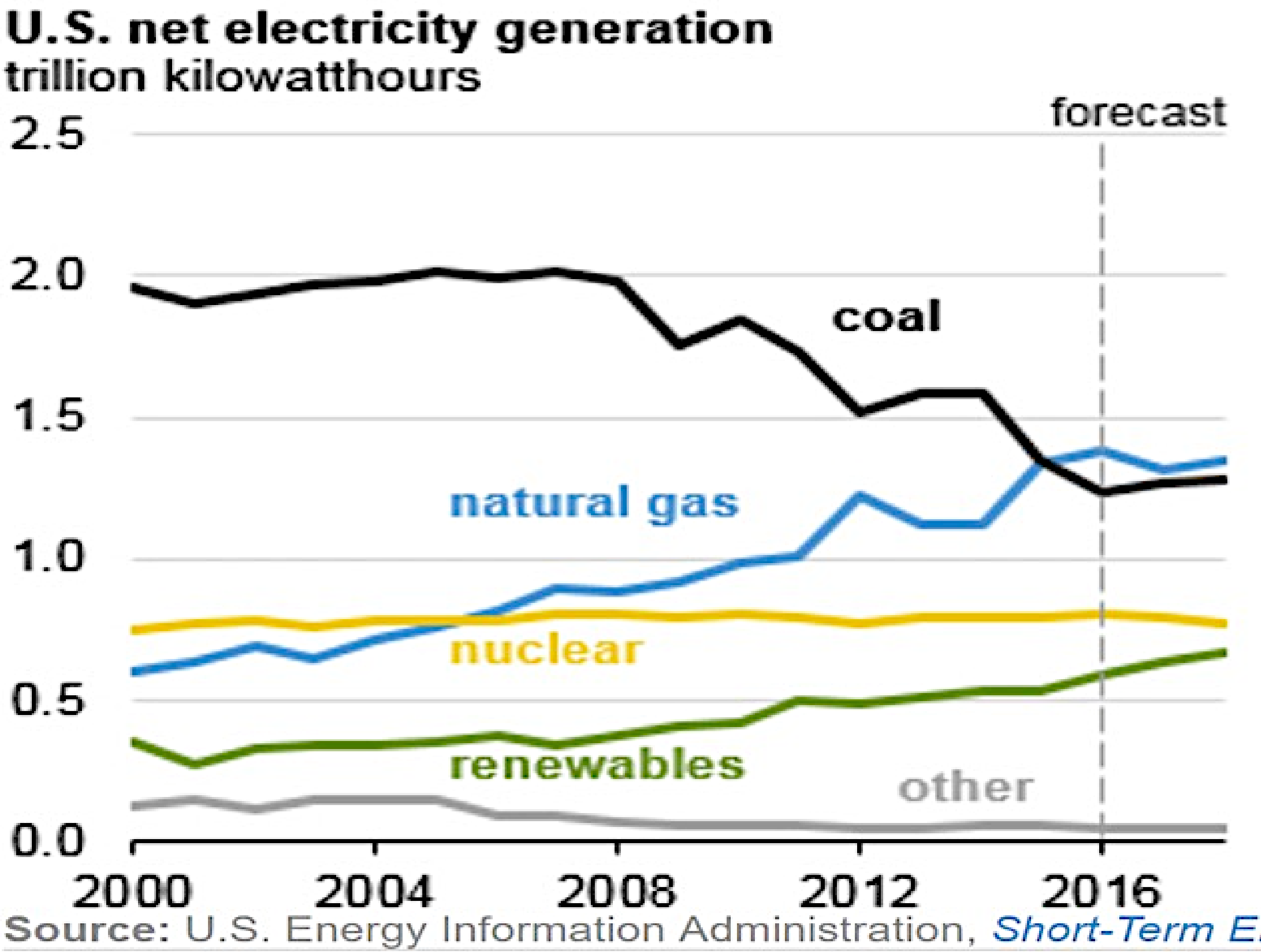
- **Long term stability: 30-year MTBF by the Navy**
- **Very large bandwidth: 5 Hz - 14,000 Hz**
- **Extremely sensitive: 100X a geophone**
- **Outstanding Vector Fidelity: (80 dB)**
- **Very High Temperature Tolerant: >320°C (700°C)**

- **Intrinsically Safe and Very Robust**

CCUS is ESSENTIAL to Maintain the USA Oil Production! Current UOG Recovery is 5-8% of OOIP at a cost of $120 Billion for the 20,000 wells drilled/year. Effective and Monitored CCUS will Double Our Oil Production & Maintaining our Energy Independence!



Natural Gas Is Critical For Electricity Generation



High Resolution is Critical Effective CCUS

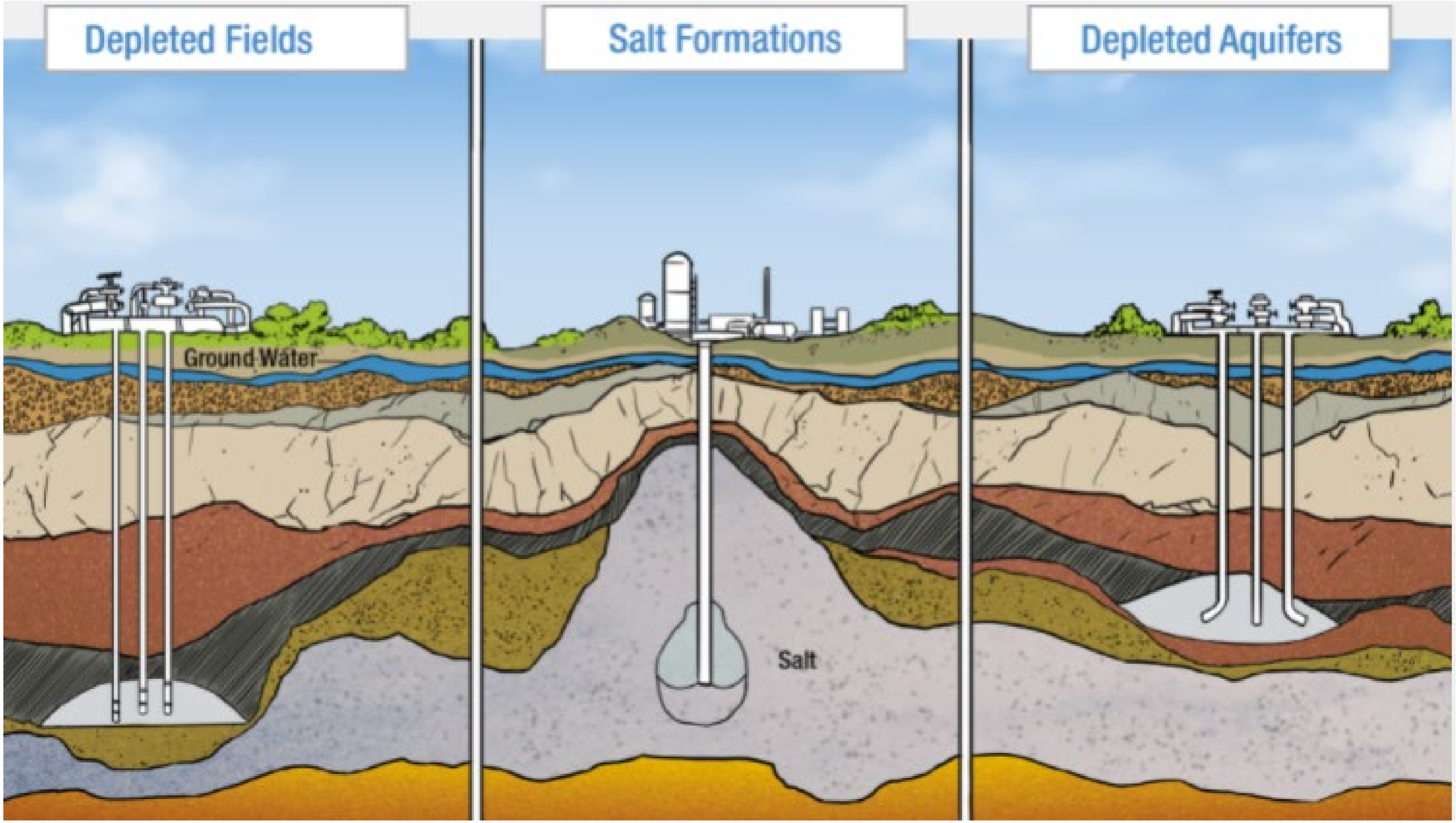
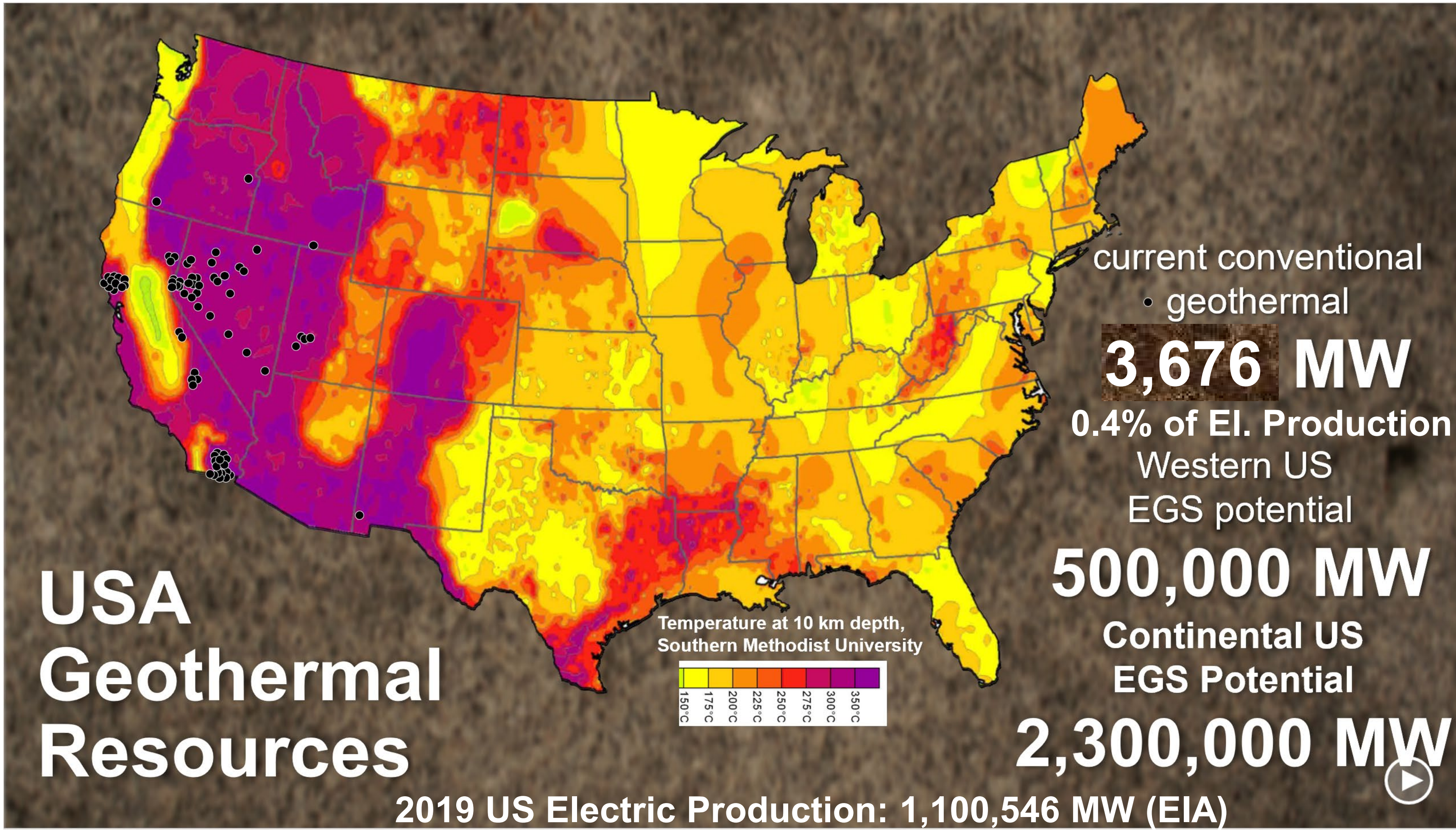
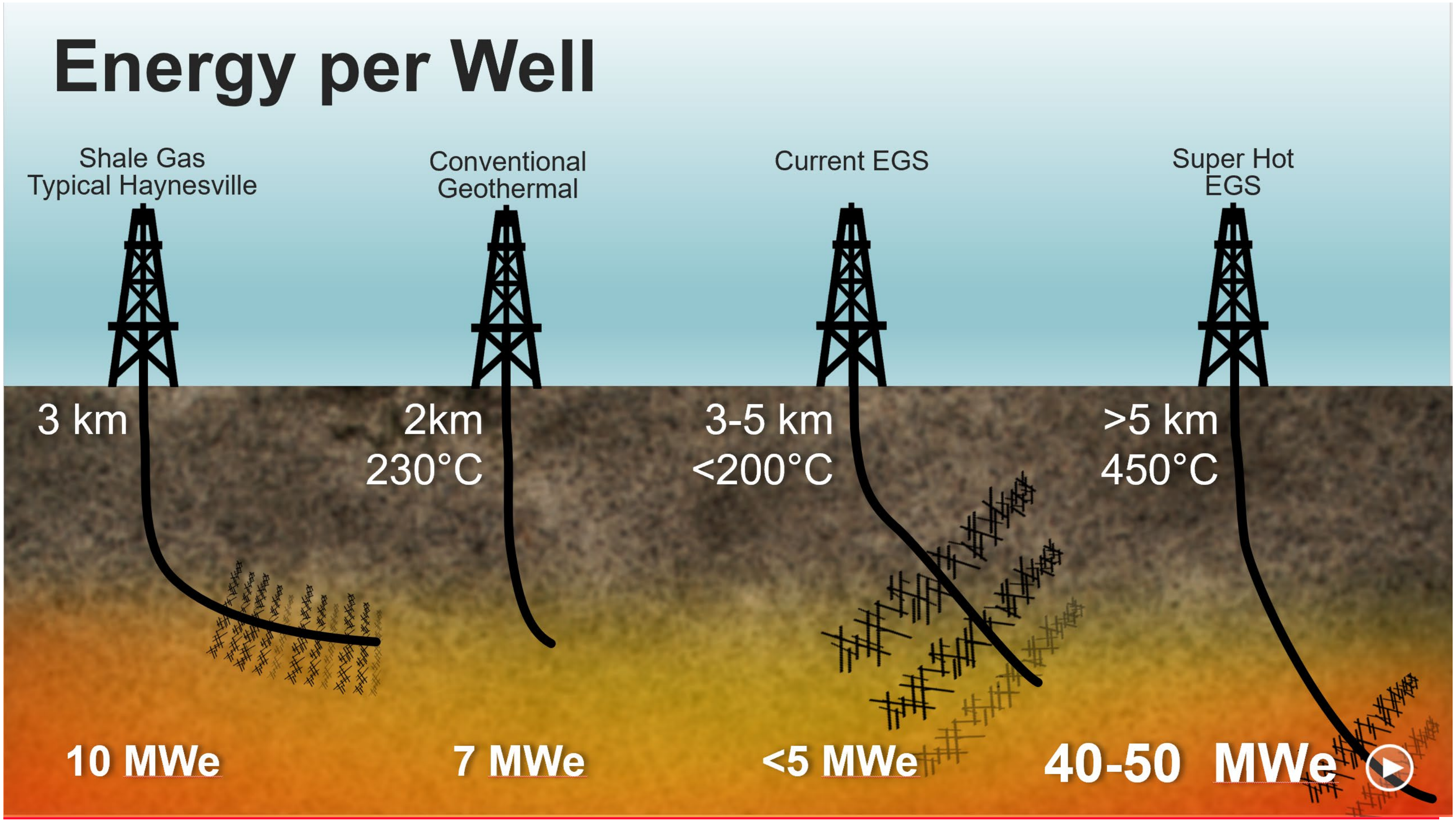


Figure from API showing three applications for improved imaging and monitoring for CCS and UGS applications. From https://energyinfrastructure.org/energy-101/natural-gas-storage.

Geothermal Energy has huge potential but current deployment only "Scratches the Surface" - Enhanced Geothermal System (EGS) potential is 625 X Current Production (4GW) or 2,300GW (New Offshore Wind California 1st step is 4GW)



Geothermal Energy Development Requires High Resolution Imaging and Monitoring of the EGS Power Generation to make it Effective!



To Produce Clean Electric Power
&
Effective Enhanced Oil & Gas (EEOG)
we must
Develop High-Resolution
Subsurface Imaging & Monitoring

Borehole Seismic Source Technologies

- Fluid Coupled Borehole Sources – All couple-in <5% of the source energy into seismic waves. >95% of the Energy Generate Tube waves.
  - Airgun: Powerful but Destructive to the Cement
  - Sparker: Non-Destructive but not enough Power
  - Piezo Electric: Non-Destructive but not enough Power
  - Dynamite: Powerful but Destructive to the Cement
  - Fluid Coupled Vibrators: Narrow Band & Highly Resonant
    - All Generate STRONG TUBE WAVES!!
- Clamped Borehole Sources – Couple in >95% of the source energy into seismic waves.
  - Hydraulic Vibrators: Powerful + Broadband but Complex
  - Piezo Electric & Magneto Strictive Vibrators: Non-Destructive, Broad Band, 3C
    - NO TUBE WAVES

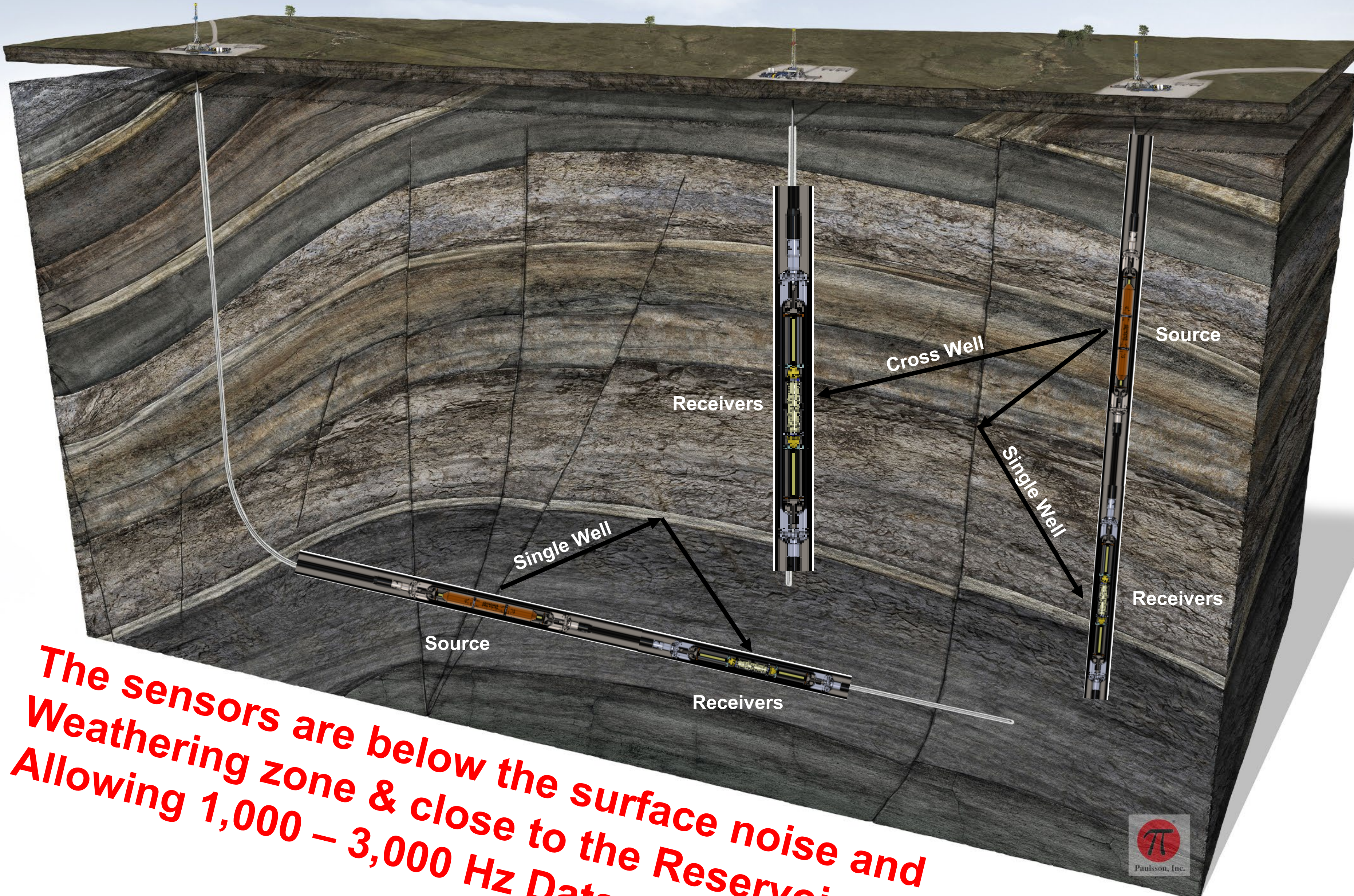
Single Well Seismic Technology

- Borehole Vibratory Source Under Development:
  1. Magneto Strictive Actuator
  2. 3C Source Technology
  3. >250°C (>482°F) capable
  4. Operate in Vertical and Horizontal Boreholes

- Borehole Seismic Receivers Developed and Fielded
  1. All Optical - Vector - 3C Clamped Receivers
  2. Combined with large aperture Rayleigh DAS
  3. Tested at 320°C (608°F) for a week!
  4. Operate in Vertical and Horizontal Boreholes

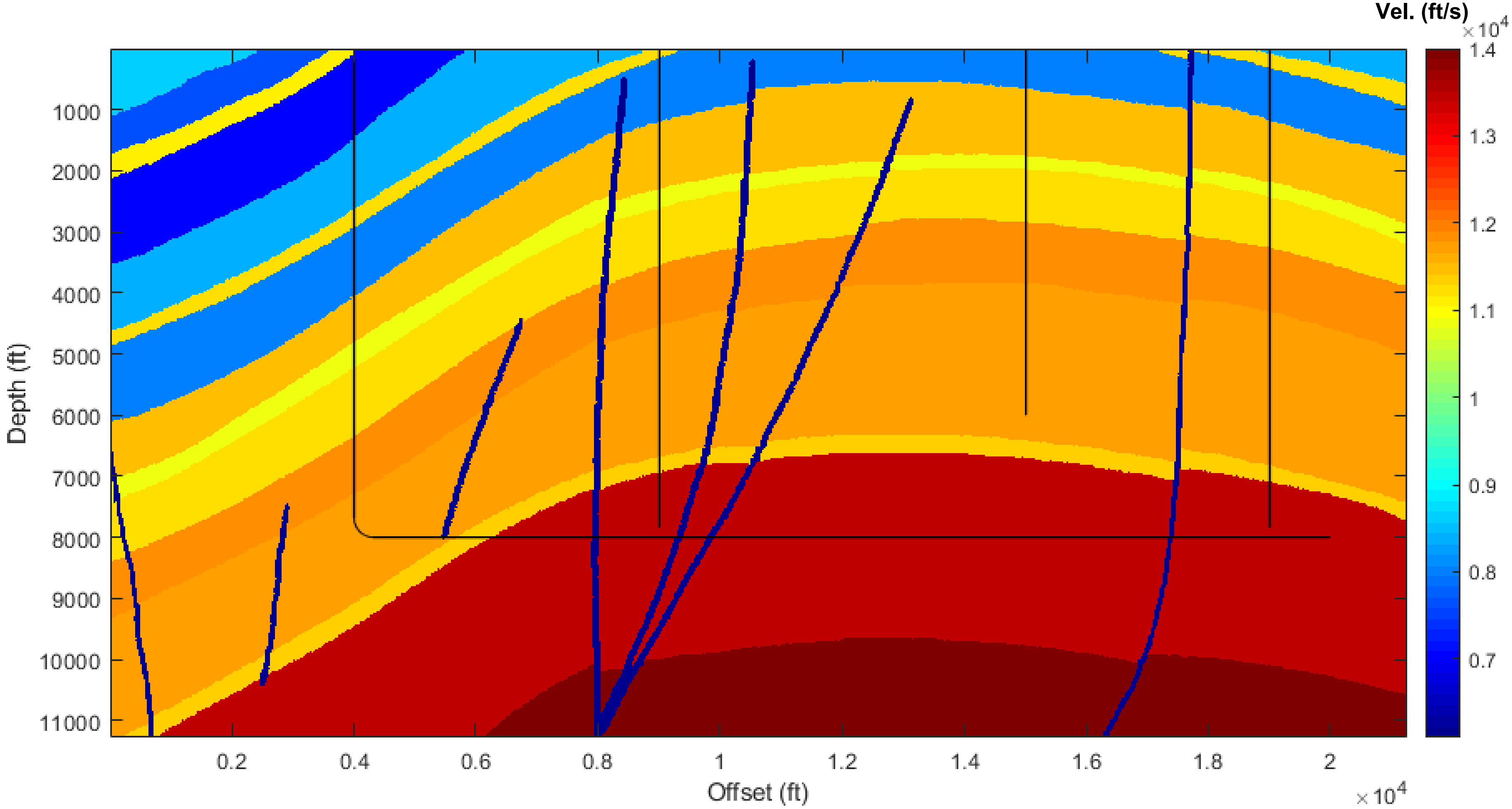
Single Well Seismic Modeling

Single Well Seismic Imaging of Faults and Geology

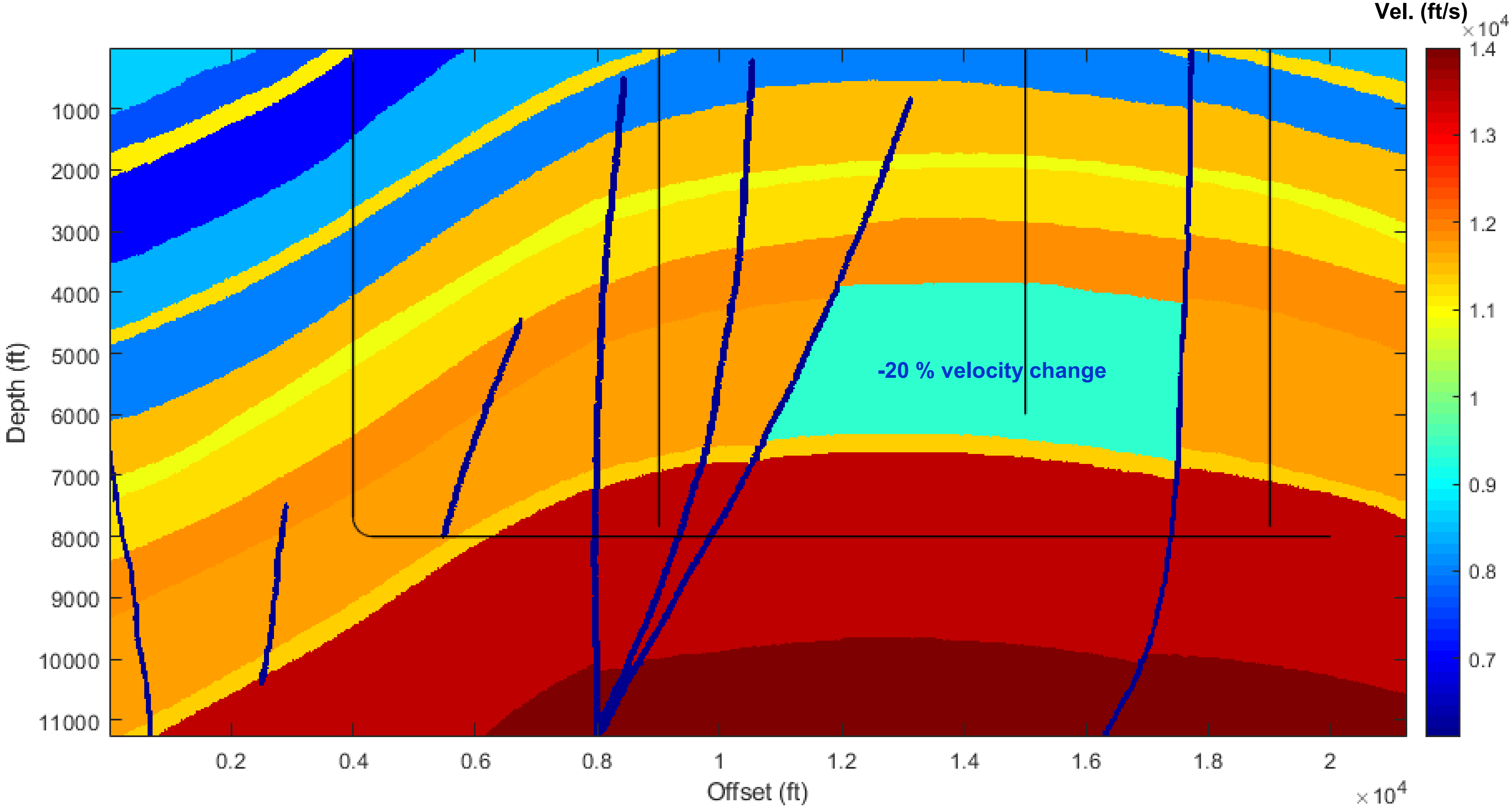


The sensors are below the surface noise and Weathering zone & close to the Reservoirs Allowing 1,000 – 3,000 Hz Data

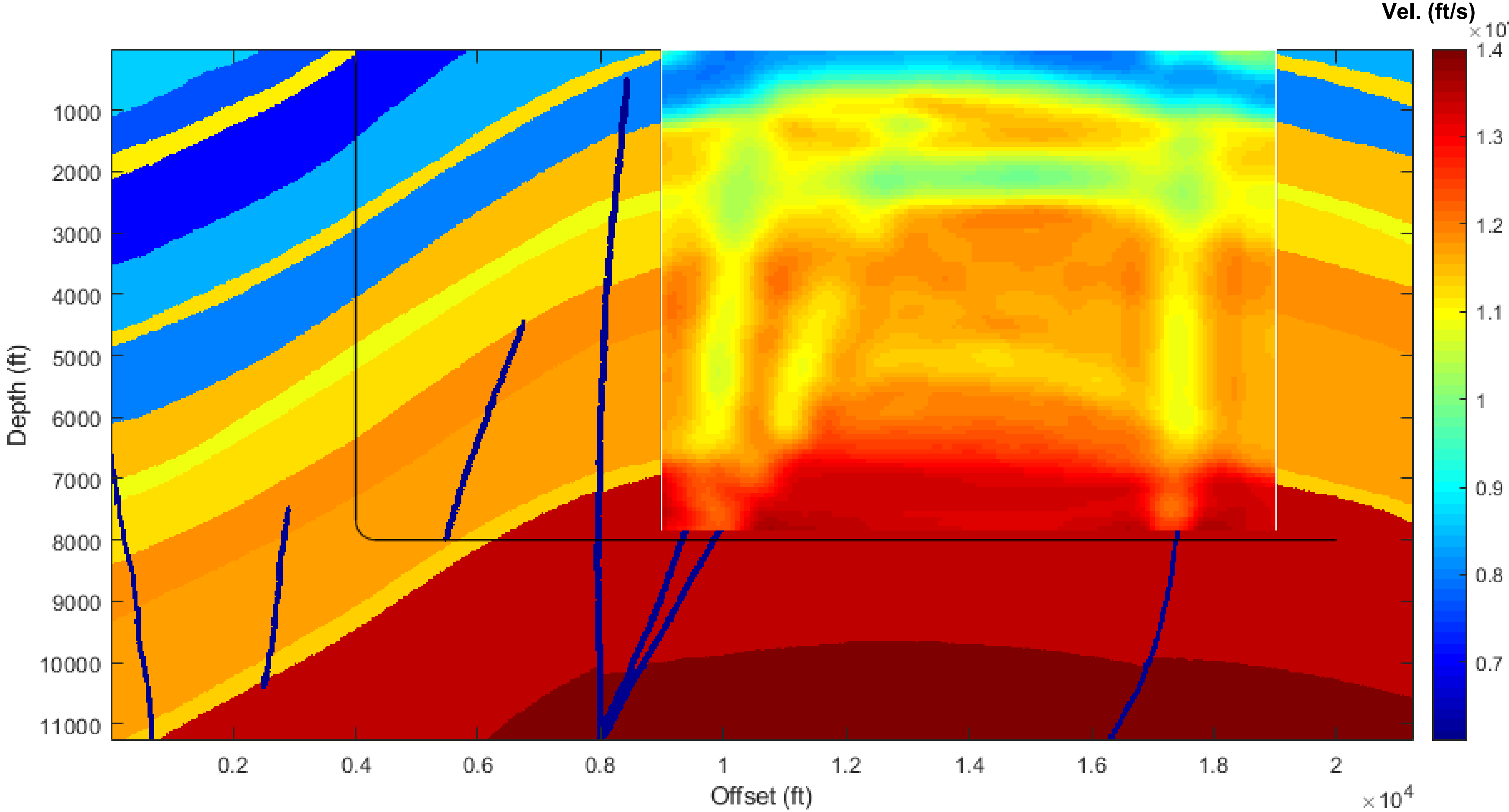
Initial Velocity Model before Fluid Injection



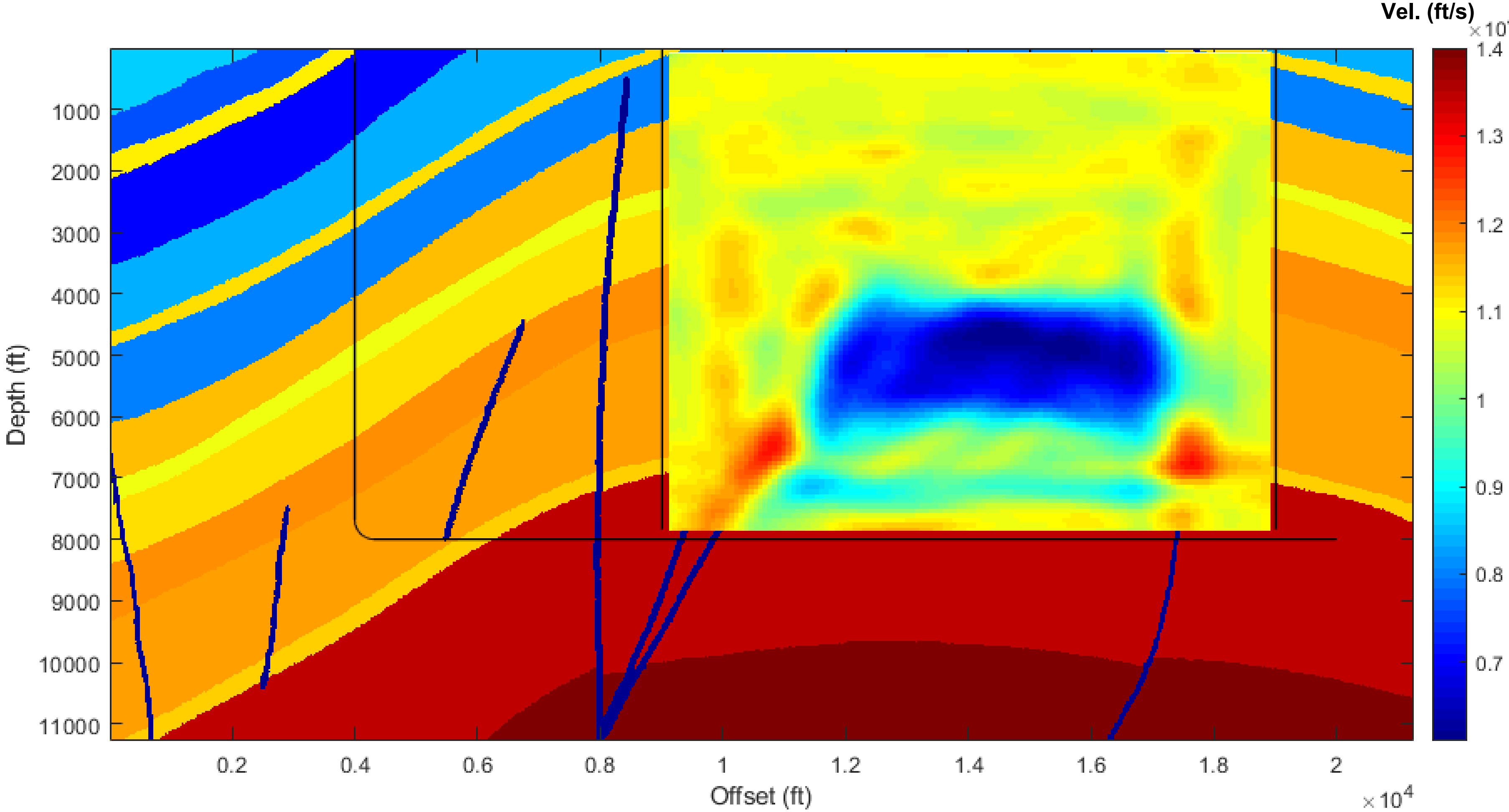
Velocity Model after Fluid Injection



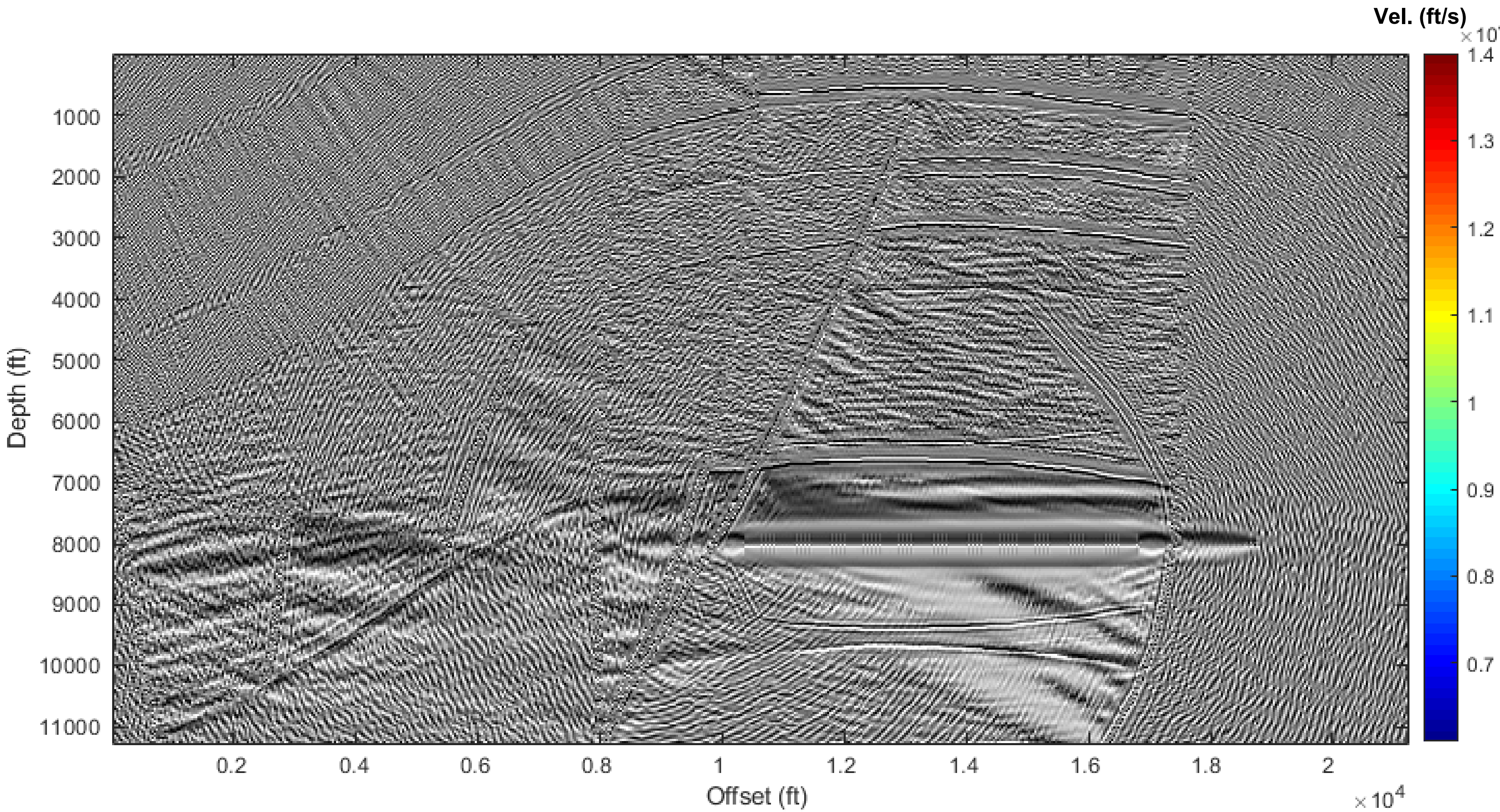
Initial Tomogram before Fluid Injection



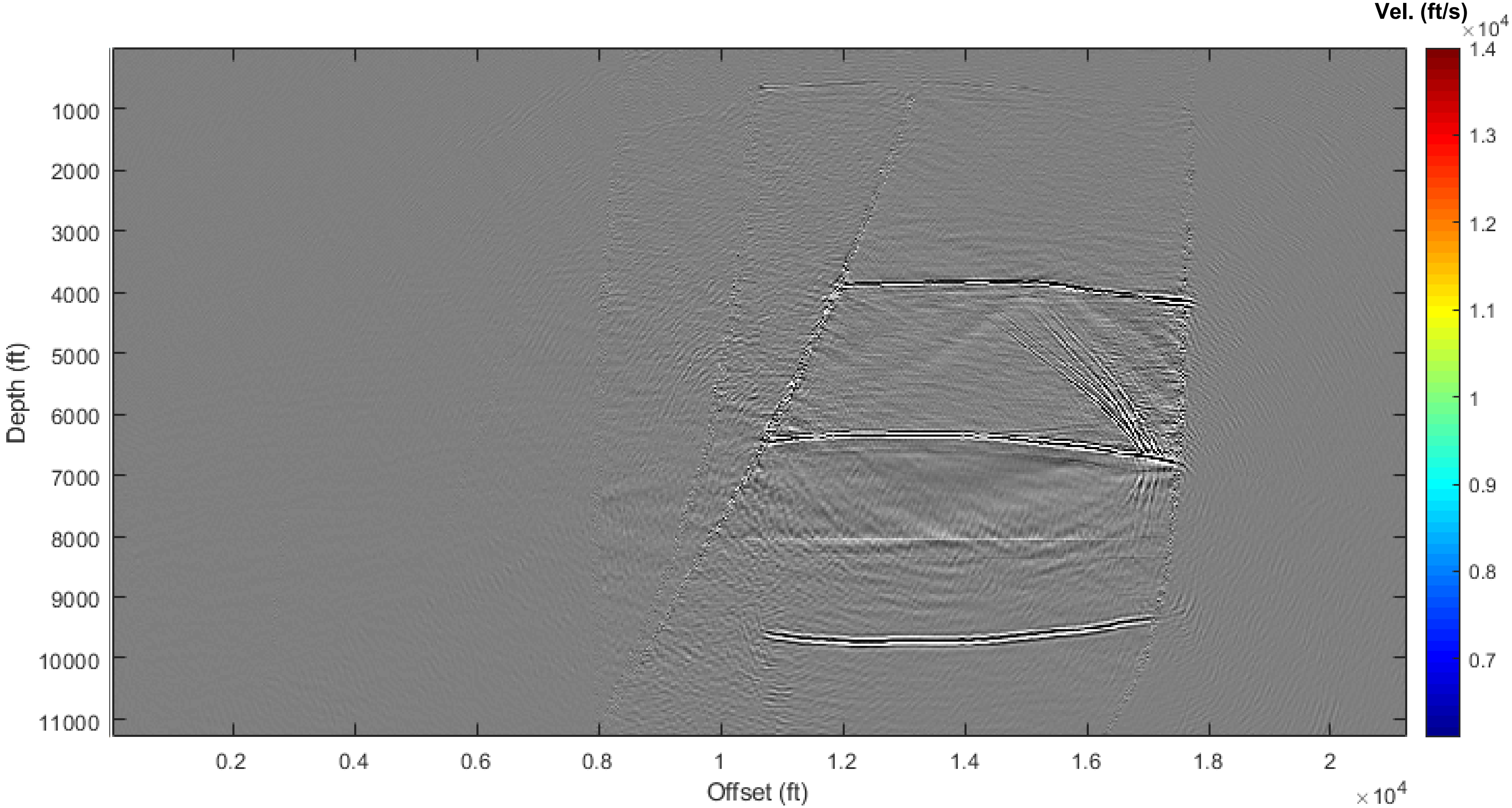
Time-Lapse Tomogram Change from Initial to after Fluid Injection



Initial Reverse Time Migration (RTM) before Fluid Injection



Time-Lapse RTM Change from Initial to Fluid Injection

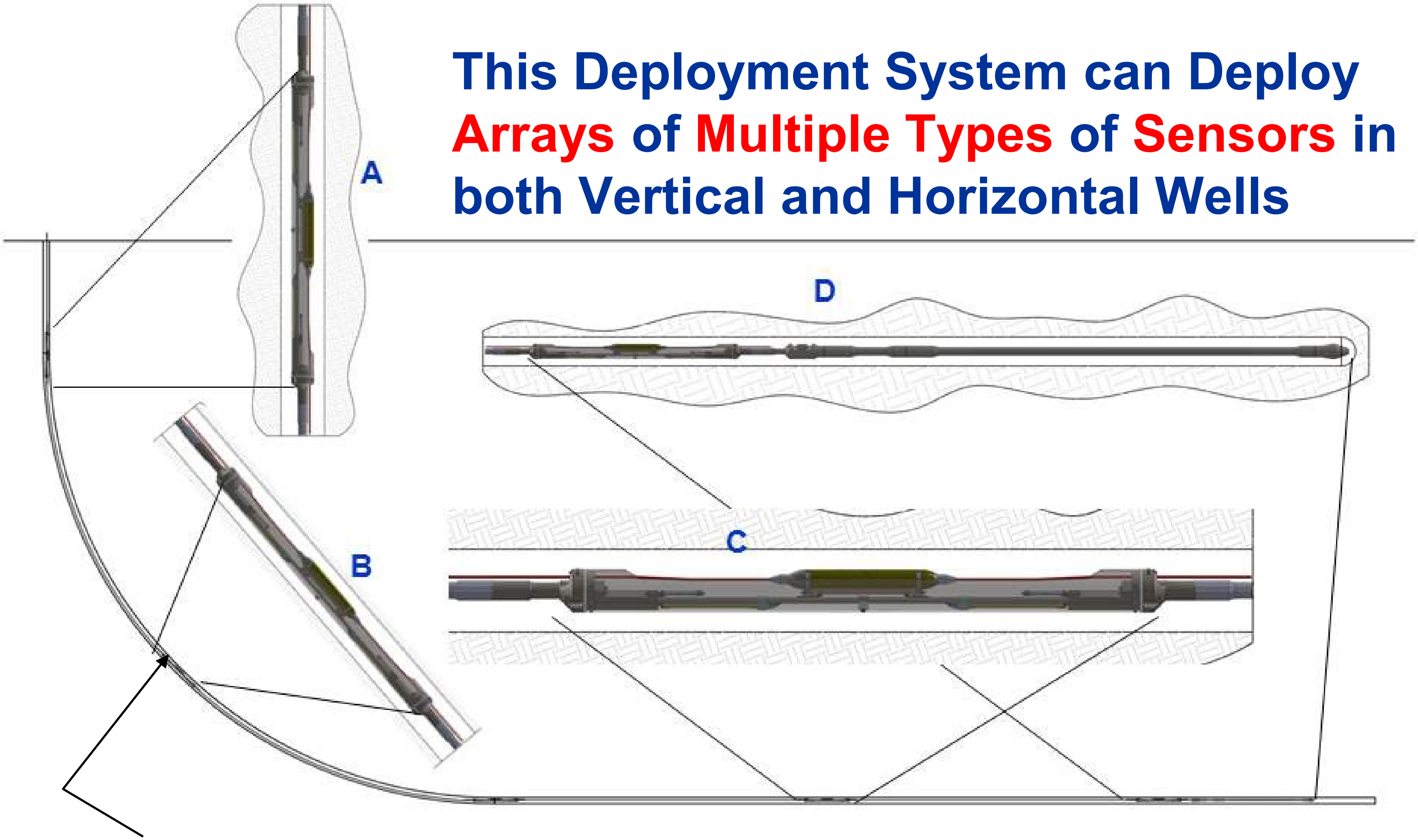


A Single Well Seismic System has two main components:

1. Receivers
2. Sources

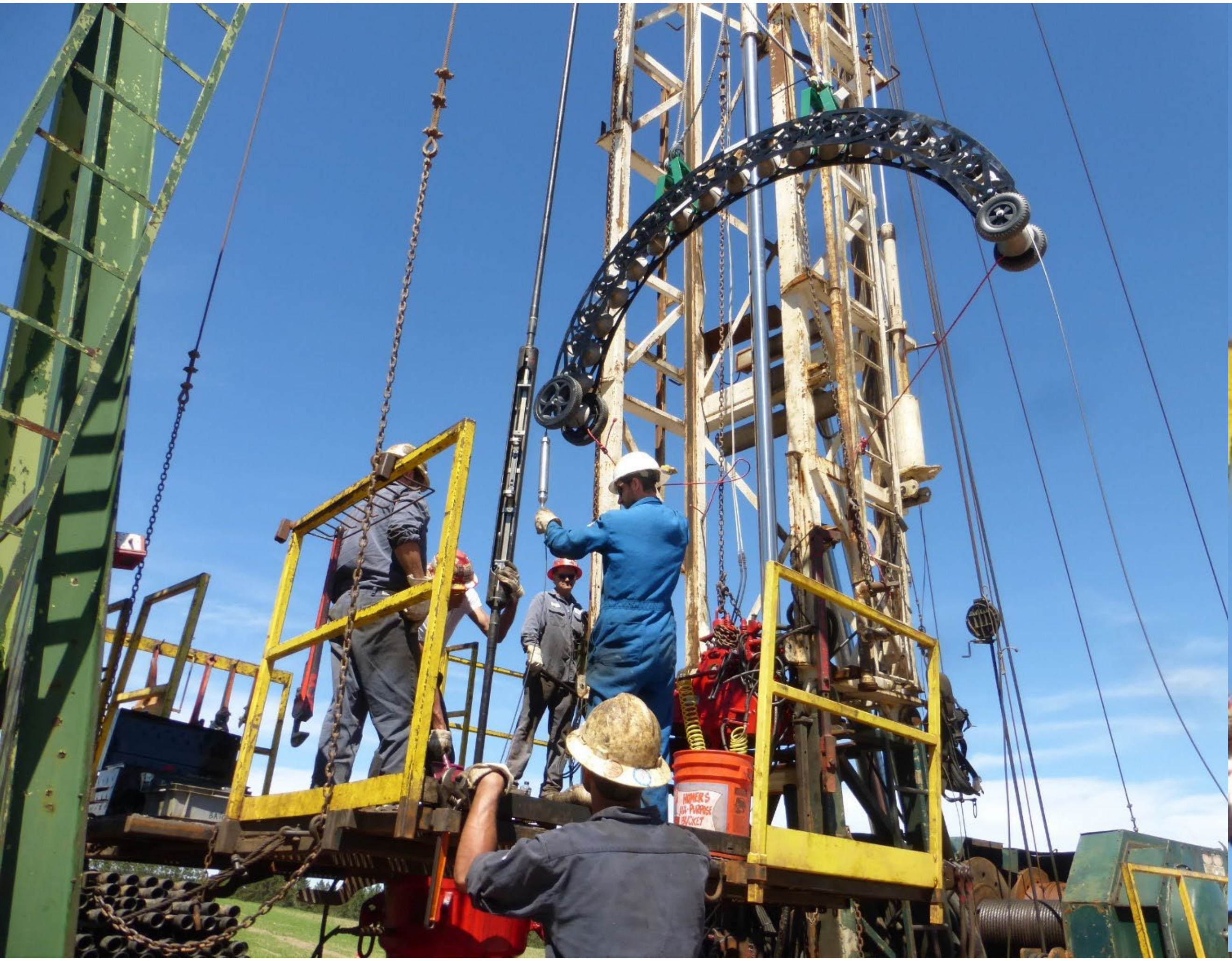
Drill Pipe Deployed System – Housing and Clamping

This Deployment System can Deploy Arrays of Multiple Types of Sensors in both Vertical and Horizontal Wells



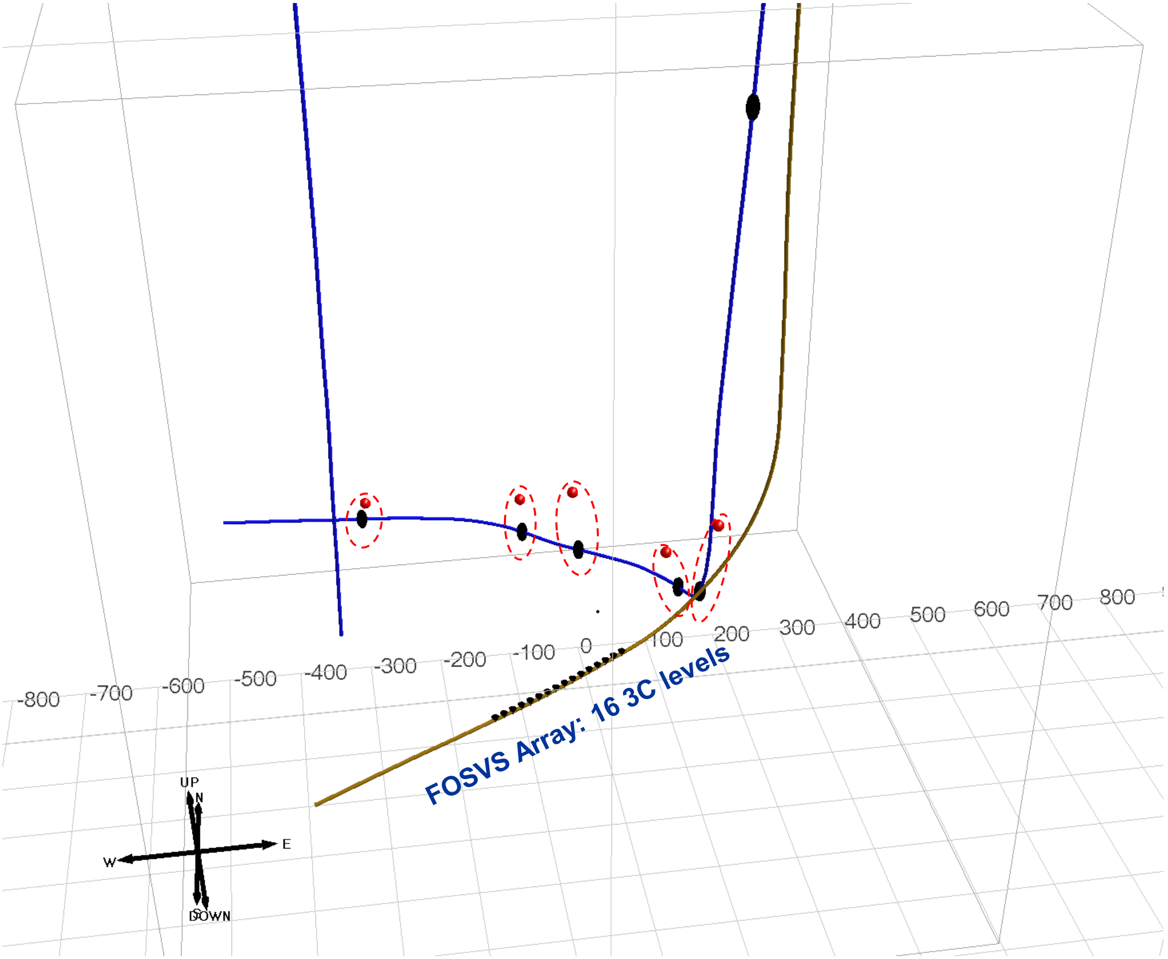
Clamping system operates by increasing the pressure inside the drill pipe and manifolds using the borehole fluid as the pressurized medium

Fiber Optic Seismic Sensor Deployment System (4th)
Battelle, Michigan June 2016 – Also for Single Well



Monitor Fluid Injection:
Field Data Recorded with Fiber Optic Seismic Vector Sensor (FOSVS)™ System

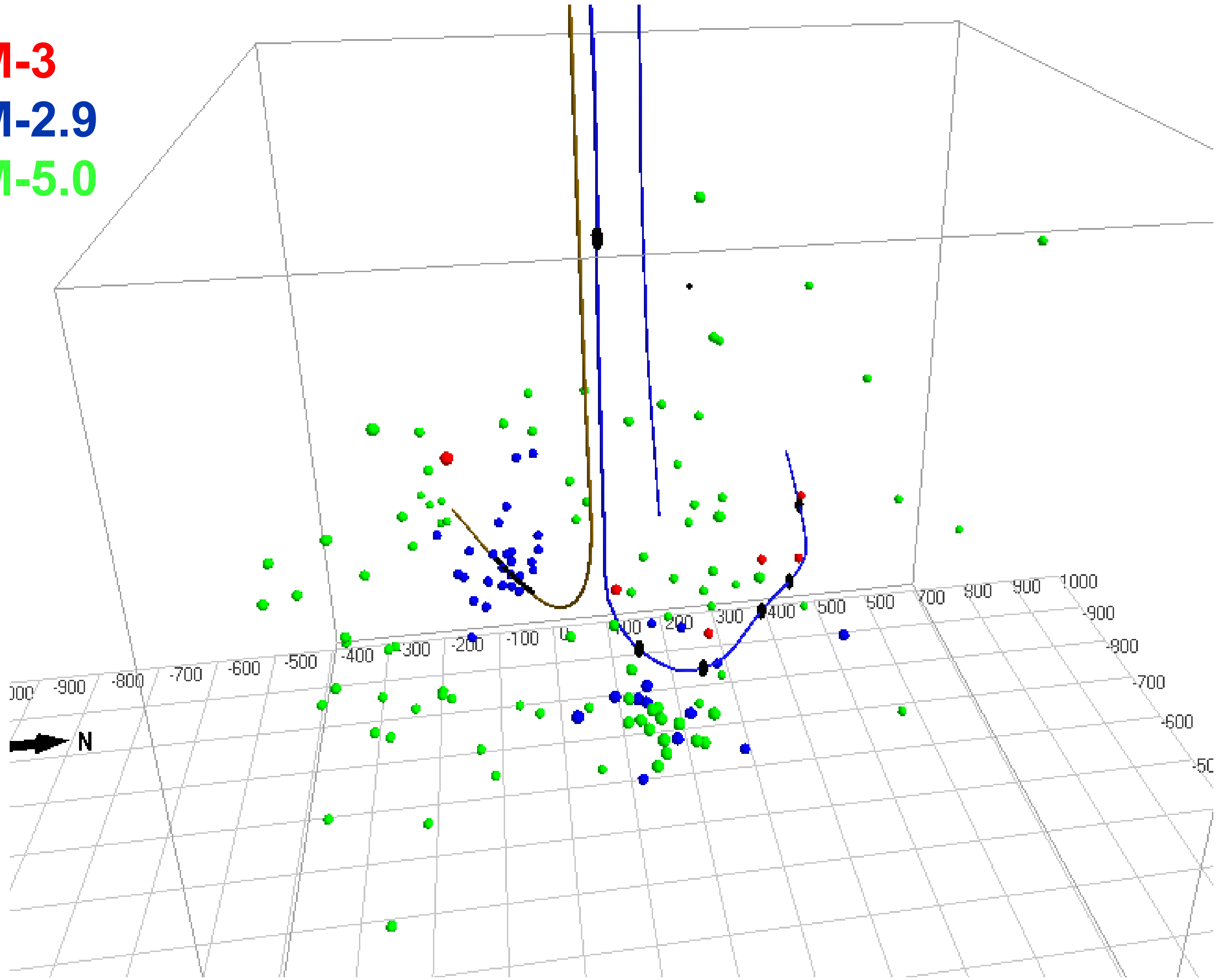
Results from Locating 0.5 gram String Shots During a Survey Recorded for Battelle in June 2016



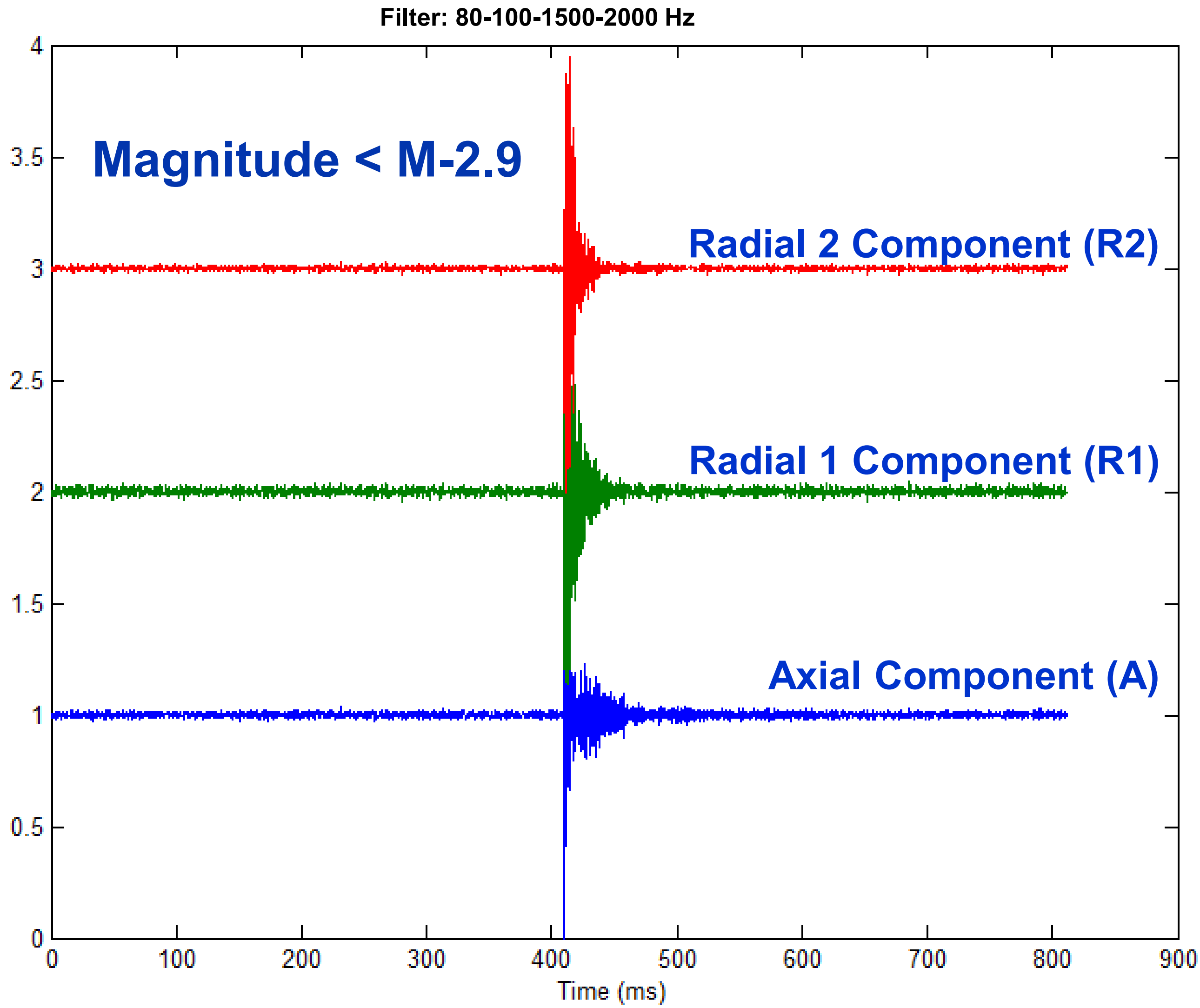
Survey for Battelle - Locating String Shots and Micro Seismic Events
Recorded >500,000 events in four weeks. Displayed here are 130 events.

Red: String Shots; Blue: Focused Micro Seismic; Green: "Fluid Flow" Events

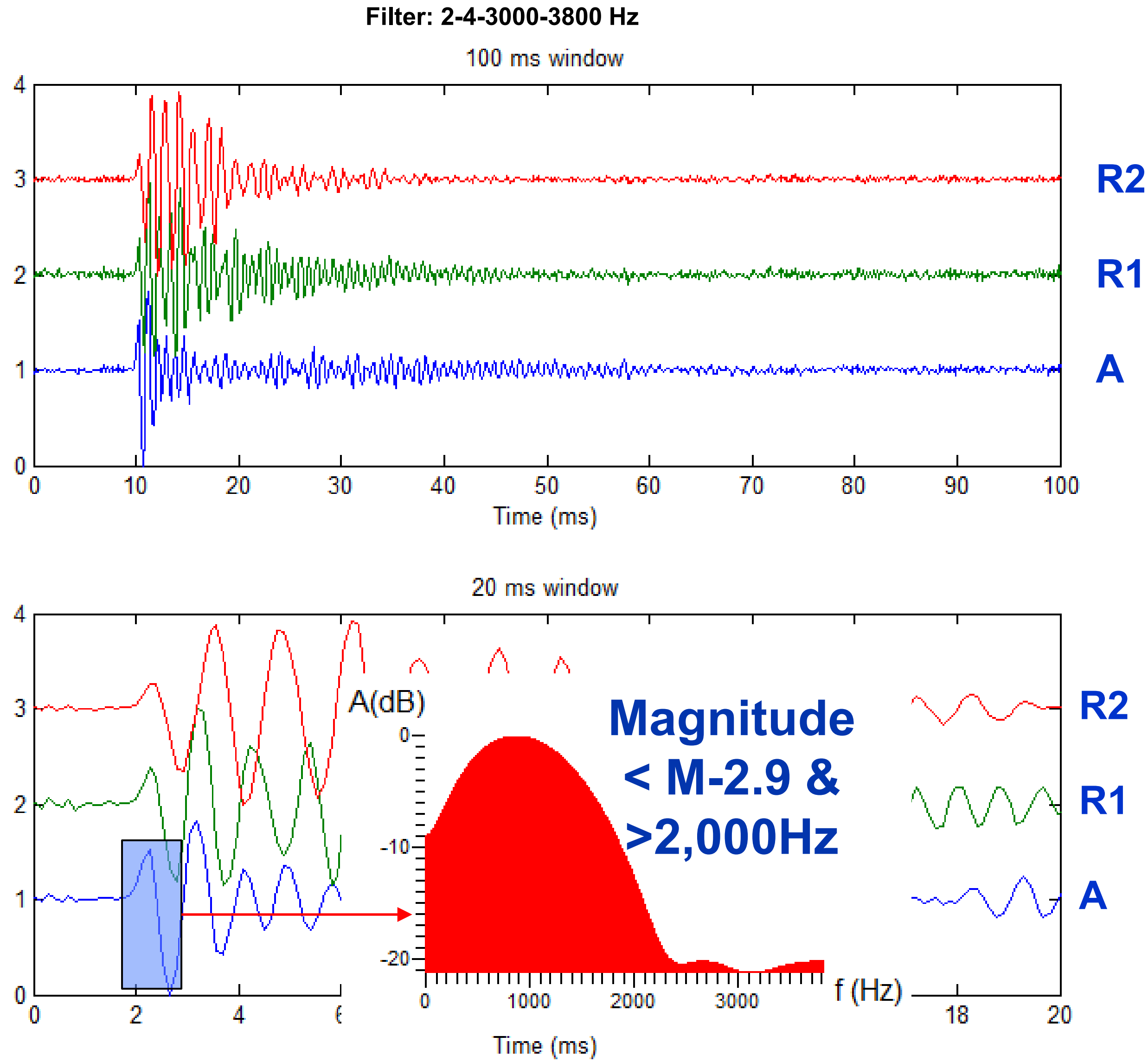
Magnitude < M-3
Magnitude < M-2.9
Magnitude < M-5.0



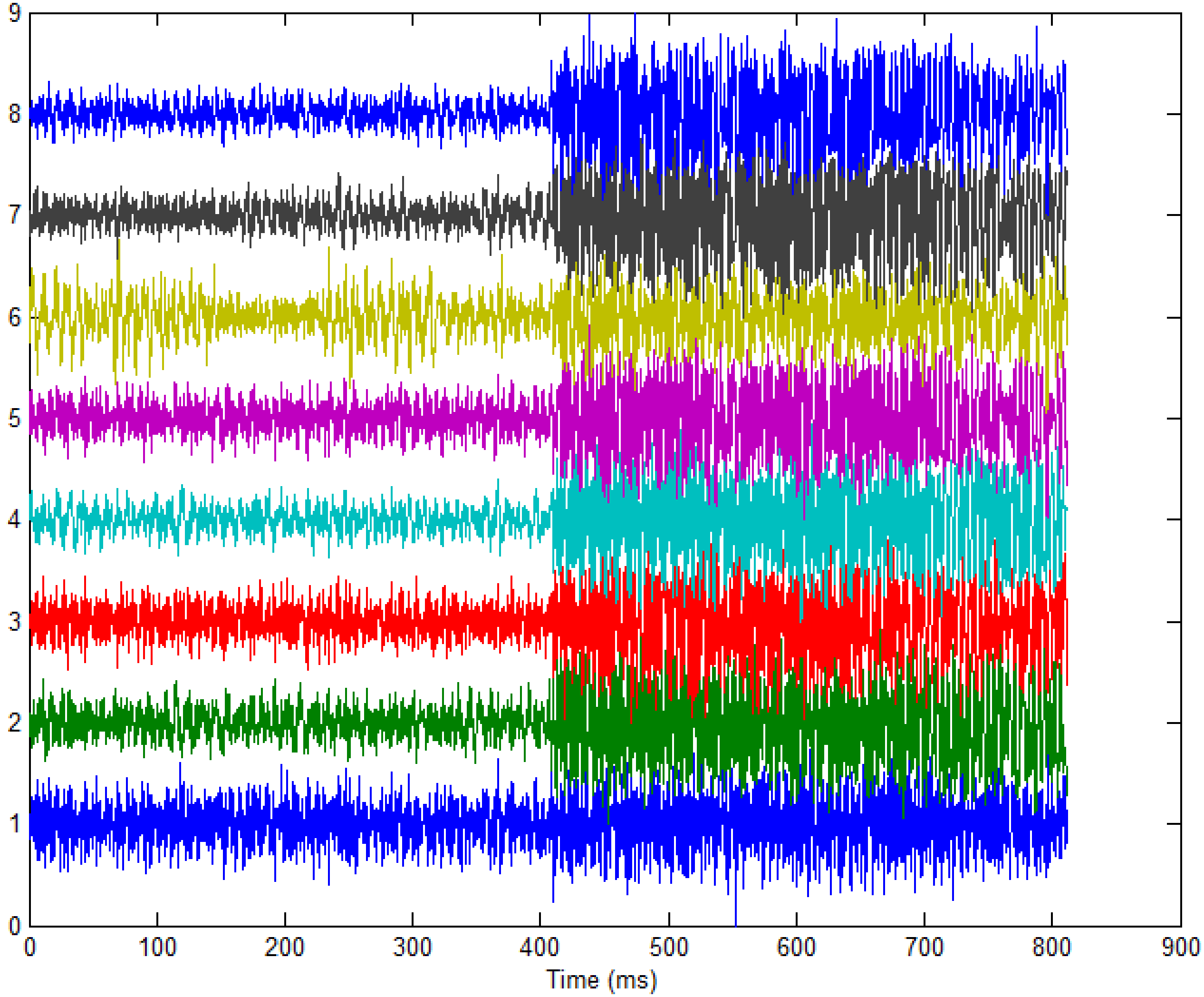
Sound of A Focused MS in 3C, Survey for Battelle, June 2016



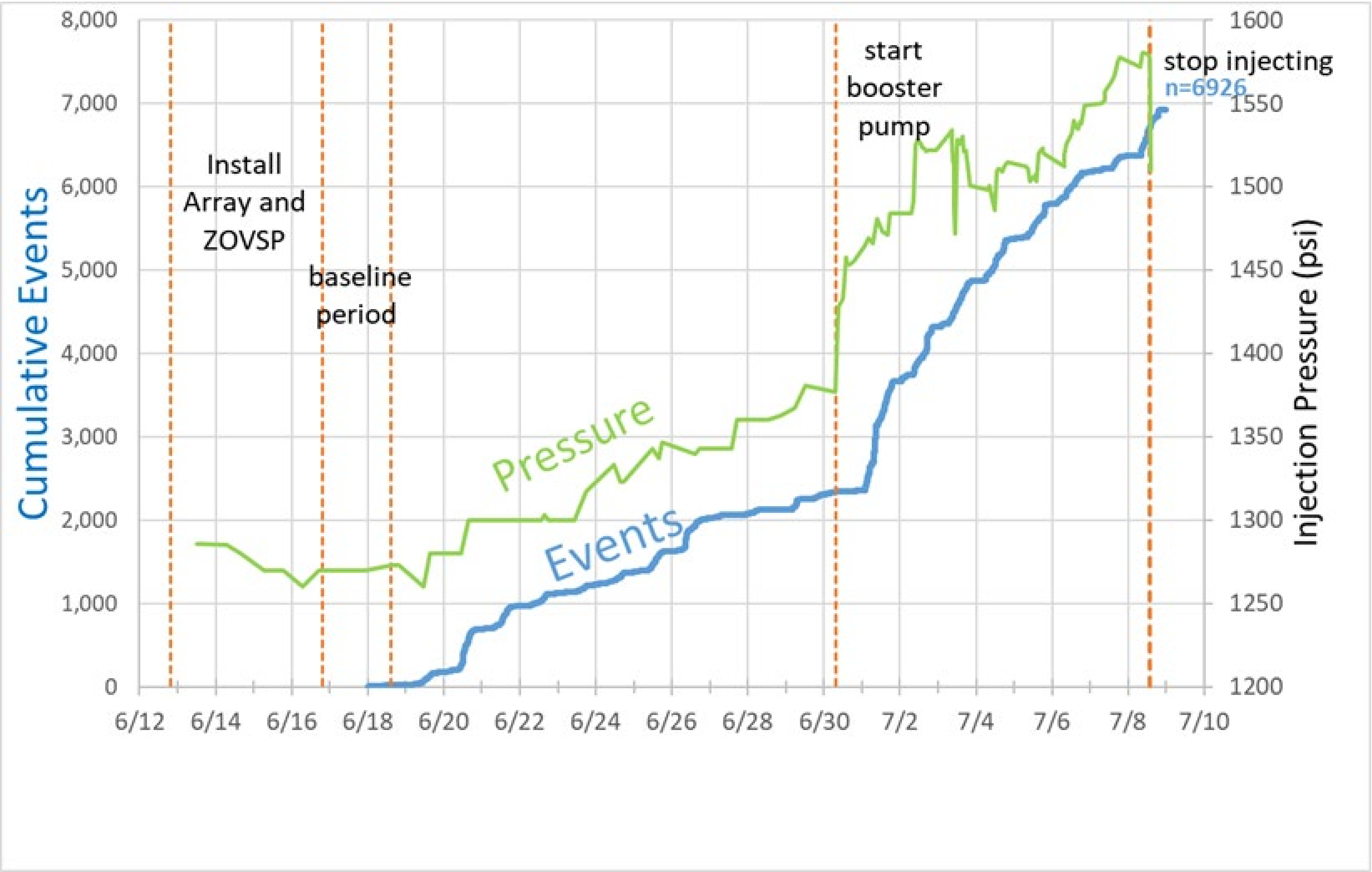
Zoomed-In Focused MS in 3C- Filter: 2-4-3000-3800 Hz



Sound of A Long Duration Event (~M-5.0) –Fluid Flow



Micro Seismic Events as Function of Injected Fluid Pressure



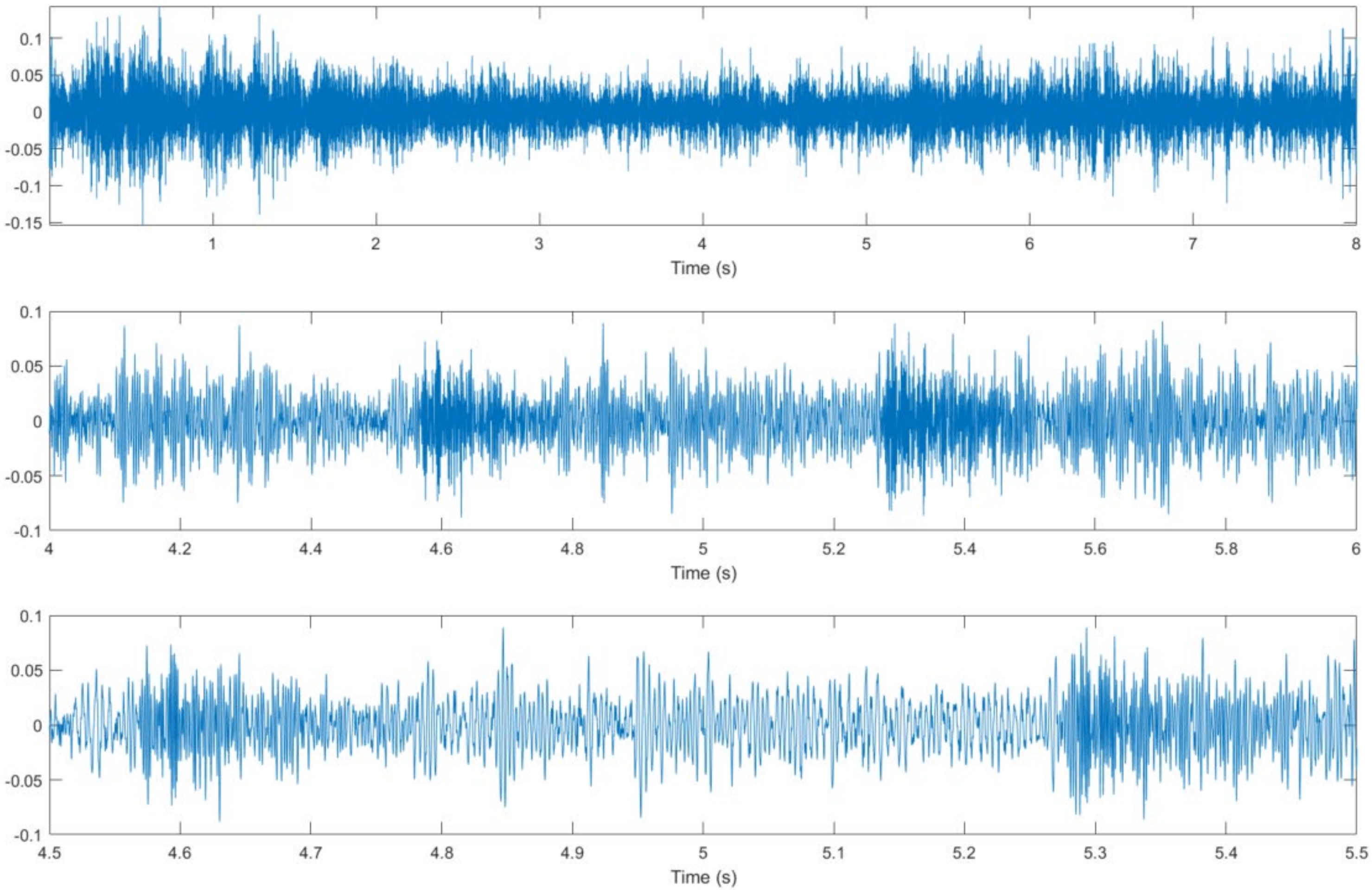
Courtesy Mark Kelley, Battelle, 2019

We looked for Analogs: Cardiac Blood Flow

8 seconds

Zoomed in 2 seconds

Zoomed in 1 second



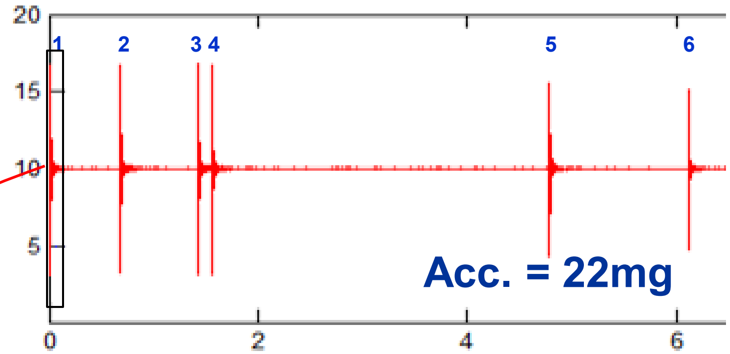
Laboratory Test of

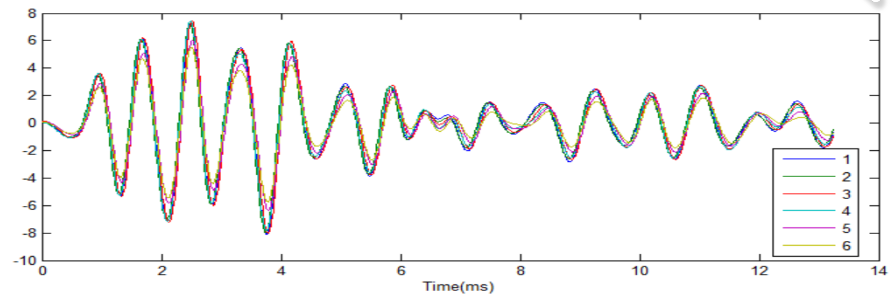
Fiber Optic Seismic Vector Sensors

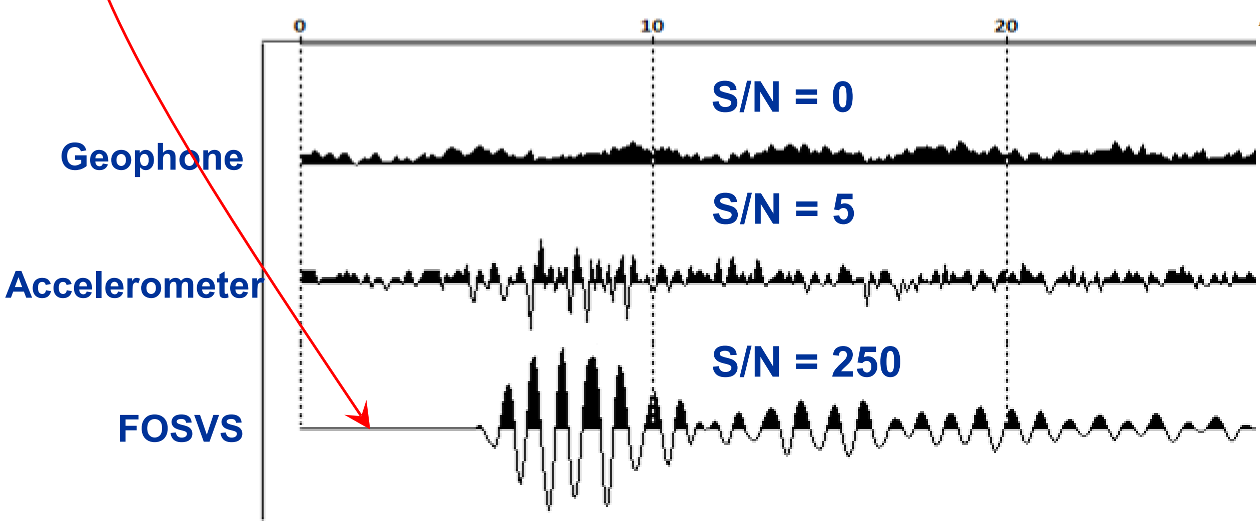
Test of Fiber Optic Seismic Vector Sensors (FOSVS) & IAME

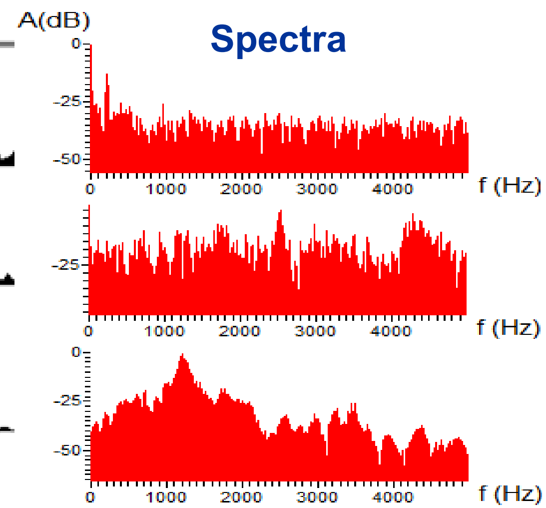
Pressure cell and sensor plate placed on a metal plate sitting on a foam mat on a metal table. Fiber sensor, geophone and accelerometer are placed approximately 20 cm (8 inches) from the pressure vessel with IAMEs

Repeatability Test: 6 IAME's recorded on FOSVS: Outstanding Repeatability.
Allow extraction of arrivals in high noise environment. IAME Energy Released: ~0.1 J = M-3.5







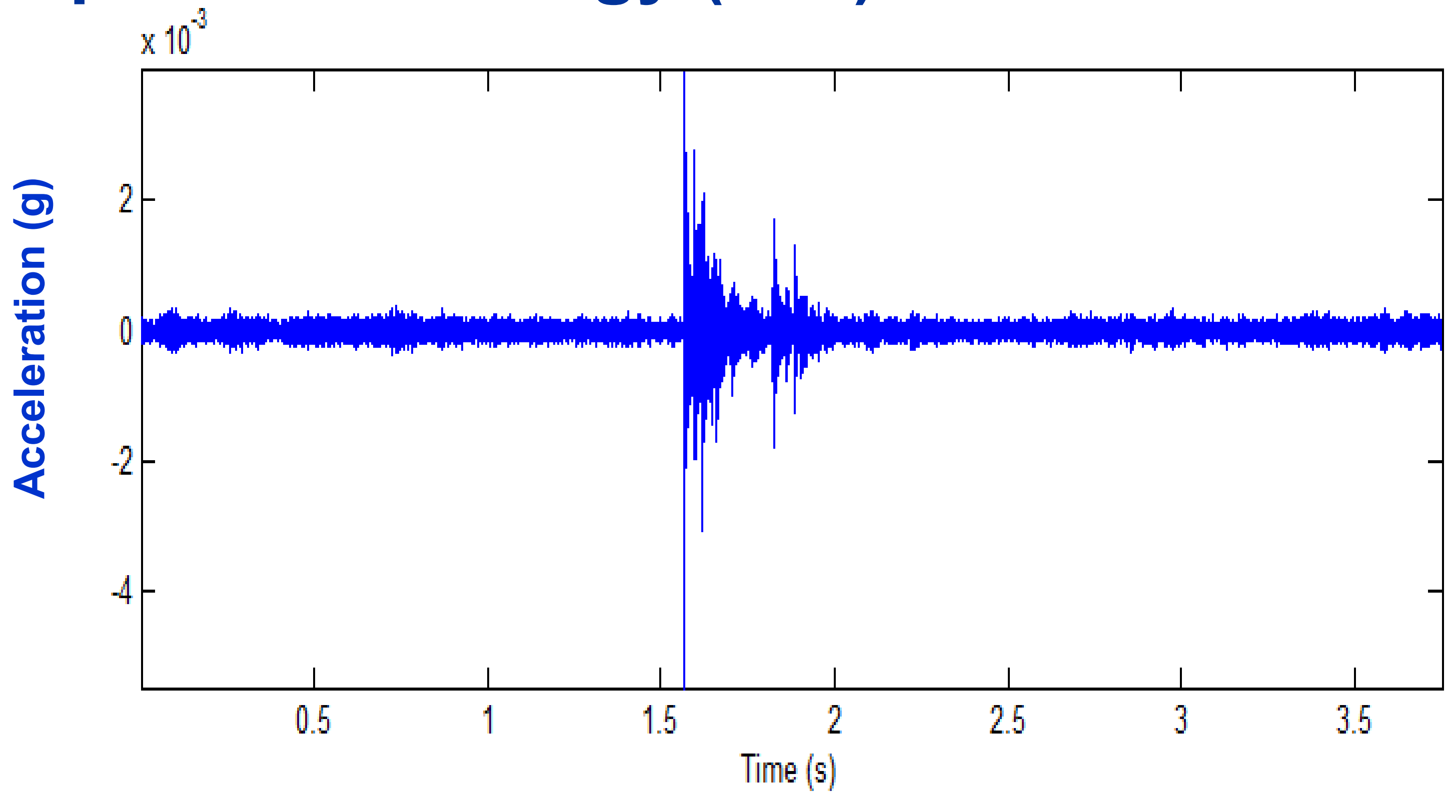


Can You Hear a Pin Drop?
Test Object: OD: 0.011”, 2” long, 24.8 mg

Pin Dropped 1 cm:
20% of the Pin Length

FOSVS Test: OD: 0.011”, 24.8 mg Pin Drop 1 cm:

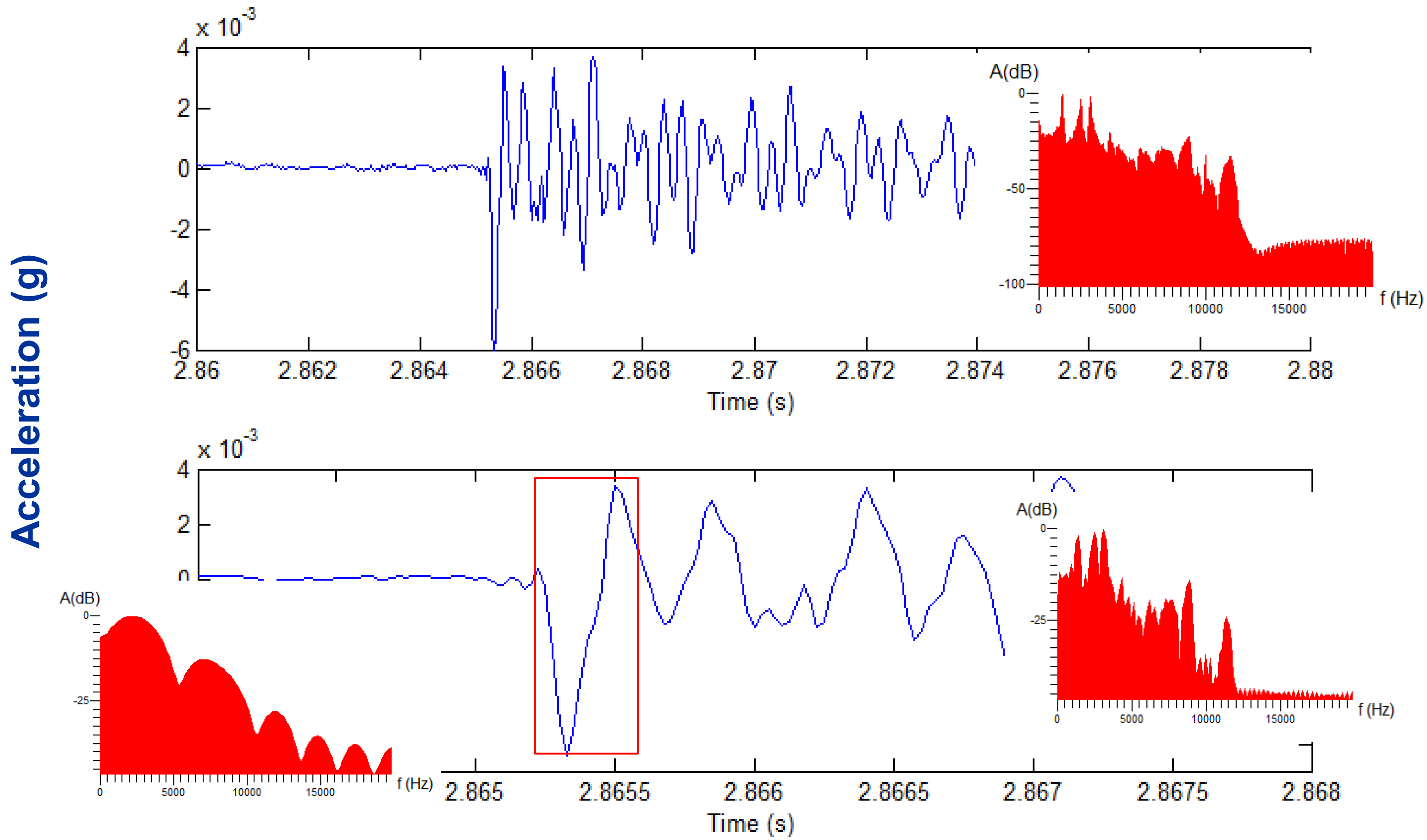
2.5 μJ kinetic energy (M-7) for 1st of 8 hits of Pin



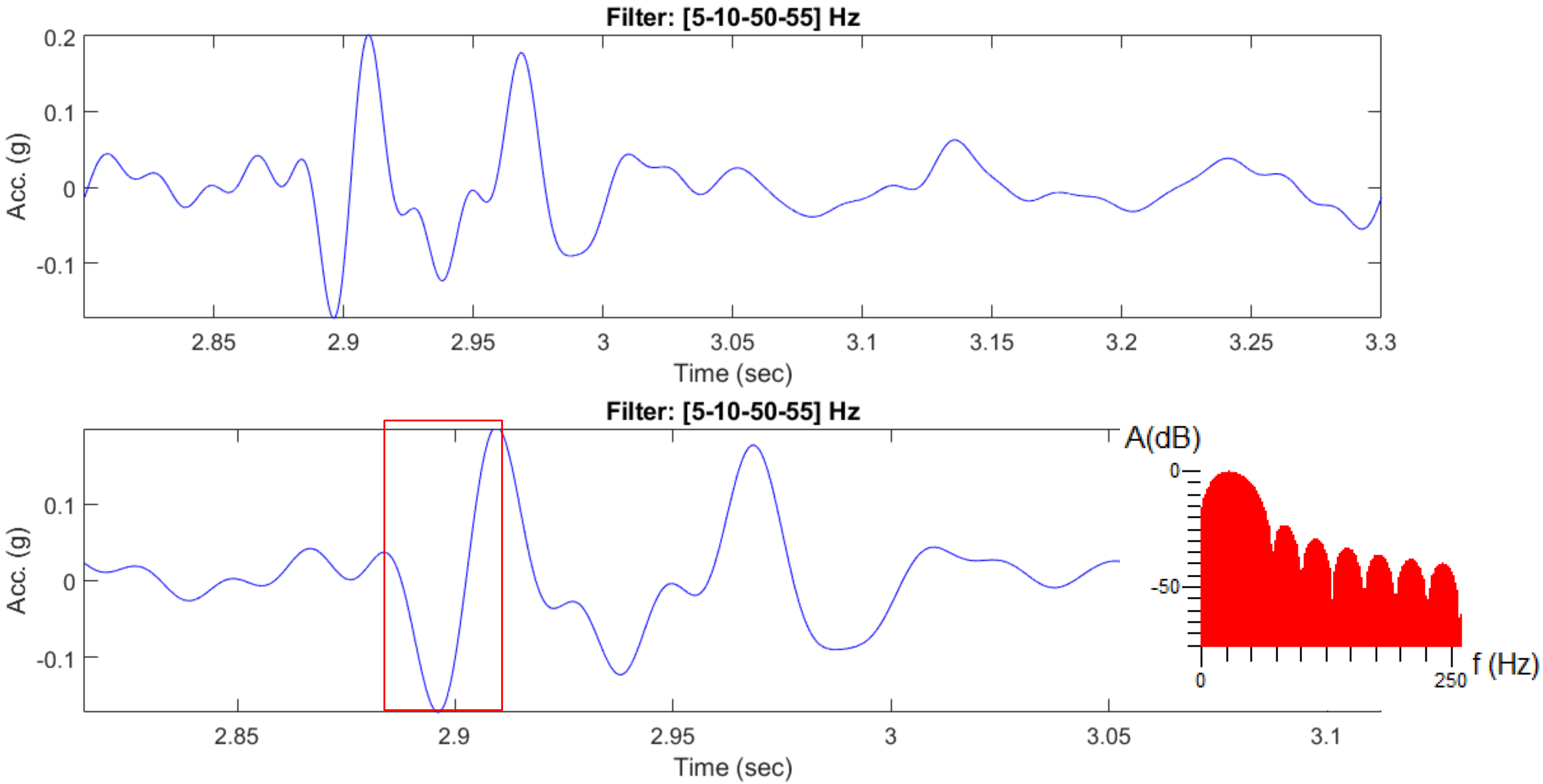
The FOSVS recorded ~17 bounces of the pin = <<M-7

FOSVS Test: OD: 0.011”, 24.8 mg Pin Drop 1 cm:

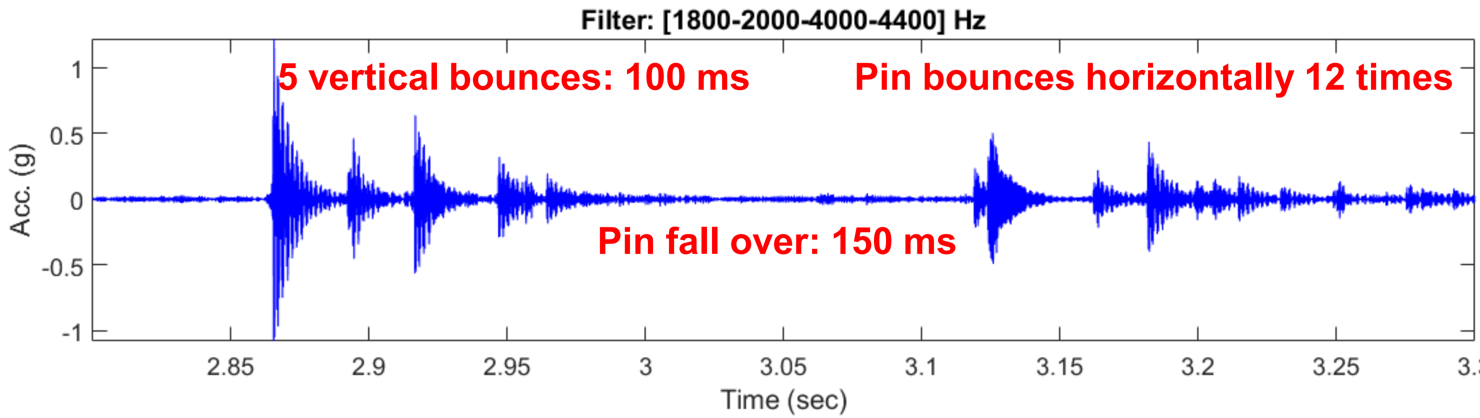
2.5 μJ kinetic energy (M-7) for 1st of 8 hits of Pin

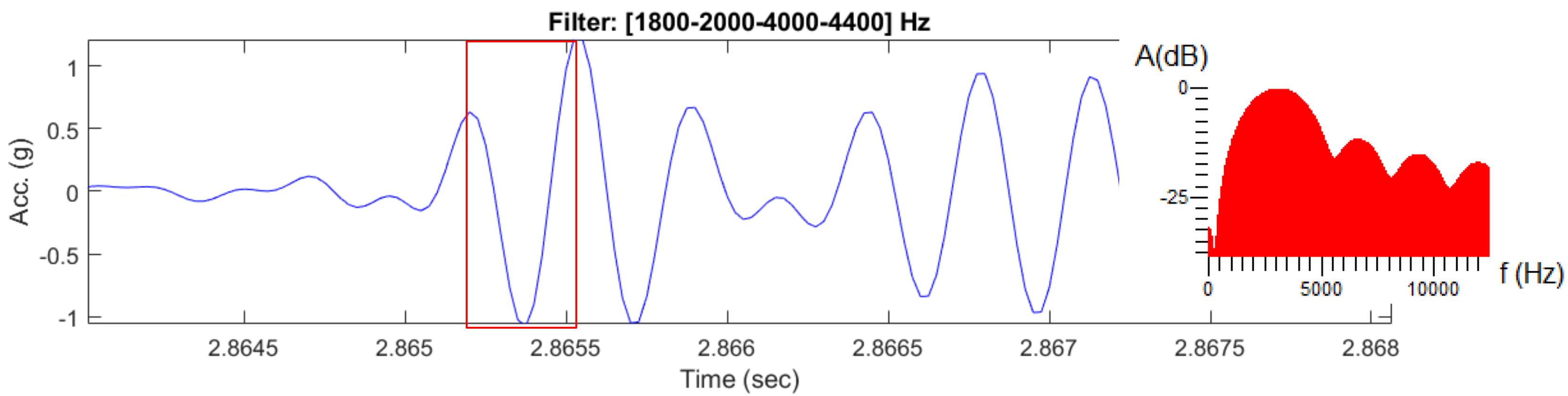


FOSVS Test: OD: 0.011”, 24.8 mg Pin Drop 1 cm: 2.5 µJ kinetic energy (M-7) on primary drop Ormsby Filter: 5-10-50-55 Hz (LOW FREQUENCY)

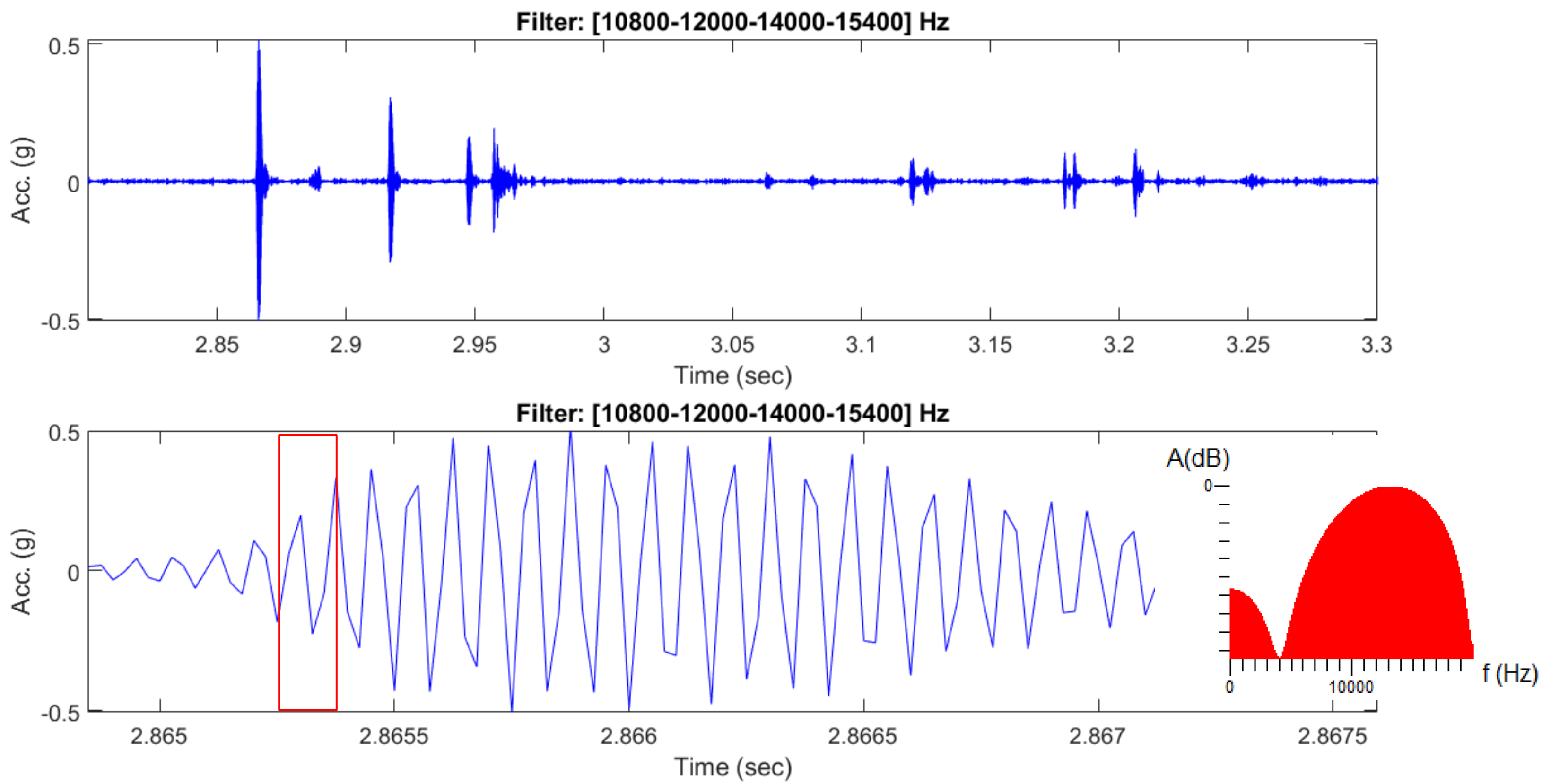


FOSVS Test: OD: 0.011”, 24.8 mg Pin Drop 1 cm: 2.5 µJ kinetic energy (Primary: M-7, Bounces: M-8) Ormsby Filter: 1,800-2,000-4,000-4,400 Hz





FOSVS Test: OD: 0.011”, 24.8 mg Pin Drop 1 cm: 2.5 µJ kinetic energy (Primary: M-7, Bounces: M-8) Ormsby Filter: 10.8-12-14-15.4 kHz (HIGH FREQ.)



Downhole Seismic Source for Single Well Seismic Tool

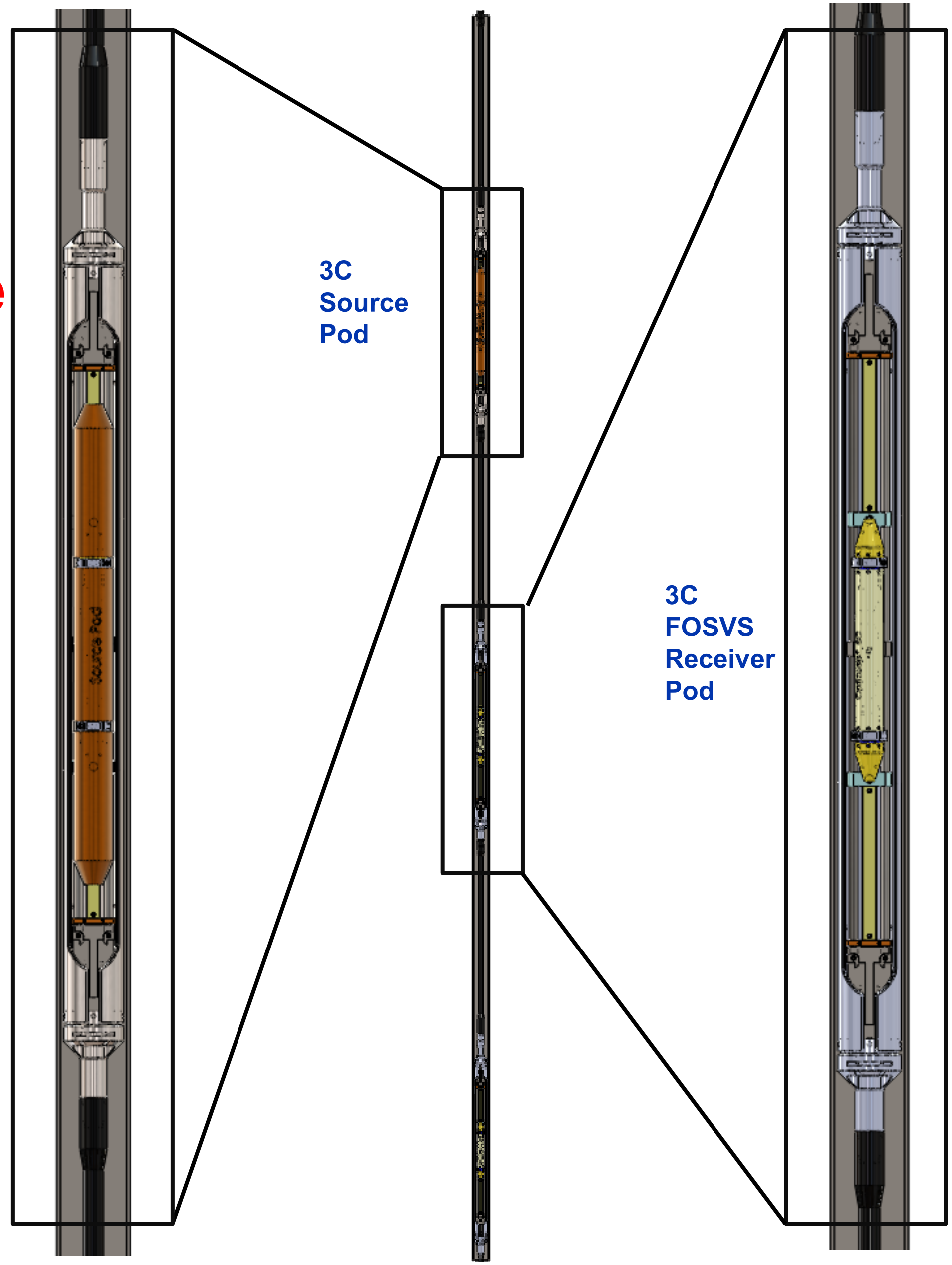
DE-SC0018613

- **By placing the Receivers in the borehole, we get 2 – 10 the resolution compared with surface seismic!**
- **By placing both the source and the receivers we should get much better than 10 times (20-30) the resolution!**

A Single Well Seismic System: Deploying the Source and the Receivers in the same well.

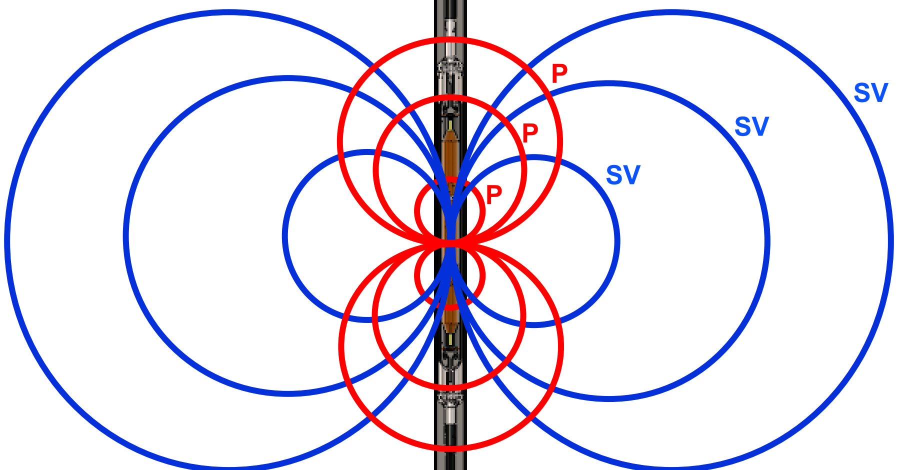
This is NOT a well Logging System – this is a Seismic System with a 10 – 3,200 Hz Operating Frequency.

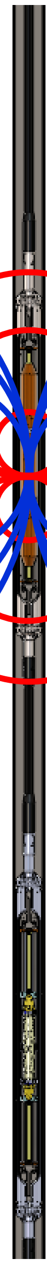
This system will be able to image to a radius of >1,000 m (3,000 ft) – Q dependent of course.



Sources:

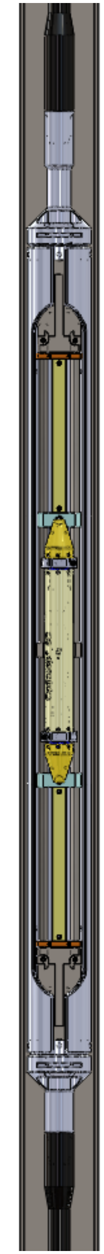
Source Radiation Patterns Heelan (1953)





1. Axial Source
2. Radial Source
3. Torsional Source

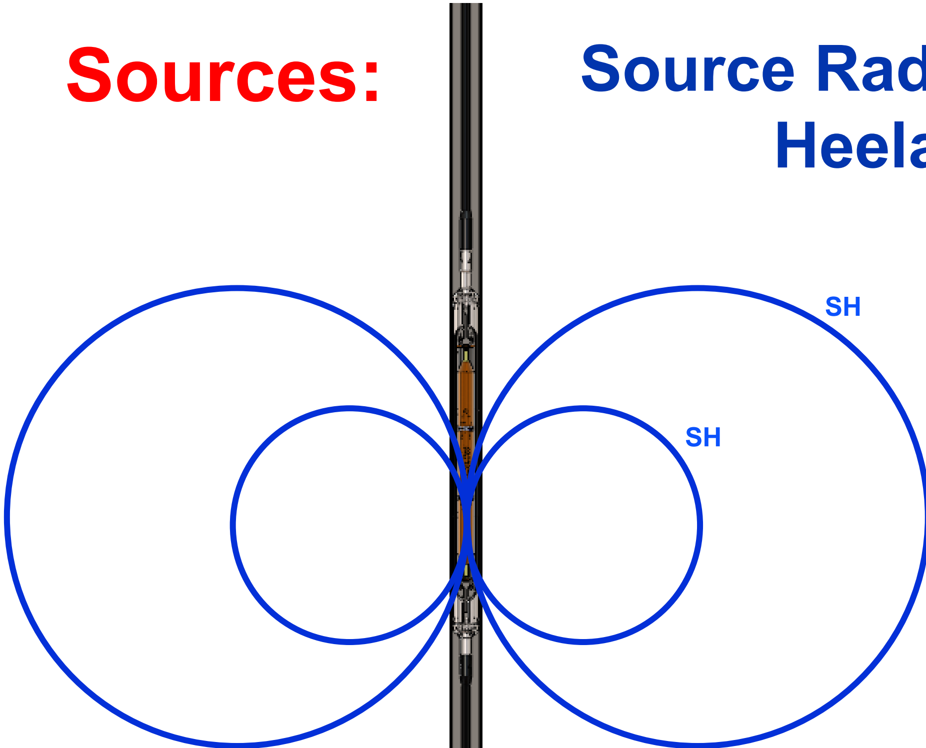
Variation of P and SV amplitudes with φ, when the source is subjected to shearing stress q(t) only



FOSVS Receiver Pod

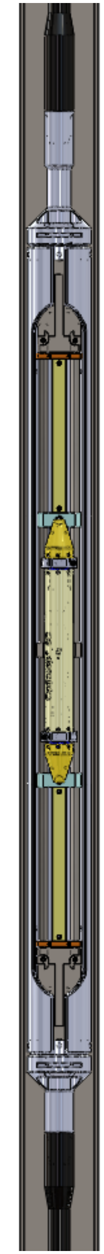
Sources:

Source Radiation Patterns Heelan (1953)

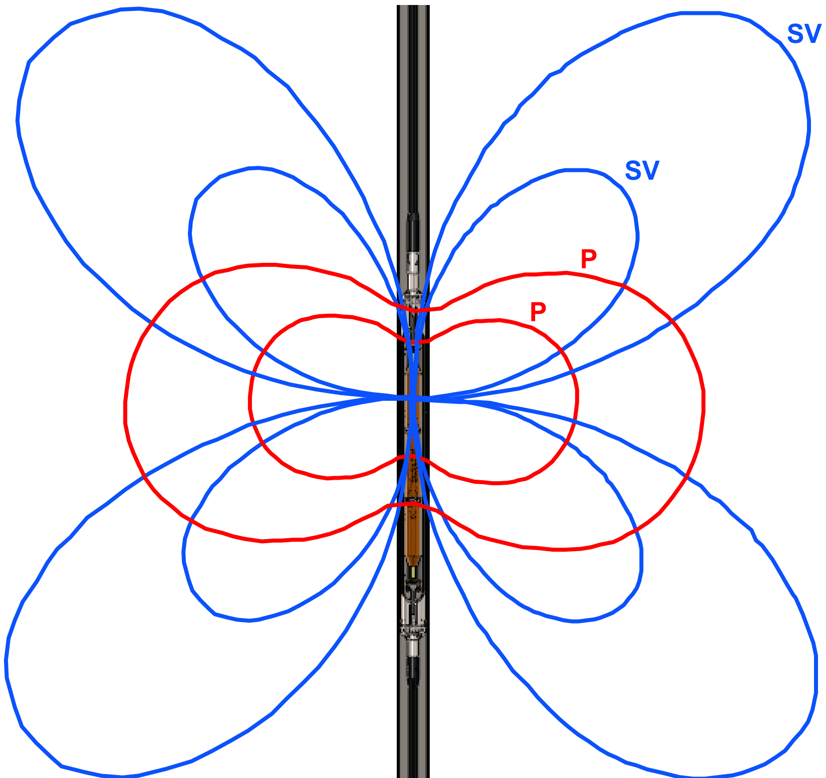


1. **Axial Source**
2. **Torsional Source**
3. **Radial Source**

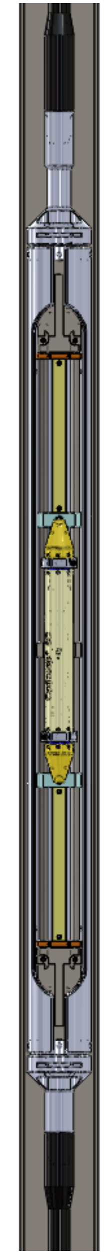
Variation of SH amplitudes with φ when the source is subjected to a horizontal shearing stress s(t) only



FOSVS Receiver Pod



Source Radiation Patterns Heelan (1953)



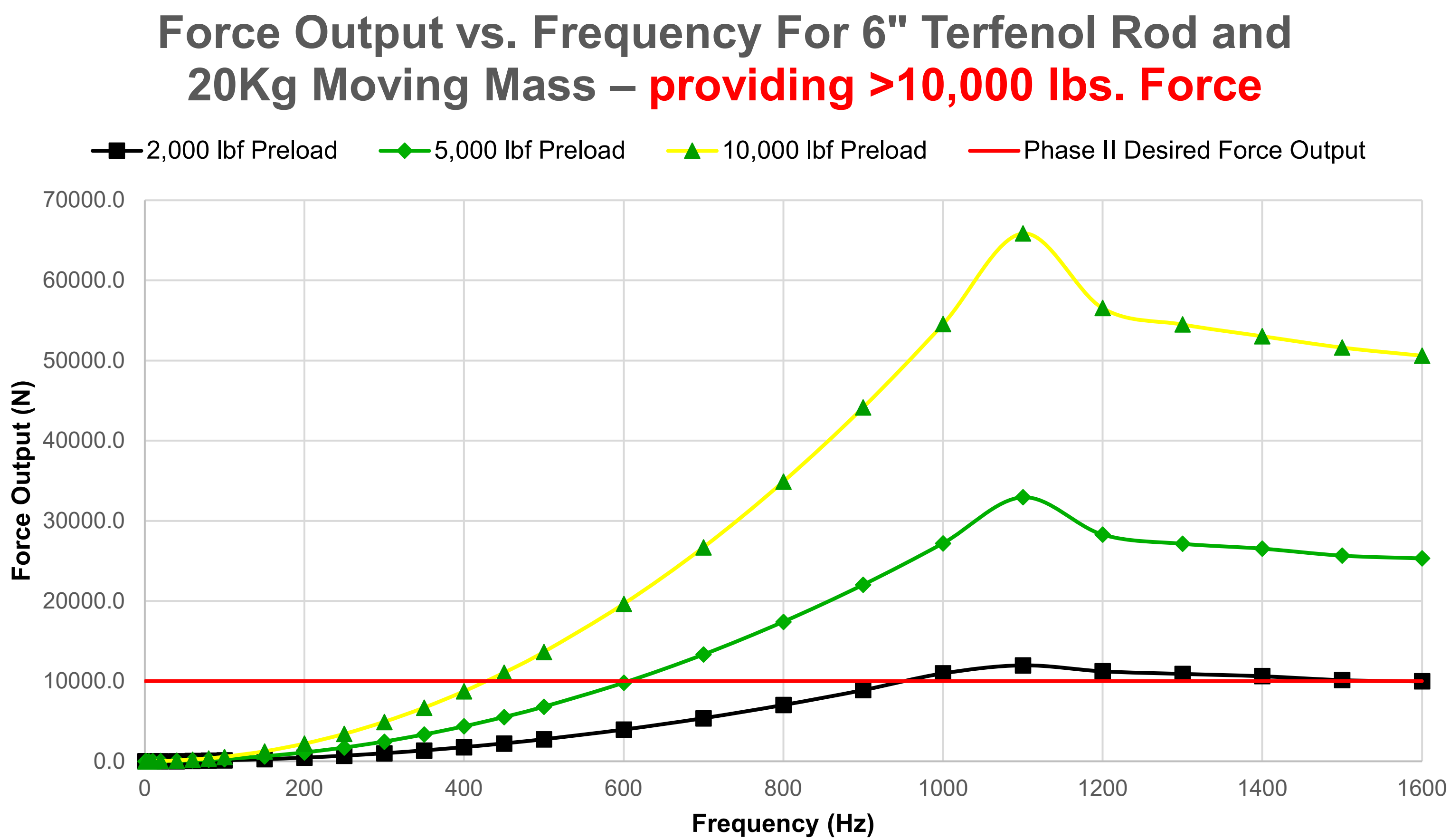
FOSVS Receiver Pod

1. Axial Source
2. Torsional Source
3. Radial Source

Variation of P and SV amplitudes with φ when the source is subjected to a pressure p(t) only

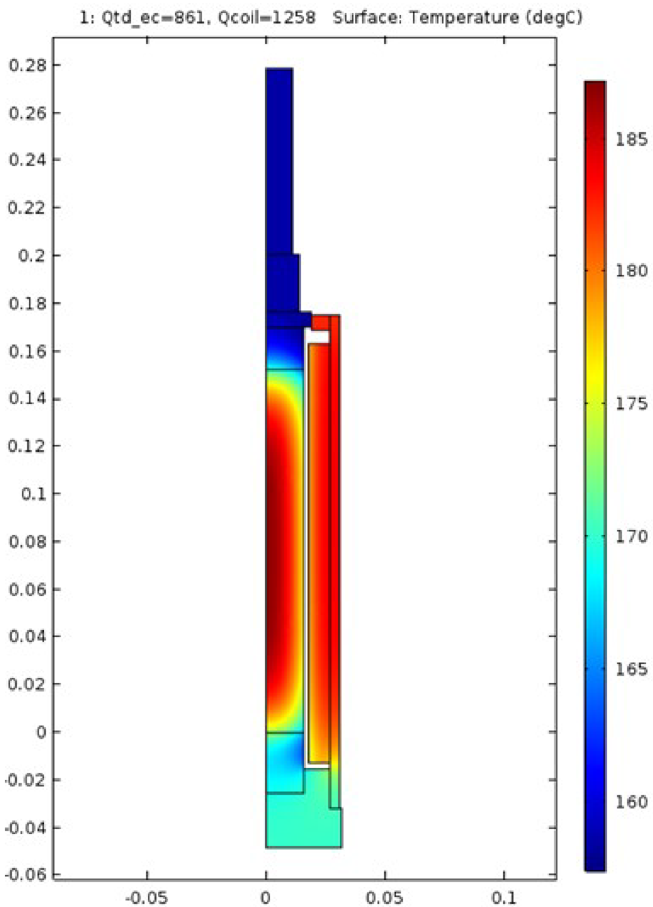
Sources:

Task 1: Preliminary Model and Lab Test Results

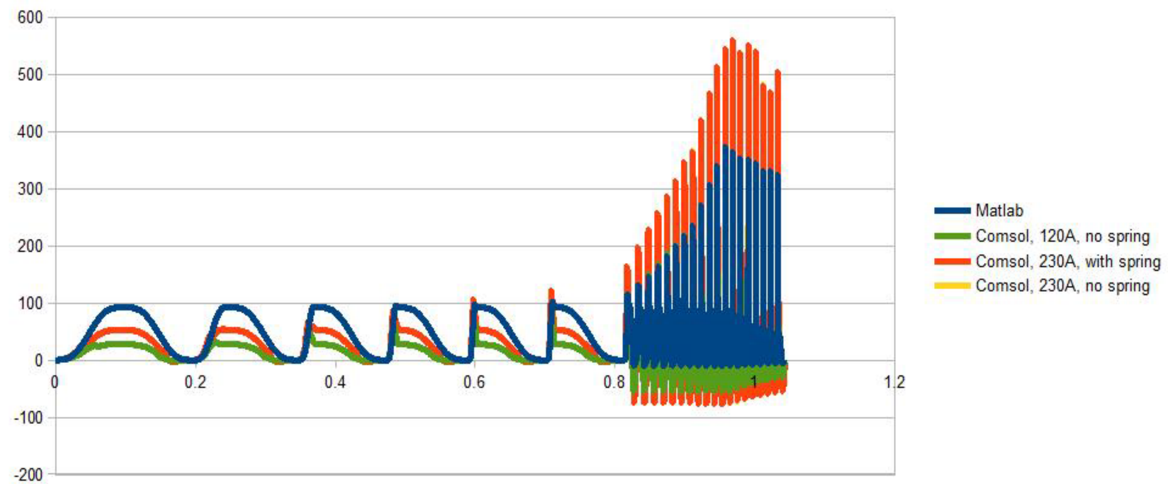


Preload has a big effect on force output. Generally, higher preload = higher force output.

Task 3: Finite Element Analyses (FEA) Using Multi-Physics By Comsol



Temperature distribution for 120 ampere peak input with turbulent flow force convection cooling.



Comparison of voltage predictions between analytical MATLAB model and Comsol finite element analysis for –9,817 lbf compression preload. Horizontal axis is time in seconds, vertical axis is voltage in volts.

Table II. Total actuator heat losses.

Current, Amperes, Dissipated Heat, Watts						
Preload	Peak	RMS	Coil	Eddy (10 Lam)	Hysteresis	Total
–2,000 psi	57	35.8	476	235	16	968
–8,000 psi	120	75.6	2,116	861	16	2,993
–8,000 psi	230	144.9	7,773	1,786	16	9,575

Heat Dissipation by Eddy Current for Different Laminations

The Multi-Physics simulation by Comsol showed large heat dissipation with the original design. The simulation exposed the primary heat source as the wire coils and the secondary heat source as the Terfenol rod.

The table below shows by increasing the number of laminations of the Terfenol rod the heat dissipated in Watts produced by the rod dramatically decreases. This is because the increase in lamination reduces the eddy current losses.

More so, reducing the eddy current losses of the rod reduces the power loss of the rod. The decrease in power loss boosts the systems efficiency and therefor minimizes power requirement of the downhole source. This allows for the reduction of the current to the wire coils.

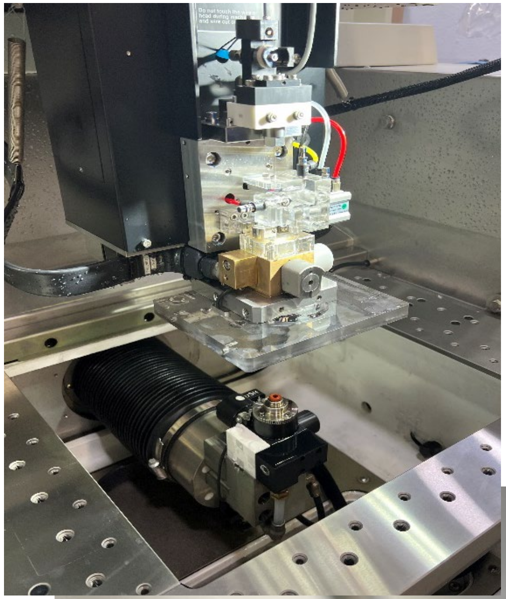
Thereby increasing the number of laminations, the system requires less power by <u>both</u> the primary heat source of the wire coil and the secondary heat source of the Terfenol rod, minimizing overall heat generation.

Assume the preload case is -8,000 psi @ 230 amps (worst case)

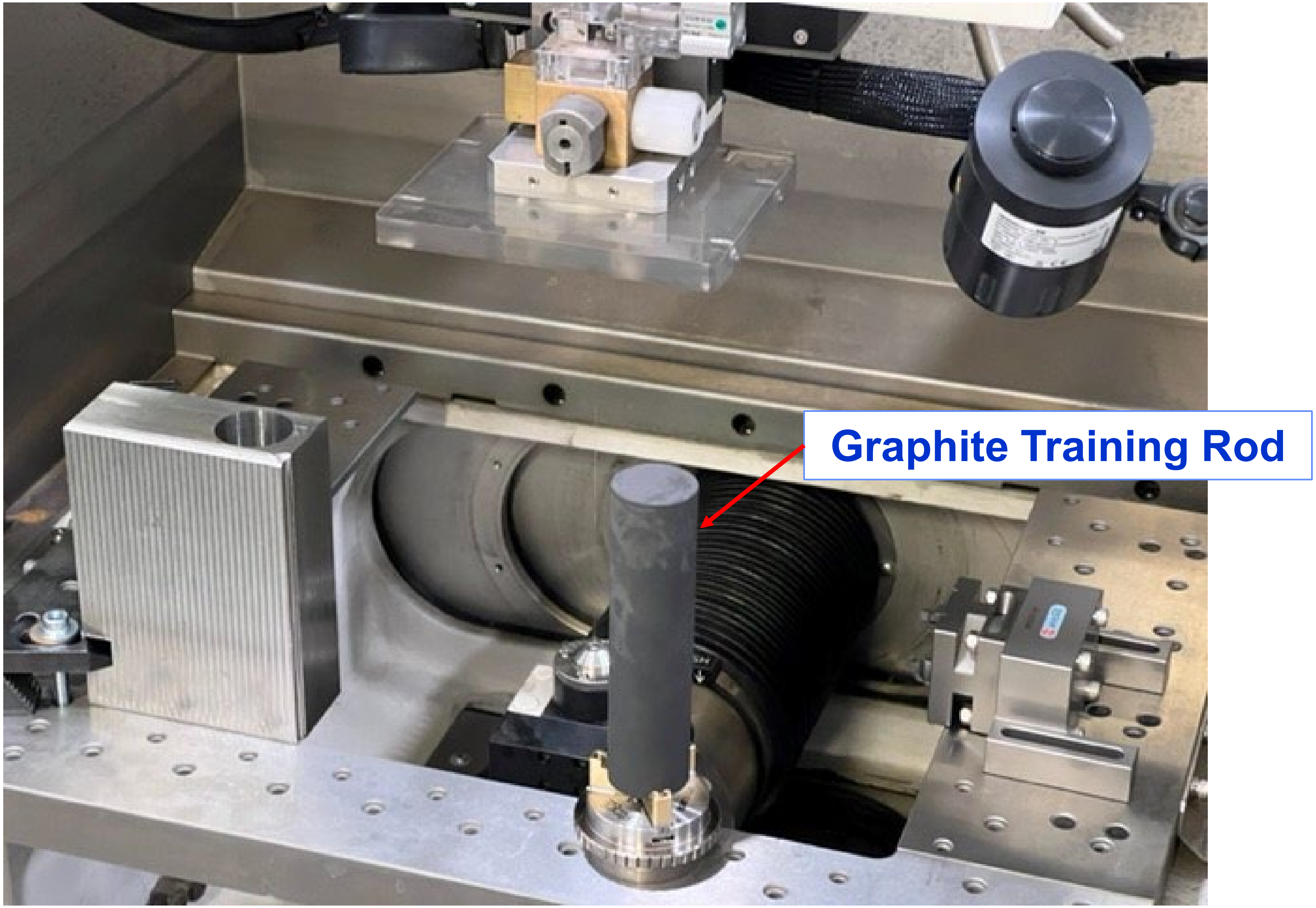
Heat Dissipated in Watts by Number of Laminations

frequency (Hz)	3	5	8	10	12	15	20	40
1600	11,023	5,650	2,556	1,786	1,154	739	416	104
3200	44,092	22,600	10,224	7,144	4,596	2,951	1,662	414
6400	176,368	90,400	40,896	28,576	18,092	11,725	6,635	1,657

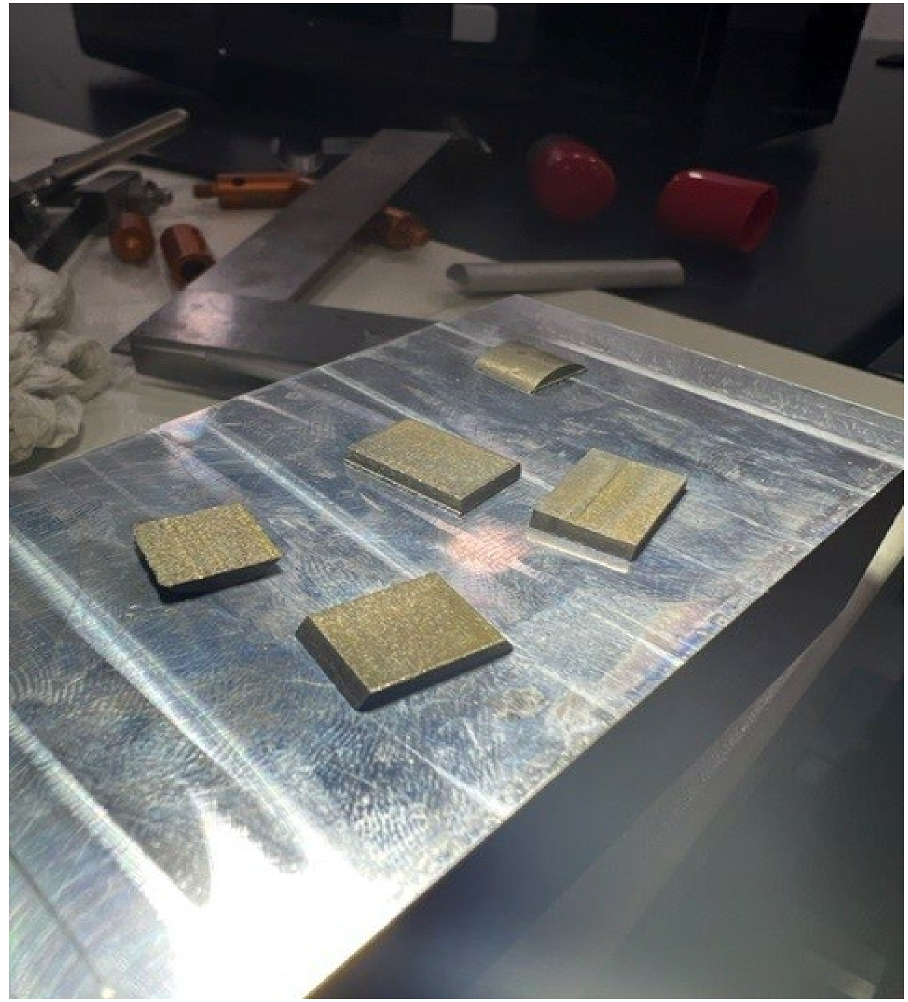
Makino U3 WIRE EDM



Current EDM set up and fixture system

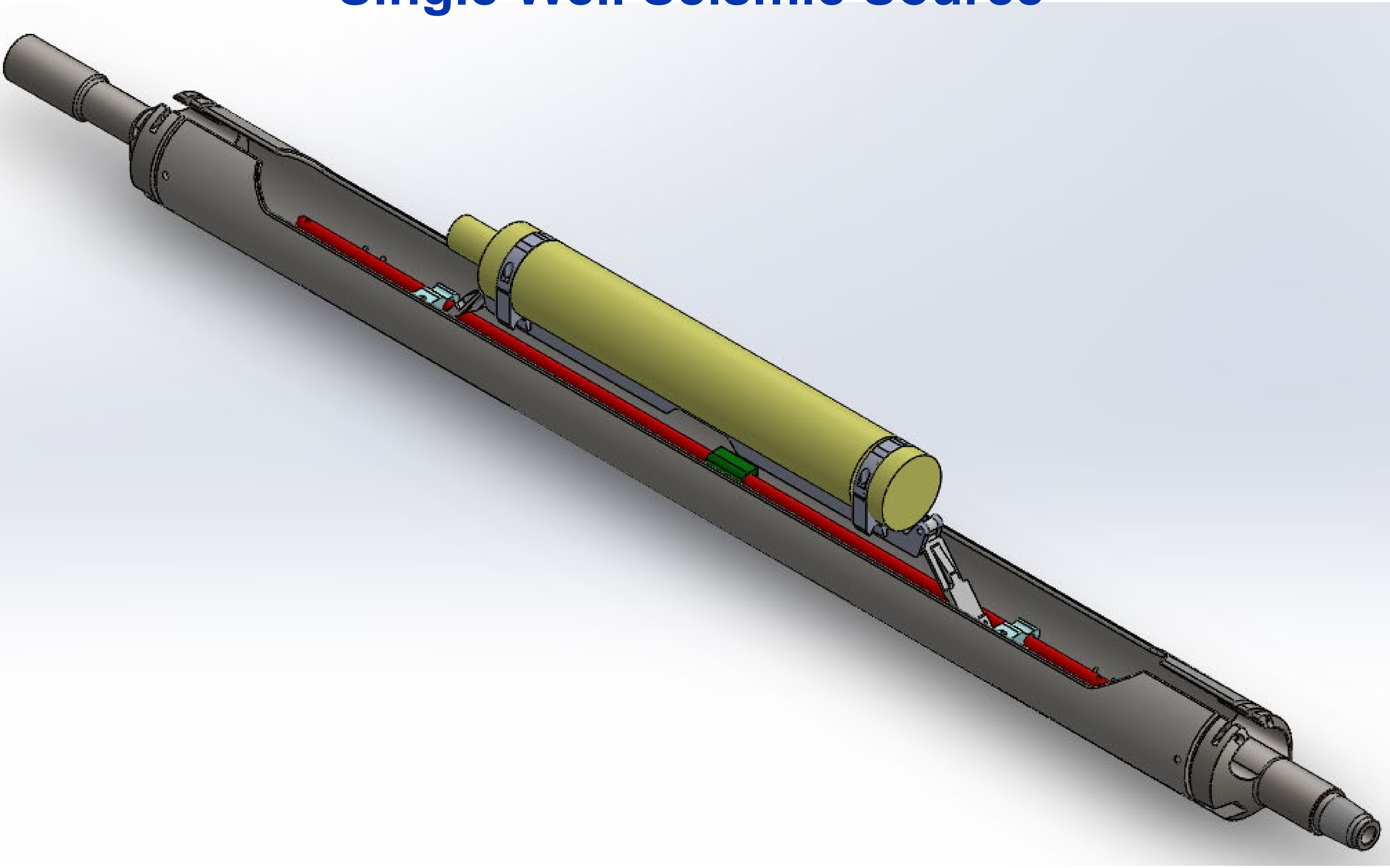


Second generation EDM fixture system and set up



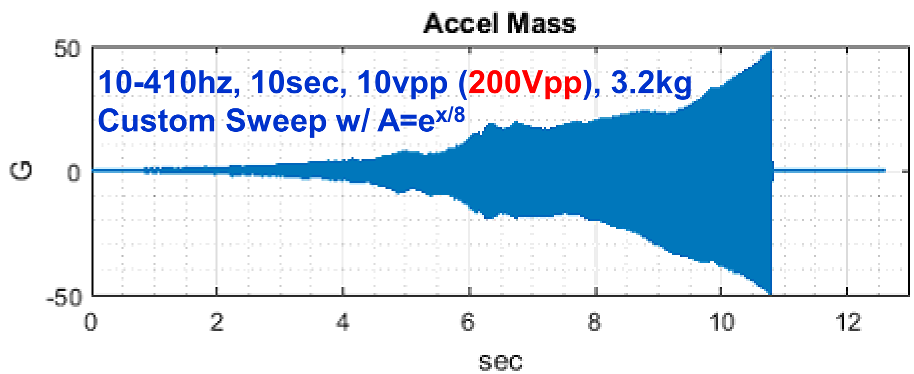
Sliced Terfenol

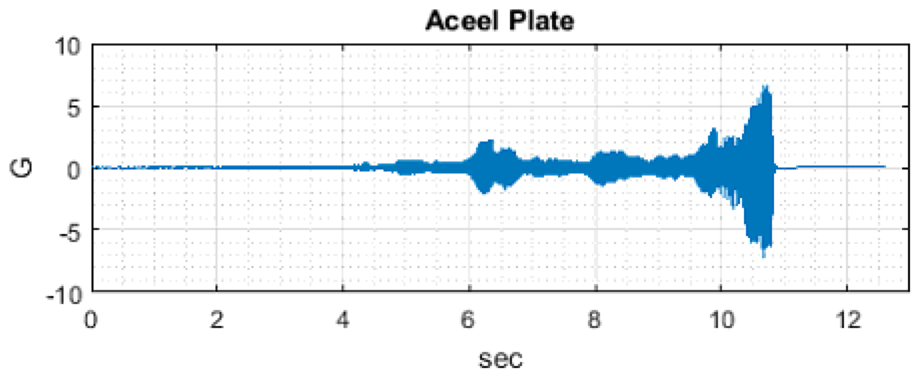
Single Well Seismic Source

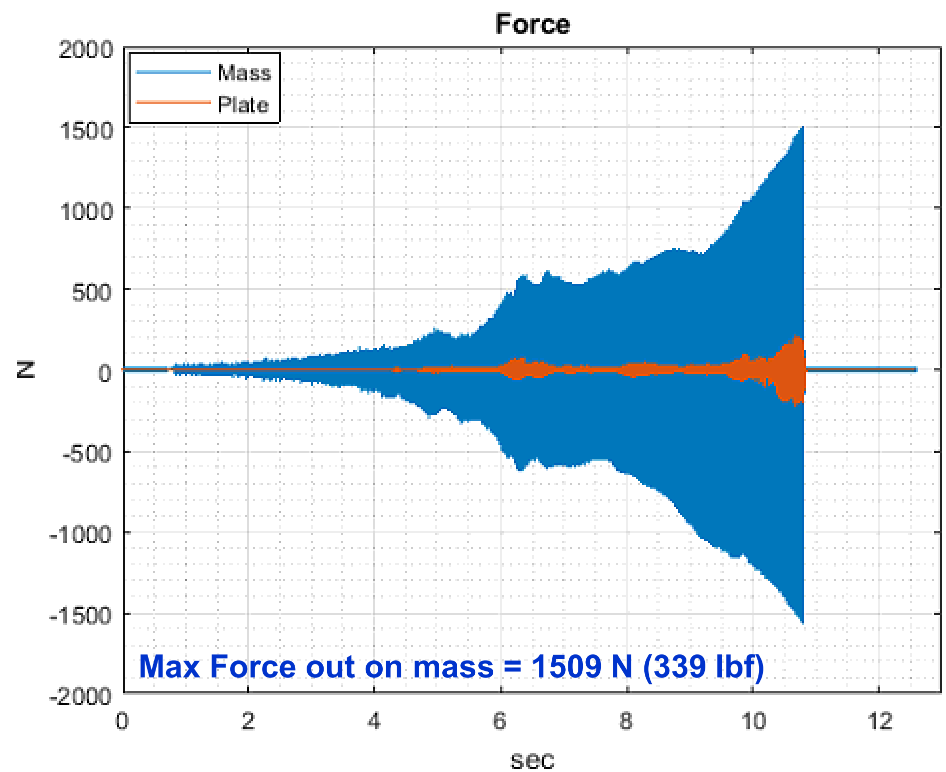


Laboratory and Small Scale Field Tests of Axial Vibrator Unit Developed under a US DOE Grant

Laboratory test of a Downhole Seismic Vibrator
The Maximum Force: 10 – 410 Hz was 1,509 N/339 lbf







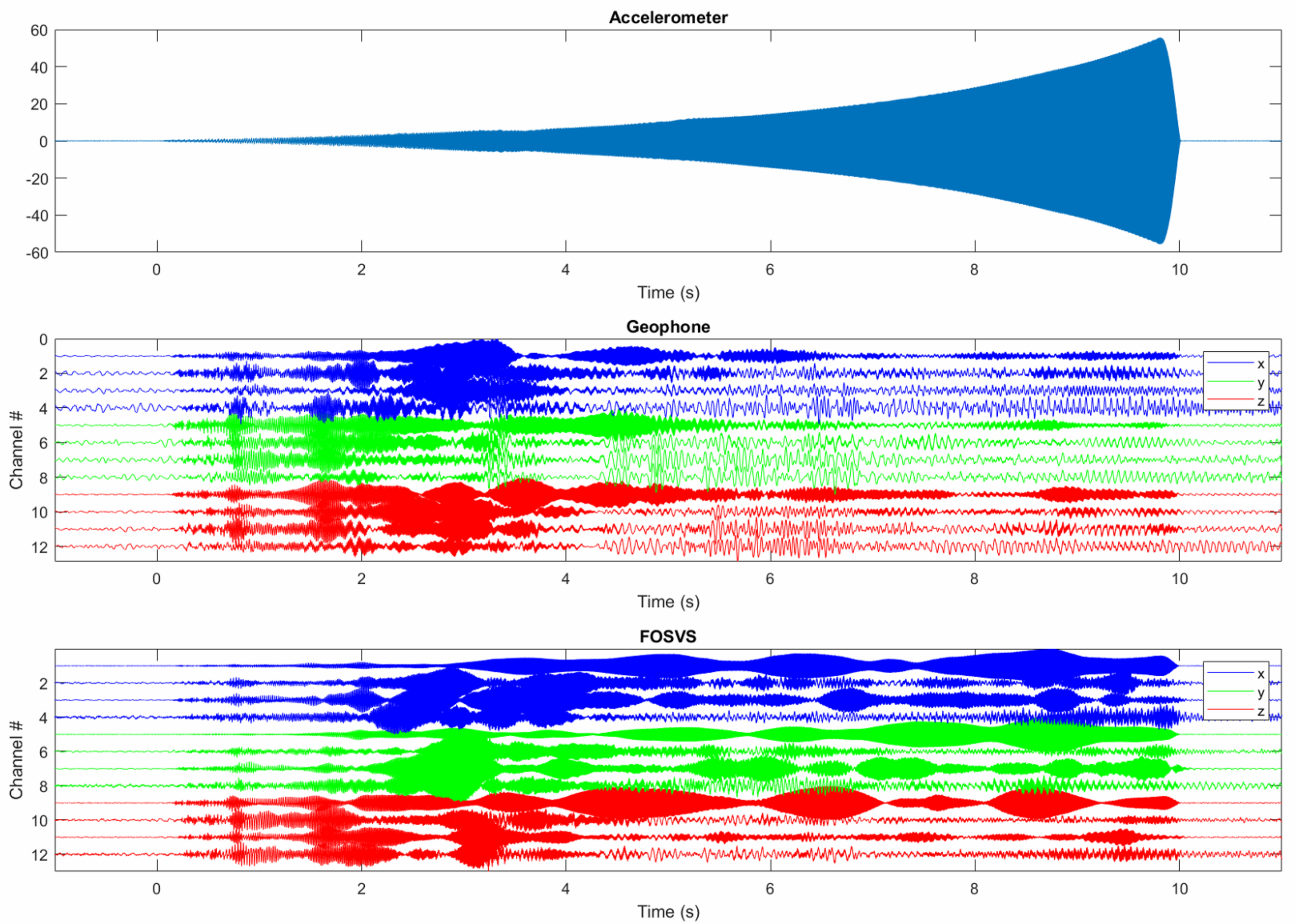
Source and Receiver On-Ground Experiment

- Sources:
  1. Impulsive source (The Piston): 50 kg (110 lbs..). ~60 g measured acceleration at impact.
     - 6,744 lbs. Force – 20X the vibratory source
  2. Vibratory Axial Source: 10-410 Hz, 10 sec, 13.6 Vpp drive, Custom Sweeps.
     - 339 lbs. Force – SAME S/N AS IMPULSIVE SOURCE
- Receivers:
  1. Geophone: 4 kHz sampling rate, 5ft, 15ft, 25ft, 35 ft offsets displayed
  2. FOSVS: 80 kHz sampling rate, 5ft, 15ft, 25ft, 35 ft offsets
  3. Mass and Baseplate Monitoring: VR Accelerometer: 75 kHz rate
- Processing:
  1. All data filtered with 5-10-410-500 Hz Ormsby filter
  2. All vibrator data correlated with custom correlation function to flatten spectrum.

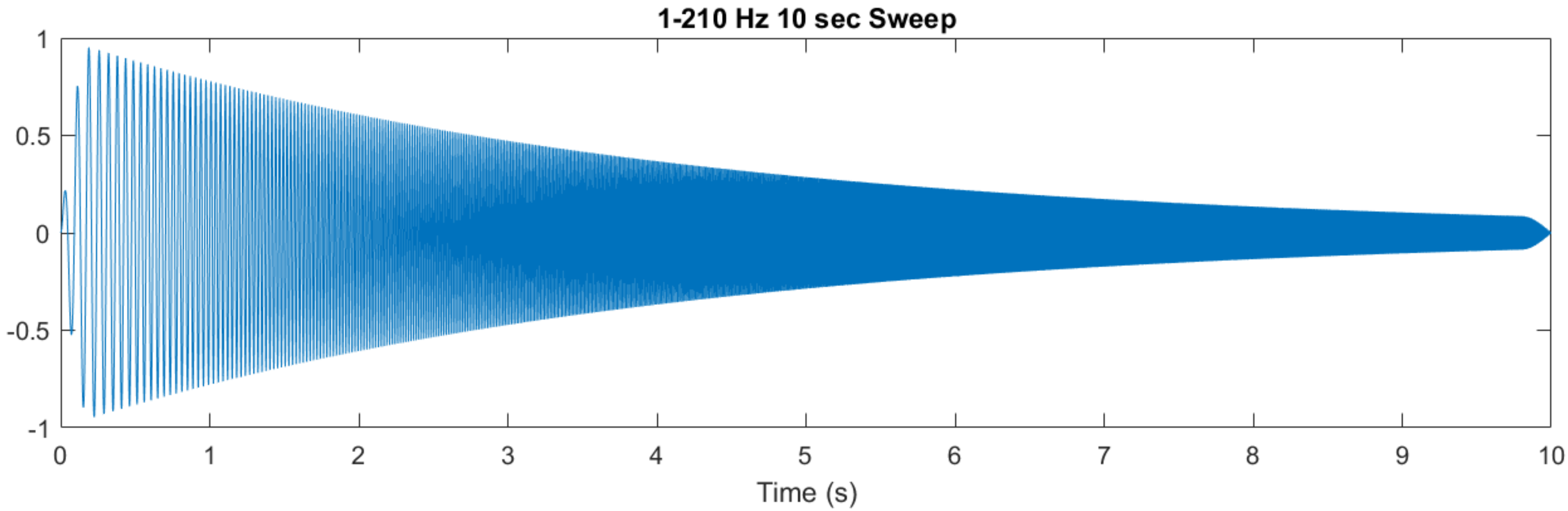
Test Fixture for a Downhole Seismic Vibrator: Actuator is the size of two soda cans

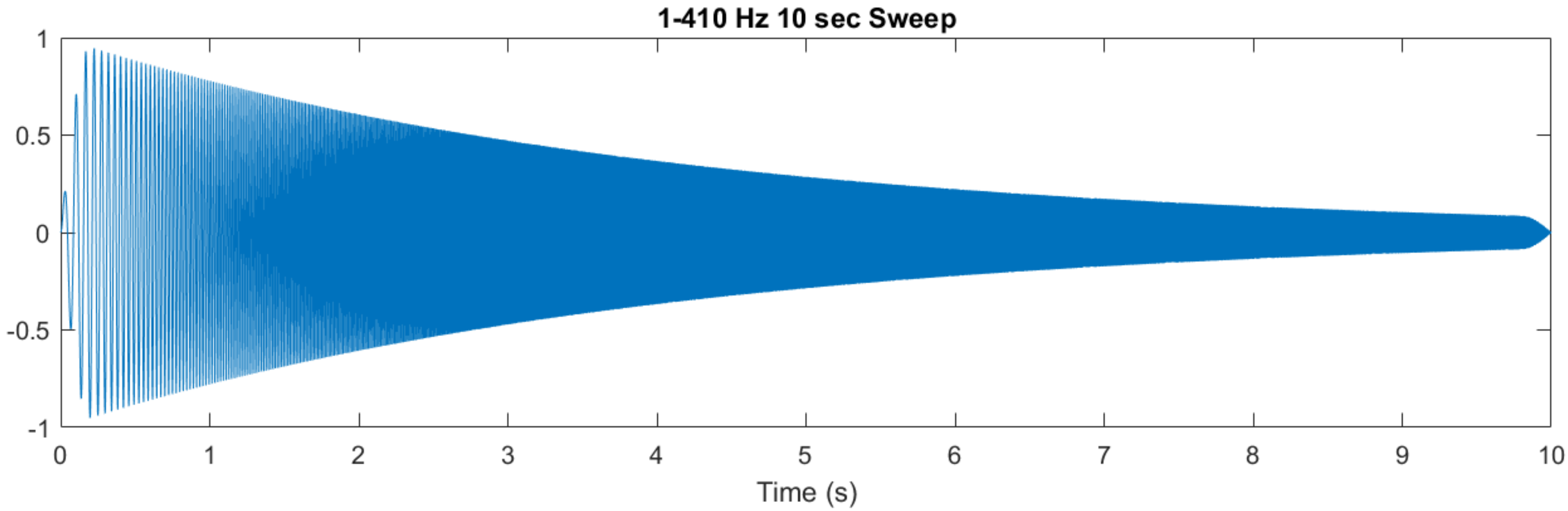
10-410hz, 10sec, 10vpp (200Vpp), 3.2kg, F=40 lbs.
Custom Sweep w/ $A=e^{x/8}$
Weight drop: 50 kg @ 60g

Vibrator Uncorrelated Data: 10-410 Hz, 10 sec sweep, 13.6 Vpp drive

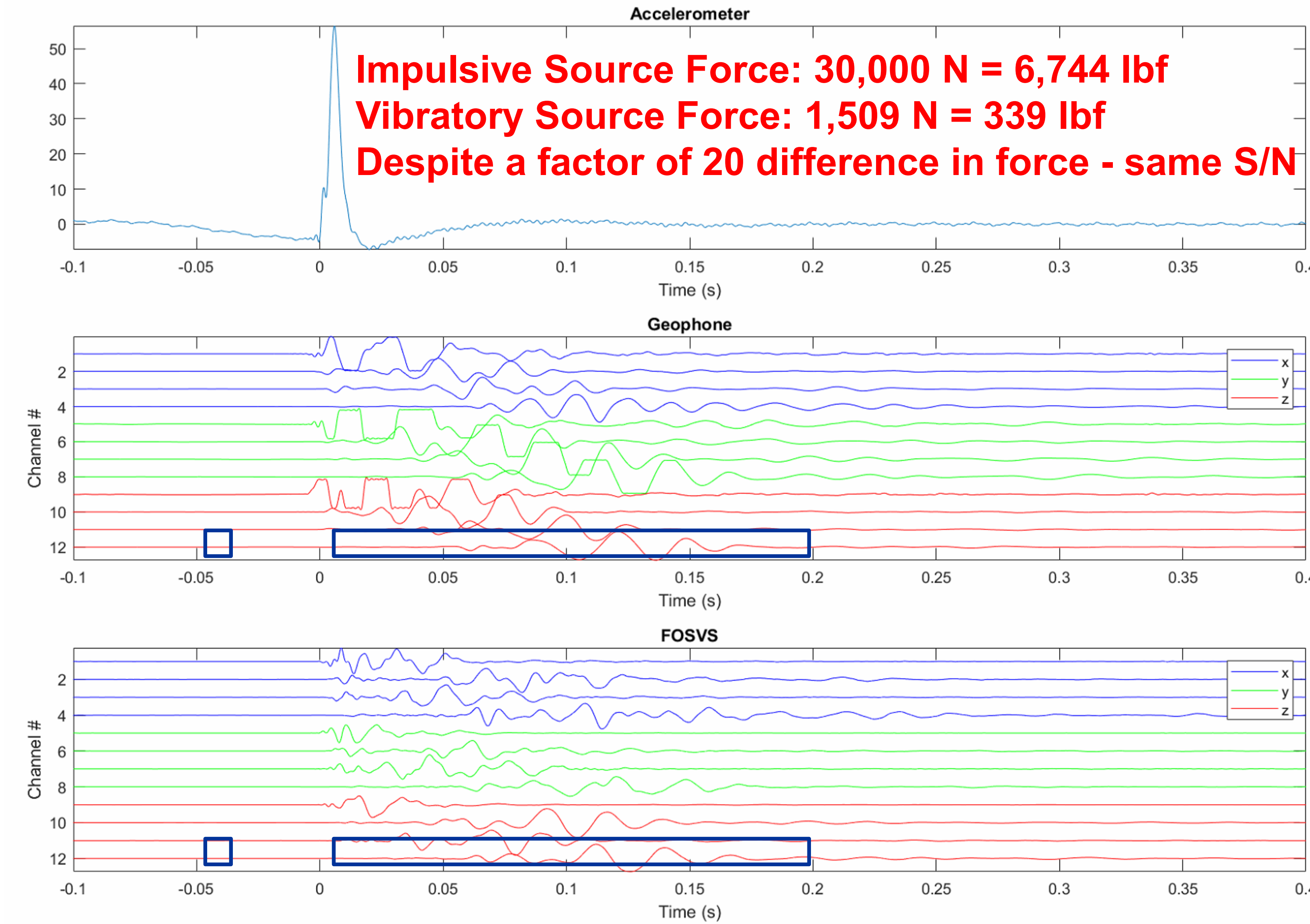


Theoretical 10 Second Sweeps used for Correlation - Case 4

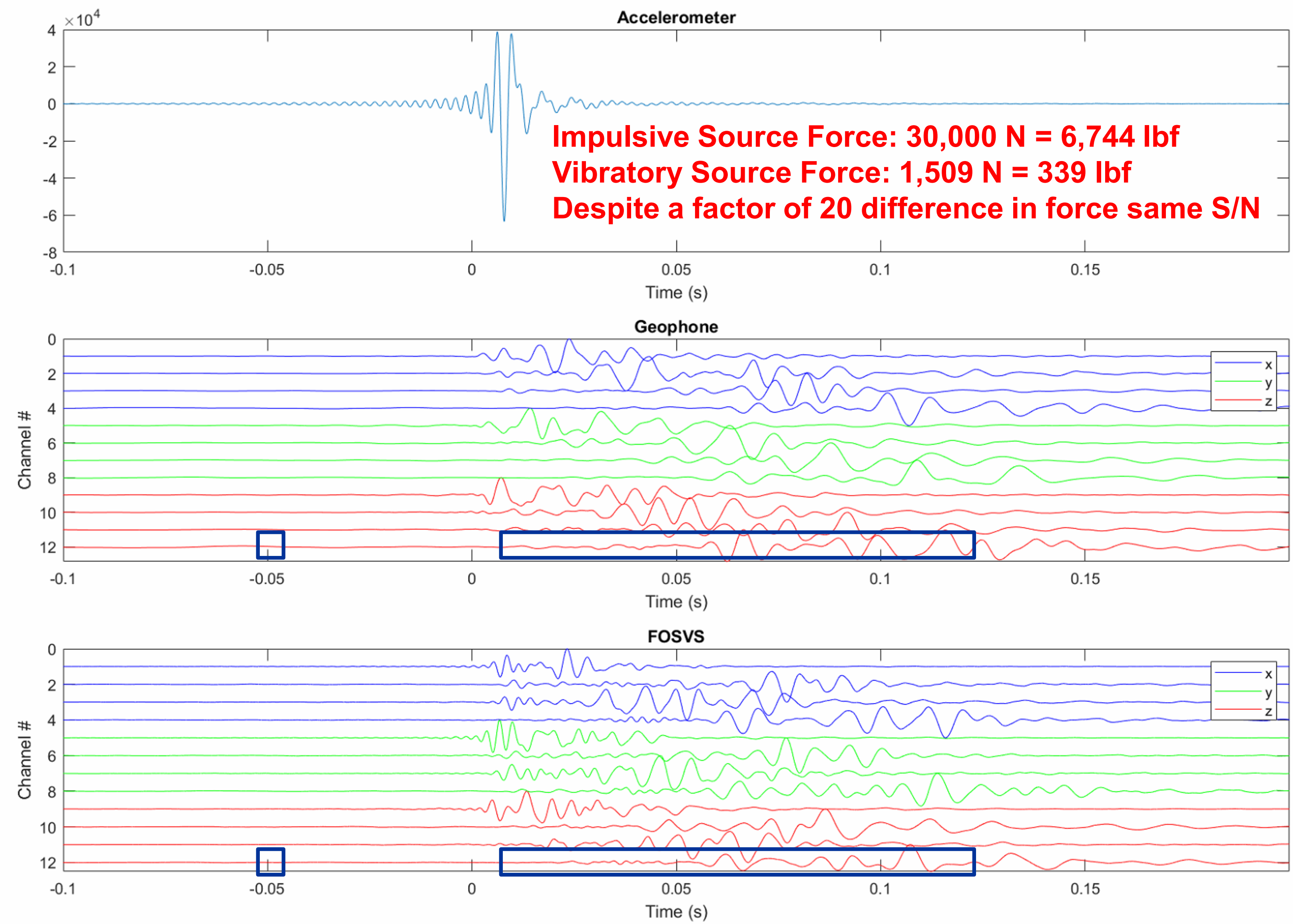




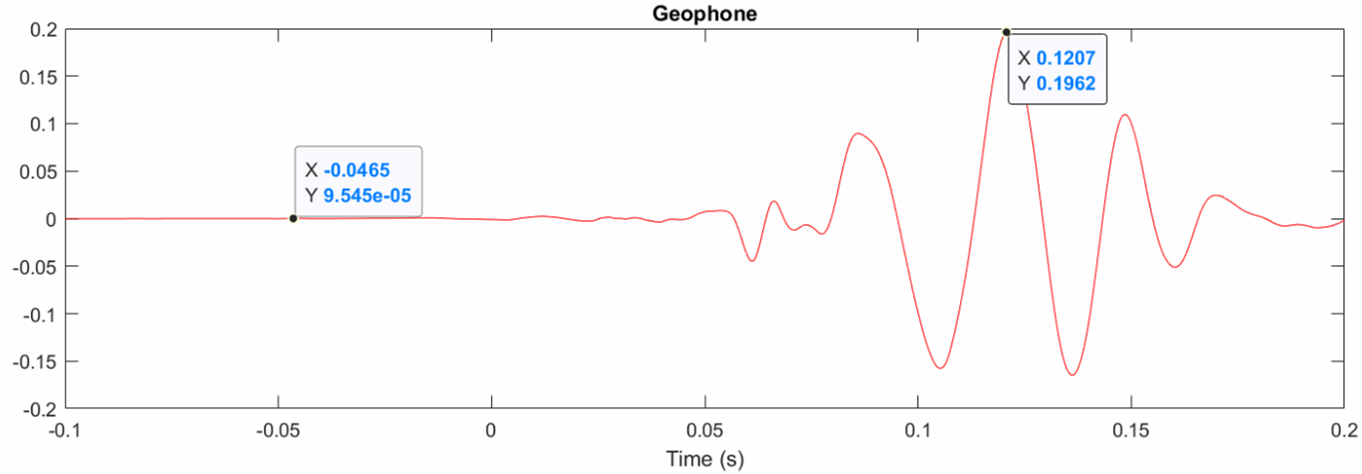
Impulsive Source: 50 kg (110 lbs..) @ 60g. Hit Data – Zoomed In

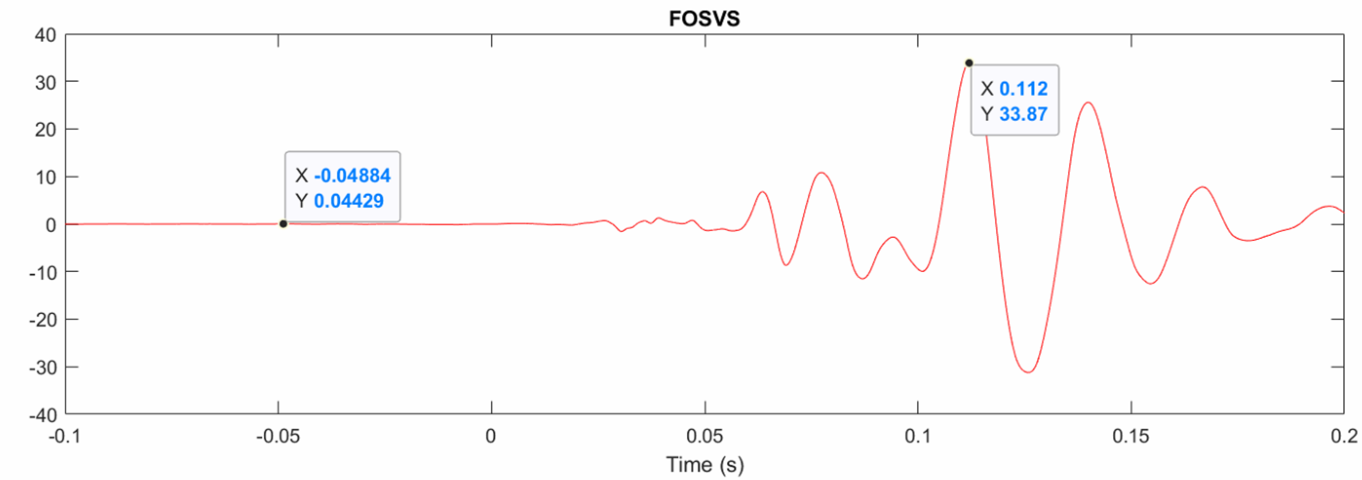


Vibrator Correlated Data: 10-410 Hz, 10 sec, 13.6 Vpp - Case 4

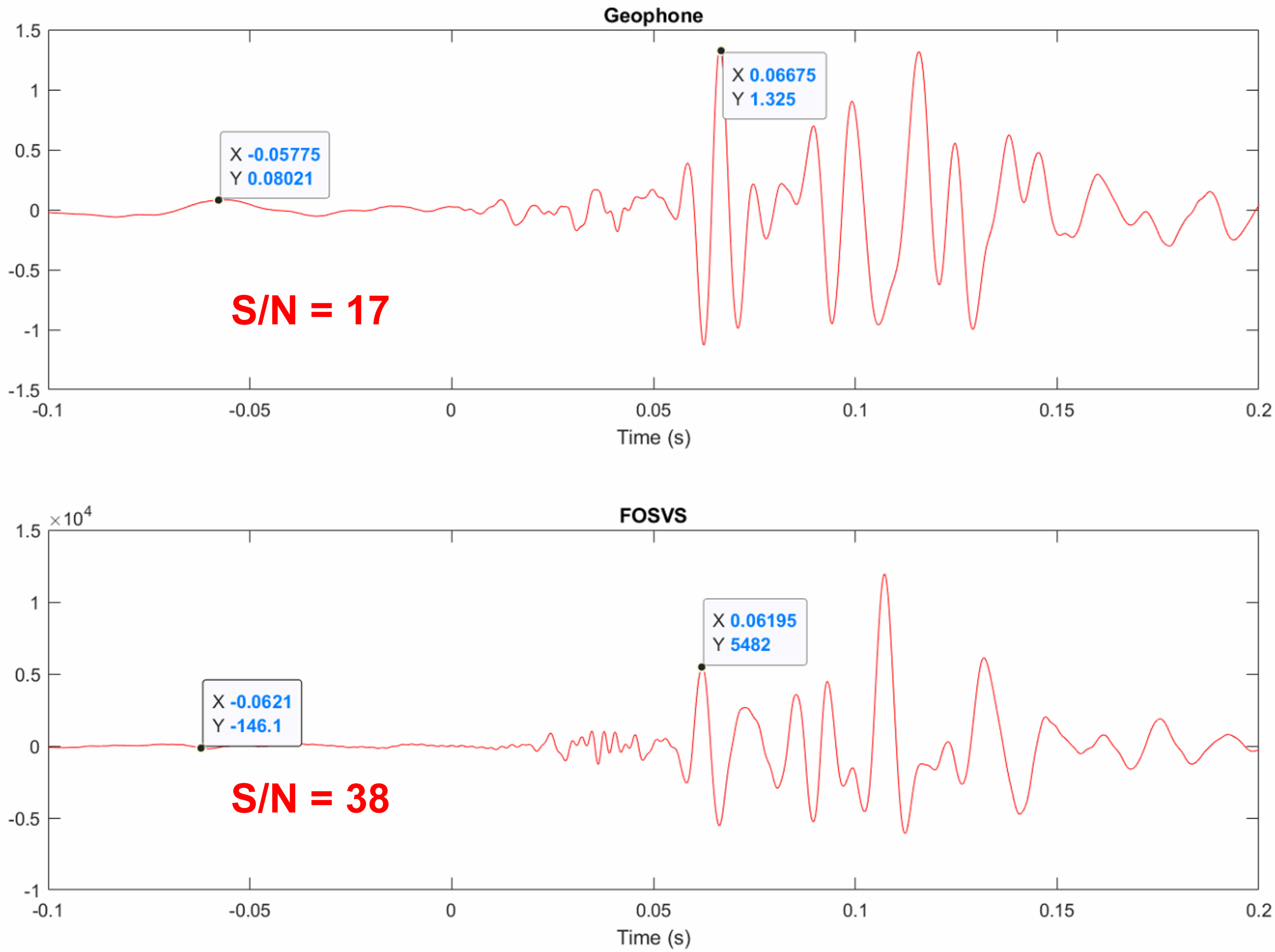


Impulsive Source: 50 kg (110 lbs..) @ 60g. Hit Data – Zoomed In



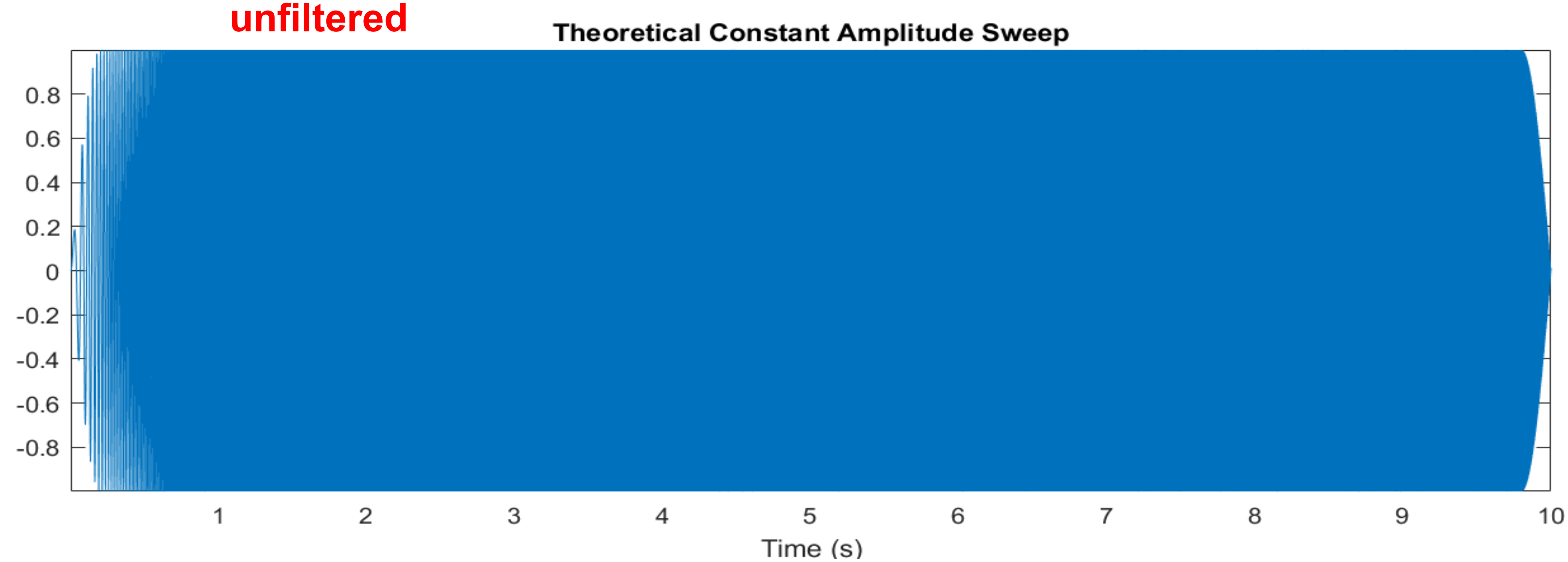


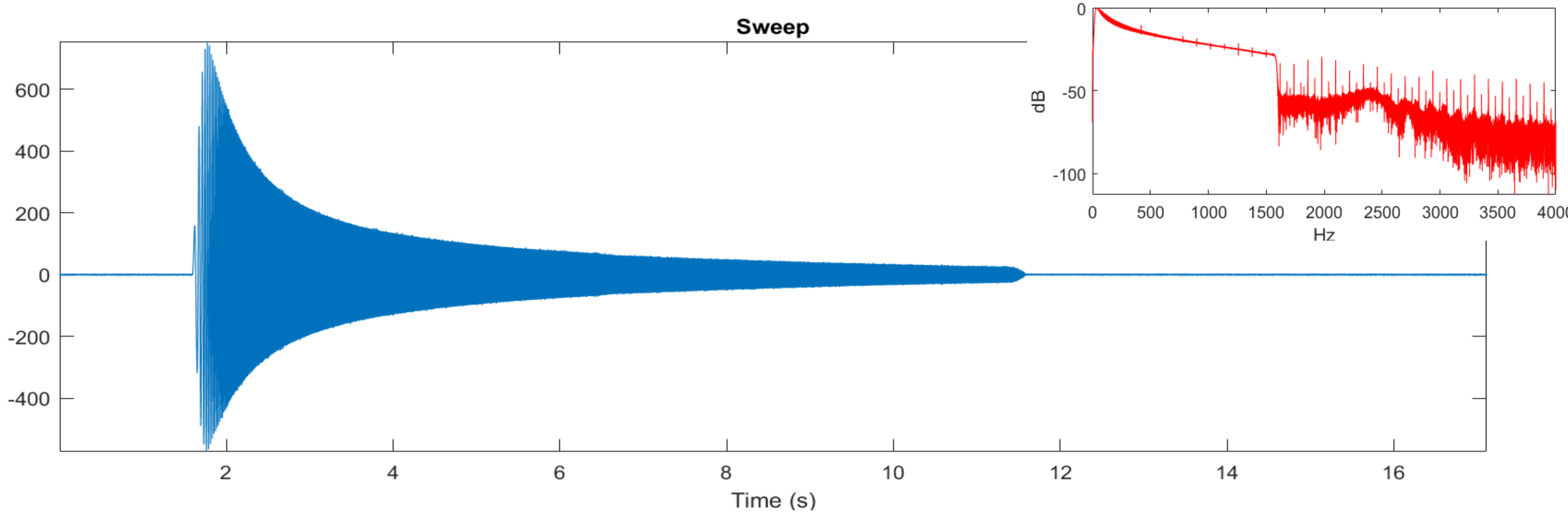
Vibrator Correlated Data: 10-410 Hz, 10 sec sweep, 13.6 Vpp drive - Case 4



Uncorrelated Data: 10-1610 Hz, 10 sec sweep, 5 Vpp drive

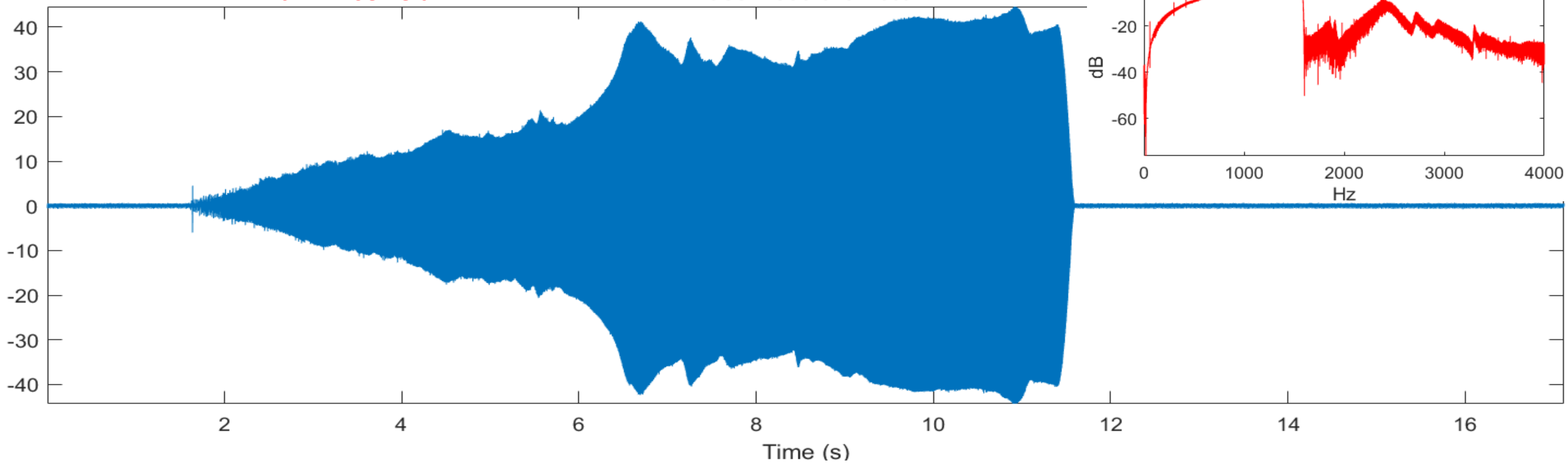
unfiltered

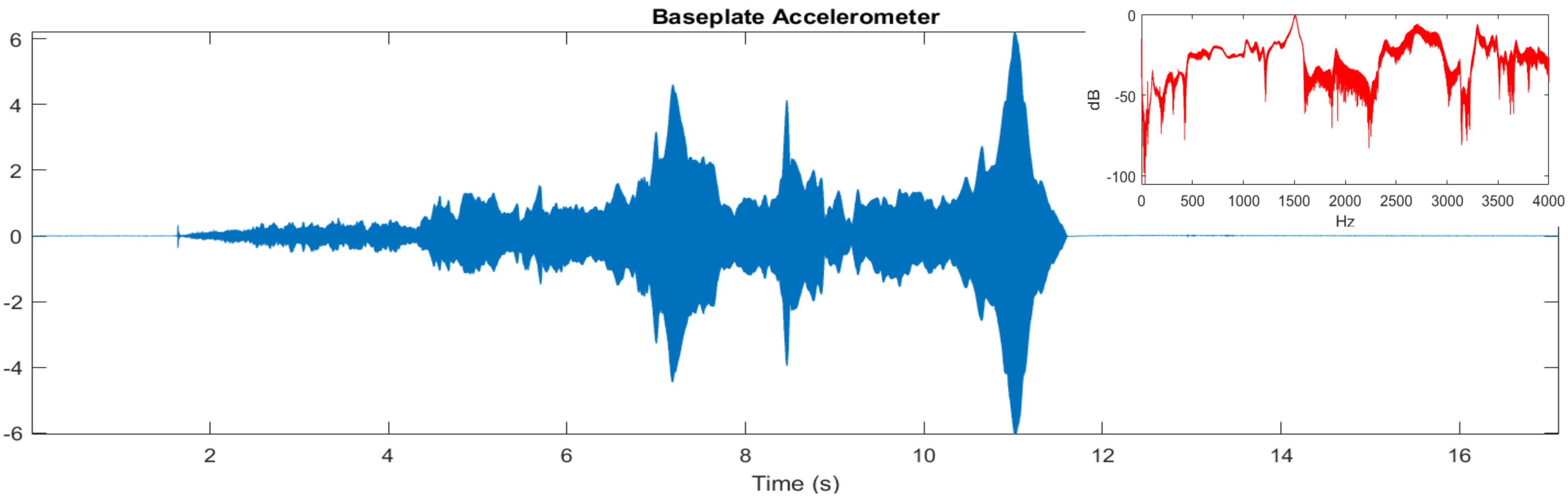




Uncorrelated Data: 10-1610 Hz, 10 sec sweep, 5 Vpp drive

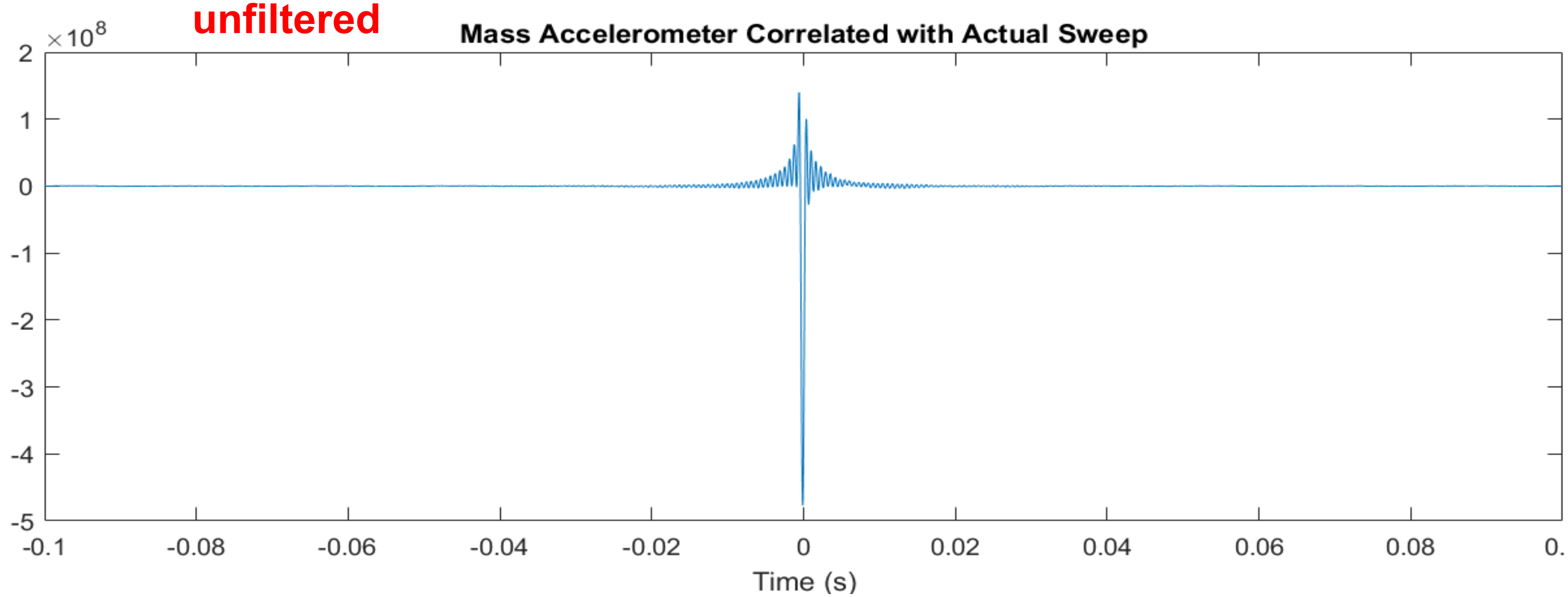
unfiltered

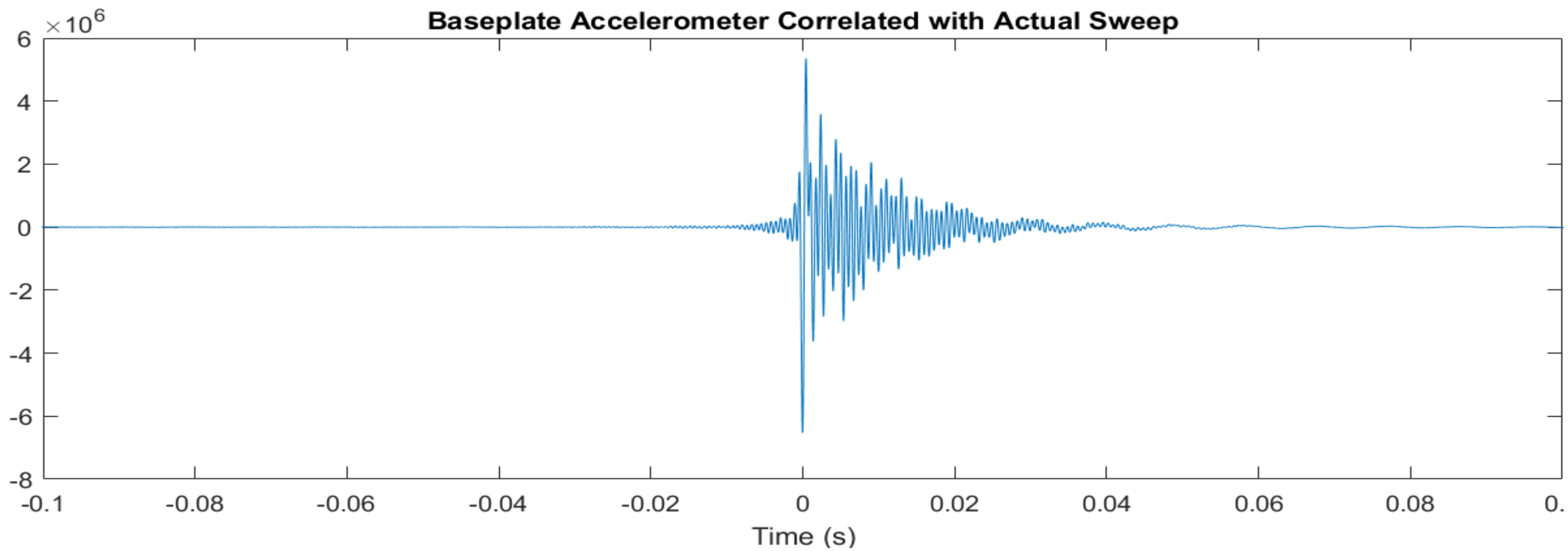




Correlated Data: 10-1610 Hz, 10 sec sweep, 5 Vpp drive

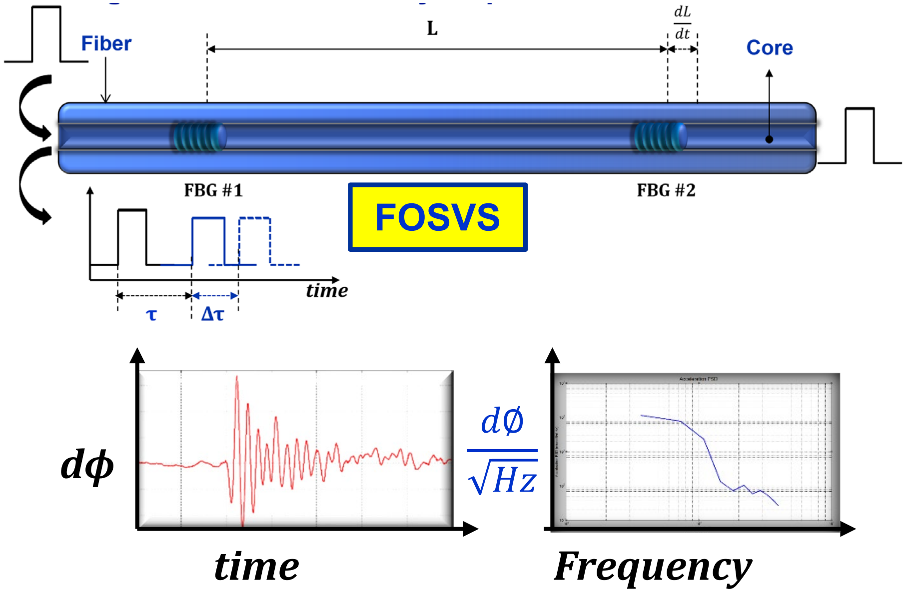
unfiltered



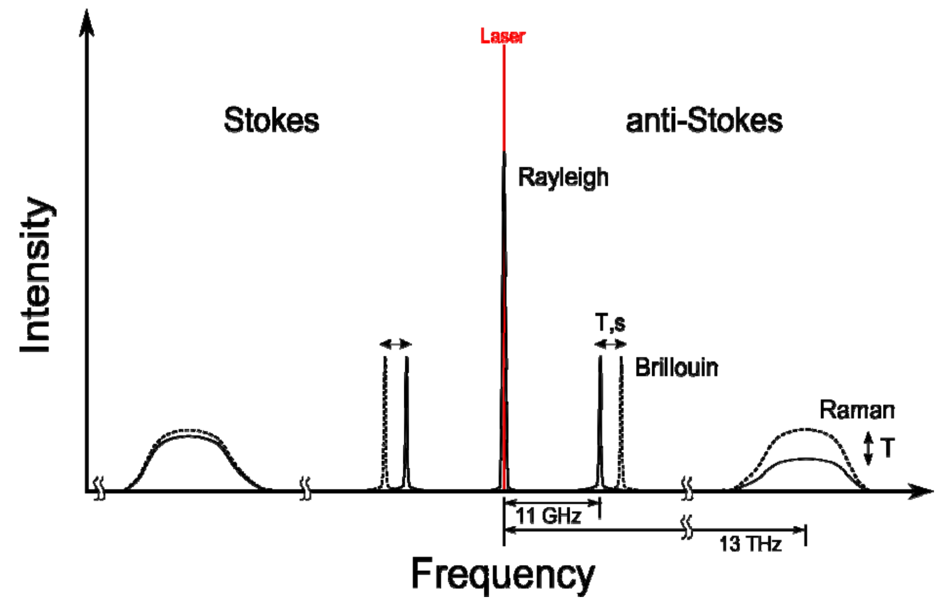


Several All-Optical Sensors are Part of Our Borehole System

DOE supported Paulsson Point Sensors include: Accelerometers, Hydrophones & Pressure Sensors.



Distributed Fiber Optic Sensor Technologies for Acoustic, Strain & Temperature measurements.



Interferometric Sensing

- Two FBGs: Measure phase changes/time between two laser reflections from the two FBG's

Rayleigh (DAS)

- Rayleigh Scattering
- **Acoustic**

Raman (DTS)

- Intensity ratio of Stokes and anti-Stokes
- **Temperature**

Brillouin (DSS)

- Frequency of Brillouin peak
- **Strain** and temperature

Summary

- To Image Geology in high enough resolution to guide injection of CCUS, UGS+H2, EGS, EEOR to we must use 3D/3C borehole seismic technology. This requires:
  - Large arrays of 3C seismic sensors
  - High frequency Borehole VibroSeis units
  - Accurate real-time on-site processing & imaging

- To Monitor CCUS, UGS+H2, EGS, EEOR production we need to use high frequency sensors that can record 2,000 – 8,000 Hz at M-5 to M-7 magnitudes
  - Fiber Optic Seismic Vector Sensors (FOSVS)

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  - RPSEA Contract 09121-3700-02 (2011)
  - DOE Contract DE-EE0005509 (2012)
  - California Energy Commission Contract GEO-14-001 (2013)
  - DOE Contract DE-FE0024360 (2014)
  - DOE SBIR II Grants DE-SC0017222 & DE-SC0017729 (2018)
  - DOE SBIR II Grant DE-SC0018613 (2018) Downhole Source

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Thank You!

For questions please contact Björn Paulsson via

e-mail: bjorn.paulsson@paulsson.com

or

Mobile: +1-310-780-2219