Development and Test of a 1,000 Level 3C Fiber Optic Borehole Seismic Receiver Array Applied to Carbon Storage
DE-FE0004522 - Paulsson, Inc.

U.S. Department of Energy

National Energy Technology Laboratory
Carbon Storage R&D Project Review Meeting
Developing the Technologies and
Infrastructure for CCS

August 12-14, 2014

Benefits to the Program

- Program goals being addressed.
  - Support industry's ability to predict CO_2 storage capacity in geologic formations to within ±30 percent.
  - Develop and validate technologies to ensure 99 percent storage permanence.
  - Develop technologies to improve reservoir storage efficiency while ensuring containment effectiveness.
  - Develop Best Practice Manuals for monitoring, verification, accounting, and assessment; site screening, selection and initial characterization; public outreach; well management activities; and risk analysis and simulation.
- Benefits statement: **The research project is developing a high resolution ultra robust seismic imaging system using fiber optic borehole seismic vector sensors. These sensors map more precisely the geology of the injected reservoir and more precisely monitor the movement of the CO_2 injected into the reservoir**. This will reduce the risk of release of CO_2 into the atmosphere resulting from poor understanding of the geology and/or poor understanding of the injection of the CO_2. The technology, when successfully demonstrated, will provide an improvement over current imaging systems in both performance and cost. This technology contributes to the Carbon Storage Program's effort of ensuring 99 percent CO_2 storage permanence (Goal).

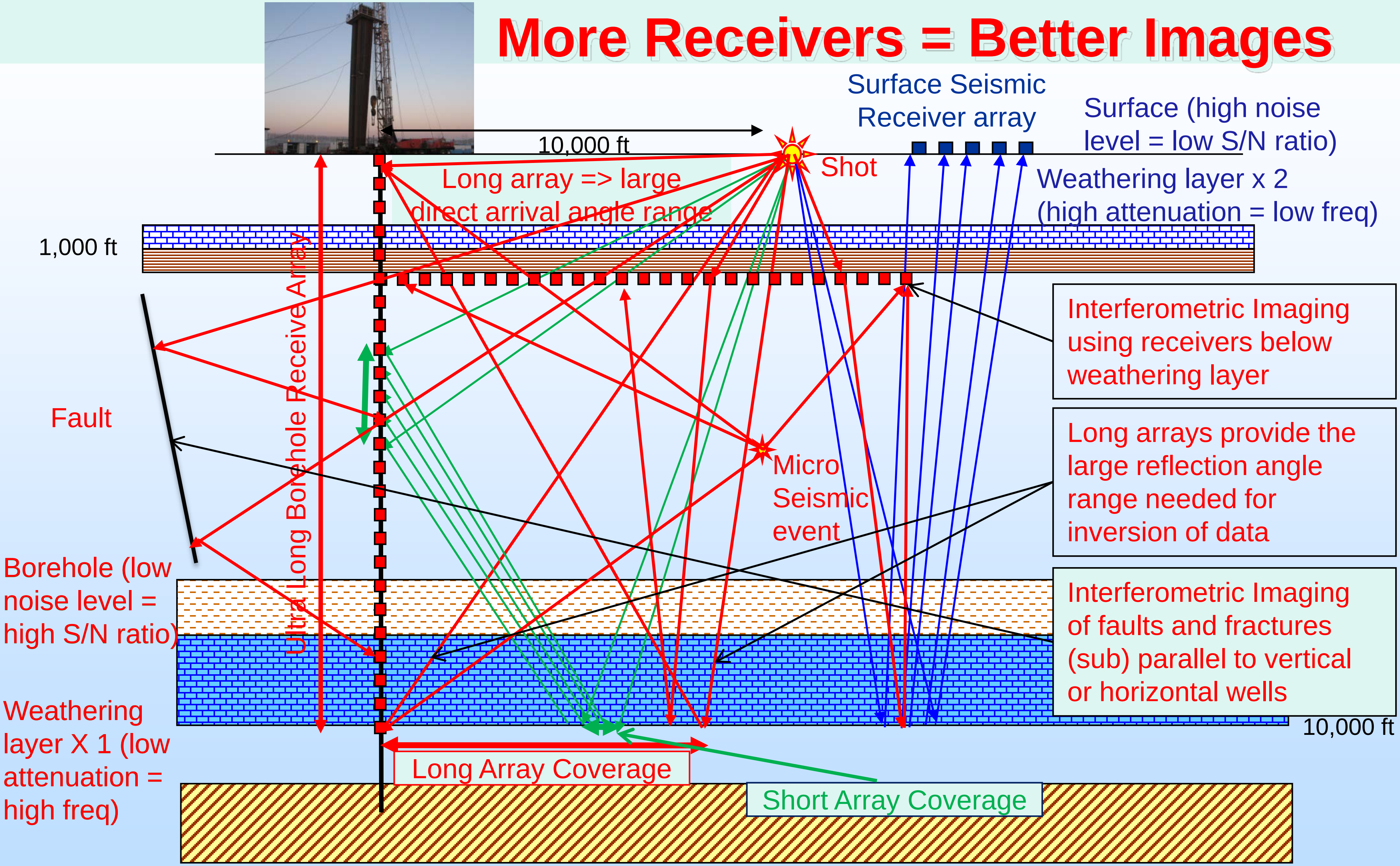
Relevance/Impact of Research

Project Objectives – How a successful development of a large Fiber Optic Seismic Sensor (FOSS)™ array will impact the Carbon Capture and Storage Program's Goals

- A large 3C high temperature borehole seismic array, i.e. a large aperture antenna, that can be deployed from the bottom to the top of monitor wells, i.e. filling the entire well, will allow the imaging of large volumes of the storage reservoir rock providing for cost effective and accurate imaging.
- A large high temperature borehole seismic array can map existing fracture zones guiding the drilling of injection wells
- A large high temperature borehole seismic array can map the micro seismic events much more accurately than short borehole arrays or seismic arrays deployed at or near the surface of the earth. More accurate mapping of the micro seismic events will provide for a more realistic dynamic reservoir model.
- The drill pipe base deployment system can deploy large arrays to a depth of 30,000 ft in both vertical and horizontal wells. The deployment system can also deploy other sensors such as temperature, pressure and chemical sensors.

Borehole Seismic Imaging with Ultra long arrays

More Receivers = Better Images



2014 Paulsson, Inc. (PI)

Project Overview
Goals and Objectives

- **Objectives :** Design, build, and test the highest performance borehole seismic receiver array system in the industry to allow cost effective geologic Carbon Capture and Storage (CCS) through improve site characterization and monitoring
- **Goal A:** Develop technology to allow deployment of a 1,000 level drill pipe deployed 3C Fiber Optic Seismic Sensor (FOSS) receiver array for deep boreholes.
- **Goal B:** Build a 15 level 3C 15,000 ft long prototype system. Test the prototype system, and conduct a borehole seismic survey at a Carbon Capture and Storage site with the fiber optic borehole seismic prototype system
- **Success Criteria**: Record high S/N ratio, broad band and great vector fidelity data in the field

Paulsson, Inc. 1,000 level Project
Accomplishments, Results & Progress

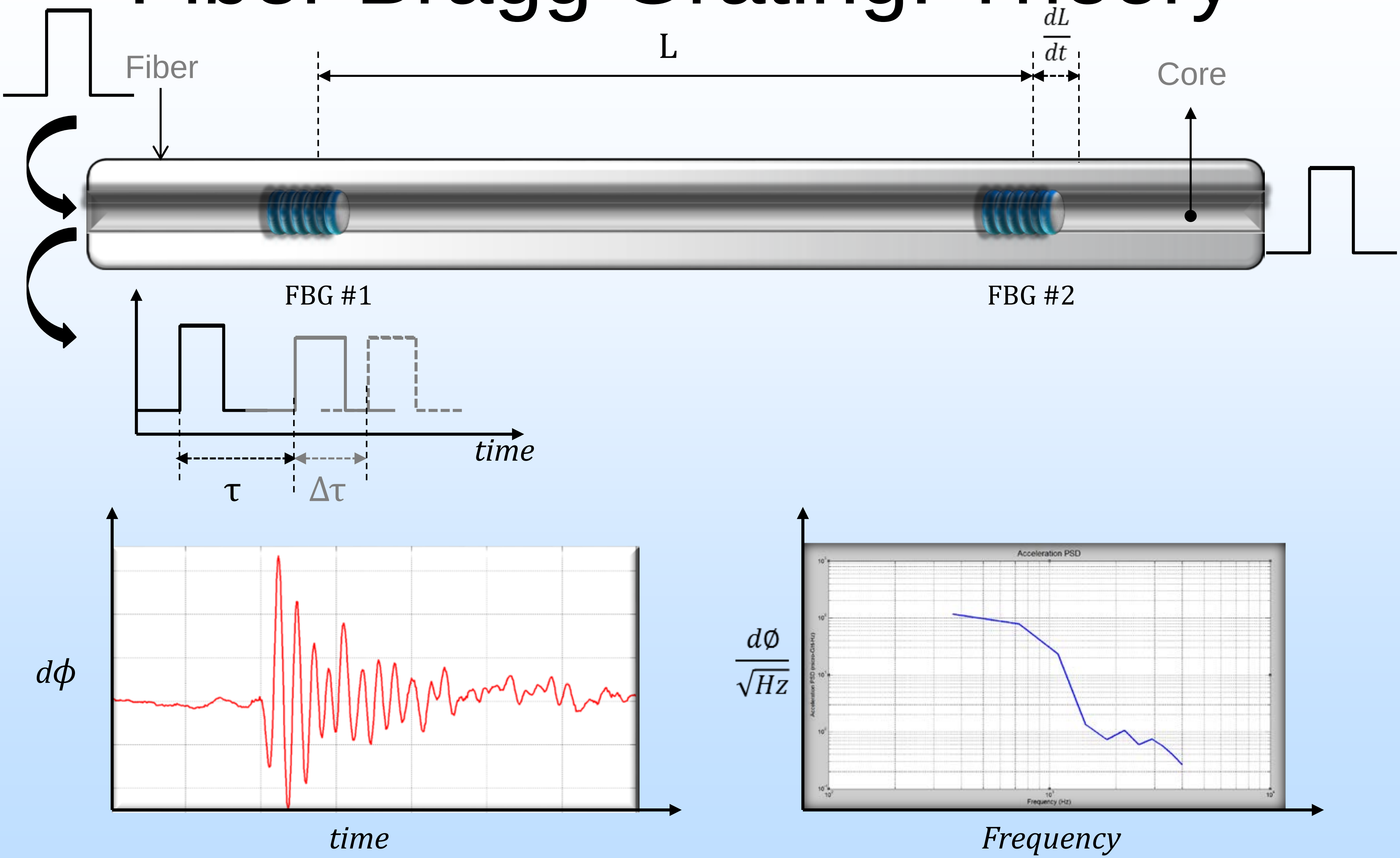
The most important technical accomplishments and progress and their significance from 10/2011 until 08/2014;

- **Test facility**
  - We have designed and installed a test facility where we can do dynamic testing of the Fiber Optic Seismic Sensor at temperatures up to 350ºC.
- **We have designed the Fiber Optic Seismic Sensor (FOSS)™**
  - Testing of the new Fiber Optic Seismic Sensors (FOSS)™ has been extremely favorable. The frequency response and sensitivity is much better than a regular geophone and we have proved they can operate to 320ºC.
- **We have designed and verified the deployment system**
  - The system is strong enough to be deployed to a well depth of 10,000 m.
- **We have field tested the Fiber Optics Seismic Sensor System**
  - We have performed two borehole field tests of the Fiber Optics Seismic Sensor (FOSS)™ system and proved that we can record data to over 2,000 Hz with outstanding sensitivity.
- **We will complete a 15 level 3C system in August 2014**
  - The system being build has a depth capability of 15,000 ft

Presentation Outline

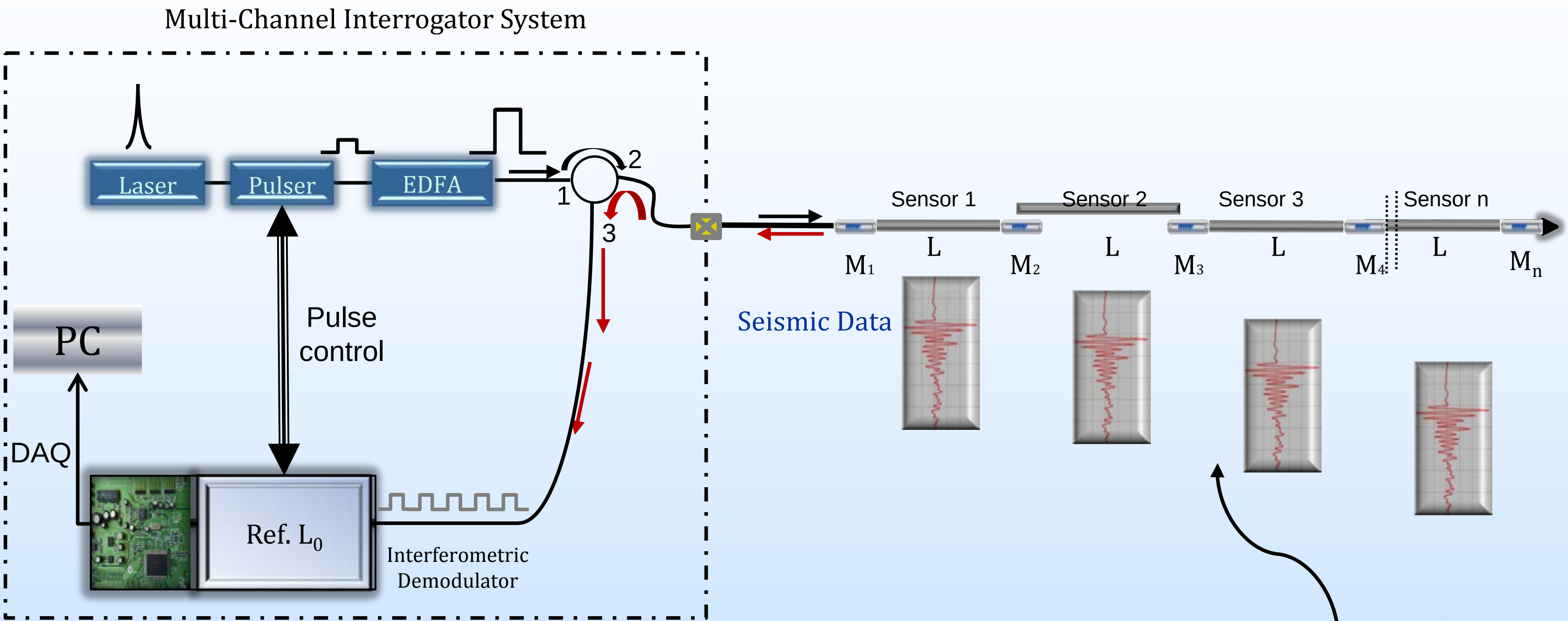
1. **Fiber Optic Seismic Sensor (FOSS)™ Development**
2. **Deployment System Development**
3. **Field Survey Results**
4. **Wrap up**

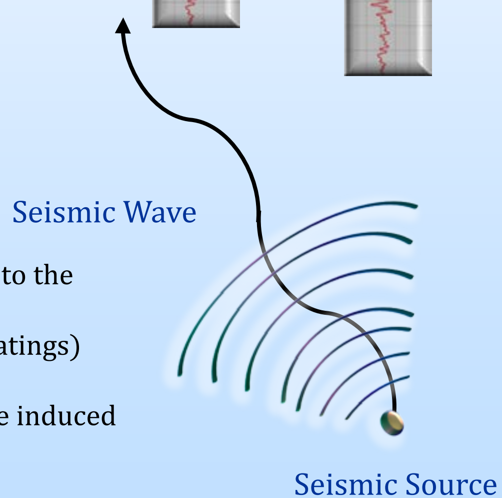
Fiber Bragg Grating: Theory



Interrogator Optical Specifications

Time Domain Multiplexing (TDM): Interrogator System Overview





Basic Process:

1.A highly coherent laser source is used to generate a modulated laser pulse that corresponds to the length of the fiber sensor L.

2.The pulse reflects from each partially reflecting mirrors M_1, M_2, M_3, M_4, ...M_n(Fiber Bragg Gratings) generating multiple interfered pulses that are compared to reference distance Ref L_0.

3.In the event of a seismic event, the returned interfered pulses are demodulated to extract the induced change in phase , $d\phi$, due to the change in length (strain)

$$d\phi = 2\pi \frac{n\Delta L}{\lambda}$$

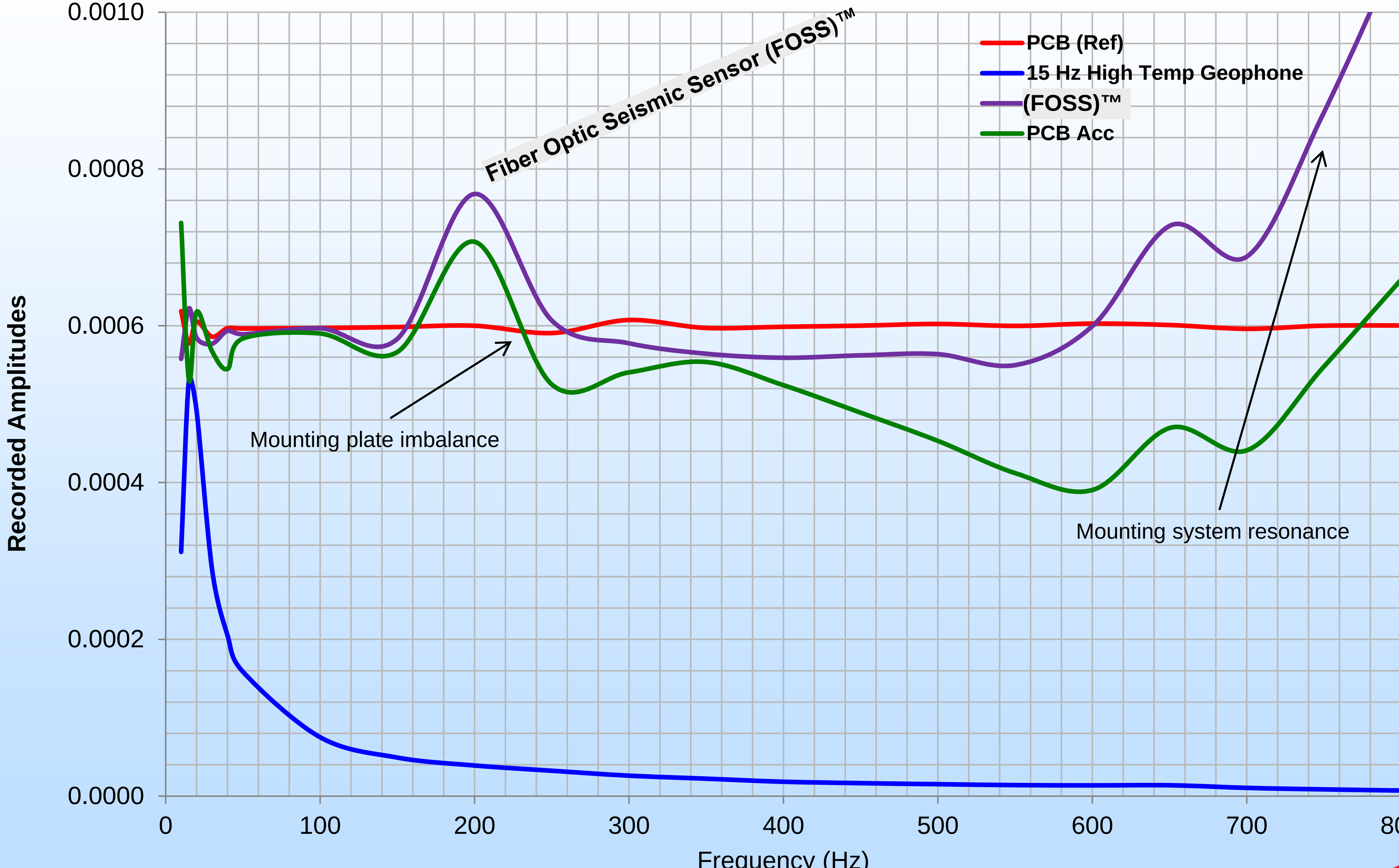
The Dynamic Test Station for the Fiber Optic Seismic Sensors (FOSS)™

THE FIBER OPTIC SEISMIC SENSOR (FOSS)™

VS.

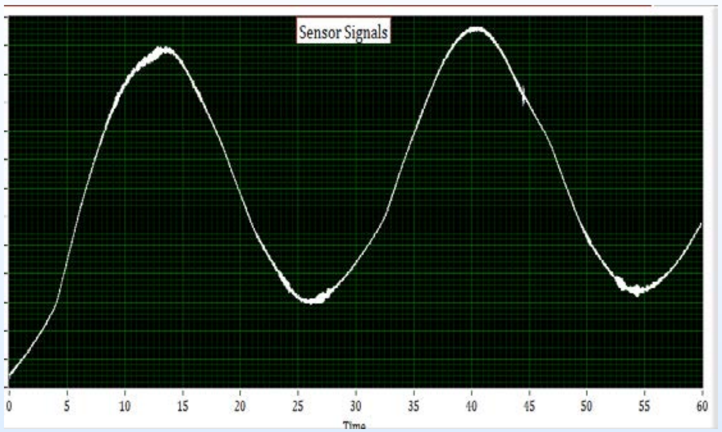
OTHER SEISMIC SENSORS @ 200°C

Frequency Response Curve - All Sensors
10 to 800 Hz, A=600 µG Sweep @ 200°C

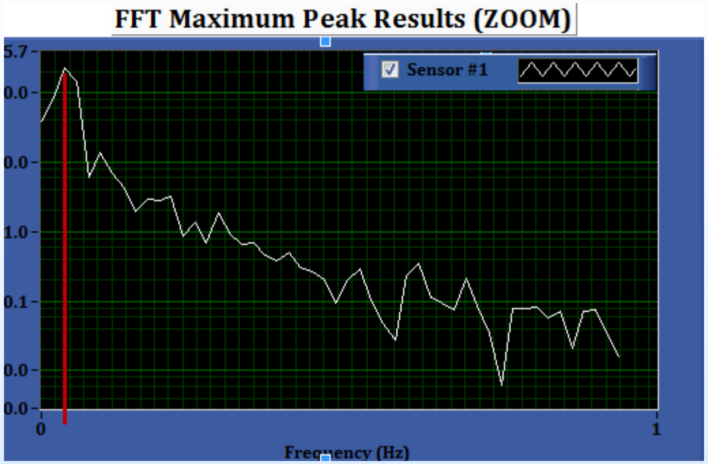


Fiber Optic Seismic Sensor Test at < 1Hz

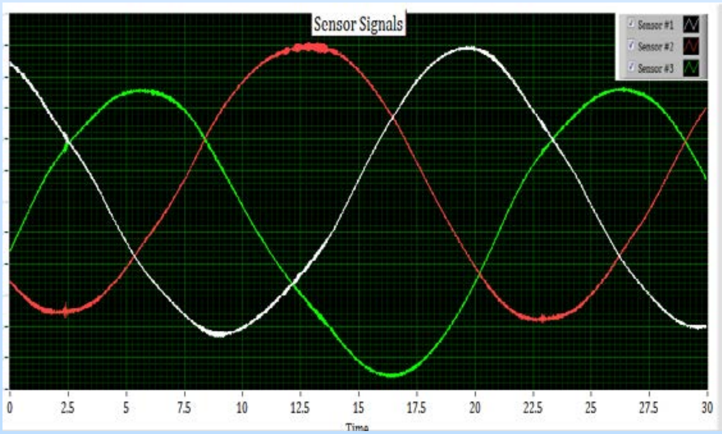
- Single FOSS sensor modulated at 0.03 Hz (33 seconds period)
- The Actuator is controlled by a PC at all frequencies (from <1 Hz to higher frequencies)



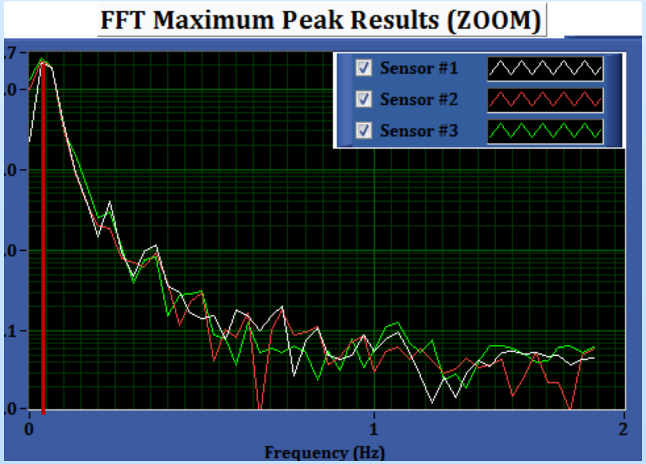
Test @ 0.03 Hz



- 3 FOSS are mounted axially to motion and modulated at 0.03 Hz (33 seconds period)
- The motion is controlled by a PC at all frequencies (from <1 Hz to higher frequencies)

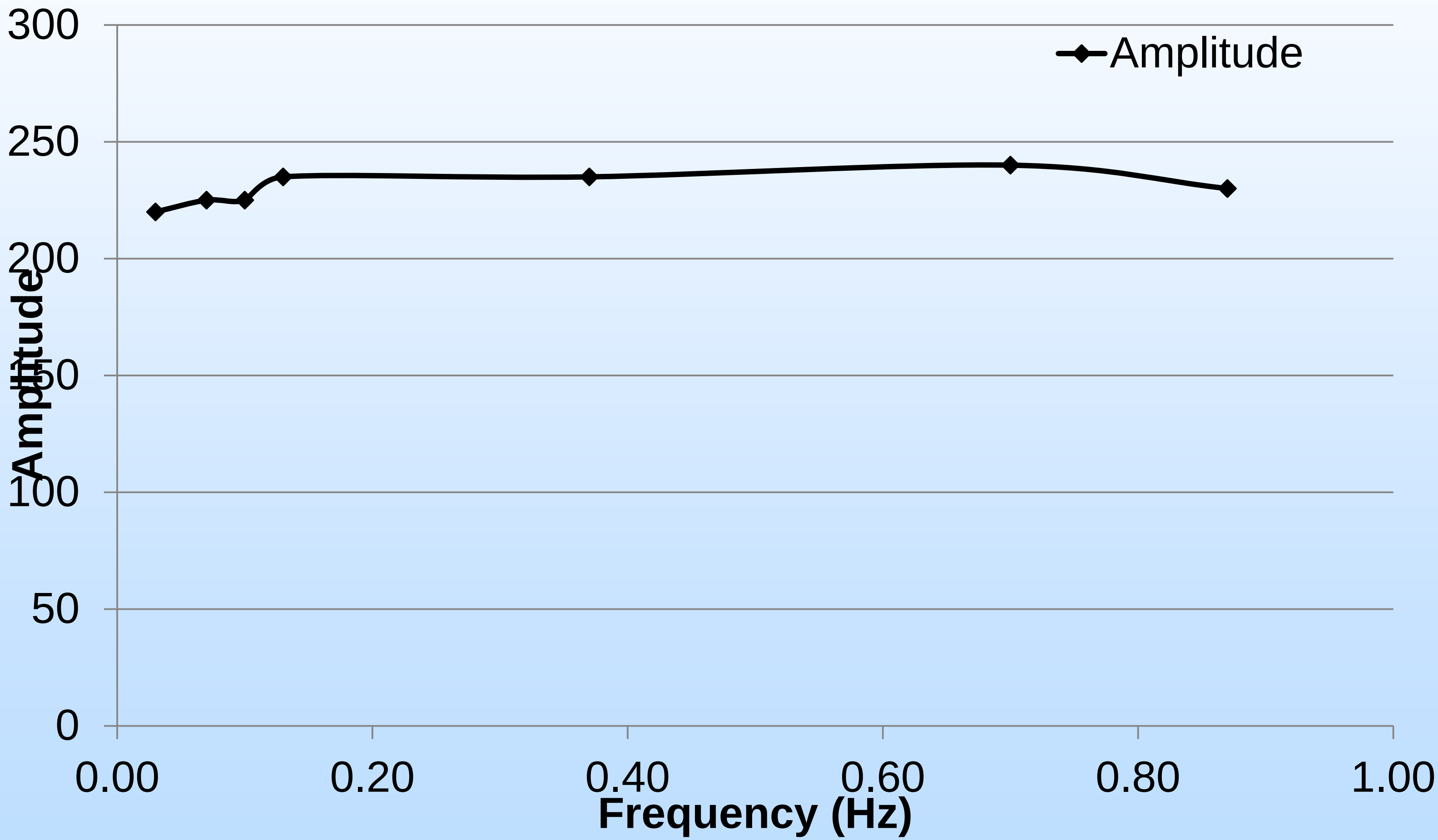


Test @ 0.03 Hz



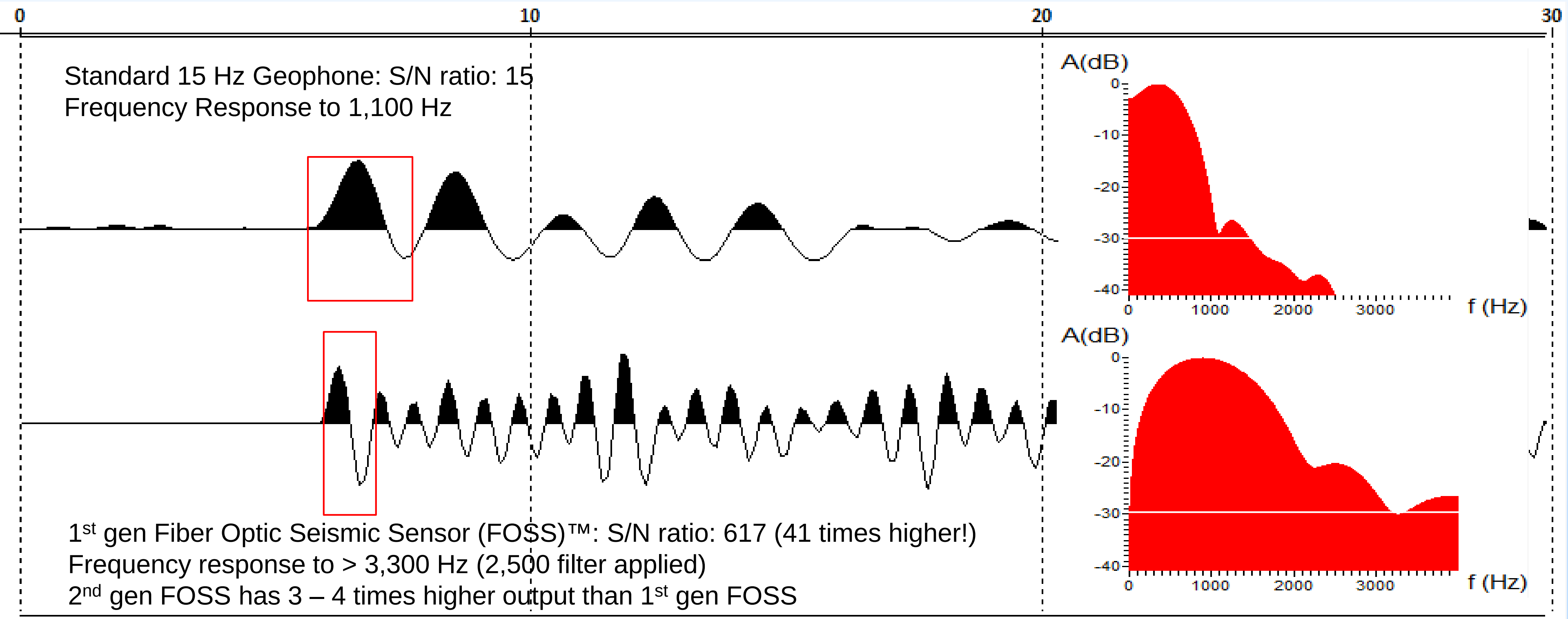
Fiber Optic Seismic Sensor Performance Test at < 1Hz Infra Sound Seismic Band

FOSS Test @ 0.03 – 0.9 Hz (33 – 1.1 sec period)



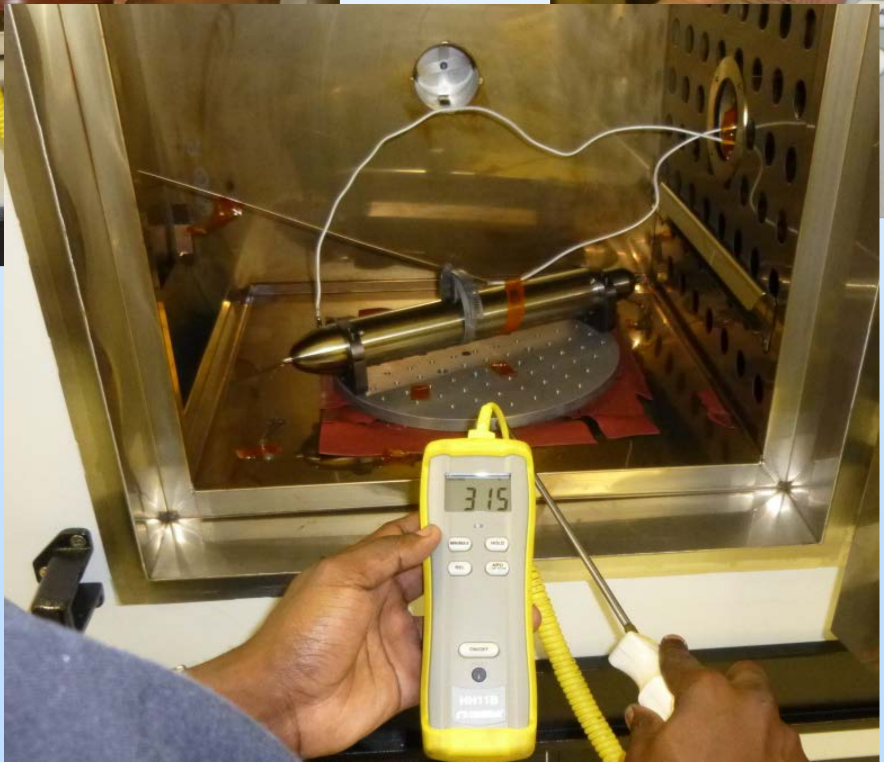
Fiber Optic Seismic Sensor (FOSS)™ vs. Standard Geophone
Data recorded simultaneously from a single tap test
Sampling rate: 8,000 Hz. High cut filter at 2,500 Hz.

- FOSS S/N ratio is 41 times higher than S/N for Geophone
- FOSS -30 dB point is 3,300 Hz vs 1,100 Hz for Geophone

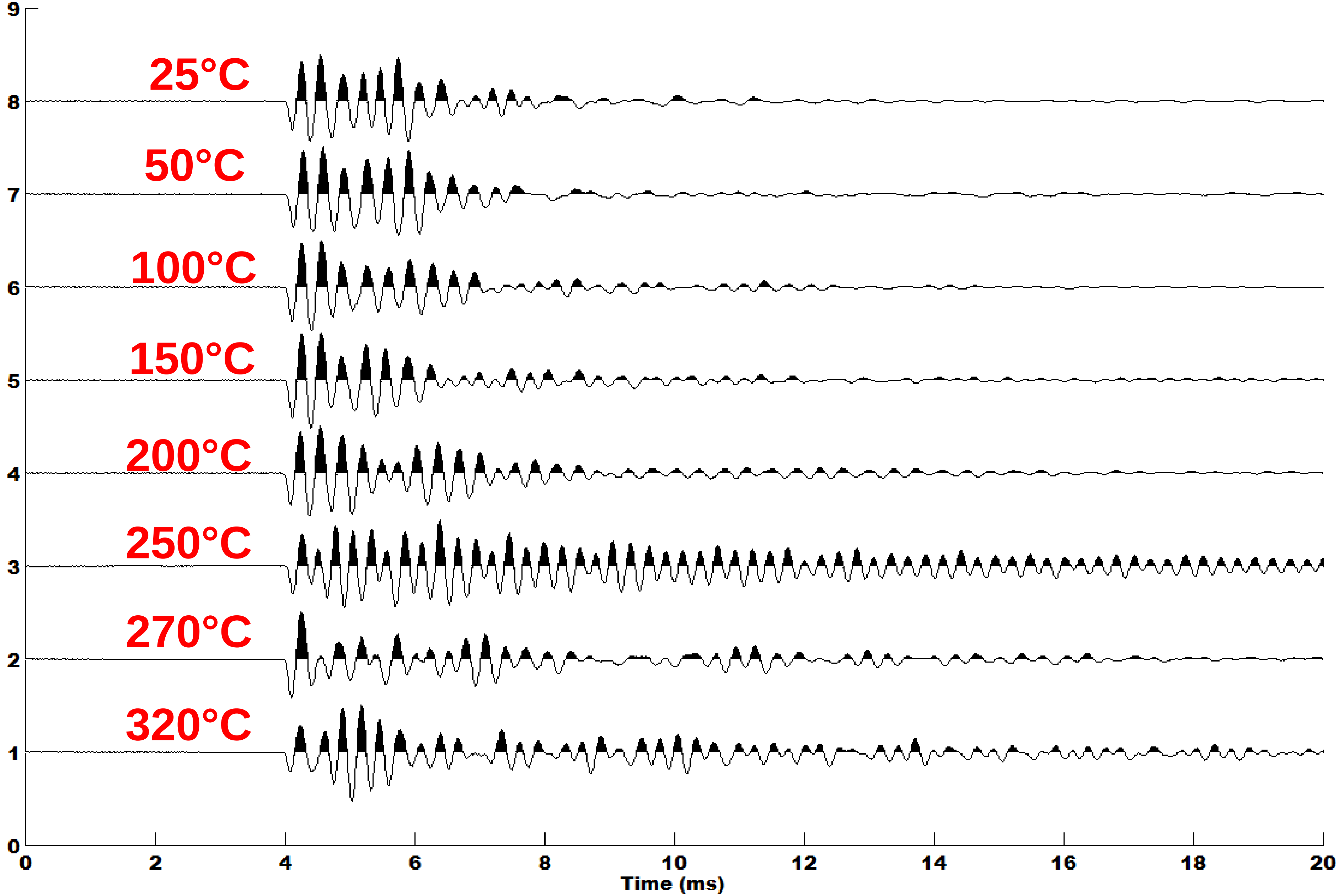


Tap Test of 3C Fiber Optic Seismic Sensors Mounted Inside a Geophone Pod @ Temperatures: 25°C - 320°C

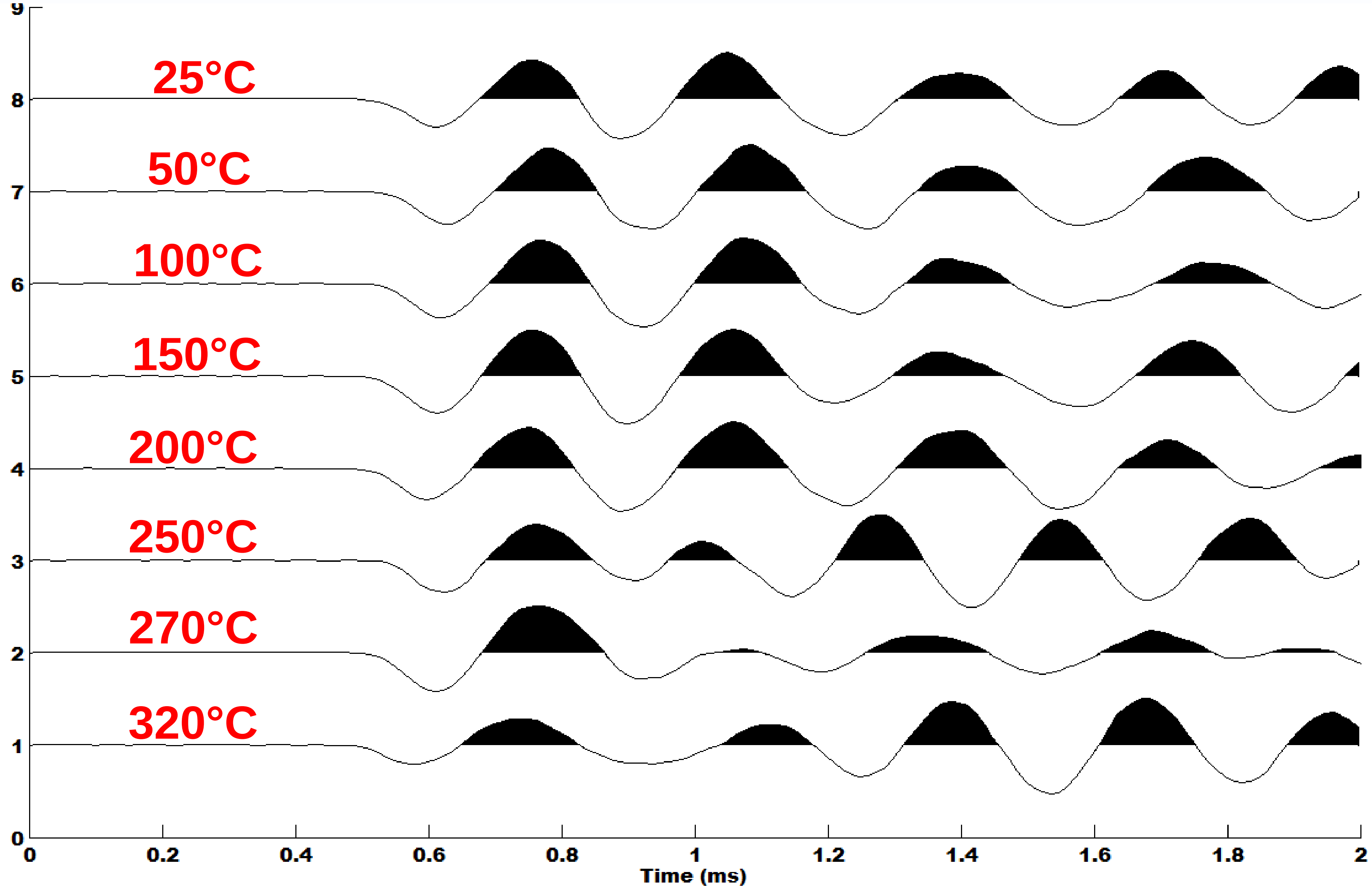
High Temperature Tests of Fiber Optic Seismic Sensors (FOSS)



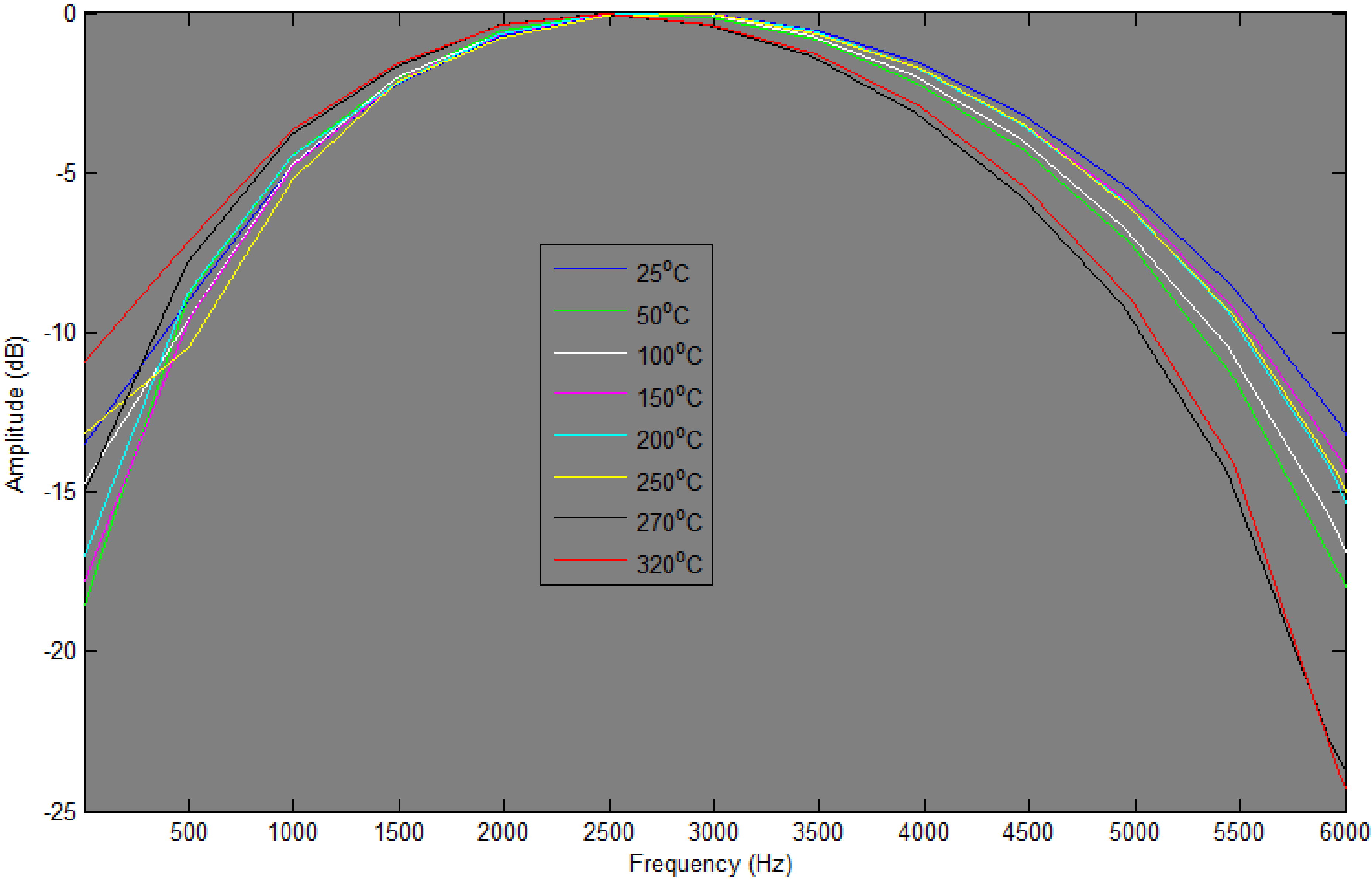
FOSS Radial Component vs. Temperature - 20 ms



Fiber Optic Seismic Sensor (FOSS)
Radial Comp. Tap Tests 25 - 320℃ – 2 ms



Fiber Optic Seismic Sensor (FOSS)™, Radial Compo. Tap Tests at 25°C - 320°C – Spectra plots



Fiber Optic Seismic Sensor (FOSS)™ Development Summary

1. The Fiber-Optic Sensor design is successful
   a. Flat frequency response over a large frequency range
   b. Low Frequency performance
   c. Very high sensitivity
   d. High Signal to Noise ratio
   e. Outstanding High Temperature Performance
   f. Interrogation system has been tuned for many channels
   g. Telemetry has been tuned for many channels

Presentation Outline

1. **Fiber Optic Seismic Sensor (FOSS)™ Development**

2. **Deployment System Development**
   a. **It works – will show how in survey slides**

3. **Field Survey Results**

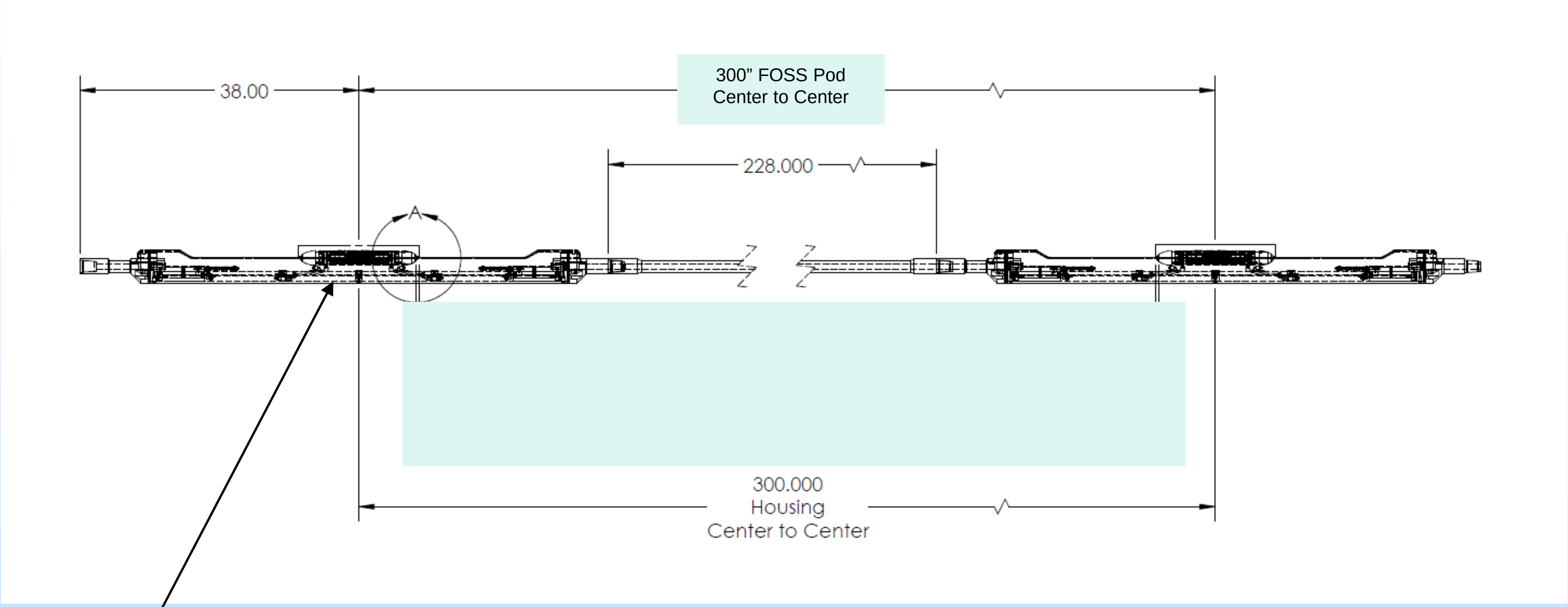
4. **Wrap up**

Measured Strength of Deployment System Components

Component	Results from Destructive Tests
Tool Joints	210,000 lbs.
Drill Pipe	145,000 lbs.
Geophone pod Housings	303,100 lbs.

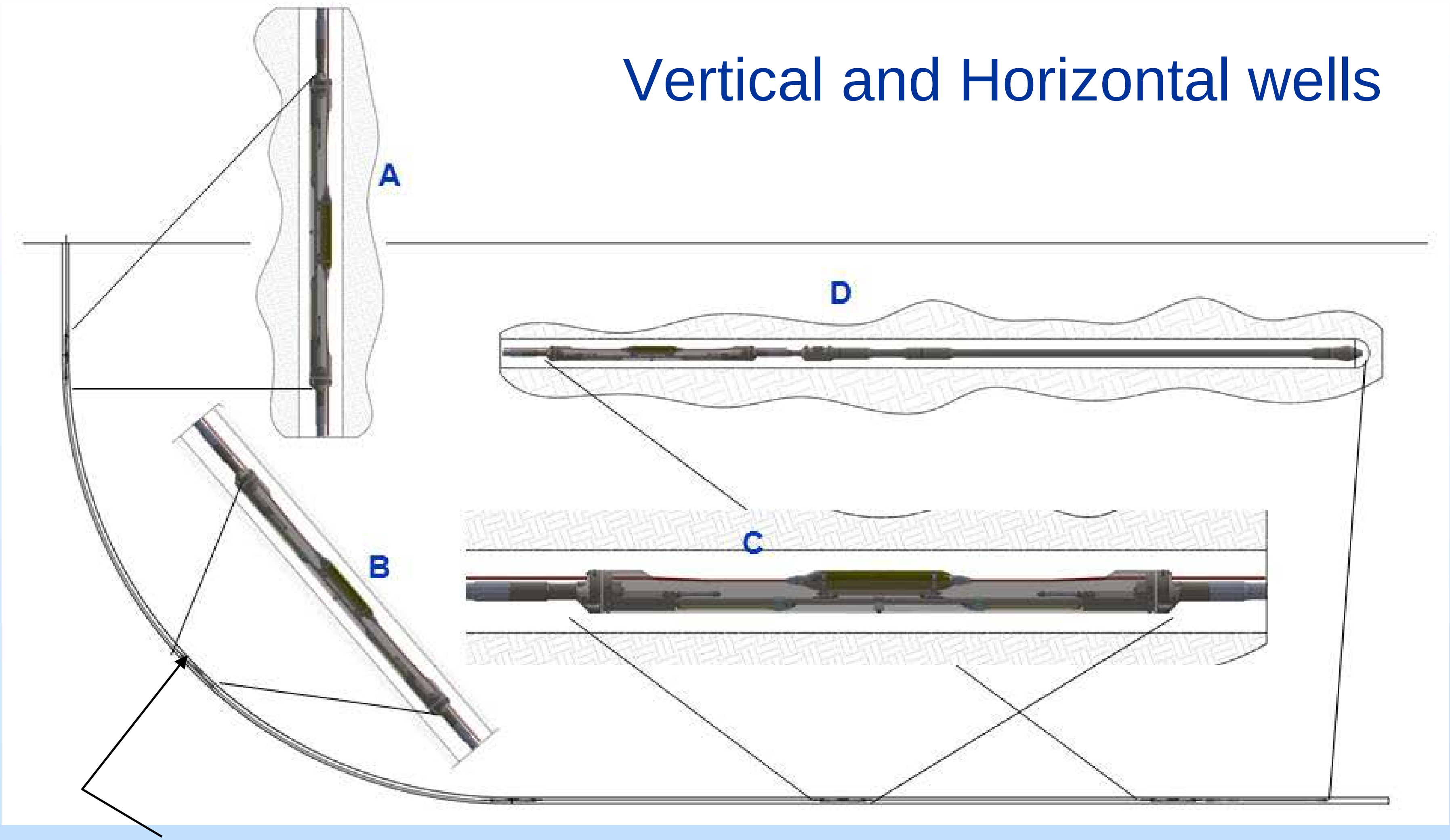
System Strong Enough to be deployed to a drilled depth of 10 km (30,000 ft) into vertical or horizontal wells

Drill Pipe Deployed System – Housing and Clamping



Clamping system operates by increasing the pressure inside the drill pipe and manifolds and uses the bore hole fluid as a medium

Drill Pipe Deployed System – Housing and Clamping



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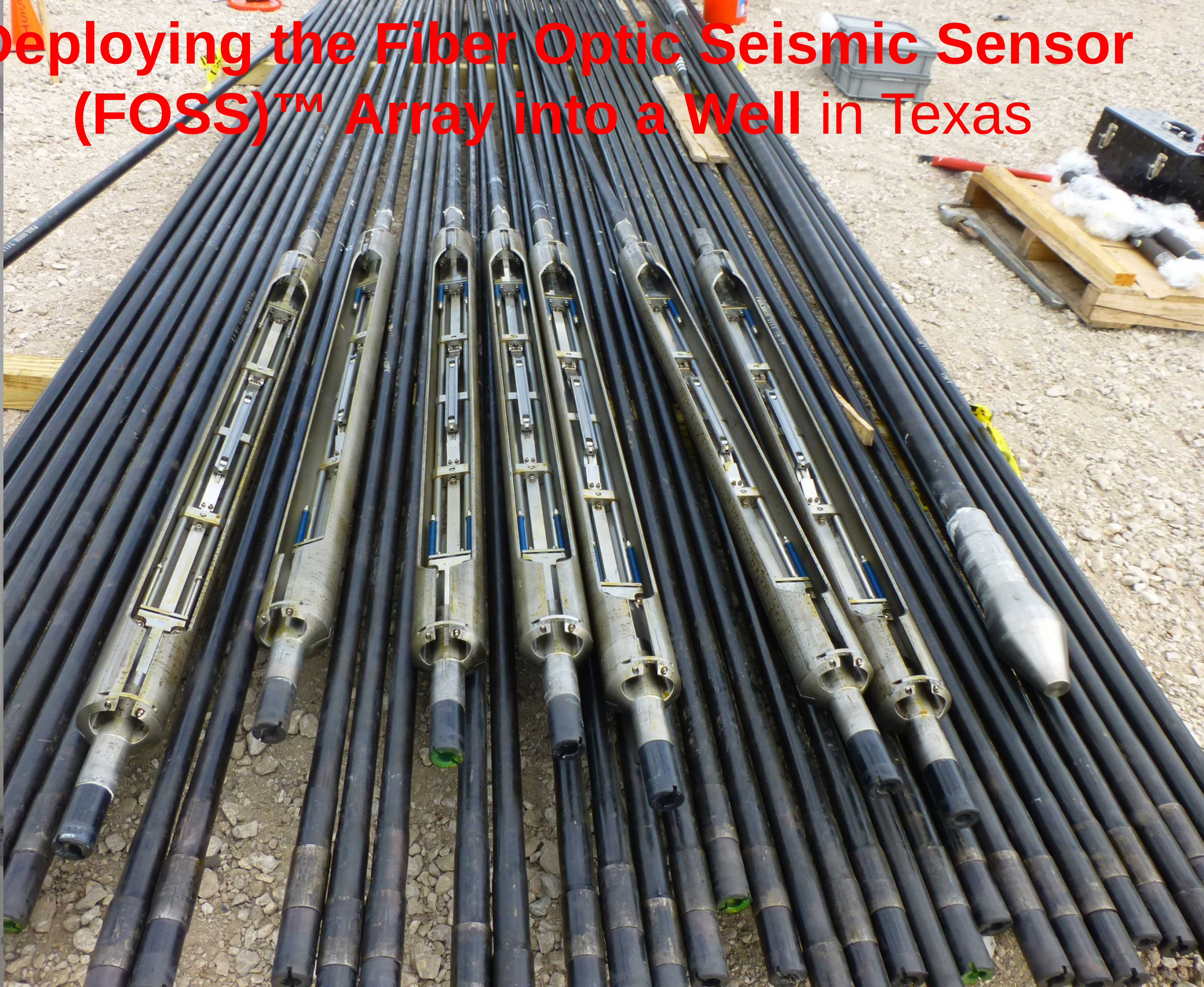
Deploying the Fiber Optic Seismic Sensor (FOSS)™ Array into a Well in Texas



Deploying the Fiber Optic Seismic Sensor (FOSS)™ Array into a Well in Texas

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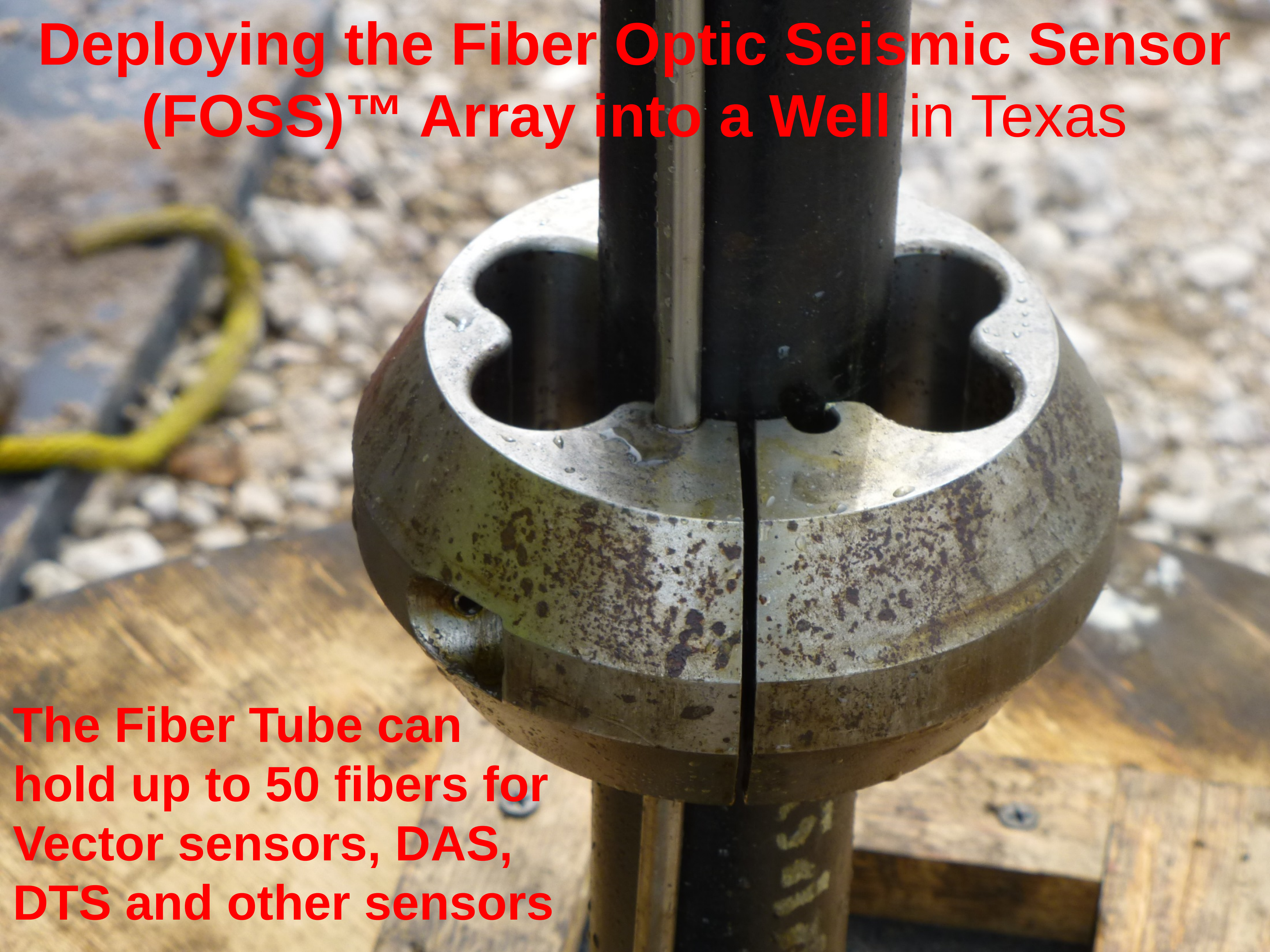


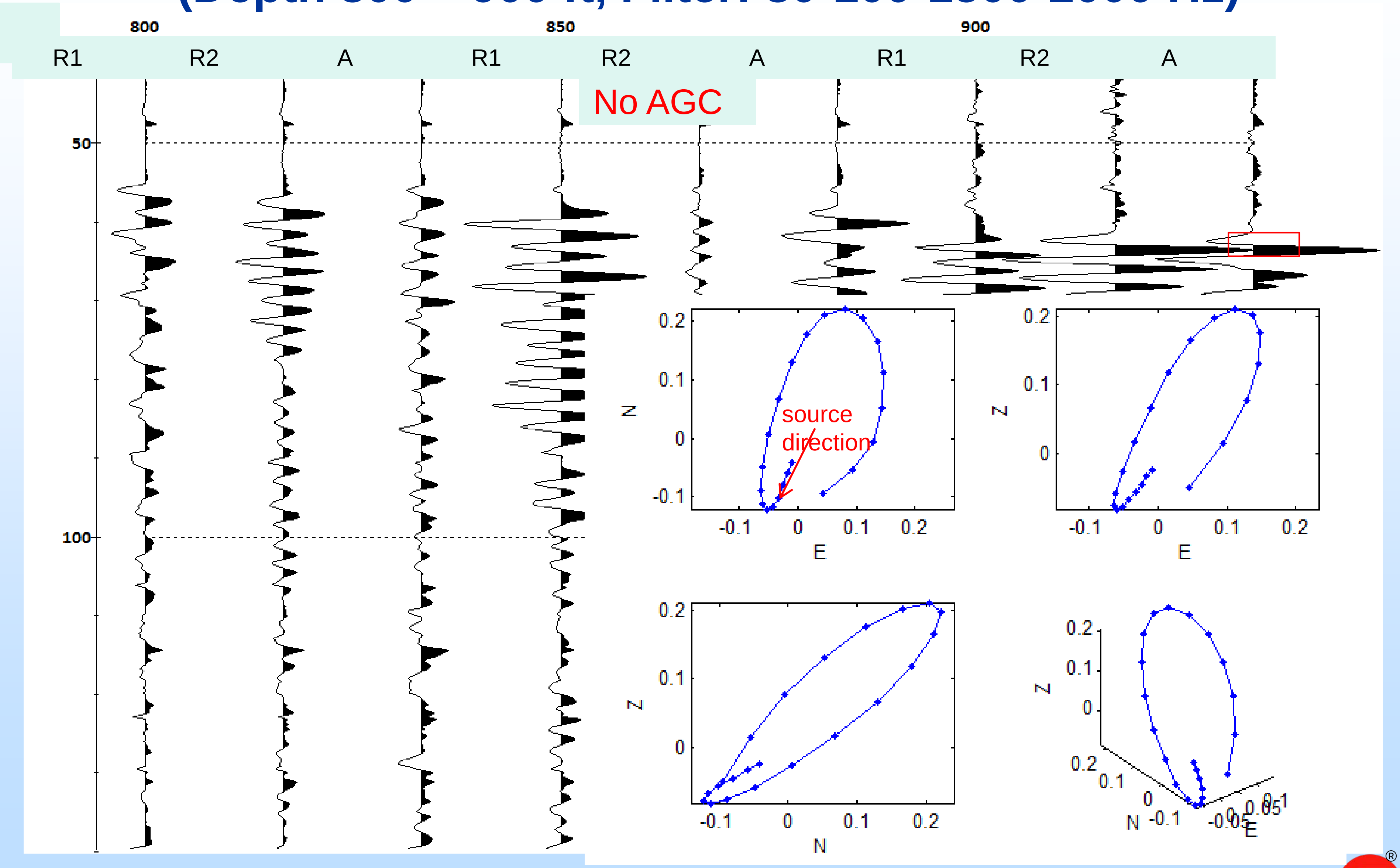
The Fiber Tube can hold up to 50 fibers for Vector sensors, DAS, DTS and other sensors

Recording data with a Fiber Optic Seismic Sensor (FOSS)™ Array in a Well in Texas

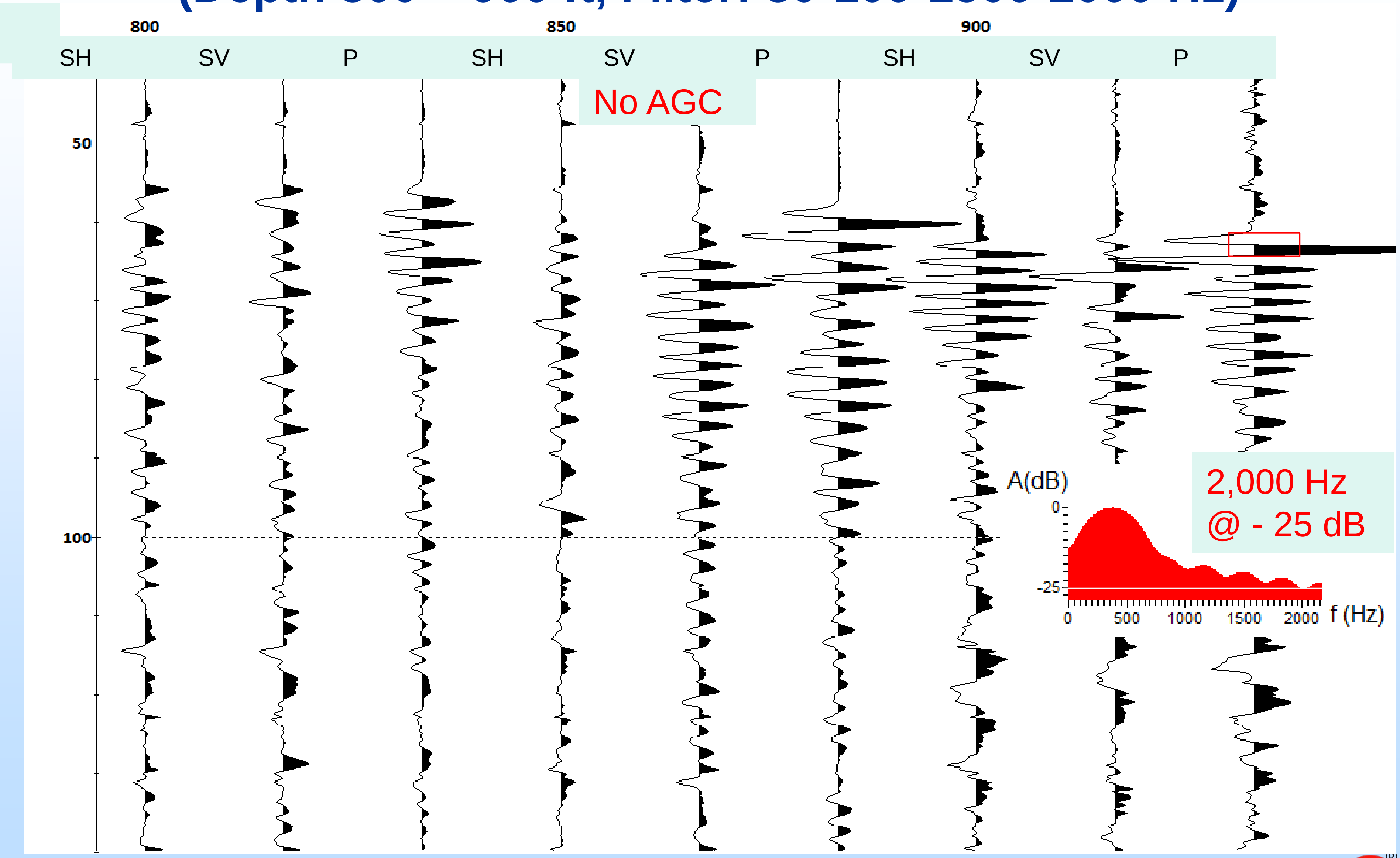

Recording data with a Fiber Optic Seismic Sensor (FOSS)™ Array in a Well
FBG Vector
Rayleigh DAS

Processing of Field Test Data Recorded with Fiber Optic Seismic Sensor (FOSS)™ System

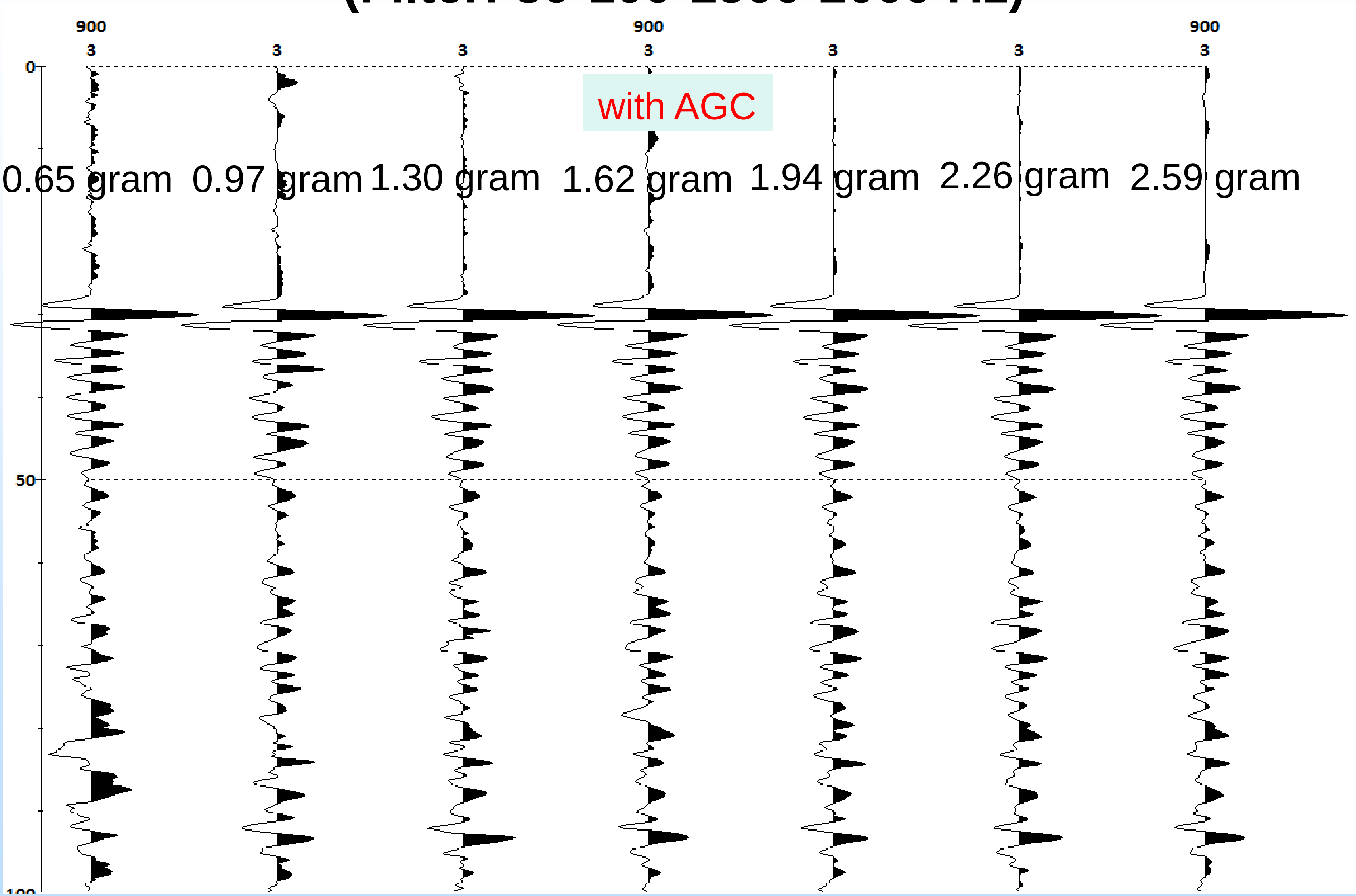
Shot: 0.65 gram @ 1,200 ft: Three 3C Pods, Pre-Rotation (Depth 800 – 900 ft, Filter: 80-100-1500-2000 Hz)



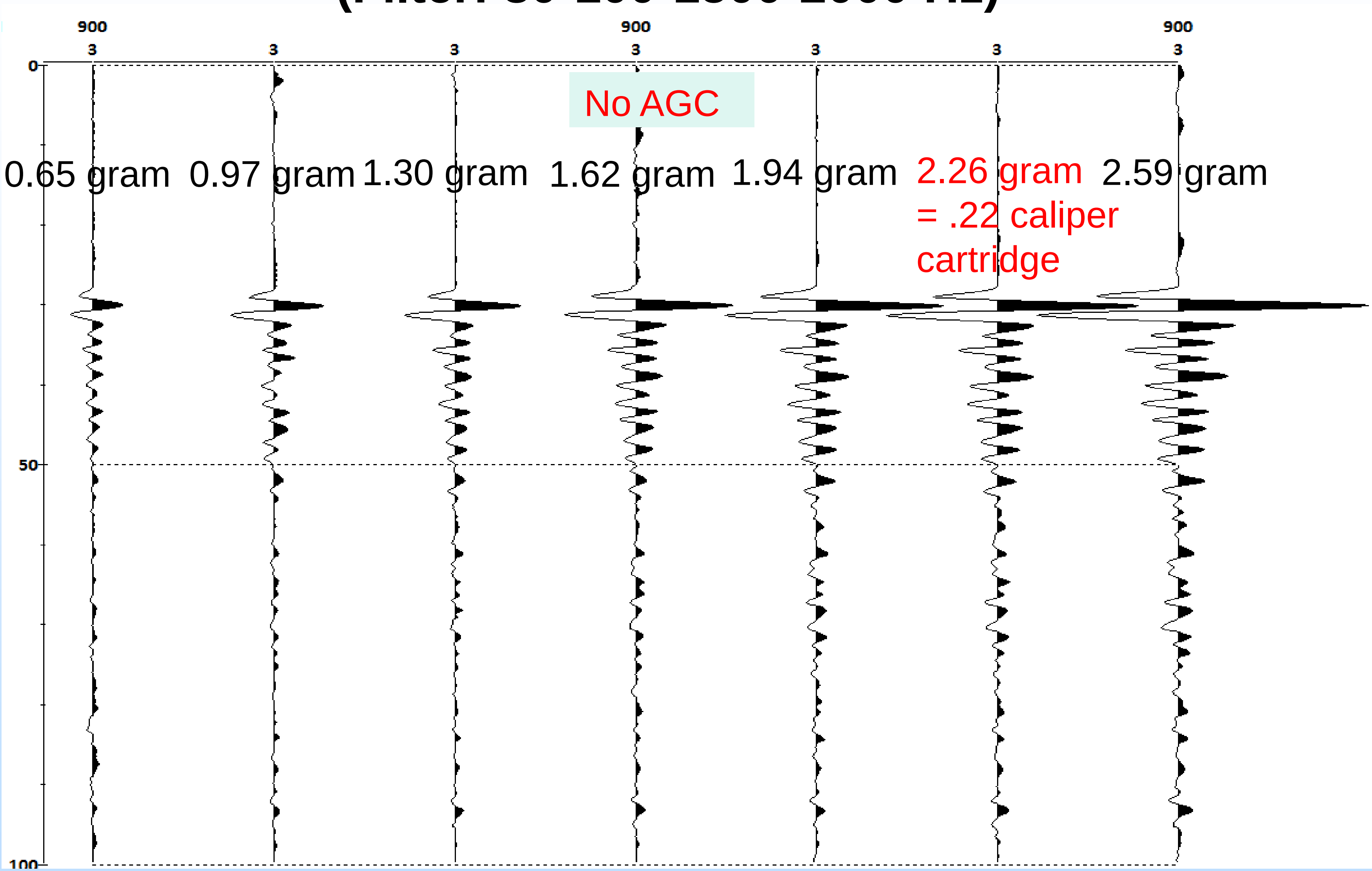
Shot: 0.65 gram @ 1,200 ft: Three 3C Pods, Post-Rotation (Depth 800 – 900 ft, Filter: 80-100-1500-2000 Hz)



Shots for POD 5 Principle Component, 1,200 ft
(Filter: 80-100-1500-2000 Hz)

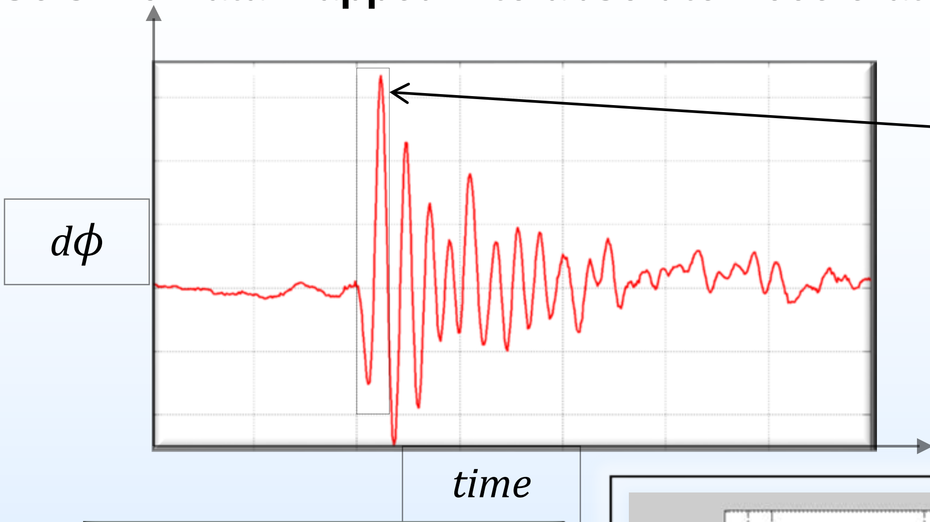


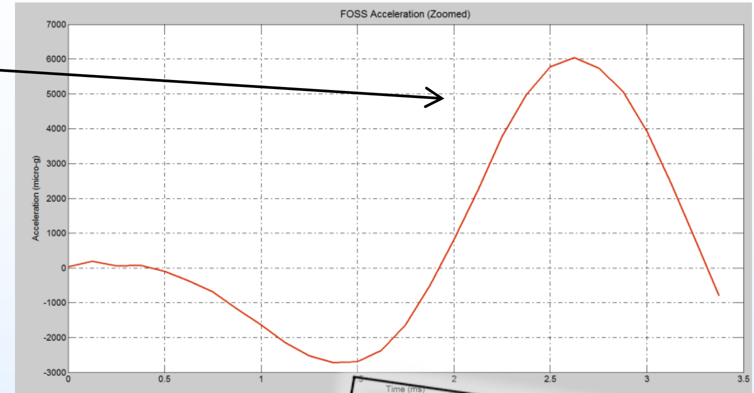
Shots for POD 5 Principle Component, 1,200 ft (Filter: 80-100-1500-2000 Hz)

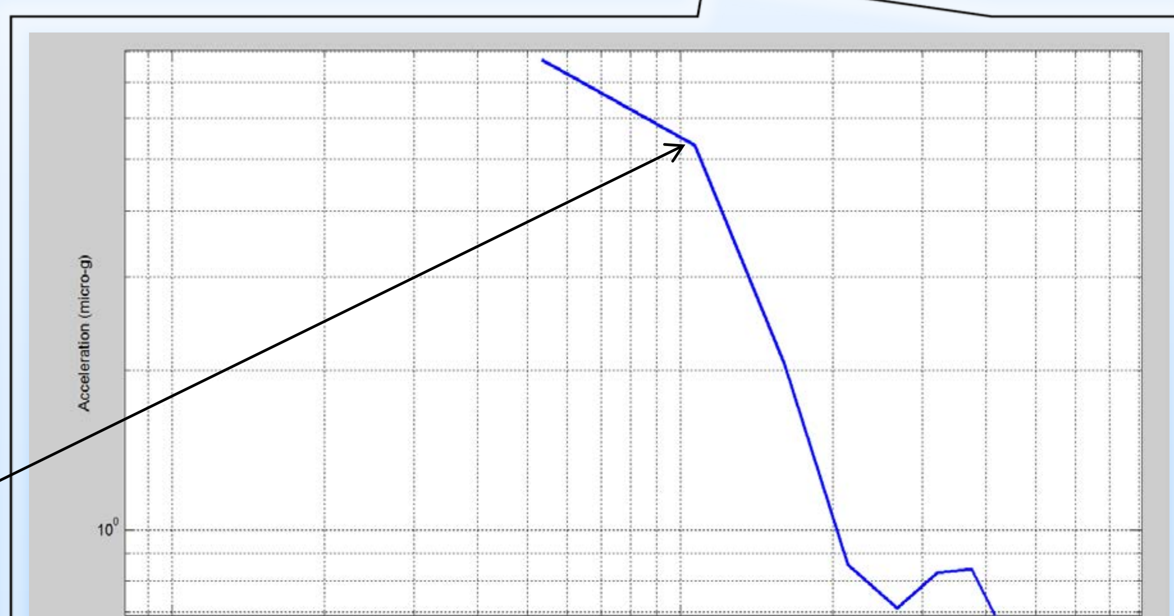


Seismic data Recorded on a Fiber Optic Seismic Sensor (FOSS)

Seismic Data mapped into absolute Acceleration using Calibrated Sensor Transfer Function



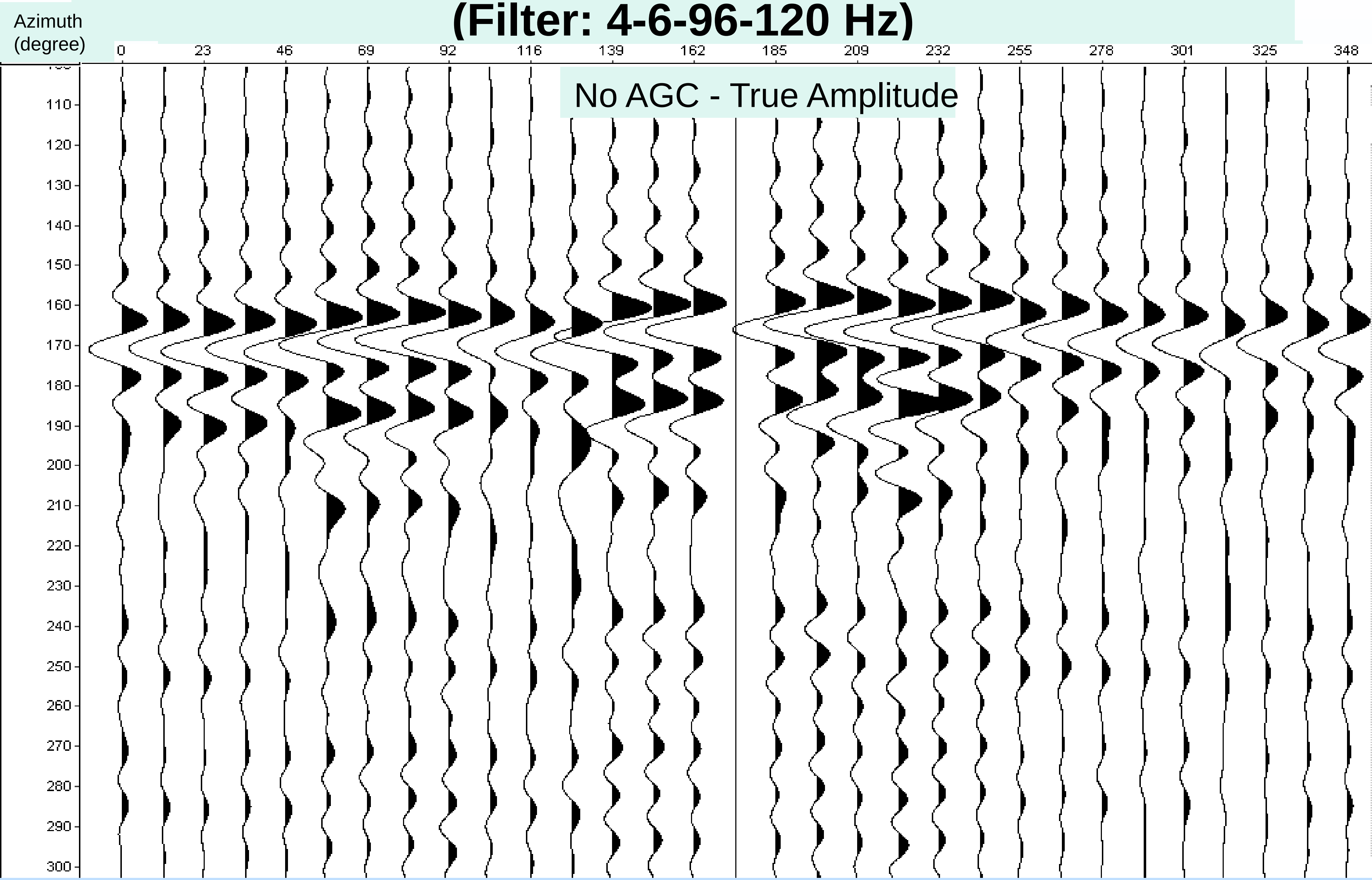




Quantitative Analysis of Data from 0.65 gram of TNT At a distance of 1,200 ft (366 m)	
Frequency (Hz)	Acceleration (µG)
600	7.3
700	6.7
800	6.2
900	5.8
1,000	5.5
2,000	2.0

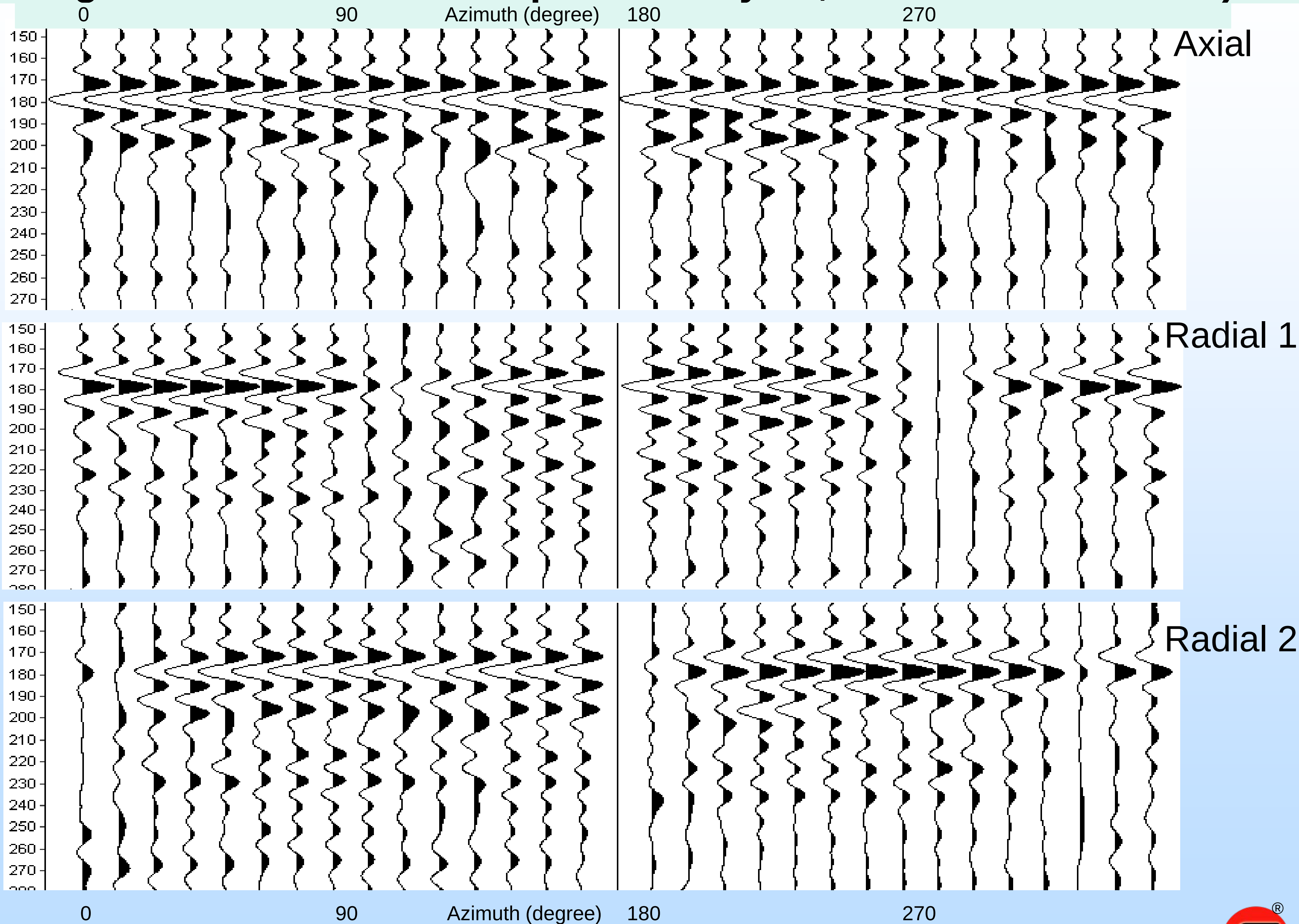
Assuming 90% of TNT energy go into tube waves = 200 Joules from 0.65 gram of TNT = Magnitude M-2.6

Vibrator walking around the receiver well – raw data (Filter: 4-6-96-120 Hz)



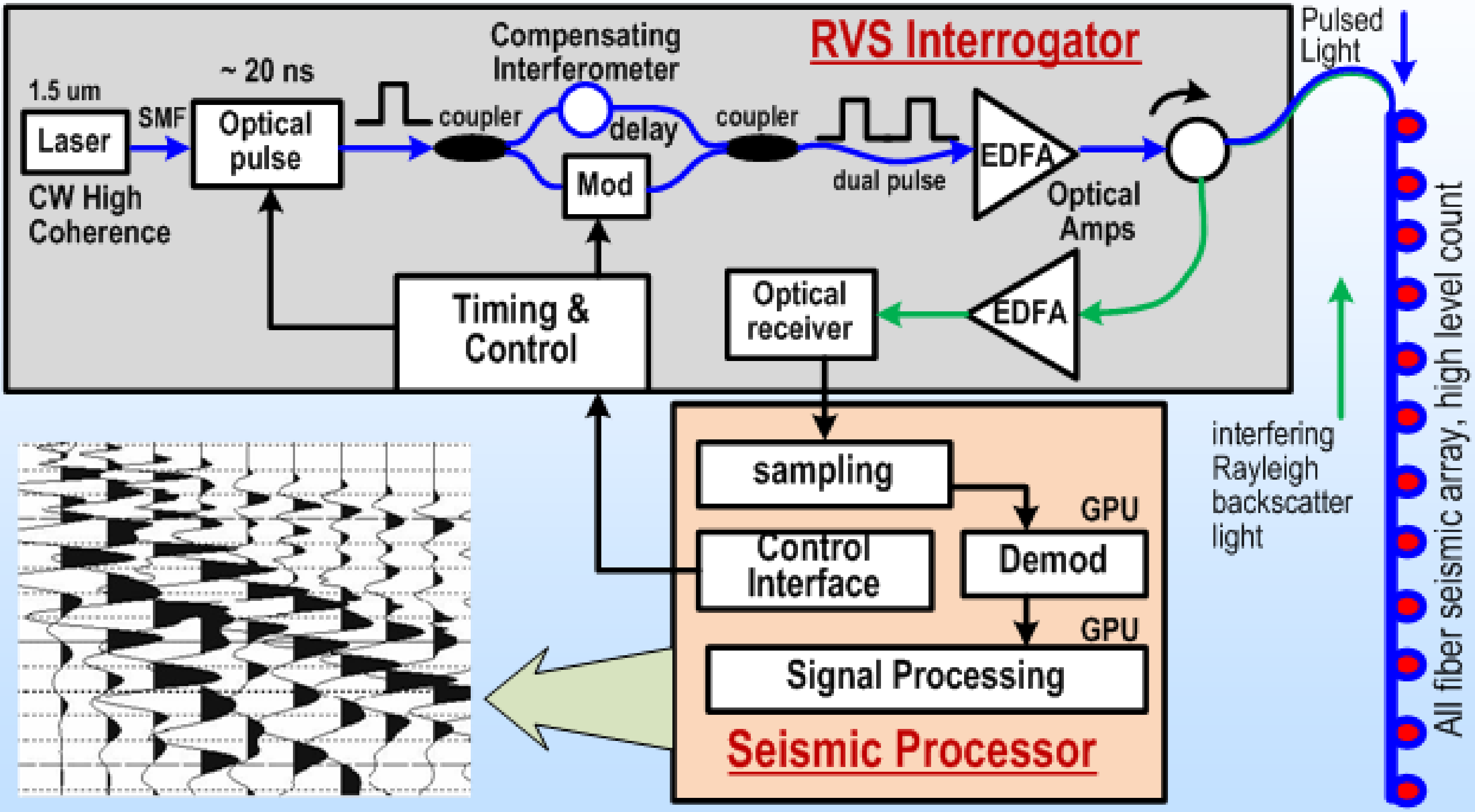
Vibrator walking around the receiver well

(Data aligned for waveform and phase analysis, Filter: 4-6-96-120 Hz)



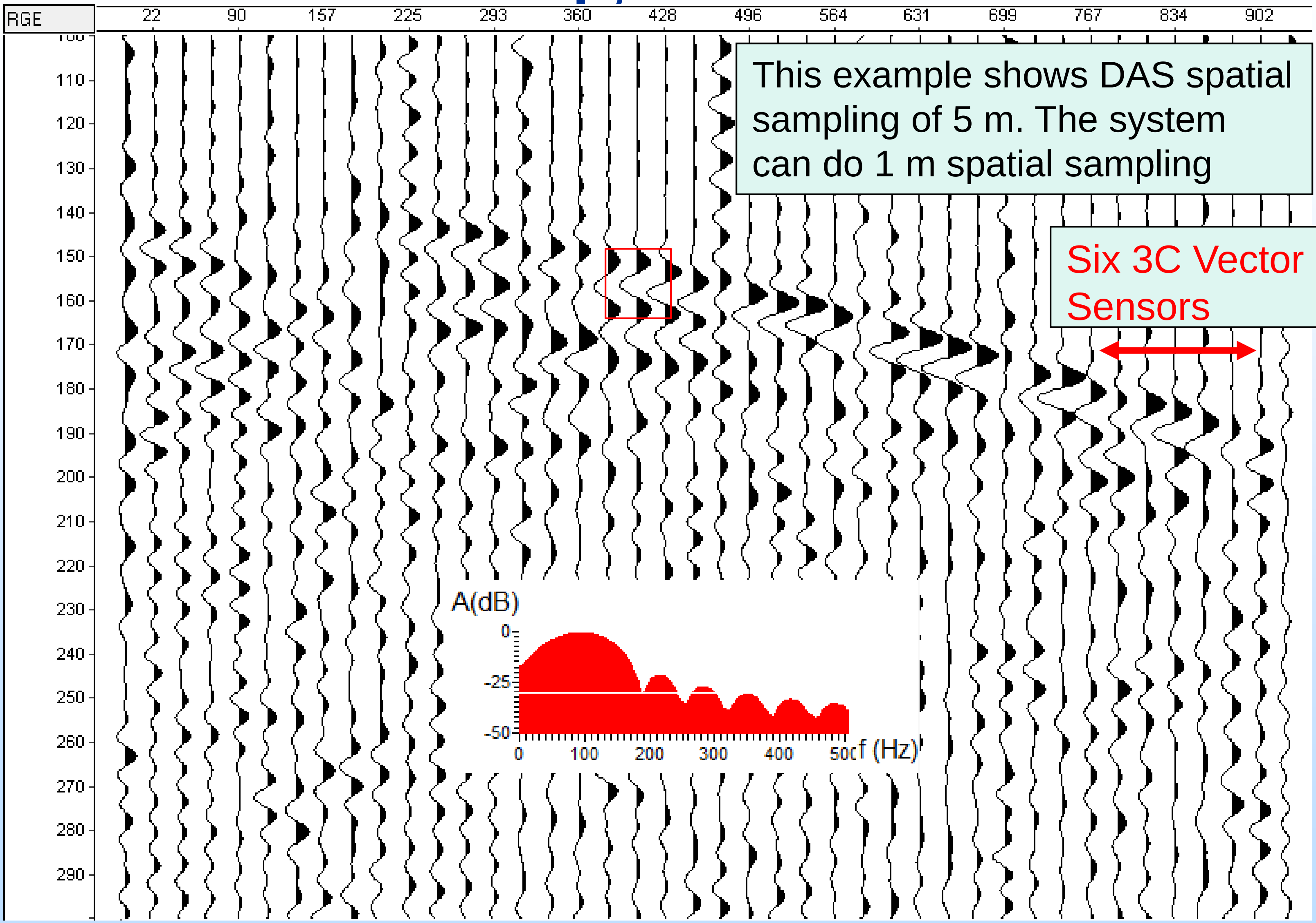
In addition to Fiber Optic Vector Sensors the Borehole Seismic System deploys Distributed Acoustic Sensors (DAS) and Distributed Temperature Sensors (DTS)

Interrogator System using self Interfering Pulse Rayleigh based Interrogation (DAS)



US Navy Technology

Simultaneously Recorded DAS Data (Lead-in Fiber) (Vibrator – one sweep, 500 ft offset: 2 – 200 Hz)



This example shows DAS spatial sampling of 5 m. The system can do 1 m spatial sampling

Six 3C Vector Sensors

Presentation Outline

1. **Fiber Optic Seismic Sensor (FOSS)™ Development**
2. **Deployment System Development**
3. **Field Survey Results**
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Accomplishments

- Developed an Ultra Sensitive, Ultra Large Bandwidth Fiber Optic Seismic Sensor (FOSS)™
- Tested the Fiber Optic Seismic Sensor at High Temperature at large Range of Frequencies and Loads
- Developed a Facility to Manufacture High Performance Fiber Optic Seismic Sensor (FOSS) Arrays
- Designed and built a 30,000 psi capable 3C geophone pod for the Fiber Optic Seismic Sensors (FOSS)™
- Developed a Deployment System strong enough to deploy a 1,000 level 3C borehole seismic arrays in vertical and horizontal boreholes.
- Manufactured components for a six level FOSS array
- Tested the array in two field surveys

Fiber Optic Seismic Sensor (FOSS)™ Development Summary

1. The Fiber-Optic Sensor design is successful
   a. Flat frequency response over a large frequency range: 0.03 – 6,000 Hz
   b. Low Frequency performance
   c. Very high sensitivity
   d. High Signal to Noise ratio
   e. Outstanding High Temperature Performance
   f. Successful field tests

2. Outstanding Issues
   a. Interrogation system tuning for many channels
   b. Telemetry testing and tuning for many channels

Thank You!

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Paulsson, Inc. 1,000 level Project Scientific/Technical Approach

Project Objectives – Highlight of innovative aspects

•We are designing and manufacturing a 300ºC borehole seismic system that requires no electric power or electric based signals to and from the borehole:

- The sensors and data transmission are fiber optic based with no electronics deployed into the well
- The deployment system is drill pipe based and clamping function is powered by drill pipe hydraulics

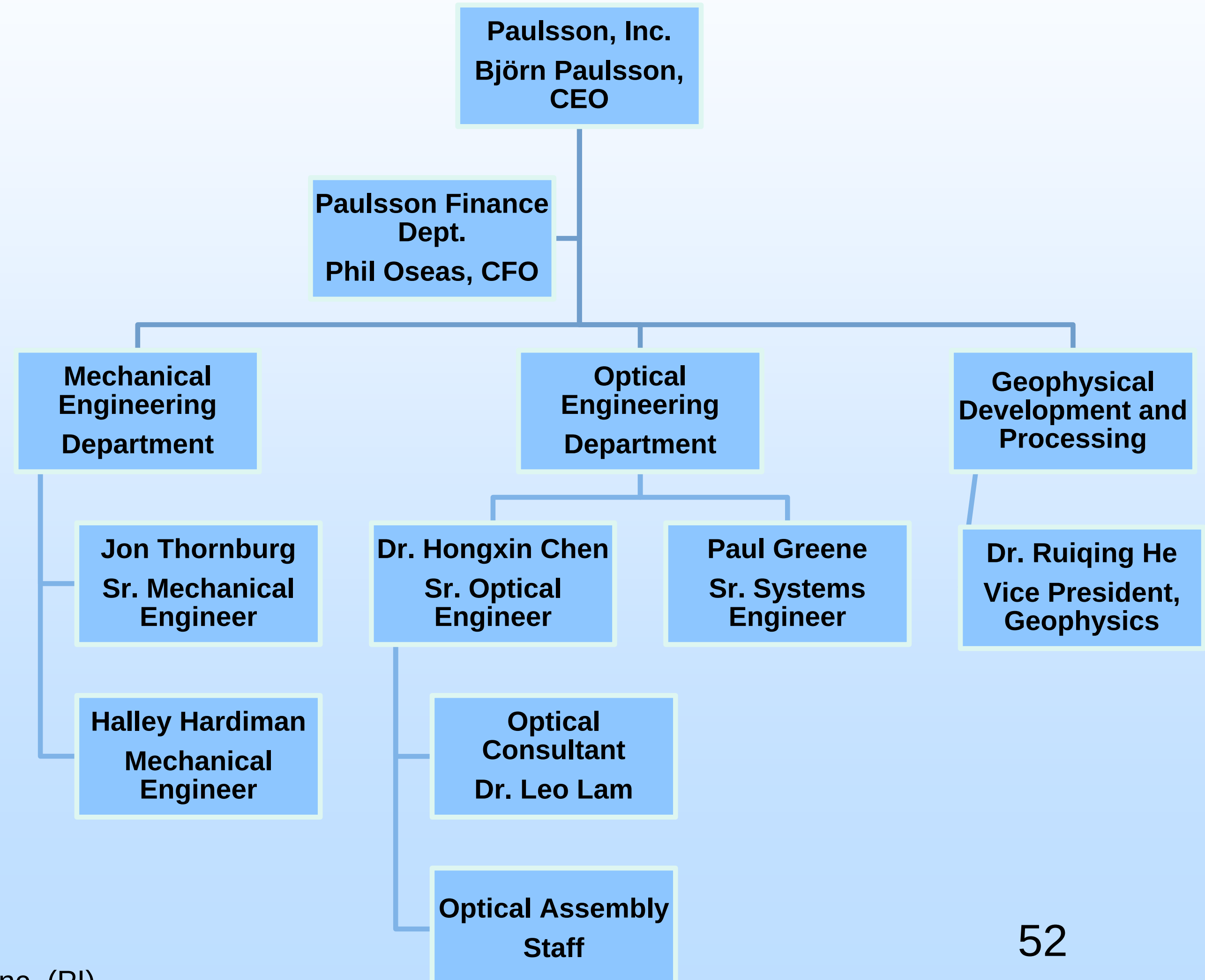
•Design, manufacture and deploy a high temperature Fiber Optic Seismic Sensor

- The fiber optic seismic sensor technology allows operation to over 300ºC and to a depth of over 10,000 m.
- Fiber optic Seismic Sensor (FOSS)™ technology allows thousands of channels to be deployed into the borehole which makes it possible to build a Ultra Large Aperture Array (ULAA) which in turn allows accurate 3D imaging and 3D micro seismic mapping
- Fiber Bragg Grating (FBG) based sensors using interferometric interrogation technology are more sensitive and have a larger bandwidth than traditional coil and magnet based geophones
- Fiber Optic Vector Array (3C) allows the determination of the vector of the recorded seismic data

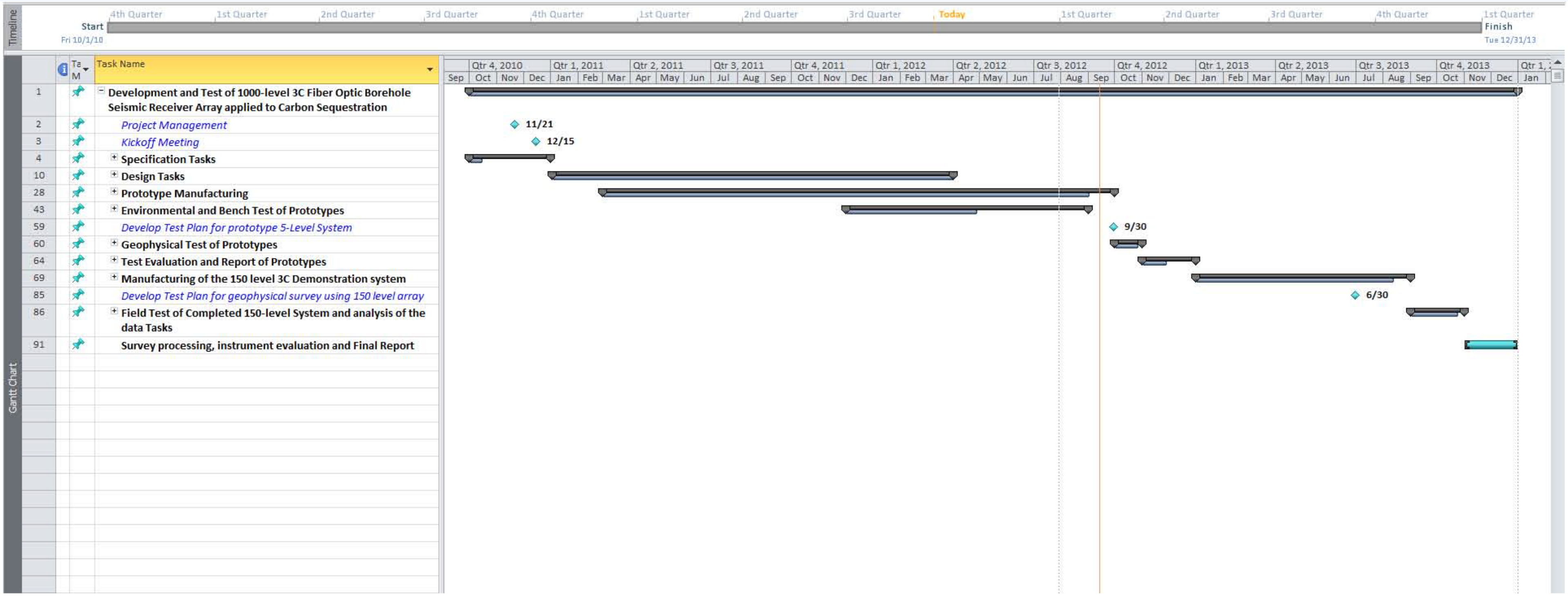
•Design, manufacture and deploy a 300ºC drill pipe based deployment system

- The deployment system is drill pipe based and is strong enough to deploy 1,000 3C pods to 10,000 m.
- The clamping function of the downhole array is powered by the drill pipe hydraulics and generates very high clamping force allowing high fidelity seismic data to be recorded
- The drill pipe based optical borehole seismic array allows deployment into deviated and horizontal wells
- A fiber optic system without electronics and clamping with pipe hydraulics will be extremely robust and have a long survival time in wells

Organization Chart



Paulsson Fiber Optic Geophone
Project Gantt Chart with Milestones



Thank You!

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