Paulsson, Inc. (PI)

Fiber Optic Seismic Vector Sensor tracking of Acoustic Micro Emitters (AME) to Optimize Unconventional Oil and Gas (UOG) Development

Paulsson, Inc., Fluidion SAS, Southwest Energy, RPSEA, NETL/DOE.

August 17, 2016

© 2016 Paulsson, Inc. (PI)

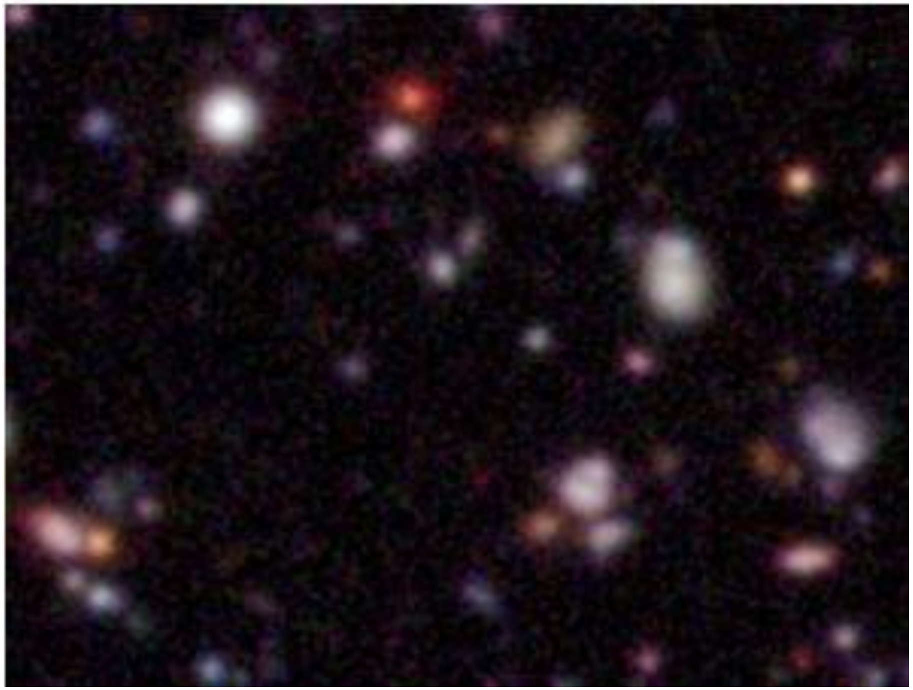
Proprietary Material – Paulsson, Inc (PI).

Focus:
Develop Better Sensors!
To support
one of the SubTer Pillars:
New Subsurface Signals

© 2016 Paulsson, Inc. (PI)

Example From Space Exploration: Images From Same Region in Space

Earth Telescope



Hubble Space Telescope

© 2016 Paulsson, Inc. (PI)

Proprietary Material – Paulsson, Inc (PI).

Project Overview: Goals and Objectives

- Main Objective: Design, build and make available to geoscience community at large the most effective borehole seismic reservoir evaluation and monitoring system possible.

- Goal A: Build a 100 3C level 15,000 ft long fiber optic based vector sensor system capable to be deployed at 30,000 psi and 600°F.

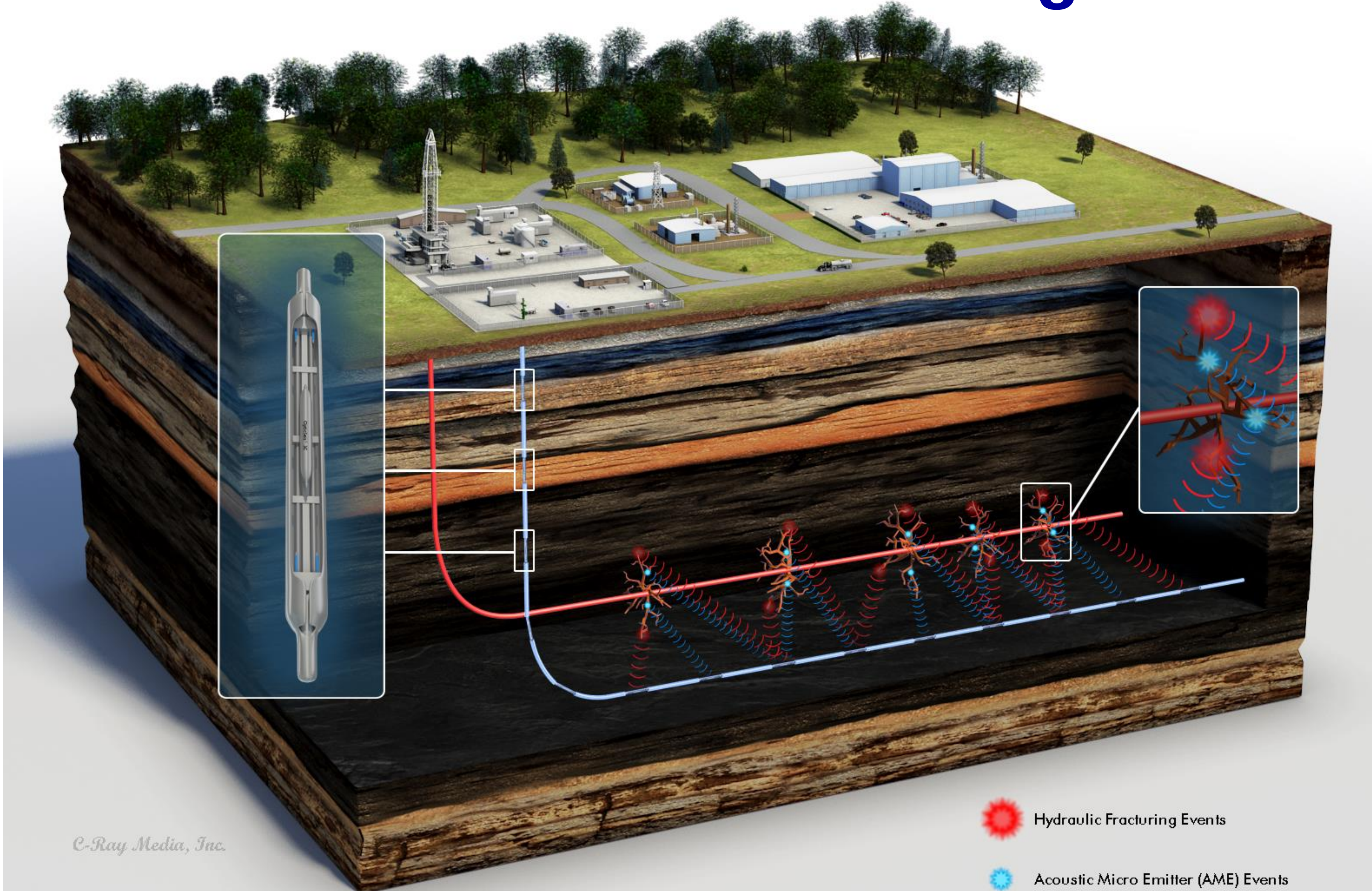
- Goal B: Develop injectable Acoustic Micro Emitters (AME's) to allow tracking of fractures and the fracture proppant.

- Goal C: Test the combined AME and optical borehole seismic system in one or more comprehensive field survey(s) to monitor the hydraulic fracturing and the injection of Acoustic Micro Emitters (AME's).

© 2016 Paulsson, Inc. (PI)

Proprietary Material – Paulsson, Inc (PI).

Effective & Accurate Monitoring of UOG



© 2016 Paulsson, Inc. (PI)

Two Technologies Developed

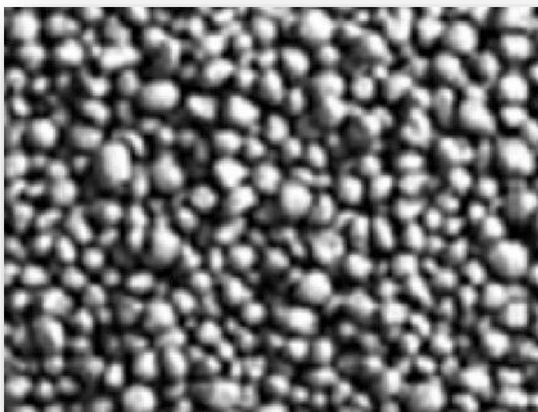
- **Acoustic Micro Emitters (AME's)**
- **Large Fiber Optical Seismic Sensor (FOSS) Array Technology**

© 2016 Paulsson, Inc. (PI)

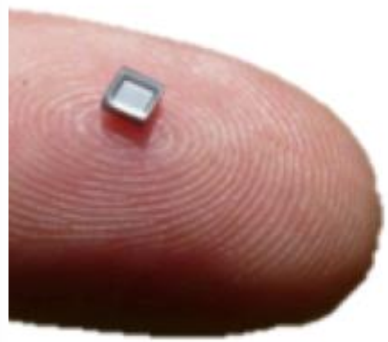
Getting most out of fracture monitoring

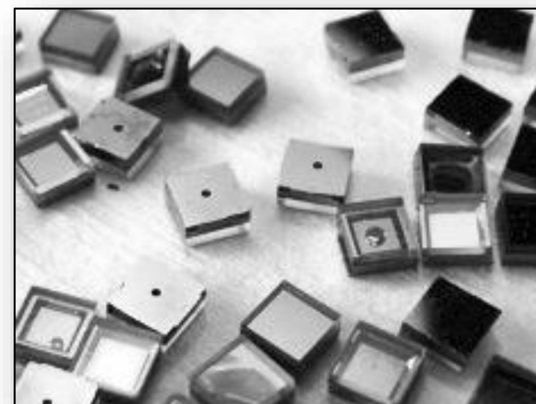
Problem: Need to know where fractures are propagating, their number, width, extent.

Answer: Embedding smart microsystems within standard proppant formulations



Typical ceramic proppant 20/40





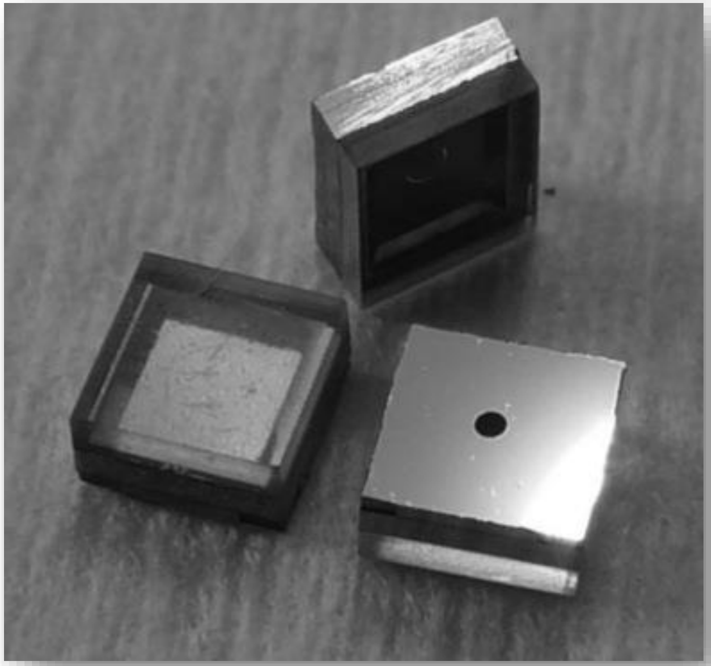
fluidion smart micro-emitter (prototype stage)

© 2016 Paulsson, Inc. (PI)

Proprietary Material – Paulsson, Inc (PI).

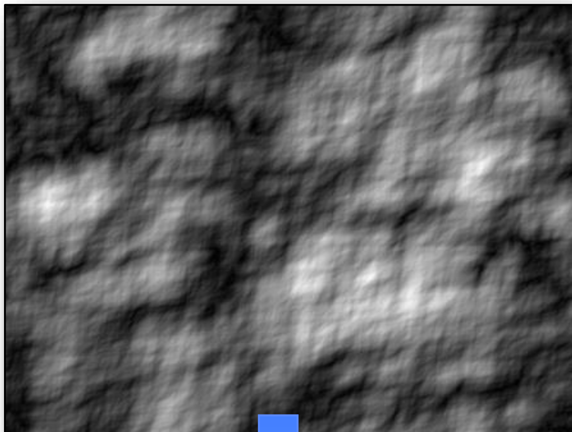
Acoustic Micro Emitter (AME) Technology

- Micro-machined fluidic components
- Multiple acoustic emissions at delayed times (hours)
- Can be highly miniaturized
- Round shape to match proppant geometry

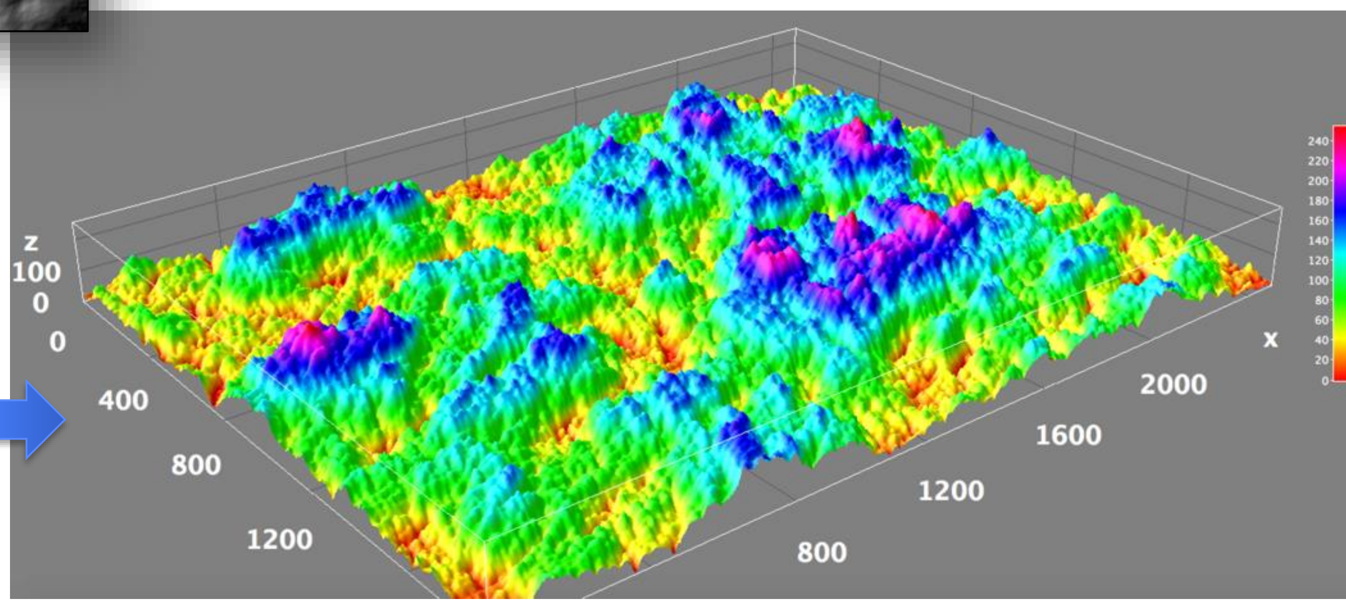


© 2016 Paulsson, Inc. (PI)

Fracture generation to investigate transport of Acoustic Micro Emmitters (AME's) in fractures



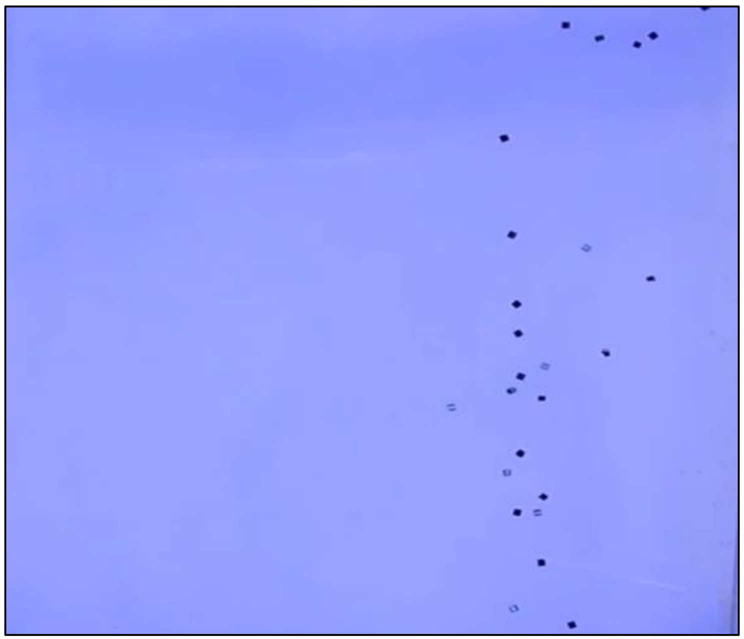
Generating accurate fracture geometries on large Scale via Matlab algorithm (custom Hurst coefficient) and large-scale manufacturing using laser ablation

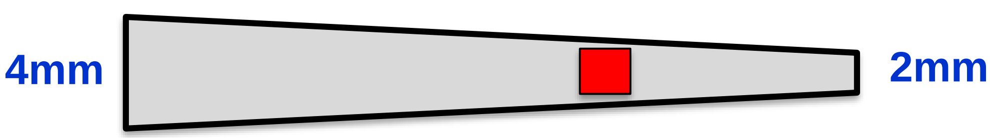


© 2016 Paulsson, Inc. (PI)

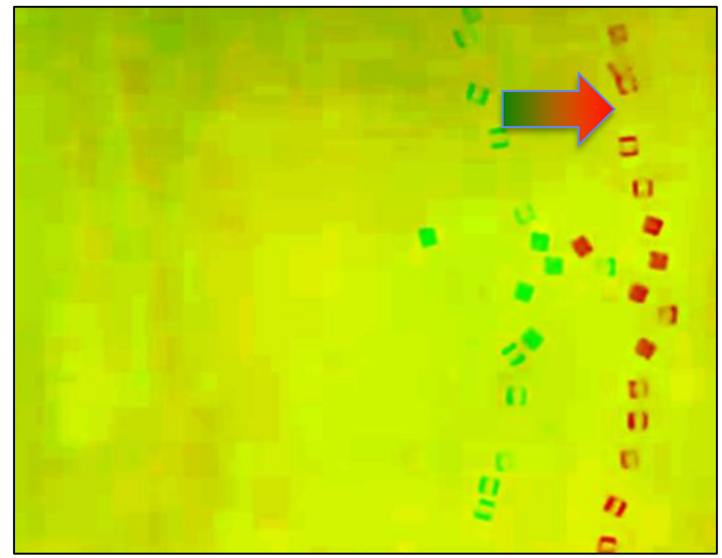
Fracture width from AME position

Wedge geometry: AME positioning





Superimposed time lapse imaging:



Dynamic fracture opening experiment:

Pressure 1 < Pressure 2

© 2016 Paulsson, Inc. (PI)

Proprietary Material – Paulsson, Inc (PI).

Smart Acoustic Micro Emitters

Compliments standard micro seismic monitoring

Allow localization of flowing fractures and fracture proppant

Can produce valuable information on
- **fracture width vs. position**
- **fracture orientation and size**
- **number of fractures per fracking zone**

In combination with effective monitoring technology the AME technology allows for effective fracture optimization

© 2016 Paulsson, Inc. (PI)

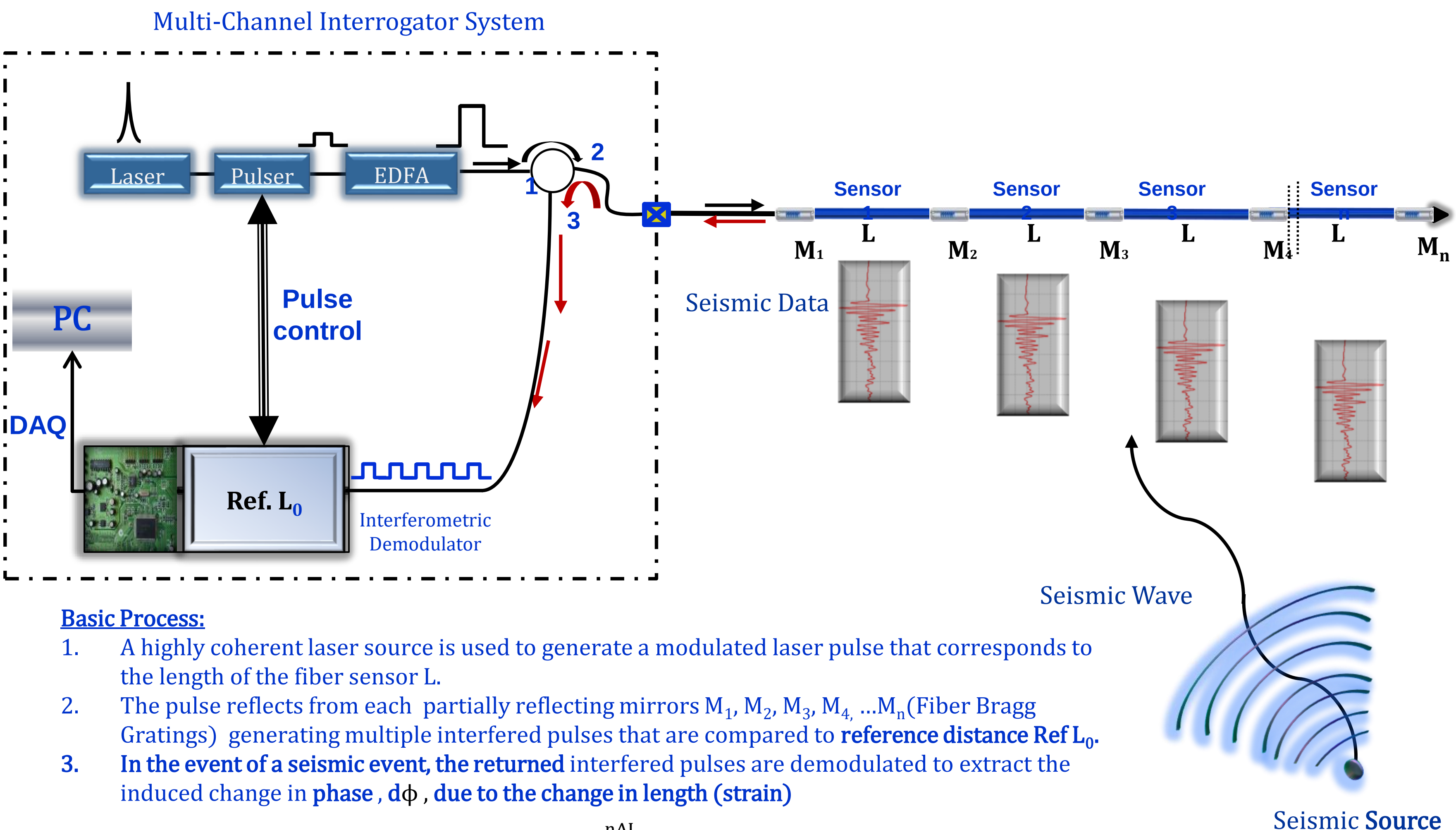
Two Technologies Developed

- **Acoustic Micro Emitters (AME's)**
- **Large Fiber Optical Seismic Sensor (FOSS) Array Technology**

© 2016 Paulsson, Inc. (PI)

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** , dϕ , **due to the change in length (strain)**

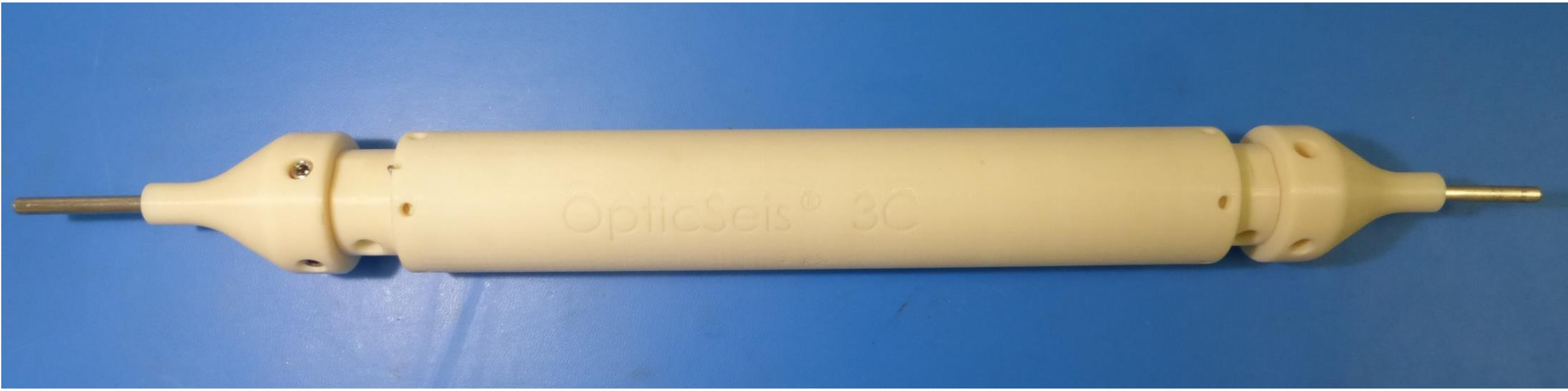
$$d\phi = 2\pi\frac{n\Delta L}{\lambda}$$

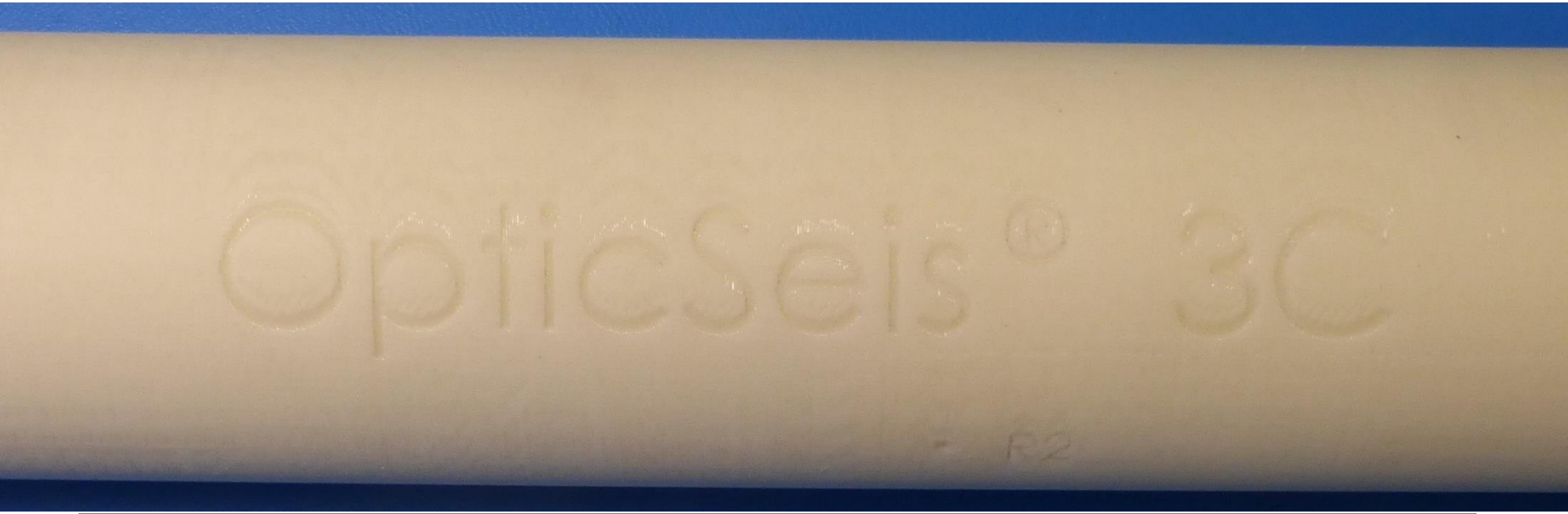
© 2016 Paulsson, Inc. (PI)

Sensors Completed

© 2016 Paulsson, Inc. (PI)

Sensor Pod Prototype





© 2016 Paulsson, Inc. (PI)

Proprietary Material – Paulsson, Inc (PI).

Fiber Optic Seismic Vector Sensor Technology

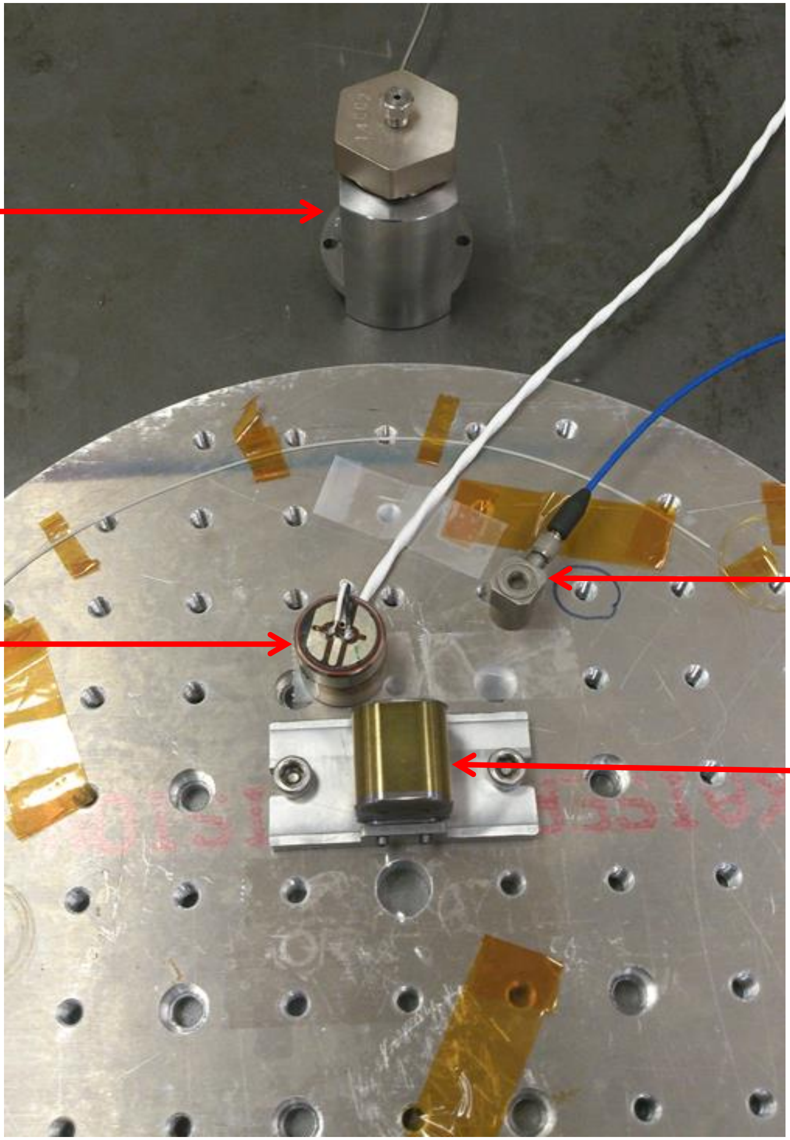
© 2016 Paulsson, Inc. (PI)

Laboratory Test of Acoustic Micro Emitters using Fiber Optic Seismic Sensors

© 2016 Paulsson, Inc. (PI)

Proprietary Material – Paulsson, Inc (PI).

AME Test #23 using FOSS – December 12, 2014



10,000 psi pressure vessel

Omni 2400 15 Hz Geophone

Setup Configuration:
Metal plate on foam matt on top of metal table. Spacing between the sensors and the pressure vessel approximately 8 inches.

Accelerometer

Fiber Optic Seismic Sensor

© 2016 Paulsson, Inc. (PI)

Proprietary Material – Paulsson, Inc (PI).

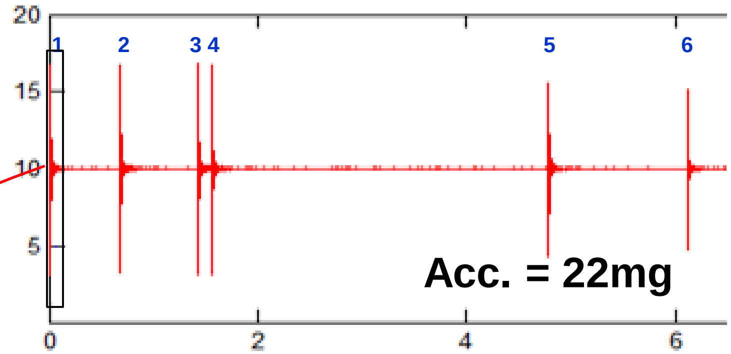
AME Test using Fiber Optic Seismic Vector Sensors

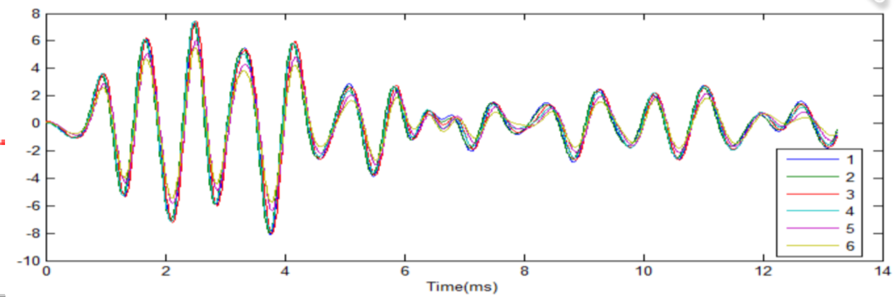
Pressure cell and sensor plate placed on a metal plate sitting on a foam mat on a metal table

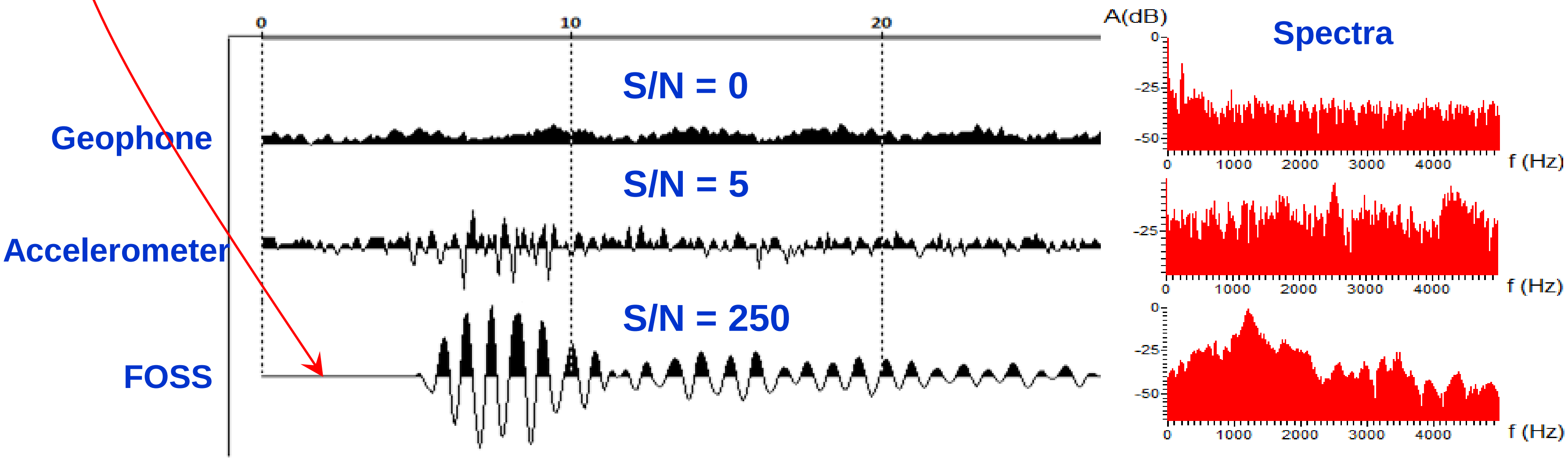
Fiber sensor, geophone and accelerometer are placed approximately 20 cm (8 inches) from the pressure vessel with AMEs

Repeatability Test: 6 AME's recorded on FOSS: Outstanding Repeatability. Allow extraction of arrivals in high noise environ

EnergyL ~2J = M-2.9

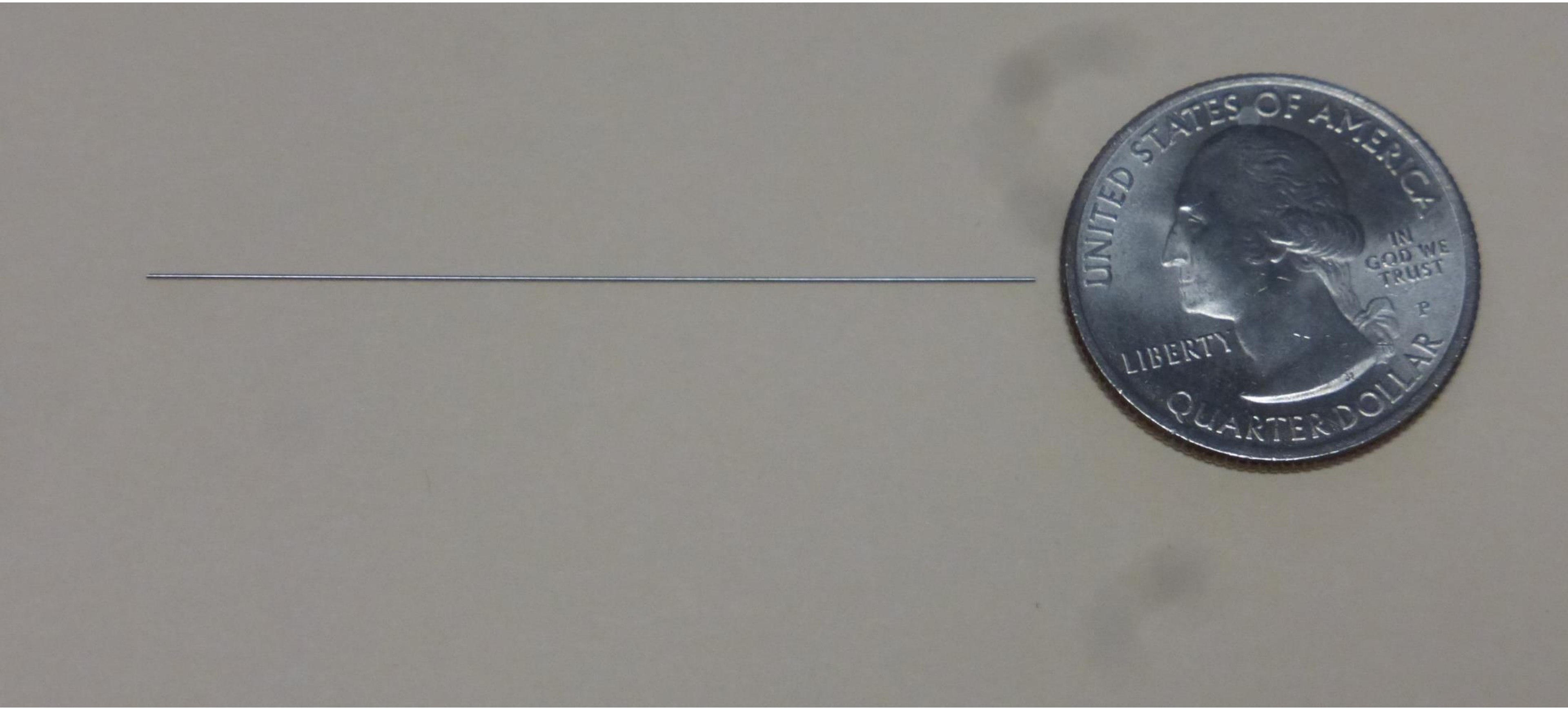






© 2016 Paulsson, Inc. (PI)

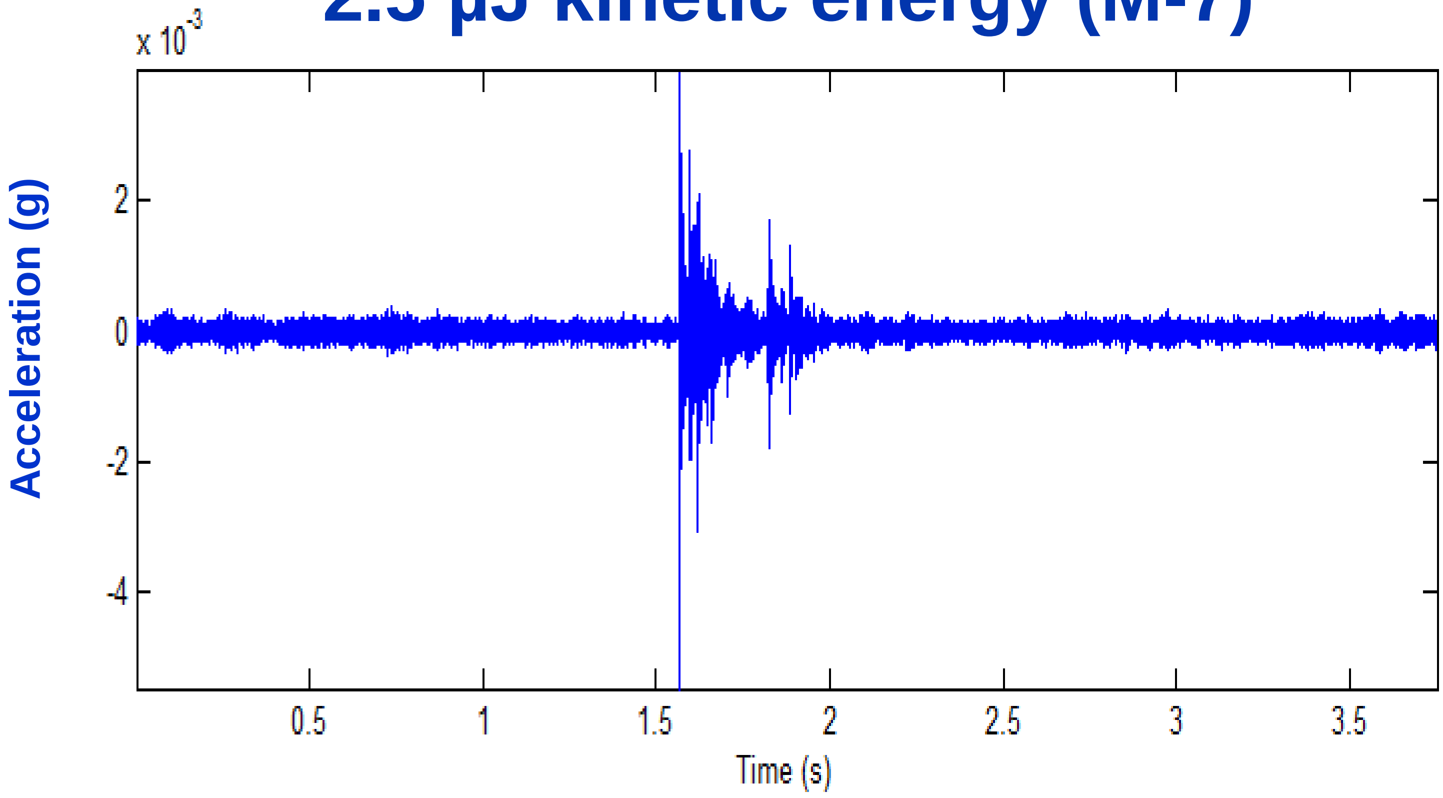
Can You Hear a Pin Drop?
Test Object: OD: 0.011", 2" long, 24.8 mg



© 2016 Paulsson, Inc. (PI)

FOSS Test: OD: 0.011", 24.8 mg Pin Drop 1 cm:

2.5 µJ kinetic energy (M-7)



© 2016 Paulsson, Inc. (PI)

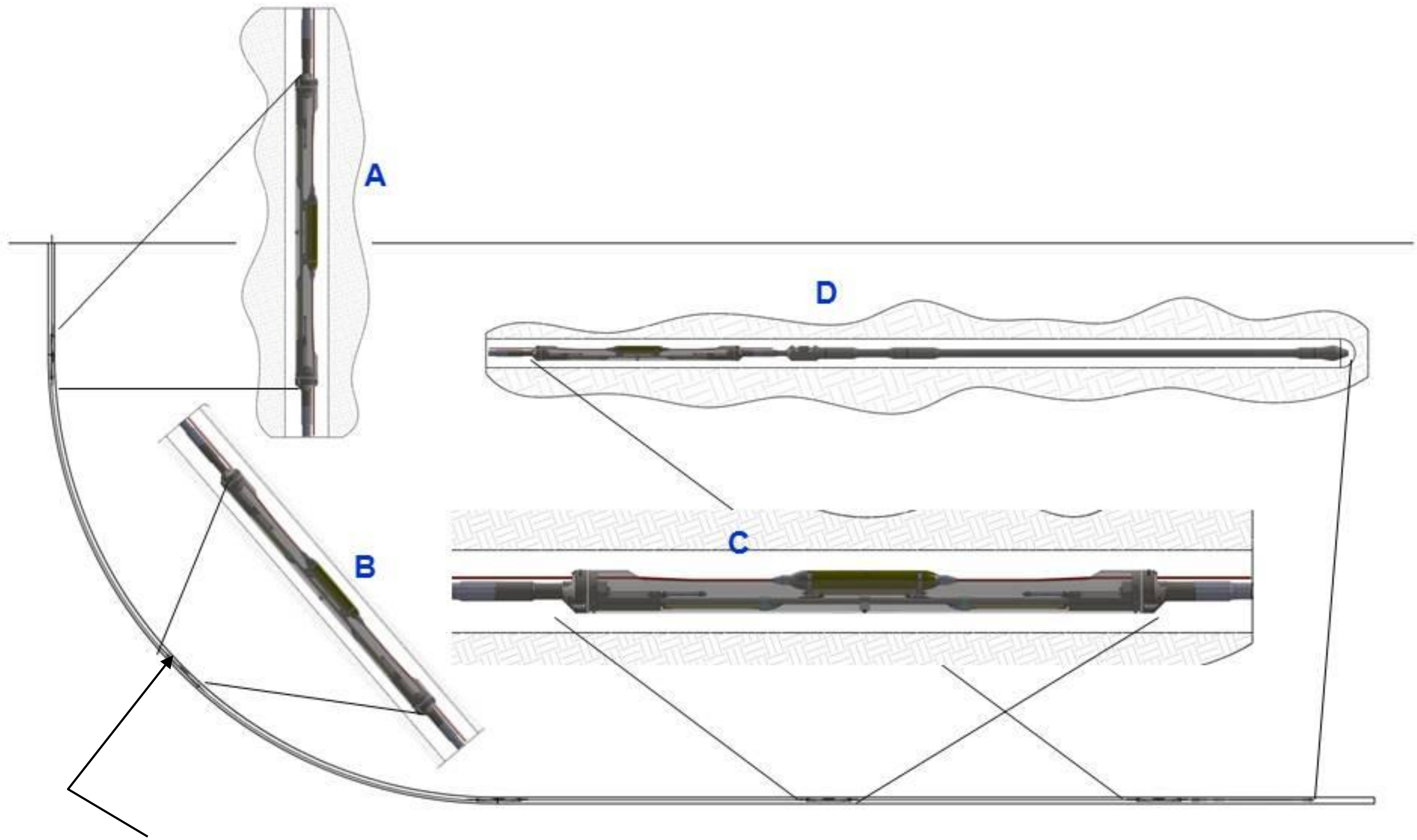
Proprietary Material – Paulsson, Inc (PI).

1. **Fiber Optic Sensor Development**

2. **Deployment System Development**

© 2016 Paulsson, Inc. (PI)

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

© 2016 Paulsson, Inc. (PI)

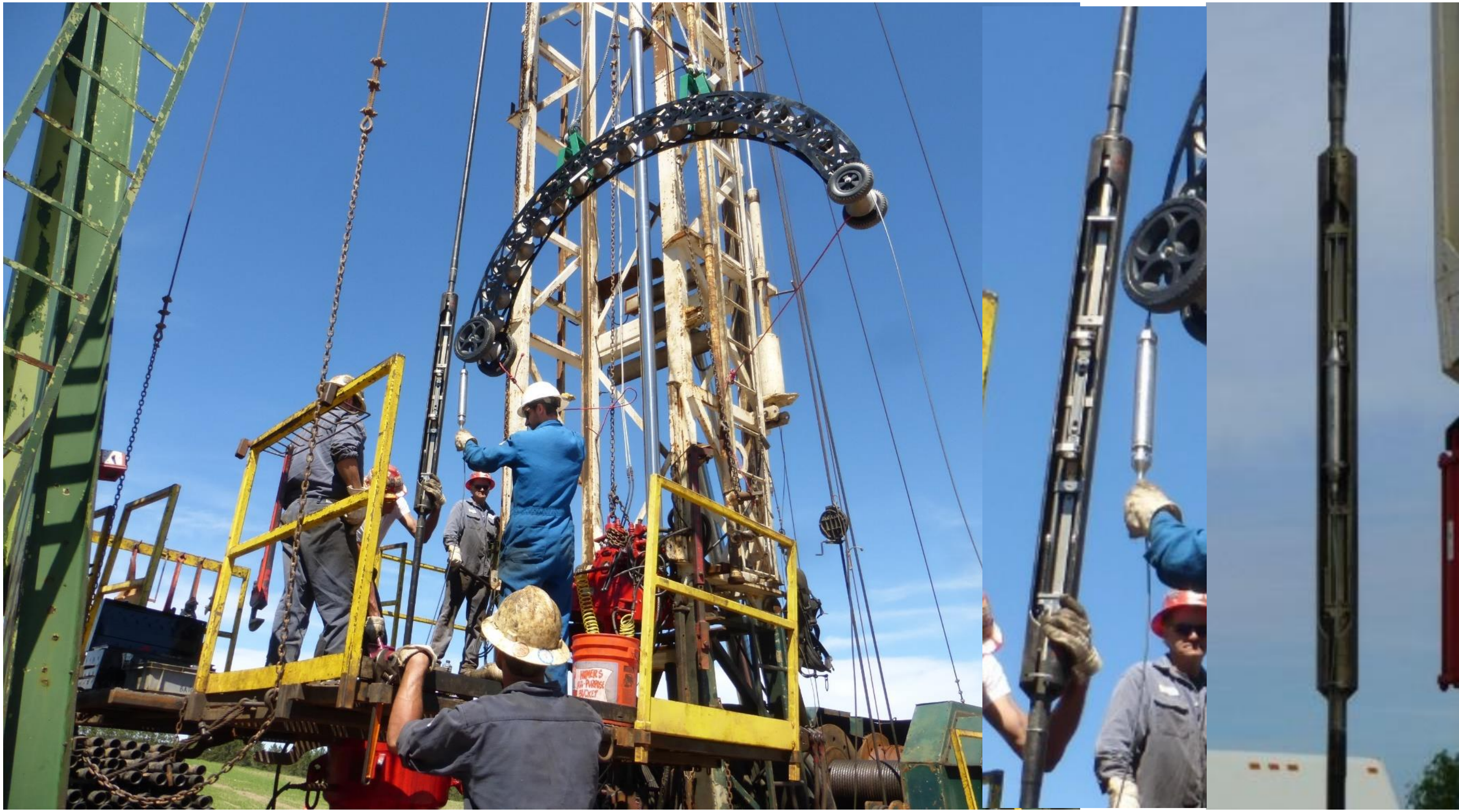
Field Tests
of
Fiber Optic Seismic Sensor (FOSS)™ System

© 2016 Paulsson, Inc. (PI)

Proprietary Material – Paulsson, Inc (PI).

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

Fiber Optic Seismic Sensor System Deployment

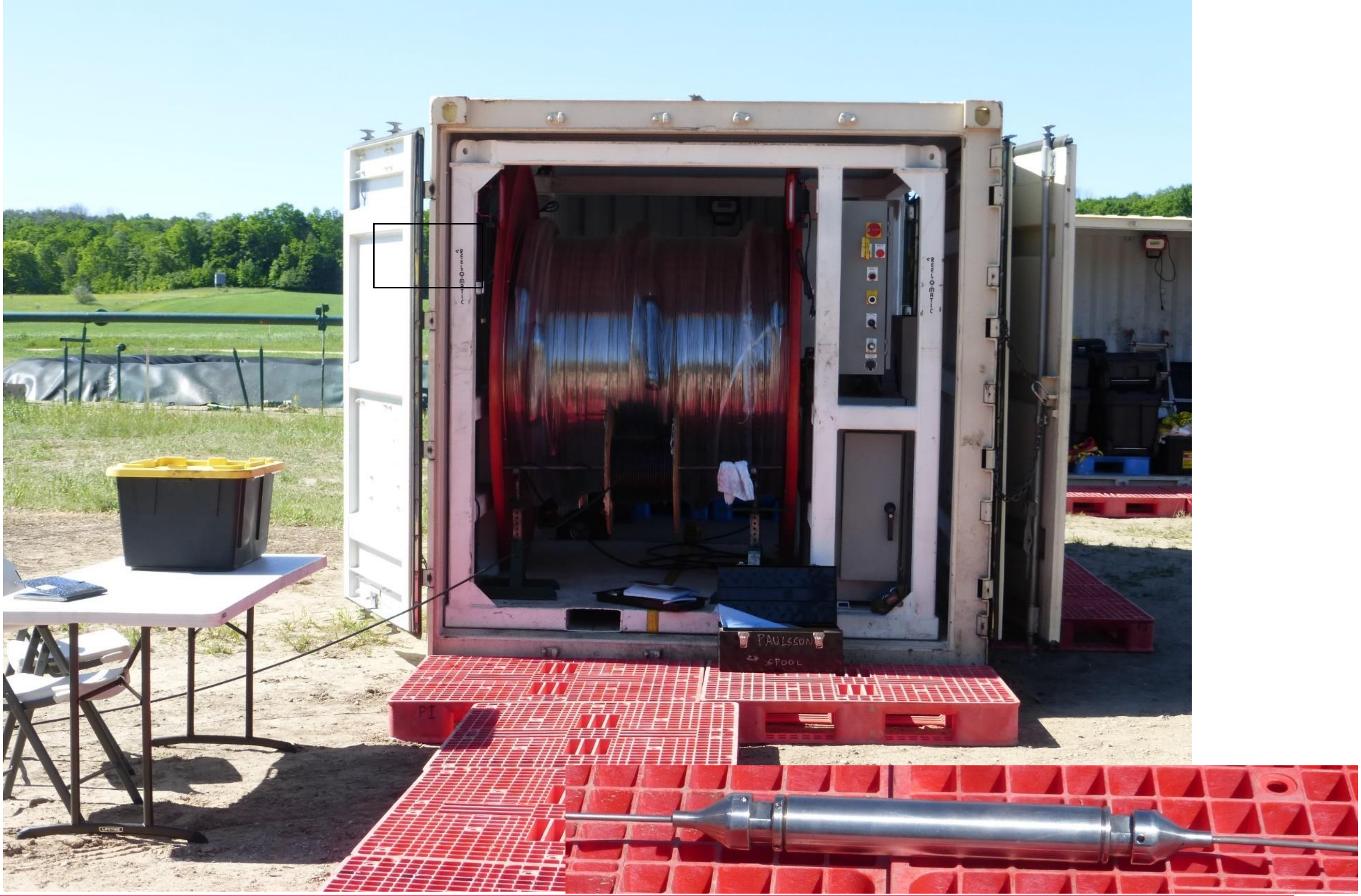


© 2016 Paulsson, Inc. (PI)

Proprietary Material – Paulsson, Inc (PI).

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

Spool for Fiber Optic Seismic 3C Sensors (CS)

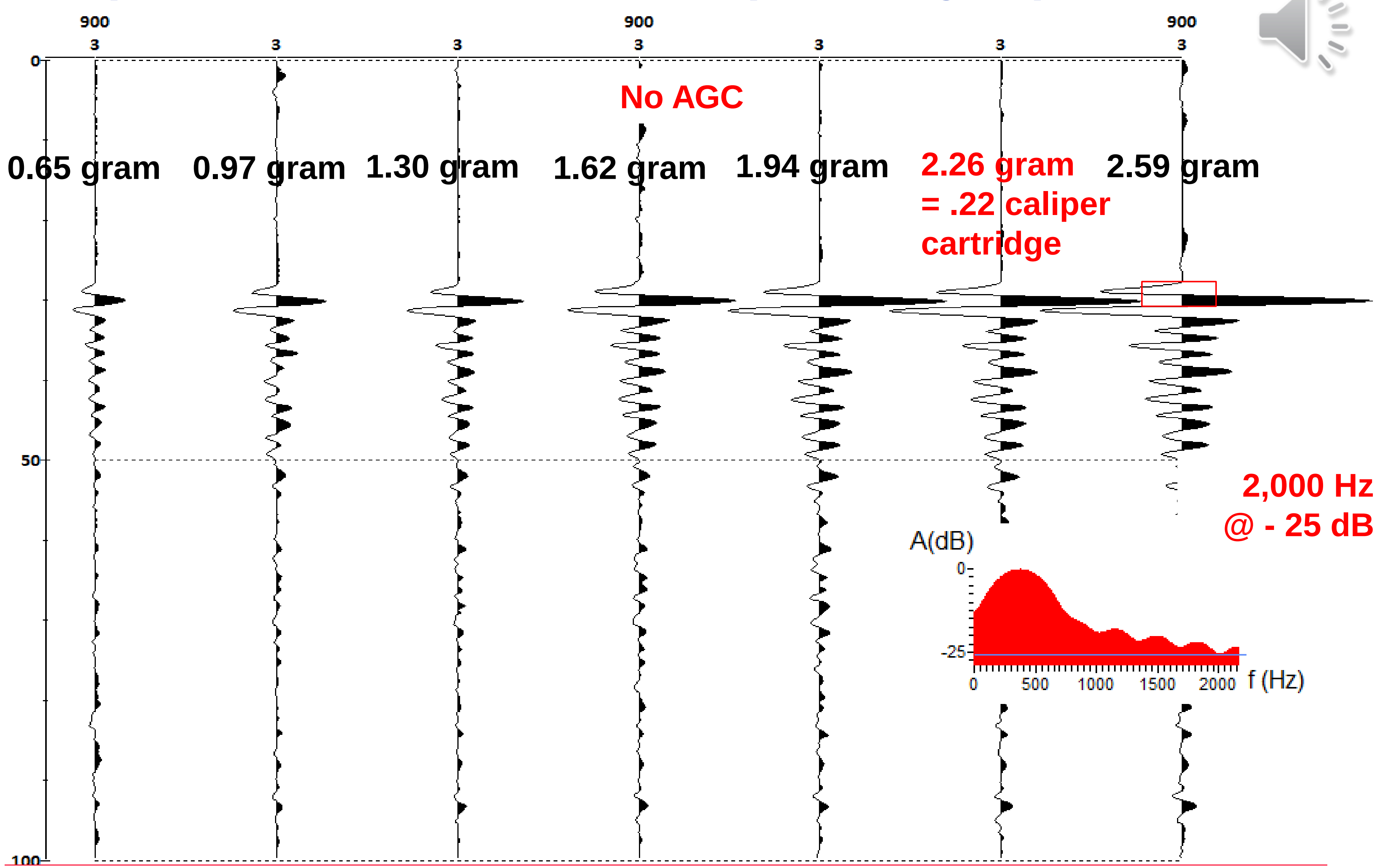


© 2016 Paulsson, Inc. (PI)

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

© 2016 Paulsson, Inc. (PI)

Shots Recorded by Principle Component @ 1,200 ft (400 m) (Filter: 80-100-1500-2000 Hz) – 0.65 g cap ~ M-2.9

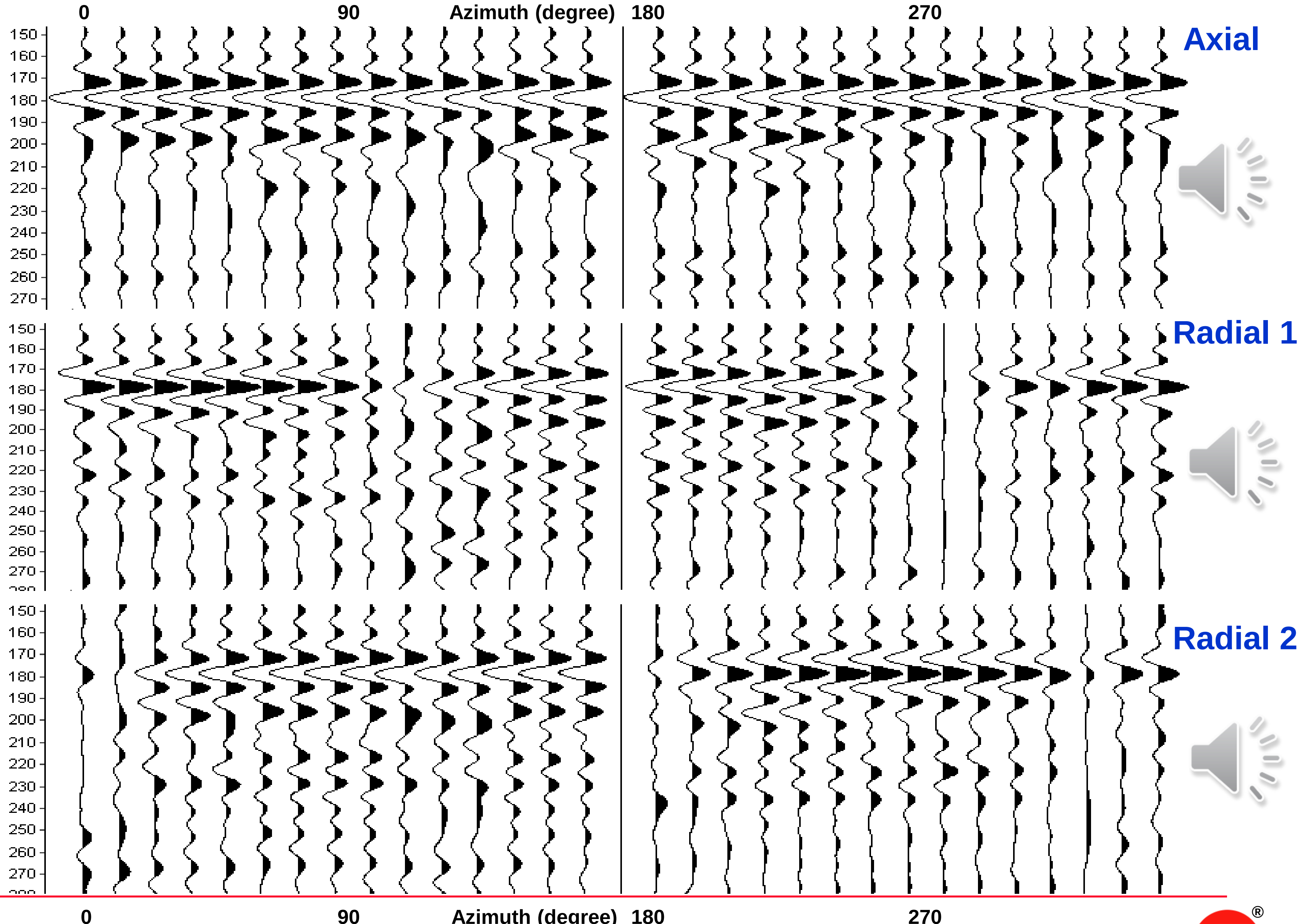


© 2016 Paulsson, Inc. (PI)

Proprietary Material – Paulsson, Inc (PI).

Vibrator walking around the receiver well @ R=500 ft

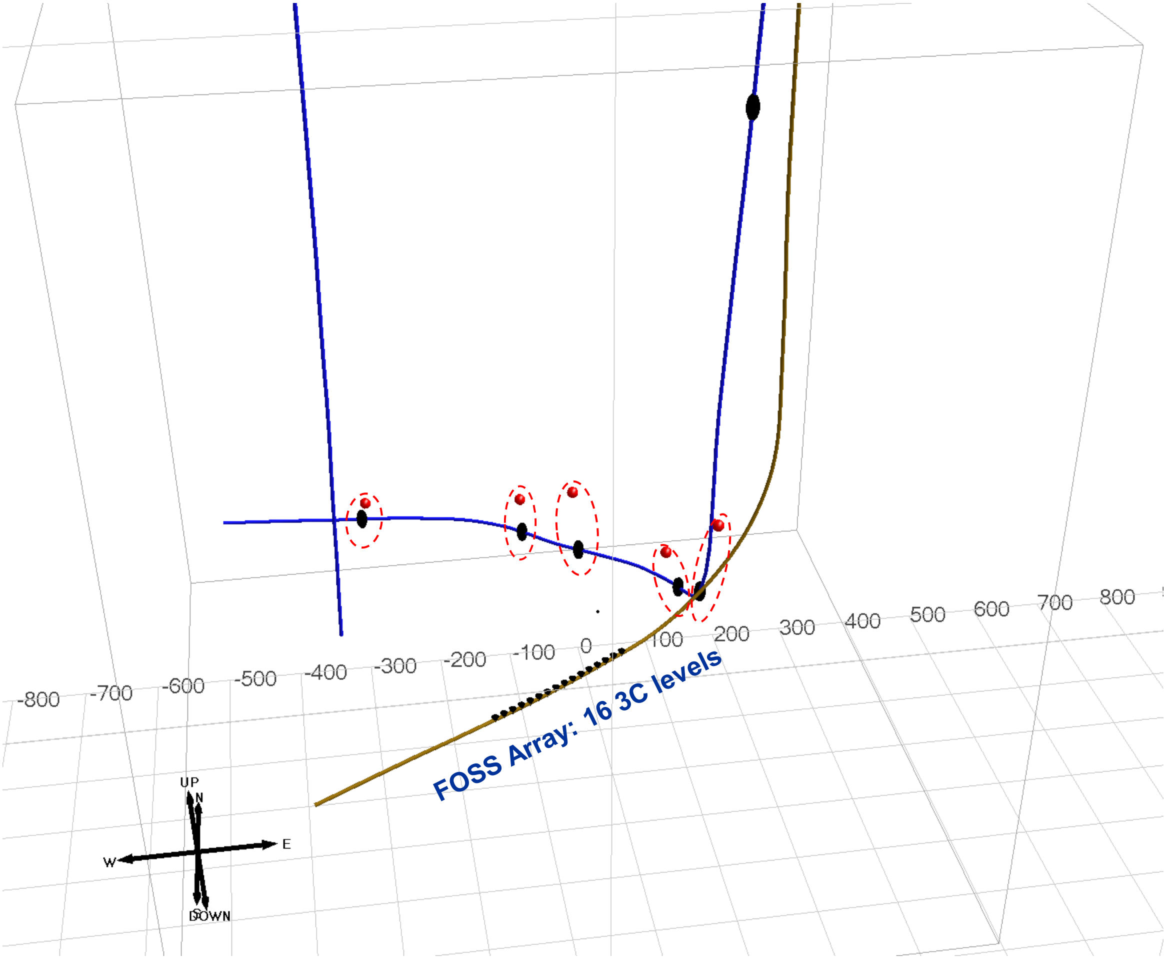
(Data aligned for waveform and phase analysis, Filter: 4-6-96-120 Hz)



© 2016 Paulsson, Inc. (PI)

Proprietary Material – Paulsson, Inc (PI).

Results from Locating String Shots during a survey for Battelle in June 2016

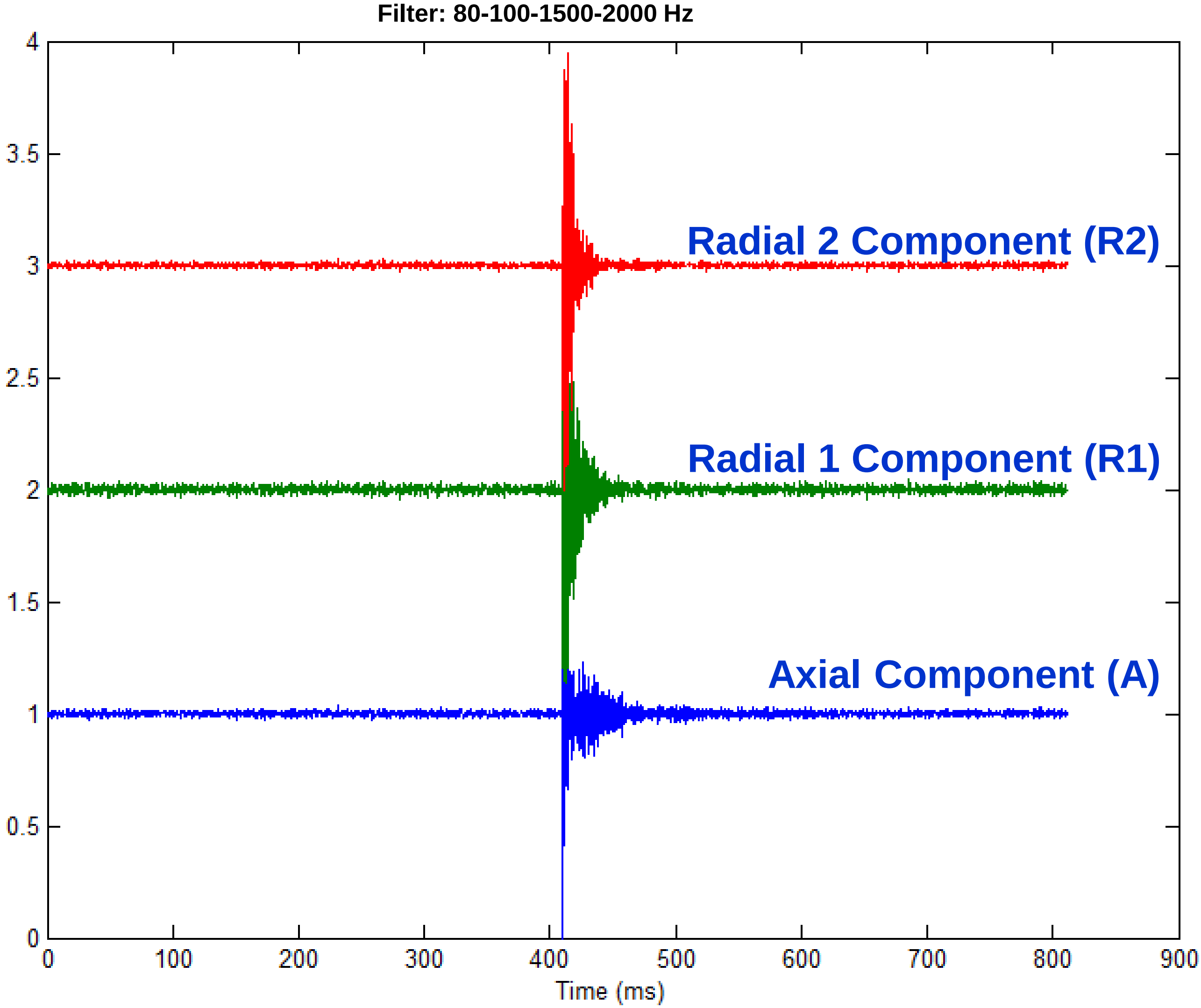


Courtesy Dr. Neeraj Gupta, Battelle

© 2016 Paulsson, Inc. (PI)

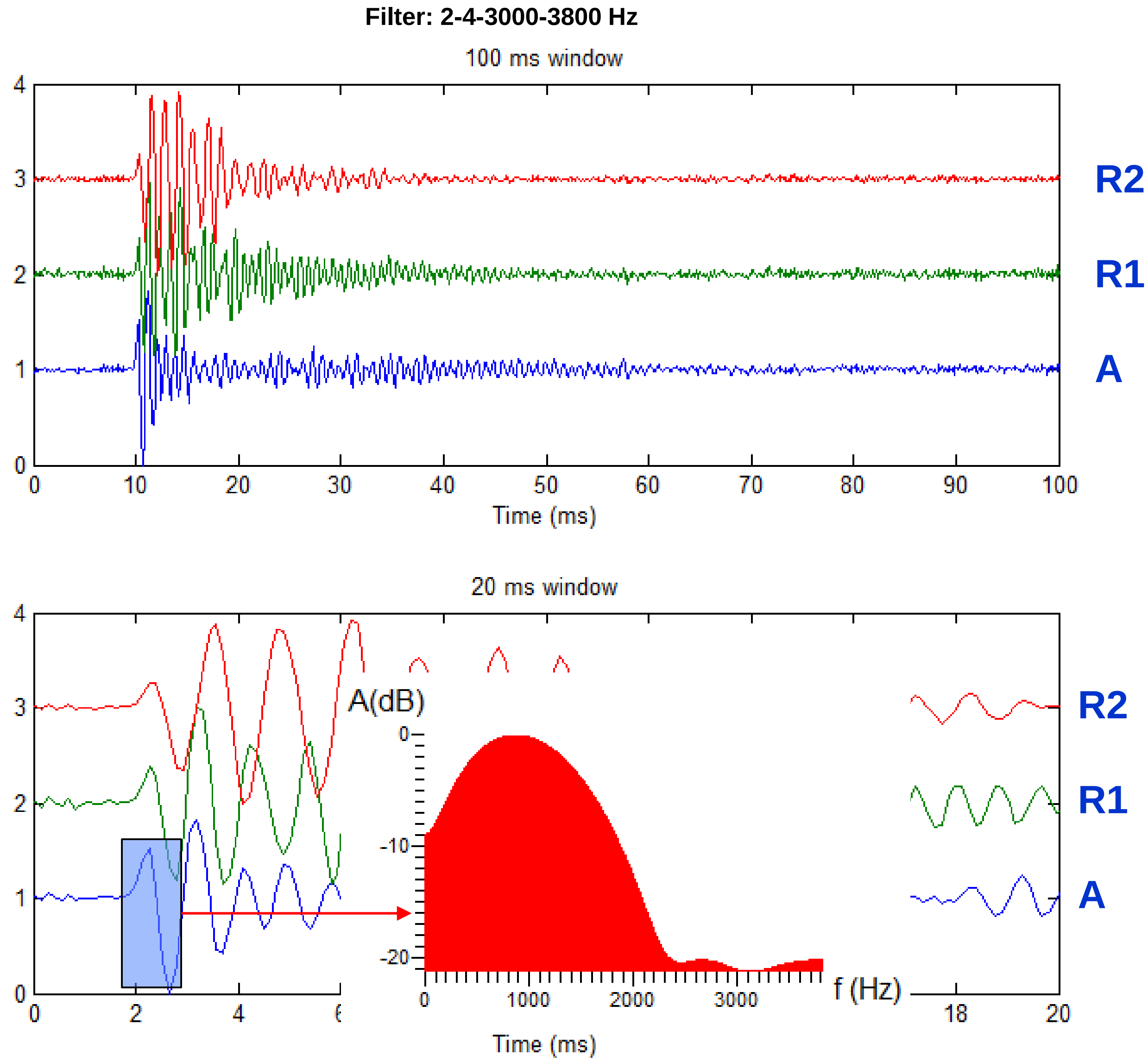
Proprietary Material – Paulsson, Inc (PI).

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



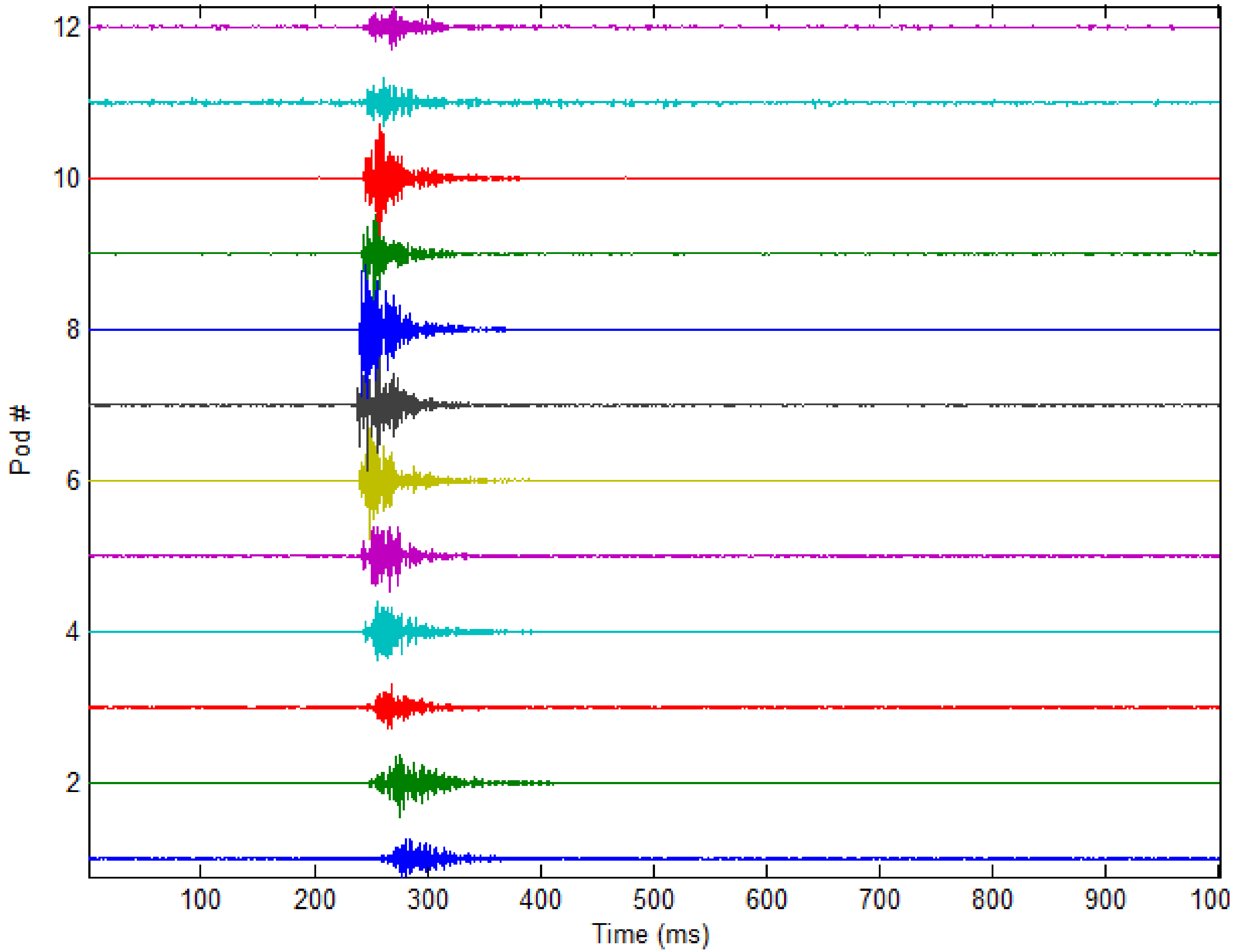
© 2016 Paulsson, Inc. (PI)

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



© 2016 Paulsson, Inc. (PI)

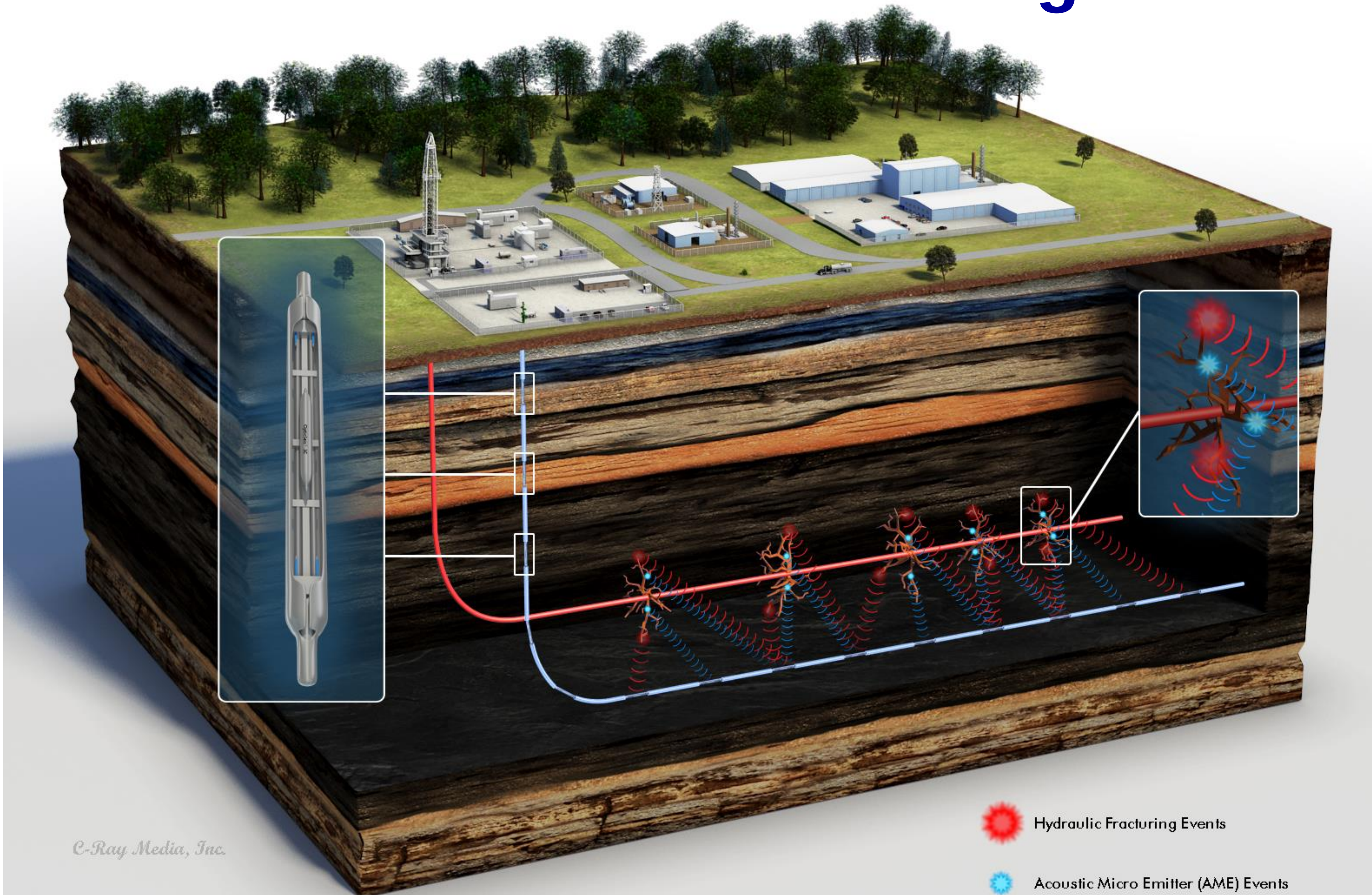
A Microseismic Data (Axial)



© 2016 Paulsson, Inc. (PI)

Proprietary Material – Paulsson, Inc (PI).

Effective & Accurate Monitoring of UOG



© 2016 Paulsson, Inc. (PI)
Proprietary Material – Paulsson, Inc (PI).

The New Technology will Address:

- The need for long borehole seismic arrays
- The need for sensitive borehole seismic arrays that are able to map very small micro seismic events – down to M-4.0 and smaller
- The need for seismic sensor technology that can operate at geothermal temperatures
- The need to operate large borehole seismic arrays in horizontal wells
- Small enough to be mounted on the outside the casing without drilling a large hole or be mounted inside casing on normal size tubing

© 2016 Paulsson, Inc. (PI)

What can we learn from the “New Signals”

- High Resolution images – much better than surface seismic
- Large volume images – much larger volumes than well logs
- 3D Velocity model to be used for surface seismic processing
- Anisotropic velocity information to focus imaging
- Outstanding structural/stratigraphic images
- Much better understanding of the dynamic processes of producing and injecting liquids and gases
  - Monitor Hydro Fracturing (Fracking) Operations
- Volumetric rock-mass stress distribution – not just at the well
- 3D Maps of Faults & Fracture distribution and directions
- Type of fluids in the reservoirs:
  - Gas vs Oil vs Water vs CO_2 vs Steam
- Temperature distribution
- Real time processing will allow us to mitigate the seismicity based on a better understanding of fault mechanisms and fluid flows

© 2016 Paulsson, Inc. (PI)

Acknowledgement

- The research discussed in this presentation has been supported by the following grants:
  - DOE Contract DE-FE0004522 (2010)
  - RPSEA Contract 09121-3700-02 (2011)
  - DOE Contract DE-EE0005509 (2012)
  - DOE Contract DE-FE0024360 (2014)
  - California Energy Commission Contract GEO-14-001

The support and assistance from these grants made it possible to develop the fiber optic sensor and deployment technology described in this presentation. The support from Karen Kluger for DE-FE0004522, Bill Head for RPSEA Contract 09121-3700-2, Bill Vandermeer for DE-EE0005509, Bill Fincham for DE-FE0024360 and Cheryl Closson for GEO-14-001 is gratefully acknowledged.

© 2016 Paulsson, Inc. (PI)

Proprietary Material – Paulsson, Inc (PI).

Thank You!
www.paulsson.com

© 2016 Paulsson, Inc. (PI)

Data by Optical Sensor Systems

Today:

- Seismic – Fiber Optic Vector Sensors (Sensitivity: 100 x Geophones and >1000 x DAS)
  - P-wave Velocities
  - SH and SV Velocities
  - Reflections
- Acoustic – Distributed (DAS) for velocity
- Temperature – Distributed (DTS) along the fiber
- Pressure – Point Sensors

Future:

- Chemical Sensors
- Pressure sensor – Distributed (DPS)
- Magnetic, Electro Magnetic, Resistivity

© 2016 Paulsson, Inc. (PI)

Proprietary Material – Paulsson, Inc (PI).