Distributed Fiber Optic Arrays: Integrated Temperature and Seismic Sensing for Detection of CO2 Flow, Leakage and Subsurface Distribution

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Infrastructure for CCS

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SECARB Southeast Regional Carbon Sequestration Partnership

Southern States Energy Board

Advanced Resources International, Inc.

Southern Company Energy to Serve Your World

Denbury

CO_2 Capture Project

Presentation Outline

- Project benefits and goals
- Principles of operation
  - Distributed acoustic sensing (DAS)
  - Heat pulse monitoring coupled with distributed temperature sensing (DTS)
- Task 2 - SECARB Citronelle Alabama
  - Cross well seismic survey (June 2014)
  - Vertical seismic profile survey (June 2014)
- Task 3 - Livingston Field Louisiana
  - Heat pulse monitoring to determine flow allocation in a horizontal CO_2 injector

Benefit to the Program

- Program goals
  - Develop and validate technologies to ensure 99 percent storage permanence.
- Benefit Statement
  - The project uses Distributed Acoustic Sensor (DAS) arrays to detect and image the CO_2 plume using seismic methods
  - Heat-pulse monitoring using Distributed Temperature Sensing (DTS) to detect vertical CO_2 leakage along the wellbore and flow outside of the casing
  - If successful, this project will contribute to the Carbon Storage Program goal to develop and validate technologies to measure and account for 99 percent of injected CO_2 in the injection zones.

Project Overview: Goals and Objectives

- **Overall objective**: Develop cost effective monitoring tools that can be used to demonstrate safe, permanent storage of carbon dioxide ($CO_{2)}$ in deep geologic formations.
- **Specific objectives include**:
  - Make hi-res spatial measurements of the CO_2 plume using permanent distributed acoustic seismic receiver arrays that utilize FO at a lower cost and with greater repeatability;
  - Monitor for CO_2 leakage out of the storage reservoir along wellbores and through the caprock for regulatory compliance;
  - Make hi-res measurements of the vertical distribution of CO_2 in the storage reservoir, allowing site operators to better manage their CO_2 floods and assess leakage risks;
  - Make hi-res spatial measurements of injection rates and CO_2 distributions in injection wells to manage and optimize EOR floods
  - Develop best available practices for deploying FO sensors in deep wells
  - Evaluate long-term robustness of FO sensor arrays in situ

Advance Monitoring Methods are Needed for Carbon Capture and Storage Projects

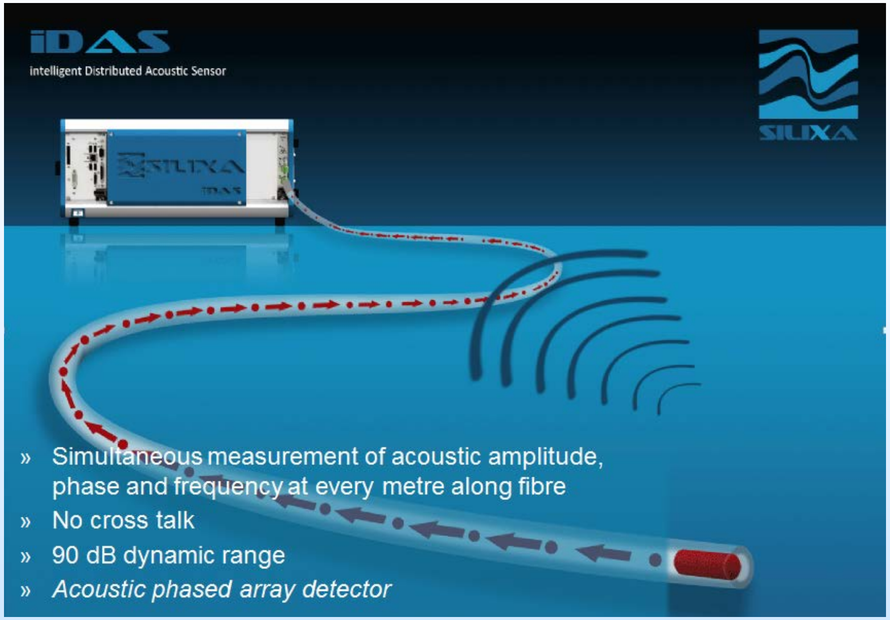
Motivation: Deep monitoring wells are expensive to drill and complete and have limited space available for instrumentation

- ✓Monitor CO_2 plume location
- ✓Reservoir pressure and temperature
- ✓Fluid sampling
- ✓Leak detection
- ✓CO_2 saturations

Distributed sensing using downhole fiber optics could address many of these needs

Principle of Operation: Distributed Acoustic Sensing (DAS) for CO_2 Plume Imaging

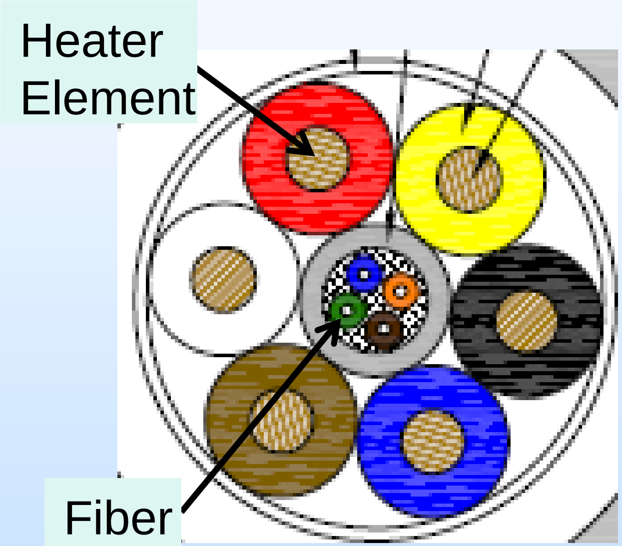
- Light emitted into a fiber is reflected throughout the fiber's length by Rayleigh scattering
- DAS system measures the modulation of the backscattered light
- An acoustic field around the fiber exerts tiny pressure/strain changes on the fiber, resulting in changes to the backscattered light
- The DAS measures these changes by generating a repeated light pulse every 100 µs and continuously processing the returned optical signal, thus interrogating each meter of fiber up to 10 km in length at a 10 kHz sample rate
- Unlike other methods, the system records the full acoustic signal, including amplitude and phase



A 10 km single mode fiber becomes a high density acoustic array with 10,000 linear sensors with 1 meter spatial resolution

Principle of Operation: Distributed Temperature Sensing (DTS) and Heat Pulse Monitoring for Leak Detection/Flow Allocation

- Measurement of Raman backscattering combined with Optical Time-Domain Reflectometry (OTDR) are used to determine distributed temperatures along the fiber length
  - DTS used for past 20 years
  - 5 km fiber: spatial resolution 25 cm, temperature resolution 0.01°C measurement time 1 s
- Copper heater elements integrated with DTS fiber in the same cable provide pulse of heat
- Fluid substitution in well or rock pores changes thermal properties in/near wellbore
- Detected by time-lapse measurement of temperature build up/fall off during/after heating
- Or can be used like a hot-wire anemometer in a CO_2 injector to measure flow



Multiple heater elements and fibers are integrated into a 3/8” OD stainless steel control line

Application at SECARB Anthropogenic Test Site, Citronelle Alabama

- First integrated CO_2 capture, transportation and storage project on a coal-fired power station using advanced amines
- Southern Co. and MHI have captured over 210,000 metric tons of CO_2 to date
- Denbury Resources has transported, injected and stored over 110,000 metric tons in the Paluxy Formation
- Total planned injection 150,000 (End injection Oct-Nov 2014)

Modular Borehole Monitoring System

- Joint research effort by SECARB and CO_2 Capture Project
    - MBM Design by LBNL
    - Deployment by SECARB/CCP
- 18 Level, semi-permanent tubing deployed, clamping geophone array (6,000-6,850 ft)
- Fiber optic cable for distributed temperature and acoustic measurements (0-9,797 ft)
    - Heat-pulse monitoring for CO_2 leak detection
    - Acoustic array for CO_2 imaging

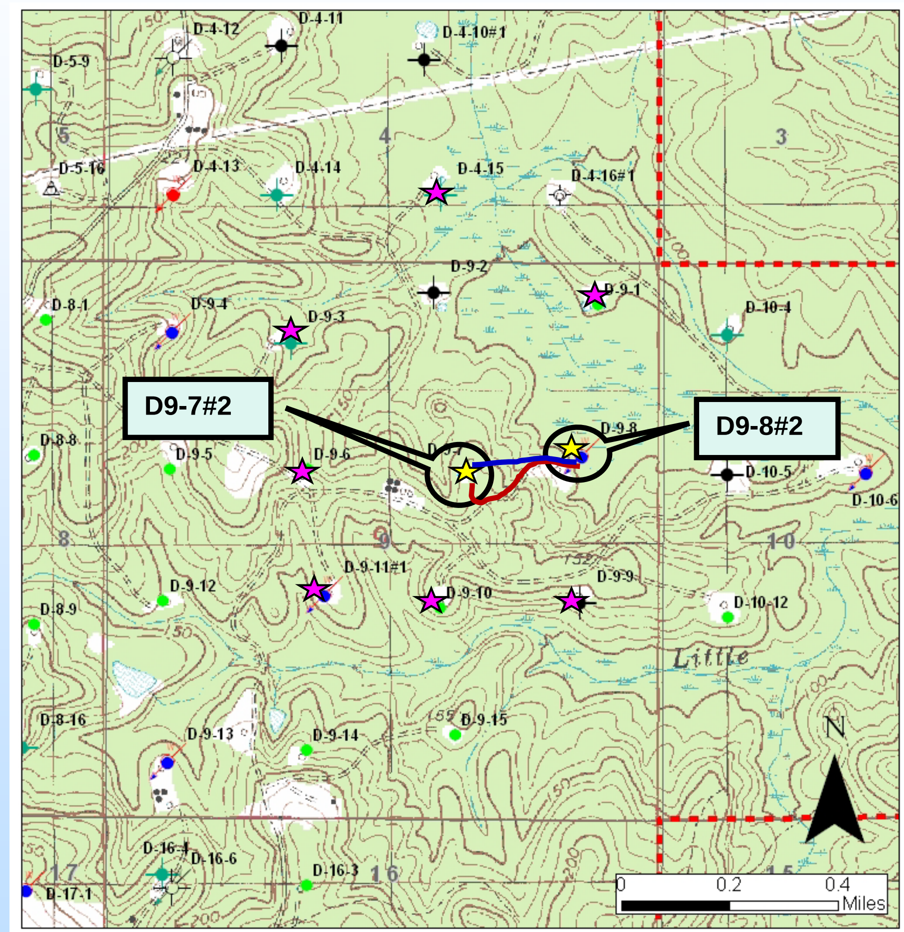
Geophone pod and clamping assembly and yellow flat pack containing fiber cable

CO2 Capture Project

SECARB Southeast Regional Carbon Sequestration Partnership

Citronelle Offers a Unique Opportunity to Compare Seismic Methods to Monitor CO_2 Plume Location

- Seismic survey configurations being performed at Citronelle include:
  - Offset vertical seismic profile (VSP) surveys using
    - Long geophone arrays deployed in the injector and D9-8#2
    - Short geophone MBM array
  - Walk away VSPs
  - Cross-well seismic surveys
- DAS and conventional geophones/hydrophones are being used



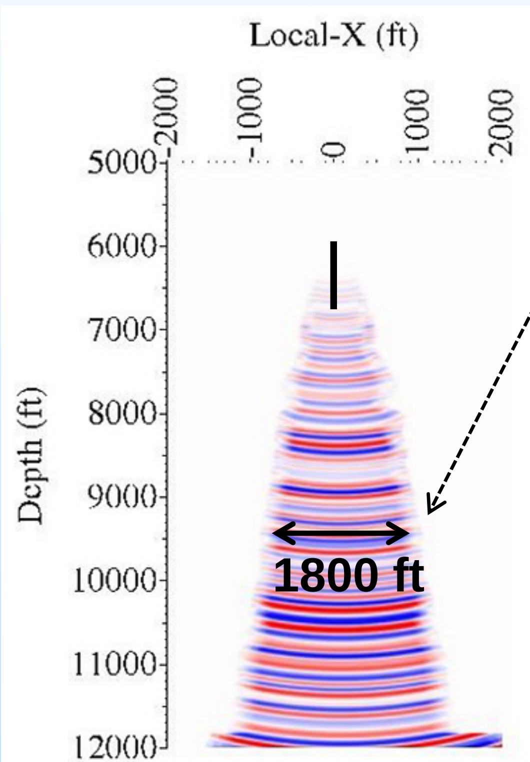
VSP source offset locations (stars), receiver locations (D9-7#2 and D9-8#2), and walk-away lines (blue and red lines)

SECARB Pre-CO_2 Injection Baseline Surveys were Performed Using Conventional Geophone Arrays in 2012

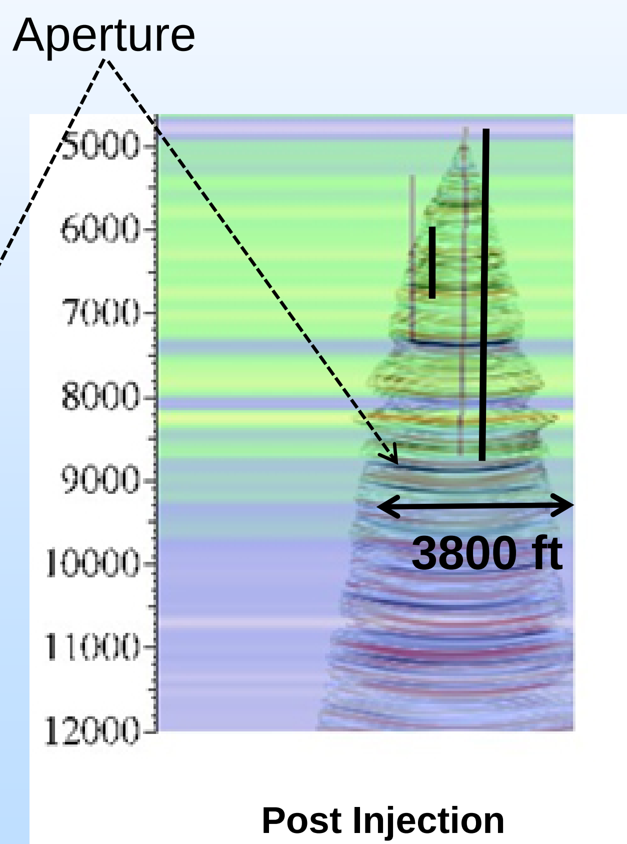
Semi-permanent short MBM 18-level geophone array

Temporary long string 80-level geophone array

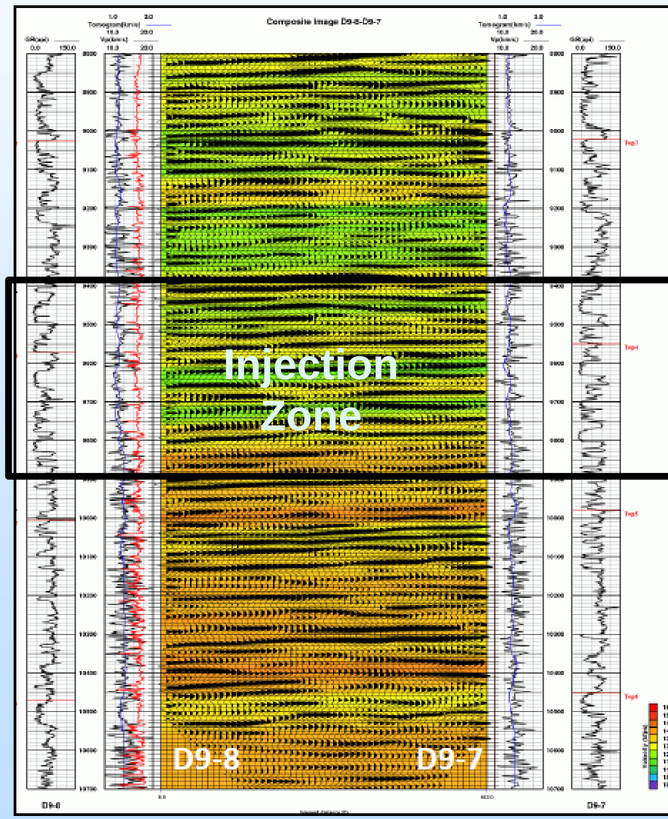
Cross well velocity tomogram



Repeats performed May '13, Aug. '13, Apr '14, Jun '14



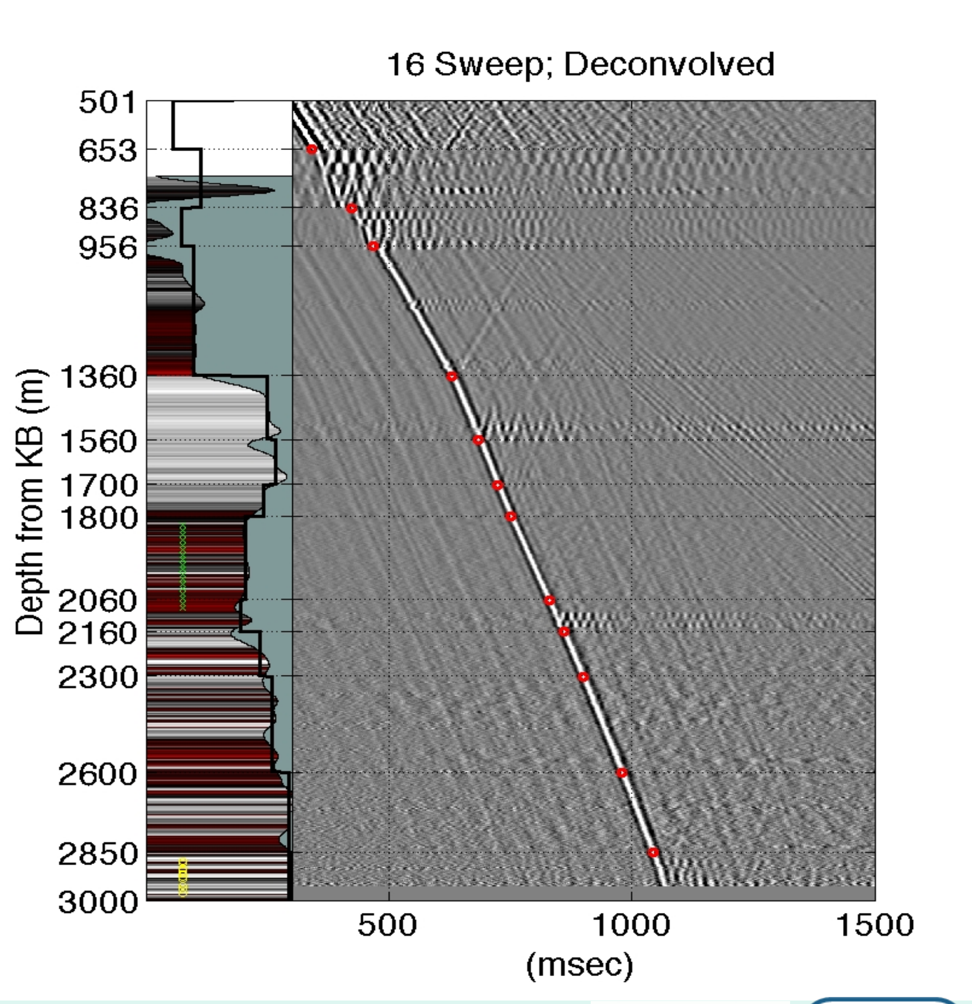
Post Injection Planned



Jun '14 and Post Injection Planned

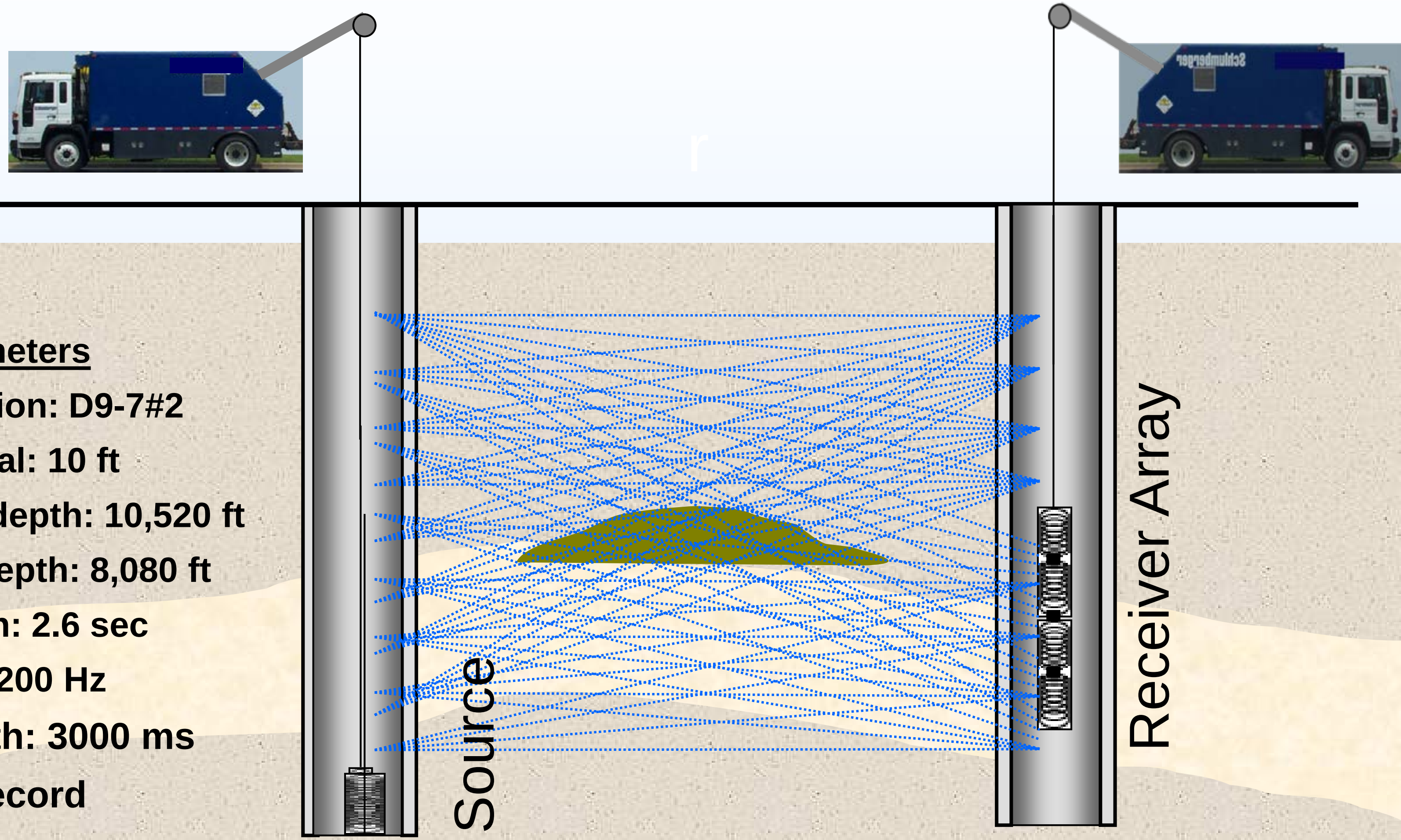
DAS VSP Walkaway Survey 2013

- Three shot points recorded using DAS during walkaway VSP survey in 2013
- Improved DAS VSP Processing



- Good tie to logs
- Reflections clear
- Strong 'ringing' in some zones

Cross Well Repeat Survey – June 2014



<u>Survey Parameters</u>

Source Location: D9-7#2

Source Interval: 10 ft

Source start depth: 10,520 ft

Source end depth: 8,080 ft

Sweep Length: 2.6 sec

Sweep: 100-1200 Hz

Record length: 3000 ms

Correlated record length: 400 ms

Source type: X-Series Piezoelectric

Illustration by:
Schlumberger Carbon Services

Hyrdophone Receiver Array at Observation Well D9-8#2 – June 2014

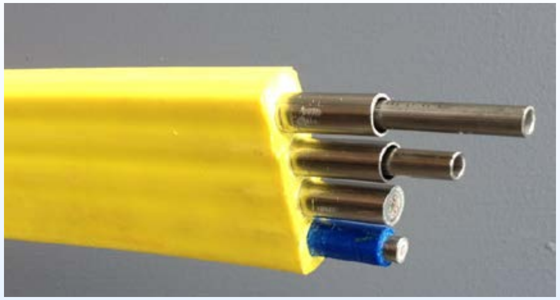
- Schlumberger Carbon Services
- Receiver array deployed inside tubing
- Receiver type: TARS Hydrophone – 10 levels
- Sample Rate: 0.25 ms
- Stack:
    - 8 sweeps for each fan
- Receiver spacing: 10 ft
- Receiver start depth: 10,590 ft
- Receiver end depth: 8,170 ft
- Data acquisition time: 5 days

Crane set up on well D9-8#2 containing hydrophone array. Photo by Michele Robertson (LBNL).

DAS Array at Observation Well D9-8#2 – June 2014

- Silixa, LLC
- Fiber cable clamped to production tubing
- Receiver type: fiber optic Tubing Encased Cable
- Sample rate: 4kHz
- Stack:

  8 sweeps were recorded for multiple ‘fans’
- 128 sweeps at 9,000 and 9,340 ft depth
- Receiver spacing: 0.25 m
- Data acquisition time: <1 day

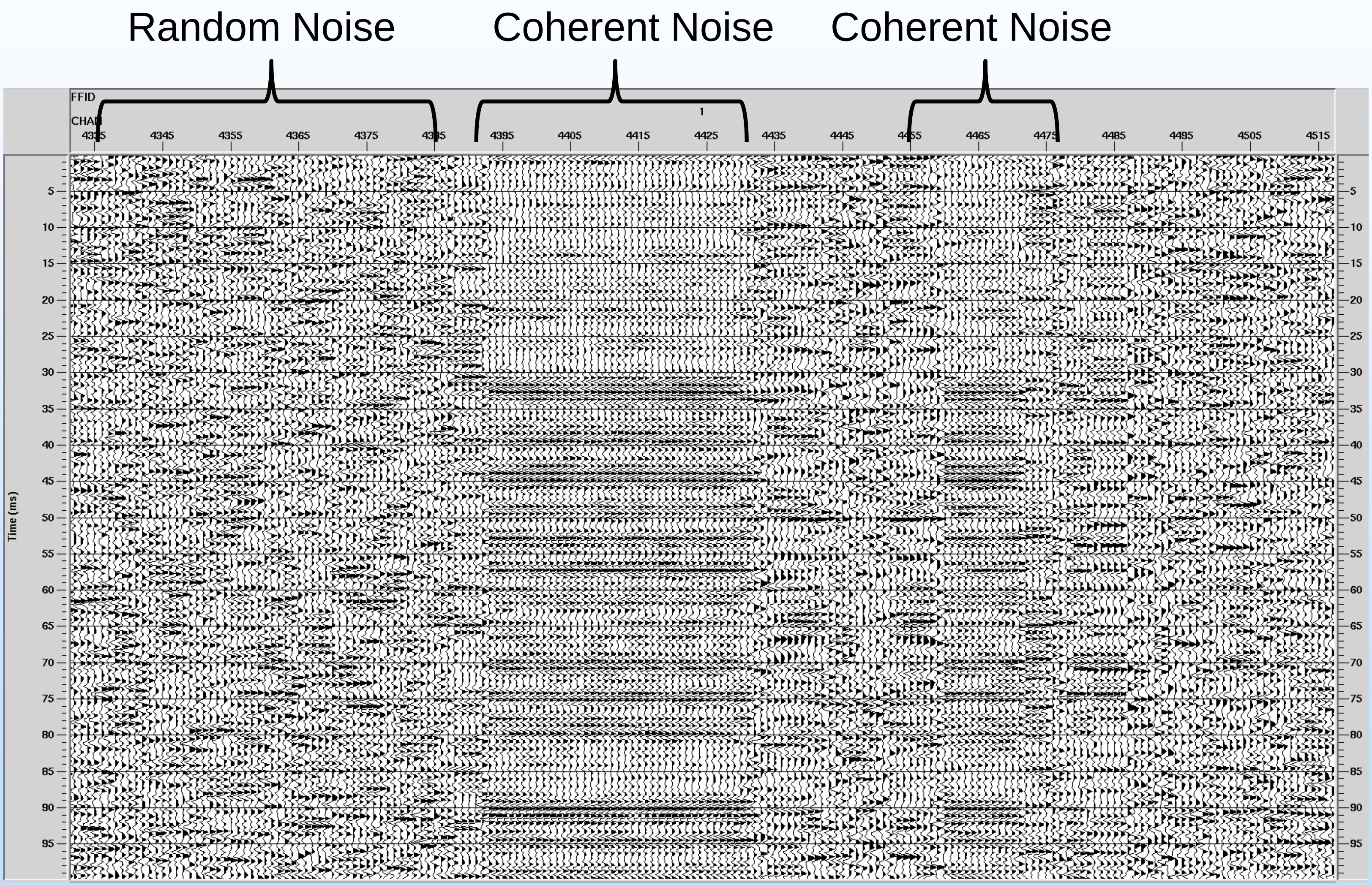


Top: Flat pack containing fiber optic cable.
Bottom: Terminus of the fiber optic cable as it is being deployed in the well

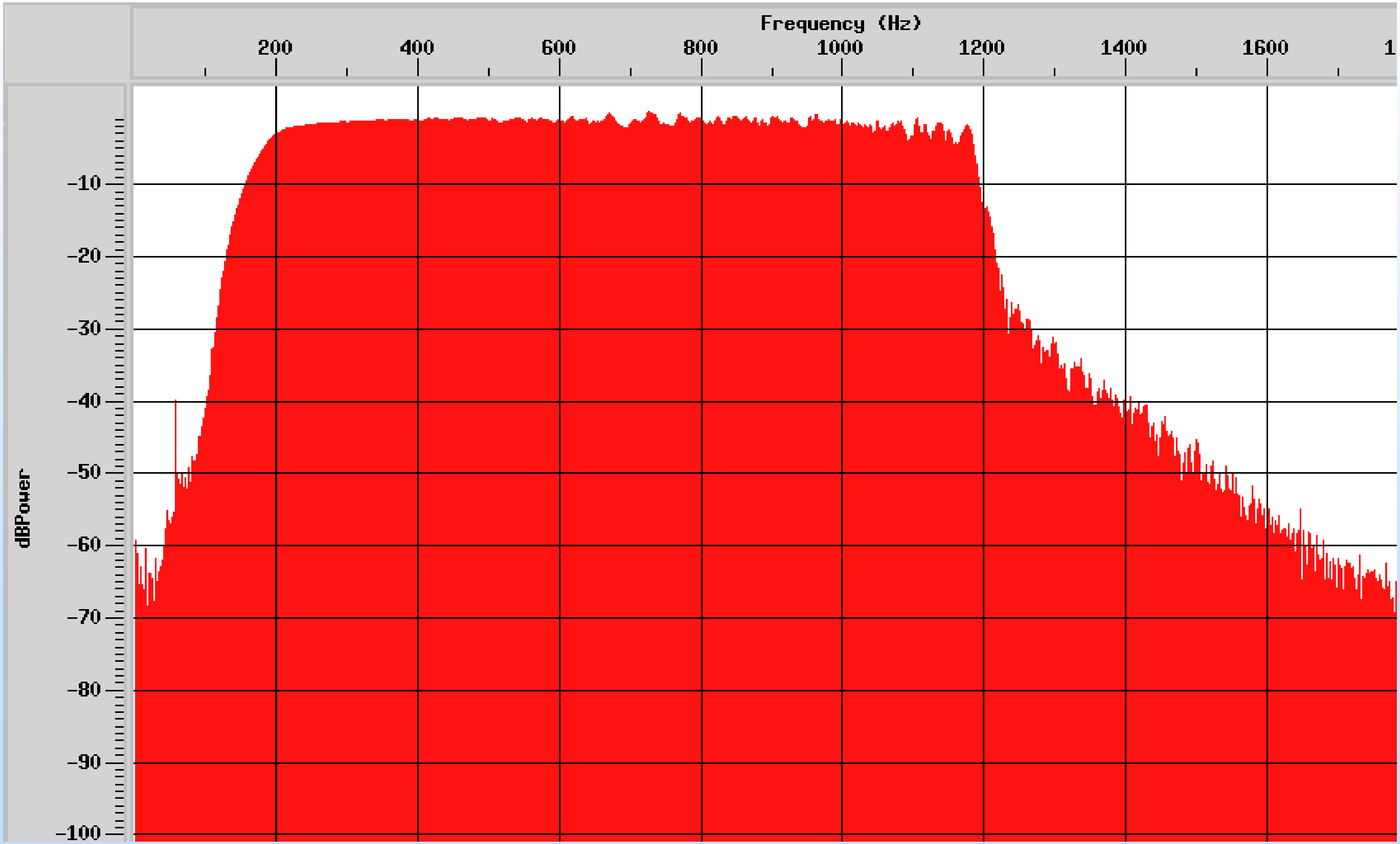
Preliminary DAS Analysis

- Initial data delivered included two shot points with 128 uncorrelated sweeps at a depth of 9,000 and 9,340 ft
- Data at 0.25 m and 0.25 ms sample rates
- Correlated with synthetic sweep
- No seismic arrivals identified
- Look at spectral analysis for indication of energy in the sweep bandwidth

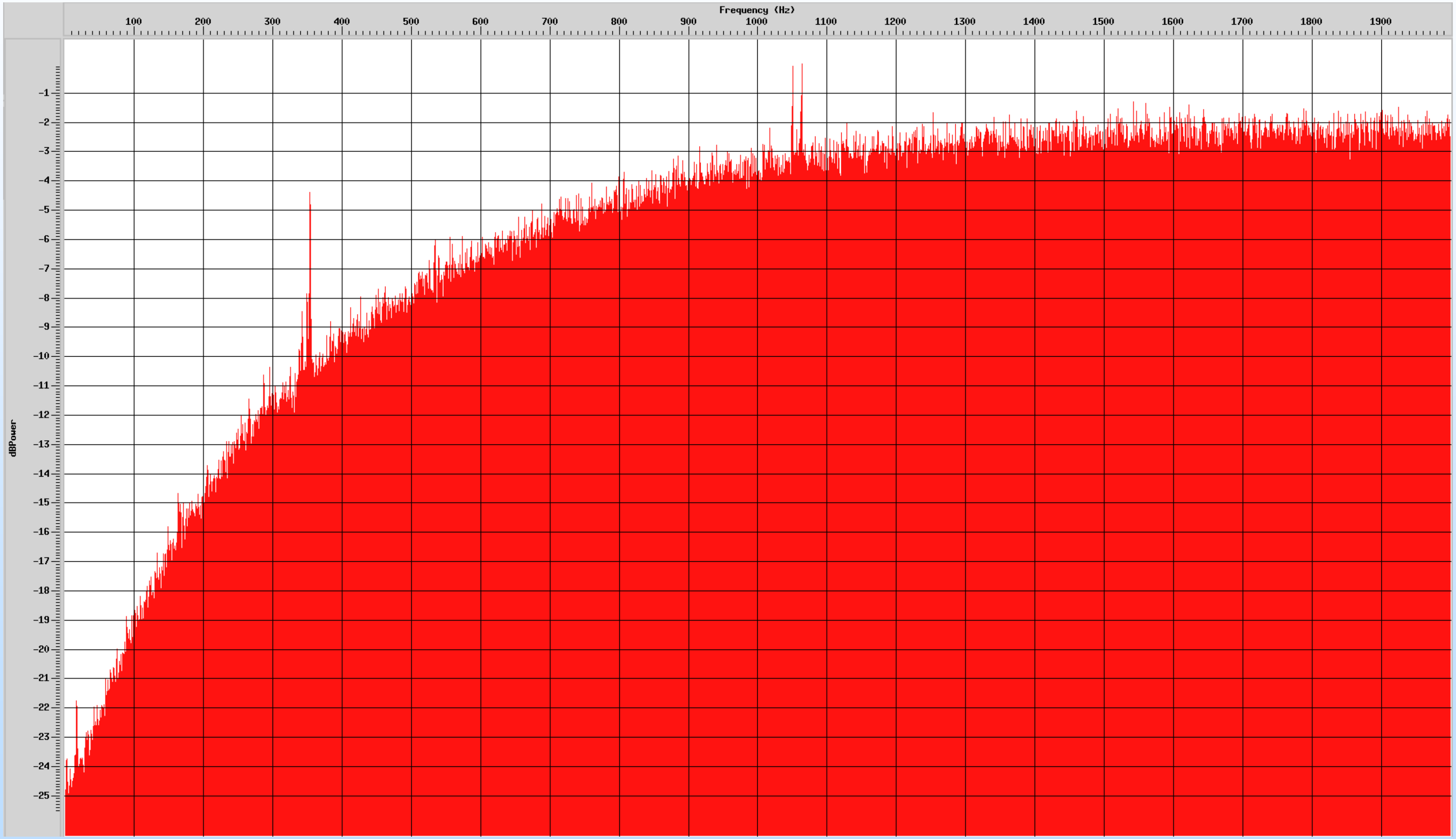
DAS Data at 9,340 ft – Only See Random Noise, Except Some Coherent Noise Not related to sweep



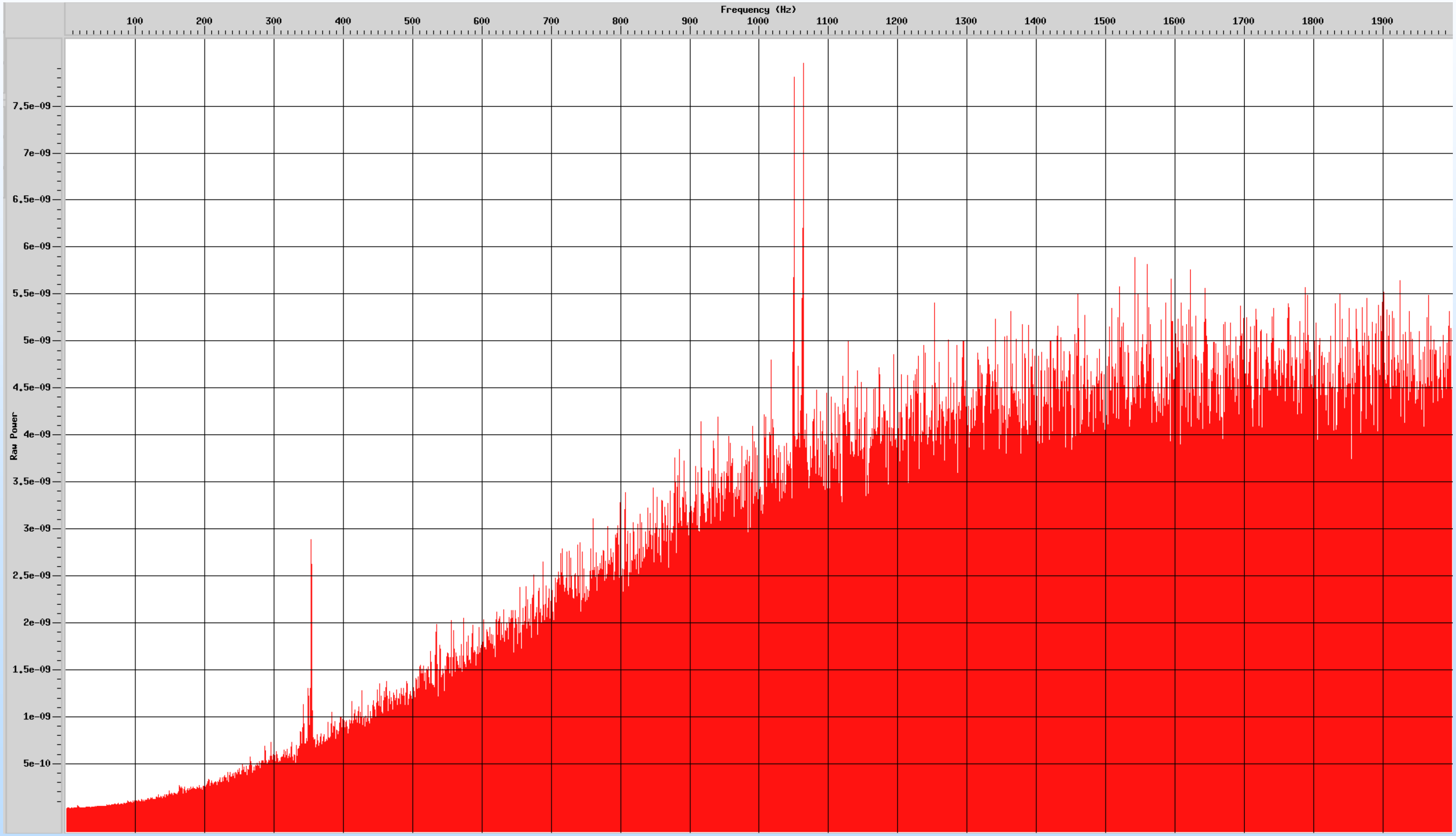
Expected Spectral Response from Synthetic Sweep Should be Flat from ~200 Hz to ~1200 Hz



Spectra of 200 traces stacked (50 m cable): Log Scale



Spectra of 200 traces stacked (50 m cable): Linear Scale



Accomplishments to Date

- **SECARB Citronelle Site**
  – Collected large cross-well and VSP data sets (10 terabytes) using DAS
  – First cross-well survey performed using DAS

- **Blackhorse Energy Livingston Field Louisiana**
  – Completed fiber optic cable design
  – Deployment likely in 2015 due to host project delay

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Summary

Recent DAS Cross Well Survey - Citronelle

- Results are very preliminary and analysis is incomplete
- DAS data noise is too large in the sweep bandwidth to allow detection of seismic waves
- Noise is approximately linearly increasing with frequency from 100 to 1000 Hz, by a factor of about 10
- Further signal processing may improve results

Summary

Future Plans

- SECARB Citronelle
  - Process the large VSP data set acquired in June 2014
  - Perform a post-CO_2 injection VSP survey and process the data
  - Investigate 'true' signal levels and acoustic noise levels from conventional hydrophone cross-well data for comparison to DAS data
- Livingston Field
  - Deploy the fiber optic cable in a horizontal CO_2 injector
  - Perform heat-pulse tests to measure flow allocation

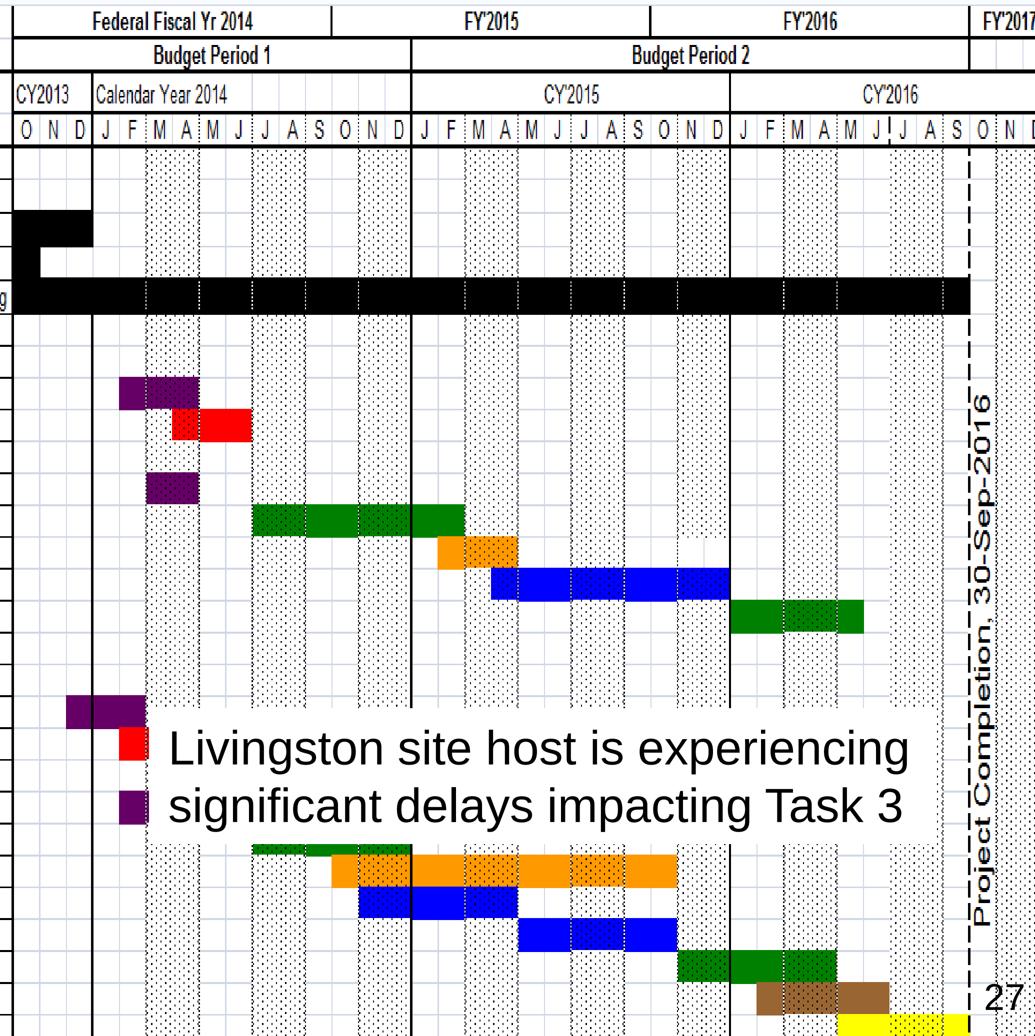
Appendix

Organization Chart

- Department of Energy, NETL
  - Andrea Dunn, PM
- Electric Power Research Institute, Project Lead
  - Rob Trautz, PI
- Kansas Geological Survey, Geophysical Services
  - Lynn Watney, Co-PI
- Lawrence Berkeley National Laboratory, Geophysical & Hydrologic Modeling & Analysis
  - Tom Daley, Co-PI
  - Barry Freifeld, Co-PI
- Sandia Technologies, LLC, Field Site Engineering
  - Dan Collins, Co-PI
- Silixa, LLC, Fiber Optic Data Acquisition
  - Joe Greer, Co-PI

Gantt Chart

Description	Start Date	End Date	Dur. Mos.
Task 1.0 Project Management			
Revise Project Management plan	10/1/2014	12/31/2013	3
NEPA field study preparation/submittal	10/1/2014	11/30/2013	1
Project management	1/1/2014	9/30/2016	Ongoing
Task 2.0 – Vertical Well – Citronelle Alabama			
Subtask 2.1 – Sensor Design and Fabrication			
Design	2/1/2014	4/30/2014	3
Purchase, fabrication and equipment delivery to site	2/1/2014	6/30/2014	5
Subtask 2.2 – Field Testing			
Survey design & planning	3/1/2014	4/30/2014	2
Baseline seismic acquisition and processing	3/1/2015	3/31/2016	6
Heat-pulse monitoring	9/1/2014	8/31/2015	12
CO2 injection*	4/1/2015	12/31/2015	9
Post-injection seismic acquistion and processing	1/1/2016	5/31/2016	5
Task 3.0 Horizontal Well – Livingston Field Louisiana			
Subtask 3.1 – Sensor Design and Fabrication			
Design	10/1/2014	1/31/2014	3
Purchase, fabrication and equipment delivery to site	2/1/2014	6/30/2014	5
Subtask 3.2 – Field Testing			
Survey design & planning	2/1/2014	3/31/2014	2
Baseline seismic acquisition and processing	7/1/2014	12/31/2014	6
Heat-pulse monitoring	10/1/2014	10/31/2015	13
CO2 injection*	11/1/2014	4/30/2015	6
Foam injection*	5/1/2015	10/31/2015	6
Post-injection seismic acquistion and processing	11/1/2015	5/31/2016	6
Task 4.0 – Data Analysis	1/1/2016	6/30/2016	5
Task 5.0 – Final Sensor Performance Report	5/1/2016	9/30/2016	5



Bibliography

List peer reviewed publications generated from project per the format of the examples below

- <u>None</u>