A 3C Fiber Optic Borehole Seismic Receiver Array used to Monitor Injection of CO2 into a Reef

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Abstract

Effective storage of CO2 is critically dependent on a precise understanding of the complexity of the geologic formations used for the storage. A successful storage program also depends on an accurate monitoring program to understand the dynamic processes of the injection and the storage of the CO2 in a geologic formation. The complex CO2 storage processes will only be understood and managed in detail if robust high-resolution reservoir imaging and monitoring technologies are available to characterize the reservoirs in the early phases of the storage process.

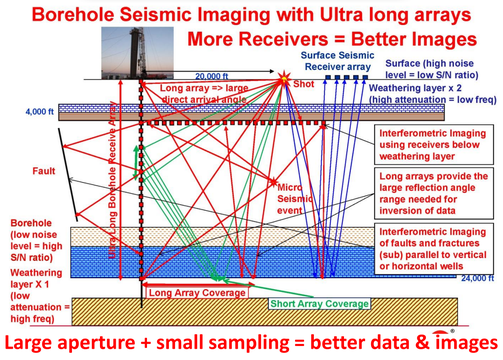
To address the critical site characterization and monitoring needs for CCS programs, US Department of Energy (DOE) awarded Paulsson, Inc. a contract in 2010 to design, build and test an all fiber optic based ultra-large bandwidth clamped borehole vector seismic array capable of deploying a large number of 3C sensor pods suitable for deployment into high temperature and high pressure boreholes. Paulsson, Inc. has completed the design of a borehole seismic system consisting of a novel drill pipe based deployment system that includes a hydraulic clamping mechanism for the fiber optic sensor pods, a new sensor pod design and most important – a unique fiber optic seismic vector sensor with technical specifications and capabilities that exceed the state of the art seismic sensor technologies.

In combination, these technologies will allow for the deployment of up to 1,000 3C sensor pods in vertical, deviated or horizontal wells. Laboratory tests of the fiber optic seismic vector sensors developed during this project have shown that the new borehole seismic sensor technology can generate outstanding high vector fidelity data with extremely large bandwidth: 0.01 – 6,000 Hz. Field tests have shown that the system can record events at magnitudes much smaller than M-3.0 at frequencies over 2,000 Hz. The sensors have also proved to be about 100 times more sensitive at higher frequencies than the regular coil geophones that are used in borehole seismic systems today. The fiber optic seismic sensors have furthermore been qualified to operate at temperatures over 300°C (572°F). The lead-in fibers used for the seismic vector sensors in the system are also used to record Distributed Temperature Sensor (DTS) and Distributed Acoustic Sensor (DAS) data allowing additional value added data to be recorded simultaneously with the seismic vector sensor data.

In 2016 Battelle and Paulsson teamed to perform a monitoring survey of a CO2 injection project in a reef based oil field operated by Core Energy located in Michigan. The ability of the fiber optic borehole seismic system to record and locate small seismic events were confirmed by shooting small 0.5-gram string shots at a distance of over 1,000 ft from the fiber optic sensors. The fiber optic sensors where deployed in the horizontal section of a monitoring well. A large number of small micro seismic events were recorded with magnitudes ranging from M-3.0 to M-5.0. Several events with short duration were recorded but the clear majority of the events recorded were long duration events lasting from 0.5 so 3 seconds. The detailed analysis of these events and the underlying reservoir processes is being investigated.

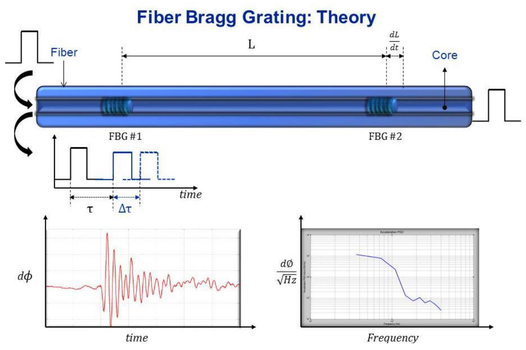
Why Long Arrays

Borehole Seismic Imaging with Ultra long arrays
More Receivers = Better Images

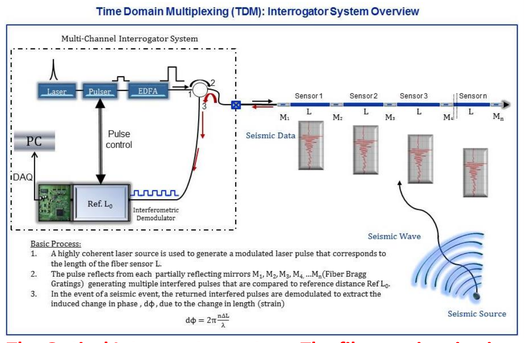


Large aperture + small sampling = better data & images

Fiber Optic Seismic Sensor (FOSS) Technology

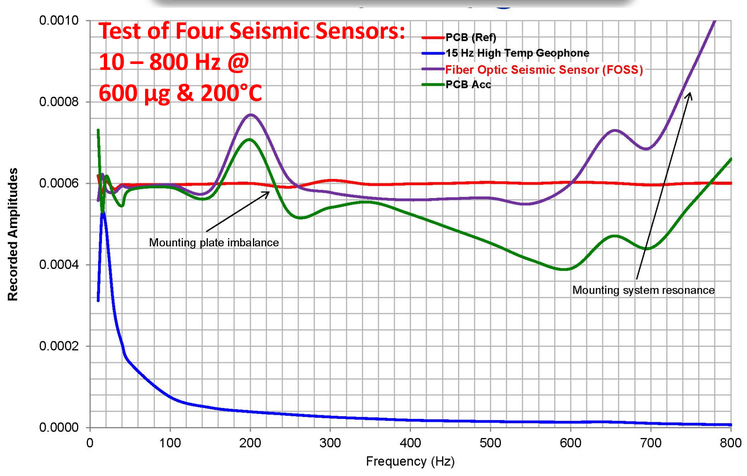


The fiber between a pair of Fiber Bragg Gratings (FBG's) respond to changing pressure, temperature and to seismic waves using interferometric measurements between two FBG's.

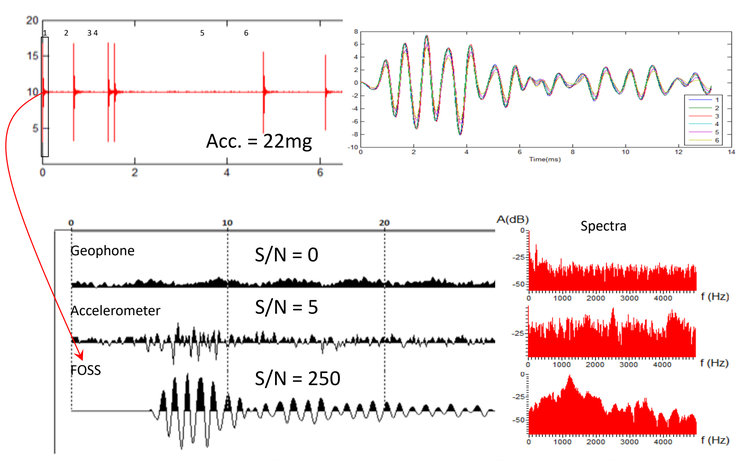


The Optical Interrogator system. The fiber optic seismic sensor system is comprised of three basic integrated building blocks; the fiber optic seismic sensor, the telemetry cable and the Optical Interrogator. The interrogator technology was first developed by US Navy Research Laboratory (USNRL).

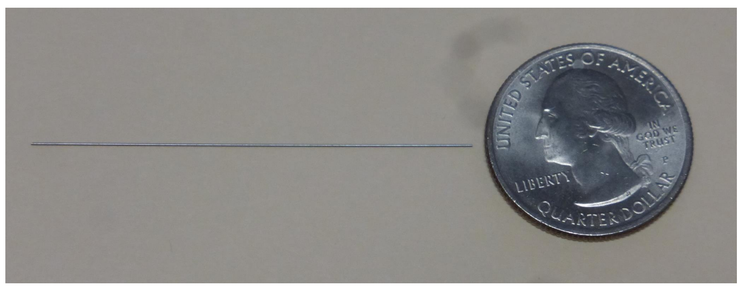
Laboratory and Field Tests



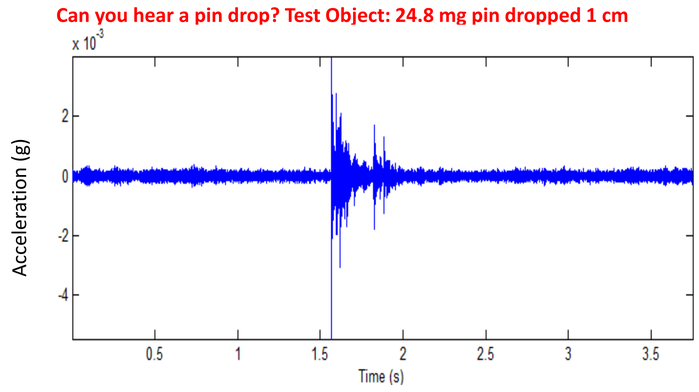
Sweep Data from four sensors: FOSS, 15 Hz Geophone and two Accelerometers



Wave forms and spectra from M-2.9 sensor tap tests on FOSS and a 15 Hz Geophone

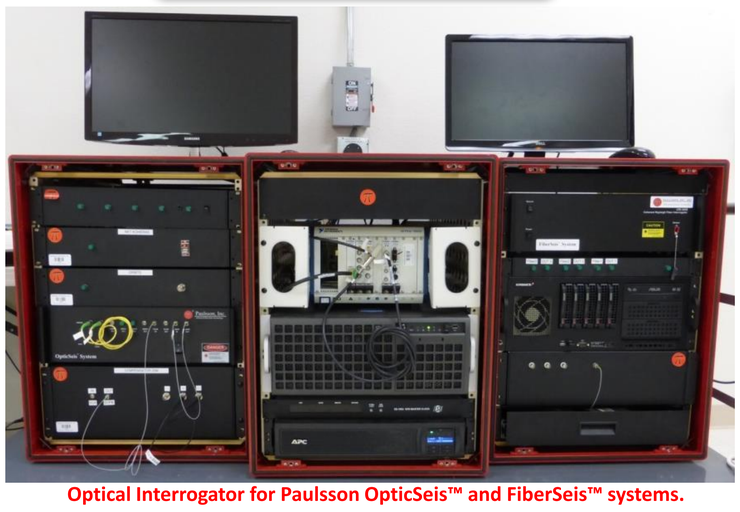


Can you hear a pin drop? Test Object: 24.8 mg pin dropped 1 cm



Waveforms from pin drop test of FOSS sensor. Kinetic energy: 2.5 µJ (<M-7)

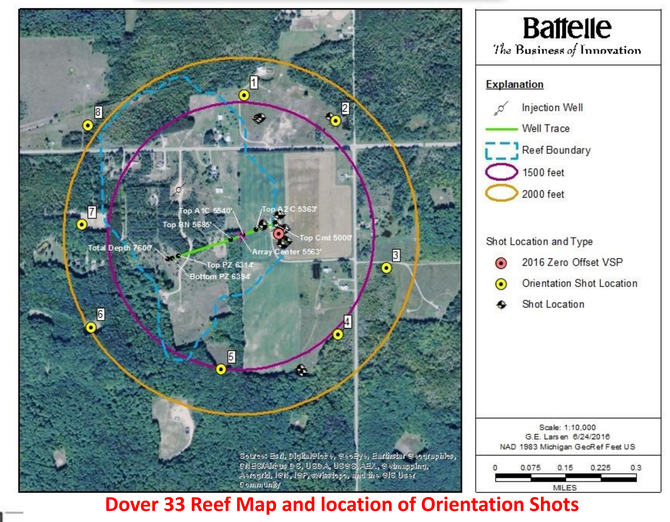
Optical Instrumentation for both lab and field tests



Optical Interrogator for Paulsson OpticSeis™ and FiberSeis™ systems.

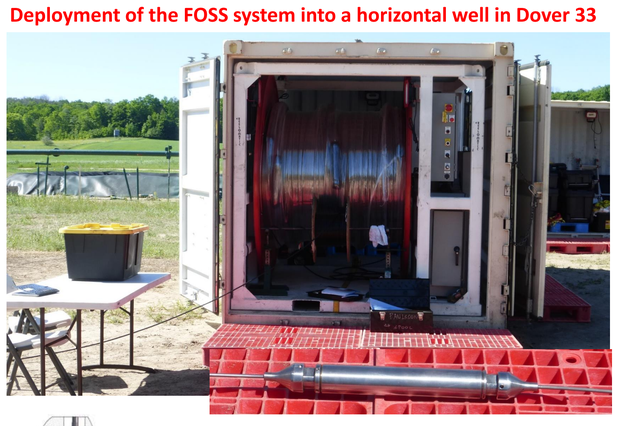
Paulsson CasingSeis® system

Field Survey

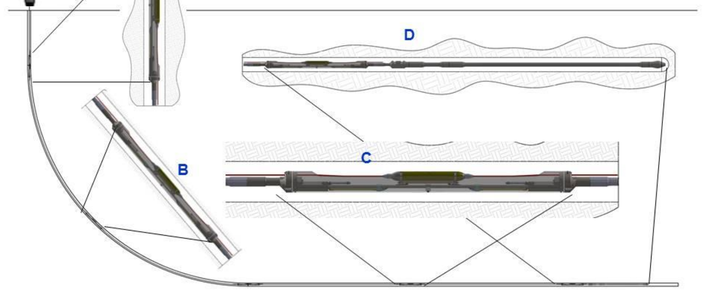


Dover 33 Reef Map and location of Orientation Shots

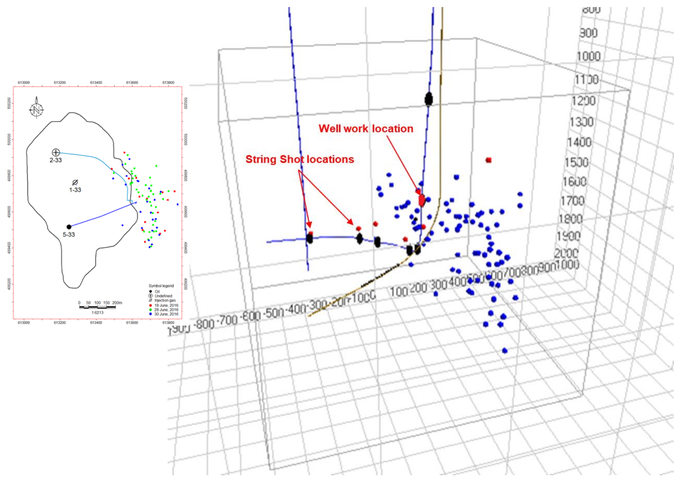
Deployment of the FOSS system into a horizontal well in Dover 33



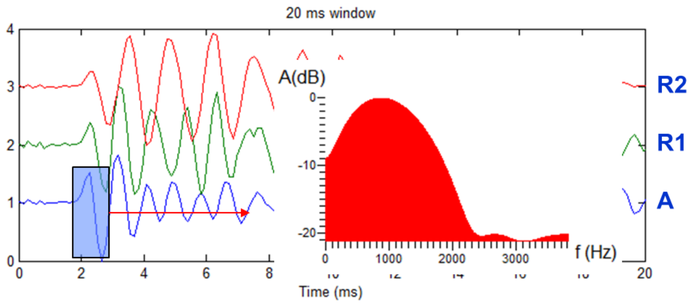
Spool system holding 15,000 ft fiber line with 15 fibers



Deployment of FOSS system into a horizontal well

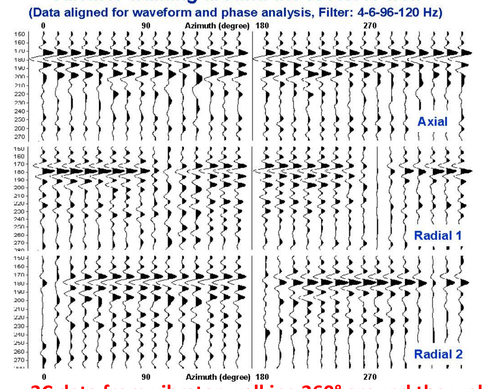


Location of Micro Seismic Data from 0.5 gram TNT caps and well work noise
Using a constant velocity model: Vp=21,325 ft/sec and Vs=11,975 ft/sec

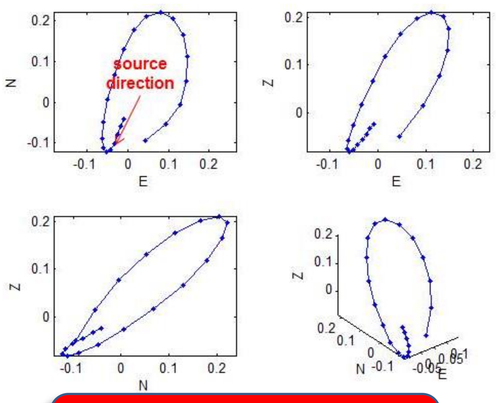


Micro Seismic data recorded on the 3C sensors. Filter 2-4-3000-3800 Hz

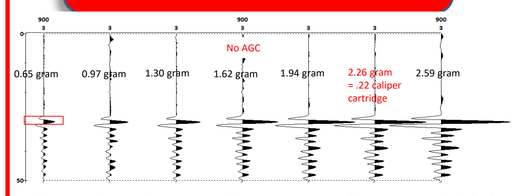
Vector Fidelity



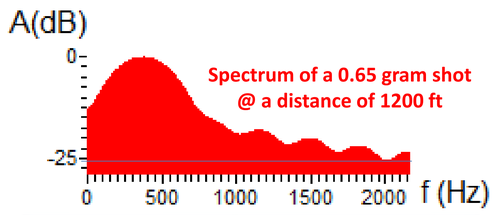
3C data from vibrator walking 360° around the well



Recording Small Events: Much smaller than M-2.6



Recording of seven micro charges. Smallest = M-2.6



Frequency (Hz)	Acceleration (µg)
600	7.3
700	6.7
800	6.2
900	5.8
1,000	5.5
2,000	2.0

Acceleration measured at different frequencies

Summary

- An Ultra-Sensitive, Ultra-Large Bandwidth, High Temperature Fiber Optic Seismic Vector Sensor array has been developed and integrated into a Fiber Optic Borehole Seismic Sensor system capable of operating at 300°C (572°F) and 30,000 psi.
- The OpticSeis® sensors have been successfully tested for one week at 320°C (608°F).
- A deployment system has been developed that is strong enough to deploy a 1,000 level 3C borehole seismic array in vertical and horizontal boreholes to a Measured Depth (MD) of 30,000 ft.
- A 16 level 3C 5 km long Fiber Optic Borehole Seismic Sensor (FOSS)™ array is now operational and a 100 level is under construction.
- Battelle and Paulsson, Inc. was funded by US DOE to perform a large borehole seismic survey at the Dover 33 reef in 2016.
- The Fiber Optic Seismic Vector Sensor technologies presented has allowed the development of a seismic vector sensor that can be mounted in a 3C pod with a OD of 1" (2.54 cm).

Acknowledgments

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