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

August 1-3, 2017
Effective & Accurate Monitoring of UOG
Key Technologies Presented

• Large Seismic Array Technology
  • Key to Record and Track small Seismic Events
• Fiber Optic Seismic Sensors
• Acoustic Micro Emitters
Borehole Seismic Imaging with Ultra long arrays

More Receivers = Better Images

Long array => large direct arrival angle range

Surface Seismic Receiver array

Surface (high noise level = low S/N ratio)

Weathering layer x 2 (high attenuation = low freq)

Interferometric Imaging using receivers below weathering layer

Borehole (low noise level = high S/N ratio)

Weathering layer X 1 (low attenuation = high freq)

Micro Seismic event

Long arrays provide the large reflection angle range needed for inversion of data

Interferometric Imaging of faults and fractures (sub) parallel to vertical or horizontal wells

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Surface Seismic Data
Borehole Seismic Data
Focus:
Develop Better Sensors
and
Deployed The Sensors Below The Noise!
Example From Space Exploration: Images From Same Region in Space

Earth Telescope

Hubble Space Telescope
Borehole Seismology

- Large Seismic Array Technology
- Fiber Optic Seismic Sensors
- Acoustic Micro Emitters
Fiber Bragg Grating: Theory

Fiber Core

FBG #1

FBG #2

\[ \frac{dL}{dt} \]

\[ \tau \]

\[ \Delta \tau \]

\[ d\phi \]

\[ \frac{d\phi}{\sqrt{Hz}} \]

Acceleration PID

Frequency (Hz)

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Laboratory Test of Acoustic Micro Emitters using Fiber Optic Seismic Sensors
AME Test using Fiber Optic Seismic Vector Sensors (FOSVS)

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 FOSVS: Outstanding Repeatability. Allow extraction of arrivals in high noise environments.

Energy ~2J = M-2.9

Acc. = 22mg

S/N = 0
S/N = 5
S/N = 250

Spectra
Can You Hear a Pin Drop?
Test Object: OD: 0.011”, 2” long, 24.8 mg
FOSVS Test: OD: 0.011”, 24.8 mg Pin Drop 1 cm:

2.5 µJ kinetic energy (M-7)
FOSVS Test: OD: 0.011”, 24.8 mg Pin Drop 1 cm:

2.5 µJ kinetic energy (M-7)
Deployment System Development
Clamping system operates by increasing the pressure inside the drill pipe and manifolds and uses the bore hole fluid as a medium.
Field Tests of Fiber Optic Seismic Sensor (FOSVS)™ System
Fiber Optic Seismic Sensor System Deployment
Field Test Data Recorded with Fiber Optic Seismic Sensor (FOSVS)™ System
Shots Recorded by Principle Component @ 1,200 ft (400 m)
(Filter: 80-100-1500-2000 Hz)

No AGC

2.26 gram = .22 caliper cartridge

2,000 Hz @ - 25 dB
Results from Locating String Shots during a survey for Battelle in June 2016
Locating String Shots and Micro Seismic Events – Work in Progress
Recorded 11,000 events in four weeks. Displayed here are 130 events.

Red: String Shots; Blue: Focused Micro Seismic; Green: “Distributed” Events
Sound of A Focused MS in 3C, Survey for Battelle, June 2016

Filter: 80-100-1500-2000 Hz

- Radial 2 Component (R2)
- Radial 1 Component (R1)
- Axial Component (A)
Zoomed-In Focused MS in 3C- Filter: 2-4-3000-3800 Hz

Filter: 2-4-3000-3800 Hz

100 ms window

20 ms window

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A Microseismic Data (Axial) – Magnitude < M-2.9
Borehole Seismology

- Large Seismic Array Technology
- Fiber Optic Seismic Sensors
- Acoustic Micro Emitters
- Joint testing of FOSVS & AME technology
Getting most out of fracture monitoring

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

Answer: Injecting SMART microsystems along with proppant

Typical ceramic proppant 20/40

fluidion smart micro-emitter (prototype stage)

www.fluidion.com
Using smart Acoustic Micro Emitters (AME)

Simple logistics:
1. Injected in well along with proppant
2. Detected using fiber optic sensor array

High added value:
Delayed acoustic emission – high S/N
Guaranteed in-fracture signal
Specific acoustic signature
Various sizes – mapping fracture width

www.fluidion.com
AME Simulation Flow Setup

Dynamic visualization of proppant and AME positioning

www.fluidion.com
Previous work

Lateral fracture view

Fracture proppant transport
Dynamic fracture opening tracking
Multiple-size proppant: wedge angle

4mm
2mm

Top fracture view

Increasing pressure

www.fluidion.com
Borehole Seismology

- Large Seismic Array Technology
- Fiber Optic Seismic Sensors
- Acoustic Micro Emitters
- Joint testing of FOSVS & AME technology
500 psi AME – to FOSVS: Experimental Parameters

1. Receivers
   a. 3C Fiber Optic Seismic Sensor (FOSVS)
   b. Fiber Optic Hydrophone
   c. Optical sampling rate: 152,439.03 Hz
   d. 3C Geophones
   e. Geophone sampling rate: 40,000 Hz

2. Sources: 4 x 4 mm Acoustic Micro Emitters (AME), 500 psi collapse version. Estimated energy 2J.

3. Offset: 20 feet

4. Processing
   a. Filter: 400-500-4000-5000 Hz
500 psi AME to FOSVS Experimental Set Up

Vessel with AME's @ 4 ft

Geophones, Hydrophone, FOSVS @ 4 ft
500 psi AME to FOSVS Experimental Set Up

3C FOSVS Pod

3C Geophone Pod

Optical Hydrophone

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Small Pressure Vessel used for the AME’s AME’s collapse at 500 psi
Note:
Coherent Pre arrival Energy from An external acoustic Source
500 psi AME to FOSVS - 20 ft Offset - Filtered Data - Zoom In

Filter: 400-500-4000-5000 Hz

Note:
Coherent Pre arrival Energy from An external acoustic Source

Fiber Optic Hydrophone
FOSVS Y
FOSVS X
FOSVS Z
4,000 and 8,000 psi AMEs Test Summary

- **Date:** Dec. 9, 2016
- **Location:** Pool
- **Source-Receiver Distance:** 20 ft
- **Receivers:**
  - **Optical:** FOSVS and optical Hydrophone
    - Sampling rate: 152,439.03 Hz
  - **Electrical:** Geophone and Hydrophone
    - **Geophone:** Omni-2400
    - **Hydrophone:** Aquarian Scientific AS-1
    - Sampling rate: 40,000 Hz
- **Sources:**
  - **AME, 4,000 psi and 8,000 psi**
Test 1: Two AMEs at 4,000 & 8,000 psi

Trace normalized display

Optical Sensor Data

Filter: 5-10-18,000-20,000 Hz

Hydrophone
Z Component
X Component
Y Component

Time (s)

5.03 5.04 5.05 5.06 5.07 5.08 5.09 5.1 5.11 5.12

5

Time (s)

8.12 8.13 8.14 8.15 8.16 8.17 8.18 8.19 8.2 8.21 8.22

8

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Observations

1. From the same AME the Fiber Optic Seismic Vector Sensors (FOSVS) generate much higher signal to noise (S/N) ratio than the electronic geophones.

2. The Fiber Optic Hydrophone (FOH) generate much higher S/N ratio than the electronic geophones.

3. A second test using 4,000 and 8,000 psi AME’s generated much higher S/N than the 500 psi AME’s
Other Projects and Applications where the FOSVS and AME Combination Can be Applied
FORGE Applications

- Inject AME’s into EGS fractures
- Use FOSVS to monitor the location of the AME’s to map the fractures to improve productivity through guided drilling
The West Flank FORGE Site

Maps from FORGE Phase 1 West Flank of Coso, CA

The Paulsson FOSVS system deployed into well 83-11 on March 12-21, 2017
An Earthquake 3.4 Miles Away M1.9

3C Rotated

PT: 2017-03-15 23:19:47

Filter: 5-10-200-300 Hz

Primary Shear Wave R T

P is the primary energy direction; R is the radial minimum energy direction; T is the transverse direction
Time Lapse Data Monitoring of CO2 injection for Enhanced Oil Recovery in 2002 - 2003
Time lapse surveys to monitor CO2 Injection
Depth Amplitude Maps at 4,800 ft showing the CO2 Plume

Simultaneous imaging and monitoring possible using FOSVS and AME in combination.

Increased reflectivity in the Monitor Survey 2003 at a depth of 4,800 ft at the well is due to the injected CO2. Also seen is the increased reflectivity around the water injector wells.
Borehole Seismology

- Large Seismic Array Technology
- Acoustic Micro Emitters
- Fiber Optic Seismic Sensors
- Field Testing & Calibration
- Offshore Applications
Devine Test Objectives

• Perform a test at a known field laboratory

• Calibrate and document the FOSVS ability to record data from the AME under controlled conditions
Devine Test Site Map

- Profile length = 2120 ft
- Receiver stations only
- Station interval = 110 ft

- Profile length = 2630 ft
- Receiver station interval = 110 ft
- Source station interval = 55 ft
- 4, 2, 9 = Test well

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DEVINE TEST SITE WELL DESCRIPTIONS

Well head
- Well 2, ID = 5.75 in
- Well 4, ID = 6.00 in
- Well 9, ID = 5.75 in

Ground Level

Casing = 10.75 in
Hole = 14.25 in
Surface casing -592 ft

Cement

Casing
- Well 2, 6.625 in, fiberglass, hole = 9.875 in
- Well 4, 6.625 in, fiberglass, hole = 9.875 in
- Well 9, 6.625 in, steel, hole = 9.875 in

Total depth = 3000 ft
Geology Profile @ the Devine test site
Geophone VSP vs Well Log Vs Geology

Pelton 8 – 128 Hz linear sweep
MaxiWave 24-level 50 ft spacing tool
Synthetic VSP vs Well Log Vs Geology

25 ft geophone spacing

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Effective & Accurate Monitoring of UOG
Borehole Seismology

• Large Seismic Array Technology
• Acoustic Micro Emitters
• Fiber Optic Seismic Sensors
• Field Testing & Calibration
• Offshore Applications – stay tuned
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
- 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 CO2 vs Steam
- Map fluid flow and fluid boundaries
- Map permeability in reservoirs
- Temperature distribution
- With AME’s - Monitor Hydro Fracturing (Fracking) Operations including mapping the location of the proppant – game changer
- Much better understanding of the dynamic processes of producing and injecting liquids and gases
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