COMPARISON OF FIBER OPTIC MONITORING WITH CONVENTIONAL GEOPHONE SYSTEM AT AQUISTORE

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ACKNOWLEDGMENTS

Thanks to:
U.S. Dept. Of Energy
National Energy Technology Laboratory
GEO-SEQ Project
Petroleum Technology Research Council
Geologic Survey of Canada
Silixa, LLC
Chevron

Funding for LBNL was provided by the U.S. Department of Energy, Assistant Secretary for Fossil Energy, Office of Clean Coal and Carbon Management through the National Energy Technology Laboratory under contract No. DE-AC02-05CH11231.

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OUTLINE

• Aquistore Background and Data Acquisition

• Distributed Acoustic Sensing (DAS)
  • DAS on fiber cable:
    • How iDAS works
    • Improvement in S/N for iDAS
  • Compare Single Mode and Multi Mode Cables
  • Compare DAS and Geophones
  • Compare Explosive and Vibroseis DAS
  • DAS VSP Processing Flow and Migration

Near the Aquistore Site
Aquistore CCS project – CO2 from Power Plant
Targeted sedimentary injection zones:
Winnipeg and Deadwood formations (~3200 m depth, 150 m thick) in the Williston Basin.

Injection well: 3396m TVD
Observation well: 3400m TVD
Spacing: ~150 m
Aquistore Observation Well: Fiber Behind Casing

- Poor cement likely between ~900 - 1600 m
- 60-level MaxiWave 1470 to 2355 m
- 15m spacing + telemetry pod
- Staging collar 2068 m
- 1x SM and 2x MM fibers broken at ~2867 m

Casing Deployment Of Fiber Optic Lines

3.7" ID casing

Source: www.aquistore.ca
DAS Recording ‘Piggyback’ on 3D Surface and VSP Recording

Field operations

- Doghouse 1 (main ops): GPS, encoder
- Doghouse 2 (wireline): GPS, slave encoder
- Doghouse 3 (fiber): GPS, +5V TTL pulse

Radio: bnc cable

Images with logos of Tesla, Geospace Technologies, Schlumberger, Carbon Services, Suecoel, and Silixa.
NOVEMBER 2013 ACQUISITION

• **Sources:**
  - 682 dynamite shots,
    - 1 kg at 15 m depth
  - 2 vibroseis
    - M18 Mertz 44,000 lbs force run at 70%
  - 54 VP’s

• **Recorders:**
  - GSR-1 surface recorders,
    - continuous mode, not triggered
  - Sercel WaveLab recorder
  - Silixa SM and MM iDAS recorders

• **Sensors:**
  - 630 surface Vert. geophones
    - 20m depth in 3 x 3 km array
  - 54 live 3C geophones
    - 1470 – 2355 m depth
  - 1x Single mode (SM) fiber
    - outside OBS well casing to 2867 m
  - 2x Multi-mode (MM) fiber
    - outside OBS well casing to 2867
PERMANENT SURFACE SEISMIC SENSORS (GREEN); EXPLOSIVE SHOT HOLES (BLUE); VIBROSEIS TEST LINE

Injection and Observation Wells Spacing ~150 m
WHAT IS iDAS? HOW DOES IT WORK?

- iDAS is Silixa Ltd DAS interrogator
- Light pulses are sent into a standard optical fibre
- Backscattered optical signal is analysed to continuously monitor local changes in optical reflectivity resulting from local dynamic strain of the fibre over a ‘gauge length’ ~ 10 m
- Output stream is converted to seismic records that are effectively continuous in both distance and time
  - Typically 1 - 2 m and 1-10 kHz
What is measured by the iDAS?

Fibre elongation at location $z$ and time $t$, $u(z,t)$, is measured over a reference distance $dz$.

Time difference $(t, t + dt)$ of elongation spatial difference $(dz)$:

$$
\left[u\left(z + \frac{dz}{2}, t + dt\right) - u\left(z - \frac{dz}{2}, t + dt\right)\right] - \left[u\left(z + \frac{dz}{2}, t\right) - u\left(z - \frac{dz}{2}, t\right)\right]
$$

Answer: fibre strain rate.
IDAS – HOW TO GET GEOPHONE-EQUIVALENT OUTPUT

• The native Silixa iDAS output is strain rate
• The industry standard is the geophone, which measures local (particle) velocity.
• We can transforms the native iDAS output into strain and then into a geophone-equivalent output of velocity.

\[ \text{Fiber particle displacement: } u(z,t) = u(\varphi) \]

Where \( \varphi = (t_0 + t \pm z/c) \) is any event (phase function) with propagation speed \( c \) along the fiber axis (apparent velocity).

The fiber particle velocity, \( v = \frac{\partial u}{\partial t} = \frac{\partial u}{\partial \varphi} \),

And fiber strain
\[ \varepsilon = \frac{\partial u}{\partial z} = \pm \frac{1}{c} \frac{\partial u}{\partial \varphi} , \]

Therefore,
\[ \varepsilon = \pm \frac{v}{c} \]
**NOISE REDUCTION AND SPECTRAL REBALANCE**

**Noise Reduction:**
- The statistics of the scattering processes influence the noise on the resultant acoustic signal.
- Advanced adaptive stacking algorithms allow the stacking to become far more efficient, giving SNR improvements in excess of one order of magnitude.

**Adaptive Rebalance:**
- The native iDAS output is strain rate along the sensing fibre.
- Noise-adaptive rebalancing combines optimally weighted averaging with rebalancing of the temporal spectrum which, to good approximation, gives strain
- Result: **axial strain**
  - not the native strain-rate
The Aquistore Observation well has both single-mode and multi-mode fiber in the same cable cemented behind casing.

Previously, DAS required single-mode fibers.

Most existing fibres are used for Distributed Temperature sensing (DTS) and are multi-mode (MM).

*This field trial showed that Silixa’s iDAS performs well with either type.*
S/N MULTI MODE VS SINGLE MODE

• RMS Signal/Noise
• Signal = P-wave (30 ms)
• Noise pre arrival (30 ms)

• Each point is one shot (symbol is source line)
Comparison: DAS and Vertical Geophone
Subset of Depths in Each Plot
DAS VS VERTICAL GEOPHONE (ALL DEPTHS)

DAS

DAS and Geophones
Geophone (red) and DAS: Single 15 m Channel
Noise Constant as Signal Decreases

Single Gain applied to match signal levels
COMPARISON OF DAS/GEOPHONE P-WAVE ARRIVAL TIMES

Fiber vs Geophone Arrival times

\[ y = 1.008x - 8.0074 \]

\[ R^2 = 0.99595 \]
GEOPHONE-DAS RATIO: SNR VS ANGLE

Geophone (V)/Fiber SNR vs Inclination Angle (measure from vertical)

Inclination (from Vertical)

Geophone (Vertical)/Fiber SNR

1509-1536 m
DAS 2D Walkaway: Dynamite vs Vibroseis Comparison

- Started with denoised data as recently delivered
- Processed Walkaway & comparable Dynamite lines using chain specified in contract
- Sensors 350 - 2510 m
- Generally good quality – some differences due to geometry differences
DAS 3D VSP Imaging: Migration Test

- 512 Dynamite Sources
- 71 SM receiver channels from good cement zone (650-930m @4m)
- TIV anisotropic model fits picked times
- 2D GRT migration of shot gathers + 3D merge of images
SUMMARY/CONCLUSIONS

• A DAS VSP test was conducted as part of CO2 storage monitoring work
  • ‘Piggyback’ on 3D surface baseline recording
• Fiber cable cemented behind casing gives good quality and repeatable response
• **Both Multi Mode and Single Mode Fibers give good quality DAS data**
  • Many multi mode fibers deployed for temperature sensing can be used for VSP
• **Understanding DAS response allows direct conversion to particle velocity**
  • Good agreement with clamped geophones
  • Consider using strain to avoid use of apparent velocity value
• Migrated DAS 3D-VSP image has good quality
  • Can be used for time-lapse monitoring
• DAS appears to be a good cost/benefit match for CO2 monitoring
  • R&D tests include: Otway, Ketzin, Citronelle, Quest
Questions!