Continuous Seismic Monitoring of CO2 injection projects

Biondo Biondi
with contributions by Ariel Lellouch, William L. Ellsworth, and Siyuan Yuan

Stanford Exploration Project
Geophysics Department
Stanford University
Periodic active seismic monitoring

4D surface seismic
Sleipner (Norway)

4D DAS-VSP
South West Hub (Australia)
Periodic active seismic monitoring

4D surface seismic & 4D DAS-VSP
Aquistore (Canada)
Continuous active seismic monitoring

4D DAS-VSP with Surface Orbital Vibrator (SOV) sources
Otway (Australia)
Continuous **passive** seismic monitoring

Induced seismicity monitoring by arrays of seismometers

Decatur (CCS)  Wellington & Farnsworth (EOR)
Continuous passive seismic monitoring by a DAS Node
Continuous **passive** and **active** seismic monitoring by a DAS Node

DAS Node
Continuous **passive** and **active** seismic monitoring by a DAS Net

DAS Node

DAS Net
Ideal continuous **passive** seismic monitoring systems

• Cost-effective long-term operations
  • Low-maintenance
  • Durability of field equipment
  • Reliable and high-bandwidth data telemetry of recorded waveforms
  • Stable coupling with the ground

• Requirements for induced seismicity monitoring
  • Detection of weak events
  • Accurate source location
  • Reliable magnitude estimation
  • Source mechanism characterization?
Pros and cons of DAS for permanent seismic monitoring

+ Cost per “virtual” receiver
+ Receiver density => Exploit moveouts => Back propagate wavefields
+ Possibility of placing receivers in otherwise inaccessible locations
+ Power and connectivity needed by interrogators but not by receivers
+ Receiver durability and resilience in harsh environments
- Receiver sensitivity is lower than geophones and highly directional
Sensitivity of seismometer vs. vertical DAS

Sensitivity to body waves recorded in vertical borehole

1) incidence angle
2) wavelength

-P waves
-SV waves

Eileen Martin’s Ph.D. thesis - May 2018
Sensitivity of seismometer vs. horizontal DAS

Sensitivity to body waves emerging at $45^\circ$ as a function of:

1) azimuth angle
2) wavelength
   - P waves
   - SH waves
   - SV waves

Eileen Martin’s Ph.D. thesis - May 2018
SAFOD fiber array
In place for ~13 years before acquisition

Richard et al, 2013

About 20 days of recording, June-July 2017
Three local quakes recorded by SAFOD DAS

Vertical incidence
M=2.5, Distance = 11.7(km)

15 Degrees
M = 0.61, Distance = 5.3(km)

37 Degrees
M = 1.36, Distance = 5.4(km)
P arrivals from same three local quakes
Estimated P velocities from DAS

• Good agreement between picking and slant-stacks
Estimated P velocities from DAS & VSP

- Good agreement between picking and slant-stacks
- Matches check-shot processing
- Geological structure
Estimated P velocities from DAS, VSP & Interferometry

- Good agreement between picking and slant-stacks
- Matches check-shot processing
- Geological structure
Estimated P velocities from DAS, VSP, Interferometry & surface seismic

- Good agreement between picking and slant-stacks
- Matches check-shot processing
- Geological structure
Estimated S velocities from DAS

- Good agreement between picking and slant-stacks
- Matches check-shot processing
- Geological structure
- S follows same structure
Estimated P/S velocity ratio from DAS

- Good agreement between picking and slant-stacks
- Matches check-shot processing
- Geological structure
- S follows same structure
- “Normal” $V_P/V_S$
Incidence-angle estimation: input data
Incidence-angle estimation: angle scans
Event-detection results
Uncatalogued event similar to a catalogued one
Uncatalogued event similar to a catalogued one

- Low signal-to-noise
- Visible P and S phases
- Short P-S difference => close event (5-7km)
- M< -.5
- Definitely it is an earthquake
P-waves arrivals – DAS vs. Broadband Z-comp

Ladera EQ M 1.8

DAS data vs. Broadband Z-comp

Distance 3.8 km
Depth 3.6 km
7:50 pm
P-waves arrivals – DAS vs. Broadband N-comp

Ladera EQ M 1.8

DAS data vs. Broadband N-comp

Distance 3.8 km
Depth 3.6 km
7:50 pm
Detection of weak EQs not detected by conventional seismometers networks

Detected precursor

Mag ≈ 0.1
May 10\textsuperscript{th}, 2017

Main E.Q. in USGS catalogue

Mag 1.35
July 12\textsuperscript{th}, 2017

Detected aftershock

Mag ≈ -0.1
July 13\textsuperscript{th}, 2017

Distance 4.0 km
Depth 3.2 km
Modeling azimuthal resolution of DAS Nodes

- Fiber length: 17 km
- Event depth: 2 km
- Event distance from well: 0.5 km
- Arc length resolution: 10 m (source depth and distance from well assumed known)
- Data frequency: 50 Hz
- DAS sensitivity threshold (receivers below that value are discarded): 40%
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Current Developments of DAS technology

• New generation of interrogator improve sensitivity by 10-20 db
• Shorter gauge length
• Engineered cables for:
  • Improved sensitivity
  • “Omnidirectional” sensitivity
  • “Discrete” or “distributed” multi-component sensors
• Wireline systems have been successfully tested in unconventional deviated wells; they provide flexibility for temporary and/or unplanned deployments.
Conclusions

• DAS Nodes can be cost-effective for long-term continuous monitoring of:
  • CO2 plumes by active seismic imaging (4D VSP + surface-to-surface)
  • Induced seismic events (detection, localization and magnitude estimation)
• As CO2 plume grows, DAS Nodes can be added as needed to make a modular DAS Net.
• Active seismic monitoring by DAS in vertical boreholes is becoming a standard, but passive monitoring of CO2 injection by a DAS Node has not been tested yet. Any interest in a pilot project?
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