Optical Monitoring Technology (HS-VOS) for Deep CO_2 Injection

Task 4, Core Carbon Storage and Monitoring Research (CCSMR) Project, FWP-ESD14095

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National Energy Technology Laboratory

2021 Carbon Management and Oil and Gas Research Project Review Meeting

August 2021

Outline

- Technical Status
  - HS-VOS sensor array
  - Deep Borehole Field Test
  - Preliminary Results
- Lessons Learned and Next Steps
- Summary

Project Goal: Demonstration of high-sensitivity wide-bandwidth hybrid acoustic monitoring technology for deployment in a deep CO_2 reservoir well for the purpose of **monitoring induced seismicity at or near basement depth**.

Technical Status

- Currently testing 3-level high sensitivity vector optical sensor (HS-VOS)
  - On hybrid wireline cable (4x copper and 18x single-mode fiber)
  - Electronics: 9-laser interrogator/demodulator recording system, w/GPS
  - Passive optical sensing, no power downhole, for up to ~3.5 km depth / 150 ºC

- Collaborating with Avalon Sciences, UK
  - Deployed HS-VOS array at Avalon's Rosemanowes test facility, 2 km depth
  - Comparing HS-VOS array performance to Avalon's Geochain system
    - » Active sources: Vibroseis, airgun
    - » Passive sources: Natural seismicity, ambient noise
    - » Local quarry shots, sledgehammer at surface

ASL Avalon Sciences Ltd

Deep Borehole Optical Sensing

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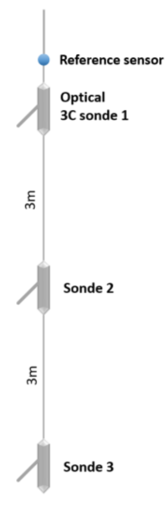
- Frequency range 3 – 600 Hz
- Sample rate 0.25 ms

- 3C vector optical accelerometers
- Wide bandwidth, high sensitivity
- Deployed on hybrid optical cable

- Operating temperatures to 150 C
- Operating depths to 3.5 km

High-Sensitivity Vector Optical Sensor (HS-VOS)

- Tight 3m sonde spacing for field testing phase
  - Compare individual optical sensor performance
- Reference optical sensor above top sonde (decoupled)
  - Test optical de-noising techniques to improve SNR
- Loop-back of fiber in wireline cable
  - Incorporate hybrid DAS / vector optical data acquisition
- Passive locking-arms for initial field test
  - Test Avalon's passive one-shot spring system



- Higher sensitivity allows data on smaller seismic events, gaining another **order of magnitude of range**, and possibly **higher resolution** for fracture creation events
- Best result for the deep HS-VOS array testing would be a wide-bandwidth response with a low noise floor and the capability to detect smaller magnitude induced seismicity events

Rosemanowes Test Site (UK)

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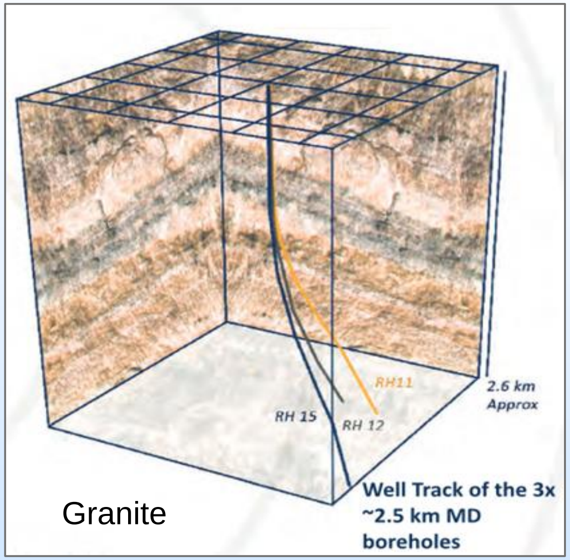
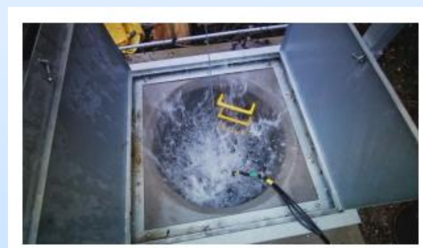
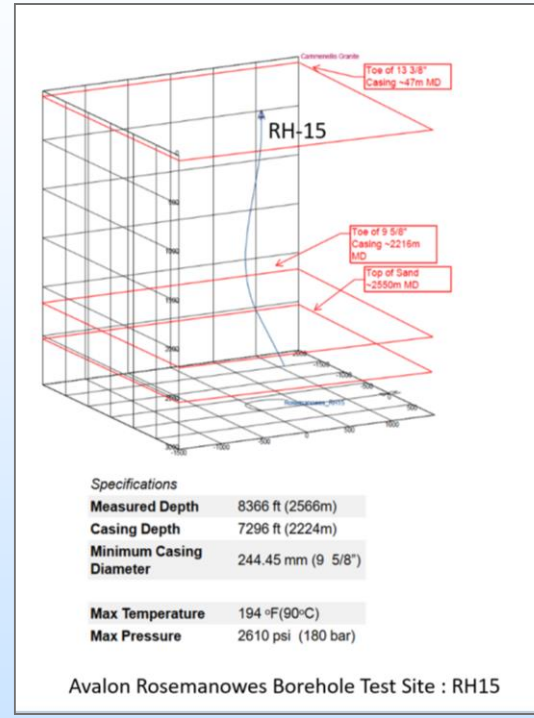


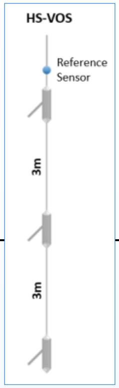
- 20,000 lb vibroseis trucks
- Surface airgun
- Nearby quarry shots





- 2.2 km cased borehole for HS-VOS array testing (RH15)
- Second 2 km borehole with Geochain array installed at 1km (RH12)

- Hybrid wireline on winch (fiber and copper)
- Control room for active-source monitoring and data acquisition
- Avalon's optical engineering team for remote deployment due to COVID-19 restrictions



Field Test Parameters

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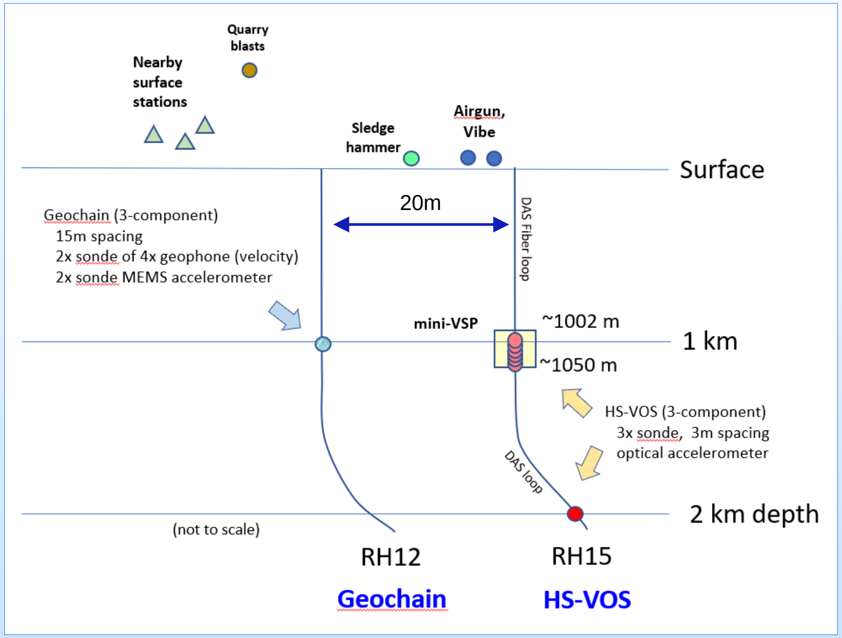


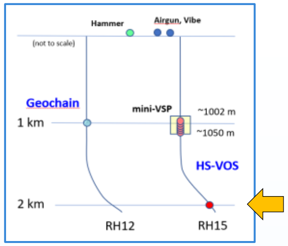
Passive Source Acquisition (Continuous mode)

-- Natural seismicity, ambient noise / sledgehammer tests

- HS-VOS array in RH15
  - 3 optical 3C sondes at 3m spacing, locked
    - 2km depth, inclined borehole ~ 30º
    - 1km depth, vertical borehole
- Geochain array in RH12, at static 1km depth
  - 4 sondes at 15m spacing, all 3C, locked
    - 2x geophone sondes (quad OMNI-2400)
    - 2x MEMS accelerometer sondes
- Fiber loop in hybrid wireline cable (4 km loop)
  - Febus DAS interrogator

Active Source Acquisition (Triggered): HS-VOS in RH15 and Geochain in RH12

- HS-VOS at 2km: Vibroseis, Airgun sources
- HS-VOS at 1km: Mini-VSP with vibroseis between 1050 – 1002 m depth.



Sledgehammer Tests

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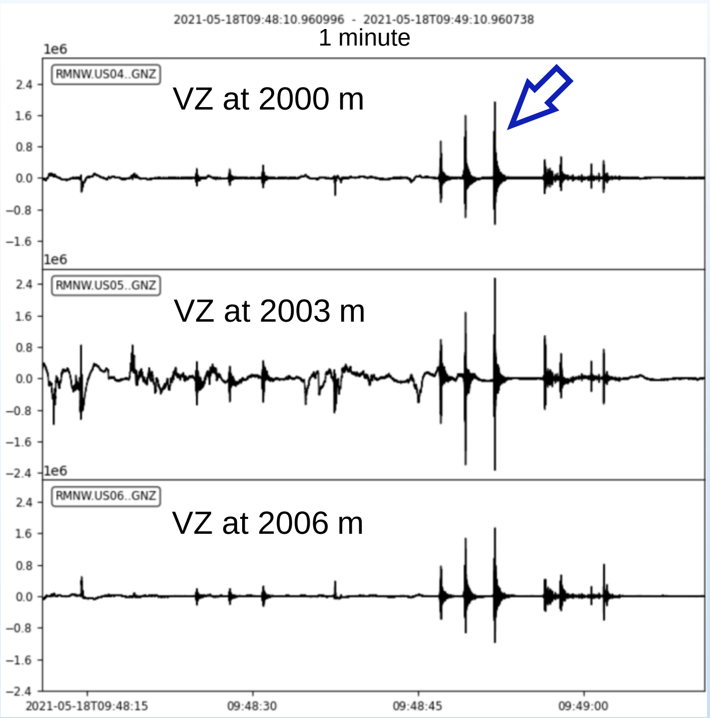
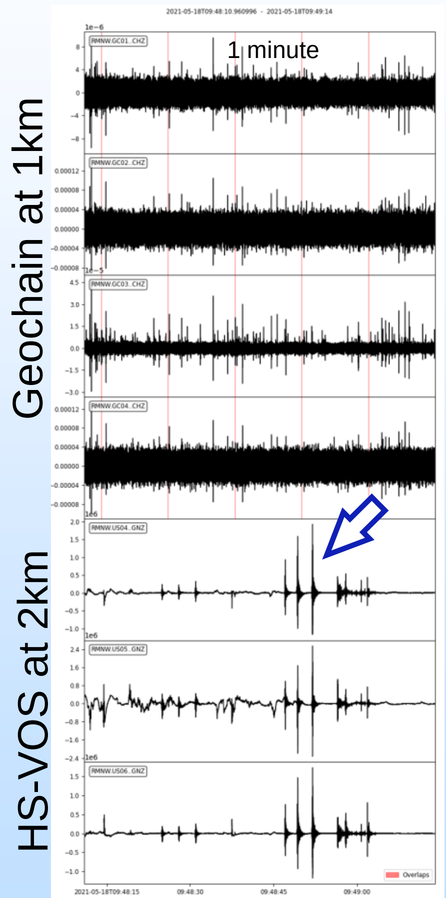
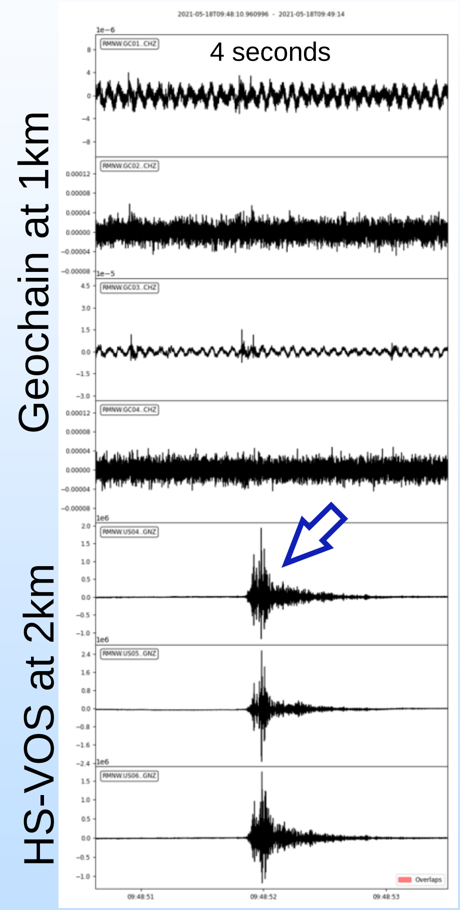
(raw data, no filtering, verticals only)

HS-VOS at 2km,
after array is at rest for >12 hrs







Geochain
4x OMNI
1000 m

Geochain
1x MEMS
1015 m

Geochain
4x OMNI
1030 m

Geochain
1x MEMS
1045 m

HS-VOS
2000 m

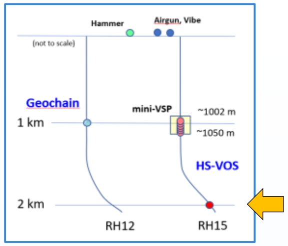
HS-VOS
2003 m

HS-VOS
2006 m

Blue arrow = same hammershot

Geochain: 15m spacing, at 1km in RH12
HS-VOS: 3m spacing, at 2km in RH15

Field test completed at end of Q3-FY21



Airgun Initial Results

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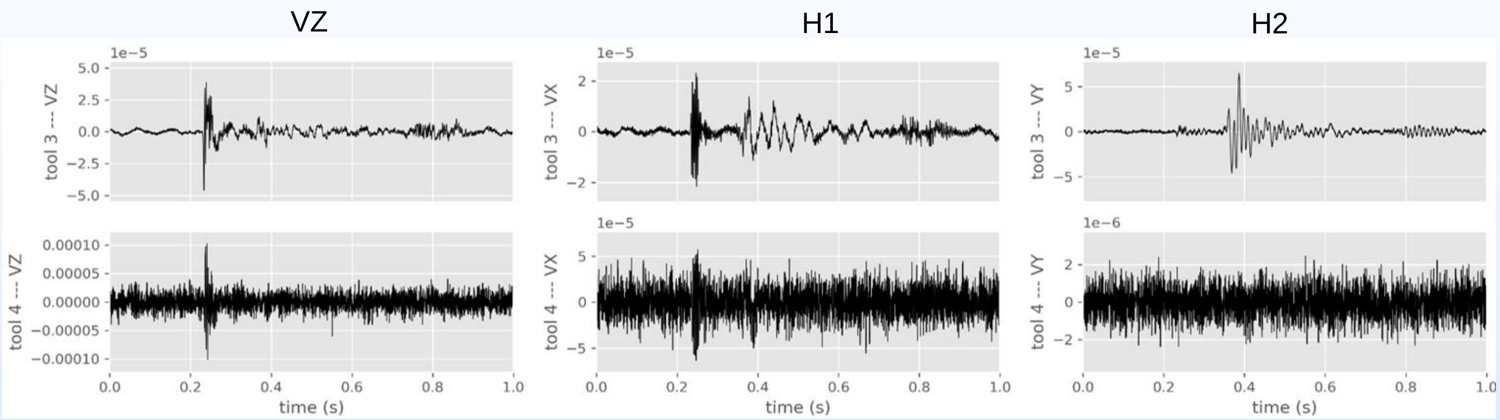
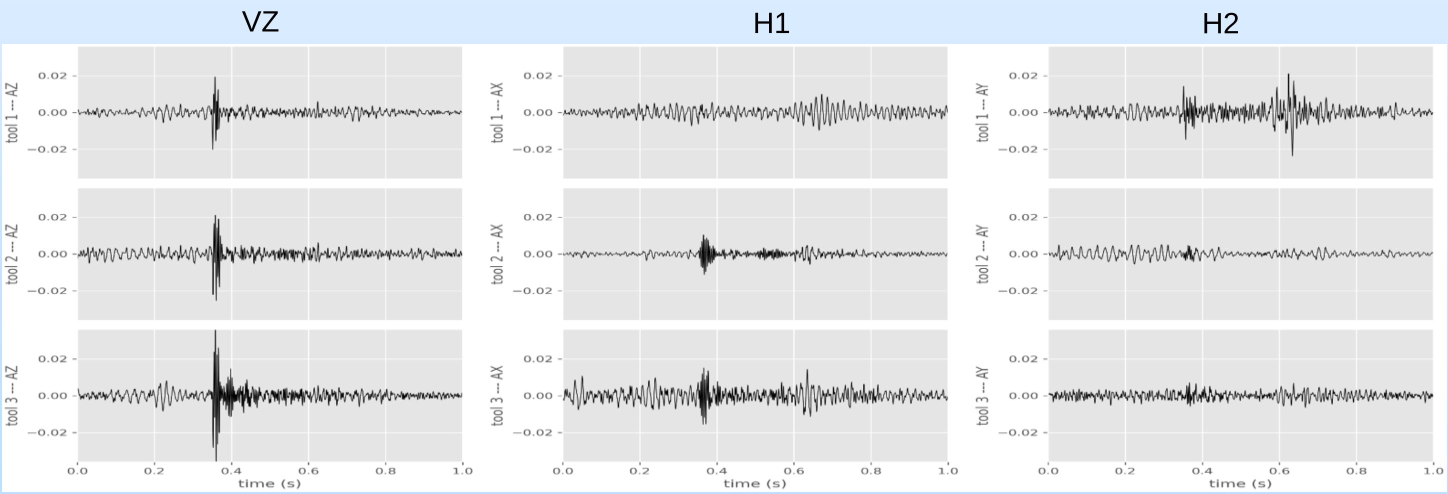
- Geochain in vertical RH12 (1km), HS-VOS in inclined RH15 (2km), single shot



1030 m
4x OMNI in series

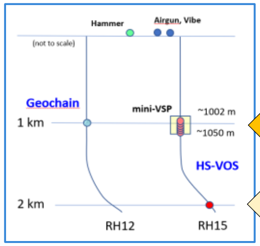
1045 m
1x MEMS



2000 m
HS-VOS Sonde 1

2003 m
HS-VOS Sonde 2

2006 m
HS-VOS Sonde 3



Mini-VSP: HS-VOS

VSP Preliminary Results

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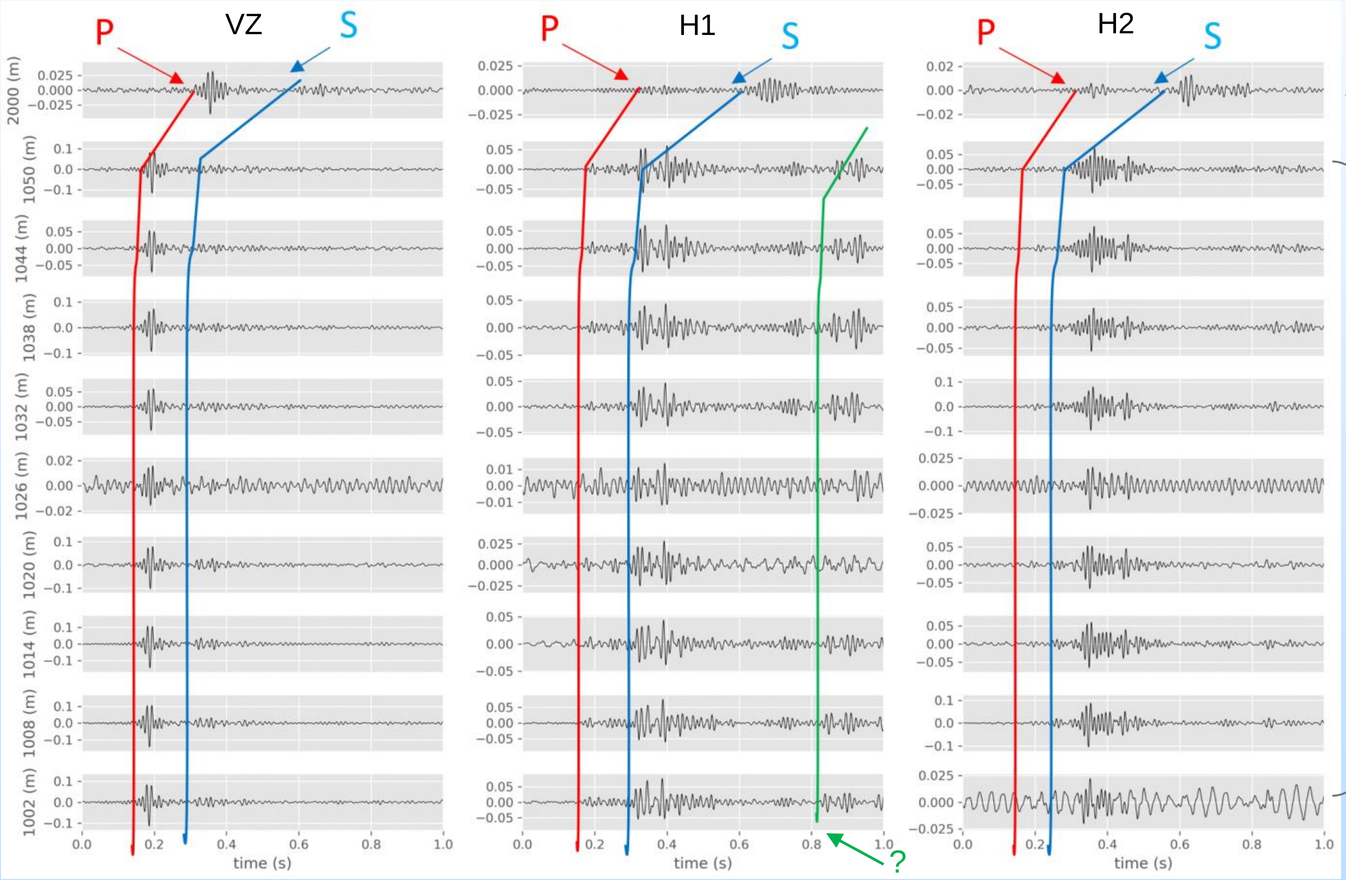
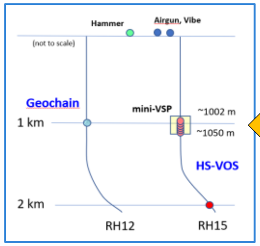
- HS-VOS vibroseis data, top sonde only, correlated with pilot signal, normalized
- 16 second linear sweep, 10 -100 Hz, 0.5s tapers, 4 second listen



- Array at 2km, inclined at ~30 degrees

(Showing top sonde only)

- Mini-VSP, nine move-ups with 6m overlap between moves, RH15, 1050-1002m



Single-level: HS-VOS

VSP Preliminary Results

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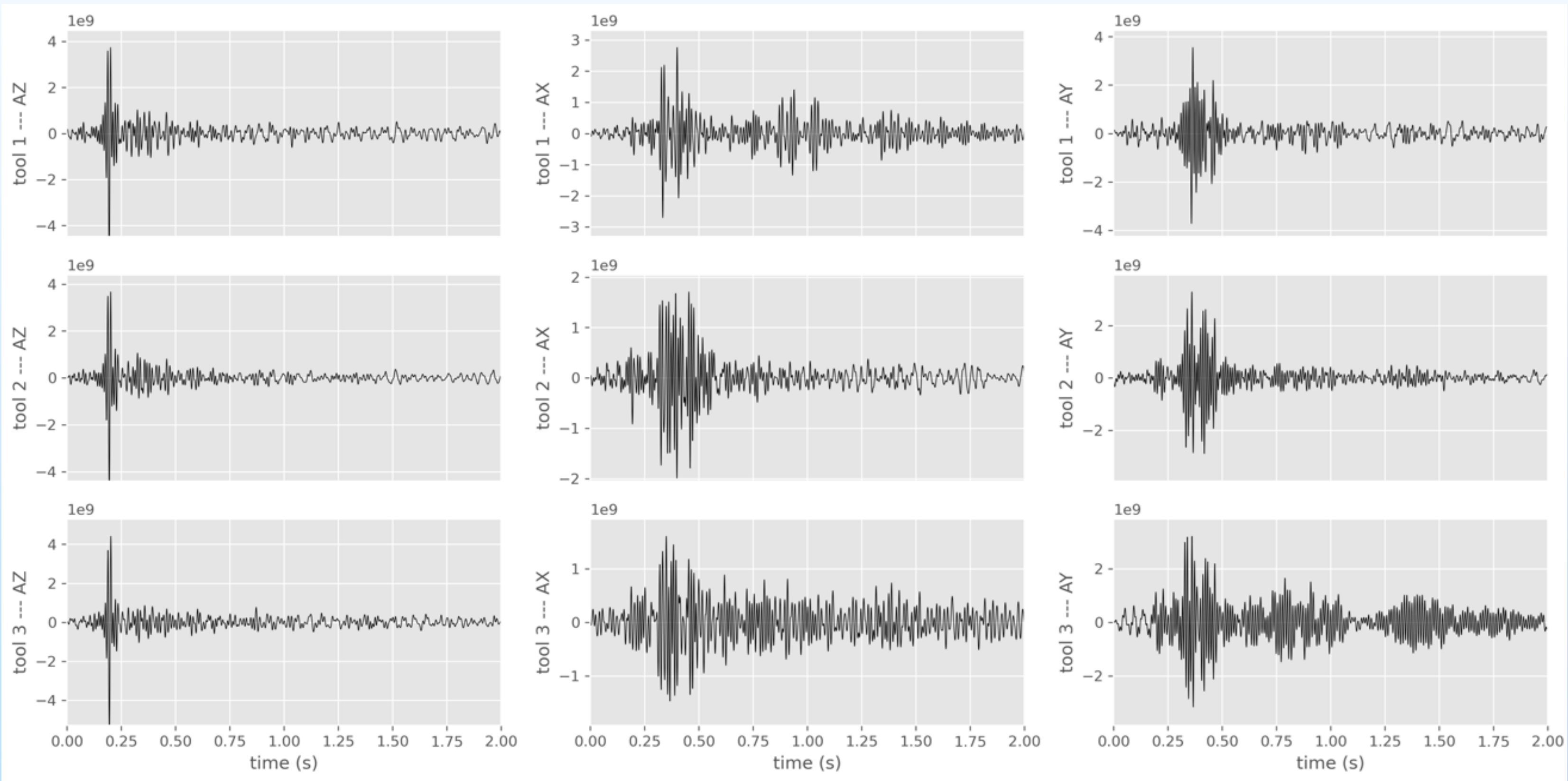
- HS-VOS vibroseis data, correlated with pilot signal, normalized
- Stack of 10 sweeps, 3x 3C sondes, with top sonde at 1050 m

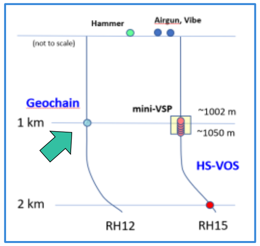
VZ H1 H2



Sonde 1
1050m

Sonde 2
1053m

Sonde 3
1056m



Geochain

VSP Preliminary Results

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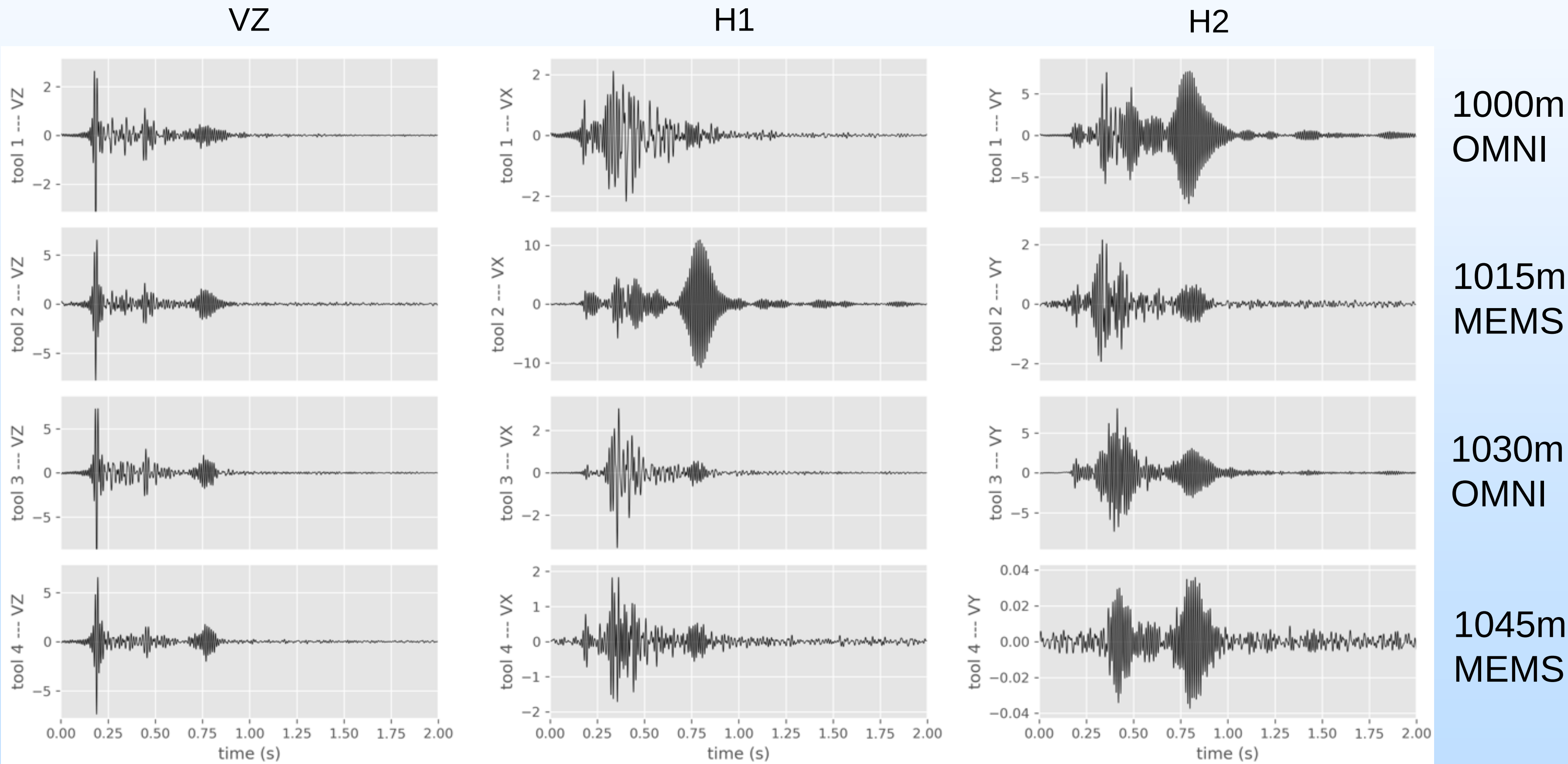
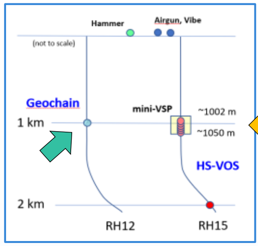
- Avalon Geochain vibroseis data, correlated with pilot signal, normalized
- Stack of 10 sweeps: 4 sondes, 3C, 15 m spacing between sondes, in RH12





Cross-comparison of initial plots

VSP Preliminary Results

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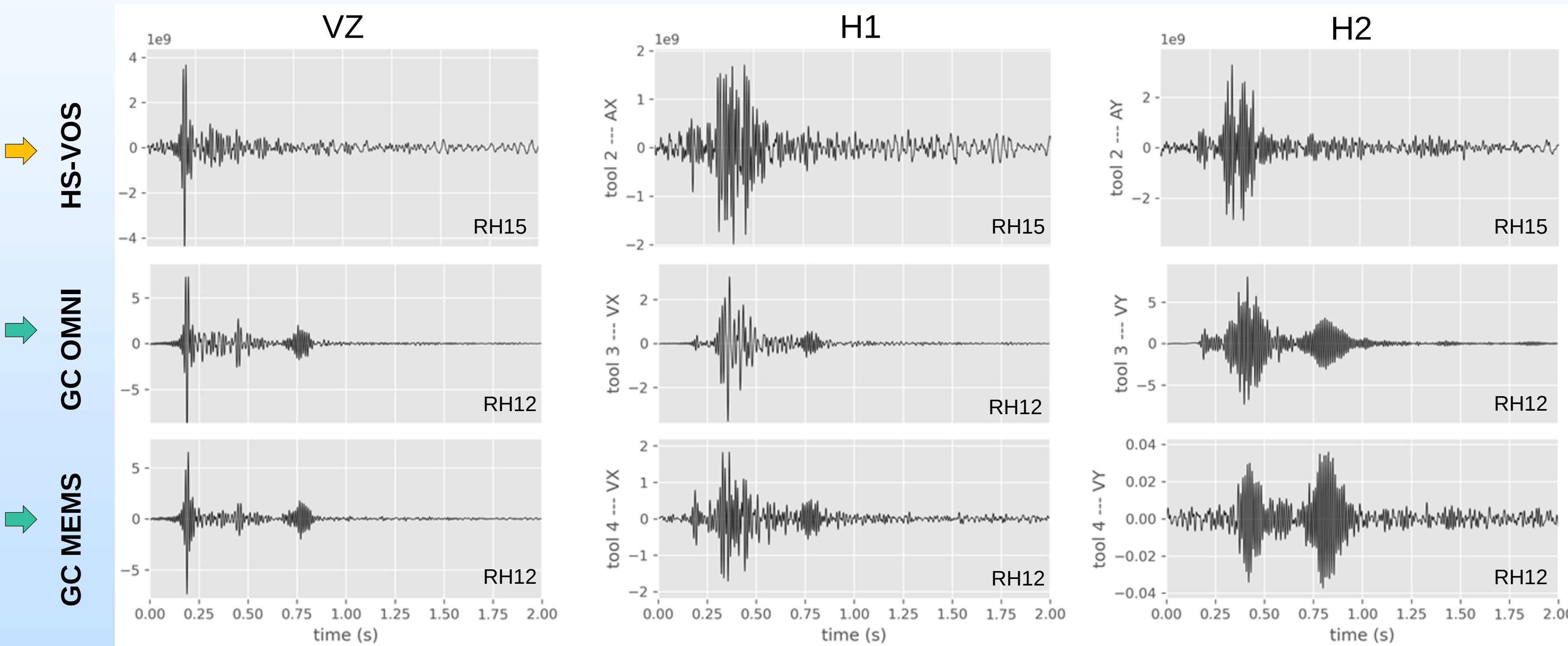
- Comparison of HS-VOS (top sonde), Geochain OMNI, Geochain MEMS sensors
- Stack of 10 sweeps, bandpass 20-100 Hz, normalized.



HS-VOS = USSI optical accelerometer
OMNI = OYO-Geospace OMNI-2400 geophone, quad package (4x geophones in series per component)
MEMS= Colibrys SiFlex capacitive accelerometer

Accomplishments to Date

– Adapted 3-level HS-VOS array for deep deployment
  - Added 9-channel reference sensor to test denoising techniques
  - Added fiber loop-back for DAS recording from surface to 1st sonde
  - Incorporated standalone passive locking arm system

– Performed field test of HS-VOS system
  - Successfully deployed at 2km depth with short VSP at ~ 1km
  - Successfully recorded active source and passive seismic data
  - Recorded in tandem with Geochain and Febus-DAS systems

– Evaluated the preliminary data from the field test
  - Full data processing and analysis of field test data are underway

Next Steps FY21-22

Geosciences Measurement Facility
LBNL

- Evaluate the HS-VOS performance from field test data
  - Active and passive sources; noise
- Compare HS-VOS performance to baseline technology
  - 3C Geophones and MEMS in adjacent borehole
- Investigate optical denoising techniques
  - Downhole HS-VOS reference sensor
- Analyze DAS data from 4km wireline loop
  - Active/passive sources; template matching

- Perform a second HS-VOS field-laboratory test, applying lessons learned and systems improvements from the first field test.

Lessons Learned

After our first preliminary look at the borehole test data:

- HS-VOS performed well at 2 km depth
  - Low noise floor
  - Good sensitivity at 2 km as compared to conventional sensors at 1 km depth
  - Avalon's passive locking arm system proved sufficient for testing
    - Good for single-level monitoring
    - ➢ Will need to modify the locking arm design for easier VSP deployments

- HS-VOS noisier during mini-VSP as compared to passive-source data
  - Good data set for testing our denoising techniques using the reference sensor
    - Remove cable noise from the sensor signal; compare against Geochain
    - ➢ Optical system is sensitive to cable noise in the well and at surface

- Need more automation for setting system parameters during setup
  - To enable easier field operations via remote; less hands-on

Synergy Opportunities

- Carbon storage and monitoring projects
  - Monitor induced seismicity at basement depth
  - Integrate HS-VOS sensing with the other CCSMR techniques for plume monitoring
    - 2nd Generation SOV-DAS
    - Joint EM and Seismic
- Fracture monitoring research at smaller field scales
  - Microearthquake and strain monitoring applying the hybrid vector-optical / DAS array approach
- Induced seismicity monitoring for Geothermal operators
  - 200 ºC optical sondes are being developed for the same system and are interchangeable.

Summary

- We have successfully completed the field test of the HS-VOS array in a 2 km deep borehole.
- Processing and analysis of the active and passive field test data are underway for the HS-VOS, Geochain, Febus-DAS, and local seismic data
- Results from initial HS-VOS data processing show low noise, high sensitivity with the array locked in at 2km, significantly higher SNR as compared to standard sensors installed at 1km (smaller events visible).
- We are developing denoising techniques using the decoupled reference sensor – important for the noisier injection environments where borehole conditions are not ideal.
- We are developing hybrid optical monitoring techniques using vector (HS-VOS) and distributed acoustic sensing (DAS) – e.g. template matching

Appendix

Benefit to the Program

- Program goals being addressed:
  - Develop and validate technologies to ensure 99 percent storage permanence.
  - Develop technologies to improve reservoir storage efficiency while ensuring containment effectiveness

- Project benefits:
  - Deployment and testing of new monitoring technologies and methodologies at an operational CCS site following a successful field test.
  - Broader learnings from leveraged international research opportunities
  - Rapid transfer of knowledge to domestic programs

Project Overview

Goals and Objectives

- This task of the Core Carbon Storage and Monitoring Research Project (CCSMR) aims to **advance emergent monitoring and field operations technologies** that can be used in commercial carbon storage projects. This effort aligns with program goals of:
  - Improving estimates of storage capacity and efficiency
  - Developing new monitoring tools and technologies to achieve 99% storage confirmation

- Success criteria is if we are able to **advance the technology readiness level (TRL)** of targeted technologies from a level of TRL 2 – 3 up to 3 – 4 through leveraged field testing opportunities.

Organization Chart

- **Lawrence Berkeley National Laboratory:**
  - Task PI, Field Lead: Michelle Robertson
  - Research Scientists: Stanislav Glubokovskikh, Chet Hopp, Julia Correa, Verónica Rodríguez Tribaldos
  - Optical Engineer: David Winslow
  - Software Systems: Sung Choi
  - Engineering Design: LBNL's Geosciences Measurement Facility (GMF)

Collaborating with:

- **Avalon Sciences, UK**
  - Optical engineers: Peter Royds, Sam Berry

Gantt Chart

	FY21				FY22				
	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	
1) Project Management									
2) HS-VOS first field laboratory test at Rosemanowes site UK			**M**						Completed Q3-FY21
3) Initial results of HS-VOS Rosemanowes field test data					**M**				
4) Analysis and evaluation of HS-VOS performance							**M**		
Active and passive sources									
Comparison with baseline technology (e.g. Geochain)									
Evaluate denoising techniques using reference sensor									
5) Second HS-VOS field-laboratory test								**M**	
Apply systems improvements from first test									

M = Milestone

Bibliography

Currently in the instrument development and testing stages, with substantial delays in 2020-2021 due to COVID-19 restrictions.

No Journal publications yet for this subtask.