CCSMR Task 4:

Resilient high-sensitivity seismometers - optical monitoring technology for deep CO_2 injections

FWP-ESD14095

Stanislav Glubokovskikh, Michelle Robertson, Chet Hopp, Todd Wood, Dave Winslow

Lawrence Berkeley National Laboratory

U.S. Department of Energy

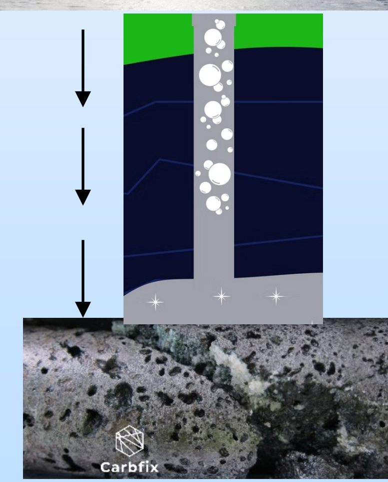
National Energy Technology Laboratory
2022 Carbon Management Project Review Meeting
August 2022

Why Optical Seismometers?

sensitivity + longevity + coupling with DAS

High-Sensitivity Vector Optical Sensor (HS-VOS)

- Passive optical sensing, no power downhole, for up to ~3.5km depth / 150C
- Broader bandwidth borehole sensors (100 sec to 1 kHz) with up to 10 × sensitivity of current conventional sensor arrays
- Hybrid DAS/3C sensing arrays = benefits of continuous dense sensors with high-fidelity data
- Ideal for sparse permanent acquisition systems



https://www.carbfix.com/protecting-our-climate-by-turning-co2-into-stone

Technical Status:
preparing to an extensive field survey

- 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 ~3.5km depth / 150C

- Collaborating with ISGS to conduct an advance borehole seismic characterization at a CarbonSAFE Phase III project site using HS-VOS:
  - 3D VSP using vibroseis trucks + passive recording
  - Testing of the μ-VSP in shallow wells
  - Field deployment of the HS-VOS in shallow boreholes to tune in the acquisition parameters

- Due to issues with optical logging equipment, the data from the HS-VOS deployment at the Rosemanowes test was of insufficient quality for benchmarking:
  - Active seismic source data (airgun and vibroseis) comparable with a baseline technology
  - Passive seismic data corrupted by noise
  - 12-day passive recording in a workshop
  - A thorough performance analysis using a mechanical seismic source

Using HS-VOS for a CarbonSAFE-III:

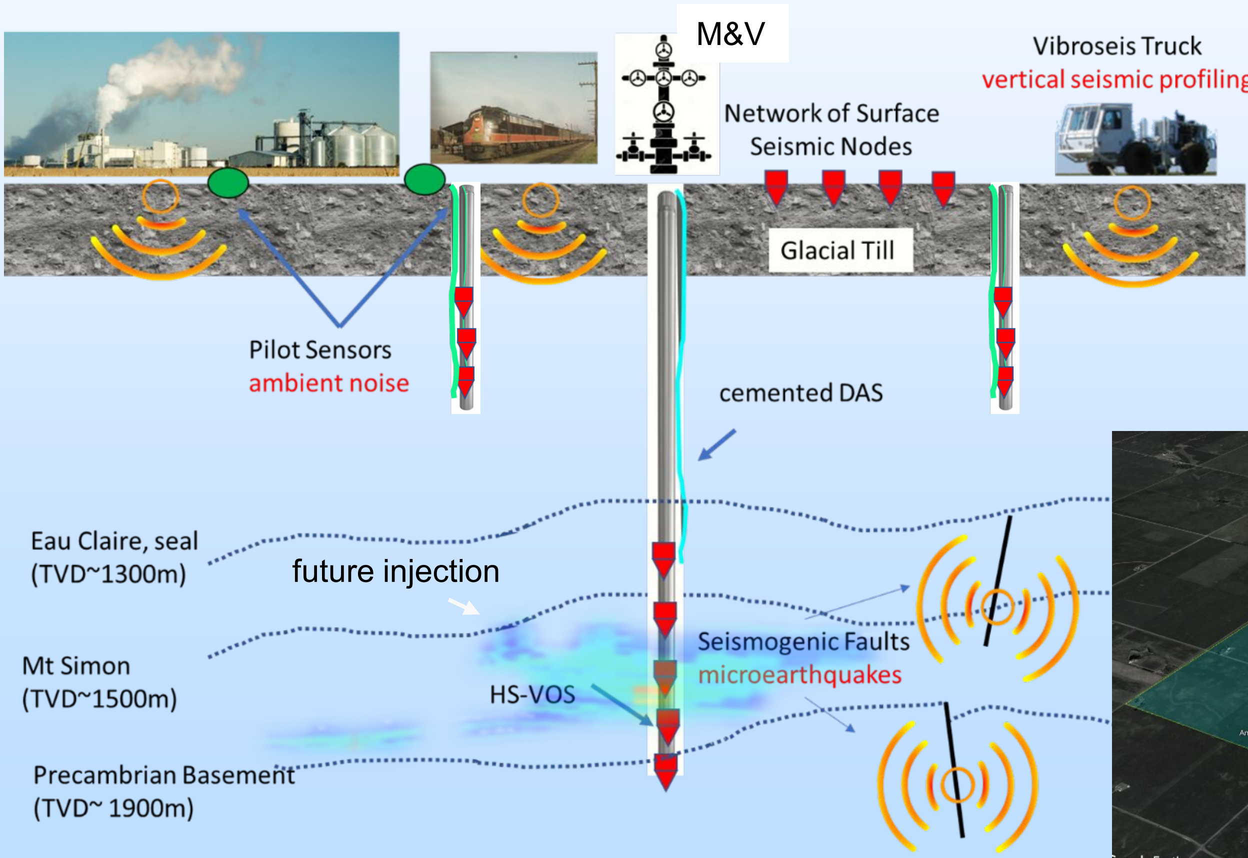
Collaboration with ISGS at the Illinois Storage Corridor

CCSMR Project
Task 4: HS-VOS

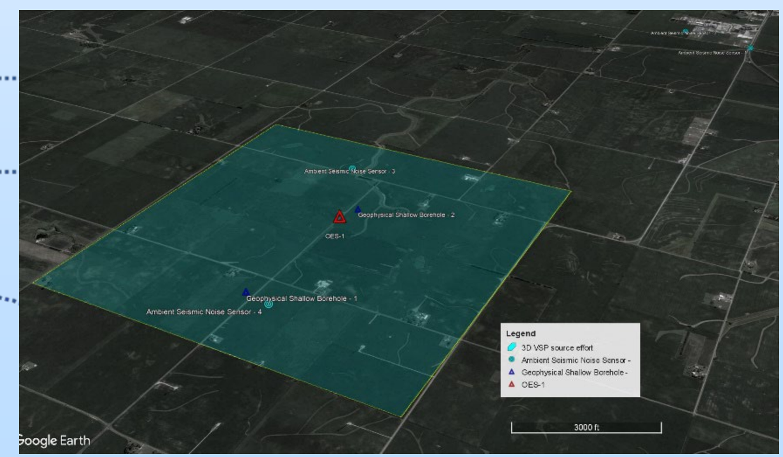
1. 3D VSP for reservoir characterization + optimization of the 4D seismic
2. Passive recording for natural seismicity and ambient noise
3. Development of high-repeatability μ-VSP in shallow boreholes

Illinois State
Geological Survey

MicroSeismic Inc



One Earth Energy site (IL)



Field deployment of HS-VOS:

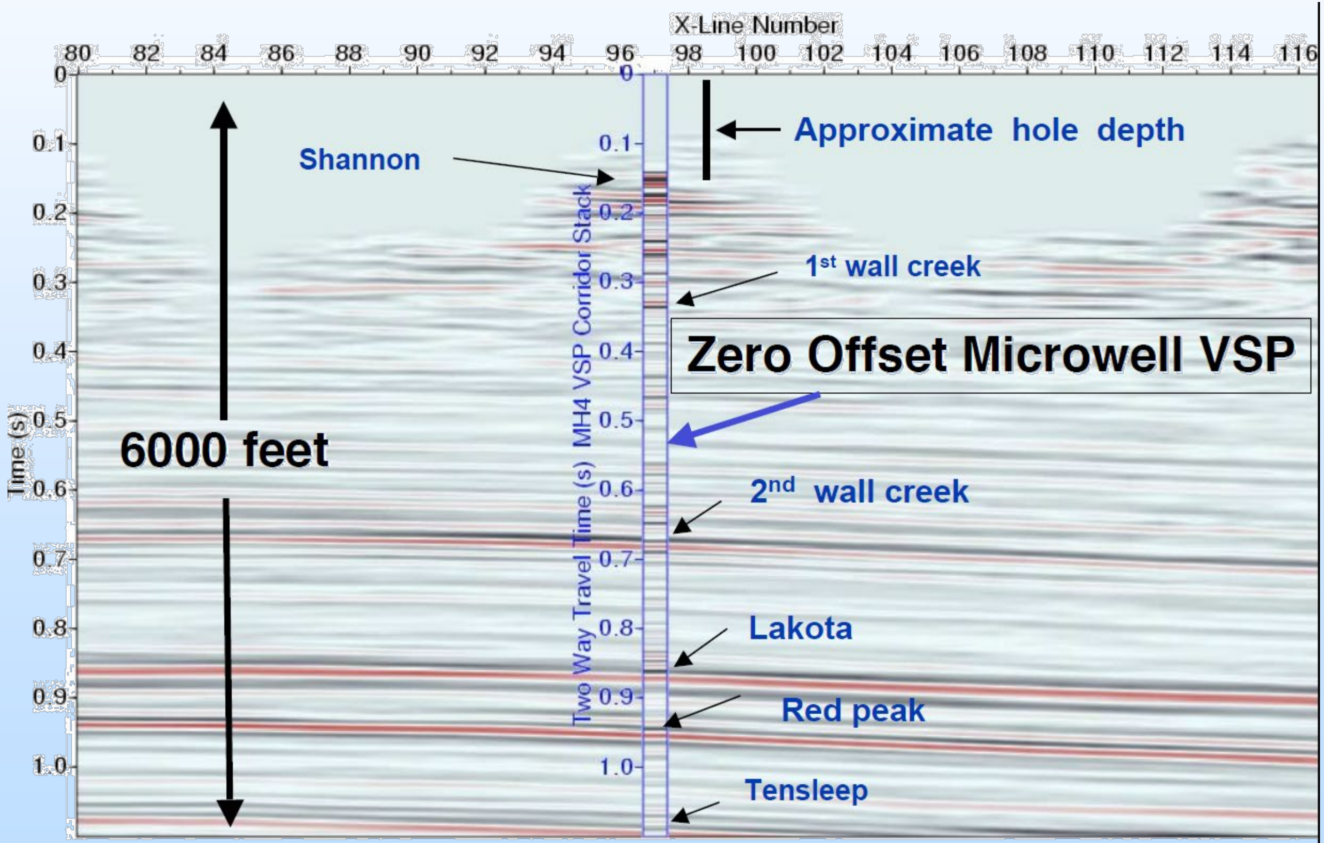
Development of high-repeatability μ-VSP in shallow boreholes

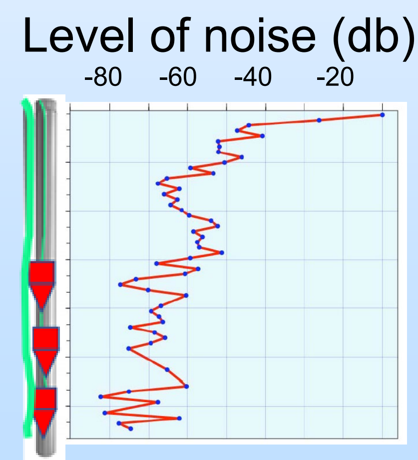
CCSMR Project
Task 4: HS-VOS

Development of high-repeatability μ-VSP in shallow boreholes

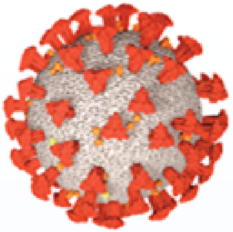
Illinois State Geological Survey

MicroSeismic Inc





Majer, Daley et al. 2008

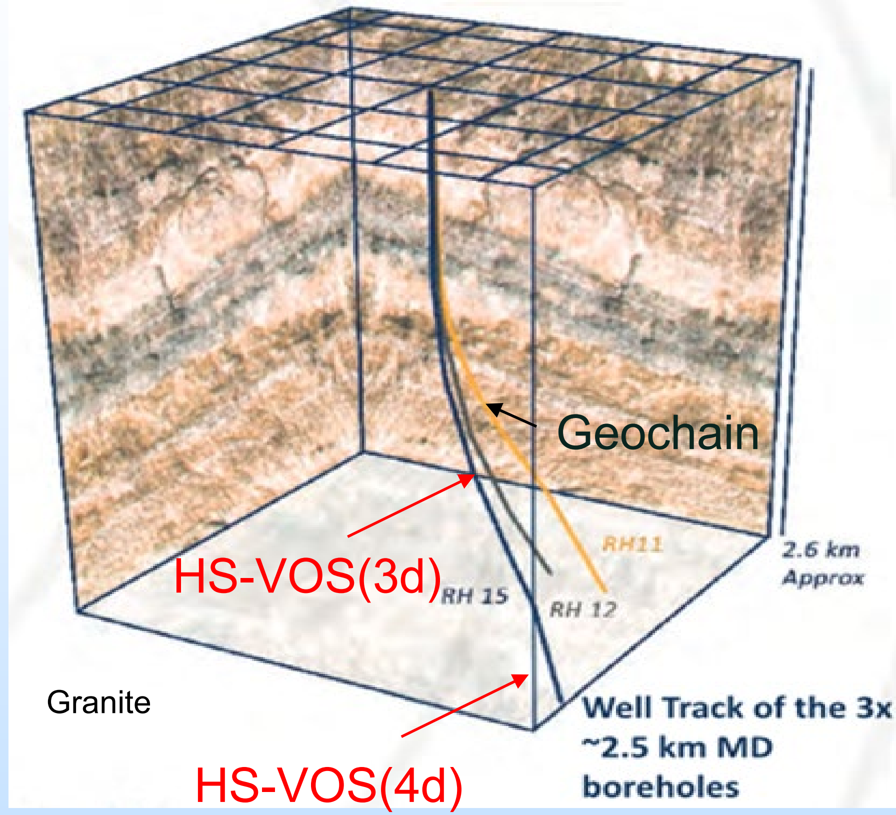


Rosemanowes Test Site (UK): operated by Avalon Sciences team

CCSMR Project
Task 4: HS-VOS

Vibes

Airgun pit



A1. 2km cased borehole for sensor testing (RH15)
A2. Second borehole with Geochain array installed at 1km (RH12)

B1. Hybrid wireline on winch (fiber and copper)
B2. 20 klbs vibroseis/airgun/hammer/EQs

Configuration of the HS-VOS:

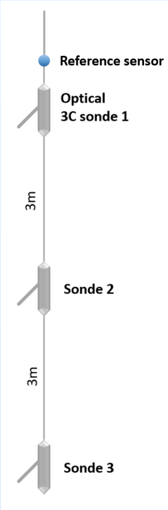
High-Sensitivity Vector Optical Sensor (HS-VOS)

- Tight 3m sonde spacing for initial field testing
  - 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
  - Avalon's passive one-shot spring system

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

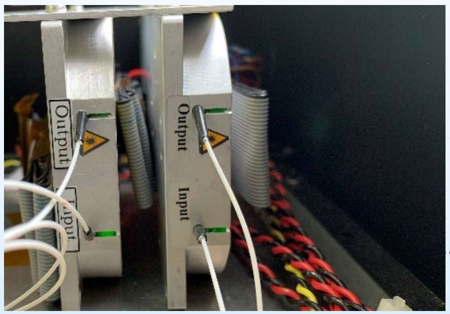
- 3C vector optical accelerometers
- Wide bandwidth, high sensitivity
- Deployed on hybrid optical cable

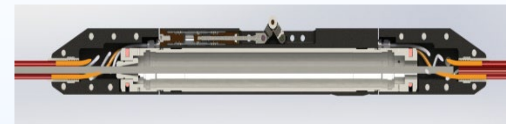
- Operating temperatures to 150 C
- Operating depths to 3.5 km



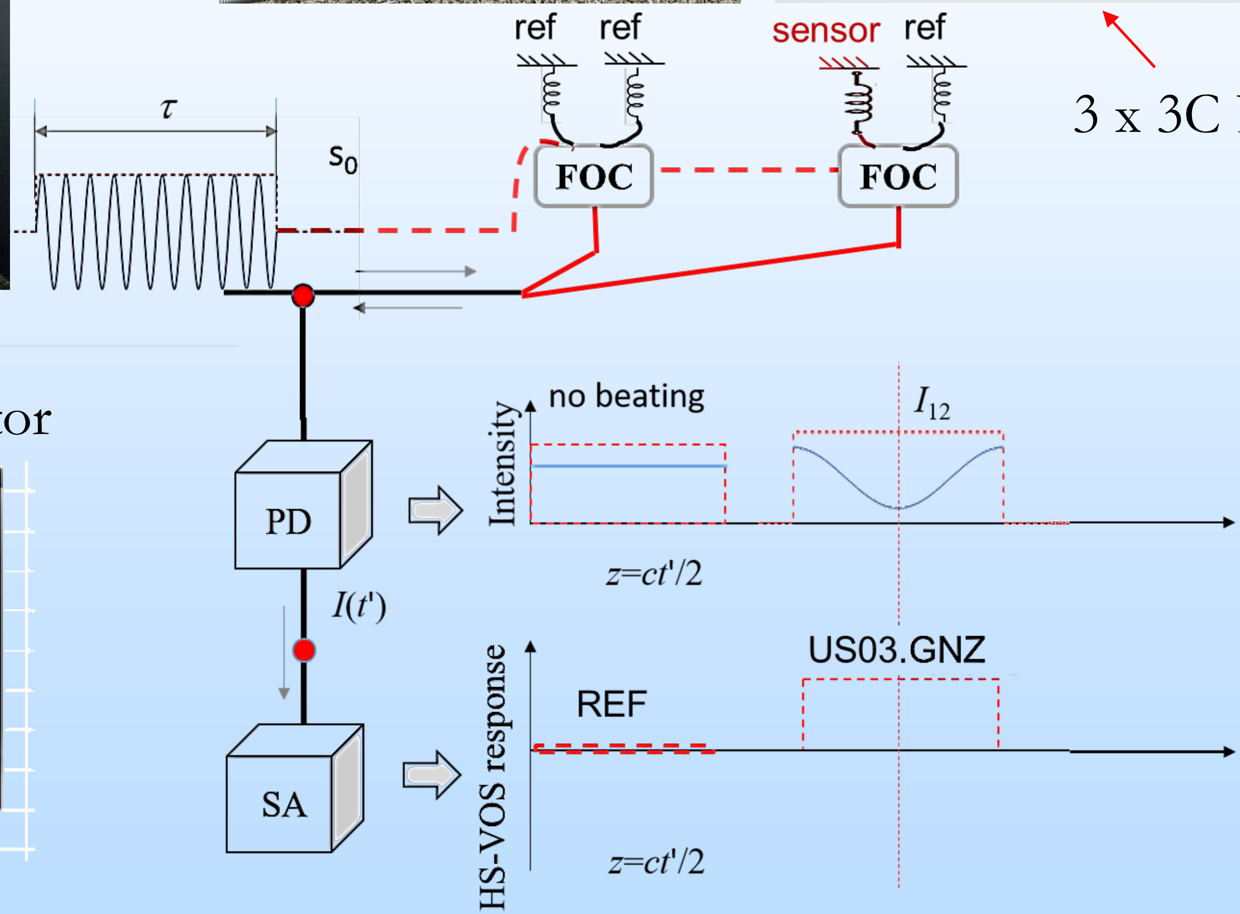
Configuration of the HS-VOS:
3 x 3-component pods + a reference channel

laser source





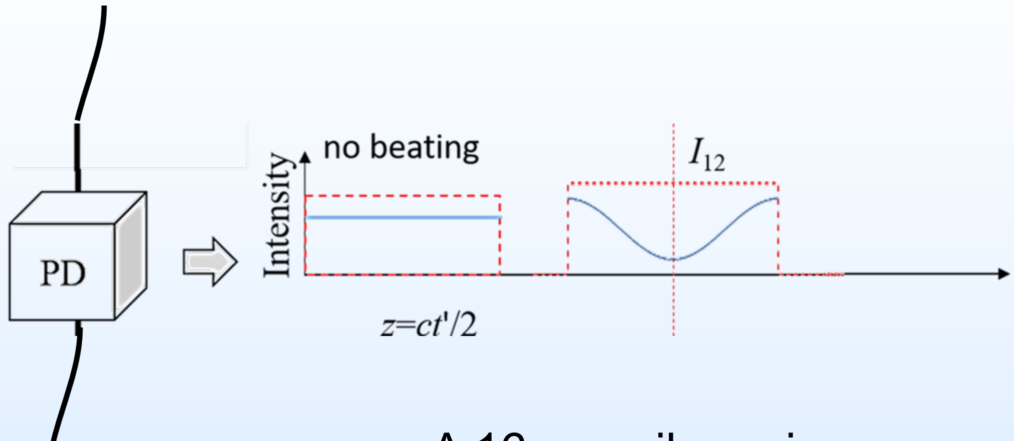
3 x 3C PODS



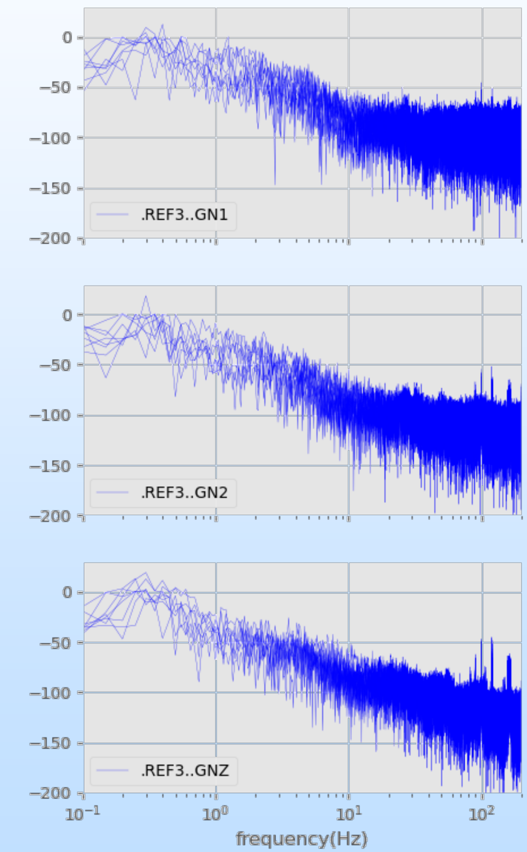
optical interrogator

Look at the Data:
Sensor vs REF, denoising?

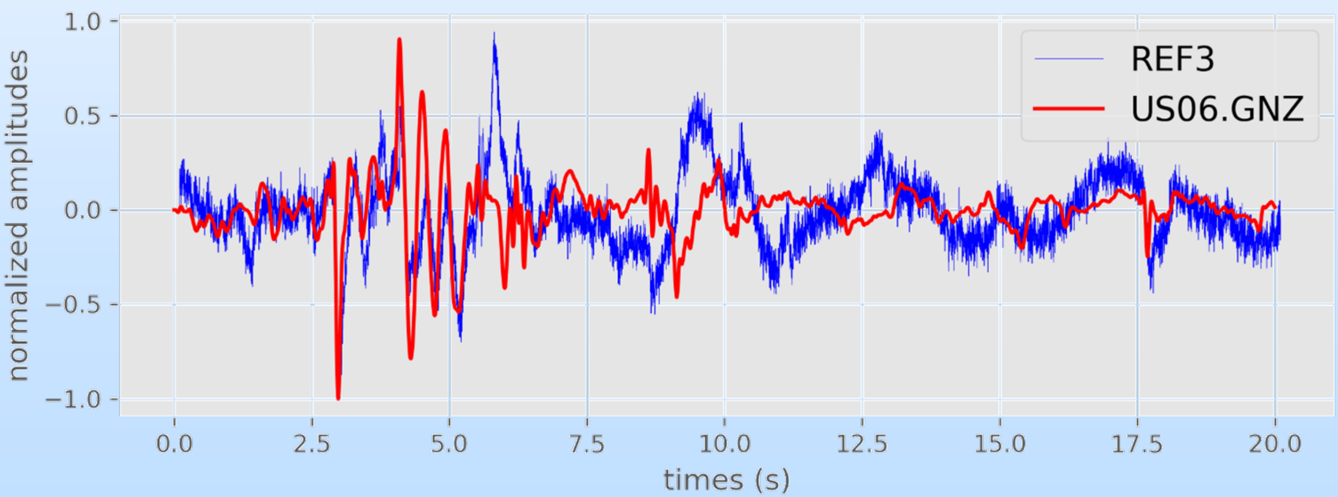
CCSMR Project
Task 4: HS-VOS



Noise PSD of 9 x sweeps



A 16-sec vibroseis sweep

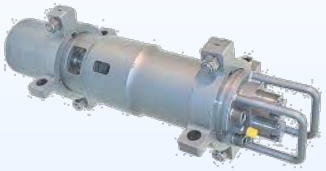


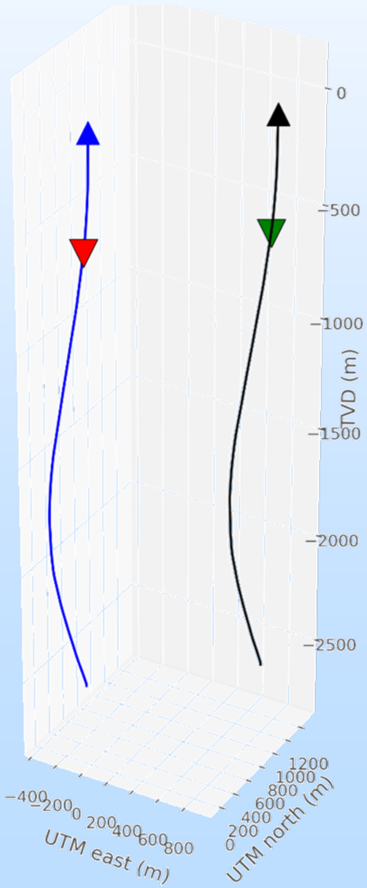
Noise is 80db down in the target frequency range!

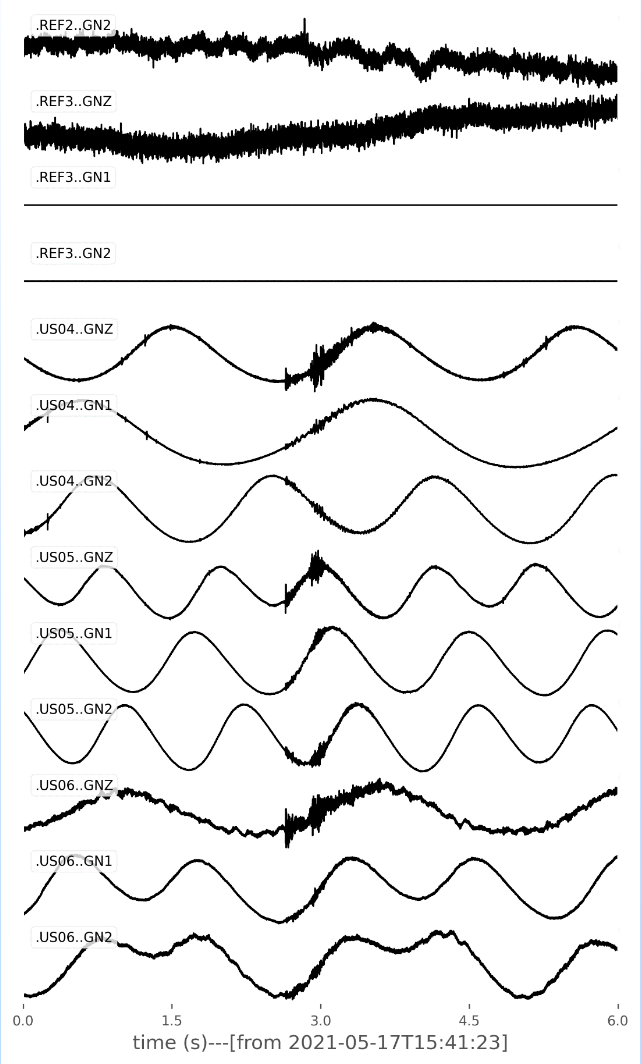
Look at the Data:
the system behaves, HQ readings

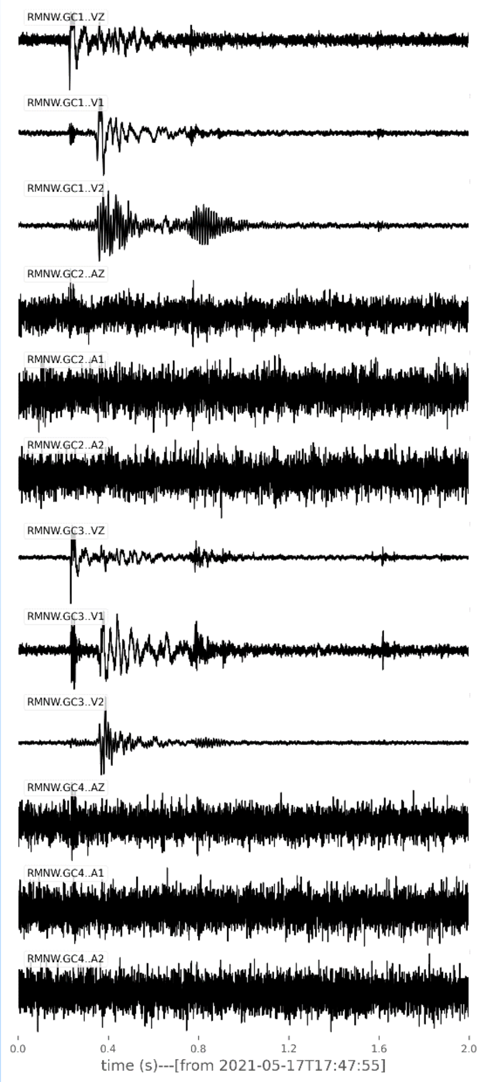
CCSMR Project
Task 4: HS-VOS

lowering the tools, 500 m, fluid-coupled, airgun









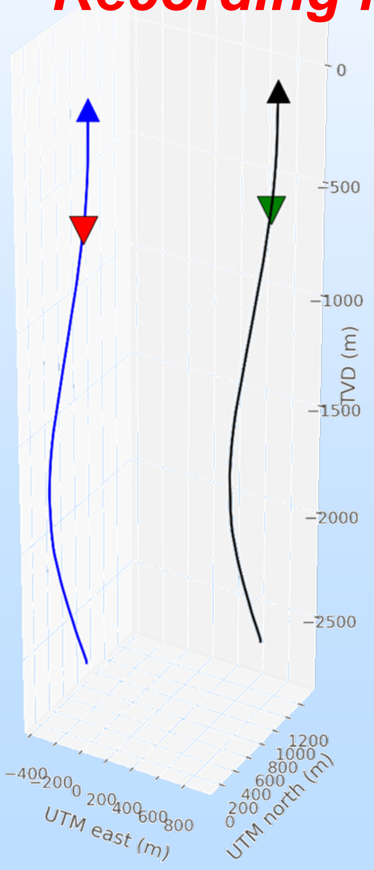
Look at the Data:
perhaps damaged the optical connector

CCSMR Project
Task 4: HS-VOS

lowering the tools to 1000 m, switching off the lasers…

17-05-2021 16:44

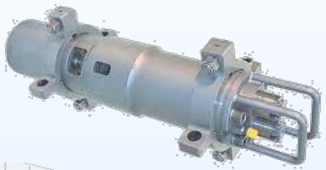
'I was still recording while I disconnected the winch. Oops. Recording now stopped. Running to 1000 m at 40 m/min'

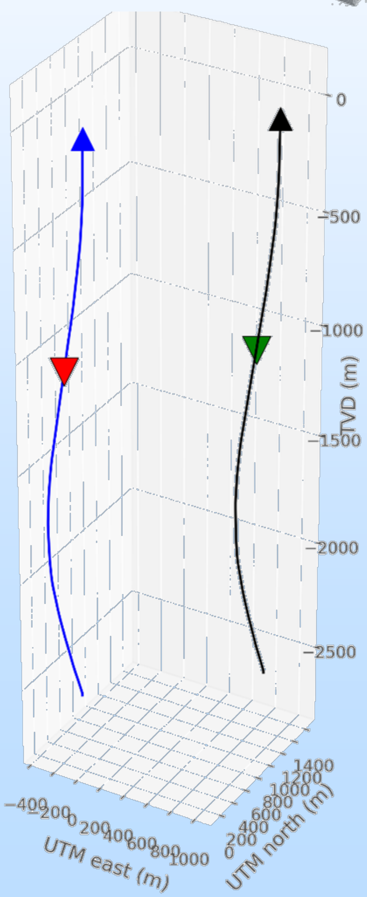


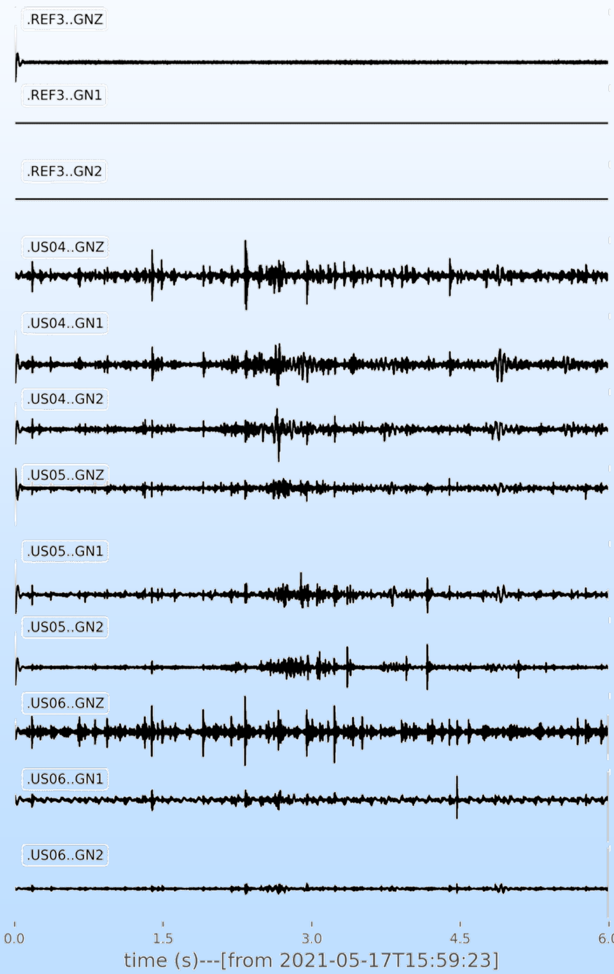
Look at the Data:
frequently repeating bursts of noise

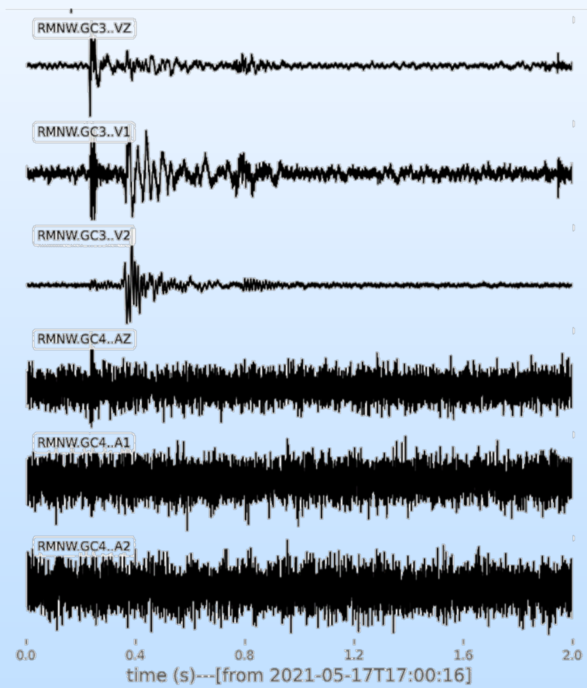
CCSMR Project
Task 4: HS-VOS

lowering the tools, 1000 m, fluid-coupled, airgun





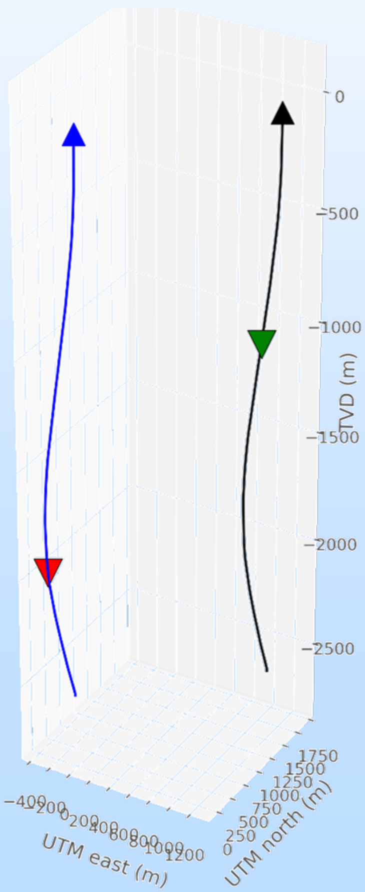


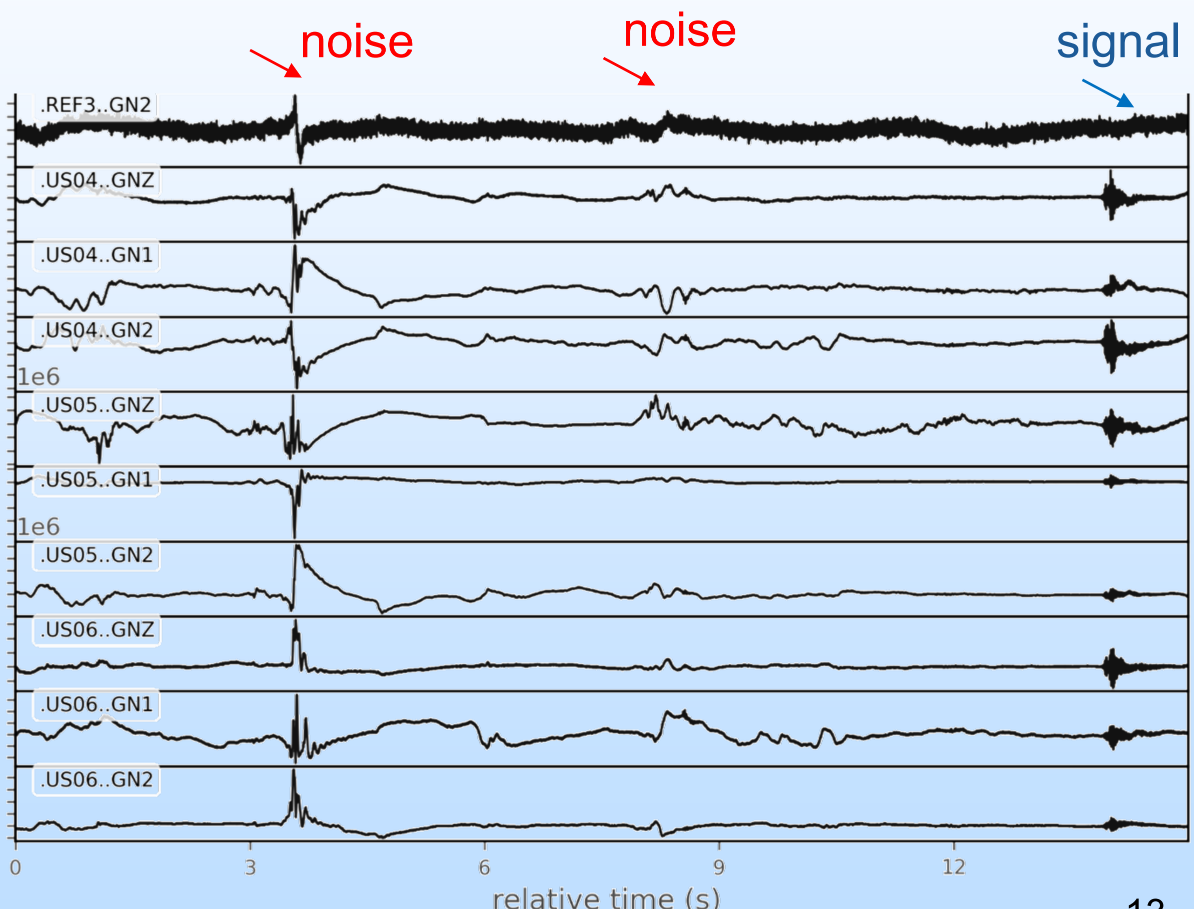


Look at the Data:
the noise bursts are weaker active source

CCSMR Project
Task 4: HS-VOS

The tools in position, 2000 m HS-VOS & 1000 base, fluid-coupled, hammer at the wellhead

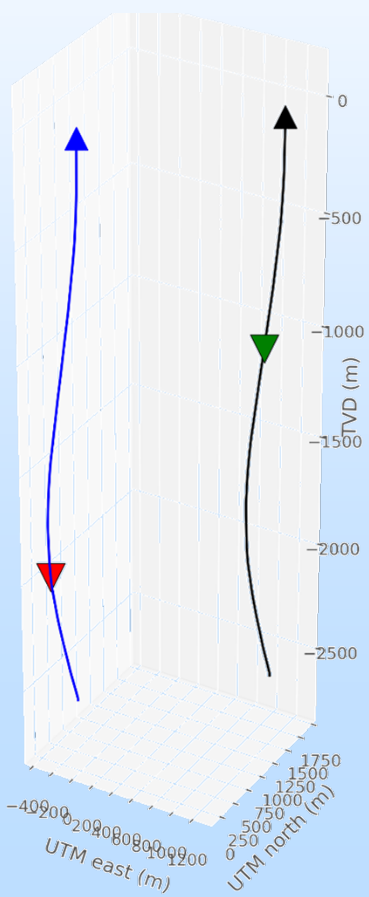




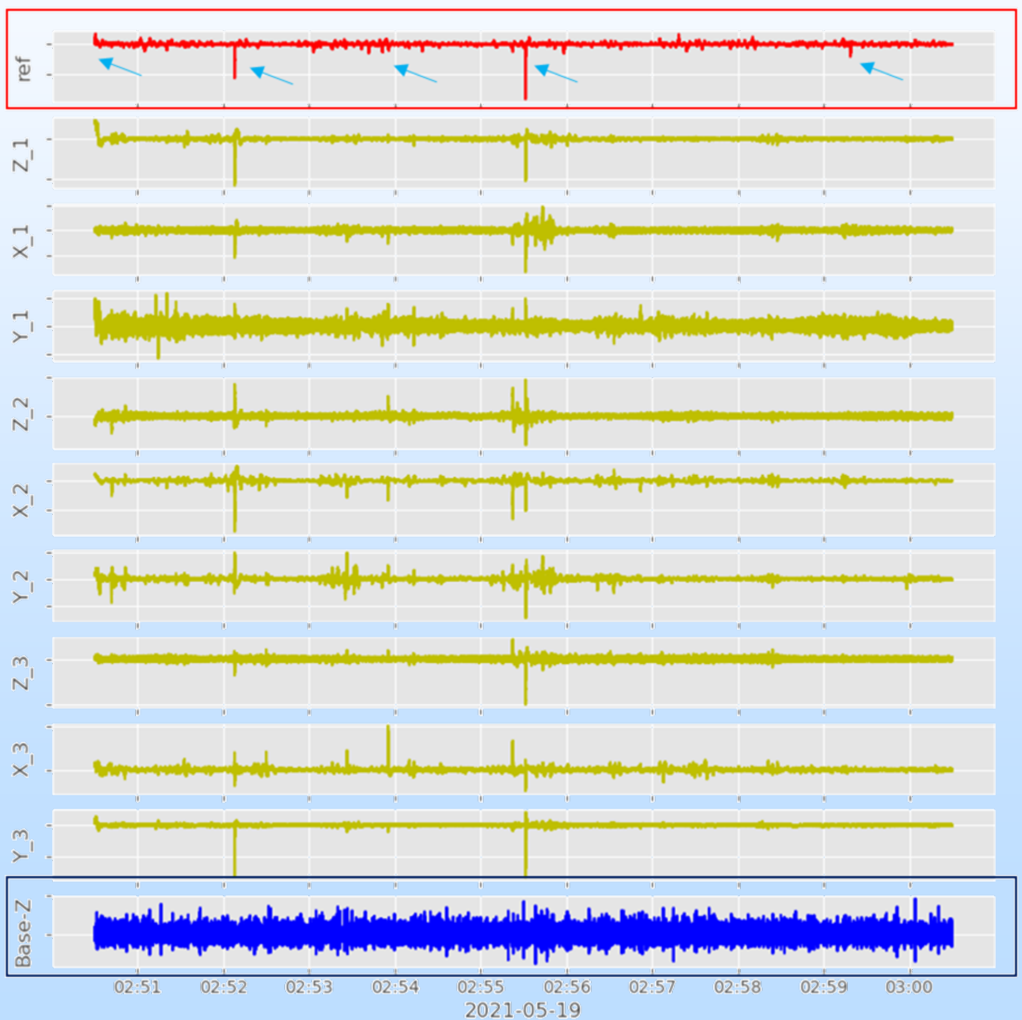
Look at the Data:
but the passive data is uninterpretable

CCSMR Project
Task 4: HS-VOS

The tools in position, 2000 m HS-VOS & 1000 base, clamped, passive



spikes and noise

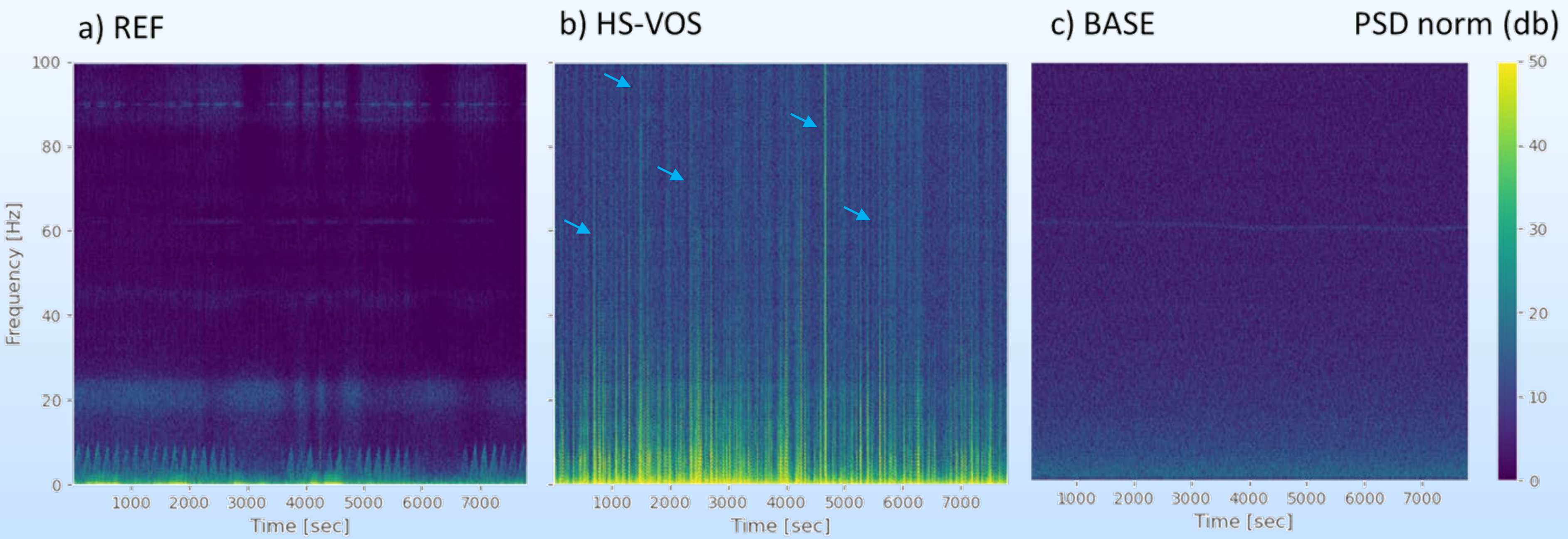


HS-VOS system at the Rosemanowes:

noise - a non-linear transformation of signal

CCSMR Project
Task 4: HS-VOS

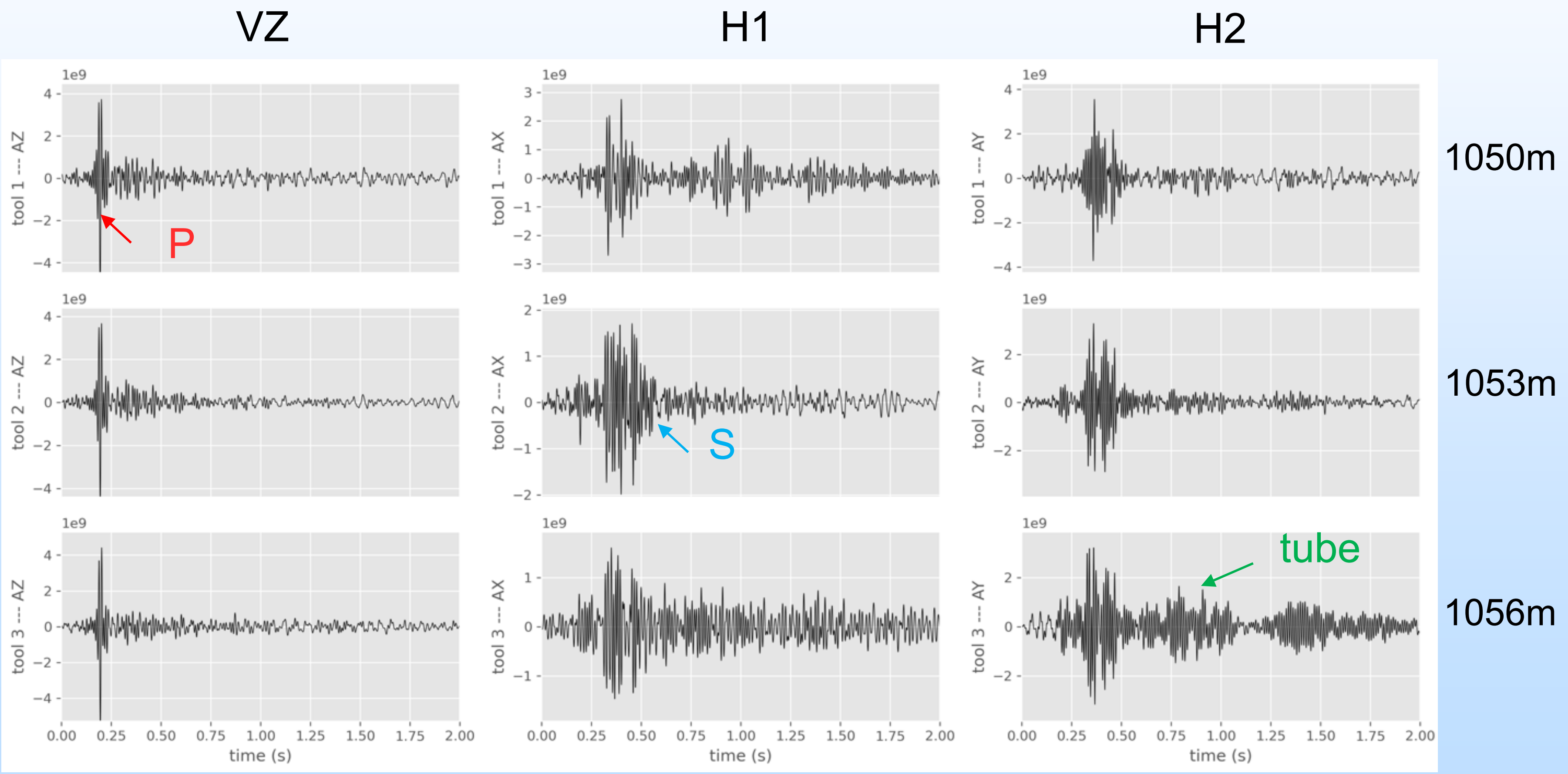
High frequencies get amplified strongly in the optical channel



VSP different sondes:
consistent amplitudes on all HS-VOS sondes

CCSMR Project
Task 4: HS-VOS

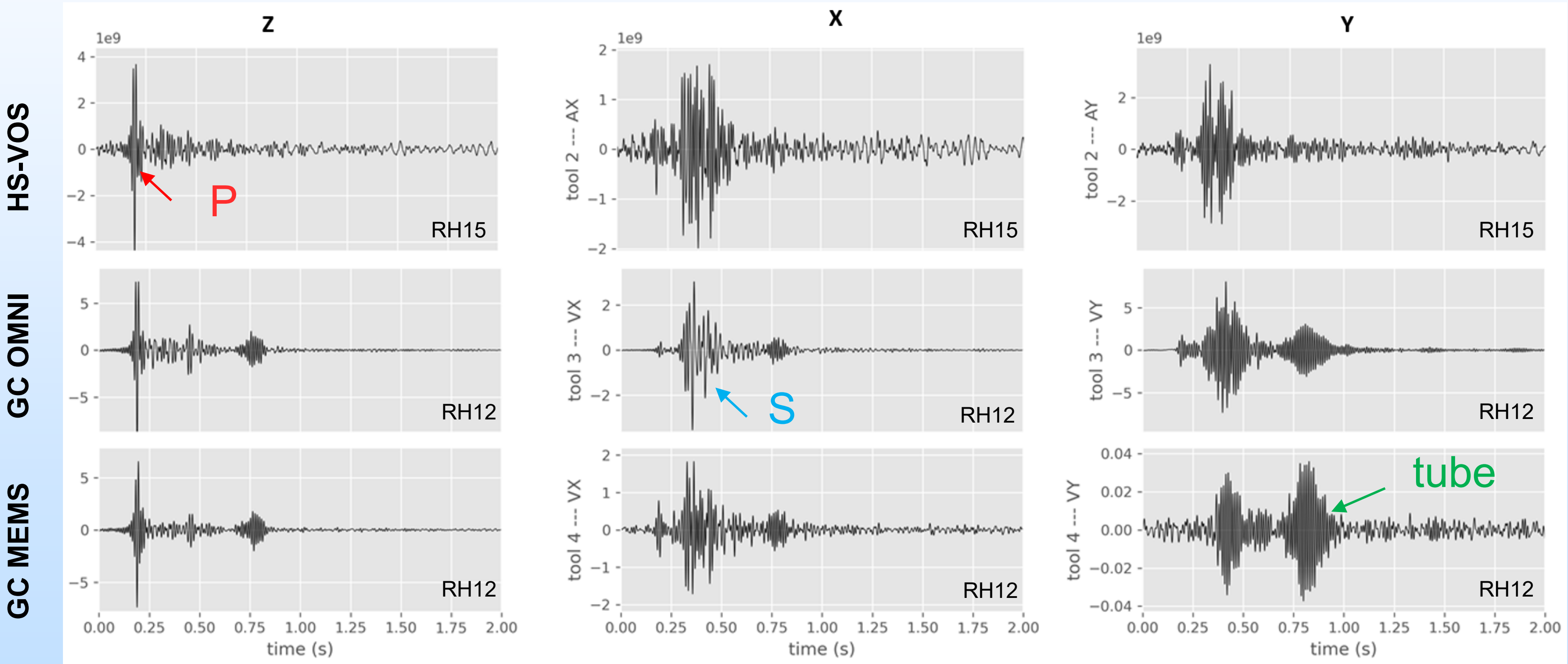
- HS-VOS vibroseis data correlated with pilot signal, array at 1050 m, vertical well
- Stack of 10 sweeps: 3 sondes, 3C, 3m spacing between sondes



VSP different systems:
electromechanical vs MEMS vs optical

CCSMR Project
Task 4: HS-VOS

- Comparison of HS-VOS, Geochain OMNI, Geochain MEMS sensors (all ~ 1 km)
- Stack of 10 sweeps, each channel: at similar depths in vertical sections of wells.

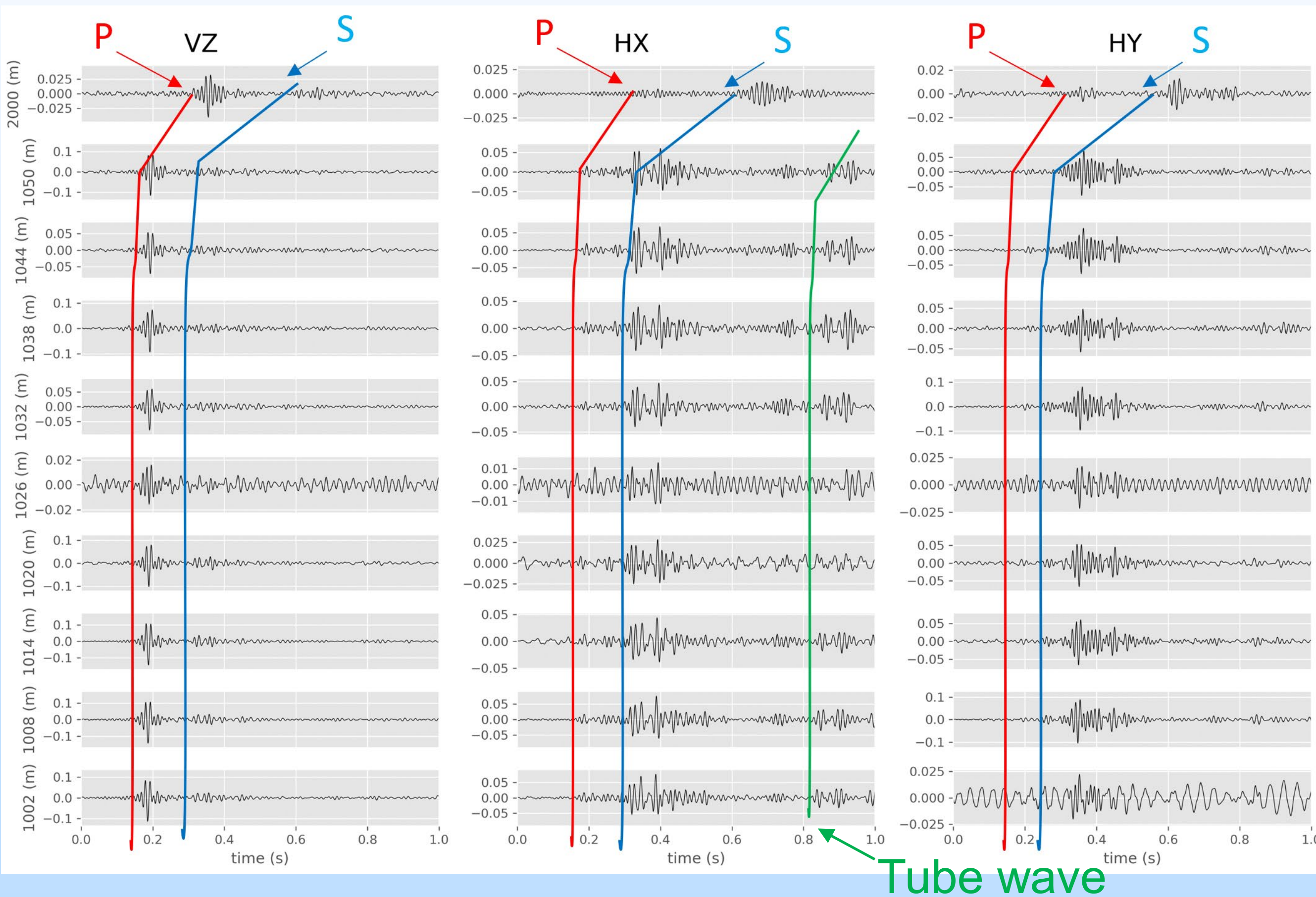


HS-VOS = USSI optical accelerometer
OMNI = OYO-Geospace OMNI-2400 geophone, quad package (4x geophones in series per component)
MEMS= Colibrys SiFlex capacitive accelerometer

VSP different levels:
Clear P- and S-waves, consistent amplitudes

CCSMR Project
Task 4: HS-VOS

- HS-VOS vibroseis data, at 2km, correlated with pilot signal (normalized plot)
- 16 second linear sweep, 10-100 Hz, 0.5s tapers, 4 second listen



- Single VSP level at 2km, in the inclined well section
- 9 levels of VSP with 6m overlap between moves, vertical well section, 1050-1002m

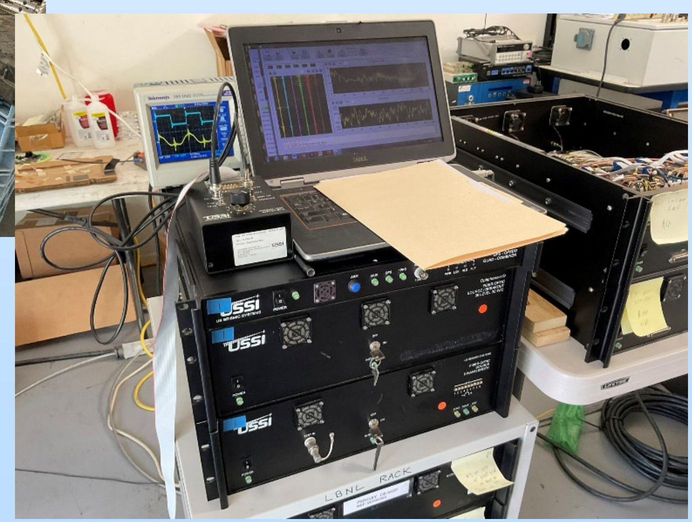
HS-VOS in the laboratory:

fixing the system + testing with a source

BERKELEY LAB
Lawrence Berkeley National Laboratory

CCSMR Project
Task 4: HS-VOS

1. Repaired the tool string and replaced the control computer
2. Successfully tested in a separate project (under NDA) tested the system with a mechanical source. Excellent results!



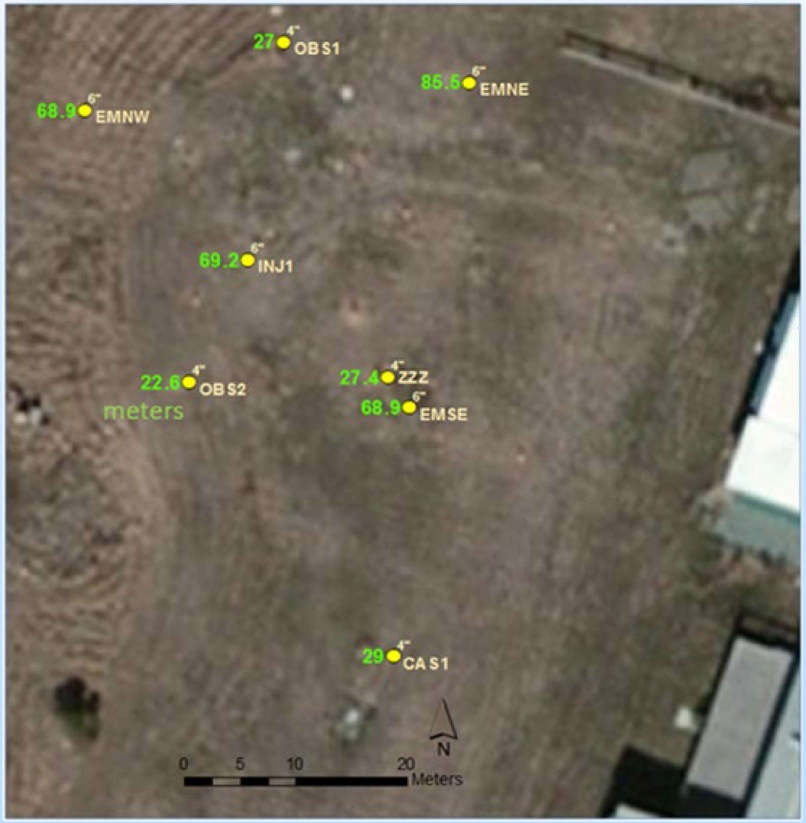
Fixing the uphole and downhole parts in the optical engineering workshop

Next steps FY22-23:
HS-VOS tuning at the LBNL testing site

1. Optimize the deployment strategy
2. Improve the stability of the system
3. Automatized data streaming

LBNL's optical logging truck

Richmond Field Station with 8 x shallow holes



RFS wells (usable)

Depths as of Oct 2013

Well names, casing size and depths in meters

Geosciences Measurement Facility LBNL

Interconnection pod + 3 x 3C sondes with One-shot clamping system

Accomplishments to Date

– Preparing for a 3D VSP survey at the Illinois Storage Corridor (FWP approved)

– Reconfigured 3-level HS-VOS array for deep deployment
  - Three levels of 3C vector-optical passive sensors
  - 9-channel reference sensor to test denoising techniques
  - Fiber loop-back for DAS recording from surface to 1st sonde
  - Incorporated standalone passive locking arm system for testing

– Completed processing of the field test of HS-VOS system at end of Q3-FY21
  - Successfully deployed at 2km depth with short VSP at ~ 1km
  - Collected active and passive source seismic data
  - Active seismic source data looks good
  - Due to issues with logging equipment passive data is uninterpretable

Lessons Learned

- Preparing for a 3D VSP survey at the Illinois Storage Corridor (FWP approved)

- Reconfigured 3-level HS-VOS array for deep deployment
  - Three levels of 3C vector-optical passive sensors
  - 9-channel reference sensor to test denoising techniques
  - Fiber loop-back for DAS recording from surface to 1st sonde
  - Incorporated standalone passive locking arm system for testing

- Completed processing of the field test of HS-VOS system at end of Q3-FY21
  - Successfully deployed at 2km depth with short VSP at ~ 1km
  - Collected active and passive source seismic data
  - Active seismic source data looks good
  - Due to issues with logging equipment passive data is uninterpretable

Appendix

Project Summary:
full-on preparation to an extensive field survey

CCSMR Project
Task 4: HS-VOS

- We are collaborating with ISGS to conduct an advance borehole seismic characterization at a CarbonSAFE Phase III project site using HS-VOS:
  - 3D VSP using vibroseis trucks + passive recording
  - Testing of the μ-VSP in shallow wells
- We are designing an extensive field deployment of the HS-VOS in shallow boreholes to tune in the acquisition parameters
- Due to issues with optical logging equipment, the data from the HS-VOS deployment at the Rosemanowes test was of insufficient quality to benchmark the system:
  - Active seismic source data (airgun and vibroseis) comparable with a benchmark technology
  - Passive seismic data corrupted by noise
- The uphole and downhole HS-VOS component were repaired after the Rosemanowes' experiment and successfully tested:
  - 12-day passive recording in a workshop
  - A thorough performance analysis using a mechanical seismic source

Synergy Opportunities

CCSMR Project
Task 4: HS-VOS

- Other Carbon Storage and monitoring projects in the US
  - Dry Fork CarbonSAFE Phase III (Wyo)
- Passive/active monitoring using shallow boreholes:
  - SBIR Phase II for MicroSeismic Inc at One Earth Energy Sequestration site (IL)
- Induced seismicity monitoring and/or crosshole seismic at CarbFIX 2 (Iceland)
  - Our 200C sondes are interchangeable with the 150C test sondes

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 CarbonSAFE sites
  - Broader learnings from leveraged international research opportunities
  - Rapid transfer of knowledge to domestic programs

Project Overview
Goals and Objectives

- This task of CCSMR develops optical seismometers capable of quantifying induced seismicity and subtle active seismic signatures to reduce the risk resulting from (a) detection of smaller microseismic events at depth and (b) potential early detection of faults and their incipient failure, thereby advancing the development and validation of technologies that enable safe, permanent geologic storage of CO_2 and further developing the ability to image basement faults.

- The success criterion for this task is the demonstration of high-sensitivity wide-bandwidth hybrid acoustic monitoring technology for deployment in a deep and multiple shallow wells at a CO_2 storage site. One Go/No-Go Decision point is set at Milestone 2, based on the assessment of initial results from the May 2021 field-laboratory test, to determine the suitability of the acquired dataset for further in-depth analysis of the HS-VOS system performance as compared to conventional sensor technologies recorded during the same test. A No-Go at this decision point would result in re-assessment of sensor hardware and survey parameters to be used in the next sonde deployment phase.

Organization Chart

- **Lawrence Berkeley National Laboratory:**
  - Task PI, Field Lead: Stanislav Glubokovskikh
  - Field Lead: Michelle Robertson
  - Senior Engineer: Todd Wood
  - 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
- **MicroSeismic Inc:**
  - Seismic processing: Michael P. Thornton
  - Project Management: Stephen Chelette
- **Illinois State Geological Survey:**
  - Illinois Storage Corridor PI: Steven Whittaker
  - Geological modelling/co-PI: Sherilyn William-Stroud
  - Seismic Acquisition: Nick Malkiewicz, Mitchell Barklage

Gantt Chart

CCSMR Project
Task 4: HS-VOS

Task	Milestone Description*	FY22	Fiscal Year 2021 Q1	Q2	Q3	Q4	Planned Start Date	Planned Completion Date (Reporting Date)**	Actual Start Date	Actual End Date	Comment (notes, explanation of deviation from plan)
Milestone 4-1 (A)	HS-VOS field-laboratory test at Rosemanowes borehole site, UK	Q4FY21	→ x				April-21	7/1/21 (7/31/21)	April-21	July-21	Completed as reported in FY21 annual report.
Milestone 4-2 (B)	Initial analysis of the HS-VOS Rosemanowes field test data	Q1FY22	x				Aug-21	12/31/21 (1/31/22)	Aug-21	Dec-21	Completed as reported in Q1FY22 annual report.
Milestone 4-3 (C)	Analysis and evaluation of the HS-VOS performance using active and passive sources; comparison with baseline technology	Q3FY22			x		Aug-21	6/30/22 (7/31/22)	Aug-21	Aug-22	Partially completed as reported in Q3FY22 annual report.
Milestone 4-4 (D)	Second HS-VOS field-laboratory test, applying systems improvements from first test.	Q4FY22				x	Aug-22	9/30/22 (10/31/22)	Aug-22	→	Underway

Bibliography

Currently in the instrument development and testing stages, with substantial delays in 2020-2022 due to COVID-19 restrictions.

No Journal publications yet for this subtask.