US - Japan Collaboration on Fiber Optic Technology

Project Number: ESD14-095 (Task#5)

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Lawrence Berkeley National Laboratory

U.S. Department of Energy

National Energy Technology Laboratory

Addressing the Nation's Energy Needs Through Technology Innovation – 2019 Carbon Capture, Utilization, Storage, and Oil and Gas Technologies Integrated Review Meeting

August 26-30, 2019

Monitoring Technology for Deep CO_2 Injection

Project Number: ESD14-095 (Task#4)

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Collaborators

Collaborators:

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Acknowledgement:

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Kirk Osadetz

University of Calgary, Carbon Management Canada (CMC), Containment and Monitoring Institute (CaMI) (Calgary, Canada)

Presentation Outline

- Distributed Optical Fiber Sensing (DOFS) Benefits
- Goal and R&D Challenges
- Why Stimulated Brillouin Scattering ?
- CaMI - Field Research Station Background
- LBNL Progress on Data Collection and Analysis
- Summary and Next Steps

DOFS Benefits

- Evaluate well integrity
- Detect leakage along the wells
- Calibrate geomechanical model:

  Static deformations occurring during injection can be used by reservoir engineers to calibrate and validate hydro-mechanical simulation models of CO_2 plume migration and predict long term containment

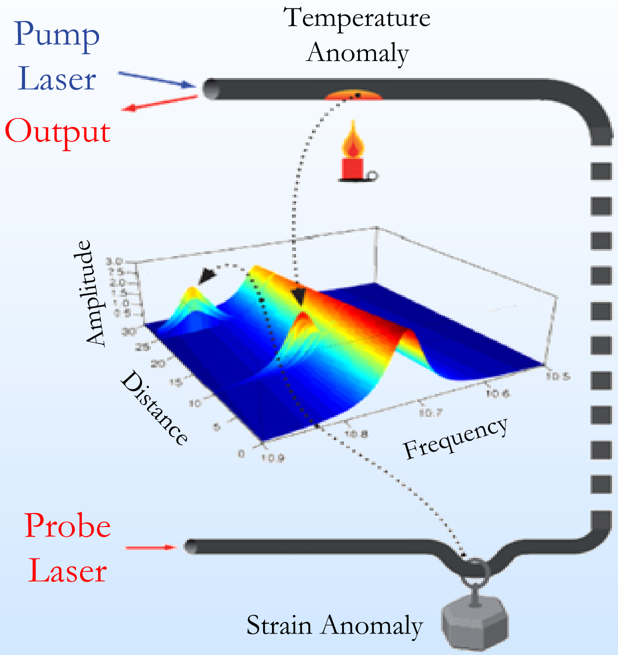
Goal and R&D Challenges

- Quantify and improve the strain sensitivity due to CO_2 injection (i.e. amount of strain caused in the rock formation by the injection)

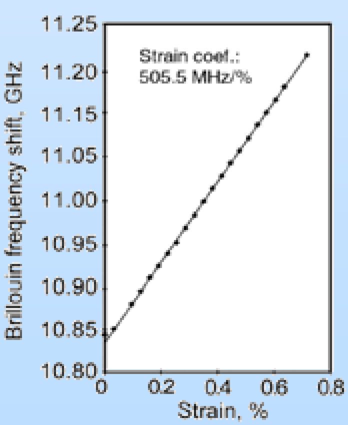
Key Requirements:

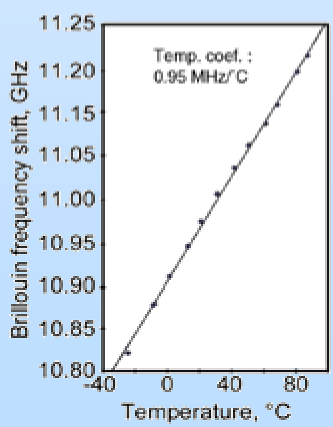
- Better understand the influence of the measurement cable design and the deployment methodology on the measurements
- Evaluate optimal coupling between casing, cement, optical fiber, and rock formation
- Understand how the axial strain measurement (along the cable) can provide information on the full 3D strain tensor
- Quantitatively compare Rayleigh and Brillouin Scattering

Stimulated Brillouin Scattering



1) Pump laser sends main signal traveling through the fiber cable
2) Probe signal is injected at the other end of the fiber
3) Variation in strain and temperature locally change the index of refraction and the frequency of the main pulse
4) Probe signal detects the main signal perturbation at locations where strain/temperature changed
5) This change is linearly correlated to amount of strain and change in temperature





Standard performance for DOFS

- Distance range: 50km
- Distance resolution: 0.1m
- Resolution: 0.1°C and 2με
- Spatial resolution (the smallest detectable event measured with 100% accuracy) up to 0.5 m but typical values are: 1m at 20km, 2m at 30km, 3m at 50km

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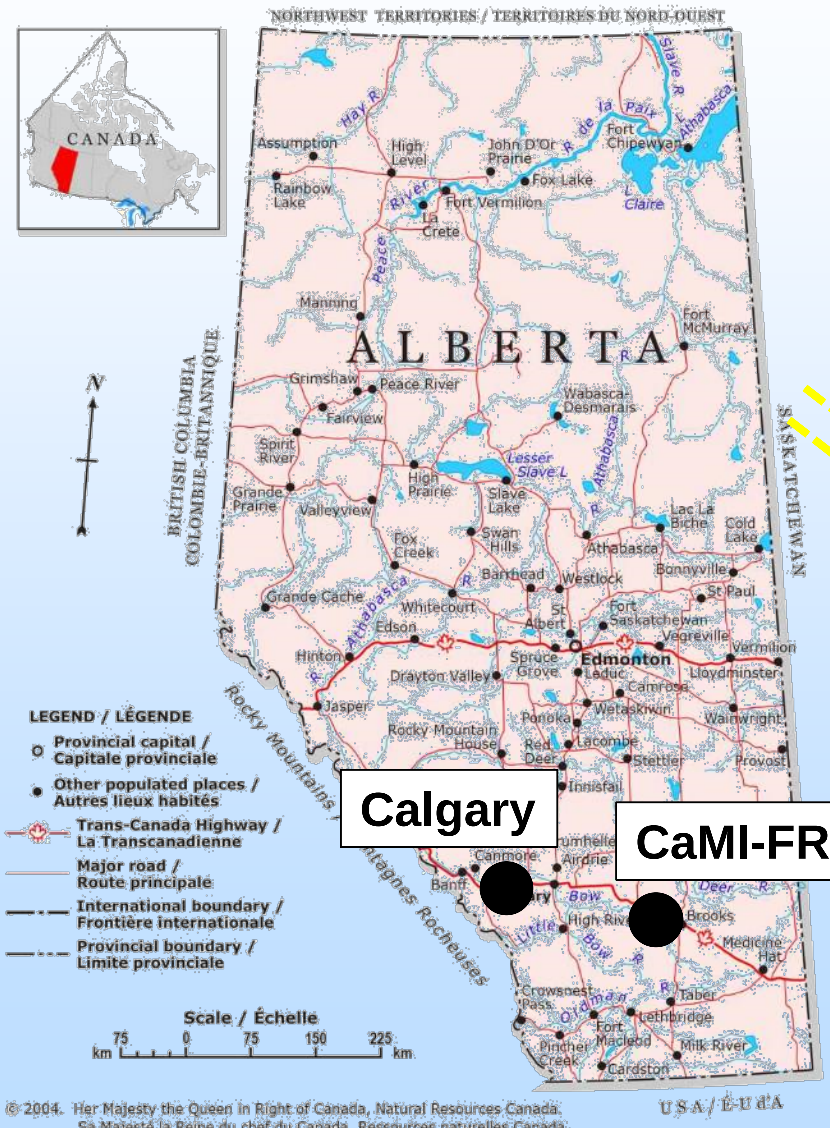
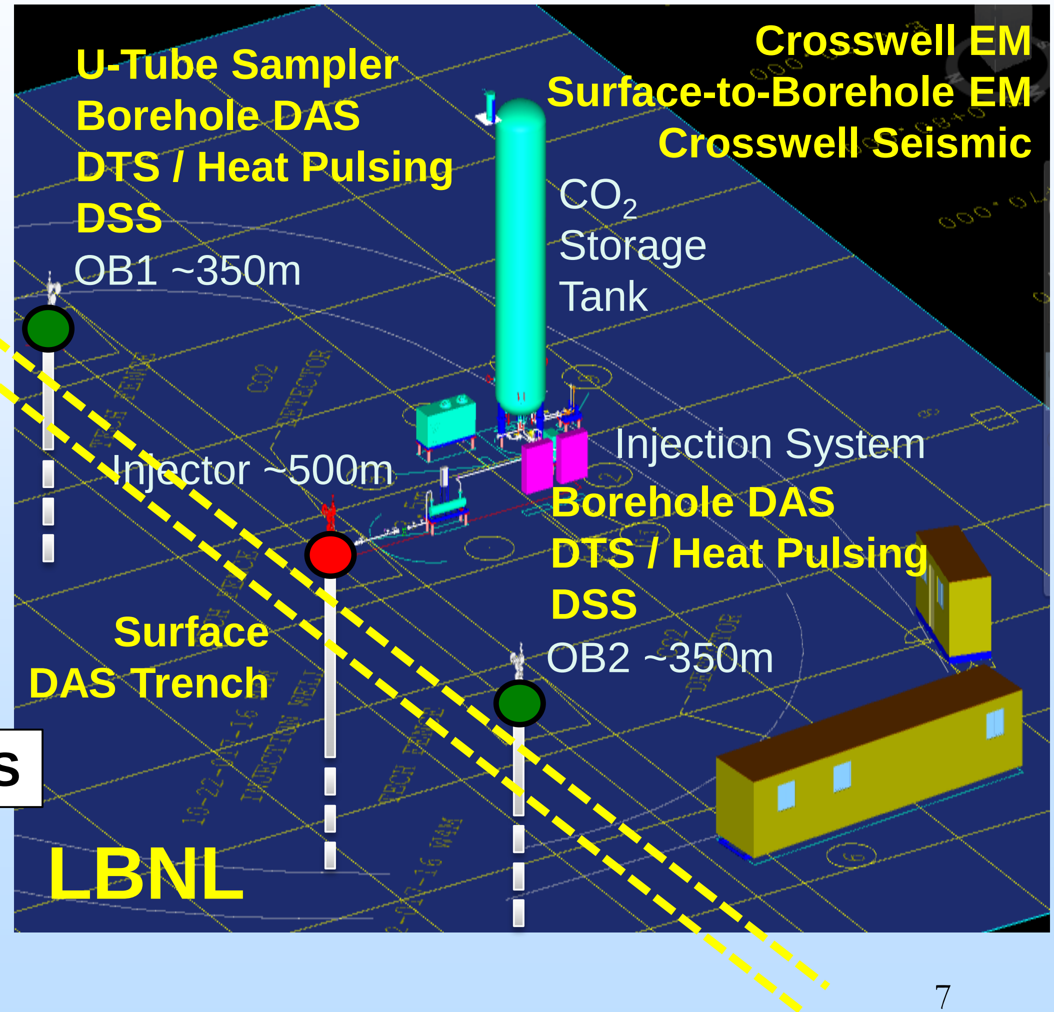
CaMI-Field Research Station (FRS)





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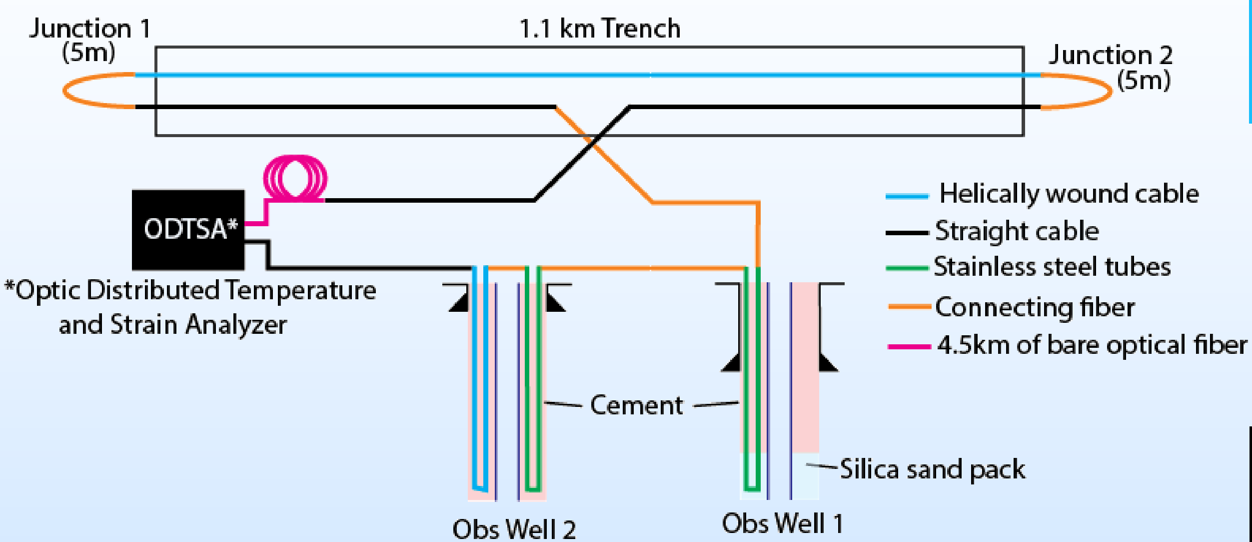
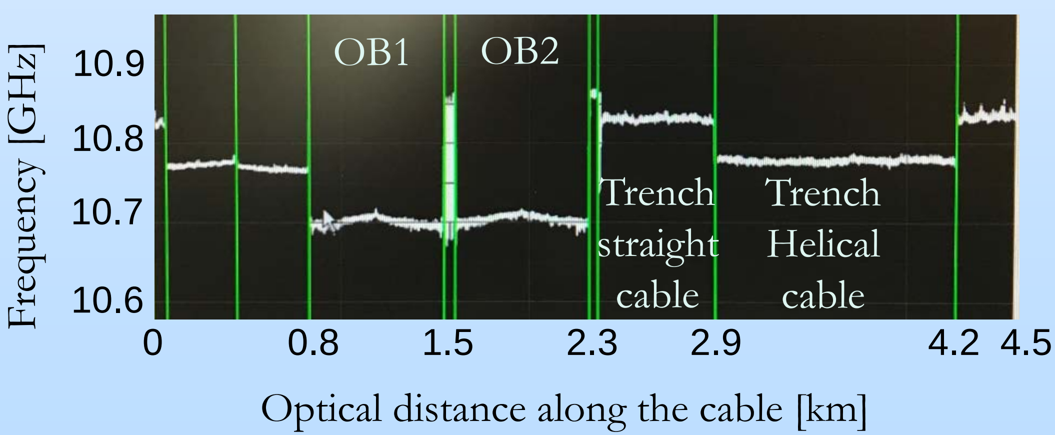
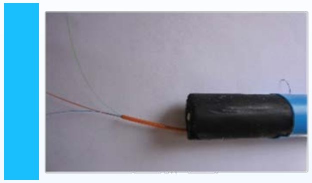
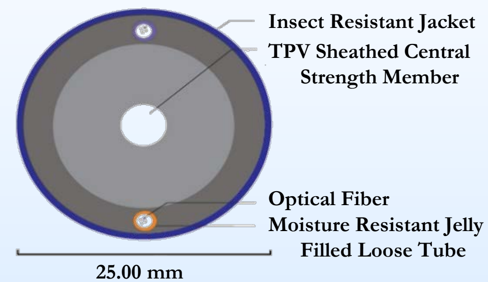
Fiber Optics Network at CaMI-FRS

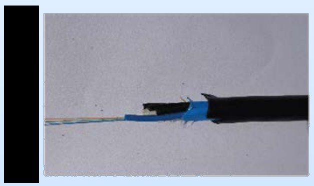




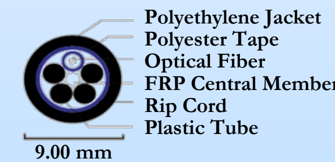


Helically Wound Cable

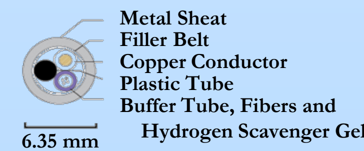




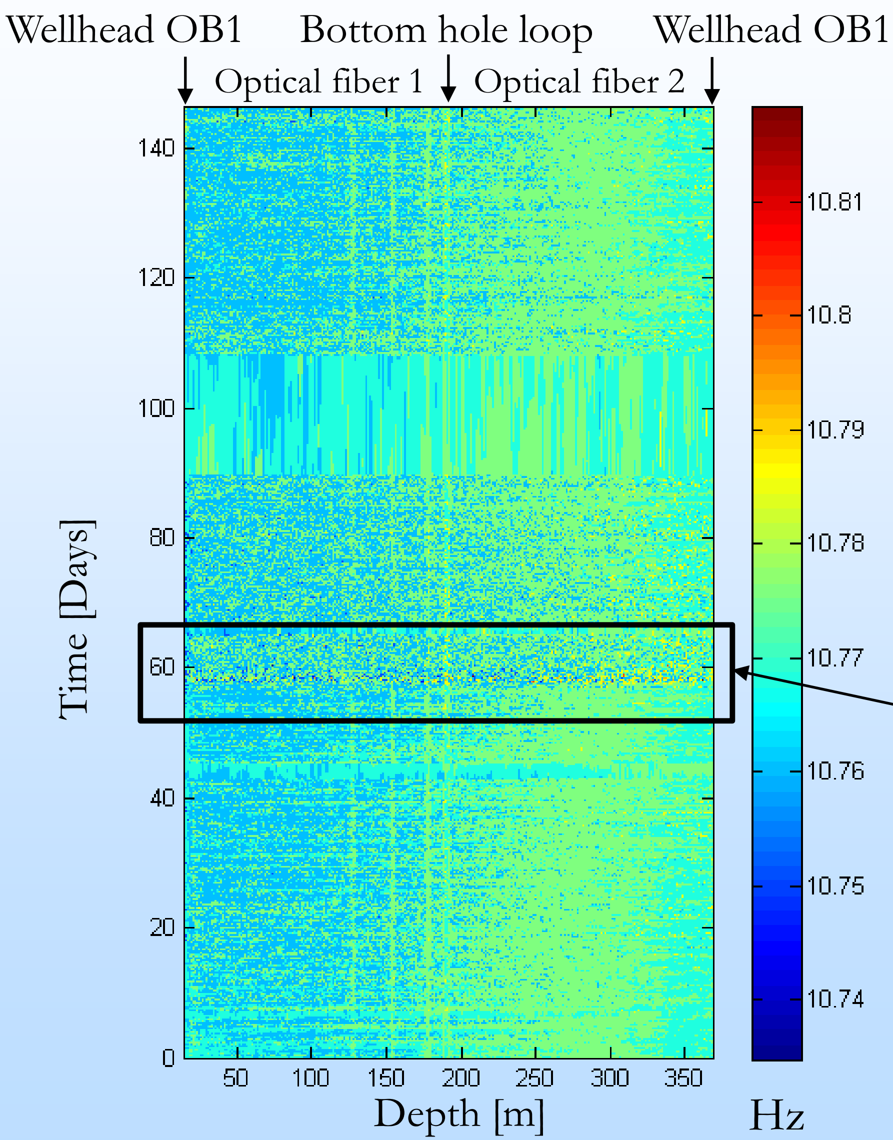
Straight Cable



Stainless Steel Tubes



DSS Monitoring, 143 days



Evolution of the Brillouin frequency monitored along the <u>helical wound cable</u> from January 23, 2019 to June 11,2019 in observation well OB2 (15 min sampling)

Signal associated with injection?
Need to compare with injection/pressure data

<u>Will visit CaMI-FRS in October 2019</u>

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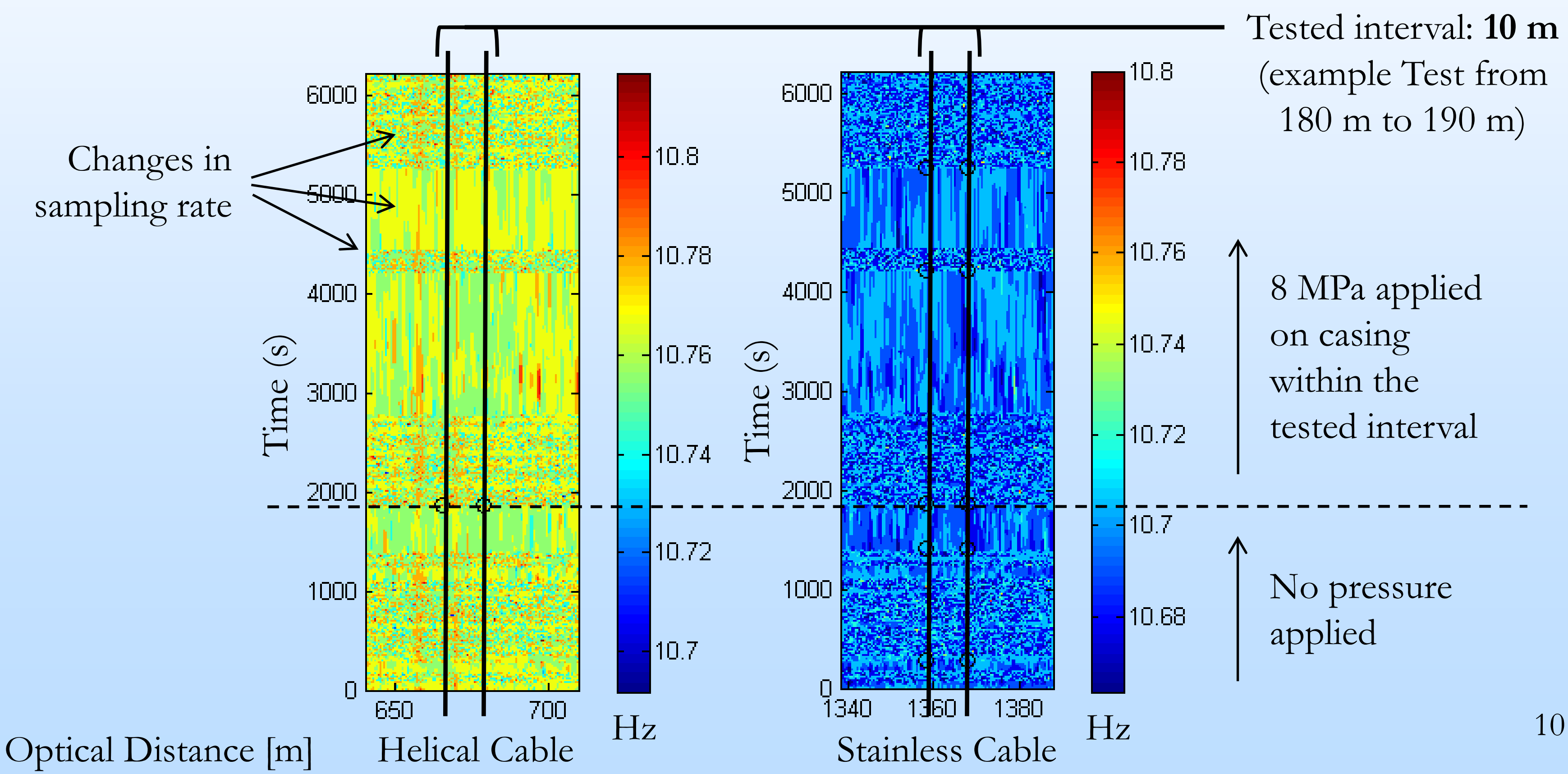
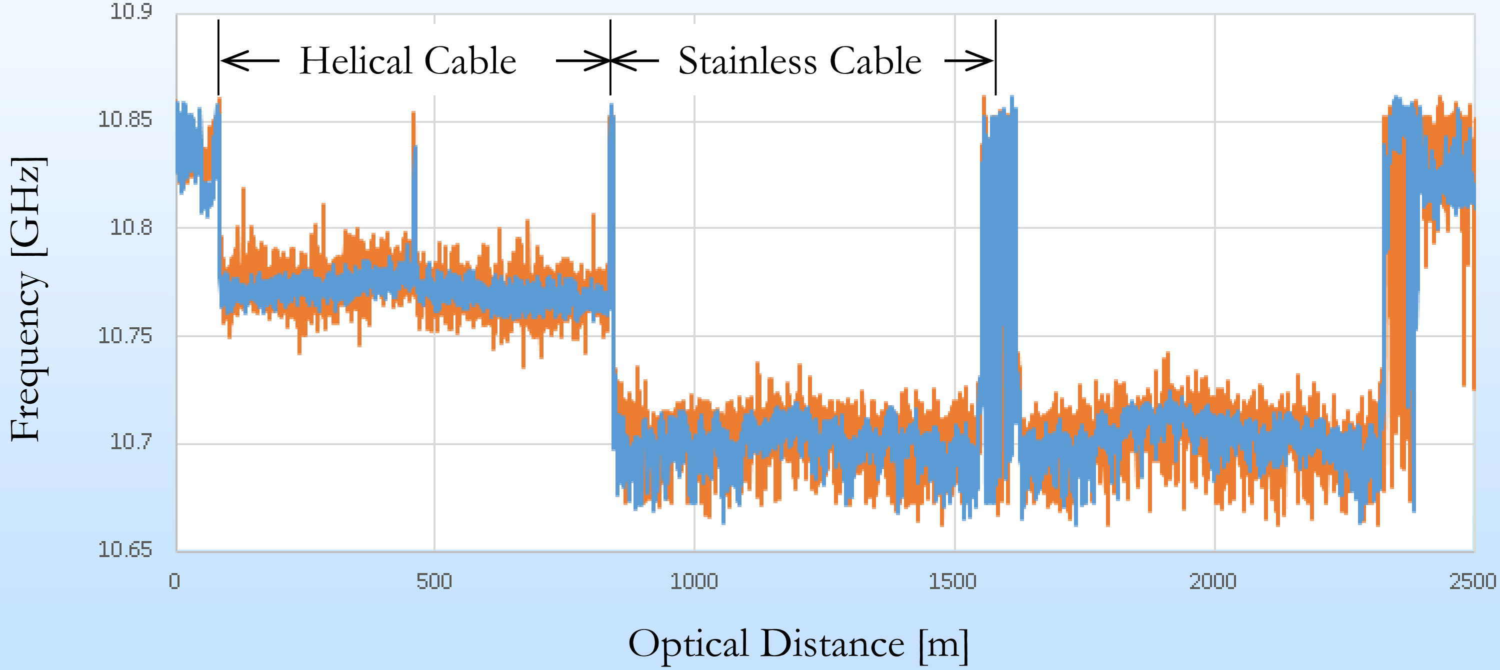
In-situ Experiment, June 2019

- Eight tests conducted at 8 different depths (from 62 to 190 m) to assess the role of the mechanical coupling between rock-cement-fiber-casing
- During each test fluid pressure (from 3 and 9 MPa) was applied for 30 to 60 minutes on a 10 m long section along Observation Well OB2: no apparent Brillouin frequency shift



In-situ Experiment, June 2019

Comparison between Brillouin scattering noise floor along the fiber network BEFORE and AFTER pressure tests



NOTE: The optical cable was bent at the wellhead during the rig operations for the pressure tests. <u>The bend might be responsible for the lack of frequency shift</u>

Accomplishments to Date

- Installed a fiber network ~9 km long composed of several optical cables (2x straight, helical wound)
- Performed strain and temperature calibration tests on the different optical cables in laboratory
- Developed a 3D geomechanical model of the CaMI - FRS with detailed discretization of storage, cap rock formations and wells designs
- Continuous monitoring from January 23, 2019 to June 11, 2019
- Performed in-situ experiment to assess the role of the mechanical coupling rock-cement-fiber-casing

Lessons Learned

Research Needs:

- Need to better characterize in-situ the mechanical coupling between the casing, the cement, the optical cable, and the rock formation
(Casing stiffness ? Weak coupling ?)
- Need to develop cables robust enough to be install behind casing without being pinched or broken, but soft enough to capture micro-strain due to reservoir deformation
- Need to improve the deployment (and testing) methodology

Technical Challenges:

- Install the optical cable behind casing without damages
- Deploy an instrument in the borehole while monitoring strain behind casing (slight bending of the optical cable at the wellhead responsible for unsatisfying data)

Synergy Opportunities

- Assessment of Leakage Pathways Using Joint EM-Seismic, Borehole and Surface Technologies (Task#3)
- The Eagle Ford Shale Laboratory: improve EOR
- The Mont-Terri experiment (FS-B): active monitor of fault leakage during CO_2 Injection.

CaMI-FRS Updates: Aug.2019

- 18 Tonnes of CO_2 injected to date (Aug. 2019)
- Injection will stop for 4-5 days (beginning of September) to change pump
- With newly installed (high-power) pump, <u>injection will be continuous</u> @0.5 Tonnes/day rate (no need for any extra step-up/down testing: all tests passed)
- Added new industrial sponsor, Petronas to the current four (Total, Equinor, Chevron, Shell)
- Current CaMI industrial sponsors highlighted their interest in DSS for continuous reservoir monitoring

Project Summary

Key Findings:

- Need to design cables robust enough to be install behind casing without damaging the fibers, but flexible enough to capture the micro-strain during the injection
- Need to design pressure testing experiments that would not affect the SNR of the fiber cable at the wellhead

Next Steps:

- Process monitoring data from January 23, 2019 to June 11, 2019 (use signal enhancing techniques)
- Compare data collected with injection rate and reservoir pressure (will visit CaMI-FRS in October 2019 for Task#3)
- Point-heating the casing for DTS testing ?
- In general: special coating, or sequentially clamp fibers inside coating ?

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Acknowledgments

- Funding for LBNL was provided through the Carbon Storage Program, U.S. DOE, Assistant Secretary for Fossil Energy, Office of Clean Coal and Carbon Management, through the National Energy Technology Laboratory (NETL), for the project "Core Carbon Storage and Monitoring Research" (CCSMR) under contract No. DE-AC02-05CH11231

- We would like to thanks the Geophysical Measurement Facility (GMF) @LBNL for technical and field support

- Carbon Management Canada (CMC) Containment and Monitoring Institute (CaMI) Field Research Station (FRS)

- We thank CMC Research Institutes Inc. for access to the CaMI Field Research Station and for logistical support during the field campaigns

Appendix

Benefit to the Program

The research project is advancing fiber optic sensing technology for monitoring carbon sequestration to:

- Ensure 99% storage permanence by reducing leakage risk through early detection mitigation
- Improve reservoir storage efficiency while ensuring containment effectiveness by advancing monitoring systems to control and optimize CO_2 injection operations
- Contributing to the Best Practice Manuals for monitoring, verification, and accounting (MVA) with regard to IMS
- Reduce overall storage cost
- Increase monitoring sensitivity
- Reduce project risk during and after the injection of CO_2

Project Overview

The technology, when successfully demonstrated, will provide the possibility to continuously measure temperatures and strain at thousands of points with a high spatial resolution along a single fiber installed in monitoring wells and/or in trench at the surface on several kilometers at a relatively low cost.

The technology can significantly improve our ability to evaluate the wells integrity and detect leakage along the wells and provide critical information on static deformations occurring during injection. Information which can be used by reservoir engineers to calibrate and validate hydro-mechanical simulation models of CO_2 plume migration and predict long term containment.

LBNL's Goal and Objectives

Contribute to a comprehensive monitoring program with:

- Integration and technology maturation of Crosswell EM and Seismic into a multi-physics monitoring approach to improve CO_2 saturation estimates and joint inversion;
- U-Tube fluid sampling;
- **Distributed Temperature Sensing (DTS) + heat pulse monitoring;**
- Surface and borehole straight + helical Distributed Acoustic Sensing (DAS);
- **Distributed Strain Sensing (DSS).**

Organizational Chart

Carbon Management Canada (CMC) organized the Containment and Monitoring Institute (CaMI), led by Don Lawton (University of Calgary).

Project field site is CaMI-Field Research Station (FRS), Newell County, Alberta, Canada

- **Research Institutions**

  British Geological Survey (UK)

  CMR (Norway)

  GFZ (Germany)

  Imperial College (UK)

  INRS (Canada)

  LBNL (USA)

  Natural Resources Canada (Canada)

  NTNU (Norway)

  Princeton University (USA)

  SINTEF (Norway)

  University of Bristol (UK)

  University of Calgary (Canada)

  University of Edinburgh (UK)

  University of Freiberg (Germany)

  University of Guelph (Canada)

- **Commercial Partners**

  Chevron (USA)

  Equinor (Norway)

  Petronas (Malaysia)

  Shell (UK-Netherlands)

  Total (France)

Gantt Chart

Task	Milestone Description*	Fiscal Year 2019				FY20	Planned Start Date	Planned Completion Date (Reporting Date)**	Actual Start Date	Actual End Date	Comment (notes, explanation of deviation from plan)
		Q1	Q2	Q3	Q4						
Milestone 2-1 (A)	SOV/DAS automated data processing algorithms and workflows			x			10/1/2018	6/30/2019 (7/31/2019)			AOP Tracked
Milestone 2-2 (B)	Data report on SOV/DAS baseline surveys and initial testing of 2nd Gen SOV				x		10/1/2018	9/30/2019 (10/31/2019)			
Milestone 2-3 (C)	Data acquisition and analysis covering monitoring period					Q1	10/1/2018	12/31/2019 (1/31/2020)			
Milestone 2-4 (D)	CO_2 plume detection - difference of DAS/SOV surveys					Q2	10/1/2018	3/31/2020 (4/30/2020)			
Milestone 3-1 (A)	Forward modeling based on baseline EM and Seismic datasets using a sequential approach and current LBNL simulation code				x		3/1/2019	9/30/2019 (10/31/2019)			
Milestone 3-2 (B)	Cross-well EM and Seismic Repeat Surveys acquisition					Q2	11/1/2019	3/31/2020 (4/30/2020)			
Milestone 3-5 (C)	Surface-to-Borehole EM Repeat Survey acquisition					Q2	11/1/2019	3/31/2020 (4/30/2020)			
Milestone 3-4 (D)	EM and Seismic feasibility tests for continuous active monitoring during injection (CASSM, CESM)					Q3	11/1/2019	6/30/2020 (7/30/2020)			
Milestone 4-1 (A)	Sonde testing plan development and test-cell fabrication plans. Planned Completion (Reporting) date: Q3 6/30/19 (7/31/19)			x			3/1/2018	6/30/19 (7/31/19)			
Milestone 4-1 (B)	Results of testing of high sensitivity sensor. Planned Completion (Reporting) date: Q4 9/30/19 (10/31/19)				x		3/1/2018	9/30/19 (10/31/19)			
Milestone 4-1 (C)	Report on deployment of sonde in deep well. Planned Completion (Reporting) date: Q3 6/30/20 (7/31/20)					Q3	11/1/2019	6/30/20 (7/31/20)			
Milestone 4-2 (D)	Sensitivity analysis of the high-sensitivity sonde and comparison with baseline technology; outline of tech-to-market pathway for new technology. Planned Completion (Reporting) date: Q4 9/30/20 (10/31/20)					Q4	11/1/2019	9/30/20 (10/31/20)			
Milestone 5-1 (A)	In-situ assessment of the mechanical coupling between formation, cement, fiber and casing			x			4/22/2019	6/30/19 (7/31/2019)			

Gantt Chart (continued)

Task	Milestone Description*	Fiscal Year 2019 Q1	Q2	Q3	Q4	FY20	Planned Start Date	Planned Completion Date (Reporting Date)**	Actual Start Date	Actual End Date	Comment (notes, explanation of deviation from plan)
Milestone 5-2 (B)	Data collection (DSS, P, T) from 01/01/2019 to 01/05/2019			x			4/22/2019	6/30/19 (7/31/2019)			
Milestone 5-3 (C)	Calibration of the hydraulic properties of our numerical model				x		6/30/19	9/30/19 (10/31/2019)			
Milestone 5-4 (D)	Data collection from 01/05/2019 to 01/12/2019				x		9/1/19	9/30/19 (10/31/2019)			
Milestone 5-5 (E)	Comparison with measurements made by the RITE institute using different technology Planned					Q1	TBD	12/31/19 (1/31/2020)			
Milestone 5-6 (F)	Lessons learn on: existing cables design, deployment technology and technology to be used					Q2	TBD	3/31/20 (4/30/2020)			
Milestone 5-7 (G)	Geomechanical numerical simulation using Cami field data					Q2	TBD	3/31/20 (4/30/2020)			
Milestone 5-8 (H)	Development of a new optical cable (TRL4).					Q3	TBD	6/30/20 (7/31/2020)			
* No fewer than two (2) milestones shall be identified per calendar year per task (per previously separate project)											**Note: Milestone reporting accompanies quarterly report, one month after end of quarter.

Bibliography

Currently no publications yet for this Task

Monitoring Technology for Deep CO_2 Injection

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Collaborators

- **Avalon Sciences UK:** Peter Royds
- **Petroleum Research Technology Centre (PTRC):** Erik Nickel
- **Natural Resources Canada (NRCan):** Don White

Geosciences Measurement Facility

LBNL

Custom Instrumentation for Earth, Energy, and Environmental Science Discovery

ptrc Petroleum Technology Research Centre

Aquistore

Natural Resources Canada

ASL Avalon Sciences Ltd

Overview

Goal & Objective

Design, deploy and analyze discrete **wide-bandwidth high-sensitivity optical 3C sensors** on hybrid DAS wireline to ~3 km depth, at or near basement, to monitor for **induced seismicity (IS)** during **deep** CO_2 injection.

Deployment Plan

Deep CO2 monitoring well

<u>Deployment and Acquisition Plan:</u>

- Deploy a 3-level sonde array at ~3 km, with
  - 3C optical accelerometers (9 components)
  - DAS fiber in hybrid cable to surface
  - DAS cemented behind well casing
- Continuous data acquisition for 2 – 3 months with triggered monitoring for microseismic events during injection.

3x 3C optical sondes –
at ~ 3 km

Motivation and Goals

- **Motivation:** Improve risk assessment of **induced seismicity (IS)** for both hazard mitigation and **deep reservoir** management (at or near basement).

- **Monitoring Technology:** Improved sensors would allow data on smaller events, gaining another **order of magnitude of range**, and **higher resolution** on fracture creation events to contribute toward improved hazard assessment.

- **Borehole Instrumentation Goal:** Capture the full dynamic range and bandwidth of induced seismicity at basement depth.

Current Technical Status

Testing phase is underway on LBNL's modified three-level 3C optical USSI sensor array for deep IS monitoring:

- 3C optical accelerometers
- Wide bandwidth, high sensitivity
- Low noise floor

- Upgraded locking-arm sondes
- Hybrid wireline: 18 fiber, 4 conductor

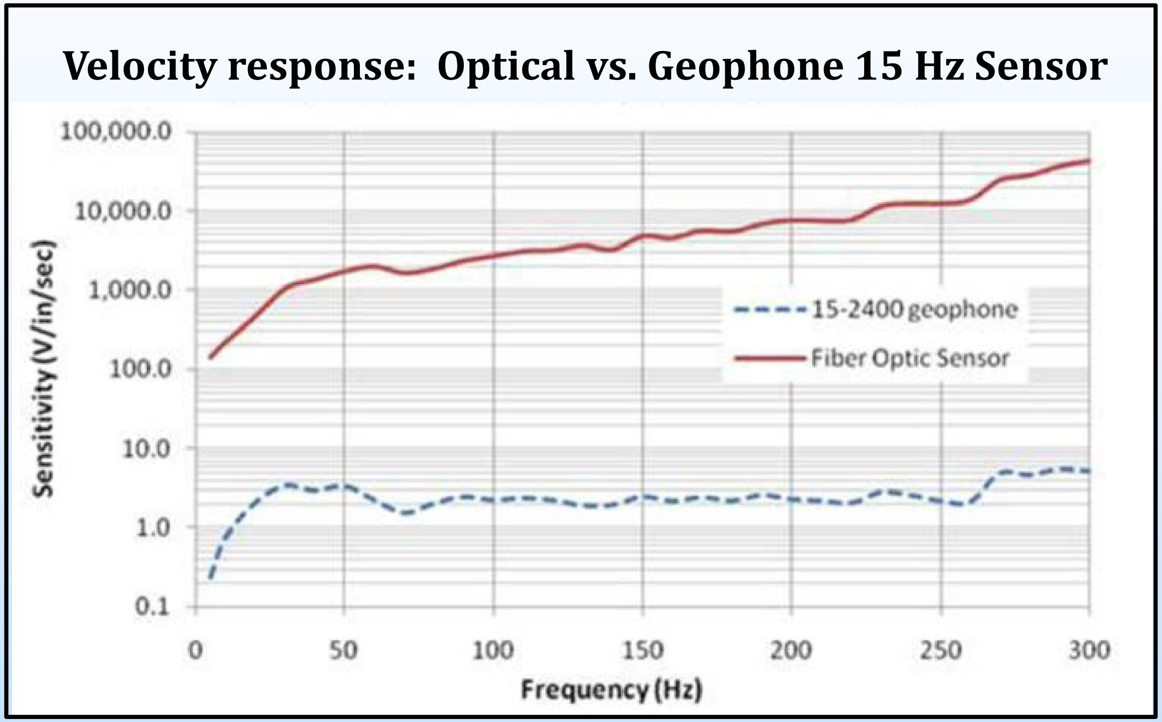
- Shake-table comparisons w/ std accel.
- Pressure and temperature testing
- Systems and software testing

ASL Avalon Sciences Ltd

(USSI now owned by Avalon Sciences Ltd)

Improved Sensitivity over Conventional Sensors

Optical accelerometer array has **2 to 3 orders of magnitude** greater sensitivity as compared to conventional borehole geophone sensors

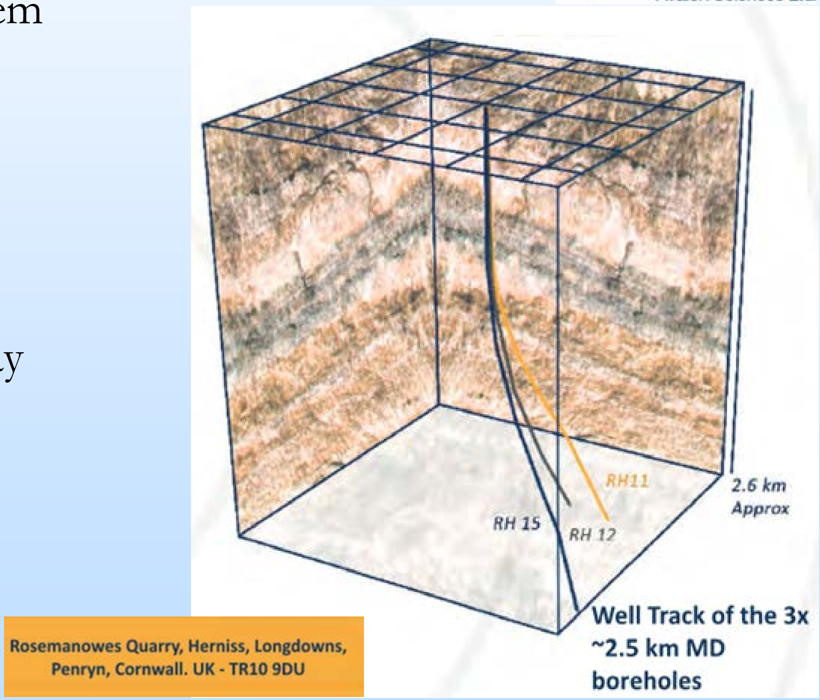


- Frequency range 3 – 600 Hz
- Sample rate 0.25 ms
- Operating temperatures to 150 C
- Operating depths to 3.5 km

Next Steps in FY20

(1) At Avalon Sciences' Rosemanowes borehole test facility

- Test 3-level optical sonde array in a cased borehole (granite)
- Test uphole electronics and acquisition system
- Deploy array up to 2 km deep (max 120 C)
- Surface vibroseis and impulsive sources
- Compare 3C optical array performance to:
    - Permanent borehole 3C geophone array
    - DAS fiber cemented behind casing



Next Steps in FY20

(2) At LBNL's Geosciences Measurement Facility (gmf.lbl.gov):

- Modify locking arms for 3.7-inch ID casing
- Add reference sensor to reduce noise from 3 km cable
- Modify software for remote continuous data acq
- Test trigger parameters for microseismic monitoring
- Test in local shallow wells using LBNL's fiber wireline truck

Geosciences Measurement Facility
LBNL

Aquistore

(3) At Aquistore CO_2 storage site (~3 km depth):

- LBNL's fiber wireline truck onsite
- Deploy the 3-level optical sensor array in OBS well
- Depth ~ 3km, near basement
- Acquire continuous data for 2 to 3 months onsite
- Including fiber behind casing + fiber in hybrid wireline
- Triggered acquisition to capture induced seismicity at depth

Project Summary

- Both carbon sequestration and the oil & gas programs need accurate and comprehensive monitoring for deep microearthquake characterization associated with fluid-induced seismicity.

- **Improved optical accelerometer sensors with hybrid wireline systems** would allow data on smaller events, gaining another order of magnitude of range, and higher resolution on fracture creation events (permeability mapping) to contribute toward improved hazard assessment

Geosciences Measurement Facility
LBNL

Acknowledgments

Funding for LBNL was provided through the Carbon Storage Program, U.S. DOE, Assistant Secretary for Fossil Energy, Office of Clean Coal and Carbon Management, through the National Energy Technology Laboratory (NETL) for the project "Core Carbon Storage and Monitoring Research" (CCSMR) under contract No. DE-AC02-05CH11231.

Appendix

Project Overview

- The Core Carbon Storage and Monitoring Research Program (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:
  - Improve estimates of storage capacity and efficiency
  - Develop 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.

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

Synergy Opportunities

- Carbon storage and monitoring projects
    - Otway project in Victoria, Australia
    - ADM, Illinois
- Fracture monitoring research
    - EGS Collab at the Sanford Underground Research Facility (SURF) mine in South Dakota
    - Mont Terri Research Laboratory, Switzerland
- Passive seismic monitoring

Organization Chart

- **Lawrence Berkeley National Laboratory:**
  - CCSMR co-PIs: Pierpaolo Marchesini and Barry Freifeld
  - Project Lead: Michelle Robertson
  - Engineering Design: LBNL's Geosciences Measurement Facility (GMF)

- **Avalon Sciences Ltd:**

  Optical engineer: Peter Royds

- **Petroleum Technology Research Centre (PTRC) ***

  Aquistore Project Management: Erik Nickel

- **Geological Survey Canada / Natural Resources Canada (NRCan)**

  Seismic monitoring: Don White

* PTRC is operating the Aquistore storage project with seismic monitoring led by Don White's group.

Bibliography

Task 4 is currently in the instrument development and testing stages. Publications of results are planned for FY20.