High-resolution Reservoir Seal Integrity Monitoring Using Optimized Borehole Sources and Distributed Acoustic Sensing

DE-FE0032058

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Dr. Yves Guglielmi (LBNL)
Prof. Tieyuan Zhu (PSU)
Dr. Nader Issa (Terra15 LLC)

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U.S. Department of Energy
National Energy Technology Laboratory
Carbon Management Project Review Meeting
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Project Overview

– Funding
  • DOE: 1.19M (over 3 years)
  • Cost-Share: 707K (Rice, SwissTopo)

– Overall Project Performance Dates:
  • July 1\textsuperscript{st}, 2021 - July 1\textsuperscript{st}, 2024

– Key Participants:
  • Rice University (Jonathan Ajo-Franklin)
  • LBNL (Veronica Rodriguez-Tribaldos, Yves Guglielmi, Michelle Robserston)
  • Penn State University (Tieyuan Zhu)
  • Terra 15 LLC (Nader Issa)

– Overall Project Objectives
  • Develop and test approaches for integrating CASSM & DAS for reservoir seal integrity monitoring.
Key Goals for GCS Storage Security

- **Goal**: Ensure that sealing formations retain integrity for the lifetime of the project, prevent transport of CO$_2$ outside of the storage reservoir.

- If seal integrity is compromised, provide information on the location of the breach (spatial resolution) in a timely manner (early in the process = good time resolution).

- Provide enough information to allow formulation of intervention (leaky fault? Zone of higher perm in seal? Opening tensile fractures?)
The Challenges of Monitoring Seal Integrity

• In contrast with CO$_2$ movement in the reservoir, small leaks in sealing units due to reactivation of faults & tensile fracture opening are a challenging imaging target.

• Clay-rich sealing units can fail aseismically; no microseismic signature of opening.

• Potentially no surface 4D seismic signature until large CO$_2$ volumes have leaked + accumulated in shallower units.

• Need a technique which can ”see” small localized changes in seismic properties.

• Don’t want to see large scale opening via geodesy (sign big alteration is happening)
A Useful Technology: CASSM

CASSM = Continuous Active Source Seismic Monitoring

Fixed repeatable source & receiver array.

- Excellent temporal Resolution (< 5 min)
- Precise repeatability (~10-100 ns)
- Stacking -> Excellent S/N
- Moving towards real-time seismic tomography

Why CASSM for Monitoring Seals?

- Microseismic provides constraints on where faults slip (most of the time): not on slow aseismic processes.
- EQs provide no constraints on fault leakage, healing or creep (long term)

Elastic moduli are locally sensitive to micro-fracture density, stress state; CASSM might access aseismic fault zone evolution

Custom piezoelectric borehole source

[Daley et al. 2007]
[Silver et al. 2007]
[Ajo-Franklin et al. 2011]
[Marchesini et al. 2017]
CASSM for Seal Monitoring? FSB at Mont Terri

- High repeatability/sensitivity makes CASSM ideal for monitoring small velocity changes associated with fault pressurization/reactivation.

- Example from Mont Terri FSB experiment: CASSM monitoring of fault reactivation experiment (w. FSB effort, PI. Y. Guglielmi)

- 5 wells, 24 sources, 48 hydrophones - 570 epochs of data acquired over 3 day experiment, 6 minute temporal resolution.

- Fault patch reactivated through series of brine injections, slip patch imaged through $V_p$ reduction (Shadoan et al. 2021)
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Limitations of CASSM for Long-Term Seal Monitoring

• So what’s missing?

• To achieve good quality data, need semi-permanent dense borehole receiver arrays (as well as sources!).

• Past experiences have shown us that this is challenging with conventional sensors (expensive), particularly in harsh environments (problems scaling hydrophone arrays, point sensors).

• GCS CASSM hydrophone arrays used in past studies (Frio 2, Cranfield) were effective (Daley et al. 2007, Marchesini et al. 2017) but failed during different stages of operation.

• For CASSM to be broadly applicable, need rugged, cost-effective, high density receiver arrays – how?
DAS to the Rescue?

- **Distributed Acoustic Sensing [DAS]** is a rapidly advancing approach for measuring the seismic wavefield using commercial fibers (SM, telecom).

- **Recent**: S/N became sufficient for seismology around 2011. Our work started ~2012/13 out of CO₂ GCS program (borehole applications).

- **Large N**: Easy to deploy in wells, behind casing. 1000s to 100,000s of channels available (big data) over 10+ km (biggest current use is VSP).

- **Very low cost per “sensor”**: $/ft for cable
- **Rugged**: handles high/low T, high pressures.

- **The solution for CASSM?**

**Courtesy Silixa LLC**

Daley et. al. 2016 (Geop Prosp.), Daley et.al. 2013, (TLE)

Pevzner et al. 2021
[Otway]
Challenges of X-well CASSM + DAS for Seal Integrity Monitoring

Despite clear advantages, some challenges

**Frequency Mismatch:**

- DAS often exhibits increasing noise at high (kHz) frequencies, presents a mismatch with high F piezoelectric sources (depends on IU). In theory should be flat in strain …..

- Field application will also require longer propagation distances

**Angular Response:**

- DAS measures extensional strain (or strain-rate), yields a \( \cos^2 \theta \) response pattern.

- Fluid-coupled CASSM sources radiate in the null of conventional receiver sensitivity at S/R offsets.
Technical Approach

**Our Goal:**
Demonstrate that the novel combination of CASSM & DAS can be utilized for monitoring seal integrity for GCS.

**Process:**

*T1:* Develop and validate a new low frequency CASSM source to improve DAS response. (should be small, inexpensive, and suitable for array deployment)

*T2:* Develop an improved processing flow using FWI and coda wave analysis tailored to the measurement combination (evaluate optimal geometries).

*T3:* Test this combination for CASSM monitoring at a well-characterized shallow test site (Rice test facility)

*T4:* Demonstrate efficacy as part of a fault reactivation experiment at Mont Terri underground laboratory.

*T5:* Develop scale-up plan for future deep GCS targets.
# Technical Approach: Milestones

<table>
<thead>
<tr>
<th>Task Number</th>
<th>Deliverable/Milestone #</th>
<th>Deliverable Title/Description</th>
<th>Deliverable/Milestone Planned Completion</th>
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Test of Opportunity: CASSM-DAS dataset with current generation sources

- Had opportunity to evaluate data collected with our chosen IU, grouted fiber, and current CASSM source designs at COLLAB (hard rock, GTO site). Will prior S/N hypothesis be proven correct?
- CASSM sources (~ 1 kHz) in a mesoscale experiment with relevant geometry.
- ~1 km long cable grouted in 4 monitoring wells continuously recording at 36 kHz frequency sampling, spatial sampling of 2.5 m and gauge length of 5 m.

Kneafsey et al. (2022)

Fiber looping through boreholes

CASSM source array
Test of Opportunity: CASSM-DAS dataset with current generation sources

- Data evaluation reveals that DAS records near-source CASSM shots, but signals are below noise floor at reasonable offsets.
- Discrimination based on frequency content is challenging due to broadband optical noise.
- Suggests that more powerful lower F source still required, even with modern DAS units.
Task 2: Development of a DAS-Oriented CASSM Source

**ST 2.1: Design of resonant source matched to DAS:**

- Initial analytical & numerical modeling to develop some plausible source geometries and driving elements.
- Design should allow tuning with small system modifications.

**ST 2.2: Prototyping of CASSM source and laboratory testing:**

- Fabrication of several prototypes and lab testing in a water tank.
- Reference hydrophones & DAS cables for evaluation.
- Compare to numerical models and extrapolation to field response.

**ST 2.3: Fabrication of LF CASSM array for field experimentation**

- Once a good design is developed, fabrication of larger array (~20) for tests
- Plan is to reuse array for tasks 4 & 5.
Progress on Task 2: Development of a DAS-Oriented CASSM Source

- Bulk of Yr 1 focused on constructing lower frequency resonant CASSM sources and evaluating (a) appropriate cavity shape and (b) transducer for excitation.

- Concept of resonant source not new – systems have been developed for marine oceanographic and seismic studies but few (any?) implemented for borehole arrays.

- Original concept: tuned dual—cavity Helmoholtz resonator. Back of the envelope modeling results for 1m split cavity below which would easily fit in a 4” well (3.11” OD). $F_c$ tuned from 1 kHz to 100s Hz.

Gettrust, Wood, & Spychalski, 2004
Task 2: Source Modeling Study

- Before prototyping, conducted series of detailed FEM modeling studies to evaluate realistic geometries (using COMSOL multiphysics).
- Used dual cavity Helmholtz design excited at one end (pressure boundary).
- Designed to fit in 4” well and be of reasonable length for array.
- In model, generated Helmholtz resonance for both cavity components + coupled & length modes.
- Weak modal coupling suggests we can independently spec. lengths.
- Can hit appropriate frequencies for DAS exp!
Task 2: Developed Source Testing Tank

- Developed a lab source testing facility for prototyping.
- ~3’ x 3’ x 4’
- First tests revealed challenges with overall tank resonances.
- Mitigated with bubble wrap (an analog ABC) which reduced reflections by x10.
- Generating good data for controlled projectors.
Task 2: First Prototype, Piezo Driven Resonant Tube

- First prototype: a series of coupled “flooded” (open-ended) tubular resonators. Hoping to start with the simplest system.

- Inspired by sources used in oceanographic surveys with compound (pipes of 2 lengths) used to broaden spectrum.

- Driven by our existing 4” CASSM sources (piezoelectric) - cylindrically poled PZT ring assembly, oil-backed. Element ~1.7” OD.

- Driven by HV amplifier at ~700 V pk-2-pk.

- Unfortunately, this piezo assembly not able to generate a clean signal of sufficient amplitude below about 700 Hz, consistent with field experience.

- Higher modes can be excited (n=3)
Task 2: Second Prototype, Electrodynamic Closed Cavity

• Second prototype: a closed resonance cavity with a planned baffle for Helmholtz resonance.

• Rubber boot to facilitate pressure transfer, filled with inert mineral oil.

• Active element is inexpensive 30 W electrodynamic actuator.

• Better low-end excitation but surprisingly high number of NL modes excited.

• Fundamental length mode excited but broad; suggests some departure from pipe resonance.

• Third prototype: planning air-backed Helmholtz resonator with similar transfer membrane.

• **Overall**: Progress on source development but still a little way to go.
Task 4: Modeling Response at RSTF site

- In preparation for first CASSM/DAS tests at RSTF, developed modeling framework for DAS response evaluation.
- Adapted viscoelastic pseudospectral code (K-wave) to generate strain-rate response with selected gauge lengths.
- Used formulation of Binder et al. (2020) for well parallel strain-rate calculation for arbitrary well trajectory – breaks array into short linear segments.
- First model runs (right, 400 Hz) suggest that direct S at intermediate/high angles might be a good wave mode for imaging.
- Will consider FWI and tomographic optimization for non-zero offset paths.
- PSU working on FWI upgrades for next testing sequence (task 3).

\[ \Delta \phi(s_i) \propto \sum_j \frac{1}{L_g} \frac{(x_{j+1} - x_j) \cdot [u(x_{j+1}) - u(x_j)]}{|x_{j+1} - x_j|} \]

- \( L_g \) = gauge length
- \( u \) = velocity
- \( x \) = location
Plans for future testing/development/commercialization

- Still in prototyping phase, but current scope involves continued laboratory (Task 2) & field testing (Tasks 4/5).
- Task 6 will involve initial design work to transfer specification more suited for deep borehole deployment (higher TRL).
- Task 6 also involves modeling/inversion tests to evaluate scale-up options for deep borehole CASSM systems.
- With design, will explore DOE or commercialization funds for deeper tool development.
• Verified challenges with current generation CASSM sources recorded by DAS using dataset of opportunity (COLLAB)

• Initiated source development process with more realistic modeling runs, verified coupled Helmholtz concept.

• Developed testing tank and two prototype sources based on simple resonance. Still refining details; 3rd prototype is in development.

• Initiated modeling to support Task 4 experiments at RSTF.

• Slow start due to retroactive start date (funds arrived Oct. 2021) and subcontracting snafus.

• Now making rapid progress (several students starting in the fall)
Gantt Chart

- 3 year project involving 6 tasks
- Spans instrument/method development to field validation
- Two field tests, second involving GCS seal leakage component
- Approximately 1 quarter behind schedule due to delay in funding.

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<tr>
<th>Task</th>
<th>Activity</th>
<th>Lead Organization(s)</th>
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<td>1        Q2    Q3    Q4</td>
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<td>Project Quarter</td>
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<td>Q1    Q2    Q3    Q4</td>
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<tr>
<td>Task 1</td>
<td>Project management and planning</td>
<td>Rice</td>
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<td>ST 1.1 Project management plan development</td>
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<td>ST 1.2 Technology maturation plan</td>
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<td>ST 1.3 Team coordination and outreach</td>
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<td>Task 2</td>
<td>Development of a DAS-Oriented CASSM Array</td>
<td>Rice (w. LBNL)</td>
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<td>ST 2.1</td>
<td>Design of resonant CASSM source</td>
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<tr>
<td>ST 2.2</td>
<td>Prototyping of CASSM source</td>
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<td>ST 2.3</td>
<td>Scale up and array fabrication</td>
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<td>Development of CASSM/DAS Processing</td>
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<td>ST 3.1</td>
<td>Timelapse FWI</td>
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<td>Coda wave interferometry</td>
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<td>Proof-of-concept field test at RSTF</td>
<td>Rice (w. LBNL, PSU)</td>
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<td>ST 4.1</td>
<td>Small scale CASSM/DAS validation study</td>
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<td>ST 5.1</td>
<td>Installation/evaluation of test array at Mont Terri</td>
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<td>ST 5.2</td>
<td>Fault reactivation/leakage experiment w. brine</td>
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<td>ST 5.3</td>
<td>Fault reactivation/leakage experiment w. gas</td>
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<td>Task 6</td>
<td>Scale-up Analysis and System Development</td>
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<td>ST 6.1</td>
<td>Source modification for deep GCS deployment</td>
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<tr>
<td>ST 6.2</td>
<td>Modeling/inversion experiments for scale-up</td>
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BACKUP
## Milestones

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Milestones

- **LF CASSM Source Validated**: LF CASSM source deemed to have sufficient low frequency response to be compatible with DAS measurement [Year 1, end of Q4]

- **FWI HiEKF Validation**: Determination that the proposed FWI HiEKF strategy is appropriate for CASSM/DAS analysis using synthetic test data. This outcome will be documented as part of D5 and hinges on sufficient computational efficiency to handle anticipated multi-epoch CASSM datasets [Year 1, end of Q4]

- **CASSM/DAS Concept Field Validated**: Determination that new LF CASSM/DAS combination yields datasets of sufficient SNR for monitoring. Validated by performing initial data Q/C to examine (a) phase repeatability < 500 ns and (b) amplitude repeatability better than 5%. [Year 2, end of Q2]

- **Successful Initial Installation and Performance at FSB Testbed**: Determination that new LF CASSM/DAS combination yields datasets of sufficient SNR for monitoring fault reactivation experiments at Mont Terri. Validated by performing initial data Q/C to examine (a) phase repeatability < 500 ns and (b) amplitude repeatability better than 5%. [Year 3, end of Q1]

- **Successful Initial Processing of FSB DAS/CASSM Dataset**: Successful initial inversions of DAS/CASSM dataset generated during fault reactivation studies. Determined by reasonable misfit of FWI inversions given SNR levels coupled to prior knowledge. [Year 3, end of Q3]
## Appendix: Funding Tables

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CASSM for GCS Monitoring?

- CASSM concept has now been tested several times in a GCS context (Frio 2, Cranfield).
- Frio 2: Borehole seismic source and receiver array downhole and measured seismic traveltime (and attenuation) as a function of time.
- Observed seismic delay introduced by plume moving between the wells.
- After inverse flow modeling, was able to constrain plume geometry and saturation (needed to make some assumptions).
- Subsequent joint analysis of attenuation (Zhu et al. 2017) improved saturation constraints (in the reservoir). But large changes, utility in the seal?

# Risks

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<td>R2</td>
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<td>R3</td>
<td>FWI Computational Efficiency Prevents Effective Use</td>
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<td>R4</td>
<td>Fault cannot be effectively reactivated</td>
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**Task 4 Work Plan:**

**ST 4.1**: Small-Scale validation study of CASSM/DAS combination

- Evaluate source strength/performance using multiple DAS IU designs.
- Evaluate timing/repeatability
- Evaluate response on reference sensors for DAS modeling.

**ST 4.1**: Small-Scale hydraulic test to evaluate time-lapse performance.

- Conduct hydrogeophysical monitoring test to evaluate sensitivity.
- Depress surficial aquifer by 1m, 9 kPa load forcing. Can we see it?

**ST 4.2**: Analysis of small-scale test using developed monitoring algorithms
Task 5: Field Deployment of CASSM/DAS at the Mont Terri Facility

- Crucial evaluation is application to seal integrity experiment.
- Will test integrated approach using new LF source array at the Mont Terri site in Switzerland.
- Several fault reactivation studies already conducted – will use CASSM/DAS approach to monitor the next sequence.
- Significant cost saving from existing site instrumentation and characterization (piggy back on FSB).

- 5 monitoring wells, all with SM/MM fiber
- Bracket fault – can be taken to failure.
- Reference hydrophone arrays (48 ch.)
- Existing 24 source HF CASSM array
- Comprehensive geomechanical monitoring
Task 5: Field Deployment of CASSM/DAS at the Mont Terri Facility

**ST 5.1**: Validation of CASSM/DAS combination at Mont Terri Site

- Evaluate source strength, performance, timing, & repeatability in deep facility.

**ST 5.2**: Fault reactivation/leakage experiment using brine.

- Monitor zone of fault pressurization, leakage, long-term response.
- Attempt to map spatiotemporal velocity changes across fault plane.

**ST 5.3**: Fault reactivation/leakage experiment using gas.

- Similar goal but a focus on CO₂ injection, gas migration.

**ST 5.4**: Processing of fault reactivation experiment datasets.
Task 6: Scale-Up Analysis and System Development

- System described previously target meso-scale experiments, not high P/T reservoir applications.

- Final project task is development of scale-up plan with selected design for deep GCS deployment.

- **ST 6.1**: Develop a larger (yet still *inexpensive*) LF CASSM source design for deep array deployment. Target 3 km depths, 110 C temperatures.

- **ST 6.2**: Conduct modeling/inversion tests to evaluate benefits of CASSM/DAS combination at a larger scale.

- Goal is understanding role of technology in industrial GCS.