Integrated Plume Monitoring using Joint EM-Seismic and Strain Sensing

Project Number: ESD14-095 (Task#3)

Pierpaolo Marchesini, Evan Um
Lawrence Berkeley National Laboratory

U.S. Department of Energy
National Energy Technology Laboratory
DOE NETL’s FE R&D Virtual Review Meeting – Carbon Storage
September 8 - 11, 2020
Coauthors/Collaborators

Co-Authors

David Alumbaugh
Michael Wilt
Edward Nichols
Donald Vasco
Liangze Zheng
Thomas Daley

Acknowledgement

Don Lawton
Kirk Osadetz
Greg Maidment
Presentation Outline

- Why Joint EM-Seismic Geophysical Monitoring?
- Background on CaMI - Field Research Station (FRS)
- LBNL Progresses on Data Analysis:
  - Integrated EM-Seismic System
  - Crosswell EM Data
  - Crosswell Seismic Data
  - Individual Data Inversion
  - Repeat surveys acquisition *Postponed due to Covid-19*
- Next Steps:
  - Framework for Joint-Inversion
  - Repeat Survey Campaigns, dates TBD
Motivation

2011 - White Paper on Field Testing Needs for Geological Carbon Sequestration (Daley et al., 2011) listed 3 priority field tests:

- A deep (supercritical CO$_2$) injection into a high permeability, near-vertical fault or fracture zone
- An intermediate injection simulating secondary accumulation from leakage of gas-phase CO$_2$
- A shallow injection studying groundwater impacts from leakage
Motivation

2011 - White Paper on Field Testing Needs for Geological Carbon Sequestration (Daley et al., 2011) listed 3 priority field tests:

- A deep (supercritical CO$_2$) injection into a high permeability, near-vertical fault or fracture zone
- An intermediate injection simulating secondary accumulation from leakage of gas-phase CO$_2$
- A shallow injection studying groundwater impacts from leakage

Crucial experiment testing monitoring gas-phase CO$_2$ at intermediate depth as an analog for a leak into a ‘thief zone’
Motivation

Crucial experiment testing monitoring gas-phase CO$_2$ at intermediate depth as an analog for a leak into a ‘thief zone’

CaMI/UofC – Field Research Station (FRS)

- A world-leading site for development and demonstration of MMV technologies for fluid containment and conformance
- Undertake controlled CO$_2$ release at 300 m (Phase 1) & 500 m (Phase 2) depth; up to 1000 t/yr
- Determine CO$_2$ detection thresholds for different monitoring technologies
- Improve and develop monitoring technologies for tracking the CO$_2$ plume migration and for cap rock assessment
- Monitor gas migration at shallow to intermediate depths and impacts on intermediate depth groundwater (CO$_2$ and CH$_4$)
- Determine fate of CO$_2$ & CH$_4$ (trapping/dissolution)
- University & industry field training & research
- Integrating engineering and geoscience
- Public outreach & education

From Lawton, 2016
Field Research Station (FRS)

FRS monitoring plan layout

Calgary

CaMI FRS

https://cmcghg.com/cami
Why Joint EM + Seismic?

- Seismic is high-resolution but has uncertainty at high CO$_2$ saturation and uncertainty in rock physics interpretation

- EM has strong sensitivity at high saturations and a single rock physics model (Archie’s relation) to complement seismic

**GOAL**
Ideally combine EM, seismic, and flow models in joint inversion for comprehensive CO$_2$ plume monitoring

Modified from Vasco et al., 2014
Inductive Method: Crosswell EM
Inductive Method: Crosswell EM

1) Time varying (sinusoidal) electric current input into solenoid transmitter
1) Time varying (sinusoidal) electric current input into solenoid transmitter
2) Time varying current produces time varying magnetic field
1) Time varying (sinusoidal) electric current input into solenoid transmitter
2) Time varying current produces time varying magnetic field
3) Time varying magnetic fields ‘induce’ secondary currents in conductive media
1) Time varying (sinusoidal) electric current input into solenoid transmitter
2) Time varying current produces time varying magnetic field
3) Time varying magnetic fields ‘induce’ secondary currents in conductive media
4) Secondary currents generate magnetic fields which are detected along with primary magnetic fields at receivers

Primarily sensitive to conductors
Crosswell Seismic

- Lead-Zirconate-Titanate ceramic rings stack
- Highly durable (lifetime of millions of cycles)
- Highly repeatable
- Broad frequency: Hz to kHz
Required for robustly tracking the movement of CO₂ and defining the boundaries of the CO₂ plume.

From Harris and Langan, 1997
Welcome to the Fully Integrated System

Signal Generation
- Independent GPS Clock
- Control PC
- Signal Generation and Pilot Recording
- Signal Power Amplifier (IGBT)
- Source Well

EM Transmitter / Seismic Source

Recording PC
- EM Lock-in Amplifier / Seismic Recorder
- Receiver Well

EM Receivers / Hydrophones
Optimization at local Field Test Site

- GPS wireless synchronized acquisition between Tx and Rx
- High/Low-frequency system testing with new EM transmitter
- Wireline speed test for autonomous seismic acquisition
Crosswell EM Baseline Survey

• A single fiberglass-steel well pair, interwell spacing is $= 50 \text{ m}$

• Baseline data acquisition:
  • 200 Hz (presented here)
  • 450 Hz (too noisy to use)

• Transmitter interval: 2 m

• Two receivers spaced at 5 m: data from the top receiver used in this work
Crosswell Seismic Baseline Survey

- **Source**: Piezoelectric stack → sweep signal at 350-2500 Hz frequency range

- **Vertical Coverage**: 257 source positions with 0.5 m increment → 128 m

- **Sensors**: Hydrophone array → 20 sensor elements at 5 m spacing

- **Vertical Coverage**: 10 array moves with 0.5 m increment → 99.5 m
Manually find a complex number that removes the casing effects at a given receiver position when the raw data are multiplied by the number
Correction for Steel-Casing Effects

- Manually find a complex number that removes the casing effects at a given receiver position when the raw data are multiplied by the number.
Crosswell EM Inversion (200 Hz)

- Upscaled/averaged resistivity logs are used as constraints
- Well deviation logs are used for correctly positioning sources and receivers
- Sparse receiver locations
- MARE2DEM (K. Key, 2016)
Crosswell EM Inversion (200 Hz)

Starting Model (Half-space)  Amplitude + Phase Inversion (Iteration #2)  Imaginary Component Inversion (Iteration #3)
Crosswell Seismic Geometry

128 m Vertical Coverage

** Showing zoom-in on full coverage (0.5 m spacing)

344 m

300 m

Planned CO₂ Injection Depth

315.5 m

** Showing zoom-in on full coverage (0.5 m spacing)

99.5 m Vertical Coverage

* Showing every 10th source & receiver positions (1% of full coverage)

VE = 0.5x
Crosswell Seismic Inversion

- Inversion based on half-space, homogeneous velocity model
- Initial velocity = 2.517 km/s
- Regularization to match well logs
- Trajectory-based approach that improves upon the eikonal equation approximation over multiple iterations
Crosswell Seismic Inversion

- Many ray-paths bend sharply into high velocity layers.
- Eikonal equation approximation appears to be breaking down.
EM vs. Seismic Inversions

OB1 Well  Un-constrained  With Log Penalty  OB2 Well

Depth [m]

P-Wave [km/s]

Distance [m]

P-Wave [km/s]

Resistivity [Ohm-m]

Delta P-Wave Velocity [m/s]

-600  0  +600

-600  0  +600
CaMI-FRS Updates: Aug. 2020

- 26 Tonnes of CO₂ injected to date (Aug. 2020)
- Switch in injection mechanism: from high rates over short periods of time towards a more constant injection rates over longer times (longest continuous injection time to date = 72 hrs.)
- Increased the injectivity up to 400 kg/week
- Recent acquisition of surface microseismic and active seismic datasets using CaMI permanent geophones array (24 x 3C)
- ERT, DTS, seismic VSP datasets indicate the presence of the injected CO₂. CaMI estimate that the extent of the plume has progressed to the halfway point between OB2 and the injection well
- Canadian border still closed to non-essential travel (Sept. 4, 2020)
Accomplishments to Date

- Continuous collaboration with CMC/CaMI on field site development and monitoring program
- Processed and analyzed EM and seismic baseline surveys
- Development of individual inversion capabilities
- Development of capabilities for forward modeling for repeat survey design
- Optimization of acquisition strategies to minimize field occupancy
- Fully integrated EM-Seismic system (shared wireline, Tx source driver, Rx recording system: raised TRL)
Next Steps

- Repeat surveys during injection: dates TBD according to international travel restrictions.
  - Optimistic plan: late October 2020
  - Realistic plan: April-May 2021

- Acquisition Plan:
  - EM+Seismic crosswell
  - EM surface-to-borehole
  - Seismic (piezo) into DAS
  - DSS (topic merged from Task #5)

- Joint inversion:
  - EM with ERT and STB in single physics approach
  - EM+Seismic multi-physics approach (sequential and joint)

Credits: M. Shevalier, UCalgary
Synergy Opportunities

- **EM**
  - Crosswell EM tomographic survey within BEST (Brine Extraction and STorage) project in Pensacola, Florida. *Michael Wilt, David Alumbaugh, Evan Um, Ed Nichols*

- **Seismic**
  - Crosswell time-lapse tomography and real-time active monitoring of steam/water injection for EOR, Lost Hills, California. *Pierpaolo Marchesini and Chevron*
  - Real-time active monitoring of rapidly-changing fluid pathways at active oil field, Cymric, California. *Pierpaolo Marchesini and Chevron*

- **EM+Seismic**
  - aCQurate Project: multi-physics dataset inversion using code developed by SINTEF (Norway). Hybrid structural-petrophysical joint inversion: robust + quantitative approach. *David Alumbaugh, Evan Um, and Michael Jordan*
    
    https://www.sintef.no/en/projects/acqurate
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

- We thank CMC Research Institutes Inc. for access to the Containment and Monitoring Institute (CaMI) Field Research Station (FRS) and for logistical support during the field campaigns
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;
  - Broader learnings from leveraged international research opportunities;
  - Rapid transfer of knowledge to domestic programs.
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 sweep 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 4 – 5 through leveraged field testing opportunities, with field sites being used as in-situ laboratories.
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 CO₂ 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).
Carbon Management Canada (CMC) organized the Containment and Monitoring Institute (CaMI), led by Prof. Don Lawton (University of Calgary) [https://cmcghg.com/cami](https://cmcghg.com/cami)

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

- **Collaborating 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)

- **Commercial Partners**
  - University of Bristol (UK)
  - University of Calgary (Canada)
  - University of Edinburgh (UK)
  - University of Freiberg (Germany)
  - University of Guelph (Canada)
  - Chevron (USA)
  - Equinor (Norway)
  - Petronas (Malaysia)
  - Shell (UK-Netherlands)
  - Total (France)
<table>
<thead>
<tr>
<th>Task</th>
<th>Milestone Description*</th>
<th>FY20</th>
<th>O1</th>
<th>O2</th>
<th>O3</th>
<th>O4</th>
<th>Planned Start Date</th>
<th>Planned Completion Date (Reporting Date)**</th>
<th>Actual Start Date</th>
<th>Actual End Date</th>
<th>Comment (notes, explanation of deviation from plan)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Milestone 3-1 (A)</td>
<td>Development of sequential and joint inversion capabilities based on baseline EM and Seismic datasets using internally-developed LBNL processing code and external partner contributions (SINTEF, Norway)</td>
<td>Q4FY20</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>7/1/2020</td>
<td>9/30/2020 (10/31/2020)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Milestone 3-2 (B)</td>
<td>Crosswell EM, Crosswell Seismic, and Surface-to-Borehole EM First Repeat Surveys acquisition. Assessment of feasibility for EM and Seismic continuous monitoring during injection using (CESM and CASSM). Tentative reporting date pending the lift of current travel restrictions</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>10/1/2020 (Tentative)</td>
<td>12/31/2020 (1/31/2021)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Milestone 3-3 (C)</td>
<td>DSS dataset acquisition during injection. Tentative reporting date pending the lift of current travel restrictions</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>10/1/2020 (Tentative)</td>
<td>12/31/2020 (1/31/2021)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Milestone 3-4 (D)</td>
<td>Sequential and joint inversion of repeat EM and Seismic datasets</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1/1/2020 (Tentative)</td>
<td>3/31/2021 (4/30/2021)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Milestone 3-5 (E)</td>
<td>Analysis of DSS datasets for strain signature of CO₂ injection and hydro-mechanical coupling</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1/1/2020 (Tentative)</td>
<td>3/31/2021 (4/30/2021)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Milestone 3-6 (F)</td>
<td>Crosswell EM, Crosswell Seismic, and Surface-to-Borehole EM Second Repeat Surveys acquisition</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>4/1/2021 (Tentative)</td>
<td>6/30/2021 (7/31/2021)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Milestone 3-7 (G)</td>
<td>Sequential and joint inversion of second repeat EM and Seismic datasets</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1/6/2021 (Tentative)</td>
<td>9/30/2021 (10/31/2021)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Bibliography

- Daley, T. M., Marchesini, P., Wilt, M., Cook, P., Freifeld, B., Lawton, D.
  Containment and Monitoring Institute (CaMI): Baseline Geophysics for CO\(_2\) Monitoring with Crosswell Seismic and Electromagnetics
  EAGE/SEG Research Workshop on Geophysical Monitoring of CO\(_2\) Injection: CCS and CO\(_2\) - EOR, Trondheim, August 28-31, 2017

- Marchesini, P., Daley, T.M., Wilt, M., Nichols, E., Cook, P.
  Baseline Data for Crosswell Seismic and Electromagnetics at CaMI
  CaMI Research Integration Workshop, Calgary, June 25-26, 2018

- Wilt, M., Marchesini, P., Daley, T.M., Um, E., Cook, P., Nichols, E., Freifeld, B., Lawton, D.
  Crosswell Electromagnetic (EM) and Crosswell Seismic Monitoring of CO\(_2\) Injection: Baseline Field Studies at the CaMI Field Site, Alberta, Canada.
  Greenhouse Gas Control Technologies Conference - GHTT-14, Melbourne, October 21-26, 2018

- Alumbaugh, D., Wilt, M., Um, E, Key, K., Marchesini, P., Daley, T.
  Electromagnetic Monitoring of CO\(_2\) Injection at the CaMI Site
  Containment and Monitoring Institute and CMC Research Institutes Subscriber Workshop, Calgary, August 19-20, 2019

- Marchesini, P., Daley, T., Nihei, K., Wilt, M., Nichols, E, Um, E., Alumbaugh, D.
  CO\(_2\) Monitoring using Cross-well Seismic at CaMI-Field Research Station
  Containment and Monitoring Institute and CMC Research Institutes Subscriber Workshop, Calgary, August 19-20, 2019

- Marchesini, P., Alumbaugh, D., Daley, Wilt, M., Nihei, Um, E.
  Geophysical Survey Design for Monitoring CO\(_2\) Injection at CaMI-FRS
  IEAGHG Monitoring and Environmental Monitoring Research Network Meeting, Calgary, August 21-22, 2019
Um, E.S., Marchesini, P., Wilt, M., Nichols, E., Alumbaugh, D., Vasco, D., Daley, T.M., and Key, K.
Joint Use of Crosswell EM and Seismic for Monitoring CO₂ Storage at the Containment and Monitoring Institute Field Site (CaMI): Baseline Surveys and Preliminary Results
SEG Extend Abstracts, 90th SEG Annual Meeting, October 11-14, 2020, Houston, TX

Um, E.S., Kim, J., and Wilt, M.
3D borehole-to-surface and surface electromagnetic modeling and inversion in the presence of steel infrastructure
Geophysics, 85(5), 1-54 (2020)