ROBUST IN SITU STRAIN MEASUREMENTS TO MONITOR CO$_2$ STORAGE

Project Number FE0028292

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Scott and Marvin Robinowitz, Grand Resources
Robust Borehole Strainmeter

• Downhole electronics
  – Cost
  – Power
  – Heat
  – Lightning
  – Water
  – Corrosion
  – Data transmission

• Robust→Optical
  – Distributed
  – Point

Gladwin borehole strainmeter
Project Goals and Tasks

1. Instrumentation
   - Point strain; ultra-high resolution, multi-component strain + tilt
   - Distributed strain; high resolution, spatial distribution
   - Temporal; DC→kHz; Tectonic ←→ seismic

2. Strain Interpretation
   - Relevant injection scenarios
   - Analytical solution
   - Inversion applications

3. Field Demonstration
   - Deploy instruments in field injection setting
   - Acquire data, interpret

Outline
- Technical Status
- Accomplishments
- Lessons Learned
- Synergy
- Summary
Michelson Interferometers

- Coherent light source (laser) input
- 3x3 splitter to divide input light
- Faraday mirrors
  - Polarization insensitive
- Phase-shifted interference fringes
  - Directional fringe information
- Real-time digital demodulation
Task 1: Single-Component Instruments

Embedded Areal Strainmeter “Smart Casing”

- Integrated reference
- Adapts to standard pipe
- “Open-Closed” design
  - Open at top
  - Closed at bottom
- “Open-Open” design
  - Open at both ends

Fiber-wrapped casing

Open top

Fully open
Task 1: Multi-Component Instruments

Horizontal tensor strainmeter (nested areal)
- Closed downhole package
- Fully potted interior, welded exterior

Input/Output Fiber
Upper Centralizer
Fiber-Wrapped Sensing & Reference Mandrel Pair
Integrated Counterweight

Design

Sensing element
Reference element
Fiber-wrapped tubes
Prototype
Task 1: Multi-Component Instruments

Horizontal tensor strainmeter (nested areal)
- Closed downhole package
- Fully potted interior, welded exterior

Design:
- Input/Output Fiber
- Upper Centralizer
- Fiber-Wrapped Sensing & Reference Mandrel Pair
- Integrated Counterweight
- Lower Centralizer
- Sensing element
- Counterballast
- Reference element

Prototype:
- Fiber-wrapped tubes
Task 1: Multi-Component Instruments

Horizontal tensor strainmeter (inclined wraps)
- Demonstrated proof-of-concept (single-component)
- Measure full strain tensor in “Smart Casing”

Dead-weight load tester
- Repeated load response to increasing mass
- Rotate sensor to get load sensitivity as a function of borehole package azimuth
Task 1: Multi-Component Instruments

Automated Dead-Weight Calibrator
- Repeated loading at a given weight
- Automated load indexing (10 @ 5 lbs)
- Manual azimuth indexing...

Indexing Mechanism

Carriage

Lifting Mechanism

Main Frame

Weight Stack

Loading Frame

Strain Sensor
Task 1: Multi-Component Instruments

Optical Fiber Michelson Interrogator

- 9-36 Volt operation, ~2.25 Watt
- 3” diameter pressure case

Fiber Cable Input
Photodetector Daughterboard
Laser Current Source
Electrical Cable Input
Power Distribution Board
ADC
Laser and Mount

1-channel board
2-channel board
3-channel board
Microwave Photonics
A new optical fiber distributed sensing technology

Optical Carrier Microwave Interferometry (OCMI)

- Use microwave (GHz frequency) to modulate light
- Optical fiber with reflectors fabricated by femtosecond laser micromachining
- Interferometers from pairs of reflectors
- The microwave signal is used to locate the reflectors
- The optical signal is used to measure displacement between reflectors
Microwave Photonics
Static-Dynamic Strain

Original OCMI
- ~1 \( \mu \varepsilon \), microwave interference

Recent Advances
- Light source → coherent
- Coherent Microwave Photonic Interferometry (CMPI)
  - New algorithm, read optical interference phase
- Interrogator
  - Portable, remote access, non-proprietary

Current Performance
- Displacement of ~1 nm
- Strain depends on spacing of reflectors
  - 0.1 \( \mu \varepsilon \) over 1 cm, 1 \( \mu \varepsilon \) over 1 m
- DC to 20 kHz
Proof-of-concept CMPI lab experiments
Static $\rightarrow$ Dynamic Loading

Column with axial pipe filled with sand

- Reflectors spaced 0.15 m apart as sensors to measure strain at 7 locations along a pipe in sand
- Static load on casing, sand
- Dynamic load, multiple frequencies from acoustic source on pipe
Proof-of-concept CMPI lab experiments
Static Loading

Static strain:
- Linear with load
- Decreases with depth
- Stiffness consistent with PVC at S1
- Increase stiffness with depth due to friction with sand
Proof-of-concept CMPI lab experiments

Dynamic Loading

Dynamic strain:

- Acoustic spectra at 7 sensors, 0.1 to 3 kHz
- Amplitude decrease w/depth similar to static
Task 2. Strain Interpretation

Subtask 2.1. Pressure distribution
Subtask 2.2. Leakage
Subtask 2.3. Ambient processes
Subtask 2.4. Data reduction, filtering
Subtask 2.5. Model-based interpretation
stochastic inversion

Concept
Gas saturation $\rightarrow$ Compressibility
Compressibility $\rightarrow$ Strain
Gas saturation $\rightarrow$ Strain

Results
Horizontal strain affected
Vertical strain larger, but relative change less
Magnitude increases with $S_{\text{CO}_2}$
Magnitude and phase with location
Detect with cross-spectrum analysis
Task 3. Field Experiment

- **Objective**: Measure/interpret strain during waterflood as analog to CO2 injection
- **Location**: Bartlesville Sandstone, Pennsylvanian North Avant Field, Osage County, OK 100+ years of oil production

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Permeable sand isopach

Drilling at AVN location

Installing strainmeter

Strainmeters at Avant Field
Accomplishments to Date

Point strain measurement, Fiber interferometer
- Monolithic tiltmeter designed, built, lab tested
- 2 areal “smart casing” strainmeters designed, built
- 2 tensor strainmeters, designed, built

Distributed strain, Microwave photonics
- New light source, New algorithm
- High resolution strain, static → 20 kHz
- Non-proprietary field interrogator
- Lab demo
Lessons Learned

High sensitivity

- Fiber packaging — armoring/coupling
- Noise — detect everything
- Calibration — limit noise

Scaling to:

- Multiple instruments
- Multiple components per instrument
- Field-based interrogator
Project Summary

Point Strain, Fiber Interferometers
- Monolithic tiltmeter, biaxial, high resolution
- Wrapped tube, ultra high resolution, component for tensor

Distributed Strain, Microwave Photonics
- High resolution static strain → seismic frequency
- Non-proprietary gear

Next Steps
- Refine instruments, lab → field
- Field tests
- Theoretical analyses
Mandatory Slides
Benefit to the Program

Program goals being addressed

**Carbon Storage Goal**: Develop and validate technologies to ensure 99 percent storage permanence

**SubTER Pillar 2**: Subsurface stress and induced seismicity

**SubTER Pillar 4**: New subsurface signals

Benefits statement

The proposed project will contribute to *Area of Interest 1 – Field Demonstration of MVA Technologies* by demonstrating a method that would improve the ability to track changes in pressure and strain in order to identify possible release pathways. Broadband, high-resolution strain is a new signal that has seen limited use in CO\textsubscript{2} storage or geothermal exploration, largely because of limitations in instrumentation and data analyses. This research will develop methods for measuring and understanding this signal, and as such will provide a secondary contribution to Area of Interest 2, as well as broader applications to the four pillars of the SubTER mission for improving understanding of subsurface processes.
Project Overview: Goals and Objectives

**Ultimate goal:** develop and demonstrate technology that can measure and interpret in-situ strain signals to improve understanding and reduce risk during the CO₂ injection processes.

1. **Instrumentation.** Refine and develop prototype instruments that can measure small in-situ strains at low cost with minimal use of downhole electronics and electrical power.

2. **Strain Interpretation.** Anticipate the strains caused by injection, and interpret strain data associated with injection of CO₂, and other related processes.

3. **Field Demonstration.** Demonstrate the use of low-cost, low-power, robust strainmeters during a commercial-scale injection project analogous to CO₂ storage, and interpret the resulting data.
## Gantt Chart

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<th>BP 2</th>
<th>BP 3</th>
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<td>2.2 Distributed instruments</td>
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<td>2.3 Multicomponent instruments</td>
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<td>3.3 Ambient Process</td>
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<td>4.4 Ambient processes</td>
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<tr>
<td>4.5 Data analysis</td>
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Bibliography


- DeWolf, S. and L.C. Murdoch. Clemson University Patent Disclosure 2018-037: An optical device to measure one or more strain components in subsurface formations (DE-FE0023313 and DE-FE0028292)

Additional Slides
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Task 1: Single-Component Instruments

Monolithic Tiltmeter
- Passive, no leveling
- Full vector

Design
Prototype

![Diagram of Monolithic Tiltmeter]

- Upper Cap
- Pendulum Mount
- Pendulum Rod
- Mount with Optical Components
- Pendulum Mass
- Lower Cap

![Graph showing Tilt Sensitivity vs. Tilt Azimuth]

- Free Period

![Graph showing Magnitude vs. Frequency]

- $x$-Tilt
- $y$-Tilt
Microwave Photonics

Characteristics
- Spatially continuous, fully distributed sensing.
- High spatial resolution (>1cm)
- Flexible gauge length (1cm – 100m)
- Long reaching distance (~km)
- Material and mode independent (glass, polymer, sapphire single-mode and multimode)
- Reflectors → High signal:noise ratio
- Standard (non-proprietary) optical electronics

Sensitivity
- Incoherent light source: με but large dynamic range
- Coherent light source: nε but small dynamic range

Dynamic measurement
- tested up to 20kHz