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

Project Number  FE0028292

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Robust Borehole Strainmeter

- Downhole electronics
  - Cost
  - Power
  - Heat
  - Lightning
  - Water
  - Corrosion
  - Data transmission

- Robust → Optical
  - Distributed
  - Point
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
Project Goals and Tasks

1. Instrumentation
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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

Monolithic Tiltmeter
Passive, no leveling
Full vector

Design
Prototype

Free Period

Magnitude (radians)

Frequency (Hz)
Task 1: Single-Component Instruments

Embedded areal strainmeter

“Smart” casing

Dedicated sensing element

Fiber-wrapped casing

M 7.7 - 198km ESE of Nikol’skoye, Russia
Task 1: Multi-Component Instruments

Horizontal tensor strainmeter (nested areal)
Closed downhole package

Design

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

Fiber-wrapped tubes
Prototype
Task 1: Horizontal Tensor Strainmeter

Von Mises stresses in deformed coordinates using reasonable values for elastic parameters.

Response from interferometers estimated by integrating hoop strain around circle where fiber will be wrapped.
Microwave Photonics
A new optical fiber distributed sensing technology

- 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

OCMI (Optical Carrier Microwave Interferometry)
Microwave Photonics
Static Strain Resolution

Original OCMI  ~1 με, microwave interference

Recent Advances
- Light source→coherent
- New algorithm, use optical interference

Current Performance
- Detect displacement of ~1nm
- Strain depends on spacing of reflectors:
  - 0.1 με over 1cm, 1 nε over 1m
Microwave Photonics
Frequency Resolution

Original OCMI ~1Hz

Recent Advances
New algorithm
Current Performance
~4kHz

Pressurized 2-inch pipe wrapped with optical fiber
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 4kHz
Task 2. Strain Interpretation

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

Strain field (scale is log(strain magnitude)) in the vicinity of an elliptical zone pressurized by 1 kPa (~0.2 psi) at 1 km depth in rock with $E = 10$ GPa. Elliptical region is 400 m by 20 m thick.
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

Coarse-grain sand isopach

Drilling at AVN location

Strainmeters at Avant Field, July 2017

Installing strainmeter
Accomplishments to Date

– Point strain measurement, Fiber interferometer
  Monolithic tiltmeter designed, built, lab tested
  Volumetric strainmeter designed, built, field tested
  Tensor strainmeter designed, fabrication in progress

– Distributed strain, microwave photonics
  New light source, New algorithm
  High resolution strain up to 4kHz
  Resolve static strains, seismic, high SNR
Lessons Learned

Lab→ Field Challenges

- Fiber packaging
- Power, 12VDC
- Temperature
- Environmental
- Coupling to rock
- Calibration
- Telemetry
- more....
Synergy Opportunities

- CO₂ applications
  - Stress state
  - Wellbore integrity
  - Microseismicity, active seismics

- CO₂ collaborations
  - Field tests

- Other synergy
  - Geodesy (tectonics, glaciers...)
  - Natural hazards (earthquakes, volcanos, landslides...)
  - Hydrology (subsidence, storage change...)
  - Infrastructure (bridges, buildings...)

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Aug 2, 2017  NETL Carbon Storage Review
### Project Summary

**Distributed Strain, Microwave Photonics**
- High resolution static strain, also sample at seismic frequency
- Non-proprietary gear

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

**Next Steps**
- Refine instruments, lab → field
- Field tests
- Theoretical analyses
Microwave-Photonics Approach

- Microwave to locate the positions of the distributed reflectors on the fiber
- Optical signal to find the distance between the reflectors,
  - strain, temperature and pressure
Optical Fiber Instrumentation

• Key advantages:
  - Inexpensive ($0.15 per meter), components ($20 to $120)
  - Completely passive (only optics downhole)
  - High resolution

• Primary disadvantages:
  - Temperature coefficient (~20 ppm/°C)
  - Need to be packaged/embedded to improve robustness
Task 1: Optical Instrument Development

a) Single-component instruments
   Michelson interferometer

b) Multi-component instruments
   Michelson interferometer or microwave photonics

c) Distributed strainmeters
   Microwave photonics
Borehole Strainmeter
Michelson Interferometer

External packaging, armor
Optical Fiber Instrumentation

System components:

1. **Sensing head** is exposed to environment (strain, temperature)

2. **Optical Fiber cable** communicates between interrogator and sensing head

3. **Interrogator** reads signal from sensing head
Optical Fiber Interrogator

- **Light source** to illuminate sensing head
- **Photodetector** to convert returning light to voltage
- **Signal processor** to convert detected light into electronic output proportional to desired measurement (strain, temperature)
Clemson Tensor Borehole Strainmeter/Tiltmeter

- Removable and expendable (grout-in) configurations
- 3 normal strains, 2 tilts
- Commercial eddy current sensors
Task 1: Horizontal Tensor Strainmeter

Configuration of materials

Mesh
Task 1: Horizontal Tensor Strainmeter

Von Mises stresses in deformed coordinates using reasonable values for elastic parameters.

Response from interferometers estimated by integrating hoop strain around circle where fiber will be wrapped.
Task 1: Horizontal Tensor Strainmeter

Volumetric strain of components for different orientations of principal stresses. Interaction between neighboring tubes gives unique orientation dependence.

Scaled length change from each interferometer as a function of orientation to principal stresses.
Task 1: Multi-Component Instruments

Embedded tensor strainmeter
  Casing segment(s)

Multi-gauge tensor strainmeter
  Closed downhole package