ROBUST IN SITU STRAIN MEASUREMENTS TO MONITOR CO_2 STORAGE

Project Number FE0028292

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U.S. Department of Energy

National Energy Technology Laboratory

Mastering the Subsurface Through Technology Innovation, Partnerships and Collaboration:
Carbon Storage and Oil and Natural Gas Technologies Review Meeting

August 13-16, 2018

Robust Borehole Strainmeter

- Downhole electronics
  - Cost
  - Power
  - Heat
  - Lightning
  - Water
  - Corrosion
  - Data transmission
- Robust→Optical
  - Distributed
  - Point

Gladwin borehole strainmeter

Project Goals and Tasks

Michelson Interferometer

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

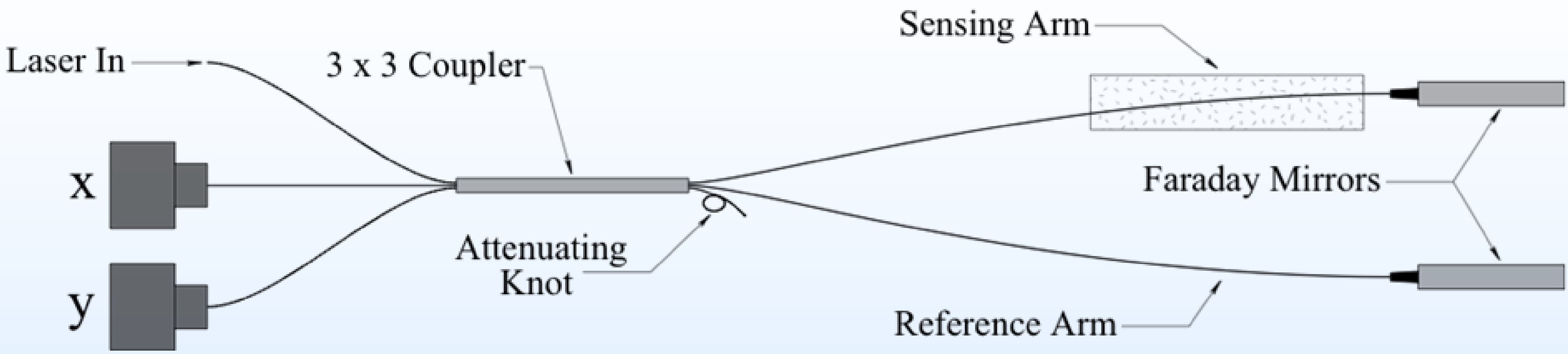
Microwave Photonics

2. Strain Interpretation
   - Relevant injection scenarios
   - Analytical solution
   - Inversion applications
3. Field Demonstration
   - Deploy instruments in field injection setting
   - Acquire data, interpret

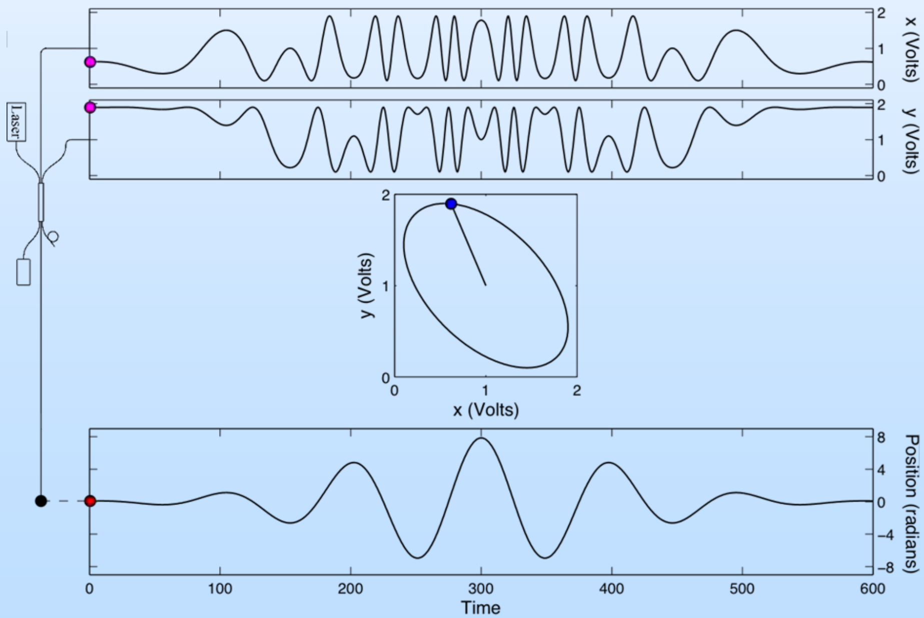
<u>Outline</u>

- Technical Status
- Accomplishments
- Lessons Learned
- Synergy
- Summary

Michelson Interferometers



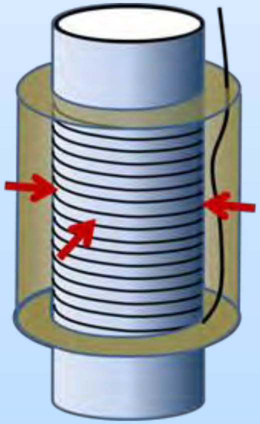
- Coherent light source (laser) input
- 3x3 splitter to divide input light
- Faraday mirrors
  - Polarization insensitive
- Phase-shifted interference fringes
  - Directional fringe information
- Real-time digital demodulation



Task 1: Single-Component Instruments

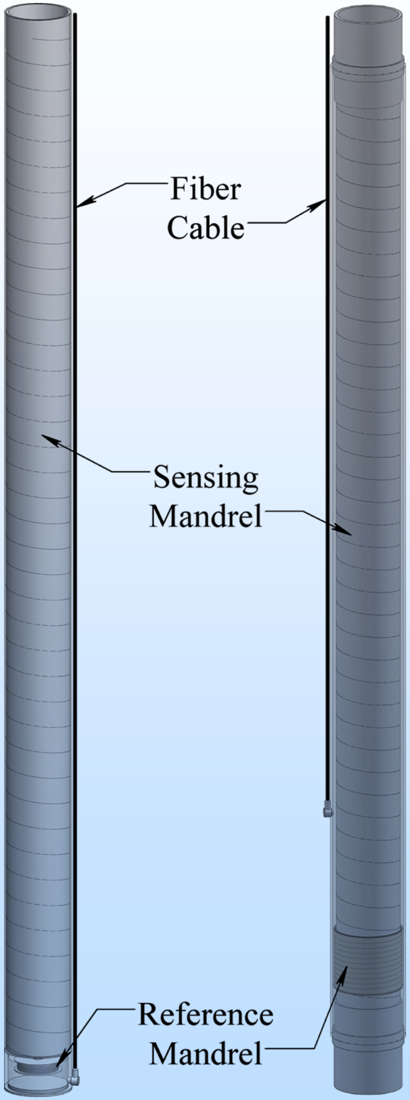
Embedded Areal Strainmeter "Smart Casing"

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

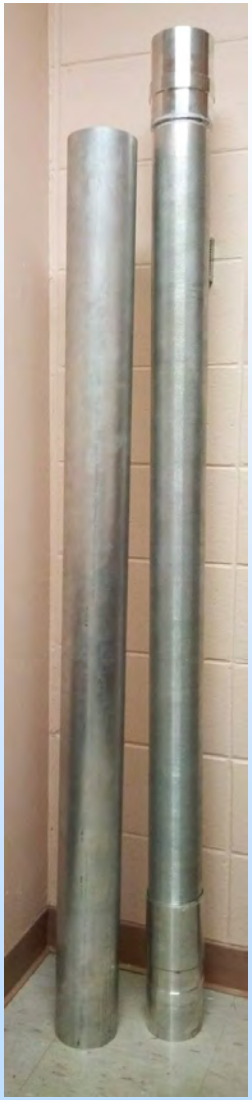


Fiber-wrapped casing

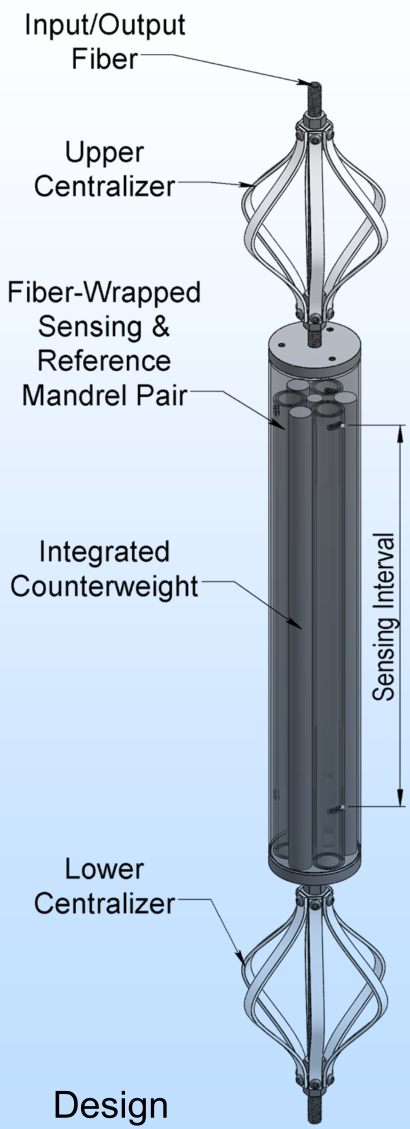
Open top

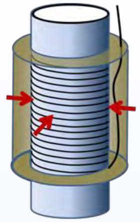


Fully open



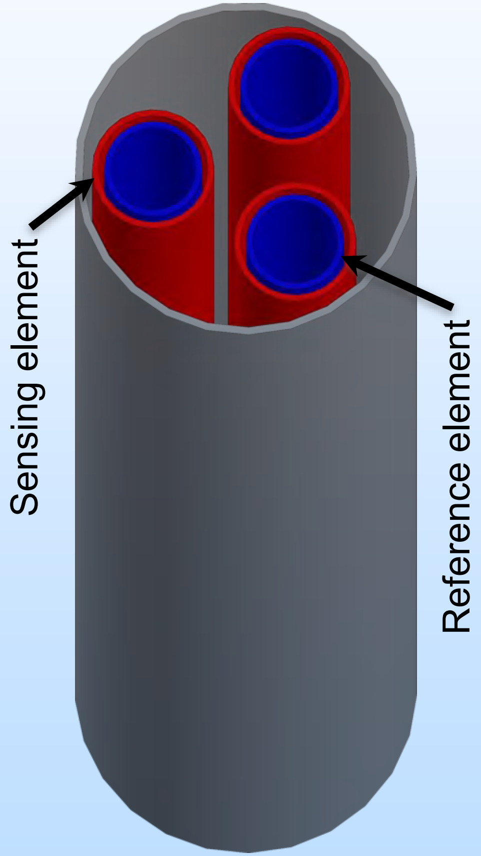
Task 1: Multi-Component Instruments





Horizontal tensor strainmeter (nested areal)

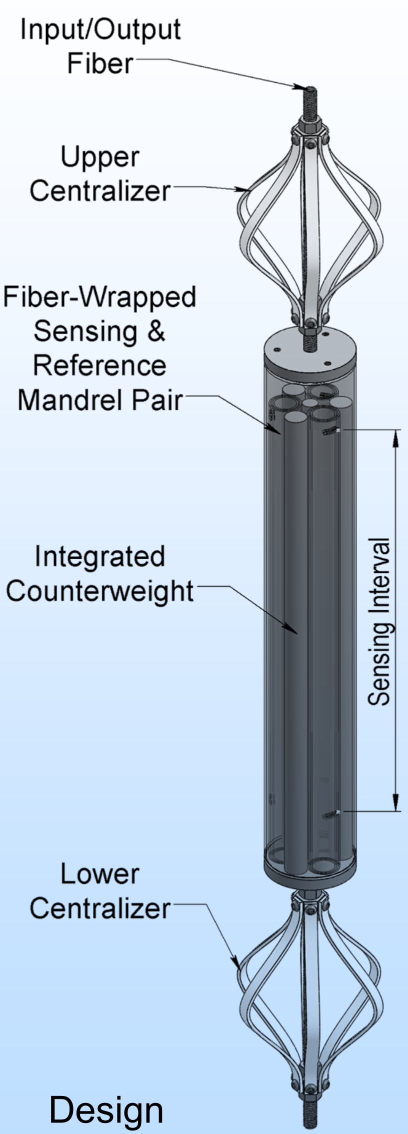
- Closed downhole package
- Fully potted interior, welded exterior

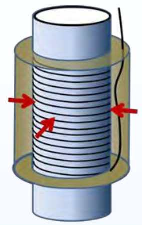


Fiber-wrapped tubes

Prototype

Task 1: Multi-Component Instruments





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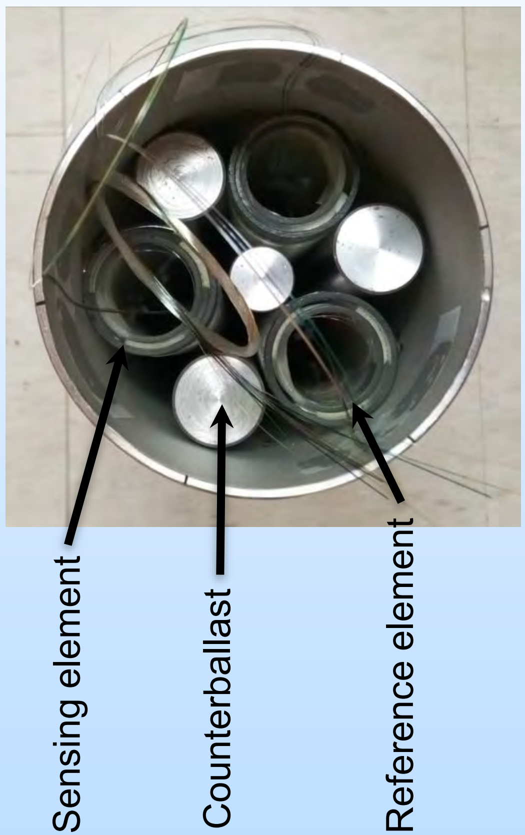

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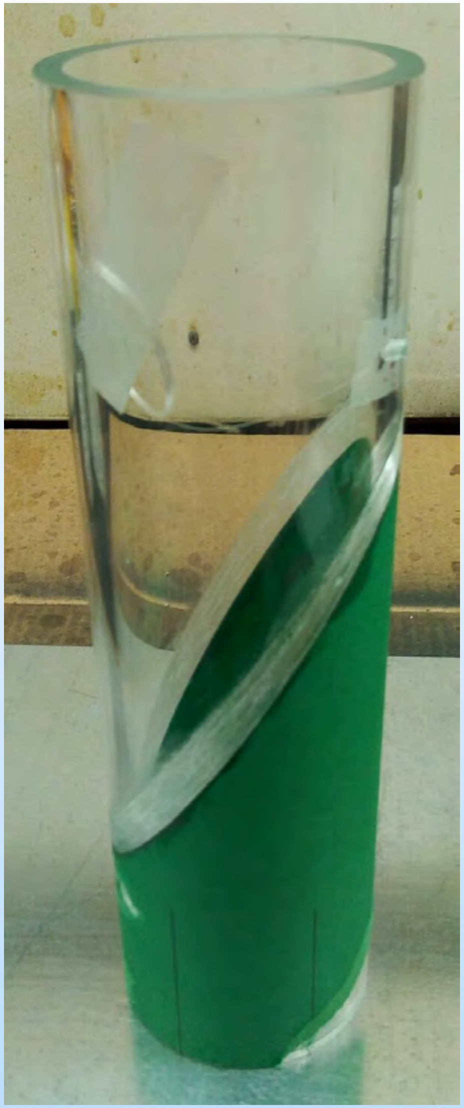
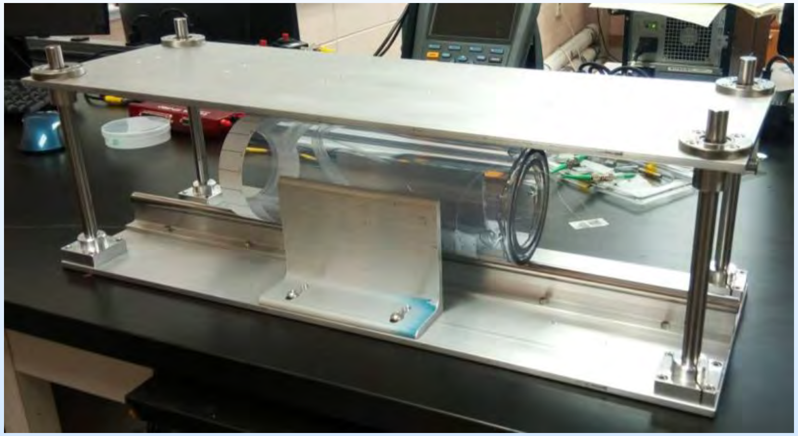
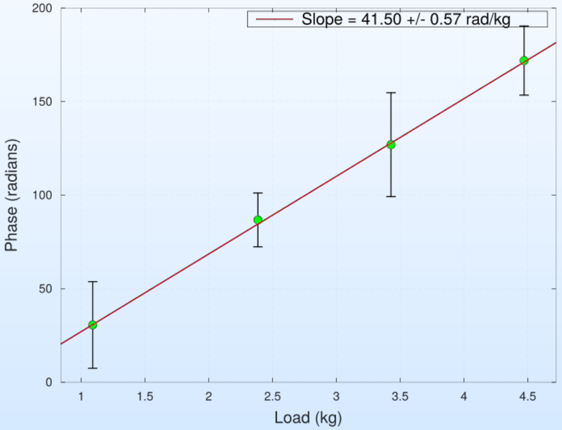


Horizontal tensor strainmeter (inclined wraps)

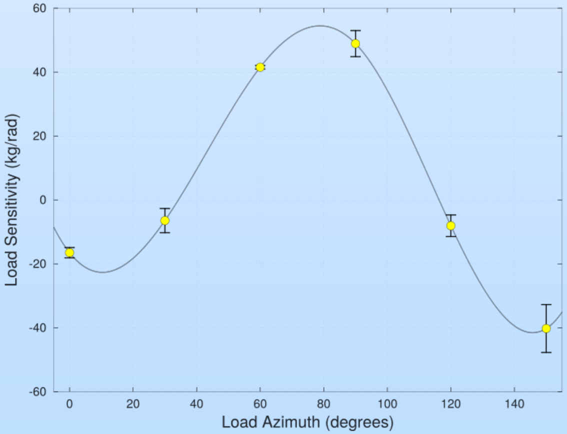
- Demonstrated proof-of-concept (single-component)
- Measure full strain tensor in “Smart Casing”





Dead-weight load tester

- Repeated load response to increasing mass
- Rotate sensor to get load sensitivity as a function of borehole package azimuth



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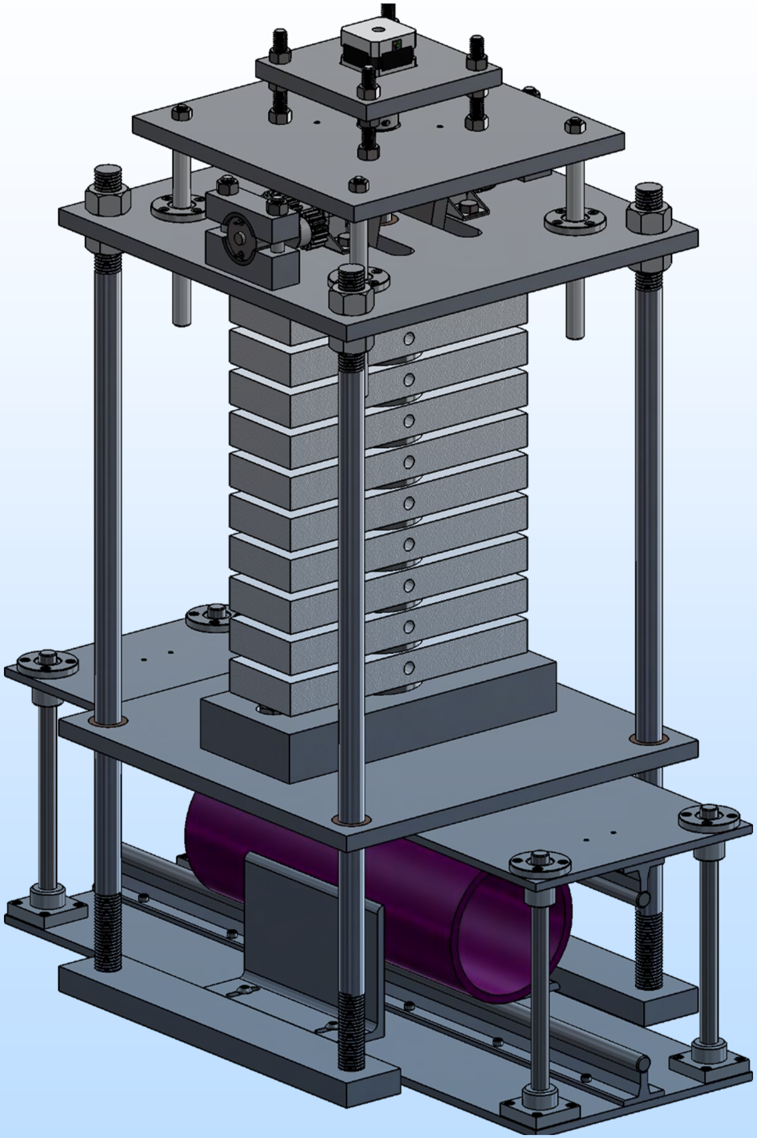
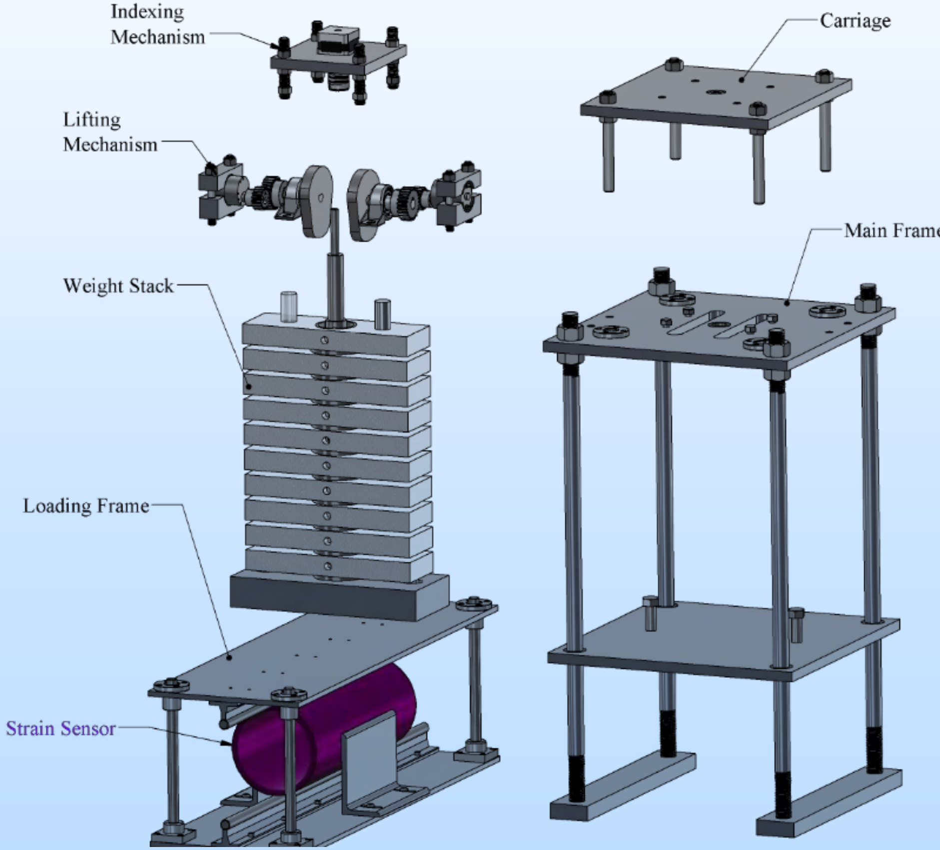


Automated Dead-Weight Calibrator

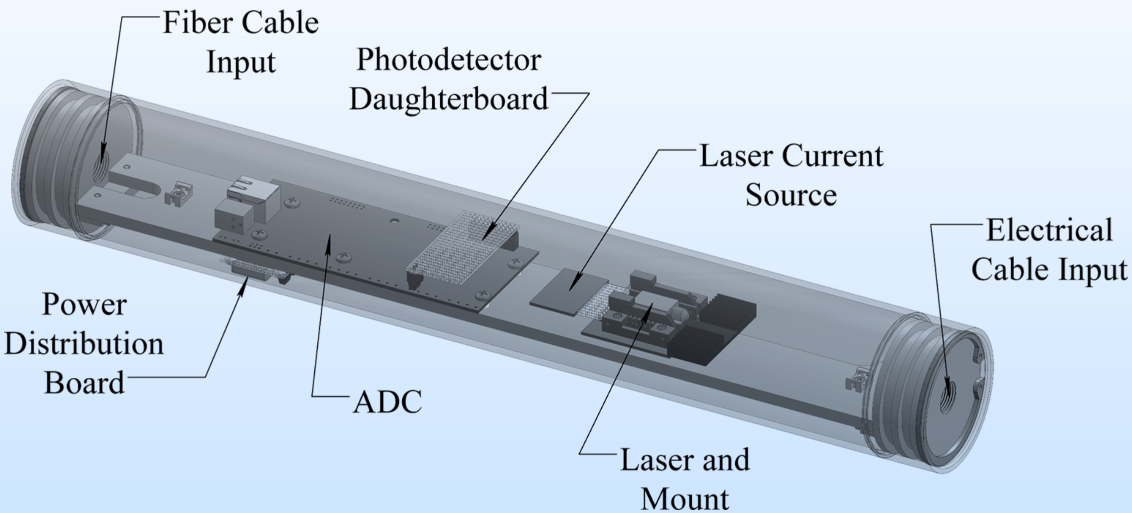
- Repeated loading at a given weight
- Automated load indexing (10 @ 5 lbs)
- Manual azimuth indexing...

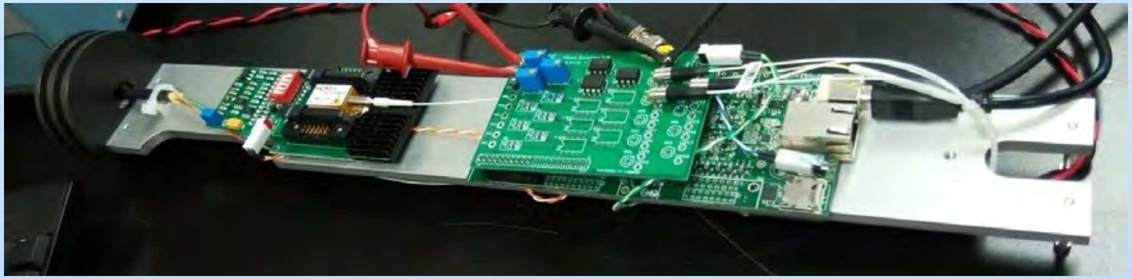


Task 1: Multi-Component Instruments

Optical Fiber Michelson Interrogator

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





1-channel board

2-channel board

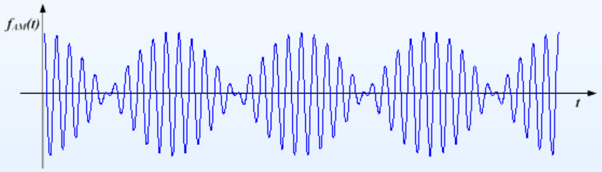
3-channel board

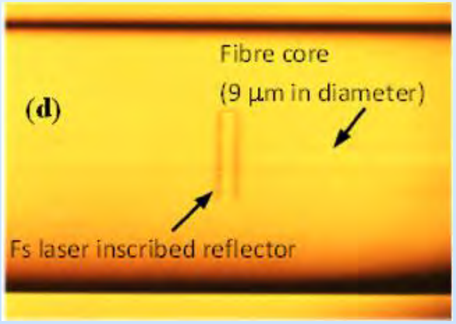
Microwave Photonics

A new optical fiber distributed sensing technology

Optical Carrier Microwave Interferometry (OCMI)

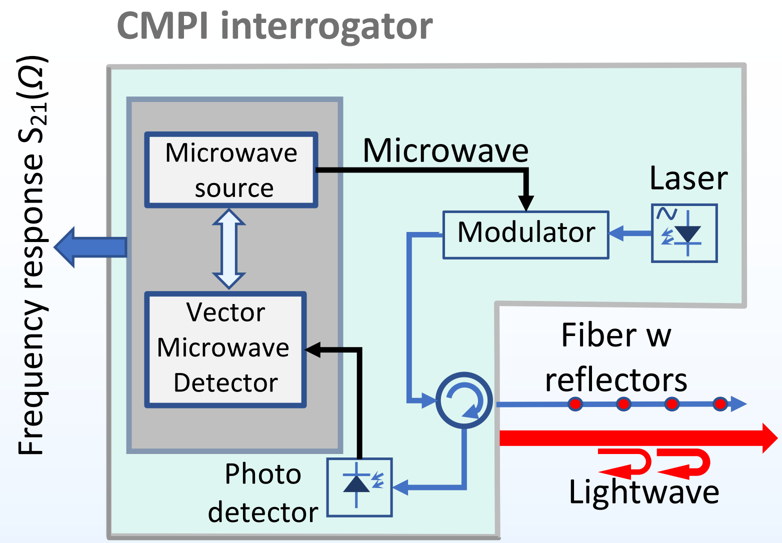
- Use microwave (GHz frequency) to modulate light
- Optical fiber with reflectors fabricated by femtosecond laser micromachining
- Interferometers from pairs of reflectors
- The microwave signal is used to locate the reflectors
- The optical signal is used to measure displacement between reflectors





Reflector in optical fiber

Microwave Photonics
Static-Dynamic Strain



Original OCMI
- ~1 με, microwave interference

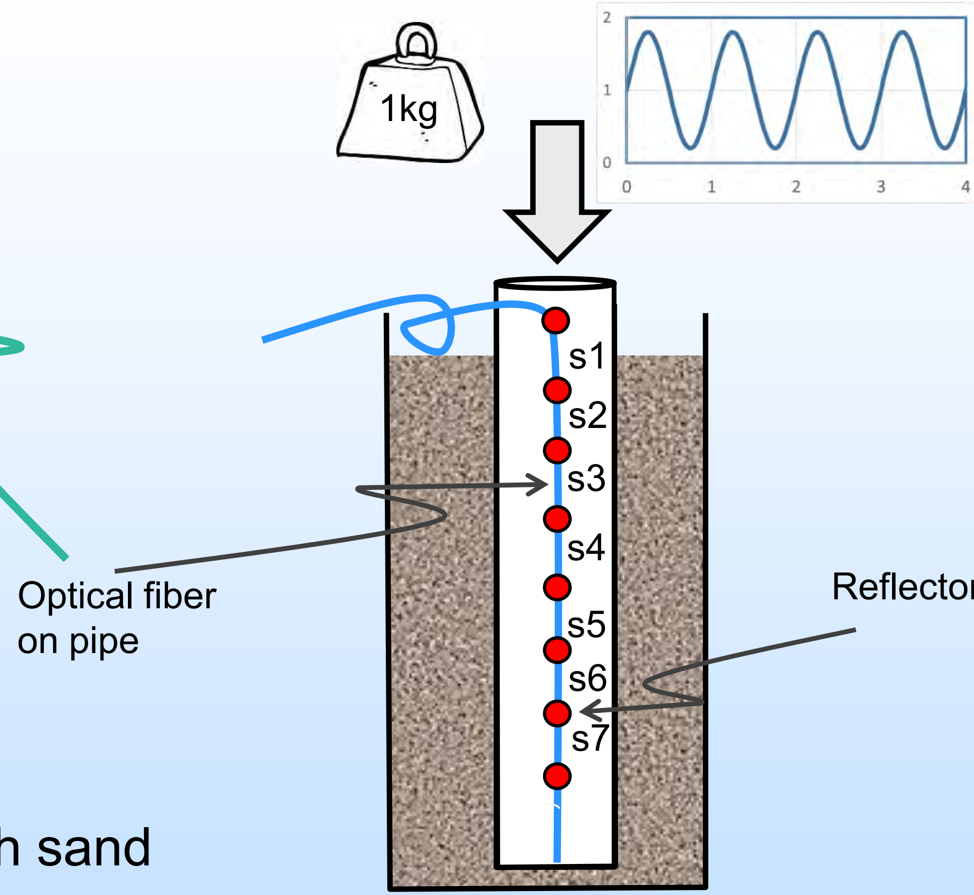
Recent Advances
- Light source → coherent
- Coherent Microwave Photonic Interferometry (CMPI)
  - New algorithm, read optical interference phase
- Interrogator
  - Portable, remote access, non-proprietary

Current Performance
- Displacement of ~1 nm
- Strain depends on spacing of reflectors
  - 0.1 με over 1 cm, 1 nε over 1 m
- DC to 20 kHz

Prototype CMPI Interrogator

Proof-of-concept CMPI lab experiments

Static → Dynamic Loading

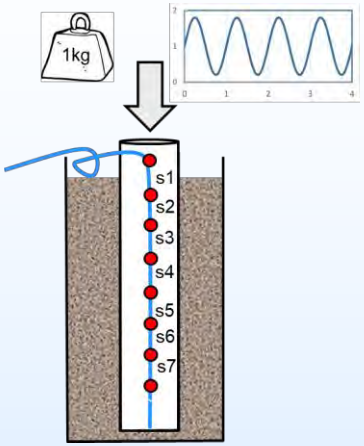


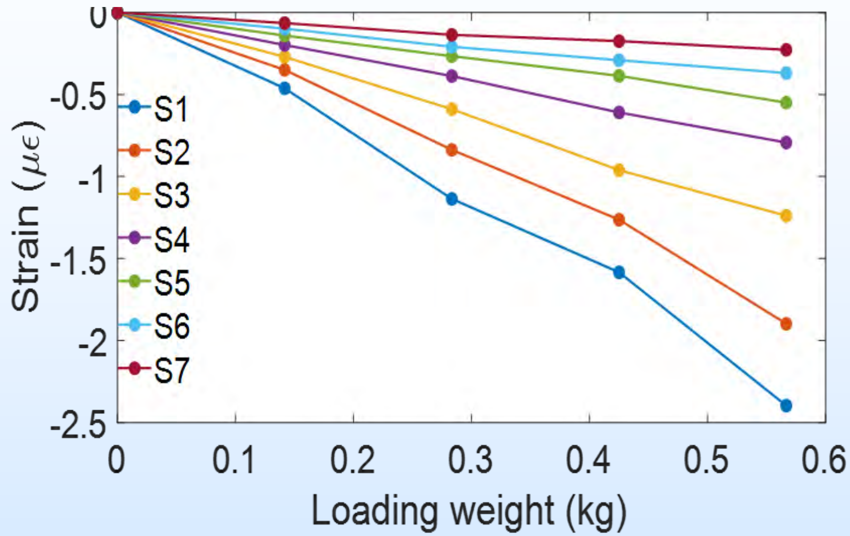
Column with axial pipe filled with sand

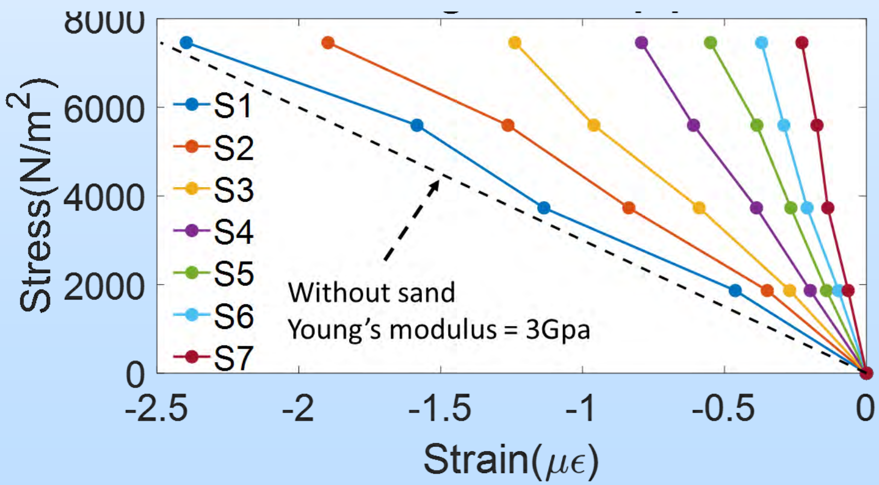
- Reflectors spaced 0.15 m apart as sensors to measure strain at 7 locations along a pipe in sand
- Static load on casing, sand
- Dynamic load, multiple frequencies from acoustic source on pipe

Proof-of-concept CMPI lab experiments

Static Loading





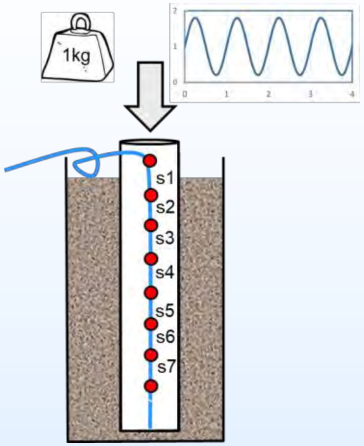


Static strain:

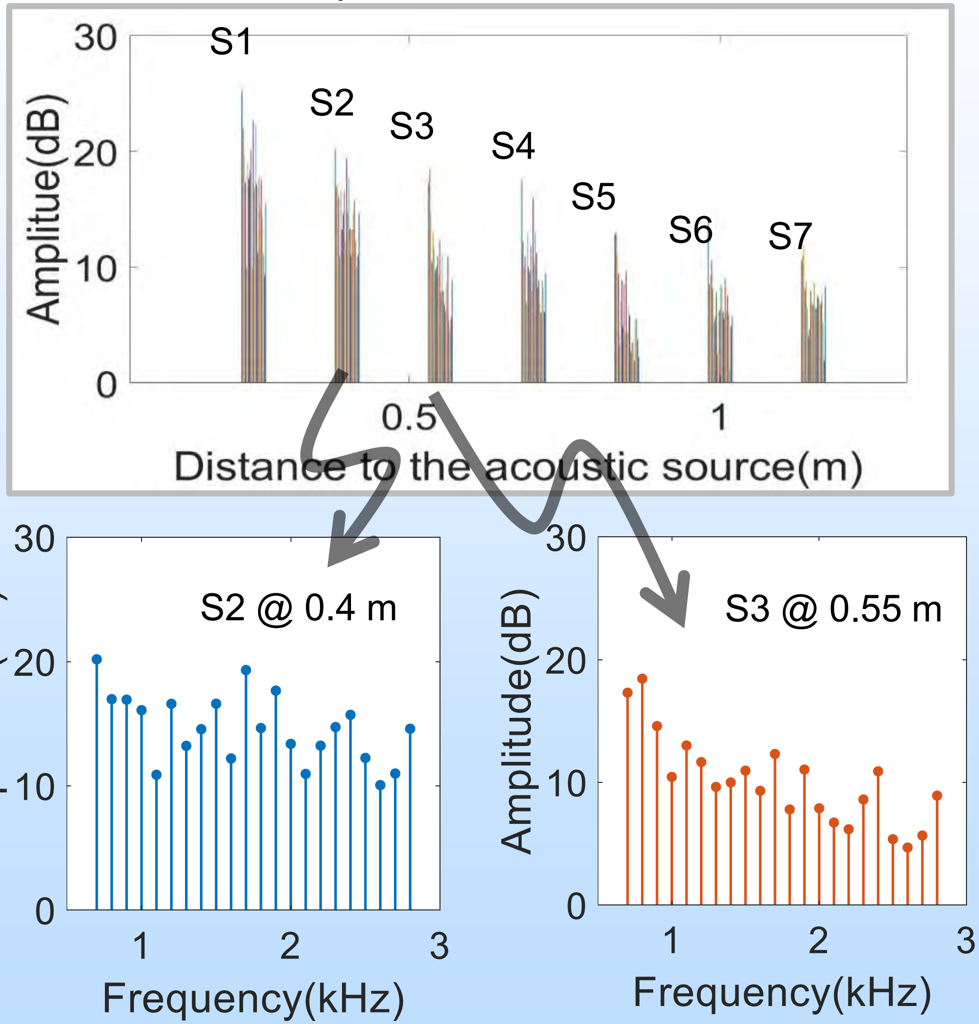
- Linear with load
- Decreases with depth
- Stiffness consistent with PVC at S1
- Increase stiffness with depth due to friction with sand

Proof-of-concept CMPI lab experiments

Dynamic Loading



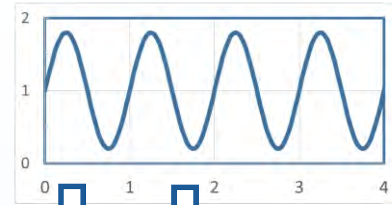
Acoustic spectra at 7 fiber sensors

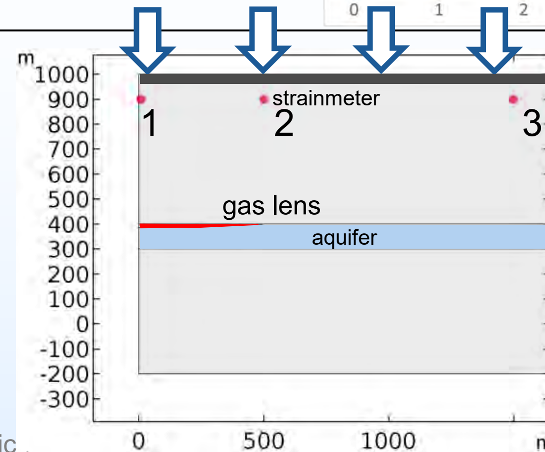


Dynamic strain:

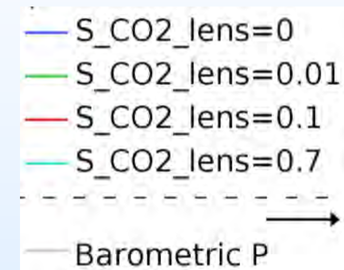
- Acoustic spectra at 7 sensors, 0.1 to 3 kHz
- Amplitude decrease w/depth similar to static

Task 2. Strain Interpretation

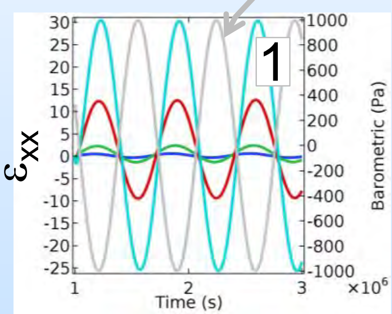


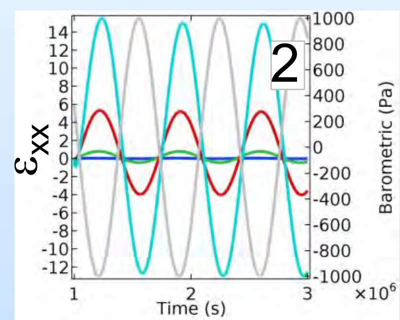


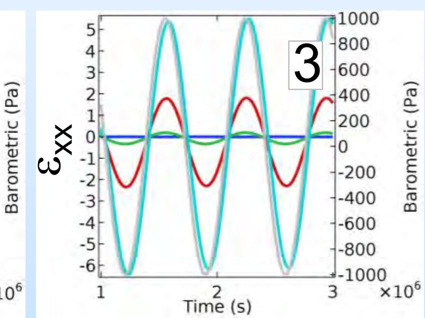
- Subtask 2.1. Pressure distribution
- Subtask 2.2. Leakage
- Subtask 2.3. Ambient processes
- Subtask 2.4. Data reduction, filtering
- Subtask 2.5. Model-based interpretation stochastic inversion



Barometric





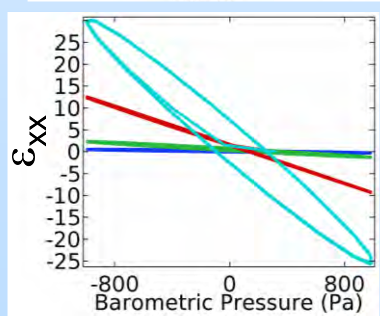


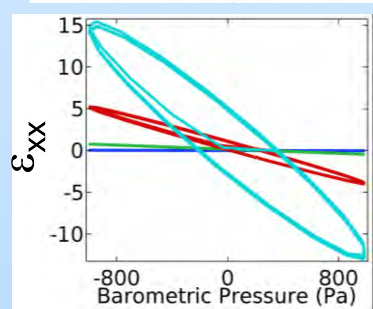
Concept

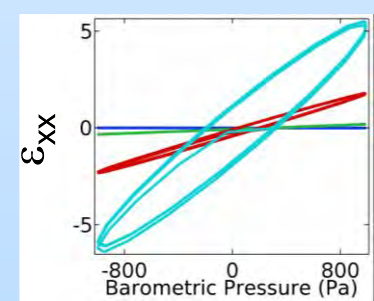
Gas saturation→Compressibility
Compressibility→Strain
Gas saturation→Strain

Results

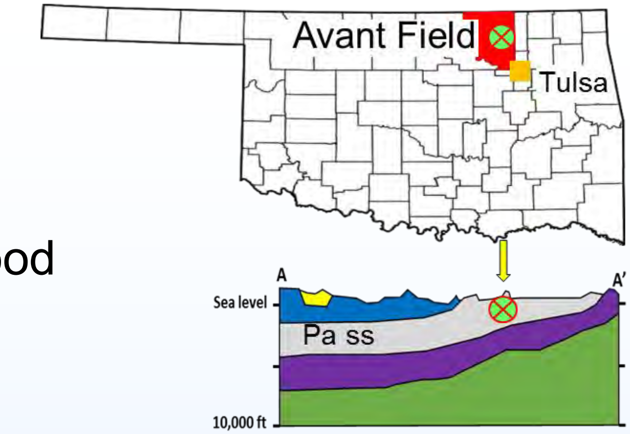
Horizontal strain affected
Vertical strain larger, but relative change less
Magnitude increases with S_CO2
Magnitude and phase with location
Detect with cross-spectrum analysis



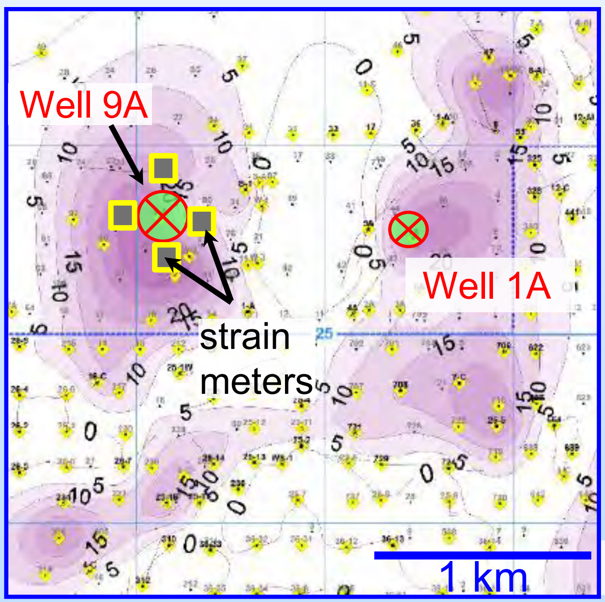




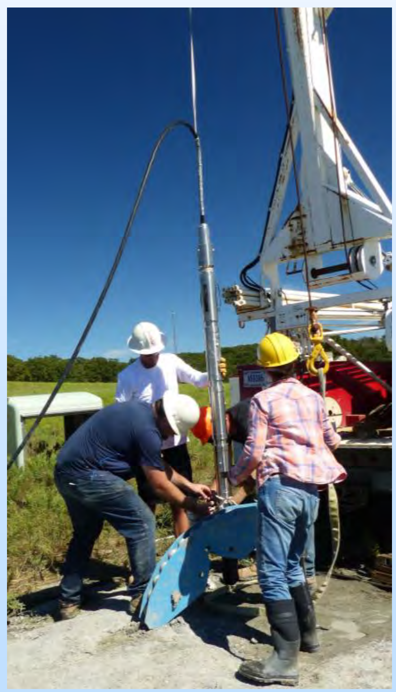
Task 3. Field Experiment



- **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



Permeable sand isopach



Installing strainmeter

Drilling at AVN location

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_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.

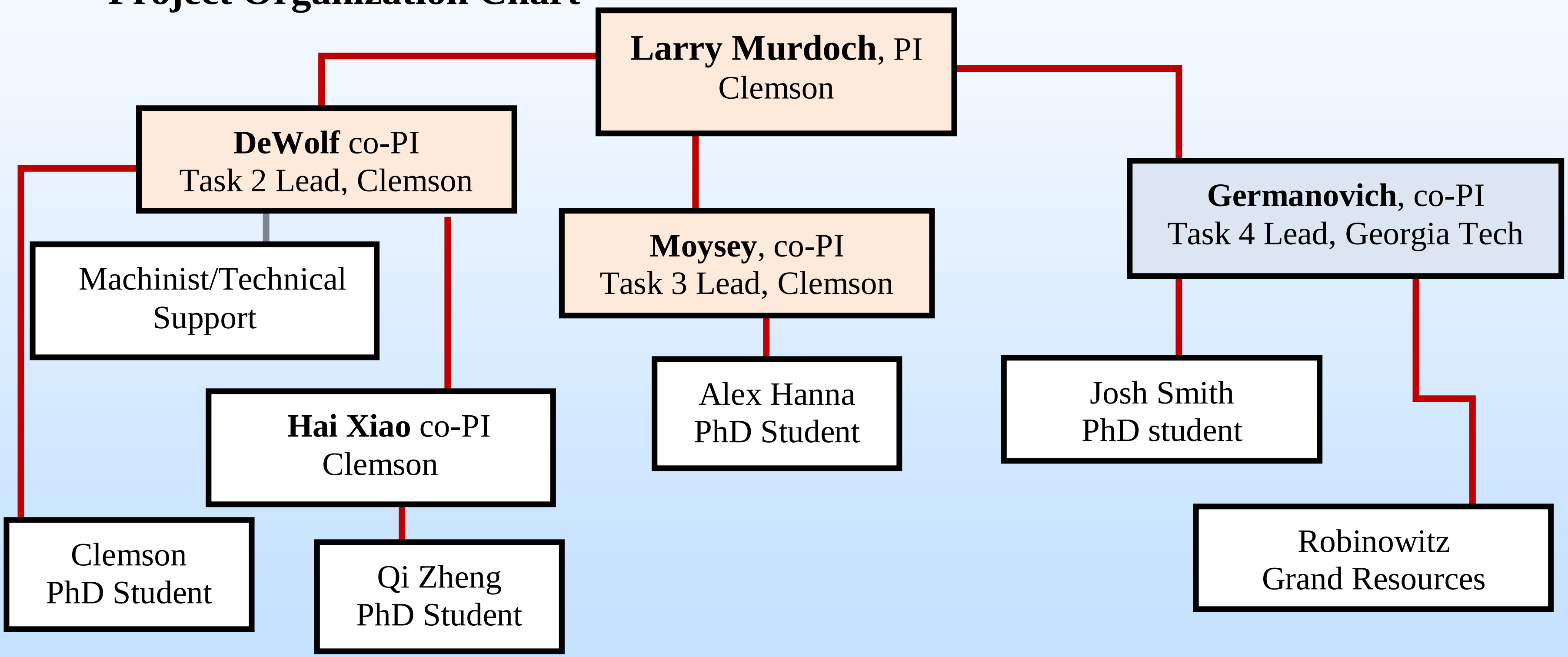
Project Overview:
Goals and Objectives

Ultimate goal: develop and demonstrate technology that can measure and interpret in-situ strain signals to improve understanding and reduce risk during the CO_2 injection processes.

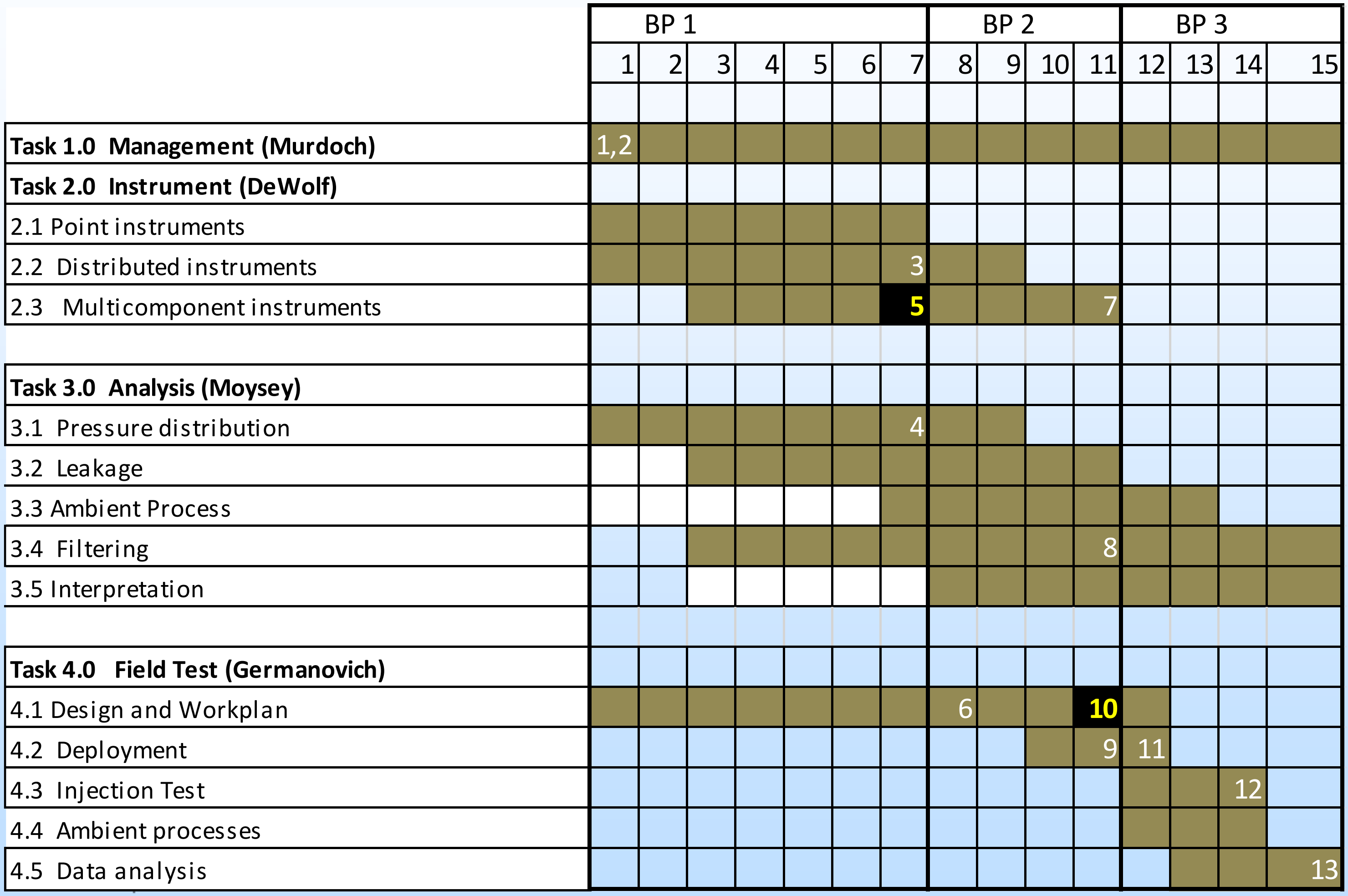
1. Instrumentation. Refine and develop prototype instruments that can measure small in-situ strains at low cost with minimal use of downhole electronics and electrical power.
2. Strain Interpretation. Anticipate the strains caused by injection, and interpret strain data associated with injection of CO_2, 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 CO_2 storage, and interpret the resulting data.

Organization Chart

Project Organization Chart



Gantt Chart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BP 2
BP 3
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Task 1.0 Management (Murdoch)
1,2
Task 2.0 Instrument (DeWolf)
2.1 Point instruments
2.2 Distributed instruments
3
2.3 Multicomponent instruments
5
7
Task 3.0 Analysis (Moysey)
3.1 Pressure distribution
4
3.2 Leakage
3.3 Ambient Process
3.4 Filtering
8
3.5 Interpretation
Task 4.0 Field Test (Germanovich)
4.1 Design and Workplan
6
10
4.2 Deployment
9
11
4.3 Injection Test
12
4.4 Ambient processes
4.5 Data analysis
13

Bibliography

- L. Hua, Y. Song, B. Cheng, W. Zhu, Q. Zhang, and H. Xiao, "Coherence-length-gated distributed optical fiber sensing based on microwave-photonic interferometry," Opt. Express 25, 31362–31376 (2017).
- L. Hua, J. Tang, S. DeWolf, L. Murdoch, and H. Xiao, "Michelson interferometer assist differential coherent microwave photonics interferometry for fully distributed sensing," IEEE Photonics Technol. Lett. (in prep).
- L. Hua, J. Tang, S. DeWolf, L. Murdoch, and H. Xiao, "Quadrature detection in coherence microwave photonics interferometry by using chirp effect of electro-optic modulator," Opt. Lett. (in prep).
- L. Hua, B. Cheng, Y. Song, S. DeWolf, L. Murdoch, and H. Xiao, "Distributed acoustic and vibration sensing based on coherent microwave photonics interferometry," Opt. Express (in prep).
- 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)
- DeWolf, S. and L.C. Murdoch. Clemson University Patent Disclosure 2018-039: A polarization and temperature insensitive interferometric optical fiber tiltmeter (DE-FE0028292)

Additional Slides

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
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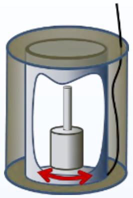
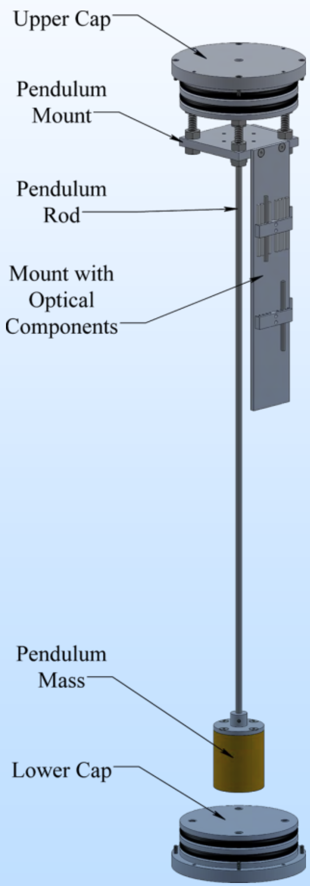
Task 1: Single-Component Instruments

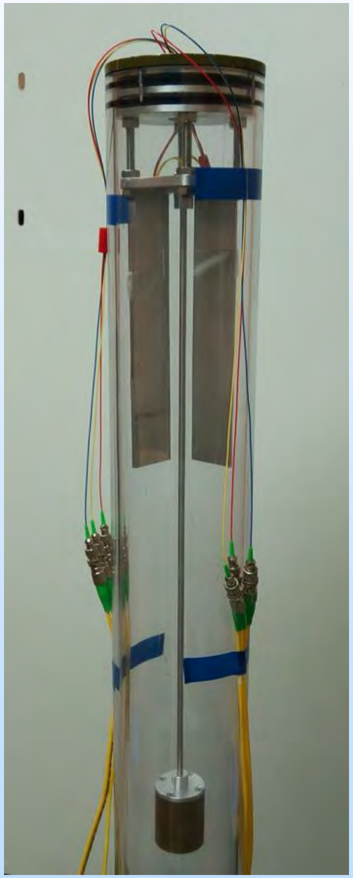


Monolithic Tiltmeter

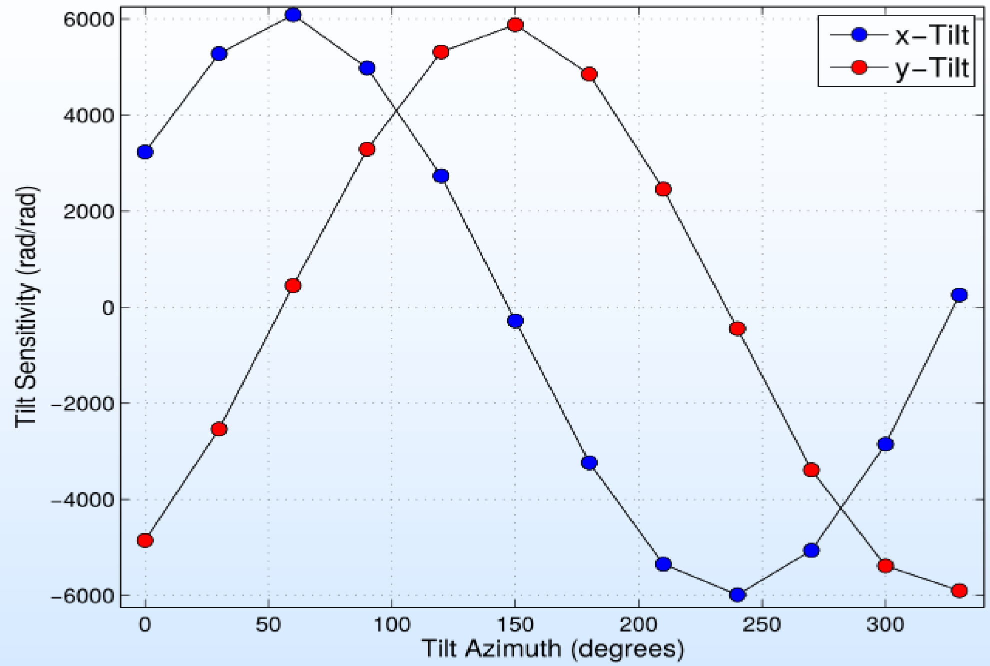
- Passive, no leveling
- Full vector

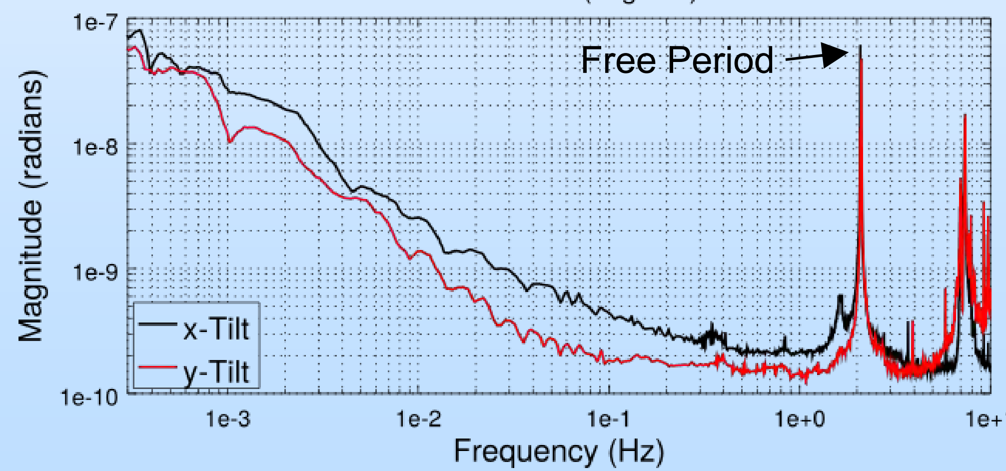


Design



Prototype





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