ROBUST IN SITU STRAIN MEASUREMENTS TO MONITOR CO_2 STORAGE

Project Number FE0028292

Larry Murdoch and Scott DeWolf, Clemson University
Stephen Moysey, Hai Xiao, *Alex Hanna, Liwei Hua* Clemson University
Leonid Germanovich, Georgia Tech; *Marvin Robinowitz*, Grand Resources

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
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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

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
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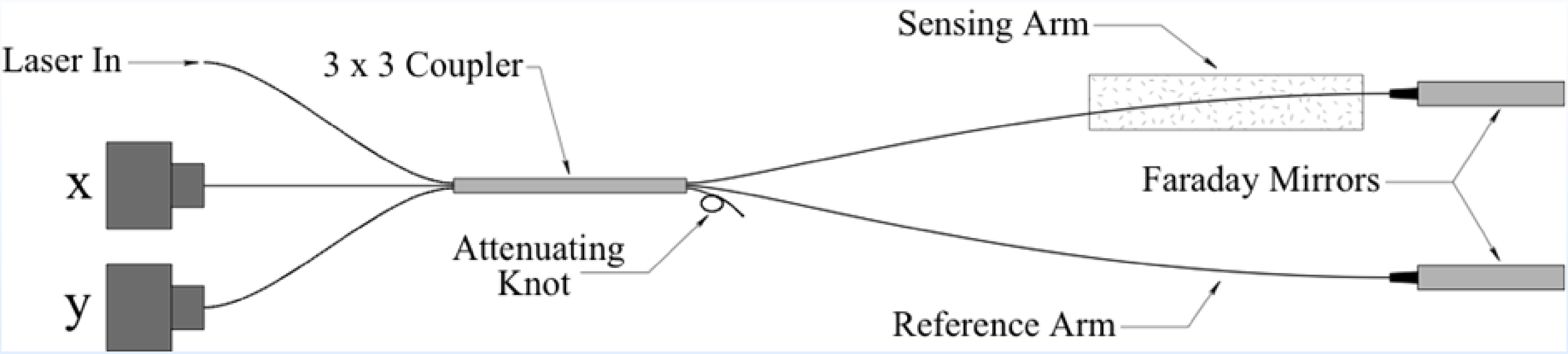
<u>Outline</u>

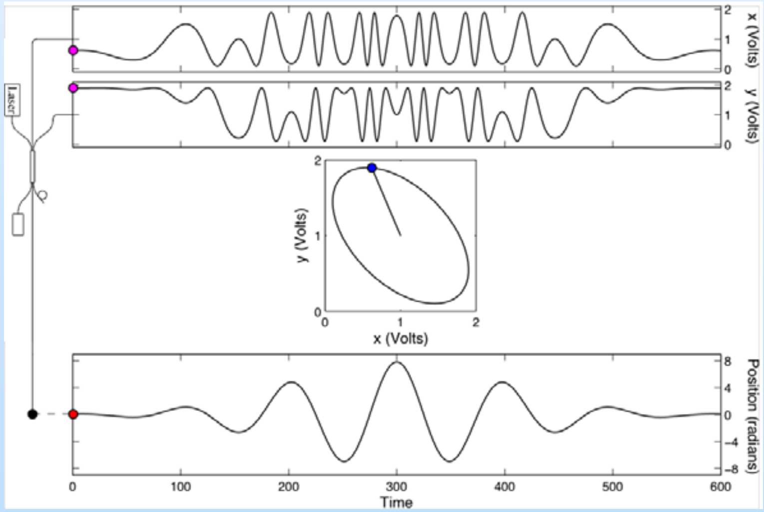
Technical Status
Accomplishments
Lessons Learned
Synergy
Summary

Michelson Interferometers

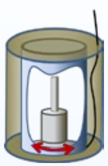

Scott DeWolf



- 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

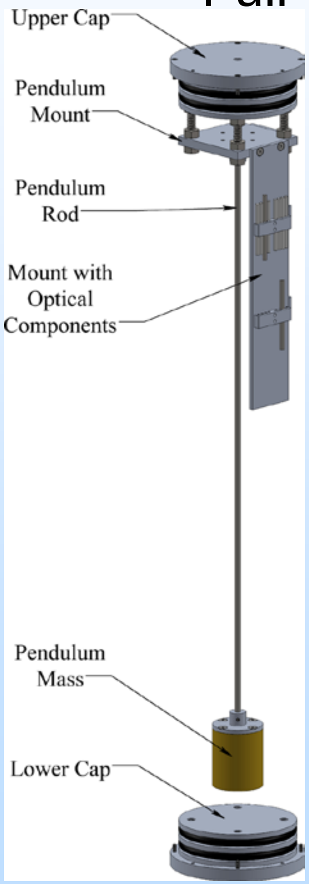


Task 1: Single-Component Instruments

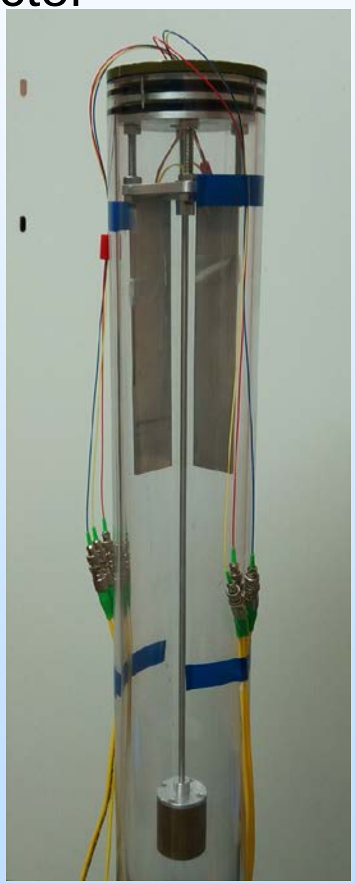


Monolithic Tiltmeter

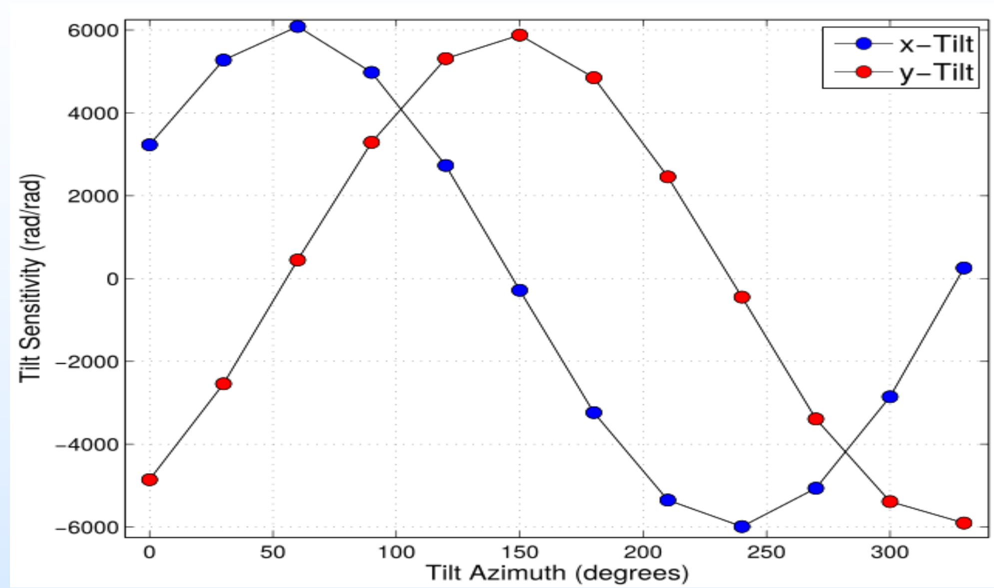
- Passive, no leveling
- Full vector

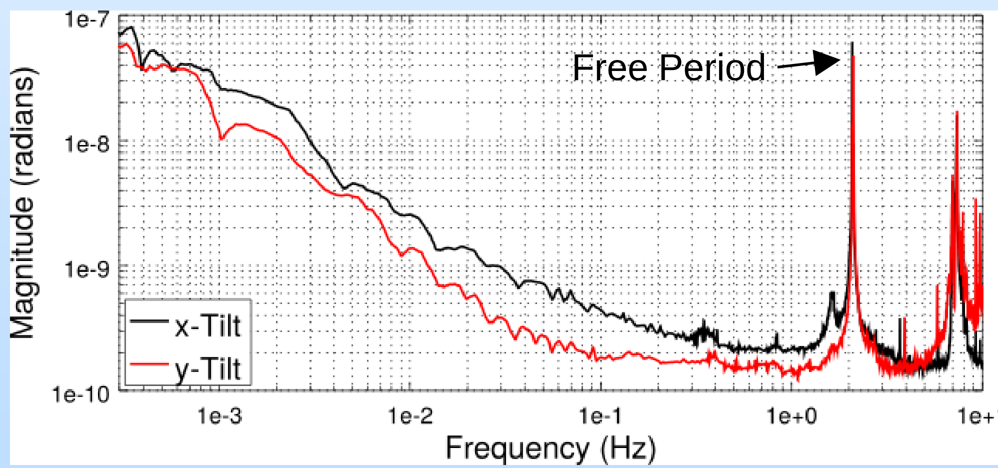


Design



Prototype

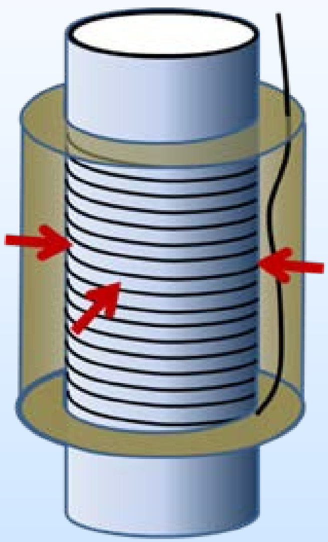




Task 1: Single-Component Instruments

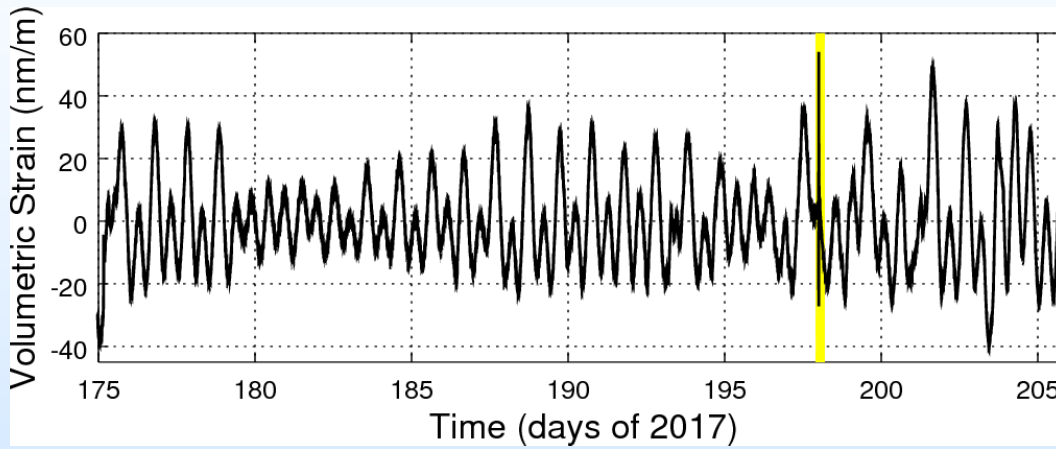
Embedded areal strainmeter

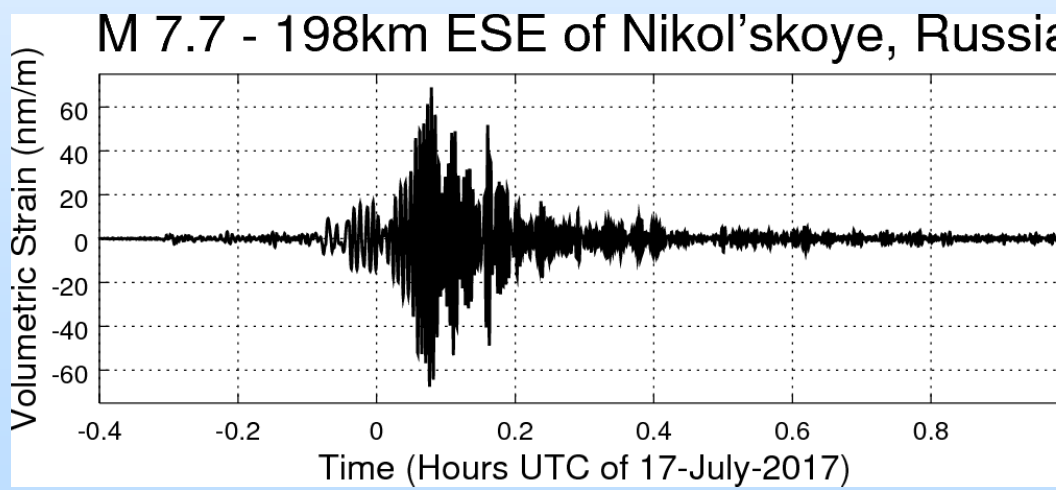
“Smart” casing



Fiber-wrapped casing

Dedicated sensing element

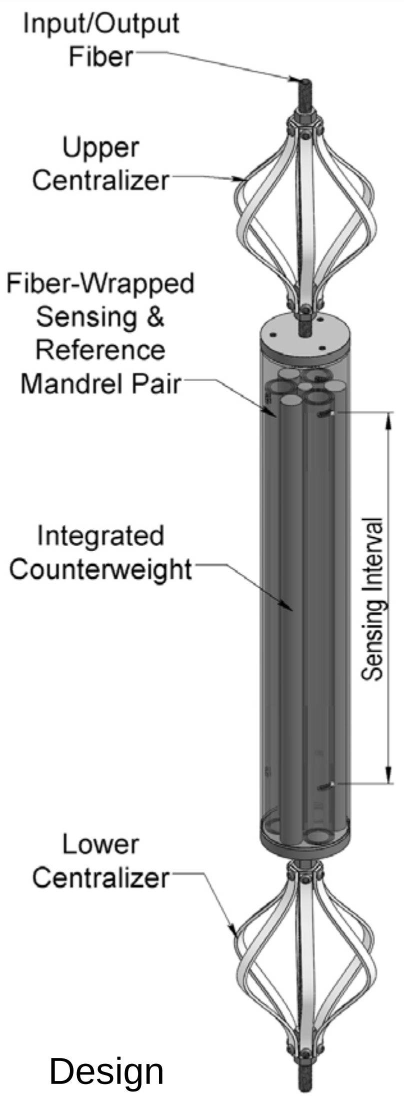


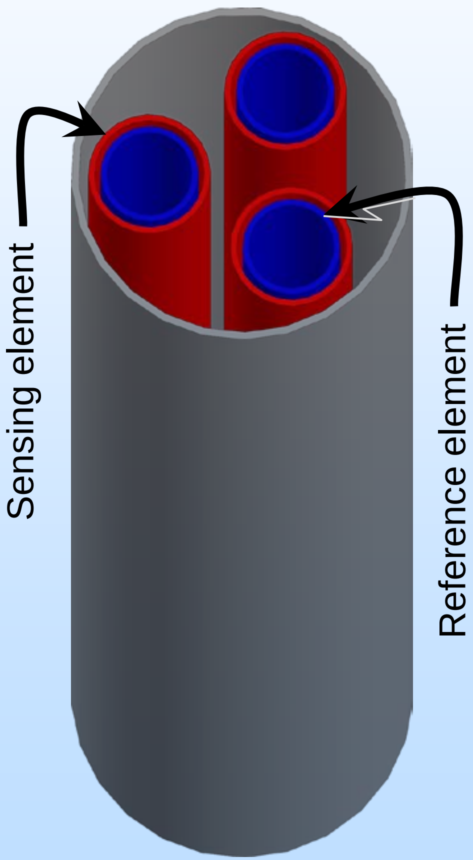


Task 1: Multi-Component Instruments

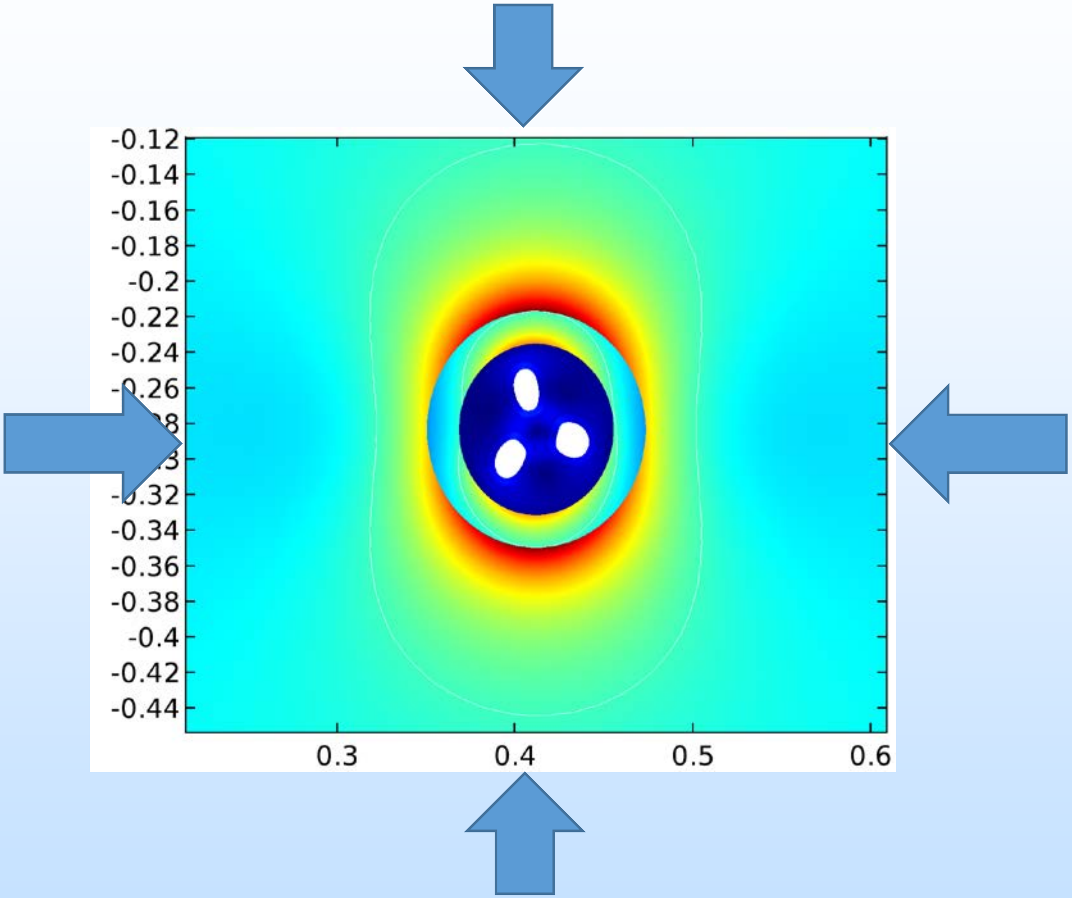
Horizontal tensor strainmeter (nested areal)

Closed downhole package

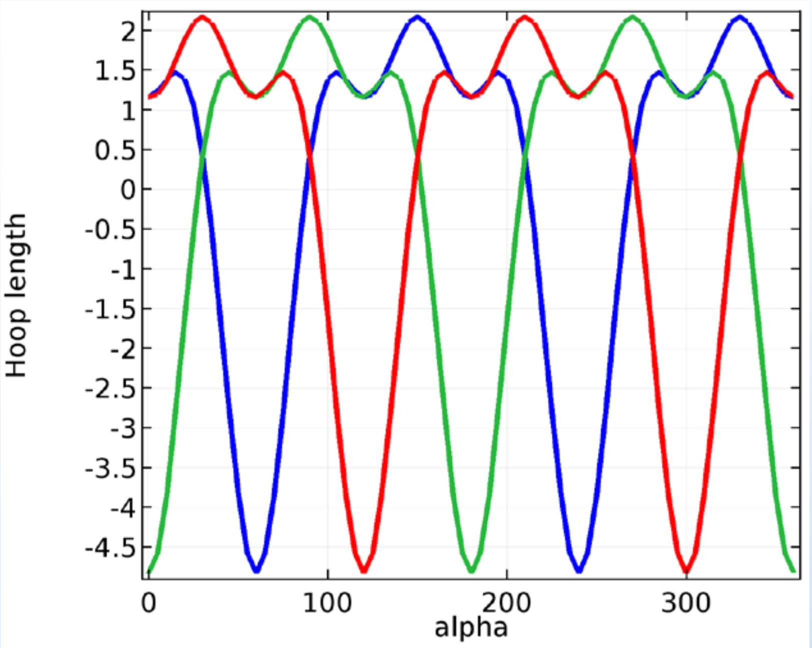




Task 1: Horizontal Tensor Strainmeter



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

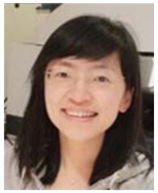


Response from interferometers estimated by integrating hoop strain around circle where fiber will be wrapped.

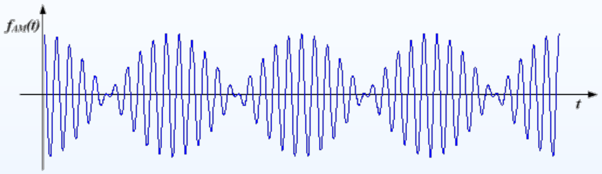
Microwave Photonics

A new optical fiber distributed sensing technology

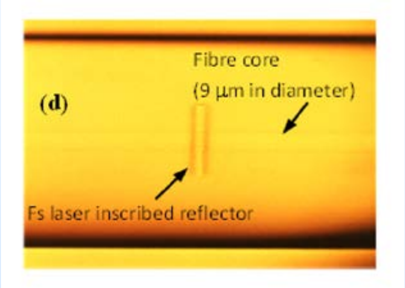
Hai Xiao



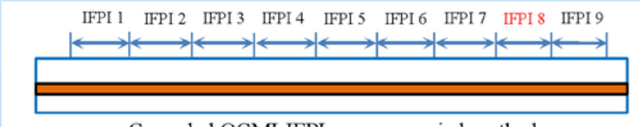
Liwei Hua



- 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

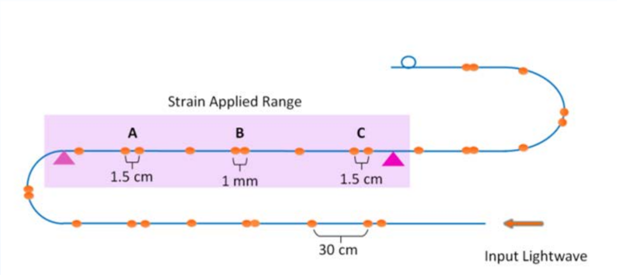


Cascaded OCMI-IFPI sensor epoxied on the beam

OCMI (Optical Carrier Microwave Interferometry)

Microwave Photonics
Static Strain Resolution

Original OCMI ~1 με, microwave interference

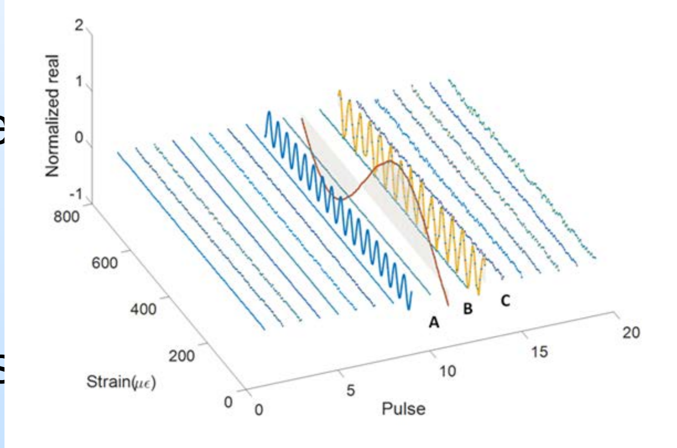


Recent Advances

- 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

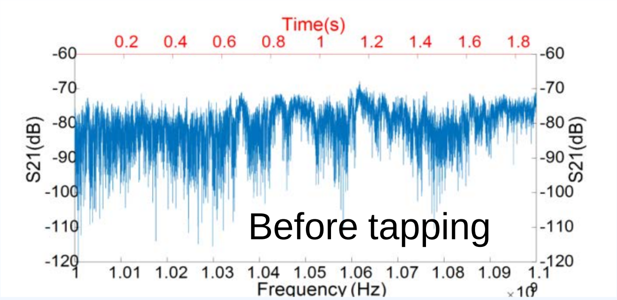
Original OCMI ~1Hz

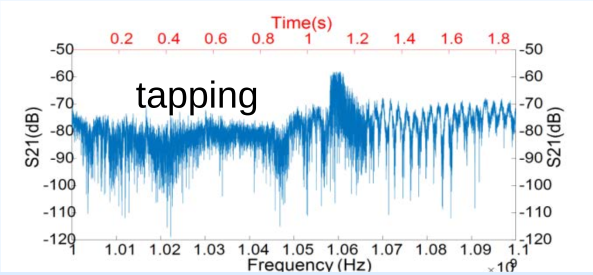
Recent Advances

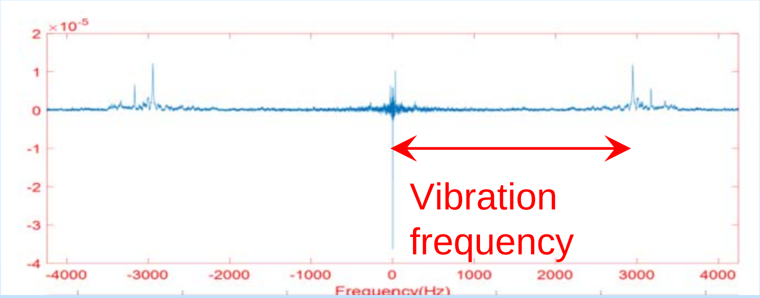
New algorithm

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

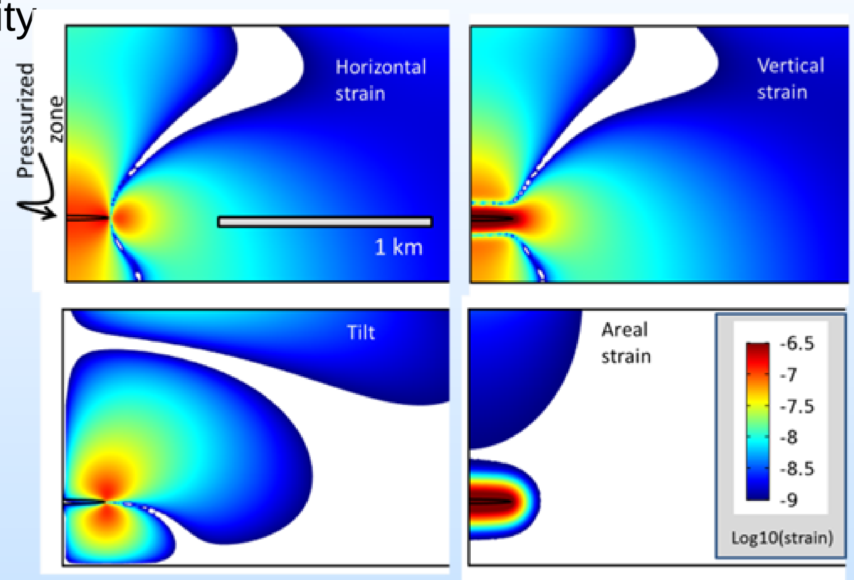
- Incoherent light source: με but large dynamic range
- Coherent light source: nε but small dynamic range

Dynamic measurement

- tested up to 4kHz

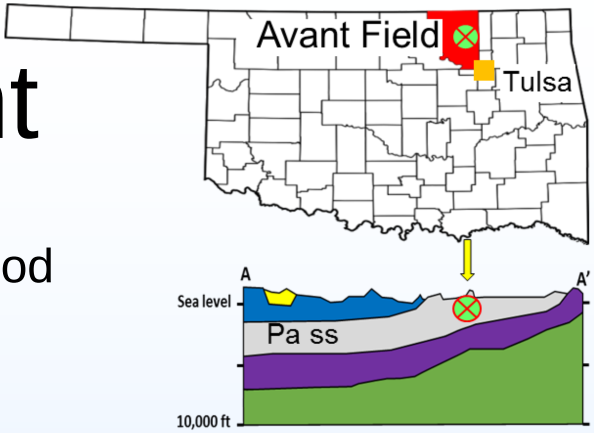
Task 2. Strain Interpretation

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

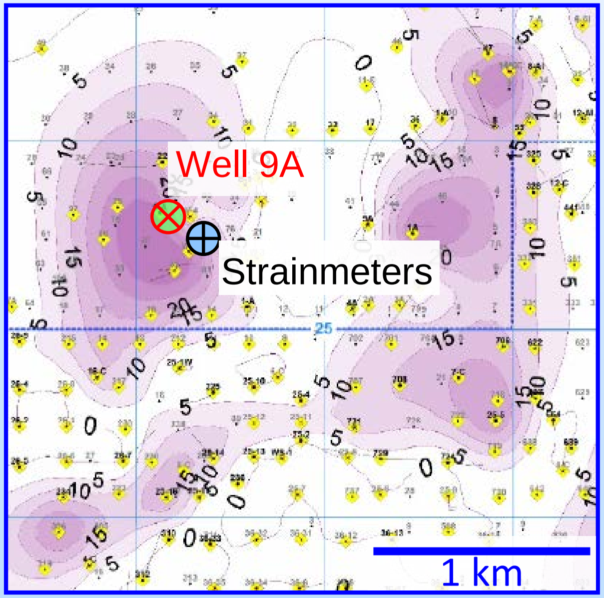


Strain field (scale is log(strain magnitude)) in the vicinity of an elliptical zone pressurized by 1 kPa (~0.2 psi) at 1 km depth in rock with *E* = 10 GPa. Elliptical region is 400 m by 20 m thick.

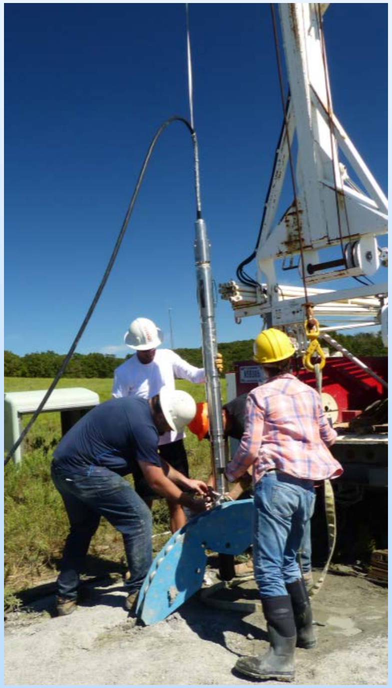
Task 3. Field Experiment



- **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



Installing strainmeter

Strainmeters at Avant Field, July 2017

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

- CO_2 applications
  - Stress state
  - Wellbore integrity
  - Microseismicity, active seismics
- CO_2 collaborations
  - Field tests
- Other synergy
  - Geodesy (tectonics, glaciers….
  - Natural hazards (earthquakes, volcanos, landslides….
  - Hydrology (subsidence, storage change…
  - Infrastructure (bridges, buildings…

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

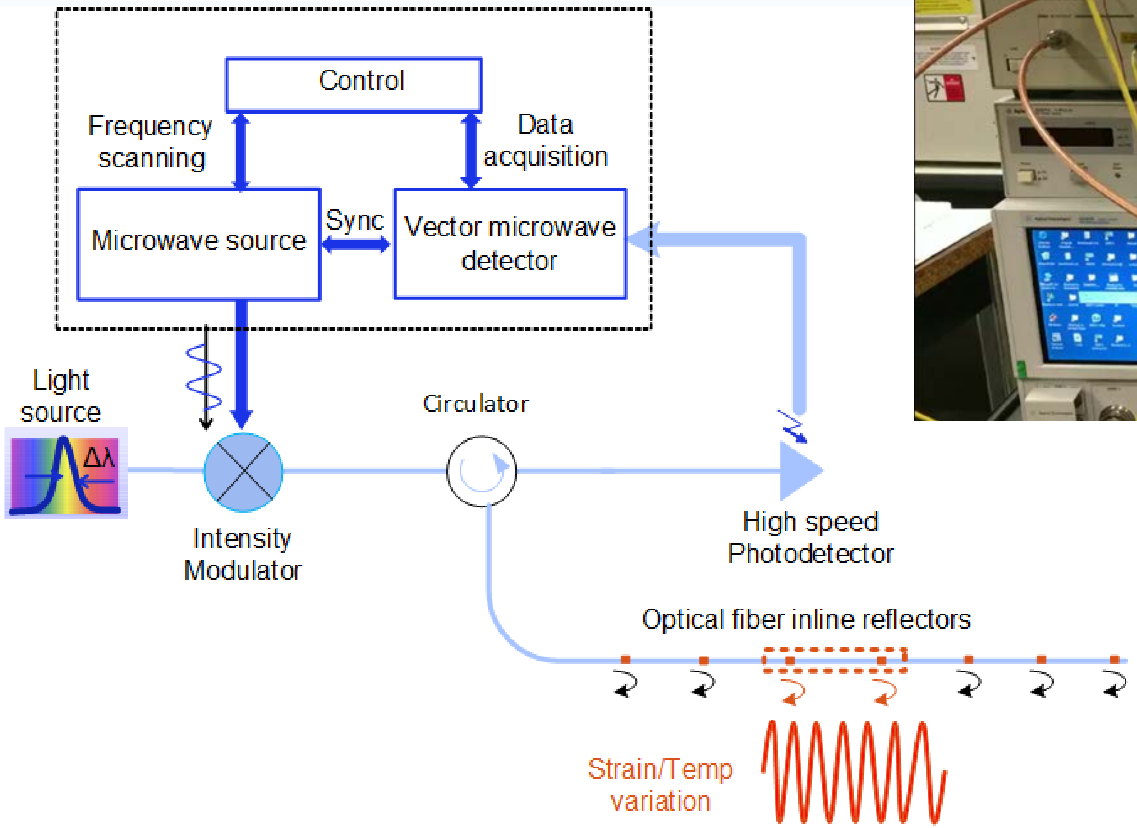
Next Steps

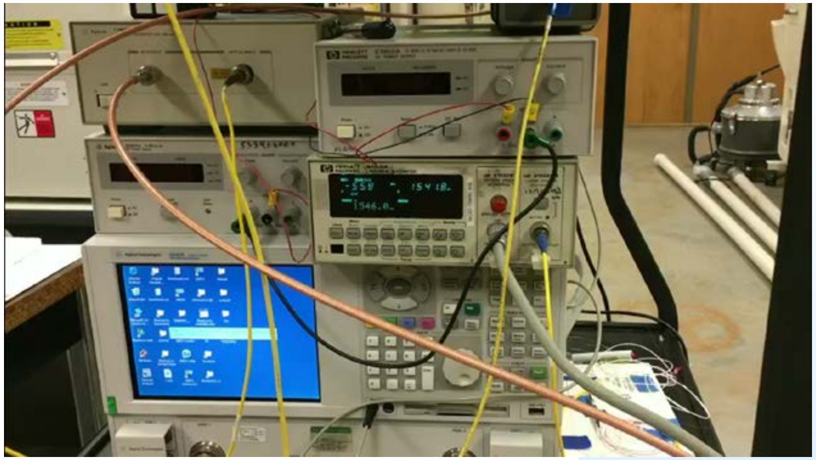
Refine instruments, lab → field

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

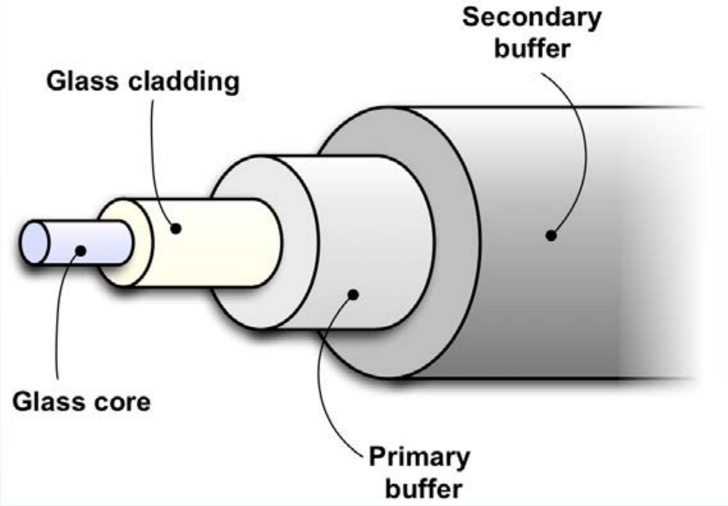
b) Multi-component instruments

Michelson interferometer or microwave photonics

c) Distributed strainmeters

Microwave photonics

Borehole Strainmeter
Michelson Interferometer

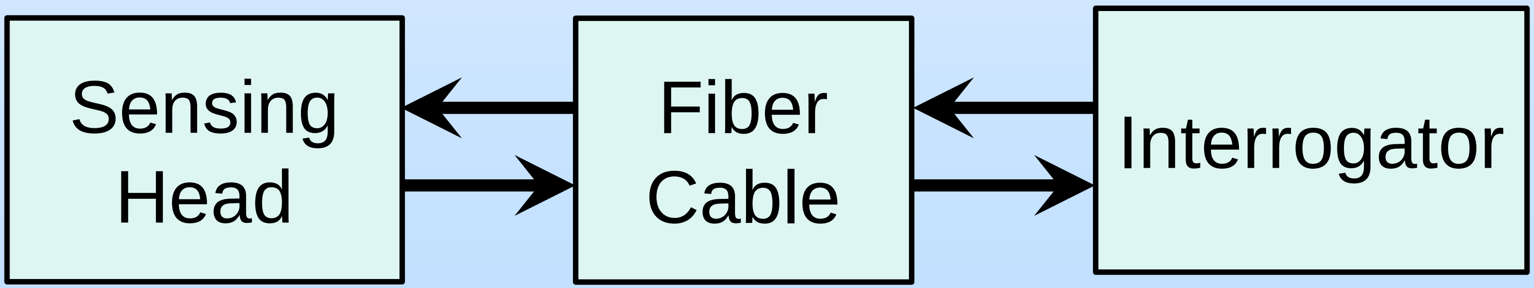


External packaging, armor

Optical Fiber Instrumentation

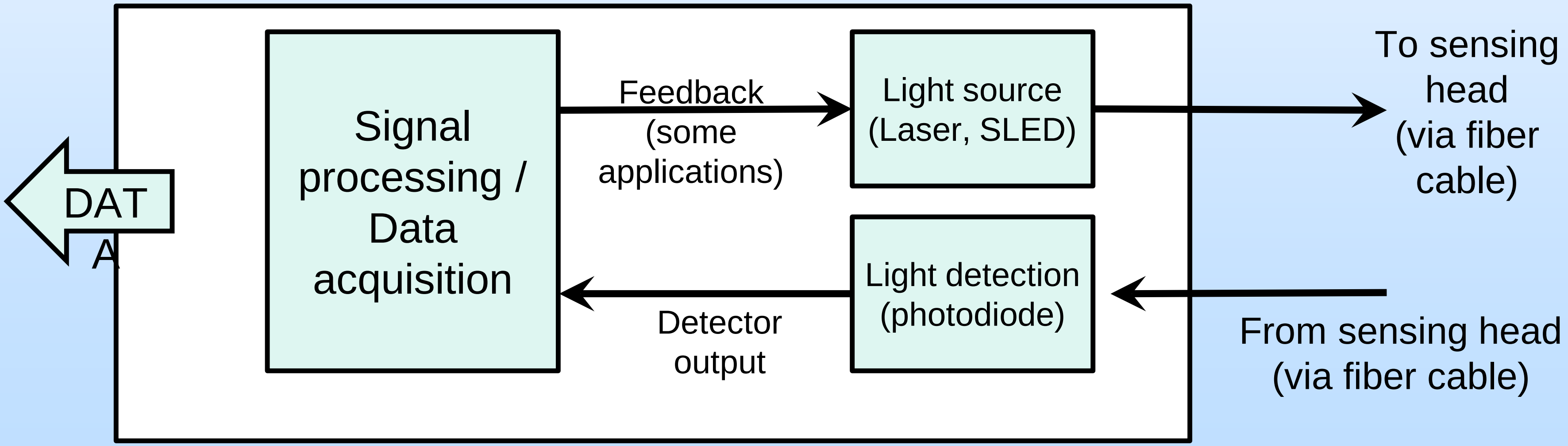
System components:

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

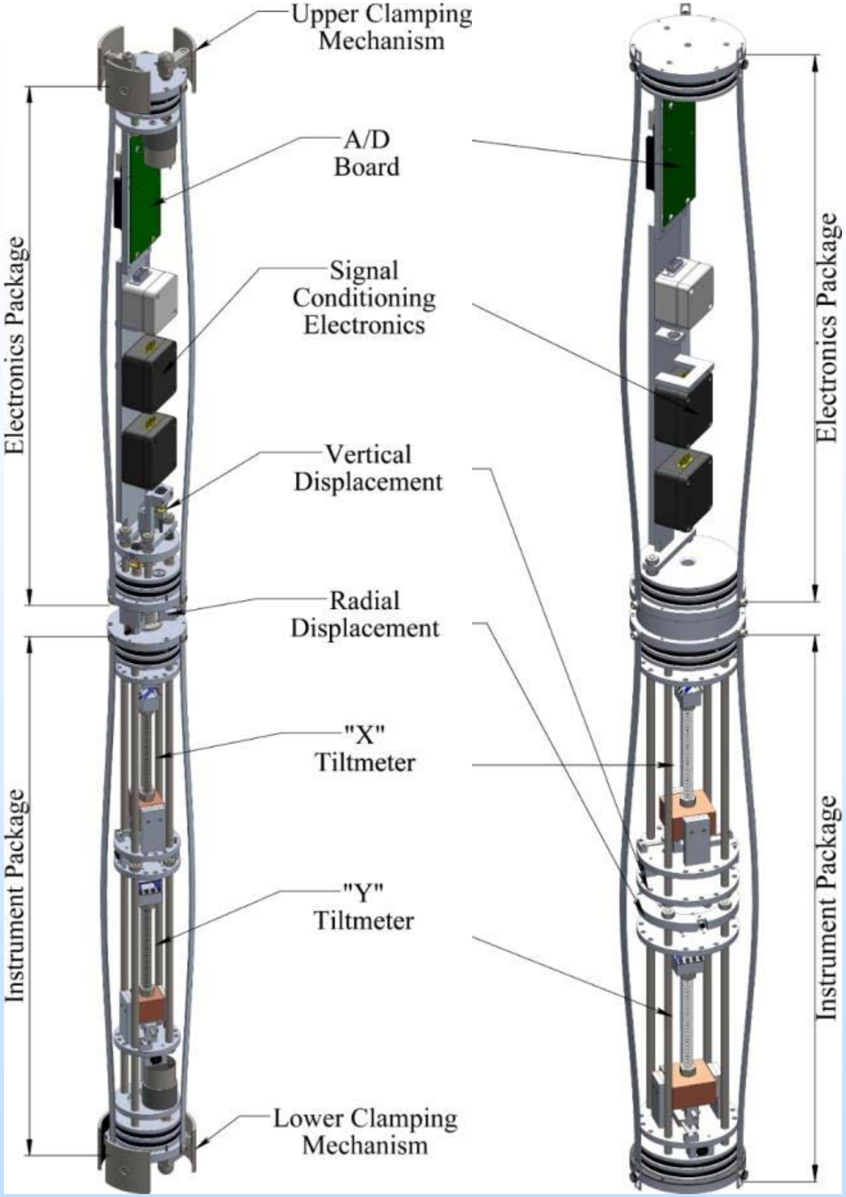


Optical Fiber Interrogator

- **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

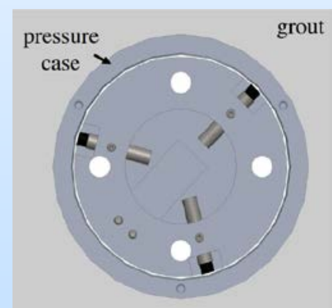


Removable

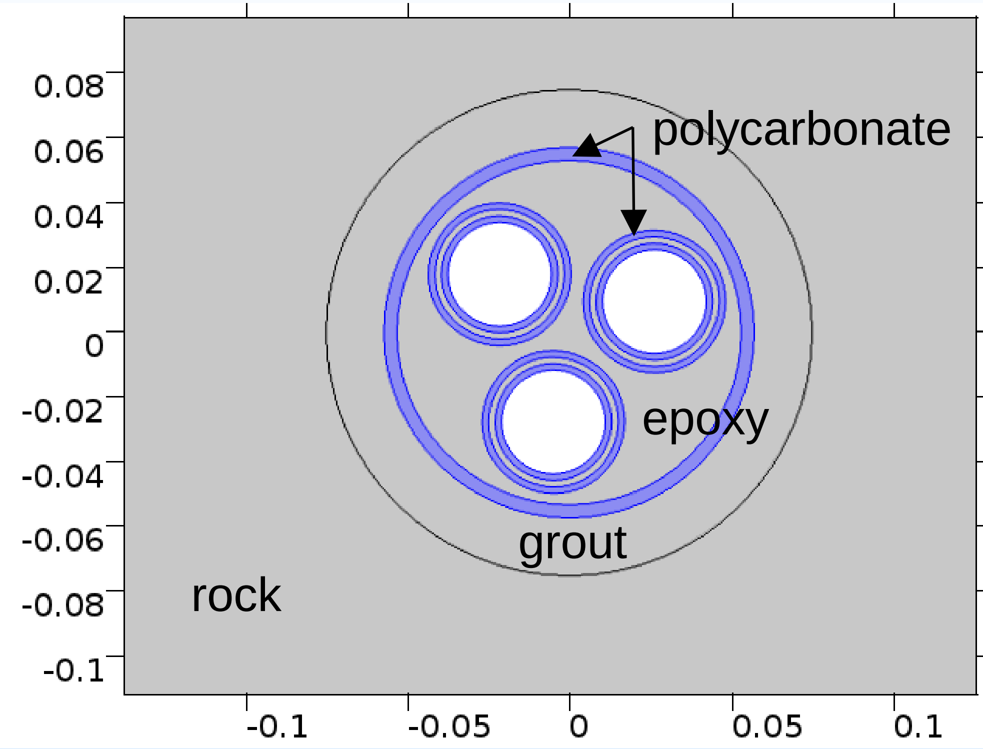
Grout-in

- Removable and expendable (grout-in) configurations
- 3 normal strains, 2 tilts
- Commercial eddy current sensors

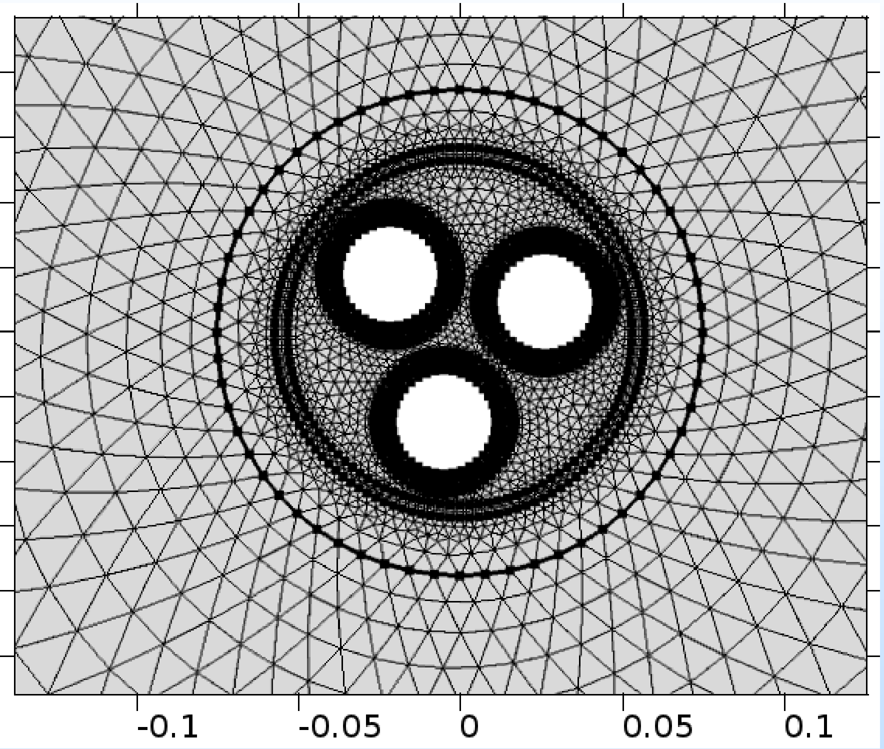
Tilt meter



Task 1: Horizontal Tensor Strainmeter

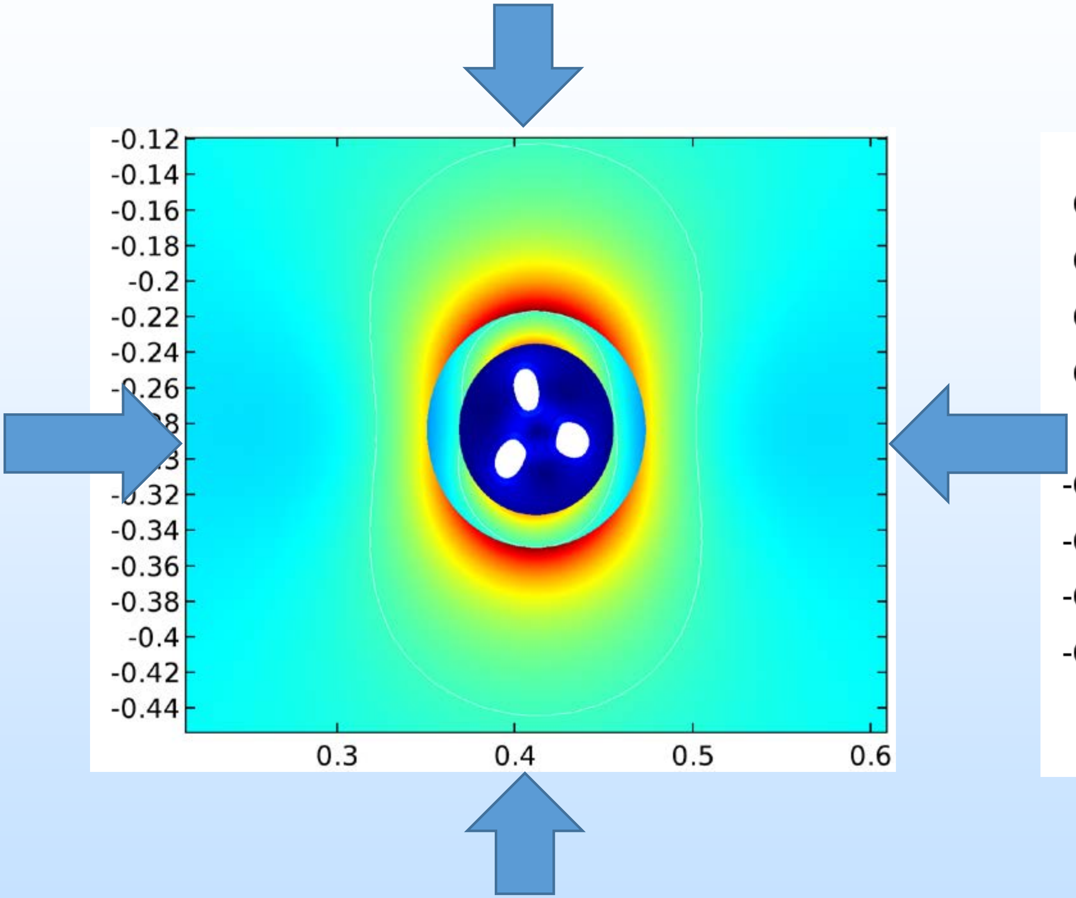


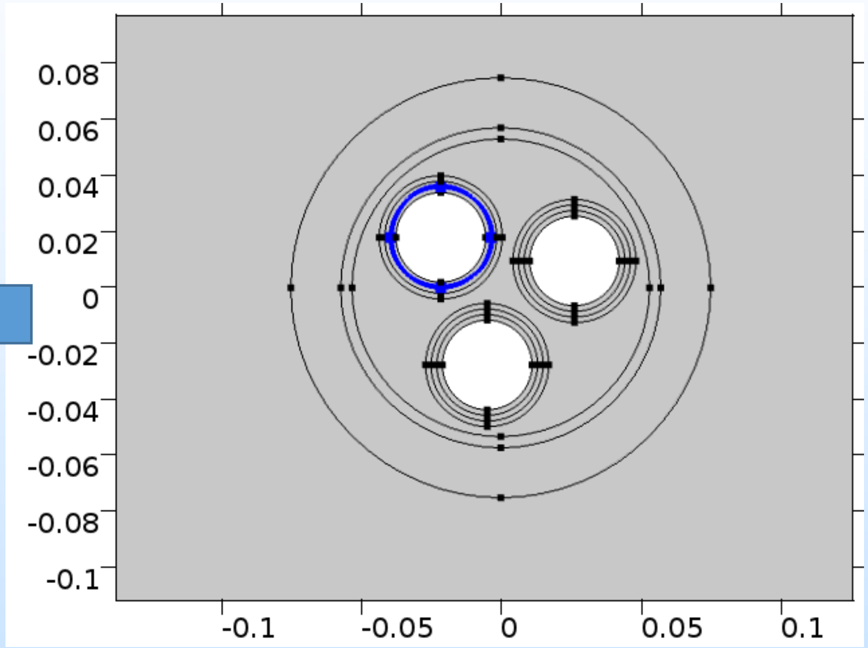
Configuration of materials



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.

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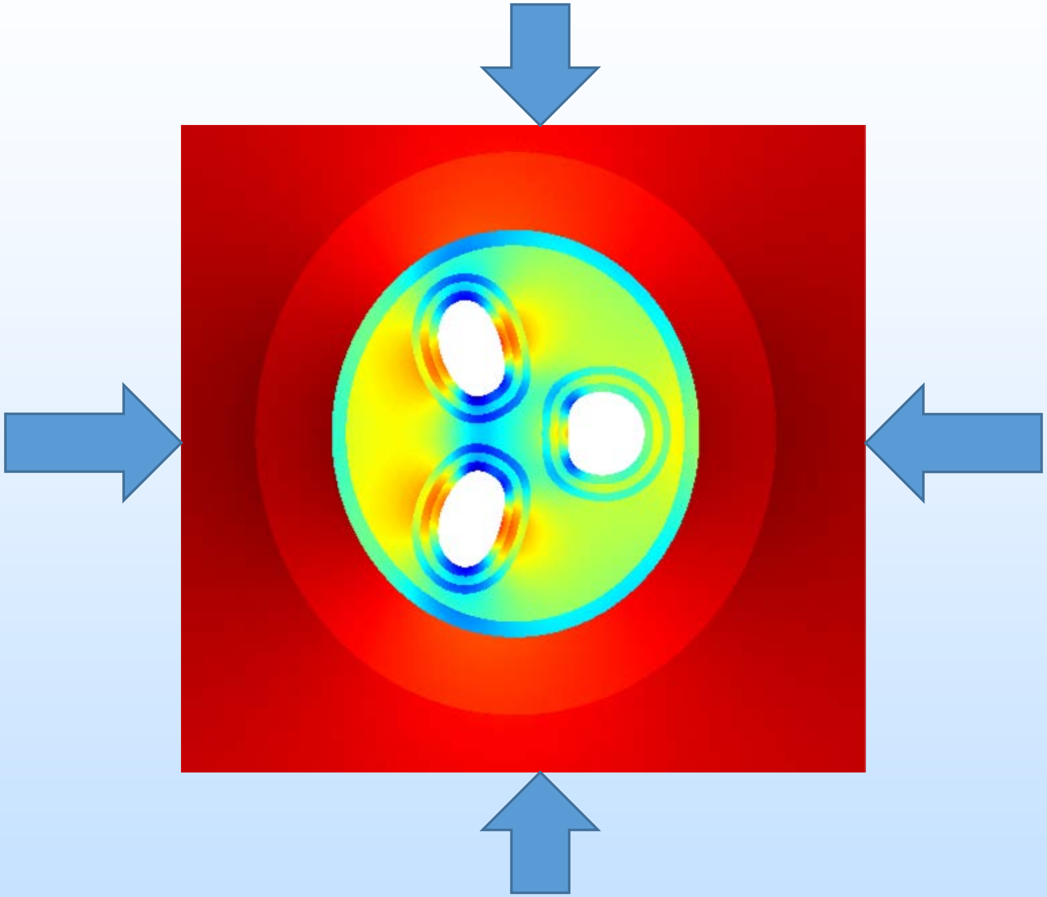
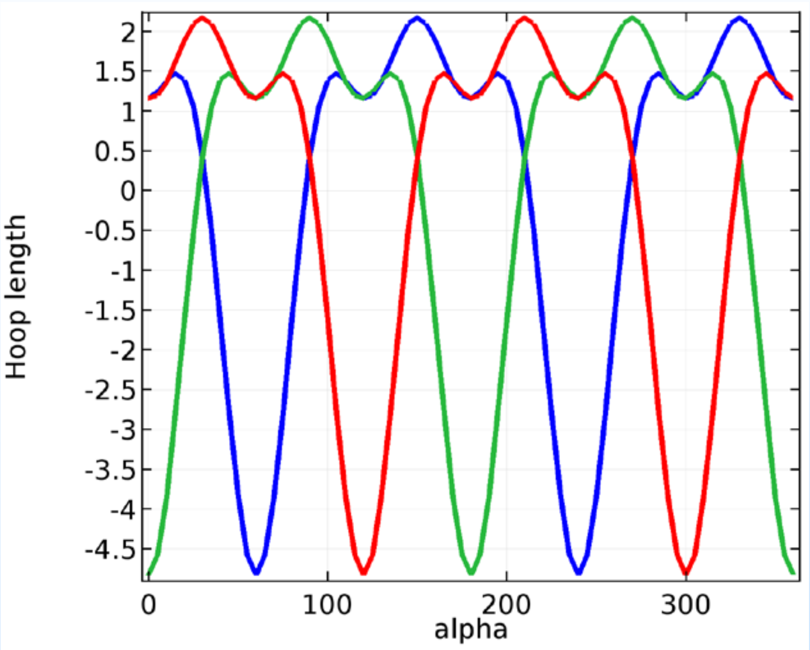


Volumetric strain of components for different orientations of principal stresses. Interaction between neighboring tubes gives unique orientation dependence.

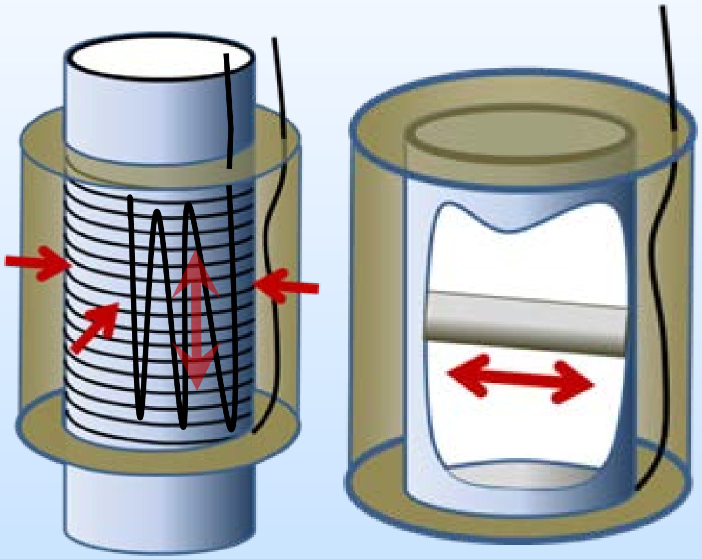


Scaled length change from each interferometer as a function of orientation to principal stresses.

Task 1: Multi-Component Instruments

Embedded tensor strainmeter

- Casing segment(s)



Multi-gauge tensor strainmeter

- Closed downhole package