Designs and Results from Three New Borehole Optical Fiber Tensor Strainmeters

Scott DeWolf[1], Larry Murdoch[1], Leonid Germanovich[2], Robert Moak[1], and Micheal Furgeson[1]

[1]Clemson University
[2]Georgia Institute of Technology Main Campus

December 09, 2019

Abstract

The time evolving strain field contains a wealth of information that can be used to interpret subsurface behavior. For example, injecting or removing fluids from reservoirs or aquifers causes deformation that can be used as a diagnostic signal in some cases, while it can interfere with geodetic interpretations in other cases. We've recently completed a field study that demonstrated the feasibility of measuring the strain tensor at a depth of 30 m caused by injection into a reservoir at 530 m depth. The observed strain signals were interpreted using four independent analytic and numerical methods that resulted in estimates of the poroelastic properties and geometry of the reservoir that was consistent with data from well logs. However, studies like these are only possible if these deformations can be reliably measured. Advances in optical fiber sensing systems have led to their introduction in a number of areas including quasi-static and dynamic subsuface deformation monitoring. Optical fiber-based interferometers are capable of measuring very small displacements while being completely passive in their operation. The low attenuation and significantly reduced bending loss in rare-earth doped, high numerical aperture glass optical fibers allows for the embedding of long lengths of fiber into compact, durable and exceptionally sensitive downhole sensing packages. We have expanded on years of lab and field work developing and deploying long baseline and embedded single-component borehole strainmeters to the design of three novel horizontal tensor strainmeters. Each design represents a unique embedding approach for measuring directional strain across the diameter of a borehole with differing advantages in terms of ease of fabrication and assembly, as well as directional resolution. We will present the design details along with laboratory calibration results and preliminary field data comparing their relative performances across tidal and seismic frequencies.

Designs and Results from Three New Borehole Optical Fiber Tensor Strainmeters

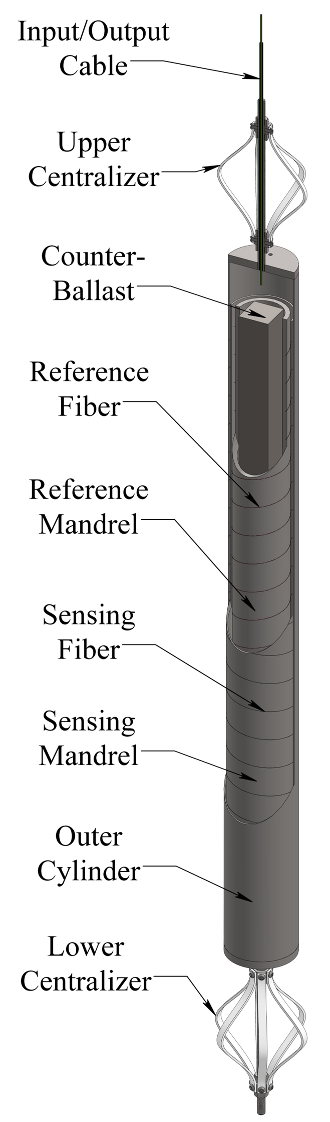
Scott DeWolf (scott@scottdewolf.com), Larry Murdoch (lmurdoc@clemson.edu), Leonid Germanovich (leonid54@gmail.com),
Robert Moak (rmoak@g.clemson.edu) and Michael Furgeson (mfurges@utexas.edu)

ABSTRACT: The time evolving strain field contains a wealth of information that can be used to interpret subsurface behavior. For example, injecting or removing fluids from reservoirs or aquifers causes deformation that can be used as a diagnostic signal in some cases, while it can interfere with geodetic interpretations in other cases. We've recently completed a field study that demonstrated the feasibility of measuring the strain tensor at a depth of 30 m caused by injection into a reservoir at 530 m depth. The observed strain signals were interpreted using four independent analytic and numerical methods that resulted in estimates of the poroelastic properties and geometry of the reservoir that was consistent with data from well logs. However, studies like these are only possible if these deformations can be reliably measured.

Advances in optical fiber sensing systems have led to their introduction in a number of areas including quasi-static and dynamic subsurface deformation monitoring. Optical fiber-based interferometers are capable of measuring verysmall displacements while being completely passive in their operation. The low attenuation and significantly reduced bending loss in rare-earth doped, high numerical aperture glass optical fibers allows for the embedding of long lengths of fiber into compact, durable and exceptionally sensitive downhole sensing packages.

We have expanded on years of lab and field work developing and deploying long baseline and embedded single-component borehole strainmeters to the design of three novel horizontal tensor strainmeters. Each design represents a unique embedding approach for measuring directional strain across the diameter of a borehole with differing advantages in terms of ease of fabrication and assembly, as well as directional resolution. We will present the design details along with laboratory calibration results and preliminary field data comparing their relative performances across tidal and seismic frequencies.

0. Previous Work & Motivation

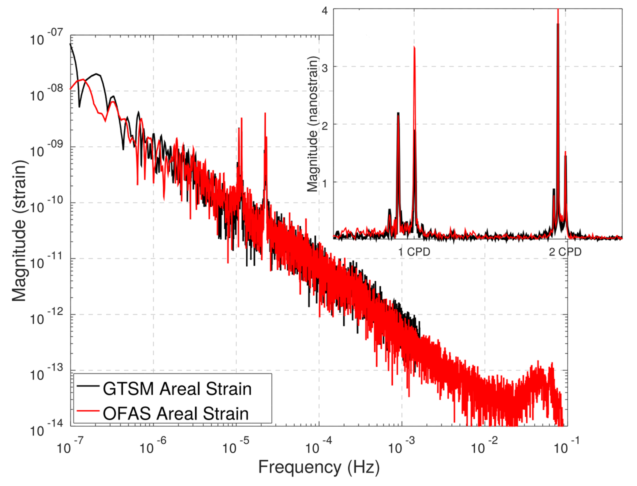


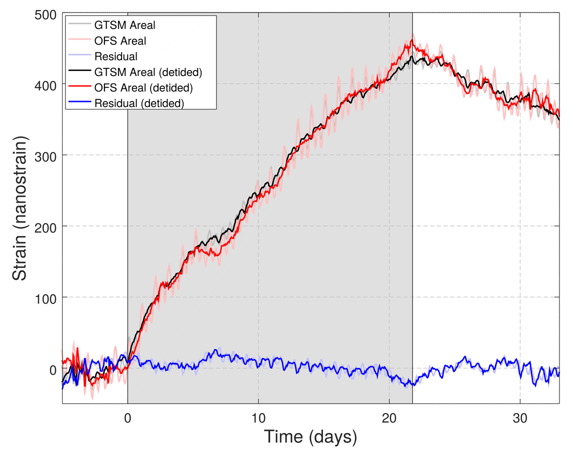
We have been developing strainmeters and tiltmeters over the past 5 years as a part of our ongoing research in geologic carbon storage monitoring. Previous work included both electromagnetic and optical fiber based systems. This was due to the near obsolescence of existing geodetic resolution (<10^{-9} strain) borehole technologies such as the Gladwin and Sacks-Evertson strainmeters.

Optical Fiber Areal Strainmeters (OFASs) like the one shown on the left deployed at our injection analog site in Northern Oklahoma two years ago has multiple advantages over other technologies such as:

- Extremely high sensitivity
  - O(10^{-15}) strain least-count
- Passive downhole operation
- Robust packaging
  - Fully potted interior
  - Welded stainless steel exterior
- Separable interrogator
  - Deployed ~5 m downhole

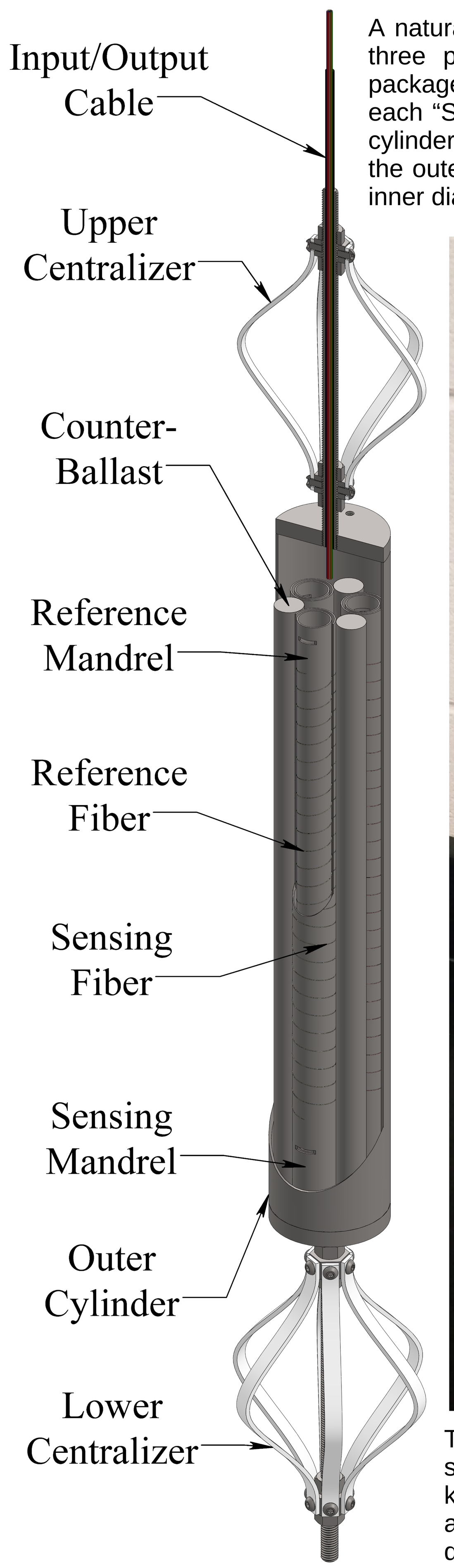
Our Oklahoma field site includes a nearly co-located Gladwin Tensor Strainmeter (GTSM) approximately 20 m from the above OFAS, both at a depth of 30 m. Spectra from the 5-minute GTSM Level 2 areal data and OFAS show a very similar response over overlapping frequency bands and a very similar signal-to-noise in the intertidal. Both strainmeters show a very similar response to a 21-day water injection into a nearby hydrocarbon reservoir located about 500 m away at 500 m depth.



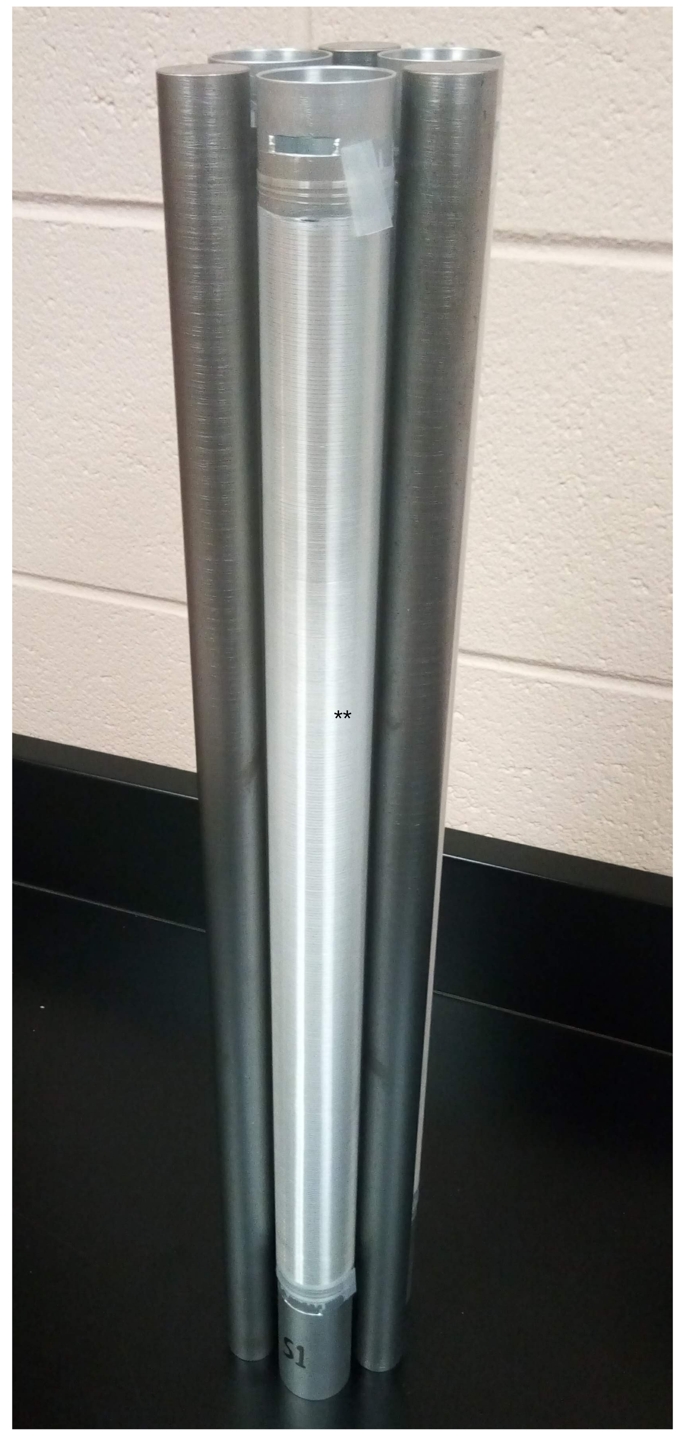


The success of these Optical Fiber Areal Strainmeters has led to additional funding to extend this technology for measuring multiple components of strain and tilt

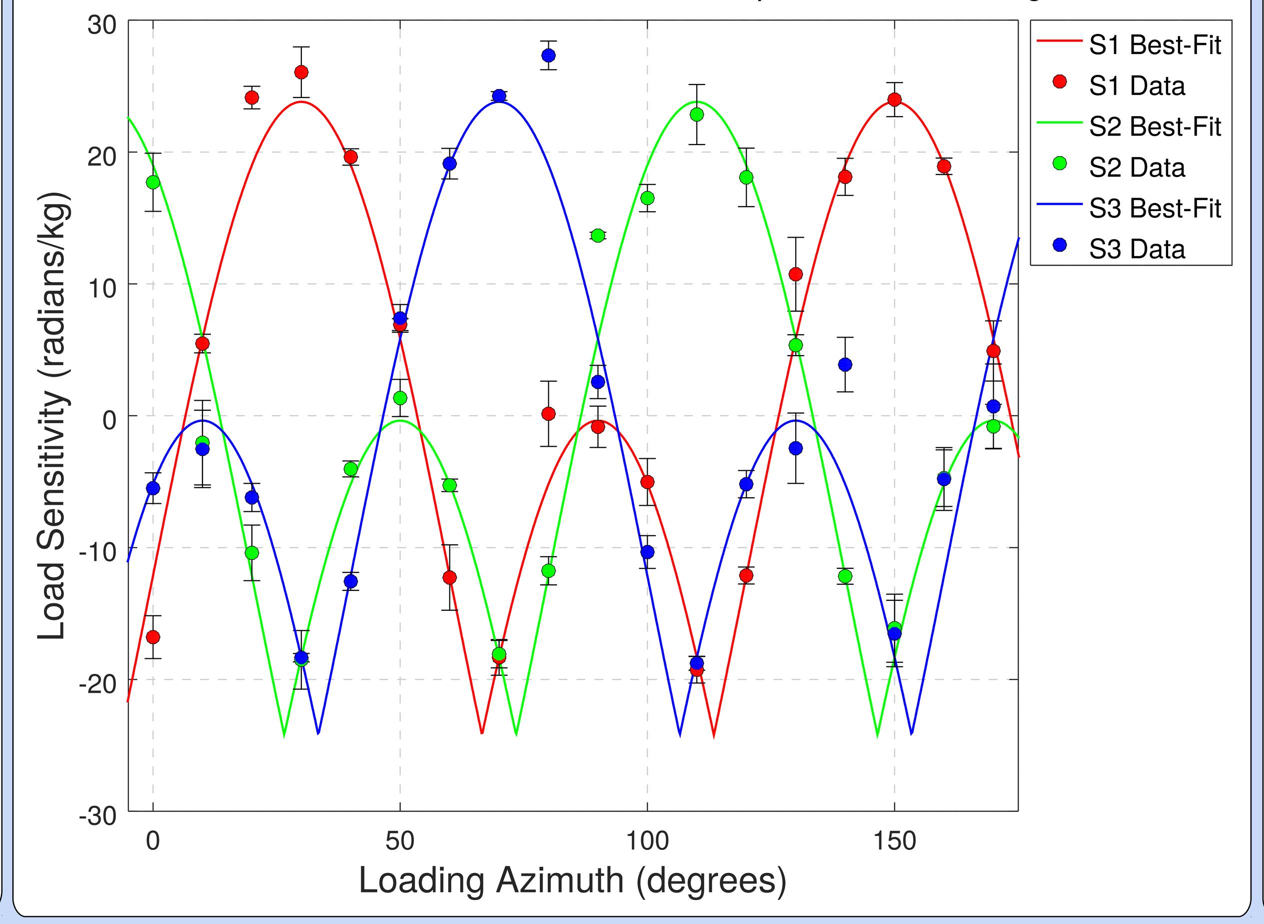
1. Triple Mandrel (Nested Areal)



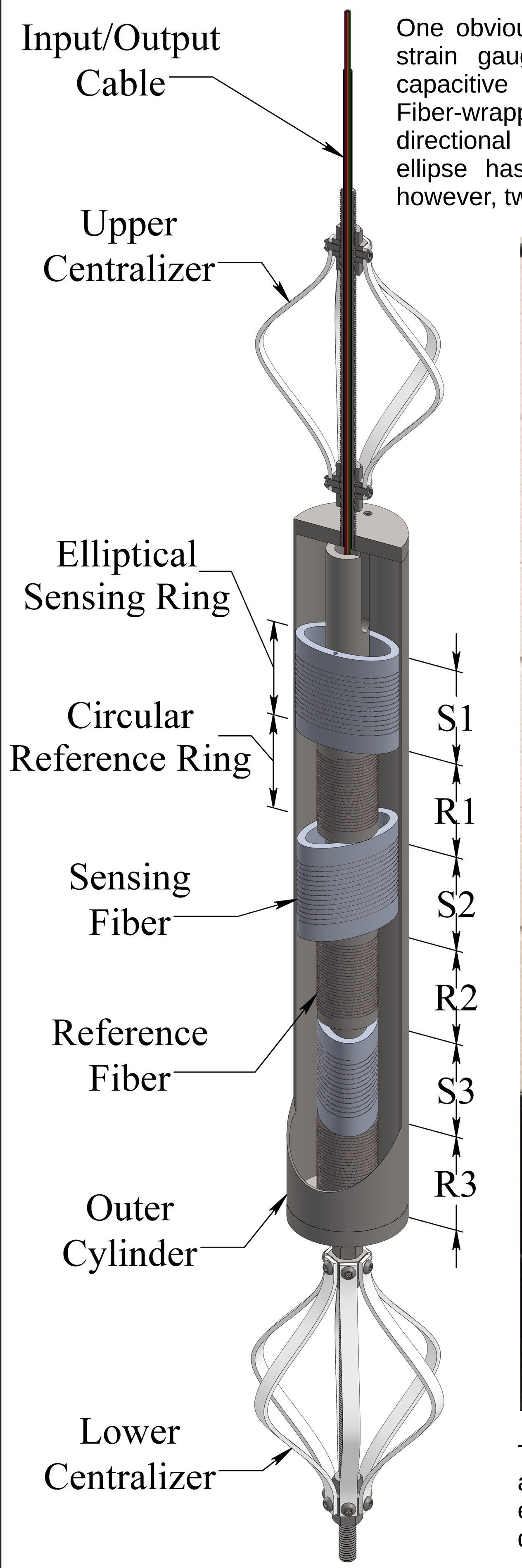
A natural extension of the OFAS concept is to include three pairs of fiber-wrapped cylinders into a single package like the borehole prototype shown below. While each "Sensing Mandrel" is directly coupled to the outer cylinder, an air gap decouples the fiber wrapped around the inner diameter of the "Reference Mandrel" from the inner diameter of the Sensing Mandrel.



The plot below shows the dead-weight load sensitivity in radians of optical phase change per kilogram of applied weight as a function of azimuth to illustrate the potential directional discrimination potential of this design.

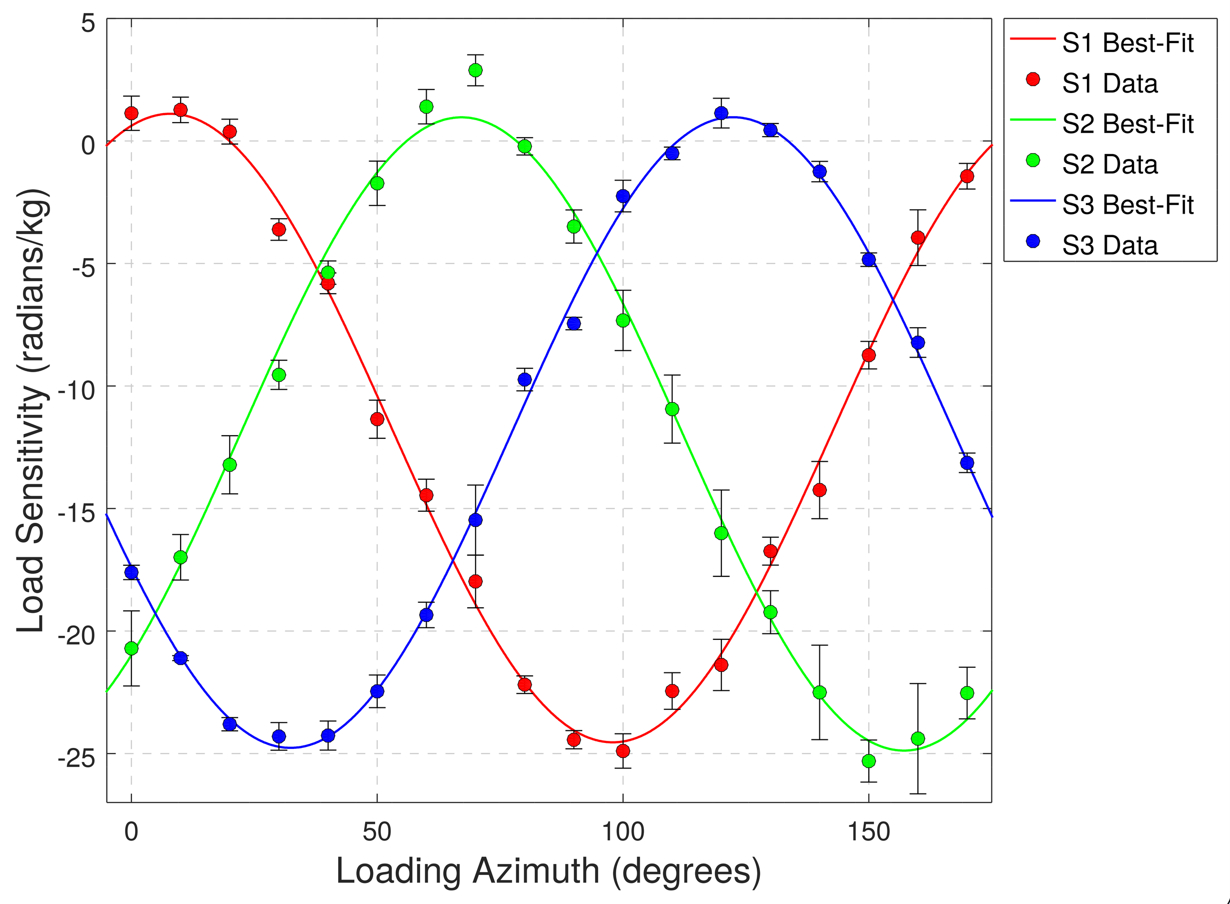


2. Elliptical Ring (Optical Fiber GTSM)

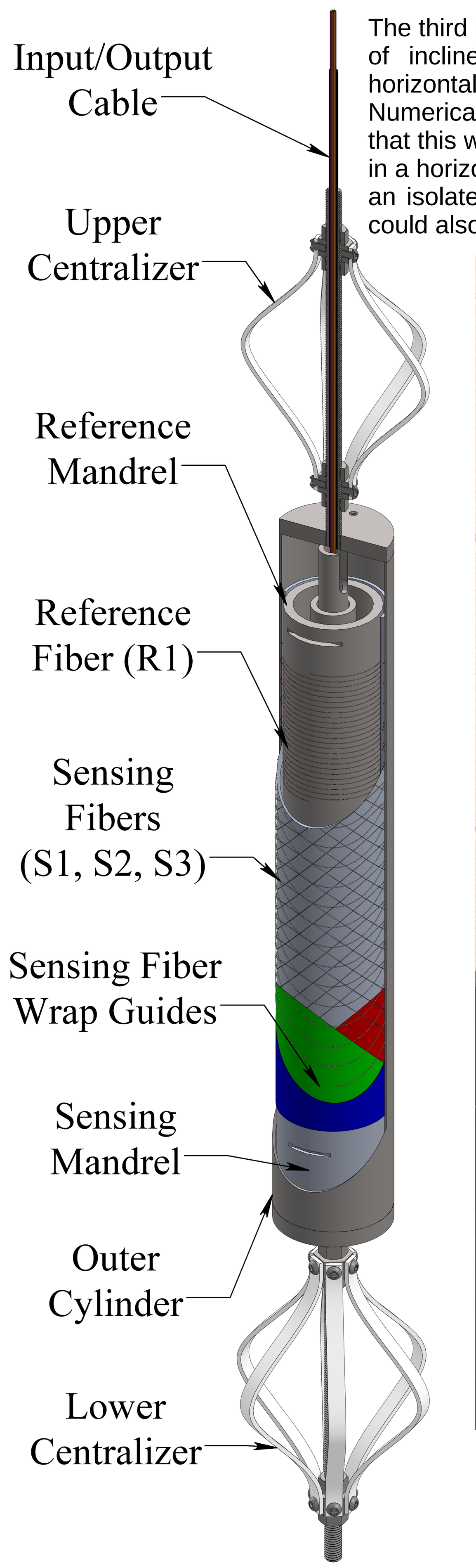


One obvious approach is to use the GTSM stacked strain gauge design and the simply replace the capacitive sensors with optical fiber interferometers. Fiber-wrapped elliptical rings are one way to create a directional response in an embedded system. Each ellipse has an omnidirectional (circular) reference, however, two orthogonal rings could also be used.

The plot below shows the load sensitivity as a function of azimuth revealing the expected sinusoidal behavior and 60-degree offset between gauges.

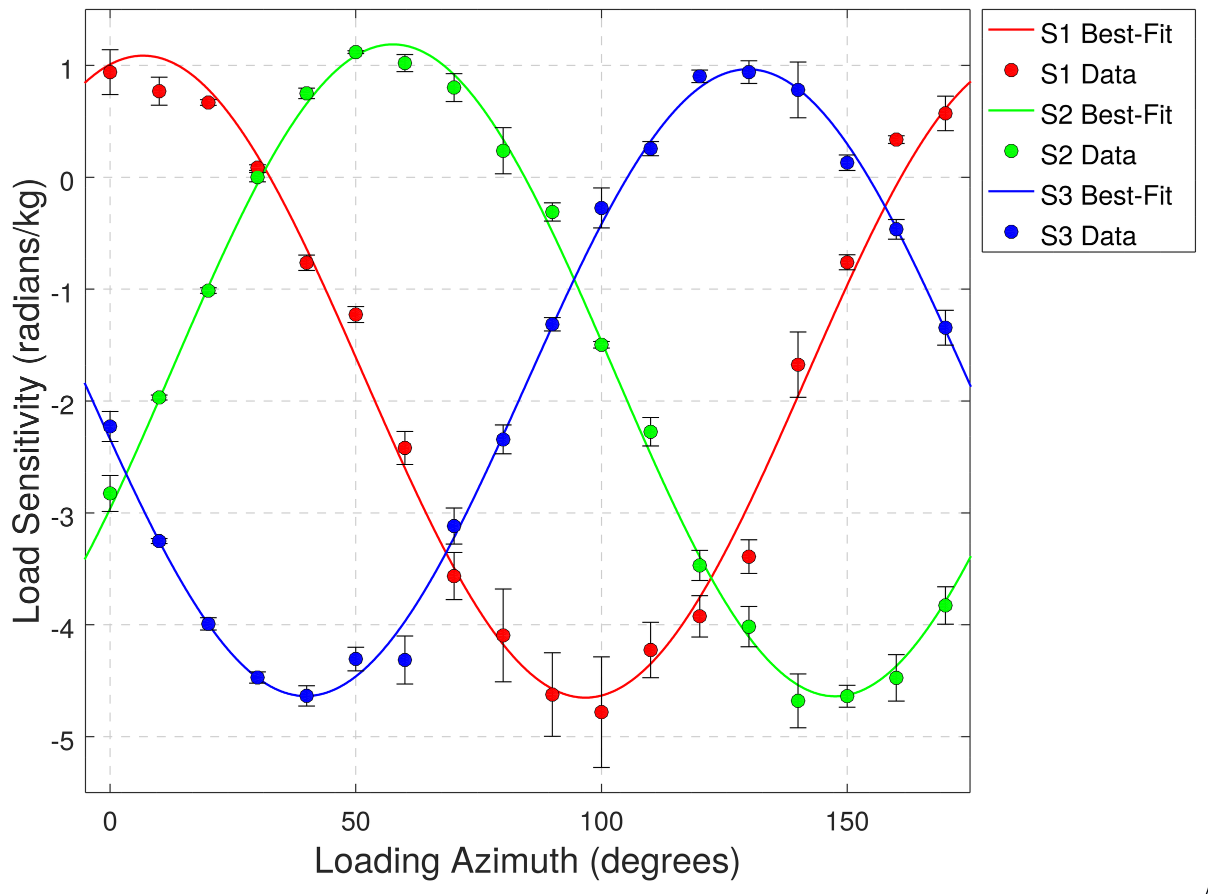


3. Inclined Helical Wrappings



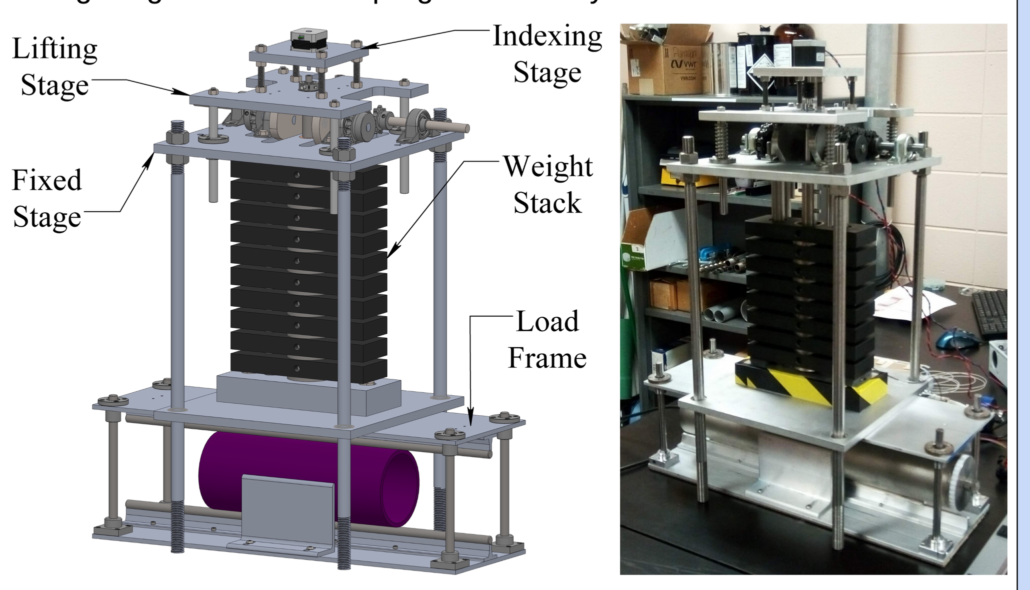
The third prototype system uses three successive layers of inclined helical fiber wrappings rather than the horizontal wraps used in the previous designs. Numerical simulations and earlier prototypes showed that this will produce a directionally-dependent response in a horizontal bi-axial stress field. This version includes an isolated reference similar to the Triple Mandrel, but could also contain orthogonal inclined wraps.

The plot below shows the load sensitivity as a function of azimuth revealing the expected sinusoidal behavior and 60-degree offset between gauges.

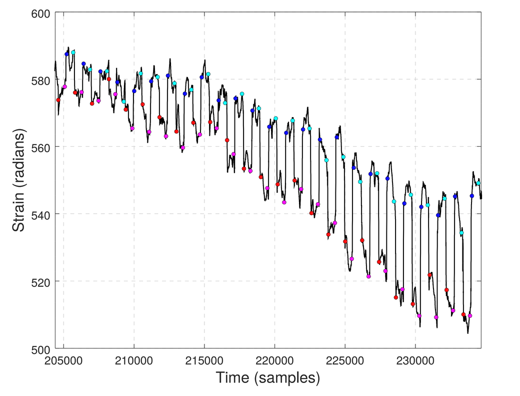


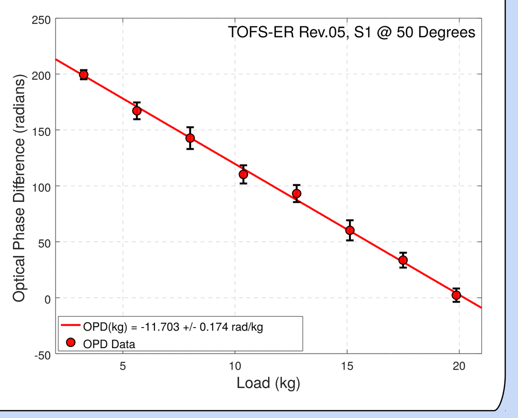
4. Automated Dead-Weight Load Calibrator

Calibration of borehole strainmeters is a well-known challenge and is most often done in-situ. This can also difficult in the lab given the proportionally large temperature coefficient of optical fibers. We have designed and built a load frame to compress a single sensor azimuth along with an automated loading system consisting of a stack of up to ten 2.3 kg weights that can be programmatically set onto the load frame.



The plots below show a typical load test for a given azimuth wherein a time series of the strain can be sectioned into load and unload cycles such that the strain change per selected load can be averaged as needed to counteract drift. Strain vs. applied load can be fit to determine the load sensitivity, and repeated for different sensor orientations.





5. Conclusions

Three different horizontal tensor optical fiber strainmeter designs were assembled and tested in the lab using an automated dead-weight calibration system. Each design has its own set of advantages and disadvantages that can be summarized as:

Triple Mandrel

- More parts than the inclined wrap design, but they are easy to fabricate and moderately easy assemble. Rather unusual abs(cos) azimuthal response.

Elliptical Ring

- Same number of parts as the Triple Mandrel, but more expensive to fabricate. It is the easiest to assemble of the three and yields a very predictable directional response.

Inclined Wrap

- Fewest and simplest parts to fabricate but very challenging to wrap without automation. Similar response to the Elliptical Ring.

Next step is to get all three in the ground!

This material is based upon work supported by the U.S. Department of Energy (DOE) National Energy Technology Laboratory (NETL) under Grant Number DE-FE0028292. This project is managed and administered by the Sequestration Division and funded by DOE/NETL and cost-sharing partners.

AKNOWLEDGEMENTS: The authors are grateful for the excellent work and service provided by Machining and Technical Services at Clemson University. We would also like to thank Marvin Robinowitz and Scott Robinowitz of Grand Resources; Rodney Merck, Rodney Morgan and Briana Peele of Clemson University.