Development of High-Sensitivity Optical Fibers for Distributed Acoustic Sensing

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National Energy Technology Laboratory
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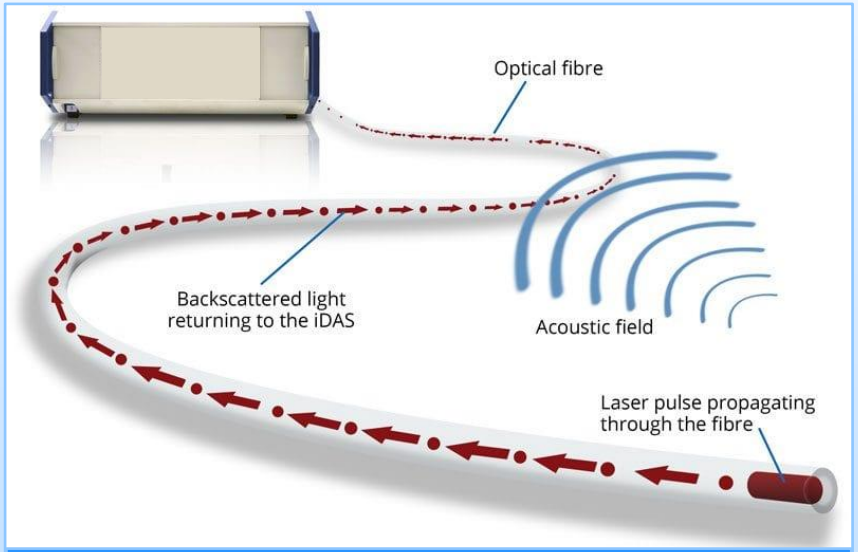
Presentation Outline

- Motivation for new fibers
- High-sensitivity fibers
  - Bragg-enhanced fibers
  - Geometry-enhanced fibers
- Field testing
  - Measurements of geometry-enhanced fibers
  - Progress on Bragg-enhanced cable
- Summary

Distributed Acoustic Sensors

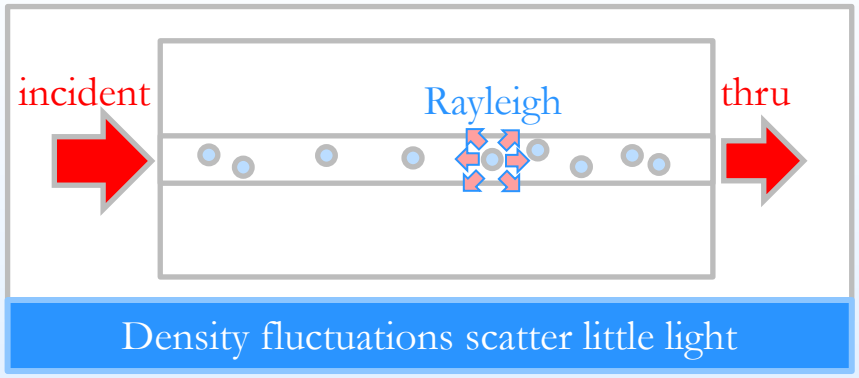
- All optical fibers scatter some of the light they carry
  - Throughout their lengths
- DAS interferes the back-scattered light with a reference beam to sense acoustically-induced strain changes



DAS senses acoustically-induced strains

Rayleigh Scattering

- Rayleigh scattering is inescapable and small
  - Ten-meters of fiber scatters only 0.05% of the light that passes through it
  - Only 0.4% of the scattered light returns to interrogator

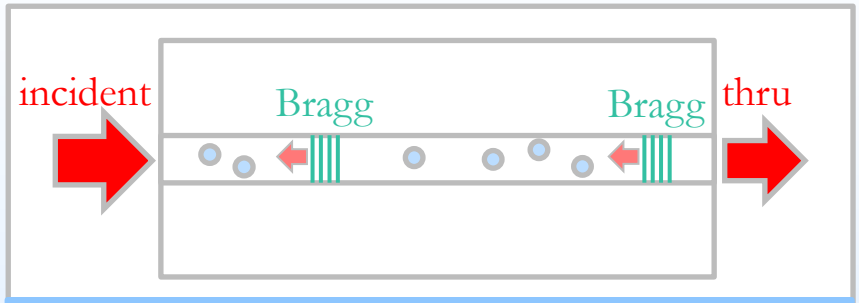


Density fluctuations scatter little light

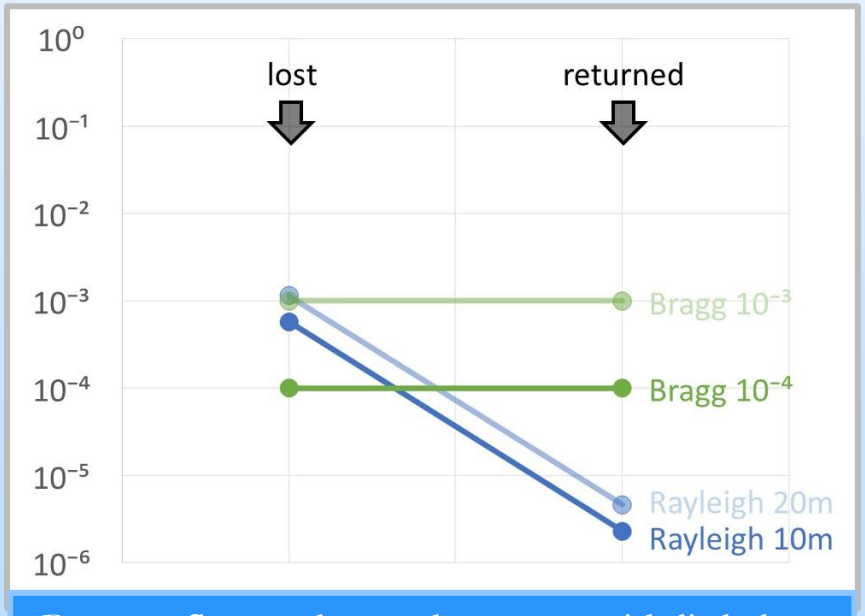
Only small fraction of scattered light is returned

Bragg reflections

- Rayleigh scattering is inescapable and small
  - Ten-meters of fiber scatters only 0.05% of the light that passes through it
  - Only 0.4% of the scattered light returns to interrogator
- Bragg gratings return all the light they remove from the beam



Bragg-resonant structures can scatter more light



Bragg reflectors boost the return with little loss

Status of Bragg-enhanced fibers

- Unfortunately, the LLNL team cannot (yet) write gratings
  - System is installed and operational
  - We will likely need two-months of effort to write our first gratings
- Today, other teams are investigating these fibers
  - Ping Lu et al, "Distributed optical fiber sensing: Review and Perspective," Appl Phys Rev (2019)
  - Zhaoyong Wang et al, "Recent Progress in Distributed Fiber Acoustic Sensing with Φ-OTDR," Sensors (2020)
- And today, enhanced fibers are becoming commercially available

UV excimer laser
248nm, 150mJ
Coherent Laser Corp

Programmable rewinder
Technical Dev. Corp
Huntersville, NC

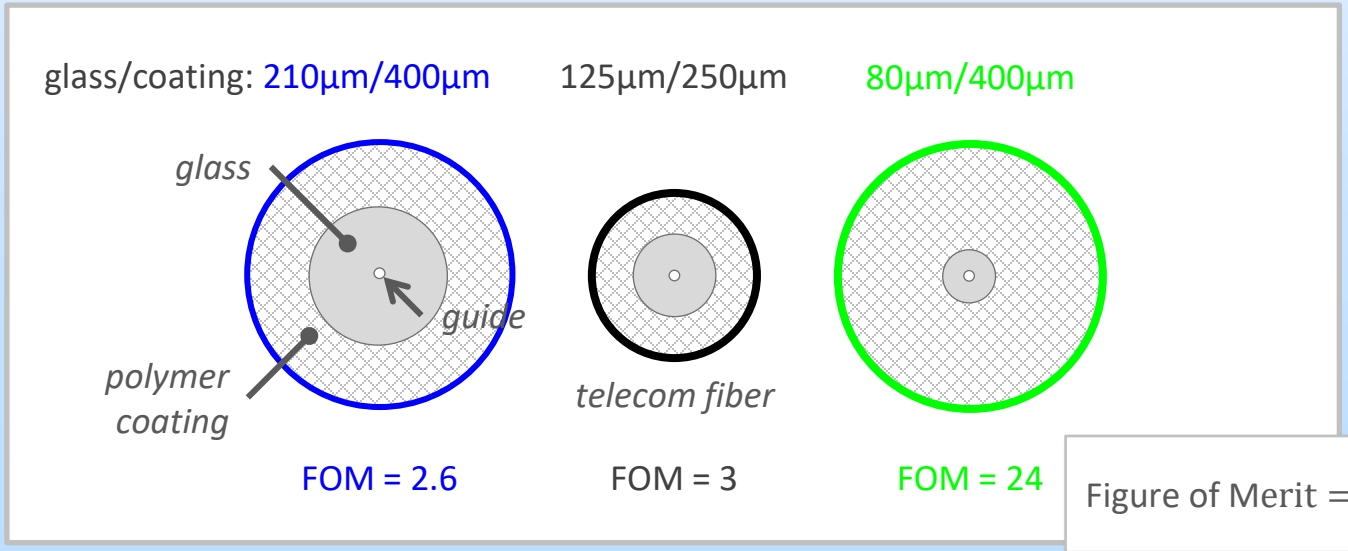
Path forward

- Purchase enhanced fibers from two commercial sources
  - OFS Labs (New Jersey)
  - FiberCore (Southampton UK)
- Build enhanced fibers into a custom cable
  - Cable designed by LBNL team
  - Cable manufactured by Prysmian Downhole Tech (New Jersey)
- Include conventional telecom fibers in the cable for…
  - Baseline comparisons
  - Loop-back measurements

Several companies, including OFS of New Jersey, now offer Bragg-enhanced fibers

Modified-geometry fibers

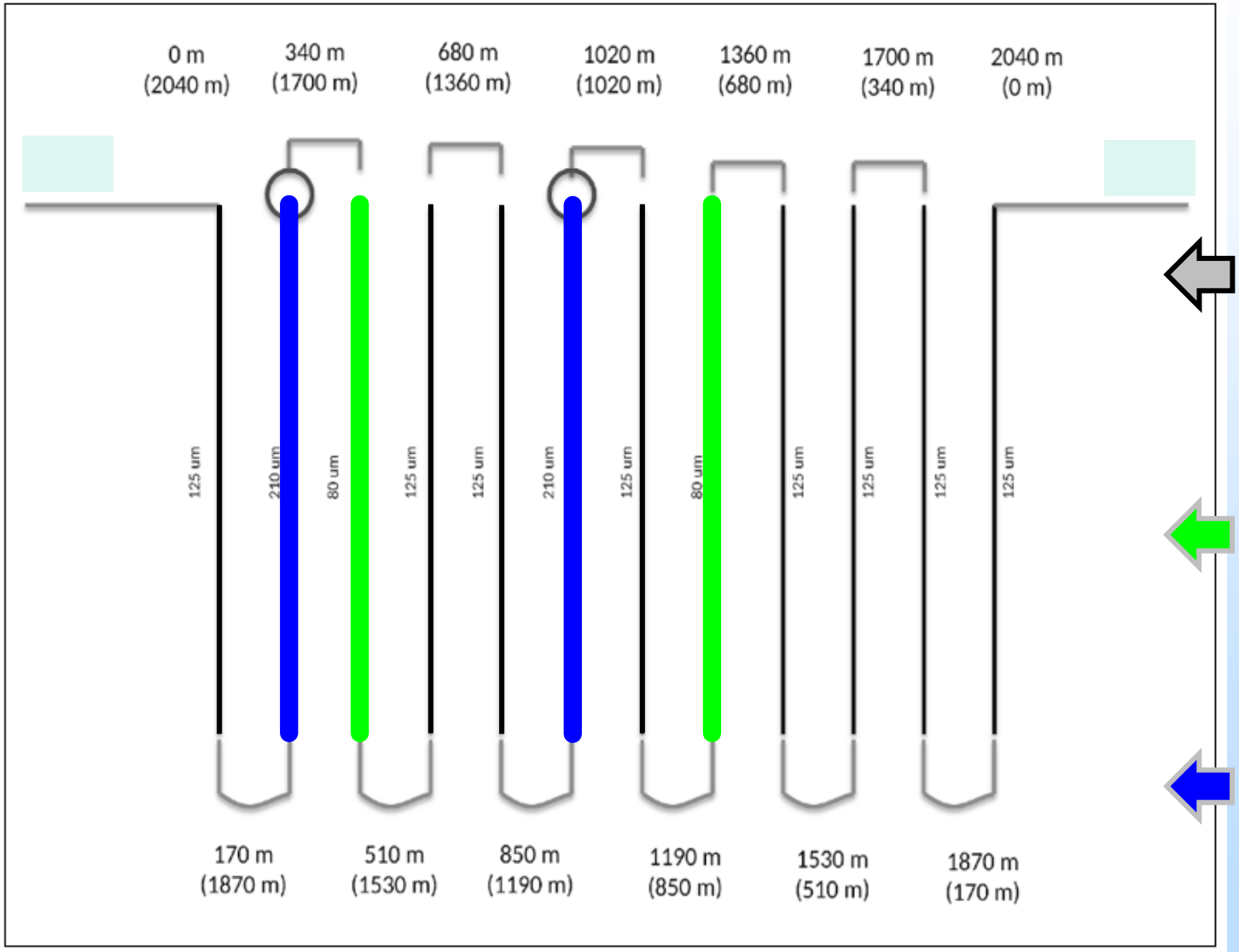
- Models developed by US Navy in 1970s and 1980s suggest that thick-coatings over thin-fibers could increase acoustic sensitivity nearly 10×
  - Enhances the Poisson effect
  - G.B. Hocker, "Fiber-optic sensing of pressure…," Applied Optics (1979)
- In late 2020, LLNL shipped a 175m cable to LBNL
  - Cable is a remnant from a different program
  - Cable contains a geometry-sensitized fiber and a desensitized fiber



Tests of modified fibers

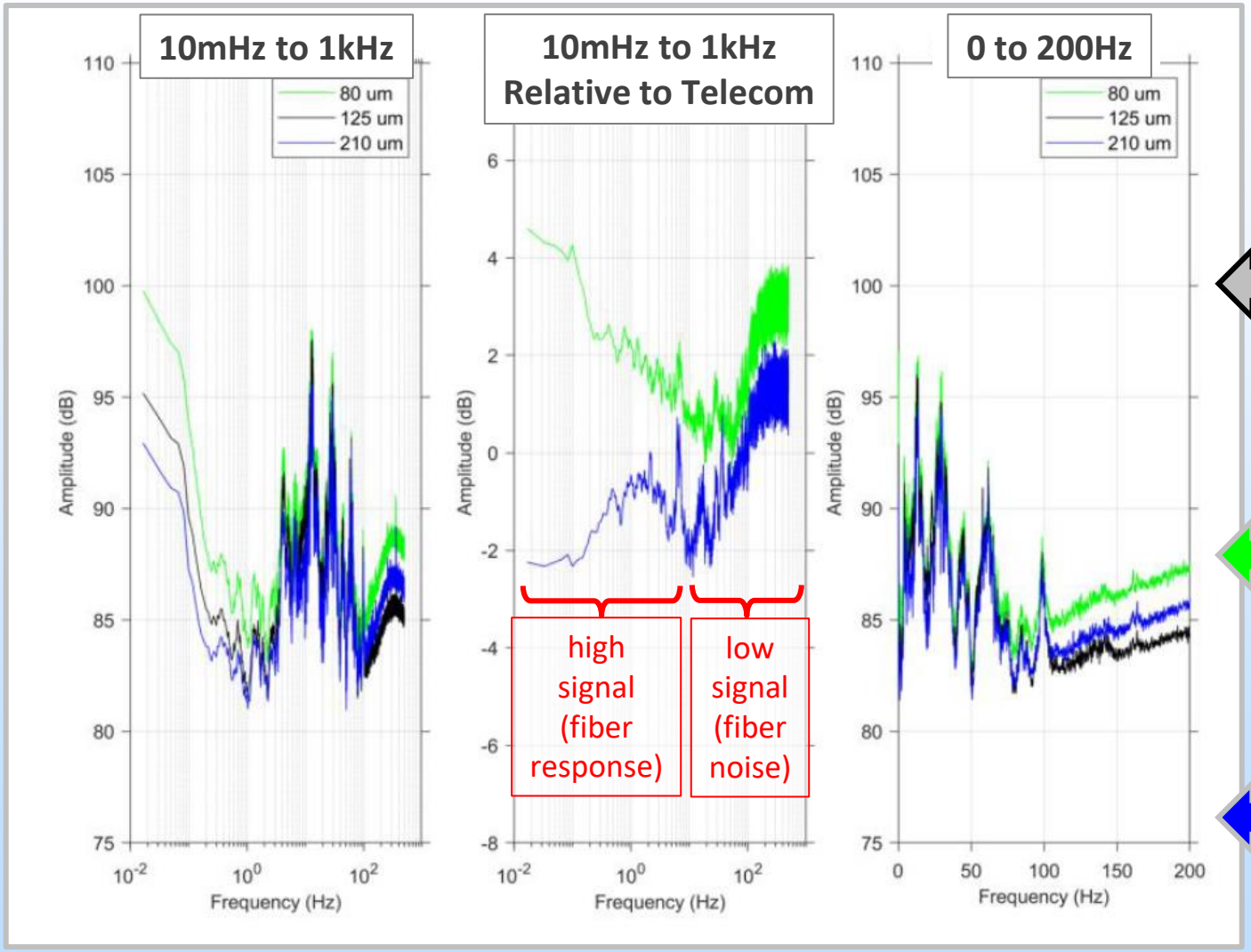
- Tests conducted at UC Berkeley's field station in Richmond CA
- Cable layout
  - 100m horizontal along surface
    - » Sandbags enhanced coupling
  - 70m vertical in PVC-cased well
    - » Borehole is fluid-filled
- Generated impulses via sledgehammer
  - Strikes at 1, 5, 10, and 20m from hole
  - In future, will generate acoustic signals via a surface orbital vibrator
- Fibers monitored with a commercial DAS interrogator
  - Geophones placed for comparison

Loop-backs allow direct comparisons



Early DAS results

Hammer strike at 20m



At low frequencies, the 80/400µm is significantly more sensitive than is a conventional fiber

Accomplishments to Date

1) Attempted to write gratings with UV LEDs already mounted on tower
- ✓ Tested, though unsuccessful

2) Attempted to write gratings with LLNL's on-site lasers
- ✓ Searched, but found no appropriate on-site lasers

3) Writing gratings with program-purchased laser
- ✓ Purchased, installed, and commissioned UV Excimer laser
- ✓ Purchased, installed, and commissioned custom off-line rewinder
- ✘ Write gratings (began writing on Aug-2019)

4) Fabricate custom fibers
- ✓ Fabricated UV-sensitive fiber
- ✘ Fabricate custom fiber having UV-transparent coating

5) Design and commission custom DAS cable
- ✓ Purchasing two commercial Bragg-enhanced fibers
- ✓ Cable design and commissioning are underway

6) Field test DAS cables
- ✓ Completed field test of geometry-enhance fibers
- ✓ Field test of two Bragg-enhanced fibers will begin in late 2021

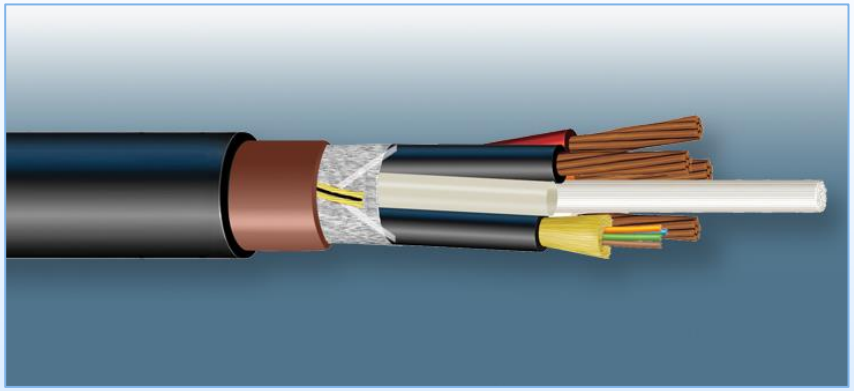
Lessons Learned

- We successfully anticipated the potential benefits of Bragg-enhanced fibers
  - Bragg gratings can increase signal 10×, and are compatible with off-the-shelf DAS interrogators
- We did not anticipate key grating-writing challenges
  - Including laser-installation challenges and alignment of UV interferometer
- Changes for next time
  - We have identified a consulting team, with combined 50 years of Bragg-writing experience, to guide the alignment of the Bragg interferometer

- LBNL's field tests in Richmond CA (now imminent) will provide valuable feedback for the development of future fibers

Synergy Opportunities

- Strengths
  - LBNL: Seismology, data analysis, and testing in field environments
  - LLNL: Fiber fabrication, and photonics-based interrogators
- Our teams will continue to seek ways to apply custom fibers to new sensing applications
- Carbon sequestration and energy production applications will continue to steer LBNL/LLNL research and commercialization efforts



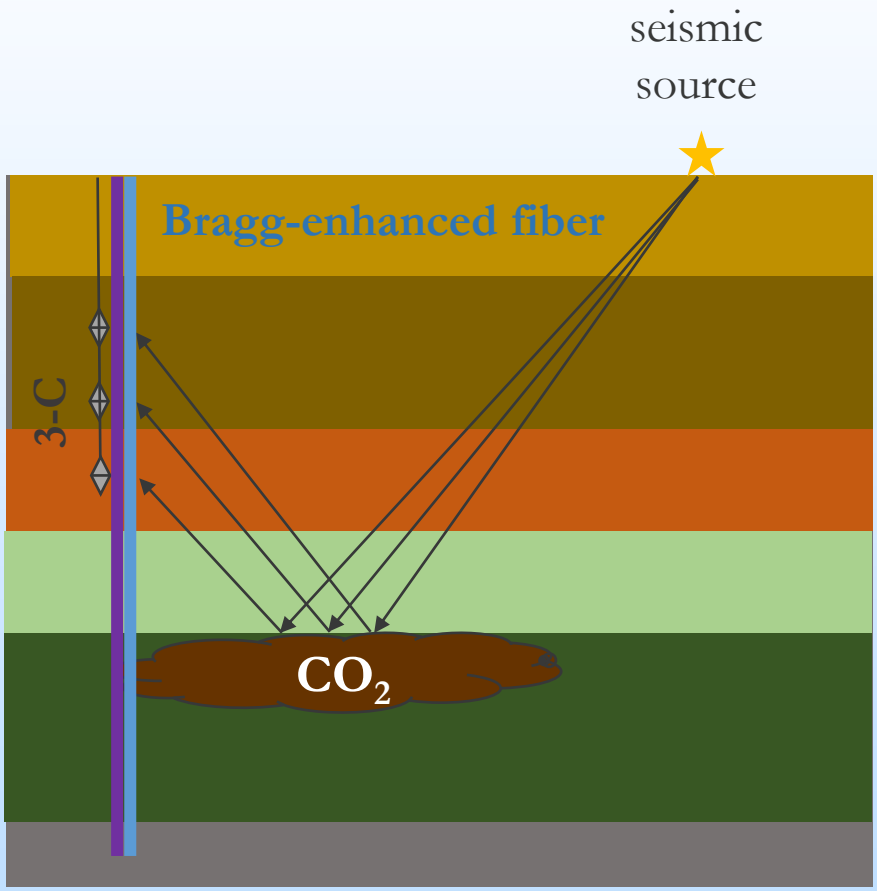
Project Summary

- Key findings
  - Over the past several years, Bragg-enhanced fibers have proven to significantly increase the signal-to-noise of DAS sensors
  - An off-line Bragg-writing process, based on a UV laser, can overcome many manufacturing challenges
- Next steps
  - LLNL: Deliver Bragg-enhanced cable to LBNL for testing
  - LBNL: Field-test Bragg-enhanced cable

Appendix

Benefit to the Program

- Sensitivity-enhanced DAS fiber would allow for…
  - More rapid imaging of CO_2/pressure plumes
  - Higher-resolution characterization of faults and fracture networks
  - Improved detection of fluid flows
  - Detection and diagnosis of imminent wellbore integrity problem



Project Overview

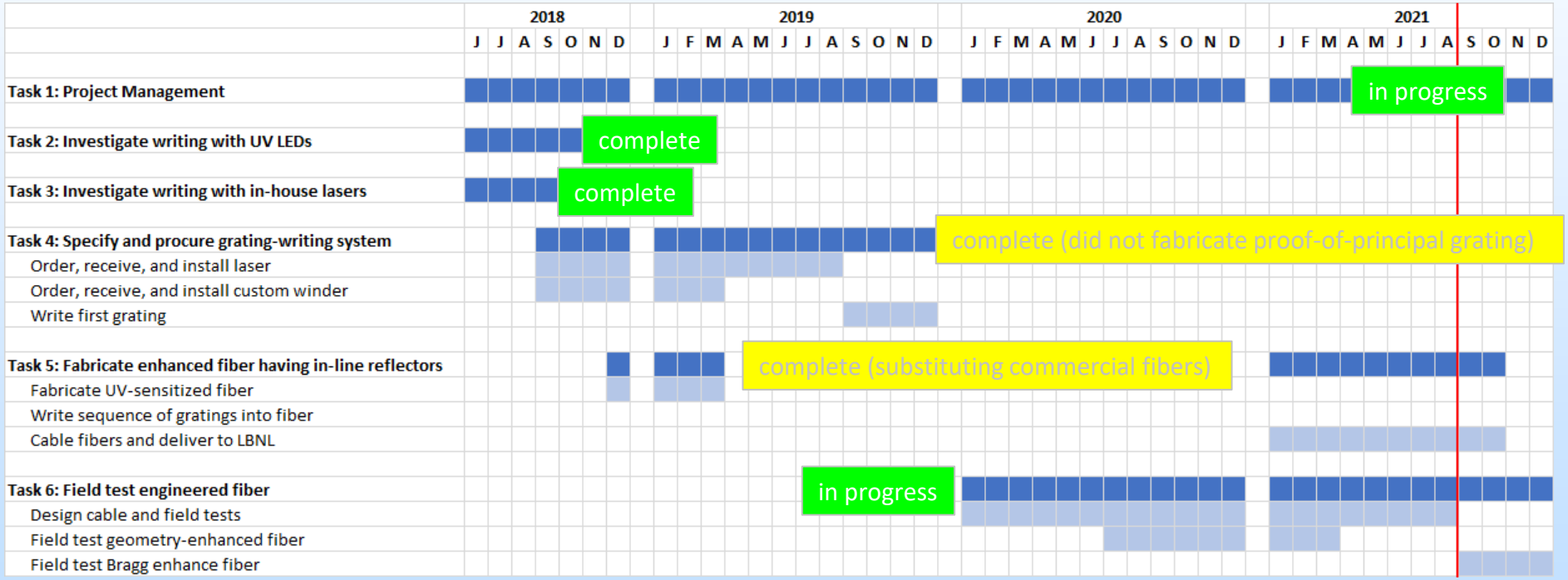
Goals and Objectives

- Goal: Combine LBNL's DAS field expertise and LLNL's optical fiber expertise to enable:
  - Rapid imaging of CO_2/pressure plumes
  - Higher-resolution characterization of faults and fracture networks
  - Improved detection of fluid flows
  - Detection and diagnosis of imminent wellbore integrity problem
- Objectives
  - Deliver field-ready cable having one or more Bragg-enhanced fibers, of length greater than 500m
  - Field test Bragg- and geometry-enhanced cables, and demonsterate greater than ten-fold improvement in DAS signal-to-noise ratio

Organization

- LBNL
  - Objective: Field test custom optical fiber cable
  - Lead scientists
    - Michelle Robertson, Julia Correa
    - Barry Freifeld (now with Class VI Solutions)
  - Resource Analyst: Helen Prieto
- LLNL
  - Objective: Develop custom fibers, including Bragg-enhanced fibers
  - Lead scientists
    - Michael Messerly (optical fibers)
    - Robert Mellors (Geophysics, now with UCSD)

Gantt Chart


2018
2019
2020
2021
J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D
Task 1: Project Management
in progress
Task 2: Investigate writing with UV LEDs
complete
Task 3: Investigate writing with in-house lasers
complete
Task 4: Specify and procure grating-writing system
complete (did not fabricate proof-of-principal grating)
Order, receive, and install laser
Order, receive, and install custom winder
Write first grating
Task 5: Fabricate enhanced fiber having in-line reflectors
complete (substituting commercial fibers)
Fabricate UV-sensitized fiber
Write sequence of gratings into fiber
Cable fibers and deliver to LBNL
Task 6: Field test engineered fiber
in progress
Design cable and field tests
Field test geometry-enhanced fiber
Field test Bragg enhance fiber

Bibliography

- No journal submissions to date