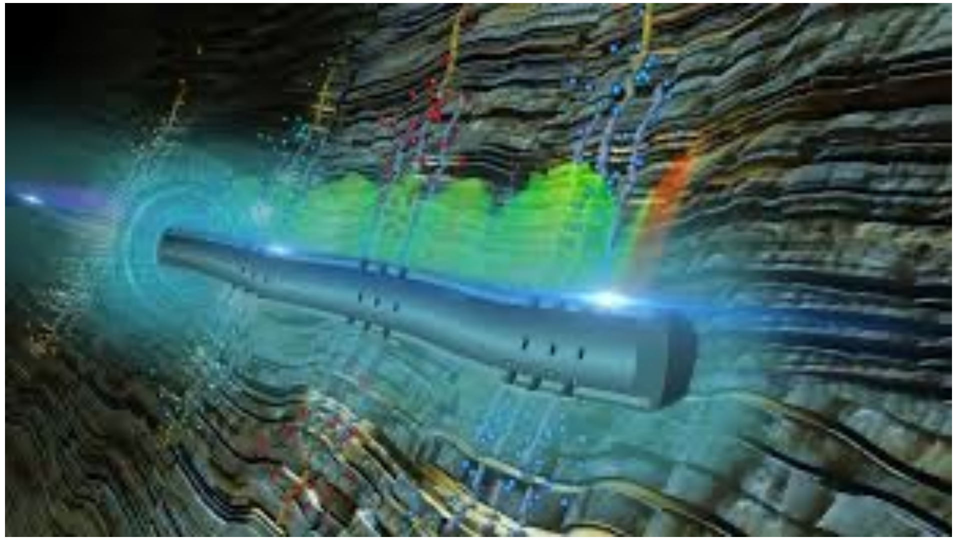
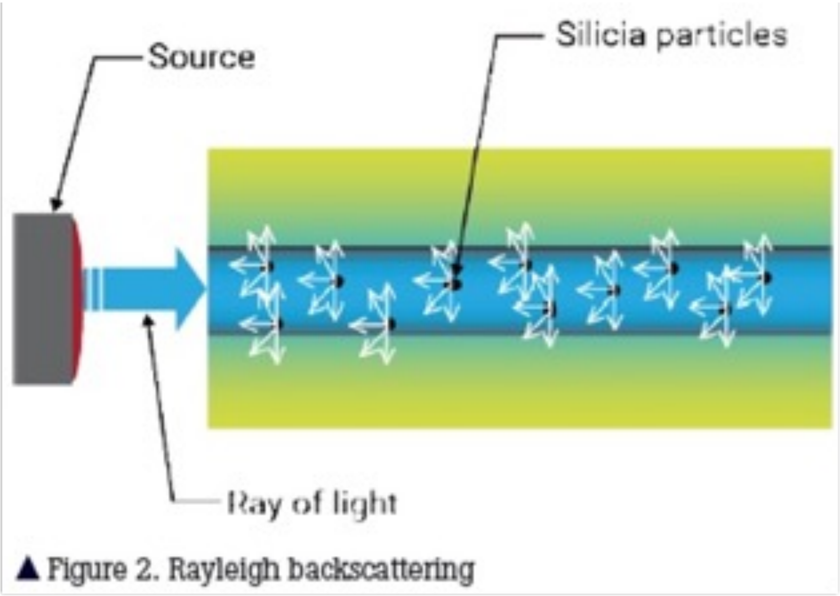
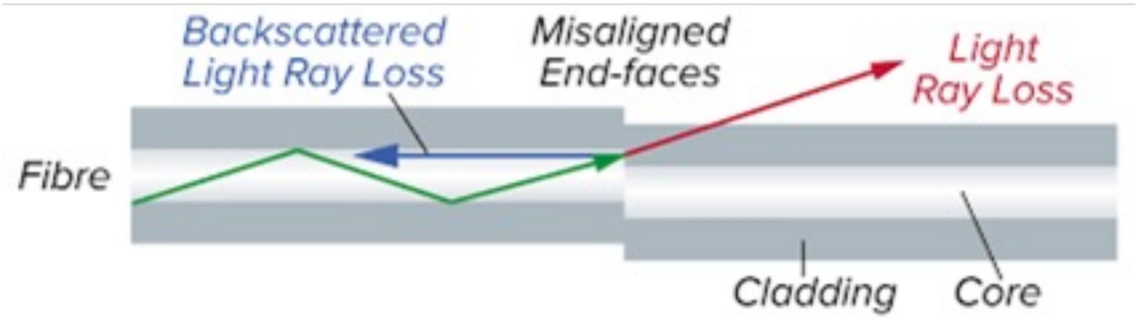
Distributed Acoustic Sensing Limitations

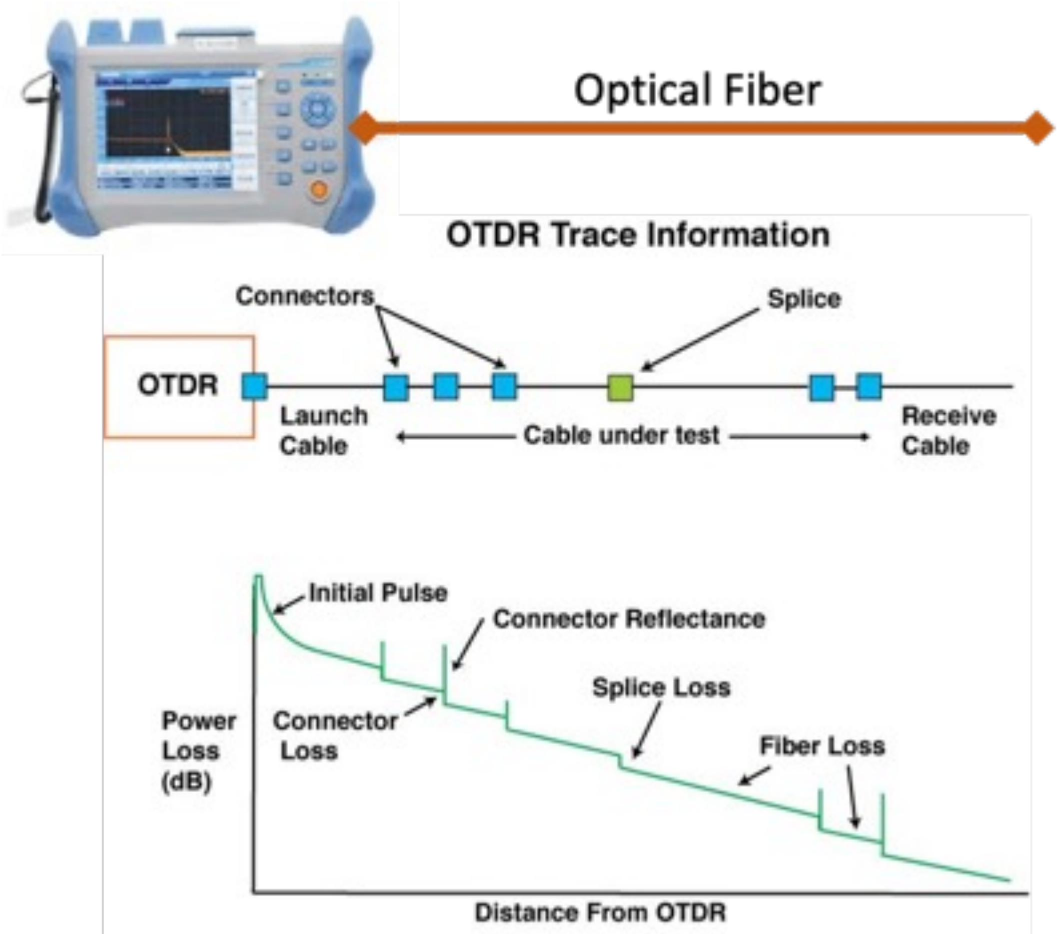
- DAS systems are expensive
  - $10,000 operating cost per day
- Data volumes are massive
  - Terabytes per fiber-km per day
- High power requirements
- Problems must have significant near-term value for motivation
- Good uptake in energy industry
- Lower cost systems are needed for public applications



Optical Time Domain Reflectometer (OTDR)

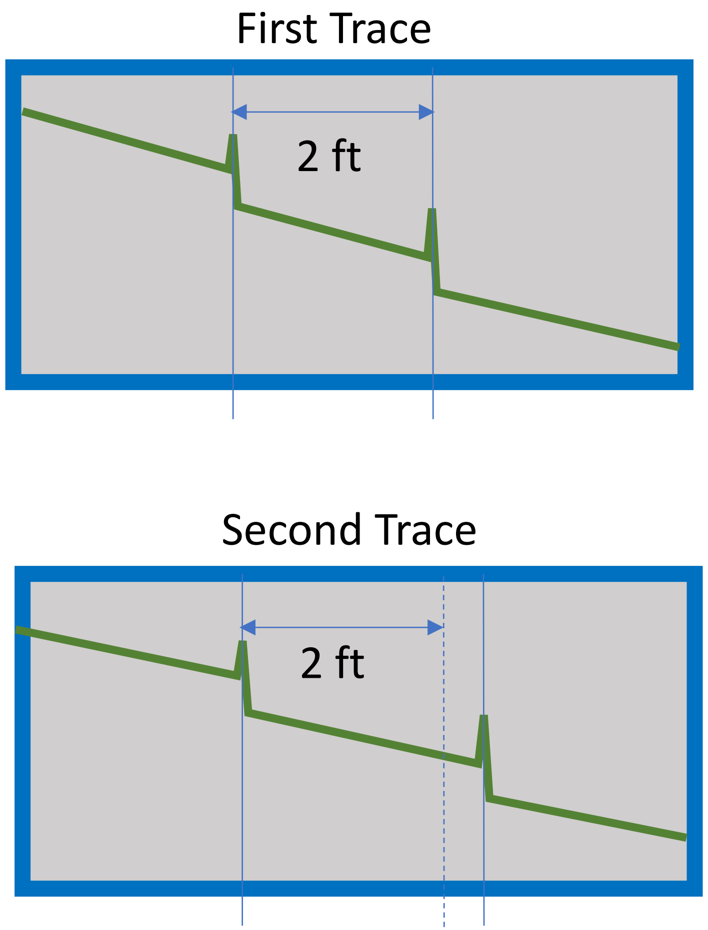






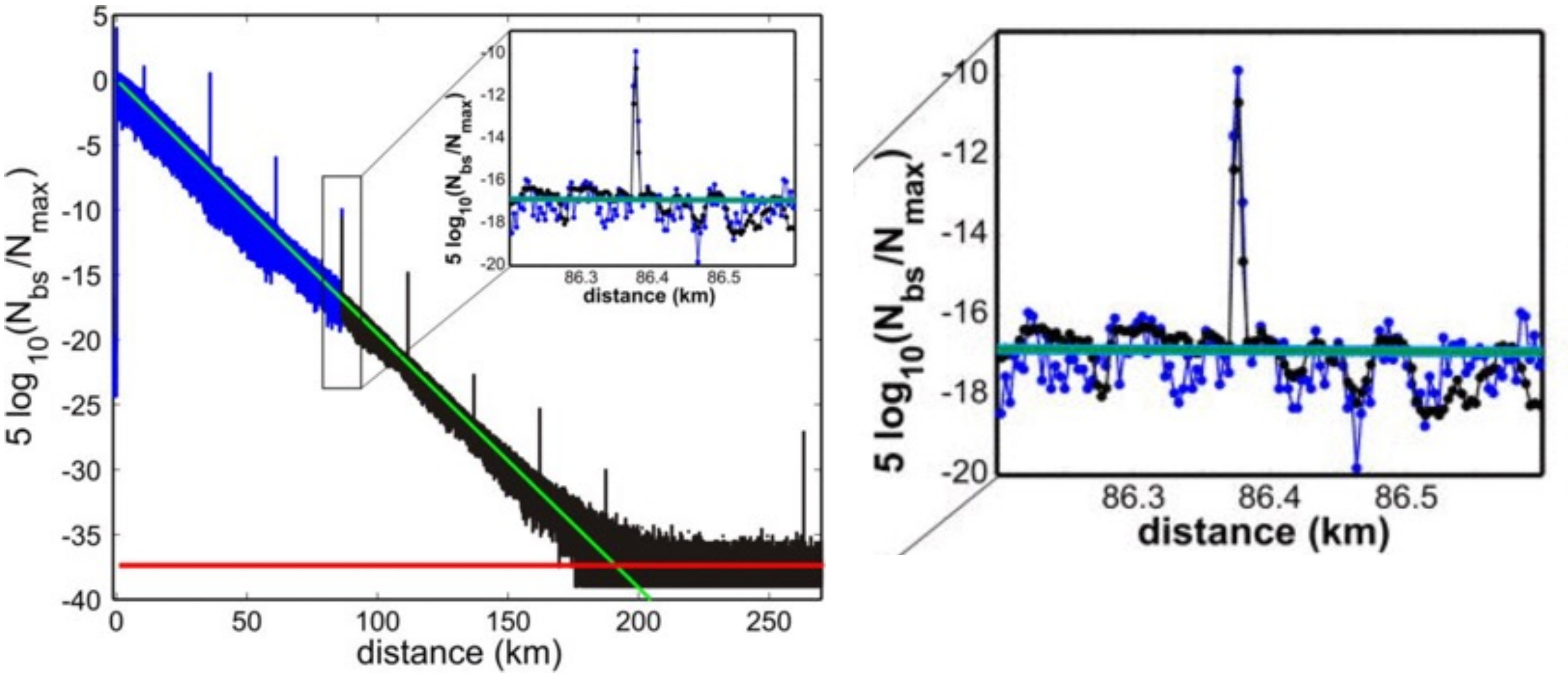
What happens if the fiber is stretched ?

Here is a cartoon example of a fiber that has two connectors that create reflections. In the first measurement, the fiber is under normal conditions and we get a trace with two reflections that are 2 feet apart. If the cable is stretched, then the distance between the two connectors will increase. A a second trace collected while the cable is stretched will then show a distance greater that 2 ft between the reflections. From this information we can estimate how much the cable has been stretched.



There are small imperfections all along the fiber

If we zoom in on an OTDR trace we see that in addition to the connectors, we can also see many other imperfections. This allows us to make continuous and detailed measurements of strain even on fibers with no connectors or splices.



Could we use a fiber to measure strain ?

- There are many systems today that use fiber to measure strain
- They tend to be expensive and require specially made fibers
- Could we use a low-cost OTDR to make repeated measurements on the typical fibers used for telecommunications ?
- I decided to build a lab in my basement to see if this was possible

An alternative to DAS: OTDR

Repeatable sensitivity of optical-time-domain-reflectometry–based strain measurement*

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ABSTRACT

Optical time-domain reflectometry (OTDR) is a simple and rugged technique for measuring quantities such as strain that affect the propagation of light in an optical fiber. For engineering applications of OTDR, it is important to know the repeatable limits of its performance. The authors constructed an OTDR-based, submillimeter resolution, strain measurement system from off-the-shelf components. The system repeatably resolves changes in time of flight to within ± 2 ps. Using a 1-m, single-mode fiber as a gauge and observing the time of flight between Fresnel reflections, we observed a repeatable sensitivity of 400 microstrains. Using the same fiber to connect the legs of a 3-dB directional coupler to form a loop, we observed a repeatable sensitivity of 200 microstrains. Realizable changes to the system that should improve the repeatable sensitivity to 20 microstrains or less are discussed.

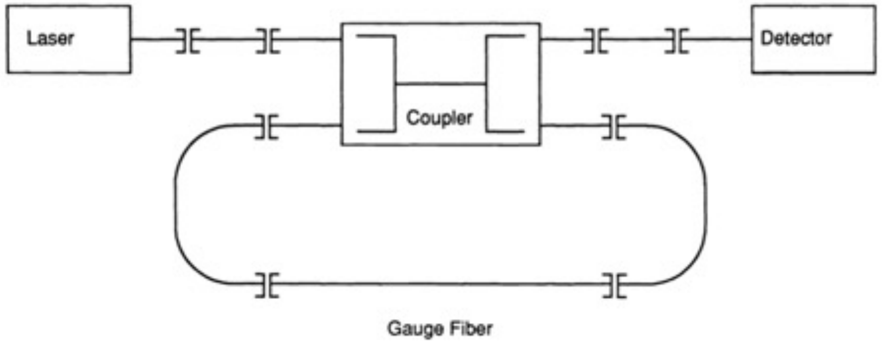


Fig. 2. Loop optical-time-domain-reflectometry configuration.

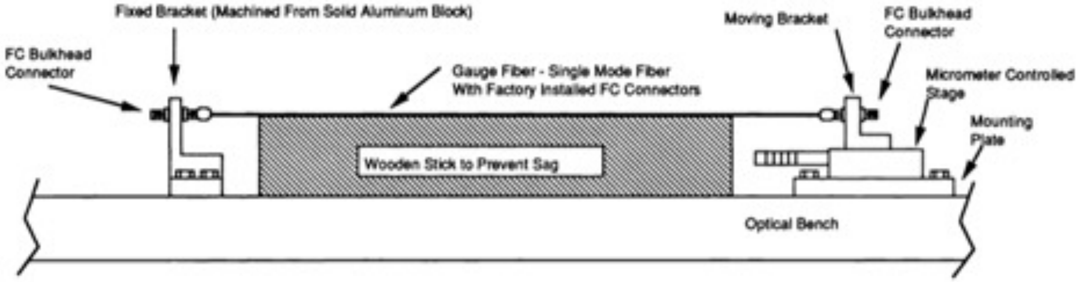
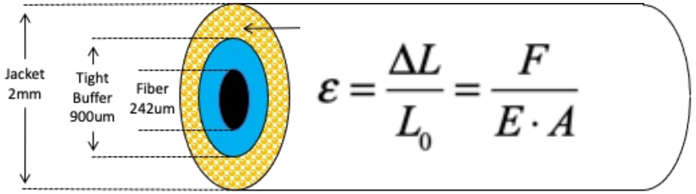
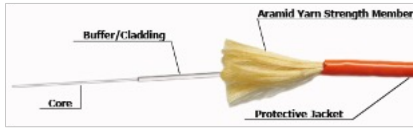


Fig. 4. Mechanical support of gauge fiber.

Chuck’s Basement OTDR Lab



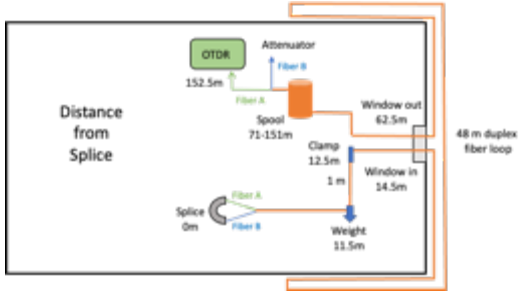
$$\varepsilon = \frac{\Delta L}{L_0} = \frac{F}{E \cdot A}$$

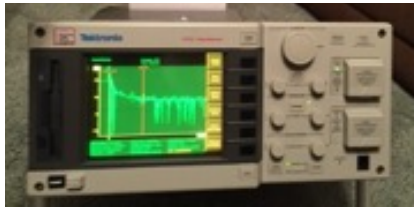


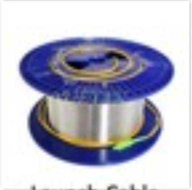
- Bare fiber: Core, Cladding, Coatings, E_{eff}=22 GPa
- Tight Buffer: Nylon, E=3 GPa
- Strength Member: Kevlar 29 Aramid Yarn, E=150 Gpa
  - Filament diameter 12 um, E=150
  - 1000 filaments
- Protective jacket: Nylon, negligible impact on elastic behavior

Tektronix FiberMaster
From 1987, $300

Siemans Fusion Splicer
From 1998, $200

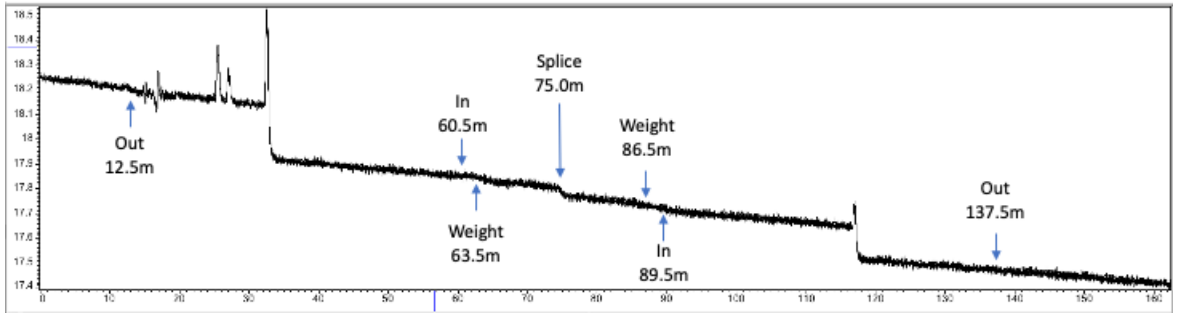






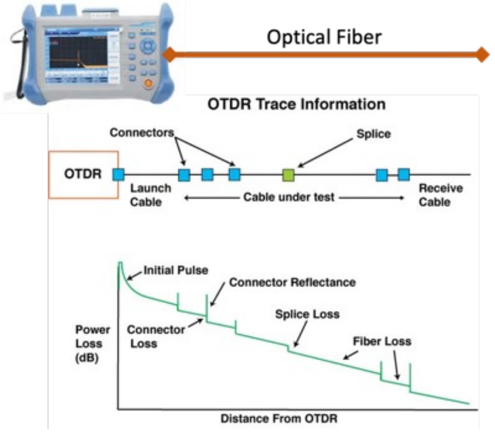
Launch Cable
$100

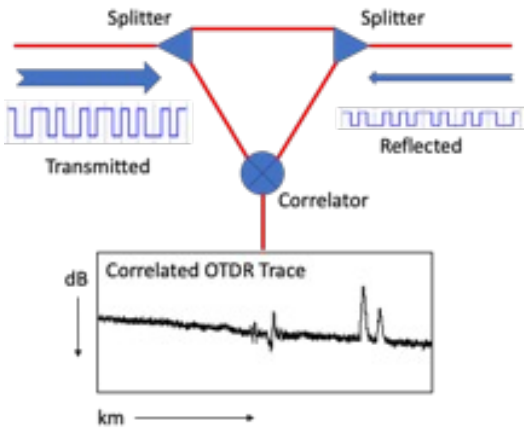
Tools and Supplies
$100



MoMacMo Technology for Low Cost Strain

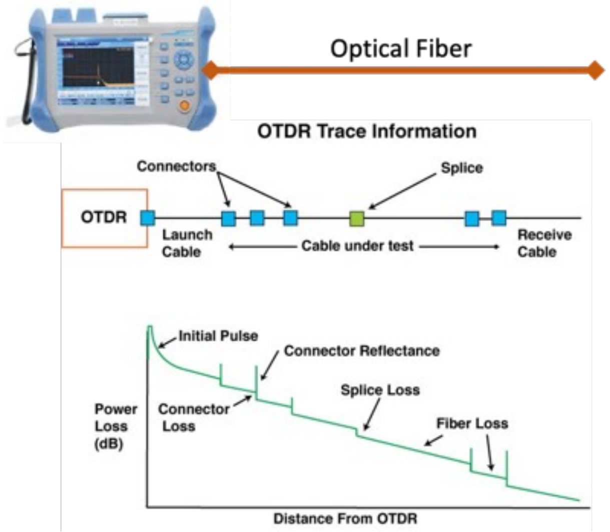
- DSS-OTDR: Distributed Strain Sensing with Optical Time Domain Reflectometers
    - Low cost strain monitoring for 1-10 km fibers (~$500 per sensor)
- DSS-IoT: DSS Internet of Things
    - Thousands of sensors connected by IoT communication networks
- DCSS: Digital Communication Strain Sensing
    - Uses binary signals on internet fibers as an encoded strain sensor
- DSS-Cloud: Cloud-based DSS processing
    - Geophysical inverse and machine learning solutions for global strain

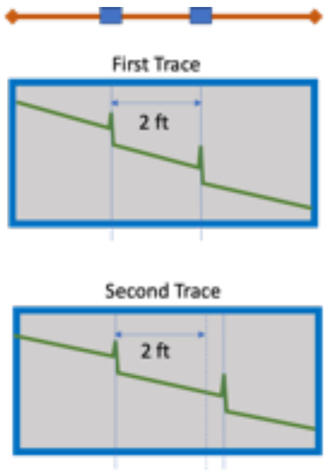




Distributed Strain Sensing with OTDR (DSS-OTDR)

- Distributed Strain Sensing with Optical Time Domain Reflectometers
  - Uses Commodity-Off-The-Shelf Optical Time Domain Reflectometers
  - Acquires a ”trace” where reflections represent defects along fibers with lengths from 1-100 km
  - If the fiber is stretched, the time between defects will increase
  - Time Strain is defined as the change in travel time between defects when repeated measurements are made
  - Time Strain Inversion algorithms can be used to monitor strain as small as 10^{-6} at 1 cm to 10 m resolution
  - COTS OTDR can acquire traces at 1 to 60 second intervals





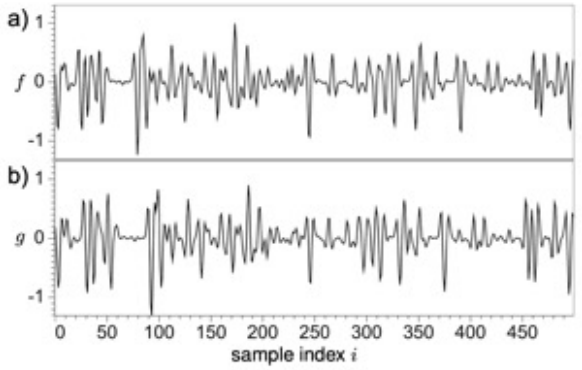
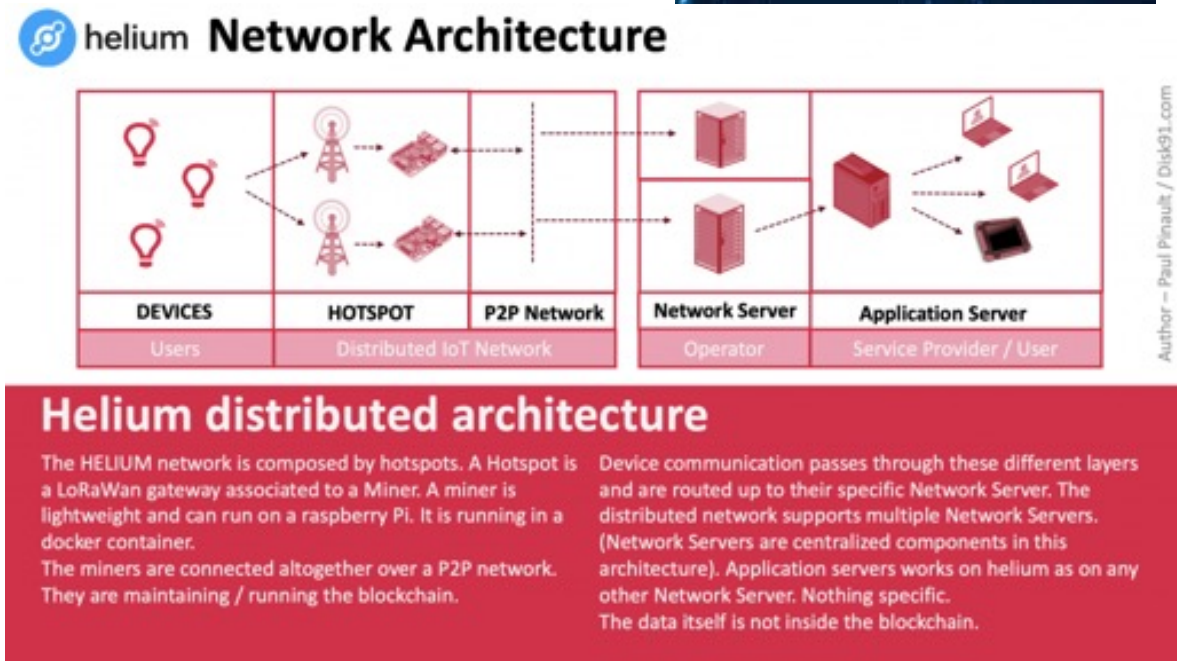


Figure 2. Two synthetic seismograms $f[i]$ (a) and $g[i]$ (b) corresponding to misaligned reflection coefficients, used as inputs to the dynamic time warping algorithm. Reflections in $f[i]$ also appear in $g[i]$, but are squeezed toward the middle of the sequence.

The Helium Network

- "The People's Network"
- Low power radio wide area network (LoRaWAN)
- Funded by HNT cryptocurrency
- "Miners" deploy hotspots
- "Users" pay for access to bandwidth
- Most pervasive IoT network



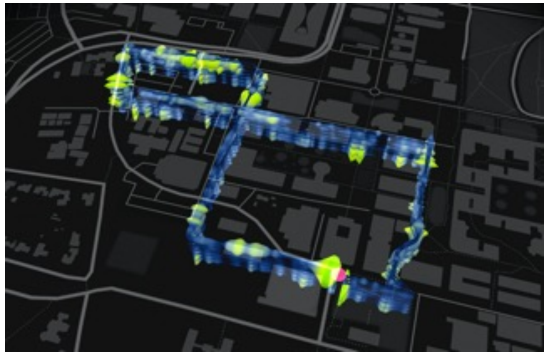
Distributed Strain Sensing IoT (DSS-IoT)

- Distributed Strain Sensing Internet of Things
  - Low cost DSS-OTDR sensor ($500 USD), fiber cost $150 per km
  - One sensor with a 10 km fiber could continuously monitor subsidence for 16 city blocks
  - IoT networks (cellular, LoRa, or mesh) can collect data from 1000’s of sensors
  - Cloud based processing and machine learning for analysis and alarms

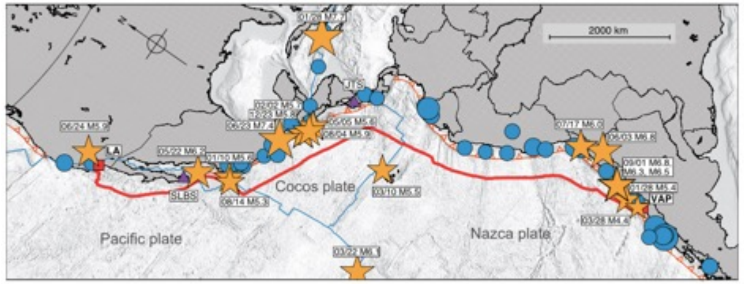
Using communication fibers for strain monitoring

- An active subject in academia
- Stanford used fibers on campus to detect earthquakes
- Berkeley used a seafloor dark fiber for DAS
- UCLA used Google's Cirrus fiber in transmission
- UW Madison has proposed "Internet Photonic Sensing"

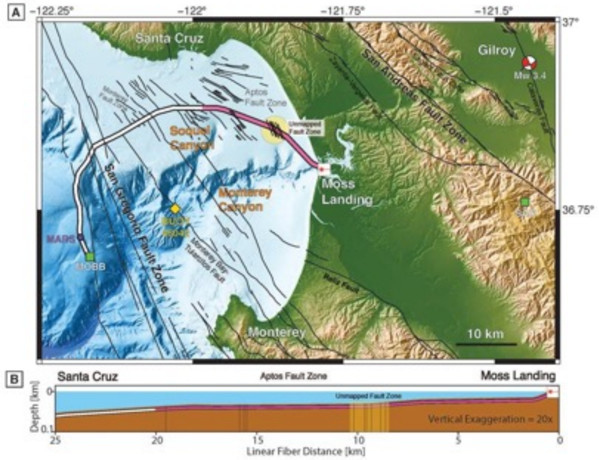
Stanford DAS



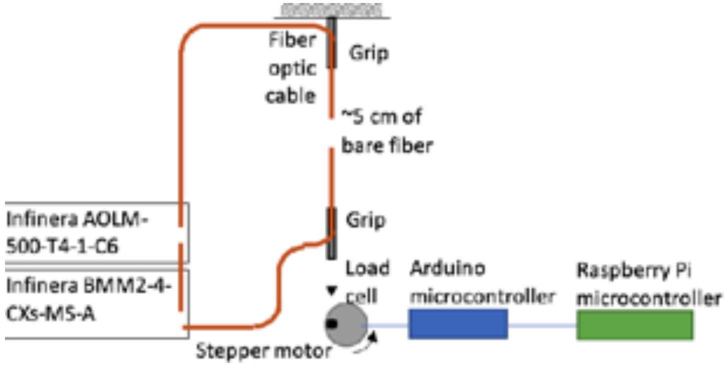
Google-UCLA Cirrus Fiber Monitoring



Berkeley Dark Fiber DAS

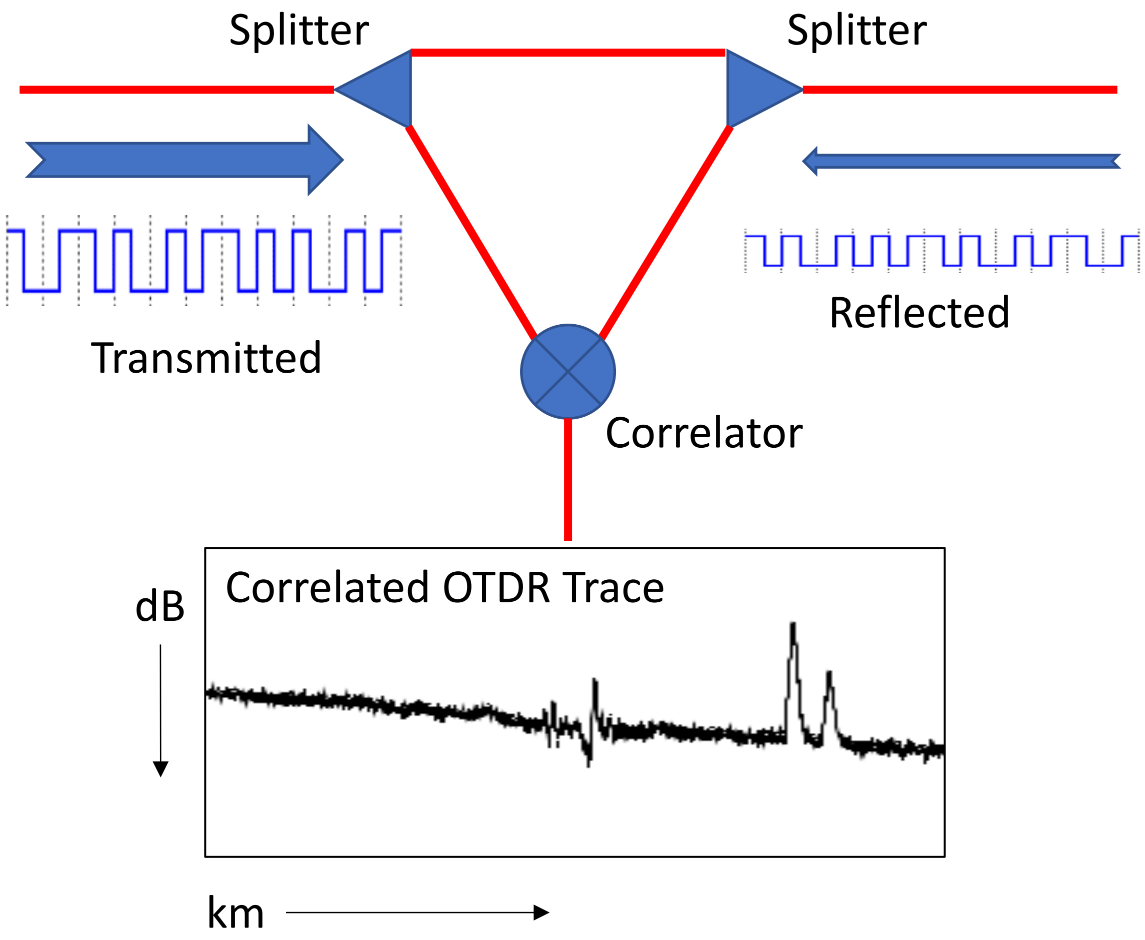


UW Madison
Internet Photonic Sensing



Digital Communication Strain Sensing

- Fibers cover the world carrying internet traffic
- The pseudo-random ones and zeros transmitted can serve as a strain sensing source
- Optical splitters and correlators can be used to construct in-line strain sensors using active traffic
- Eliminates the need for fiber installation or use of dark fiber
- Brings another component to the DSS-IoT



MoMacMo DSS Processing

- DSS systems can generate Terabytes of data per day
- Processing and management of this data is a daunting task
- MoMacMo has technology to create multi-scale versions of the data at a range of scales - days to milliseconds
- We use Amazon Web Services (AWS), Azure, Apache Spark Machine Learning, and JavaSeis.org technology for parallel I/O and compute
- Our systems can generate interpretive datasets from raw DSS data at low cost