Technology FAQ On Distributed Fiber Optic Sensing:

RC-2437 : Developing Smart Infrastructure for a Changing Arctic Environment using Distributed Fiber-Optic Sensing Methods

[Target Audience : Educated public and DoD facility operators interested in the potential uses of distributed fiber-optic sensing techniques. Note that this FAQ document targets the broader technology rather than the specific details of the RC-2437 thaw experiment.]

What are Distributed Fiber Optic Sensing (DFOS) methods? :

Distributed Fiber Optic Sensing approaches are a family of techniques which utilize laser light backscattered along a strand of optical fiber to measure local environmental properties. The fibers used in sensing applications are thin (~9 microns, size of a human hair) strands of silica glass that have optical properties which enable light illuminated at one end to travel with low losses over long distances (many km). Fiber-optic cables are commonly used to send and receive the digital signals that service the internet and telephone networks.

DFOS methods can utilize different types of scattering processes in the fiber (eg. Raman, Brillouin, Rayleigh) to estimate different physical parameters. The location of a measurement along the fiber is inferred by the time delay which the scattering is detected since the speed of light on the fiber is known a priori. The methods explored in this project include Distributed Temperature Sensing (DTS) that utilizes Raman scattering, Distributed Strain Sensing (DSS) which utilizes Brillouin scattering, and Distributed Acoustic Sensing (DAS) which utilizes Rayleigh scattering. In contrast with optical point sensors, DFOS approaches measure a parameter at every location along the fiber utilized for the measurement e.g. every meter along km of fiber. A DFOS deployment requires a compact system which generates the laser pulses and records the backscattered light, referred to as an *interrogator unit* (IU), and the fiber optic cable used for the measurement. Figure 1 provides a conceptual explanation of the DFOS approach.

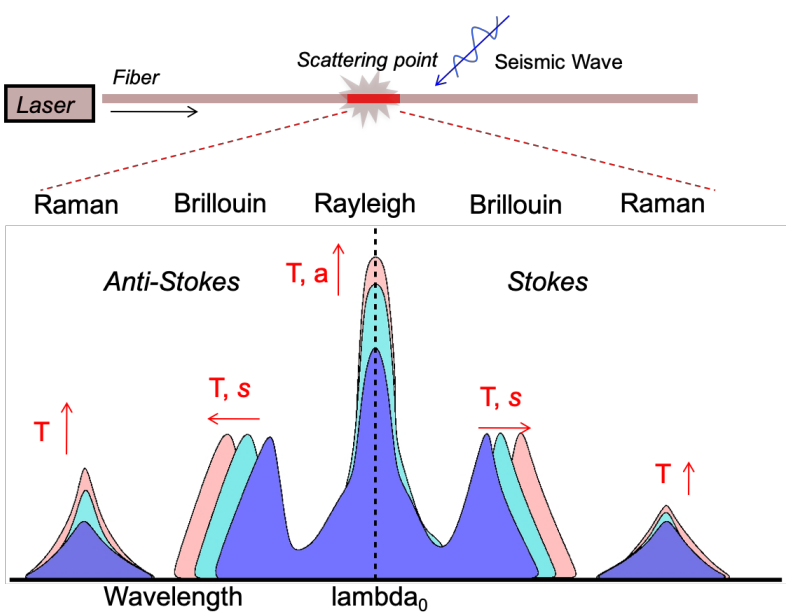

Figure 1: Conceptual diagram of DFOS approaches. Top: the interrogator unit generates brief laser pulses, scattered by different mechanisms at all points on the fiber. Bottom: the different mechanisms and their relation to the excitation wavelength (lambda).

What are some advantages of DFOS in comparison to classical sensing approaches? :
One of the primary advantages of DFOS approaches is that they are truly *distributed*; for the case of DTS, an independent measurement is obtained for every meter (or finer) along a fiber which might be kilometers in length (1000s of sample points) or longer. For modern DSS units, measurement lengths of over 80 km have been demonstrated. The cost and complexity of using conventional point sensors (e.g. thermocouples, strain gauges, geophones) for this number of measurements is often prohibitive. Another advantage is that thousands of measurements can be conducted with a single fiber rather than requiring thousands of wires; this makes for compact installation packages; for example, a fiber optic cable with 8 fibers protected from the elements might be only ¼" in diameter. Additionally, optical fibers can be quite rugged; with property packaging they can withstand both high low temperatures (-100C to 300 C), high pressures (10,000 psi), and mechanical stress. When not severed, optical cables also age well, with many telecom cables lasting decades before replacement. A last advantage is that power is only recorded at the interrogator unit rather than over the extensive distance the fiber is installed.

What parameters can DFOS approaches measure relevant to cold region infrastructure and permafrost? :
All of the measurands commonly acquired with DFOS techniques (e.g. temperature, strain, and acoustic response) are of relevance to cold region infrastructure. Temperature, measured using DTS, is perhaps the most obvious since it can be used to interrogate thermal load beneath/near infrastructure and thaw state. Accurate measurements of strain at high spatial resolutions (DSS) are also useful to monitor deformation related to ground subsidence caused by permafrost thaw. Finally, changes in seismic response, measured by DAS, can be interpreted as, and linked to, changes in soil mechanical properties that can ultimately be indicative of regions approaching thaw failure. Since the mechanical properties of permafrost start to vary before failure during thaw, DAS could potentially be used to measure "precursors" of thaw failure. Together, these measurements may provide a suite of data at a higher spatial resolution than are typically available with point sensors like thermocouples.

Figure 2 provides an example of using DSS to measure localized strain associated with thaw subsidence. In the top panel, the colormap shows strain magnitude as a function of calendar time (x axis) and distance along a transect (y axis). The localized anomaly shown by the dashed line is a zone of subsidence induced by thawing a section of permafrost. The lower panel shows the strain history at a single location along the fiber. In this case, strain is measured at thousands of locations on a larger fiber network simultaneously, allowing the easy detection of a localized area of subsidence.

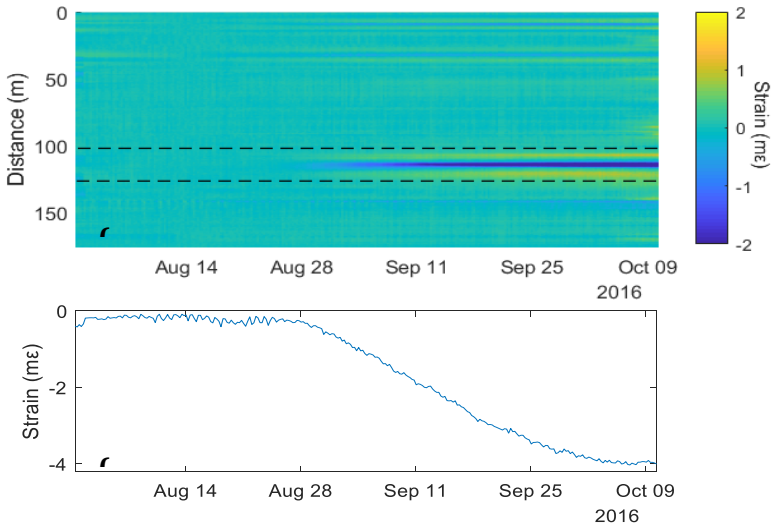

Figure 2 : Example of DSS applied to thaw subsidence at a site in Fairbanks, Alaska. Top color panel shows local strain as a function of distance and time across the array. Bottom panel shows a strain time history at a central point in the thaw zone. As can be seen, the DSS measurement provides a combination of coverage and time resolution difficult to match.

What are the typical spatial/temporal resolutions, accuracy, and extent of DFOS measurements? :

Different distributed fiber optic measurements, which exploit different scattering mechanisms, often exhibit different temporal and spatial resolutions. DTS, which exploits Raman scattering, often requires longer averaging periods with temporal resolutions in the minute range for good quality measurements. DSS and DAS which exploit stronger Brillouin and Rayleigh scattering respectively, provide better time resolutions anywhere from Hz (dynamic DSS) to high kHz (DAS). Spatial resolutions are also variable in DFOS methods, ranging from sub-meter for some DTS measurements to longer multi-meter zones (e.g. 10 m) for DAS measurements. An important comment is that strong trade-offs typically exist between spatial resolution, temporal resolution, and accuracy; e.g. an approach might enable higher temporal sampling at the expense of lower measurement accuracy. Accuracies are typically on the order of 0.1 C for DTS, 10s of microstrains for DSS, and nanostrain/s levels for DAS with variations between systems based on a variety of acquisition details. Measurement range (maximum spatial extent) is typically longer for approaches which exploit stronger scattering mechanisms and is on the order of 10s of km for most DFOS approaches. The numbers included in this section are only included to provide an idea of these ranges; resolution/accuracy specifications are available from IU manufacturers and vary widely.

How are DFOS fibers installed? :

Fiber-optics can be installed in the ground in a number of different ways depending on the application. In a vertical geometry, fiber-optic cables are commonly inserted into monitoring wells to measure depth-dependent properties like temperature without coupling the fiber to the wellbore. Alternatively, the fiber can be coupled to the wellbore, either by installing the fiber behind the wellbore casing, grouting, or mechanically clamping it to the inside of the wellbore. Depending on the measurand, e.g. temperature, strain, or seismic waves, different approaches for fiber installation may yield improved results. If a well is not available, the fiber can be installed into compliant soil using a push probe. For many environmental sensing applications, fiber-optic cables can be buried horizontally directly in the soil in shallow trenches measuring less than 1 meter depth. For DAS, the cable can be buried as shallow as 10 cm and still achieve the coupling required to see surface wave propagation. Figure 2 shows

examples of both shallow trench and borehole installations for DTS, DSS, and DAS. Lastly, sensing fibers can also be directly embedded within infrastructure components e.g. attached to rebar in a reinforced concrete structure or deployed below a pavement layer in a road.

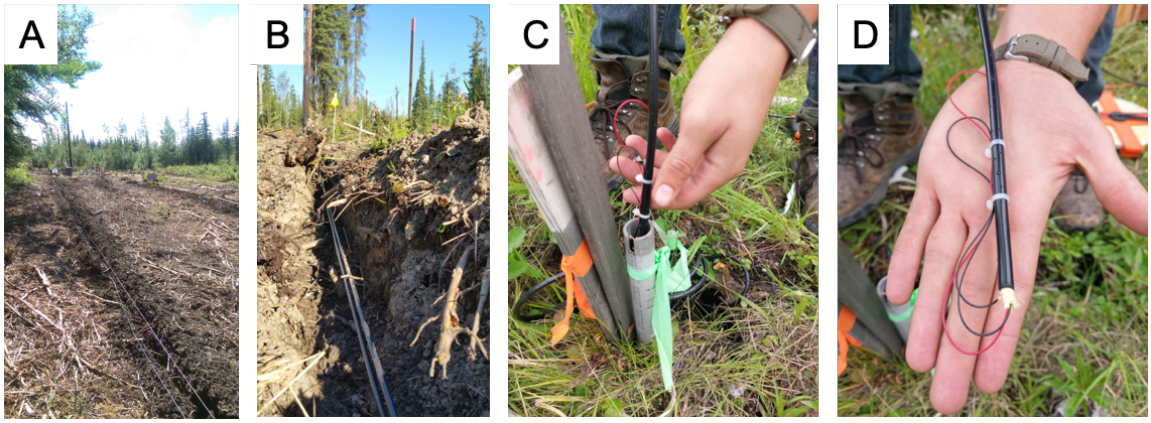

Figure 3 : Examples of different fiber optic installation techniques: Panels A & B show deployment of a fiber bundle in a shallow trench for DAS and DSS measurement while panels C & D depict installation in a shallow borehole.

How costly are DFOS approaches? :

DFOS approaches require moderate capital allocations to purchase and install but are typically much less expensive than equivalent density point sensor arrays. For a DFOS installation, the fiber optic cable itself is often the least expensive component with the raw fiber costing cents/m and the encapsulated fiber optic cable costing $1-10/m depending on coatings, fiber count, armoring, and other details. Labor and permitting for installation is typically considerably more costly than the fiber run (x2 - x10) itself, again depending on location, terrain, and labor cost structure. The cost of interrogator units depends on the target measurement and can range from 25K for inexpensive DTS units to over 300K for cutting-edge DAS systems. However, the IU costs must be compared to the costs of equivalent point sensor arrays, data acquisition systems, cabling, and power installation. Back-of-the-envelope comparisons are highly variable depending on project specifics but often show a cost cross-over point at between 100 and 300 discrete sensor locations.

What are some related use cases for DFOS as applied to infrastructure monitoring? :

DFOS techniques have found a broad range of uses in critical infrastructure monitoring beyond permafrost thaw discussed previously. One of the earliest uses of DTS for infrastructure monitoring was measurement of seepage rates from dams and levees to provide an indication of likely failure zones. Another common application is the use of DAS for pipeline intrusion monitoring. A variety of DSS applications in infrastructure have been documented including (a) crack detection and corrosion monitoring, (b) tunnel stability monitoring, and (c) railway integrity monitoring. More broadly, any infrastructure flaw or defect which manifests as a temperature, strain, or elastic properties can be probed using properly designed DFOS deployment.

What techniques are utilized to process DFOS data? :

Depending on DFOS technique, fiber optic sensing datasets can either require minimal secondary analysis before interpretation (DTS) or extensive post-processing (DAS for surface wave analysis). In all cases, DFOS data are 3D in the sense that they are 2D array datasets acquired with time resolution; as such, processing approaches can take advantage of spatial sampling to denoise or select signals, a particular strength when examining DAS signals.

In many cases, some degree of calibration is required to convert the DFOS measured values to true environmental parameters. For DTS, the sensing fiber is typically run through multiple water baths with controlled and precisely measured temperatures to allow for direct calibration. Another calibration requirement are temperature corrections for some DFOS approaches; in many cases, distributed strain measurements, based on Brillouin scattering, are also sensitive to temperature changes requiring either DTS measurements or an unstrained fiber for accurate strain values.

In almost all cases, processing is required to map DFOS measurements from fiber distances to true X/Y/Z locations. Since DFOS measurements are referenced to distance along the fiber, what the laser pulse "sees", rather than the outside world, surveying the fiber path and measuring stimuli (temperature, strain, or acoustic waves) at discrete locations is required to create a map. This is particularly important since slack sections are often present in cable deployments creating extra distance not accounted for on the surface.

Acoustic signals acquired with DAS can be analyzed using processing techniques and approaches applied to seismic data acquired using classical seismic sensors such as geophones and seismometers. For example, DAS enables the acquisition of ambient seismic noise, i.e. acoustic signals resulting from vibrations caused by natural and anthropogenic sources such as ocean waves, wind, traffic, etc. These signals can be analyzed using interferometric approaches that convert them into estimates of subsurface shear wave velocity underneath the fiber optic cable which senses them. One constraint is the potentially substantial volume of data generated by DAS over long transects; since DAS samples the wavefield at frequencies in the kHz range over 10s of km, data volumes on the TB/day level can easily be generated. Application of seismic analysis algorithms to datasets of this scale can be a time-intensive endeavor.

What is the future of DFOS?

DFOS approaches are finding increased application in a range of different environmental, infrastructure, and energy contexts. As data acquisition and optical components decrease in cost, interrogator units are becoming less expensive to deploy and closer to commodity sensors, which in turn is broadening the space of cost-effective applications. Faster wireless communication protocols are also making it simpler to move DFOS data from remote interrogators into the cloud for real-time analysis and assimilation. Lastly, advances continue to be made in the parameters which can be measured using optical approaches. While not in broad use at present, a variety of special-purpose fiber optic cables are being designed for distributed chemical sensing (DCS) over large scales, with pH and dCO2 as two recently targeted solutes. Adaptations to DFOS to allow for sensing of electrical and magnetic fields are also in development, driven in part by improvements in optical detectors and special-purpose fiber manufacturing.

Where can I learn more about DFOS techniques? :

1. CTEMPS : Center for Transformative Environmental Monitoring Programs
   https://ctemps.org/

2. Seismic Soundoff Podcast : Fiber-optic distributed acoustic sensing
   https://soundcloud.com/seismicsoundoff/27-fiber-optic-distributed-sensing-jonathan-ajo-franklin

3. Distributed Fiber-Optic Seismology: in Theory and Practice

https://www.youtube.com/watch?v=LAcQ44YRMuM

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