Internal Erosion Prize Challenge Competition Next Steps: Evaluating Distributed Acoustic Sensing (DAS) for Large Critical Infrastructure Imaging and Monitoring

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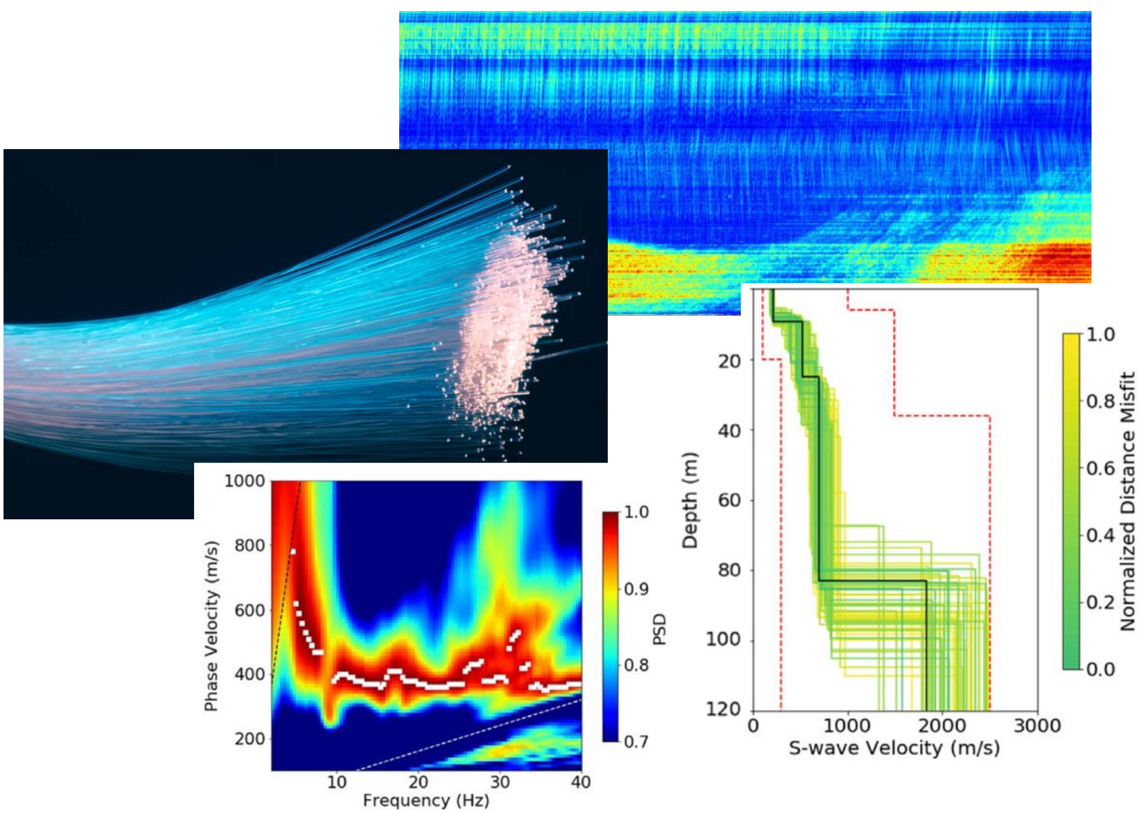

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14. ABSTRACT
The location and severity of infrastructural defects and damage is usually poorly understood. New technologies are needed to facilitate identification, characterization, and time-lapse monitoring of defects/damage/deterioration in a significantly more efficient and spatio-temporally comprehensive fashion than techniques currently used. Distributed Acoustic Sensing (DAS) is one potential sensing technology that could achieve these various goals and a variety of other technical challenges faced by Reclamation. This scoping-level research project consisted of a literature and technology review to assess the current state of the art in DAS and related sensing technologies and their capabilities and applications for structural health assessment and time-lapse monitoring of large civil structures. Results of this scoping-level research project indicate that DAS holds significant promise in the ability to help address many of Reclamation's technical challenges related to the assessment and maintenance and security of its aging infrastructure.

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Contents

Executive Summary

Problem

The US Bureau of Reclamation (Reclamation) and various other stakeholders are faced with the challenge of detecting and mitigating internal erosion which is a common failure mode of earthen dams and other hydraulic structures that is considered particularly challenging for consistent and early detection using standard inspection and condition assessment approaches. The ability to reliably detect internal erosion early in the process would help Reclamation, U.S. Army Corps of Engineers, and all dam, levee, and canal owners to assess and reduce risks by allowing intervention in the process. New technologies are needed to facilitate rapid and early identification and characterization of internal erosion in a significantly more efficient and spatially comprehensive fashion than typical techniques currently used (e.g., visual inspections, seepage rate measurements, etc.). Distributed acoustic sensing (DAS) is one potential sensing technology that could help achieve these goals and is the focus of this scoping-level research project.

Research Approach

This topic was addressed as part of the FY16/FY17 Science and Technology Prize Challenge Competition program that sought to identify new technologies capable of detecting and quantifying internal erosion phenomena within and beneath large earthen structures (i.e., earthen dams). Several crowd-sourced submissions were identified by a panel of judges as "most promising" that were awarded cash prizes and deemed worthy of pursuing during a "Next Steps" phase of the program. Among these proposed solutions, two involved the use of sensors like DAS. This scoping-level research project consisted of a literature and technology review to assess the current state of the art in DAS sensing hardware and techniques and their capabilities and applications for non-destructive testing, evaluation, and health monitoring of various structures. This scoping-level effort also aimed to assess Reclamation's current capabilities for conducting DAS studies by evaluating current resources, capabilities, and needs to support future research involving DAS.

Results and Recommended Next Steps

Results of this scoping-level research project indicate that DAS technology holds significant promise in the ability to help detect and characterize internal erosion, and for a variety of other novel applications related to characterizing, monitoring, maintaining, and securing our Nation's large critical infrastructure. Initial reviews of existing data, hardware, and software indicate that future research efforts are readily feasible using existing resources and partnerships. It is highly recommended that further conducting-level research efforts be funded and pursued to more closely evaluate and develop DAS capabilities at Reclamation.

Problem Statement and Research Goals

According to the American Society of Civil Engineers 2013 Report Card for America's Infrastructure, nearly 160,000 kilometers of levees and 85,000 dams provide flood protection, water storage, and hydropower for millions of people in the U.S. Many of these dams are owned and operated by the Bureau of Reclamation (Reclamation) or the U.S. Army Corps of Engineers (USACE), and the USACE also owns and manages a significant portion of the nation's levee inventory. There are also 1000s of kilometers of water delivery canals and pipelines in the U.S., with Reclamation owning about 13,000 kilometers of water delivery canals. Some of these structures are over a century old and considered to be "high-risk" due to their critical functions and locations relative to large downstream population centers (e.g., large economic losses and loss of life for downstream populations in the event of a catastrophic failure). Increased probability of various failure modes also contributes to the level of risk associated with failure of these structures. Internal erosion is one of many possible failure modes that is particularly difficult to detect during early stages of progression and costly to assess comprehensively using typical visual inspection and invasive techniques.

Internal erosion oftentimes initiates and progresses over a long period of time but can initiate and develop quickly following some triggering incident (e.g., from a sudden increase in hydraulic loading of a structure, or from differential settlement and transverse cracking of a dam during an earthquake). Internal erosion often remains invisible (inside or beneath a structure) until serious damage occurs. Like various structural health issues, internal erosion can also simply lead to poorly performing structures, decreased water storage or conveyance capacity, and operations and maintenance (O&M) challenges and related costs.

New technologies are needed to facilitate early identification and characterization of internal erosion processes in a significantly more efficient and spatially comprehensive fashion than typical techniques currently used. Geophysical and geotechnical surveys and explorations at embankment dams and other large infrastructure are most typically performed in a reactionary sense. These surveys are also typically performed at specific locations or with otherwise limited spatial data coverages (e.g., a few 2D tomography survey lines), which could easily miss a localized defect or developing issue. Currently, Reclamation does not have a practical means to instrument and image and monitor an entire large embankment in a holistic manner. The ability to reliably instrument and monitor for system performance issue (e.g., to detect internal erosion) would help Reclamation, USACE, and all dam, levee, and canal owners to assess and reduce risks by allowing intervention against performance issues early in the process. DAS is one potential sensing technology that could help achieve these goals and is the focus of this scoping-level literature and technology review.

The primary goals of this scoping level research project are to answer the following questions:

1. Perform a literature review to determine current state of the art of DAS technology for assessment of internal erosion and application to various other technical challenges faced by Reclamation.
2. Determine realistic technical limitations of DAS for structural health monitoring of large infrastructure (e.g., sensor spacings, typical signal-to-noise ratios, fiber length limits, spatiotemporal resolutions, practical data bandwidths, etc.).

3. Determine realistic logistical limitations and costs of field-scale implementation of DAS for structural health monitoring of large infrastructure (e.g., required hardware/software, fiber installation requirements, time for data collection, processing, etc.)
4. If deemed a promising technology, prepare a research proposal for FY21+ funding to support a follow-up conducting-level research effort.

Background

DAS Overview

What is DAS?

DAS is a sensing technology that has received a considerable amount of attention in recent years for the research and development of a variety of industry applications. DAS is capable of recording quantitative spatio-temporal changes in strain (or strain rate) related to the propagation of vibrational energy (e.g. seismic and acoustic waves) within or across the surface of a structure, through the atmosphere, or through the Earth. DAS utilizes fiber optic (FO) cables to obtain a measurement profile along the entire length of the cable at discrete sensing intervals ranging from 1-10 m. The spacing of sensing points, also referred to as "channels," is dictated by various system configurations and the length of fiber being utilized. DAS can provide thousands of independent and simultaneously sampled channels (sensing points) along a FO cable that are analogous to point-sensors that record seismic data (e.g., geophones and accelerometers).

In its most basic form, DAS involves connecting an electronic device to one end of a FO cable and sending a series of laser light pulses into the fiber that are subsequently backscattered and recorded by the same electronic device (Figure 1). This device is referred to as an "interrogator unit" in industry (Figure 2). The back-scattered laser light is characterized as having some combination of photon energy-level changes, phase changes, and frequency shifts that can be used to reconstruct the temperature and strain at each back-scattering point.

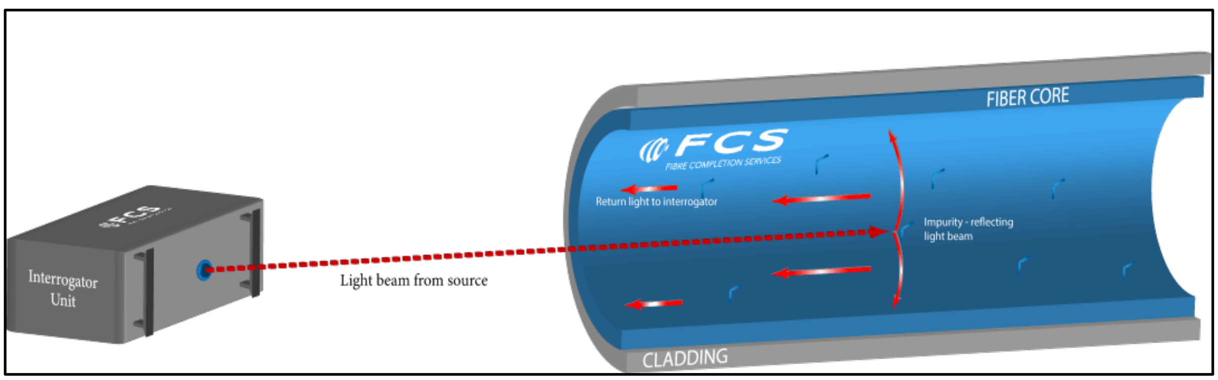

Figure 1 – Schematic of a DAS system's main components: an interrogator unit and a fiber optic cable. Modified from FCS (2020).

DAS turns a single fiber into a massive single-component seismic array (e.g., p-wave), where the optical interferometric phase of the back-scattered light is related linearly to the strain versus time of the fiber at a given back-scatter location. According to Dean et al. (2016), DAS systems “measure strain, which is the change in the length of the section of fiber divided by the gauge length.” This gauge length is adjustable and has significant effects on the characteristics of recorded data that carry major implications of the applicability of DAS for a variety of uses. These effects of gauge length and other system design parameters as discussed in more detail in subsequent sections of this report.

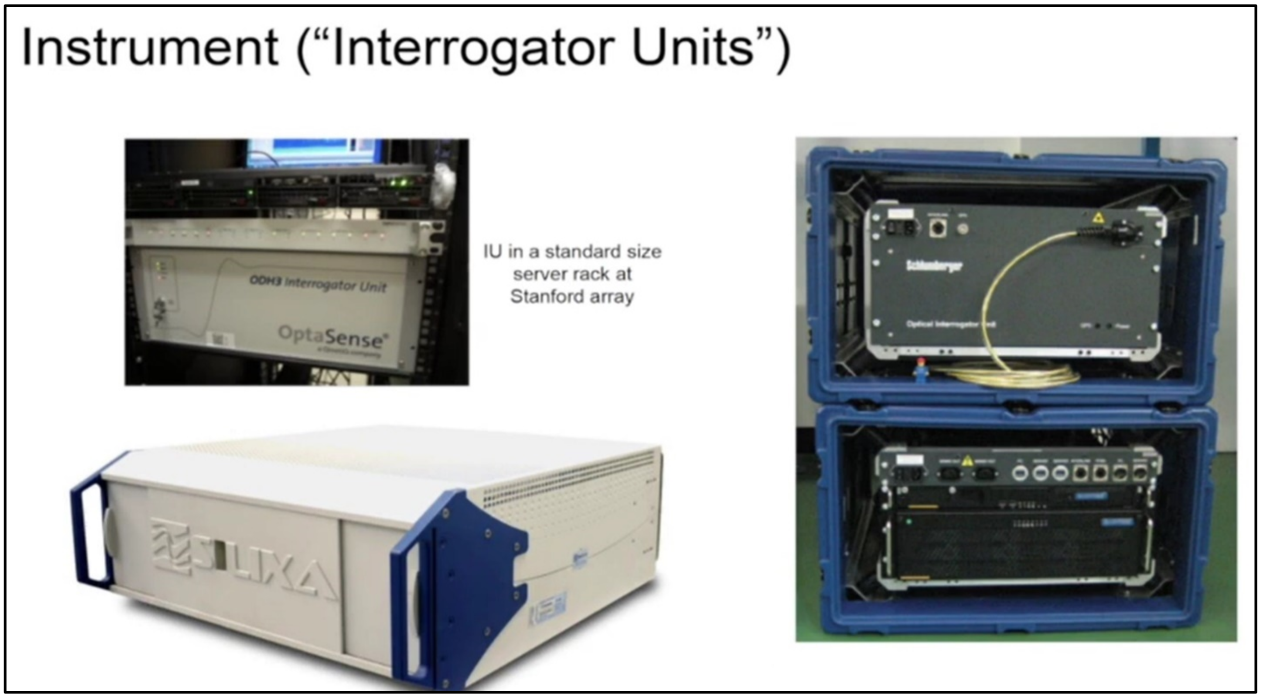

Figure 2 – Example photos of DAS Interrogator units, generally described as small semi-portable or rack-mounted electronic systems that are connected at one end of a fiber optic cable. Modified from Dou et al., (2017).

DAS requires the installation of FO cable in a manner that mechanically couples the fiber to the ground or object of interest. This is typically done by burying a FO cable (e.g., burying in shallow trenches along profiles or grids, as shown in Figure 3), within back-filled boreholes, or by surface-mounting FO cable on rigid bodies such as pipelines or on concrete surfaces. Once a fiber is installed, the interrogator unit is simply connected to one end of the fiber and is used to inject laser pulses and record the back-scattered light.

Due to its simplicity, DAS can also make immediate use of existing buried telecommunication fiber optic cables for recording seismic data by simply splicing onto a fiber and recording data within hours. This has been shown to work with both “dark fiber” networks (fiber not being currently used for other purposes) and for active telecommunication fiber without causing interference (Ajo-Franklin et al., 2019; Lindsey et al., 2019, 2020;). A single interrogator unit can record data along up to 50 kilometers of fiber in some applications with sensing points as dense as 10m (~30ft) along the entire length of fiber (OptaSense, 2020b). The length of FO cable that can be interrogated with a single unit depends on several factors, as discussed in more detail below.

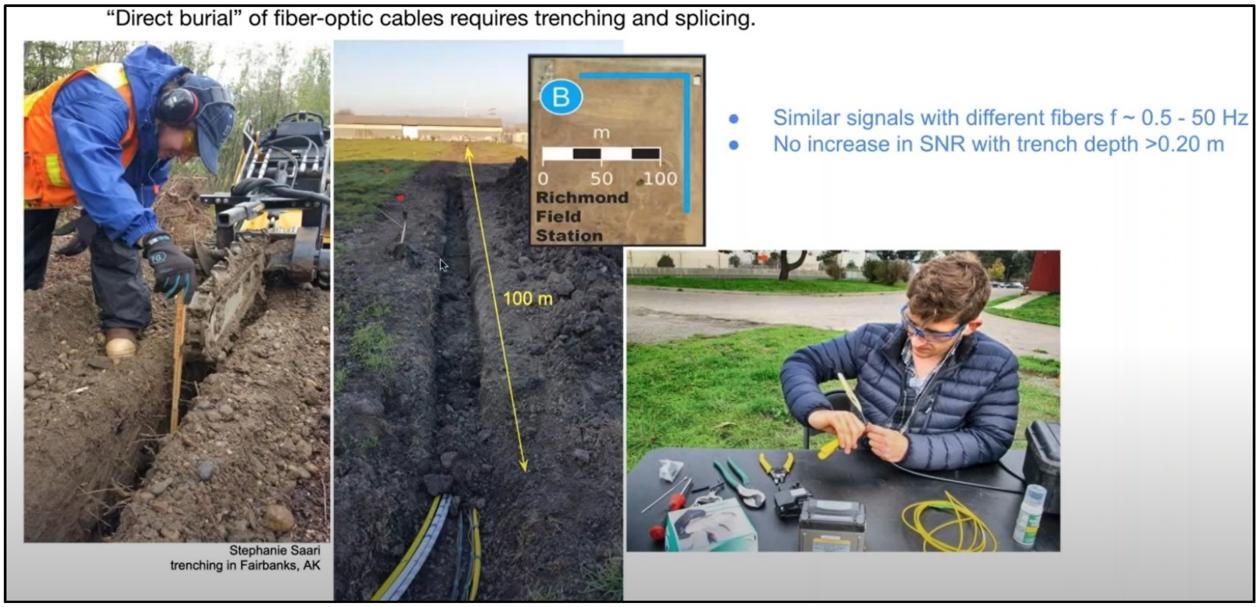

Figure 3 – Photographs showing the installation and splicing of DAS fibers at a site near Fairbanks, Alaska. Modified from Dou et al., (2017).

How Does DAS Work?

As described above, DAS operates on the principle of recording back-scattered light from various points along a FO cable, and inferring the strain of the cable at those locations. Generally, there are three types of photonic processes (i.e., optical scattering mechanisms) that occur within fiber optic cables and can be used for different sensing purposes, depending on the application and specific goals. These include Raman scattering, Rayleigh scattering, Brillouin scattering:

- Raman scattering is a photonic phenomenon that is primarily sensitive to the molecular-level vibrational nature of material, and can thus be used for distributed temperature sensing (DTS). This sensing technique is generally looking at frequencies above and below the input frequency of laser light (e.g., corresponding to a wavelength of 1550nm commonly used in industry), where temperature affects the energy transfer to other frequencies (i.e., amplitude and phase spectra of back-scattered light in neighboring frequency bands changes as a function of temperature)
- Rayleigh scattering is primarily sensitive to strain, which can be used for DAS, also referred to as "distributed vibration sensing" (DVS) or the more general term "coherent optical time-domain reflectometry" (COTDR). Here, at a given frequency of light, the phase shift of back-scattered light (delay in two-way time of flight) is related to the strain along the fiber at various points versus time (Strain field oriented parallel to the fiber only, as this stretches or compresses the cable). Temperature effects must be accounted for in low frequency ranges.
- Brillouin Scattering is sensitive to both temperature and strain along a FO cable, but is primarily used for distributed strain sensing (DSS) applications. Here, Brillouin scatter occurs due to the interaction between the light and acoustic "phonons" travelling in the fiber. As the light is scattered by a moving phonon, its frequency is shifted by the Doppler effect by around 10 GHz. Light is generated at both above (anti-Stokes shift) and below

(Stokes shift) the original optical frequency. The intensity and frequency shifts of the two components are dependent on both temperature and strain and by measuring the shifts, absolute values of the two parameters can be calculated using a distributed temperature and strain sensing (DTSS) system (Wikipedia, 2020). In some cases, DSS and combined distributed strain and temperature sensing (DSTS) techniques require that two lasers of slightly different frequencies be applied from opposite ends of a single fiber, this requiring access to both ends of a FO cable.

In the Case of DAS, naturally occurring impurities within a FO cable can act as back-scatter points at various "Random" locations along a FO cable. The locations of these back-scattering points used to create a sensing point are known, based on the known speed of light in the FO cable (i.e., two-way travel-time of back-scattered light can be directly used to calculate the location of back-scattering). Similarly, engineered semi-reflective points referred to as "Fiber Bragg Gratings" can be placed at specific locations along the fiber with the use of an ultraviolet laser (etches the FO cable core). As vibrations impinge upon the FO Cable, the associated dynamic strain is applied to the fiber optic cable from stretching and compressing of the fiber. Strain (dL/L) is defined as a change in length (dL) of a material divided by the original base line length (L). This change in the length of the fiber results in a measurable change in the associated two-way travel time of a laser light pulse. This change in travel time is characterized as a phase shift (Φ) in the back-scattered light that is linearly proportional to the strain along the fiber.

Here, L is defined by the spacing between two Fiber Bragg Gratings, or by a pre-determined length of cable that is used to define a measurement interval. This interval is also referred to as the "gauge length" (dz) which can be "selected according to the application, but is normally in the order of 2, 10, or 20 m. The underlying measurement is effectively a measurement of local relative strain made in a continuously moving window as the laser light moves down the fiber from the instrument to the far end. Measurements are normally made at 25-cm increments (channels) along the fiber. The DAS response at each channel and time is linearly proportional to the change in average elongation over the gauge length per time sample at the channel location," (Naldrett, et al., 2018; Lindsey et al., 2019, 2020; OptaSense, 2020a). Channel intervals can be set to be shorter, equal or longer than the gauge length, but a gauge segment is always centered on a given channel and gauge segments will overlap and hold information correlated with adjacent channels that have overlapping gauge segments.

According to Naldrett, et al. (2018), "while DAS technology is less than 10 years old, it has been able to use the same fiber-optic deployment methods developed for the more mature DTS technology. Indeed, it is often beneficial to deploy simultaneously both DAS and DTS in combination as they provide independent, but complimentary information along profiles. While DAS and DTS require separate interrogator units, connected to individual fibers, these fibers can be bundled into the same cable. This single cable therefore becomes sensitive to both the acoustic and thermal fields."

What Is DAS Measuring? System Response of DAS

One of the primary questions about the use of DAS is with regards to what DAS actually is measuring and how it compares with more industry standard point sensors (e.g. geophones). There are generally two different categories of factors that influence the recorded signal, including:

- Sensor installation and coupling
- System and Receiver response

The end-goal of DAS for geophysical applications is to be able to record vibration signals along the entire length of FO cable at various points (channels) that each have quality equal to industry-standard point sensors (e.g., geophones or broad-band seismic monitoring sensors used in seismological studies and applications). An example comparison of DAS and broad-band seismic sensor data are presented in Figure 4. This close match is one of the primary goals of current research and development of DAS systems. While the example shown in Figure 4 is for relatively low frequencies associated with a real earthquake event, higher frequencies typically encountered in shallow seismic imaging applications are more challenging for DAS to accurately record, as discussed below.

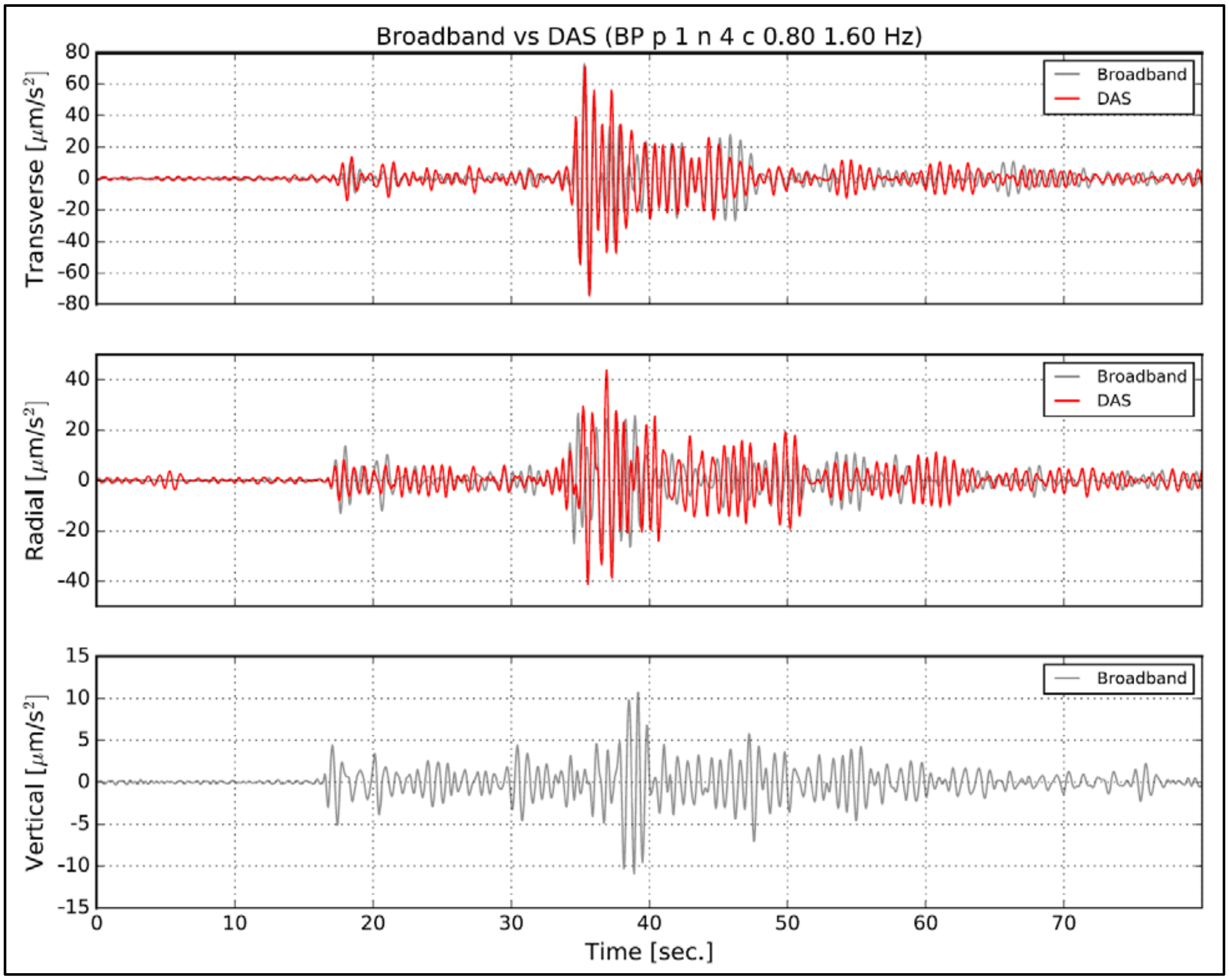

Figure 4 – Comparison of earthquake ground motion from the 26 August 2016 M3.8 Central Alaska event recorded by (red) the Silixa iDAS using fiber installed horizontally in two orthogonal trenches and (black) a co-located Trillium Posthole Compact 120 s inertial seismometer. Distributed fiber-optic acceleration records in (top) transverse and (middle) radial directions were gained to peak sample of seismometer (a factor of 5) and then averaged over 20 m (1 channel/m) centered on the location of the seismometer shown in Figure 1a using a median stack. The two horizontal seismometer components were rotated into the fiber array directions, following removal of the instrument and digitizer responses. A zero-phase four pole bandpass filter was applied in the 0.8–1.6 Hz range. From Lindsey et al. (2017).

Sensor Installation and Coupling

One of the most fundamental aspects of a DAS system that effects quality and usefulness of the resulting data for a given application, is the approach used for FO cable installation and resulting mechanical coupling with the ground or target feature (e.g., pipeline). Here, several options to FO cable installation are available, but generally include the following:

- Draping or laying the sensing cable on the ground surface
- Surface-mounting the FO cable via adhesive or glue
- Direct burial of the FO cable in backfilled trenches or down boreholes
- Placing FO cables inside of conduits that are mounted on the outside of a pipeline, that are run underground, or inside of cased conduits

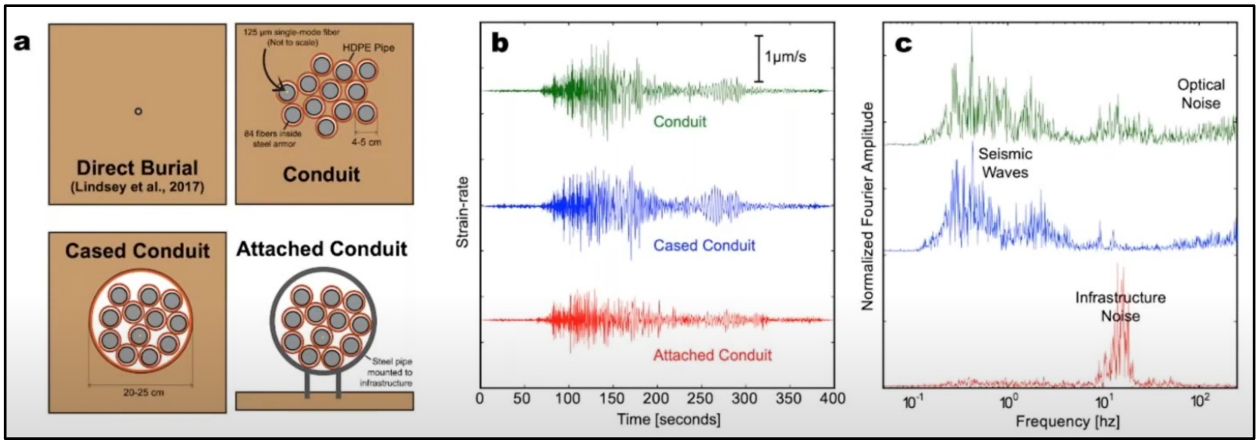

Figure 5 – Graphic depicting various options for installation and mounting (e.g., coupling) of DAS system fiber cables (a), and comparisons of the resulting data in the time-domain (b), and related amplitude spectra (c). As seen, each approach to mounting or installing DAS fiber affects the resulting recorded data characteristics, where the amplitudes of low-frequency modes are mostly affected. (Modified from Lindsey, N., 2020)

There have been several studies on the differences in data quality related to the type of fiber used and method of fiber installation in recent years. Recent research has indicated that there is relatively little difference in recorded data quality for different types of FO cables, especially for lower frequencies below approximately 15Hz. For example, Figure 6 depicts results from a side-by-side comparison of four common types of FO cable sheathing. The results generally indicate that there is little difference in DAS sensitivity for traditional straight single-mode cables. Hence when deciding cable packaging for DAS installations, cost, durability, and ease of installation should be the main considerations.

The larger factors involved in data quality regarding installation techniques revolve around the mechanical coupling of the fiber to the object (e.g. pipeline) or medium (e.g., soil) in which vibrations (or strain and temperature fluctuations) of interest are located. In the case of surface-mounting, a continuous adhesive or glue-type product should be used to couple the FO cable to the target surface. In the case of direct-burial, it has been shown that a minimum burial depth of 20-30cm below ground surface is ideal, and that burial at greater depths doesn't significantly improve data quality (Dou et al., 2017).

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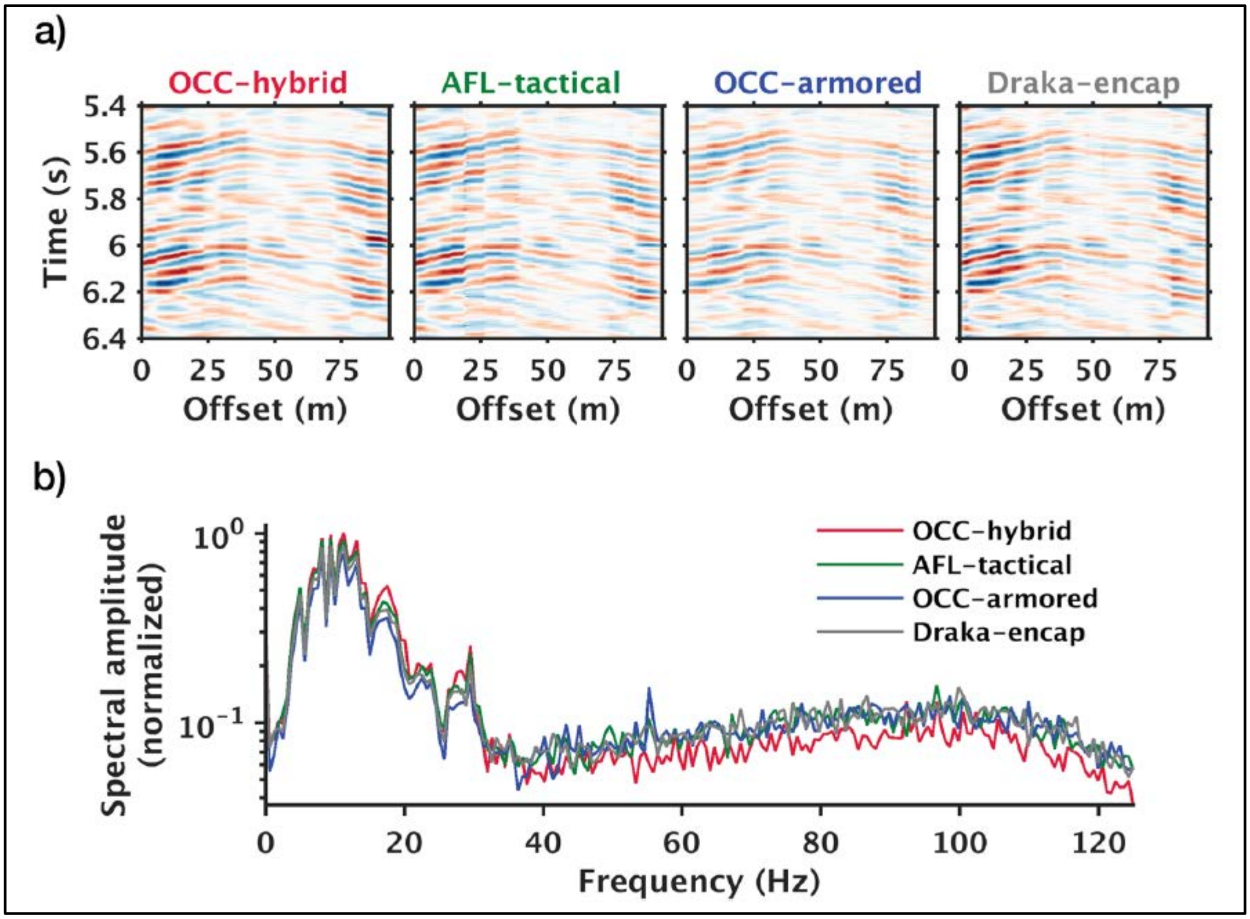

Figure 6 – Comparisons of identical traffic noise recorded by fiber-optic cables of different packaging. (**a**) Zoom-in view of 1-second noise records. (**b**) Mean spectral amplitudes computed using identical spatial and temporal windows (spatial window = offset range as in (**a**); temporal window = 1 minute). From Dou et al. (2017).

System and Receiver Response

Another primary area of interest for DAS data, is what the photonic system (interrogator unit) is doing and what the fiber cable is doing to the recorded wavefield signal (e.g., system noise and filtering of the recorded energy). There are four primary factors involved in a DAS system's frequency response and sensitivity, including the following:

- Laser pulse width (in units of time or distance based on speed of light in the FO cable)
- The gauge length
- The FO cable orientation relative to a seismic signal's wavefront and associated particle motion
- The FO cable length

Pulse Width

The duration of the laser light pulse that is sent into the DAS fiber (A.KA., "pulse width") has significant impacts on the resulting data quality and frequency response of a DAS system. This is primarily related to the amount of photons that are back-scattered and result in a proportional signal to noise ratio (SNR). Essentially, the more photons that are sent into a fiber, the more intense and clear of a signal is received for each back-scattering event. This concept is depicted in Figure 7, where better quality data is obtained with longer pulse widths. Additionally, the more photons that are sent into a fiber, the more photons there are that continue down the cable after each back-scattering event. This later point results in longer ranges of sensing, and thus longer segments of FO cable that can be used with a single interrogator unit before signal attenuation becomes an issue. Fundamentally, the pulse width cannot exceed the gauge length, but SNR is greatly increased with increase in pulse width, especially for pulse width of half the gauge length or more.

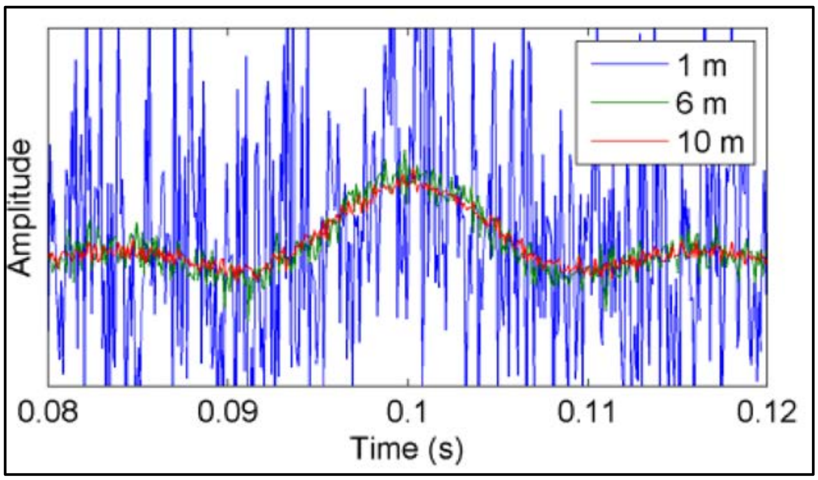

Figure 7 - Three synthetic Klauder wavelets (8 to 80 Hz) calculated using a gauge length of 20 m, a velocity of 2,000 m/s, and pulse widths of 1, 6, and 10 m. Modified from Dean and Hartog (2016).

However, there is an inherent tradeoff between pulse width and the frequency content that is achievable, where longer pulse widths result in filtering of higher frequency content. This effect is can be seen in Figure 8, where the synthetic DAS system spectral response of five different pulse widths are plotted. Here, the shorter pulse widths are seen to result in increased sensitivity to higher frequencies, and longer pulse widths result in low-pass filtering of the recorded data (i.e., high frequencies are filtered out). "Although effects from the pulse width are evident, the spectrum of the resulting wavelet is principally affected by the gauge length," (Dean and Hartog, 2016). Here, the filter response from a gauge length of 10m is indicated with the black curve in the right-hand plot (c). This curve could be flattened (less filtering) by means of decreasing the gauge length, as discussed in more detail below.

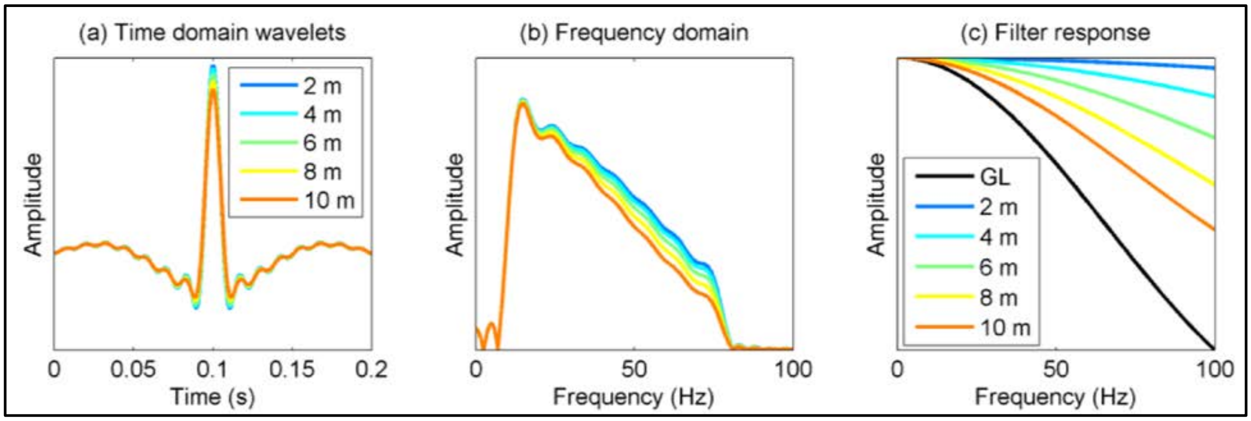

Figure 8 - Examples of Klauder wavelets (8 to 80 Hz) travelling at 2,000 m/s for a gauge length of 20 m. Modified from Dean and Hartog (2016).

Gauge Length

Secondly, the gauge length is a programmable system parameter that has serious implications on DAS system sensitivity and response characteristics that affect the quality of recorded data. As described above, the gauge length is a constant distance interval used to make measurements of strain or strain rate (i.e., vibration) at various locations (channels) along the FO cable. Each channel of data is located at the center of a given gauge segment, and these gauge segments are essentially shifted by the desired channel spacing to achieve a data stream from each point along the FO cable. Figure 9 depicts this concept of sliding the gauge window or segment to achieve a measurement point at each channel location. According to Dou et al., (2017), "channel spacing can be as small as 25 cm (as it only needs to be longer than the spatial duration of the laser pulse), gauge length needs to be long enough (typically ≥8 meters) to ensure optimal signal-to-noise ratio. The effect of gauge length is equivalent to applying a moving average filter to the spatial axis of strain measurements that have a sampling interval of channel spacing. In this way, although the spatial resolution of a stand-alone DAS channel is close to the gauge length, the spatial resolution of a DAS array is intermediate between the channel spacing and the gauge length."

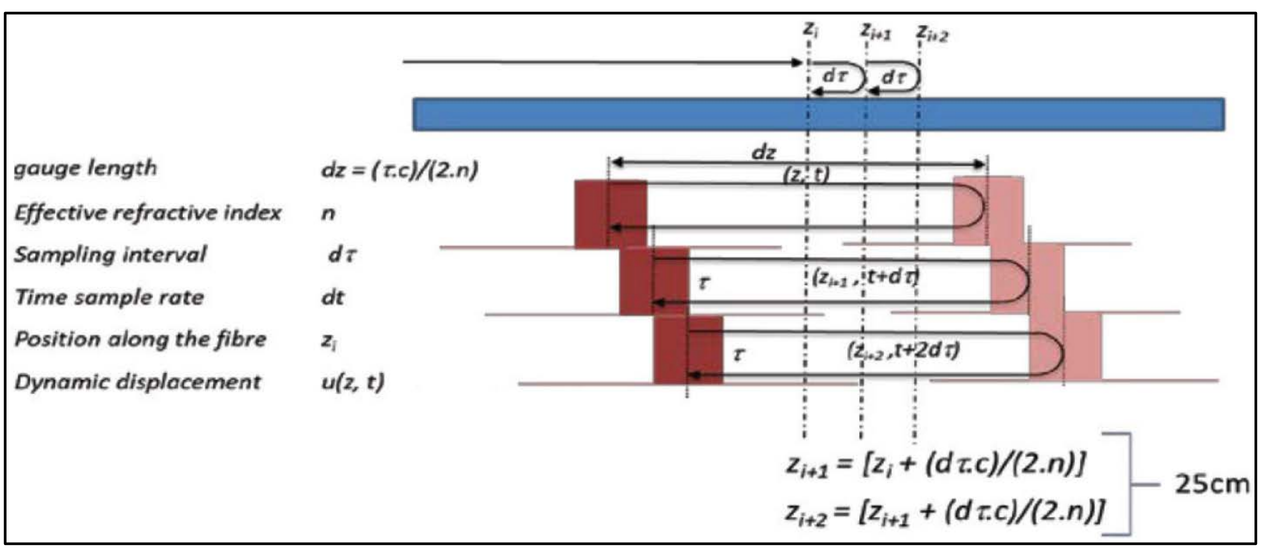

Figure 9 - Illustration of the measurement principles as well as the gauge length along a fiber. Modified from Naldrett et al., (2018).

According to Martin, E., and Lindsey, N., (2018), the gauge length is determined directly by the interrogator laser pulse duration and the data digitization write rate (e.g., the sampling interval of back-scattered light). This gauge length is one of the primary factors that determine what frequencies a particular DAS system is sensitive to.

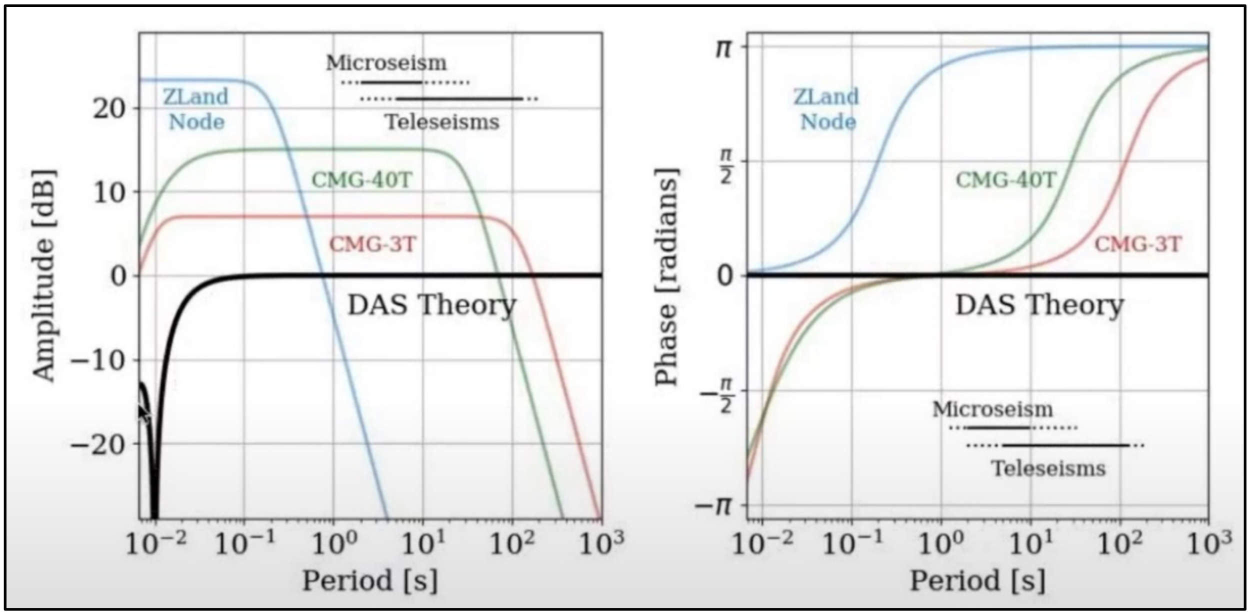

Figure 10 - Graphic depicting the instrument responses of various broadband seismometer instruments (labeled colored lines) and typical DAS systems (bold black line) with amplitude and phase spectra presented in left and right plots, respectively. Modified from Lindsey, N., (2020).

One of the more common gauge lengths that is designed into most DAS interrogator units is 10m. As depicted in Figure 10, DAS systems with a typical pre-defined gauge length of 10m have a corresponding frequency response curve that exhibits a problematic notch centered near 100Hz (left plot). Here, typical phase velocities of seismic waves in Earth materials near this frequency of 100Hz have wavelengths of less than 10m, and thus the positive and negative "lobes" of a waveform will average out to nearly zero in the recorded system response (e.g., strain effects across each ~10m gauge segment are cancelled out or otherwise negligible). This spectral notch can be thought of as a frequency notch-filtered data characteristic, where the DAS system response inherently removes frequency content near 100Hz from recorded data. This is problematic for many near-surface seismic imaging approaches, as much of near-surface seismic imaging techniques rely on a spectral band that is nominally centered near 100hz (e.g., 0-200Hz). For example, sledgehammer impactive seismic sources (A.K.A., "seismic shots") typically have a peak frequency content near 60Hz.

While this typical system response is potentially problematic, there is still a non-zero system response in this frequency range of interest to shallow seismic exploration. Furthermore, modern advancement in the data collection interrogator hardware has allowed for much smaller gauge lengths on the order of 1m or less. This smaller gauge length equates to shorter data sensing point intervals and shifts this DAS system response frequency notch towards higher frequencies, helping to alleviate concerns related to the use of DAS for relatively high-frequency near-surface seismic applications. According to Ning and Sava (2016), "DAS systems that operate on coherent optical time-domain reflectometry (COTDR) provide average axial strain measurement through analyzing the perturbed phase difference between back-scattered light along the optical fiber from two points separated by a distance known as gauge length. Acceptable signal-to-noise ratio (SNR) measurements can be achieved using conventional DAS systems that require a gauge length of around 1 m."

Fiber Orientation

Thirdly, an important factor that dictates how a DAS systems respond to a seismic wavefield relates to the particle motion vector direction relative to the orientation of a DAS fiber (i.e., DAS can only sense changes in axial strain oriented tangentially to the DAS fiber at a given sensing point). Due to this directionality of DAS sensitivity, DAS fibers respond differently to shear-waves (s-waves) and compressional-waves (p-waves). The different response to p-waves and s-wave results from differing particle motions. Here, s-waves have a particle motion that is transverse (i.e., perpendicular) to the direction of wave propagation, and p-waves have a particle motion that is parallel to the direction of wave propagation. The angle of incidence of wave propagation relative to the orientation of a segment of DAS fiber is depicted in the top plot (a) of Figure 11. The corresponding DAS system frequency response (spectral sensitivity) as a function of this incidence angle and frequency are presented in center plot (b) and bottom plot (c) for p-wave and s-wave energy, respectively (Chambers, K., 2020).

In Figure 11, a gauge length of 10m, and P-wave and S-wave velocities of 2500 m/s and 1560 m/s are assumed, respectively. Here, the assumed gauge length and seismic p-wave and s-wave velocities are important, as these values dictate the wavelength at a given frequency and the associated differential particle displacement (e.g., strain) that is imparted across a 10m gauge length. As seen in plots (b) and (c) of Figure 11, certain incidence angles result in the DAS system response trending towards zero (no sensitivity), depending on particle motions associated with the type of wave. This image indicates why DAS fiber installations using single straight fiber segments have certain null-angles, where the system will not record vibrations emanating from specific azimuths. Conversely, DAS fiber installs that employ right-angle segments or spirals of fiber contain a full azimuth of sensitivity.

Fiber Length

Lastly, the FO cable length is a fundamental aspect of any DAS system design that directly affects the "Nyquist frequency" (i.e., the highest frequency that can reliably be recorded, which is always half the sample rate, or laser pulse interval in the case of DAS). Specifically, the next laser pulse can't be transmitted into the FO cable until the previous pulse has had time to travel to the far end of the fiber and for the reflections from there to return to the interrogator unit. "Otherwise, reflections would be returning from different sections of the fiber at the same time and the system would not operate properly. For a fiber 50 km long the maximum pulse rate is just over 2 kHz. Therefore, strains can be measured which vary at frequencies up to the Nyquist frequency of 1 kHz (1ms sample interval)," (Wikipedia, 2020). While 1ms sampling interval is typically adequate for most geophysics applications, the use of a shorter FO cables enables higher acquisition rates if needed.

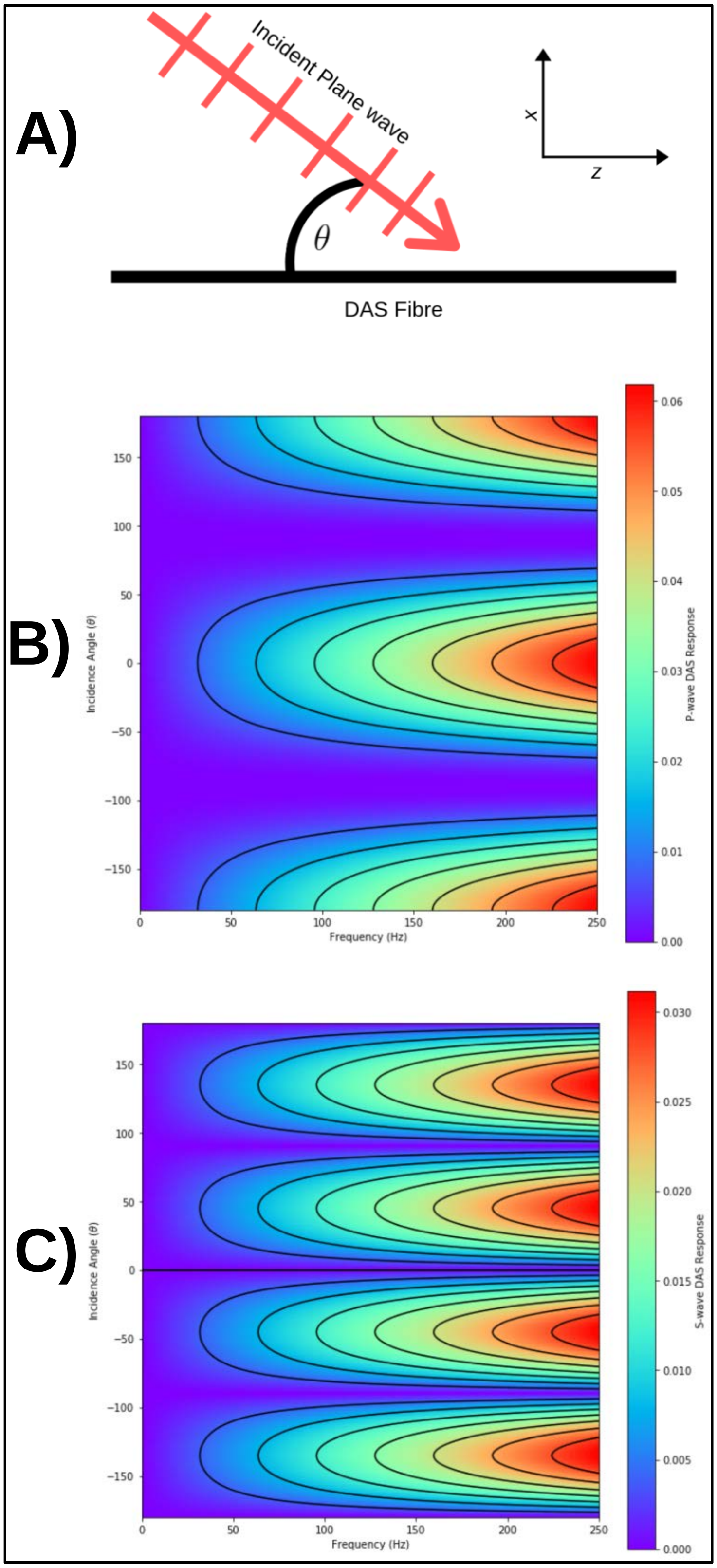

Figure 11 – Schematic of the angle of an incident plane-wave relative to a DAS fiber's normal vector (A), the amplitude response spectrum of DAS as a function of frequency and incidence angle for p-waves (B), and for s-waves (C). Modified from Chambers, K. (2020).

Previous Work and Existing Resources

As depicted in Figure 12, there has been a significant interest in DAS-related research and notable increase in related publications in the last two decades. While over 50 publications on the general topic of DAS were reviewed, an extensive presentation of the literature review is beyond the scope of this report. However, it should be stated that several notable publications related to the use of active DAS for civil engineering and NDT applications were identified.

Most recent advancements have involved improvement and expansion of hardware capabilities and subsequent data processing and modeling techniques for various applications. Most of these efforts have been related to the use of DAS for petroleum industry applications (e.g., oil and gas exploration, hydrocarbon reservoir characterization and monitoring), earthquake seismology, and pipeline health performance, and perimeter security monitoring applications. However, there has been considerable increase in interest of DAS for a variety of near-surface military, environmental, civil, and geotechnical applications.

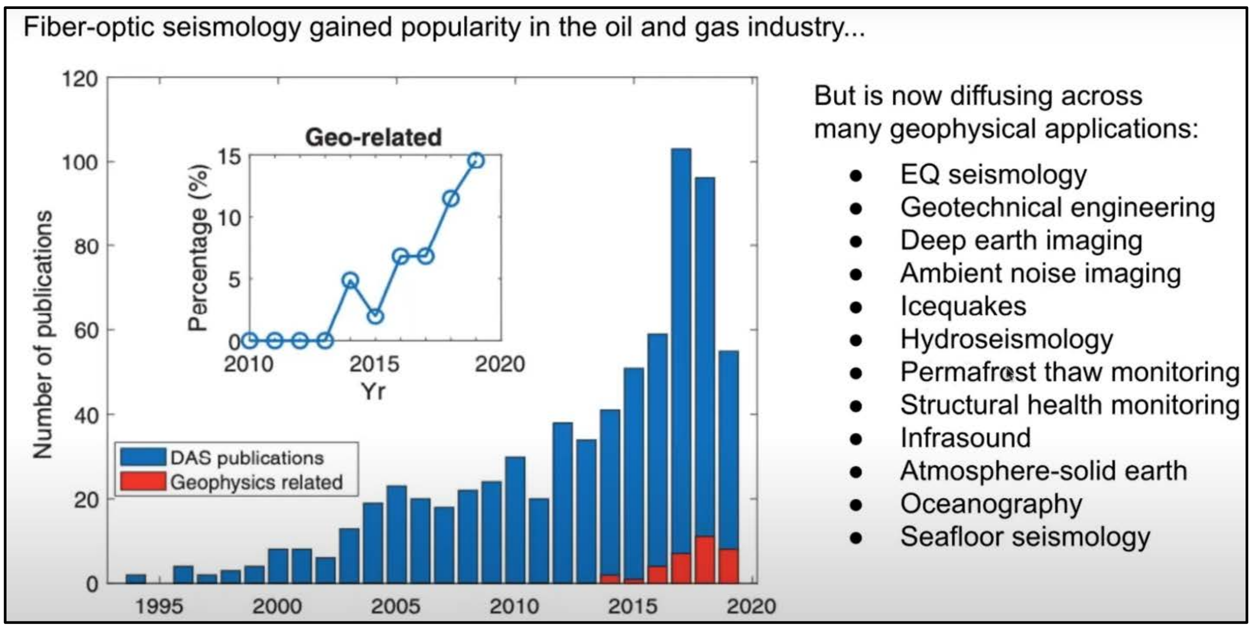

Figure 12 – Graphic showing recent publication trends related to the use of DAS technology for geologic and geophysics-related topics. Modified from Zhan, 2019; Lindsey, N., 2020)

General Previous DAS Work from Industry and Academia

Distributed fiber-optic sensors were first developed in the early 1980s (Hartog, 1983) and introduced into the oilfield in the 1990s. According to Naldrett et al (2018), "the initial areas of interest, and commercially available technologies, were related to the use of DTS and DSS for oil well and reservoir monitoring. DTS was applied to oil and gas well leak detection, flow profiling and steam flood-monitoring applications (Smolen and van der Spek, 2003). DSS focused mainly on wellbore integrity, monitoring strain induced on wellbore casings (Li et a., 2004).

In the late 1990s, research was carried out on the use of optical fibers for distributed vibration sensing (Shatalin et al., 1998), which would later lead to the development of DAS. It should be noted here that while there is no consistency in industry naming conventions, there are technical differences between DVS and DAS. Specifically, the term DAS is used for fiber optic sensing that can quantitatively measure the acoustic amplitude, phase and frequency of disturbances along a fiber. Conversely, "DVS systems are typically able to detect and locate a disturbance but may not be able provide a measurement response proportional to the magnitude of the disturbance. DVS systems also typically lack acoustic-phase coherence. This means that while a DVS system can detect the disturbance, it cannot tell if the disturbance is extending or compressing the fiber," (Naldrett et al., 2018). After the advent of DAS, there was a significant increase in the use of the technology for earth science applications, especially in the field of geophysics as depicted in Figure 12.

As mentioned above and depicted in Figure 12, extensive industry-based and academic-based research and development of DAS technologies and applications have taken place over the past three decades. Much of these efforts have focused on the use of DAS for recording passive seismic-vibrations related to earthquake seismology and a variety of other earth science applications, including environmental monitoring (Shanafield et al., 2018; AP Sensing, 2020), oceanography (Lindsey et al., 2019; Lindsey, 2020), geothermal exploration and characterization and monitoring (Trainor-Guitton et al, 2019; AP Sensing, 2020), atmosphere-solid earth processes and interactions (Zhu and Stensrud, 2019), and earthquake seismology (Lindsey et al., 2017, 2019; Wang et al., 2018; Ajo-Franklin et al., 2019; Zhan, 2019; Lindsey, 2020; SSA 2019, 2020).

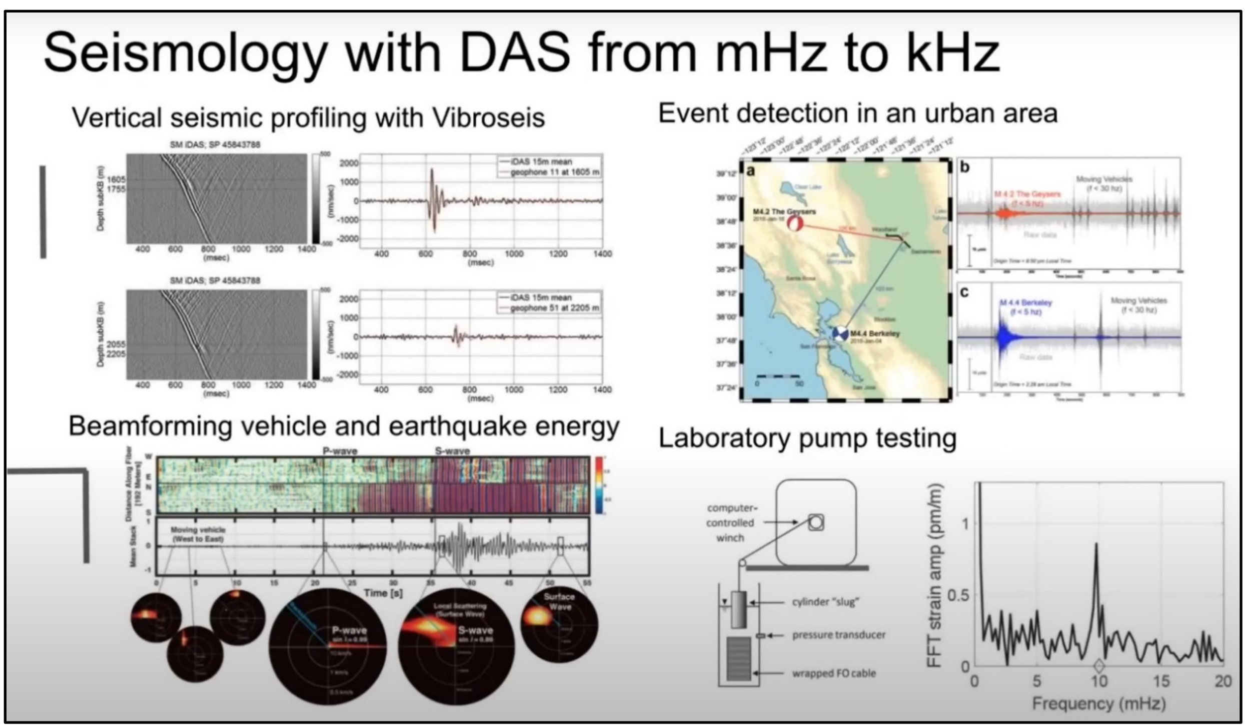

Figure 13 – Graphics depicting various applications and aspects DAS system-recorded data being compared with more industry-standard seismic sensors: Direct time-domain comparisons of recorded seismic traces using DAS and standard downhole seismic sensors (upper-left), event detection of earthquakes in noisy environments (upper-right), beam-forming to locate the direction of a vehicle (lower-left), and looking at very low-frequency DAS fiber responses during a cyclic loading experiment (lower-right). Modified from Lindsey, N. (2020).

The petroleum industry has also made significant contributions to the development and use of DAS technology. These include fundamental research and development of DAS technology for improving the resolution and sensitivity of DAS (Dean et al., 2016; Ning and Sava, 2018; Yuan et al., 2019). Most applications and research interests for use of DAS in the petroleum industry are related to geophysical (seismic) imaging and exploration (Figure 14), and production well and hydrocarbon reservoir monitoring (Smolen and van der Spek., 2003; Li et al., 2004; Mateeva et al., 2012, 2013; Wu et al., 2015; Dou et al., 2016; Chalenski et al., 2016; Naldrett et al., 2018; Lellouch et al., 2019).

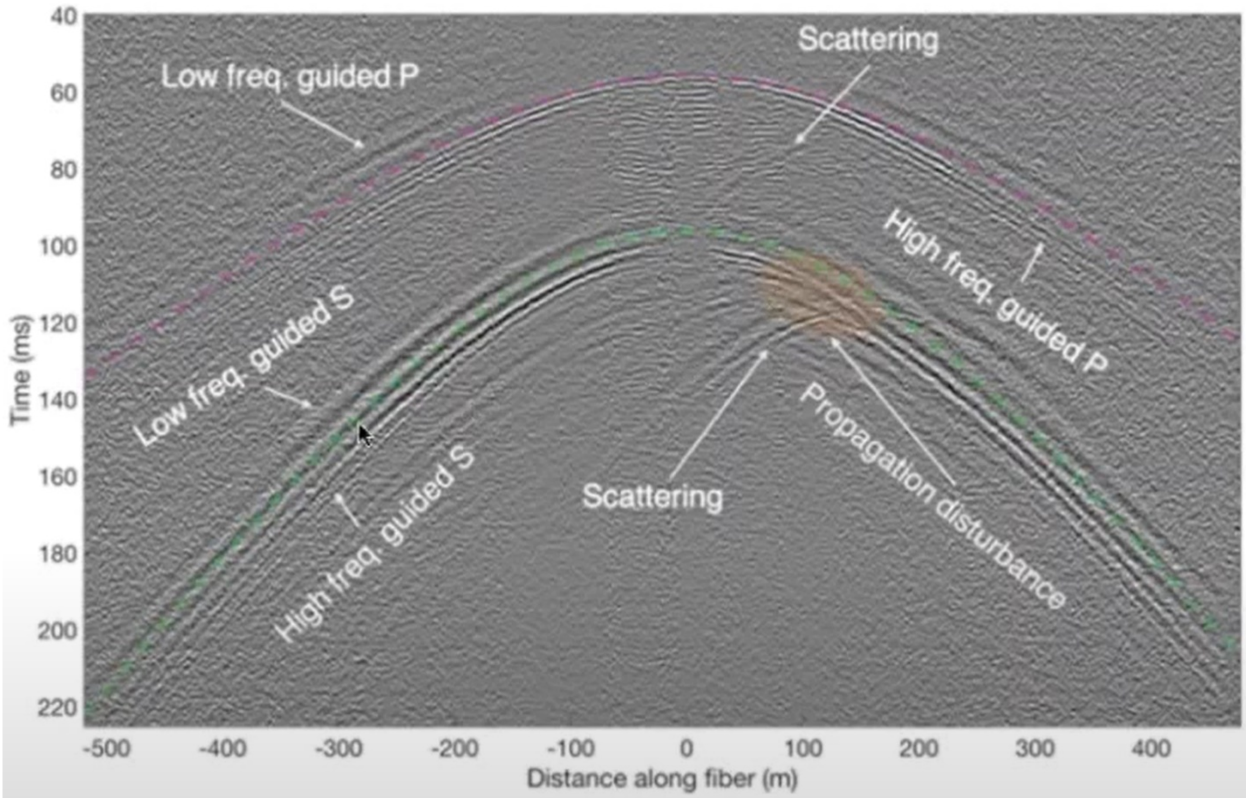

Figure 14 – Example of real seismic data collected along a single DAS fiber with sensing intervals of approximately 1m (3.28ft) along a 1000m long fiber (Lellouch et al., 2019).

As discussed above, one of the limitations of standard DAS fiber (single mode FO cables) is related to azimuthal sensitivity of the fiber to different wave types (i.e., s-waves and p-waves). This limitation results in only a single component of the strain field being measured at any given point along a FO cable. Specifically, strain is a tensor field (six independent components), but typical single-mode DAS systems can only record the component that is tangential (i.e., parallel) to the fiber at a given channel location along the fiber. To address this shortcoming of the sensing technology, much recent effort has been made at developing the use of multiple fibers along a single array and changing the geometry of the FO cable fibers to be sensitive to different components of strain at a given point along the fiber. Namely, including coils and helically wrapped fibers as depicted in Figure 15 enables recovery of the other components of the strain field, and these novel FO cable designs have opened up a new set of quantitative applications of DAS for seismic exploration and imaging (Ning and Sava, 2018).

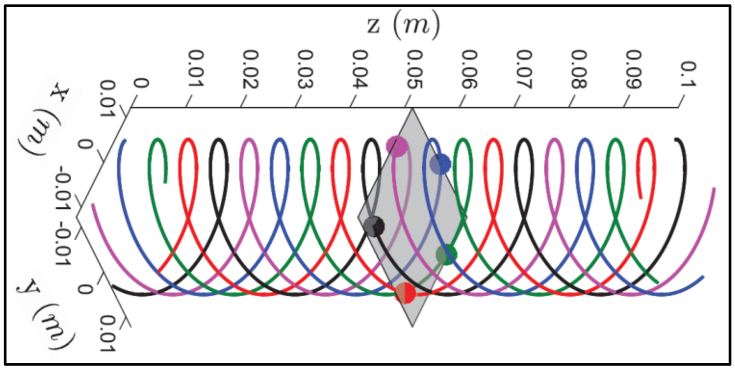

Figure 15 - Example of five equally spaced helical optical fibers with a diameter of 2.44 cm and a pitch angle of 20◦. The dots represent measurement at the same length along respective fibers, which refer to the same portion of the cable indicated by the horizontal plane. Modified from Ning and Sava (2018).

Previous DAS Work Specific to Civil Infrastructure

There are several novel applications of DAS (and DTS and DSS) already being implemented for civil infrastructural applications in industry, as indicated in Figure 16. Some of these include geothermal system performance monitoring, high voltage power line monitoring and fire detection, pipeline leak detection, and seismic data collection for various geophysical and seismological applications (Liang et al., 2019; Lindsey et al., 2020). In the case of pipeline leak detection, a variety of commercial hardware and software solutions have been developed and are being deployed around the world (Chambers, 2020; FCS, 2020; HMS, 2020; OptaSense, 2020a, 2020b).

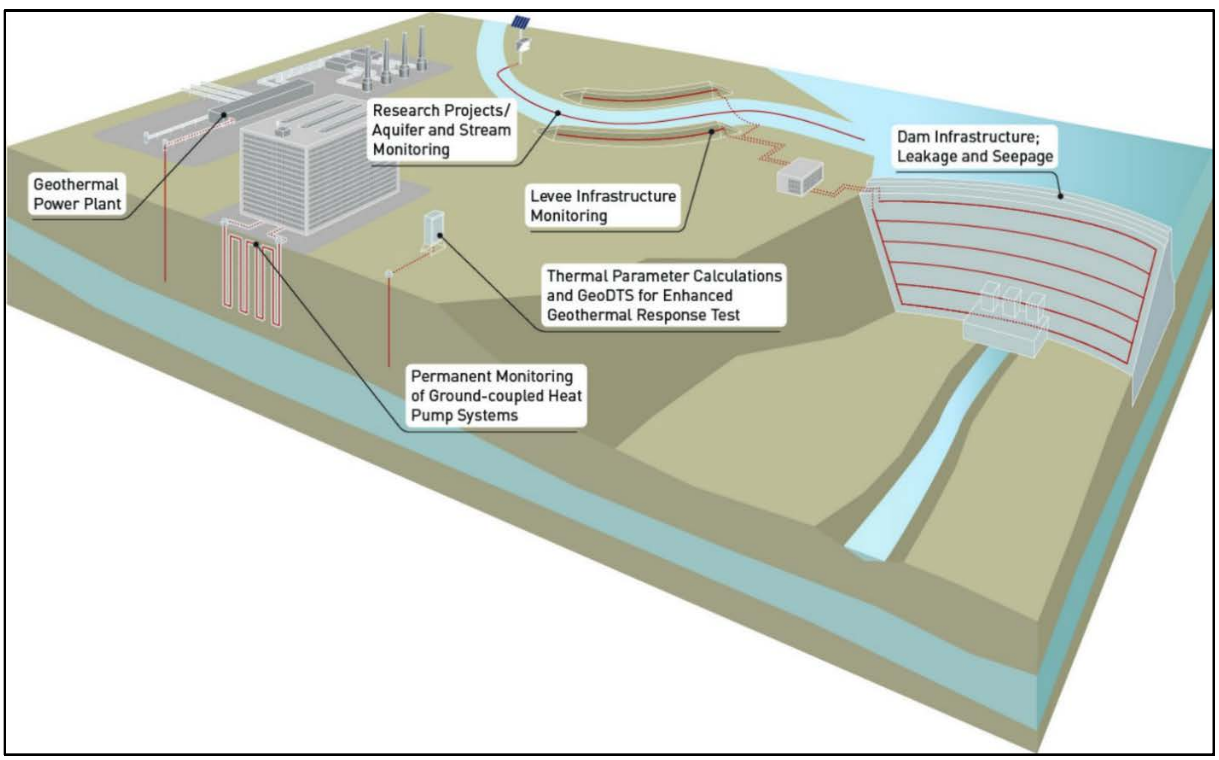

Figure 16 – Schematic of various applications of DAS (and DTS and DSS) already being implemented in industry. Modified from AP Sensing (2020).

Due to the linear and distributed nature of FO cables used in DAS (and DTS and DSS), this sensing technology naturally lends itself to long and linear civil structures, such as roads, train tracks, tunnels, boarders and fences, pipelines, levees, canals, power-lines, etc. In many cases, the FO cable can be surface mounted on infrastructural components, and a single mode FO cable can be used to support the use of DAS as well as DTS and DSS for more robust system monitoring. Additionally, specialized multi-fiber FO cables have been developed to maximize the sensitivity of multi-purpose sensing applications that make use of DAS, DTS, and DSS technologies. As depicted in Figure 17, a combination of DAS, DTS and DSS can be used to detect and characterize pipeline leaks based anomalous changes in vibrational energy (DAS), temperature (DTS), and strain of the pipeline or underlying soil (DSS). These sensing technologies can be deployed along several 10s of kilometers of pipeline in real-time (Chambers, 2020; FCS, 2020; HMS, 2020; OptaSense, 2020a, 2020b).

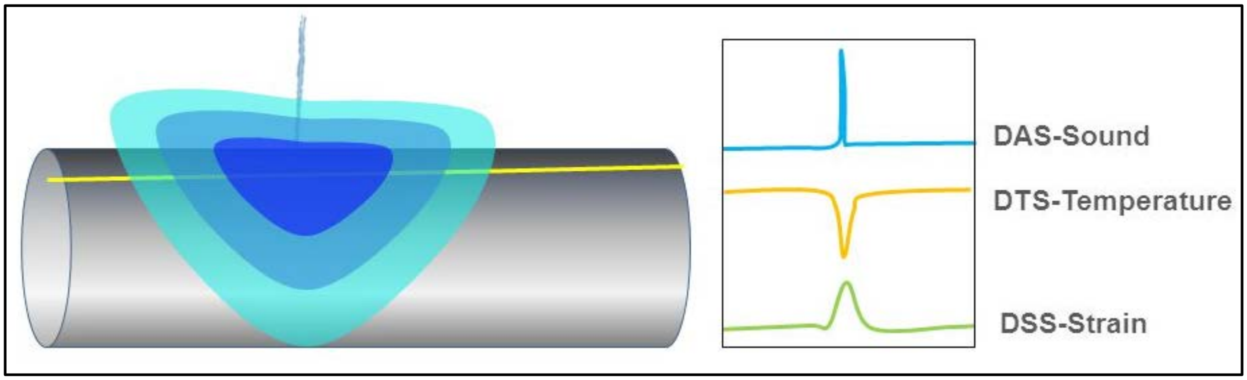

Figure 17 – Schematic of pipeline leak detection using DAS, DTS, and DSS technology. Modified from Hawk Measurement Systems (2020).

Another novel application of DAS involves detection of vibrations related to vehicle and human activity for perimeter security monitoring and alarm systems (Costley et al., 2016; Glaser et al., 2019; Peterson et al., 2020; Jakkampudi et al., 2020; OptaSense, 2020a). Here, the location of the source of vibration can be determined and tracked in an automated fashion. Furthermore, automated signal classification algorithms have been developed for identifying vehicle types, vehicle counts, and for data signature recognition of walking of a biped (i.e., humans) versus a quadruped. An example of raw DAS data that shows vehicle and human activity during the 2020 Rose Parade is shown in Figure 18. Here the location, velocity and various other source characteristics can be determined directly from the raw DAS data, and directional beam-forming can be performed to locate the azimuthal direction and expected distance of a signal source that is remotely located relative to the DAS FO cable, as indicated in Figure 13.

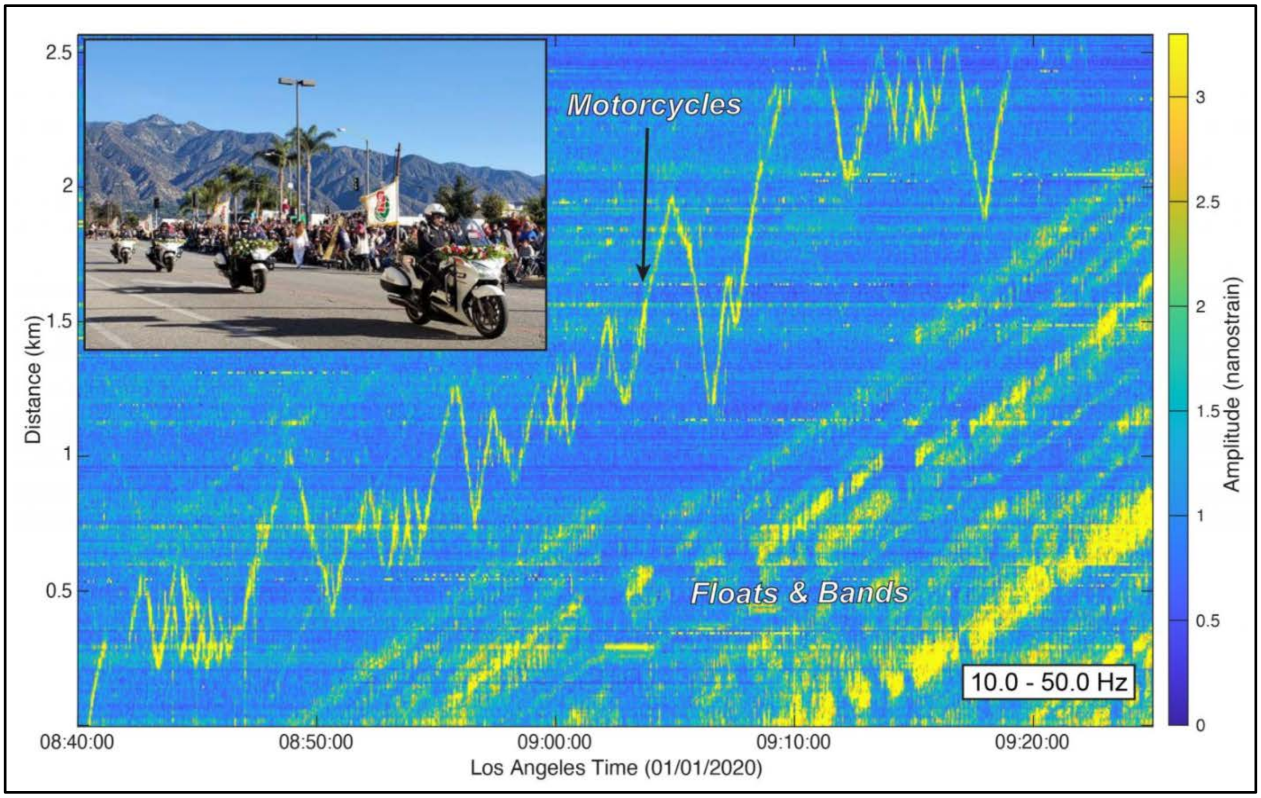

Figure 18 – DAS records showing seismic vibrations caused by motorcycles, marching bands, and floats during 2020 Rose Parade. Modified from SRL (2020).

Applications of seismic sensing and imaging for shallow depth intervals and time-lapse infrastructure assessment are discussed throughout literature such as the work of Snieder and Shafak (2006) that investigates the use of vibration sensors placed in buildings to assess the structure's spectral acceleration response to earthquakes and other strong motion loading. This application of DAS is particularly relevant to Reclamation's Dam Safety activities, where FLAC analysis of dynamic failure modes oftentimes requires information related to this response spectrum, and this is oftentimes a data gap in risk analysis efforts.

Similar studies have subsequently been performed to evaluate the use of remotely-sensed vibrations (e.g., laser doppler vibrometers) for ambient vibrational (AV) analysis of tall buildings (Jolivet et al., 2008). According to the authors, "most of AV surveys consist of installing accelerometers or velocimeters in the target building and recording ambient vibrations using digital and handheld acquisition system. It can also be worthwhile and safe to have the possibility to get the resonance frequency of buildings using remote system: worthwhile because of the repeatability of the measurements without entering in buildings, and safe in case of post-earthquake assessment of the building integrity when aftershocks are able to collapse the damaged buildings," (Jolivet et al., 2008). Existing telecommunications FO cables or new dedicated DAS fiber installs in vulnerable buildings and other structures can help assess structural integrity and detect damage post-earthquake.

There has been significant interest and research on the use of DAS for near-surface imaging and characterization that is directly relevant to civil and infrastructural health monitoring (Costley et al., 2016, 2018a, 2018b; Dou et al., 2017; Esra, 2019; Shragge et al., 2019; Spikes et al., 2019; Fang et al., 2020; Luo et al., 2020; Yuan et al., 2020; Zhang et al., 2020). Much of this work makes use of ambient background vibrational energy, namely vehicular traffic and other human activities, to record surface waves and support dispersion analysis of surface waves.

Previous DAS Work Relevant to Near-Surface Hydrogeology and Seepage and Internal Erosion Detection and Characterization

There has been recent research related to the use of DAS for instrumenting levees and other earthen embankments for detection of slope stability issues and other performance health concerns related to hydraulically loaded structures (OptaSense, 2020a, 2020b; AP Sensing, 2020; Costley et al., 2018a, 2018b). Here, vibrations related to seepage are likely detectible with DAS arrays, temperature fluctuations related to seepage are likely detectible with DTS arrays, and soil movement and related changes in strain related to slope-stability issues and shifting soils near concentrated seepage pathways experiencing internal erosion are most likely detectible with DSS arrays. Additionally, there has been significant work on passive seismic interferometry and surface wave dispersion analysis techniques to reconstruct the s-wave velocity distribution as a function of depth within the shallow subsurface (see Planès et al, 2017 for more details).

Passive seismic surface-wave and interferometry techniques have particularly poignant relevance to earthen embankment monitoring and seepage and internal erosion detection: the focus of the S&T Prize Challenge Competition topic (internal erosion of dams). The following excerpt related to the use of DAS for shallow time-lapse monitoring of s-wave velocity structure by Dou et al., (2017) is worth quoting at length:

> *"For near-surface monitoring, DAS could be an enabling technology particularly for ambient-noise-based approaches. Ambient seismic-noise methods utilize the ubiquitous vibrations generated by natural or anthropogenic sources such as wind, rivers, and vehicles. By cross-correlating ambient noise recorded by a receiver pair, we can retrieve coherent waves that travel from one receiver (acting as a virtual source) to the other without using active or passive seismic sources (e.g., earthquakes, explosives). The resulting ambient-noise interferometry approaches are particularly useful for seismic monitoring since they do not require repeated source deployment. Nevertheless, because sensors amenable for monitoring are often sparsely distributed, information retrievable from a typical noise-based monitoring system can rarely extend beyond apparent-velocity perturbations along paths of a few station pairs (often referred to as dV/V measurements). This allows the detection of changes along the paths, but not where on the paths the changes are occurring. With the dense spatial sampling provided by DAS, spatial distributions of near-surface changes can be better resolved through time-lapse imaging.*
>
> *In particular, DAS allows time-lapse imaging of shear-wave velocity (VS) structures using methods such as multichannel analysis of surface waves (MASW). Although surface waves often dominate virtual wavefields that are generated with ambient-noise interferometry, multichannel arrays rarely are*

available for continuous recordings of ambient noise. Consequently, time-lapse VS imaging studies often use surface waves that are acquired from periodically repeated active-source surveys. The limitations of this approach are twofold: (1) Great care must be taken in the surveys to ensure repeatability; (2) Temporal resolution of the monitoring is limited (dictated by the acquisition interval). With DAS, multichannel recordings of surface waves can be continuously retrieved with ambient-noise interferometry, hence making noise-based approach applicable to time-lapse VS imaging."

As described in the above quote, passive surface-wave imaging techniques such as MASW or virtual source interferometry have several advantages for semi or fully-automated time-lapse monitoring of large infrastructure, specifically for the purpose of detecting and imaging spatio-temporal changes in s-wave velocity distributions within the shallow subsurface that are related to dynamic hydrogeologic processes of interest. Conveniently, seepage and internal erosion of earthen embankments (and other embankment damage phenomena such as differential settlement and cracking) are known to be associated with localized changes in s-wave velocities and lends these passive seismic imaging techniques to this problem faced by Reclamation and other stakeholders (Dou et al., 2017; Planès et al, 2017; Costley et al., 2018a; Fang et al, 2020; Luo et al., 2020).

Dou et al., 2017 recently carried out experiments to investigate the use of DAS with telecommunications fibers for collection of seismic data capable of supporting the reconstruction of s-wave velocity distributions within the shallow subsurface using MASW inverse modeling techniques. This study used traffic noise that was continuously recorded on linear DAS arrays over a three-week period. According to Dou et al. (2017), because DAS enables "both high sensor counts ("large N") and long-term operations ("large T"), time-lapse imaging of shear-wave velocity structures is now possible by combining ambient noise interferometry and MASW." The results of this study show excellent corelation with local hydrogeologic conditions (Figure 19). Furthermore, the results depicted in Figure 20 demonstrate a time-lapse repeatability of about 2% in the model domain (velocities should not be changing during the study time-frame, as no dynamic subsurface processes that would otherwise affect seismic velocities were expected). This repeatablility error is low enough to support observing subtle near-surface changes such as water content variations and soil stiffness alterations.

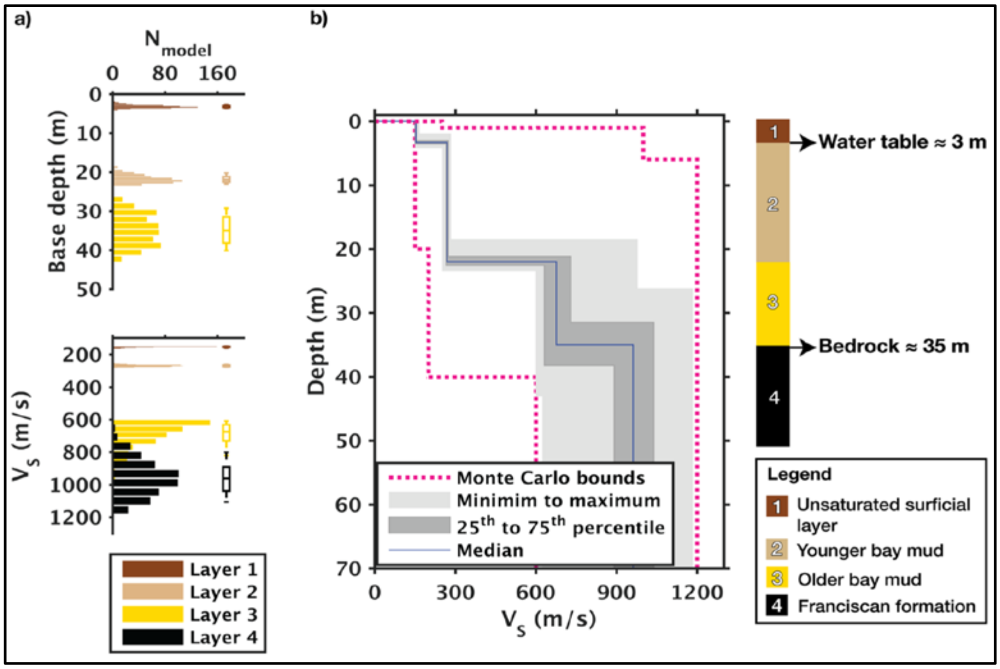

Figure 19 - Error analysis and geologic interpretation of the best-fit *Vs* profiles. (**a**) Histogram and box plots illustrating distributions of base depth and *Vs* in each layer. (**b**) Error bounds, median *Vs* profile, and corresponding geologic features (Dou et al., 2017).

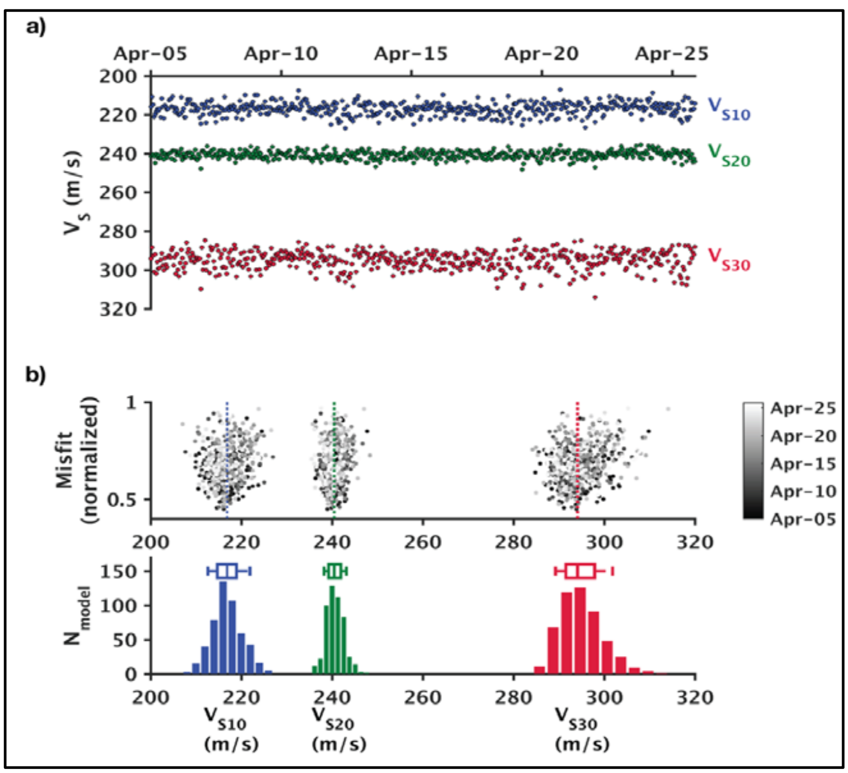

Figure 20 - Average shear-wave velocities (VS10, VS20, and VS30) estimated from best-fit models of all 502 epochs. (a) Average VS displayed as functions of calendar time. (b) Distributions of VS10, VS20, and VS30 (lower) and corresponding misfits (upper) (Dou et al., 2017).

Similarly, researchers at the Colorado School of Mines (CSM) have recently investigated the use DAS systems for collection of seismic data capable of supporting the reconstruction of s-wave velocity distributions within the shallow subsurface using MASW inverse modeling techniques (Luo et al., 2020). This study was conducted using a dedicated DAS fiber array that was recently installed on the college campus in Golden, CO. Results of this research are depicted in Figure 21, showing a "dispersion curve" image and the associated one-dimmensionaly (1-D) vertical distribution of s-wave velocity. The resulting s-wave sounding model is compared to known local geology within the uppermost 120m of the subsurface, helping to validate the results of the data processing and inversion results.

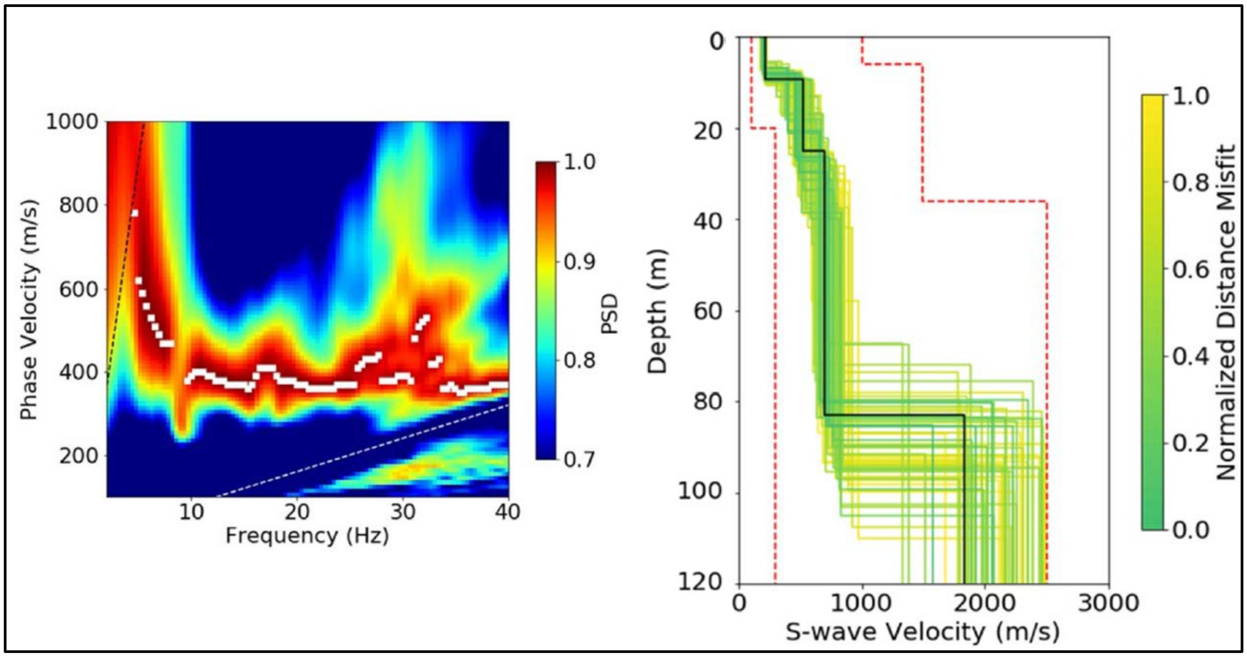

Figure 21 – Dispersion image of a 5-min chunk of passive seismic data and the picks of dispersion data points depicted with white squares (left). The accepted final MASW modeled S-wave velocity profiles color-coded by normalized distance misfit (right). Black solid curves denote the best-fitting model with least distance misfit. Red dashed curves mark the model parameter boundaries for inversion. Modified from Luo et al., (2020).

Another relevant study was performed to investigate the use of passive seismic interferometry for delineation and mapping of seepage and internal erosion features (e.g. preferential seepage pathways and sand-boils) along sea levees with the use of remote traffic as a passive-source vibrational excitation of the levee structure (Planès et al, 2017). While this study made use of industry-standard accelerometers (point-sensors) for data collection, the research focused on a data analysis workflow similar to those described in the DAS studies above. The goal of the research was to demonstrate that passive surface-wave interferometry techniques are capable of detecting and imaging localized time-lapse changes in near-surface s-wave velocity distributions that are directly related to seepage beneath an earthen embankment. As depicted in Figure 22, the locations of preferential seepage pathways and associated sand-boils were positively correlated to the lateral locations of seismic velocity perturbations. The study indicates promising results in terms of identifying subsurface damaged zones or preferential seepage pathways and internal erosion processes simply based on the time-lapse changes in seismic velocities.

While the Planès et al (2017) study did not make use of DAS technology directly, this concept could be implemented using DAS arrays as indicated by other related studies (Dou et al., 2017; Luo et al., 2020). The same techniques potentially lead to the use of DAS for time-lapse monitoring of embankments and other large civil structures for changes in structural health and performance.

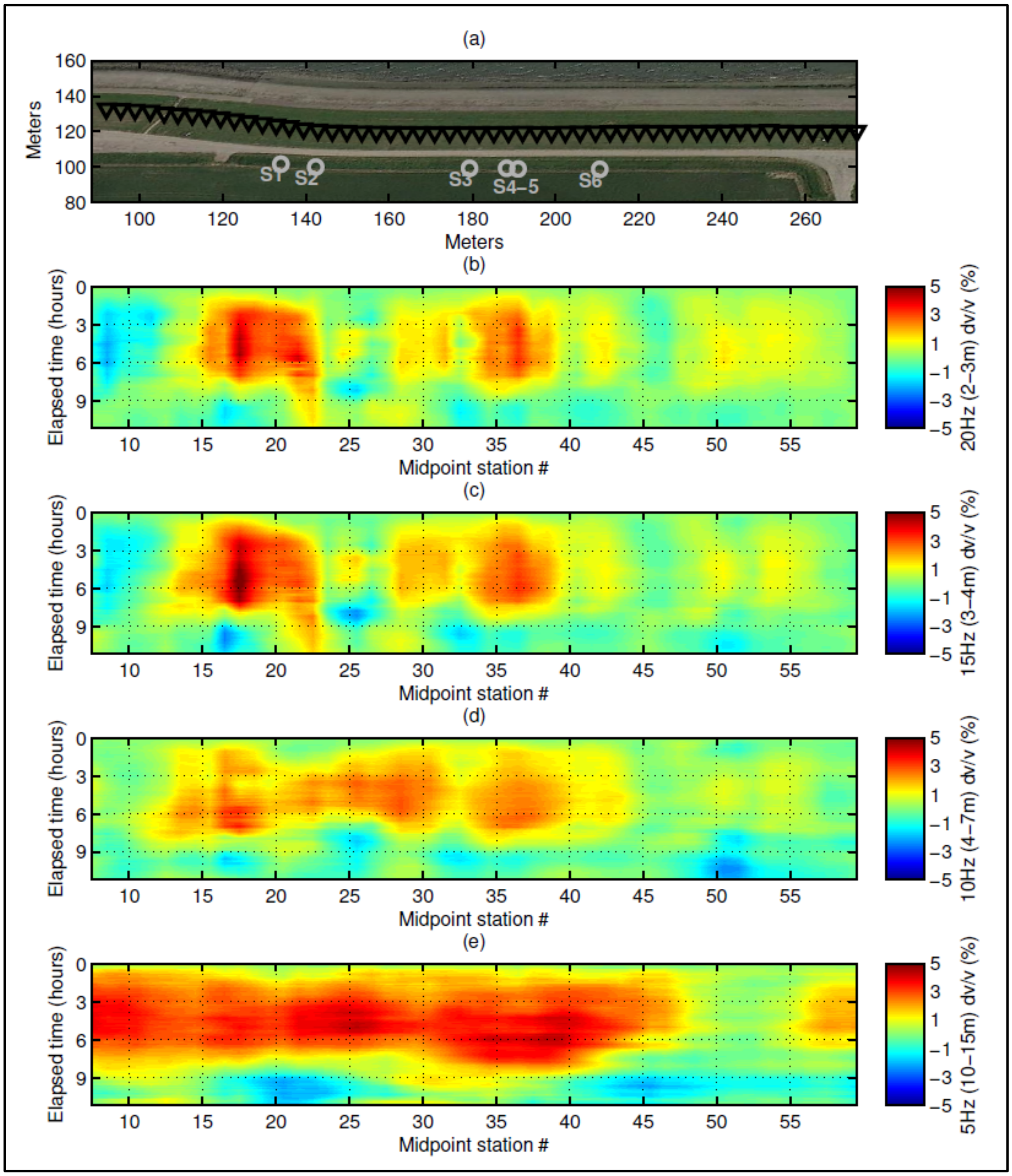

Figure 22 - Maps of relative velocity changes during the 12h tide cycle, along a 180m-long section of the levee. Di_erent frequencies - i.e. depths - are investigated: 20Hz/2-3m (b), 15Hz/3-4m (c), 10Hz/4-7m (d), 5Hz/10-15m (e). A plan view of the monitored section aligned with the velocity variation maps is shown in (a). Note the spatial correlation between lateral locations of sand-boils and peak dV/V changes shown in red (Planès et al., 2017).

Existing DAS Hardware and Technology Resources Applicable to Future DAS Research

As part of this scoping-level study, research into commercially available technologies and hardware/system solutions related to DAS were researched. Several communications were made with leading US-based manufacturers of DAS systems and software. Several webinars were attended, and several conference calls were held to discuss the capabilities, functionality, and limitations of commercially available DAS systems. Additionally, existing DAS-related resources and several future research partnerships were identified, and willingness to support future research endeavors through Reclamation's Science and Technology Program were confirmed.

Reclamation does not currently have any DAS-specific hardware resources, except for telecommunication FO cables that could potentially be used for DAS experiments. However, several of the identified tentative future research partners already have DAS FO arrays installed and already own DAS interrogator units. These partnerships would be able to provide access to interrogator units for initial testing and experimentation which would translate to enormous cost savings to any DAS-related research effort, as the interrogator units are by far the most expensive components to a DAS system.

In addition to commercially available units for rental or purchase, at least two potential external research partners have been identified that already possess and actively conduct lab-based and field-based research with the use of DAS systems. These entities include the Colorado School of Mines Geophysics Department, and federal colleagues at the USACE and Sandia National Labs. Specifically, CSM researchers have an undisclosed OptaSense DAS Interrogator Unit and a FO cable array grid installed on the CSM campus in Golden, CO. The USACE currently owns an the most recently developed and highest sensitivity and resolution OptaSense Interrogator Unit called the Plexus. Additionally, USACE has at least one DAS fiber array installed, and one DAS fiber array grid installation planned.

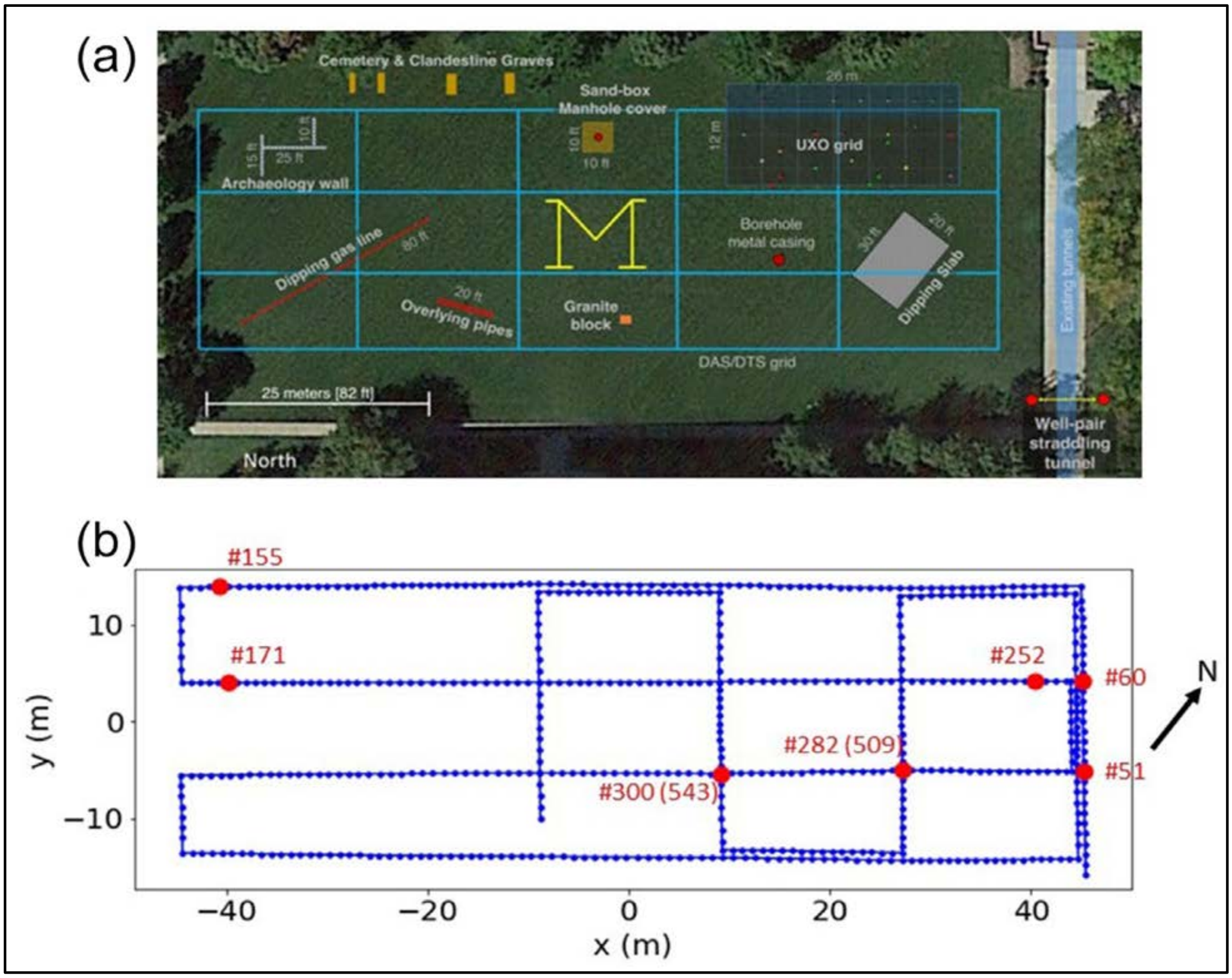

Figure 23 - Map of Kafadar Geophysical Laboratory buried anomalies, including the 27 m by 90 m DAS (blue) grid. (b) DAS fiber-optic cable (blue curve) geometry and calibrated channel locations (blue dots). Red dots mark the channels mentioned in this paper. Modified from Luo, B., et al., (2020).

Existing Reclamation Resources Related to Future DAS Research

Reclamation has not performed previous work related specifically to DAS. However, Reclamation has a variety of facilities that have undergone extensive field testing and numerical analysis of geologic and seismic properties and behaviors (e.g., spectral response to earthquakes, Vs30 of foundations, detailed seismic wave velocity imaging, geologic borehole data, piezometer installations, etc.) that are readily available for ground-truthing of any DAS array testing. TSC geophysicists commonly implement a variety of seismic survey types, and Reclamation owns several standard seismic data collection systems that can be made available for testing in subsequent research efforts.

Lastly, at least two hydraulics laboratory scaled physical models of embankments (Hydraulics lab housed in Building 56 of the Denver Federal Center) are still constructed and could likely be used for future seepage and internal erosion monitoring studies involving the use of DAS technology. An example of one of these physical models, the "Embankment breach test facility," is depicted in Figure 24:

Figure 24 - Embankment breach test facility viewed from the upstream end of the headbox, overlooking the completed test embankment.

Potential Applications and Benefits Specific to Reclamation Infrastructure

The reduction to practice of using DAS and related sensing technologies (DTS and DSS) would help Reclamation develop new monitoring capabilities that would help address some of the most difficult technical challenges related to our deteriorating infrastructure. The Use of DAS could provide Reclamation a means of monitoring its critical structures and help managers and engineers in making informed decisions on future modifications, repairs, and mitigation efforts. The use of DAS would enable high-resolution seismic imaging and change detection in a time-lapse monitoring sense. A variety of seismic monitoring and imaging techniques could be enabled with the installation of DAS arrays on large infrastructure, including active seismic surveys and passive seismic imaging techniques as discussed above. Some specific examples of the potential applications of DAS and related sensing technologies (DTS and DSS) are listed below by infrastructure category:

Dams and Canals and Levees – Distributed fiber optic sensing techniques, such as DAS, DSS or DTS are powerful tools for the monitoring of large structures and long, linear assets. In each of the applications listed below, distributed fiber optic sensing offers clear benefits in the ability to cover a wide area from a central monitoring point. Consequently, these approaches fit perfectly with specific requirements of monitoring earthen embankments, where they can fulfill objectives in various areas:

- Enable high-resolution time-lapse seismic monitoring and imaging
- Tracking the position and speed of flow changes
- Monitor areas of seepage
- Detect right-of-way activity (work crews, trespassers)
- Detect rockfall and landslide events in the vicinity of the embankment
- Detect if a breach is pending or if one occurs

Pipelines and Penstocks – Monitoring the following conditions is very important to a pipeline or powerplant operator. Third party interference, whether intentional or not, as well as excessive strain can lead to a potential pipeline leak or rupture, which needs to be immediately reported to the pipeline operator. The main uses for distributed fiber optic sensing in monitoring pipelines are:

- Detecting pipeline or penstock water leaks (or valve operation).
- Detecting unauthorized (or unexpected) third party interference in the vicinity of the pipeline or penstock.
- Detecting excessive strain being applied to the pipeline or penstock due to shifts in the soil caused by subsidence, landslides or other geotechnical reasons.

Transmission Lines – The most prevalent sensing technology for power utility applications is DTS which monitors temperatures related to the past and present electric current loads of power cables. Because fiber optic systems are powerful tools for monitoring of long, linear assets, these approaches fit perfectly with specific requirements of the power industry, where they can fulfill objectives in various areas:

- Monitor the temperature power cables, overhead lines, generators, transformers and other assets
- Monitor the sag of overhead lines
- Localizing faults in power cables
- Detect activity along the cable route (work crews, trespassers, cable tampering)
- Monitor mechanical load (tension, bending, torsion) during production, loading, transport, installation and operation of power cables

Highways, tunnels, security fences and other long linear assets – Distributed fiber optic sensing techniques, such as DAS, DSS or DTS work especially well for monitoring long, linear assets. Consequently, these approaches fit perfectly with specific requirements of the roadways, tunnels, and security fences where they can fulfill objectives in various areas:

- Traffic, people and animal monitoring applications
- Vehicle count (where the fiber runs perpendicularly underneath the road)
- Hazard detection applications
- Fire detection in tunnels
- Structural Health Monitoring (SHM) of civil structures like bridges and tunnels
- Road and fence damage detection
- Road weather/condition change detection

Furthermore, the various possible research topics involving the use of DAS would meet or partially align with the Fiscal Year 2018 – 2021 S&T Priorities in the priority research areas of Water Infrastructure (WI) and Power and Energy (PE) Research Categories:

- Dams
  - Methods and materials to detect and fill or repair voids under spillway slabs (cross cutting with Canals), specifically in low probability, high consequence scenarios like Oroville Dam
  - Through tools to develop procedures for calibrating the FE models at different complexity levels and verifying and interpreting the analysis results considering various input parameters
- Canals
  - Through meeting the needs of enhanced methods for rehabilitation and maintenance of urbanized canals and immediate response systems for changes to these canals
  - Methods and materials to detect and fill or repair voids under canal lining (cross cutting with Dams)
  - Improved inspection methods to reduce siphon pipe failure rates. Less expensive repair methods to repair pipe in lieu of replacement and associated costs (cross cutting with Pipelines)
- Pipelines
  - Improve tunnel condition assessment techniques and repair methods.
  - Detecting leaks
  - Demonstrate low- or no-power tools or sensors for detecting or monitoring metallic corrosion when embedded in concrete pipes including prestressed concrete cylinder pipes(cross cutting with Canals).
- Miscellaneous Water Infrastructure.
  - Data standards - Evaluate standardized data collection approaches for inspections to facilitate improved data processing or predictive maintenance.
  - Data processing - Develop solutions, tools, and practices to improve analysis of large datasets, such as from photogrammetry or other detection methods.
  - Predictive maintenance - Research machine learning, artificial intelligence, algorithms, or other solutions to develop a predictive maintenance approach for assets.
  - Safety - Research projects that focus on improving the safety of Reclamation personnel, such as robotics, improved hearing protection, improved hazardous energy detection, etc.
  - Security - Develop solutions, tools, and practices to further Reclamation's understanding of security risks at its facilities using qualitative and quantitative data. The research should result in data and conclusions that can be integrated into Reclamation's security program to provide Reclamation

with an enhanced capability to evaluate and manage risk at its critical infrastructure.

- Hydro Powerplants
    - Improves safety and occupational health.
    - Increases reliability, power generation, and performance.
    - Improves operations and maintenance practices.
    - Examines new operations and maintenance philosophies, such as new sensor technologies, data sampling strategies, and analytical systems.
    - Mechanical equipment – penstocks. Develop or advance inspection and coating application and repair methods for large pipes and penstocks with difficult-to-access or dangerous geometries (e.g., complex geometry, steep slopes, drops, etc.). Inspection methods should improve data quality and reduce inspection time.
    - Mechanical equipment - turbine runner and wicket gates. Develop or improve existing tools to recommend effective operational limits that can distinguish erosive (damaging/ metal or material loss) cavitation from non-erosive cavitation.
- Pumping Plants
    - Investigate nondestructive inspection tools, such as ultrasonic testing, to improve efficiency and effectiveness of inspections in hard to access areas.
    - Vibration testing of exposed pipe in pump discharge basins.

There may be other, tangible uses for this research product in the research area of environmental issues for water delivery and management (EN); Research Category; Water Delivery Reliability. In the research area of developing water supplies; Research Category; System Water Losses, and others where temperature measurements of other linear monitoring may be applicable.

Challenges and Limitations of DAS

Some of the main challenges related to the adoption of DAS for infrastructure monitoring are briefly listed below:

- FO cable installations on existing structures: This most typically requires direct burial, as discussed above. Trenching and invasive excavation activities for FO cable installs (even if only shallow ~30cm deep) may not be feasible or practical in certain situations.
- The noise and sensitivity of data within higher frequency bands coulld pose issues in processing workflows making use of certain seismic imaging schemes.
- Data volumes associated with DAS systems are quite large (upto 1Tb of data per day), and data harvesting, management and processing schemes are oftentimes challenging.

Potential Partnerships and Resources for Future Research

There have been several entities that have addressed interest in this project and would like to pursue a collaborative effort in the future. These include the following:

- U. S. Army Corps of Engineers ERDC, with their interest on the technology use for sensing and monitoring of earthen dams
    - Dan Costley, Research Mechanical Engineer, richard.d.costley@usace.army.mil, 601-618-8390
        - Interested in general inter-agency research collaborations
        - Actively pursuing DAS-related research
        - Experience in DAS data collection and processing
        - Currently owns an OptaSense Plexus Interrogator Unit
        - Have an existing dedicated DAS fiber installed along the main Mississippi River Levee
        - Currently working on installation of dedicated DAS fiber array (grid) install

- U. S. Department of Energy, Sandia Laboratories
    - Budi Gunawan, Kris Kuhlman, bgunawa@sandia.gov, klkuhlm@sandia.gov
        - Interest in applications to penstocks and hydroelectric turbines, seismic techniques
        - Actively pursuing DAS-related research
        - Experience in DAS data collection and processing
        - Seeking internal funding for future research related to FBG
        - Currently owns multiple Luna Odisi Interrogator Units

- OptaSense, a global company and leader in DAS technology who has offered to provide their technical support and knowledge transfer to Reclamation

- Colorado School of Mines, who has expressed an interest in collaboration on DAS sensing and monitoring of earthen dams
    - Paul Sava and Jeffrey Shragge (Interim Dept. Head and professors), psava@mines.edu, jshragge@mines.edu,
        - Interested in general research collaborations
        - Actively pursuing DAS-related research
        - Seeking funding support of one or more graduate-level students to work on DAS with Reclamation
        - Experience in DAS data collection and processing

    - World leaders in seismic data collection, processing, inversion
    - Access to network of other experts and graduate-level researchers
    - Currently own an OptaSense Interrogator Unit
    - Have an existing dedicated DAS fiber array (grid) installed on campus in Golden, CO

- Several Reclamation internal field sites have also expressed their interest in the technology

Conclusions

Based upon the literature and technology review performed as a part of this scoping-level research project, it is apparent that DAS could be applied to monitor various facilities and components in Reclamation's infrastructure inventory to help identify locations of defects/damage/deterioration in a far more efficient and spatially comprehensive fashion compared to typical sensing techniques currently used (e.g. spot-checking conditions via standard geophysical techniques, visual inspections, or drilling/coring programs).

While there is still much to learn on the practical limitations of DAS for large infrastructure assessment efforts, DAS offers promise as a means to interrogate and monitor large structures for changes in performance and structural health, and tracking structural properties and dynamic processes in a far more comprehensive fashion. This would by far surpass current seismic data collection and damage/deterioration detection and mapping production rates, would add value of information obtained from field exploration efforts, and would likely drastically improve the benefit/cost ratios of operational and maintenance efforts conducted by Reclamation and other stakeholders.

In addition to lab-based testing and development of analysis techniques, subsequent research efforts could immediately incorporate data collection at large structures, adding value to the results obtained. At a minimum, DAS technology could provide a means to rapidly categorize and prioritize large numbers of structures/components within Reclamation's inventory for subsequent inspection and/or repair efforts. Furthermore, this technology could be extended to long-term (repeated) monitoring and change-detection at a given structure.

Several DAS Interrogator Units are available for rental or purchase, with off-the-shelf and integrated data acquisition and analysis software available. Additionally, interested research partners already own or have access to Interrogator Units and DAS fiber arrays. OptaSense Inc., Colorado School of Mines researchers, Sandia National Laboratory researchers, and USACE researchers have all voiced interest in supporting and partnering on future conducting-level DAS research initiatives.

Recommendations for Next Steps

The primary recommendation stemming from this scoping level effort is to support continuation of DAS research by funding subsequent conducting-level research activities.
Specific recommendations for next steps include the following:

1. Conduct various lab-based tests with engineered targets or controlled testing facilities
2. Further develop data collection techniques and analysis and modeling software to provide quantitative material and defect properties (e.g., elastic moduli estimation) in manual and/or continuous scanning modes of data collection.
3. Assess DAS sensitivity to various infrastructure failure modes, types of damage, and material property variations
4. Assess the limits of sensitivity and resolution of DAS in active and passive seismic experiments
5. Install a large dedicated DAS fiber array at a field test site to enable further testing and development of high-resolutions seismic imaging workflows directly applicable to Reclamation's needs.
6. Identify field-scale structures that are candidates for installation of DAS and carry out large-scale imaging and monitoring on select structure(s).

References

Advanced Photonic Sensing (AP Sensing), 2020. Geo- and Hydrological Applications; Fiber Optic Sensing for Geophysical Problems, overview website: https://www.apsensing.com/application/geo-hydrological-applications, Date Accessed 7/15/2020.

Ajo-Franklin, J. B., S. Dou, N. J. Lindsey, I. Monga, C. Tracy, M. Robertson, V. R. Tribaldos, C. Ulrich, B. Freifeld, T. Daley, and X. Li, 2019. Distributed acoustic sensing using dark fiber for near-surface characterization and broadband seismic event detection: Scientific Reports, 9, 1328, doi: https://doi.org/10.1038/s41598-018-36675-8.

Chalenski, D., M., Tatanova, Y., Du, A., Mateeva, J., Lopez, and H., Potters, 2016. Climbing the staircase of ultralow-cost 4D monitoring of deepwater fields using DAS-VSP. 86th Annual International Meeting, SEG, Expanded Abstracts, 5441–5445.

Chambers, K., (2020). What is DAS and What is it Measuring?, Motion Signal Technologies Website, Available at https://motionsignaltechnologies.com/what-is-das-and-what-is-it-measuring/, Date Accessed 6/20/2020.

Costley, R.D., G., Galan-Comas, K., Hathaway, S., Ketcham, and C., Kirkendall, 2018. Distributed acoustic sensing for near-surface seismic applications. The Journal of the Acoustical Society of America. 144. 1702-1703. 10.1121/1.5067562.

Costley, R.D., G., Galan-Comas, C.K., Kirkendall, J.E., Simms, K.K., Hathaway, M.W., Parker, S.A., Ketcham, E.W., Smith, W.R., Folks, T.W., Milburn, and H.M., Wadman, 2018. Spectral Analysis of Surface Waves with Simultaneous Fiber Optic Distributed Acoustic Sensing and Vertical Geophones. Journal of Environmental and Engineering Geophysics. 23. 183-195. 10.2113/JEEG23.2.183.

Costley, R.D., G., Galan-Comas, C.K., Kirkendall, S.A., Ketcham, M.W., Parker, W.L., Folks, K., Kent, K.K., Hathaway, and E.W., Smith, 2016. On the Repeatability and Coherence of Fiber Sensors. *Proceedings of the Joint Meeting of the Military Sensing Symposia Specialty Group on Battlespace Acoustic, Seismic, Magnet, and Electric-Field Sensing and Signatures*, (June 2016).

Dean, T., A., Hartog, T., Cuny, and F., Englich, 2016. The Effects of Pulse Width on Fibre-optic Distributed Vibration Sensing Data. 10.3997/2214-4609.201600684.

Dou, S., J., Ajo-Franklin, T., Daley, M., Robertson, T., Wood, B., Freifeld, et al. 2016. Surface orbital vibrator (SOV) and fiber-optic DAS: field demonstration of economical, continuous-land seismic timelapse monitoring from the Australian CO2CRC Otway site. 86th Annual International Meeting, SEG, Expanded Abstracts, 5552–5556.

Dou, S., N. Lindsey, A.M., Wagner, T.M., Daley, B., Freifeld, M., Robertson, J., Peterson, C., Ulrich, E.R., Martin, and J.B., Ajo-Franklin, 2017. Distributed Acoustic Sensing for Seismic

Monitoring of The Near Surface: A Traffic-Noise Interferometry Case Study, Sci Rep 7, 11620 (2017). https://doi.org/10.1038/s41598-017-11986-4

Esra, A., 2019. SEISMIC ARRAYS FOR THE IMAGING OF ALLUVIAL DEPOSITS AND MONITORING ENGINEERING SYSTEMS, Masters Thesis, UNIVERSITY OF WISCONSIN – MADISON, available at https://minds.wisconsin.edu/handle/1793/79317

Fang, G., Y.E., Li, , Y., Zhao, and E.R., Martin, 2020. Urban near-surface seismic monitoring using distributed acoustic sensing. Geophysical Research Letters, 47, e2019GL086115. https://doi.org/10.1029/2019GL086115

Fiber Completion Services (FCS), 2020. Distributed Acoustic Sensing Systems, technique overview website: https://fibrecompletions.com/distributed-acoustic-sensing-das/, Date Accessed 4/31/2020.

Glaser, D., R.D., Costley, K., Hathaway, G., Boitnott, and J., Weale, 2019. Snow Coupled Distributed Acoustic Sensing for Intrusion Detection of Polar Bears in Arctic Camps. 10.13140/RG.2.2.28022.75848.

Hartog, A., 1983. A Distributed Temperature Sensor Based on Liquid-Core Optical Fibers, Journal of Lightwave Technology, 1(3), 498–509. DOI: 10.1109/JLT.1983.1072146.

Hawk Measurement Systems, 2020. Praetorian Fiber Optic Sensing Pipeline Monitoring, Leak Detection System, product overview website: https://www.hawkmeasurement.com/assets/products/literature/e_Praetorian_FOS_Pipeline_Brochure_v1.44_1.pdf, Date Accessed 7/15/2020.

Jakkampudi, S., J., Shen, W., Li, A., Dev, T., Zhu, E. R., Martin, 2020. Footstep detection in urban seismic data with a convolutional neural network, The Leading Edge, 10.1190/tle39090654.1, 39, 9, (654-660).

Jolivet, V., P., Gueguen, C., Michel, and A., Schveitzer, 2008. ON THE FULL SCALE DYNAMIC BEHAVIOUR OF RC-BUILDINGS USING COHERENT LASER RADAR VIBROMETER. The 14th World Conference on Earthquake Engineering. Beijing, China.

Lellouch, A., S., Horne, M.A., Meadows, S., Farris, T., Nemeth, and B., Biondi, 2019. DAS observations and modeling of perforation-induced guided waves in a shale reservoir. The Leading Edge ; 38 (11): 858–864. doi: https://doi.org/10.1190/tle38110858.1

Li, X., T., Parker, M., Farhadiroushan, and D., Blacklaw, 2004. Evaluating a Concept of Using Distributed Optical Fiber Temperature and Strain Sensor for Continuous Monitoring of Casing and Completion Mechanical Deformation in Intelligent Wells, Paper OTC-16285 presented at the Offshore Technology Conference, Houston, Texas, USA, 3–6 May. DOI: 10.4043/16285-MS.

Liang, S., X., Zhao, R., Liu, X., Zhang, L., Wang, X., Zhang, Y., Lv, and F., Meng, 2019. Fiber-Optic Auditory Nerve of Ground in the Suburb: For Traffic Flow Monitoring, IEEE Access, 10.1109/ACCESS.2019.2952999, 7, (166704-166710).

Lindsey, N., 2020, IRIS Webinar, January 28, 2020. Available at: https://www.youtube.com/watch?v=Q2XyMu_3fqY&list=PLD4D607C2FA317E6D&index=17, Date Accessed 4/30/2020.

Lindsey N. J., E. R., Martin, D.S., Dreger, B., Freifeld, S., Cole, S. R., James, B. L., Biondi, and J. B., Ajo-Franklin, 2017. Fiber-optic network observations of earthquake wavefields. Geophysical Research Letters, 44, 11,792–11,799. https://doi.org/10.1002/2017GL075722

Lindsey, N.J., S. Yuan, A., Lellouch, L., Gualtieri, T., Lecocq, and B., Biondi, 2020. City-Scale Dark Fiber DAS Measurements of Infrastructure Use During the COVID-19 Pandemic, Geophysical Research Letters, 10.1029/2020GL089931, 47, 16.

Lindsey, N.J., T.C., Dawe, and J.B. Ajo-Franklin, 2019. Illuminating seafloor faults and ocean dynamics with dark fiber distributed acoustic sensing, Science, 10.1126/science.aay5881, 366, 6469, (1103-1107).

Luo, B., W., Trainor-Guitton, E., Bozdağ, L., LaFlame, S., Cole, and M., Karrenbach, 2020. Horizontally orthogonal distributed acoustic sensing array for earthquake- and ambient-noise-based multichannel analysis of surface waves, Geophysical Journal International, 10.1093/gji/ggaa293, 222, 3, (2147-2161).

Mateeva A., J., Mestayer, B., Cox, D., Kiyashchenko, P., Wills, J., Lopez, et al., 2012. Advances in distributed acoustic sensing (DAS) for VSP. 82nd Annual International Meeting, SEG, Expanded Abstracts, 1–5.

Mateeva A., J., Lopez, J., Mestayer, P., Wills, B., Cox, D., Kiyashchenko, et al., 2013. Distributed acoustic sensing for reservoir monitoring with VSP. The Leading Edge 32, 1278–1283.

Naldrett, G., C. Cerrahoglu, and V. Mahue, 2018. Production Monitoring Using Next-Generation Distributed Sensing Systems, PETROPHYSICS, 59, 4; 496–510; DOI: 10.30632/PJV59V4-2018a5

Ning, I.L.C., and P. Sava, 2018. High-resolution multi-component distributed acoustic sensing, Geophysical Prospecting, 66, 1111–1122, doi: 10.1111/1365-2478.12634.

OptaSense, 2020a. DAS Technology Overview webinar and verbal communications. 4/31/2020.

OptaSense, 2020b. PLEXUS INTERROGATOR UNIT, product overview website: https://www.optasense.com/technology/plexus/, Date Accessed 4/31/2020.

Peterson, D., A., Meyer, K., Dunn, S., Vecherin, D., Glaser, R.D. Costley, A., Wheeler, B., Jones, E., Dunn, and M., Moran, 2020. Improving detection of acoustic sources by coiling fiber optic cable, Proc. SPIE 11418, Detection and Sensing of Mines, Explosive Objects, and Obscured Targets XXV, 114180B (24 April 2020); https://doi.org/10.1117/12.2559133

Planès, T., J.B., Rittgers, M.A., Mooney, W., Kanning, D., Draganov, 2017. Monitoring the tidal response of a sea levee with ambient seismic noise, Journal of Applied Geophysics, Volume 138, Pages 255-263, ISSN 0926-9851, https://doi.org/10.1016/j.jappgeo.2017.01.025.

Seismological Society of America (SSA), 2019. Seismologists see future in fiber optic cables as earthquake sensors. *Science Daily*. Available at: www.sciencedaily.com/releases/2019/12/191204113223.htm, Date Accessed September 21, 2020.

SSA, 2020. Fiber Optics Capture Seismic Signatures of the Rose Parade, News , Journals, 6 May, 2020. Available at: https://www.seismosoc.org/news/fiber-optics-capture-seismic-signatures-of-the-rose-parade/, Date Accessed 7/12/2020.

Shanafield, M., E.W., Banks, J.W., Arkwright, and M.B., Hausner, 2018. Fiber-Optic Sensing for Environmental Applications: Where We Have Come From and What Is Possible, Water Resources Research, 10.1029/2018WR022768, 54, 11, (8552-8557).

Shatalin, S., V.N., Treschikov, and A.J., Rogers, 1998. Interferometeric Optical Time-Domain ReÀ ectometry for Distributed Optical-Fiber Sensing, Applied Optics, 37(24), 5600–5604. DOI: 10.1364/AO.37.005600.

Shragge, J., J., Yang, N.A., Issa, M., Roelens, M., Dentith, and S., Schediwy, 2019. Low-frequency ambient Distributed Acoustic Sensing (DAS): Useful for subsurface investigation?, SEG Technical Program Expanded Abstracts : 963-967. https://doi.org/10.1190/segam2019-3216479.1

Smolen, J., and A., van der Spek, 2003. Distributed Temperature Sensing: A DTS Primer for Oil and Gas Production, Shell International Exploration and Production (SIEP), publication EP 2003-7100.

Snieder, R., and E. Shafak, 2006. Extracting the building response using seismic interferometry; theory and application to the Millikan library in Pasadena, California: Bull. Seismol. Soc. Am., 96, 586-598.

Spikes, K.T., N., Tisato, T.E., Hess, and J.W., Holt, 2019. Comparison of geophone and surface-deployed distributed acoustic sensing seismic data, GEOPHYSICS, VOL. 84, NO. 2 (MARCH-APRIL 2019); P. A25–A29, 10.1190/GEO2018-0528.1.

Trainor-Guitton, W., A., Guitton, S., Jreij, H., Powers, and B., Sullivan, 2019. 3D Imaging of Geothermal Faults from a Vertical DAS Fiber at Brady Hot Spring, NV USA, Energies, 10.3390/en12071401, 12, 7, (1401).

Wang, H., X., Zeng, D.E., Miller, D., Fratta, K.L., Feigl, C.H., Thurber, and R.J., Mellors,2018. Ground motion response to an ML 4.3 earthquake using co-located distributed acoustic sensing and seismometer arrays, Geophysical Journal International, 10.1093/gji/ggy102, 213, 3, (2020-2036).

Wikipedia, 2020. Distributed acoustic sensing overview website: https://en.wikipedia.org/wiki/Distributed_acoustic_sensing#Strain_resolution, Date Accessed 9/11/2020.

Wu, H., W.F., Wong, Z., Yang, P., Wills, J., Lopez, Y., Li, et al., 2015. Dual-well 3D vertical seismic profile enabled by distributed acoustic sensing in deepwater Gulf of Mexico. Interpretation 3, SW11–SW25.

Yuan, Q., F., Wang, T., Liu, Y., Liu, Y., Zhang, Z., Zhong, and X., Zhang, 2019. Compensating for influence of laser-frequency-drift in phase-sensitive OTDR with twice differential method, Optics Express, 10.1364/OE.27.003664, 27, 3, (3664).

Yuan, S., A., Lellouch, R.G., Clapp, and B., Biondi, 2020. Near-surface characterization using a roadside distributed acoustic sensing array, The Leading Edge, 10.1190/tle39090646.1, 39, 9, (646-653).

Zhan, Z., (2019). Distributed Acoustic Sensing Turns Fiber-Optic Cables into Sensitive Seismic Antennas. Seismological Research Letters; DOI: 10.1785/0220190112

Zhang, Z., M., Alajami, and T., Alkhalifah, 2020. Wave-equation dispersion spectrum inversion for near-surface characterization using fibre-optics acquisition, Geophysical Journal International, 10.1093/gji/ggaa211, 222, 2, (907-918).

Zhu, T., and D.J., Stensrud, 2019. Characterizing Thunder-Induced Ground Motions Using Fiber-Optic Distributed Acoustic Sensing Array, Journal of Geophysical Research: Atmospheres, 124, 23, (12810-12823), https://doi.org/10.1029/2019JD031453