Overview of the Stanford DAS Array-1 (SDASA-1)

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ABSTRACT

Permanent dense seismic arrays are costly to install and maintain using traditional point sensors. Fiber optic Distributed Acoustic Sensing (DAS) arrays show promise as a low-cost alternative that can be left in place with thousands of sensors run by a single power source. However, the trenching process used in some surface DAS arrays can be costly and logistically prohibitive in some cases. To mitigate these issues, we designed an experiment to investigate the potential for fibers in slim holes underground, with an eye towards repurposing existing telecommunications infrastructure. Our experiment has three primary goals: ambient noise interferometry, earthquake detection, and recording active seismic shooting. In August 2016, 2.4 km of fiber optic cable was deployed in a two-dimensional array in existing telecommunications conduits underneath the Stanford University campus. This array has been continuously recording since Sep. 3, 2016, and is planned to continue for at least one year in the current configuration, known as the "Stanford DAS Array-1" or SDASA-1.

INTRODUCTION

Over the past decade, Distributed Acoustic Sensing (DAS) has become increasingly popular in the oil and gas industry for time-lapse and continuous monitoring, both for seismic event detection and imaging. DAS provides some advantages over other acquisition systems. Consider that as a traditional array of point sensors contains more sensors, the probability of having a number of sensors broken or out of power grows. But with a DAS array, there's a single power source to maintain. Each point sensor costs more than a channel of fiber optic cable. While the startup cost of a single DAS channel may be higher, the scalability to thousands of permanent sensors is much better. Additionally, fiber's flexibility means that a DAS interrogator unit may be plugged into a fiber run just under the surface as an array, then that same fiber may continue to run down the well(s) providing full field monitoring coverage throughout all stages of production. Furthermore, other types of laser interrogators may be plugged into either the same fiber or other fibers in the same bundle for information about other properties: temperature, static strain, potentially chemical composition.

The majority of work has been on using fibers in wells, but the same benefits of DAS have also led to multiple experiments on the use of DAS arrays buried in shallow trenches, both for active (Dou et al., 2016), (Kendall, 2014) and passive experiments (Ajo-Franklin et al., 2015), (Martin et al., 2016), (Zeng et al., 2017). Compared to trenching, telecommunications companies have found that the installation of slim boreholes within a few meters under the surface is often a more cost effective choice. In areas with soil contaminants or permafrost, it requires less environmental risk. In urban or suburban areas, trenching may simply not be logistically possible, and there are often existing conduits underground previously installed for telecommunications fibers.

Using existing conduits can greatly reduce the cost of installing an array if one is willing to be constrained by existing conduit geometry. There are currently two ways to take advantage of existing conduits and/or fibers: (i) run a new cable in the empty space in those conduits, or (ii) plug into an unused fiber, called "dark fiber" in an existing bundle. For this experiment, we pursued option (i) so that we could more easily choose our conduit geometry without requiring fiber splices between distinct existing cables.

This report serves as an overview of the array and observations during the first 7 months of recording. First, we describe the array geometry and design process with respect to the angular sensitivity of DAS, then we describe the method for assigning spatial points to distances along the fiber given uncertainties in the instalation. We show some examples of a variety of noises and events recorded by the array and the spectral response of the array and heterogeneities in the background noise field throughout the site and over time. This is an incredibly versatile data set. We have only begun to scratch the surface with our analyses in other reports, so we provide a list of open questions that might be answered using these data.

ARRAY DESIGN AND GEOMETRY

After discussions with Stanford IT, we decided it would be more cost effective for us to run a new fiber in the existing telecomm conduits rather than splicing leftover fibers from multiple bundles together. If we had been willing to go with a more linear array design, or if we were in a different town with a different cost structure for installation work, this decision might have changed. This array was installed in the same way that all other fiber optic cables are installed in telecommunications conduits around campus. The fibers were spooled up and brought down into manholes, then pulled either by hand or with a machine along narrow (10-15 cm wide) conduits connected between the manholes. The fibers sit loosely in the conduits, and where they are inside manholes (small underground rooms roughly 8 feet high and 3-4 ft by 6-9 ft wide) the fibers are zip-tied to a bracket on the side of the wall. There were two locations with 150 feet of fiber spooled up and strapped to the wall (with a vertical and horizontal component): one at Campus Dr. and Via Ortega, and another just south of Allen on Via Pueblo.

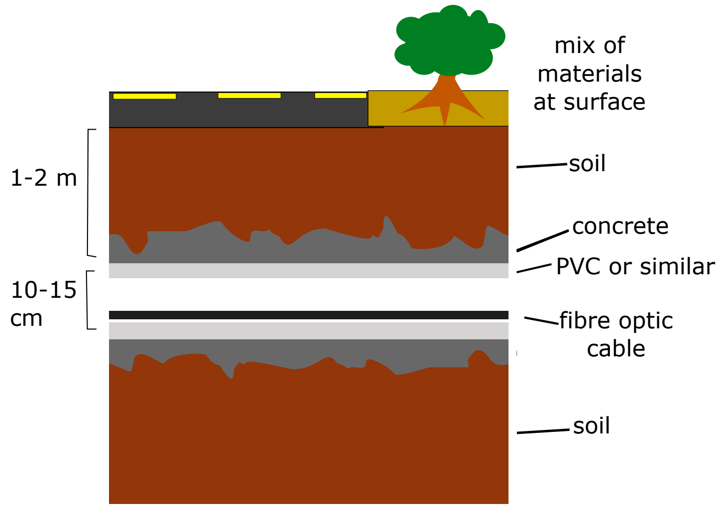


Figure 1: The campus has a mix of near surface materials, both natural and manmade. One to two meters below the surface sit conduits for telecommunications. These are generally 10-15 cm in diameter, and usually made of PVC or similar materials, and in some parts of campus are surrounded by concrete or cement slurry before being buried. Our fiber optic cable is roughly 1 cm in diameter and rests in the conduits loosely. [**NR**]

Because a straight segment of fiber is only sensitive to extensional strain along its length, DAS has less sensitivity to plane waves at an angle than geophones (Mateeva et al., 2012) ($\cos^2(\theta)$ versus $\cos(\theta)$ for a planar P-wave), and no sensitivity to broadside waves. This is one of the biggest limitations of DAS, so we designed our array to include fibers in two orthogonal directions to have some sensitivity to waves in all angles as seen in Figure 2.

The array has two recording modes currently configured: active and passive.

- **Active** mode records 2500 samples per second at a gauge length of 7.14 m and channel spacing of 1.02 m.
- **Passive** mode records 50 samples per second at a gauge length of 7.14 m and channel spacing of 8.16 m.

Note that the gauge length is the length of the subset of fiber over which average strains are reported. The vast majority of the time, the array is recording in passive mode so as to keep the data size manageable. When we do active tests (including geometry calibration tap tests), we switch to active recording mode. The switch between these two configured modes can be handled remotely and no physical access to the box is required after installation. Although their gauge length is the same,

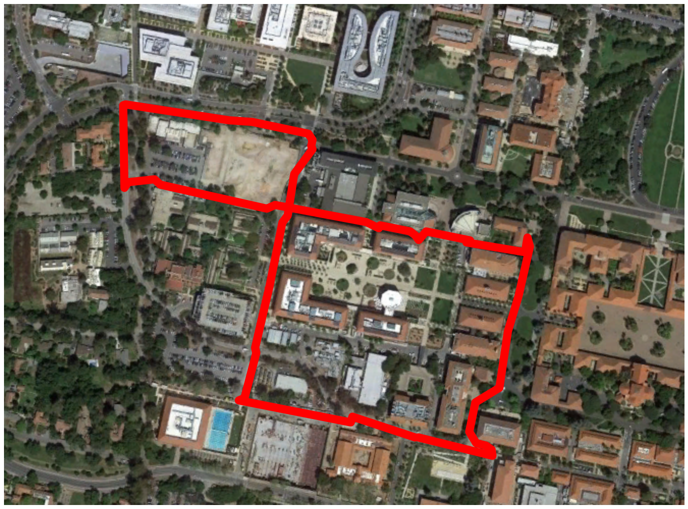


Figure 2: The layout of the fiber following telecommunications conduits overlaid on the map. The longest linear section is roughly 600 meters wide. Some deviations from straight lines had to occur due to existing conduit geometry constraints. [**NR**]

the active mode data can have more options to add together neighboring channels to simulate a variety of gauge lengths (and thus, a variety of wavenumber sensitivity profiles, which can be beneficial). An example of a recording without any active shots but recorded in active mode can be seen in Figure 3. There is generally energy in anthropogenic frequency ranges rolling along from the northeast to the southwest, possibly coming from the town of Palo Alto, or from Highway 101, but this needs to be further investigated.

ARRAY LOCATION CALIBRATION

Unfortunately, there is currently no easy way to tie the data recorded on each channel to specific spatial locations without some manual labor. Stanford IT provided us with a scale map of manhole locations along our path, so we used many of these points for calibration. The channels in manholes tended to have poorer coupling since the fiber was strung partially along the side of a wall instead of sitting on the bottom of the conduit with gravity assisting it. We also did many sledgehammer tests, as well as a few betsy gun shots. Both types of tests can be seen in Figure 4a and 4b. We recorded these in active mode, so we had to scale distances by roughly a factor of 8 for the passive channel points. Additionally, we used the change in angle of waves coming in to the array as an indicator of array angle changes. An example of the kinds of passive noise revealing array geometry can be seen in Figure 3.

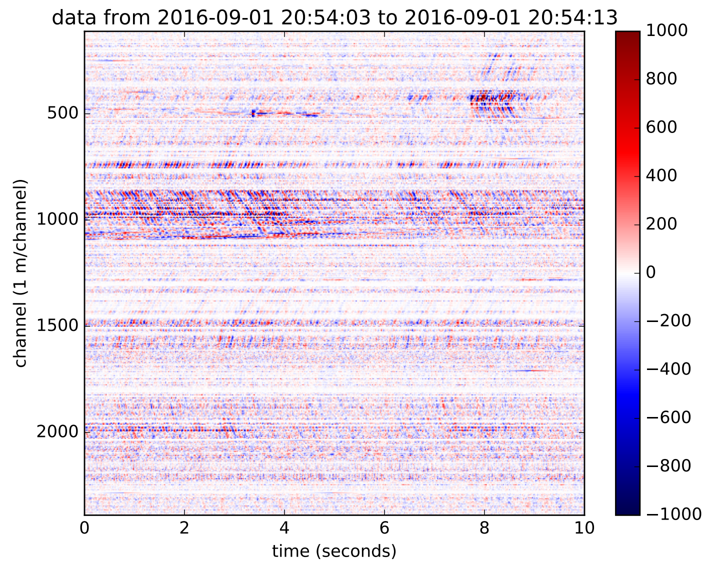
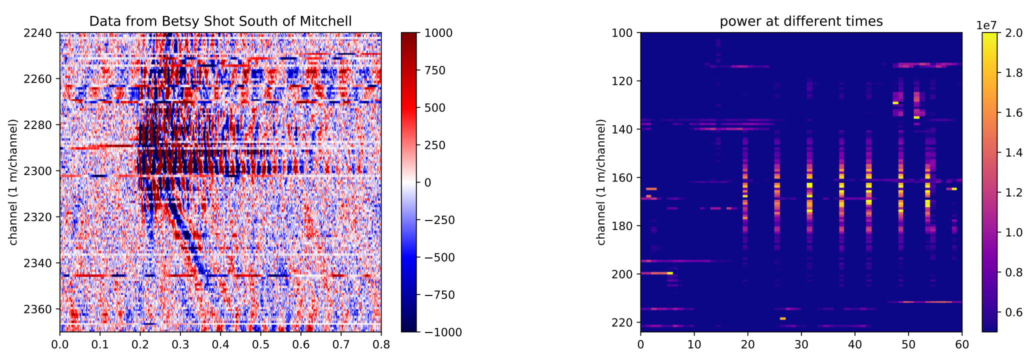


Figure 3: An example of 10 seconds of data recorded in active mode but without any controlled active sources. Active channels 400-500 are near a construction zone for Roble Parking Garage, which may explain the bump at 7-9 seconds. Active channels 800-1100 are around the area following Campus Dr. which gets quite a bit of vehicle traffic. [**CR**]



(a) (b)

Figure 4: (Left) A betsy gun shot south of Mitchell on 2016-10-04 as recorded on channels 2240 to 2370 in active recording mode starting 1016-10-04 12:57:42.2 UTC. (Right) The power of small windows of time on each channel during 8 lbs. sledgehammer tests west of Green Building from 2016-10-04 from 12:36:43 to 12:45:42 UTC. [**CR**]

Label	Channel Number	East UTM	North UTM
Start S. of Green	14	573088.0	4142497.0
Between Roble & HEPL	25	573000.58	4142531.35
Arrillaga Corner Start	48	572851.00	4142560.00
Arrillaga Corner End	49	572851.00	4142560.0
Via Ortega & Panama	58	572871.35	4142626.52
Via Ortega By Y2E2	70	572889.00	4142710.00
Via Ortega & Via Pueblo NS	83	572920.19	4142817.00
NW Corner of Allen	96	572961.29	4142909.74
Campus Dr. Coil Start	100	572942.64	4142936.69
Campus Dr. Coil End	107	572942.64	4142936.69
Panama & Campus	138	572694.11	4142985.43
Panama Near Pine	155	572693.26	4142866.36
Panama Curve Start	157	572695.88	4142872.24
Panama Curve End	165	572736.10	4142875.45
NW Corner of Pine	167	572740.38	4142868.55
Via Ortega & Via Pueblo EW	184	572922.4	4142826.52
Coil by Allen Start	203	573047.61	4142791.85
Coil by Allen End	209	573047.61	4142791.85
S of Hewlett Start	225	573172.14	4142767.36
S of Hewlett End	228	573172.14	4142767.36
Sequoia Jog Start	240	573249.00	4142746.00
Sequoia Jog Top	245	573258.00	4142770.00
Moore	261	573221.45	4142639.24
Bike Racks By Skilling	269	573205.43	4142563.1
NW Corner of Mitchell	274	573173.9	4142544.07
W Side of Mitchell	280	573161.0	4142501.0
S of Mitchell Start	283	573188.0	4142468.0
S of Mitchell End	288	573188.0	4142468.0
End S. of Green	302	573088.84	4142497.62

Table 1: List of physical points used to compare signals from particular channels to geometric locations

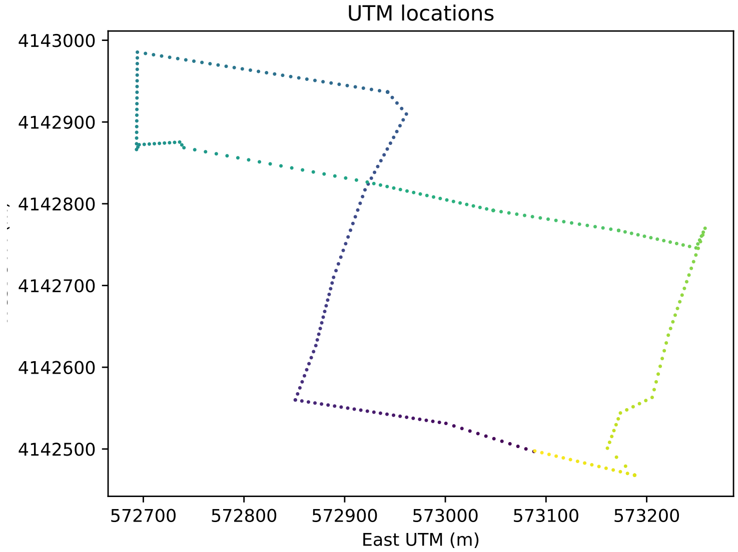


Figure 5: After including calibration points from Table 1, the center of each channel is marked in UTM coordinates without projection. [**ER**]

SPECTRA

We often look at strain rate of the data, rather than the strain, by taking a forward difference in time for each channel. In large part, this is because the spectrum of each channel (a temporal derivative of a spatial derivative of displacement in the fiber direction) more closely matches spectra recorded by geophones, which measure velocities (a temporal derivative of displacement). Also, as seen in Figures 6a, 6b, 6c, 6d, the spectrum of the strain is so dominated by low frequencies that it is very difficult, even on a log scale, to visualize anthropogenic noise.

LIST OF ACTIVE RECORDING PERIODS

Some active recording periods of interest (in UTC time) include:

- Between 2016-08-30 23:00 and 2016-08-31 00:30, active recording of mid-afternoon mallet tests near a few manholes
- Between 2016-09-01 10:10 and 20:50, active recording of early afternoon Dropatron 5000 (a weight drop source designed by OptaSense) tests
- Between 2016-09-01 23:50 and 2016-09-02 00:30, passive recording of mid-afternoon Dropatron 5000 tests
- Between 2016-10-04 12:00 and 14:00, active recording of one betsy gun shot south of Mitchell as well as two mallet tests

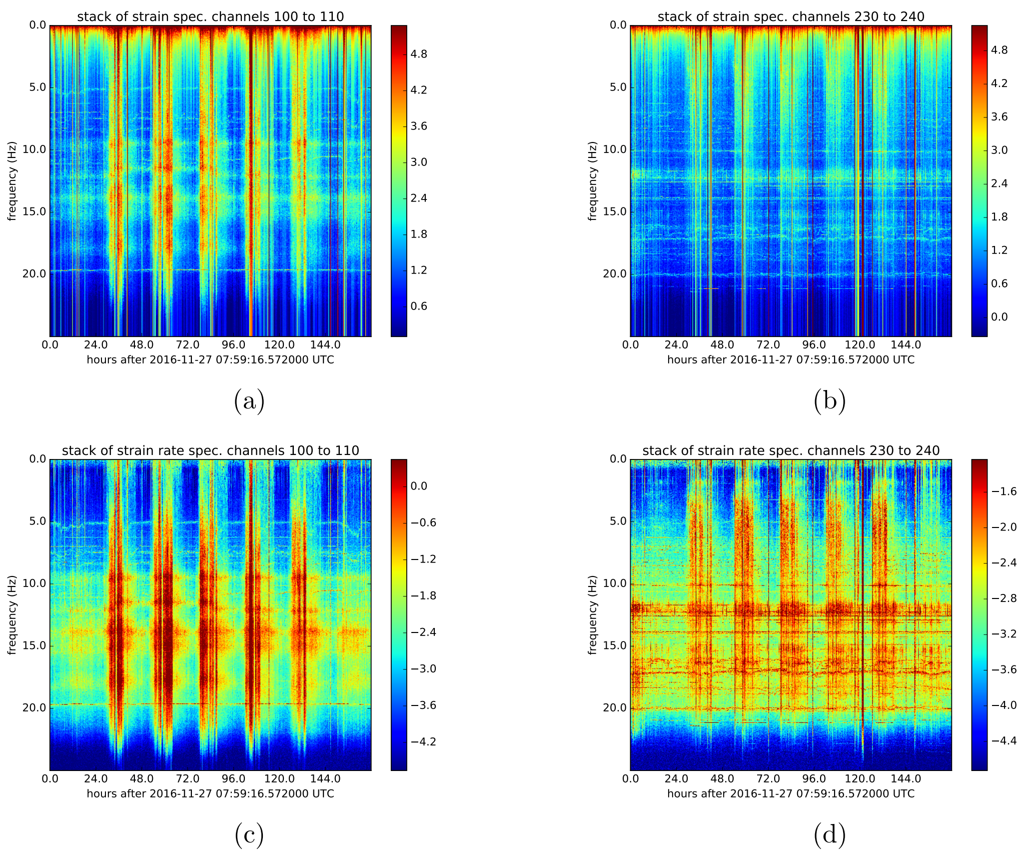


Figure 6: One week worth of the log of the average spectrum of the (top) strain and (bottom) strain rates of channels every 10 minutes (left) 100 to 110 and (right) 230 to 240. Channels 100 to 110 are along Campus Drive, and 230 to 240 are on Via Pueblo close to its intersection with Lomita Mall. [**CR**]

- Between 2016-10-06 15:00 and 16:10, active recording during mallet tests on Lomita Mall and around Mitchell
- Between 2017-01-16 13:30 and 15:20, active recording during multiple betsy shots over a few blocks south of Mitchell
- Between 2017-03-18 18:00 and 2017-03-20 23:00, off-and-on active recording during multiple tests using 500+ sledgehammer hits and several dozen betsy gun shots, also concurrently recorded by a line of three-component nodes

DISCUSSION AND FUTURE WORK

Motivated by the successes of DAS in trenched arrays (Kendall, 2014), (Ajo-Franklin et al., 2015), (Martin et al., 2016), (Dou et al., 2016), (Lindsey et al., 2016), (Zeng et al., 2017), we have been collecting a multi-purpose data set testing the utility of DAS in telecommunications conduits. We have been testing it for ambient noise interferometry (Martin et al., 2017a), earthquake detection (Biondi et al., 2017), and active seismic survey recording (Martin et al., 2017b). We plan to publicly archive around ten earthquake recordings from the array in an IRIS assembled data set. We also plan to pull shots from the continuous recordings of the DAS array and 3C node array from the weekend of 2017-03-18, an experiment aimed at imaging the Stock Farm Monocline and comparing the two systems to improve our understanding of how to quantitatively use DAS. As described in (Huot et al., 2017), we are investigating methods to automatically aide geophysicists in exploring the noise field with the goal of quickly identifying potential calibration points and speeding up the process of developing ambient noise pre-processing.

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