PROCEEDINGS, 46th Workshop on Geothermal Reservoir Engineering
Stanford University, Stanford, California, February 16-18, 2021
SGP-TR-218

Seismic Monitoring of the Sacramento Basin Using Dark Fiber and Distributed Acoustic Sensing (DAS)

Dennise Templeton[1], Christina Morency[1], Eric Matzel[1], Emily Maher[1], and Jonathan Ajo-Franklin[2]

[1] Lawrence Livermore National Laboratory, Livermore, CA USA

[2] Rice University, Houston, TX USA

templeton4@llnl.gov

Keywords: Microseismicity, seismicity, fiber, virtual seismometer method, distributed acoustic sensing, DAS

ABSTRACT

We use a pre-existing fiber optic cable, previously installed as part of a telecommunication network that is currently not in use (so resource called dark fiber) and distributed acoustic sensing (DAS) techniques to develop seismic processing approaches to identify and map local microseismic events within the Sacramento Basin. We use this high-density passive seismic dataset to investigate the optimal pre-processing strategies and techniques to identify small natural tectonic events recorded by the fiber while excluding the more common anthropogenic seismic sources, such as cars driving along highways. We further evaluate the virtual seismometer method (VSM), which is a seismic interferometric technique that is very sensitive to the source parameters (location, mechanism and magnitude) and to the earth structure in the source region. VSM provides a precise estimate of the Green's function between two seismic sources by cross-correlating waveforms generated by each source and recorded at the same geophones. Here, we will demonstrate the capability of VSM using fiber datasets. The ultimate aim here is to transform this type of data collection and processing techniques into products useful for basin-scale geothermal system characterization and subsurface mapping.

1. INTRODUCTION

The overall objective of the project is to use dark fiber optic cables for basin scale geothermal exploration, where dark fiber refers to fiber optic cables that have been previously installed as part of a general telecommunication network, but which are currently not being used for data transmission. There are currently tens of thousands of kilometers of fiber optic cables available for lease or purchase within the US. These existing cables can be used as high-spatial-resolution sensors to measure the strain along the fiber at almost the meter scale as seismic waves or temperature fluctuations perturb the fiber over time. In this way we can use existing resources, in this case the telecommunication fiber, for a new application, seismic monitoring.

To this dark fiber resource, we are applying the DAS technique which uses pulses of light that are continuously transmitted down the fiber optic cable. The backscattered light that is returned when these light pulses interact with the natural imperfections within the fiber cable itself can be measured. When the fiber is stretched or contracted, the reflected light pulses change their pattern. These changes can be measured by an interrogator unit, which is connected to the fiber, and then converted to strain, or strain rate, in the direction of the fiber. We can then use this information to detect seismic events.

We describe the application of advanced microseismic techniques to the Sacramento Basin DAS experiment. This experiment consisted of 27 km of fiber stretching from West Sacramento, CA to Woodland, CA (Ajo-Franklin et al., 2019). Data was available between July 28, 2017 to January 18, 2018. A Silixa iDAS interrogator was used and data was collected at 500 Hz. The channels spacing was 2 m with a 10 m gauge length. A portion of the fiber of located near the busy I-5 interstate highway, so anthropogenic noise was a factor of concern especially since it is known that the Sacramento Basin is tectonically quiet with relatively few natural seismic events. Due to the pandemic, LLNL only had easy access to 15 days of data from Sacramento Basin experiment spanning between September 22, 2017 to February 15, 2018. To this dataset we investigated optimal processing routines for the analysis of local microearthquakes and applied the virtual seismometer method (VSM) to this dataset by creating synthetic waveforms of two known events recorded by both the fiber array and a nearby network of geophones.

2. PASSIVE SEISMIC ANALYSIS

We first explored optimal processing approaches for detecting both anthropogenic and natural seismic events recorded on the Sacramento DAS dataset, based on the observed frequency distribution of the seismic events. The objective was to identify a processing approach that would enhance the seismic signals of interest. The seismic processing consisted of reading in the tdms files, removing the mean and trend of the data, performing a stack of neighboring traces, removing the mean and trend again, and then performing a second stack of the data. We optionally filtered the data after the second stacking. When stacking, we iterated between 1 – 15 stations in the first stack and 1 – 3 stations in the second stack, with the goal of stacking events within a similar horizontal distance for each iteration. Stacks were either conducted as a median stack or as a linear (average) stack.

Results showed that, for larger amplitude events, the order and type of stack could does not obscure the original event. For example, for one particular anthropogenic seismic event we applied a 15 median stack for the first stack and a 1 median stack for the second stack (in this case essentially having only one stacking phase) and compared it to resulting waveforms from applying a 5 linear stack for the first stack and a 3 linear stack for the second stack (Figure 1). The event was clearly identifiable regardless of the pre-processing steps.

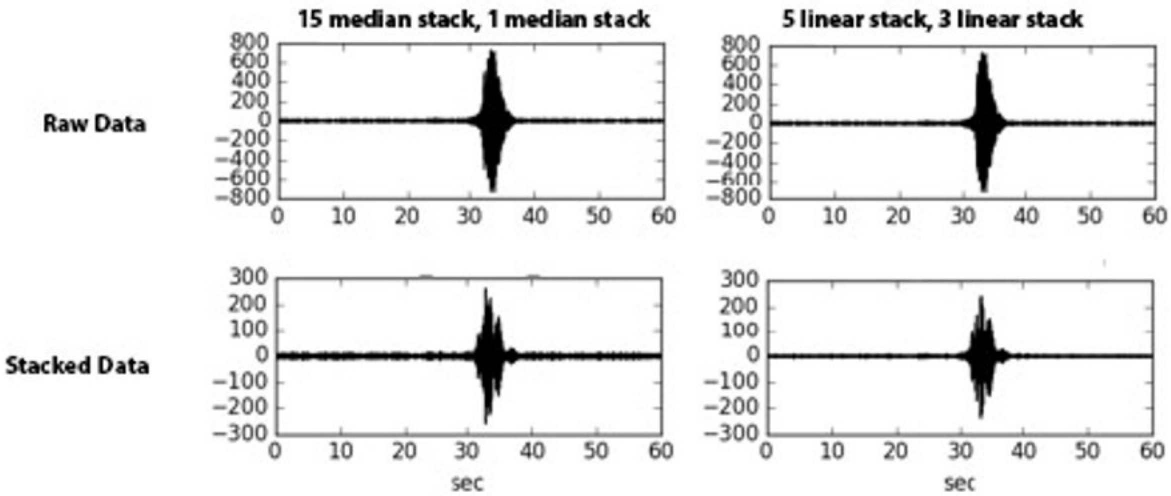

Figure 1: Comparison of raw and stacked data of larger amplitude anthropogenic seismic event using two different stacking methodologies. The order and type of stack does not obscure the original event.

For small amplitude events however, the order and type of stack could either enhance or obscure the original event. For example, for one particular anthropogenic seismic event we first applied a 15 median stack for the first stack and a 1 median stack for the second stack and compared it to resulting waveforms from applying a 5 linear stack for the first stack and a 3 linear stack for the second stack (Figure 2). The event was either enhanced or obscured depending on the pre-processing steps. Unfortunately, after a thorough analysis of several small amplitude anthropogenic events and two small amplitude tectonic events, we determined that there was no single type of pre-processing scheme that consistently enhanced all seismic signals using the current methodology.

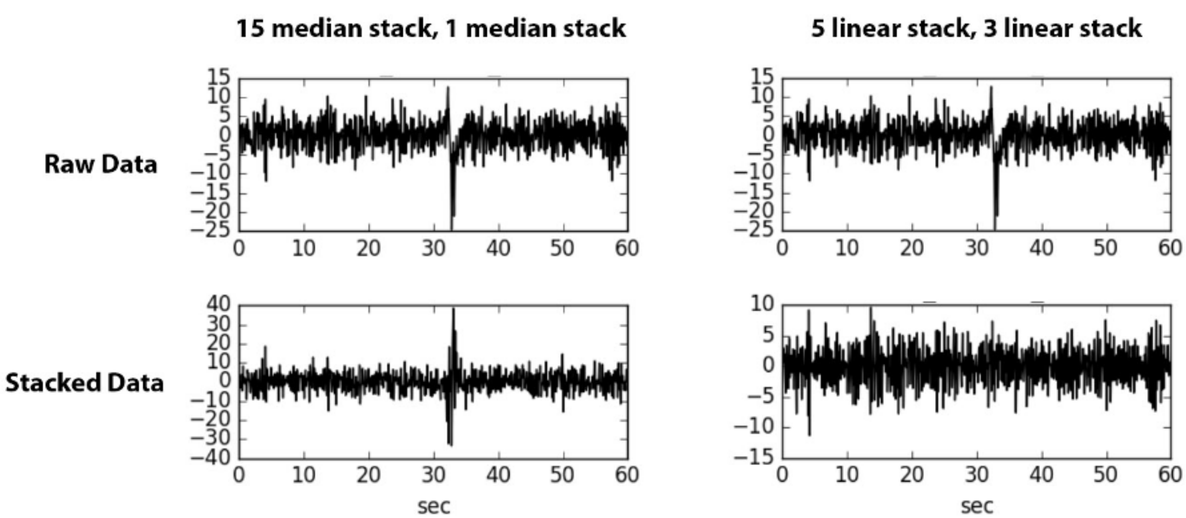

Figure 2: Comparison of raw and stacked data of smaller amplitude anthropogenic seismic event using two different stacking methodologies. The order and type of stack can either enhance or obscure the original event.

Larger magnitude regional events and seismic signals associated with vehicle traffic are clearly and easily identifiable on the DAS dataset. In the 15-day dataset that LLNL investigated, only two local events were identified to have occurred in this tectonically quiet environment. One is shown in Figure 3.

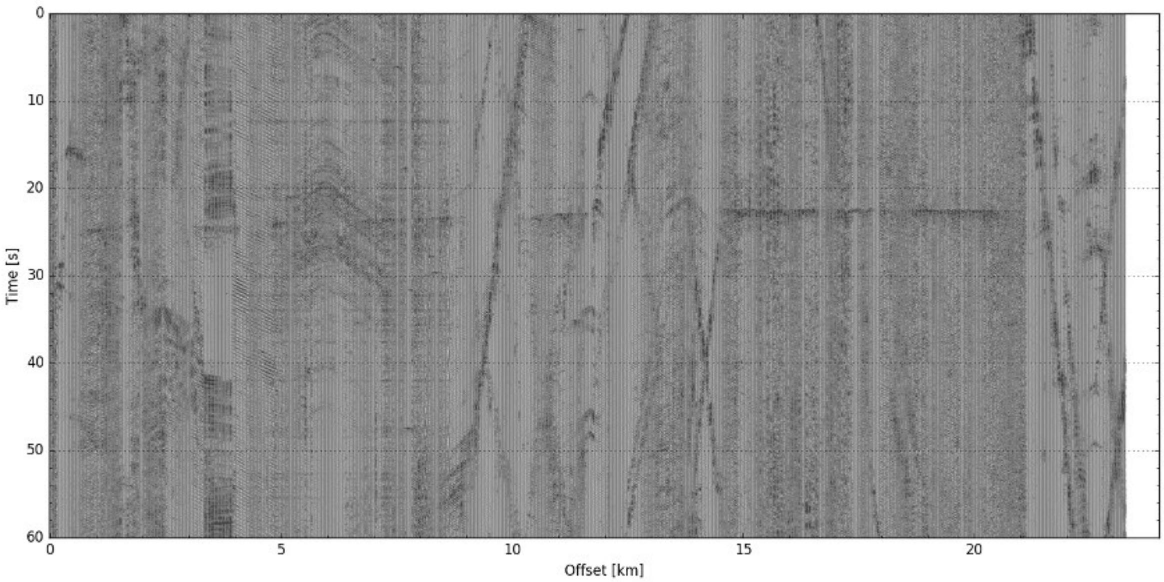

Figure 3: DAS data showing the arrival of a local event. The start of the event can be seen on all channels at approximately 25 seconds after the start of the record.

3. VIRTUAL SEISMOMETER METHOD

The VSM uses the reciprocity principle to essentially turn each earthquake into a virtual seismometer which can record the earthquake signals of events around it (Curtis et al., 2009). We can then (1) use these virtual seismometers to invert for the moment tensor of these events, thereby obtaining information on an earthquake's strength and fault orientation, and (2) directly use the Green's function along the path between events to invert for local physical properties. Here we test our implementation of VSM by creating synthetic waveforms of two known events in the Gulf of Mexico (Figure 4) recorded by a network of geophones as well as the fiber array (Ajo-Franklin et al., 2019) located in the Sacramento area (Figure 5).

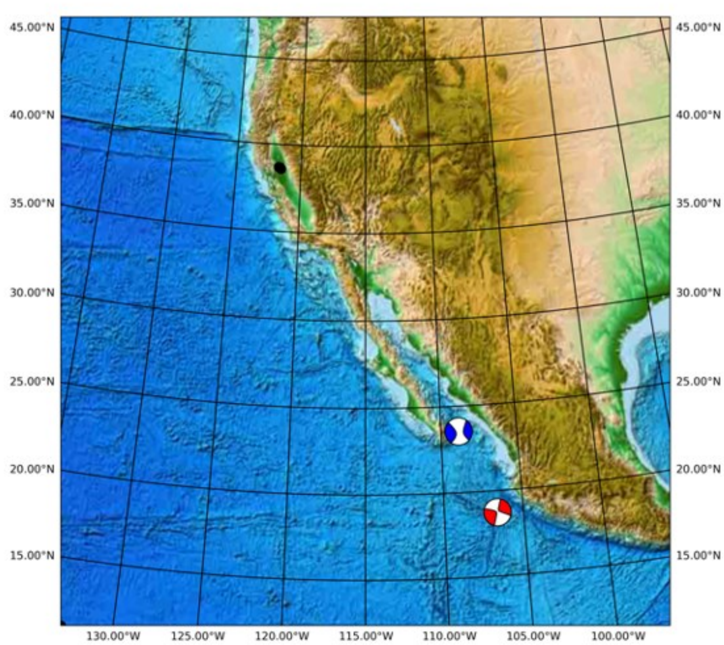

Figure 4: Location of the fiber array is plotted as a black dot. Location and focal mechanism of the M5.6 2017-Sept-22 Gulf of California (blue, which will be used as our virtual seismometer (VS)) event and M5.7 2017-Nov-03 Off Coast of Jalisco, Mexico (red, which will be used as the recorded target) event are displayed.

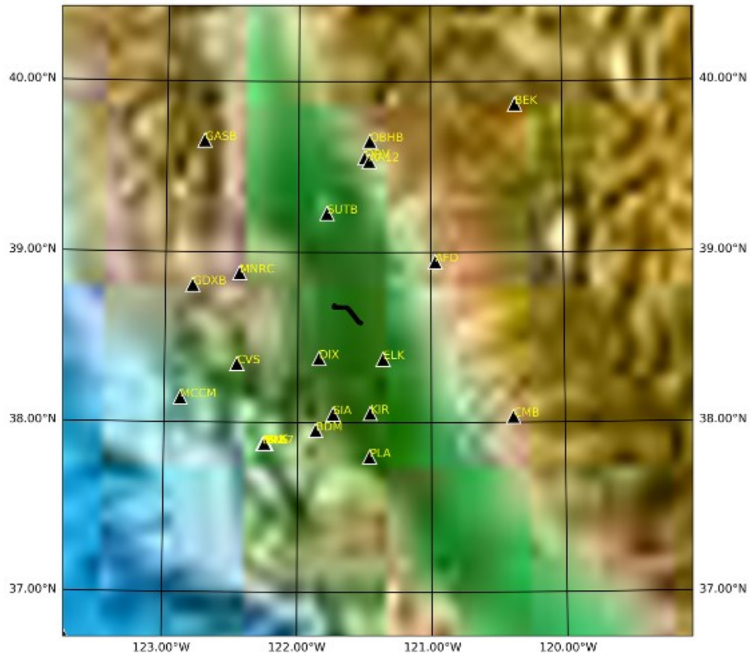

Figure 5: Zoomed into the Sacramento area, showing the geophone network (triangles) and fiber array (black line).

The open source SPECFEM3D_GLOBE is used for forward full seismic wave calculations. Outputs consist of both displacements and strain tensors. To mimic the fiber strain dataset, we wrote a Perl script to project the output strain tensor from each fiber channel onto the fiber direction. Figure 6 shows a good comparison between fiber and collocated geophone waveforms for both events, which we consider as validation of our script used to derive fiber strain data.

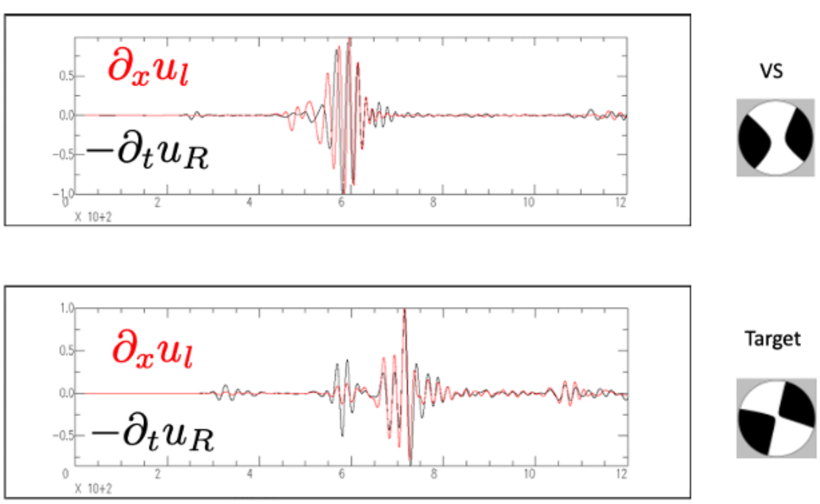

Figure 6: Collocated geophone (radial velocity in black) and derived fiber (in red) signals show good agreement for the target event and virtual seismometer (VS). Normalized waveforms were filtered between 20-100s.

VSM, as originally introduced by Curtis et al. (2009), uses ground motion recorded at geophones. First, as summarized on Figure 6, using Curtis et al. classical approach, we show the calculated waveform of the virtual seismometer (red), using the two synthetic event waveforms recorded at the geophones network from Figure 5, and compare it with a synthetic calculation of what a waveform would look like if we actually had a seismometer at depth (black). We see that the arrival times and phases look similar for both the virtual seismometer and the modeled synthetic. In the future, we plan to try to decrease the amplitude differences between the two by focusing on specific seismic phases instead of the entire waveform as we have done here. Nevertheless, these comparisons show good agreements.

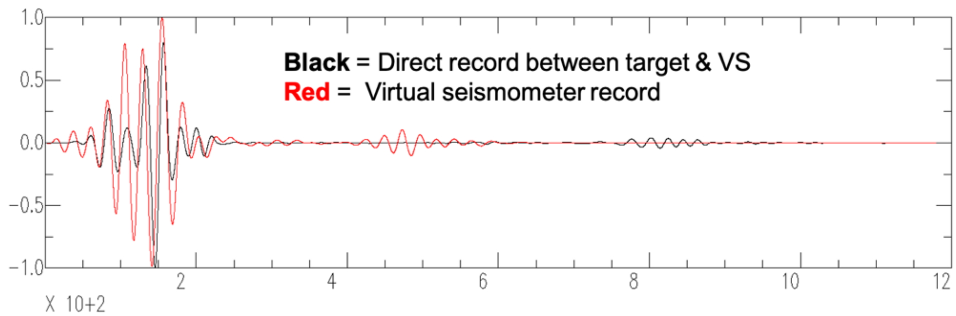

Figure 7: Comparison of calculated waveform of the virtual seismometer (red), using the two synthetic event waveforms recorded at the geophones network from Figure 5, and a synthetic calculation of what a waveform would look like if we actually had a seismometer at depth (black).

Next, we modify the VSM mathematical relation derived by Curtis et al. (2009) based on ground velocities recorded at geophones to strains, using the relationship between ground velocity and strain derived by e.g., Wang et al. (2018). We then repeat the same comparison than Figure 7, but this time using calculated waveform of the virtual seismometer (red) using the two synthetic event waveforms recorded at the fiber. Results displayed in Figure 8 show good agreements as well.

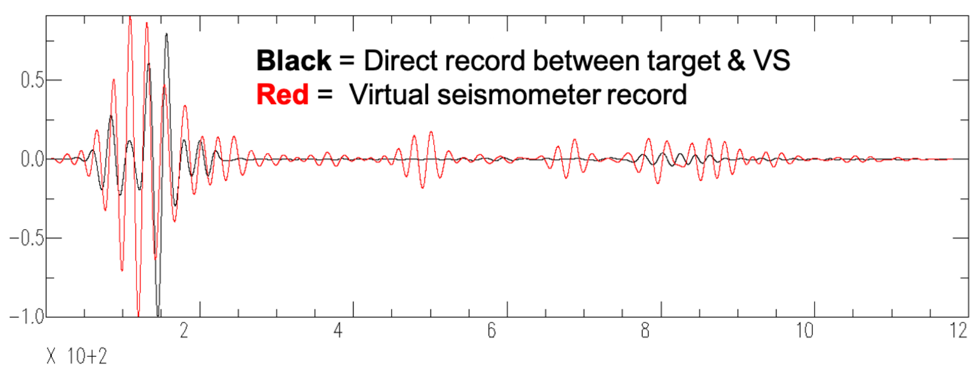

Figure 8: Comparison of calculated waveform of the virtual seismometer (red), using the two synthetic event waveforms recorded at the fiber array from Figure 5, and a synthetic calculation of what a waveform would look like if we actually had a seismometer at depth (black).

4. CONCLUSIONS

Processing approaches for microearthquake analysis to enhance observed signals performed well for larger magnitude events. For smaller magnitude events however, processing approaches, specifically stacking variants, produced inconsistent results, with some approaches obscuring rather than enhancing the seismic signals. We tested the VSM calculation synthetically for teleseismic events. This allowed us to validate the mathematical expression of VSM, initially derived by Curtis et al. (2009) using ground velocity, specifically for a fiber strain dataset.

AUSPICES AND DISCLAIMER

This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344. This document was prepared as an account of work sponsored by an agency of the United States government. Neither the United States government nor Lawrence Livermore National Security, LLC, nor any of their employees makes any warranty, expressed or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States government or Lawrence Livermore National Security, LLC. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States government or Lawrence Livermore National Security, LLC, and shall not be used for advertising or product endorsement purposes.

REFERENCES

Ajo-Franklin, J.B., S. Dou, N. J. Lindsey, I. Monga, C. Tracy, M. Robertson, V. Rodriguez Tribaldos, C. Ulrich, B. Frifield, 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.

Curtis, A., H. Nicolson, D. Halliday, J. Trampert, and B. Baptie (2009). Virtual Seismometers in the Subsurface of the Earth from Seismic Interferometry, *Nature Geoscience*, 2, 700 - 704.

Wang, C.T., and Horne, R.N.: Boiling Flow in a Horizontal Fracture, *Geothermics*, **29**, (1999), 759-772.

Wang, H.F., X. Zeng, D.E. Miller, D. Fratta, K.L. Feigl, C.H. Thurber, 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*, 213, 2020-2036.