Applying interferometry to ambient seismic noise recorded by a trenched distributed acoustic sensing array

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ABSTRACT

We deployed a shallow trenched distributed acoustic sensing (DAS) array consisting of multiple fiber optic cables and casings to assess the suitability of DAS to recording ambient noise for near-surface characterization. We briefly describe the acquisition of an ambient noise dataset, our processing workflow, and preliminary results of interferometry on a small data subset. The approximate virtual source responses show reasonable Rayleigh wave velocity estimates compared to geophones. The results of several types of cable casings are comparable, which is encouraging for surveys deployed in conditions requiring durable materials. We show coherent virtual source responses at a relatively high frequency range and short recording period relative to most passive seismic surveys.

INTRODUCTION

DAS uses a standard fiber optic cable as both a strain rate sensor and a means of transmitting data to a storage array. A laser probes the cable with a pulse the length of a channel (in our experiments 1 m), then optical Rayleigh backscattering is recorded (Daley et al., 2013). Modifications of the optical time-domain reflectometry (OTDR) technique are used to convert the optical backscattering profile into acoustic traces associated with each 1 m channel. Refer to Bakku (2015) for more details on DAS.

DAS is becoming more popular due to its low cost per sensor, its dense spatial sampling, the potential for flexible geometries, and the possibility of deployment in situations that would be prohibitive for traditional sensors (Mateeva et al., 2013). Its limitations include noise spikes, directional sensitivity, and power loss along long cables. DAS only detects strain changes in-line with the cable. Additionally, the method for generating acoustic traces acts as a spatial derivative, leading to a $\cos^2 \theta$ sensitivity to plane waves at an angle θ with the cable. This increased directionality has been verified experimentally with active sources for both surface DAS arrays (Lancelle et al., 2014) and borehole deployments (Mateeva et al., 2012; Ajo-Franklin et al., 2014).

Most DAS surveys in the literature use cables deployed in wells and active sources. DAS has been used to passively record microseismic events in a reservoir (Webster et al., 2013). The detection and analysis of active sources and microseismic events is quite different from the use of interferometry on ambient microseismic noise. Ambient noise interferometry is a powerful and cost effective technique that shows promise for characterizing the near surface (Wapenaar et al., 2006; Bensen et al., 2007; Chang et al., 2014; de Ridder, 2014).

We present a novel survey designed as a pilot study on the suitability of DAS to ambient noise studies, particularly for applications requiring low-cost continuous monitoring of the near surface.

SURVEY DESIGN

We deployed a trenched DAS array made up of several types of fiber optic cables and recorded data using a Silixa iDAS interrogator unit at the Richmond Field Station (RFS) in Richmond, CA, as shown in Figure 1. We also deployed a helical cable, but only present the results of the straight cables here. The trenches were approximately 2 ft. deep and all cables were laid flat along the bottom before the trench was backfilled. Along the east-west trench, we installed 24 three-component geophones at approximately 3 m spacing for comparison purposes. Further details of the deployment are described in Ajo-Franklin et al. (2015).

Sensitivity analysis of DAS with respect to incoming plane wave angle and frequency shows survey design greatly influences the information detected. This survey was oriented to detect Rayleigh waves produced by noise sources including a nearby road and railway. The DAS data presented here were recorded at 2 kHz, and the geophone data were recorded at 1 kHz.

AMBIENT DAS DATA

As seen in Figures 2 and 3, the raw traces from a DAS channel and a geophone show some clear differences. There are differences in frequency sensitivity of DAS and geophones. An obvious difference is the presence of spikes in the DAS traces, a known issue in DAS data (Bakku et al., 2014). There are coherent events during some periods due to the presence of nearby large trucks and train tracks.

Although we expected the response of all channels to be relatively uniform, we observed significant variation both in trace noise and time-varying gather noise. We are continuing to investigate the source of this variation. Channels were normalized against each other by scaling by the 1-norm of each trace.

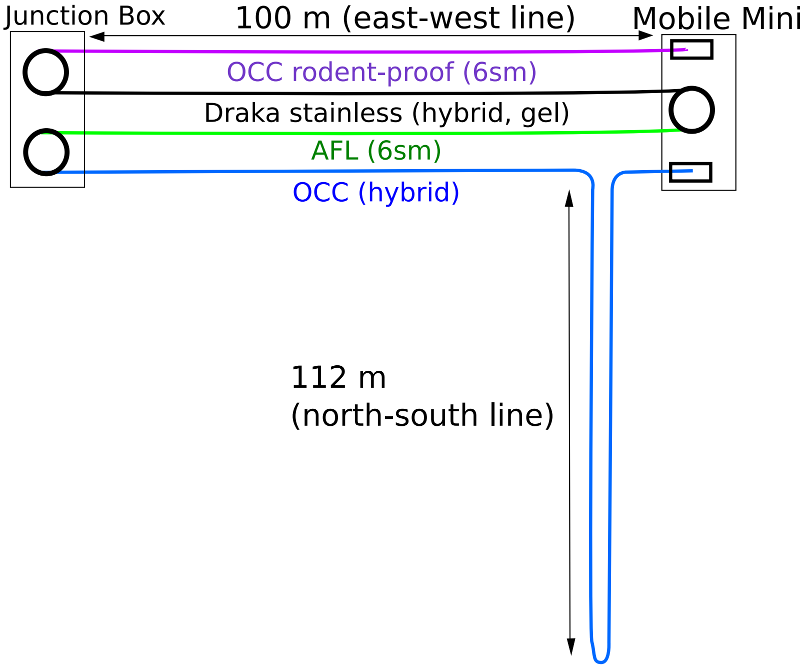


Figure 1: The trenched DAS survey at Richmond Field Station. We tested four types of straight fiber optic cable spliced end to end. The control unit and recording system are in the Mobile Mini. The cables pictured are: OCC hybrid 6 sm (blue), AFL 6 sm (green), Draka stainless-steel encased hybrid (black), and OCC rodent-proof 6 sm (purple). [**NR**]

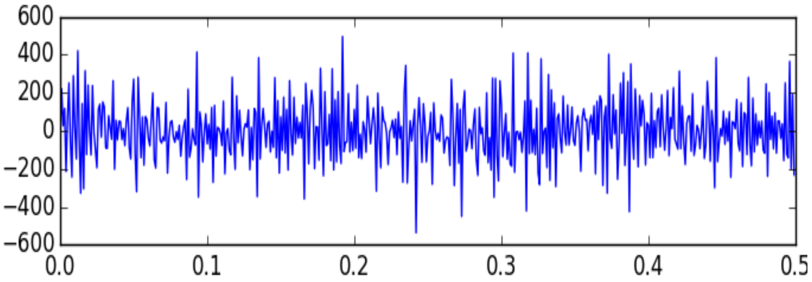


Figure 2: A raw ambient noise trace from the east end of the survey at channel 370 of the hybrid OCC cable. The DAS traces are recorded in DAS units so this is on a different scale from geophone traces. [**ER**]

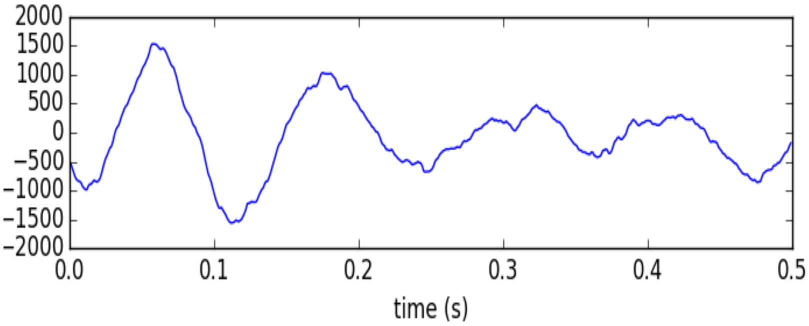


Figure 3: A raw ambient noise trace from the east end of the survey collected by the in-line component of a geophone. [**ER**]

PROCESSING WORKFLOW

For these initial results, we modified the standard ambient seismic noise interferometry workflow (Bensen et al., 2007) as seen in Figure 4. Despiking eliminates data points with absolute value more than twice the median absolute value in a small window (Bakku et al., 2014). Whitening boosts the magnitude of the spectrum up to a threshold chosen to be the median magnitude in the frequency band of interest.

Geophones and DAS measure different physical quantities, so we did not expect the raw geophone and DAS traces to look the same, even after filtering. The estimators of virtual source responses (result of cross-correlations) are also not expected to look the same, but we hope to have some qualitative similarities between the DAS and geophone cross-correlations, particularly in the kinematics of observed events. In the final step of the processing workflow we hope to have dispersion curves revealing somewhat similar velocities. For each virtual source, the cross-correlation of the one minute windows are weighted by the inverse of the energy of the source (sum of the squared entries of the trace) then stacked.

VIRTUAL SOURCE RESPONSES FROM DAS

After the preprocessing described in Figure 4 has been completed, we cross-correlate channels along the same side of the array. This is done for each channel, and the cross-correlations of each channel with every other channel serve as an estimator for the response to a virtual source located at that channel.

In Figures 5(a) and 5(b) we see the approximate response functions for 10 minute stacks of cross-correlations with a virtual source at the southern end of the hybrid OCC cable. We show this for two frequency ranges. In many ambient noise interferometry studies, a much longer recording time is needed to generate coherent virtual source response estimators, but these data were recorded in a particularly noisy area which contributed favorably to the convergence of the response estimators. There

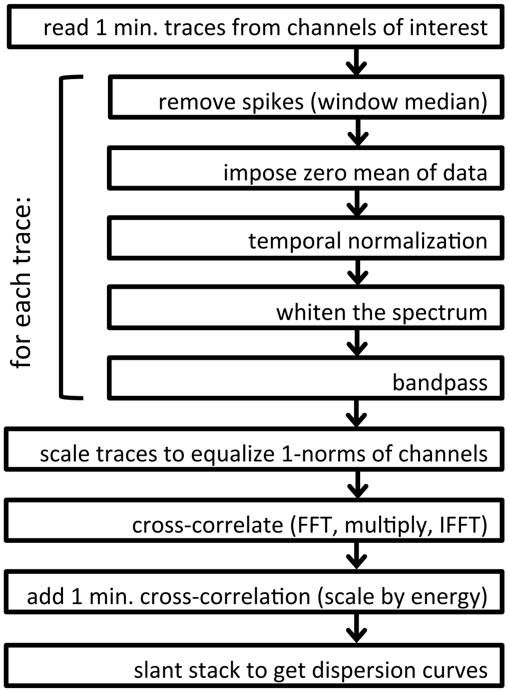
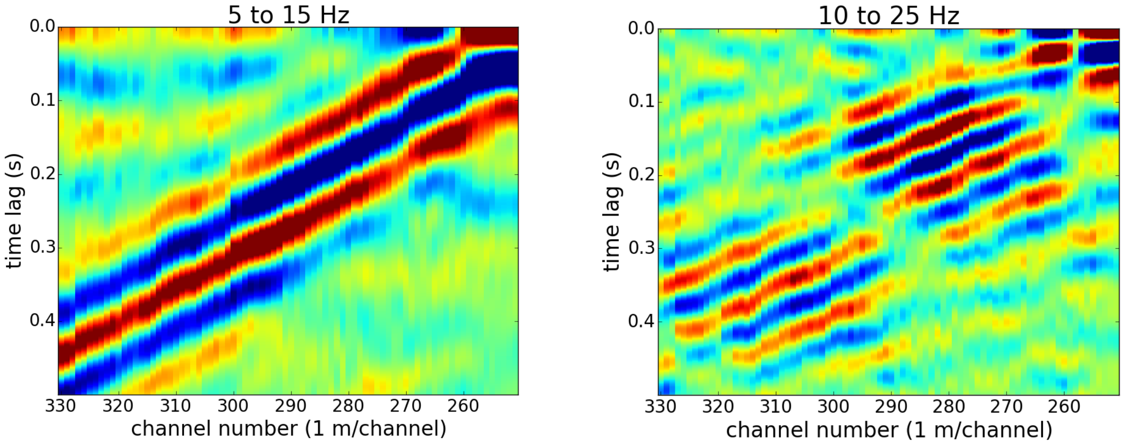
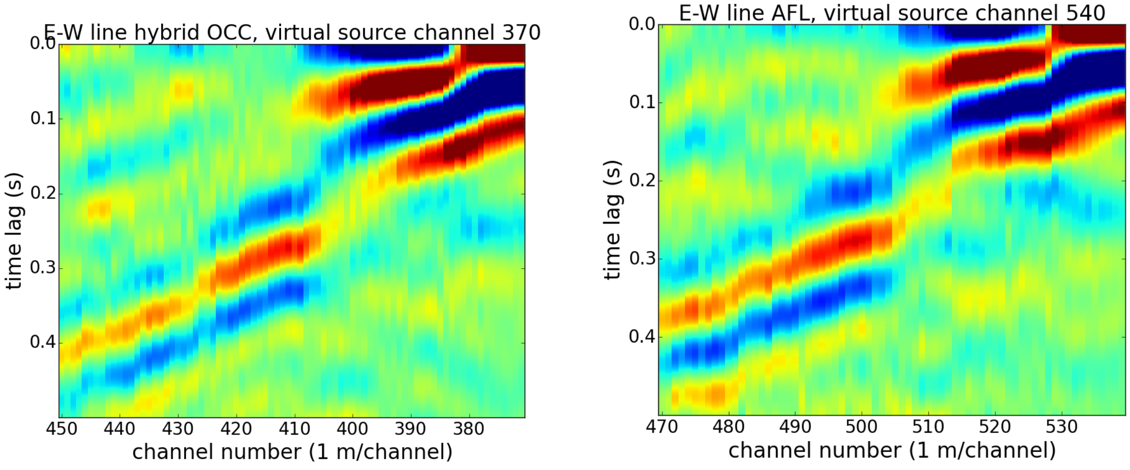


Figure 4: Our processing workflow is similar to the standard ambient seismic noise workflow. Despiking is necessary for DAS data. [**NR**]



(a) (b)

Figure 5: Approximate virtual source responses from 10 minutes of data along the north-south hybrid OCC cable (cross-correlations with channel 250). The frequency ranges pictured are 5-15 Hz (left), 10-25 Hz (right). Positive and negative time lags are folded. [**ER**]



(a) (b)

Figure 6: The estimated response to a virtual source at channel 370 on the east end of the east-west line of the hybrid OCC cable (left), and at channel 540 on the east end of the AFL cable (right). The frequency range pictured is 5-15 Hz, and this uses 10 minutes of ambient noise data. [**ER**]

is little naturally occurring noise above the 20 Hz range, making it more difficult to pick a velocity from cross-correlations resulting from a short recording period. The response estimators show a dominant Rayleigh wave velocity between 200 and 400 m/s.

As seen in Figures 5(a), 5(b) and 6(a), the virtual source response approximations of both the north-south and east-west lines of the hybrid OCC cable show reasonable Rayleigh wave velocities. We expect different portions of the survey to display some variations in virtual sources response. It is promising that both trenches (north-south and east-west) can detect noise sources well enough to yield coherent virtual source responses, and that both the OCC hybrid and AFL cable show similar results.

DAS AND GEOPHONE COMPARISON

We deployed 24 three-component geophones at approximately 3 m spacing along the east-west trench, and analyzed the in-line components. Using the workflow from Figure 4 (except for the despiking step), we cross-correlated the in-line horizontal components of the geophones to estimate virtual source responses. The results in the 5-15 Hz frequency band for DAS channels and a geophone on the eastern end of the E-W line are shown in Figures 6(a) and 7, respectively. They appear qualitatively similar, although there are noticeable differences.

The geophone cross-correlations look rough in comparison to the DAS cross-correlations. Even when these virtual source responses contain higher frequency

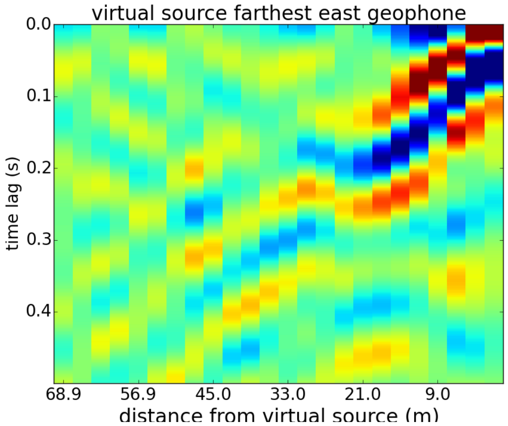


Figure 7: Cross-correlations of 40 minutes of ambient recording representing a virtual source from the eastern-most geophone's in-line component from 5-15 Hz. This is comparable to the cross-correlations from nearby DAS channels in Figure 6(a). [**ER**]

information, the virtual source response estimates look very smooth compared to geophones. This is likely because the traces are calculated as a difference over a gauge length (about 10 m), which in theory could cause a spatial spreading of any virtual source response estimates. Further analysis and data integration is needed to conclude whether these data reveal the same Rayleigh wave speed. The velocities appear to be in approximately the same range.

CONCLUSIONS

We deployed a novel survey design, a trenched DAS array to record ambient seismic noise. We developed a processing workflow to estimate virtual source responses using ambient noise interferometry. Using a small subset of the recorded ambient noise, this workflow resulted in estimated virtual source responses that showed Rayleigh wave velocities between 200 and 400 m/s for the frequency bands from 5-25 Hz. Compared to most passive seismic surveys, this is a relatively high frequency range.

The results presented here are the early analysis of a pilot test towards a system for low-cost continuous monitoring of the near surface. We aim to incorporate more data to estimate virtual source responses with more certainty, and to conduct statistical analyses to understand uncertainties and convergence. Although interferometry revealed reasonable results for Rayleigh wave velocities, the directional sensitivity of DAS effectively modifies a theoretical assumption justifying the use of interferometry. In particular, the theory assumes that random vibration sources are uniformly distributed around the receiver, but DAS is unable to detect vibrations perpendicular to the cable. Further theoretical work is needed to support the use of ambient noise interferometry on DAS data in a general context. In Summer 2015 we look forward to a larger scale deployment in Alaska, where we hope to image permafrost regions in the subsurface.

ACKNOWLEDGEMENTS

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