Continuous Subsurface Monitoring by Passive Seismic with Distributed Acoustic Sensors - The“Stanford Array” Experiment

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Abstract

Continuous seismic monitoring can be a crucial tool to optimize hydrocarbon production as well as to provide early warning of potentially hazardous conditions developing in the subsurface. However, the cost of continuous monitoring is a significant obstacle to its widespread application. Distributed Acoustic Sensors (DAS) recording systems hold the promise to enable the recording of seismic data at much lower cost. We deployed a 2.45 km long DAS array with 610 virtual receivers under Stanford University campus and started to record passive seismic data continuously in September 2016. Preliminary analysis show that the data recorded by our DAS array can be used to monitor dynamic processes in the subsurface thanks to sufficient sensitivity to low-amplitude wavefields in the frequency band between .5 and 10 Hz. Our conclusion is supported by the coherency and the frequency content of recorded events corresponding to teleseismic and regional earthquakes as well as of the virtual sources synthesized by using interferometry.

Introduction

Continuous seismic monitoring can be a crucial tool to optimize hydrocarbon production as well as to provide early warning of potentially hazardous conditions developing in the subsurface. However, the cost of continuous monitoring is a significant obstacle to its widespread application. Permanent installation of geophones, at the seabed offshore or buried below near-surface heterogeneities onshore, can be extremely expensive. Distributed Acoustic Sensors (DAS) recording systems hold the promise to enable the recording of seismic data at much lower cost. Chalenski et al. (2016) have demonstrated effective monitoring by VSP-DAS data. Land-based DAS monitoring by trenched or cemented fibre-optic cables have also been presented, as for example by Martin et al. (2016). Our “Stanford DAS Array” experiment aims at studying the feasibility of using a DAS array that record data using a fibre-optic cable “free-floating” in a PVC conduit buried in the ground. Coupling between the fibre cable and the surrounding rocks relies exclusively on gravity and friction. This recording configuration could deliver huge savings by enabling the exploitation of existing infrastructure developed for telecommunication purposes (like in our experiment) and/or enabling the use of ad-hoc inexpensive “slim-holes” with PVC casing buried sufficiently deep to bypass the nearsurface and avoid degradation of the recorded data caused by near-surface scattering and attenuation.

The frequent deployment of active seismic sources is another substantial cost of permanent monitoring. Therefore, in our experiment we focus on the possibilities of extracting useful information on dynamic processes in the subsurface by passive seismic recording. We investigate the capability of the DAS system to record low-intensity seismic events in and/or around the reservoir by analysing teleseismic and local earthquakes that are also recorded by a nearby conventional broadband seismic station. Finally, we plan to image the near surface by using interferometry applied to seismic noise generated by both natural sources (the coast line is about 22 km away) and anthropogenic sources. Brenguier et al. (2014) demonstrated the feasibility of subsurface monitoring by interferometry using a sparse seismological array; de Ridder and Biondi (2103) demonstrated that changes in the subsurface could be measured by using a dense industry-type array and traveltime tomography applied to the “virtual sources” synthesized by applying interferometry to the recorded data.

Stanford DAS Array Experiment

Starting the beginning of September 2016, we have been continuously recording seismic data as sensed by a fibre-optic cable placed under Stanford University campus and measured by an OptaSense DAS system. Figure 1 shows the geometry of our DAS array. Each circle in the figure corresponds to a “virtual” seismic channel; the channels are separated by approximately 8 m. The colour (blue or red) and colour saturation indicate the sign and the amplitude of the recorded signal, respectively, at a fixed time after frequency band-pass from .2 to 12 Hz. The time snapshot shown in the figure is within the time window of the shear-wave arrival generated by a 5.8 magnitude earthquake that occurred under Pawnee (OK) on September 3rd, 2016. This figure visually shows two important characteristics of our DAS array: 1) its sensitivity (the distance between Stanford and Pawnee is approximately 2,200 Km,) and 2) its directivity (the sign of the recorded signal is strongly correlated to the direction of the fibre cable.) This directivity is a well-known characteristic of DAS recording systems. The evaluation of the array sensitivity, and therefore of the usefulness of the recorded data, is one of the main objectives of our experiment.

Our seismic experiment is unique, because the fibre cable was laid in an air-filled PVC conduit instead of being clamped to a conveyance or cemented/tamped in place, as is often the case. Figure 2 provides a pictorial sense of the physical layout of the fibre cable we used; it shows a photo of six PVC conduits used for the fibre telecommunication network managed by Stanford University as they terminate into a service manhole. The total length of the fibre cable is about 2.45 km; at the opposite end of the cable from the laser interrogator two fibre strands that share the same jacket are connected and the "returning" fibre strand is terminated at the same location as the laser interrogator. Therefore, the total linear length of the arrays is about 4.9 km but the effective length is half of that, with two sets of sensors sharing the same spatial location, though slightly shifted with respect to each other. The precise spatial location of each virtual sensor was determined by conducting several active seismic surveys along the array using a hammer as a source. When in "passive mode", the data are continuously recorded by 610 channels with a Nyquist frequency of 25 Hz. Accurate time synchronization is assured by a GPS antenna placed close to the roof of the building hosting the recording equipment.

Recording of teleseismic and local seismic events

The recording of low-intensity seismicity in the reservoir related to hydrocarbon production, either caused by fluid withdrawal or fluid injection, is one of the potential applications to permanent reservoir monitoring of DAS arrays that we are investigating using the Stanford array. Our array is located only a few miles away from the notorious San Andreas Fault; therefore, we expect to record plenty of low-intensity events that can be used to test the feasibility of this application. Furthermore, we can confirm arrival times and waveform characteristic of any significant event by comparing our recorded data with the data recorded at the "Jasper Ridge Biological Preserve" by a broadband seismometer that is managed by the Berkeley Digital Seismic Network. This station is located on Stanford campus and about 6 km from the DAS array. By the time of this abstract submission, we have recorded and analyzed in some details several teleseismic events (including the Pawnee event discussed above) and one 3.5 magnitude earthquake that occurred under Piedmont (CA) on September 13th, 2016. Piedmont is located across the San Francisco Bay and about 45 km from our DAS array. The left panel in Figure 3 shows an example of the recordings from the Piedmont event. It shows 31 contiguous channels oriented in the East-West direction (close to the horizontal direction in Figure 1.) The recordings have variable amplitudes and coherency, but the arrival of different phases (e.g. P, S, and surface waves) is clearly identifiable above the background noise. The right panel in Figure 3 shows the time-frequency spectrum of the average of the traces shown in the left panel. It shows the broad-band nature of the signal starting form the early P-arrivals with peak frequency around 5 Hz to the later coda with signal all the way down to about .5 Hz, and possibly further below.

Interferometry using natural and anthropogenic seismic noise

Another main objective of our experiment is to evaluate the feasibility of performing noise interferometry on data recorded by DAS arrays taking advantage of both natural and anthropogenic sources of seismic noise. Chang et al. (2016) show that freeway traffic is an excellent source of seismic noise between 3 and 15 Hz in metropolitan regions like the San Francisco Bay Area, and our preliminary interferometry results confirm this assessment.

Figure 4 shows the result of weighted cross-correlation often referred as cross-coherence, between one channel (located in the middle of the plot and marked as channel 75), and 25 channels on either side. A total of 48 hours of recording over 6 consecutive nights were used as input to produce the two panels shown in Figure 4. The left panel was produced after band-passing the data from .2 to 3 Hz, whereas the panel on the right was produced after band-passing the data from .2 to 7 Hz. The low frequency cross-correlation shows clearly that the seismic noise was mostly propagating from the high channel-number towards the low channel-number; that is, in the North to South direction. The busiest freeway in the area (US 101) runs North of the array in the NW-SE direction. The high frequency cross-correlation (right panel) is not as one-sided as the low-frequency one; it shows some energy coming from the South, though much weaker than the energy coming form the North. The apparent velocities of these two arrivals are slightly different; the low-frequency arrival propagates at a higher velocity than the high-frequency one. This frequency dispersion is consistent with increasing seismic velocity with depth. Measuring cross-coherency between the different sides of the array, and performing a complete velocity-dispersion analysis and tomographic inversion of these crosscoherency results should enable the estimation of soil properties within a hundred meters depth.

Conclusions

The "Stanford DAS Array" experiment has been operational for little more than two months, but there are already strong indications that the data recorded by the array can be used to monitor dynamic processes in the subsurface. Strong teleseismic as well weaker local events have been recorded with remarkable fidelity and bandwidth. Preliminary interferometry results show that the DAS arrays has sufficient sensitivity to generate coherent "virtual sources" at the frequencies where we can expect to observe both wave-generated and traffic-generated noise. Further analysis must be performed to confirm that: 1) useful information such as location and source mechanism can be derived from the earthquake data, and 2) virtual sources obtained by interferometry can be effectively inverted for nearsurface soil properties.

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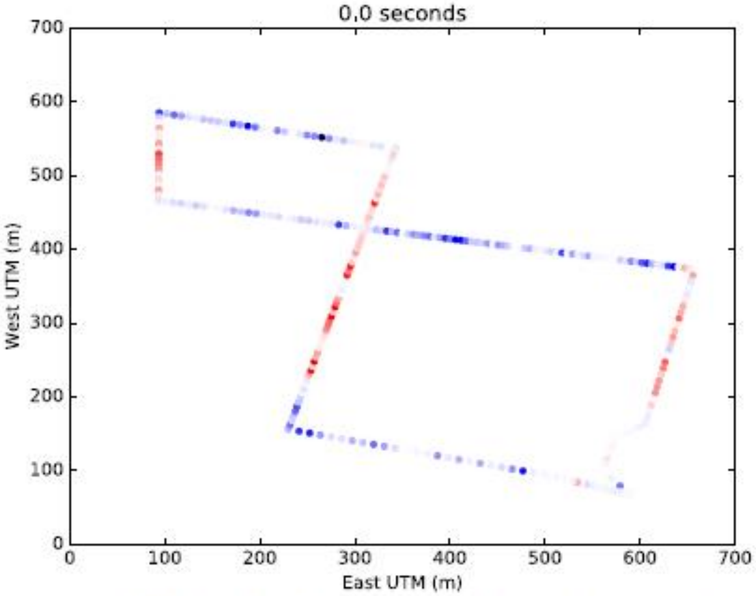

***Figure 1** The geometry of the Stanford DAS array. Each circle in the figure corresponds to a "virtual" seismic receiver. The colour (blue or red) and colour saturation indicate the sign and the amplitude of the recorded signal, respectively, at a fixed time.*

***Figure 2** Photo of six PVC conduits like the ones used to host the fibre-optic cable used by our experiment. The photo was taken in a service manhole and shows how the telecommunication cables are laying at the bottom of the PVC conduit, which is surrounded by concrete.*

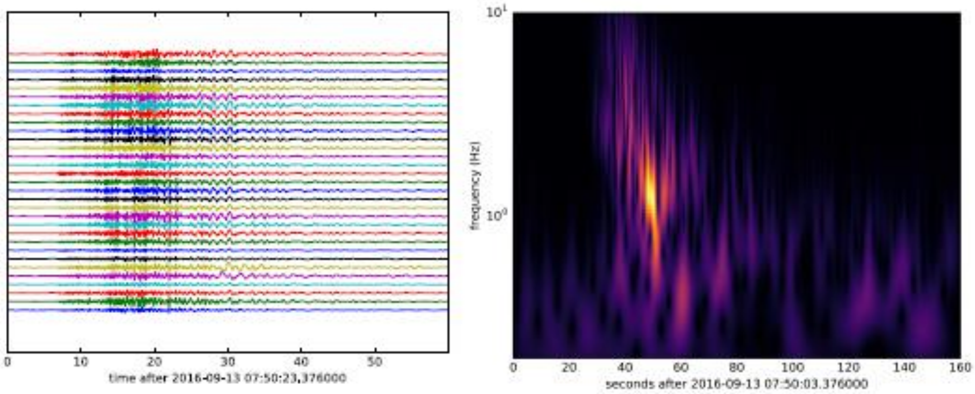

***Figure 3** Left: Wiggle plot of 32 seismic traces recorded by the DAS array at the time corresponding to the arrivals of the seismic energy generated by the Piedmont earthquake (magnitude 3.5 at a distance of about 45 km.) Right: Time-frequency spectrum of the average of the traces shown on the left. Coherent signal above the noise level is recorded within a .5 to 8 Hz frequency band.*

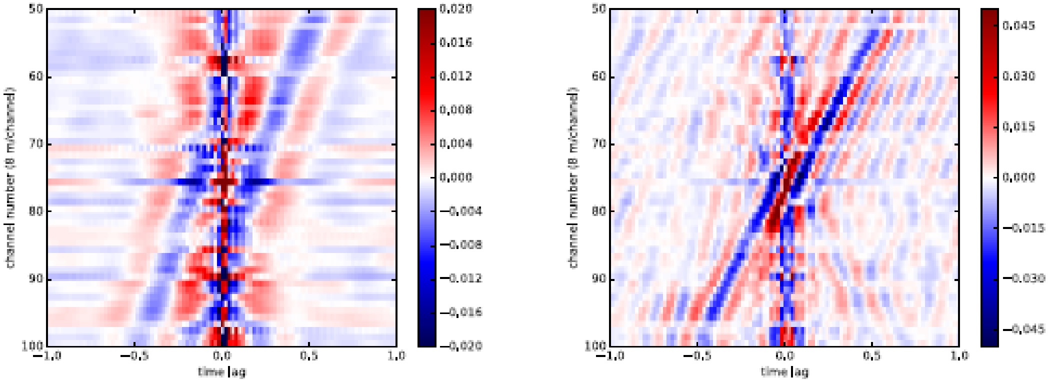

***Figure** 4 Cross-coherency (weighted cross-correlation) computed using 48 hours of recording after band-passing the data from .2 to 3 Hz (left panel) and from .2 to 7 Hz (right panel). The asymmetry of the arrival around zero lag indicates that most of the seismic noise propagates from North to South.*