Continuous passive-seismic monitoring of CO2 geologic sequestration projects

Investigators
Biondo Biondi, Professor, Geophysics; Sjoerd de Ridder, Jason Chang, Graduate Researchers, Stanford University.

Abstract
The tomographic inversion of the virtual-source data obtained by processing five days of passive seismic data recorded over the Valhall oil field in Norway demonstrates that reliable information can be obtained on subsurface velocity from passive data. Given the well-established effect of CO2 in decreasing seismic velocities, our results show that passive-seismic monitoring of CCS projects is feasible. The processing of different (overlapping) frequency bands provides velocity information at different depths in the subsurface; lower frequencies image deeper layers. CO2 plumes can thus be tracked as they move upward before they arrive at the surface and create human hazards. Analysis of the convergence rate of passive-data correlations and the statistical stability of the tomographic images demonstrate that reliable information can be extracted on a daily schedule. Passive seismic imaging is therefore ideal for early warning of CO2 plumes formations in the near subsurface.

Processing of a data set recorded onshore over the Long Beach oil field in South California shows that the method can work to monitor onshore CCS projects as well as offshore projects. Land data are noisier than marine data, and longer correlation periods are needed. Therefore, reliable information might become available weekly rather than daily, but still quickly enough to provide early warning of imminent dangers. The Long Beach data also show that human-generated noise (e.g. freeway traffic) can be effectively used to synthesize virtual seismograms to be used for tomographic inversion. Consequently, passive seismic monitoring might be feasible in diverse geographical settings, in addition to offshore (Valhall) or close to the ocean (Long Beach). Furthermore, careful processing shows that body-waves arrivals can be synthesized in addition to interface-waves arrivals. This observation opens the possibility that the method can provide information on processes taking place much deeper in the subsurface than the ones illuminated by interface waves.

Introduction
Monitoring by seismic data is likely to become essential for safe and effective operations of carbon capture and storage (CCS) projects. Both laboratory and field-data evidences [1] demonstrate that the presence of CO2 in the rock pore space has strong and easily detectable effects on seismic properties; it causes a substantial decrease in seismic velocity. However, active seismic surveys are expensive. Acquisition of active seismic data as frequently as needed for timely detection of CO2 leaks would add a substantial cost to CCS projects.

We investigated whether passive seismic imaging by interferometry is a reliable and feasible low-cost alternative to active seismic monitoring. Because CCS projects are
planned in both marine and land environments we analyzed two high-quality passive data sets: the first data set was recorded on the sea bottom in the Norwegian North Sea (Valhall), and the second data set was recorded on land in South California (Long Beach). These data sets were recorded by using semi-permanent installations that had been deployed with the goal of developing and monitoring oil reservoirs, not CCS projects. However, the lessons learned from the analysis of these data sets could be used to design, and possibly execute, a passive seismic acquisition targeted specifically to monitoring a CCS project.

Our marine data were recorded in a quieter environment than our land data. We could therefore analyze the convergence of the results as a function of the data frequency and of the length of the data subsets that were used as input. Estimates of the rate at which we can produce repeatable and reliable subsurface images are important because they determine the expected temporal resolution of the monitoring system. Our land data were recorded in an urban environment. They enabled us to investigate the possibility of using man-made noise, in particular traffic noise, as a useful source of seismic energy to be used for interferometric imaging.

Background

Cross-correlations of ambient seismic noise recordings retrieve the impulse response between two stations [2], thus turning one station into a virtual seismic source [3]. It has been shown that at the crustal scale [4], tomographic inversion of the retrieved impulse responses provides information on the propagation velocity in the subsurface. Hadzioannou et al. [5] and Seats et al. [6] have presented application of tomography from interferometric data of velocity changes at the crustal scale. It remains an open question whether sufficient accuracy and resolution can be achieved at the scale of a CO2 sequestration project to make passive seismic a reliable tool for CO2 plumes monitoring. Our work is unique, because we process massive amount of data recorded by high-density industry-standard receiver arrays. This kind of data acquisition are more similar to the likely CO2 sequestration monitoring than the sparse arrays of seismic stations used in earthquake seismology.

Results

Valhall Field, Norwegian North Sea

We analyzed a little over 5 days of continuous ambient seismic noise recorded in 8896 channels at 2224 stations of an OBC array at Valhall, a dataset of 7.7 Terabytes. The vertical component of each station is dominated by Scholte waves travelling along the sea floor [7,8]. These Scholte waves form a random wave field with characteristics that make it suitable to use seismic interferometry to extract virtual seismic sources emanating from receiver stations. Traveltimes can be extracted from these virtual sources and inverted for velocity maps.

Traveltimes were measured by the following procedure. First the waves where band passed using a Hann filter with flat response within the desired frequency range. Then the travelt ime of the wave-group is picked as the maximum of the envelope of the analytic signal. Tomography is done using a straight ray kernel. First the average velocity is computed and its contribution is subtracted from all travel-time picks. The
traveltime perturbations are then inverted using straight rays and a regularization term is added by constraining the second derivative of the velocity field to be smooth. This technique is named ‘ambient seismic noise tomography’ (ASNT), because it is a tomography of waves and traveltimes extracted from ambient seismic noise.

We make traveltime measurements for different data frequencies. We find lower frequencies to travel faster than higher frequencies, a phenomenon known as frequency dispersion. Frequency dispersion is expected because lower-frequencies waves propagate with longer wavelength than higher-frequencies waves. Longer wavelengths sense deeper regions of the subsurface that are typically more compacted than shallower layers, and thus have higher wave velocity.

Figure 1 shows the result of the Scholte-wave tomography at two different frequency ranges: a) 0.55-1.15 Hz, and b) 1.15-1.75 Hz. We compare these results with P-wave velocity maps extracted at constant depth from a velocity cube obtained from active seismic by full waveform inversion (Sirgue et al., 2010); these maps are shown in panels c) and d). Although the Scholte-wave group velocity maps have an integrated sensitivity over depth, they exhibit peak depth-sensitivities of half the wavelength. Figure 1a compares well to Figure 1c that is a velocity depth-slice obtained from FWI between 60-105 m. Figure 1b compares well to Figure 1d that is a velocity depth-slice obtained from FWI between 105-150 m. No unique mapping exists between Scholte-wave velocities and P-wave velocities, but each reflects the underlying geology that shapes the velocity anomalies. Clearly imaged by the group velocity tomography above 1.15 Hz are the high-velocity buried channels in the top 150m of the subsurface. In the group velocity images below 1.15 Hz a bigger channel becomes visible along the eastern end of the array (Figure 1b). Another subsurface feature imaged below 1.15 Hz is a low-velocity anomaly crossing the array east west. This low velocity zone reflects a combination of channel fills and sub platform low-velocities.

To estimate the rate at which we can expect repeatable and reliable information we analyze the statistical stability of both the correlation results as well as of the inverted images. We first investigate how much time is needed to gain stable correlation functions from the ambient seismic noise: the convergence rate. In order to investigate the convergence rate of cross-correlations, we compare the cross-correlation signal of shorter subsets of data to the cross-correlation result of the whole dataset. The similarity, measured by a correlation coefficient, provides a measurement for convergence rate.

Figure 2 displays an aggregate of many such measurements. They are displayed as a function of correlated recording length, and the distance between virtual sources and receivers. The 0.95 contour shows how correlations of shorter recording length only deviates 5% from correlating 5 days worth of data. For lower frequencies (Figure 2a) this contour lies at much smaller recording-length then at higher frequencies (Figure 2b), indicating that correlation convergence rate is faster at lower frequencies than at higher frequencies.
Figure 1: Direct comparison of Scholte-wave velocities obtained using ambient seismic noise tomography, 0.55-1.15 Hz in (a) and 1.15-1.75 Hz in (b), and P-wave velocities obtained using waveform inversion of controlled-source P-wave data (Sirgue et al., 2010). Velocity slices 150-195 m below the sea floor in (c) and 105-150 m below the sea floor in (d).

To investigate the statistical stability of the tomography results, we create 12 different velocity maps shown in Figure 3. Six for a frequency range between 0.55-1.15 Hz (left six Figures shown in 3a) and six for a frequency range between 1.15-1.75 Hz (right six Figures shown in 3b). Each six contain 5 velocity maps based on processing independent 24-hour recordings, and one based on processing all 5 days of recording. Notice how all maps obtained from just 24 hours of data look very alike, and how they all compare well
to the map obtained from 5 days of data. Because each map is based on ~1 million traveltime picks, the estimation of only ~4000 grid cells is an over-determined problem. Consequently, the image-space convergence rate of the tomographic images (Figure 3) is higher than the data-space convergence rate of the raw cross-correlations (Figure 2).

![Figure 2: Data space correlation convergence. (a) 0.50-0.75 Hz and (b) 1.50-1.75 Hz. Vertical axis denotes inter station distance, horizontal axis denotes correlated recording time. Dashed line denotes a 95% convergence level with respect to the full 5-day recording cross-correlation result.](image)

**Long Beach, California**

Since the large majority of CCS projects are likely to be on land, we analyzed a data set recorded onshore by over 2400 stations distributed across Long Beach, California. This dataset comprises 48 Terabytes. Figure 4 shows two maps of the station locations where each dot (black and colored) represents an individual station. The colored dots identify the subsets of stations used for the spectrogram analysis (Figure 4a) and beam forming (Figure 4b) discussed below.

Figure 5 shows the spectral characteristics of the ambient noise versus time for a location close to the beach and a location close to interstate 405 (red and blue respectively in Figure 4a). The variations in spectral content are shown over 48 hours spanning 15-17\textsuperscript{th} February 2012. We observe a clear diurnal pattern, where energy is higher during the day then during the night. We also find stronger low frequencies (between 0.1-1Hz) near the ocean than near the interstate. This is likely the seismic energy excited by wave noise pounding on the beach. These energies also seem to vary diurnally; perhaps wind energy that excites ocean waves is varying systematically with the time of day.

Next we produced a spectral density map at 4 Hz shown in Figure 6. Each dot in Figure 6 reflects a station location, red colors denote high spectral energy and blue colors denote low spectral energy. Notice the red colored zone that crosses the array east west in the northern half of the array. This high energy reflects the seismic noise created by
traffic on interstate 405. The red colored zone in the southeastern section of the array is linked with softer sediments near the ocean that cause amplification of the seismic noise.

Figure 3: Scholte-wave group-velocity tomography for 0.55-1.15 Hz in left 6 images (a) and 1.15-1.75 Hz in right six images (b). Both sets contain maps obtained using five independent, daylong passive recordings and a map obtained using the five-day passive recording. In the images for day 5 the high-velocity channels are annotated by red circles, and the sub-platform and channel fill low-velocity zone is annotated by a blue circle.

To investigate the origins of the energy in the ambient seismic field, we performed beam-forming experiments. Nine such experiments are shown in Figure 7, for three locations and three distinct times of day. The first row in the figure shows the beam forming results for the patch of receivers located just north of the interstate (top green circle in Figure 4b), the second row shows the results for the patch located just south of the interstate (middle green circle in Figure 4b), and the third row shows the results for the patch clear of the freeway and reasonable removed from the beach (bottom green circle in Figure 4b). Beam forming was performed for data recorded in the early morning (left column), early afternoon (middle column), and late afternoon (right column). In general we can observe sets of rings in each beam forming experiment, all but the rings centered at the origin are related to spatial aliasing and should be ignored. Observe that in early morning and late afternoon we can identify strong energy radiating northwards just north of the interstate, and southwards just south of the interstate. This energy is clearly related to interstate traffic. Traffic noise is much weaker in early afternoon than during rush hours (early morning and late afternoon). For the stations further removed of
the interstate, we see there is a more homogeneous azimuthal distribution of noise sources; these are likely to be associated with secondary roads and the direction of propagation are thus more evenly distributed.

**Figure 4** Station map of the acquisition project over Long Beach in California. Each black dot represents a single-component seismic station. In panel a) the red and blue patches correspond to the receivers used for the spectral density analysis. In panel b) the three green patches correspond to the receivers used for beam forming.

**Figure 5** Frequency spectra versus time. (a) Near the freeway. (b) Near the ocean.
Figure 6 Spectral density plot for frequencies at 4 Hz, red depicts high spectral energy and blue depicts low spectral energy. In the northern half of the array, the interstate 405 stands out, as the softer soil in the southeast of the array.

Figure 8 shows the cross-correlation results for two different frequency bands, after symmetrizing in time the earth’s impulse response between two stations. A snapshot from the low-frequency (0.5-2 Hz) correlation is shown in Figure 8a, and one from the high-frequency (2-4 Hz) correlation is shown in Figure 8b. As discussed above, low-frequency signal is related to ocean waves, whereas high-frequency signal is related to traffic noise. On the low-frequency snapshot we can identify two distinct wavefronts, corresponding to the fundamental Rayleigh wave and its first overtone. The high-frequency snapshot is noisier than the low-frequency one, but it still shows a clearly identifiable wavefront that could be used for tomographic inversion using the procedure applied to the Valhall data set. Notice that the circular shape of the high-frequency wavefront has a shorter radius than the low-frequency one, indicating a lower propagation velocity and thus showing frequency-dispersion effects similar to the ones discussed for the Valhall data set. To generate Figure 8a we used cross-correlations of data recorded for 8 days. In contrast, three weeks of data were necessary to generate the snapshot shown in Figure 8b. This difference can be explained by the different strength of the noise sources as well as by the difference in convergence rate between frequencies, as we discussed in the previous section about the Valhall data.

Figure 8b shows that the energy generated by surface road traffic can be effectively used for synthesizing virtual sources at higher frequencies than the virtual sources enabled by microseism energy related to ocean waves. Furthermore, the fact that the traffic energy is generated locally means that we have the chance of identifying, and thus using for subsurface monitoring, waves traveling along vertical paths in addition to surface waves traveling along horizontal paths. Figure 9 confirms this exciting possibility. To boost up the signal-to-noise ratio we average the results for different
virtual-source and receiver couples with similar offsets. Figure 9 shows the resulting virtual-source gathers for two overlapping frequency bands: 2-4 Hz on the left and 3-4 Hz on the right. The lower two images are identical to the upper two images, but straight segments are superimposed onto the data to help the interpretation of the events. We observe strong Rayleigh waves, potentially multiple modes travelling very slow with an approximate velocity of 220 m/s. However, we can also identify a coherent event at early arrival times (<5 s) and long offsets (>2 km); this is a fast wave propagating with an apparent velocity of about 2 km/s. We interpreted it as a refracted P-wave.

![Figure 9](image)

**Figure 7** Beam forming experiments showing where there energy is incident from. From left to right: early morning, late morning, and late afternoon. From top to bottom: Stations north of the freeway, stations just south of the freeway, stations clear of the freeway.

**Conclusions**

The tomographic results shown in Figure 1 demonstrate that reliable information on near subsurface seismic velocities can be extracted from passive data using interferometry. Furthermore, by processing and inverting data in (overlapping) frequency bands we can achieve a degree of vertical resolution in velocity estimation. This result is important to the proposed application of passive seismic as an early warning of the presence of a CO2 plume that is moving upward in the subsurface.
Figure 8 Snapshots at 5 seconds of a virtual seismic source generated: (a) using ocean wave energy between 0.5-2.0 Hz, and (b) traffic energy between 2.0-4.0 Hz.

When seismic energy related to interface waves (Scholte or Rayleigh waves) is used, as in the case of the results shown in Figure 1, the realistic deepest estimate from passive data is about 200 meters. The analysis of the Long Beach data shows that there is a potential of using body waves in addition to interface waves. Body waves could provide monitoring information on deeper subsurface processes and thus even more useful information for CCS monitoring. However, it is likely that the synthesis of body waves by interferometry is only possible when the sources of seismic energy are local, such as the freeway traffic in Long Beach.

We analyzed the statistical convergence of the data cross-correlations and of the tomographic images obtained from the Valhall data set. Our analysis demonstrates that reliable information could become available on a daily basis when data are recorded in quite environments, such as the ocean bottom. The preliminary analysis of Long Beach data shows that in noisy environments, such as onshore and close to large urban centers, a weekly interval would be a more realistic estimate for the availability of new monitoring information.

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![Figure 9](image)

**Figure 9** Gathers of virtual seismic sources at higher frequencies. Left panels show gathers between 2-4 Hz, right panels show the same gathers between 3-4 Hz. Bottom panels show the same data as top panels, but with added annotations. We find Rayleigh wave modes and a refracted p-wave mode.

**Publications and Patents**

References


Contacts

Biondo Biondi: biondo@stanford.edu
Sjoerd de Ridder: ridder@stanford.edu
Jason Change: jason@sep.stanford.edu