Imaging and monitoring of subsurface structures using reflections retrieved from seismic interferometry

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The seismic-reflection method with body waves is the most frequently used exploration method for imaging and monitoring subsurface structures with high resolution. It has proven its qualities from the scale of regional seismology to the scale of near-surface applications that look just a few meters below the surface. The seismic-reflection method makes use of controlled active sources at known positions to generate propagating body waves that are recorded at known receiver positions. The two-wave travel information of the recorded reflections is used to extract desired subsurface information about a structure, for example a geothermal reservoir.

When obtaining information of a subsurface structure is required on a frequent basis, like for example in monitoring of geothermal reservoirs, utilization of controlled active sources might be costly. Because of that, optimal use of the data they generate is required to effectively reduce their cost. The active sources would provide desired information, but they cannot be used continuously for monitoring purposes. Furthermore, when used again after some time, the seismic conditions of the near surface might have changed, which might lead to lower resolution of the seismic results. All this issues could be addressed by different applications of seismic interferometry.

Seismic interferometry is a method that retrieves new seismic responses from the correlation, coherence, convolution, or deconvolution of existing responses (Schuster, 2001; Wapenaar et al., 2002; Campillo & Paul, 2003; Schuster et al. 2004; Snieder, 2004; Wapenaar, 2004). For this, one can make use of recordings from controlled active sources, passive sources – microseismicity, earthquakes, ambient seismic noise.

A very promising application of seismic interferometry for geothermal applications is for retrieval of the reflection response between receivers at the surface from passive recordings (Fig. 1) from subsurface sources. The passive sources might be connected to the activity of a subsurface reservoir or unrelated to it.

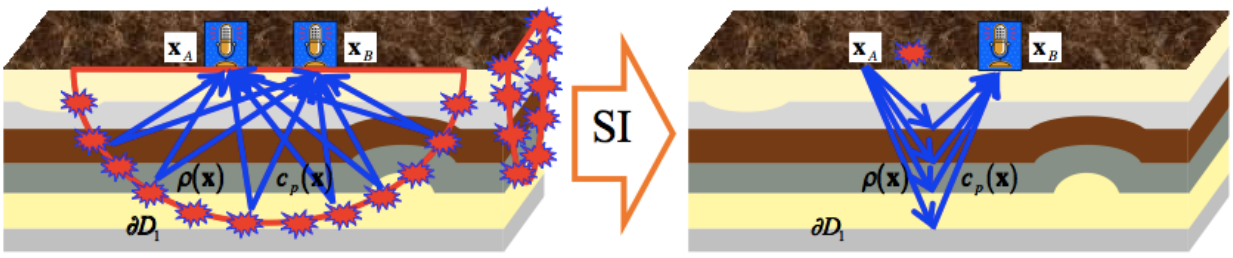

Figure 1. (left) Recordings at two receiver positions from subsurface sources, acting separately in time or overlapping in time. Using seismic interferometry (SI) these recordings can be used to retrieve the reflection response at one of the receivers as if the other receivers were a source (right). The retrieved source is also labeled as virtual sources.

Fig. 2 (left) shows the pseudo-3D image of the subsurface obtained below a 2D patch of surface seismic recorders along eight parallel lines. The survey was carried out in Libya and recorded ambient seismic noise for about 11 hours along (Draganov et al., 2009; 2013). The ambient noise was preprocessed to enhance retrieval of body-wave reflections. After that, seismic interferometry by cross-correlation was applied to retrieve the reflection response between virtual sources and receivers along each of the lines. The retrieved recordings were processed per line to obtain an image of the subsurface below each line. The images from the separate lines were interpolated to obtain the pseudo-3D image. The purpose of this field application was to test the applicability of seismic interferometry with ambient noise for exploration imaging.

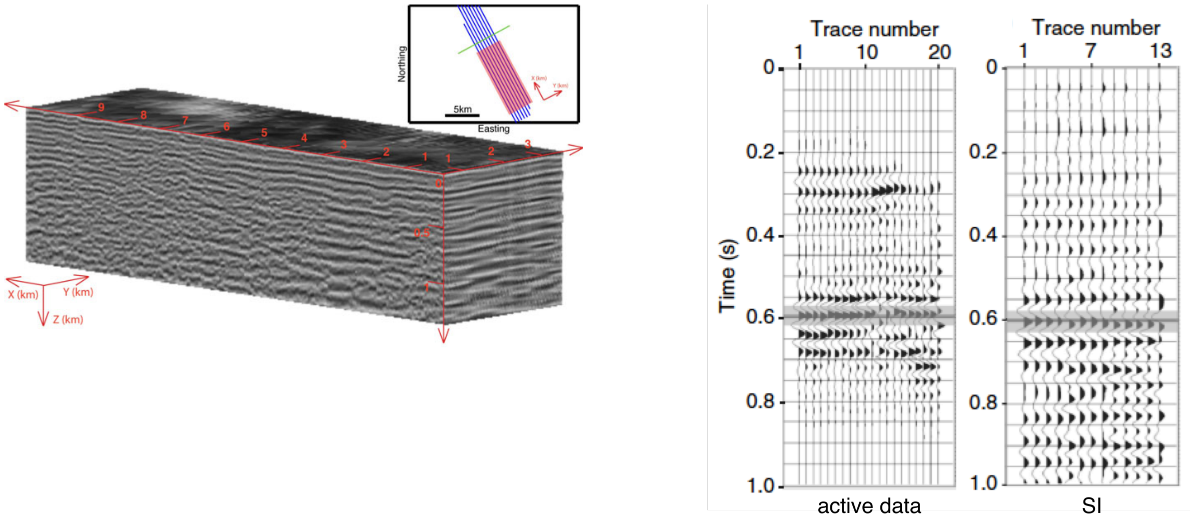

Figure 2. (left) Image of the subsurface down to about 1.5 km below the red part of eight survey lines (see the inset) that recorded about 11 hours of ambient noise. The image was obtained from reflections retrieved from seismic interferometry. (right) Ketzin stacked section obtained from active source at the surface compared with the result retrieve from seismic interferometry by autocorrelation applied to ambient noise (modified from Boullenger et al., 2015). The gray line indicated the expected arrival from the K2 marker reflector.

Fig. 2 (right) shows the result of application of seismic interferometry with ambient noise for monitoring of CO_2 sequestration (Boullenger et al., 2015). The ambient-noise data was recorded at the Ketzin test site, Germany. The continuous recording at the site started after the CO_2 front passed the passive array. The array was composed of 13 four-component recorders buried at a depth of 50 m and forming a line. Because the total length of the array is 120 m and because the target is at about 800 m depth, here seismic interferometry was applied using autocorrelation with the goal to retrieve the zero-offset reflection response at each receiver from a coinciding with it virtual source. In total, one day of noise was used. The retrieved result clearly shows the tuned reflections from the marker K2 reflector (gray), which forms the top of the reservoir formation (on average 80 m thick). For comparison, also a stacked section is shown, which was obtained using recordings from active sources at the surface.

Because the passive recordings started only after the CO_2 front passed the array, a real monitoring experiment could not be conduced. Instead, Boullenger et al. (2015) carried out numerical-modelling feasibility study for detecting changes due to CO_2 injection at Ketzin. The response to ambient-noise sources, confined below the reservoir, was modelled before injection and after injection. Seismic interferometry by autocorrelation was applied to both modelled datasets for retrieval of the zero-offset reflection response. Taking the difference of the two retrieved results showed clear amplitude changes of the reflection signals at the reservoir level.

The above two examples show the feasibility of using ambient noise for imaging and monitoring subsurface reservoirs. But also active-source recordings from surface sources could be used with seismic interferometry for monitoring purposes. Such application is very useful for describing layer-specific changes of velocity at the reservoir and cap-rock layer, for example (Draganov et al., 2012).

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