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## A Feasibility Study of Time-Lapse Seismic Noise Interferometry for CO2 Monitoring at Ketzin

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### SUMMARY

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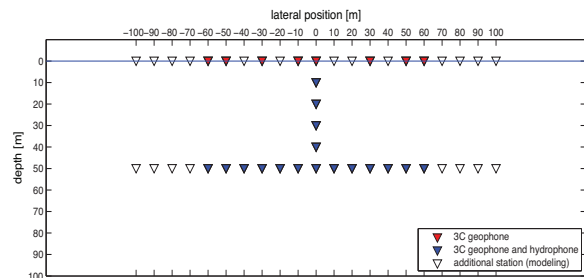
Since 2008, CO<sub>2</sub> has been injected at the demonstration site for CO<sub>2</sub> sequestration in Ketzin, Germany. Since 2009, a permanent array of seismic receivers installed by TNO at the injection site has recorded passive data continuously. It is the intention of TNO to use seismic interferometry (SI) by cross-correlation applied to the recorded ambient noise as a cost-effective technique for time-lapse monitoring. Under specific conditions, SI by cross-correlation can retrieve reflection data that may be interpreted in terms of subsurface layer properties. To assess the feasibility of this monitoring technique, we model base and monitor passive experiments for recording the response from noise sources and cross-correlate the recorded synthetic traces. The best results are obtained when the stationary-phase regions for the Green's functions are sampled densely enough by noise sources and, at the same time, the noise contributions from non-stationary regions cancel to a sufficient extent. Conversely, non-favourable noise conditions will cause wrong retrieval of the Green's functions and possibly deteriorate the monitoring potential of the technique. However, we show that being selective with the recorded noise in terms of illumination characteristics prior to correlation will improve the retrieved reflection data for further monitoring interpretation.

## Introduction

Since 2008, CO<sub>2</sub> has been injected at the demonstration site for CO<sub>2</sub> sequestration near the town of Ketzin in Germany. The target reservoir is a relatively thin layer in a saline aquifer at a depth of around 650 m. In 2009, TNO installed a permanent array of seismic receivers at the injection site. This array is composed of 3-component geophones and hydrophones divided in three lines – a horizontal line at the surface, another at a depth of 50 meters and a vertical line which connects the previous two (Figures 1 and 2). Since then, the array has recorded passive seismic data continuously. Clear passive body-wave arrivals have already been observed at Ketzin (Santonicio et al., 2012; Xu et al., 2012). It is the intention of TNO to use seismic interferometry (SI) by cross-correlation applied to the recorded ambient noise (ideally body-wave noise) as a cost-effective technique for time-lapse monitoring of CO<sub>2</sub> sequestration.



**Figure 1** Satellite view of the injection site. The injection well is depicted in blue, observation wells in yellow and TNO's permanent surface receivers in red.



**Figure 2** Monitoring system installed by TNO. Filled triangles depict existing stations whereas empty triangles are additional receiver locations. used for the numerically modeled datasets.

## Theory

In passive SI by cross-correlation, the Green's function between a virtual source at  $x_A$  and a receiver at  $x_B$  can be retrieved by cross-correlating the recorded seismic signals radiated from passive sources and integrating over the sources (Wapenaar and Fokkema, 2006). This result is valid when the passive sources lie on a closed surface boundary that surrounds the pair of receivers. Such a spatial configuration is depicted in Figure 3 with part of the closed surface being the Earth's free surface and with receivers located at the surface. Note that when part of the closed boundary is a free surface, sources are required only on its remaining part  $S_0$ .

It was shown that not only transient sources but also noise sources could be used to retrieve the Green's function between the pair of receivers (Wapenaar and Fokkema, 2006). Transient sources have the advantage to be a realistic representation of natural or induced seismic phenomena (micro-seismicity) occurring in the subsurface at a CO<sub>2</sub> injection site. However, the responses of the transient sources must be recorded separately, which might not be simple because of overlapping body-wave noise arrivals. Instead, a representation for simultaneously acting noise sources does not require separate measurements as long as the noise sources are uncorrelated or in other words are white sources.

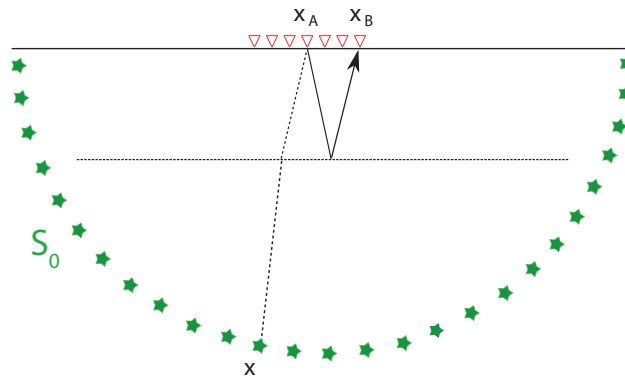
With simultaneously acting noise sources on  $S_0$ , the total observed wavefield at  $x_A$  (respectively  $x_B$ ) can be written as the Green's function (impulse response) from a noise source at  $x$  to  $x_A$  (respectively  $x_B$ ) convolved with the noise source's signature and then integrated over the noise-source positions:

$$\hat{u}^{obs}(x_A, \omega) = \oint_{S_0} \hat{G}(x_A, x, \omega) \hat{N}(x, \omega) d^2x, \quad (1)$$

where  $\hat{N}$  refers to the spectra of the noise sources. If, in addition, the noise sources are uncorrelated, the Green's function retrieval is governed by a relatively simple expression that directly relates it to the cross-correlation of the total recorded wavefields at  $x_A$  and  $x_B$ . This relation is the basis for our synthetic SI experiments:

$$2\Re\{\hat{G}(x_B, x_A, \omega)\}\hat{S}(\omega) \approx \frac{2}{\rho c} \langle \hat{u}^{obs*}(x_B, \omega) \hat{u}^{obs}(x_A, \omega) \rangle, \quad (2)$$

where  $\hat{S}$  is the power spectrum of the autocorrelation of the noise sources, the asterisk denotes complex conjugate and  $\langle \cdot \rangle$  denotes ensemble averaging. This relation holds for any arbitrary inhomogeneous acoustic medium inside  $S_0$ , but relies on a far-field approximation as well as the assumption that the medium is homogeneous at and outside  $S_0$ . Although relation 2 was derived for passive sources lying on a smooth contour, in our synthetic SI experiments the noise sources are randomly distributed in an area of the subsurface in order to model more realistic noise scenarios.



**Figure 1** Ideal configuration for passive seismic interferometry. Green stars denote passive sources distributed regularly on a smooth contour  $S_0$ . Receivers depicted by red triangles are at the Earth's free surface.

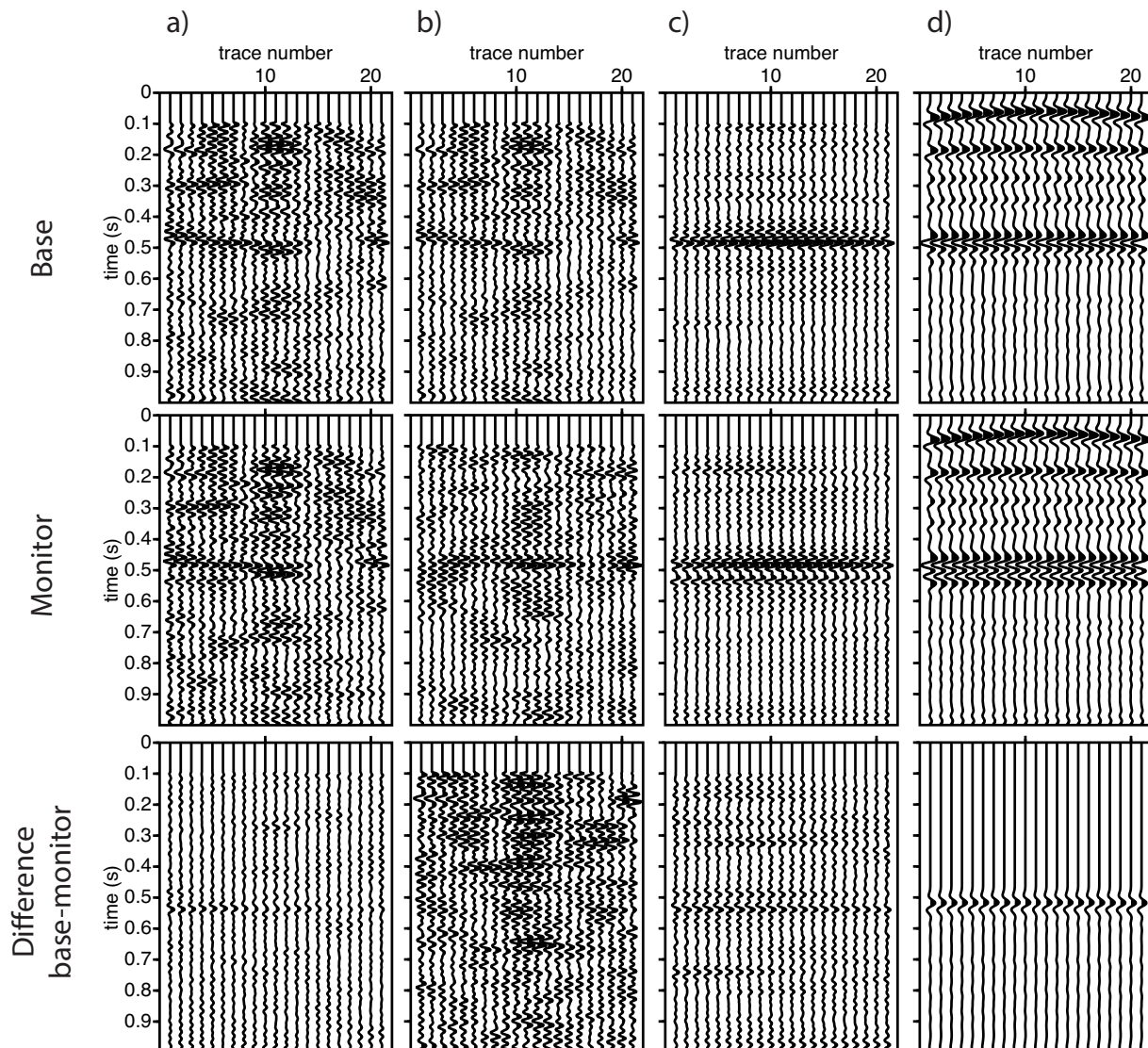
## Numerical modelling

Using a 1-D acoustic velocity model based on sonic well-log data at the storage site and a seismic array based on the existing in-situ monitoring system (Figure 1), we perform base and monitor passive experiments for recording the full response to (randomly distributed) noise sources and cross-correlate the recorded synthetic traces. By doing so, we retrieve so-called virtual common-shot gathers that we use to investigate the dependence of the retrieved reflectivity and the monitoring potential on the characteristics of the recorded body-wave noise.

For generating the numerical data, we use a 2-D finite-difference modelling code recently developed at Delft University of Technology. This algorithm is especially designed for efficient computation of long-duration passive seismic experiments (Thorbecke and Draganov, 2011). A passive experiment is characterized by the noise parameters, such as the number of sources, their spatial distribution, their maximum duration and their frequency bandwidth. To fulfil as good as possible the assumption of uncorrelated noise sources, we model their signatures and positions within a specified area randomly.

In a first step, the distribution of the noise sources is kept exactly the same for the base and monitor passive experiments. For the base scenario and the extreme monitor scenario (corresponding to a velocity decline of 20% in the  $CO_2$  reservoir), we show how the retrieved reflection response is dependent on the characteristics of the noise sources (number, average duration, active area). For example, when the stationary-phase regions (the regions that contribute constructively in the SI

process to the retrieval of the reflections) are sampled densely enough by noise sources, the retrieved reflection responses for the base and monitor surveys are improved (compare top and middle rows of Figures 4.a and 4.c). In general, the retrieval gains in accuracy when the noise configuration converges to the one depicted in Figure 3. When the stationary-phase regions are not sampled densely enough, there are more artefacts present, as shown in Figure 4.a. Nevertheless, because the exact same noise is recorded for the base and monitor surveys, these artefacts are the same and the amplitude difference between the retrieved virtual common-shot gathers can be easily interpreted as occurring only due to the velocity change in the reservoir.



**Figure 2** Retrieved virtual common-shot gathers for the surface receiver-line only. Base and monitor shot gathers are displayed at the top and middle rows, respectively. At the bottom row is shown the differences obtained by subtracting the top and middle rows. For the passive experiments, 100 noise sources with a maximum duration of 1 s and a maximum frequency of 50 Hz were randomly generated. In a) the exact same distribution is used for the base and monitor, the noise region is relatively large and the same for both. In b), the sources are distributed differently for the monitor experiment. c) is as in b), but with a noise region considerably reduced below the target reservoir. d) Reference results from an active shot at the surface with muted direct arrivals.

In a further step, the distribution of the noise sources is changed for the base and monitor passive experiments (note, however, that the active area (viz. the area in which the noise sources occur) is kept the same). As expected, the amplitude differences between the retrieved base and monitor virtual common-shot gathers become impossible to interpret if the noise configuration is not favourable enough (Figure 4.b). This is due to the loss of noise repeatability from base to monitor that generates different artefacts and/or non-consistent reflectivity.

This undesirable effect can be counter-balanced by choosing more favourable noise configurations for the base and the monitor surveys. This can be obtained by modelling the body-wave noise as coming from a favourable area of the subsurface (including stationary-phase regions) that is sampled densely enough by noise sources. In our result of Figure 4.c, this is done by choosing a spatially limited active area in a homogenous part of the subsurface below the target reservoir. This has the benefit to allow consistent illumination of the receiver array for both the base and the monitor surveys. In this way we are able to interpret again the relative amplitude variations in the retrieved signals (bottom of Figure 4.c). Note that, in practice, the enhanced repeatability could be achieved by illumination diagnostics (e.g. Almagro Vidal et al., 2011).

## Conclusion

For the extreme case of perfect repeatability of the noise sources for the base and monitor passive experiments, the retrieved virtual common-shot gathers exhibit relative amplitude differences that we can directly relate to the velocity change in the reservoir. When the noise-source positions vary randomly from base to monitor, the active area and their number being the same though, one cannot interpret the retrieved panels for seismic monitoring purposes. However, favourable noise illumination of the monitoring array from a region small enough to result in dense noise-source sampling can be sufficient to preserve the monitoring potential of the technique. With real field data, this favourable noise configuration may be a matter of chance but may be reached, more likely, by prior noise selection and processing.

## Acknowledgements

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