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Thomas Kremer, Pascal Mouquet, Alexandre Kazantsev, Arnaud Grauls, Christophe Voisin. Monitoring geological gas storage sites with ambient noise interferometric methods: focus on seismic attenuation changes for gas movement detection.. 16th International Conference on Greenhouse Gas Control Technologies, GHGT-16, Oct 2022, Lyon, France. 10.2139/ssrn.4274245 . hal-04283847

**HAL Id: hal-04283847**

**<https://hal.science/hal-04283847>**

Submitted on 14 Nov 2023

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16th International Conference on Greenhouse Gas Control Technologies, GHGT-16

23<sup>rd</sup> -27<sup>th</sup> October 2022, Lyon, France

Monitoring geological gas storage sites with ambient noise interferometric methods:  
focus on seismic attenuation changes for gas movement detection.

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## Abstract

Recording the ambient seismic signal over an array of multiple sensors and applying ambient noise seismic interferometric (ANSI) methods can give access to the characterization of seismic wavefields which can in turn be analyzed to infer the seismic properties of the investigated medium and/or to monitor these properties over time. One advantage of those passive seismic methods - in addition to their relatively low cost of implementation - is that they do not require any active seismic source, which allows for their use even in areas where active source deployment is complicated (e.g., inhabited areas, dense industrial infrastructures), and can therefore be relevant to monitor natural gas or CO<sub>2</sub> geological storage sites.

In this paper, we analyze the temporal evolution of a seismic wavefield obtained with ANSI methods to monitor the structural changes and fluid distribution evolution occurring within a natural gas geological storage site where fluid movements induced by gas injection/production operations take place. The local seismic wavefield was reconstructed for the whole monitoring period and thoroughly analyzed. We addressed our effort into monitoring a specific attribute of the reconstructed seismic waves: the *waveform coherency*. This attribute reflects the variations of the subsurface attenuation properties, which are sensitive to the fluid distribution within the rock matrix and hence adapted to geological gas storage monitoring.

Our results demonstrate the sensitivity of this passive seismic monitoring approach to gas movements within the reservoir. We note the existence of a relationship between a significant drop of the wavefield coherency values estimated at the reservoir level and a gas injection phase of about one month duration where significant pressure increase is observed. When no significant gas injection or extraction is performed, the coherency of the wavefield remains stable. This experiment hence confirms the interest of the wavefield coherency as a quantity suited to monitor geological gas storage sites evolution and potentially detect prospective gas leakage paths.

*Keywords:* Passive seismic methods, ambient noise interferometry, geological gas storage, monitoring, waveform coherence, attenuation properties, fluid movements.

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## 1. Material and methods

### 1.1. Site description and data acquisition

The study site is a geological storage structure where natural gas injection and extraction operations are conducted. The monitoring time extended for a duration of 8 months, period during which a significant gas injection phase occurred for one month.

The ambient seismic noise was recorded continuously during the 8 months monitoring period using an array composed of 48 SG-5Hz sensors (single component), connected to WTU acquisition units (fabrication from *Sercel*). A comparison was performed with broadband accelerometers which confirmed that the seismic information recorded with the SG-5Hz sensors in this area was exploitable down to a frequency of 0.2 Hz thanks to a sufficiently high level of seismic noise. Figure 1 shows the repartition of sensors at the surface along with the approximate reservoir structure.

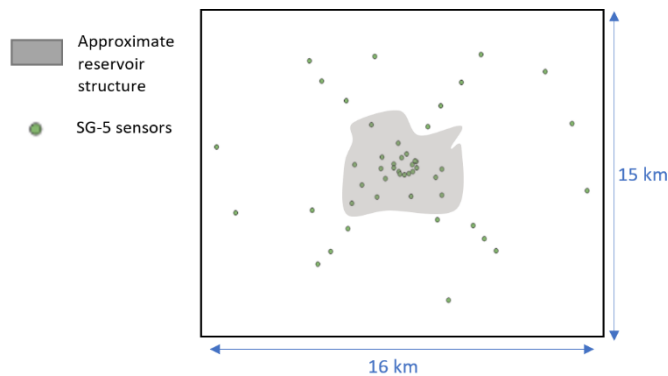


Fig. 1: spatial repartition of the single component seismic sensors. The grey area represents the approximate structure of the reservoir.

### 1.2. Ambient noise seismic interferometry (ANSI)

ANSI methods [1] have been developing increasingly in the past two decades with the objective of providing affordable tools for the seismic characterization and monitoring of the subsurface at different scales. Those techniques consist of analyzing a seismic wavefield that has been reconstructed beforehand using the seismic continuous signal, also referred to as seismic ambient noise.

The seismic waves reconstruction is achieved through cross-correlations operations of noise signals recorded at different locations. If some conditions are met, surface or body waves will emerge through those operations. Such emergence can be attempted for all stations pairs composing the seismic array.

Once a seismic wavefield is obtained, several kinds of analysis can be applied, such as the study of dispersion behaviors to infer seismic velocity models of the subsurface [2], or the production of seismic images like what is obtained in active seismic studies [3].

Regarding monitoring applications, the classical approach consists of measuring the changes in the seismic waves phase arrivals, hence following the seismic velocity variations of the studied medium [4]. In this paper, we propose a new approach that rather focuses on the attenuation variations in the medium by analyzing the temporal coherency of the reconstructed waveforms.

### 1.3. Temporal Coherency analysis

The coherency analysis principles are illustrated on Fig. 2. For each station pair composing the seismic array (1128 pairs in this study), seismic waves are reconstructed through interferometric processes (Fig. 2a) for multiple time steps of the monitoring period (Fig. 2b). For each time-step, the coherency of the waveform compared to a reference waveform (in this case the first time-step waveform) is computed as a value between 0 and 1, resulting in a coherency

time-series covering the whole monitoring period (Fig. 2c). Low coherency values indicate that the spectral content of the reconstructed wave has changed compared to the reference, which can be related to variations of seismic properties in the propagating medium. High values indicate that the seismic waveforms are stable and that the seismic properties of medium have not been subject to significant changes.

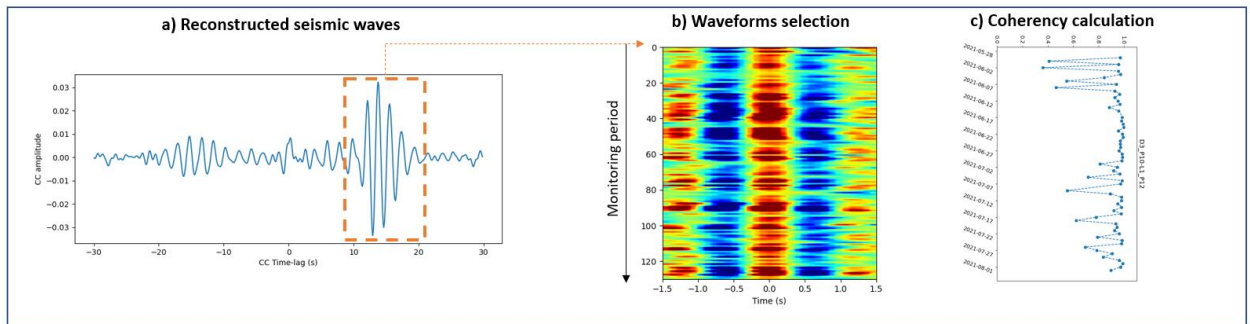


Fig. 2: Illustration of the coherency analysis for one pair of seismic sensors. a) Reconstruction of seismic waves after a cross-correlation operation. b) Multiple reconstructions during the monitoring period and selection of the waveforms. c) Final coherency time-series for one station pair.

## 2. Results

### 2.1. Wavefield reconstruction

Figure 3 shows the results of the interferometric processes conducted in the frequency range 0.5 – 1 Hz. This choice of frequency was made following a Rayleigh wave sensitivity study that indicated maximal sensitivity to the reservoir depth in this range.

For all stations pairs, the reconstructed seismic signals (the cross-correlations) are displayed according to the distance between each station (Fig. 3). This kind of representation allows the visualization of several components of the wave field propagating within the studied medium. We note that surface waves are particularly well reconstructed (high signal-to-noise ratio) and will be the focus of the coherency analysis in the following study.

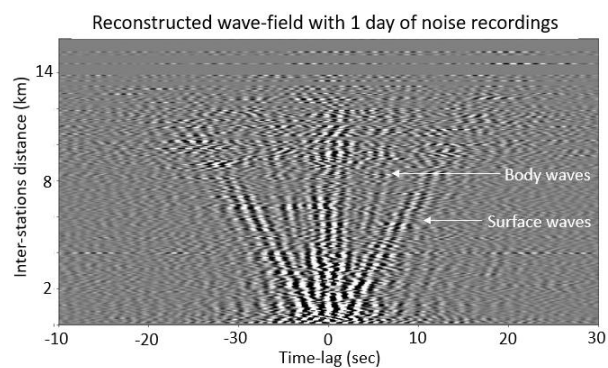


Fig. 3: “Shot gather” representation of the reconstructed seismic wavefield for one day of noise records. All reconstructed waveforms are displayed depending on their corresponding inter-station distance. Several wave trains are visible, the surface wave train is the most energetic.

## 2.2. Spatialization - Coherency maps

Figure 4 illustrates the principles and the results of a spatialization process based on average binning that aims at producing 2D coherency maps for each time-step of the monitoring period, hence allowing to visualize the spatial distribution of the coherency variations and to detect areas where seismic properties of the medium are changing in time. The average binning process implemented in this study consists of discretizing the studied area with a regular grid, then distributing the coherency values obtained for each pair of station along the straight ray path that links both stations, and finally averaging all the values in each cell (Fig.4a). This process results in 2D coherency maps that give a first order estimation of the spatial distribution of changes in the studied media (Fig.4b).

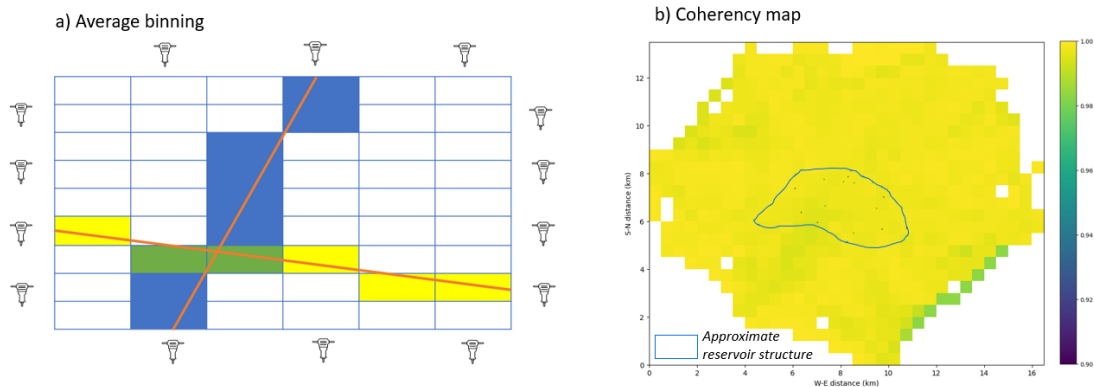


Fig. 4: a) Illustration of the average binning principle. b) Results of the average binning process in the studied case. Coherency map reconstructed for the first time-step of the monitoring period.

We address the temporal evolution of the medium by reconstructing 2D coherency maps for all time-steps of the monitoring period. Figure 5 shows a mosaic representation of the coherency maps produced with a time-step of three days. We observe stable periods of several weeks where the coherency values are close to 1 all over the studied area, indicating stability, as well as some unstable periods where significant coherency reduction is observed in the center of the maps (e.g., blue rectangle).

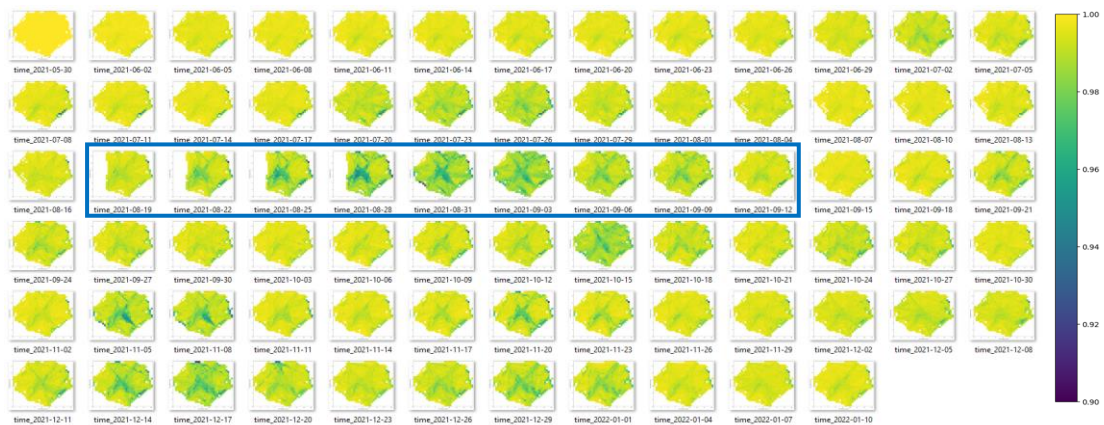


Fig. 5: Mosaic representation of the 2D coherency maps produced for the whole monitoring period. Time steps evolve from left to right, then down each line. The blue rectangle highlights a period where important coherency drops are observed in the central part of the map, that is, at the reservoir level.

### 2.3. Comparison with storage activity

To better address the temporal evolution of the seismic properties at the level of the reservoir, we plot on Fig.6 the average coherency time-series computed taking coherency values from a 2km wide square at the center of the map, and at the center of the reservoir (Fig.6a).

This average coherency time-series is plotted against the pressure evolution recorded at a control well connected to the center of the reservoir. A significant coherency diminution and recovery is observed ranging about the 10<sup>th</sup> of August and the 20<sup>th</sup> of September. This event occurs simultaneously to a continuous increase in pressure in the control well related to a significant gas injection phase, suggesting the existence of a physical relationship between both observations.

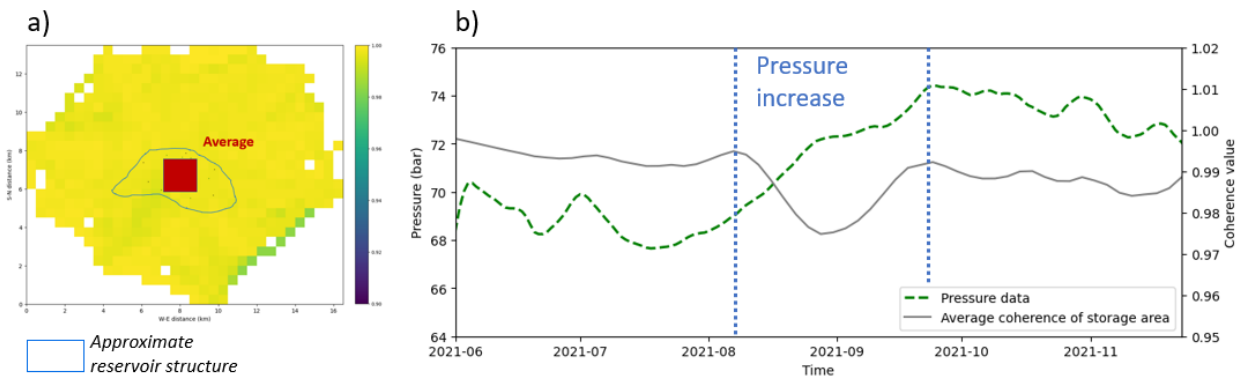


Fig. 6: (a) Illustration of the area selected for averaging coherency values. (b) Comparison between averaged coherency time series and pressure data measured within a control well central to the reservoir.

Several verifications were made to investigate the reality of the physical relationship possibly relating gas movements within the reservoir and seismic coherency observations. Those verifications all aimed at studying the prospective influence of ambient noise sources variations upon the observed changes in coherency values, with a specific attention given to prospective noise signals produced by the storage industrial facilities:

- Focus was given to the central part of the array, where a high number of sensors are set-up close to the industrial infrastructure of the gas storage site that could potentially produce high energy seismic events recorded locally. The coherency analysis was repeated while removing all those central sensors, and the coherency decrease was nevertheless observed, indicating that coherency variation information is not only focused on the central sensors but are also carried by seismic waves propagating between sensors that are far for the industrial installations.
- The spectrograms and power spectral density time-series of all stations were also visually analyzed to check if the coherency diminution could be related to a synchronous change in the spectral content of the ambient noise signals. No specific event or sudden change in spectral amplitude could be identified.
- Finally, a coherency analysis was conducted using a network of sensors used for microseismic monitoring of the gas storage site. Those sensors are all located at depth ranging between 50 and 250 m depth and are therefore much less sensitive to ambient noise source variations occurring at the surface. The results of this analysis also showed a significant coherency drop simultaneously to the injection phase in the month of august and september, supporting again the fact that coherency variations are not dependent to ambient noise source variations.

### 3. Discussion and perspectives

#### 3.1. Discussion

The verifications described in the previous paragraph help excluding the possibility that the observed decreasing coherency period be related to changes in the spectral content of ambient noise sources, and hence support the hypothesis that a relationship exists between the coherency behavior and the physical phenomena associated with gas injection during the same period.

However, the exact nature of this relationship remains to be determined. It is noteworthy that the coherency reduces and then goes back to its original level even though the pressure in the reservoir remains at a level different from the level prior to injection. At this stage we propose two hypothesis that aim to account for this behavior.

- *Sensitivity to gas saturation:*

The seismic attenuation properties of geological media are sensitive to variations in fluid saturation [5]. Based on this initial assumption the "return to equilibrium" behavior of the coherence anomaly could then be explained by gas dissolution processes that occur with a lag time on the start of the injection. The scenario evoked would therefore be that of an increase in gas saturation at the beginning of the injection, followed by a return to the initial global saturation as part of the injected gas dissolves. To gain insights on this possibility, discussions with experts in the behavior of gas storage reservoirs, and possibly modelling work are considered for future work.

- *Sensitivity to pressure gradients:*

The physical mechanisms that control the seismic attenuation of the medium (and hence the waveform coherence) occur at several scales (microscopic, mesoscopic, and macroscopic). For all these scales the basic mechanism invoked is an energy loss associated with the fluid flows in the rocks that result from the passage of the seismic wave and the local pressure gradient that it induces [6].

When a storage site rises in pressure, a macroscopic pressure gradient is induced in the overall system. What is the effect of such a gradient on the elastic and anelastic properties of a geological medium? This is the question underlying hypothesis n°2. To study it, a bibliographical study must be carried out, which can then be supported by modelling work.

#### 3.2. Perspectives

This field study has provided important elements supporting the possibility of monitoring gas movements within a geological gas storage site using the proposed passive seismic methodology. However, the physical phenomena underlying the relationship between coherency variations and gas movements remains to be studied. To this end, we plan to carry on modeling work, both of petrophysical and geochemical effects occurring in the reservoir during injection of extraction activity, as well as seismic wave propagation behaviors associated with such dynamic media.

Another perspective of this work will consist of quantifying the effect of possible bias induced by ambient noise sources amplitude variation upon coherency values. We have already demonstrated that those bias were not the cause of the decreasing coherency anomaly, yet it remains important to fully quantify those effects, and assess whether they can be fully neglected or if taking them in account can improve the accuracy of the method.

Finally, the 2D coherency map construction process proposed in this paper proves useful to get a first order visualization of the coherency values distribution in space, yet it remains relatively unperfect due to a sensitivity to the network geometry. In the current state, it prevents accurate spatial interpretation, which is why some work will be dedicated to improving spatialization tools, mostly through development of a suited inversion scheme.

## Acknowledgements

We greatly acknowledge the technical and logistical partnership of Terega and Storengy for the realization of this work. We also acknowledge the CITEPH innovation program that allowed the construction of this project.

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