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The use of passive seismic interferometry for the monitoring of subsurface fluids – from shallow groundwater to native or storage gas reservoirs

Utilisation de l'interférométrie en sismique passive pour la surveillances des fluides de subsurface – des eaux souterraines aux réservoirs de gaz

Thomas Kremer*,[1], *Christophe* Voisin[1,2], *Thomas* Gaubert-Bastide[1], *Jean-Michel* Ars, *Pascal* Mouquet, *Frédéric* Moinet and *Jean-Charles* Ferran[1]

[1] Geolinks services, Paris, France
[2] Univ. Grenoble Alpes, Univ. Savoie Mont Blanc, CNRS, IRD, Univ. Gustave Eiffel, ISTerre, 38000 Grenoble, France

Abstract. Passive (ambient noise) seismic interferometry provides multiple ways to gather information about the subsurface seismic properties using recordings of the seismic ambient noise signal. While the first developments and applications of this method showed a useful capacity to either image geological contrasts or monitor the structural properties of the soil, an increasing momentum is observed toward applications related to fluid monitoring of different types (liquid, gas), at all the scales of the subsurface (from meters to kilometers). In this paper we summarize the existing possibilities and technics of seismic interferometry analysis for subsurface fluid detection and characterization and elaborate on their respective deployment in different contexts. We also present a new approach based on estimating and continuously measuring seismic attenuation proxy within interferometric-based surface wavefields, which show a high sensitivity to fluid dynamics and the associated petrophysical variations. The method is illustrated through a field case study related to geological gas storage monitoring, and we elaborate on its potential respective deployment at the industrial scale and for different applications.

Résumé. En sismique passive, l'interférométrie du bruit sismique ambiant permet de recueillir des informations sur les propriétés sismiques du sous-sol à l'aide d'enregistrements du signal sismique continu. Alors que les premiers développements et applications de cette méthode ont montré une

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* Corresponding author: thomas.kremer@geolinkservice.com

capacité à imager les contrastes géologiques ou à surveiller les propriétés structurelles du sol, un élan croissant est observé vers des applications liées à la surveillance des fluides de différents types (liquide, gaz), à toutes les échelles de la subsurface (de quelques mètres à quelques kilomètres). Dans cet article, nous résumons les possibilités et les techniques existantes d'analyse par interférométrie sismique pour la détection et la caractérisation des fluides de subsurface et nous discutons leur déploiement respectif dans différents contextes appliqués. Nous présentons également une nouvelle approche basée sur l'estimation continue des variations d'atténuation sismique, via l'analyse de d'ondes de surface reconstruites par interférométrie. Cette méthode montre une grande sensibilité à la dynamique des fluides et aux variations pétrophysiques associées. Un cas d'étude est présenté dans le contexte de la surveillance de stockage géologique de gaz, et nous discutons son déploiement potentiel à l'échelle industrielle, pour différentes applications.

1 Introduction – from seismic velocity to seismic attenuation

The basics of ambient noise seismic interferometry were described in the early 2000s (e.g. [1]). Applied to the continuous seismic signal, which is composed of many unknown contributions and is therefore not informative in its raw native shape (diffuse noise), the principle of interferometry allows for extracting coherent seismic wavefields from those passive signals. Having propagated within the ground, those wavefields intrinsically carry information about the seismic properties of the subsurface.

The first developments and technics emanating from passive seismic interferometry focused on analysing the seismic velocity properties of the ground. The tomographic approach involves examining dispersion behaviours to deduce seismic velocity (3D) models of the subsurface [2]. Another analysis angle involves the reconstruction of seismic images, akin to those produced in active seismic studies [3]. Regarding monitoring applications, the conventional method involves tracking changes in the phase arrivals of seismic waves, which enables the observation of seismic velocity variations within the studied medium [4].

On the first order, seismic velocity analysis of ambient noise based seismic wavefields is mostly sensitive to the structural parameters of the subsurface. That is, shear-wave velocity models reconstructed through tomographic approaches are usually used for geological characterization and delineation of major lithological contrasts. For monitoring applications, the most advanced contexts from an application point of view are the monitoring of tailing dam structures, where soil deconsolidation impacts the mechanical cohesion of the geotechnical system and usually results in the observation of small yet measurable seismic velocity decrease [5]. However, in the last decade, application of seismic velocity based interferometric studies have been increasingly tested in subsurface contexts where fluids play an important role, for example relating to hydrogeologic monitoring at the shallow subsurface scale (e.g. [6, 7, 8, 9]), or at the meso-scale [10], or for the characterization and monitoring of geothermal systems [11], among other contexts.

More recently, interest has been raising regarding the possibility of studying the seismic attenuation properties of the subsurface using interferometric-based seismic reconstructions. This possibility was for instance validated numerically by [12], and [13] is an example of subsurface attenuation estimation in the marine-offshore context. Later, [14] applied a similar approach to produce an attenuation map of the United States in the micro seism frequency band. However, the use of interferometric attenuation analysis for subsurface fluid characterization has not been discussed until recently. Yet, [15] for instance illustrated through Biot-Gasmann modelling on an effective media how attenuation properties (quality factors) are more sensitive to fluid saturation level changes than velocity properties. The use of attenuation to detect gas reservoirs is also known as a relevant approach in the active seismic context [16]. In this paper, we present the Coherency analysis of Cross-correlated Waveform (CCW) method, an approach that attempt to connect seismic attenuation-based fluid monitoring with ambient noise based interferometric reconstruction of surface waves.

2 Velocity analysis for groundwater management

The interest for seismic velocity monitoring using interferometric reconstructed wavefields relies on two major characteristics:

1. Passive seismic interferometry allows for continuous data recording, hence allowing for a monitoring strategy with quasi-continuous temporal resolution.
2. The amplitude of velocity variations that can be measured is very small (on the order of 1% and much lower in some cases), allowing for seismic velocity changes detection compatible with the saturation or desaturation processes associated with groundwater movements.

Those intrinsic advantages have been used to demonstrate the feasibility of hydrogeological monitoring with interferometric-based velocity variations, at multiple scales. That is, measuring velocity variations time-series that correlate well with piezometer information available at the survey site. Recently, an important step forward has been taken relating to the possibility of producing interpolated 2D maps of piezometric level variations (through an inversion process, e.g. [9]), a significant progress axis toward the spatial interpretation of velocity variations and a better understanding of the groundwater system's full complexity by filling the actual gap related to the local nature of piezometric measurements.

Those advances open the way forward to new additional applications that can provide valuable information to hydrogeologists and help orientate groundwater management authorities' decisions.

Figure 1 proposes a panel of propositions for such applications, sorted along their respective associated subsurface scale, and their value in terms of groundwater management interest. In all cases, interferometric studies can provide piezometric information in addition or in replacement to existing wells, for a low cost of implementation. For instance, in the case of a pumping test destined to estimate aquifer dynamic properties, the use of an interferometry-based assessment of the depression cone could avoid the digging of secondary wells, hence saving significant costs. At the catchment basin scale, a high-resolution interferometric characterization of the temporal and spatial changes of piezometric levels can identify the main infiltration pathways in the groundwater system, designating areas that must be particularly controlled to avoid contamination from the surface. On a more global level, additional information provided by interferometry can help reduce hydrogeological models' uncertainties.

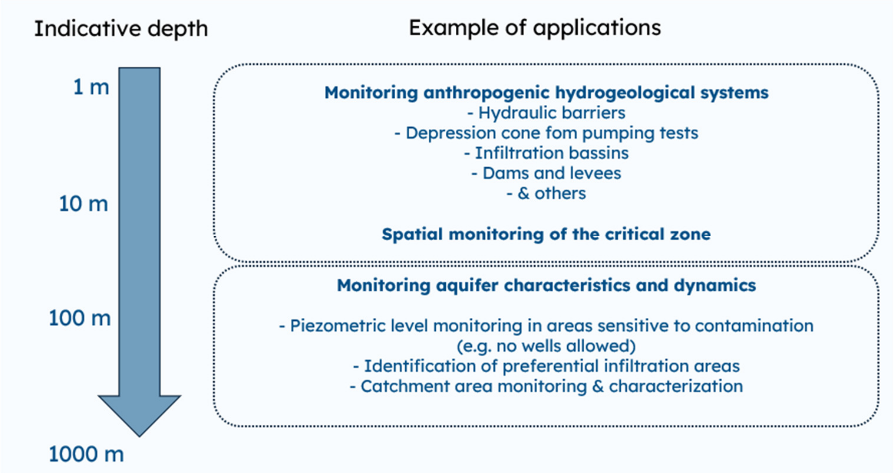

Figure 1. Illustrative scheme of the different application of interferometric-based piezometric levels variations.

3 Attenuation analysis for gas reservoir exploration and monitoring

At relatively shallow depths (< 100 m), the density contrast between water saturated rocks and unsaturated formations is strong enough to be captured by the interferometric-based velocity monitoring approach which allows detection threshold as low as 1% (and lower in some cases). However, at more important depths, as pressure and temperature are increasing this contrast becomes smaller and differences between rocks that are fully or partially saturated with fluids becomes more challenging to detect. A typical example of this situation arises in the context of CO_2 geological storage, where the injected CO_2 reaches the supercritical state at depth larger than about 800 m. In this situation, the injected gas density becomes very close to that of a liquid, making the differentiation between brine filled rocks and CO_2 invaded rocks more difficult.

Facing this challenge, an opportunity exists in the analysis of the seismic attenuation properties of the rock, using interferometric reconstructed wavefields. Indeed, attenuation values contrasts (or quality factors) between saturated and unsaturated rocks are known to be about one order of magnitude higher than velocity contrasts (e.g. [15, 17]). Elaborating on the previous example, the injected CO_2, even in its supercritical state, still possesses a viscosity value close to that of a gas and significantly different from that of the water/brine. As viscosity of fluids is an important parameter that drives the magnitude of intrinsic (also called anelastic) attenuation, gas reservoir location and dynamics can be monitored by taking advantage of the seismic attenuation response of the subsurface.

The CCW methodology has been developed bearing such an objective. It aims at following attenuations changes on interferometric reconstructed surface waves by analysing the evolution in time of the waveform coherence. The general process is described in detail in Kremer et al. [18, 17]. In short, the coherence of surface waves reconstructed through interferometric processes over a dense array of passive seismic sensors (110 sensors) are computed in time and integrated through an inversion process into a spatial visualisation (2D map) of coherence distribution of the area of the storage, computed for multiple time-step of the monitoring period.

Figure 2 shows the results of applying the CCW method for attenuation properties analysis of the subsurface in the context of the monitoring of geological gas (CH_4) storage reservoir. A significant gas injection occurring continuously during a period of one-month correlates very closely with the appearance of a coherence anomaly at the location of the reservoir, indicating significant sensitivity of the CCW method to the underlying fluid movements occurring within the reservoir.

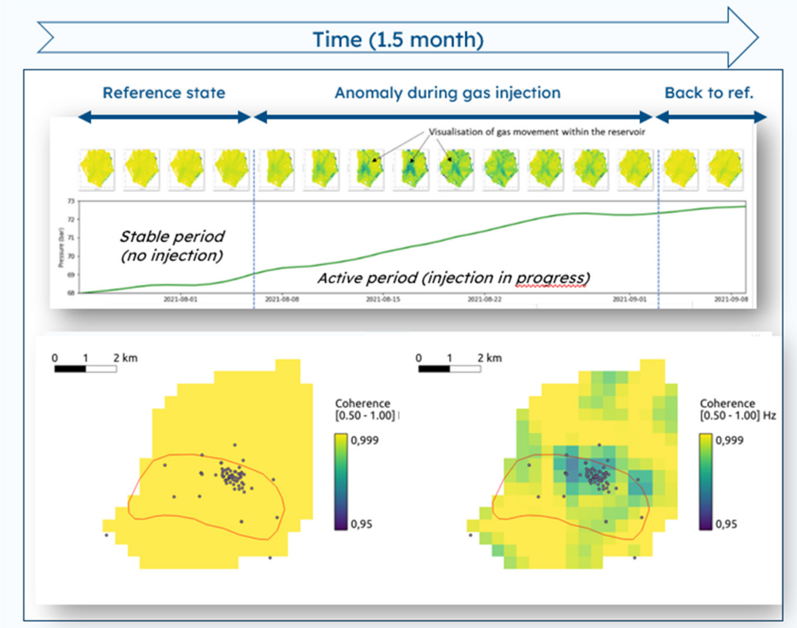

__Figure 2.__ Illustration of applying the CCW method for the monitoring of geological gas storage sites. Upper : timeline of coherence spatial distribution maps reconstructed every 3 days, compared to the gas injection dynamics occurring at the storage site. Lower: zoom on a map reconstructed during a stable (no gas injection or production) period (Left) and an active period (Right).

4 Conclusions

Passive seismic interferometry provides ways of continuously monitoring the evolution of seismic properties within the subsurface, for a low cost of implementation. In particular, velocity monitoring has initially been dedicated to structural monitoring of soils but has more recently demonstrated high promises for hydrogeological applications that can directly serve the design of groundwater management strategies, which will become more crucial as tension on water resources increases along with climate change.

For deeper fluids related issues, e.g. geothermal systems, geological gas storage monitoring, native gas exploration [17], we propose an innovative approach based on attenuation monitoring through the measure of waveform coherence. This method demonstrated temporal and spatial sensitivity to reservoir dynamics at a geological gas storage site and possesses a high potential for all applications implying fluid movement detection and localisation.

Overall, the intrinsic advantages of passive seismic interferometry (temporal and spatial continuity), combined with accessible costs of implementation, constitutes an important set of methods to face the geoscientific challenges awaiting in the domain of energy and resources.

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