Proceedings World Geothermal Congress 2020+1
Reykjavik, Iceland, April - October 2021

Monitoring of EGS Reservoir with Ambient Seismic Noise Interferometry: Case study of Rittershoffen Site (France)

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Keywords: Passive reservoir monitoring, ambient seismic noise, wave scattering, reservoir geomechanics

ABSTRACT

The monitoring of EGS reservoirs using ambient seismic noise is emerging as a potentially interesting tool for a low cost and continuous survey of deep geothermal reservoirs. We apply here ambient noise coda wave interferometry to almost 6 years of continuous data at two short period seismic stations located in the vicinity of a deep geothermal EGS project located in Rittershoffen (northern Alsace, France), seven kilometers to the southeast of the historical EGS pilot project of Soultz-sous-Forêts. The reservoir is located 2.5 kilometer deep and the exploitation is continuous since second half of 2016. Using a multiple reference approach, we compute the matrices of the optimal stretching coefficient and related maximum coherence for every pair of days and for the nine pairs of components and apply a weighted scheme to recover seismic velocity variations over time. For the 3 analyzed frequency bands (2-5Hz, 1-3Hz, 0.1-0.5Hz) we observe stable cross correlation functions and coherent velocity variations. Times series are compared to the various stages of the stimulation and exploitation of the Rittershoffen geothermal reservoir. To interpret the observed velocity variations, we developed a direct modeling of the effect of reservoir deformation on coda wave interferometry due to acousto-elastic strain induced by annual fluid pressure changes related to the fluctuations of the water table elevation. The model is based on a combination of a wave propagation modeler (Specfem2D) and a THM open source code (code Aster). Accounting for such surface effects appears to be a mandatory step to allow for the monitoring of deep reservoir using ambient noise interferometry.

1. INTRODUCTION

The northern Alsace region, part of the Upper Rhine Graben, hosts one of the most important geothermal anomaly of mainland France. Several deep geothermal projects based on the Enhanced Geothermal System (EGS) technology have been initiated in the area over the past few years (Lu, 2018). In this study, we focus on the Rittershoffen project (ECOGI), located seven kilometers to the southeast of the historical pilot plant of Soultz-sous-Forêts. It consists in a doublet of wells drilled during fall 2012 for the first one (GRT1) and spring 2014 for the second one (GRT2), reaching 2526 and 2708m depth (TVD) respectively, and crossing a major normal fault zone where hot water is expected to circulate (Baujard et al., 2017). A hydraulic stimulation has been performed in April 2013 to enhance the productivity of GRT1. For GRT2, production and circulation tests have shown that no reservoir development was required. The site has entered its operational phase in May 2016 and is producing up to 24 MWth of heat. Long term geophysical monitoring of such deep geothermal reservoirs is of primary importance for the continuous assessment of the reservoir productivity and the management of environmental risks like induced seismicity, aseismic deformation or sub-surface leakeages. Among the various geophysical monitoring tools, a permanent seismic network is often mandatory. In Rittershoffen, such a seismic network has been operated since 2012 and allowed the monitoring of the micro-seismicity induced during the GRT1 stimulation (Lengliné et al., 2017). Here, we want to take advantage of this long and almost uninterrupted time series to study the applicability of recently developed monitoring approaches based on the ambient noise coda wave interferometry (Sneider, 2006). Indeed, such technique can potentially highlight tiny seismic velocity changes in the subsurface from the related variations in the coda of cross-correlation functions computed from ambient noise recorded at pair of stations (Lehujeur et al., 2017).

The application of such ambient noise-based monitoring techniques to the abundant data from the permanent seismic stations installed around geothermal plants, opens perspectives for the monitoring of the evolution of deep geothermal reservoirs using a non-intrusive monitoring technique. Past applications of ANI techniques prove that ambient noise-based monitoring methods could support the reservoir management in various geotechnical contexts, by opening perspectives for the development of a tool enabling to detect and locate an aseismic evolution within the reservoir. Obermann et al. (2015) show in St-Gallen that a significant loss of waveform coherence is measured in the ambient seismic noise cross correlations, starting with fluid injections aiming the development of the reservoir when other processes conducted by the operator in the wells did not lead to such change in the waveforms. The continuous monitoring of the deep geothermal reservoir from ANI measurements could have made it possible to anticipate unwanted evolution in the reservoir and may have avoided the closure of the deep geothermal project due to the gas kick. Applied to the stimulation of the reservoir of the Bales project, such noise based monitoring techniques showed to provide important observables which are complementary to results obtained with standard micro seismicity tools and which could be applied to support the reservoir management in a variety of geotechnical contexts, such as for fluid injection or hydraulic fracturing (Hillers et al., 2015). In particular, Hillers et al. (2015) detected and located an aseismic transient deformation induced by the 2006 Basel EGS stimulation using these ambient seismic noise techniques.

Ambient noise interferometry is a highly sensitive technique but the methods still suffer from problems for the interpretation of the measurements. For example, the understanding of the time-serie of the ANI and of the annual variability, repeated from year to year, highlighted when filtering the cross-functions in the [1-3] Hz band (Lehujeur et al., 2015), remains uncertain. Indeed, the physical processes at the origin of the measurements are not clearly identified. More generally, the physical processes at the origin of the CWI measurements are not well understood. Physically, the measurements are usually interpreted as small variations of seismic velocities, owing to different factors such as water table elevation variations, temperature perturbations, or changes in the stress state (Lockner et al., 1977; Planès and Larose, 2013; Snieder, 2002). Deformation is a contribution to the measurements that is generally neglected, as velocity changes are supposed to dominate the signals (Yamamura et al., 2003). Moreover, the measurements usually encompass all the sensitivity of the diffusive waves toward the multiple processes involved in the perturbation of the medium, which makes it difficult to decipher the different contributions toward the measurements. The study of the processes at the origin of the measurements is therefore of key importance. Here, we developed a new numerical modeling that aims at a better understanding of the physical changes deduced from CWI, with a focus on the influence on interferometry measurements of the non-linear elastic deformation of the sample.

2. DATA AND PROCESSING

The permanent seismic network around the Rittershoffen site is operated since mid 2012 and consists in 4 stations equipped with 3-components short period 1Hz sensors (L4C 3D) and digitized by Quanterra Q330S at 100Hz or 200Hz (Fig. 1). Here we focus our study only on the RITT and BETS stations which are 2.6km apart and located in the vicinity of the geothermal power plant, respectively 1.6km to the east and 1.0km to the west of the platform (Baujard et al, 2017, Lengliné et al, 2017). A spectral analysis of the continuous records has been performed to estimate the various sources of ambient noise in the area. The spectrograms show a clear change in the noise pattern at ~1Hz. At lower frequencies, the dominant sources of noise correspond to the secondary microseismic peak originating from the interaction between ocean swells and sea floor in the North Atlantic Ocean (Lehujeur et al., 2015), exhibiting a clear annual periodicity with stronger amplitudes during winter periods. At frequencies higher than 1Hz, we observe weekly and diurnal periodicities typical of anthropogenic sources due to human activities in the villages and traffic along nearby roads. The drilling periods of the GRT1 and GRT2 wells are also clearly visible at frequencies higher than a few Hz. We also observe occasional transient events lasting for several weeks at frequencies between 0.5 and 2Hz. These transients do not show any clear periodicity but are characterize by a very similar spectral signature arguing for a common source, not yet identified.

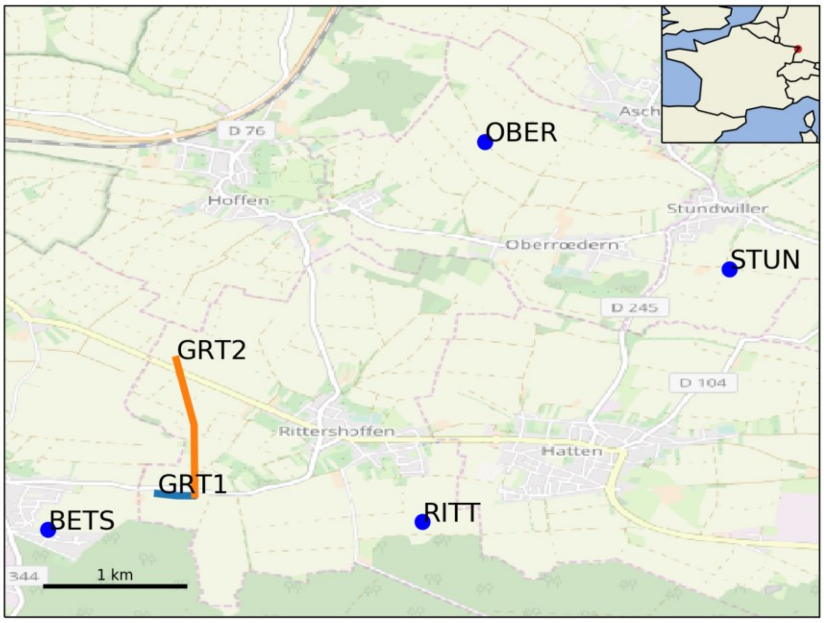

Figure 1: Map of permanent stations located around GRT1 and GRT2 boreholes at Rittershoffen site.

The preprocessing of the continuous records at the RITT and BETS stations includes a sequencing in 1 day long records, a down sampling at 24 sps, a spectral whitening (by replacing the amplitude spectrum with a step window between 0.1 and 11 Hz), and a 1-bit time domain normalization (keeping only the sign of the signal). These modified 1-day records are cross-correlated to produce ambient noise cross-correlation functions (ANCF) which are then averaged over 10 days with a one-day time step. This processing is similar for the nine pairs of components between the two stations. For each pair of component, we compare each ANCF to all the other ones using a multi-reference stretching approach in a way similar to Sens-Schönfelder et al. (2014). We look for the stretching coefficient that maximizes the coherence between one reference ANCF and all the other ones and iterate over the reference ANCF. The optimum stretching coefficients and related coherence values are stored in two matrices (Fig. 2). The analysis is performed between -80s and +80s on the ANCF without rejecting the central part of the correlation function where the ballistic waves of the empirical Green function are expected.

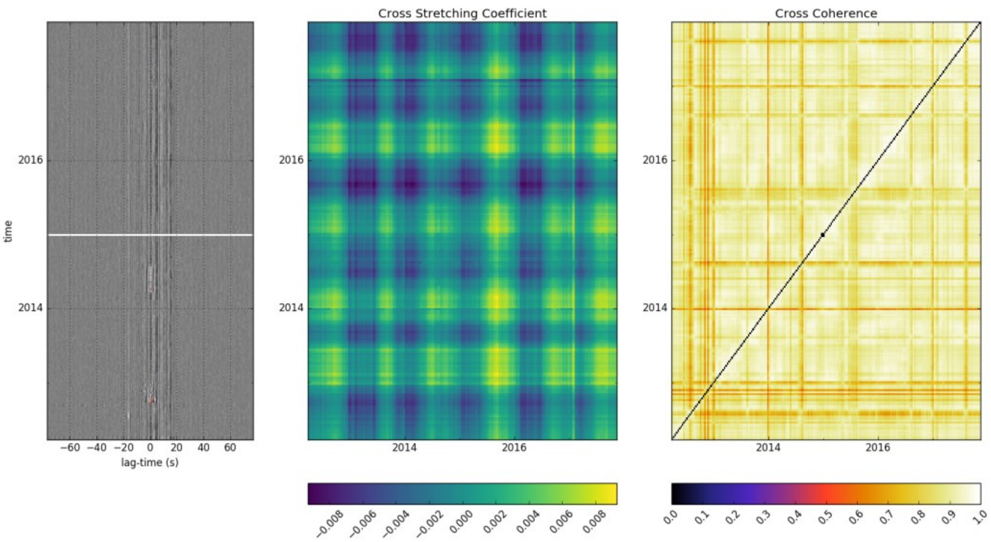

Figure 2: (left) Ambient noise cross-correlation functions (ANCF) between North components of stations RITT and BETS averaged over 10 days and filtered between 1 and 3Hz. (middle) Cross matrix of the optimum stretching coefficient between each daily ANCF pair. (right) Cross matrix of the maximum coherence coefficient between each daily ANCF pair for the optimum stretching value.

3. ANALYSIS IN THREE FREQUENCY BANDS

Considering the depth of the targeted structures (down to 3 km depth) and the bandwidth of the instruments, our frequency range of interest extends from ~0.1Hz to 5Hz. We analyze the nine pairs of components of the ANCF in three different frequency bands (2 to 5Hz, 1 to 3Hz and 0.1 to 0.5Hz) roughly spanning the various type of noise sources we inferred from the analysis of the raw data. For each pair of component and each frequency band we compute the time series of the velocity variations around the stations by averaging each line of the cross-stretching coefficient matrix weighted by the cross-coherence matrix. This weighting scheme tends to favor days when the coherence is higher in the estimation of the velocity variations, mitigating effects due to changes in the origin of the noise sources.

3.1 The 4-5Hz frequency band

In the 4-5Hz frequency band the nocturnal noise has been shown to be more stable over time and, therefore, more suitable for temporal analysis of the ANCF (Lehujeur et al., 2015, 2017a, 2017b, 2018). Both on the causal and acausal side, the times series of the optimal stretching coefficient shows a positive drift with a sudden 0.4% drop in June 2013, coinciding with the drilling of the GRT1 well. Moreover, a decrease in the coherence is observed in June 2014, just after the hydraulic stimulation of this well. These changes were first suspected to be linked to operations on the geothermal site.

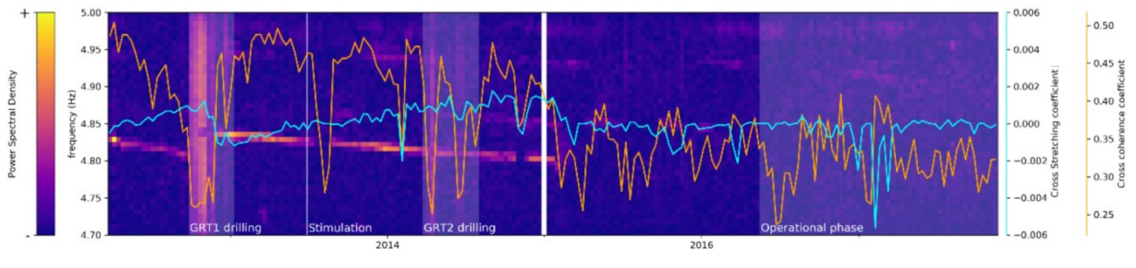

Figure 3: Time series of the optimum stretching coefficient (cyan line) and the average coherence coefficient (orange line) for the vertical components of RITT and BETS stations and filtered between 4 and 5 Hz. Background figure represents the spectrogram of the ANCFs over the 4.7-5Hz frequency band. Shaded area indicates the major phases of the geothermal project.

However, a pervasive spectral line with similar patterns (drift in frequency, sudden drop in June 2013, interruption in June 2014) is observed around 4.8Hz in the raw data spectrograms. The visualization of spectrum filtered to 4.7-5.0Hz is shown in the background of Fig 3. We observe the spectral line from the beginning of the dataset, at the beginning frequency of spectral line is 4.84Hz and it decreases with linear trend down to 4.8Hz that reaches in the end of 2012. It’s not visible in last months of 2012, most probably due to the saturation of spectrum with signal generated by drilling of GRT1 borehole. When the drilling finishes, in the beginning of 2013, spectral line becomes visible again. When it happens, it starts at frequency of 4.85Hz and it decreases down to 4.8Hz which it reaches in the beginning of 2015. There are two minor breaks in visibility of spectral line, in mid-2013 and around November 2014. The frequency does not change after those breaks. Due to some major similarities in observation of frequency shift trend of spectral line and the trend of change of stretching coefficient, we interpret this apparent velocity change as to be caused by this line. When the spectral line is visible, the apparent velocity change (cyan line) is also following a stable linear trend. When the line fades out, the trend in apparent velocity change also fade out. It leads to a conclusion that the trend in dv/v is caused by that spectral line, even though the line is very narrow and a band in which the stretching was calculated is much wider.

Due to the effect of this spectral line into velocity variation analyses, it is extremely important to understand its characteristics and its origin. Proper understanding of the phenomenon is necessary in order to avoid invalid interpretations. Similar spectral lines were observed and analyzed before. Some of them were observed in very repeatable patterns and linked to human induced sources such as railroad activity (Fuchs et al., 2018). Other studies link narrow band signals with frequency of power grid and thus with machines working with similar frequency (Bokelmann & Baisch, 1999). Similar lines on much lower frequency, were studied by multiple research teams (Holcomb, 1998; Shapiro et al., 2006) and were recorded worldwide linked to natural sources.

Figure 4 is showing spectrograms of signal coming from two stations located about 70 kilometers from each other, on both the spectral line was observed. The spectral line of interest starts in the January of 2010 and lasts with minor breaks to January of 2015. Actually, the spectral line was observed up to 250 km away from the Rittershoffen site at numerous regional seismic stations with a maximum amplitude loosely centered in the Upper Rhine Graben. Subsequently, this spectral line is probably due to an anthropogenic source, perhaps a nearby pipeline, and its frequency evolution spuriously translates into artificial velocity variations unrelated to the reservoir evolution, as already observed by Zhan et al. (2013) for another frequency range.

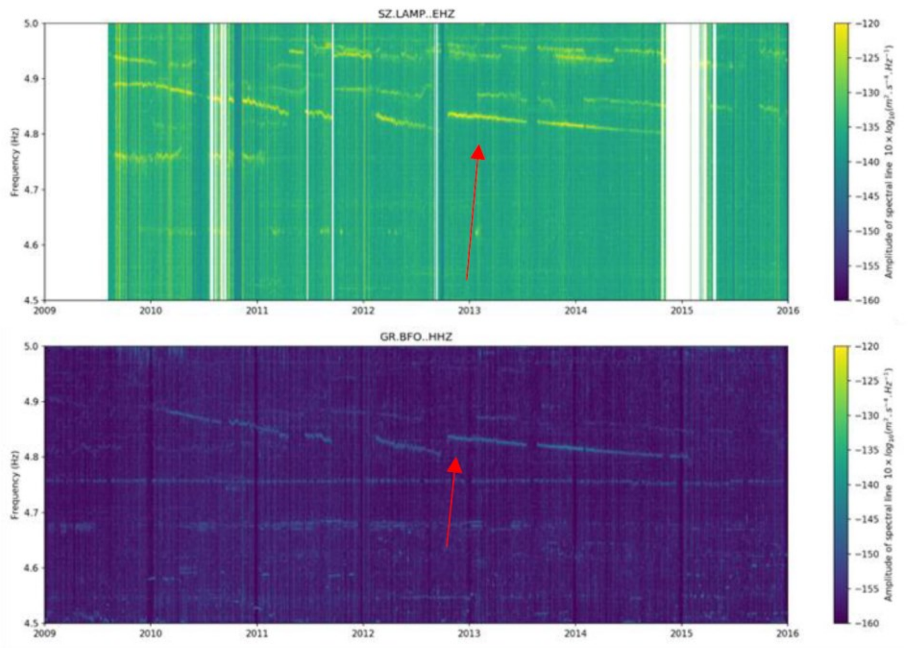

Figure 4: Spectrograms of Z channels of SZ.LAMP and GR.BFO stations separated by 70 km where the same spectral lines were observed. Spectral line of interest is marked with red arrows.

3.2 The 1-3Hz frequency band

In the 1-3Hz frequency band we observe a high mean coherence value of the ANCF for most of the period but with sudden drops during the transient events seen on the spectrograms at RITT and BETS (Fig. 5). These drops do not strongly affect the temporal variations of the seismic velocity which show a clear annual periodicity. Both the phase and the relative amplitudes of these velocity variations fit well with changes in the local water table elevation (Fig. 5), located at a few meters depth in the area. The ability to monitor changes in the water table with ambient noise interferometry has already been observed in other contexts (Voisin et al., 2016). This means that, in the sensitivity frequency band, the water-table induced velocity variations have to be modeled and removed in order to detect potentially smaller velocity variations related to the stimulation or exploitation of the geothermal reservoir.

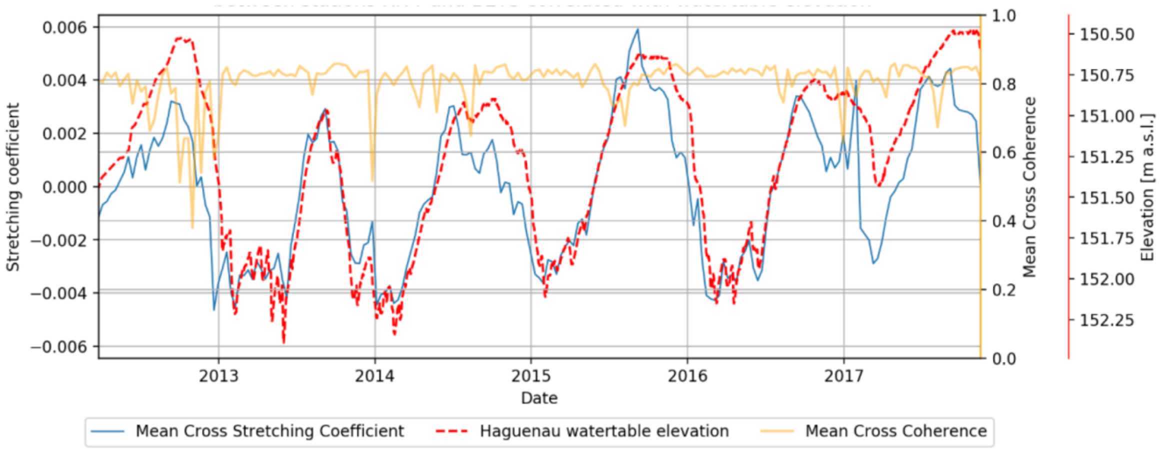

Figure 5: Comparison between the time series of the optimum stretching coefficient between the North components of RITT and BETS and filtered between 1 and 3 Hz (continuous blue line) with the evolution of the water table elevation at the nearby Haguenau hydrological station (red dotted line).Time series of the average coherence coefficient is shown in orange.

3.3 The 0.1-0.5Hz frequency band

In the 0.1-0.5Hz frequency band we also observe an annual periodicity of the seismic velocity variations (Fig. 3 top). However, these variations are not in phase with the ones observed in the 1-3Hz band and are therefore probably not related to changes in the water-table elevation. They may be related to other environmental effects at greater depth or they may be artifacts related to the temporal variability of the frequency content of the secondary microseismic peak which has a similar periodicity. Whatever the mechanisms, this may again hide effects related to the deep geothermal reservoir evolution.

Interestingly, a unique drop in the ANCF coherence (Fig. 3 bottom) is observed following the GRT1 stimulation and does not seem to be linked to any known changes in the noise characteristics. We suspect that this decorrelation may be related to changes in the diffracting pattern within and around the geothermal reservoir due to the fluid injection. A much more important decorrelation has already been observed during a gas kick accident at the Saint-Gallen geothermal site (Obermann et al., 2015).

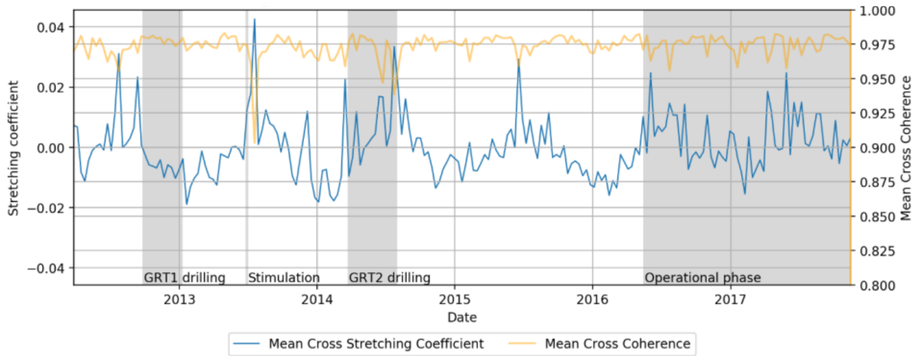

Figure 6: Time series of the optimum stretching coefficient between the vertical components of RITT and BETS and filtered between 0.1 and 0.5 Hz (blue line) and corresponding time series of the average coherence coefficient (orange line). Gray shaded area and vertical line indicate the drilling phase of GRT1, the hydraulic stimulation of GRT1, the drilling of GRT2 and the operational phase of the power plant. Note the annual periodicity of the stretching coefficient with maximal values during winters and the decoherence occurring just after the GRT1 hydraulic stimulation.

4. NUMERICAL MODELING

When the data are filtered in the [1-3] Hz range, the time-series of the CWI measured between stacked ANCFs shows clear annual periodicity (Fig. 5). The physical processes at the origin of the trend are not well understood. The filtering band as well as the reproducibility of the measurements suggest that natural surface phenomena, acting at shallow depth and strongly reproducible, are at the origin of the measurements. Surface temperature and water table elevation variations are among the natural phenomena showing such a reproducibility from year to year. But these natural processes could also bias the monitoring of the reservoir evolution: the applicability of ambient noise based techniques to support the reservoir management in various geotechnical contexts (fluid injection or stimulation operations, for example) necessitates that the contribution of the change in the reservoir can be distinguished from the contributions of natural surface phenomena. The identification of the processes at the origin of the measurements is important to better our understanding of the time series measured but also to open perspectives for the removing of such unwanted effects in the reservoir monitoring.

To get insight in the process at the origin of these measurements, we developed a numerical model aiming at modelling the stacked time-serie measured in the vicinity of the Rittershoffen project. The numerical sample is a 2D representation of a geological section of the geothermal reservoir, made of thick granitic layer covered by a sedimentary cover that includes up to five layers (Fig. 7). The The lower part of the model is extended to include large round heterogeneities behaving as numerous scatterers which create a strong impedance change between the bulk and these inclusions. We combined the elastic deformation of the sample including acousto-elastic effects, resulting from the variations of water table elevation using a finite element approach (*Code_Aster*) and, to the simulation of the wave propagation using a spectral element approach (SPECFEM2D) (Azzola et al, 2018, 2020). The one year loading procedure is discretized in successive stages of one month.

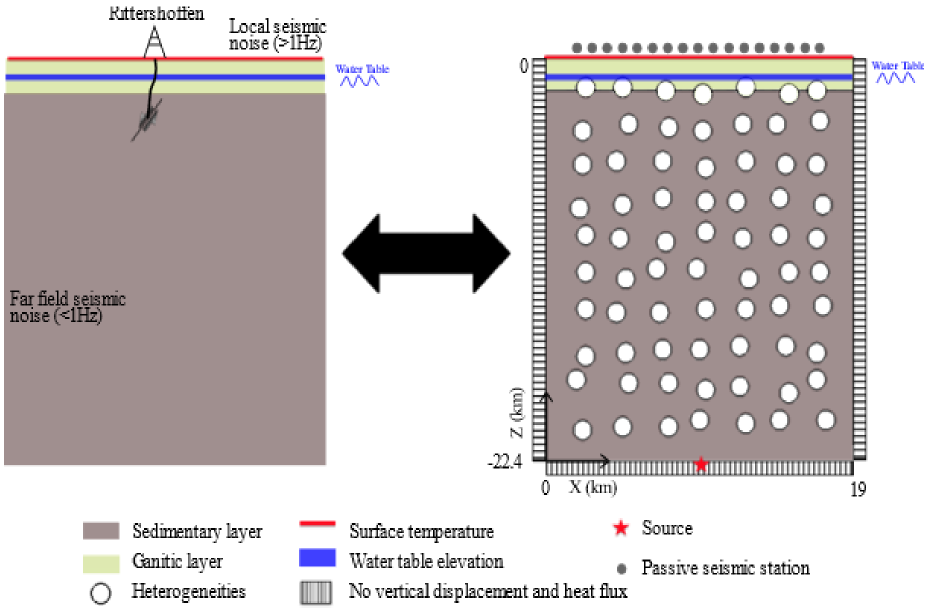

Figure 7: principle of the numerical model developed to model the signature on the interferometry measurements of annual surface temperature and water table elevation variations and local changes within the reservoir. The sample consists in a 2D representation of a geological section of the reservoir under Rittershoffen extended down to 22.4km to include a large number of scatters. The boundary conditions for the deformation modelling (i.e. pressure variations) act superficially and the deep part with large heterogeneities aim at scattering the wavefield propagated from the source in the seismic propagation modelling.

The numerical model aims at reproducing the impact of the annual variations of the water table elevation measured in the vicinity of Rittershoffen. These perturbations, which are applied at the top boundary of the sample, act mechanically through the whole sample. The lower part of the model with a dense population of asperities (Figure 7) intend to strongly scatter the wavefield in order to retrieve the same scattering conditions in the numerical model than with the field recorded ambient noise in the vicinity of Rittershoffen reservoir. In addition to model the signature on the CWI of the ambient noise cross-functions of annual perturbations in water table elevation, the numerical model aims also at studying the influence of a pressure perturbation at depth in the reservoir, which could potentially be related to a transient deformation. We model here increases of pressure (1, 10 or 100 MPa) in a kilometric region centered at the bottom of the Ritterhoffen deep wells (around 2.5 km deep).

For a validation of the approach, we first compare the scattering properties deduced from the ambient noise recorded in a pair of stations in the vicinity of Rittershoffen, to those retrieved from the numerical model (Figure 8). We base our comparison on the measure of the temporal variation of the dimensionless seismic energy U(r,t) and on the estimation of the mean free path from a least square regression comparing the measurement to a simple diffusion model (Wegler and Luhr, 2001; Olivier et al, 2015; Azzola et al, 2018).

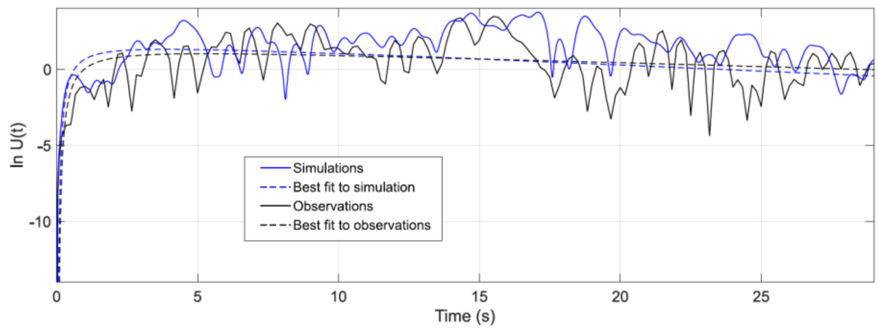

Figure 8 : The scattering properties are characterized from the measurement of the temporal variation of the seismic energy using the cross-functions of the north components of the RITT and BETS stations (black line), and from the cross-functions measured in the simulation (blue line). We show a logarithmic and normalized expression of the energy

density, enabling to estimate by least square regression to a diffusion model, the mean free paths. Dotted lines show the best fit determined by the least square method.

Figure 8 shows the evolution of ln(U(t)) calculated from simulated (blue lines) and field measurements (black lines), using the 40 s long causal and acausal parts of the cross-correlation functions of the seismic noise. In Fig. 8, we show the progressive stabilization of the seismic energy which is characteristic of the diffusion regime. It shows that the numerical model reproduces well the scattering behaviour of the geological domain sampled by the ANCFs. Figure 8 also represents the best fit of the energy function assuming a diffusion model. From this fit, we deduce the mean free path $\ell = 1.27$ km in the numerical case and $\ell = 1.24$ km with the measurements at the RITT and BETS stations. The agreement between the estimated mean free paths also indicates that the numerical model reproduces the wave scattering of the deep reservoir.

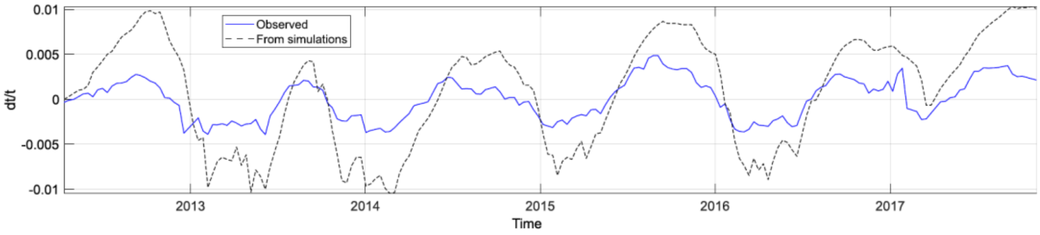

Figure 9: annual variation of the stretching coefficient obtained from the simulation (black dotted curve), by modelling the influence of the water table elevation (Fig. 5). The measurements are compared to the time series of the stretching coefficient for the North components of RITT and BETS (blue curve).

The application of ANI techniques requires the establishment of a strong scattering regime; i.e. the emitted wavefield is expected to encounter heterogeneities several times before being recorded by the receiver if the wavelength λ of the incident wave is of the same length or shorter than the size of the heterogeneity. To assess strong scattering condition, the mean free path ℓ, the wavelength λ, the defect size d and the distance from source to receivers D are expected to satisfy the inequality: $\lambda < d \leq \ell < D$ (Planes and Larose, 2013). In our simulations, we neglect attenuation effects and we do not consider in the inequality the intrinsic absorption characteristic length ℓ_a included in the inequality proposed by (Planès and Larose, 2013). The mean free paths inverted using simulated record ($\ell = 1.27$ km) or field records ($\ell = 1.24$ km) satisfy this inequality. In the numerical model, the diameter of the heterogenities is d = 1.2 km and the wavelength, which is calculated in the case of the simulations using the wave velocity and source frequency considered, is λ = 1 km. This inequality and the progressive stabilization of the seismic energy highlighted from Fig. 8 proves that the multi-scattering condition is satisfied in the numerical case and using the ambient seismic noise recorded in the vicinity of Rittershoffen.

We show that the time series measured from the North component of the RITT-BETS station pair, operating in the vicinity of Rittershoffen, is retrieved in the numerical model (blue and black curves in Figure 9 respectively). The time-series is correlated to the annual variation in water table elevation. Considering the similarity of the approaches and the good agreement between the annual variations measured in the simulations and from the field observations, we show that the water table elevation variations have a dominating influence on the annual time series in the vicinity of the deep geothermal reservoir in Rittershoffen.

The identification of the processes at the origin of the interferometry measurements opens new perspectives for the monitoring of the reservoir. We show that natural surface phenomena, unrelated to the reservoir evolution, can induce potential bias in the monitoring of the reservoir evolution. After removing these biases, the evolution of the deep geothermal reservoir, such as an increase in pressure at depth, could be monitored from ambient noise based passive monitoring techniques. The impact of non-elastic processes, related for example to the creation of new fractures or the growth of pre-existing ones, are not included in our study. Such processes, which could be related to the development of damage, are expected to strongly modify the scattering properties of the medium. The waveform coherence is expected to provide complementary information for the monitoring of such medium perturbation.

5. CONCLUSION

From 6 years of continuous seismic data recorded at two stations the vicinity of the Rittershoffen deep geothermal power plant, and spanning its various construction phases, we computed the ambient noise correlation functions and analyze them to estimate changes in the velocity or diffracting character in the surroundings of the reservoir in different frequency bands. This work illustrates how changes in the noise characteristics over time or natural phenomena (such as changes in the water table elevation) can hide the signal related to the stimulation or exploitation of the reservoir.

We propose a numerical model aiming at identifying the surface processes at the origin of the temporal variations measured using the ambient noise recorded in the vicinity of Rittershoffen geothermal site. The identification of the processes at the origin of the measurements opens perspectives for the removing of possible biases in the monitoring of the reservoir evolution. Our measurements show that changes in relative time delays could be interpreted in the field by slight changes in the stress state intervening in a reservoir rock mass. The loss of coherence between the waveforms could be interpreted by a local development of damage related to the growth or birth of new fractures. Such interferometry technique could interestingly be applied to seismic activity monitoring or to track the propagation of a hydraulic fracture, providing important observables which are complementary to results obtained with standard microseismicity tools.

By using permanently recording permanent seismic networks generally densely deployed around geothermal plants, the high resolution and the strong sensitivity of CWI could support the reservoir management and contribute to the anticipation of fast evolutions such as transient aseismic deformation intervening possibly during the reservoir development. However, the development of monitoring methods based on ambient seismic noise requires an increase in the number of observables and the processing of the abundant seismic noise data in order to cross-reference the measurements and make the observations reliable.

Acknowledgments

This work has been performed under the framework of the LABEX ANR-11-LABX-0050-G-EAU-THERMIE-PROFONDE as part of the 'Investments for the Future' program. It has also been funded by the EGS Alsace grant from ADEME, the consortium COGEOS (Electricité de Strasbourg/EOST) and a Grant from Storengy/Engie.

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