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Investigating a Deep Geothermal Reservoir Using Ambient Noise Correlation

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ABSTRACT

The ambient noise cross correlation technique is widely used in seismology and many examples of its can be found in the literature. The method determines the Green's function between a pair of receivers by correlating sufficiently long seismic noise records. However, few applications of the method have been performed at a local scale and at periods lower than 5s, where the seismic noise is mostly dominated by anthropogenic sources. This represents the context of our study in the area of Rittershoffen (North-East of France) where a deep geothermal plant (2500m) is about to be installed (ECOGI project). The aim of this study is to build an image of the geothermal reservoir using ambient noise cross-correlation at high frequencies (0.2 to 5 Hz) and to follow the evolution of the reservoir during the production period. We have applied the standard surface-wave ambient noise cross-correlation technique to about 3 years of continuous data recorded by short-period permanent stations in this region. At periods below 0.5 s, the dispersion curves are poorly constrained and the correlation functions are less stable over time. It appears that the non uniform distribution of the noise sources plays a major role in the poor quality of the correlation functions in this period range. An on-going approach based on beamforming from local seismic arrays is shown to provide significant improvements.

1. INTRODUCTION

The quality of a deep geothermal site relies not only on the presence of high temperatures at shallow depths but also on the existence of fluids and their ability to flow through the fracture network. Knowledge of the structures and their evolution in time is necessary to understand and predict the reservoir behavior. In this study, we work on the site of Rittershoffen, next to the site of Soultz-sous-Forêts (GEIE-PMC), where a deep geothermal loop is about to be installed (ECOGI project). An Enhanced Geothermal System (EGS) will be established at ~2500m depth using a combination of 2 wells. Our objective is to monitor the reservoir (~10 km² large / 3 km deep) through the estimation of the seismic wave velocities as a function of space and time in order to follow the reservoir's life during the exploration and the exploitation periods. Seismic tomography is an appropriate method to perform this task. The usefulness of such monitoring was demonstrated by Calò et al. (2011) who performed a 4D tomographic study of the reservoir of Soultz-sous-Forêts based on a joint inversion (location and velocity model) of micro seismic events generated by a hydraulic stimulation. Strong variations of the P wave velocities were suggested in the reservoir from the stimulation of well "GPK2" in 2000 but not from later stimulations (Calò and Dorbath, 2013). Another potential method is the use of ambient noise tomography. Many studies over the past 20 years have shown that seismic noise can be used to infer the medium properties and follow their evolution in time with a resolution of weeks to months (e.g. Shapiro et 2005, Brenguier et 2008). Compared to individual micro seismic events, ambient noise provides continuous information, and does not require seismic source locations and origin times. However the method of ambient noise correlation requires long continuous records to provide a reliable image of the subsoil. In addition, the theory of noise correlation relies strongly on the assumption of uniform source distribution. The validity of this assumption may vary depending on the frequency of interest. Within the frequency range used in this study (0.2 to 5 Hz), the noise is a combination of several sources. The secondary micro-seismic peak, which is usually attributed to pressure variations induced on the sea bottom by interfering oceanic waves (Longuet-Higgins, 1950), dominates the ambient noise at ~0.2 Hz, while the noise recorded above 1 Hz is dominated by local sources often related to human activity (Campillo et al., 2011). Above 2 Hz, the noise is generated by very local sources whose distribution is clearly not uniform. For this reason, the efficiency of the classical correlation method becomes very poor and a better knowledge of the high frequency noise properties is required.

2. DATA

The data used in this study results from the combination of two networks of permanent stations as well as two temporary arrays (Fig. 1). The sensors are short period velocimeters with a cut off frequency of 1Hz. Four years of continuous recording are available from the Soultz network. Early in 2012, four additional permanent stations were installed to extend the network towards the future geothermal plant. Two temporary arrays (AKUL, ARIT) were installed next to the permanent stations KUHL and RITT during two months including the final drilling stage. Each array is made of seven seismometers separated of 30 to 150 m, connected with wires to a single digitizer allowing a very accurate time synchronization of the sensors. The two arrays were installed following a helical configuration in order to optimize both azimuthal coverage and sensor separation distribution. Sampling frequencies vary from 100 to 200 Hz depending on the stations.

3. CORRELATION FUNCTIONS AND DISPERSION CURVES

The Cross Correlation Functions (CCFs) of all possible combinations of vertical component of each sensor where computed providing 28 different station couples before the installation of the Rittershoffen network and 66 afterwards. For each pair of stations, we correlate the noise from the eastern receiver with the western one. So the effects of the western sources appear on the positive part of the CCFs (Stehly et al. 2006). The data is sequenced per hour. It is systematically pre-processed prior to the correlation, following the work of Bensen et al. (2007). This pre-processing consists in linear trend removal and cosine tapering, instrument response removal, spectral whitening, 0.1 to 30 Hz band-pass filtering and one bit digitalization. The correlation functions are then averaged over various time periods ranging from one week to one year. The CCFs averaged over 2012 are displayed on Fig. 2 (band-pass filtered between 0.2 to 1Hz, 1 to 2Hz and 2 to 5 Hz). They are sorted as a function of inter-station distance. The aspect of the CCFs varies with frequency range. Between 0.2 to 1Hz, the CCFs are asymmetric with a higher Signal to Noise Ratio (SNR) on the positive part of the CCFs (Fig. 2a). This indicates that the majority of low frequency sources are located west of the network. This is oceanic noise coming from the Atlantic and the North Sea and dominating the signal around 0.2 Hz. From 1 to 2 Hz, the CCFs are more symmetric and the average SNR is a bit lower (Fig. 2b). This is caused by regional to local anthropogenic sources that are more or less uniformly distributed around the site. Above 2 Hz, no coherent signal can be identified over the full network (Fig. 2c). Indeed the high frequencies propagate in the shallow structures affected by strong spatial variations and will produce very different results for each station pair. In addition, this frequency range is polluted by very local sources and, due to attenuation, the signal generated by many of these low energy sources never propagates far enough to be recorded by several stations, reducing the coherency of the noise records over the network.

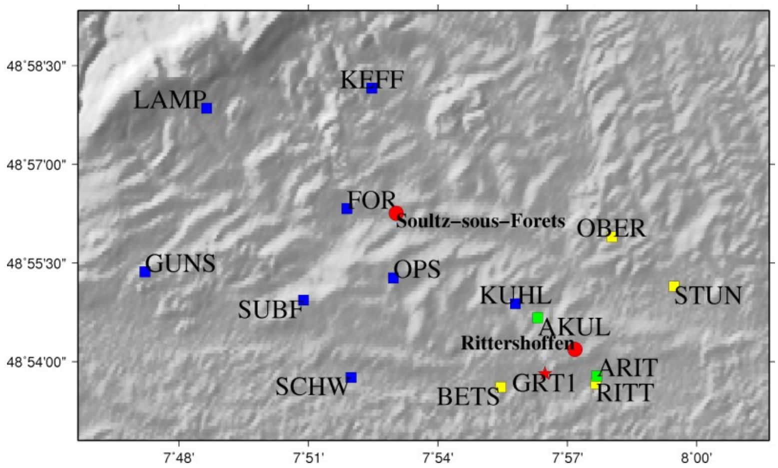

Figure 1: Seismologic station networks of Soultz (blue), Rittershoffen (yellow), and 2 arrays (green).

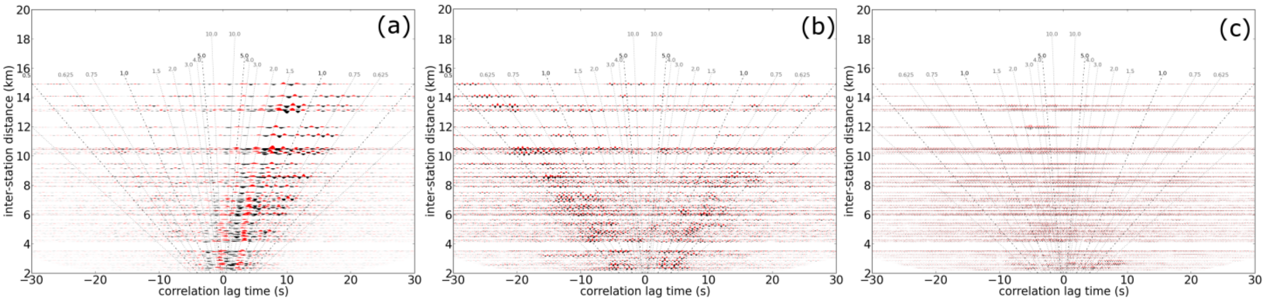

Figure 2: CCFs sorted by inter-station distance filtered between (a) 0.2-1Hz, (b) 1-2Hz, (c) 2-5Hz and normalized to their standard deviation

The averaged cross-correlation of long noise records provides an estimation of the Green's function between the recording points (Shapiro et al. 2005, Sabra et al. 2005, Roux et al. 2005). The Green's function is the full response of the medium and therefore describes the behavior of all wave types (direct and reflected body waves, surface waves). Since the surface waves dominate the signal in amplitude, they are also expected to provide the best SNR. Thanks to the dispersive behavior of these waves, it is possible to identify them using frequency-time analysis. The group velocity dispersion curves from the large majority of station couples are well defined below 1 Hz with a maximum SNR between 0.2 and 1 Hz. The signal is poor above 2 Hz because of a high noise level, hiding the dispersion curve (Fig. 3).

4. TIME VARIABILITY OF THE CCFS

Time variation of the medium properties can be estimated by applying the ambient noise correlation technique at different successive periods. To do so, the CCFs are averaged on a sliding time window providing an estimation of the evolution of medium properties through time (Brenguier et al, 2008). We compute the average CCF of each station pair on a sliding window running over 2012. The window width has been set to 24 hours with a 50% overlap. Good stability of the low frequencies is observed as well as strong continuity over the year (Fig. 4). This indicates that the sources responsible for the low frequencies occur quite continuously over the year (no clear seasonal effect is observed at low frequencies but application of the method on several years would be required) and a time averaging of 24 hours is sufficient to obtain a good quality of the CCFs at low frequencies. Lower repeatability of the high frequency content appears on the daily CCFs. The high frequency content of the CCFs observed end of 2012 (Fig. 4) is interpreted as the noise generated by the drilling of the first well GRT1 at 3km depth. This signal occurs close to the zero lag time of the CCFs due to the position of the drilling platform with respect to the stations RITT and BETS. Indeed, the platform is close to the middle of the RITT-BETS segment and the drilling noise is recorded by both stations quite simultaneously. By averaging the CCFs on extremely long time periods, this kind of local effects should theoretically cancel out and contribute to the exact medium response between receivers. However, short-time averaged CCFs can be very different from the Green's function due to non uniformity of the spatial source distribution.

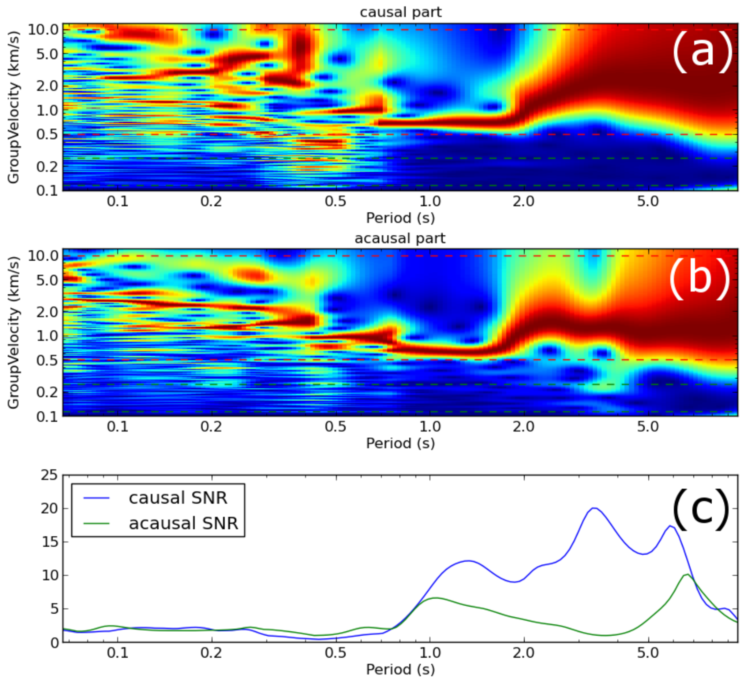

Figure 3: Dispersion curves obtained from the (a) causal and (b) acausal part of the FOR-LAMP CCF averaged over 2012 and (c) corresponding SNR curves.

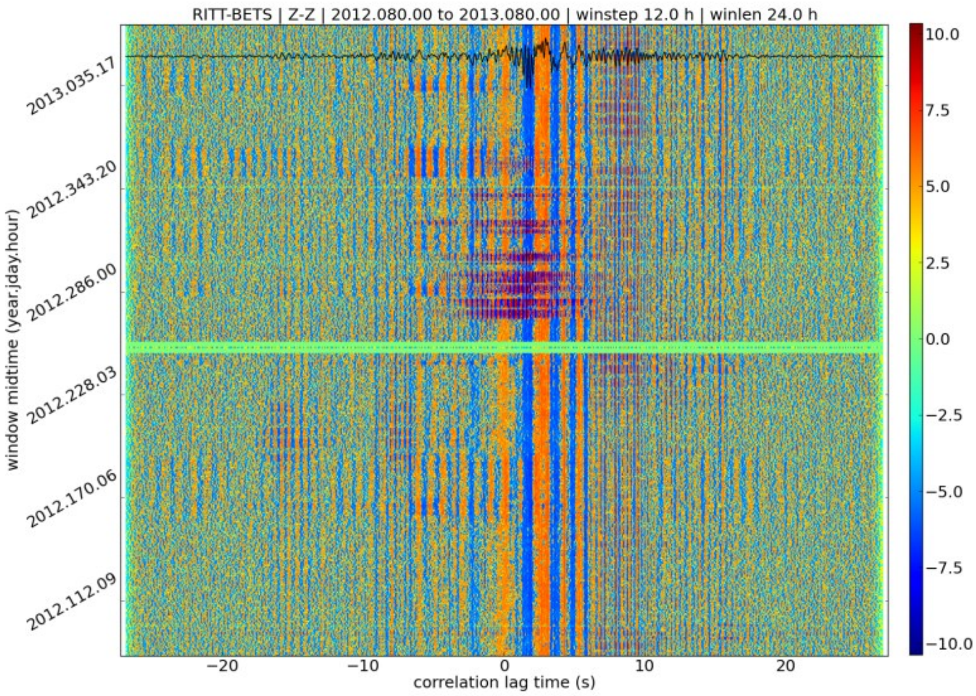

Figure 4: Variability of the daily CCFs of the RITT-BETS station couple over 2012 band pass filtered between 0.2 – 5 Hz.

5. ORIGIN OF HIGH FREQUENCY NOISE SOURCES

As compared to individual stations, seismic arrays provide spatial information allowing the estimation of incoming noise propagation direction and phase velocity using the beamforming method. The two temporary arrays ARIT and AKUL were installed in order to better understand the origin of the high frequency noise sources in the area. We bound the frequency range to 1 – 8Hz because of the array dimensions: higher frequencies will be spatially aliased and lower frequencies will produce too small time delays between receivers to be reliably detected. Knowing the noise propagation direction and the amount of seismic energy received by the array as a function of time, we estimate the major directions of incoming energy at each array. Results are presented at 3Hz for both day-time and night-time data (Fig. 5). The spatial analysis shows that the major high frequency sources are located in the neighboring villages especially during day time. In addition, some very localized sources can be identified and become prominent during the night. These sources could be related to industrial activities. A clear signal pointing toward the drilling platform (GRT1) is identified. This indicates that the high frequency sources always occur at the same locations and long-time recording is not sufficient to obtain the spatial source randomization required by the method. A potential solution for this problem is to select the noise sources occurring along the station axis. Indeed it can be demonstrated that the averaged cross correlation of noise coming from such sources also converges toward the Green's function of the medium. This source selection can be done at each array individually using the spatial information provided by the arrays. We first estimate the average phase velocity dispersion curve under the array by using a classical beamforming method at several frequencies. Then we correct the signal recorded by each receiver by an appropriate time delay computed from the knowledge of the phase dispersion curve and the azimuth we want to isolate. The time-corrected traces of each receiver are then stacked. This results in a constructive summation of the noise coming from the selected azimuth and a destructive summation for all other azimuths. Finally, we cross correlate the azimuth filtered traces of the two arrays. The work is still on progress but encouraging results have been obtained showing that a clear enhancement of the dispersion curve definition can be expected at high frequency.

Figure 5: histograms showing the incoming directions of seismic noise energy. Computed at 3Hz on (a) day-time and (b) night-time data between 12/18/2012 and 02/13/2013. Source : « Rittershoffen » 48.903135°N, 7.953114°E, Google Earth. December 31, 2007. May 20, 2014. The scale is given by the distance Rittershoffen/Hatten which is 1.87km.

6. CONCLUSION

This study aims to provide a reliable image of a geothermal reservoir and observe its time variability. The use of ambient noise seems to be a good candidate because of its continuity over time. However, the method of ambient noise correlation relies on a set of assumptions that must be satisfied to ensure the stability of the results. In this work we focus on the properties of the noise recorded by a permanent network in the area of Rittershoffen in the frequency range adapted to the expected scale of the reservoir (0.2 – 5 Hz). The noise is mainly composed of two kinds of sources; (1) oceanic gravity waves that generate a signal with a dominant frequency of 0.2 Hz and propagating from the North-West toward the South-East and (2) local sources dominating the signal between 1 and 5 Hz whose origin is mainly related to human activity. The efficiency of the noise correlation method is directly related to the origin of the noise sources. Below 1 Hz, the method works very well, with a clear definition of the Rayleigh wave dispersion curve associated with high repeatability of the measurements. This will lead to the ability to observe large-scale structures of the geothermal reservoir as a function of space and time. However, the noise recorded above 2Hz is generated by very localized sources such that, long time recording is not sufficient to obtain a spatial randomization of the noise sources. This is the reason for the low efficiency of the correlation method above 2Hz. On-going work focuses on methods allowing to select the noise sources as a function of their location with respect to the receivers and how to adapt the method of ambient noise correlation in the context of non uniform source distribution.

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