On the feasibility of passive interferometry on a dense network for imaging and monitoring a geothermal reservoir

Lehujeur, M., Vergne, J., Schmittbuhl, J. and Maggi., A.

IPGS; Université de Strasbourg/EOST, CNRS; 5 rue René Descartes, 67084 Strasbourg Cedex, France.

Introduction

Over the past decade, a new seismic imaging technique has emerged. Known as "ambient noise correlation", the technique allows us to perform tomographic imaging without deterministic sources. The cross-correlation function (CCF) of long noise records has been proved to converge toward the Green's function between each pair of stations (Lobkis & Weaver, 2001; Shapiro & Campillo, 2004; Sabra et al., 2005a). Therefore, tomographic imaging can be applied using all possible pairs of stations over a network (Shapiro et al. 2005; Sabra et al. 2005b). The resolution of the recovered seismic velocity models only depends on the number of stations and the geometry of the network. Beyond its use in seismic tomography, the continuous nature of seismic noise can also be exploited to observe subtle variations in the seismic velocity or the diffracting character of the crust (Wegler & Sens-Schönfelder, 2006; Brenguier et al., 2008). Using a very dense seismic network designed to observe the first 5 km of the crust around the two geothermal sites of Soultz-sous-forêts and Rittershoffen, we compute the CCFs over time periods ranging from a few months to several years. Taking the characteristics of the noise recorded between 0.2s and 5s into account, we investigate the reliability of the Green's function reconstruction as well as the ability to monitor speed variations induced at depth by geothermal activities.

Data

A very dense network of seismometers is now available around the two geothermal sites of Soultz-sous-forêts and Rittershoffen. Two permanent networks (SZ and RT, figure 1) were first installed to monitor the natural and induced seismicity. They form a network of 12 short period stations equipped with 1 Hz L4C sensors and digitizers sampling at rates from 100 to 200 Hz providing high quality continuous recordings available since 2010 for the Soultz-sous-Forêts network (SZ) and since 2012 for the Rittershoffen (RT) network. More recently, several temporary networks have been installed. Sixteen short period sensors (1Hz corner frequency) were installed in May 2013 by the Karlsruhe Institute of Technology and Ecole et Observatoire des Sciences de la Terre of Strasbourg and completed next by 15 other stations (KIT1 and KIT2, figure 1). The network has been extended to longer distances and periods using seven broad band seismometers (20s corner period) installed at the beginning of 2014 on a radius of 15 km around the site of Rittershoffen. In order to extend our understanding of the origins of seismic noise to higher frequencies, we deployed two small aperture arrays that operated for two months during fall 2012. Each array contained 6 vertical short period sensors (1Hz corner frequency) with one 3-component L4C sensor at the center. All the sensors were connected by cables to a central acquisition system that provided a common time reference for the 9 recorded channels. They were deployed in a helical configuration with a 300m maximum aperture.

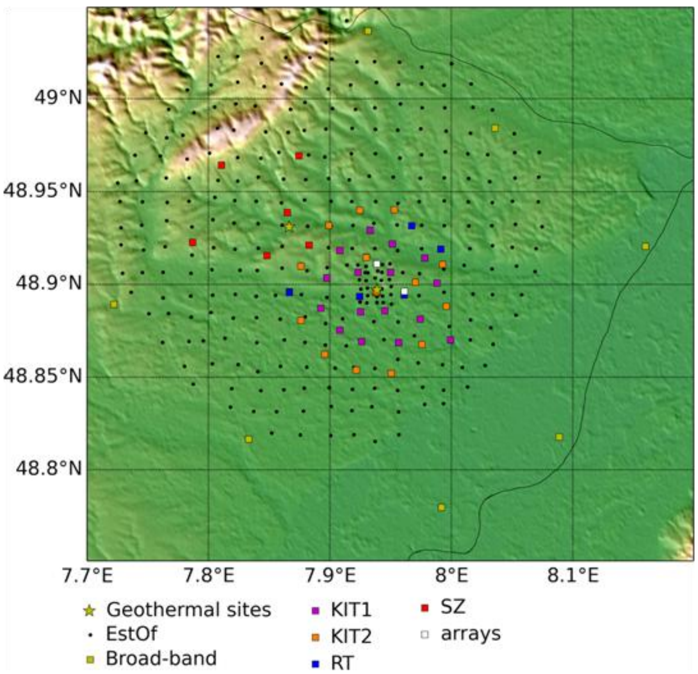

Figure 1 : Map showing the geothermal sites (Soultz-sous-Forêts and Rittershoffen) and the permanent and temporary networks available in the area.

Finally, a large scale project named EstOF is currently underway. It is included in the project "LabEx G-eau-thermie profonde" supported by Groupe Electricité de Strasbourg and GEIE (Exploitation minière de la chaleur) of Soultz-sous-forêts. It is also co-funded by the IPGS (Institut de Physique du Globe de Strasbourg). This experiment consists in applying methods of passive interferometry on a network that emphasizes spatial coverage before seismometers quality. The technique has already been applied previously in various contexts such as urbanized areas (Lin et al., 2013) or active volcanic systems, but this is the first time such an experiment is conducted in metropolitan France and for geothermal purposes. 250 seismometers (single component, 10 Hz corner frequency) have been deployed in august 2014 for 30 days. A seismometer has been installed each 1.5 km on a disk covering about 500 km^2 centered on the Rittershoffen site. A thinner mesh of 1 node every 200 meters has been designed over $1km^2$ around the Rittershoffen platform. A very large data set continuously acquired during 1 month and sampled at a rate of 250 Hz is currently processed.

Noise correlation functions

The CCFs have been computed for all possible station pairs of networks "RT", "SZ", "KIT1" and "Broad-band" (Figure 1), the other data sets being currently acquired or processed. Each one hour long segment of noise is processed individually prior to correlation (Bensen et al. 2007). Classically, the CCFs are represented as a function of the inter-station distance (hodograms, figure 2). Thanks to the very high number of available sation pairs, the reconstructed Green's function can be observed continuously for inter-station distances ranging from a few kilometers up to 30km. Between 0.2 and 1Hz, the Rayleigh waves can be unambiguously identified on almost all station pairs (figure 2, left side). The stronger amplitudes of the positive parts of the correlations are a consequence of the directivity of the seismic noise (Stehly et al., 2006). This noise mainly originates from the northern Atlantic ocean located West-Northwest of the network. At frequency 1 Hz, the Rayleigh wave can still be identified despite a lower SNR. The recent densification of the network has significantly improved the spatial resolution of the network, which allows us to identify a consistent arrival on the causal part of correlations. This arrival has only be observed at distances lower than 15 km and frequencies around 1Hz. Its high propagation speed of about 3.5 km/s suggests it corresponds to body waves. Several studies have demonstrated that such seismic waves can indeed be observed in the correlations (e.g. Roux et al., 2005; Poli et al., 2012). Finally, at frequencies above 1Hz, no coherent wavefield can be clearly observed, and the SNR is very low even by averaging the CCFs over very long time periods.

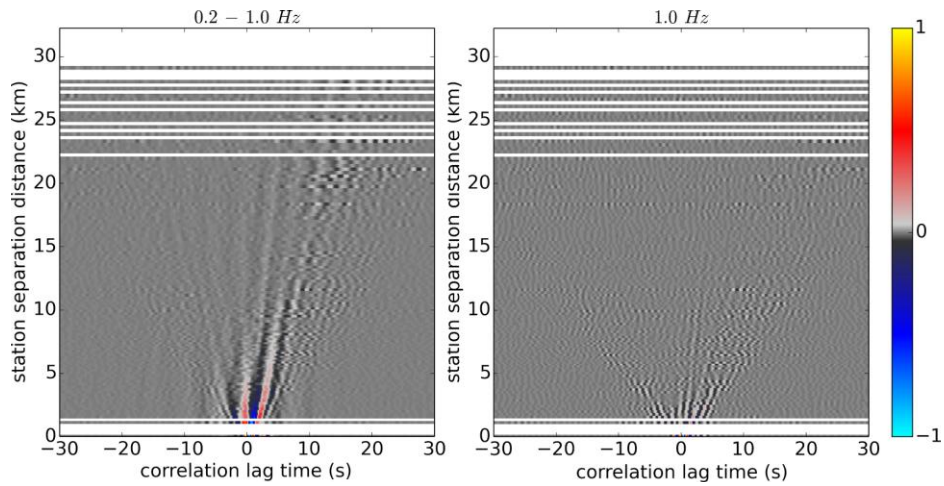

Figure 2 : Cross correlation functions computed over all station pairs of networks RT, SZ, KIT1 and “Broad-band”. The CCFs are bandpass filtered in two frequency bands. The color code corresponds to normalized amplitudes.

Applying tomography requires to measure and interpret the dispersive behavior of the surface waves reconstructed in the correlations. This is classically done by measuring the time needed by the signal envelop to propagate from a station to the other, which provides measurements of the group-speed of the surface waves as a function of frequency. Unfortunately, performing this measurement is difficult on many station pairs because of too short inter-station distance resulting in too weakly dispersed wave trains (for instance, Bensen et al. (2007) recommend the station separation to be at least three times the wavelength). Alternatively, the phase of the CCFs appears to be easier to identify especially at short distances. It seems that the non-uniform spatial distribution of the noise sources, which varies with the frequency, significantly affects the phase of the CCFs. Based on accurate characterization of the noise directivity measured by array processing, we expect the phase of the CCFs to provide reliable information on the spatial variations of the phase velocity in the first 5 kilometers of the crust.

Temporal variation of the CCFs

The late part of the correlation function (coda) results from diffuse wave fields recorded coherently at both stations (seismic waves refracted on scatterers while traveling from one station to the other). Wegler & Sens-Schönfelder (2006) proposed to study the variability of the CCFs coda over time to highlight velocity changes within the medium. For this application, the noise sources may be inhomogeneously distributed, but in this case they must be repeatable. If the seismic noise sources move too much over time, the resulting changes in the signal could be mistaken for perturbations of the medium (Hadziioannou et al., 2009; Weaver et al., 2011). The repeatability of the coda part of the CCFs has been investigated. Above 1 Hz, the noise is shown to be more stable at night time due to reduced human activity. Around 5 Hz, we observe two sudden drops in the phase velocity (about 0.4% slowing) on dates corresponding to the drilling of wells GRT1 and GRT2 on Rittershoffen's platform. This changes could be due to cooling induced nearby the borehole by the circulation of drilling muds. Further investigations are needed to determine whether these changes result from actual variations of the phase speed at depth or from changes in the noise environment caused by the drilling itself.

Conclusion

In this work, we benefited from the high station density available close to the two geothermal sites of Soultz-sous-Forêts and Rittershoffen and the long duration of available data (up to 4 years). The recent deployment of temporary networks in the region is shown to refine our understanding of high-frequency noise and how it can be used for tomographic and monitoring purposes. This will lead to a better characterization of the geothermal reservoir. The network will be completed soon by the EstOf project and an exceptional spatial resolution is expected with more than 45,000 station pairs.

Acknowledgment

The project is supported by Groupe Electricité de Strasbourg and is in the framework of the LabEx project G-EAU-THERMIE PROFONDE (Investissements d'Avenir) ANR-11-LABX-0050. We thank the Geophysical Instrument Pool Potsdam (GFZ) for providing temporary seismological units, as well as E. Gaucher (KIT), V. Maurer (ES-G), H. Wodling, H. Jund and M. Grunberg (EOST) who deployed the stations and collected the data.

References

Bensen, G.D., M.H. Ritzwoller, M.P. Barmin, A.L. Levshin, F. Lin, M.P. Moschetti, N.M. Shapiro, and Y. Yang. 2007. "Processing Seismic Ambient Noise Data to Obtain Reliable Broad-Band Surface Wave Dispersion Measurements." Geophysical Journal International 169 (3): 1239–60. doi:10.1111/j.1365-246X.2007.03374.x.

Brenguier, F., N. M. Shapiro, M. Campillo, V. Ferrazzini, Z. Duputel, O. Coutant, and A. Nercessian. 2008. "Towards Forecasting Volcanic Eruptions Using Seismic Noise." Nature Geoscience 1 (2): 126–30.

Brenguier, Florent, Daniel Clarke, Yosuke Aoki, Nikolai M. Shapiro, Michel Campillo, and Valerie Ferrazzini. 2011. "Monitoring Volcanoes Using Seismic Noise Correlations." Comptes Rendus Geoscience 343 (8-9): 633–38. doi:10.1016/j.crte.2010.12.010.

Gaucher, Emmanuel, Vincent Maurer, Hervé Wodling, and Marc Grunberg. 2013. "Towards a Dense Passive Seismic Network over Rittershoffen Geothermal Field". 2nd European Geothermal Workshop, Strasbourg, France: KIT, EOST.

Hadziioannou, Céline, Eric Larose, Olivier Coutant, Philippe Roux, and Michel Campillo. "Stability of Monitoring Weak Changes in Multiply Scattering Media with Ambient Noise Correlation: Laboratory Experiments." *The Journal of the Acoustical Society of America* 125, no. 6 (2009): 3688–95.

Lin, Fan-Chi, Dunzhu Li, Robert W. Clayton, and Dan Hollis. 2013. "High-Resolution 3D Shallow Crustal Structure in Long Beach, California: Application of Ambient Noise Tomography on a Dense Seismic Array." *Geophysics* 78 (4): Q45–56. doi:10.1190/geo2012-0453.1.

Lobkis, Oleg I., and Richard L. Weaver. 2001. “On the Emergence of the Green’s Function in the Correlations of a Diffuse Field.” The Journal of the Acoustical Society of America 110 (6): 3011–17. doi:10.1121/1.1417528.

Poli, P., M. Campillo, and H. Pedersen. 2012. “Body-Wave Imaging of Earth’s Mantle Discontinuities from Ambient Seismic Noise.” Science 338 (6110): 1063–65. doi:10.1126/science.1228194.

Roux, P., K. G. Sabra, P. Gerstoft, W. A. Kuperman, and M. C. Fehler. 2005. “P-Waves from Cross-Correlation of Seismic Noise.” *Geophysical Research Letters* 32 (19): L19303.

Sabra, K. G., P. Gerstoft, P. Roux, W. A. Kuperman, and M. C. Fehler. 2005a. “Extracting Time-Domain Green’s Function Estimates from Ambient Seismic Noise.” *Geophysical Research Letters* 32 (3): L03310.

Sabra, K. G., P. Gerstoft, P. Roux, W. A. Kuperman, and M. C. Fehler. . 2005b. “Surface Wave Tomography from Microseisms in Southern California.” *Geophys. Res. Lett* 32 (14): L14311.

Sens-Schönfelder, C., and U. Wegler. “Passive Image Interferometry and Seasonal Variations of Seismic Velocities at Merapi Volcano, Indonesia.” *Geophysical Research Letters* 33, no. 21 (November 1, 2006): L21302. doi:10.1029/2006GL027797.

Shapiro, Nikolai M., Michel Campillo, Laurent Stehly, and Michael H. Ritzwoller. 2005. “High-Resolution Surface-Wave Tomography from Ambient Seismic Noise.” Science 307 (5715): 1615–18. doi:10.1126/science.1108339.

Stehly, L., M. Campillo, and N. M. Shapiro. 2006. “A Study of the Seismic Noise from Its Long-Range Correlation Properties.” Journal of Geophysical Research 111 (B10): B10306.

Weaver, Richard L., Céline Hadziioannou, Eric Larose, and Michel Campillo. “On the Precision of Noise Correlation Interferometry.” *Geophysical Journal International* 185, no. 3 (June 1, 2011): 1384–92. doi:10.1111/j.1365-246X.2011.05015.x.