Imaging and monitoring with industrial seismic noise.

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also:

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Passive imaging: Long range correlations

Source in A ⇒ the signal recorded in B characterizes the propagation between A and B.

⇒ **Green function** between A and B: $G_{AB}$

$G_{AB}$ can be reconstructed by the correlation of noise or « diffuse » (equipartitioned) fields recorded at A and B ($C_{AB}$)

A way to provide new data with control on source location and origin time
Seismological application: coda waves

Individual cross-correlations: fluctuations dominate.

Emergence of the Green function
Stacks of 196 cross-correlations
Theoretical Green tensor at 69 km distance

After averaging over 100 EQs

(Paul and Campillo, AGU 2001; Campillo and Paul, Science, 2003)
Cross-correlations of coda and noise records\(\approx\) Green functions = virtual seismograms

-demonstrated for the retrieval of surface waves (e.g. Paul and Campillo, 2001; Campillo and Paul, 2003; Shapiro and Campillo, 2004....) or body waves (e.g. Zhan et al., 2010; Poli et al., 2012).

High resolution velocity map of California obtained from ambient noise (Rayleigh) (Shapiro, Campillo, Stehly and Ritzwoller, Science 2005)

Earth’s mantle discontinuities from ambient noise (phase transition \(\Rightarrow\) \((P,T)\))
(Poli, Campillo, Pedersen, Science 2012)

Large N sensor array \(\Rightarrow\) \(N^2/2\) correlations
Smaller scale, industrial environment

Active mine: various sources of noise tunnels (scattering)

Results from Olivier, Brenguier, Campillo, Lynch and Roux, 2015 GEOPHYSICS, VOL. 80, NO. 3 (MAY-JUNE 2015); P. KS11–KS25
Numerical simulation in presence of the tunnels

Synthetics vs Diffusion approximation

Actual event vs Diffusion approximation
Nature of the noise: example of a 5s record

impacts of a hammer drill

multiple sources
incl. (pumps, fans, etc.)

microseismic event
Correlation functions (ZZ)

Selective stacking: optimal time windows for body wave contributions:

Removing of monochromatic sources
ZZ time-distance sections

Noise correlations: blind stacking

Noise correlations: optimal stacking

Synthetics
Convergence of the ZZ correlation function
Scattering properties from noise correlations

Diffusion approx.
Travel time tomography from noise correlations
Investigation of coseismic and postseismic processes using in situ measurements of seismic velocity variations in an underground mine

Results from Olivier, Brenguier, Campillo, Roux, Shapiro and Lynch, 2015 *Geophysical Research Letters*


Investigation of coseismic and postseismic processes using in situ measurements of seismic velocity variations in an underground mine

12 day stack

Hourly correlation functions for 12 days

Lag time window (scattered waves) for the delay analysis
Detecting a small change of seismic speed: coda waves

Comparing a trace with a reference under the assumption of an homogeneous change

The ‘doublet’ method: moving window cross spectral analysis of the delays

Relative velocity change:
\[
\frac{dV}{V}(t) = -\frac{d\tau}{\tau}(t)
\]
Temporal evolution of the seismic velocity measured from all correlations involving a particular sensor (4 hour window)

The relaxation time is larger than the one deduced from detected seismicity.
Comparison of velocity changes and volumetric stress changes

Instaneous velocity drop

‘Static’ change
Velocity change due to blast and excavation

- **Fast dynamics**
- **Slow dynamics**

Change of baseline due to static stress change

**Instantaneous change**

**Static change**
Conclusions:

Passive (noise based) imaging is possible in industrial environment like mines.

It requires a careful analysis of the noise properties.

Body waves are retrieved and could be used for imaging.

Time dependent elastic properties can be inferred giving new clues on the geomechanical evolution.
Measuring slight changes of seismic velocity using coda waves (long travel time)
Numerical simulations in a scattering medium

2D spectral elements, anisotropic intensity of sources

Comparison of correlations with Green function

Colombi, Chaput, Hillers et al., 2014 in press
Effect of scattering (single source)

Beam forming

Colombi, Chaput, Hillers et al., 2014 in press
Measure of the bias induced by a strong anisotropy of the wave field (delay with respect to the Green function)

Colombi, Chaput, Hillers et al., 2014
For a single path:

\[ t_f = \frac{l_f}{V} \]

\[ \delta t \sim \frac{B''(\theta)}{2 \ t_f \ \omega_0^2 \ B(\theta)} \]

We have to compute the contributions of paths with first scatterers at all distances \( l_f \) and all azimuths \( \theta \)
We have to consider that the distribution of distance between scattering events is exponential:

\[ P(l_f) = \frac{1}{l} e^{-\frac{l_f}{l}} \]

where \( l \) is the mean free path

\[ <l_f> = l \quad t_f = l_f / V \]

We make use of

\[ \delta t \sim \frac{B''(\theta)}{2 \, t_f \, \omega_0^2 \, B(\theta)} \]

valid for \( l_f > \lambda \)
Applications

Numerical simulations

\[ l = 0.5m, \quad c = 2000m/s, \]
\[ f_0 = 30000Hz, \quad B_2 = -0.6 \quad \text{and} \quad \tau_m = 0.002s \]

\[ \Rightarrow \quad \text{fractional error } \frac{\delta t(\tau_m)}{\tau_m} \quad \text{of } 10^{-4} \]