Ambient noise imaging

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with Bérénice Froment, Piero Poli, Pierre Boué, Philippe Roux, Laurent Stehly, Gregor Hillers, Anne Paul, Nikolai Shapiro, Helle Pedersen, …
-Introduction

-Reconstruction and limits

-Surface waves and body waves
Large networks – continuous recordings

- 24 bit
- 100 Hz
- 2 sec delay
- Bore holes deeper than 100m

NIED: Hi-net
(approx. 800 stn)

Seismology: huge data sets consisting for a large part of ‘ambient noise’.
Availability: IRIS,...
Global ‘noise’ sources in the microseism band (extended ≈2-50s)

Strong contribution from oceanic waves

Example of a global comparison

Deterministic description of the sources?

*Hillers et al., 2012*
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

Experimentally verified with seismological data:
Coda waves: Campillo and Paul, 2003;…..
Ambient noise: Shapiro and Campillo, 2004,…..
Processing:

- preprocessing: stationarity of amplitude (ex: 1-bit introduced for coda waves)
- correlation of long time series (fluctuations decrease with integration time...)
- adaptative filtering...
- removing of earthquakes from ambient noise
- noise imaging/monitoring could involve large data sets and huge sets of CCs....
Refined imaging within a large array

*(Pierre Boué 2013)*

With ray bending
Surface wave imaging with seismic noise..... it works

Map of Rayleigh group velocity $V_g$
(linear inversion)

18 s cross-correlation

3D shear velocity model
1) $V_g(x, y, T)$
2) $V_s(x, y, z)$ local non linear inversion

The Moho beneath the Alps


Stehly et al., 2009
Arbitrary medium: an integral representation written in the frequency domain

\[ G_{12} - G_{12}^* = \frac{4i\omega k}{c} \int_V G_{1x} G_{2x}^* \, dV + \oint_S \left[ G_{1x} \vec{V} \left( G_{2x}^* \right) - \vec{V} \left( G_{1x} \right) G_{2x}^* \right] \, d\vec{S} \]
Surface term:
\[ \kappa = 0 \text{ (no attenuation)} \]

\[ G_{12} - G_{12}^* = \oint_S \left[ G_{1x} \tilde{V}(G_{2x}^*) - \tilde{V}(G_{1x}) G_{2x}^* \right] dS \]

If the surface is taken in the far field of the medium heterogeneities

\[ G_{1x} \sim \frac{1}{4\pi|\vec{x} - \vec{r}_1|} \exp(-ik|\vec{x} - \vec{r}_1|) \text{ and } \tilde{V}(G_{1x}) \sim ik G_{1x} \]

and we obtain a widely used integral relation:

\[ G_{12} - G_{12}^* = -2i \frac{\omega}{c} \oint_S G_{1x} G_{2x}^* dS \]
Volume term: \[ G_{12} - G_{12}^* = \frac{4i\omega\kappa}{c} \int_{\mathcal{V}} G_{1x} G_{2x}^* dV \]

\( \kappa \) is finite (attenuation)

\( S \) is assumed to be sufficiently far away, for its contribution to be neglected (spreading and attenuation)

Note that scatterers can be regarded as internal sources \( \rightarrow \) coda correlations
**BEAAR experiment**

**Coda Correlations**

**Time scales**
Hours (coda) to months-years (ambient noise)

**Short time windows**
Time symmetry: energy flow

(Paul et al., 2005)
Using ambient noise

Let’s be practical:

We have no control on the noise sources and we cannot perform field experiments with such ideal distribution of sources...

At short period, we are usually NOT in the far field of the heterogeneities

We cannot measure easily the gradients of the fields....
Location of the sources that contribute to the correlation.
Ray approximation for direct waves: the end fire lobes

Difference of travel time between A and B with respect to the position of the source
Stationary phase and end fire lobes: actual data

From Gouédard et al., 2008
End fire lobes

Contributions to direct waves in the GF

Contributions to scattered waves in the GF

Extension to scattered waves by H. Sato
In practice, the noise sources are not evenly distributed and the field is not made isotropic by scattering.

At first order we can study the effect of non isotropy of the incident field intensity on the receivers.

It results in bias on the measurements of direct path travel times.
Correlation of direct waves

Bias in the travel time

Increasing anisotropy of the noise intensity $B$

\[ B(\theta) = 1 + B_2 \cos(2\theta) \]

\[ \delta t = \left. \frac{1}{2t \omega_0^2 B(0)} \frac{d^2 B(\theta)}{d\theta^2} \right|_{\theta=0} \]
Correlation of coda waves

Increasing anisotropy of the noise intensity $B$

$B(\theta) = 1 + B_2 \cos(2\theta)$

No bias in the correlation of coda waves!

From Froment et al., 2011.

Noise records contain direct and scattered waves
We can construct virtual seismograms between stations pairs from noise records.

They contain the information about structures, but also all the complexity of actual seismograms.

Specifically they contain the scattered waves (coda waves). This is attested by the fact that we can also construct ‘virtual’ seismograms from the correlation of noise based virtual seismograms

- **$C^3$ method** \(\text{(Stehly et al., 2008; Garnier et al., 2011)}\)
- **can even be iterated in $C^5$** \(\text{(Froment et al., 2011)}\)
- **long travel times = strong sensitivity to changes**
Illustration of C3

(a) Computation of noise correlations (virtual seismograms)

(b) Correlations of noise correlation codas (stations as virtual sources)

Remove the influence of actual source distribution- or extracting multiply scattered waves
Physical significance of the coda of noise correlation
Surface wave imaging with seismic noise..... it works

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Stehly et al., 2009
Surface wave tomography ➔ body waves (deep reflections)

Comparison of high frequency (1Hz) 1-year noise correlation with earthquake data

Poli et al. 2012a

POLENET/LAPNET array in Finland

Z-Z noise correlations

Z comp. actual earthquake
Comparison with synthetic Green functions

C_{ZZ} (data)  \quad GF_{ZZ} (theory)  \quad C_{RR} (data)  \quad GF_{RR} (theory)

Reconstruction of P and S multiple reflections

Polarisation: noise correlation vs synthetics

Good reconstruction of phase and relative amplitudes of the components of the reflected waves. (amplitude discussed by Prieto)

A favorable context: distance vs. mean free path, amplitude in actual earthquake records

⇒ Deep phases

Poli et al., 2012a
Earth’s mantle discontinuities from ambient seismic noise (crystalline phase transition (P,T))

Poli et al. Science 2012
GLOBAL TELESEISMIC CORRELATIONS (periods 25-100s)

Boué, Poli et al., GJI 2013
Numerous phases can be identified
Short periods 5-10 s

Japan to Finland

Finland to Japan

Standard pre-processing (Shapiro and Campillo, 2004; Sabra et al. 2005) eliminates the contamination by EQ ballistic waves.
Examples of applications:

Telesismic delays in the Yellowstone region using USArray-LapNet subarrays
Examples of applications:

Periods 5-10s

Imaging the core-mantle boundary
Examples of applications:

Measure of the anisotropy of the inner core: (polar paths are faster than equatorial paths)

A

Latitude

Time from P'P'df (s)

B

Residuals (s)

Latitude (deg)

C

Longitude | Latidude
---|---
-52.5° | -7.5°
-82.5° | -37.5°
-82.5° | -52.5°
-37.5° | -67.5°
-82.5° | -67.5°
-52.5° | -82.5°

Boué, Poli et al., GJI 2013

⇒ Numerous applications to come!
Perspectives: imaging and monitoring

Correlation functions as approximate Green functions

Direct waves are sensitive to noise source distribution (errors small enough for tomography ($\leq 1\%$) but too large for monitoring (goal $\approx 10^{-4}$))

Stability of the ‘coda’ of the noise correlations = frozen distribution of scatterers
La Réunion

Seismic speed changes before the eruptions...

![Graph showing seismic speed changes and volcanic activity](image-url)
4D passive imaging of a volcano

Local change of speed

Local change of scattering properties

Anne Obermann PhD 2013