Solar powered seismology: high resolution imaging from ambient seismic noise

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Acknowledgements:
Misha Barmin, Craig Jones, Ludovic Margerin,
Eric Larosse, Richard Weaver, Arnaud Derode,
Anne Paul, Bart van Tiggelen
Natural sources of seismic signals

- Solar power
- Atmospheric disturbances
- Oceanic microseisms
- Volcanoes
- Earthquakes
- Earth’s internal heat
Why using solar powered sources (*noise*)?

1. Measurements in absence of earthquakes:
   - improved resolution
   - repetitive measurements:
     monitoring of temporal changes (volcanoes, fault zones)

2. Possibility to study the coupling between the Solid Earth, the Ocean, and the Atmosphere
Limitations de tomographie à partir des ondes de surface telesismiques

- Les mesures sont faites à partir des longues trajets
- Les mesures sur des courtes périodes (<20s) sont difficile à obtenir
- Les incertitudes dans les localisations et le mécanismes de séismes produisent des erreurs dans des modèles obtenues

Conséquence:
la résolution finale est limitée
distribution of $M>4$ earthquakes during 1.5 months (July, 2003-December, 2004)
one day of seismic record
one day of seismic record
one day of seismic record

ballistic waves used in traditional tomography
one day of seismic record

noise

coda

ballistic waves used in traditional tomography
Seismic coda and ambient seismic noise - random seismic wavefields

**Coda** - result of multiple scattering on random inhomogeneities

**Noise** - seismic waves emitted by random ambient sources
Origins of the idea:

The ‘fluctuation-dissipation theorem’ links random fluctuations (equipartition) of a system with its response to an external source (e.g. Kubo, 1966). The origin of the idea can be tracked in works on Brownian motion by Einstein (in 1905!).

\[ \text{FT(Green function A->B)} \sim \text{FT(time correlation of fields in A and B)} \]

Applications with mechanical waves (under different names):

- Helioseismology: Duvall et al. (1993)+…
- Laboratory Acoustics: Weaver and Lobkis (2001)+…
- Sesimic coda waves: Campillo and Paul (2003)+…
- Ambient seismic noise: Shapiro and Campillo (2004)+…
Correlations of random wavefields

Random wavefield - sum of waves emitted by randomly distributed sources

Cross-correlation of waves emitted by a single source between two receivers
Sources are in constructive interference when respective travel time differences are close to each other.

Effective density of sources is high in the vicinity of the line connecting two receivers.

Cross-correlation extracts waves propagating along the line connecting two receivers.
Cross-correlations of regional coda

From Campillo and Paul (2003)
1. Raw data (January 18, 2002)
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2. Filtered seismograms (0.01-0.025 Hz)
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3. One-bit normalization

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[Map showing locations ANMO and CCM in the United States]

[Graphs showing time-sampled data]

[Graph showing time-sampled data with a waveform pattern]

[Graph showing time-sampled data with frequency bands indicated]
1. Raw data (January 18, 2002)

2. Filtered

3. One-bit normalization

4. Compute cross-correlation

5. Stack results for 30 days
1. Raw data (January 18, 2002)

2. Filtered seismograms (0.01-0.025 Hz)

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Cross-correlations from ambient seismic noise: ANMO - CCM

cross-correlations from 30 days of continuous vertical component records (2002/01/10-2002/02/08)

frequency-time analysis of the broadband cross-correlation

prediction from global group velocity maps of Ritzwoller et al. (2002)
Cross-correlations from ambient seismic noise at US stations

Frequency-time analysis of broadband cross-correlations computed from 30 days of continuous vertical component records.
Cross-correlation from ambient seismic noise in North-Western Pacific

broadband cross-correlation computed from 30 days of continuous vertical component records
broadband cross-correlation computed from 30 days of continuous vertical component records
Cross-correlation of seismic noise in California
Cross-correlation of seismic noise in California

cross-correlations of vertical component continuous records (1996/02/11-1996/03/10)
0.03-0.2 Hz

3 km/s - Rayleigh wave
Comparison with signals from earthquakes

- signal from earthquake
- one-year cross-correlation (2002)
  - one-month cross-correlation (January, 2002)
  - one-month cross-correlation (April, 2002)
  - one-month cross-correlation (July, 2002)
  - one-month cross-correlation (October, 2002)
Examples of Rayleigh-wave dispersion curves
Measurements from two different months
Repetitive tomography
dispersion maps

18 s cross-correlation

Franciscan formation

Salinean block

Sierra Nevada

Peninsular Ranges

group velocity (km/s)
dispersion maps

7.5 s cross-correlation

Central Valley

Vantura basin

LA basin

Imperial Valley

group velocity (km/s)

1.4 1.9 2.2 2.5 2.6 2.8 2.9 3.2 3.5 4.0
Comparison between noise-based and earthquake-based tomographies.
Extraction of surface waves from seismic noise

Measurements without earthquakes

Improved resolution

Possible applications:
- imaging of the crust and the uppermost mantle
- structure of sedimentary basins for seismic hazard
- seismic calibration for nuclear monitoring
- monitoring of volcanoes and fault zones

Remaining questions:
- optimal duration of noise sequences
- spectral range
- optimal inter-station distances
- optimal station orientation
- Other than Rayleigh waves (Love, body waves)
Perspectives of noise-based continental-scale imaging in USA

courtesy of Greg Bensen (CU Boulder)
CMB
CCM
WCI
20 s Rayleigh wave group velocity measurements from ambient seismic noise (Nov., 2003-Feb., 2004; 4121 paths)
Reference dispersion map (CUB global tomographic model)
Inversion of noise-based measurements (Var. reduction 63%)
Tracing the origin of the seismic noise
courtesy of Laurent Stehly (LGIT, Grenoble)
Tracing the origin of the seismic noise
Tracing the origin of the seismic noise
Tracing the origin of the seismic noise
Seismic noise sources (10-20 s)

Winter

TOPEX/POSEIDONE

Summer
the end
Extracting Green functions from the random wavefield by field-to-field correlation: theoretical background

Seismic noise is excited by randomly distributed ambient sources (oceanic microseisms and atmospheric loads)

Modal representation of the random field:

- Eigenfunctions
- Eigenfrequencies
- Modal excitations, uncorrelated random variables:
- Spectral energy density

Cross-correlation between points \( x \) and \( y \):

Differs only by an amplitude factor \( F(\omega) \) from an actual Green function between \( x \) and \( y \)
Correlations computed over four different three-week periods

- Band-passed 15 - 30 s
- Band-passed 5 - 10 s

Repetitive measurements provide uncertainty estimations

Estimation of errors
PHL - MLAC 290 km

correlations computed over four different three-week periods

band-passed 15 - 30 s

band-passed 5 - 10 s

repetitive measurements provide uncertainty estimations

estimation of errors
Cross-correlations from teleseismic codas: ANMO - CCM

distance 1405 km

vertical component stack from 13 earthquakes
Cross-correlations from teleseismic codas: ANMO - CCM

distance 1405 km
Cross-correlations from teleseismic codas: ANMO - CC

distance 1405 km

vertical component stack from 13 earthquakes

normalized envelope

0.03-0.01 Hz

time from origin (s)

0 100000
Cross-correlations from teleseismic codas: ANMO - CCM

distance 1405 km

vertical component
stack from 13 earthquakes
 Measurement Procedure

• Select a long time series at each station (1 month - 1 year).
• Filter data in a narrow frequency band (e.g., 5 s - 10 s period).
• Create 1-bit signal (improves homogeneity of the signal with azimuth).
• Remove sequences following large earthquakes.
• Cross-correlate to produce the Green function.
• Measure the group speed at the center of the band.
• Repeat for different frequency bands.
traditional approach: using teleseismic surface waves

- extended lateral sensitivity
- sample only certain directions
- source dependent
- difficult to make short-period measurements

Consequence: limited resolution

Alternative solution: making measurement from random wavefield (ambient seismic noise)

- localized lateral sensitivity
- samples all directions
- source independent
- may allow many short-period measurements

May improve resolution