13. Passive Seismic and Interferometry

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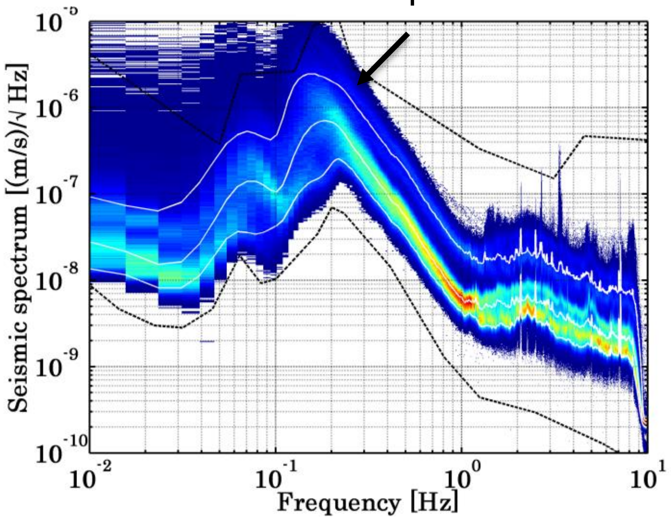
ERSE 210 Seismology

Earth’s Noise

Modern seismometers have high sensitivity and good SNR at low-frequencies → record trustworthy ground motion also in the absence of earthquakes

5-8 s period: microseism peak



Microseism noise:

- High-freqs: wind and cultural noise
- Low-freqs: **ocean waves*** and atmosferic effects

* Mechanism explained in the ’50s, due to standing waves in the ocean due to interaction of ocean waves in different directions

Earth’s Noise

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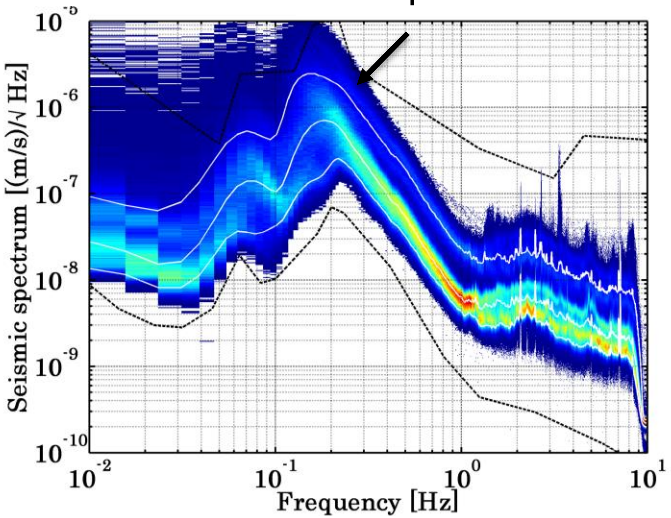

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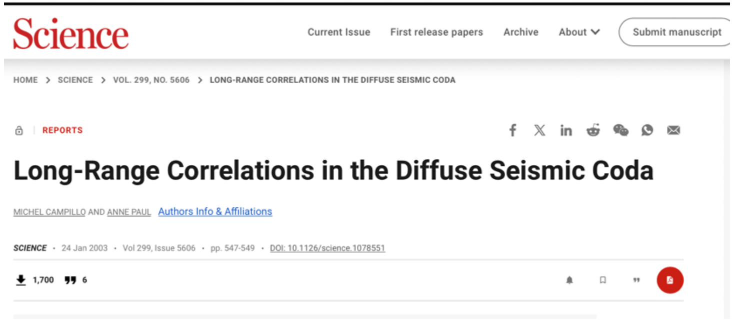
Seismic Interferometry - discovery

Until 2000: ‘Noise’ is useless and actually damaging the main arrivals from small earthquake

Then…

An exp**erimental discovery** changes completely this perspective:



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REPORTS

Long-Range Correlations in the Diffuse Seismic Coda

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1,700 6

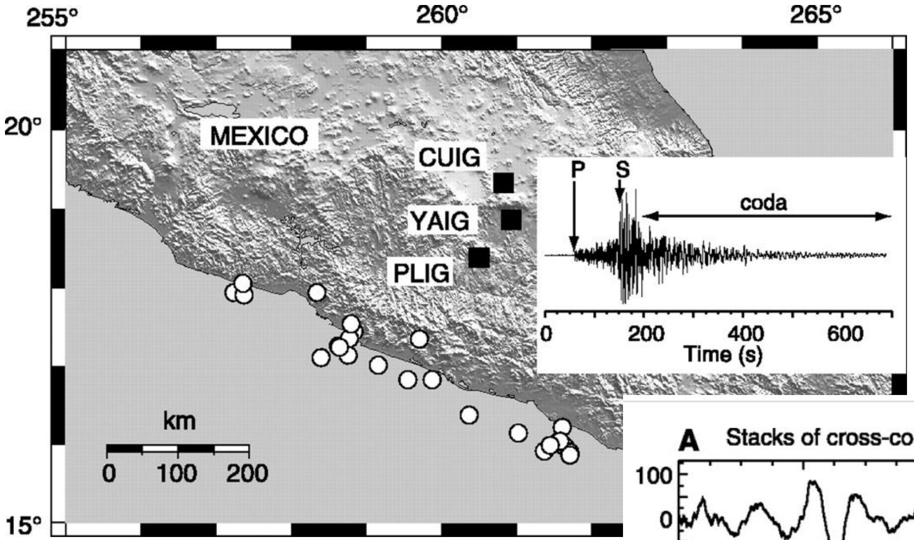
By cross-correlating the noise recordings at two stations for a long enough period of time yields the station-to-station ‘surface wave’ Green’s function

Seismic Interferometry - discovery

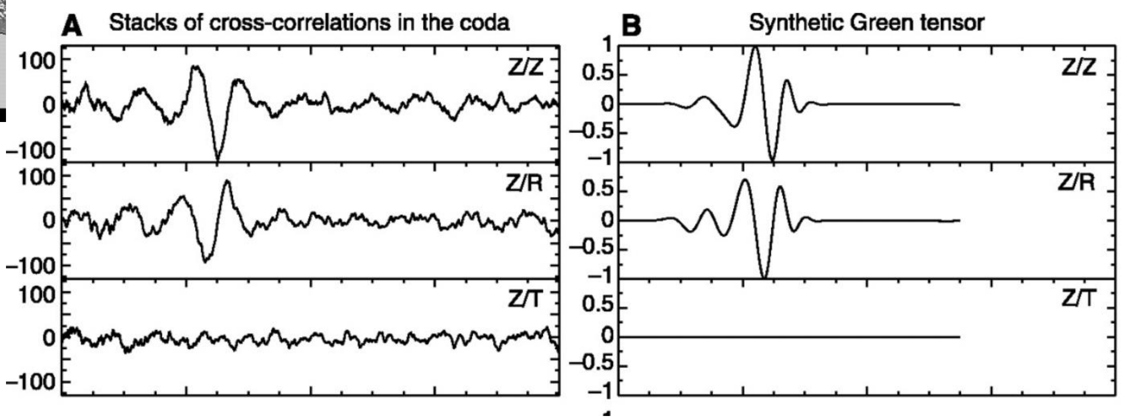
Abstract

The late seismic coda may contain coherent information about the elastic response of Earth. We computed the correlations of the seismic codas of 101 distant earthquakes recorded at stations that were tens of kilometers apart. By stacking cross-correlation functions of codas, we found a low-frequency coherent part in the diffuse field. The extracted pulses have the polarization characteristics and group velocities expected for Rayleigh and Love waves. The set of cross-correlations has the symmetries of the surface-wave part of the Green tensor. This seismological example shows that diffuse waves produced by distant sources are sufficient to retrieve direct waves between two perfectly located points of observation. Because it relies on general properties of diffuse waves, this result has potential applications in other fields.

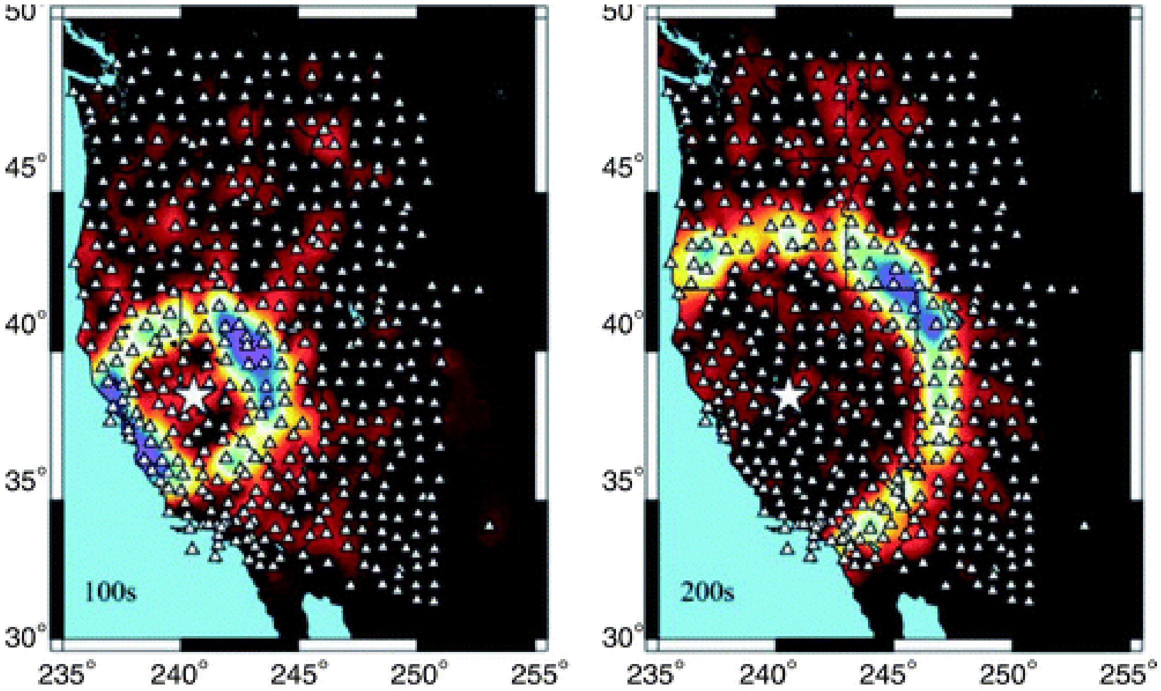
Seismic Interferometry – early days



Campillo and Paul, 2003

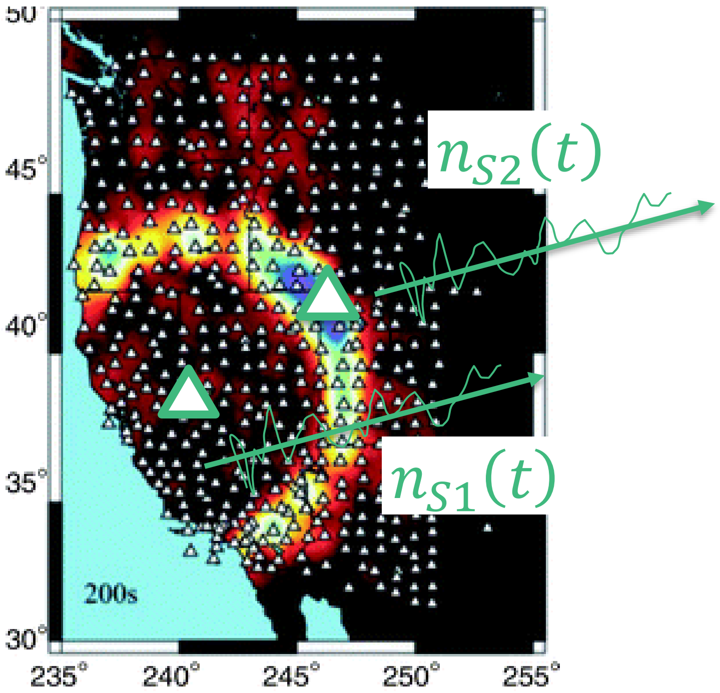


Seismic Interferometry – early days



Lin et al., 2009

Seismic Interferometry – early days

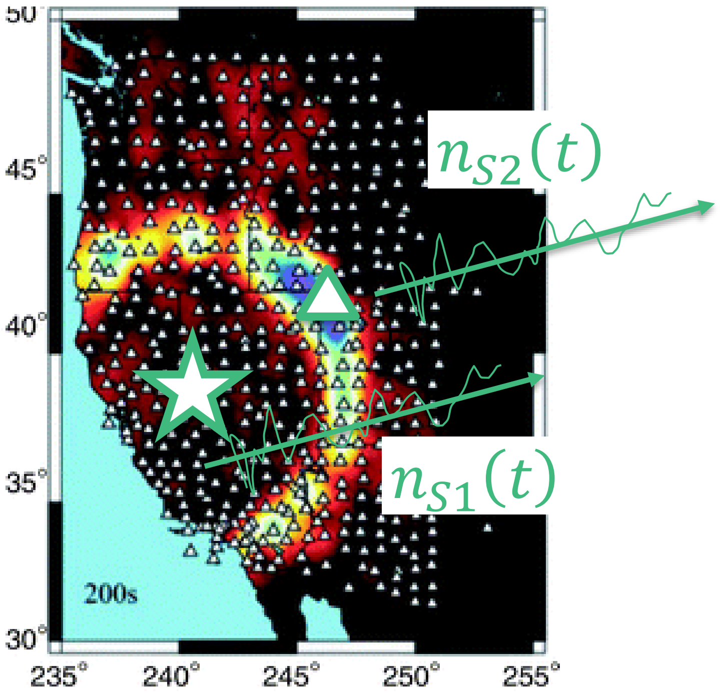


$$n_{S1}(t) \otimes n_{S2}(t)$$
$$\approx G(S2, S1, t) + G(S2, S1, -t)$$

$t: 0 - \mathrm{T}$ (T: days/weeks)

3 years in paper!

Seismic Interferometry – early days



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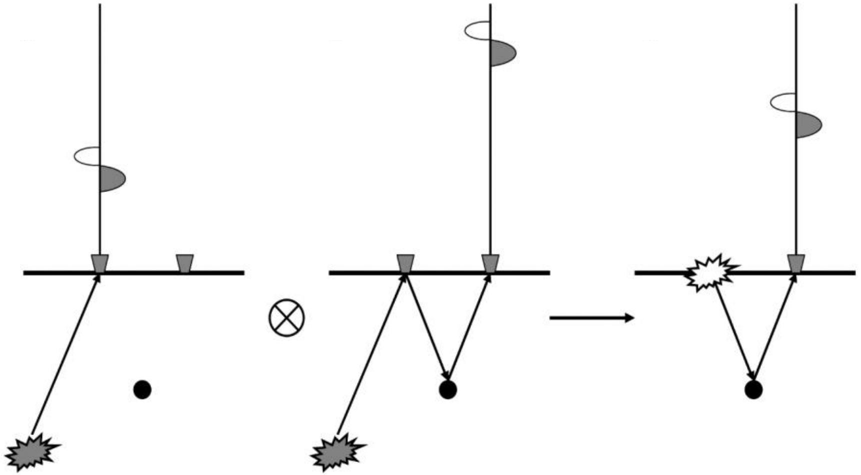
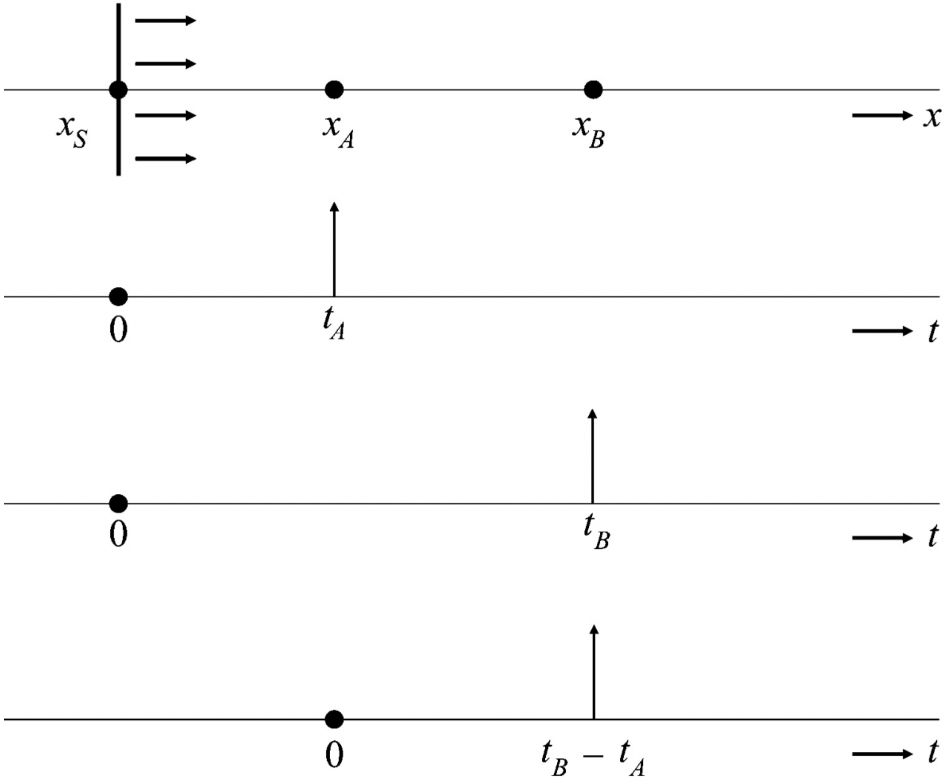


$$T(t) \otimes T(t)$$
$$\approx -R(t) - R(-t) + \delta(t)$$

Claerbout, J. F., 1968, Synthesis of a layered medium from its acoustic transmission response: *Geophysics*, 33, 264–269.

Seismic Interferometry – 1d intuition



Seismic Interferometry – theoretical formalism

In the early 2000, Prof. Kees Wapenaar and collaborators showed that the physical phenomenon underlying seismic interferometry can be mathematically explained using reciprocity relations → **representation theorems**

Starting from the 1st order acoustic wave equation (in frequency domain):

$$j\omega\rho v_i + \partial_i p = f_i$$

$$j\omega\kappa p + \partial_i v_i = q$$

Seismic Interferometry – theoretical formalism

We define the so-called interaction quantity:

A, B: states (combination of medium parameters, source parameters, boundary and initial conditions)

$$\partial_i\{p_A^* v_{i,B} + v_{i,A}^* p_B\}$$

$$\downarrow$$

$$\partial_i p_A^* v_{i,B} + p_A^* \partial_i v_{i,B} + \partial_i v_{i,A}^* p_B + v_{i,A}^* \partial_i p_B$$

and insert the previous equations for :

$$(f_{i,A}^* + j\omega\rho v_{i,A}^*)v_{i,B} + p_A^*(q_B - j\omega\kappa p_B) + (q_A^* + j\omega\kappa p_A^*)p_B + v_{i,A}^*(f_{i,B} - j\omega\rho v_{i,B})$$

$$f_{i,A}^* v_{i,B} + \cancel{j\omega\rho v_{i,A}^* v_{i,B}} + p_A^* q_B - \cancel{j\omega\kappa p_A^* p_B} + q_A^* p_B + \cancel{j\omega\kappa p_A^* p_B} + v_{i,A}^* f_{i,B} - \cancel{j\omega\rho v_{i,A}^* v_{i,B}}$$

Seismic Interferometry – theoretical formalism

So we get:

$$\partial_i\{p_A^* v_{i,B} + v_{i,A}^* p_B\} = f_{i,A}^* v_{i,B} + p_A^* q_B + q_A^* p_B + v_{i,A}^* f_{i,B}$$

Applying a volume integral on either sides:

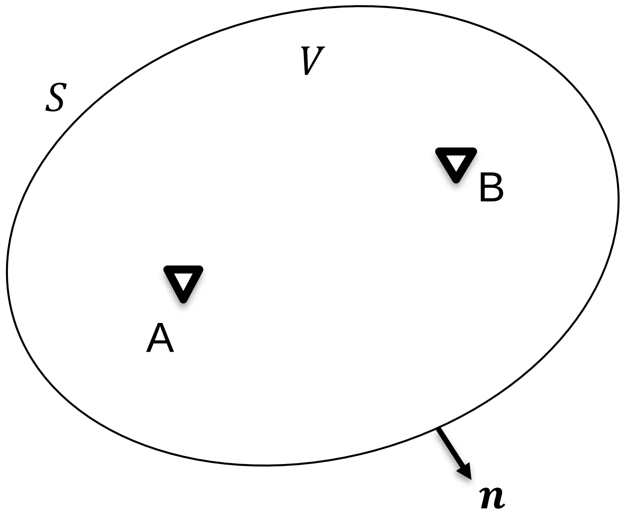
$$\int_V \partial_i\{p_A^* v_{i,B} + v_{i,A}^* p_B\} dV = \int_V (f_{i,A}^* v_{i,B} + p_A^* q_B + q_A^* p_B + v_{i,A}^* f_{i,B}) dV$$

and using Gauss theorem ($\int_V \partial_i f_i \, dV = \oint_S f_i n_i dS$)

$$\oint_S (p_A^* v_{i,B} + v_{i,A}^* p_B) n_i dS = \int_V (f_{i,A}^* v_{i,B} + p_A^* q_B + q_A^* p_B + v_{i,A}^* f_{i,B}) dV$$

Seismic Interferometry – theoretical formalism

Let us know assume the following geometry and states



State A:

$$f_{i,A} = 0 \qquad q_A = \delta(x - x_A)$$

$$p_A = G(x, x_A, \omega) \qquad v_{i,A} = -\frac{1}{j\omega\rho}\partial_i G(x, x_A, \omega)$$

State B:

$$f_{i,B} = 0 \qquad q_B = \delta(x - x_B)$$

$$p_B = G(x, x_B, \omega) \qquad v_{i,B} = -\frac{1}{j\omega\rho}\partial_i G(x, x_B, \omega)$$

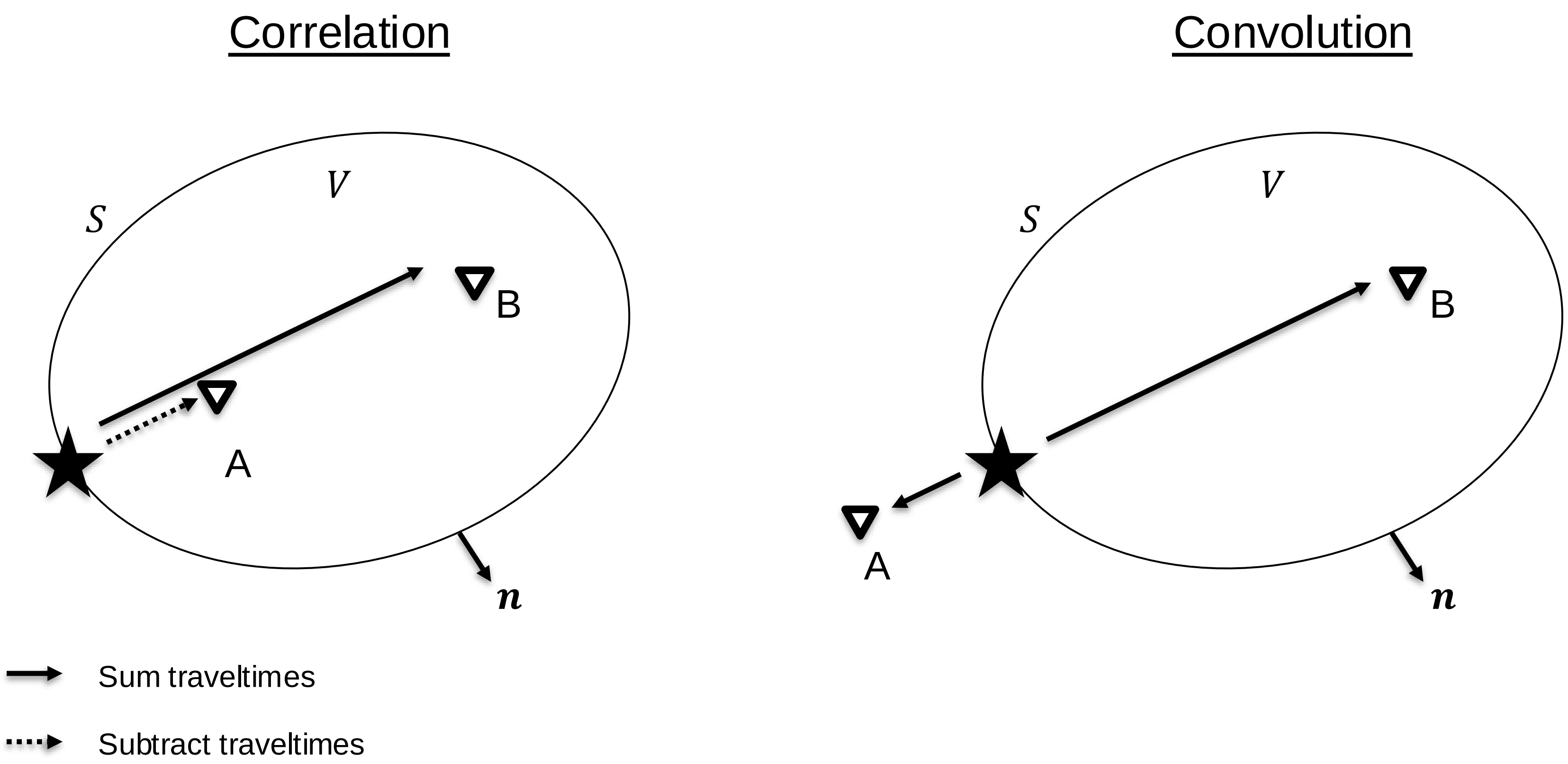
Seismic Interferometry – theoretical formalism

And insert them in the previous equation:

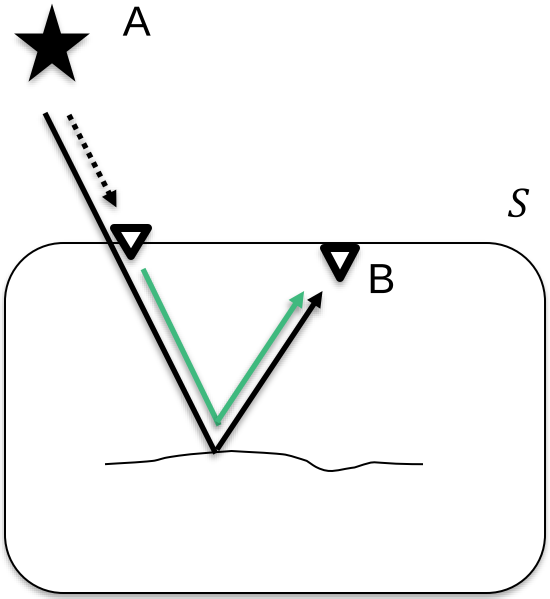
$$\oint_S -\frac{1}{j\omega\rho}\underbrace{(G^*(x,x_A,\omega)\partial_i G(x,x_B,\omega) + \partial_i G^*(x,x_A,\omega)G(x,x_B,\omega))}_{\text{Correlation of Green's functions between receivers and sources along the boundaries}}n_i dS = \underbrace{G(x_{,A}\ x_B,\omega) + G^*(x_B,x_A,\omega)}_{\text{Causal and Acausal Green's function between two receivers}}$$

Similar derivation can be done for other combinations of states and interaction quantities:
e.g., $\partial_i\{p_A\, v_{i,B} + v_{i,A}p_B\} \rightarrow G(x_{,A}\ x_B,\omega) = G\,(x_B,x_A,\omega)$ (wavefield reciprocity)

Seismic Interferometry by correlation vs convolution

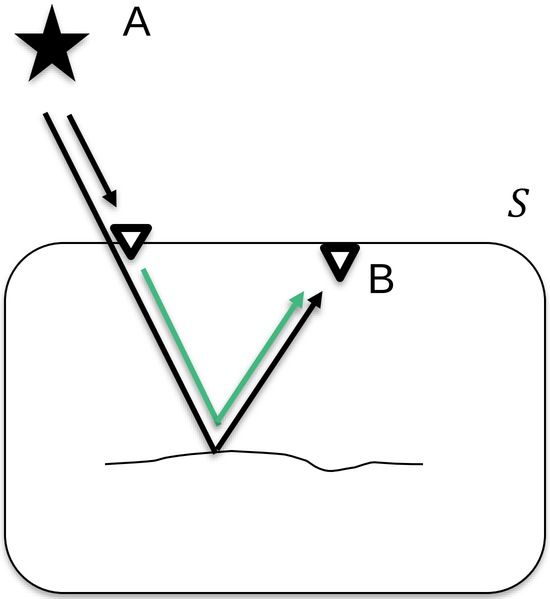


Seismic Interferometry by deconvolution



$$\underbrace{G(x_B, x, \omega)}_{\text{Unknown}} = \oint_S -\frac{1}{j\omega\rho} \underbrace{G(x_B, x_A, \omega)\partial_i G^*(x, x_A, \omega)}_{\text{Measured}} dS$$

Seismic Interferometry by deconvolution



$$\underbrace{G(x_B, x, \omega)}_{\text{Unknown}} = \oint_S -\frac{1}{j\omega\rho} \underbrace{G(x_B, x_A, \omega)\partial_i G^*(x, x_A, \omega)}_{\text{Measured}} dS$$

$$\underbrace{G(x_B, x_A, \omega)}_{\text{Measured}} = \oint_S -\frac{1}{j\omega\rho} \underbrace{G(x, x_A, \omega)}_{\text{Measured}}\partial_i \underbrace{G(x, x_B, \omega)}_{\text{Unknown}} dS$$