Program	Monday, May 11th	Tuesday, May 12th	Wednesday, May 13th	Thursday, May 14th	Friday, May 15th
8:30 AM	introduction				
8:45 AM-9:45 AM	Campillo	Shapiro	Fink	Van Der Hilst	Sato
9:45 AM -10:45 AM	Weaver	Garnier	Wapenaar	Larose	Beroza
10:45 AM- 11:15 AM	coffee break	coffee break	coffee break	coffee break	coffee break
11:15 AM -12:15 AM	Kuperman	Johnson	Forgues	Ben Zion	Catheline
12:30 AM	lunch	lunch	lunch	lunch	lunch
1:30 PM-4:00 PM	beach & discussion	beach & discussion	Poster session	beach & discussion	2:00 -2:45 PM Tsai 2:45 – 3:30 PM Yao
4:00 PM-5:00 PM	Williams	Gueguen		Sabra	beach & discussion
5:00 PM-6:00 PM	De Rosny	Sanchez-Sesma		Schubnel	
6:00PM – 6:15 PM	break	break		break	
6:15 PM-7:15 PM	Roux	Brenguier		De Hoop	
	Welcome drink				

Introduction

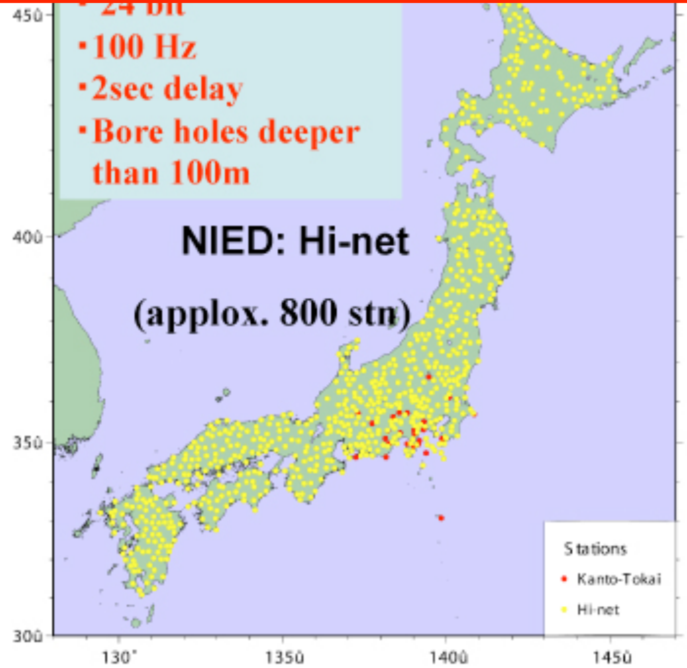
Laboratory Acoustics
Underwater Acoustics
Wave physics
Mathematics
Imaging
Seismology

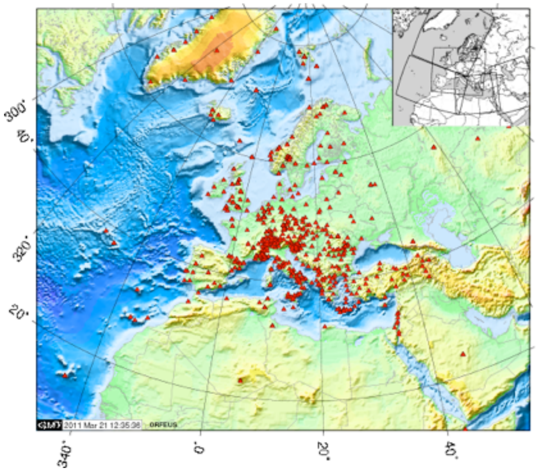
Seismology as an example

- Continuous recording: ambient noise
- Scattering
- Correlation
- Reconstruction of every physical arrivals?
- Precision for Imaging and monitoring

Arrays– continuous recordings

TALKS BY W. KUPERMAN, N. SHAPIRO AND P. ROUX

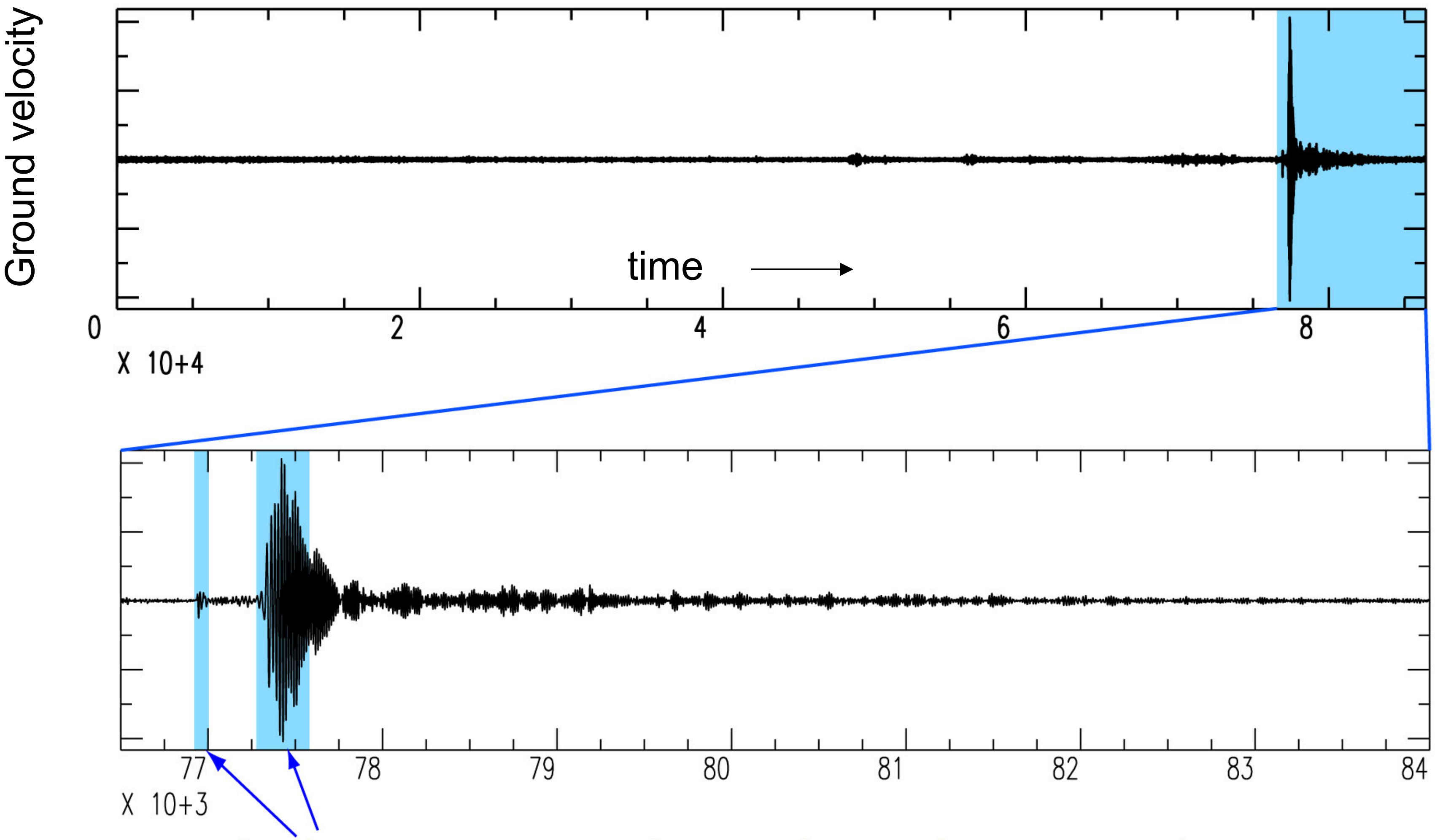




Seismology : huge data sets consisting for a large part of 'ambient noise'..

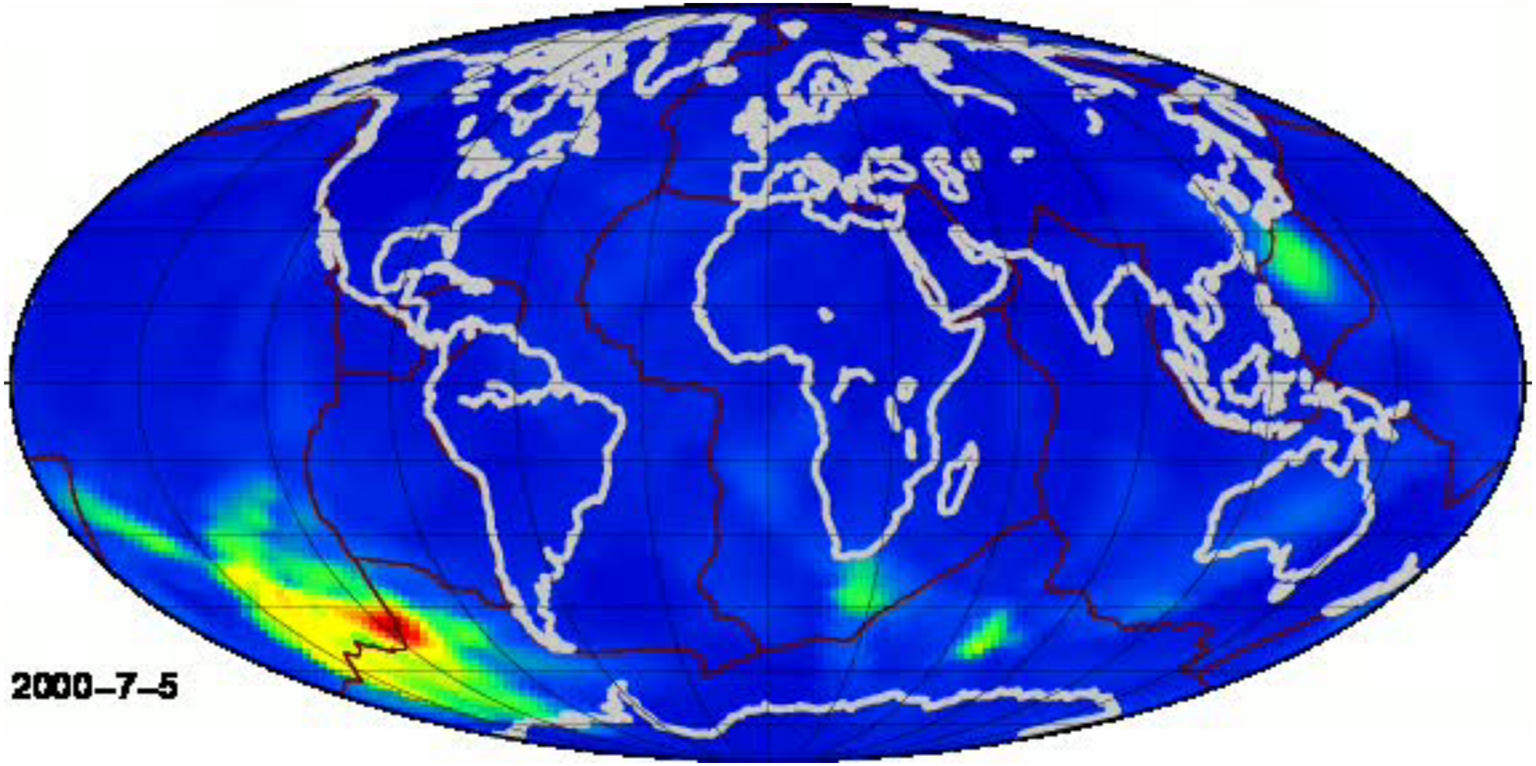
Availability: open data centers

one day of seismic record



ballistic waves used in traditional tomography

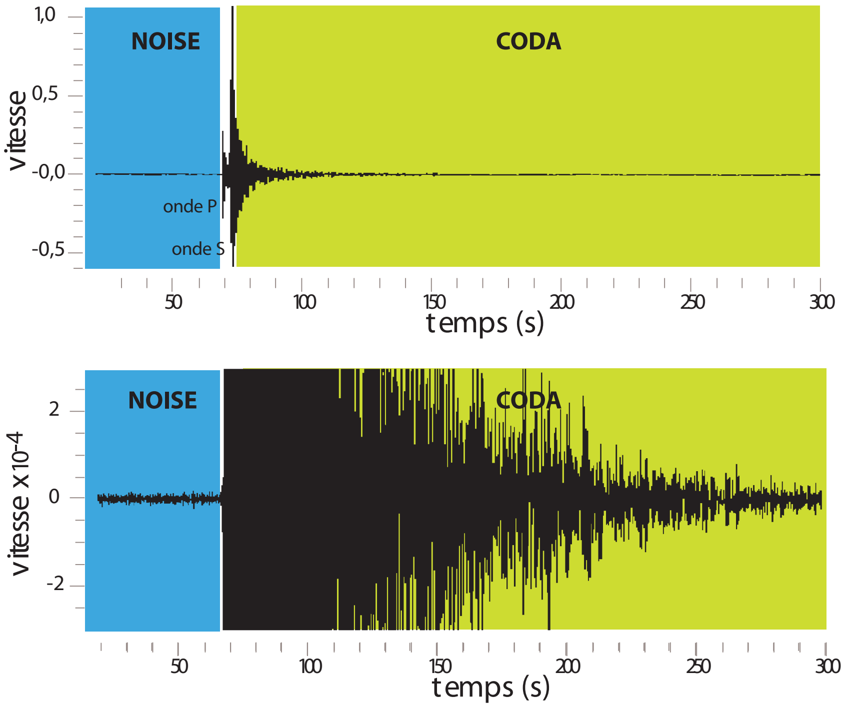
The origin of the noise in the period band 5-10s



VARIABLE SOURCE LOCATIONS

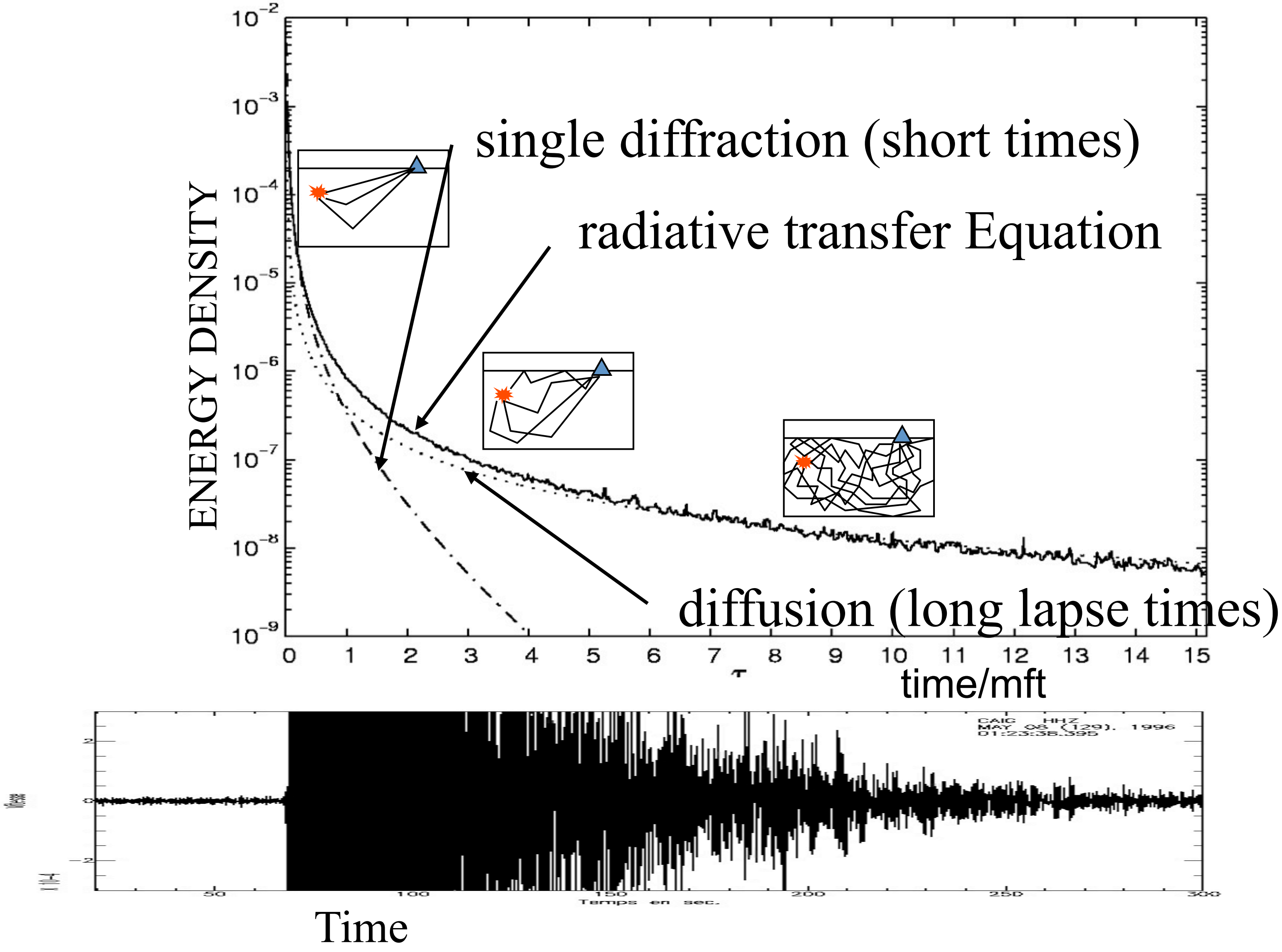
Landès et al., 2010

A typical records of a local earthquake (0.1-10Hz)



IMAGING WITH SCATTERED WAVES? TAKING ADVANTAGE OF SCATTERED WAVES?: TALKS BY E. WILLIAMS AND M. FINK

Propagation regimes and energy description



single diffraction (short times)

radiative transfer Equation

diffusion (long lapse times)

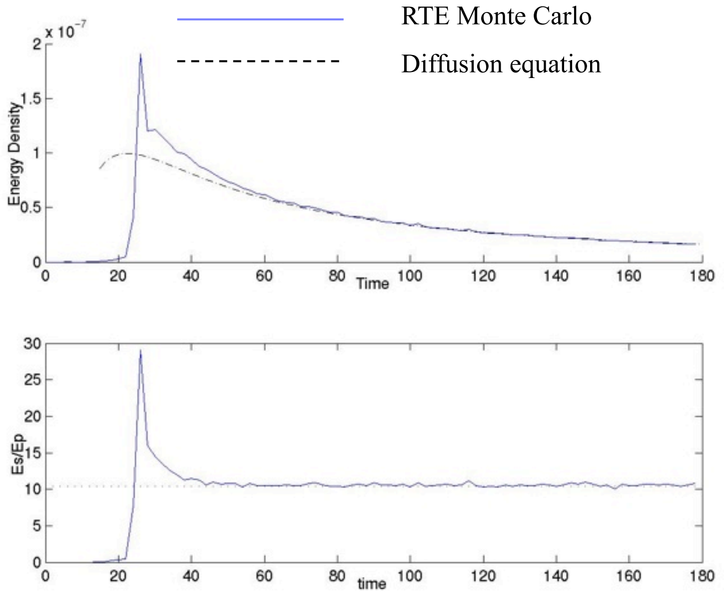
TALKS BY R. WEAVER, J. DE ROSNY , H. SATO AND E. LAROSE

Searching for a marker of the regime of scattering...

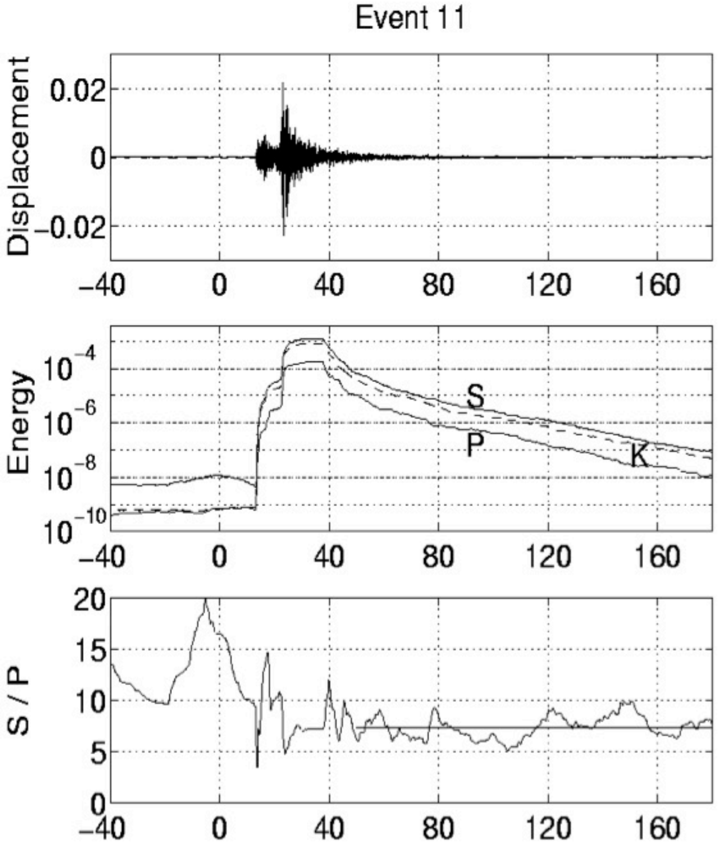
Equipartion principle for a completely randomized (diffuse) wave-field: in average, all the modes of propagation are excited to equal energy.

Implication for elastic waves (Weaver, 1982, Ryzhik et al., 1996): P to S energy ratio stabilizes at a value independant of the details of scattering!

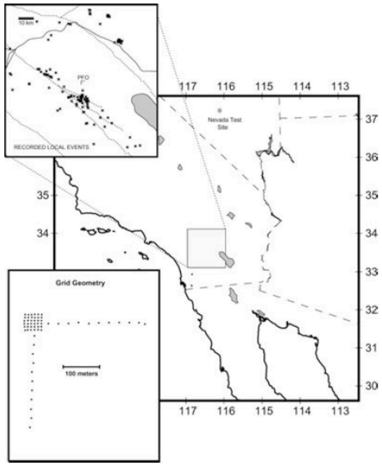
Numerical simulation



Observations



Es/Ep or Eh/Ev can be predicted

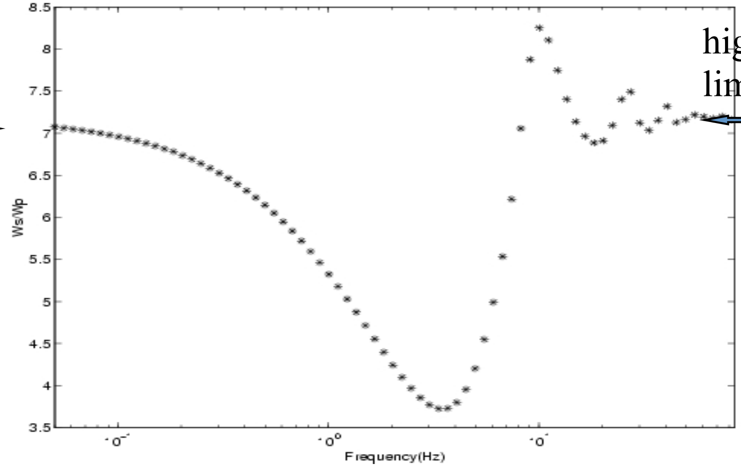


Geophys. J. Int. (2009) **177,** 571–585 doi: 10.1111/j.1365-246X.2008.04068.x

Energy partition of seismic coda waves in layered media: theory and application to Pinyon Flats Observatory

L. Margerin,[1] M. Campillo,[2] B. A. Van Tiggelen[3] and R. Hennino[2,3]

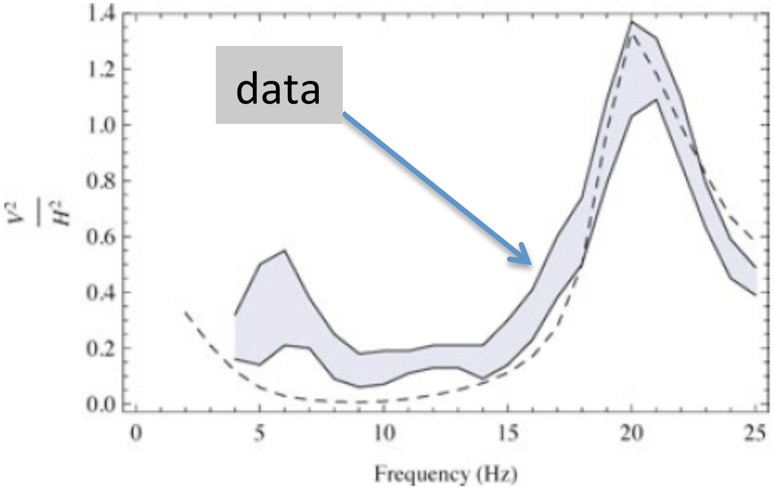
Theory for S-P energy ratio



low frequency limit: half space

high frequency limit: half space

Theory and data for vertical to horizontal energy ratio

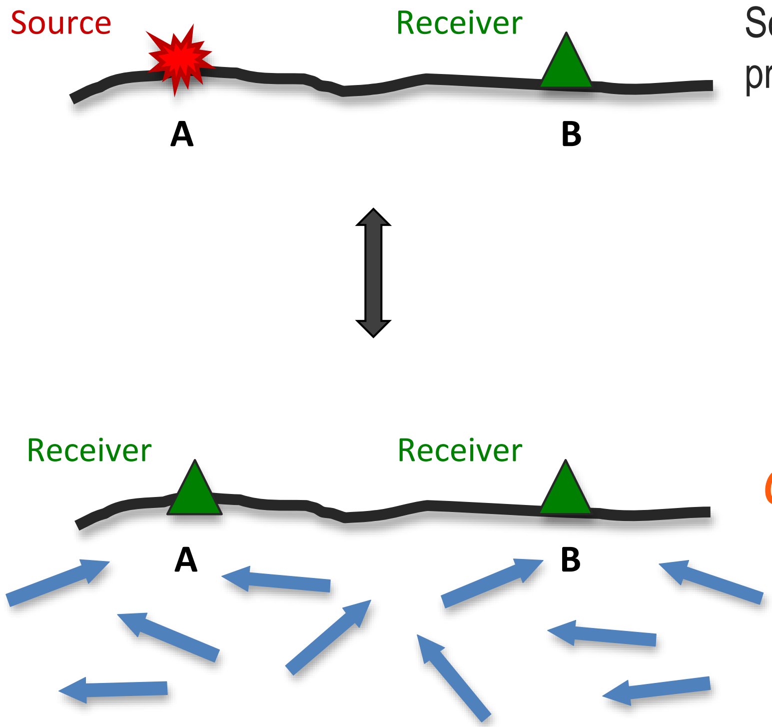


data

TALK BY F. SANCHEZ-SESMA

This leads to an inversion method to extract the layering from a single measurement (Margerin et al., 2009; Sanchez-Sesma et al., 2011;….).

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

How, when and why?

TALKS BY J. GARNIER, M. DE HOOP, V. TSAI

Representation theorem for correlation: passive imaging

Arbitrary medium: an integral representation written in the frequency domain

$$G_{12} - G_{12}^{*} = \frac{4i\omega\kappa}{c}\int_{\mathcal{V}} G_{1x}G_{2x}^{*}\,dV + \oint_{S}\left[G_{1x}\vec{\nabla}\left(G_{2x}^{*}\right) - \vec{\nabla}\left(G_{1x}\right)G_{2x}^{*}\right]\vec{dS}$$

Volume term

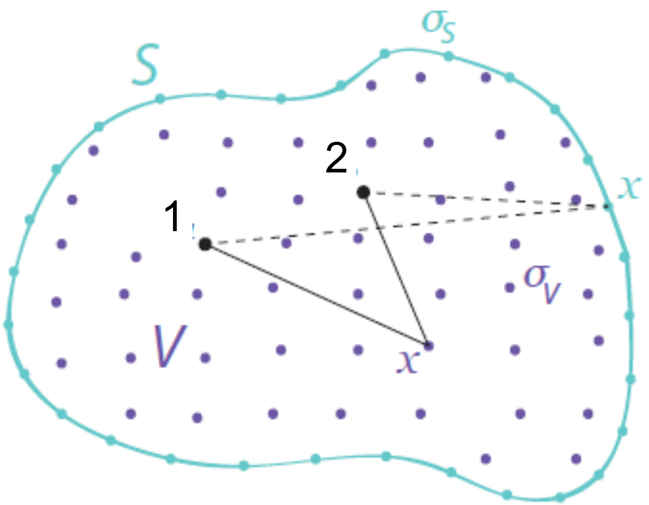
Surface term

FT of *G(-t)*

Absorption coefficient

FT of *G(t)*

Source average over
« correlation terms »



e.g. Weaver et al., 2004, Snieder 2007,….

Surface term: $\oint_S \left[G_{1x}\vec{\nabla}\left(G^*_{2x}\right)-\vec{\nabla}\left(G_{1x}\right)G^*_{2x}\right]\overrightarrow{dS}$

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

$G_{1x} \sim \frac{1}{4\pi\left|\vec{x}-\vec{r}_1\right|}\exp\left(-ik\left|\vec{x}-\vec{r}_1\right|\right)$ and $\vec{\nabla}\left(G_{1x}\right) \sim i\vec{k}\,G_{1x}$

and we obtain a widely used integral relation:

$$\oint_S \left[G_{1x}\vec{\nabla}\left(G^*_{2x}\right)-\vec{\nabla}\left(G_{1x}\right)G^*_{2x}\right]\overrightarrow{dS} \approx -2i\frac{\omega}{c}\oint_S G_{1x}G^*_{2x}\,dS$$

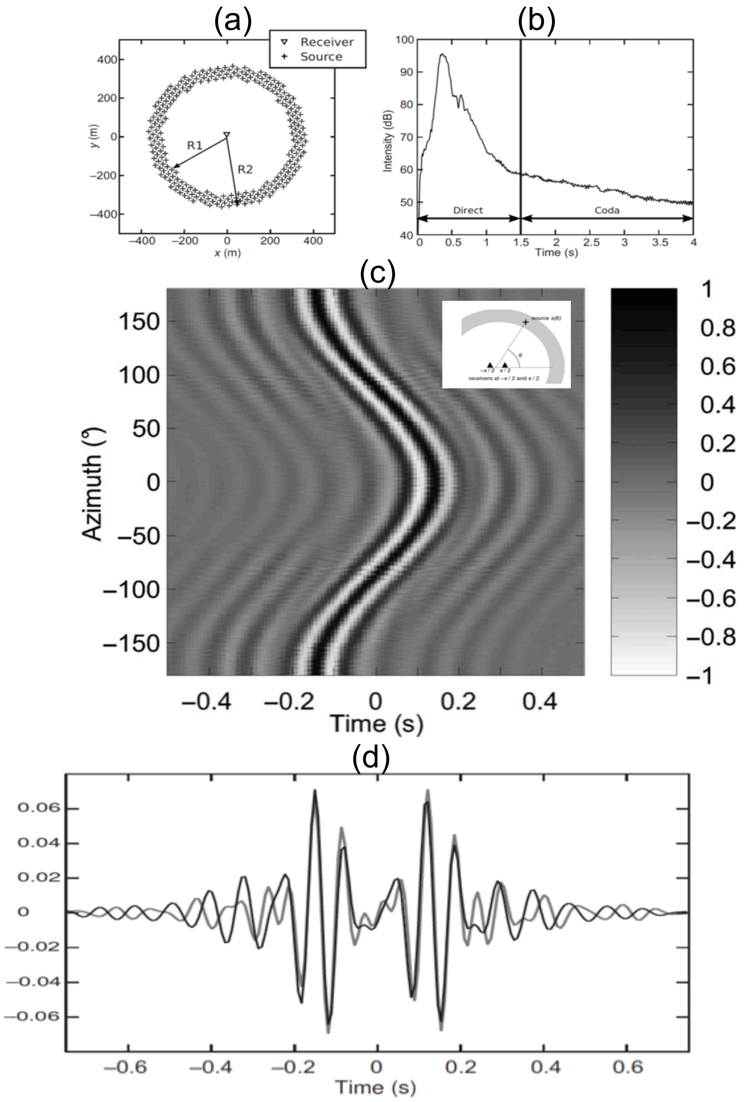
Source average over
« correlation terms »

➔Derode et al., 2003: Analogy with Time reversal mirrors
➔Wapenaar 2004

TALK BY K. WAPENAAR

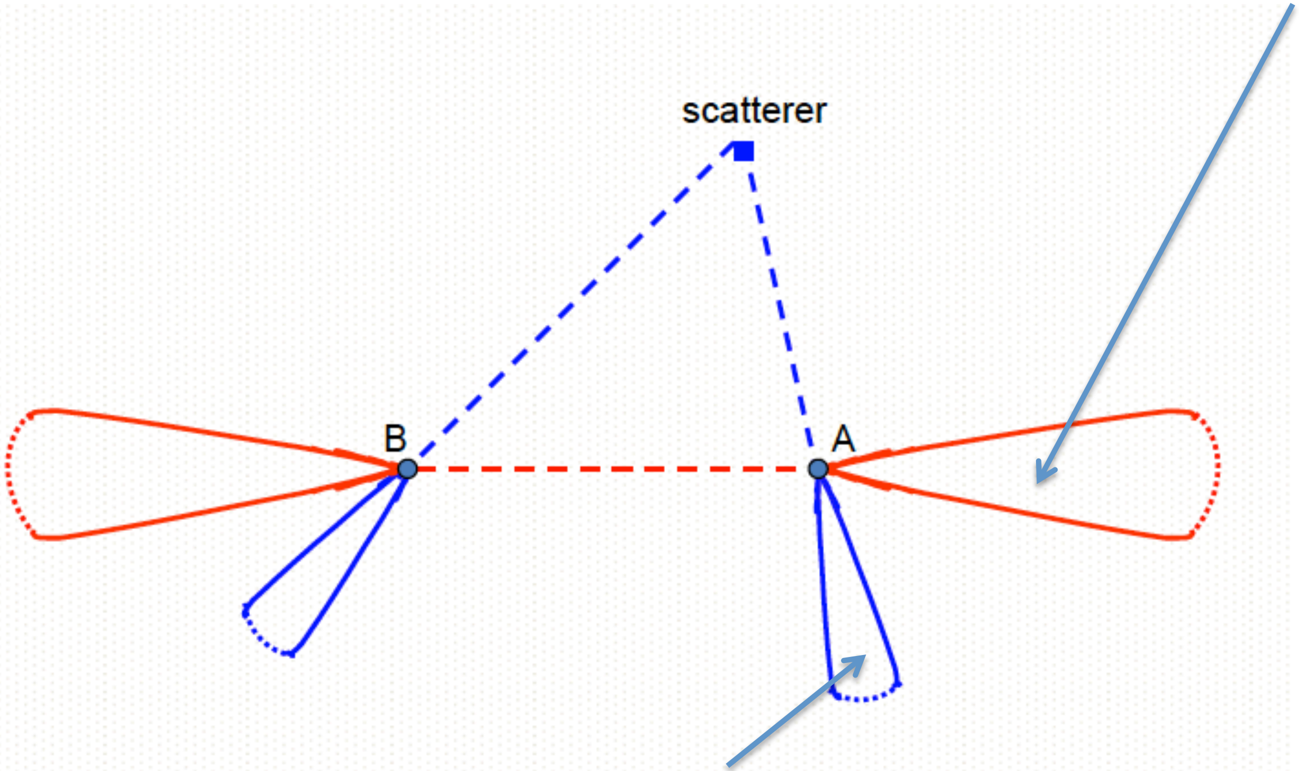
For surface waves: distant sources of noise at the surface of the sphere (≈2D problem)

Stationary phase and end fire lobes: actual data



From Gouédard et al., 2008

End fire lobes➔source noise kernels



Contributions to direct waves
in the GF

Contributions to scattered waves
In the GF

Several hundreds of applications of surface wave tomography in the last 10 years!

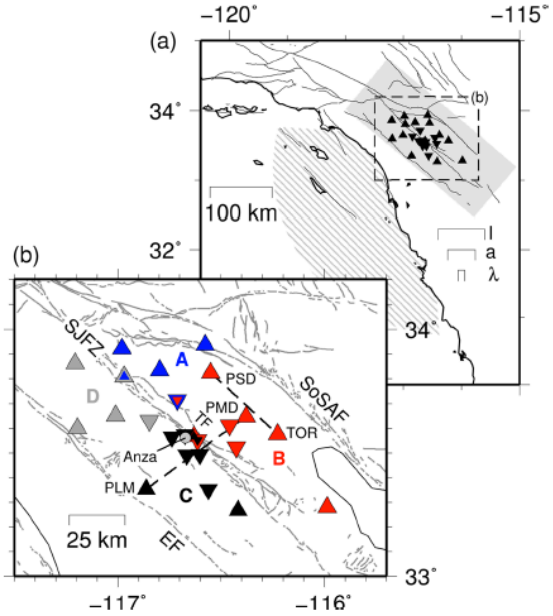
An issue for surface wave tomography:

In practice, the noise sources are not evenly distributed and the field is not made fully isotropic by scattering.

The absence of isotropy of the intensity of the field incident on the receivers results in a bias on the measurements of direct path travel times.

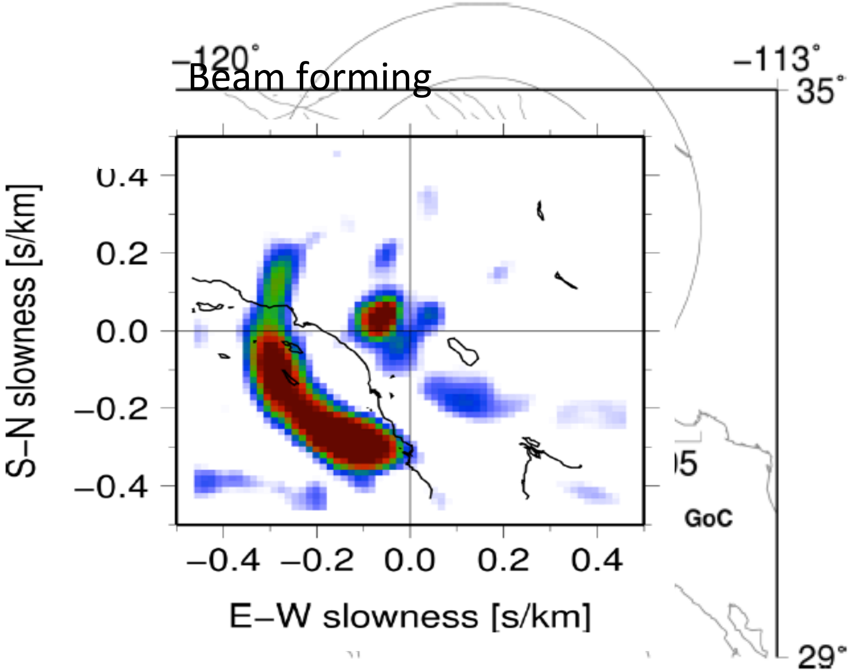
Anisotropic intensity of the noise: the example of the San Jacinto fault

From Hillers et al., 2013 G3



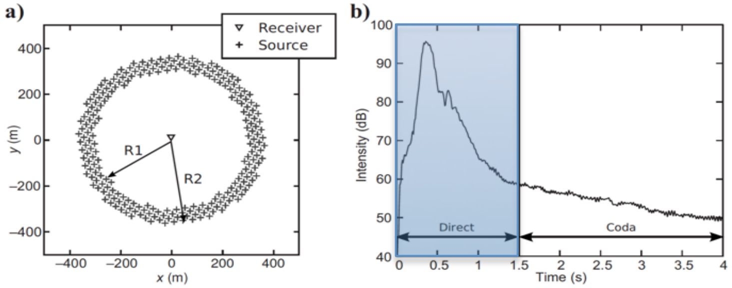
Anisotropic intensity of the noise
(measured for winter and summer and from different components)

Beam forming

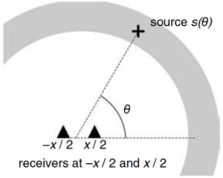


Correlation of direct waves:

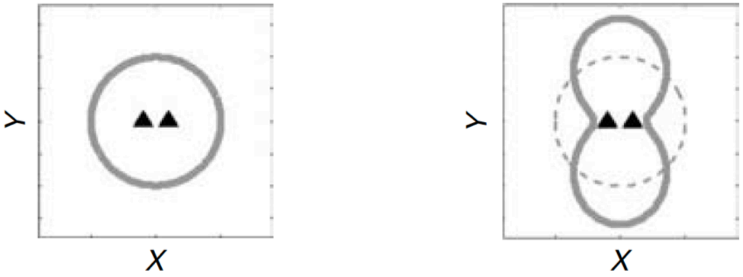
Bias in the travel time



Increasing anisotropy of the source intensity *B*

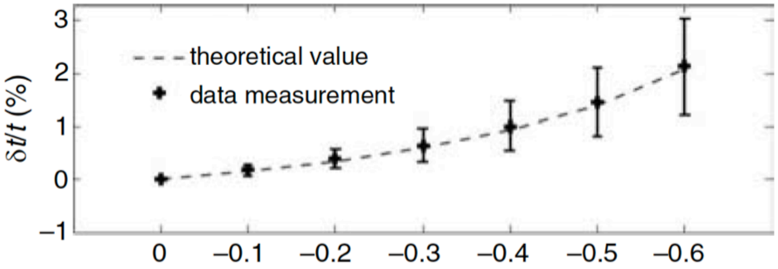


Azimuthal distribution of source intensity



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

Travel time error wrt the observed Green function



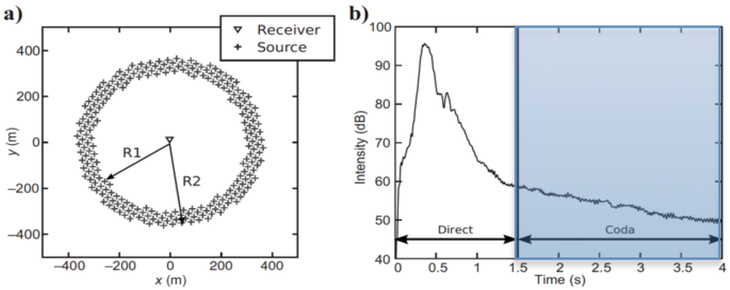
$$\delta t = \frac{1}{2t\omega_0^2 B(0)} \left.\frac{d^2 B(\theta)}{d\theta^2}\right|_{\theta=0}$$

valid with t (travel time) > T (period)

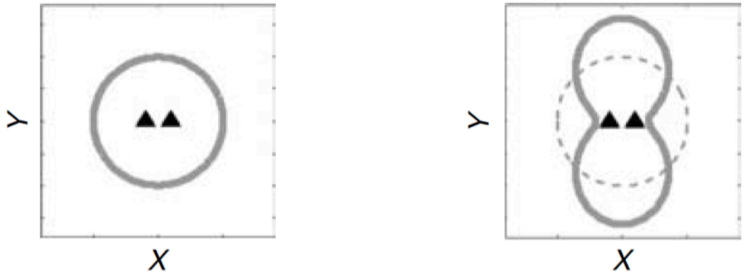
From Weaver, Froment, Campillo (2009) and Froment, Campillo, Roux, Gouédard, Verdel and Weaver 2011.

In presence of scattering:
Correlation of coda waves

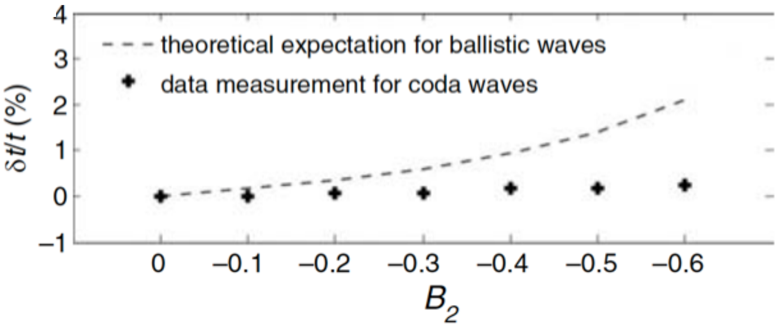
- -isotropy improvedby multiple scattering



Increasing anisotropy of the source intensity *B*



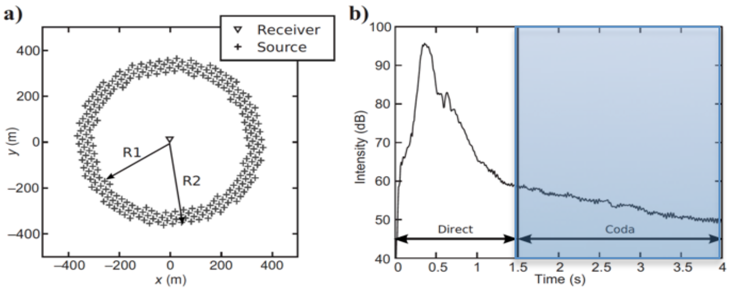
$$B(\theta) = 1 + B_2 \cos(2\theta)$$



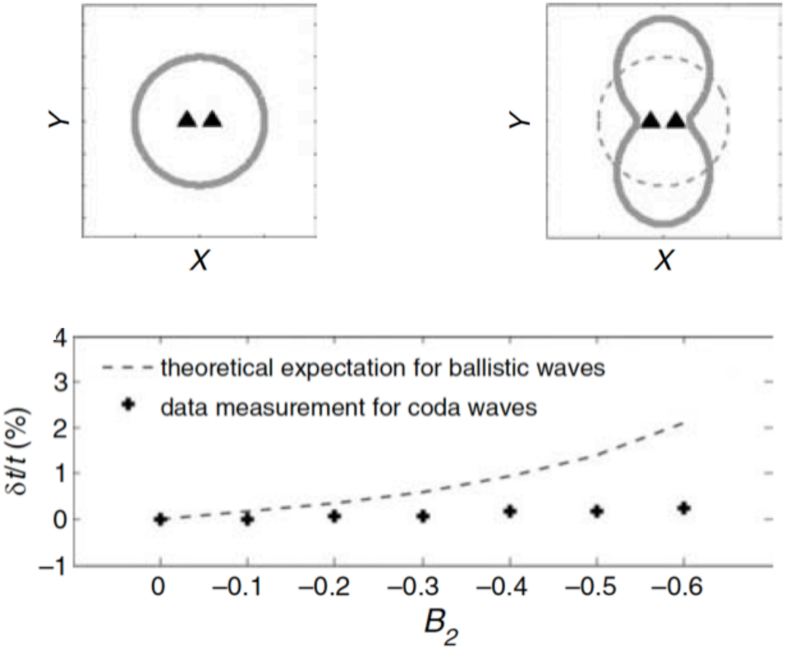
No bias in the correlation of coda waves!

From Froment, Campillo, Roux, Gouédard, Verdel and Weaver 2011.

In presence of scattering:
Correlation of coda waves
-isotropy provided by multiple scattering



Increasing anisotropy of the source intensity *B*



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

Scattering provides the diversity of incidence directions ➔isotropization of intensity

No bias in the correlation of coda waves!

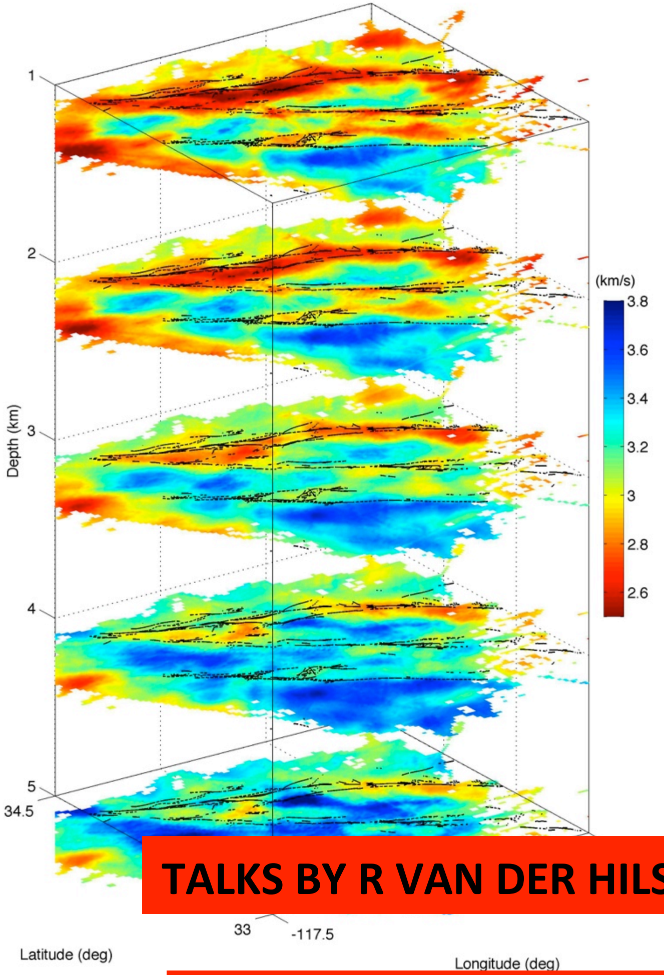
Noise records contain direct **and** scattered waves:

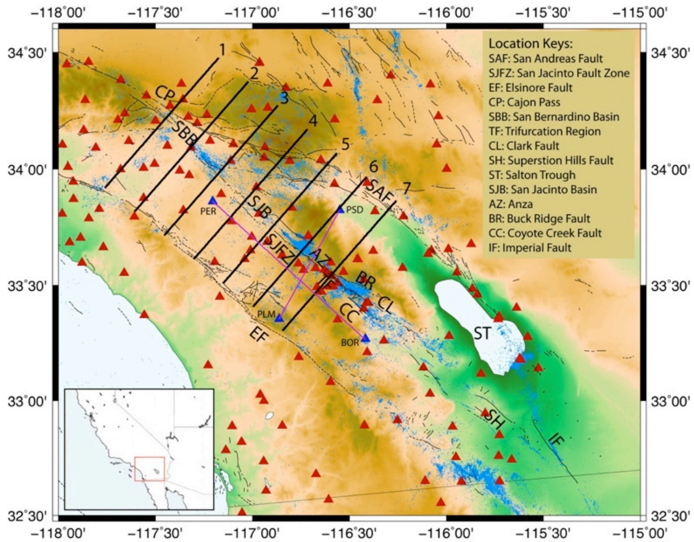
➔ the biases of direct wave travel times are generally small enough for imaging purpose

➔ Importance of processing strategies

From Froment, Campillo, Roux, Gouédard, Verdel and Weaver 2011.

3D shear velocity





- Damaged fault zone
- Flower-like patterns
- Diffuse seismicity associated with low-velocity (damaged) area between SAF and SJFZ

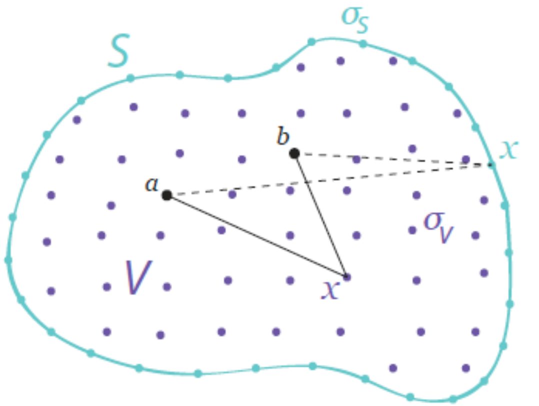
TALKS BY R VAN DER HILST, Y. BEN-ZION, H. YAO, AND S. CATHELINE

OTHER APPLICATIONS OF GF RECONSTRUCTION: TALK BY G. BEROZA

From Zigone, Ben-Zion, Campillo and Roux, 2014

Consider now the problem of body waves at the global scale with noise sources at the surface:

A problem of a different nature, although indeed the uneven distribution surface noise sources is still there.



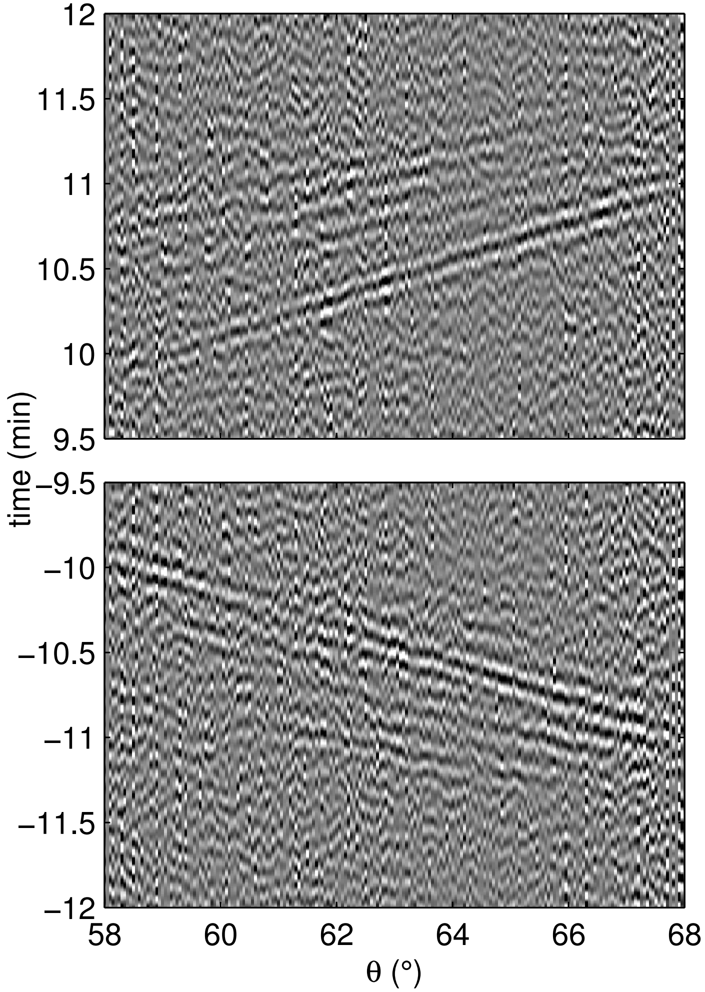
$$G_{12} - G_{12}^{*} = \oint_{S} \left[G_{1x} \vec{\nabla}\left(G_{2x}^{*}\right) - \vec{\nabla}\left(G_{1x}\right) G_{2x}^{*} \right] \overrightarrow{dS}$$

This representation is not formally valid on the free surface: the integral vanishes. GF reconstruction would require a more complex procedure (Ruigrok et al., 2008)

Here also, the correlation of multiply scattered waves should lead to the Green function.

Short periods 5-10 s ➔ strong scattering

P and PcP

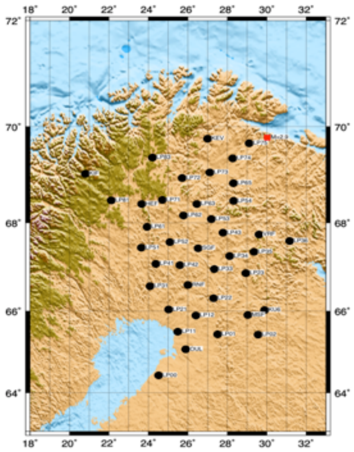


Japan to Finland

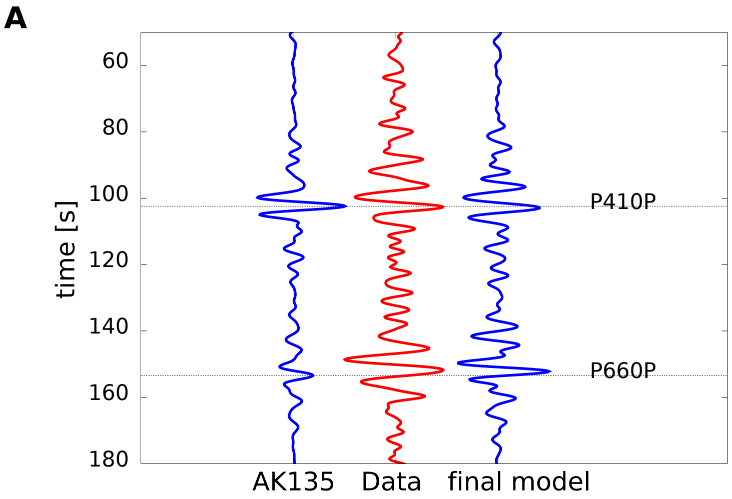
Finland to Japan

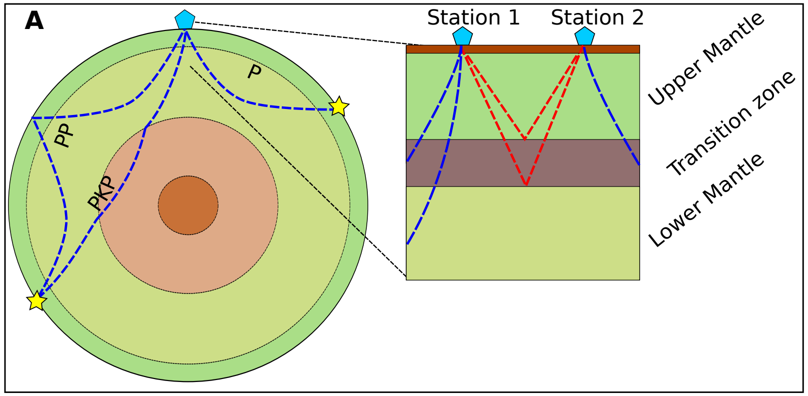
Standard (surface-wave) pre-processing (Shapiro and Campillo, 2004; Sabra et al. 2005) eliminates the contamination by EQ ballistic waves.

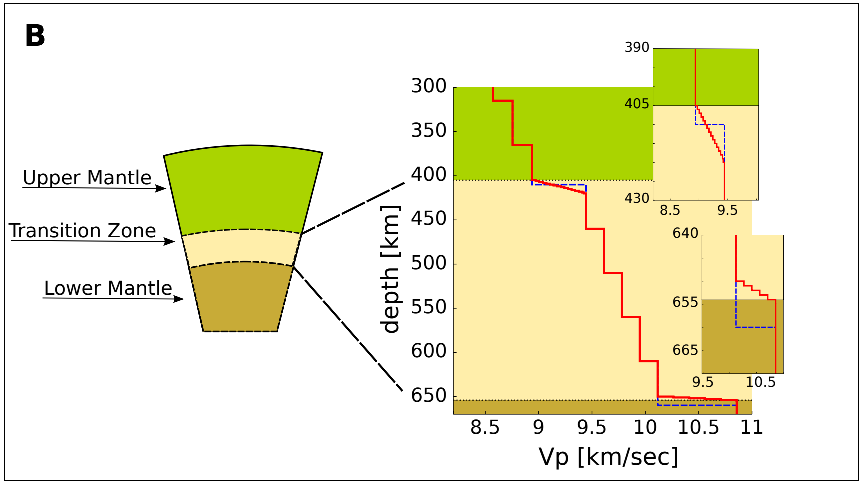
➔Earth's mantle discontinuities from ambient seismic noise (phase transition ➔ (P,T))



Poli et al. Science 2012





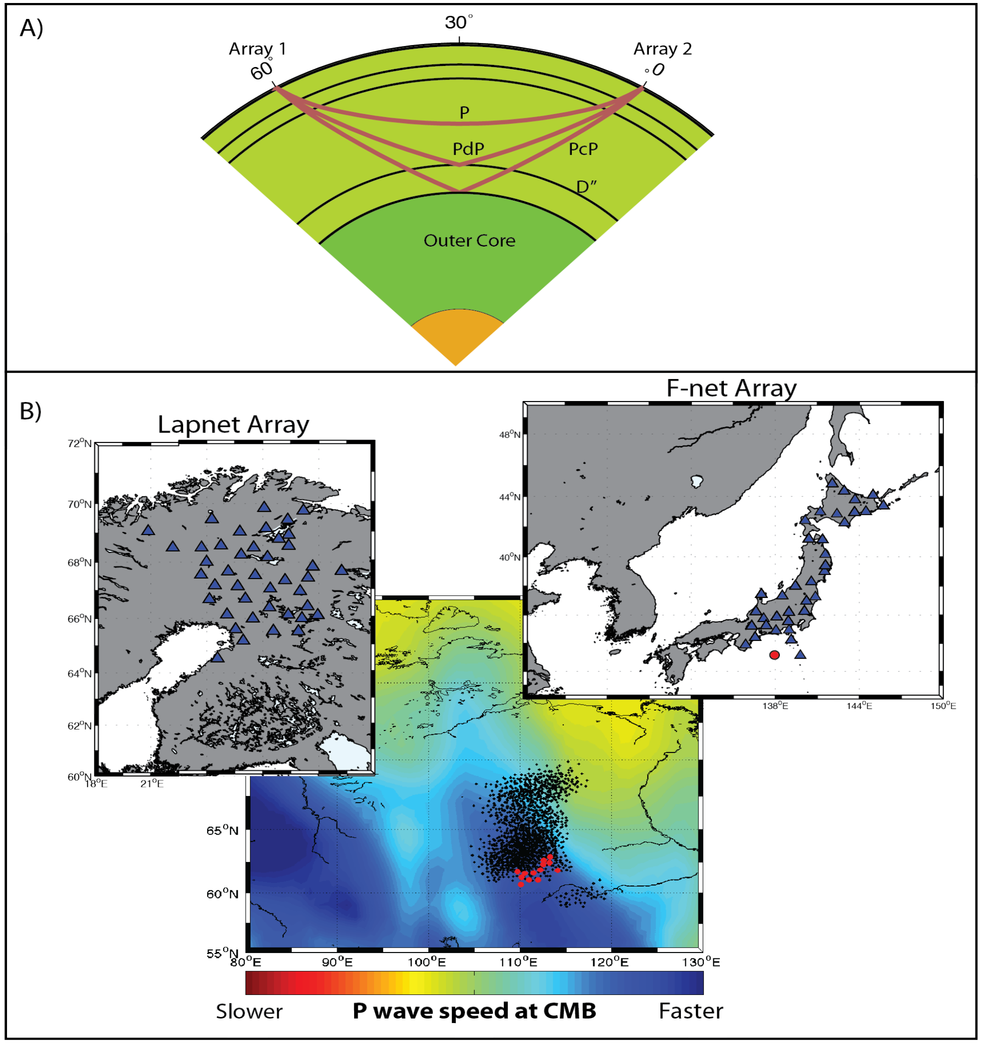


In agreement with receiver functions (Alinaghi et al. 2003)

Core phases PcP and PdP

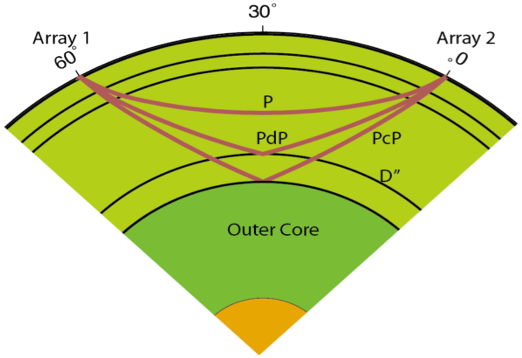
D'': - different hypotheses for the nature of the layer

  - PdP difficult to observe
  - lack of earthquake data

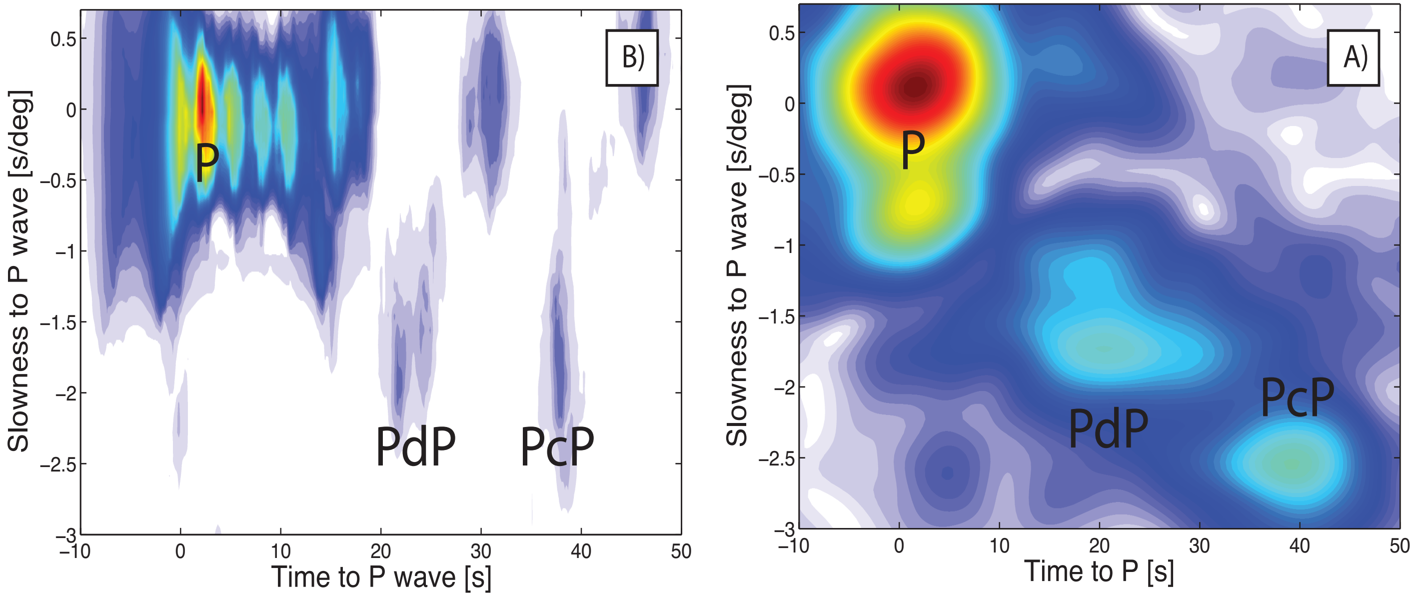


From Poli, Thomas, Campillo and Pedersen 2014

Advantage of noise vs earthquake records:
- -surface to surface
- -impulsive wavelet
- -double beam forming



Stacked vespagrams for:



Earthquakes

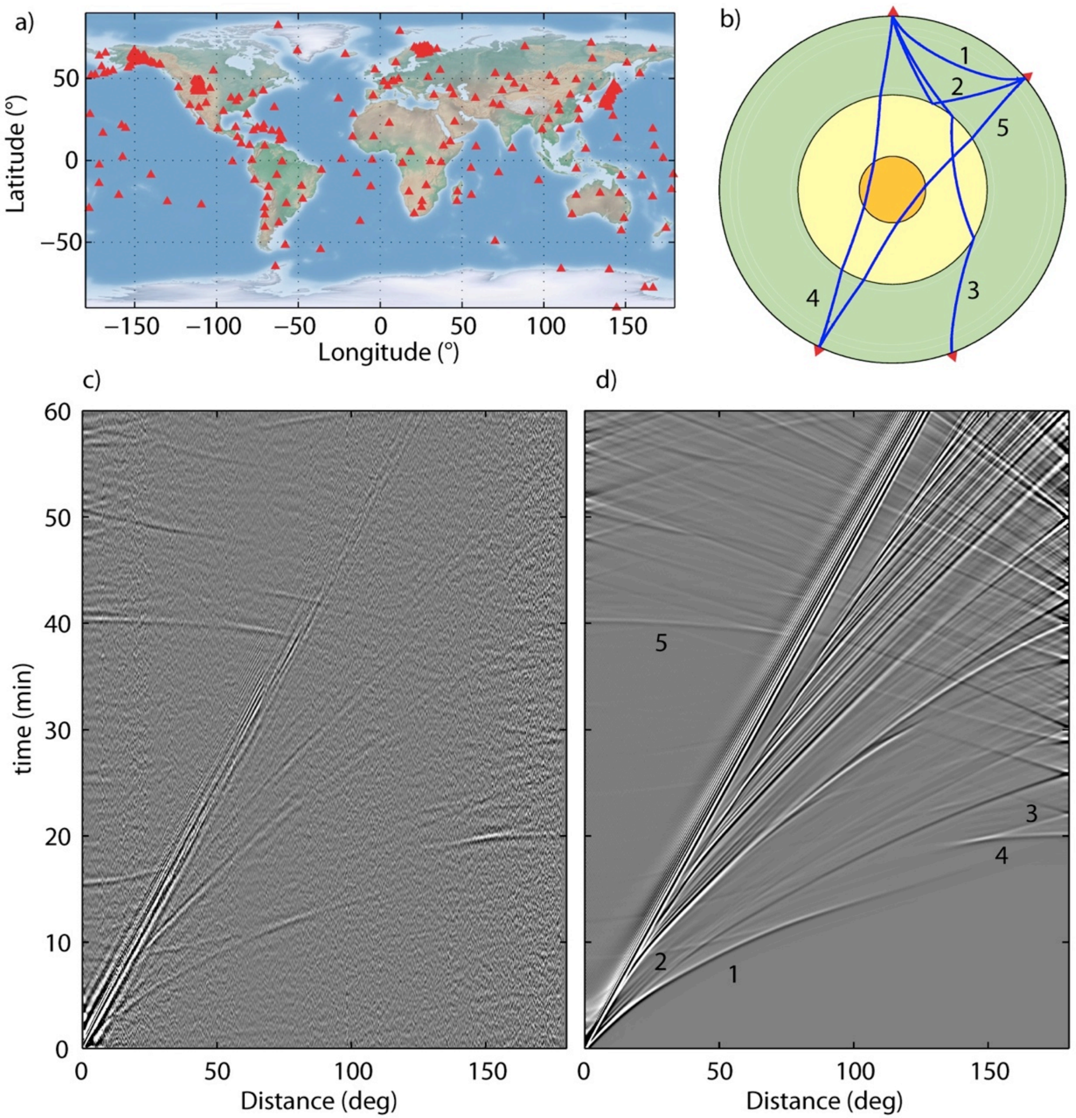
Noise

A 5% increase of velocity at 2530 km depth….

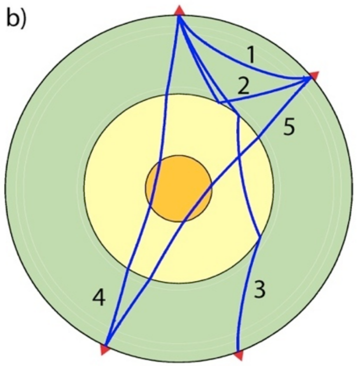
From Poli, Thomas, Campillo and Pedersen 2014

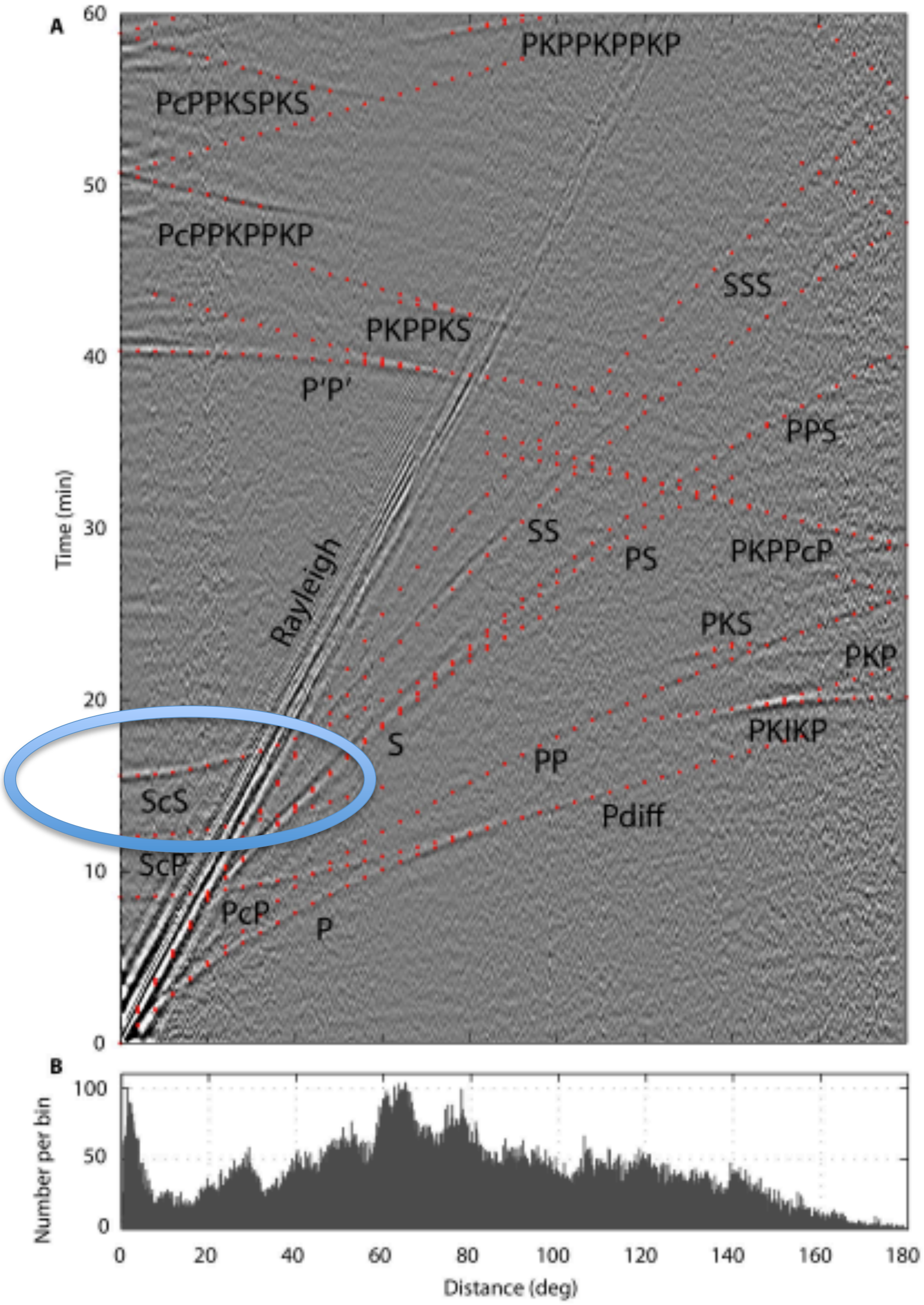
GLOBAL TELESEISMIC CORRELATIONS (periods 25-100s vertical components)

Boué, Poli et al., GJI 2013



Numerous phases can be identified



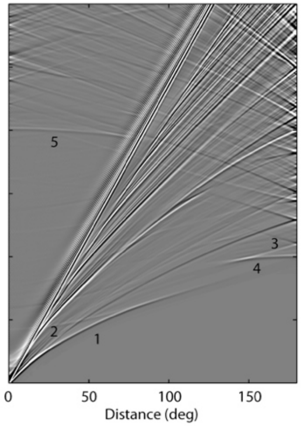


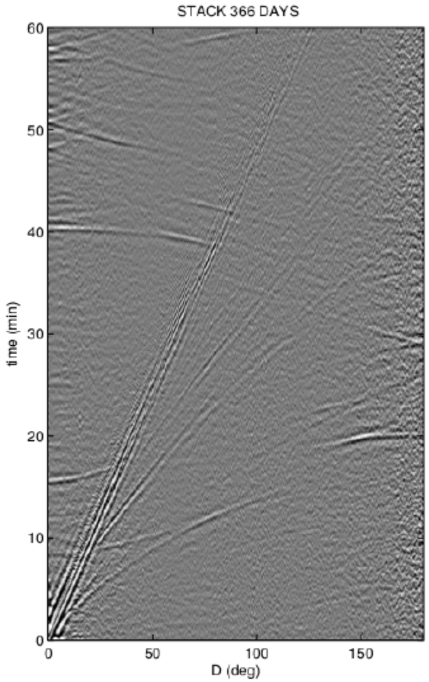
Vertically incident S waves on the vertical component??

Long periods (25-100s)

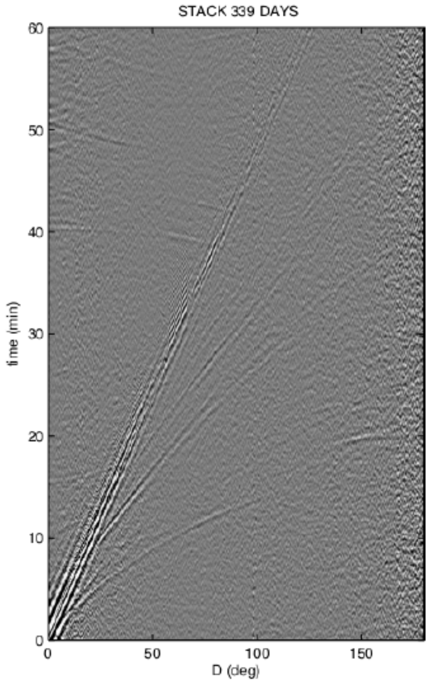
Processing: separating EQ and coda from ambient noise

AXISEM synthetics

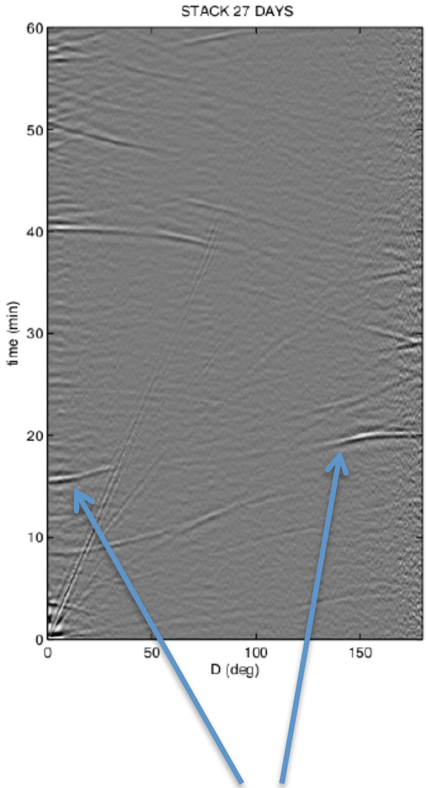




Low daily coherence



High daily coherence (EQs)

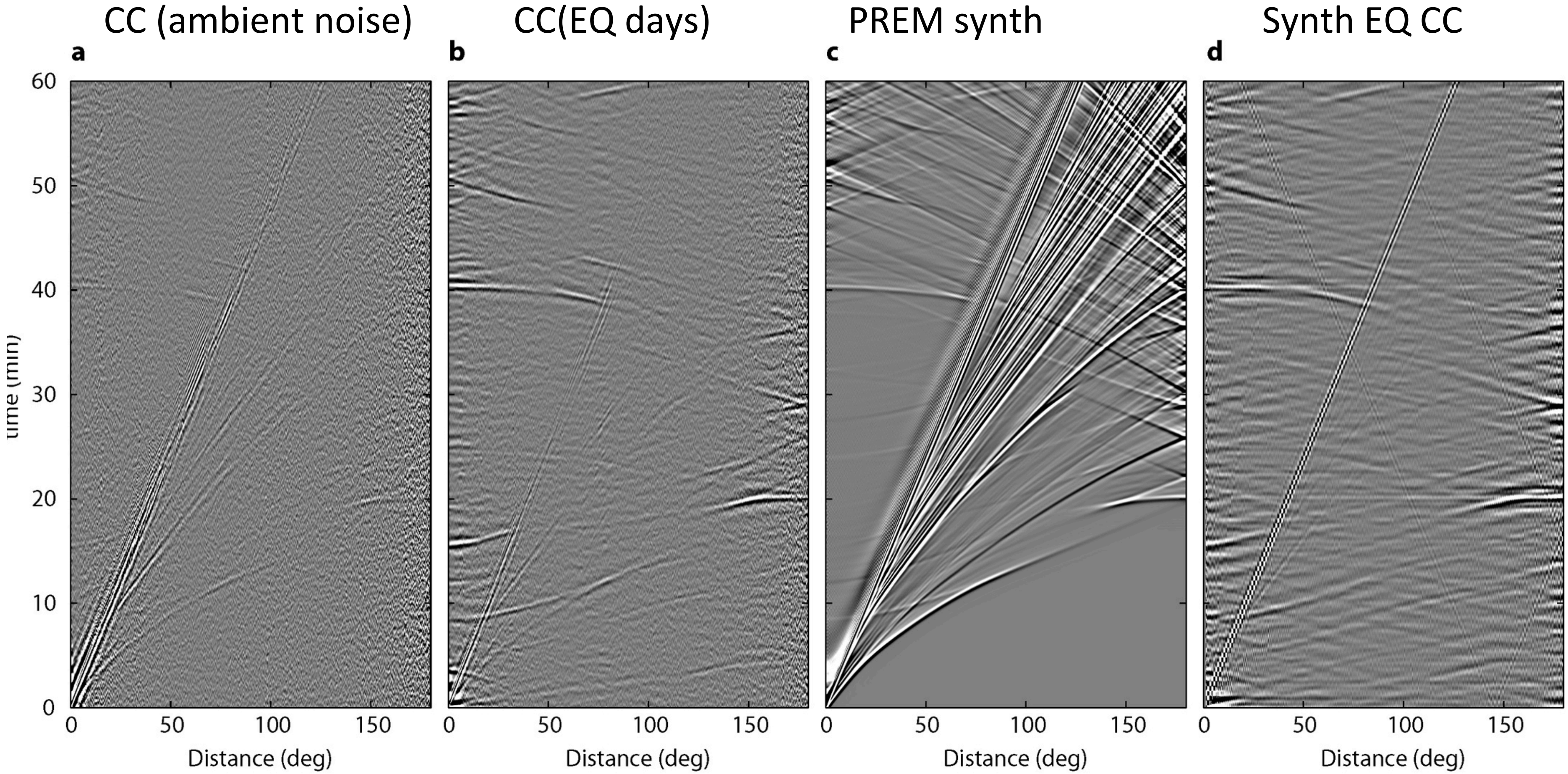


High amplitude spurious

High coherence=days following large earthquakes

Long periods (25-100s)

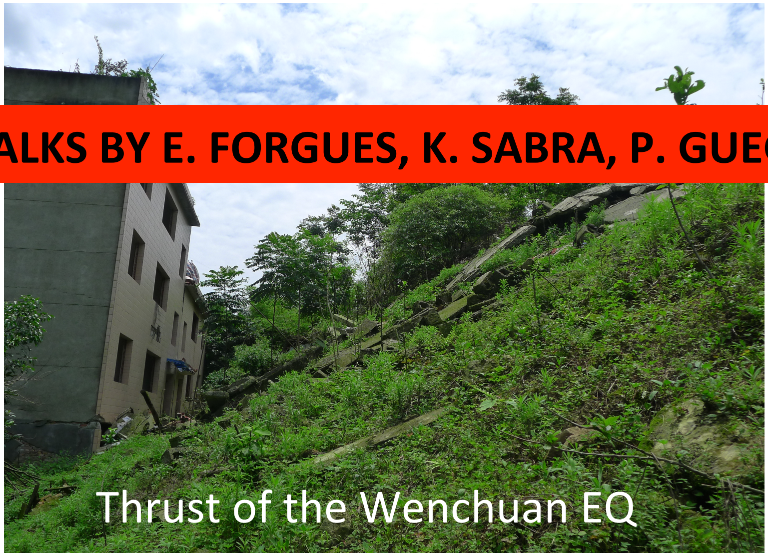
Spurious arrivals and numerical simulation



Very clear pulses in the correlations, likely holding information about the deep Earth, but should not be interpreted directly as components of the Green function

From Boué et al., 2014

TALKS BY E. FORGUES, K. SABRA, P. GUEGUEN, F. BRENGUIER


Thrust of the Wenchuan EQ


Hydraulic loads

Monitoring temporal changes in the solid Earth with seismic velocities


Tides

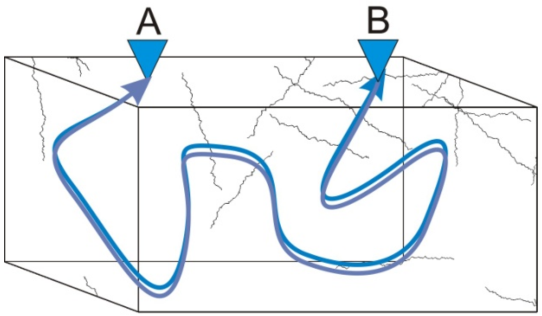

Eruption at Piton de la Fournaise

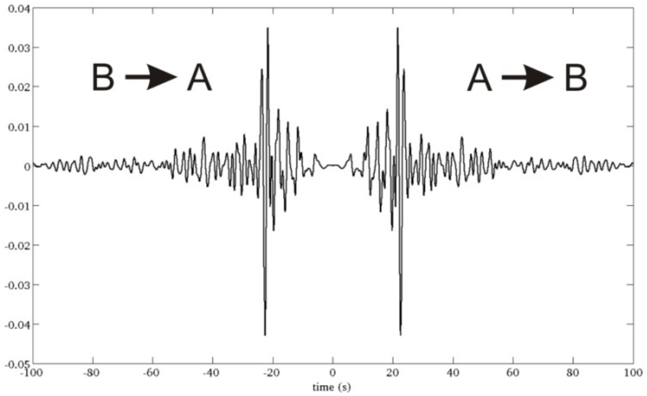

Geothermal – fracking..

Noise based seismic velocity temporal changes

Because seismic noise is continuous in time, it is possible to reconstruct **repeating virtual seismic sources** and perform **continuous monitoring of seismic velocities**.

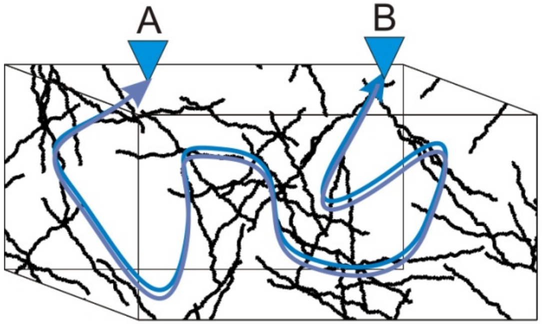
Normal state

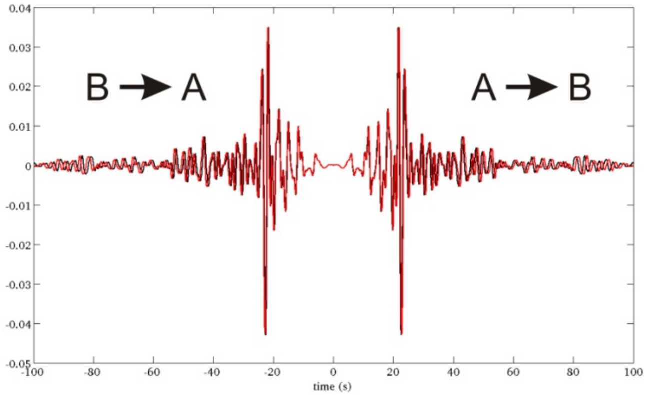




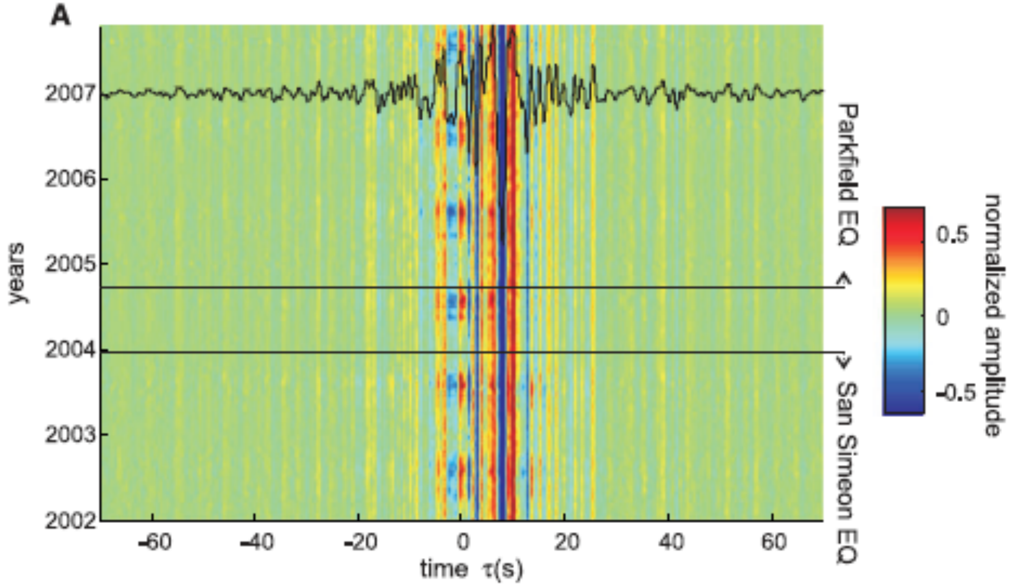
ΔV ⇩

Velocity decrease





Correlation functions as approximate Green functions

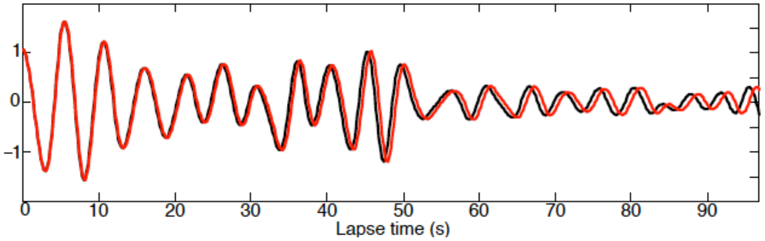


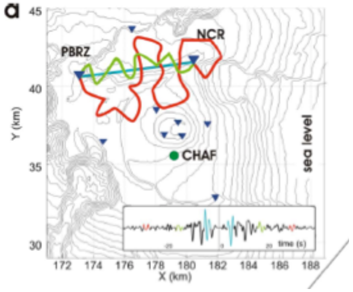
Direct waves are sensitive to noise source distribution (errors small enough for tomography (≤1%) but too large for monitoring (goal ≈ 10^{-4})

Stability of the ‘coda’ of the noise correlations

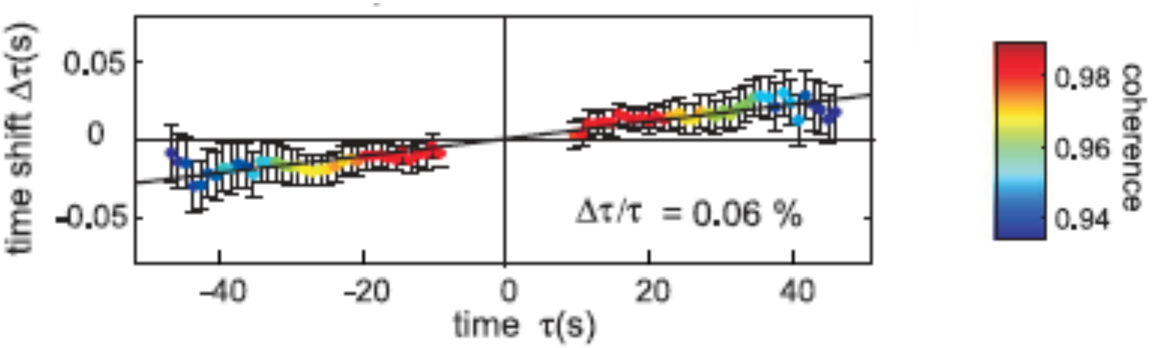
Detecting a small change of seismic speed: coda waves

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





The ‘doublet’ method: moving window cross spectral analysis (phase measurements)

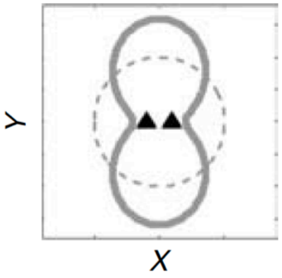


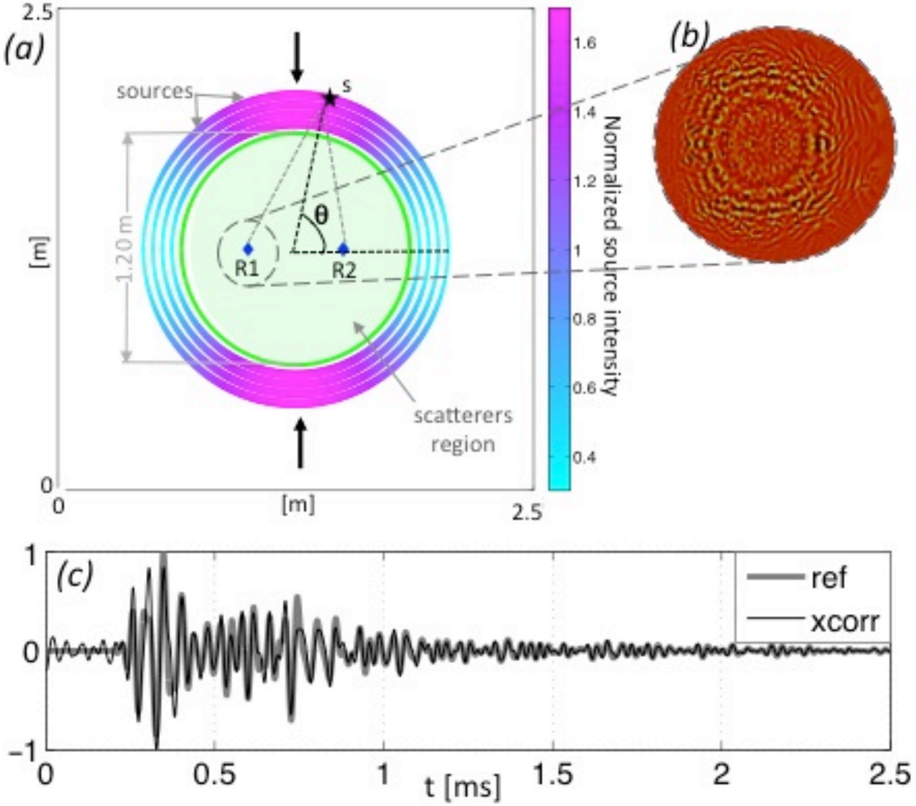
Alternative technique: stretching

Precision of the measure of delay/velocity variations in the coda

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



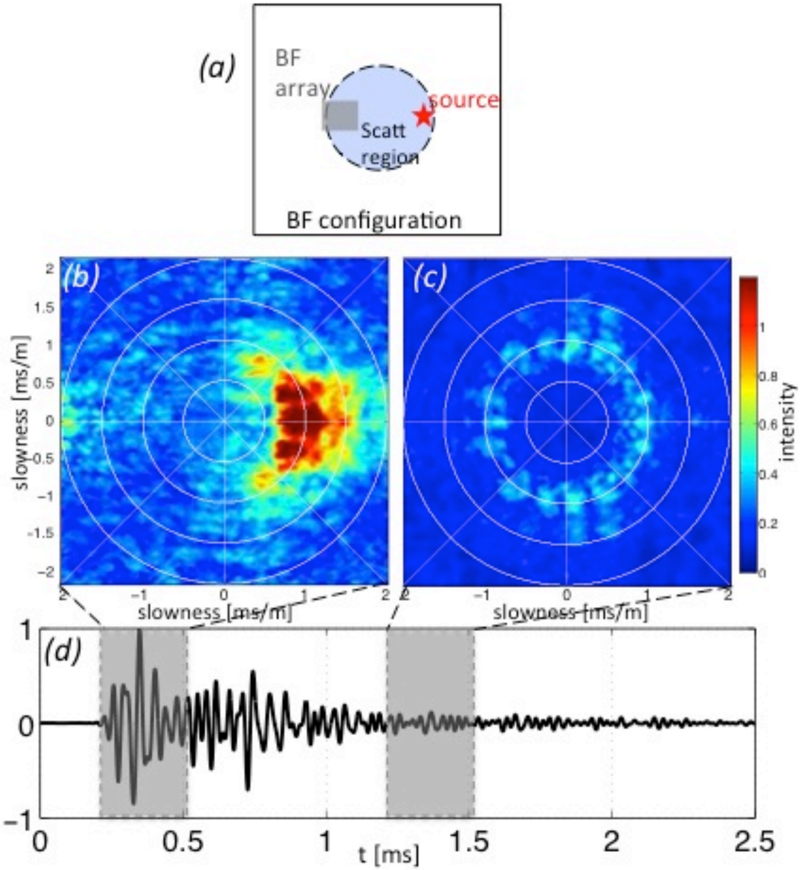


Comparison of correlations with Green function

Colombi, Chaput, Hillers et al., 2014 in press

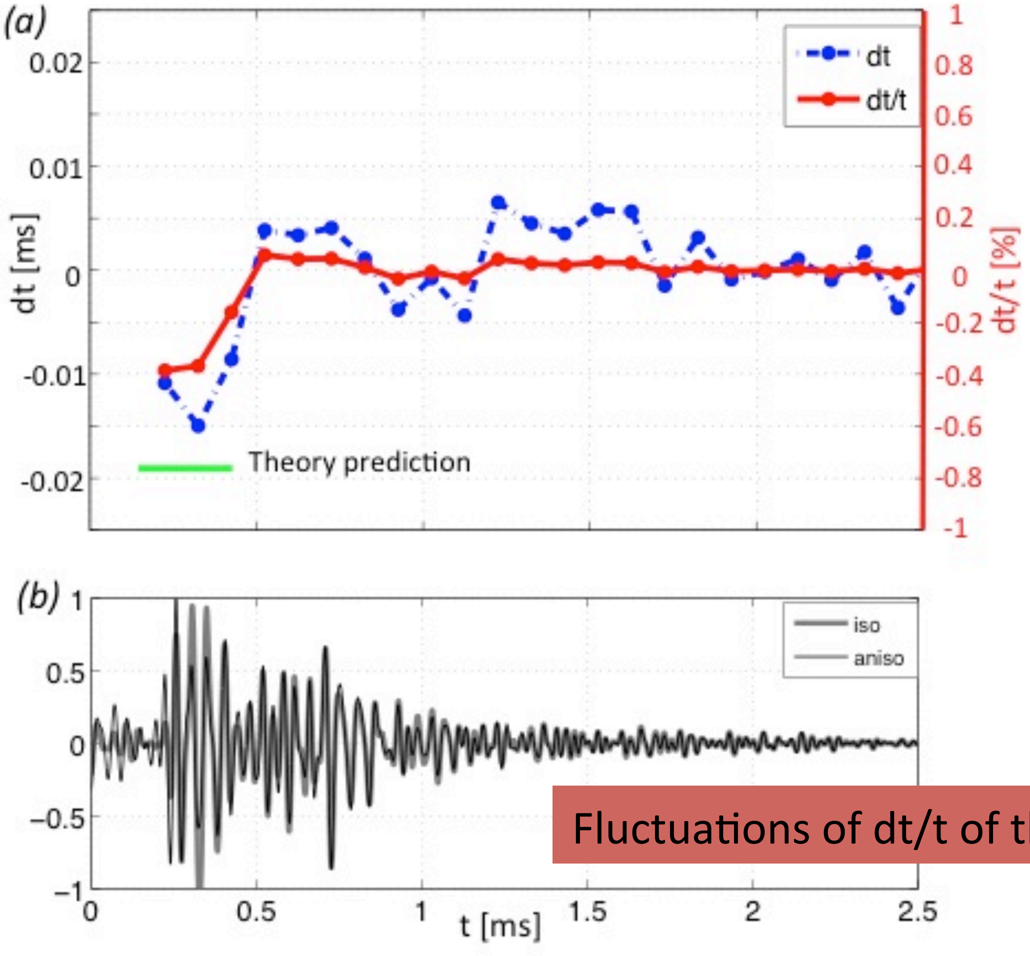
Effect of scattering (single source)

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)



Blue: delay

Red: relative delay

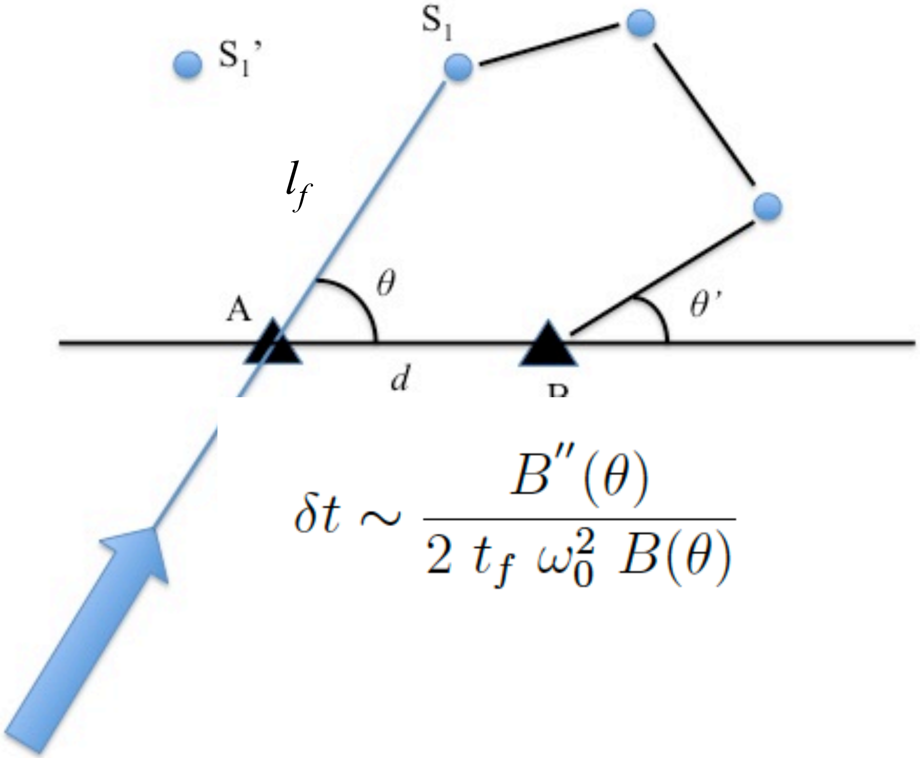
Fluctuations of dt/t of the order of 10^{-4}

Colombi, Chaput, Hillers et al., 2014

Representation of coda waves as the sum of contributions of numerous paths

For a single path:

$t_f = l_f / V$



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

We have to compute the contributions of paths with first scatterers at all distances l_f and all azimuths θ

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

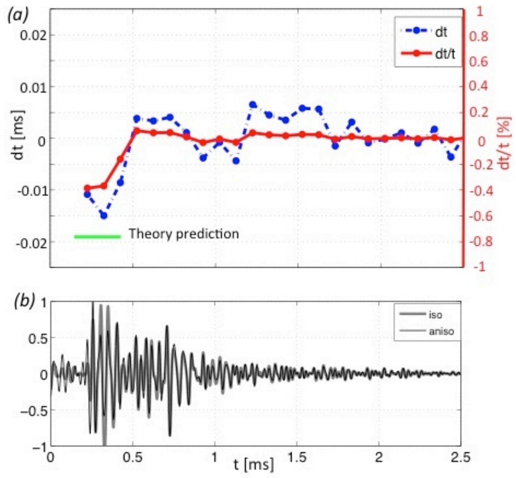
$$<l_f> = l \qquad t_f = l_f / V$$

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

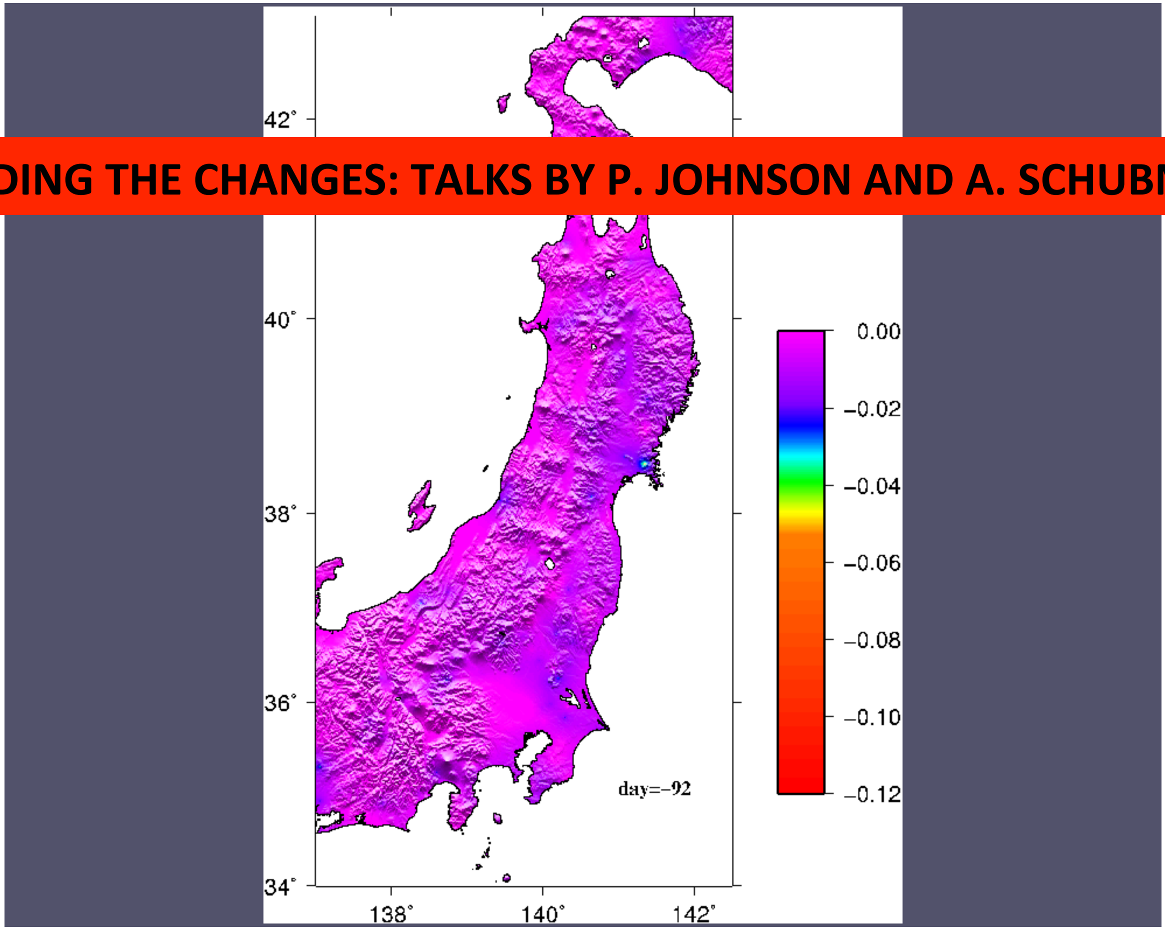
$$l = 0.5m,\ c = 2000\text{m/s},$$

$$f_0 = 30000\text{Hz},\ B_2 = -0.6 \text{ and } \tau_m = 0.002\text{s}$$

➔ $\text{fractional error } \frac{\delta t(\tau_m)}{\tau_m} \text{ of } 10^{-4}$.

Relative velocity change (in %) measured in the band 0.1-0.9 Hz

UNDERSTANDING THE CHANGES: TALKS BY P. JOHNSON AND A. SCHUBNEL



Calendar time measured in days with respect to March 11 (M9 Tohoku EQ)

From Brenguier, Campillo, Takeda, Aoki, Shapiro, Briand, Emoto and Miyake, Science 2014

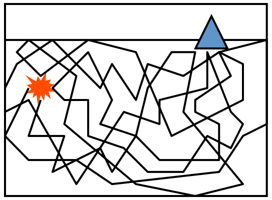
Could we show that the late part of the correlation function contains the scattered waves?

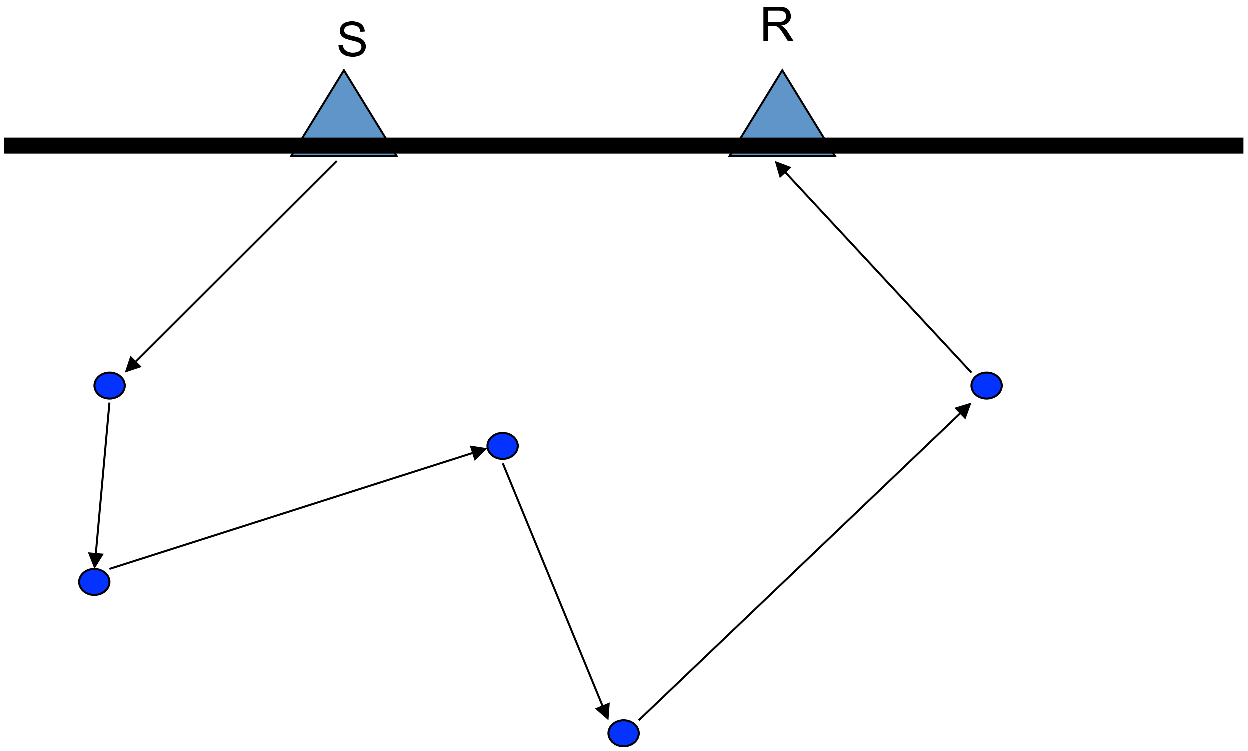
-energy decay (e.g. Sens-Schoenfelder and Wegler, 2006)

-long range correlation (C^3: correlation of coda of noise correlation ➔ Green function) (e.g. Stehly, Campillo, Froment and Weaver, 2008)

-weak localization?

Coherent backscattering/weak localization and the multiple scattering regime

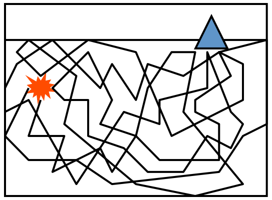


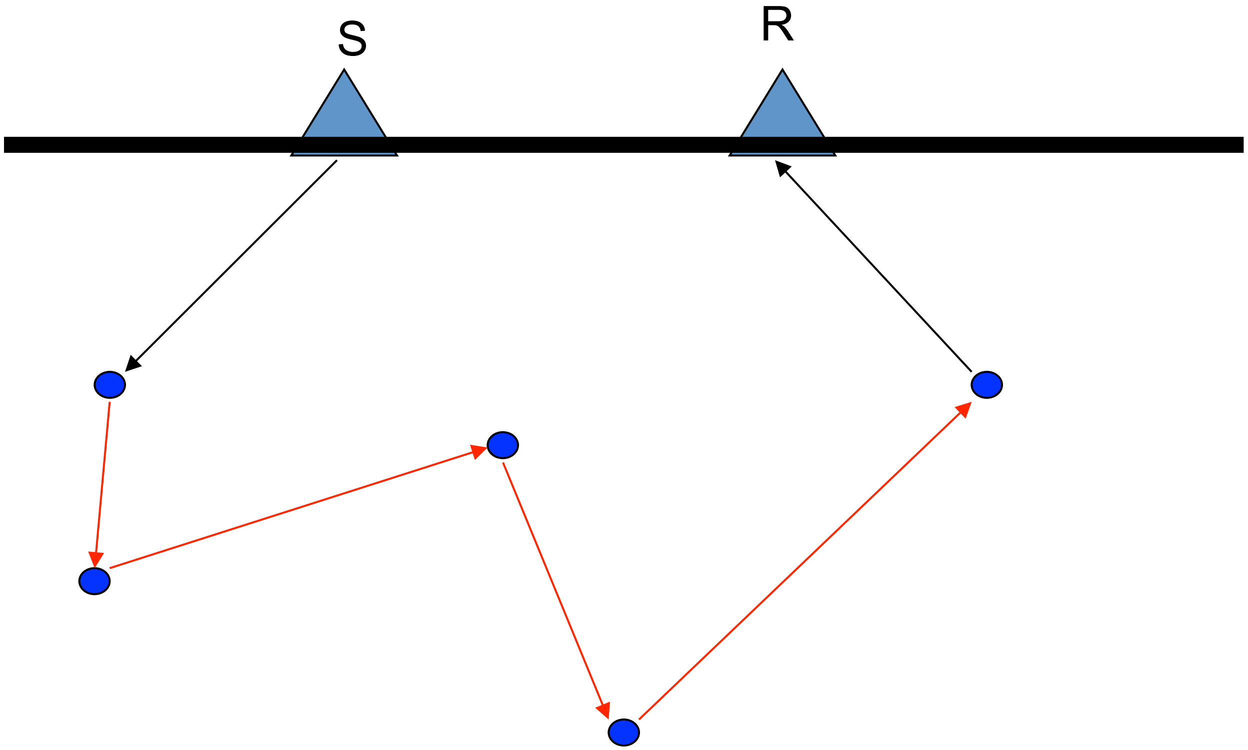


Energy density is represented by the sum of contributions of scattering paths

RTE for <intensities>, DE for <energy density>,… but the actual signal results from deterministic waves

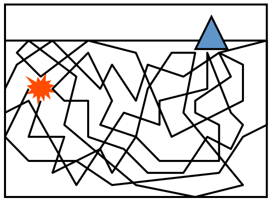
.

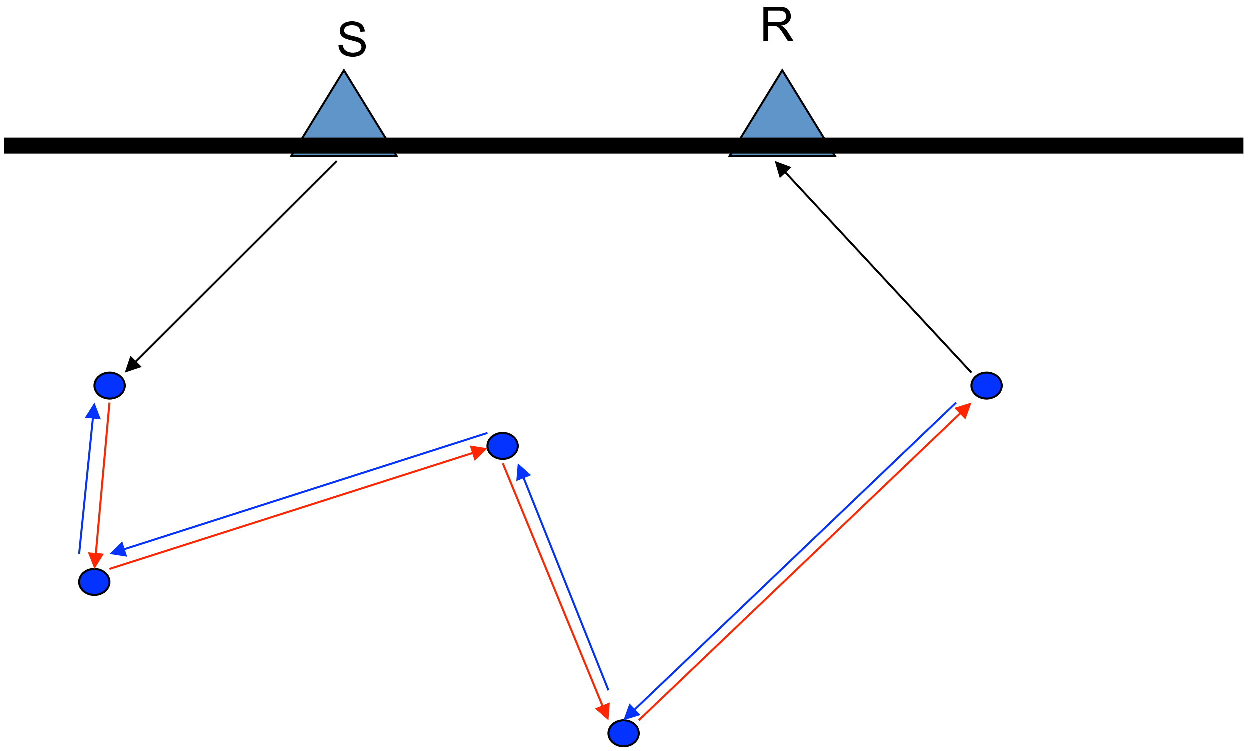




If this path exists..

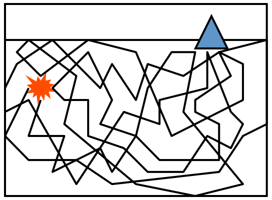
.

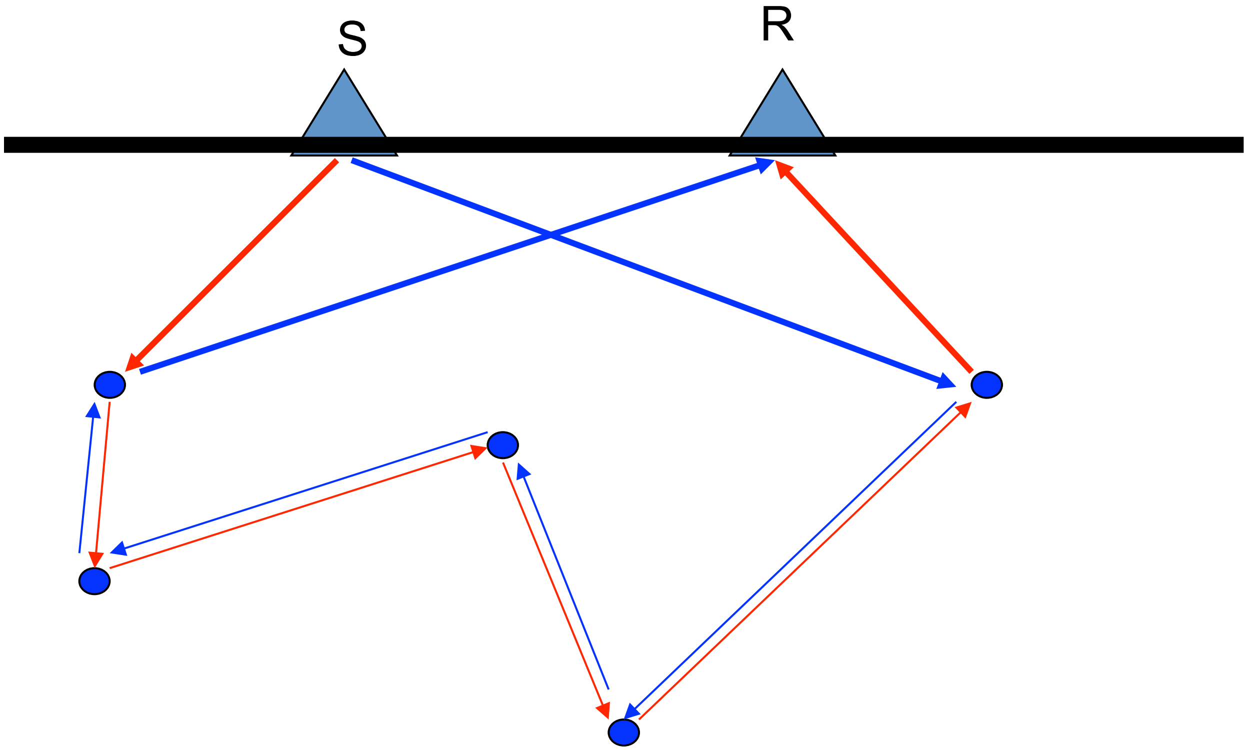




If this path exists, the reciprocal path exists too.

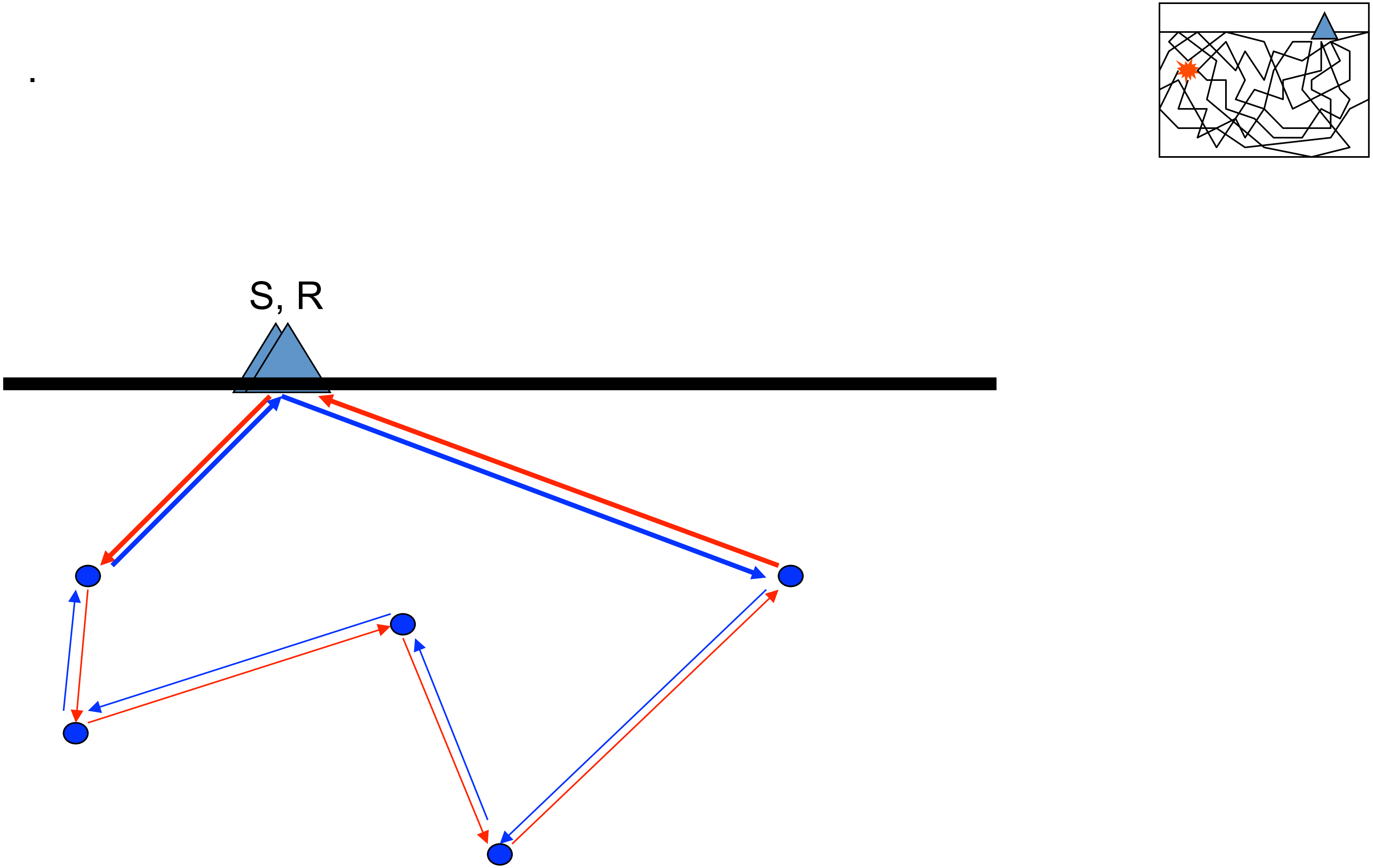
.





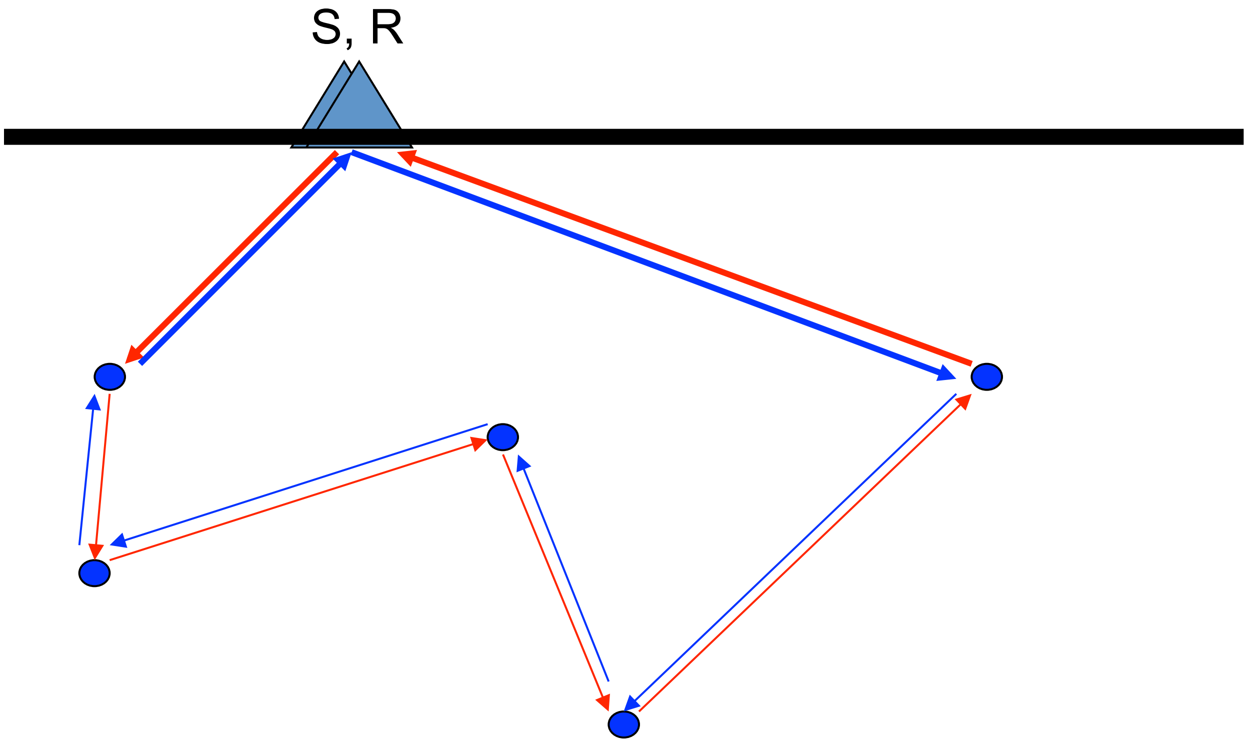
Phase difference: location of the scatterers…

.



Phase difference: location of the scatterers…
Except if R and S are at the same place

.

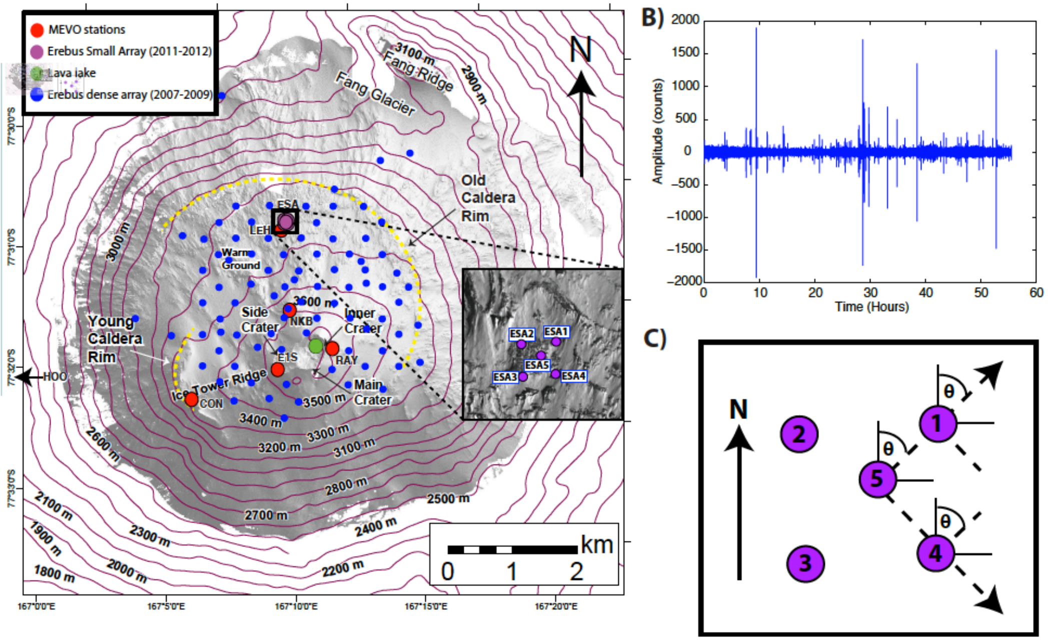


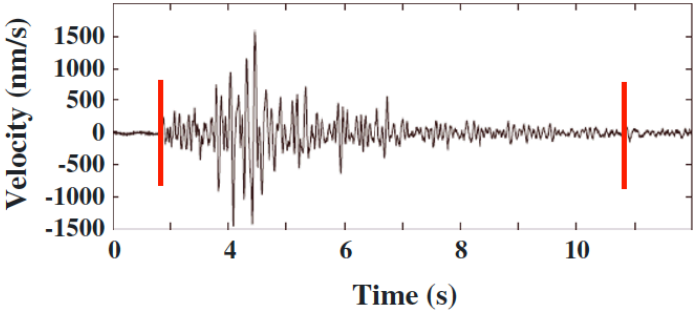
Coherent summation ➔Spot of intensity enhancement at the source: factor 2

Consequence of first principles, namely reciprocity.

Consider now correlations as virtual Green functions (Julien Chaput et al. 2015 –see Poster).

Erebus volcano: icequakes

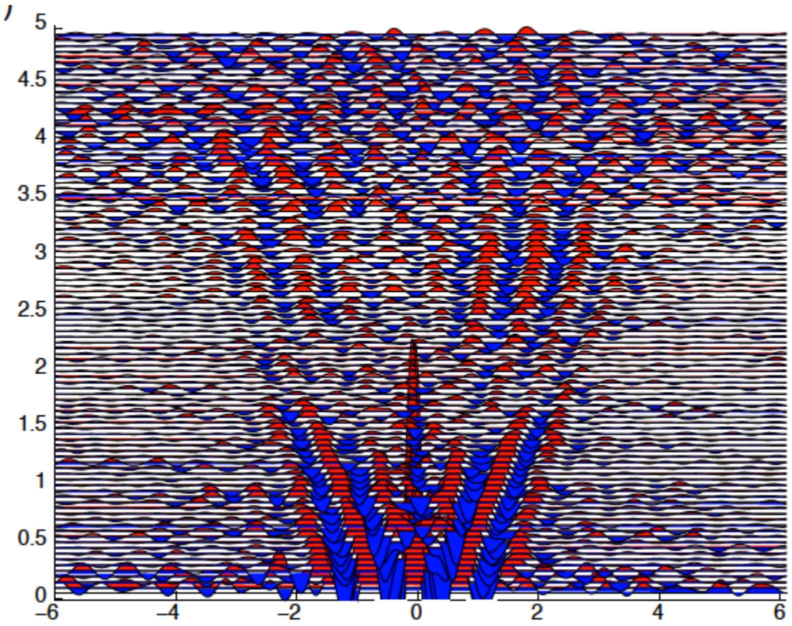




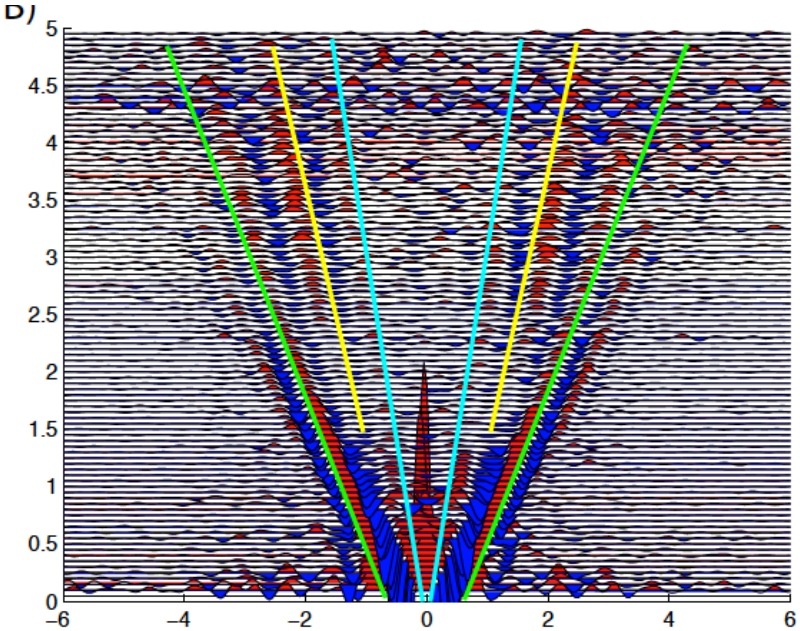
Chaput et al., JGR 2015

Coda Correlations

44 ‘large’ events

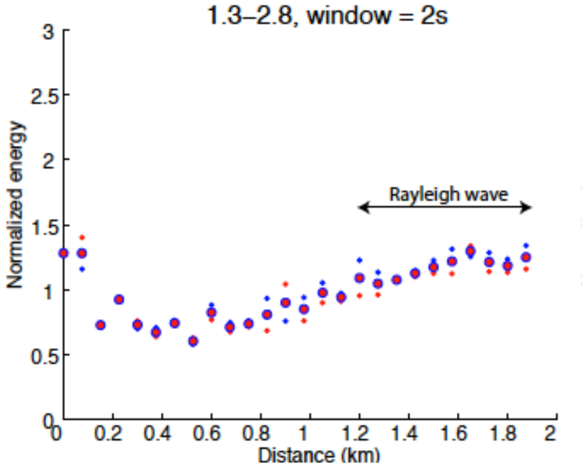


All 3318 events



ZZ correlations: reciporcity holds

Energy vs distance at a given time



Weak localization can be observed in correlations!
(➔mean free path…)
Not possible from earthquake data (reciprocity)