The Abdus Salam
International Centre for Theoretical Physics

United Nations
Educational, Scientific
and Cultural Organization

International Atomic
Energy Agency

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"8th Workshop on Three-Dimensional Modelling of
Seismic Waves Generation, Propagation and their Inversion"

25 September - 7 October 2006

Solar powered seismology: surface wave imaging from ambient seismic noise

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Solar powered seismology: surface wave imaging from ambient seismic noise

Nikolai Shapiro

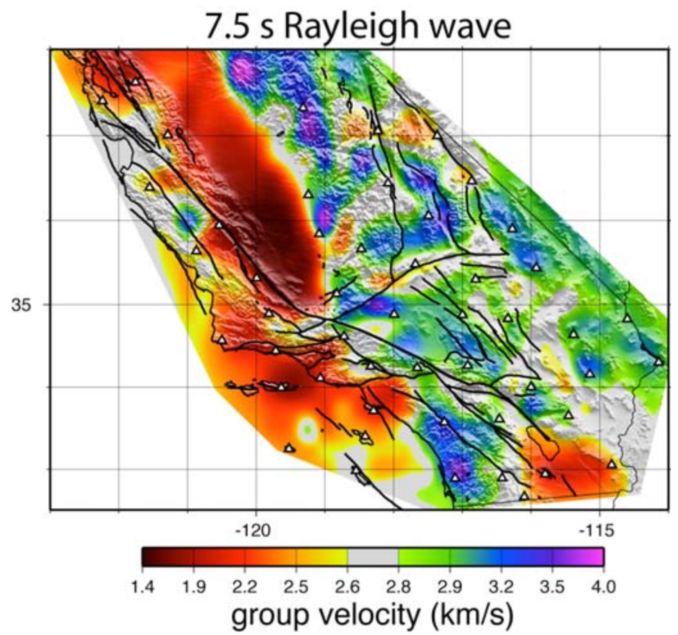
IPGP, France

"8th Workshop on Three-Dimensional Modeling of Seismic Wave Generation, Propagation and their Inversion"
ICTP, Trieste, Italy, September 28, 2006.

Collaborators:

Michel Campillo, Laurent Stehly, Florent Brenguier, Ludovic Margerin, Bart van Tiggelen (LGIT, Grenoble)

Mike Ritzwoller, Anatoly Levshin, Yingjie Yang, Morgan Moschetti, Misha Barmin, Greg Bensen (CU Boulder, Colorado, USA)



More information in publications at: http://www.ipgp.jussieu.fr/~nshapiro

Outline

1. Natural sources of seismic signals
2. Traditional surface wave tomography and its limitations
3. Measurements from random wavefields: background
4. Measurements from random wavefields: examples in seismology
    1. Regional coda
    2. Teleseismic coda
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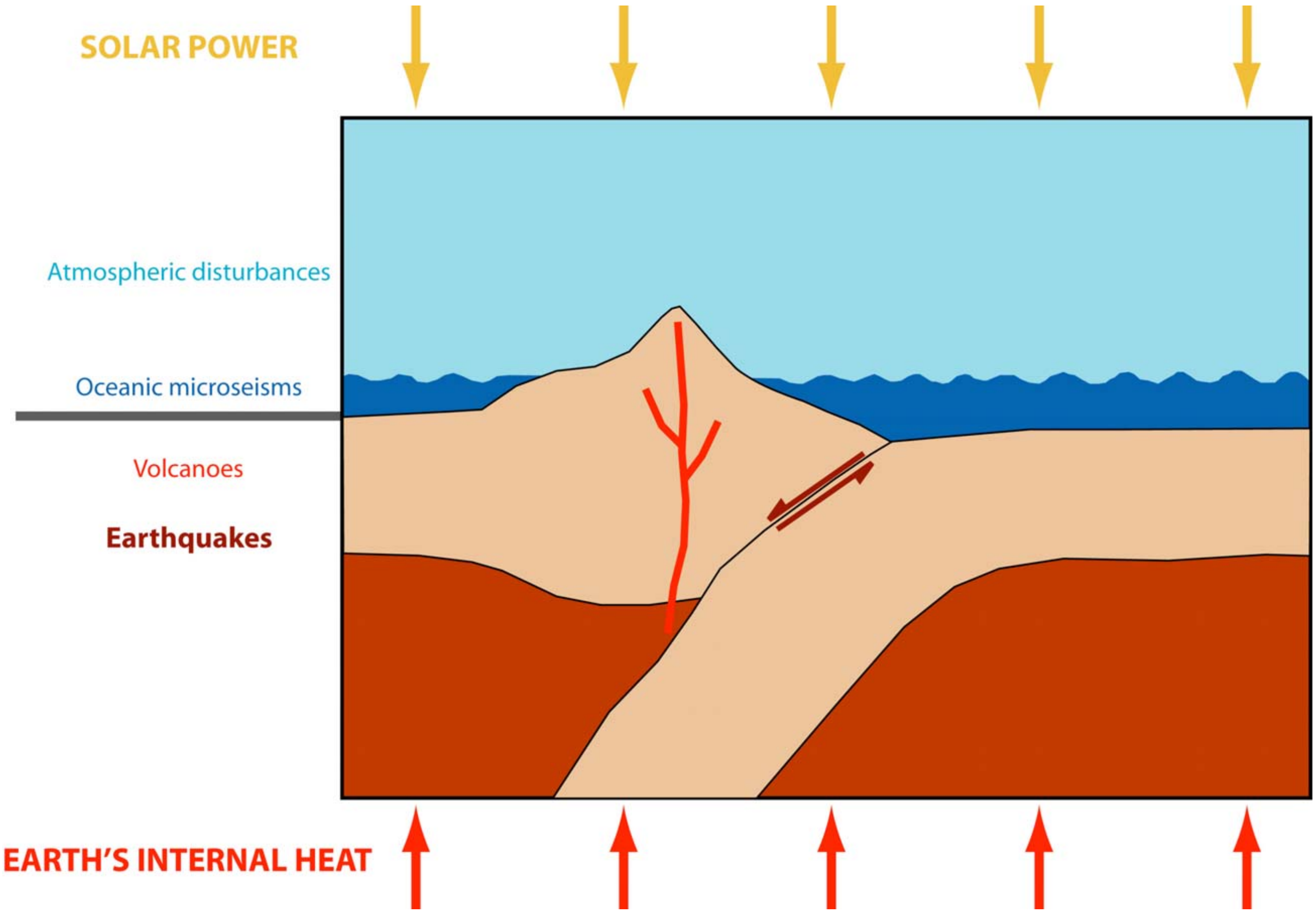
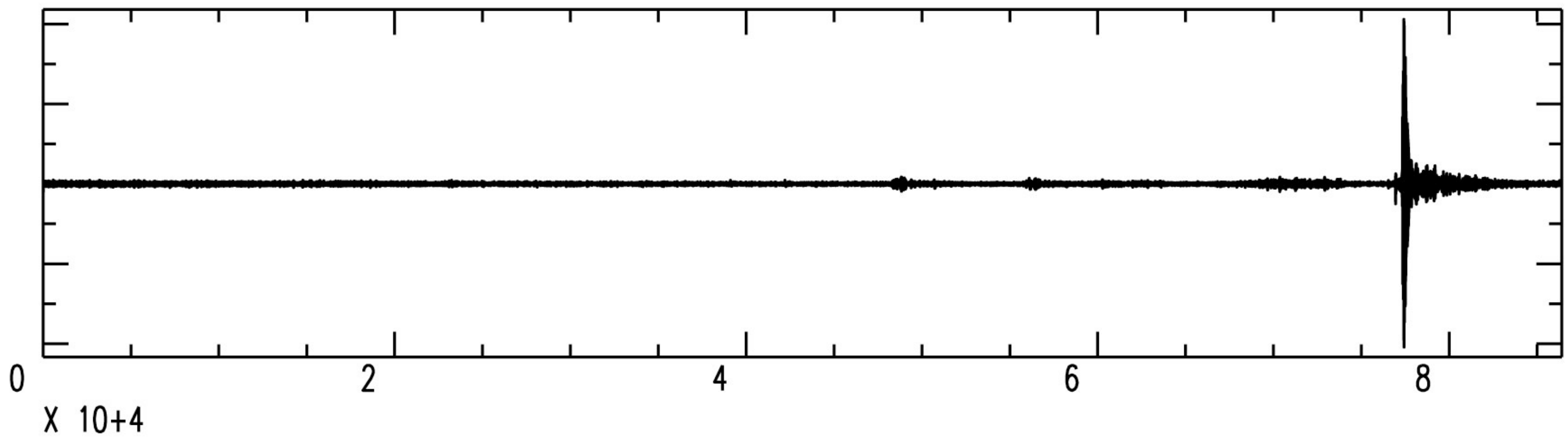
    1. California
    2. Europe
7. Tracing the origin of the seismic noise
8. Most recent results and future directions

Natural sources of seismic signals



one day of seismic record



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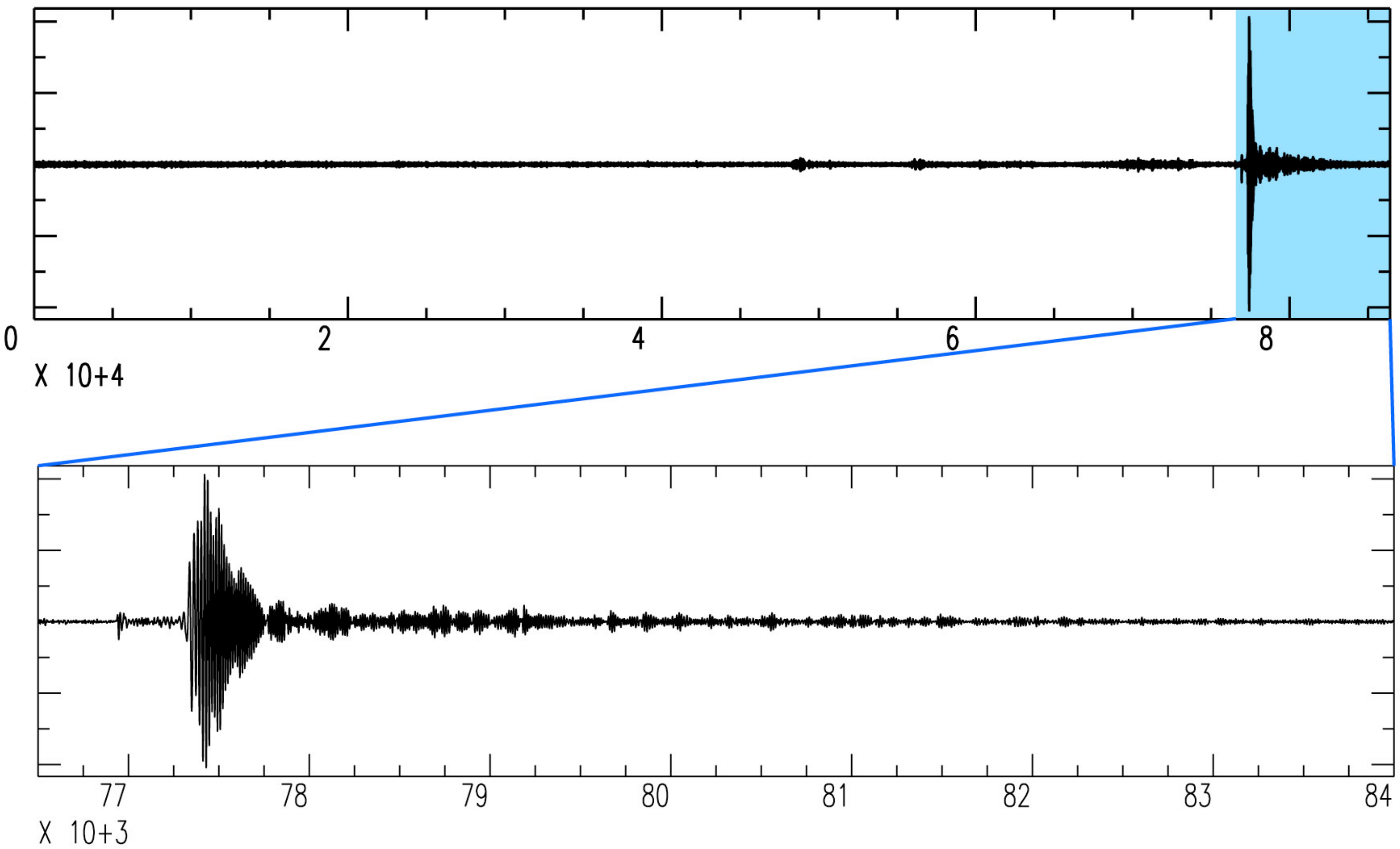
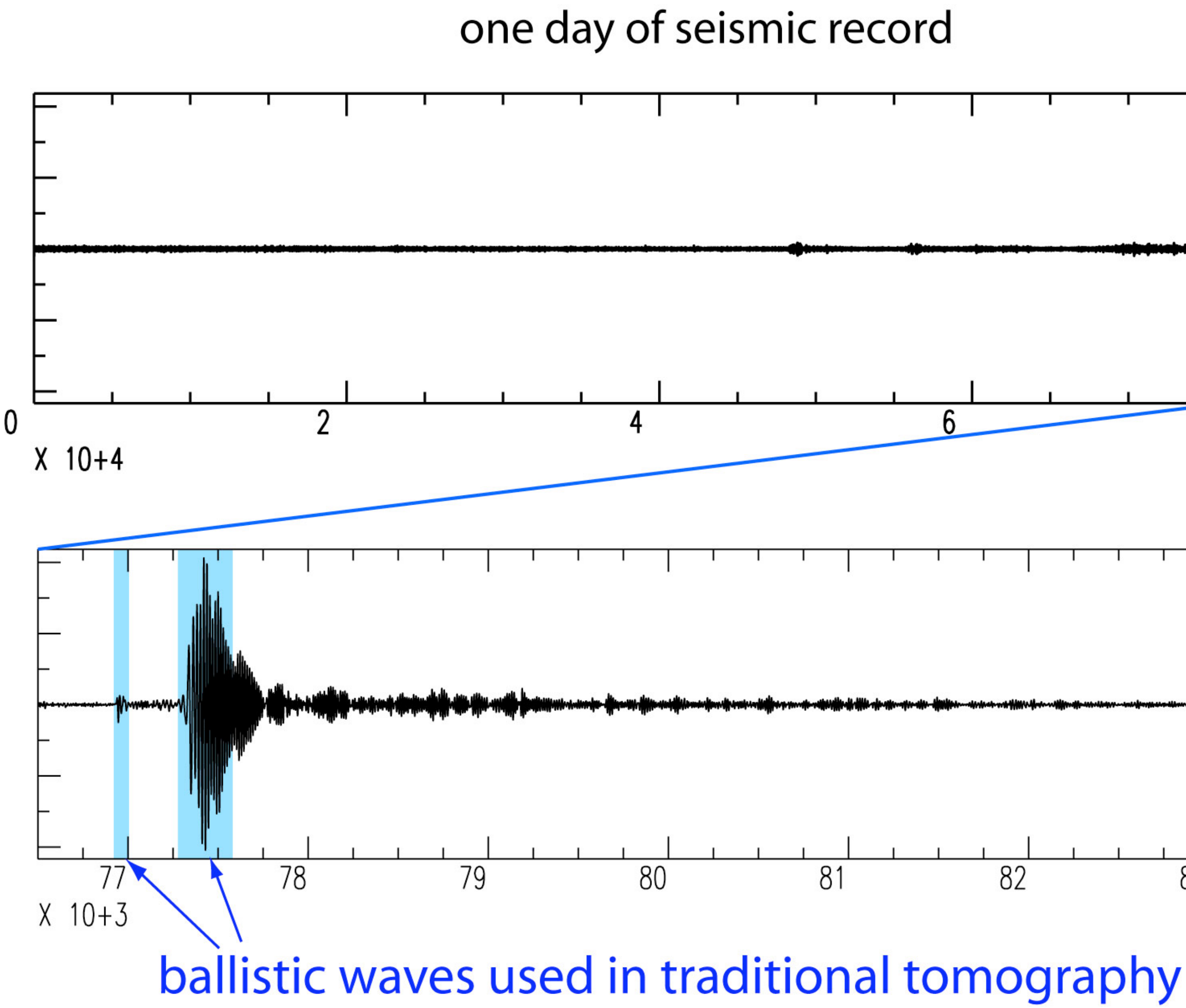
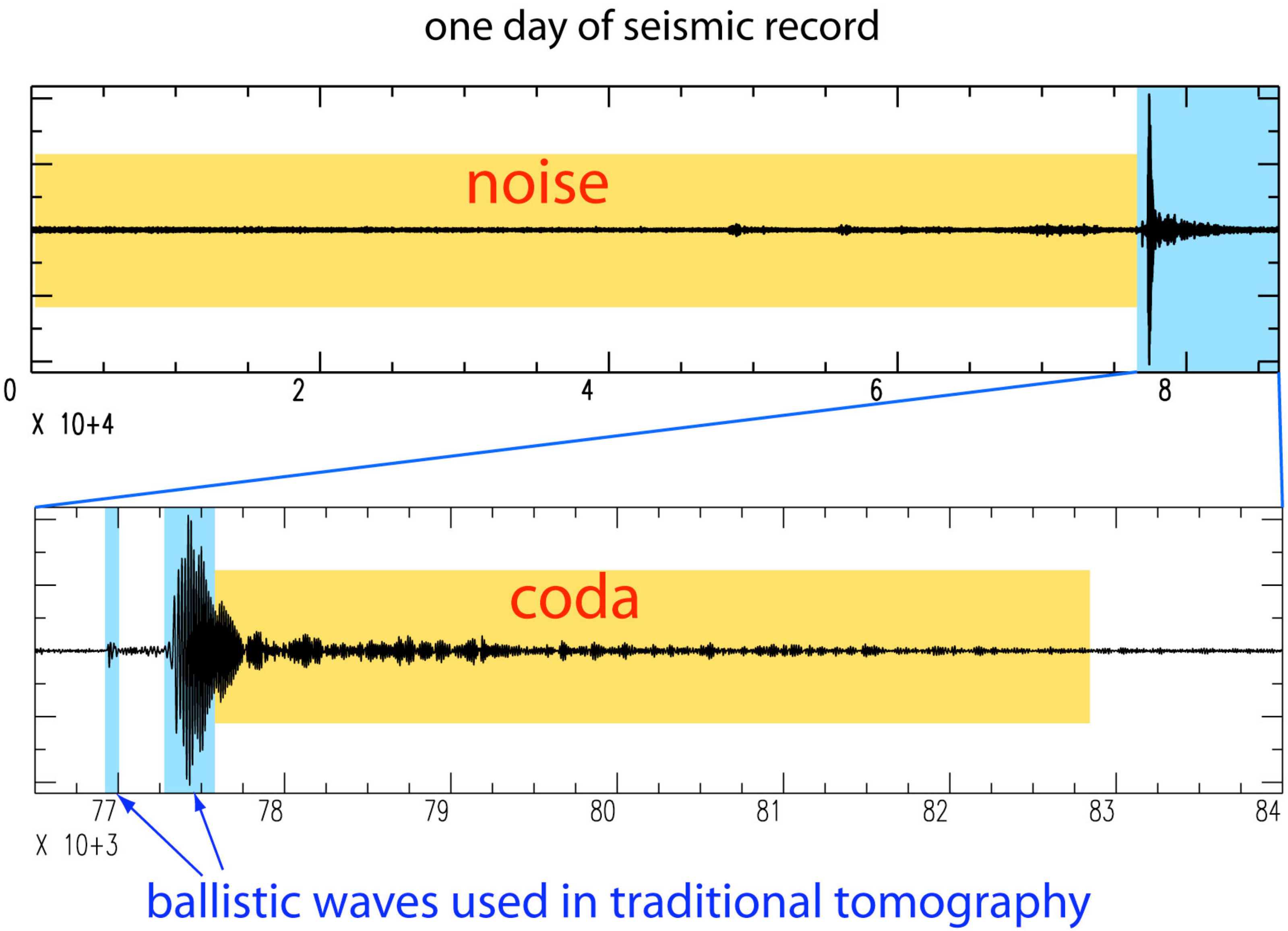




one day of seismic record
0
2
4
6
8
X 10+4
77
78
79
80
81
82
83
84
X 10+3
ballistic waves used in traditional tomography



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noise
0
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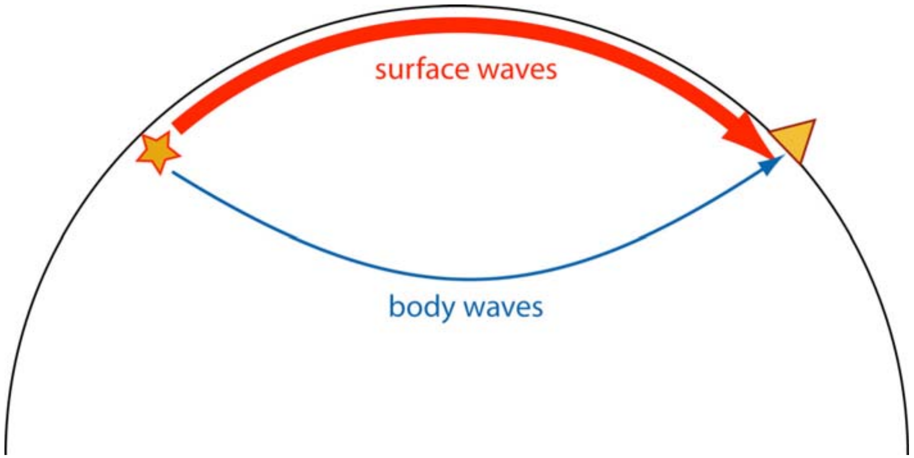
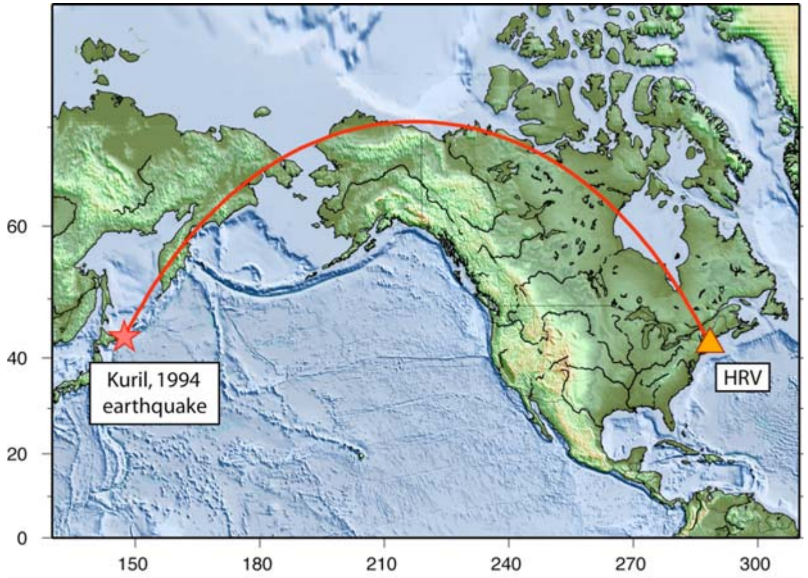
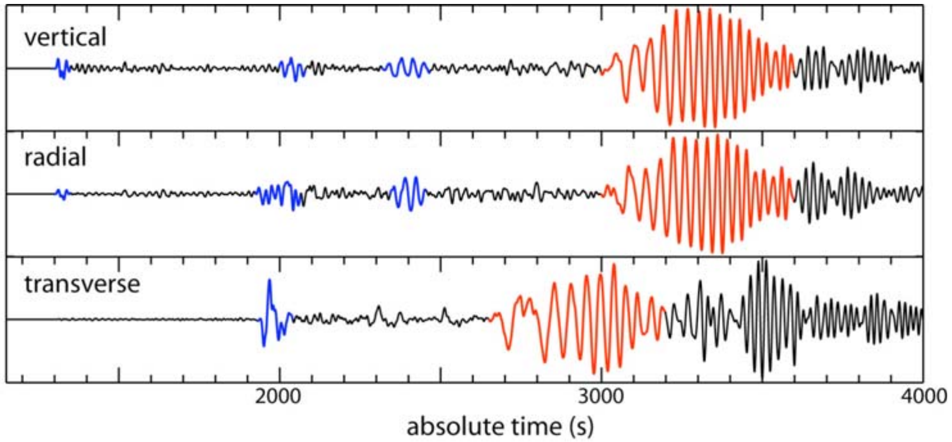
traditional surface-wave tomography

(from lecture of A. Levshin)

Seismic data







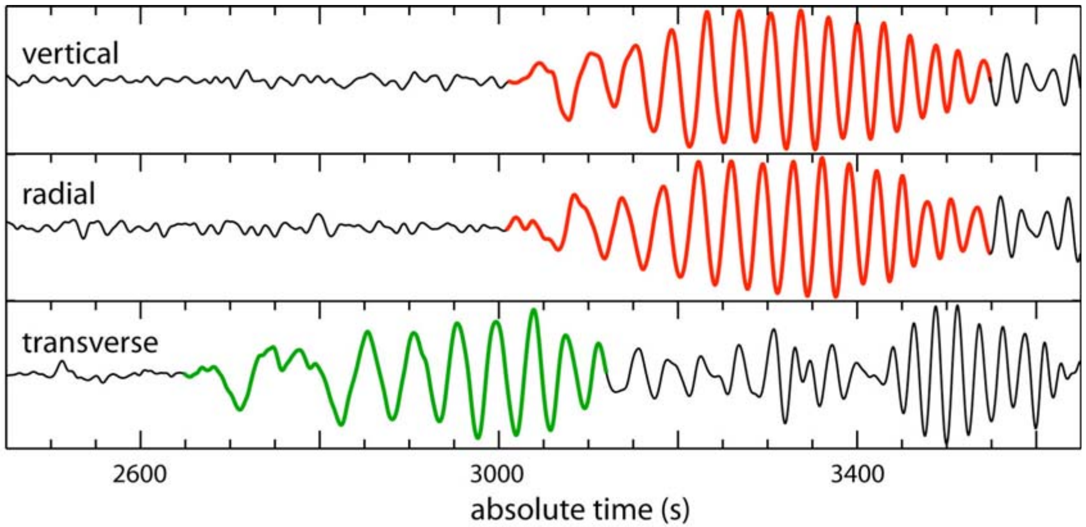
Body waves sample deep parts of the Earth

Surface waves sample the crust and upper mantle

traditional surface-wave tomography

(from lecture of A. Levshin)

Seismic surface-waves

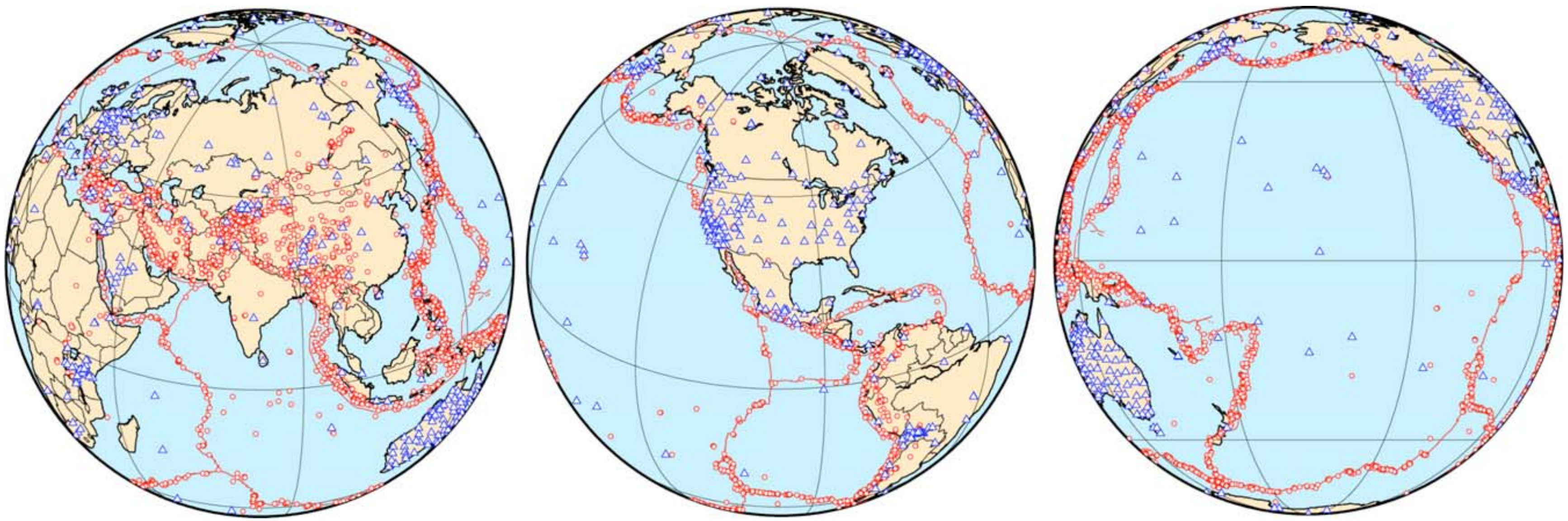


1. Two types: **Rayleigh** and **Love**
2. **Dispersion**: travel times depend on period of wave
3. Two types of travel time measurements: **phase** and **group**

traditional surface-wave tomography

(from lecture of A. Levshin)

distribution of paths for dispersion measurements

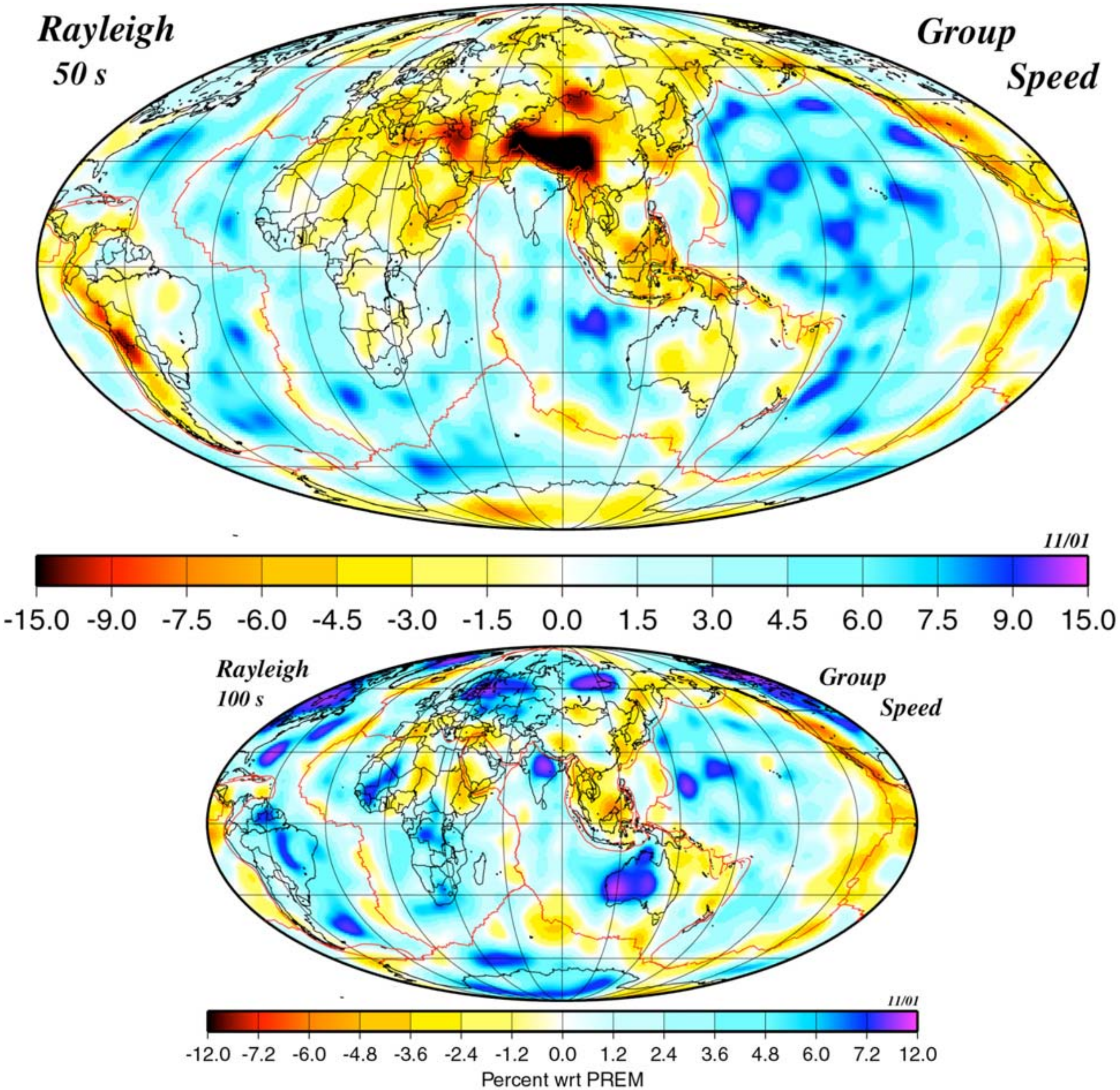


- More than 200,000 paths across the Globe
- Rayleigh and Love wave phase velocities (40-150 s) (Harvard, Utrecht)
- Rayleigh and Love wave group velocities (16-200 s) (CU-Boulder)

traditional surface-wave tomography

(from lecture of A. Levshin)

Dispersion maps

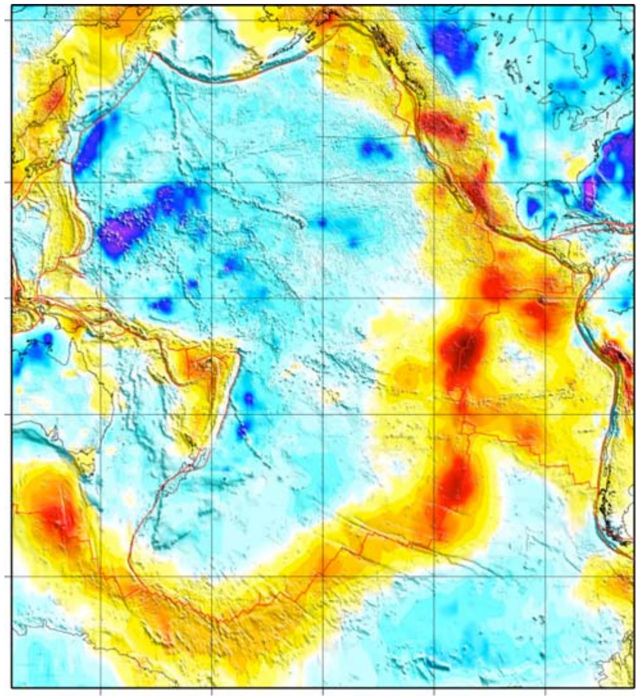


traditional surface-wave tomography

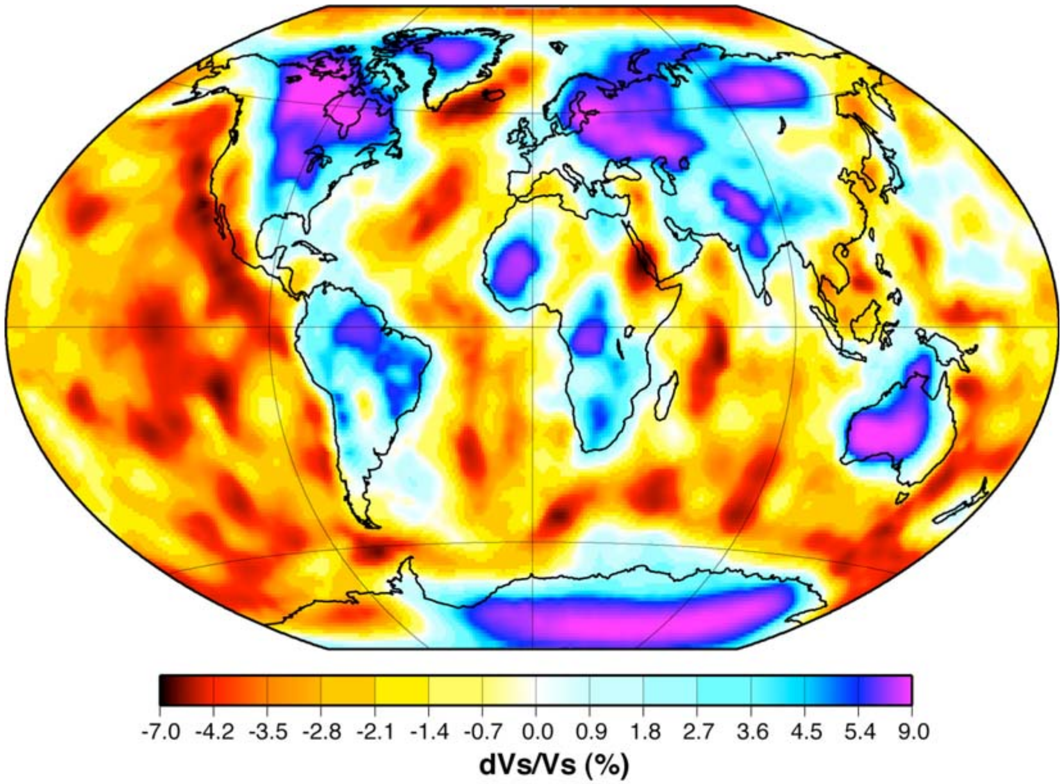
(from lecture of A. Levshin)

global 3D tomographic model

50 km



150 km

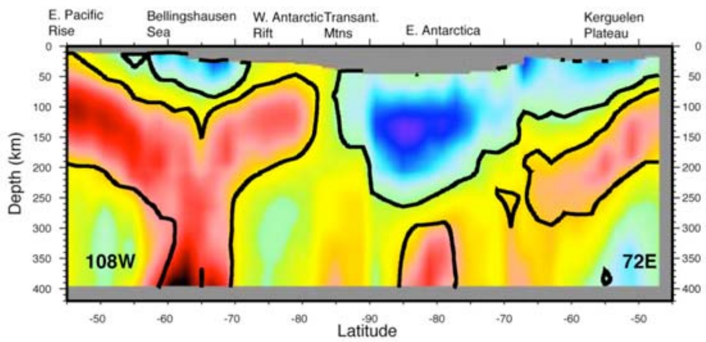


traditional surface-
wave tomography

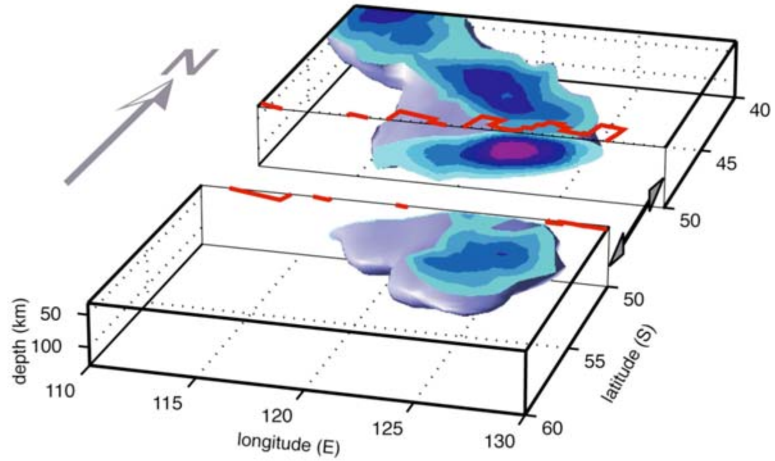
(from lecture of A. Levshin)

regional 3D tomographic models

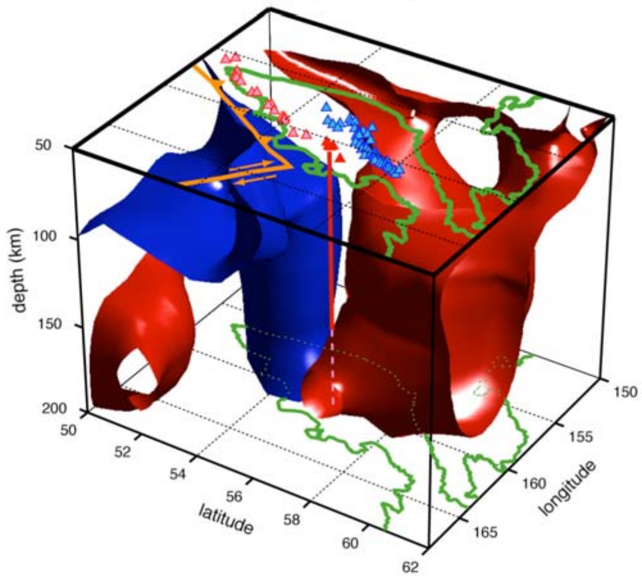
West Antarctica



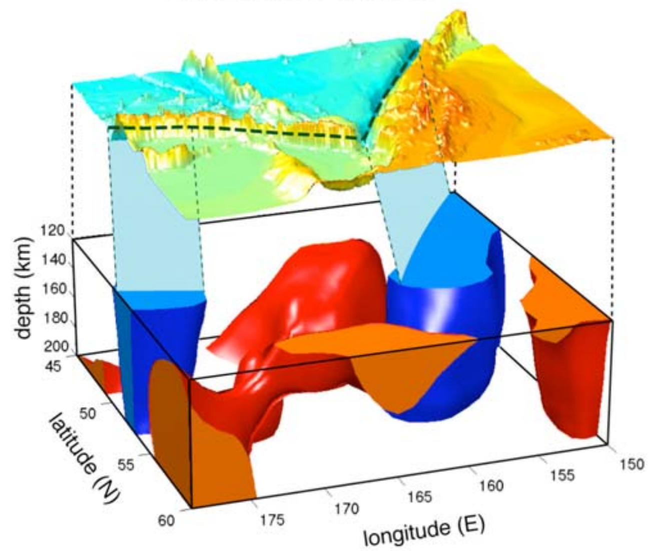
Australian Antarctic Discordance



Kamchatka



Aleutian Islands



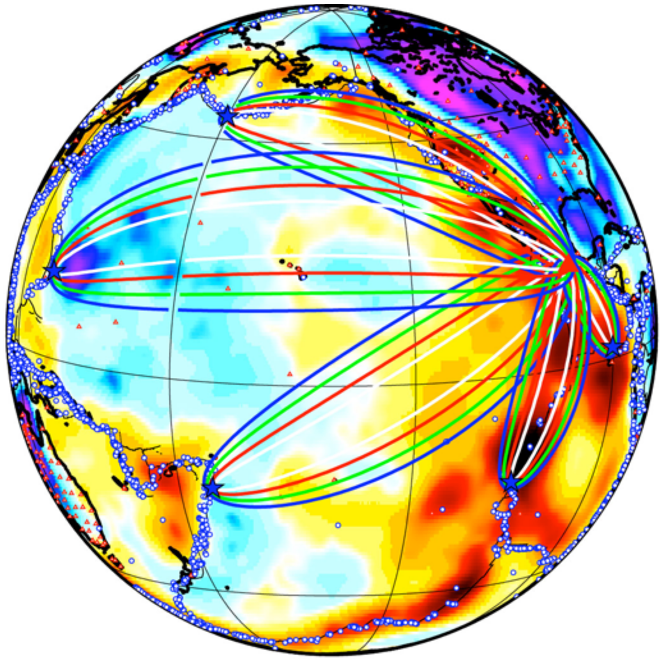
Resolution of seismic models

✓Distribution of earthquakes and seismic stations is inhomogeneous
✓Resolution of seismic tomographic models is better in regions well covered by sources and receivers

Resolution of seismic models

Diffraction effects result in extended sensitivity kernels, especially for long paths

Short-period measurements are difficult to obtain for long paths



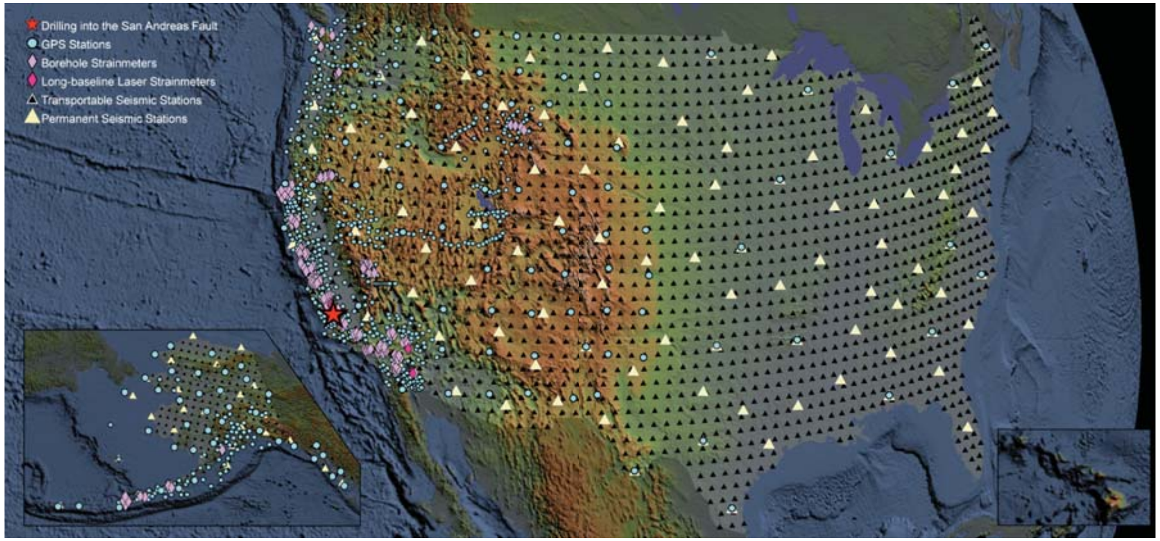
Resolution of seismic tomographic models is better in regions covered by short paths

How can we improve the resolution?

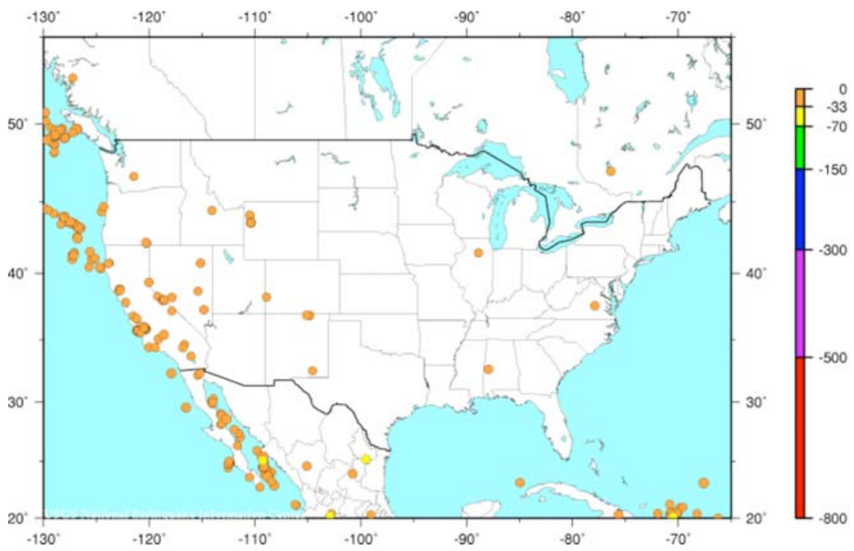
1. install more stations

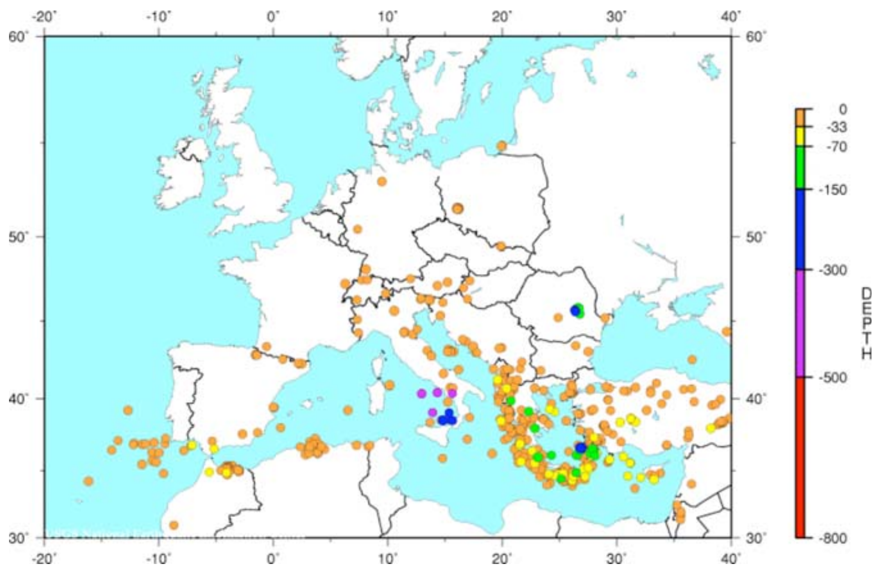
2. **new types of measurements**

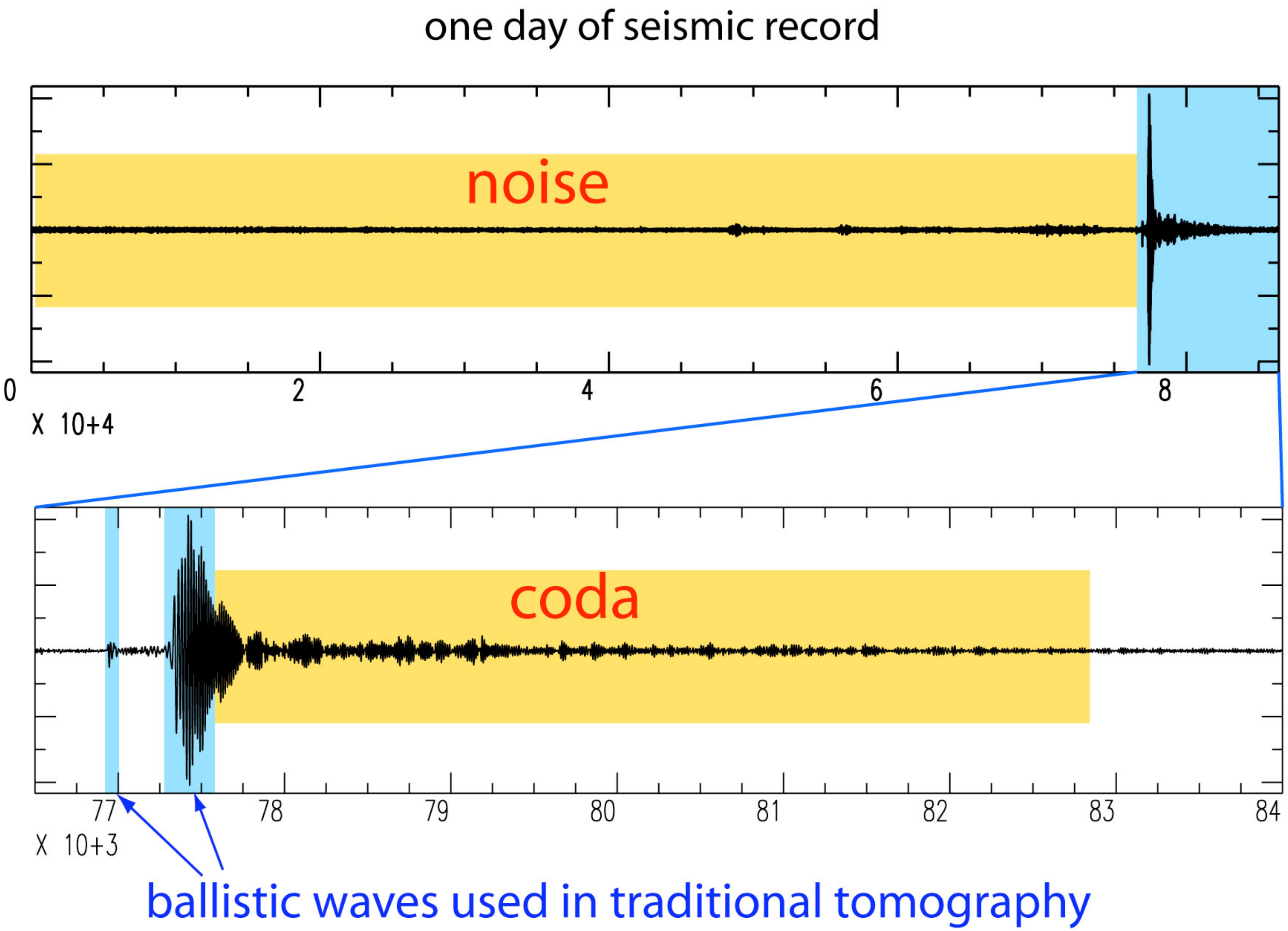
Earthscope USAarray



distribution of M>4 earthquakes during 1.5 months (July, 2003-December, 2004)



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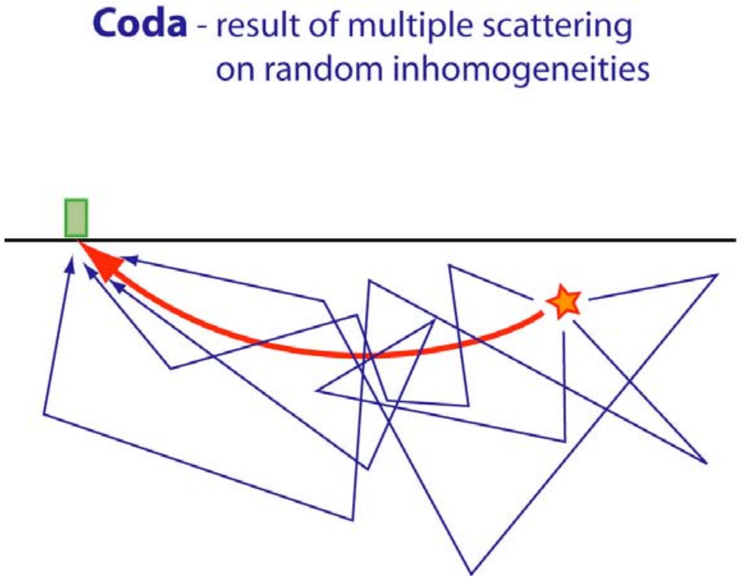
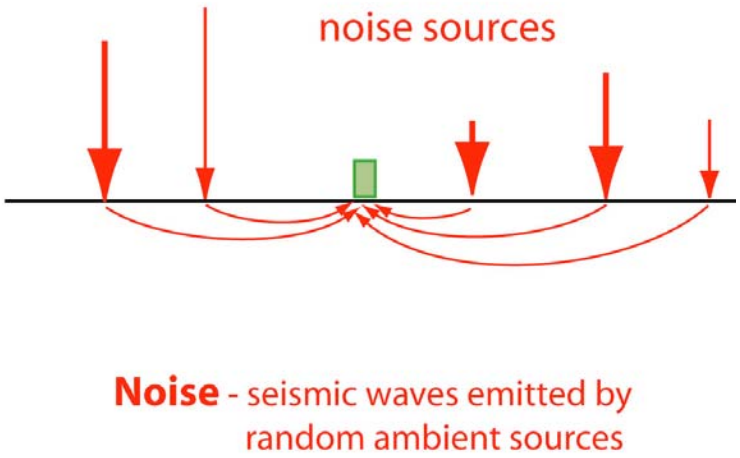
Seismic coda and ambient seismic noise - random seismic wavefields





Extraction of Green functions from random wavefields

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!)*.

FT(Green function A->B) ~ 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)+…
Marine acoustics: Roux et al., (2003)+…
Ambient seismic noise: Shapiro and Campillo (2004)+…

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

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

modal representation of the random field: $$\phi(x,t) = \sum_n a_n u_n(x) e^{i\omega_n t}$$

u_n - eigenfunctions

ω_n - eigenfrequencies

a_n - modal excitations, uncorrelated random variables:

$$\langle a_n a_m^* \rangle = \delta_{n,m} F(\omega_n)$$

$F(\omega)$ - spectral energy density

cross-correlation between points x and y :

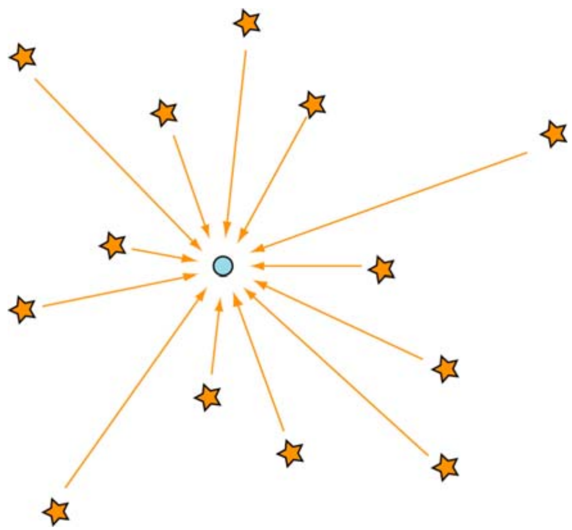
$$C(x,y,\tau) = \sum_n F(\omega_n) u_n(x) u_n(y) e^{-i\omega_n \tau}$$

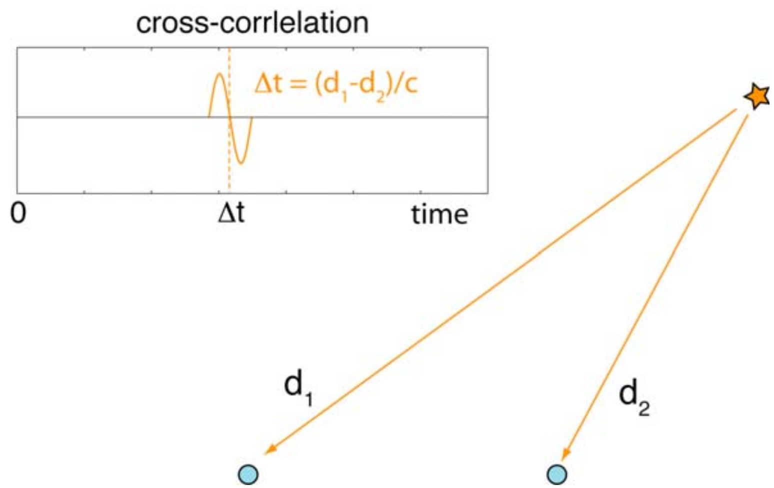
differs only by an amplitude factor $F(\omega)$ from the derivative of Green function between x and y

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

Random wavefield - sum of waves emitted by randomly distributed sources

Cross-correlation of waves emitted by a single source between two receivers





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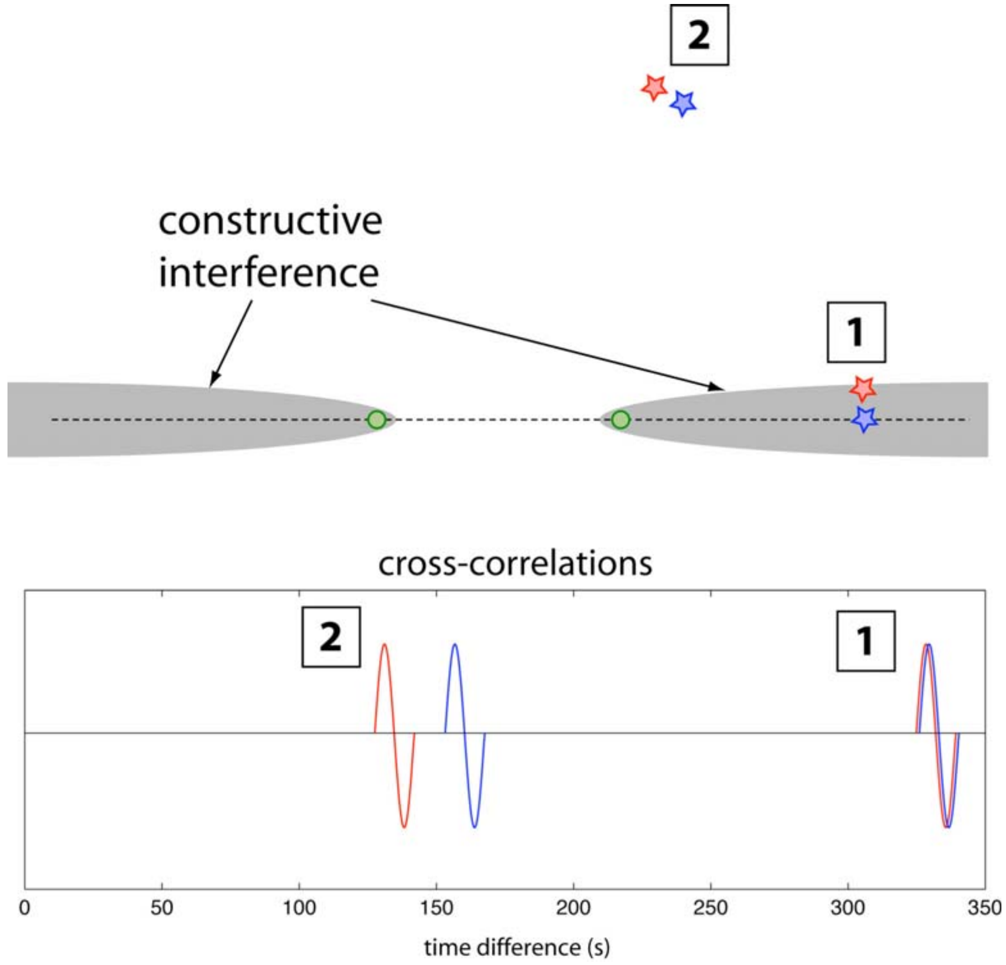
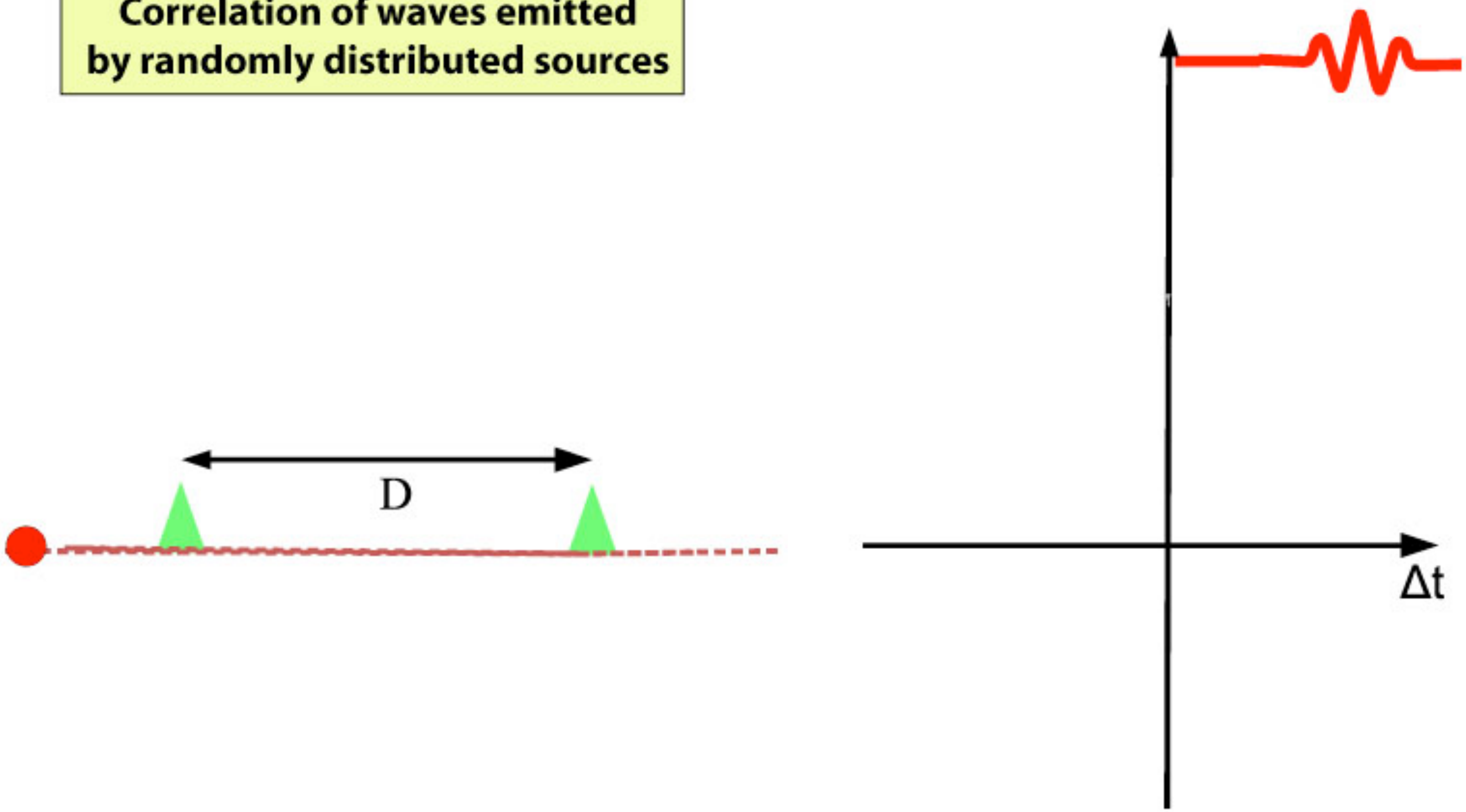


Sources are in constructive interference when respective travel time difference are close to each other

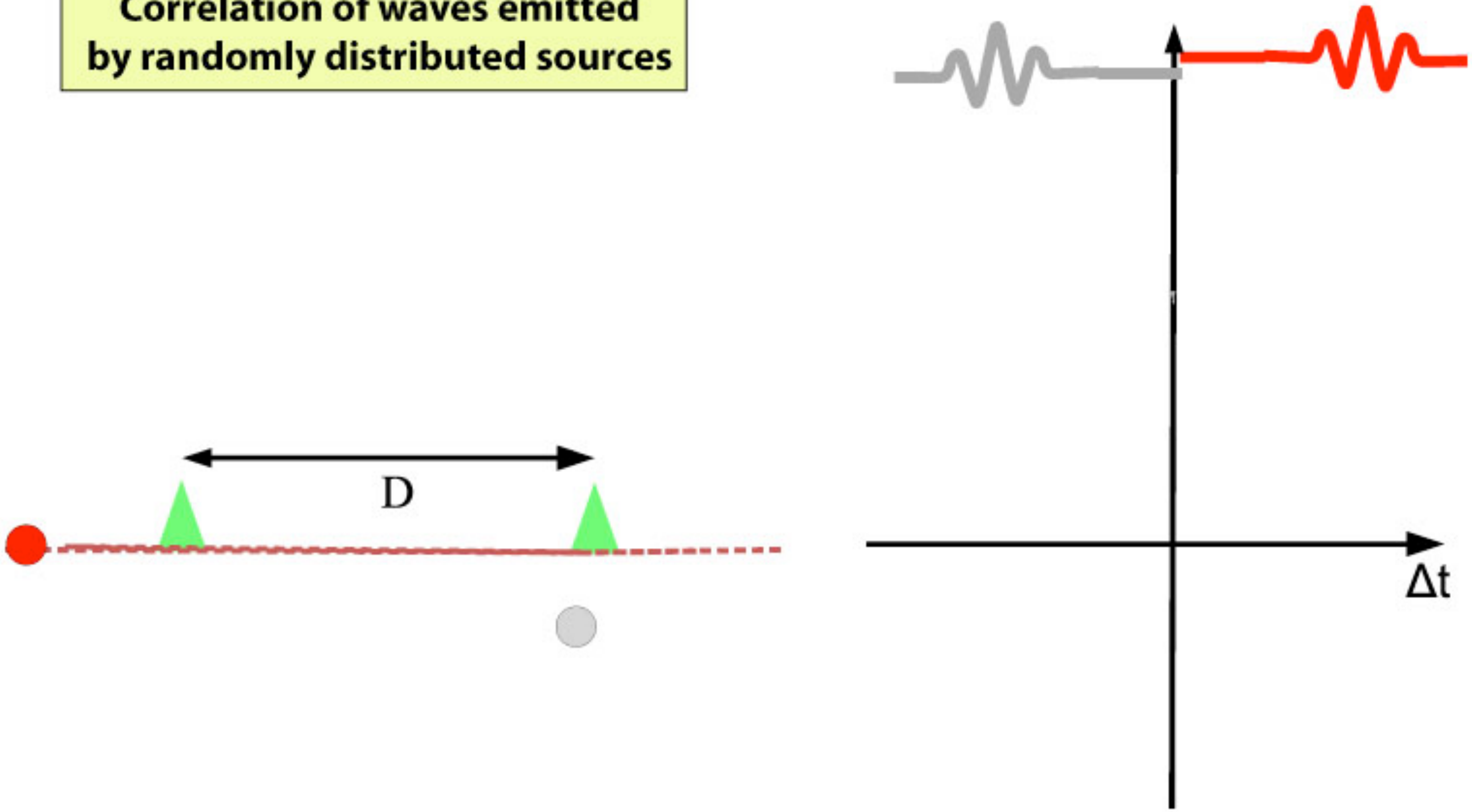
Effective density of sources is high in the vicinity of the line connecting two receivers

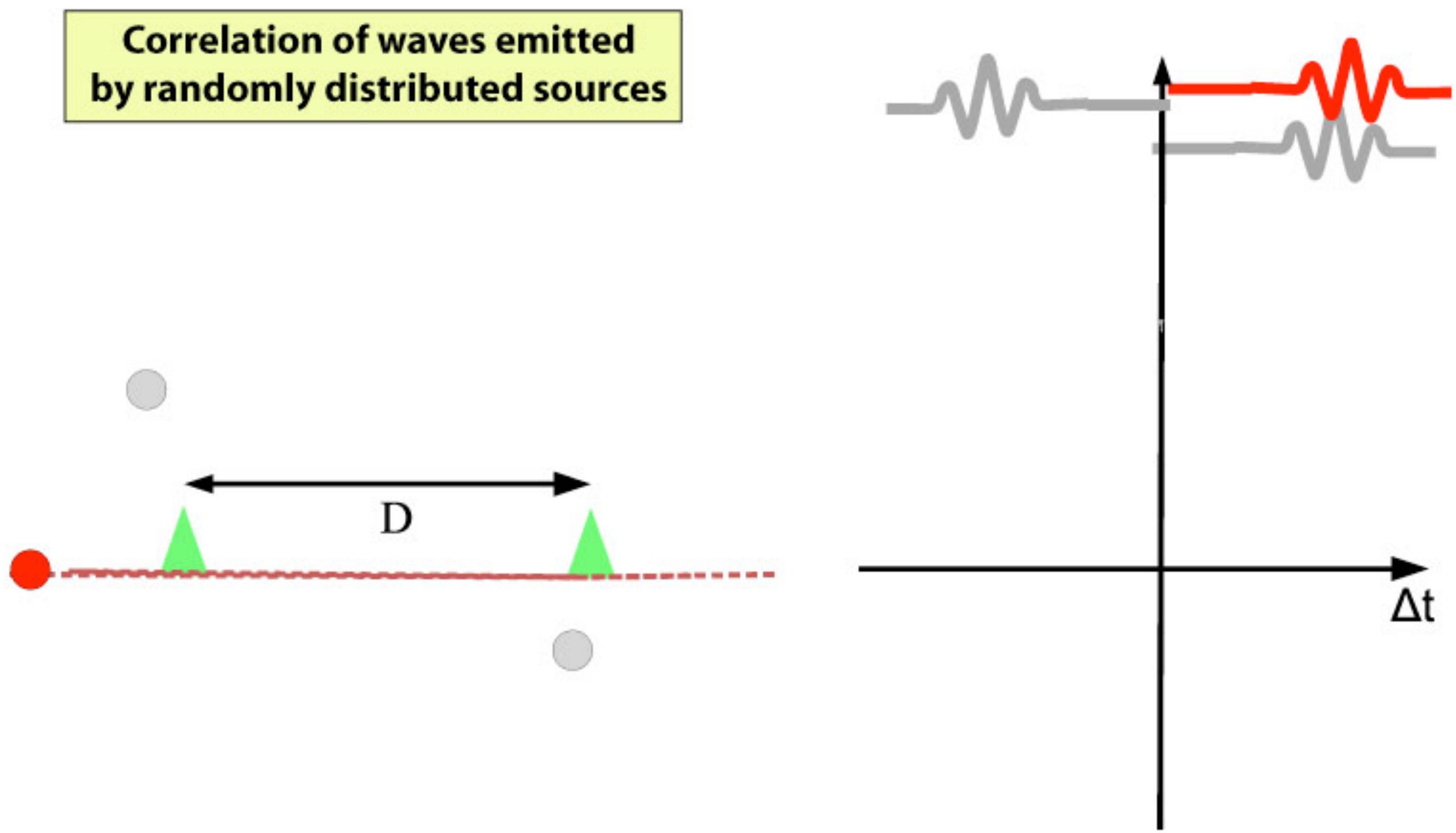
Cross-correlation extracts waves propagating along the line connecting two receivers

Correlation of waves emitted by randomly distributed sources

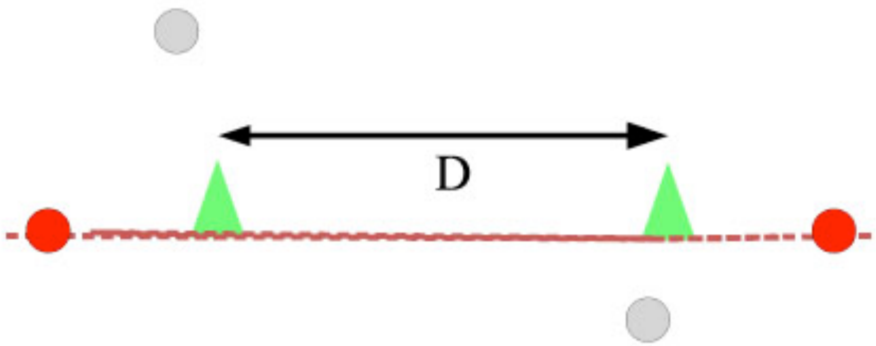


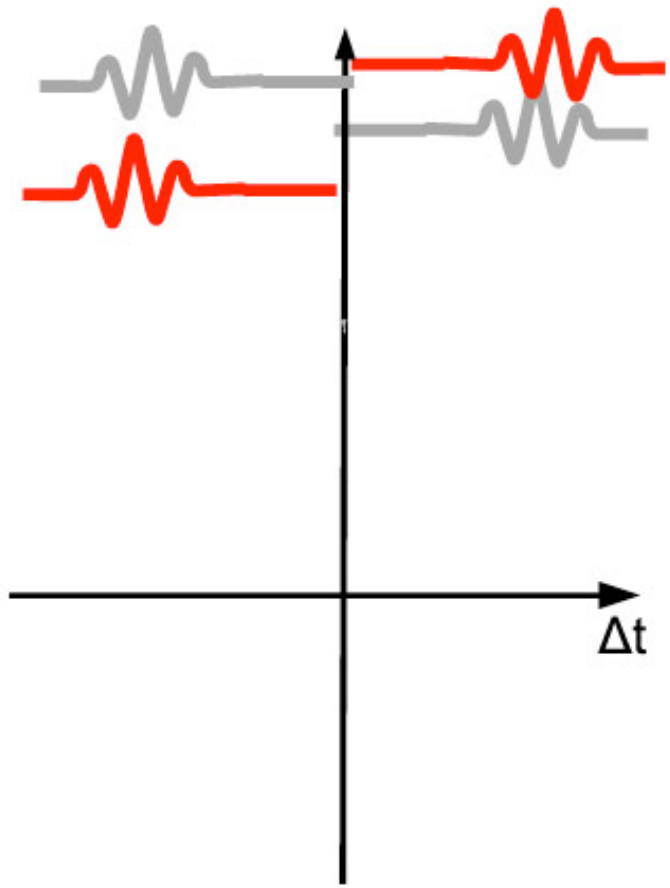
Correlation of waves emitted by randomly distributed sources




Correlation of waves emitted
by randomly distributed sources
D
Δt

Correlation of waves emitted by randomly distributed sources





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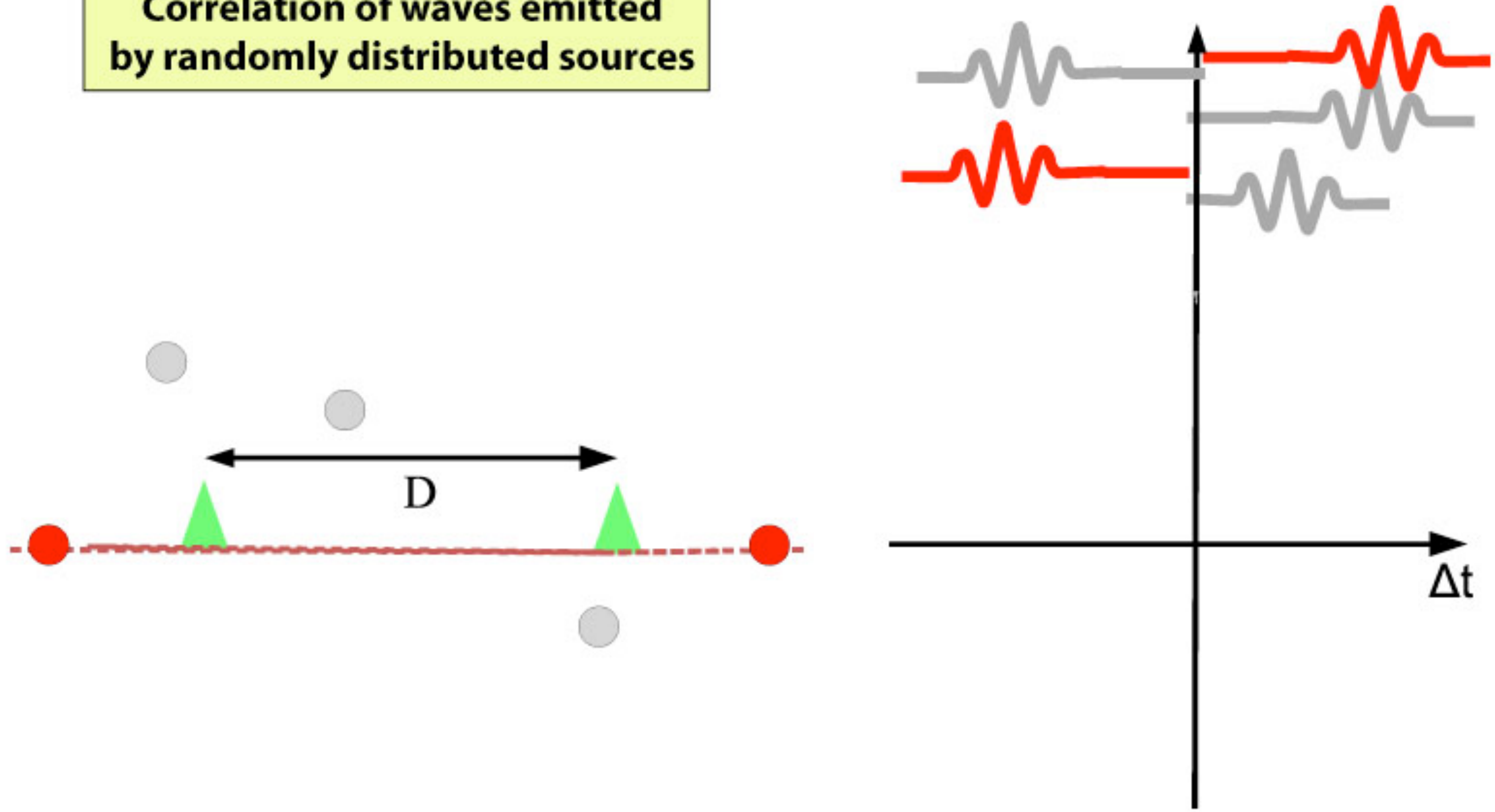

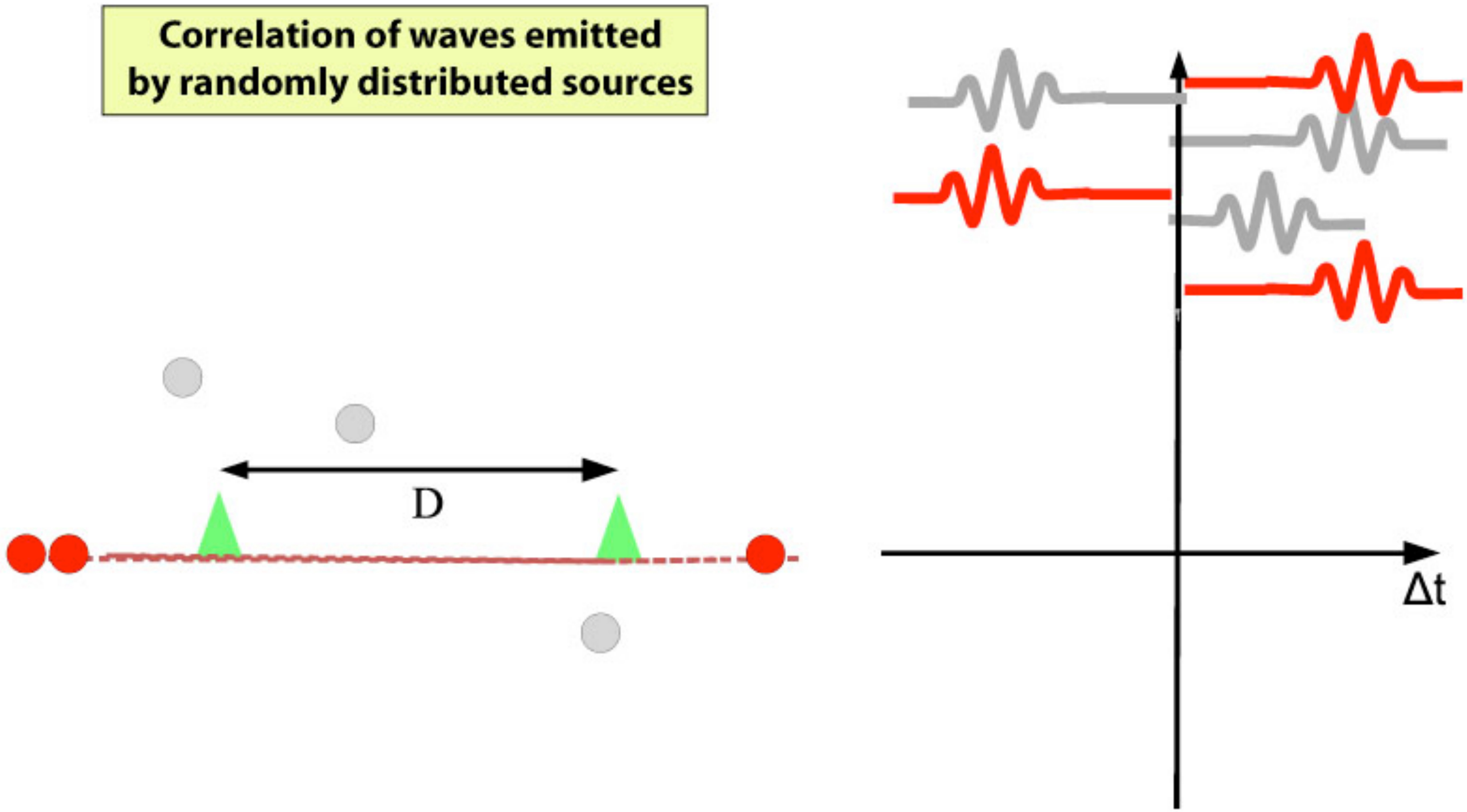

Correlation of waves emitted by randomly distributed sources
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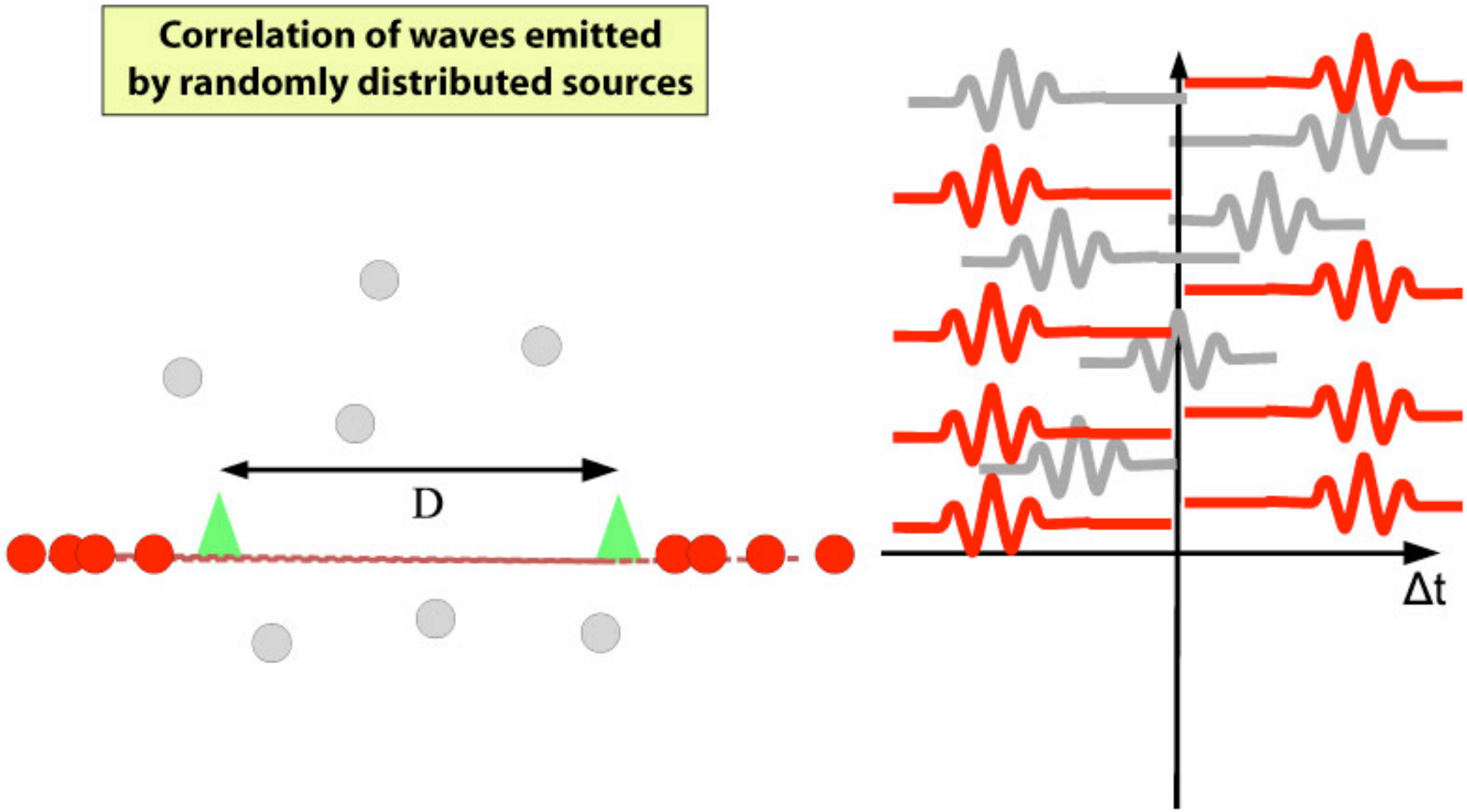
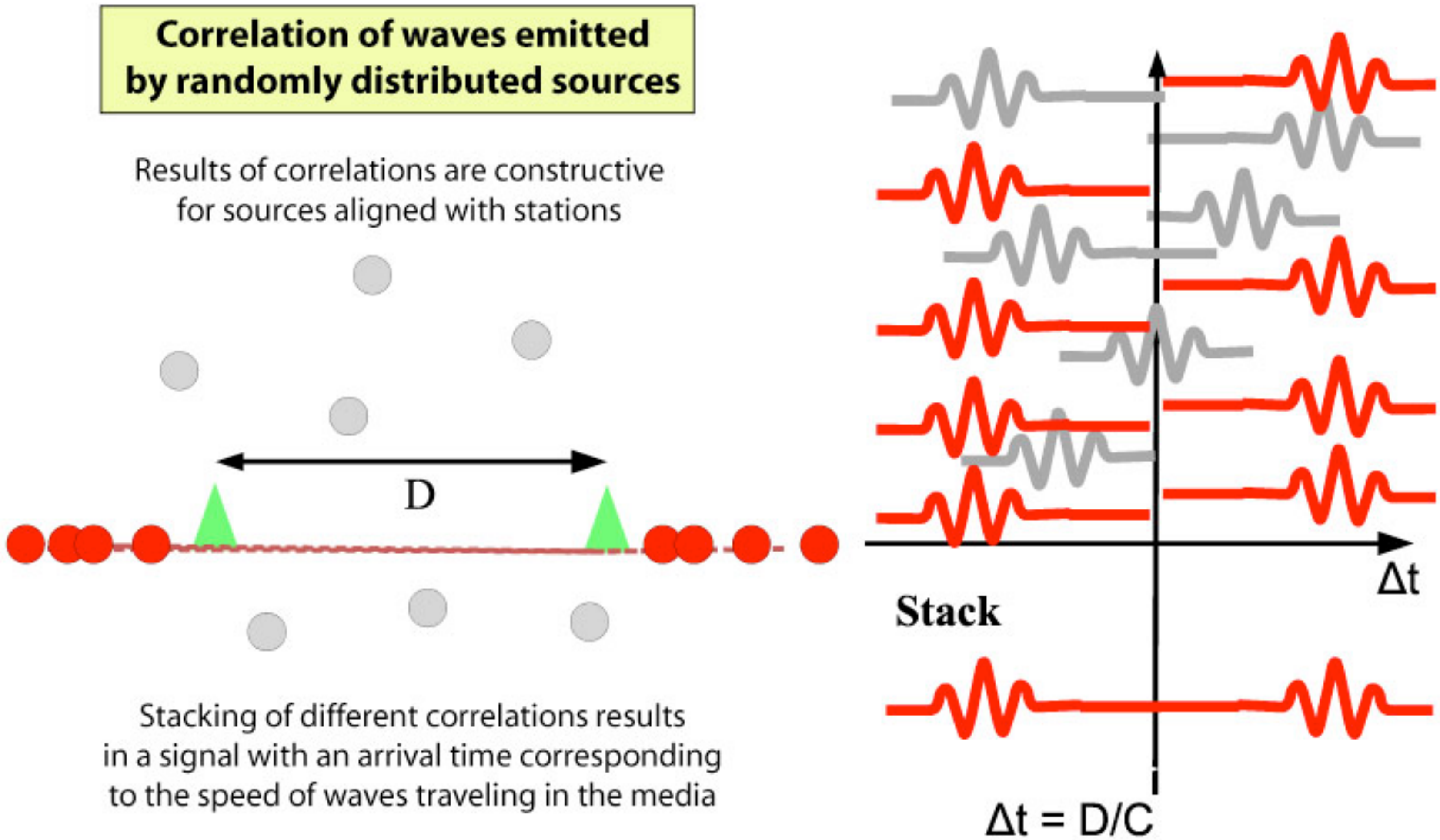
Δt



Correlation of waves emitted by randomly distributed sources
D
Δt


Correlation of waves emitted by randomly distributed sources
Results of correlations are constructive for sources aligned with stations
D
Stacking of different correlations results in a signal with an arrival time corresponding to the speed of waves traveling in the media
Δt
Stack
Δt = D/C

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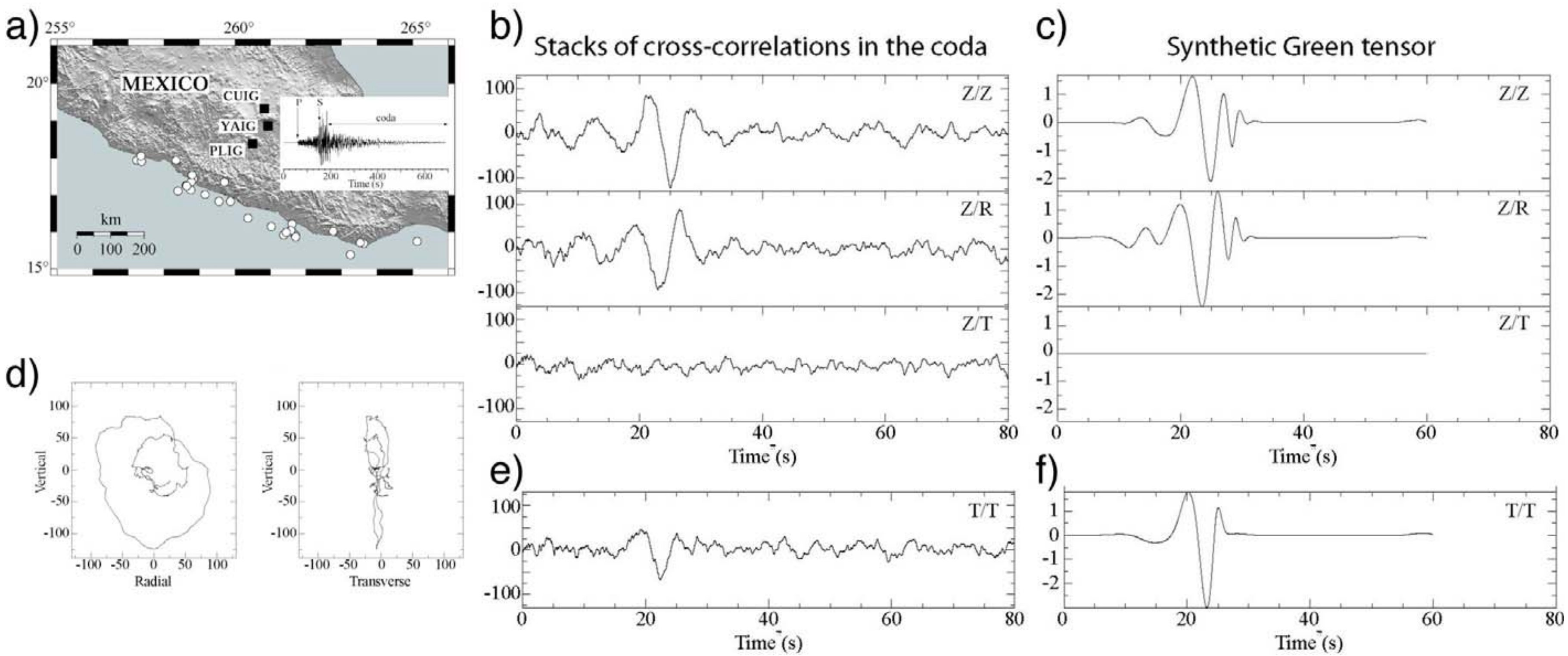
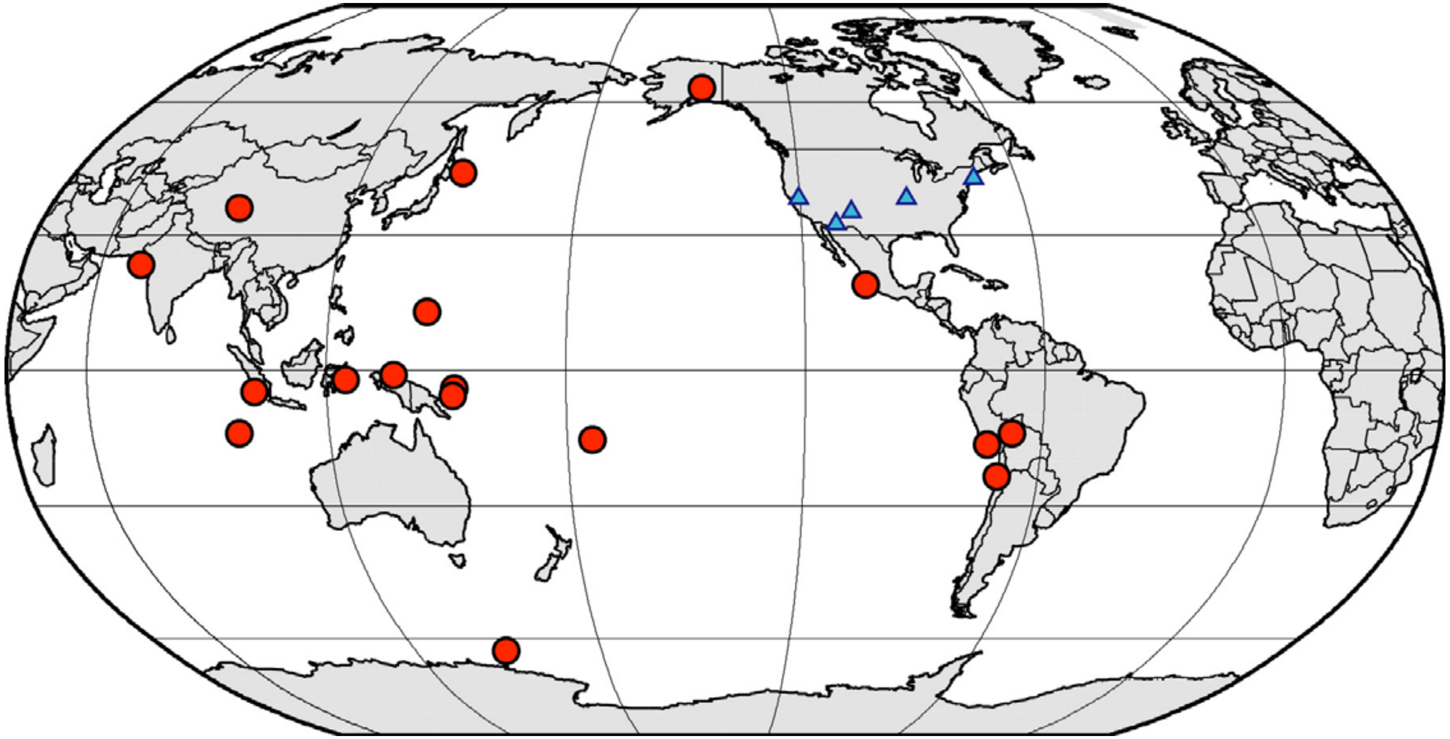
Cross-correlations of regional coda

From Campillo and Paul (2003)



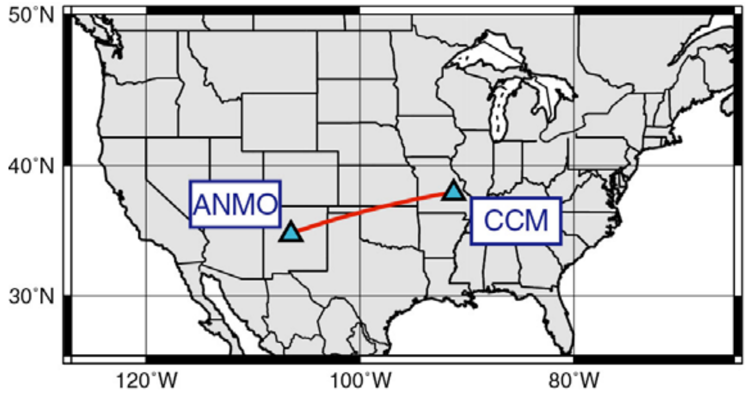
Cross-correlations from teleseismic codas: data

records at five US permanent seismic stations from 17 M≥8 earthquakes occurred between 1993 and 2002

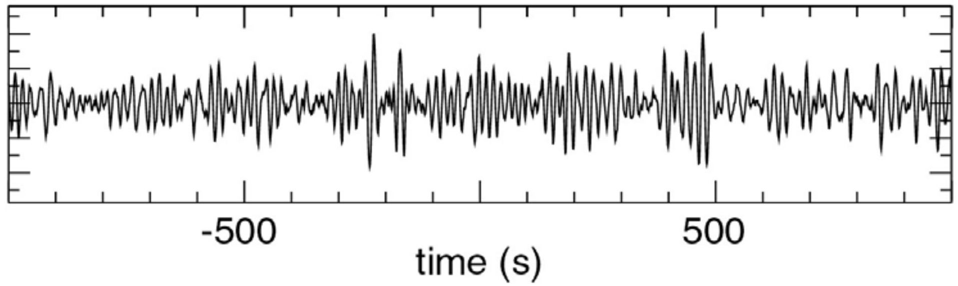


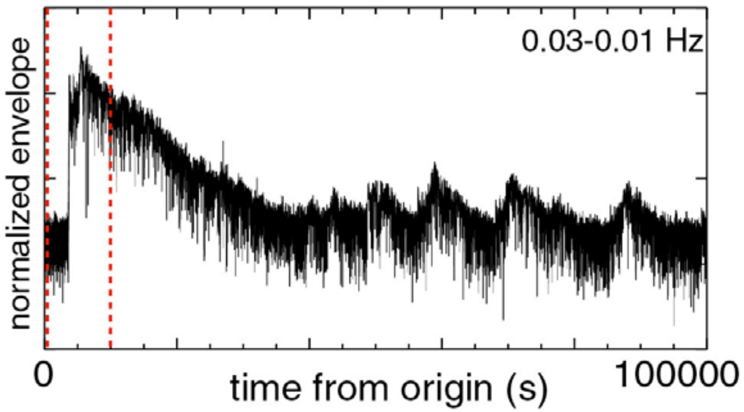
Cross-correlations from teleseismic codas: ANMO - CCM

distance 1405 km



vertical component
stack from13 earthquakes





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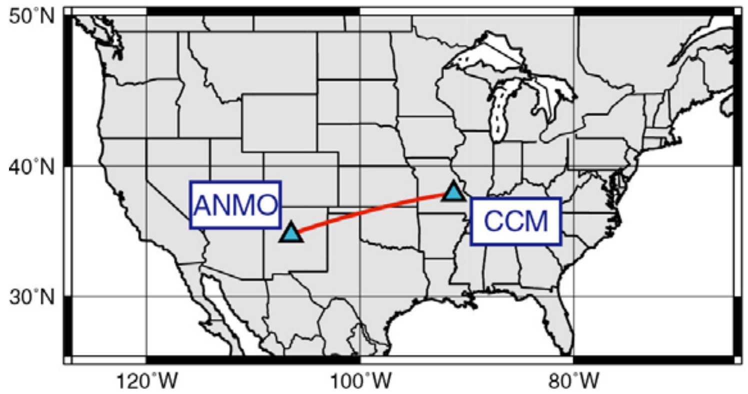

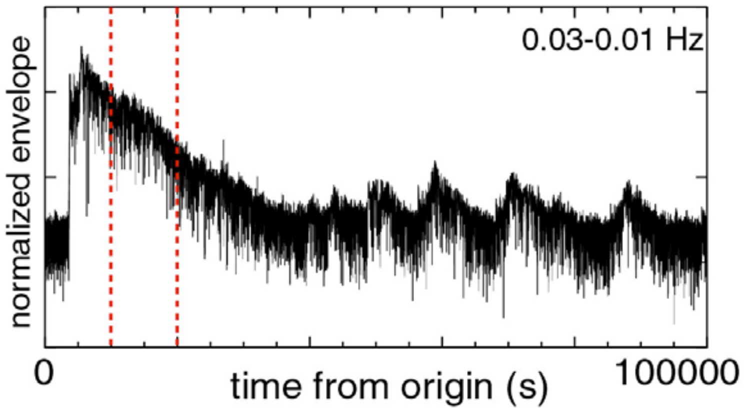

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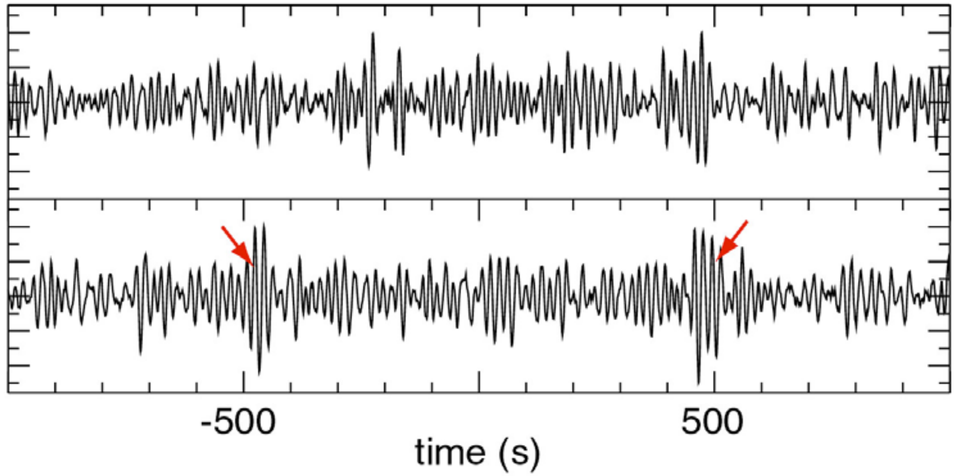

Cross-correlations from teleseismic codas: ANMO - CCM

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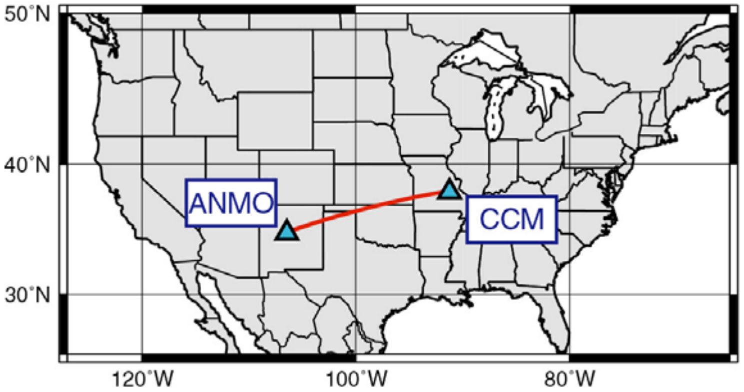

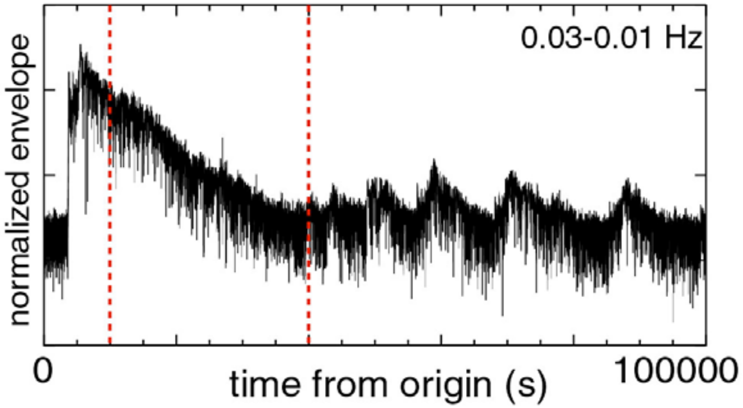

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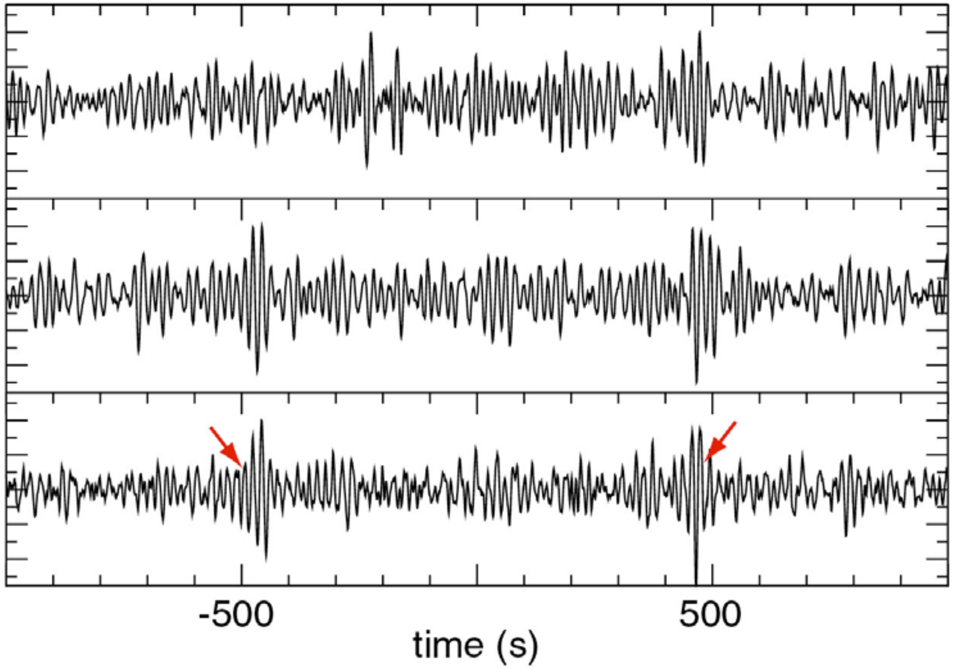
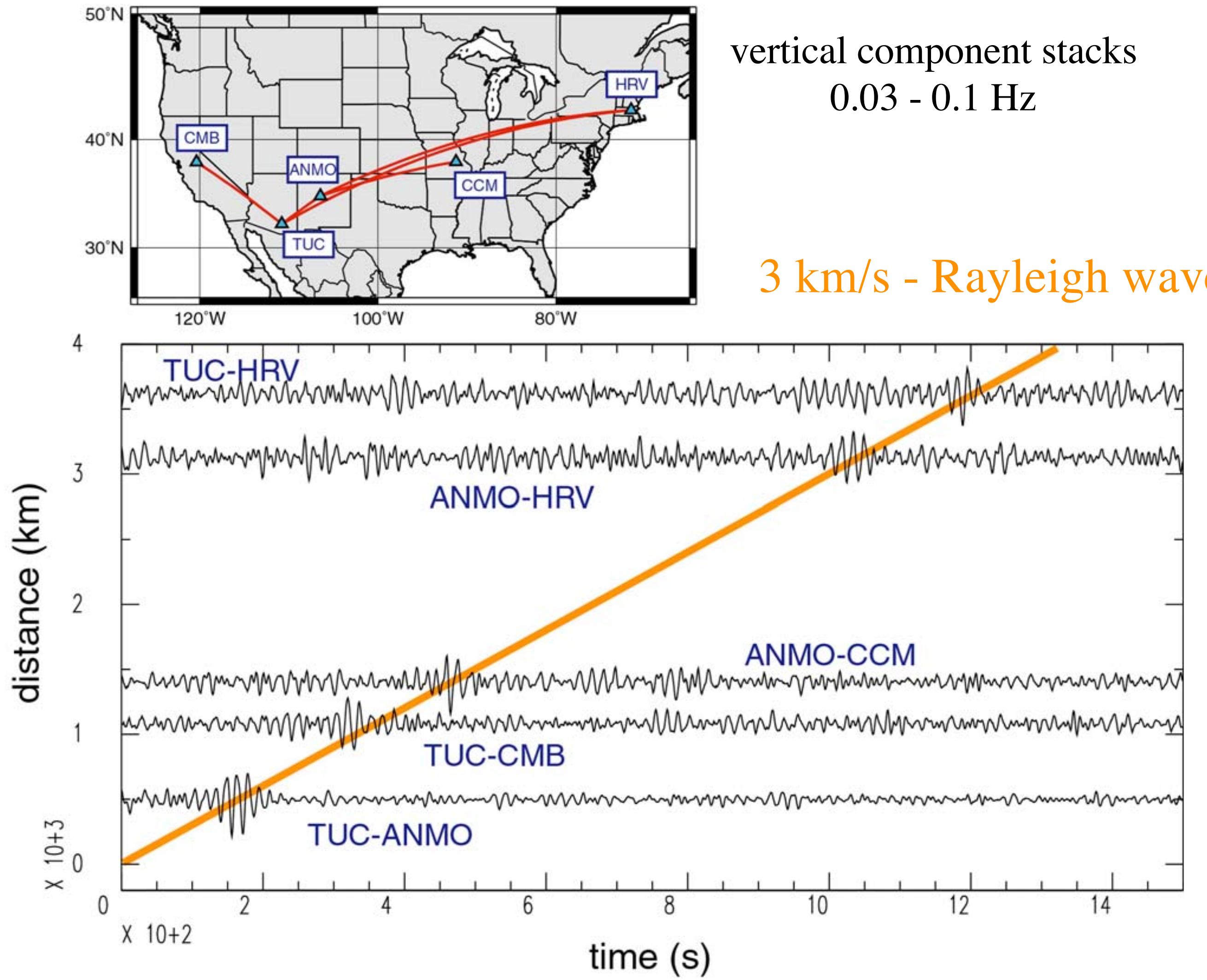


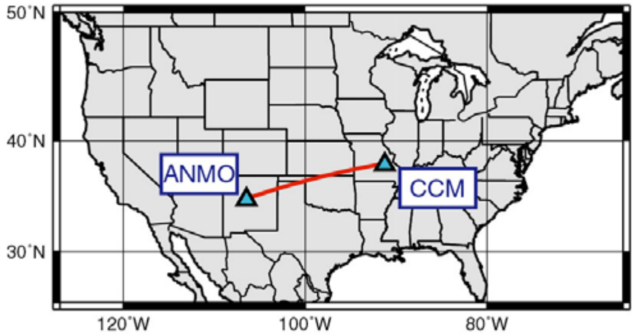
Cross-correlations from teleseismic codas at US stations



vertical component stacks
0.03 - 0.1 Hz

3 km/s - Rayleigh wave

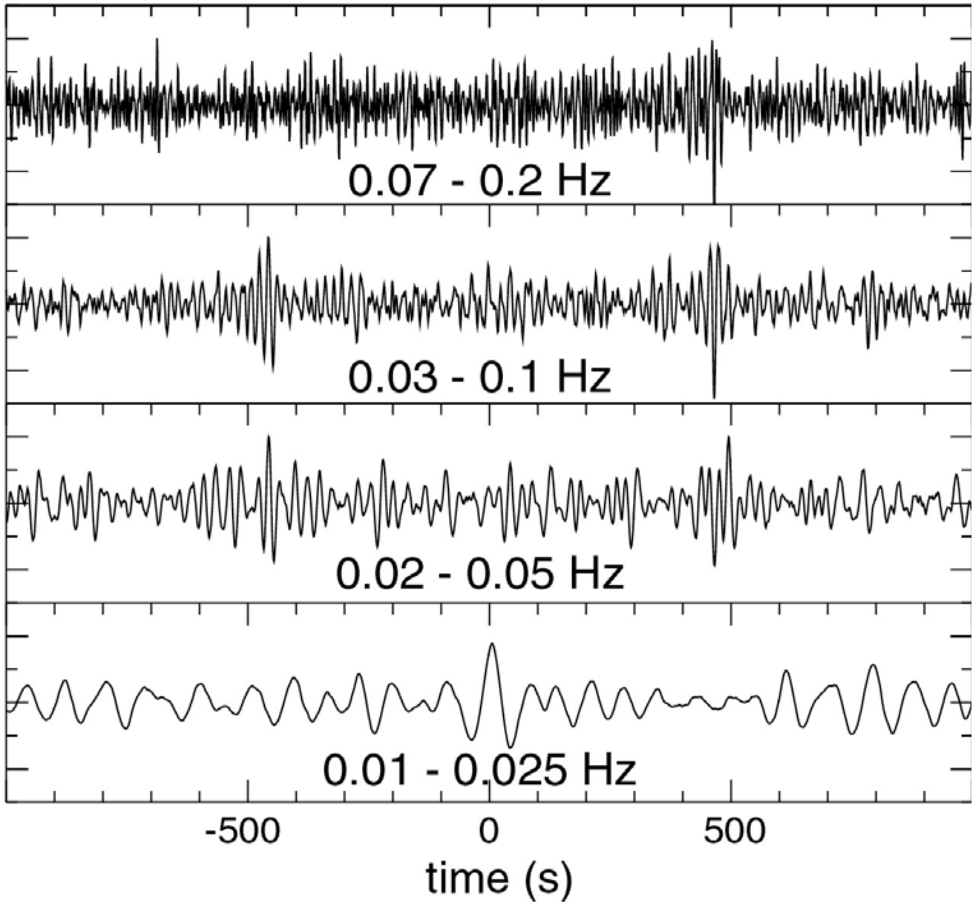
Cross-correlations from teleseismic codas: ANMO - CCM



at long periods:

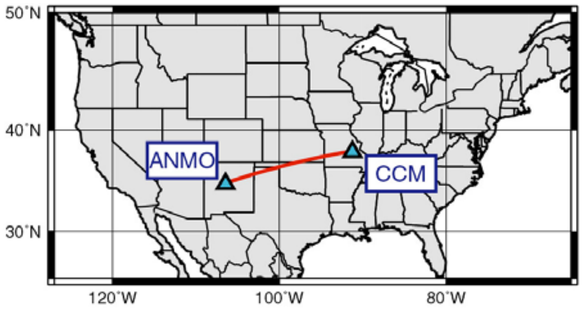
1. scattering is weaker
2. telesesmic coda is not fully diffuse
3. coherent signals disappear in cross-correlations

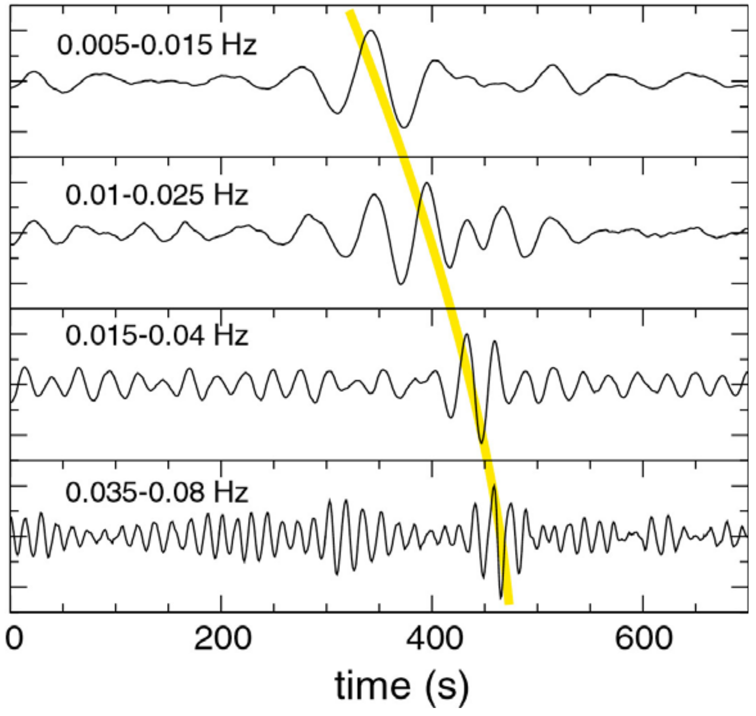
vertical component stacks from 13 earthquakes



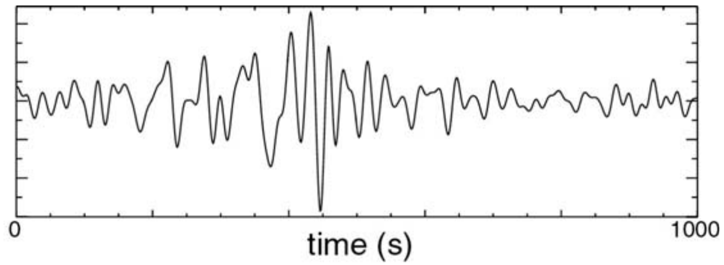
Cross-correlations from ambient seismic noise: ANMO - CCM

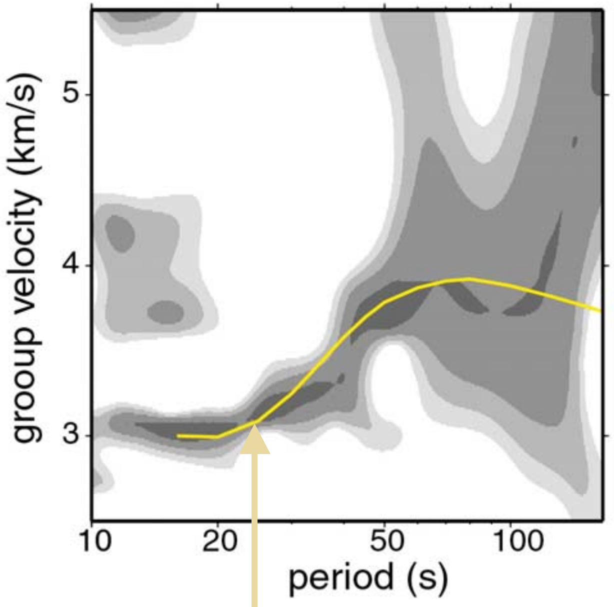
cross-correlations from 30 days of continuous vertical component records (2002/01/10-2002/02/08)





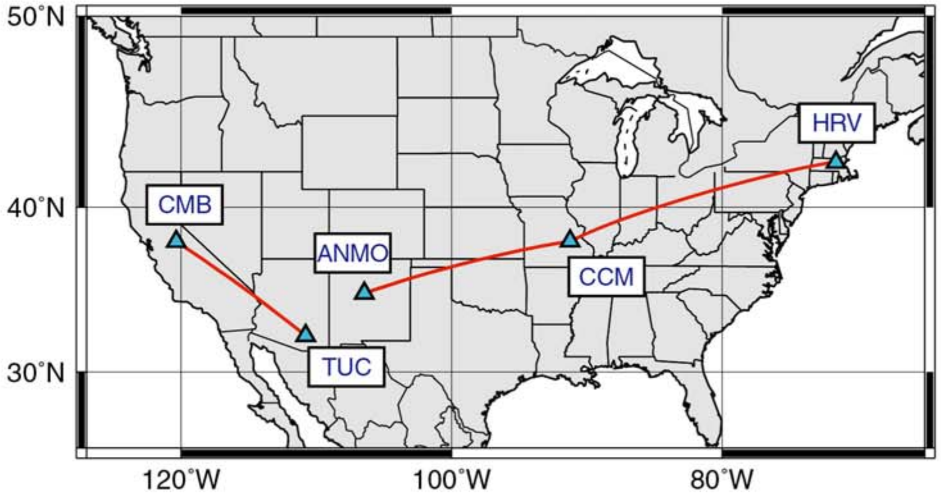
frequency-time analysis of the broadband cross-correlation



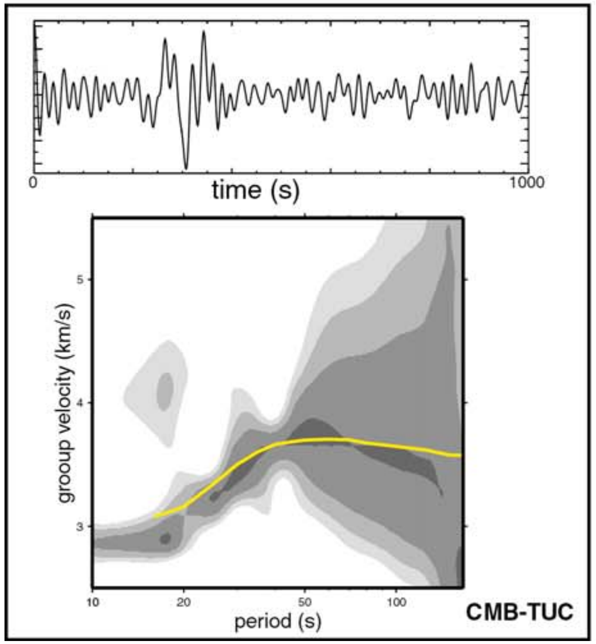


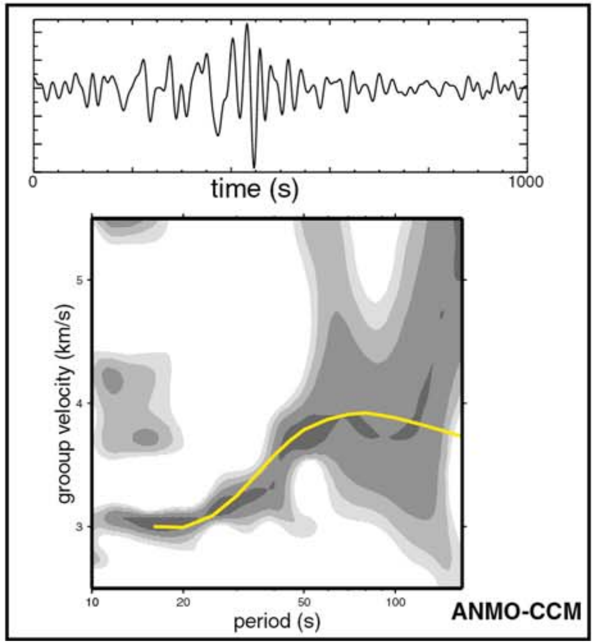
prediction from global group velocity maps of Ritzwoller et al. (2002)

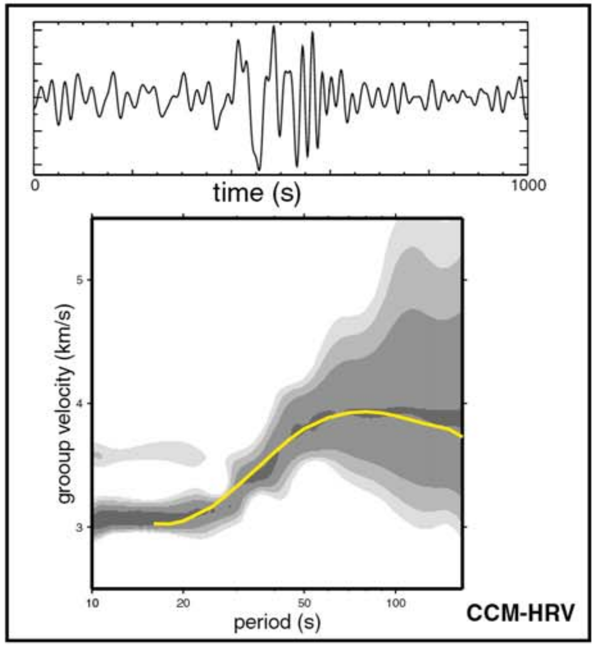
Cross-correlations from ambient seismic noise at US stations



frequency-time analysis of broadband cross-correlations computed from 30 days of continuous vertical component records

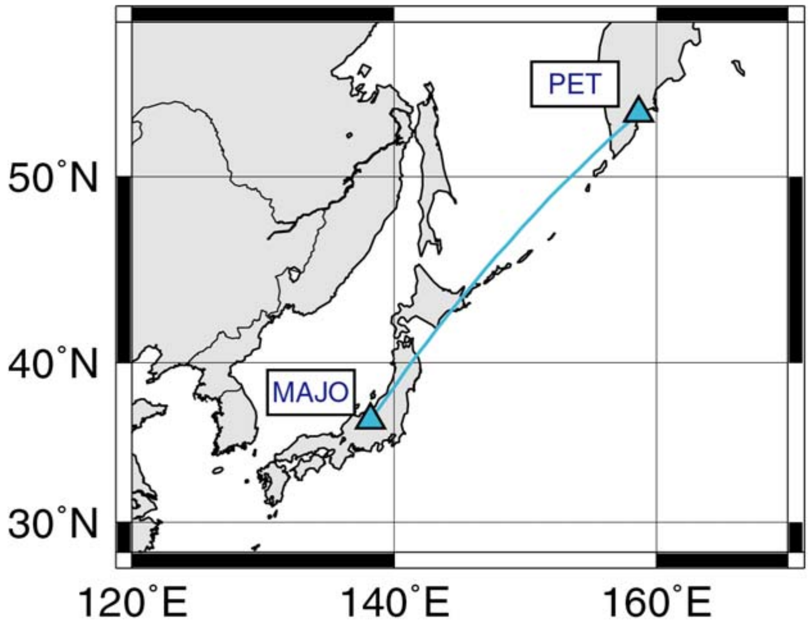


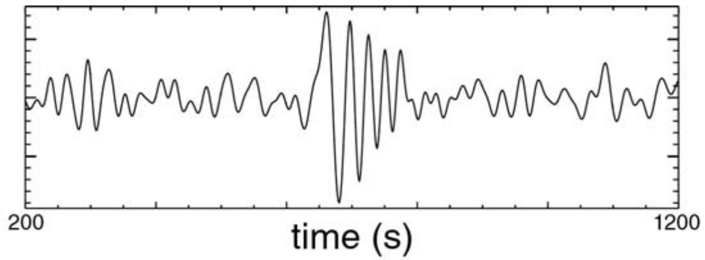


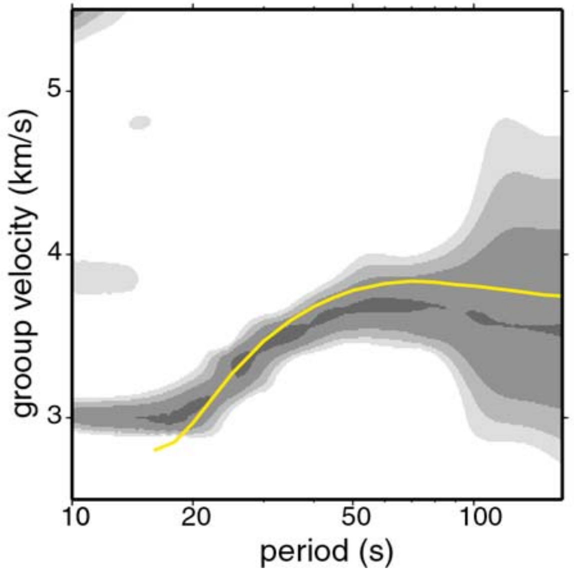


Cross-correlation from ambient seismic noise in North-Western Pacific

broadband cross-correlation computed from 30 days of continuous vertical component records

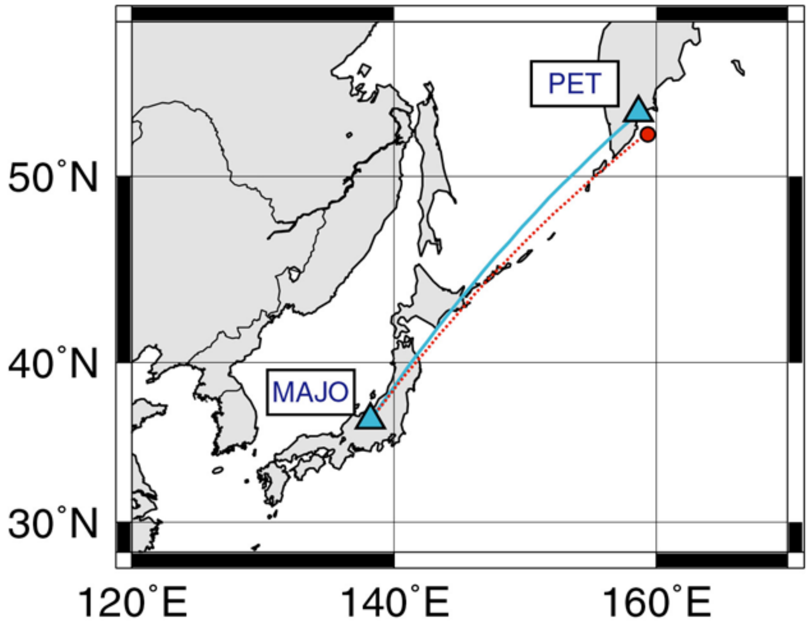


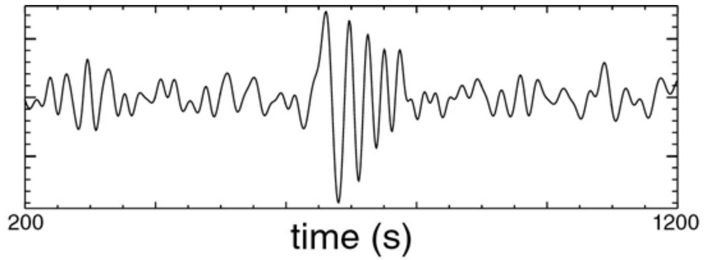


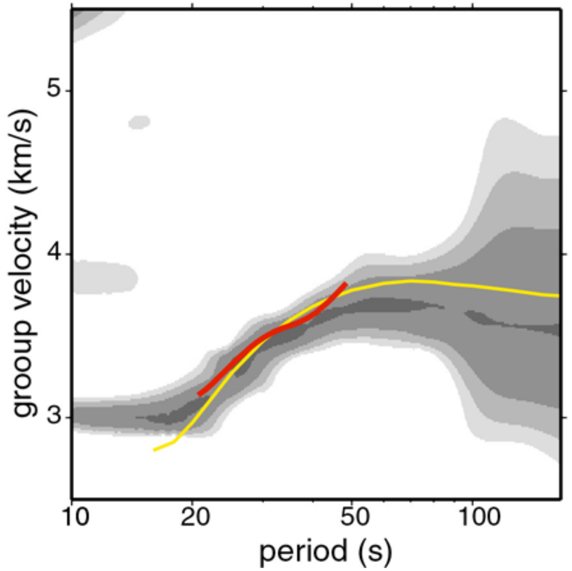


Cross-correlation from ambient seismic noise in North-Western Pacific

broadband cross-correlation computed from 30 days of continuous vertical component records







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    2. Europe
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8. Most recent results and future directions

Why using solar powered sources (***noise***)?

1. Measurements in absence of earthquakes:

   - improved resolution

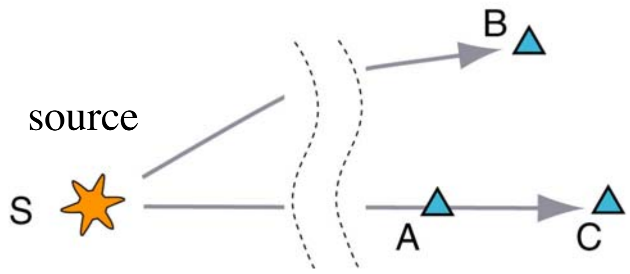
   - repetitive measurements:

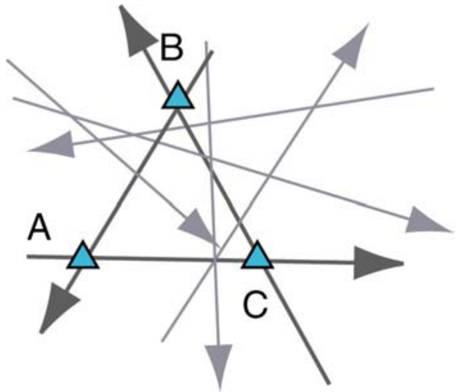
     monitoring of temporal changes (volcanoes, fault zones)

2. Possibility to study the coupling between the Solid Earth, the Ocean, and the Atmosphere

traditional approach:
using
teleseismic surface waves

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





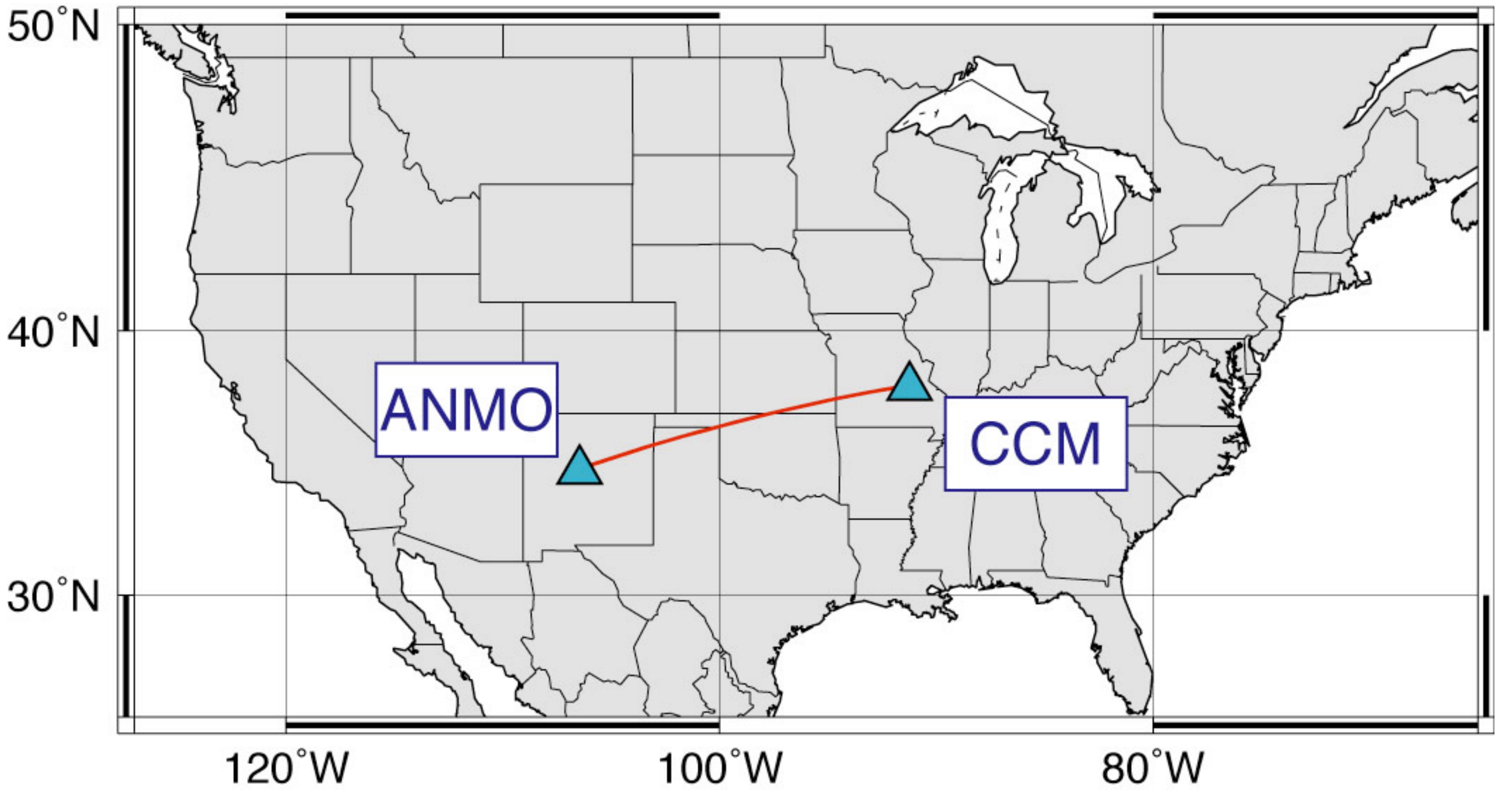
- extended lateral sensitivity
- sample only certain directions
- source dependent
- difficult to make short-period measurements

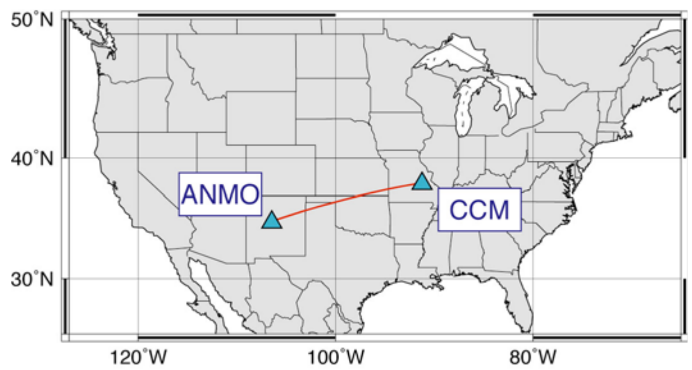
- localized lateral sensitivity
- samples all directions
- source independent
- may allow many short-period measurements

Consequence: **limited resolution**

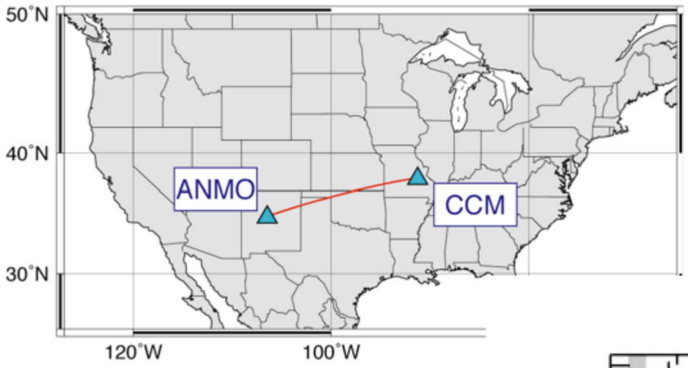
May improve resolution

Correlation of seismic noise: data processing

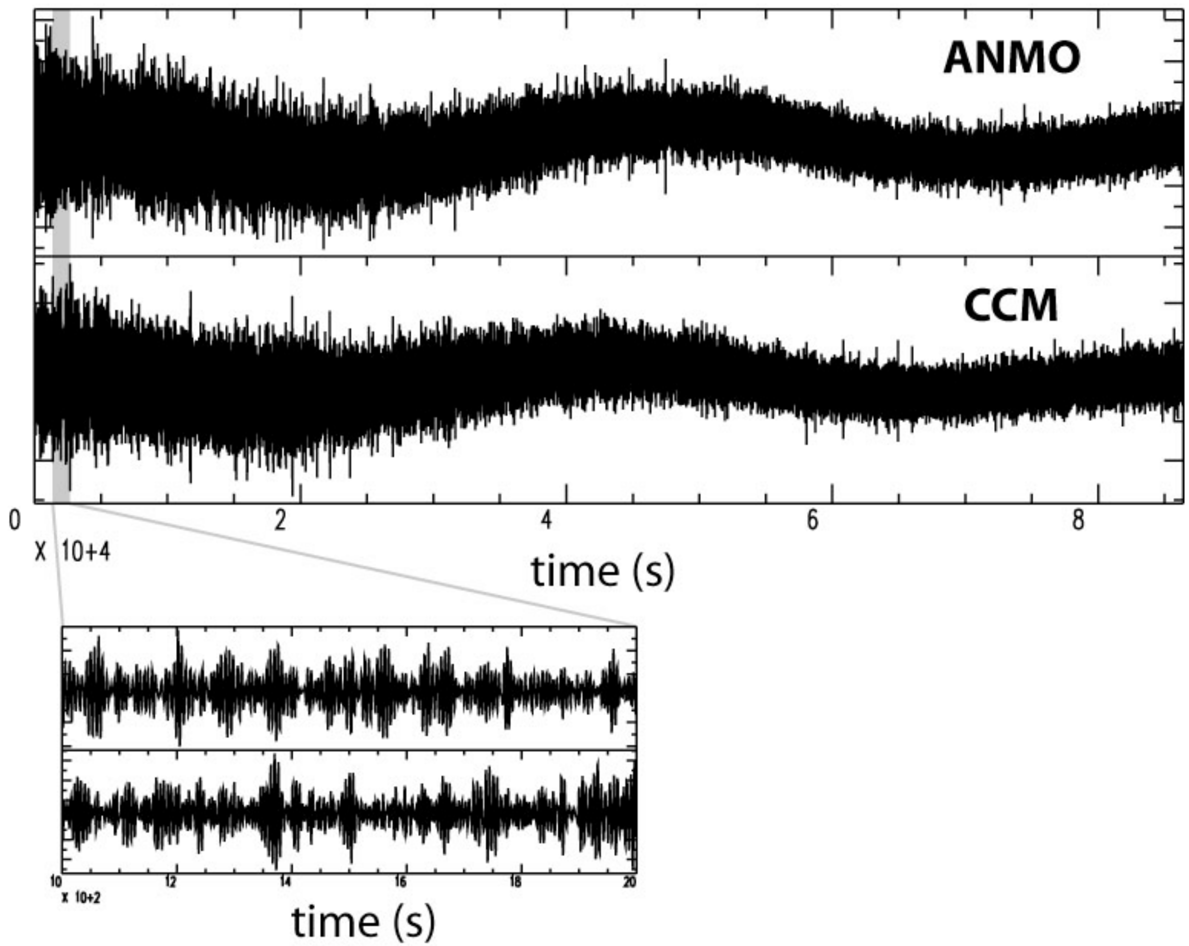


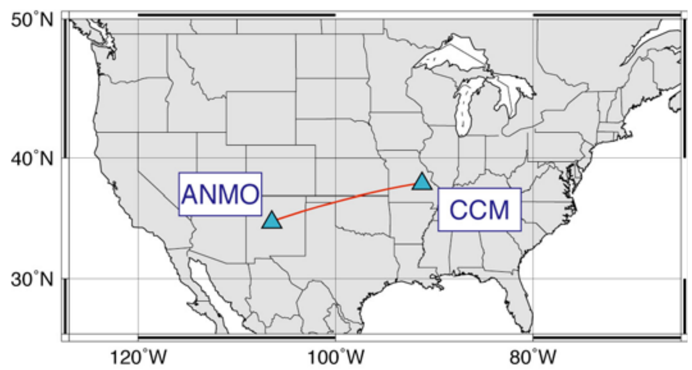


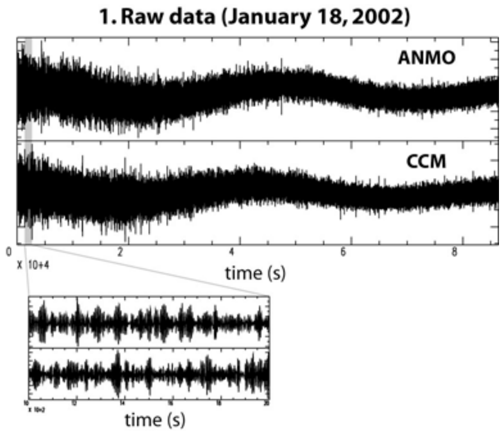
50°N
40°N
30°N
120°W
100°W
80°W
ANMO
CCM

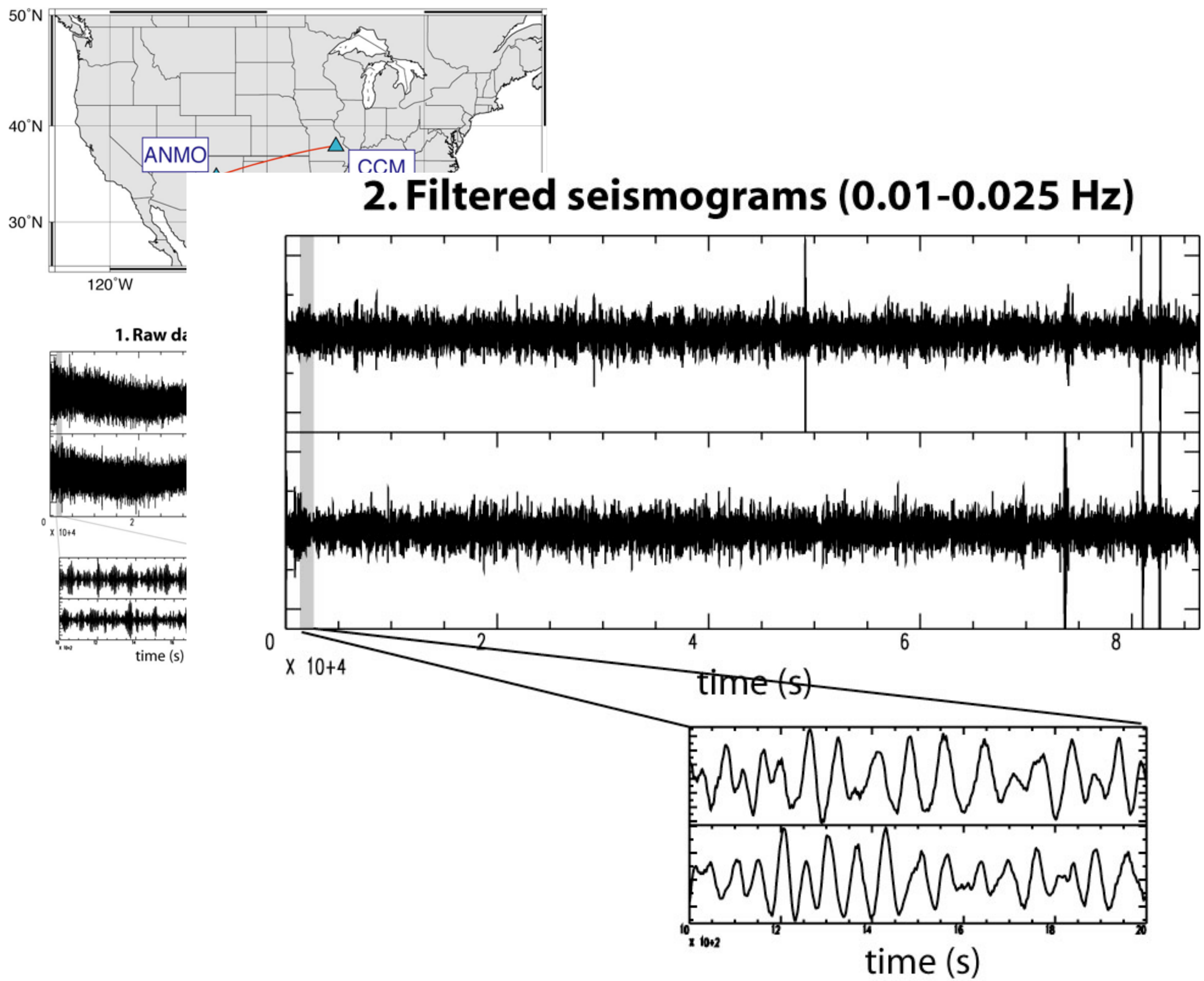


1. Raw data (January 18, 2002)

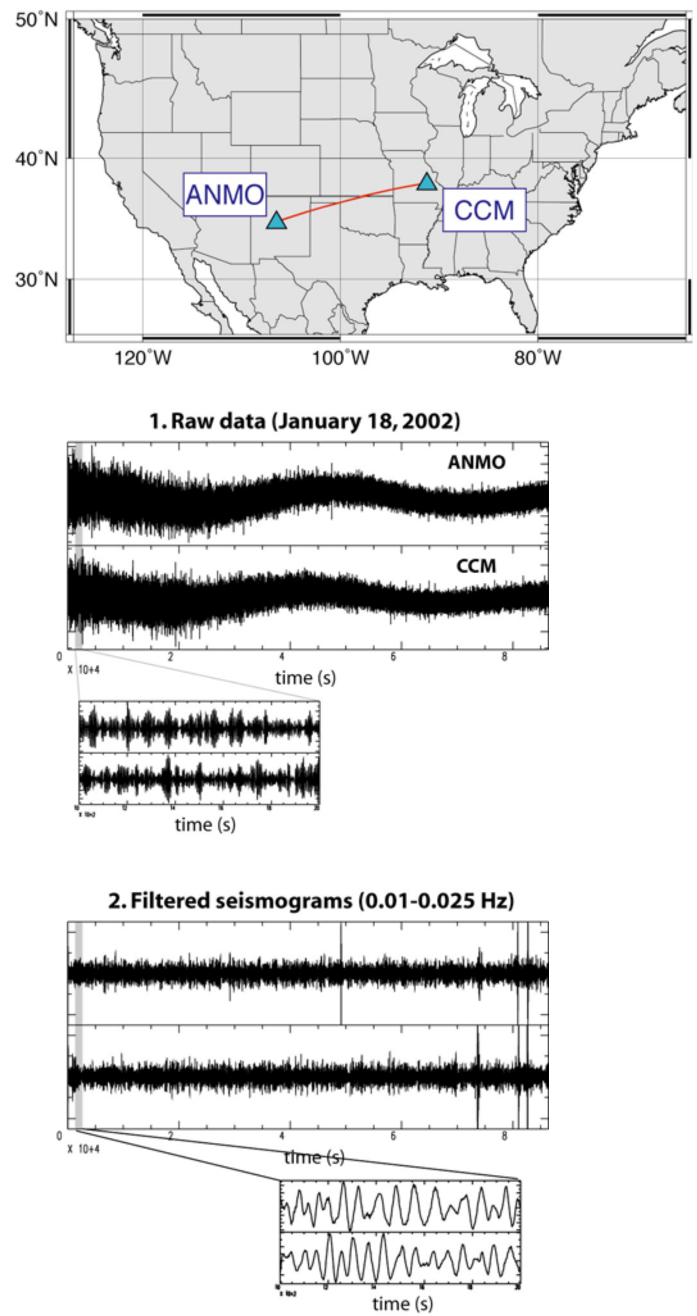


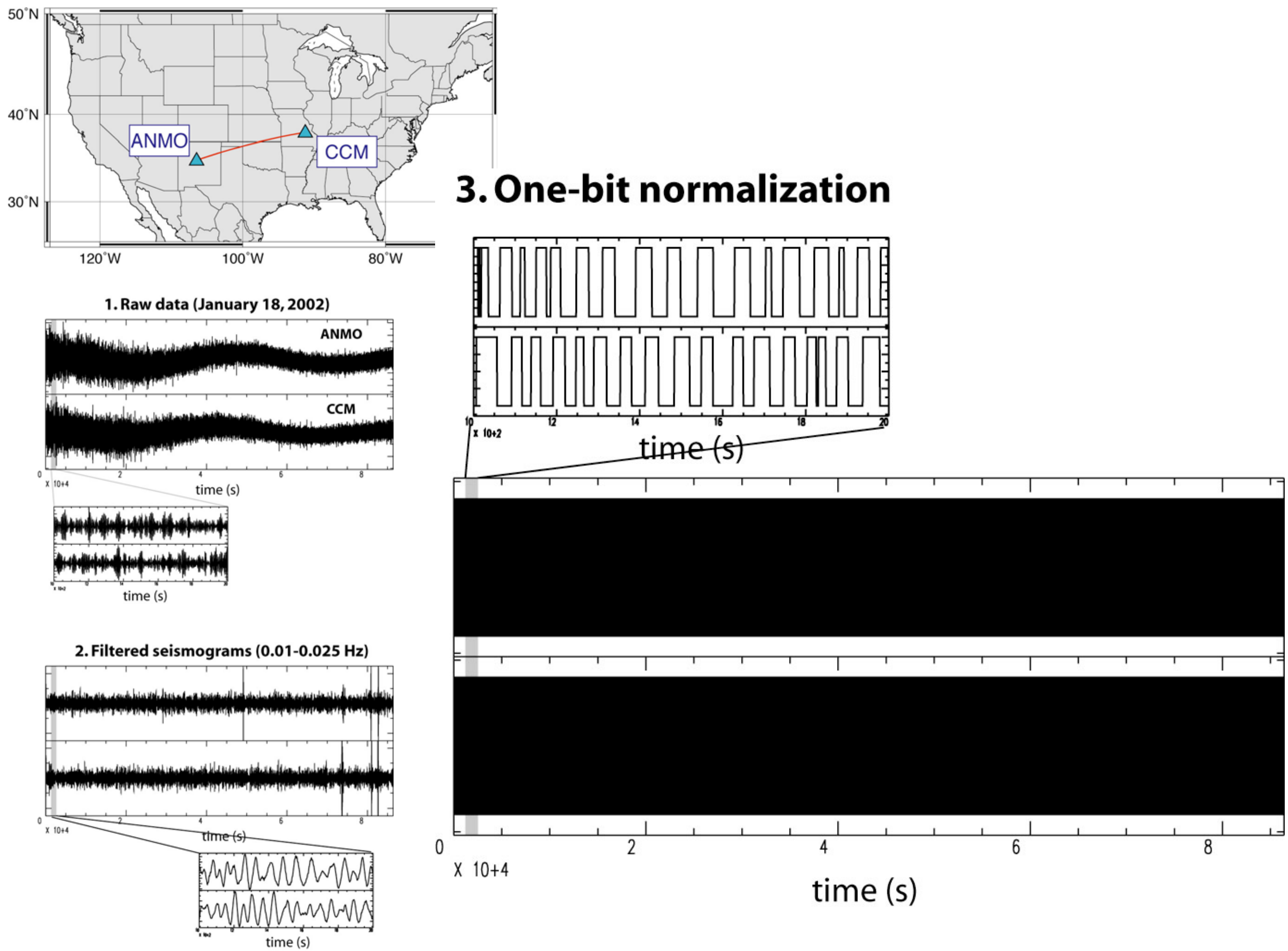

50°N
40°N
30°N
120°W
100°W
80°W
ANMO
CCM


1. Raw data (January 18, 2002)
ANMO
CCM
0
2
4
6
8
x 10+4
time (s)
time (s)

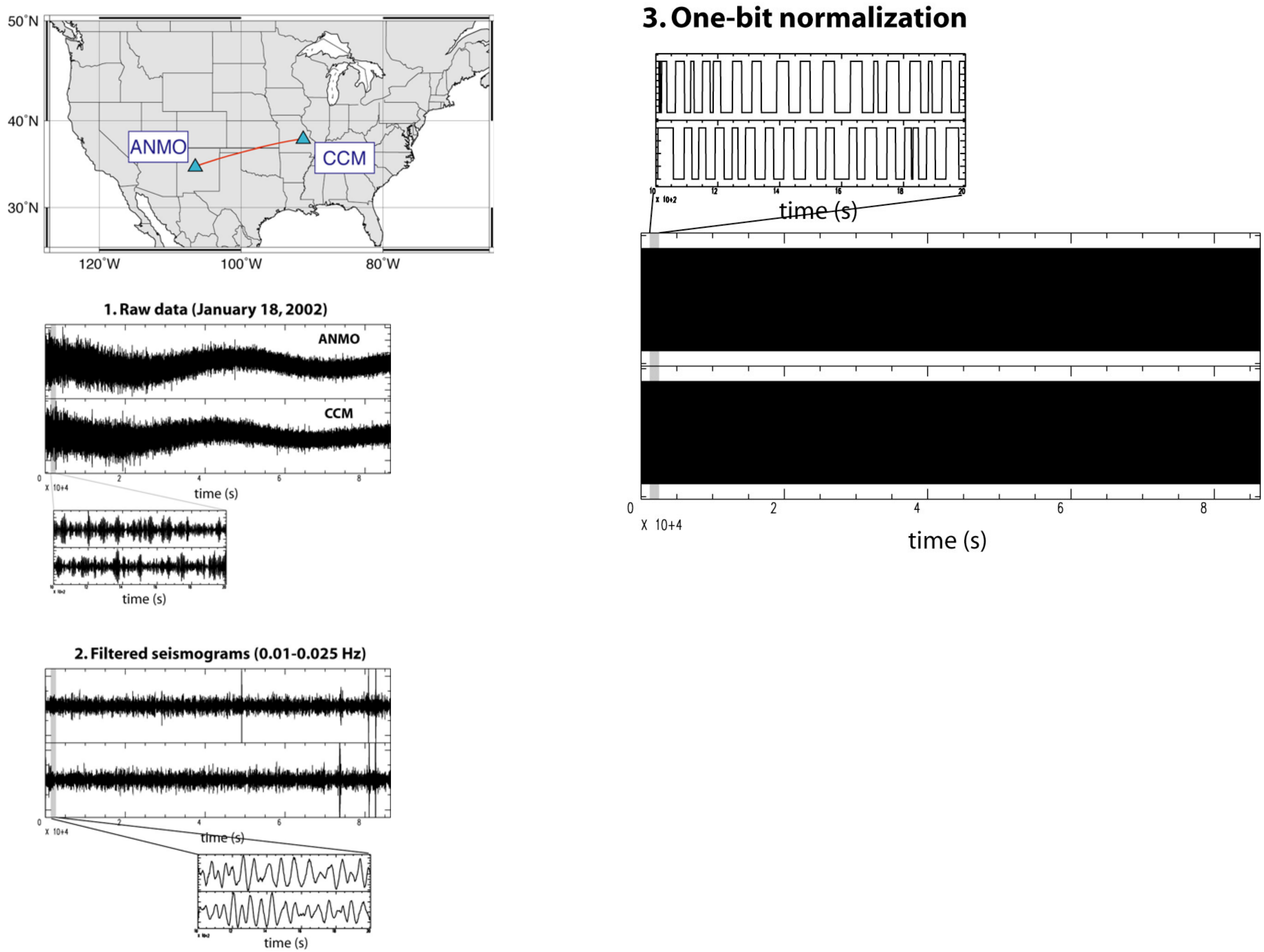


50°N
40°N
30°N
120°W
ANMO
CCM
1. Raw da
time (s)
2. Filtered seismograms (0.01-0.025 Hz)
0
2
4
6
8
X 10+4
time (s)
time (s)

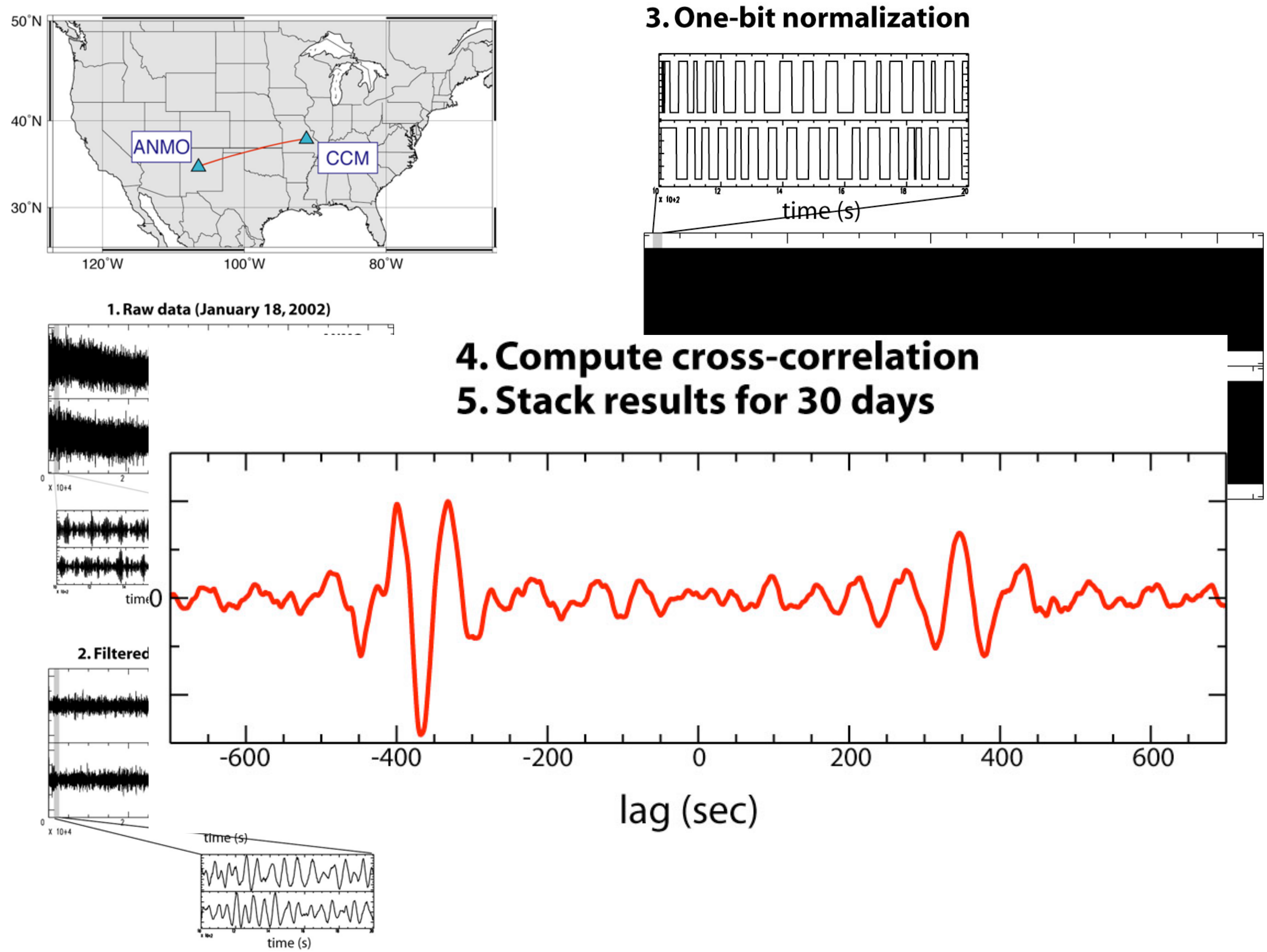

50˚N
40˚N
30˚N
120˚W
100˚W
80˚W
ANMO
CCM
1. Raw data (January 18, 2002)
ANMO
CCM
time (s)
time (s)
2. Filtered seismograms (0.01-0.025 Hz)
time (s)
time (s)

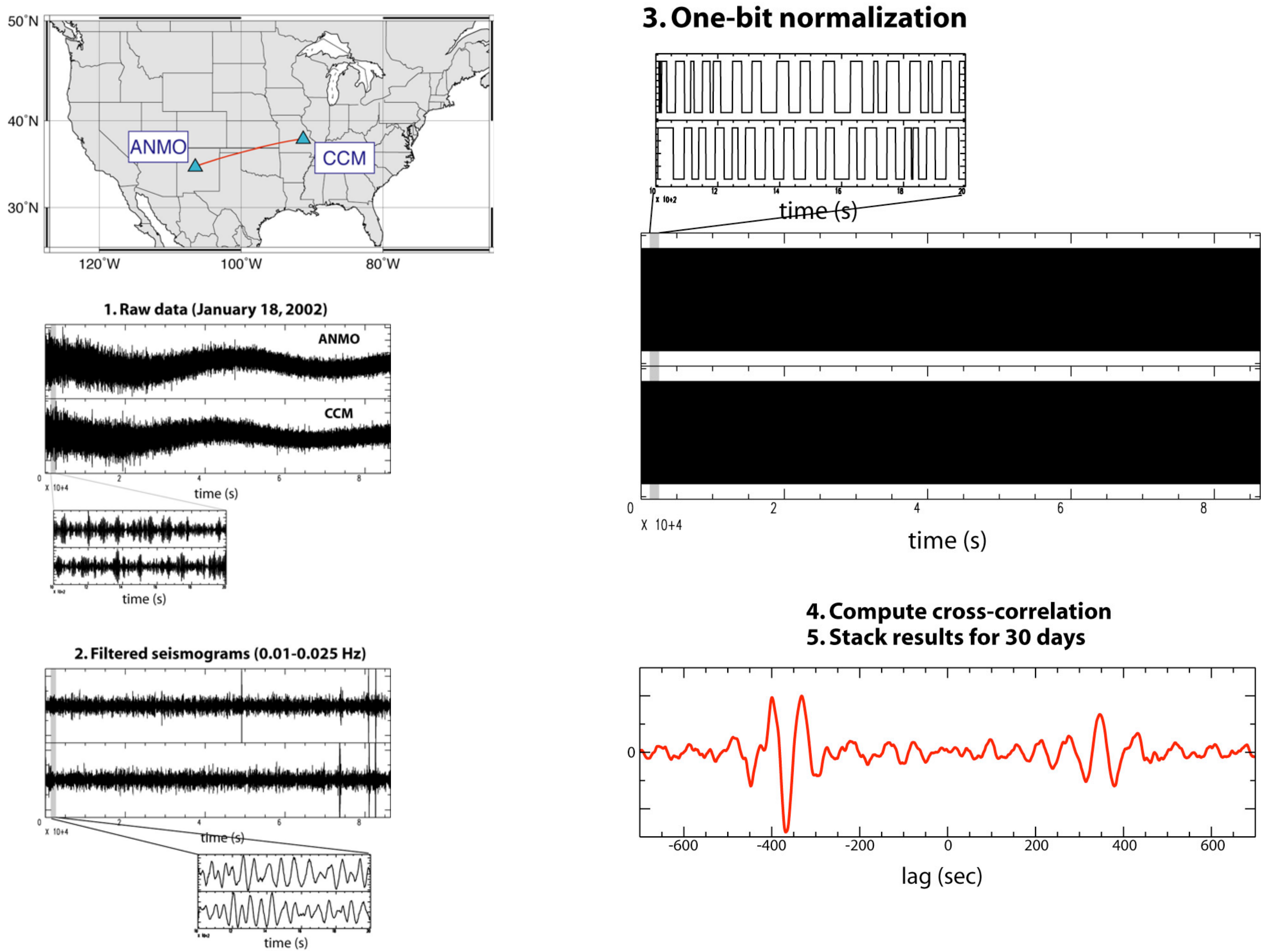


50˚N
40˚N
30˚N
120˚W
100˚W
80˚W
ANMO
CCM
1. Raw data (January 18, 2002)
ANMO
CCM
time (s)
time (s)
2. Filtered seismograms (0.01-0.025 Hz)
time (s)
time (s)
3. One-bit normalization
time (s)
0
2
4
6
8
X 10+4
time (s)



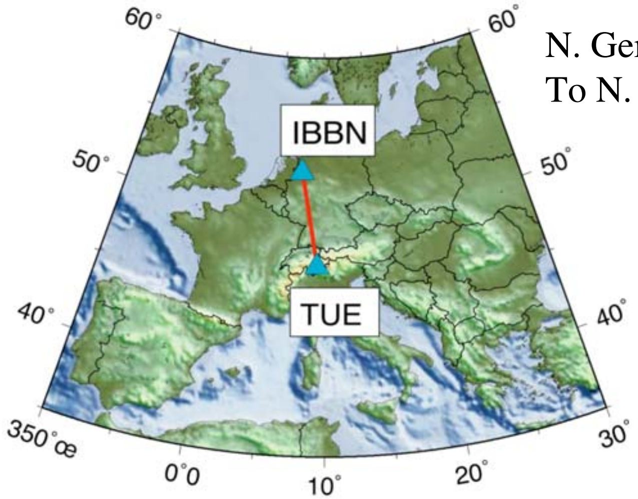
50°N
40°N
30°N
120°W
100°W
80°W
ANMO
CCM
1. Raw data (January 18, 2002)
ANMO
CCM
time (s)
time (s)
2. Filtered seismograms (0.01-0.025 Hz)
time (s)
time (s)
3. One-bit normalization
time (s)
X 10+4
time (s)


50°N
40°N
30°N
ANMO
CCM
120°W
100°W
80°W
3. One-bit normalization
time (s)
1. Raw data (January 18, 2002)
2. Filtered
time (s)
time (s)
4. Compute cross-correlation
5. Stack results for 30 days
0
-600
-400
-200
0
200
400
600
lag (sec)


50°N
40°N
30°N
120°W
100°W
80°W
ANMO
CCM
1. Raw data (January 18, 2002)
ANMO
CCM
time (s)
time (s)
2. Filtered seismograms (0.01-0.025 Hz)
time (s)
time (s)
3. One-bit normalization
time (s)
X 10+4
time (s)
4. Compute cross-correlation
5. Stack results for 30 days
lag (sec)

Group velocity measurement

1. For each station pair, perform a series of narrow band-pass filters on each day of data:
   5-15, 10-25, 20-40, 33-66, 50-100, 70-150 sec.
2. Perform temporal and spectral whitening of each time series.

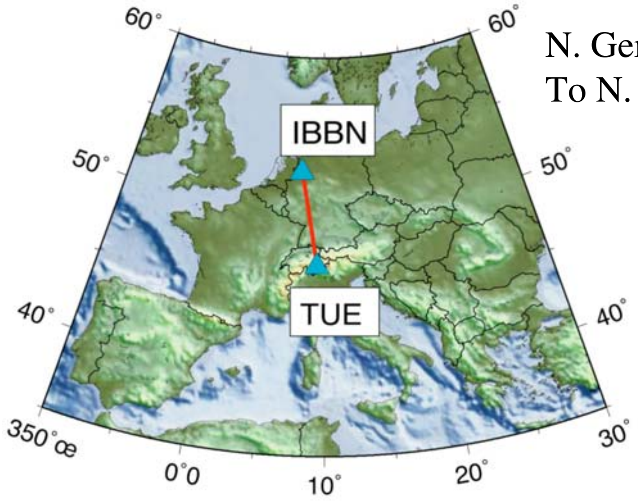


N. Germany
To N. Italy

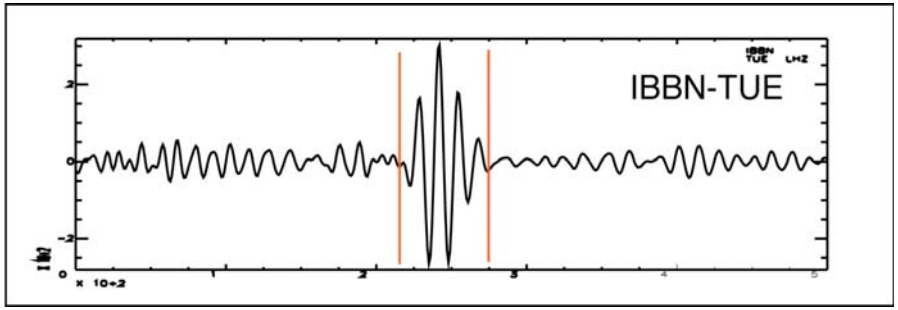
Group velocity measurement

1. For each station pair, perform a series of narrow band-pass filters:

   5-15, 10-25, 20-40, 33-66, 50-100, 70-150 sec.
2. Perform temporal and spectral whitening of each time series.
3. Stack results in daily, monthly, tri-monthly, & yearly increments.



N. Germany
To N. Italy

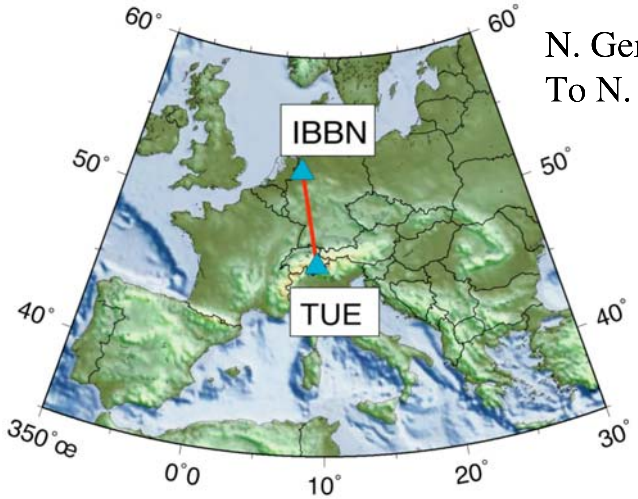


Symmetric component of 1 year stack.

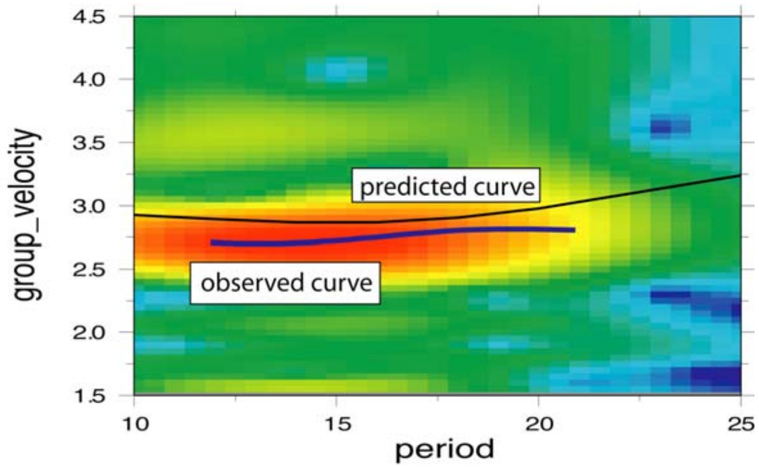
Group velocity measurement

1. For each station pair, perform a series of narrow band-pass filters:

   5-15, 10-25, 20-40, 33-66, 50-100, 70-150 sec.
2. Perform temporal and spectral whitening of each time series.
3. Stack results in daily, monthly, tri-monthly, & yearly increments.
4. Measure surface wave dispersion in each period band.

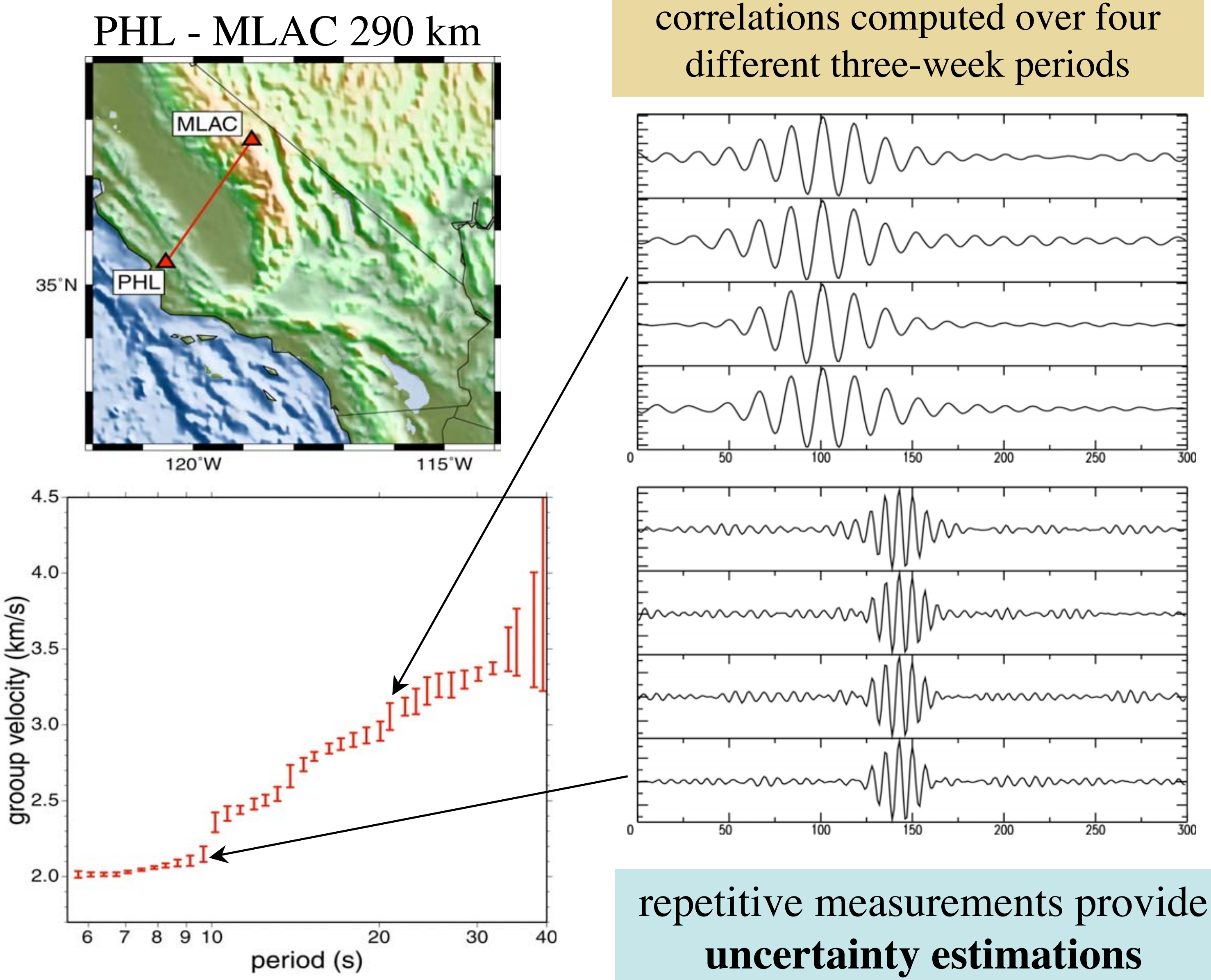


N. Germany
To N. Italy



Predicted curve from CUB model

estimation of errors



correlations computed over four different three-week periods

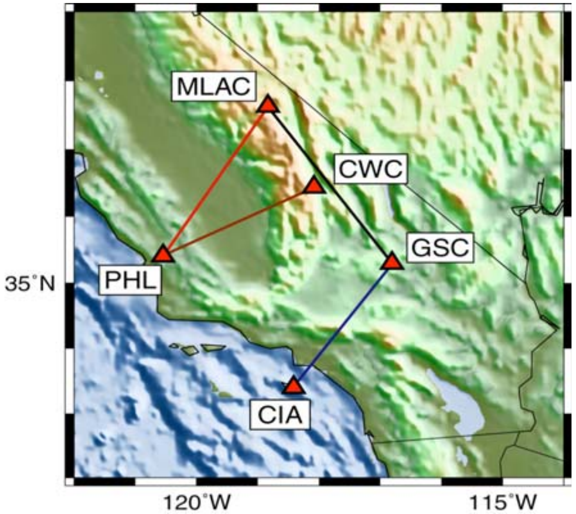
band-passed 15 - 30 s

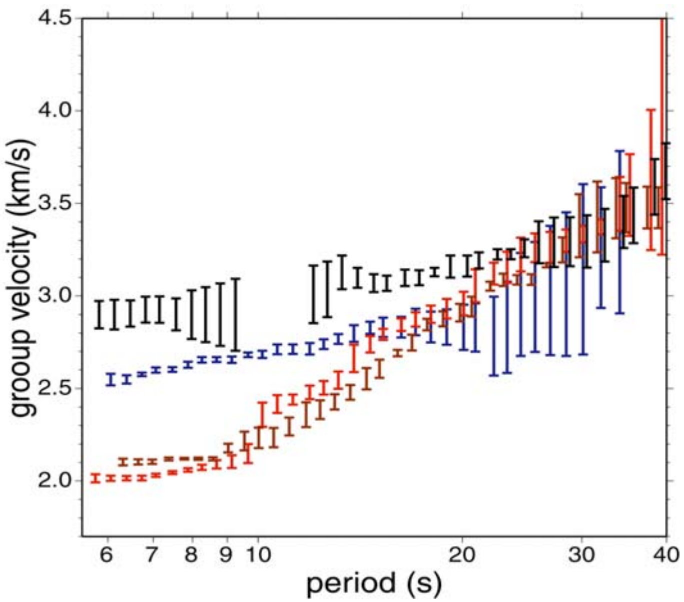
band-passed 5 - 10 s

repetitive measurements provide **uncertainty estimations**

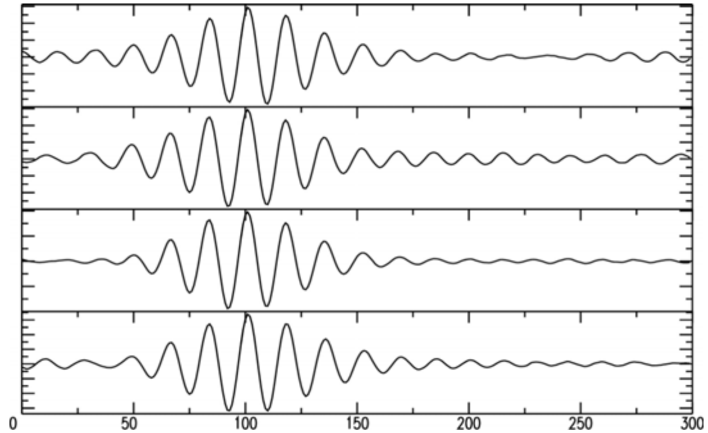
estimation of errors

PHL - MLAC 290 km

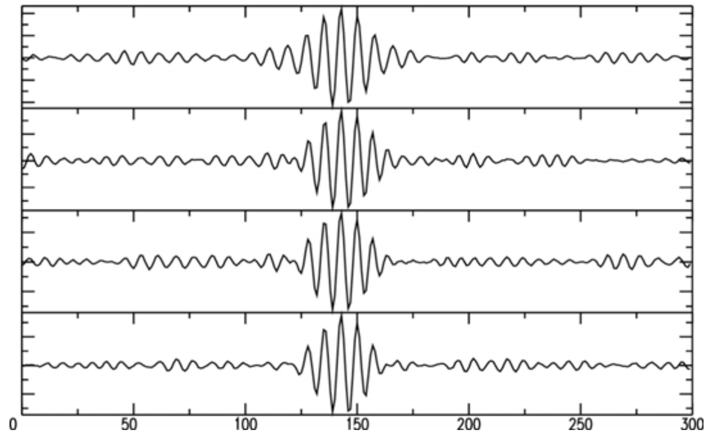




correlations computed over four different three-week periods



band-passed 15 - 30 s



band-passed 5 - 10 s

repetitive measurements provide **uncertainty estimations**

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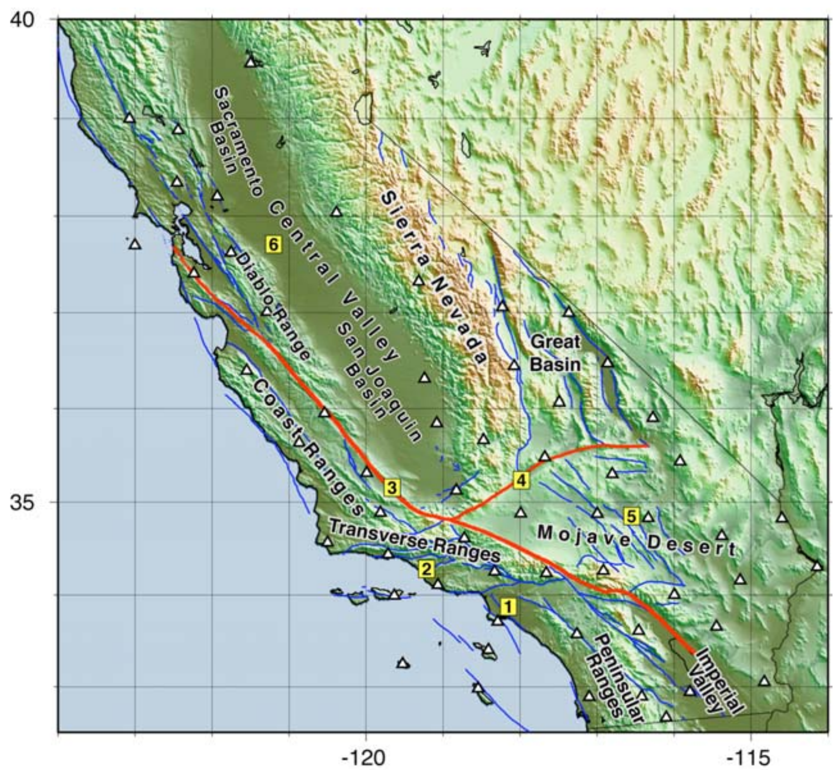
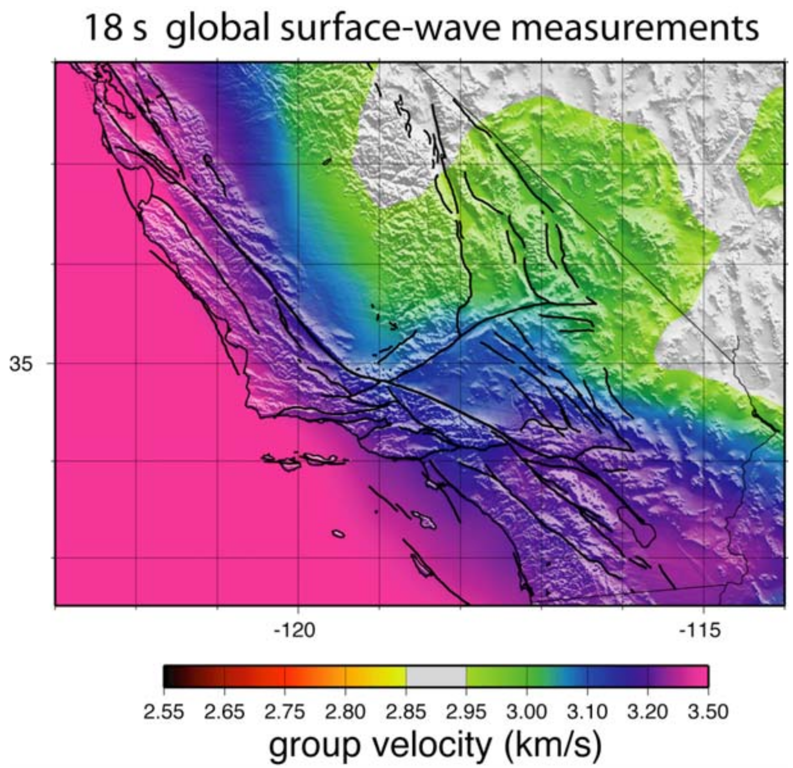
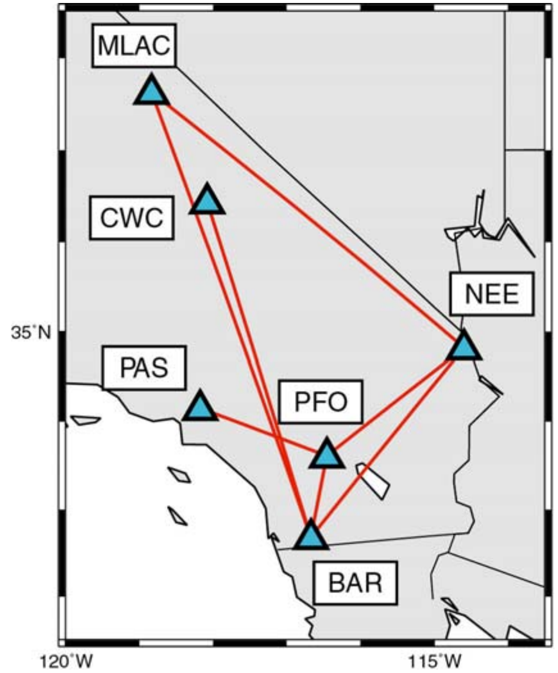
Cross-correlation of seismic noise in California

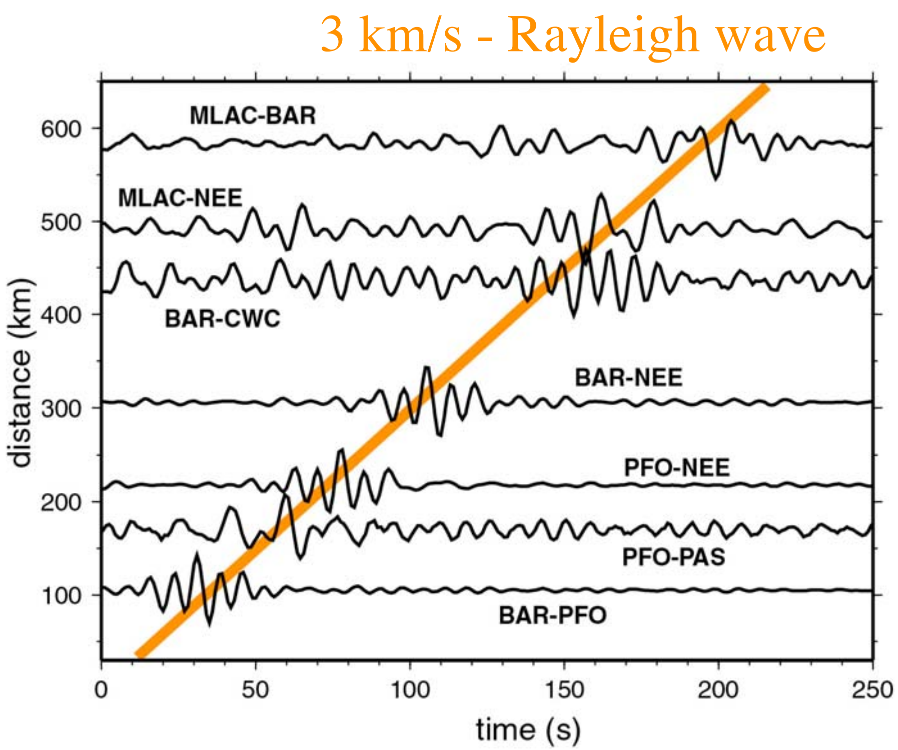




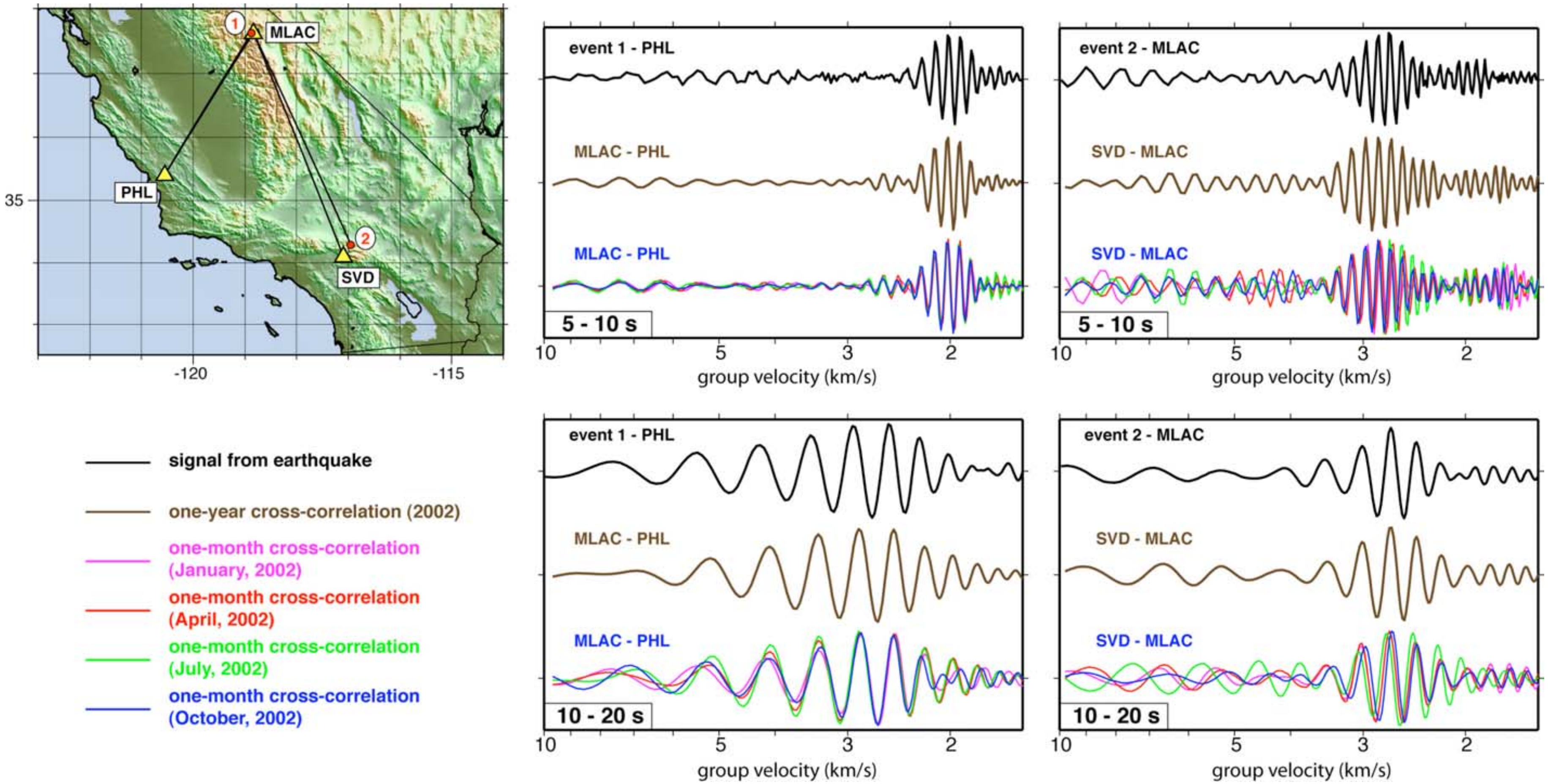
Cross-correlation of seismic noise in California

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

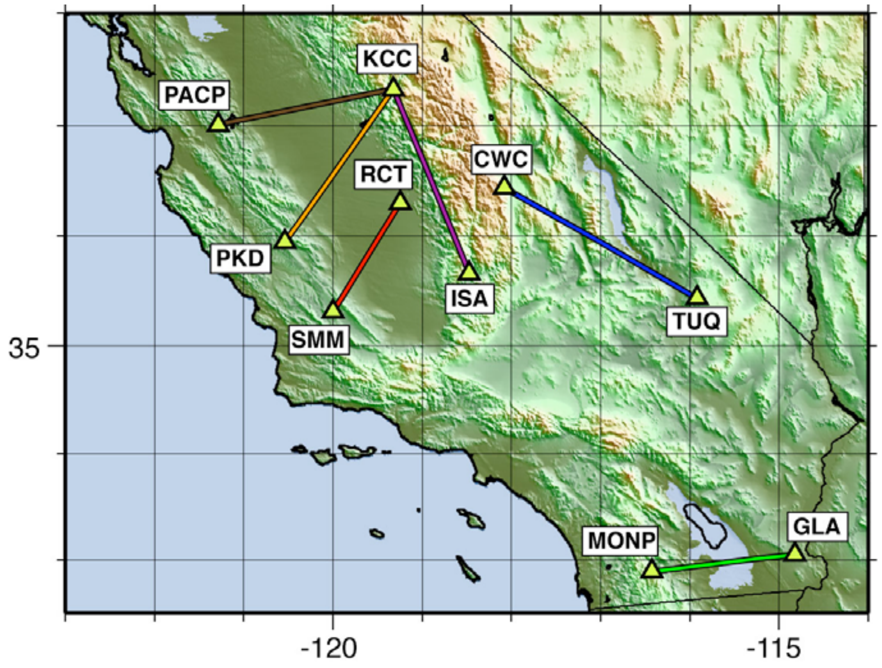


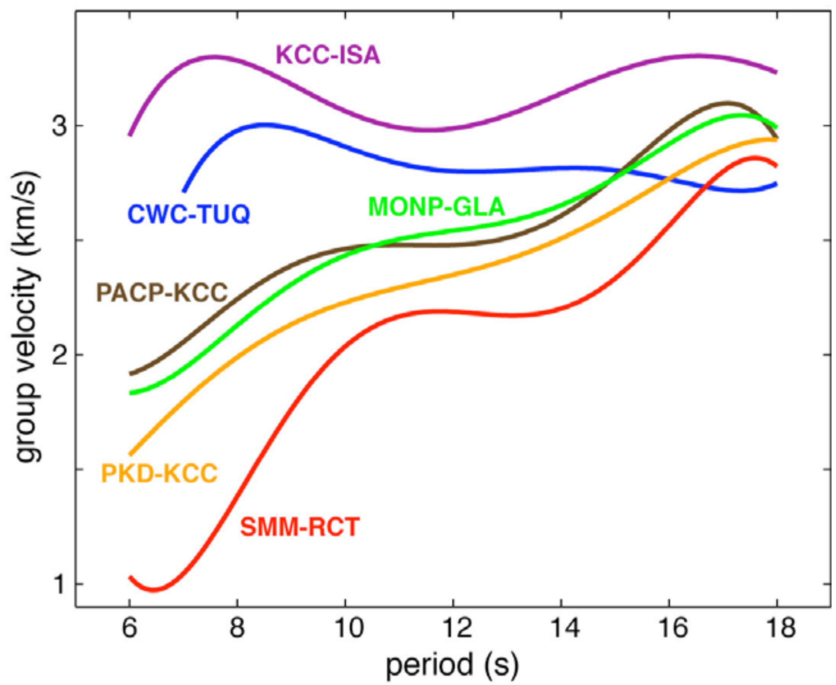


Comparison with signals from earthquakes

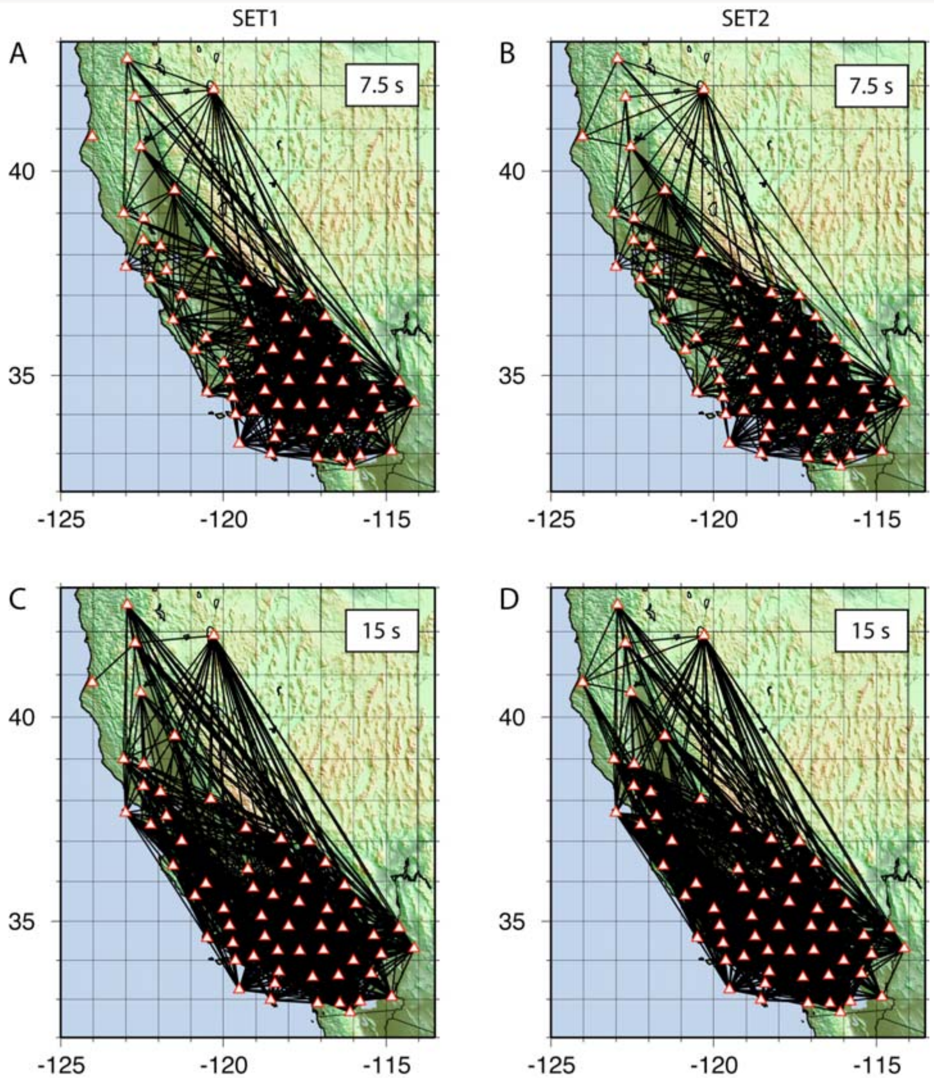


Examples of Rayleigh-wave dispersion curves

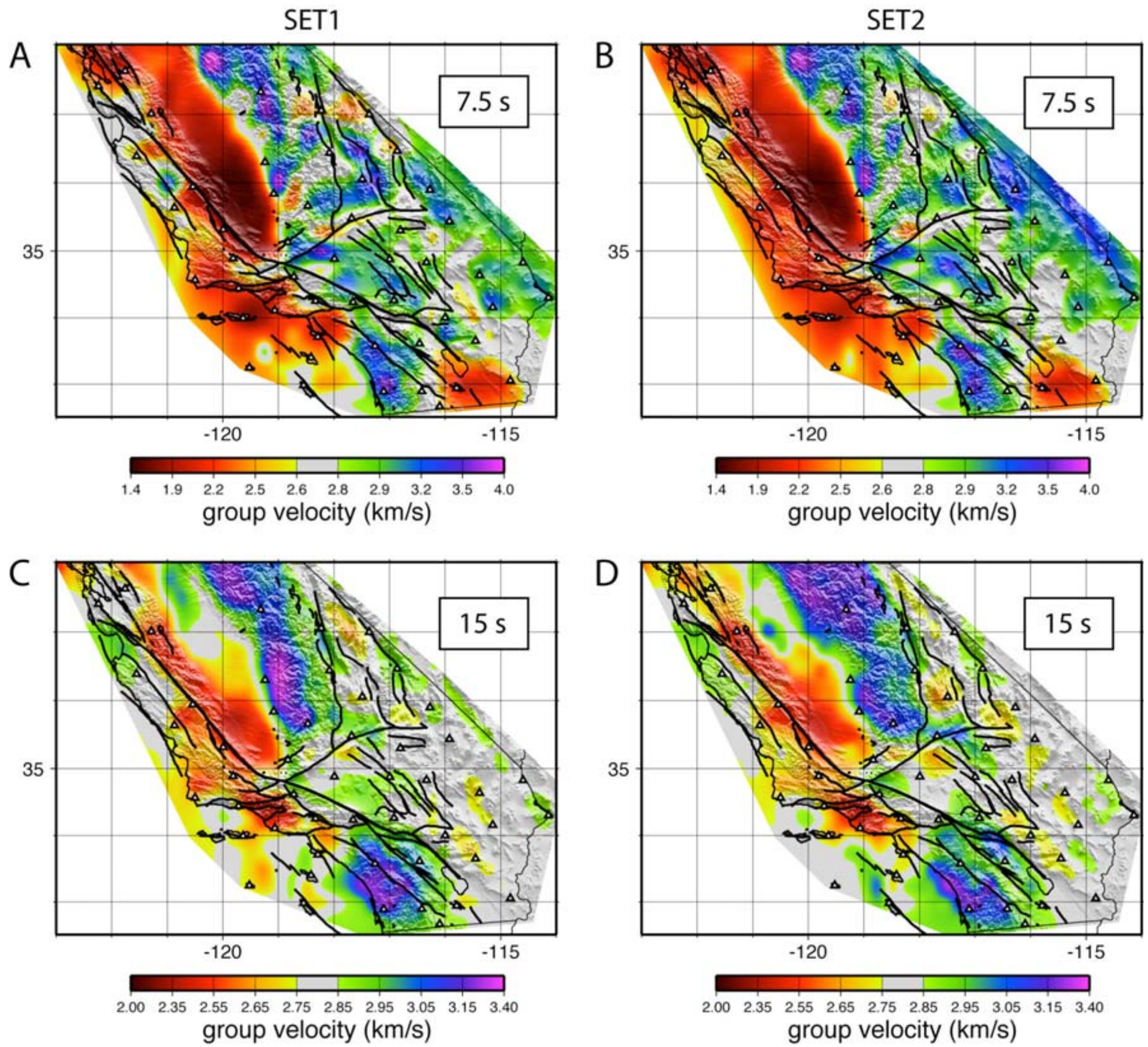




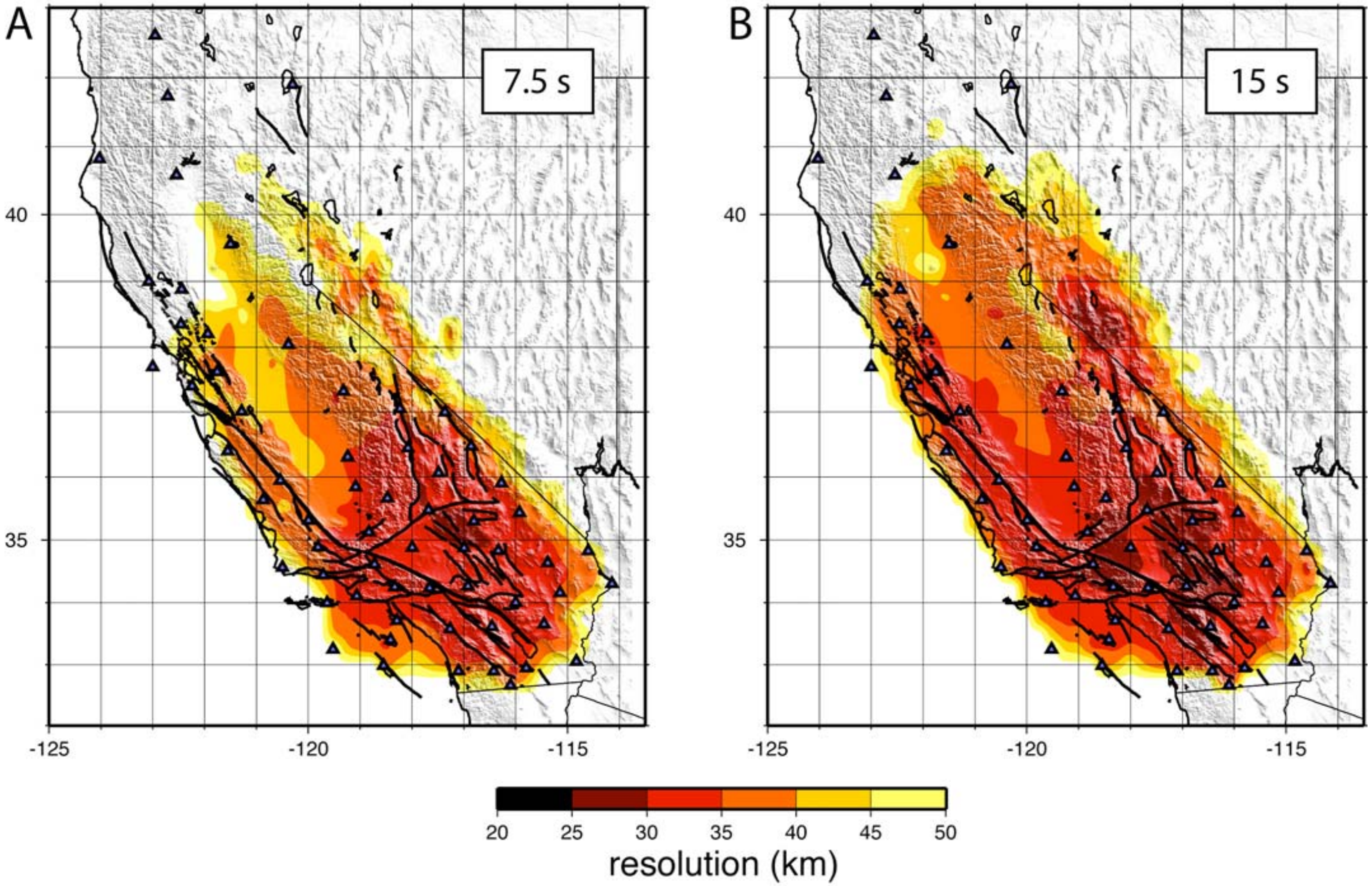
Measurements from two different months



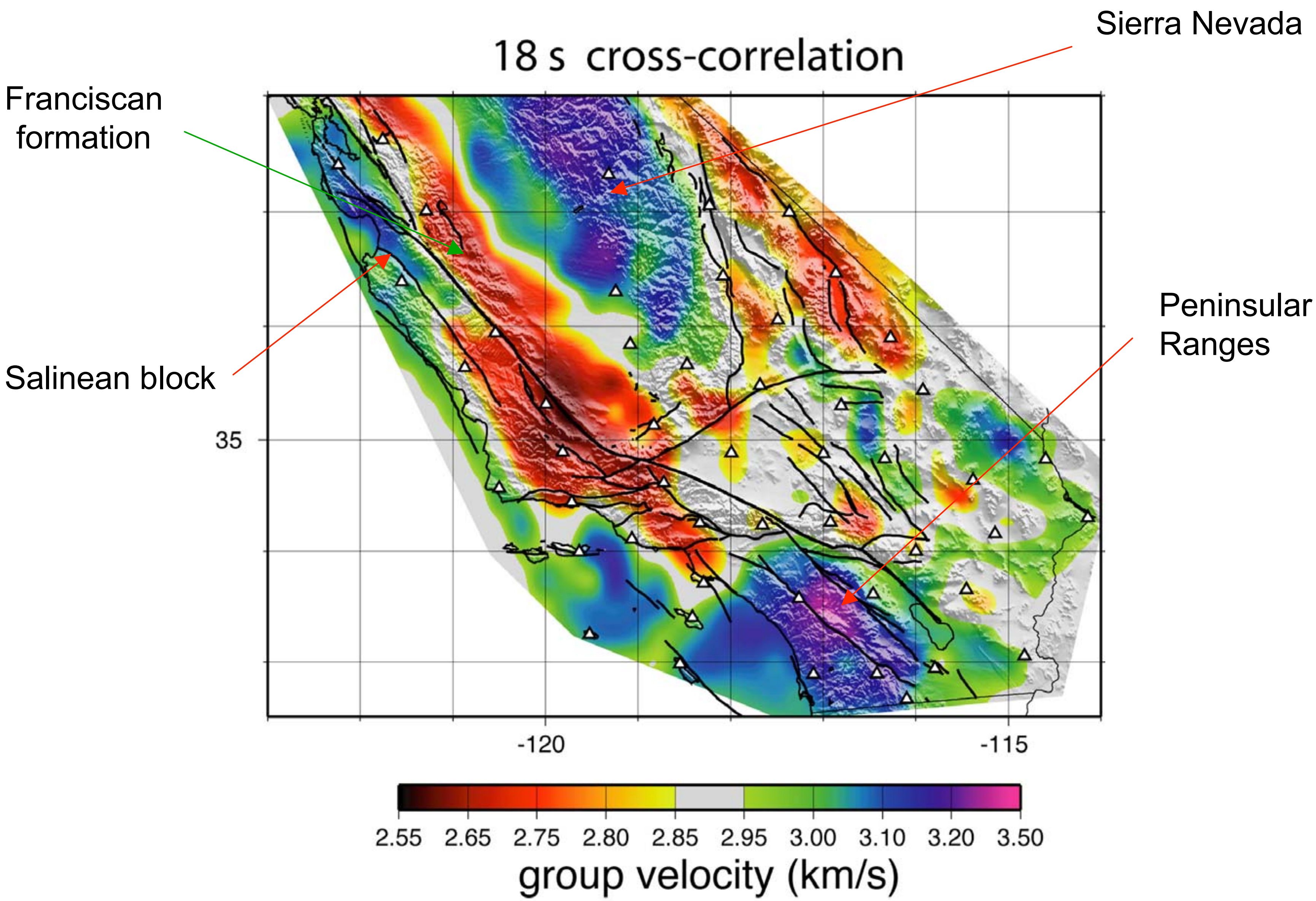
Repetitive tomography



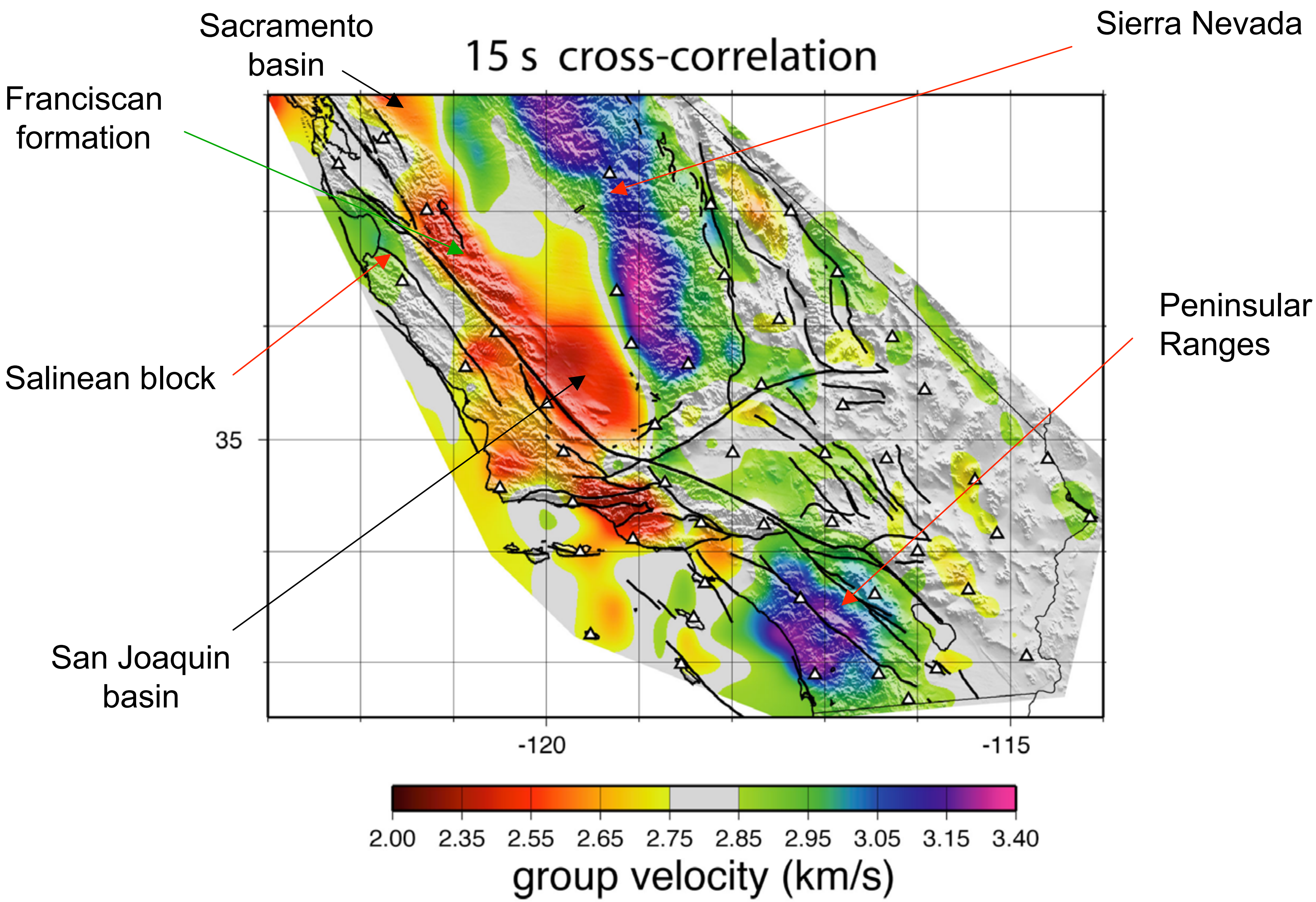
Resolution



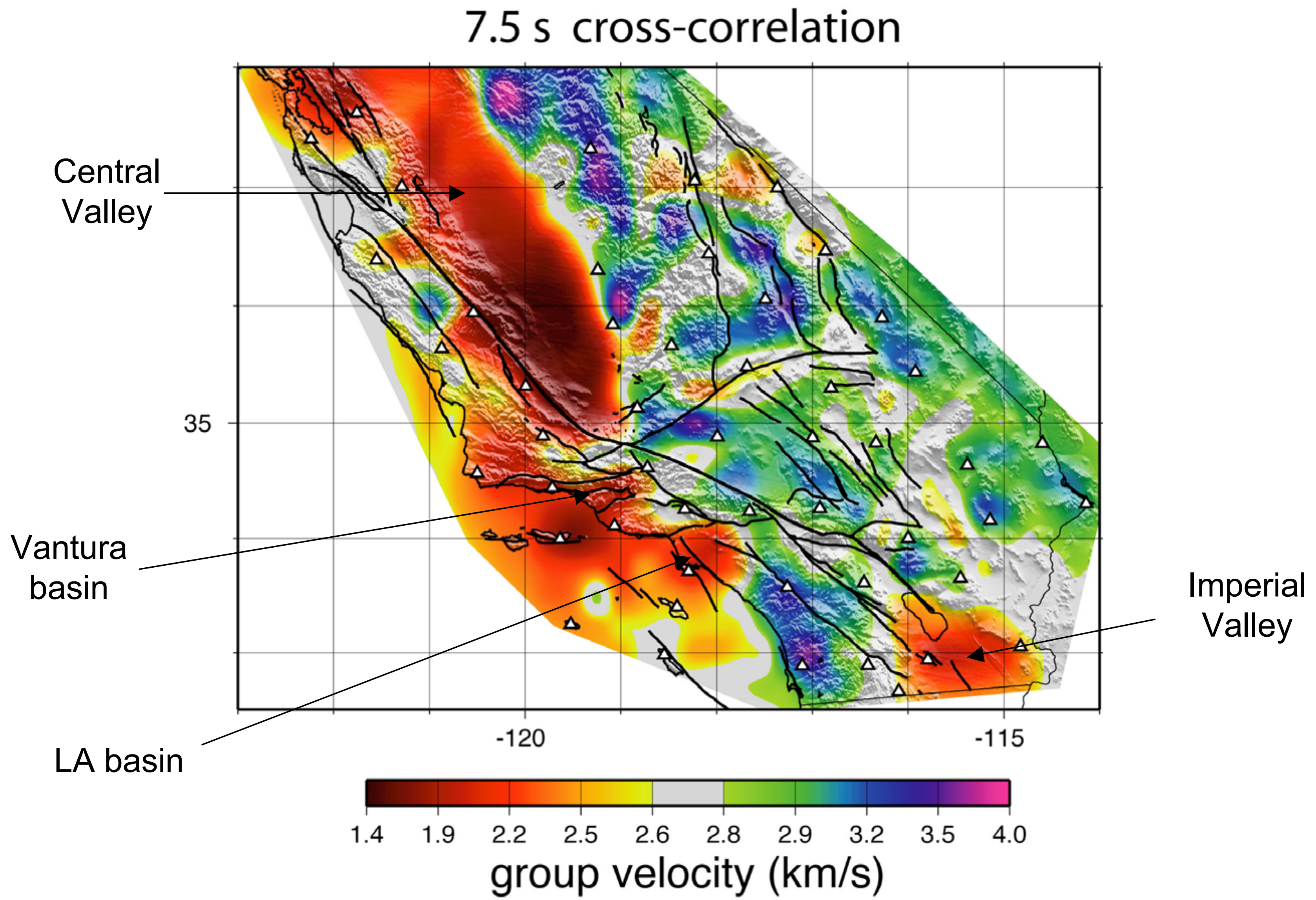
dispersion maps



dispersion maps

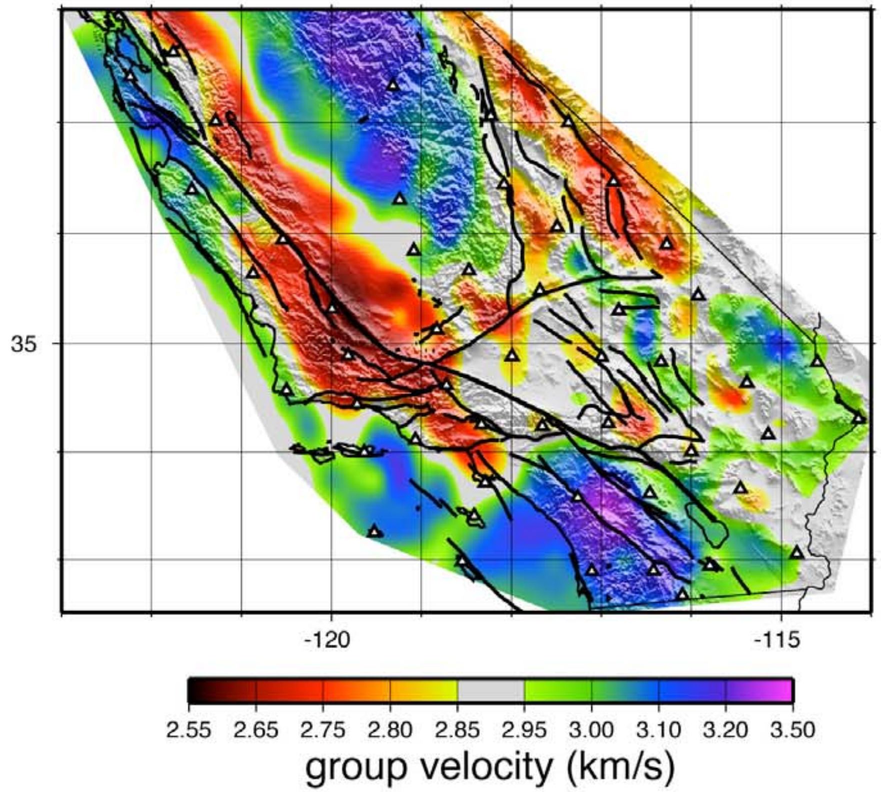


dispersion maps

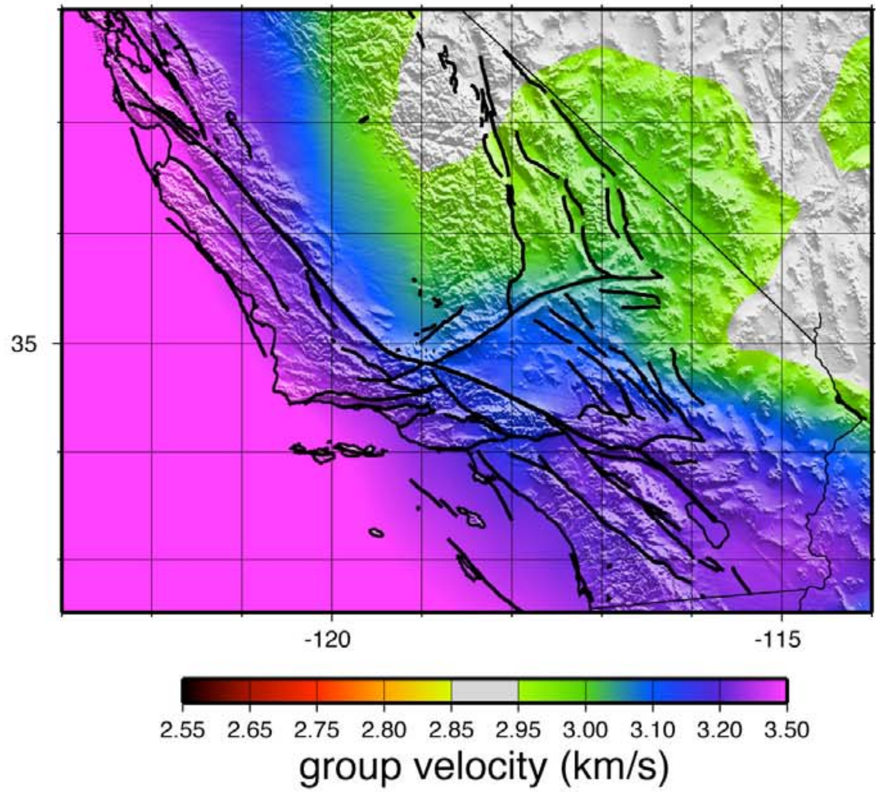


Comparison between noise-based and earthquake-based tomographies

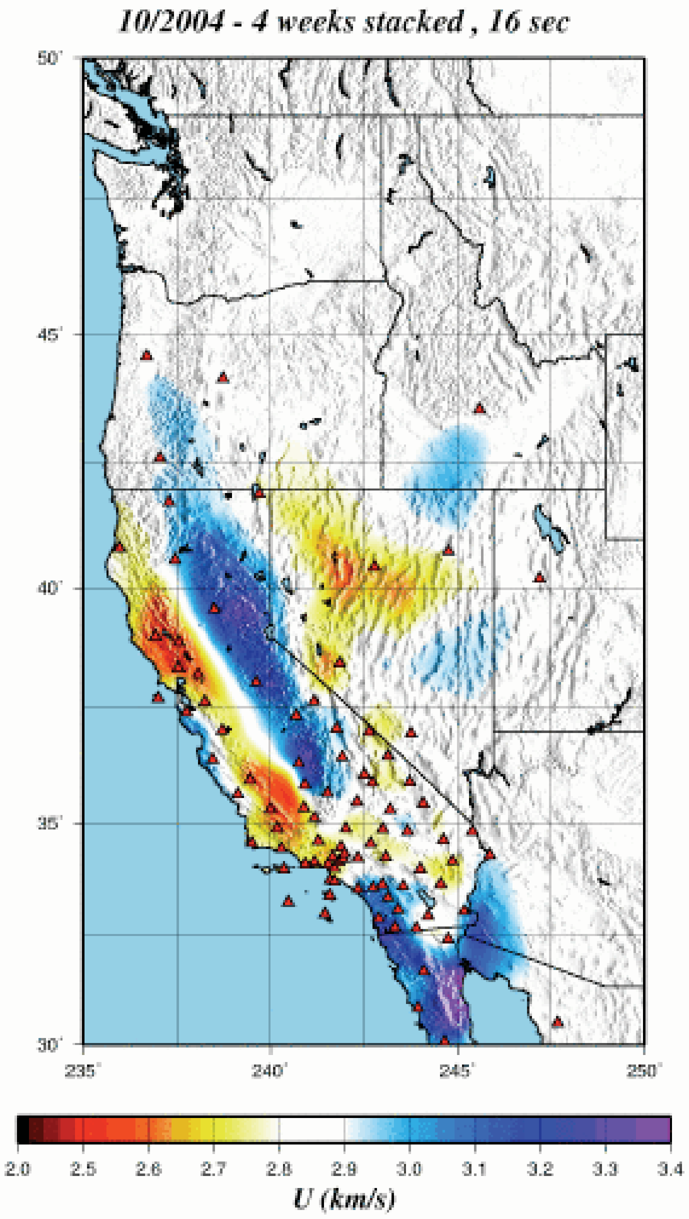
18 s cross-correlation



18 s global surface-wave tomography



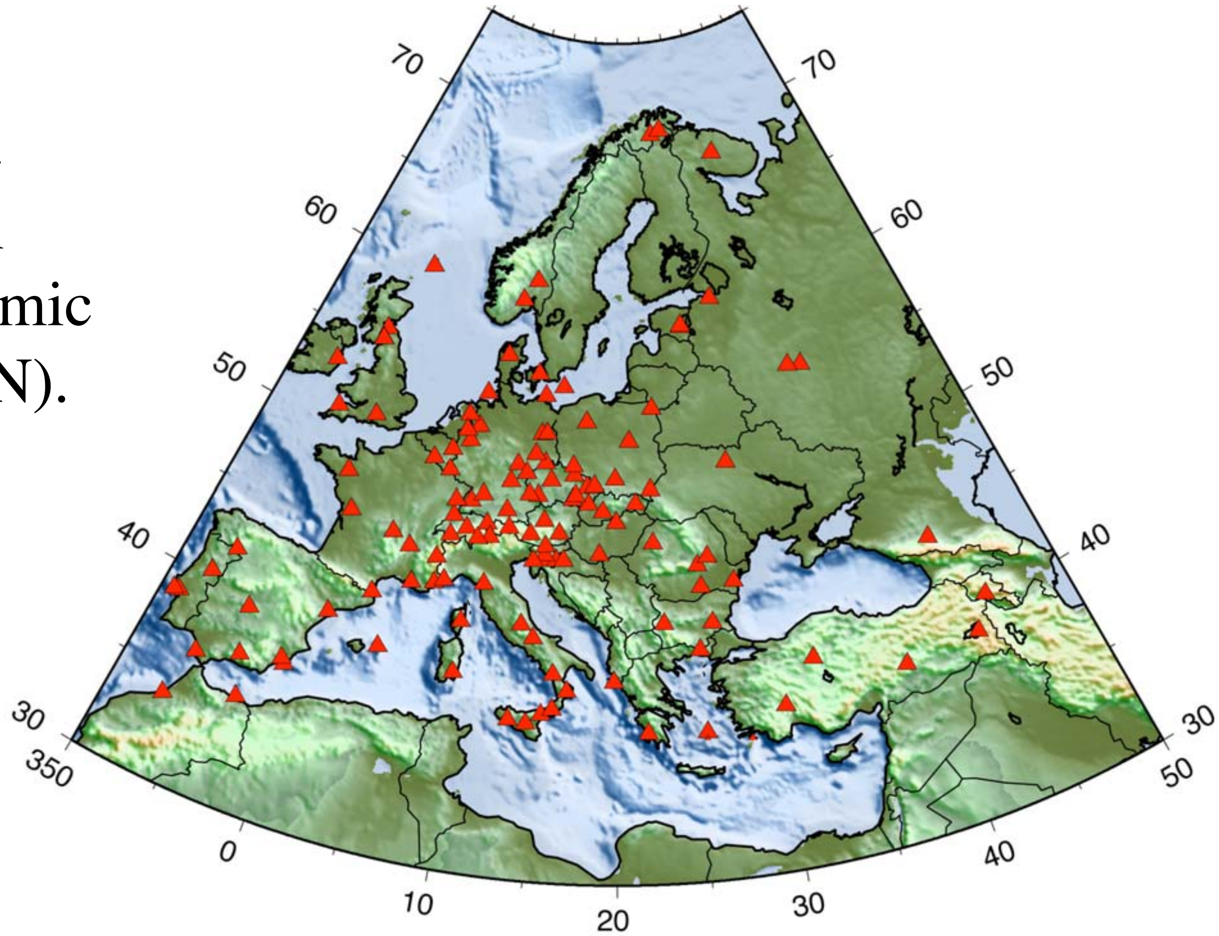
ongoing processing of the USArray data (M. Moschetti)



Ambient Noise Tomography Across Europe
(Yingjie Yang)

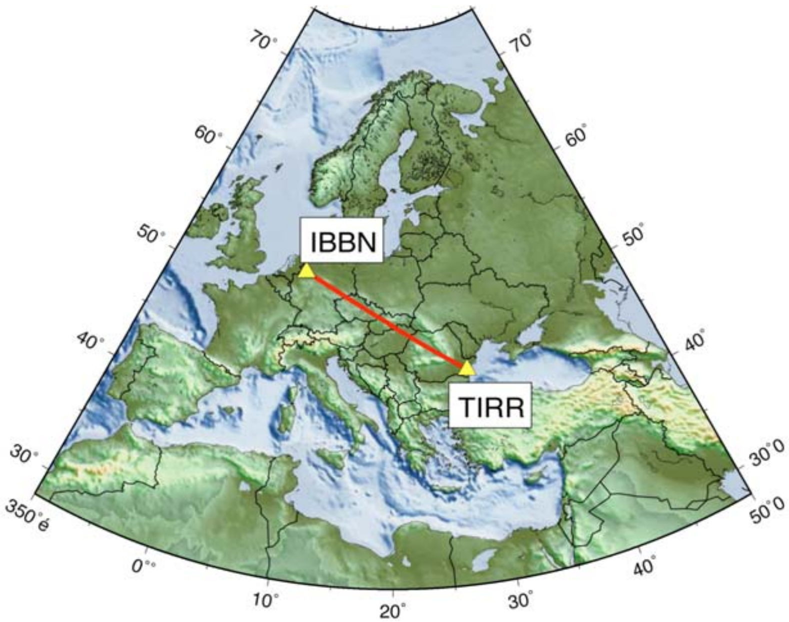
Stations from the Virtual European Broad-Band Seismic Network (VEBSN).

~125 stations

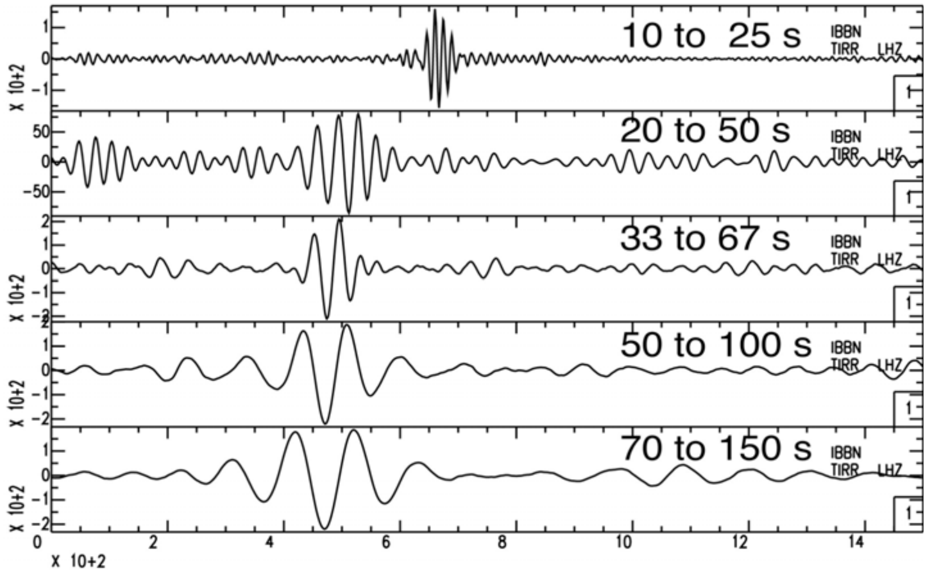


Example of Broad-Band Cross-Correlograms

Path: N. Germany to Romania



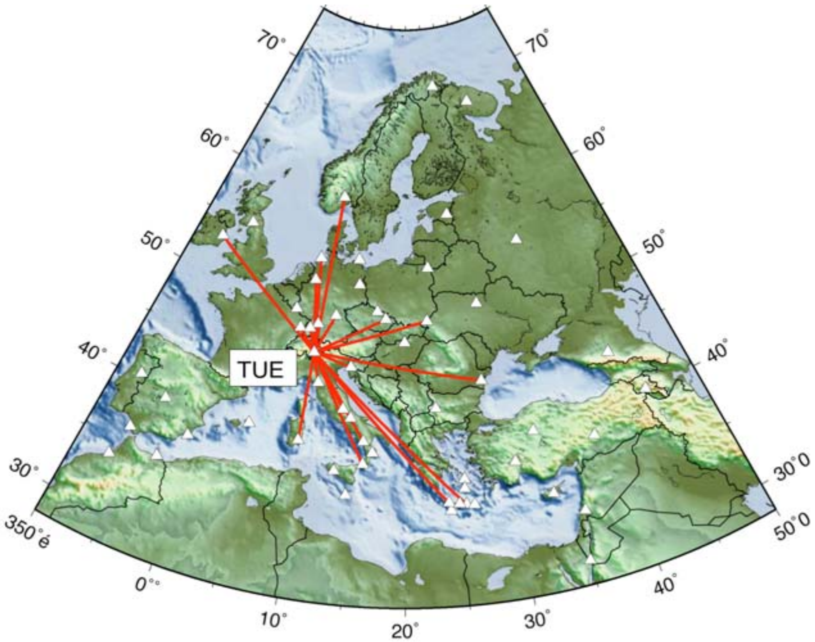
1-year stack



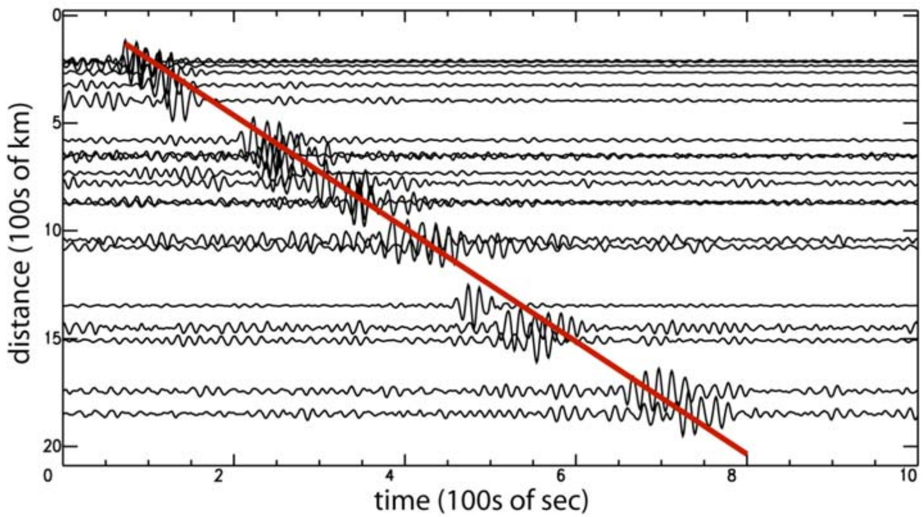
time (sec/100)

Sample Record Section

N. Italy to Stations Across Europe

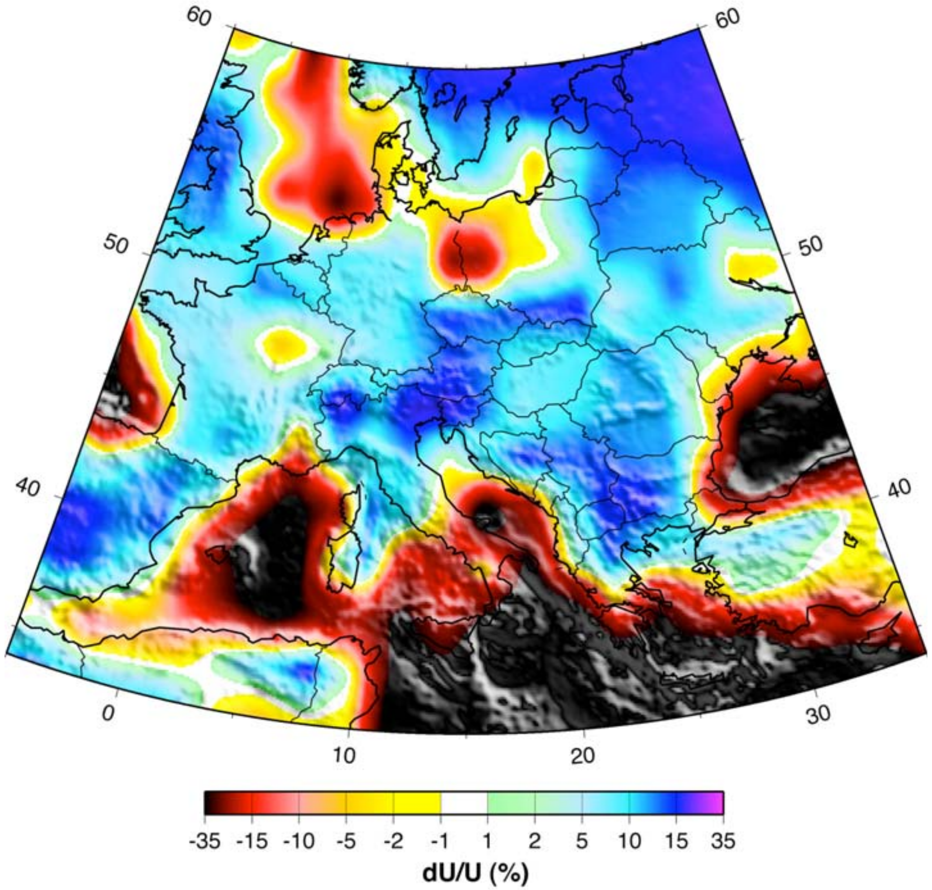


33-66 sec, 1 year stack, symmetric component

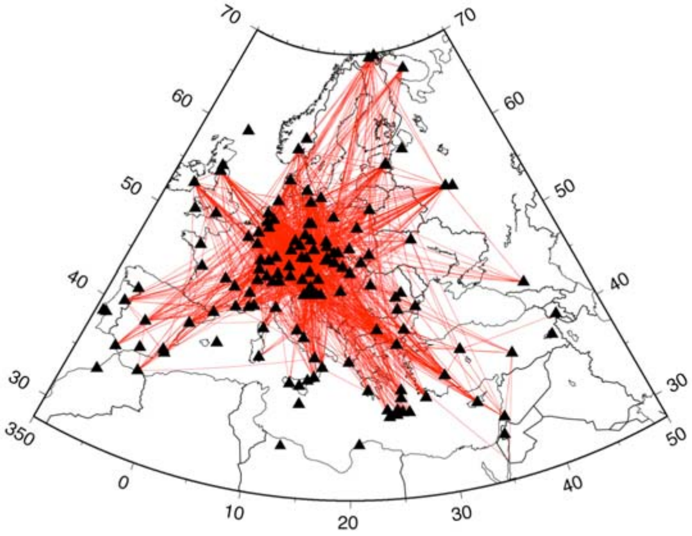


Group Speed Maps Across Europe: 12 sec

From CUB 3-D Model

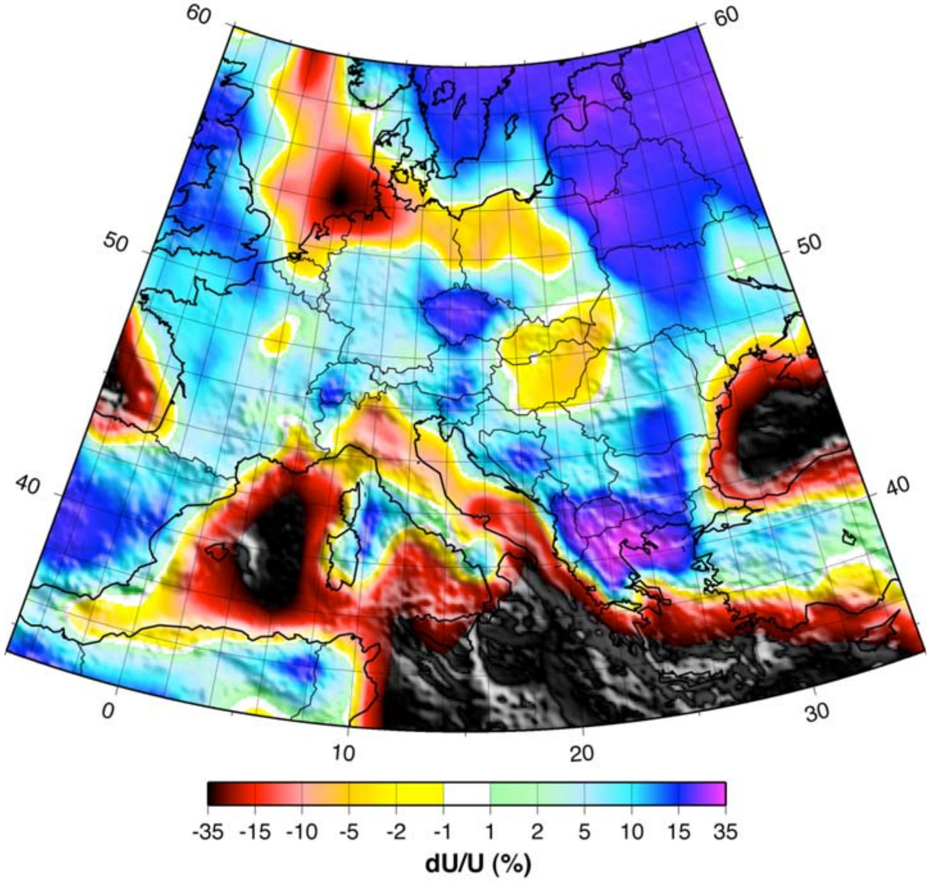


Group Speed Maps Across Europe: 12 sec



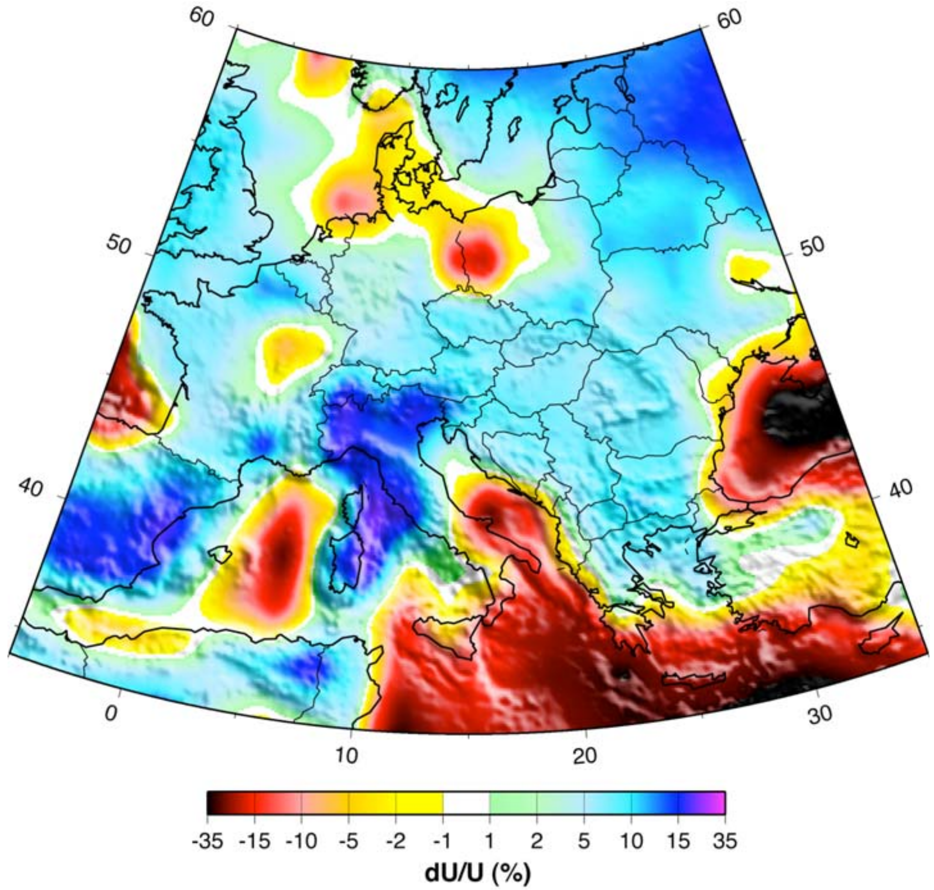
SNR > 5
1664 paths

Ambient Noise Tomography

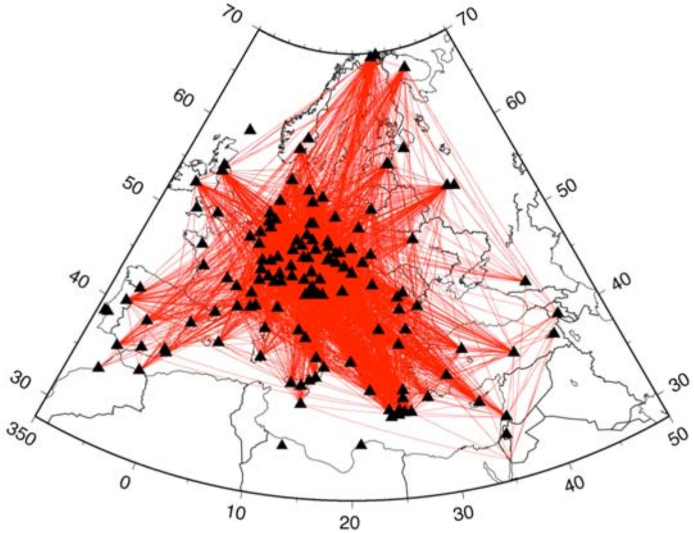


Group Speed Maps Across Europe: 16 sec

From CUB 3-D Model

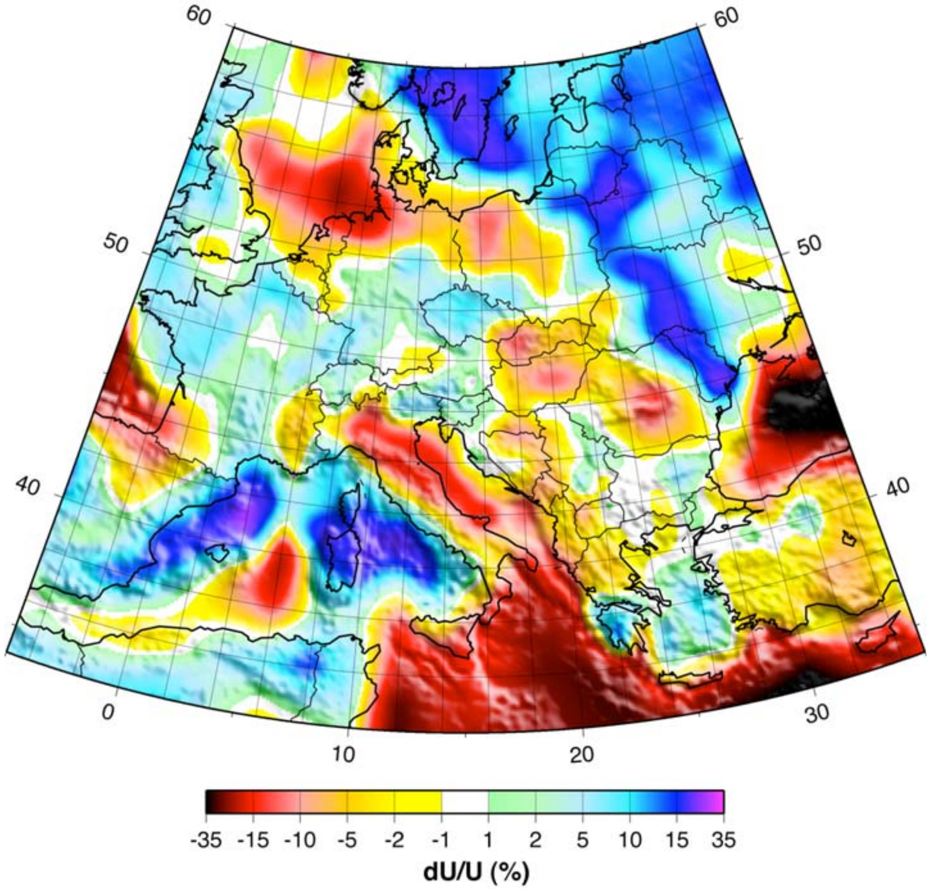


Group Speed Maps Across Europe: 16 sec



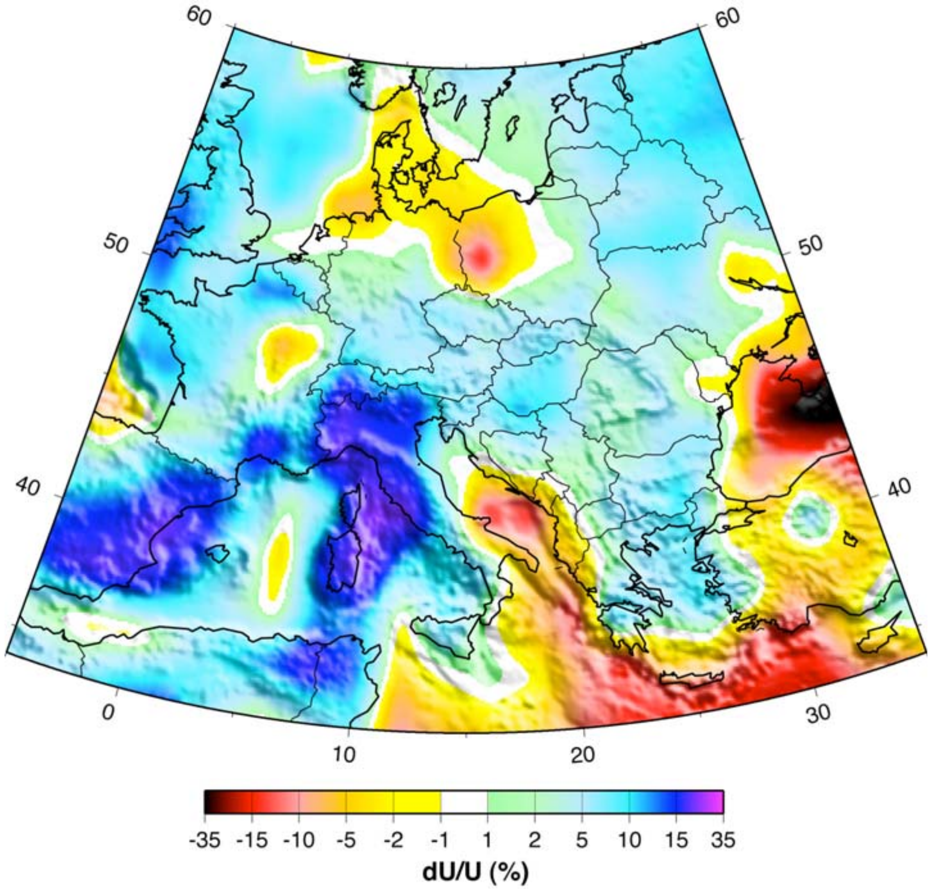
SNR > 5
3241 paths

Ambient Noise Tomography

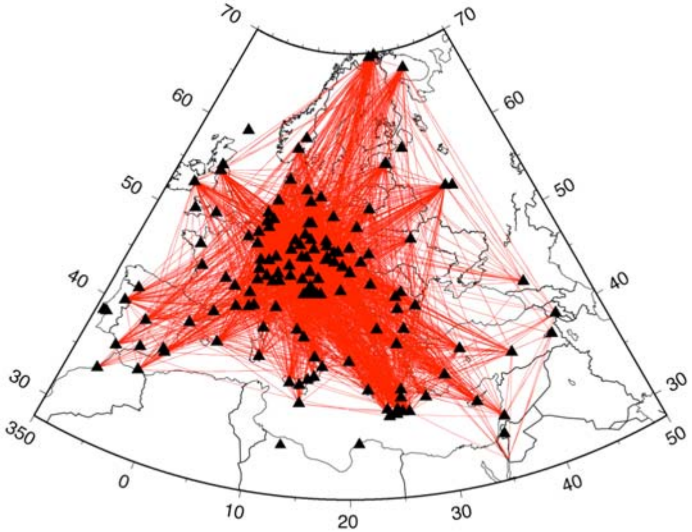


Group Speed Maps Across Europe: 20 sec

From CUB 3-D Model

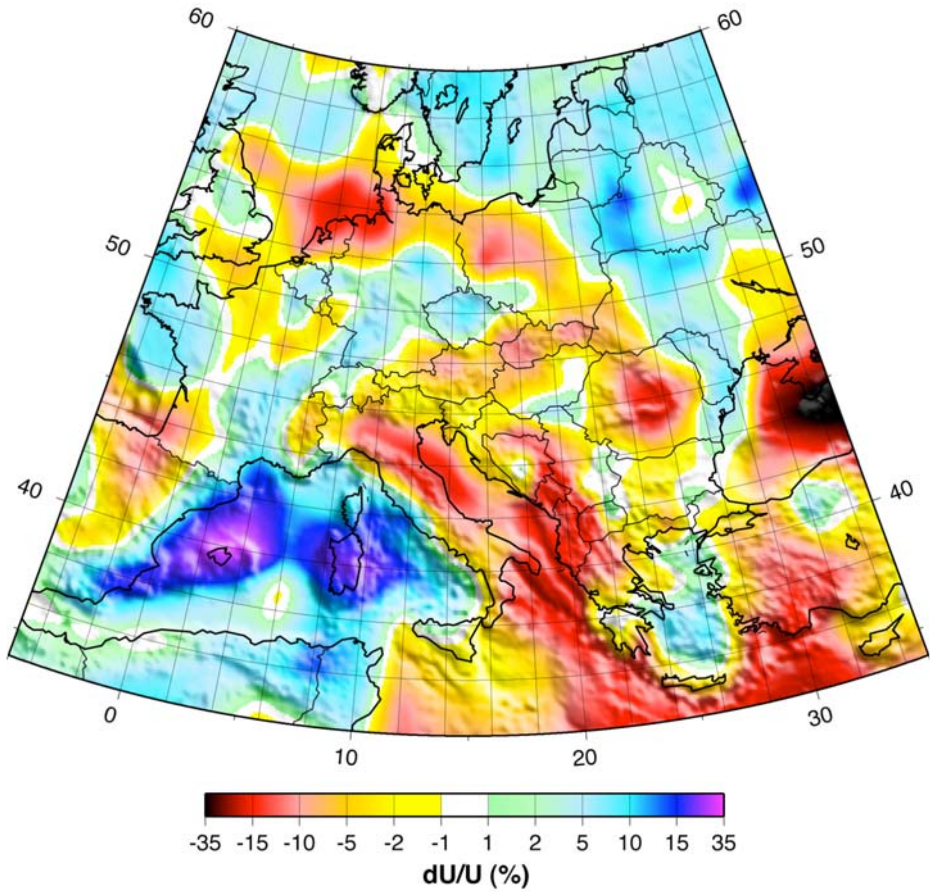


Group Speed Maps Across Europe: 20 sec



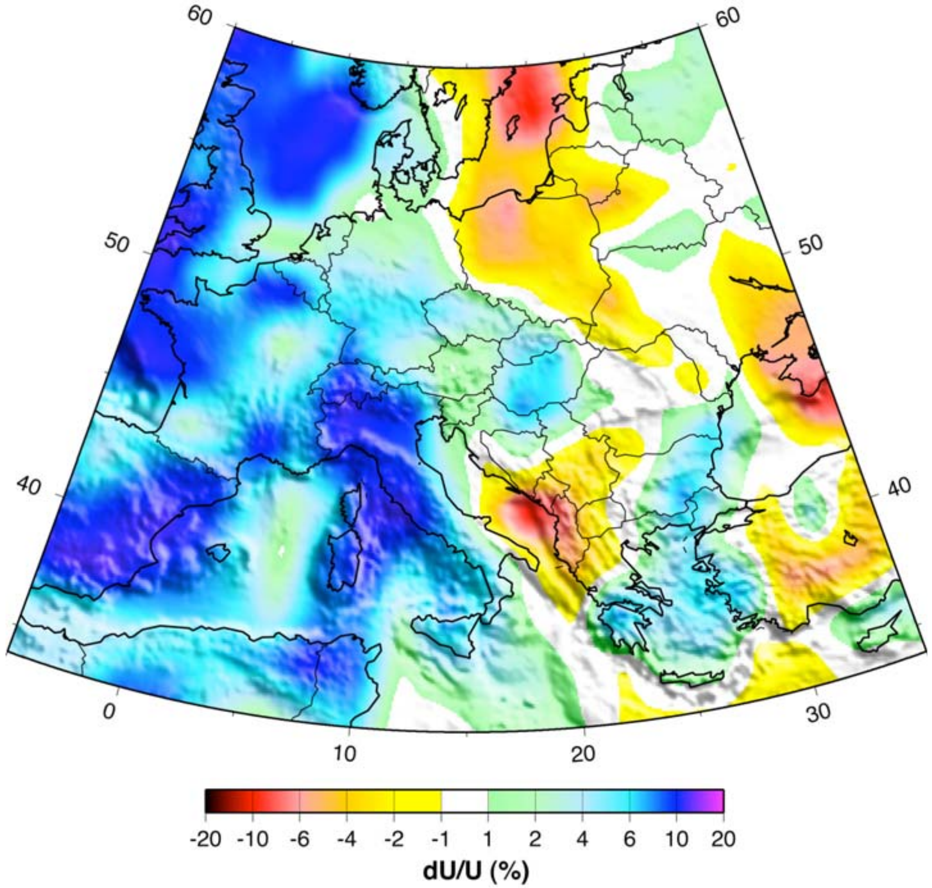
SNR > 5
3057 paths

Ambient Noise Tomography

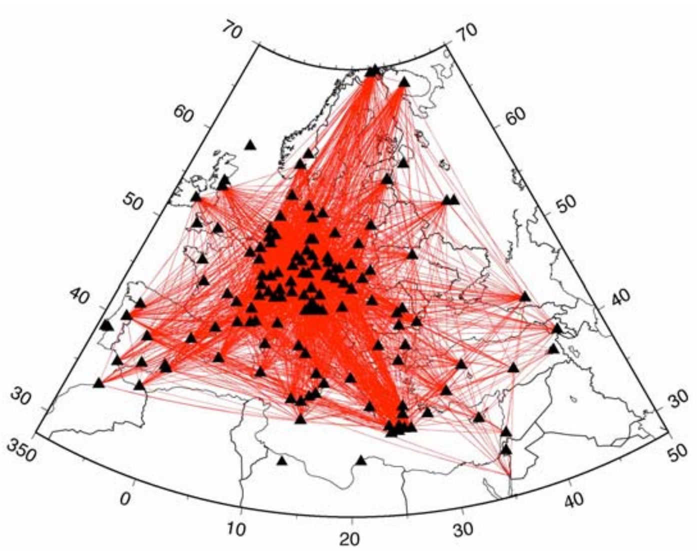


Group Speed Maps Across Europe: 30 sec

From CUB 3-D Model

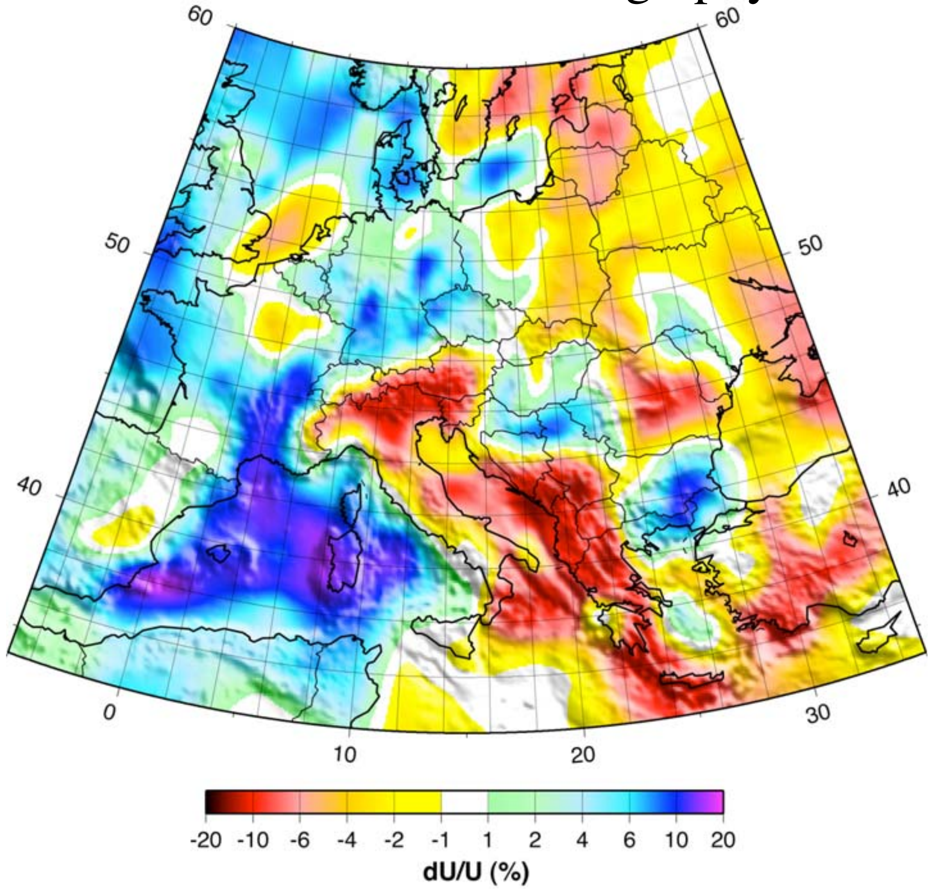


Group Speed Maps Across Europe: 30 sec



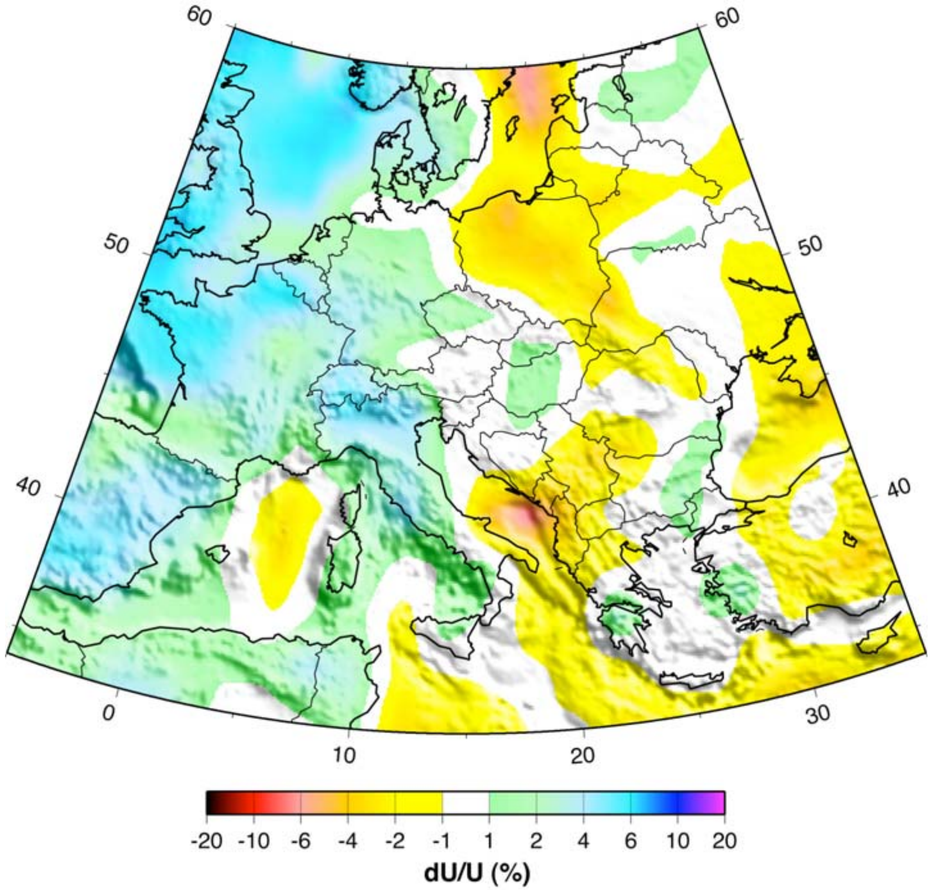
SNR > 5
2450 paths

Ambient Noise Tomography

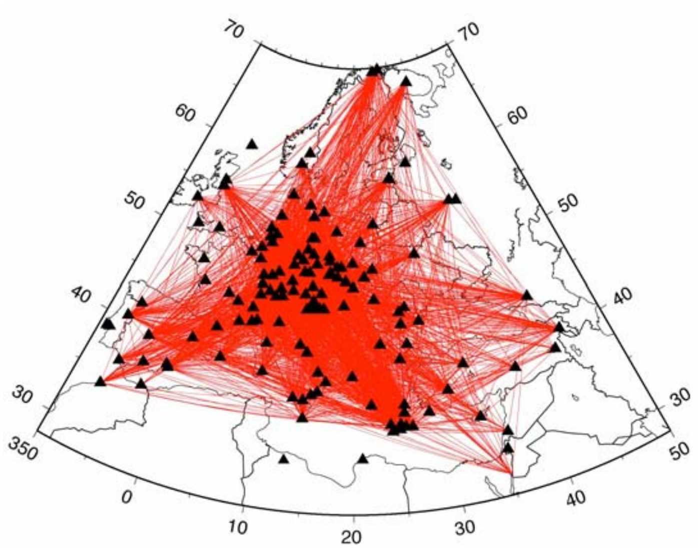


Group Speed Maps Across Europe: 40 sec

From CUB 3-D Model

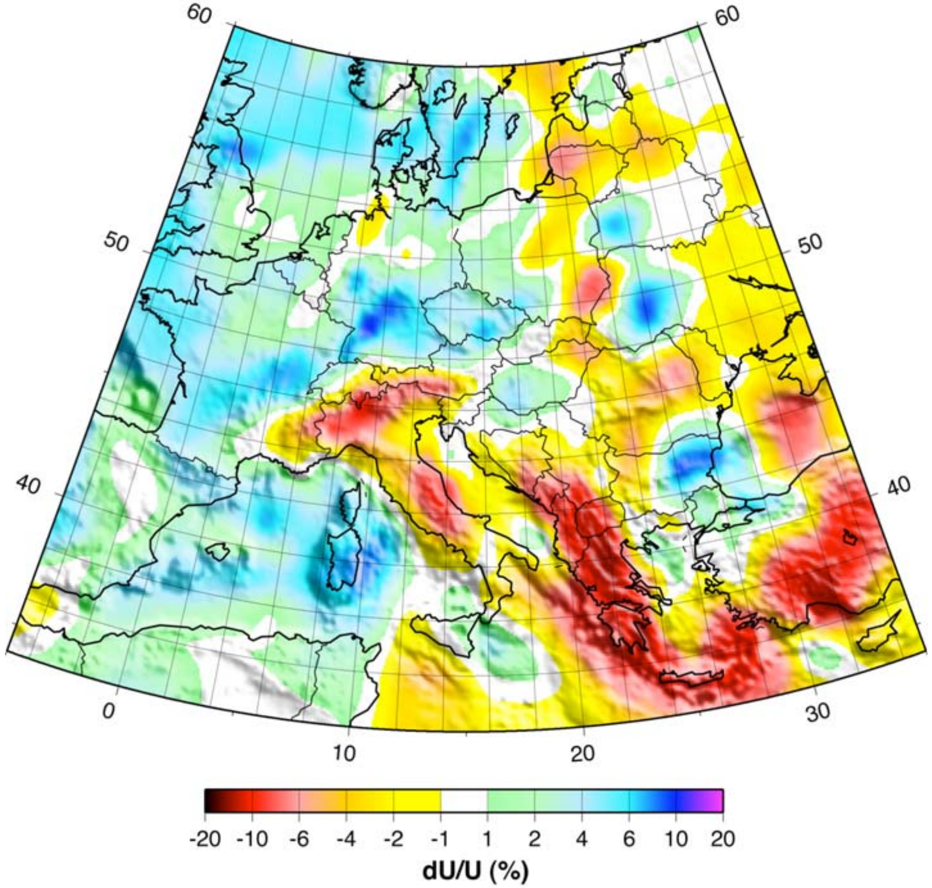


Group Speed Maps Across Europe: 40 sec



SNR > 5
2760 paths

Ambient Noise Tomography



How do we Know if These Results are an Improvement Over Traditional Earthquake Tomography?

Various lines of evidence:

- Agreement with known structures.

  e.g., sedimentary basins, crustal thickness.
- Repeatability of measurements.

  May yield uncertainty estimates on the measurements.
- Coherence of measurements.

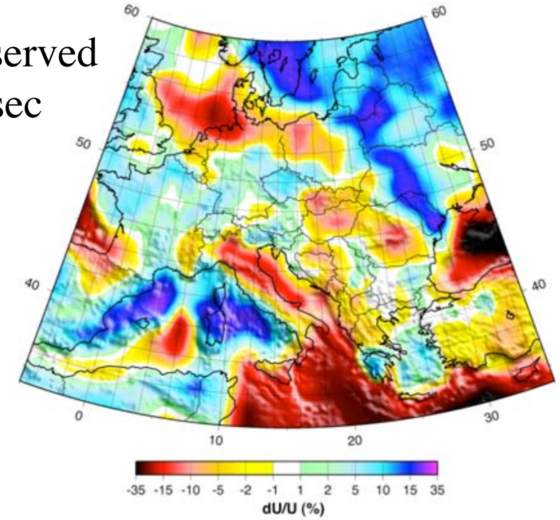
  Fit to ambient noise measurements during tomography, compared with fit to earthquake based measurements during tomography.

Agreement with Location of Sedimentary Basins?

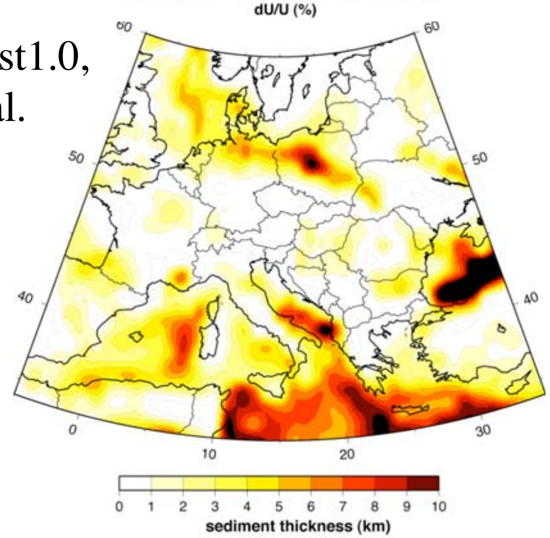
Many of the basins across Europe are reflected in the short period dispersion maps (e.g., 16 sec here):

N. Sea Basin,
Silesian Basin (N. Germany, Poland),
Panonian Basin (Hungary, Slovakia),
Po Basin (N. Italy),
Rhone Basin (S. France),
Basins in Adriatic and Mediterranean Seas.

Observed
16 sec



From Crust1.0,
Laske et al.

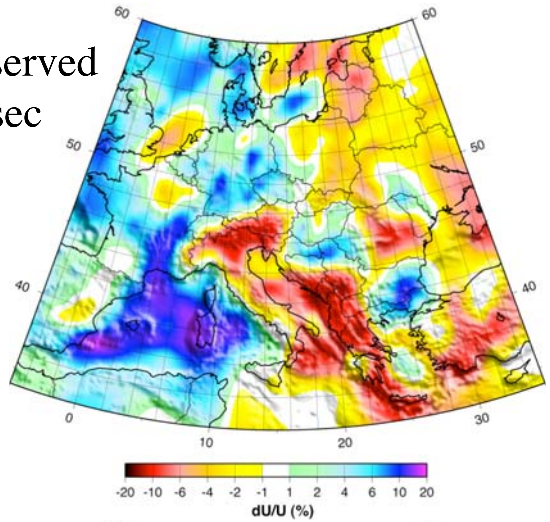


Agreement with Expected Crustal Thickness?

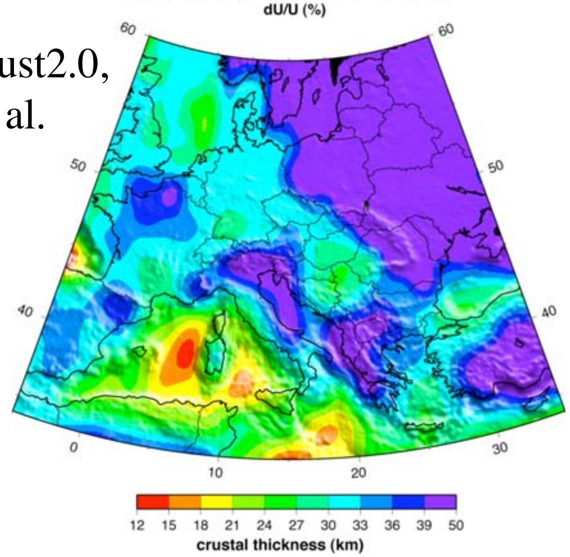
Low speed anomalies across Europe are associated with mountains belts, consistent with thickened crust; e.g.,

Alps,
Balkans,
Carpathians.

Observed
30 sec



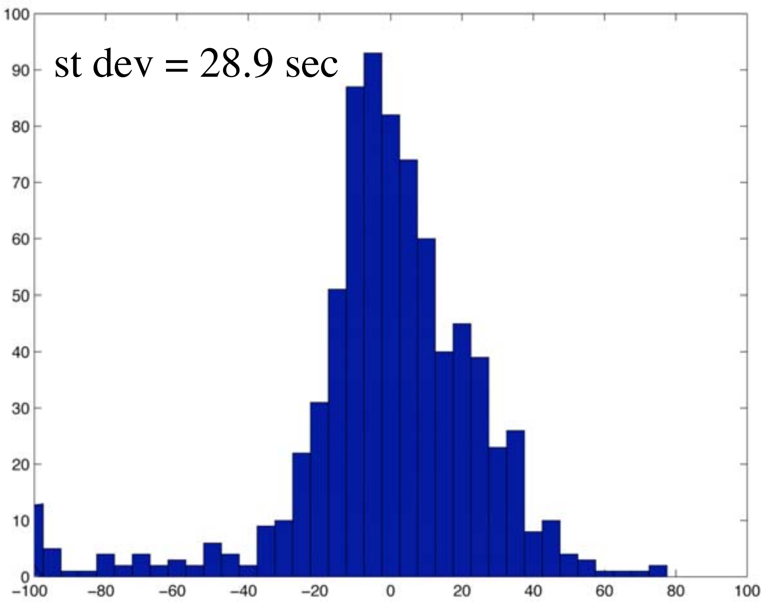
From Crust2.0,
Laske et al.



Coherence Among Measurements -- 12 sec period?

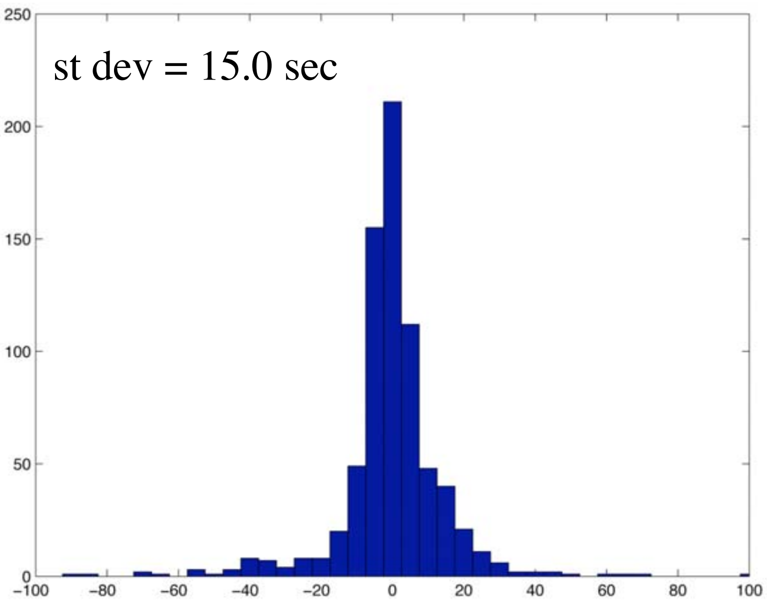
As measured by the ability to fit data sets when doing tomography…..

Misfit to Earthquake Measurements
From Earthquake Tomography



misfit (sec)

Misfit to Ambient Noise Measurements
From Ambient Noise Tomography

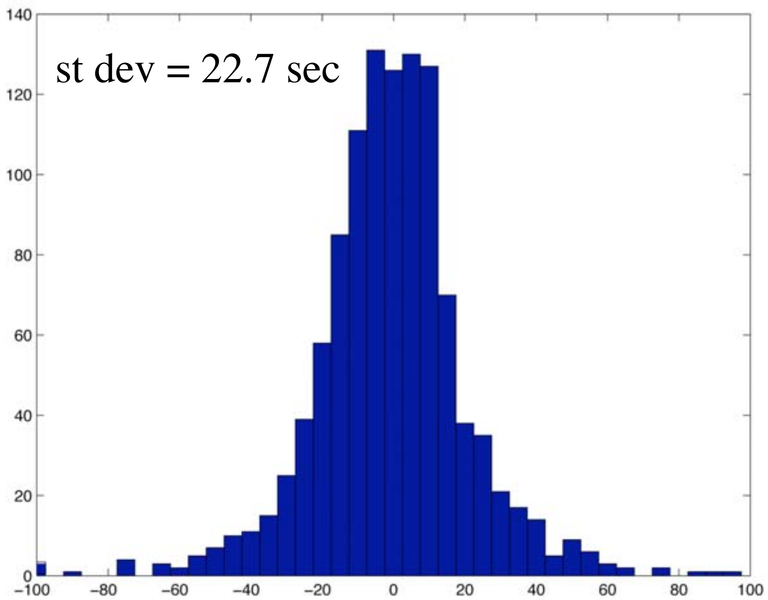


misfit (sec)

Coherence Among Measurements -- 16 sec period?

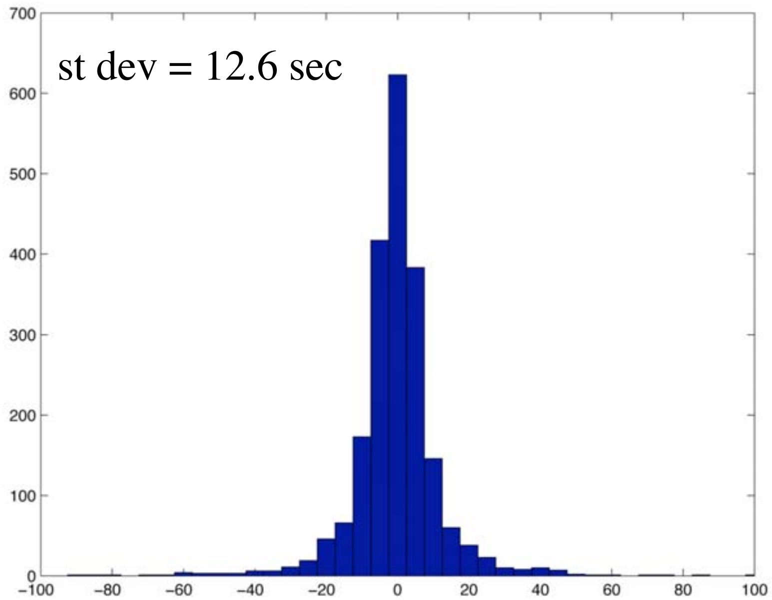
As measured by the ability to fit data sets when doing tomography…..

Misfit to Earthquake Measurements
From Earthquake Tomography



misfit (sec)

Misfit to Ambient Noise Measurements
From Ambient Noise Tomography

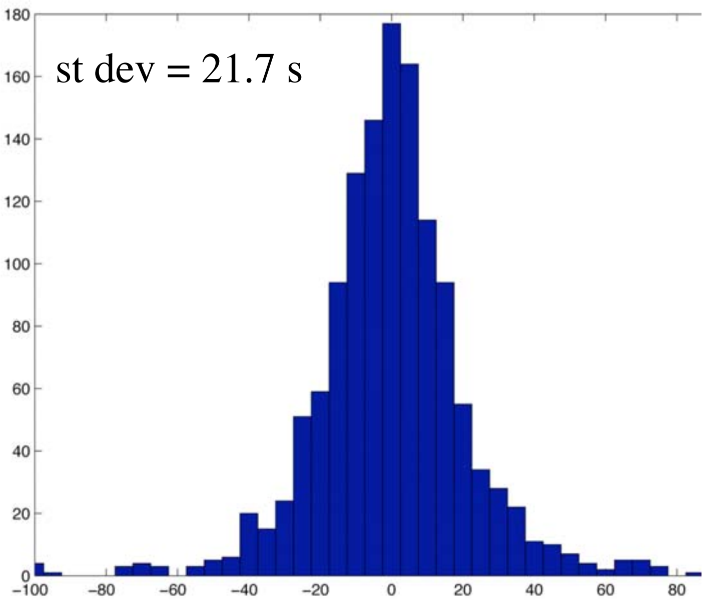


misfit (sec)

Coherence Among Measurements -- 20 sec period?

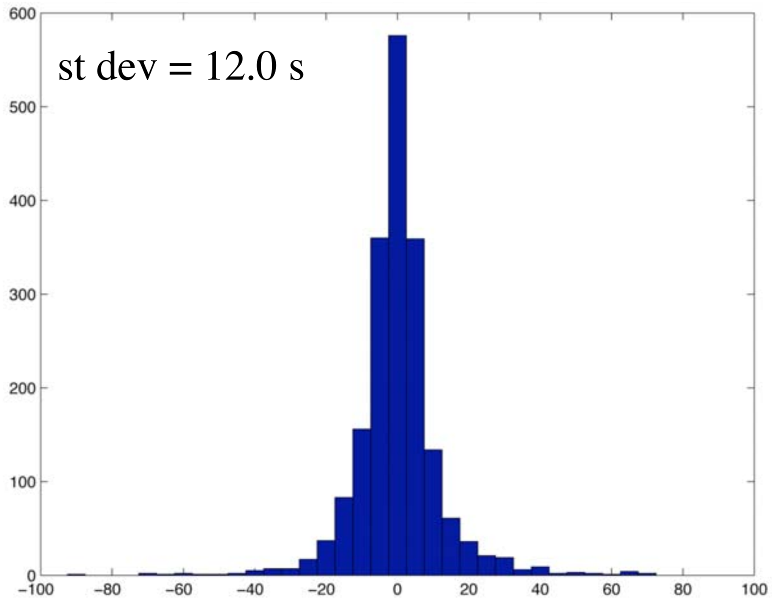
As measured by the ability to fit data sets when doing tomography…..

Misfit to Earthquake Measurements
From Earthquake Tomography



misfit (sec)

Misfit to Ambient Noise Measurements
From Ambient Noise Tomography

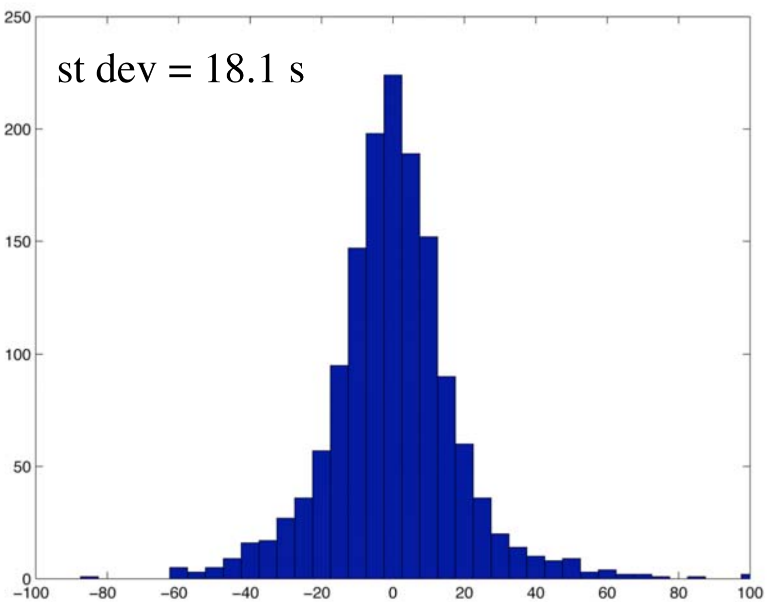


misfit (sec)

Coherence Among Measurements -- 30 sec period?

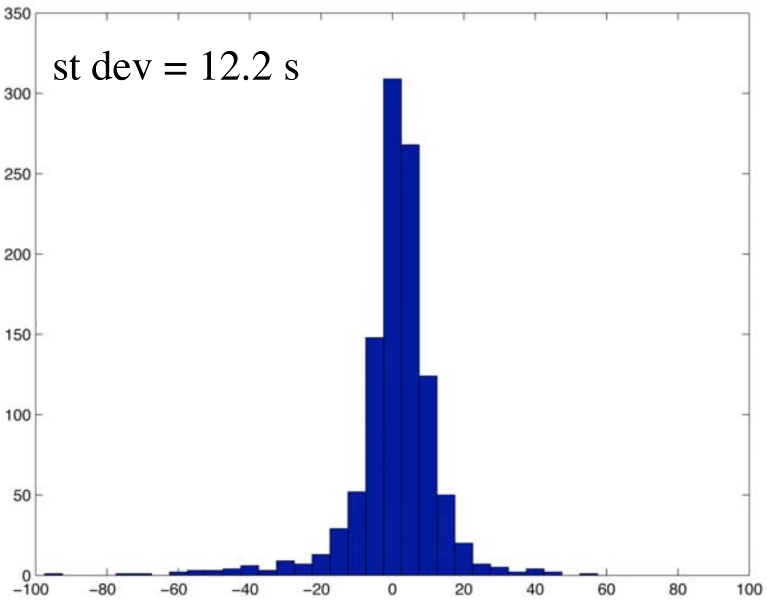
As measured by the ability to fit data sets when doing tomography…..

Misfit to Earthquake Measurements
From Earthquake Tomography



misfit (sec)

Misfit to Ambient Noise Measurements
From Ambient Noise Tomography

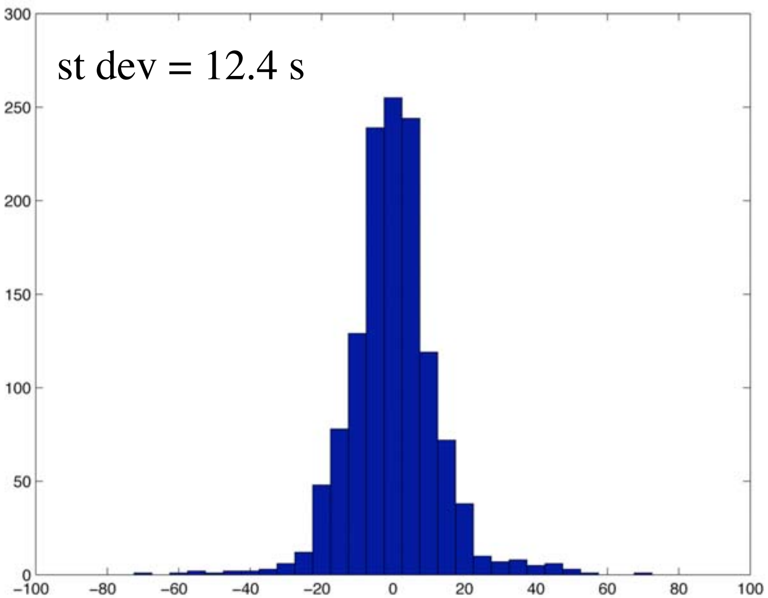


misfit (sec)

Coherence Among Measurements -- 40 sec period?

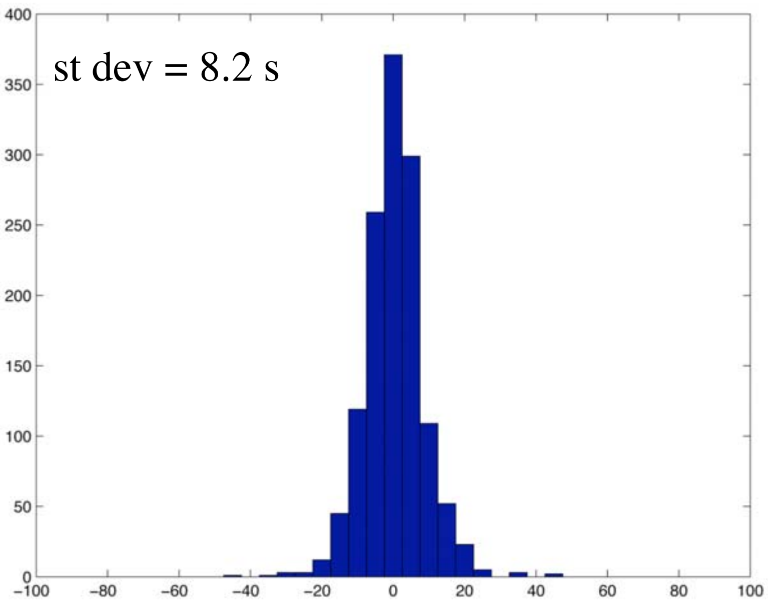
As measured by the ability to fit data sets when doing tomography…..

Misfit to Earthquake Measurements
From Earthquake Tomography



misfit (sec)

Misfit to Ambient Noise Measurements
From Ambient Noise Tomography



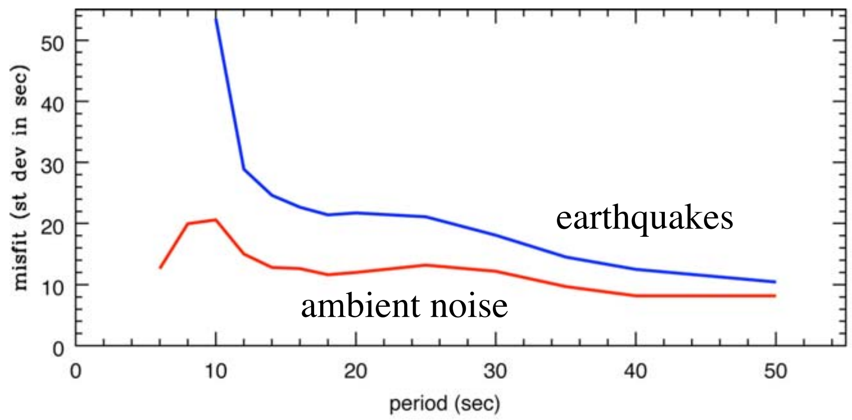
misfit (sec)

Coherence Among Measurements -- Summary

As measured by the ability to fit data sets when doing tomography…..

Dispersion measurements from ambient noise are more internally consistent than measurements following earthquakes:

+ earthquake measurements are difficult to obtain below ~ 20 sec,
+ source processes, mislocation, etc. are eliminated.



Above ~30 sec, earthquake measurements are about as reliable as ambient noise measurements and the data sets can be combined without degrading the ambient noise measurements.

Outline

1. Natural sources of seismic signals
2. Traditional surface wave tomography and its limitations
3. Measurements from random wavefields: background
4. Measurements from random wavefields: examples in seismology
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    2. Teleseismic coda
    3. Ambient seismic noise
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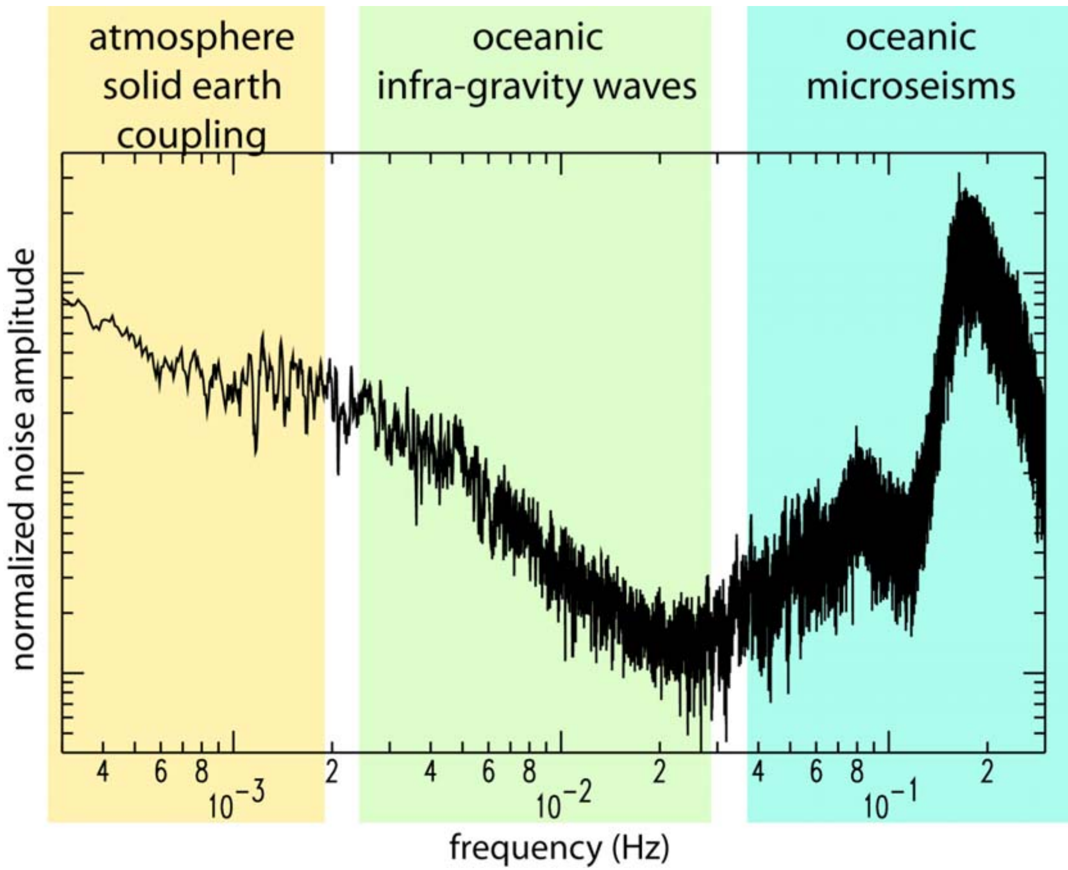
    1. California
    2. Europe
7. Tracing the origin of the seismic noise
8. Most recent results and future directions

Understanding the origin of the seismic noise

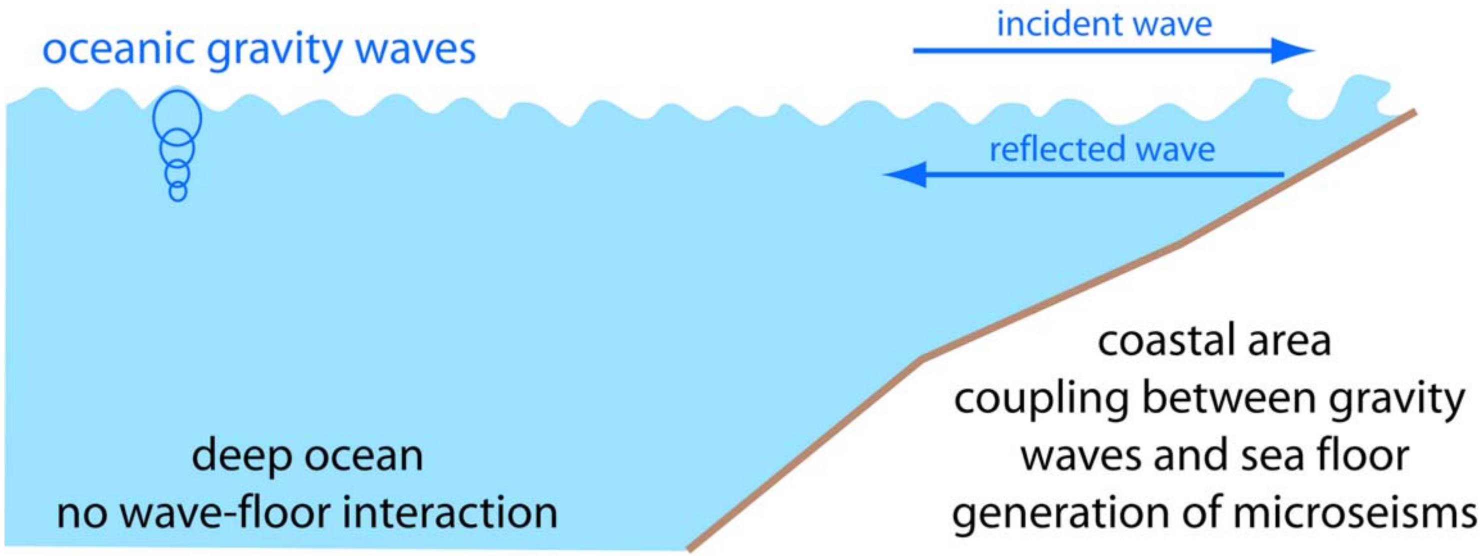
Motivations:

- Optimizing nose-based imaging
- Obtaining information about process in the ocean and the atmosphere

Fourier spectrum from one day of seismic noise (August 21, 2003; station OBN)



Origin of oceanic microseisms: traditional explanation

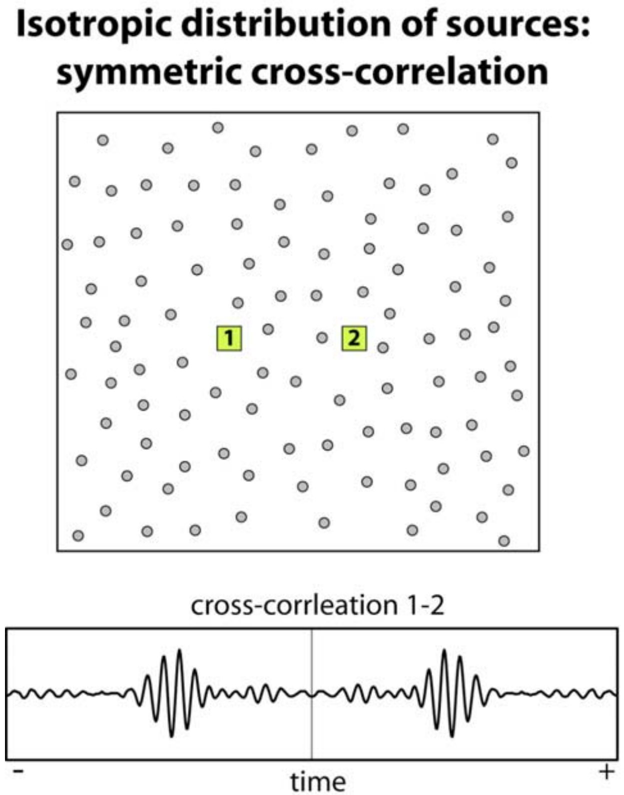


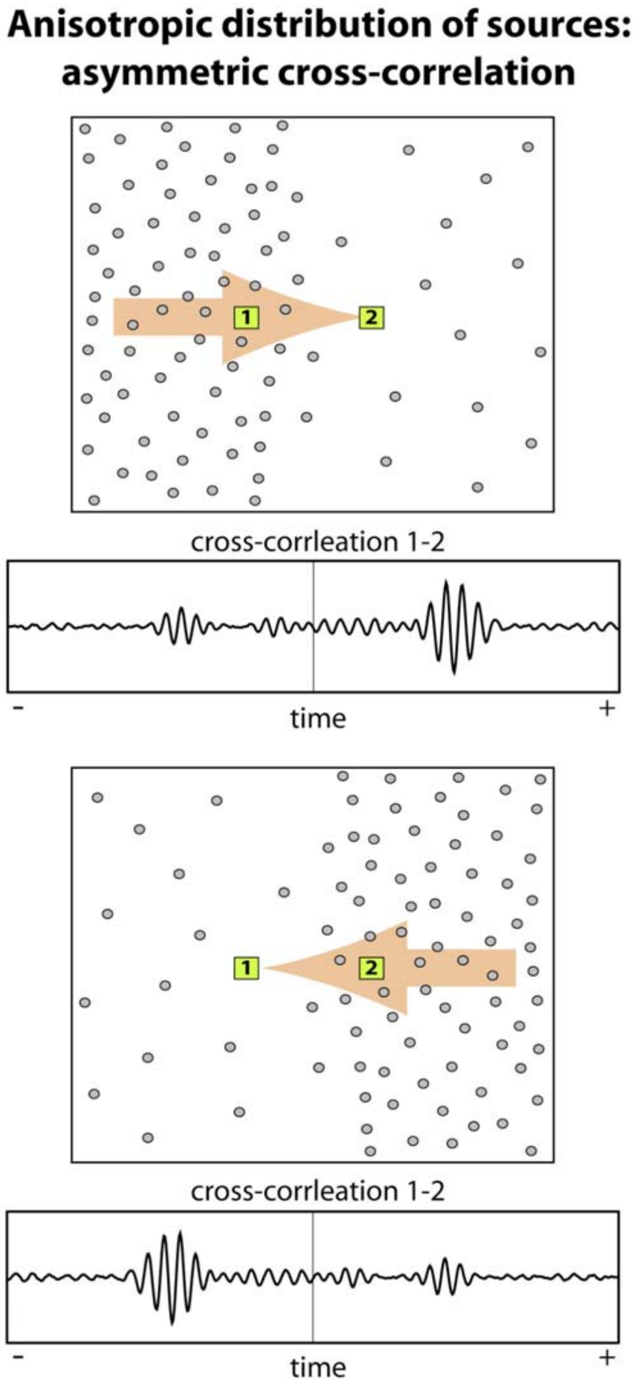
primary microseism is excited at frequencies corresponding to the spectrum of incoming oceanic gravity waves (periods of **10-20 s**)

secondary microseism is exited at doubled frequencies due to the nonlinear interaction between incident and reflected waves (periods of **5-10 s**)

both microseims originate in coastal areas

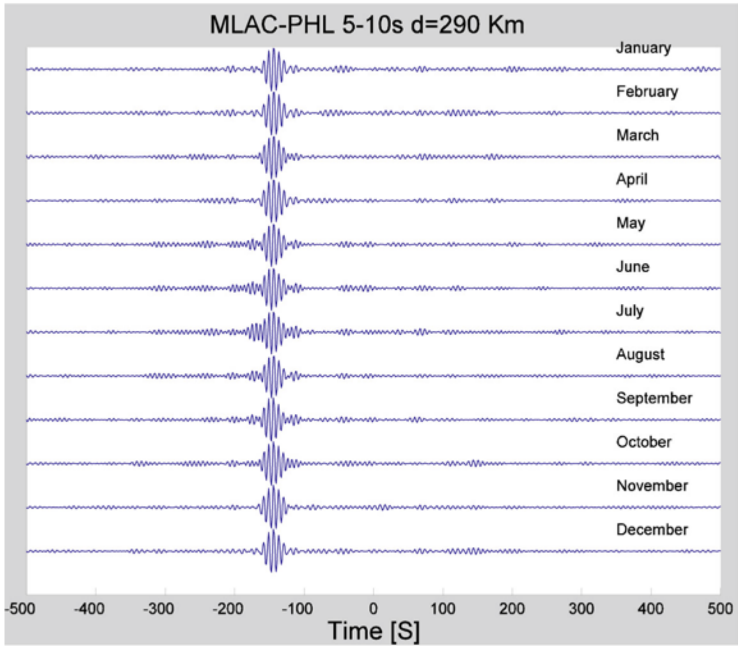
Tracing the origin of the seismic noise

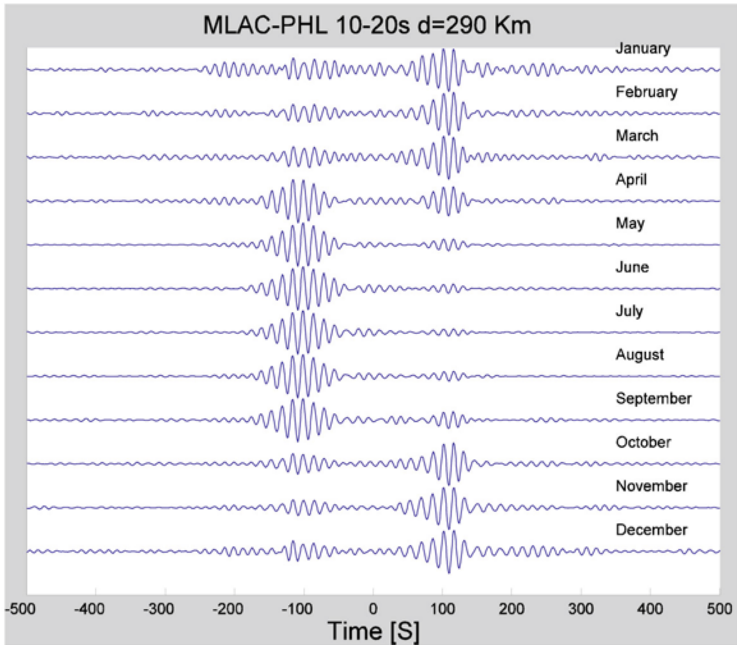




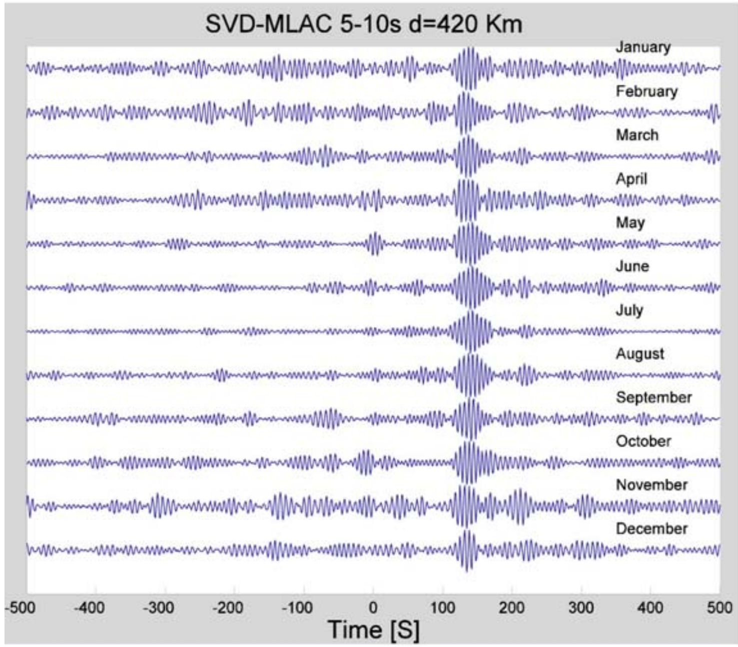
courtesy of Laurent Stehly (LGIT, Grenoble)

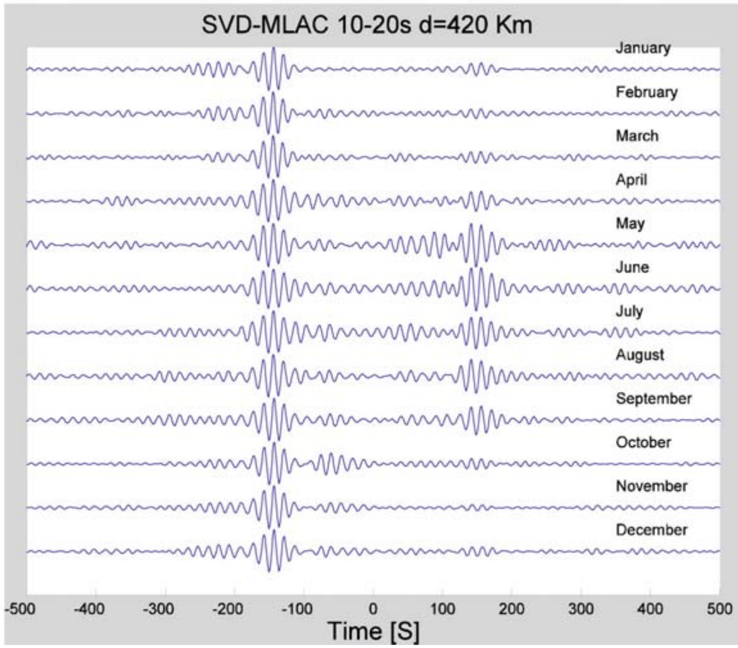
Tracing the origin of the seismic noise

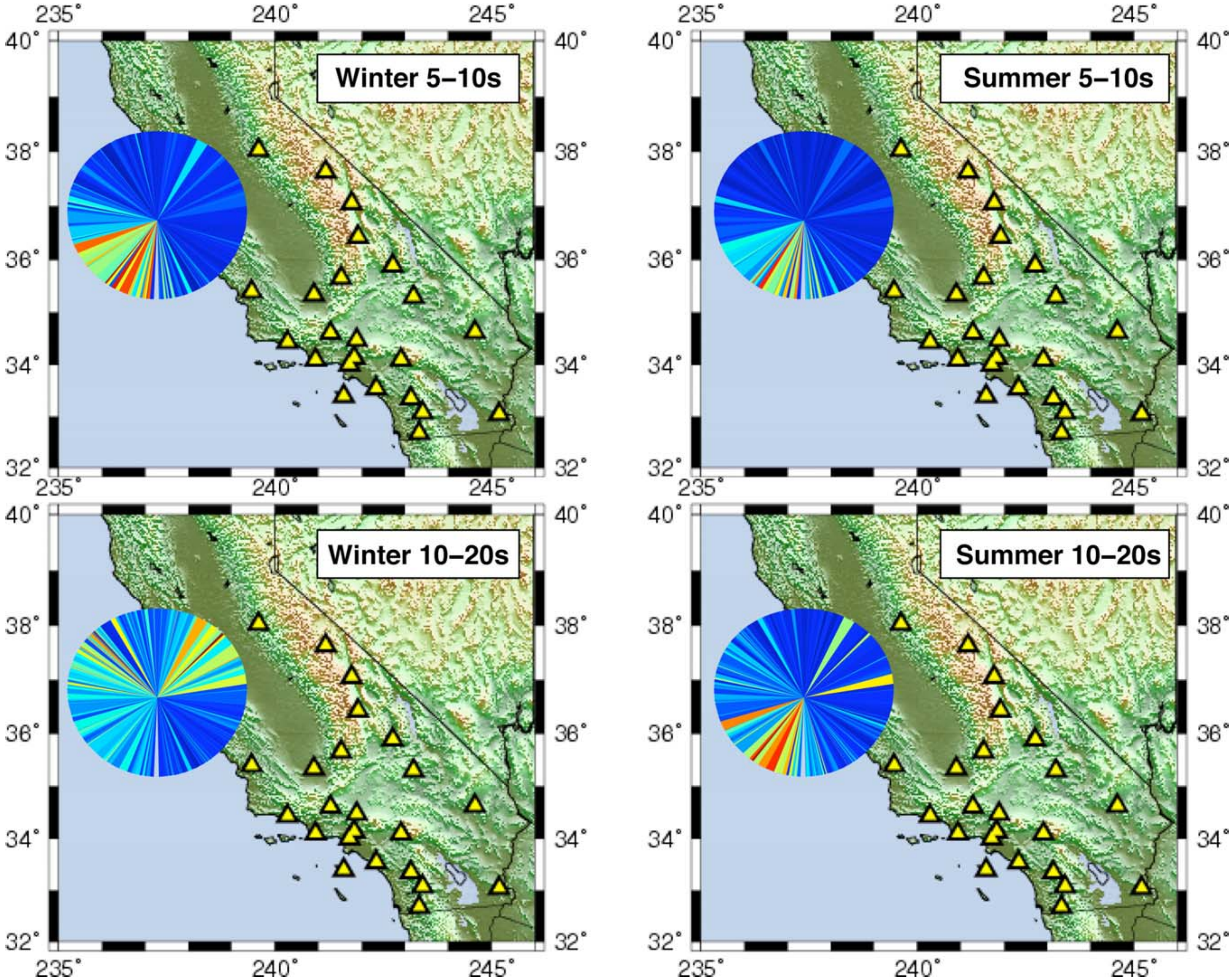




Tracing the origin of the seismic noise



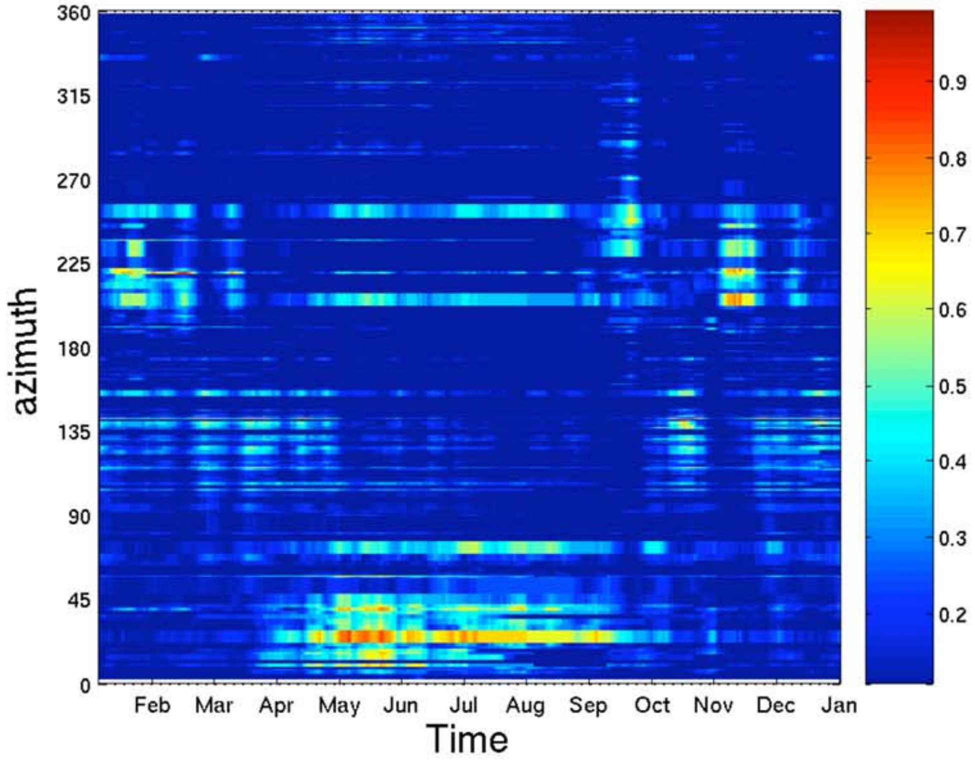


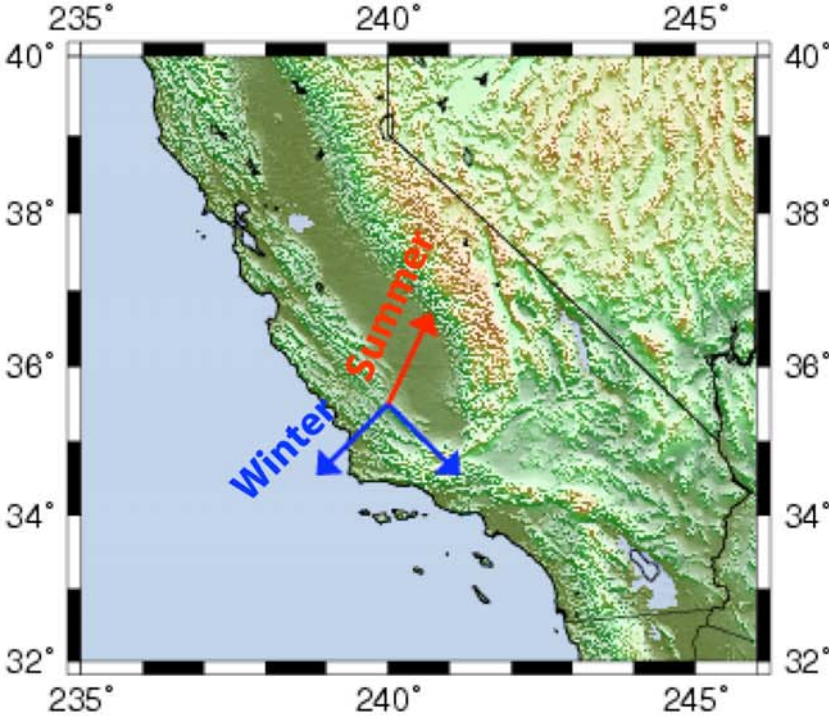


Winter 5–10s
Summer 5–10s
Winter 10–20s
Summer 10–20s
235°
240°
245°
32°
34°
36°
38°
40°

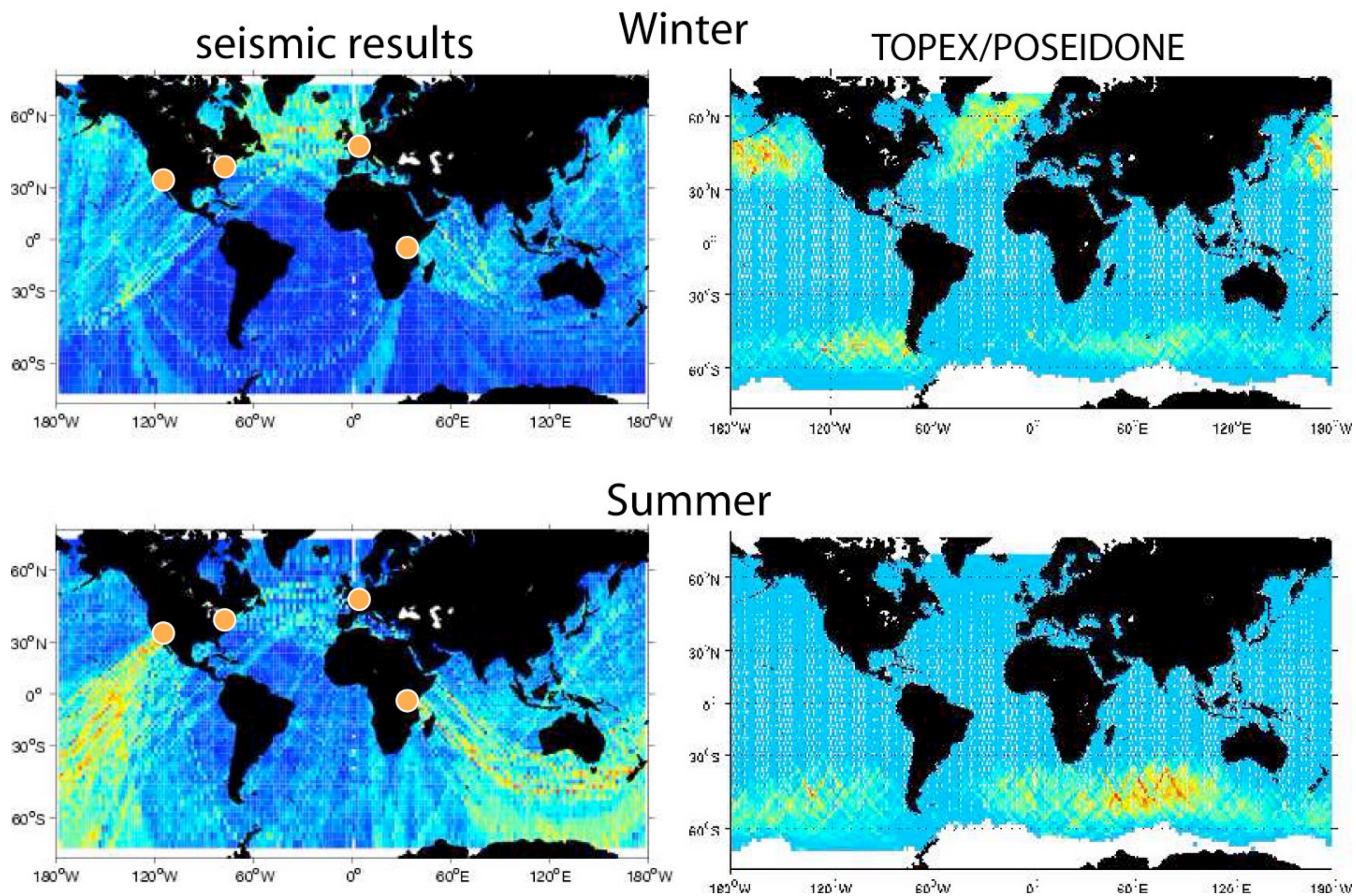
Tracing the origin of the seismic noise

10 - 20 s





Seismic noise sources (10-20 s)



Origin of oceanic microseisms: new results

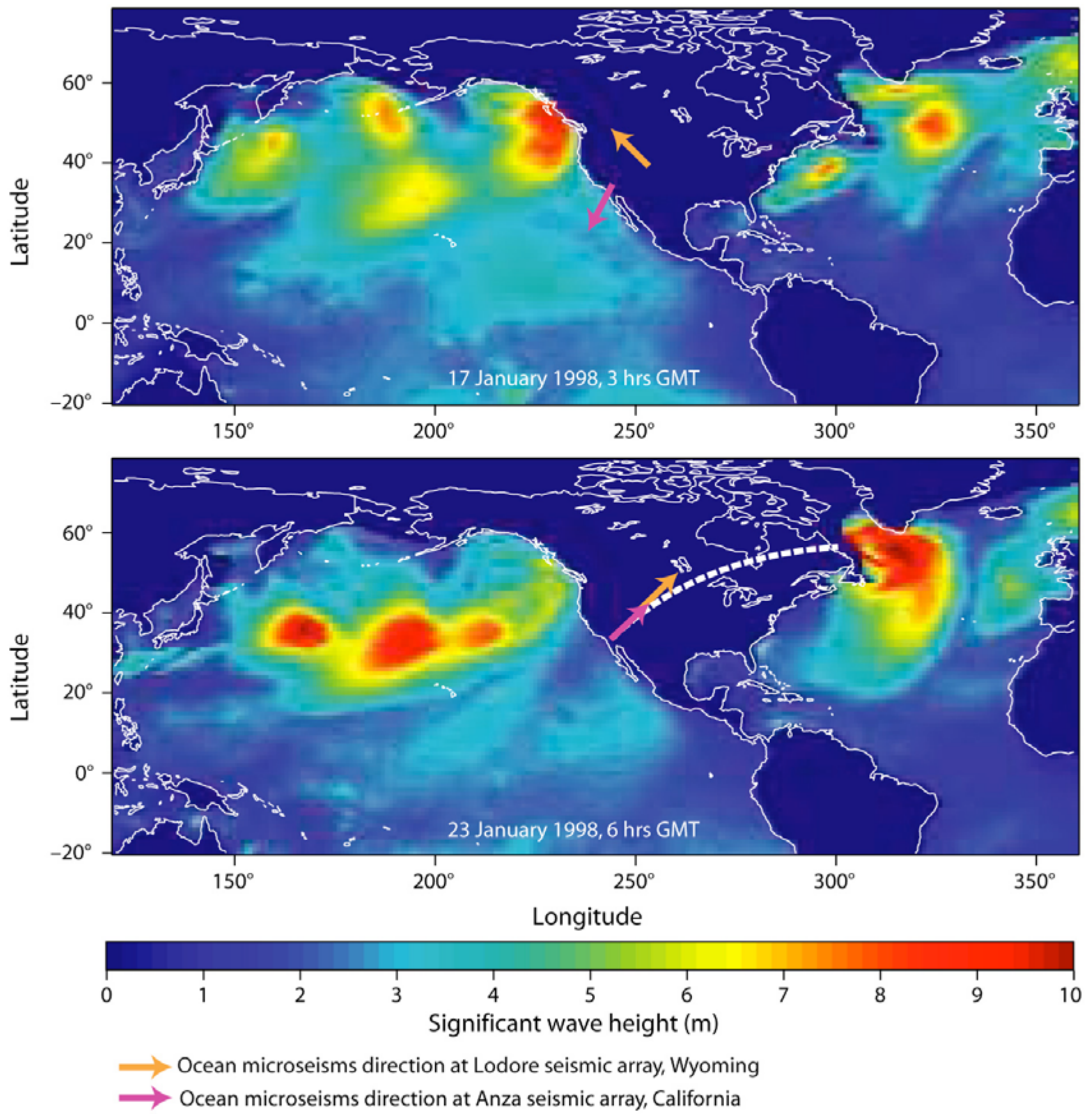
- primary and secondary microseisms do not originate from the same areas
- prominence of the primary microseism is strongly seasonal

  the seasonality must be accounted for during travel time measurements for the tomography; better to use long time series (> 1 year)

- primary microseism seems to originate in the deep ocean
- primary microseism is clearly related to the meteorological conditions in the ocean:

  possibility to study climate-related phenomena from seismic data

Schulte-Pelkum et al (2004)



Tracking wave-wave interactions. The maps show global wave heights [from the NOAA Wave Watch III model (*12*), see color scale at bottom] and arrival directions of ocean microseisms at U.S. seismic arrays (from seismic data; colored arrows). (Top) Microseisms recorded in Wyoming are dominated by wave-wave interactions near the British Columbia coast, and those recorded in southern California by interactions off the coast of Baja California. (Bottom) A North Atlantic storm swell hitting the steep Labrador coast triggers transcontinental microseisms.

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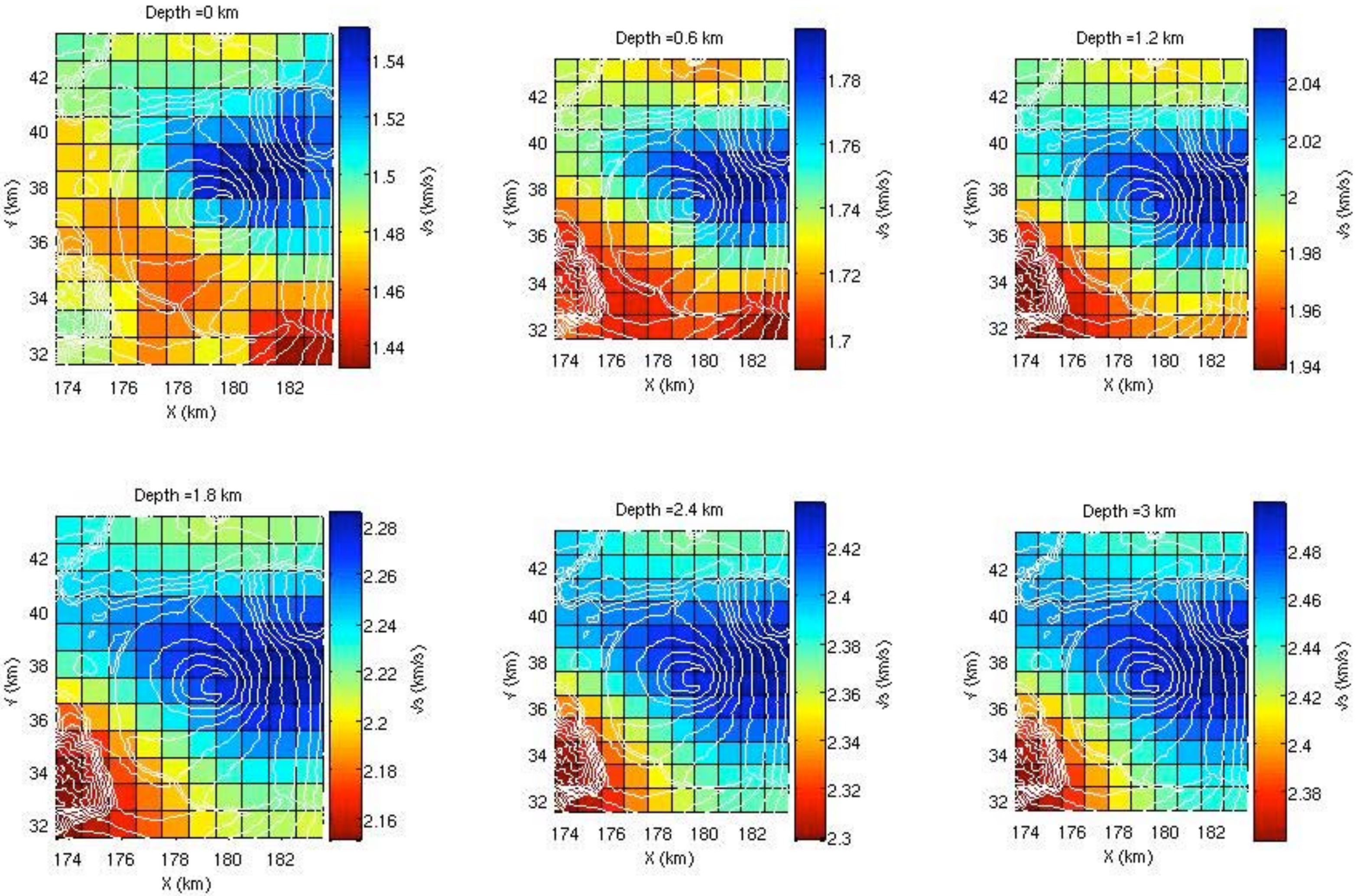
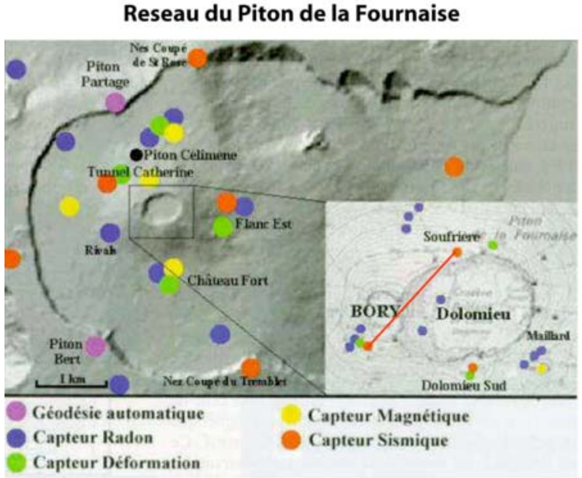
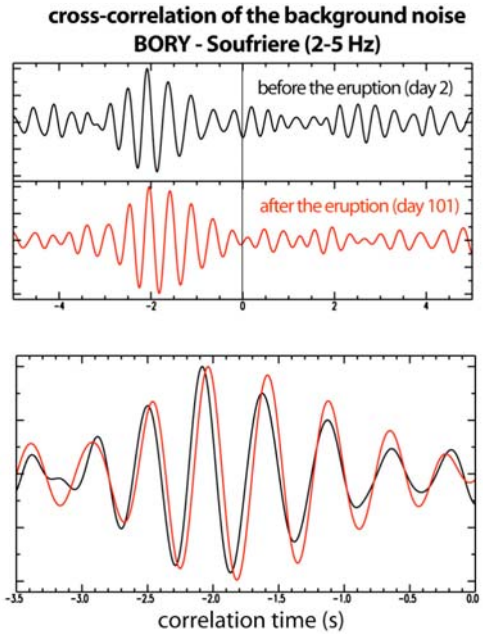
Imaging volcanic edifices (La Réunion)

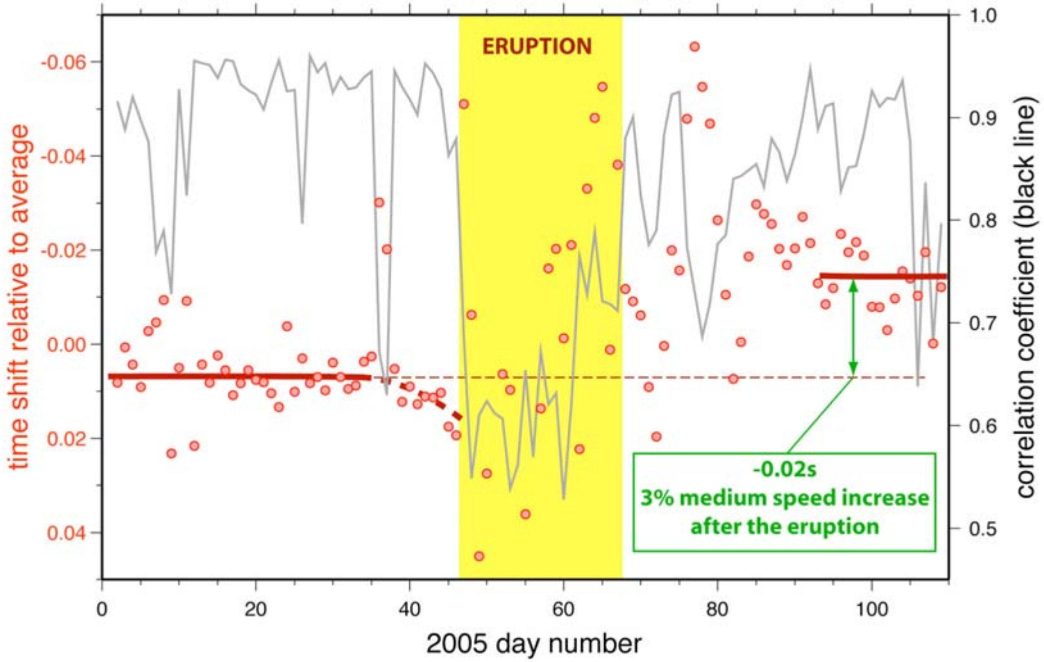
inversion of noise-based surface-wave group-velocity measurements obtained form the La Réunion volcano monitoring seismic network (20 stations) at periods between 0.2 and 1 s (Florent Brenguer)



Monitoring volcanoes
(La Réunion)







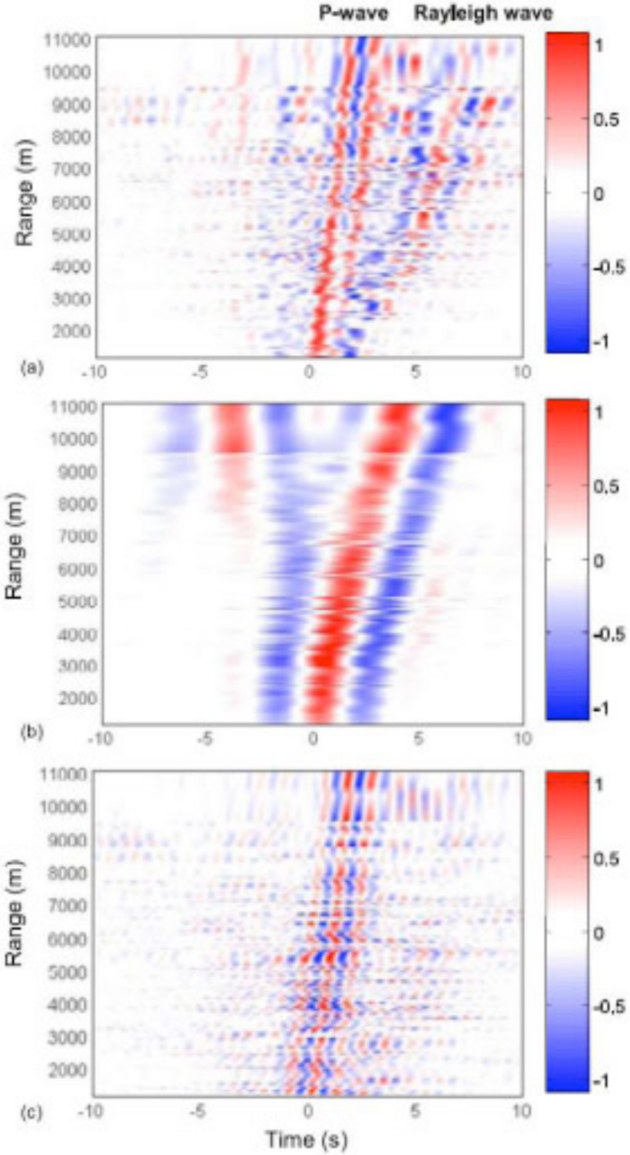
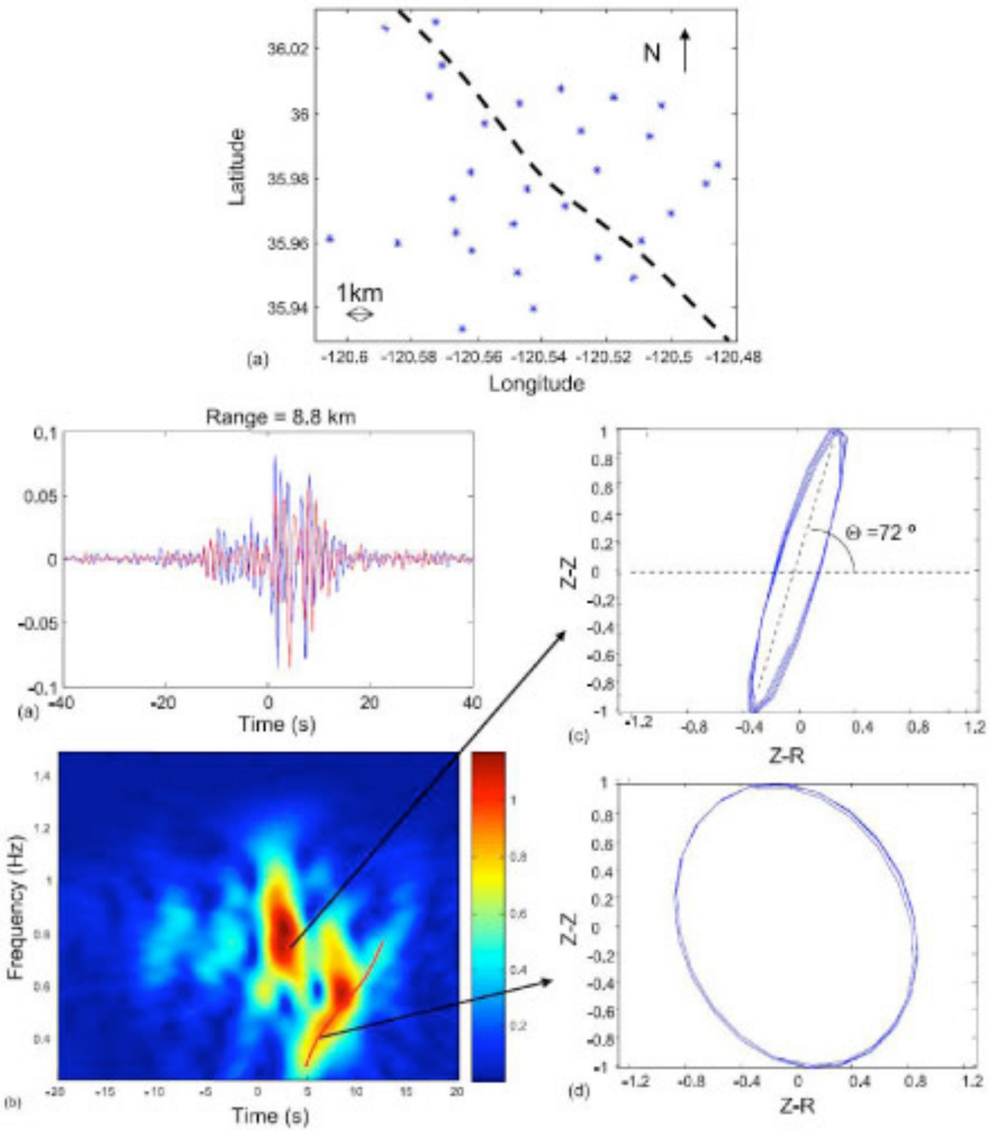


Figure 2. Range-time representation of the Z-Z component of the noise correlation tensor averaged over one month in three frequency bands (a) [0.1–1.3 Hz], (b) [0.1–0.45 Hz], and (c) [0.7–1.3 Hz]. Each plot has been normalized by its own maximum.

Possibility to recunstruct P-waves



Roux et al. (2005)

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
- studying process in the ocean and the atmosphere

Remaining questions:

- optimal duration of noise sequences
- spectral range
- optimal inter-station distances
- optimal station orientation
- Other than Rayleigh waves (Love, body waves)

the end