Solar powered seismology: high resolution imaging from ambient seismic noise

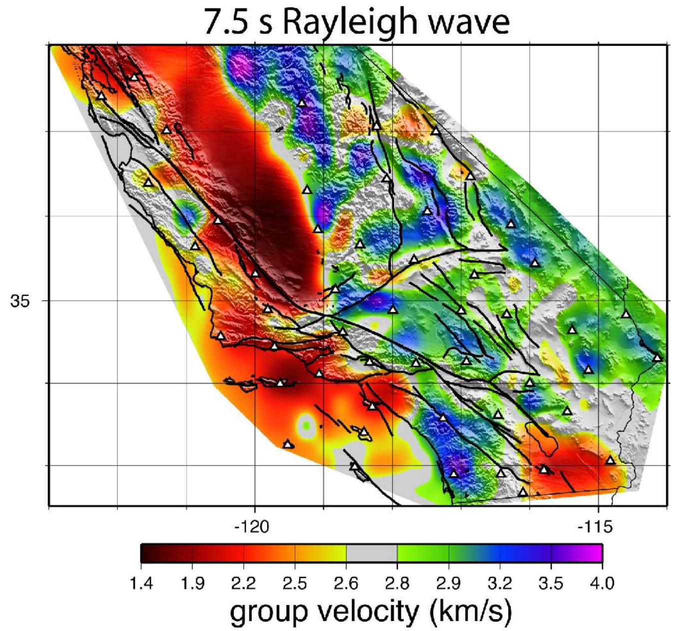
Nikolai Shapiro
University of Colorado at Boulder

Collaborators:

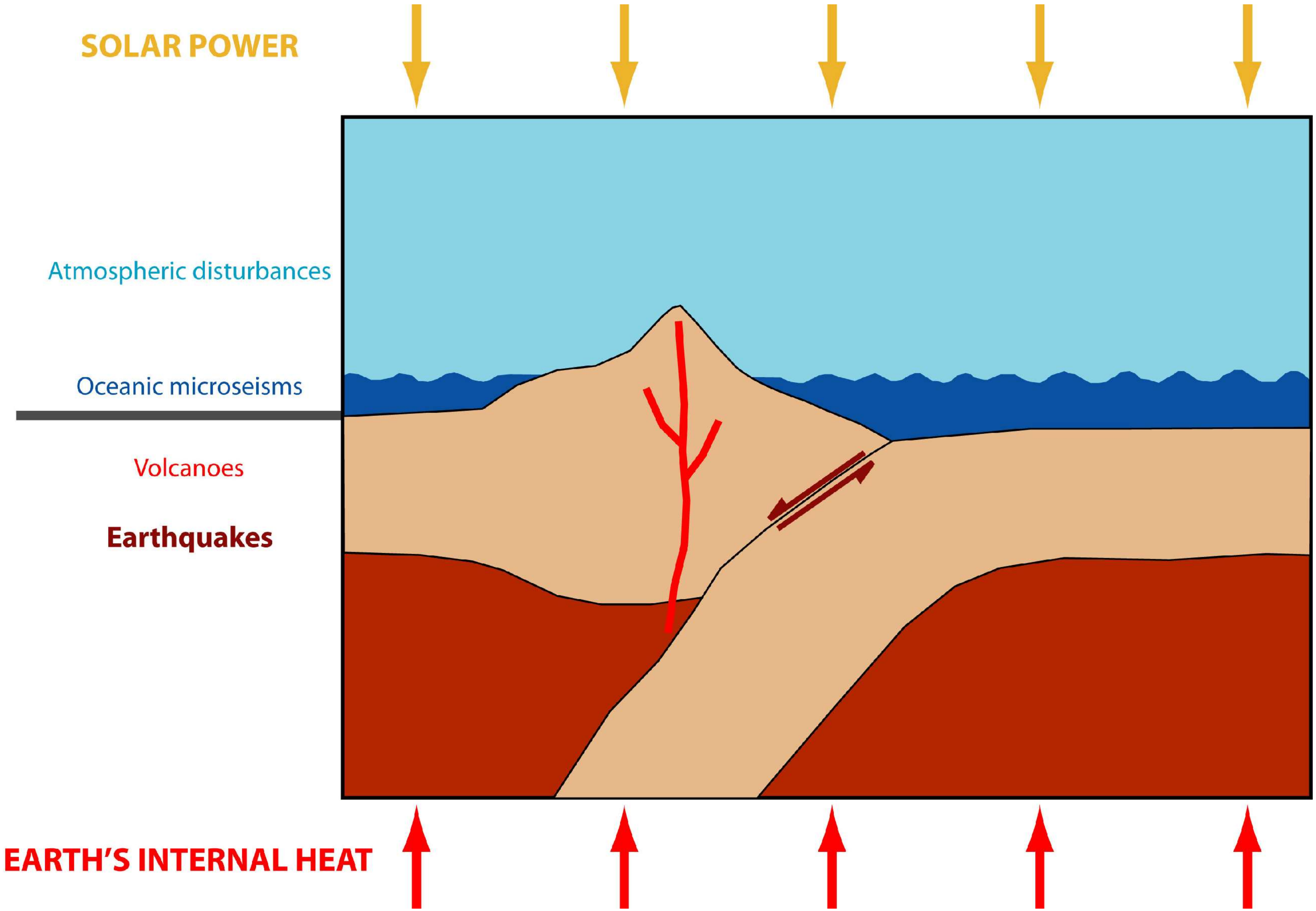
Michel Campillo, Laurent Stehly,
Mike Ritzwoller, Greg Bensen

Aknowledgements:

Misha Barmin, Craig Jones, Ludovic Margerin,
Eric Larosse, Richard Weaver, Arnaud Derode,
Anne Paul, Bart van Tiggelen



Natural sources of seismic signals



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

1. Measurements in absence of earthquakes:

   - improved resolution

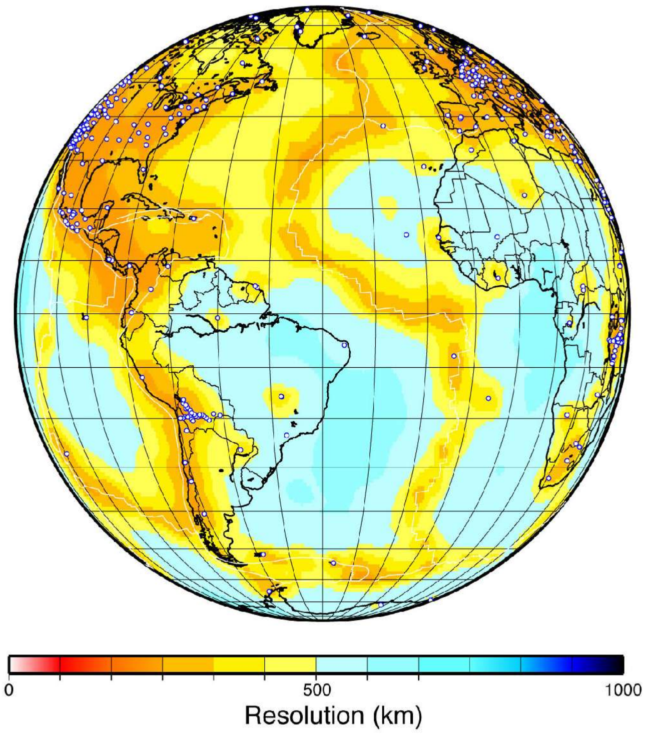
   - repetitive measurements:

     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

Rayleigh wave group velocity, 100 km

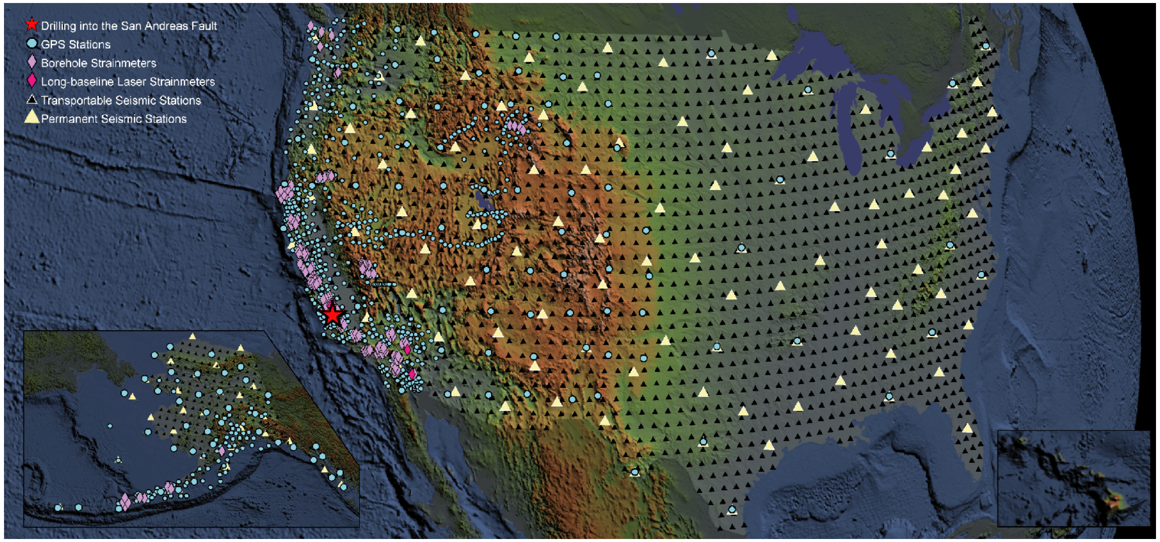


- Les mesures sont faites à partir des longues trajets
- Les mesures sur des courtes périodes (<20s) sont difficiles à obtenir
- Les incertitudes dans les localisations et le mécanismes de séismes produisent des erreurs dans des modèles obtenues

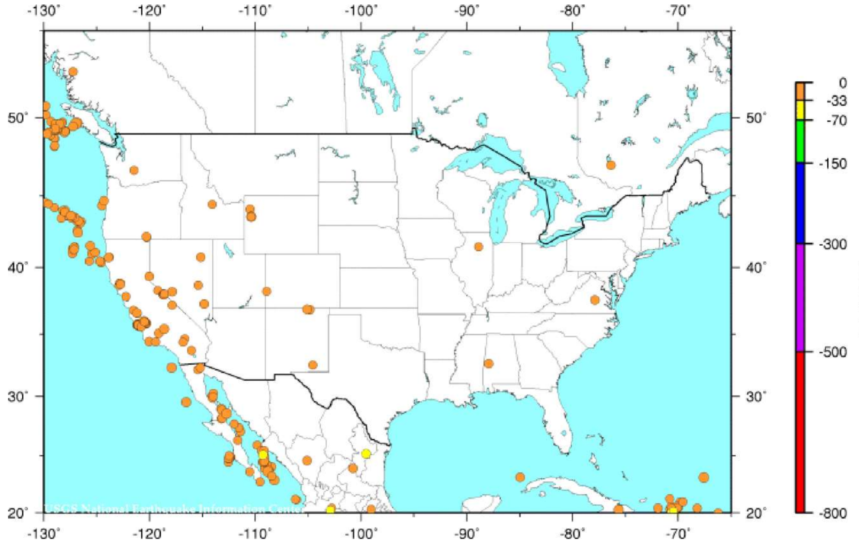
Conséquence:

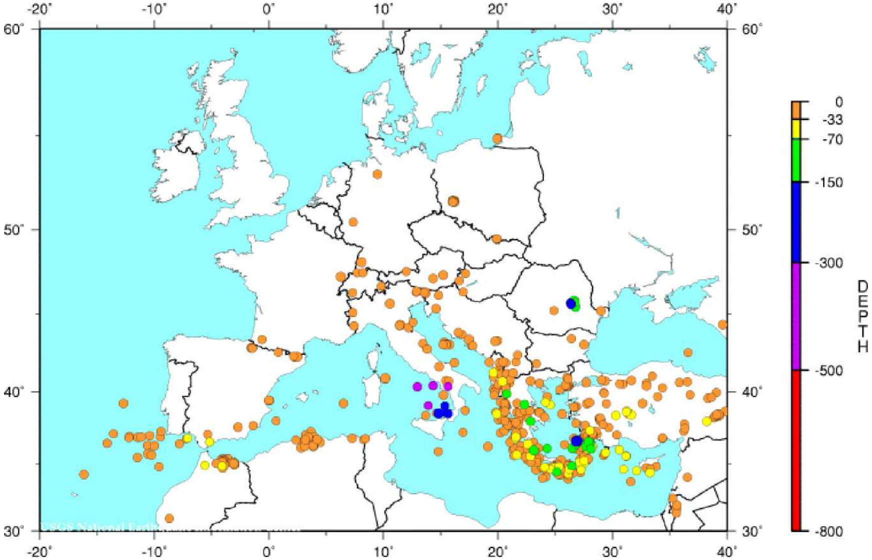
la résolution finale est limitée

Earthscope USAarray

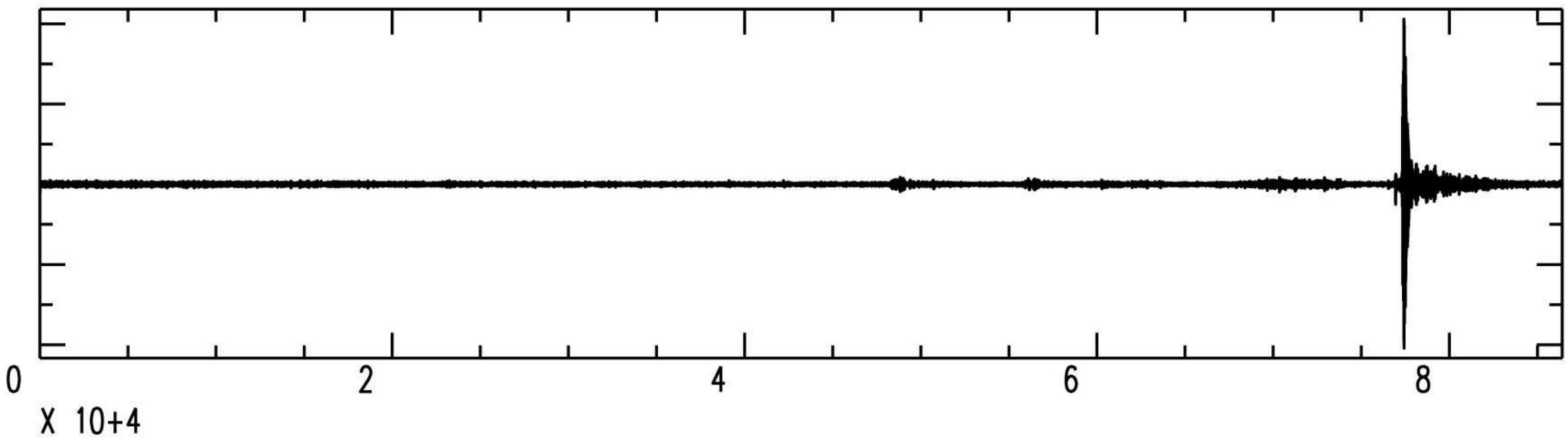


distribution of M>4 earthquakes during 1.5 months (July, 2003-December, 2004)

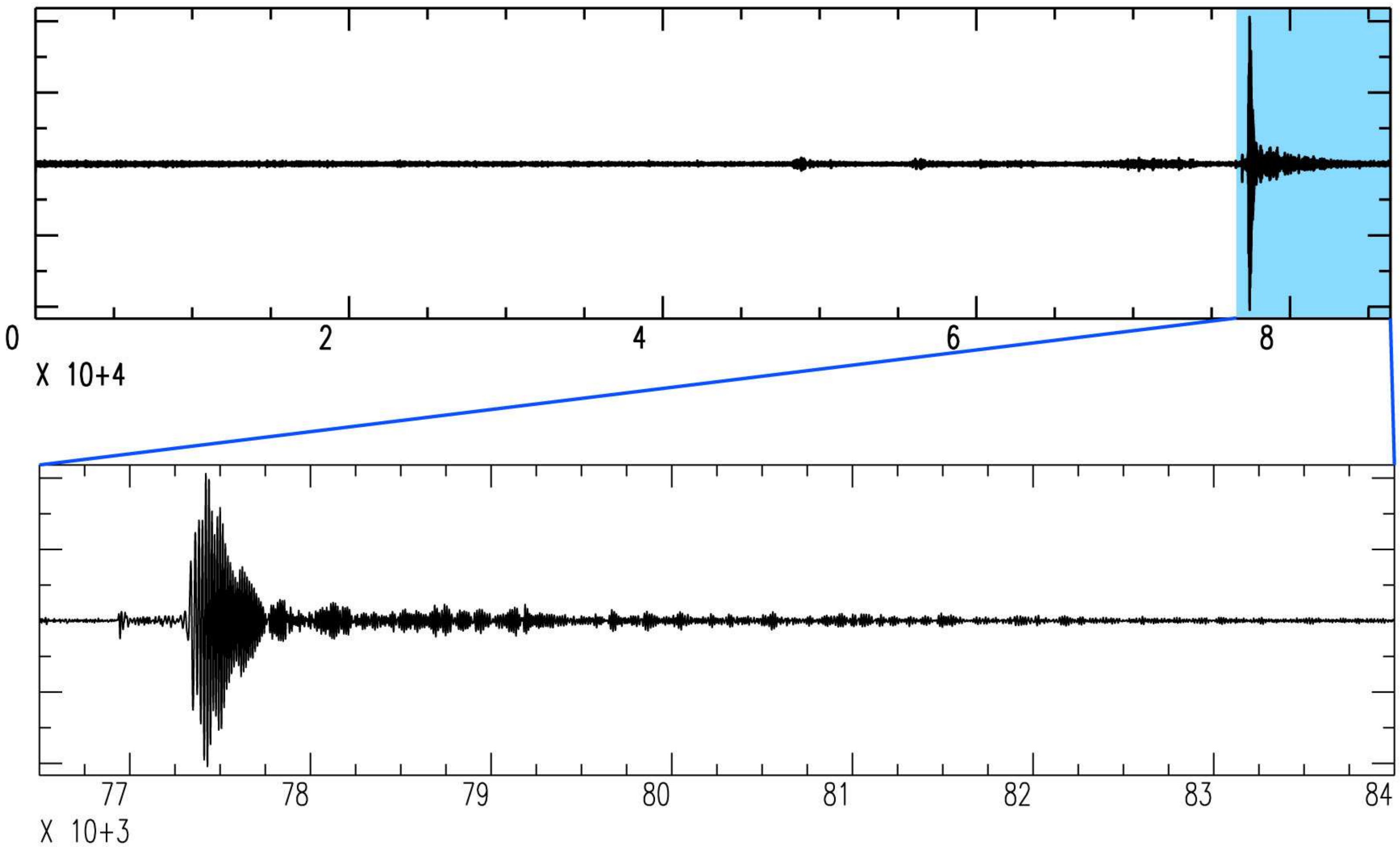




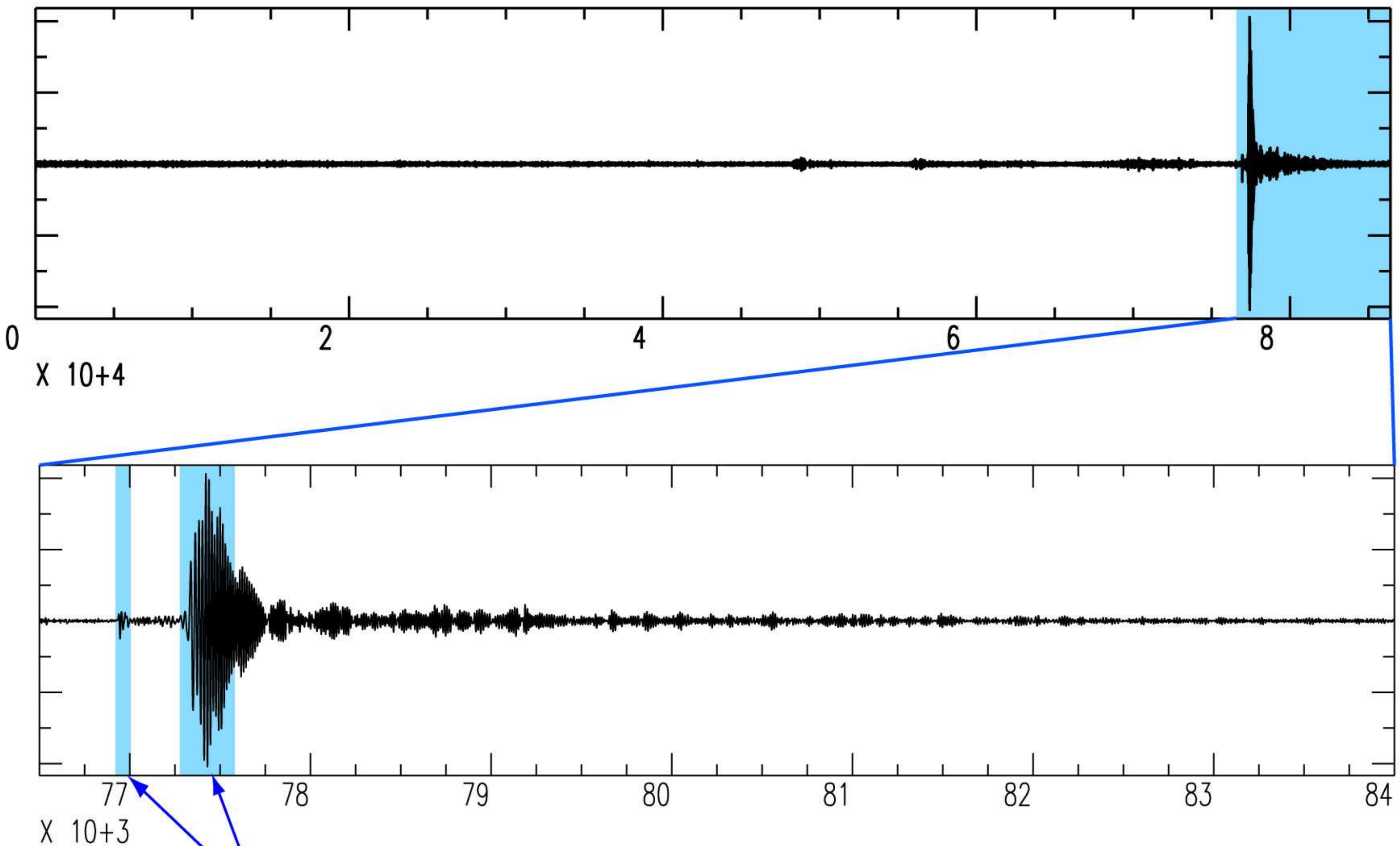
one day of seismic record



one day of seismic record

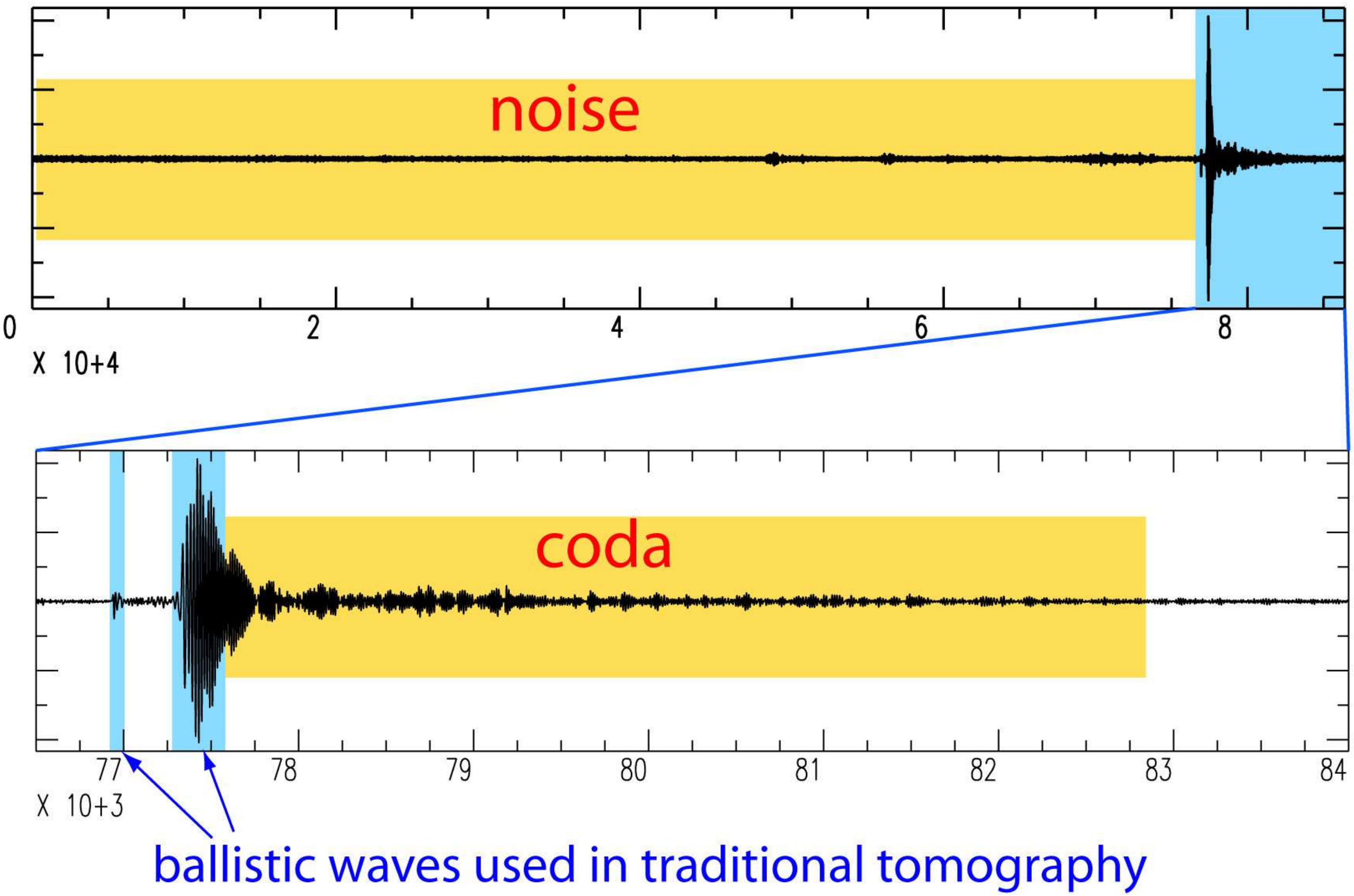


one day of seismic record



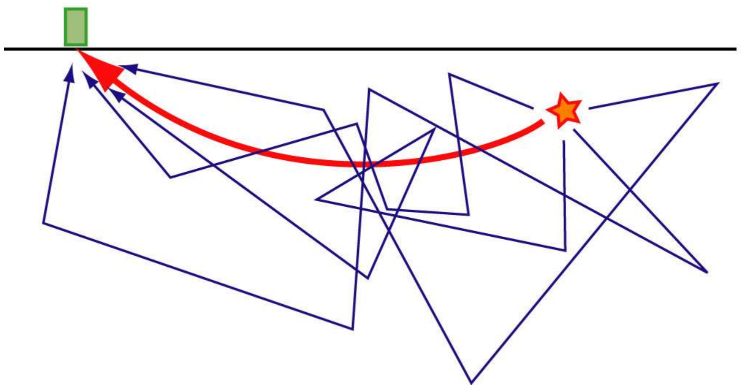
ballistic waves used in traditional tomography

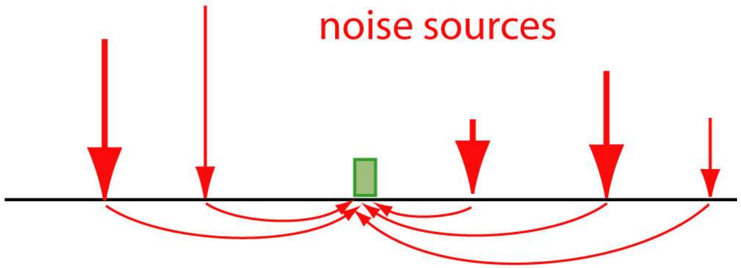
one day of seismic record



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

Extraction de fonctions de Green de champs d'onde aléatoires

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!)*.

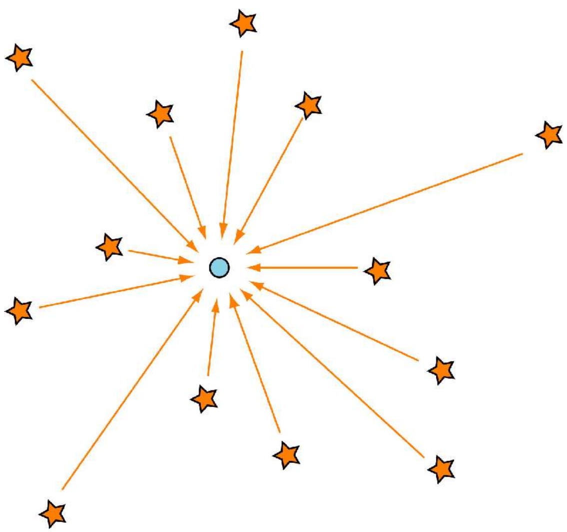
FT(Green function A->B) ~ FT(time correlation of fields in A and B)

<u>Applications</u> with mechanical waves (under different names) :

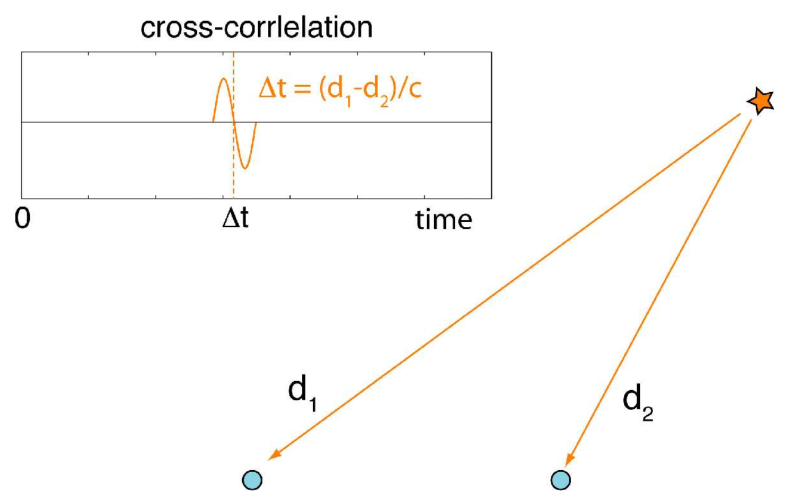
Helioseismology: Duvall et al. (1993)+….
Laboratory Acoustics: Weaver and Lobkis (2001)+…
Sesimic coda waves: Campillo and Paul (2003)+…
Marine acoustics: Roux et al., (2003)+…
Ambient seismic noise: Shapiro and Campillo (2004)+…

Correlations of random wavefields

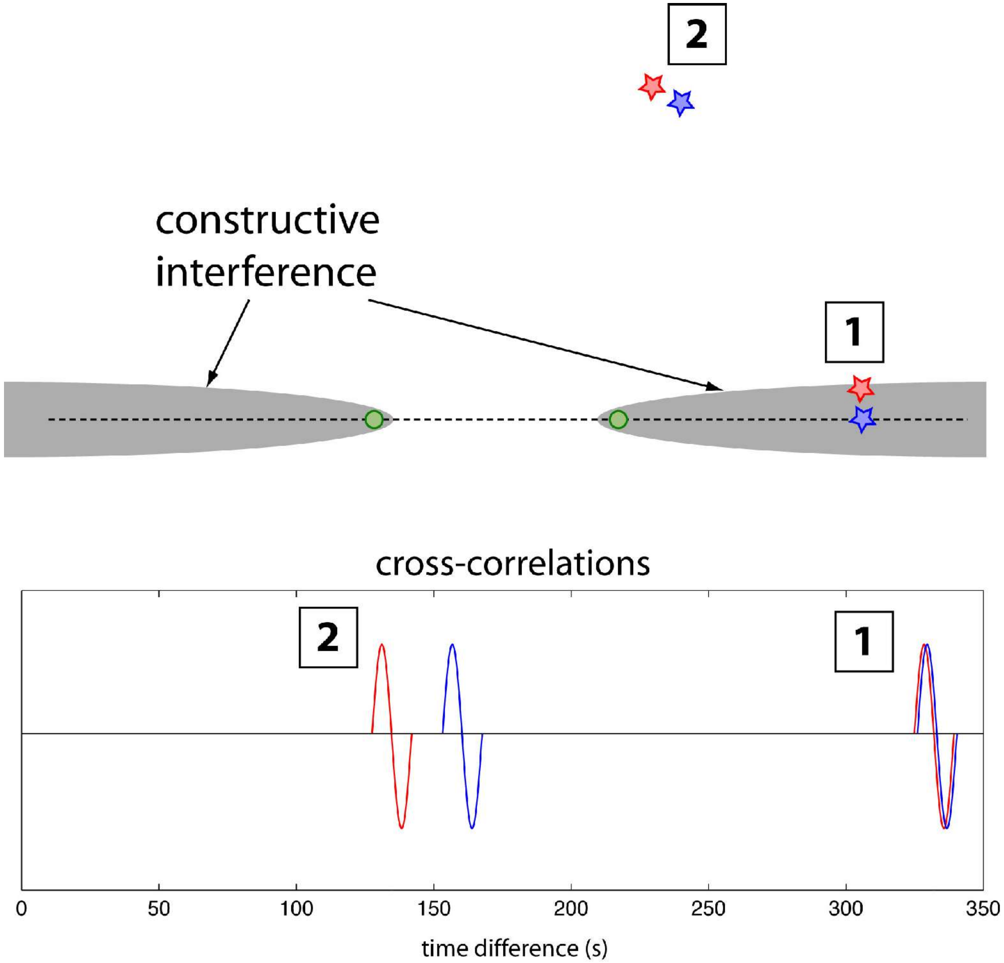
Random wavefield - sum of waves emitted by randomly distributed sources



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



Correlations of random wavefields



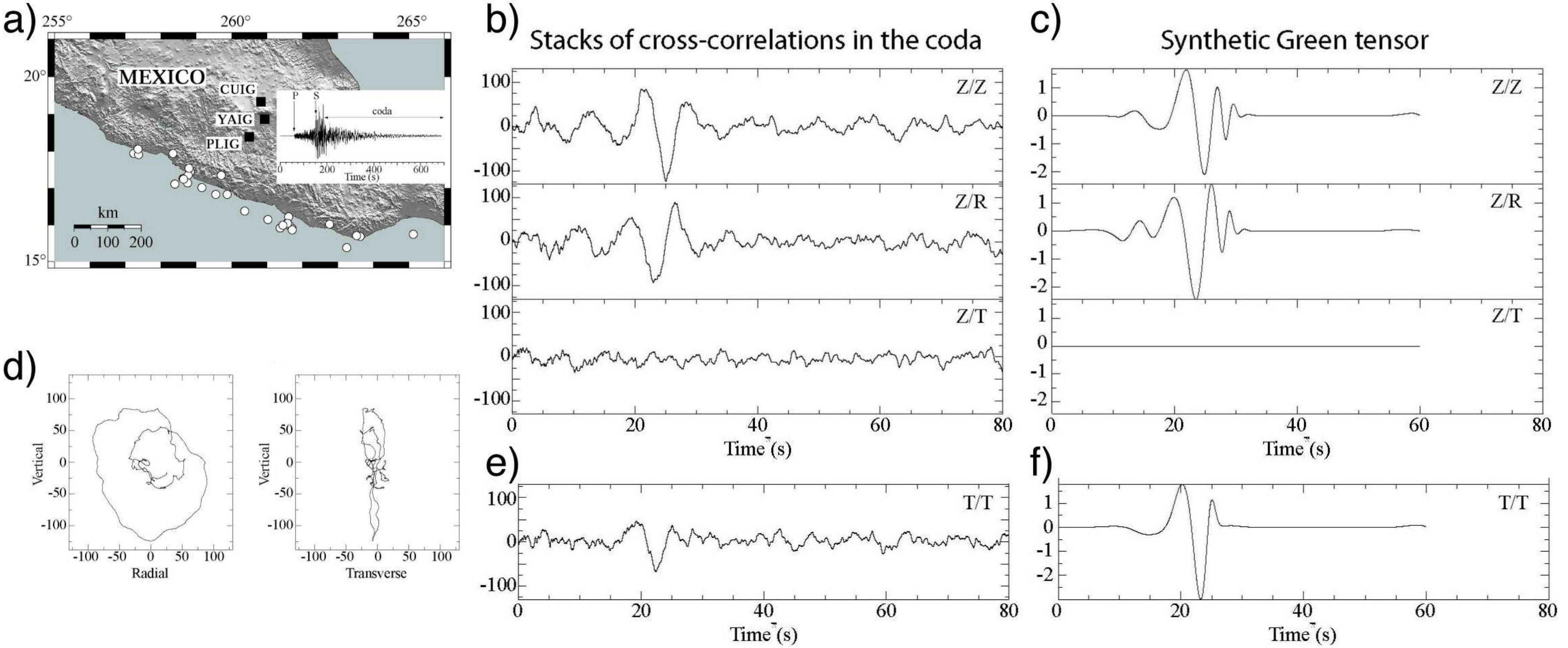
Sources are in constructive interference when respective travel time difference are close to each other

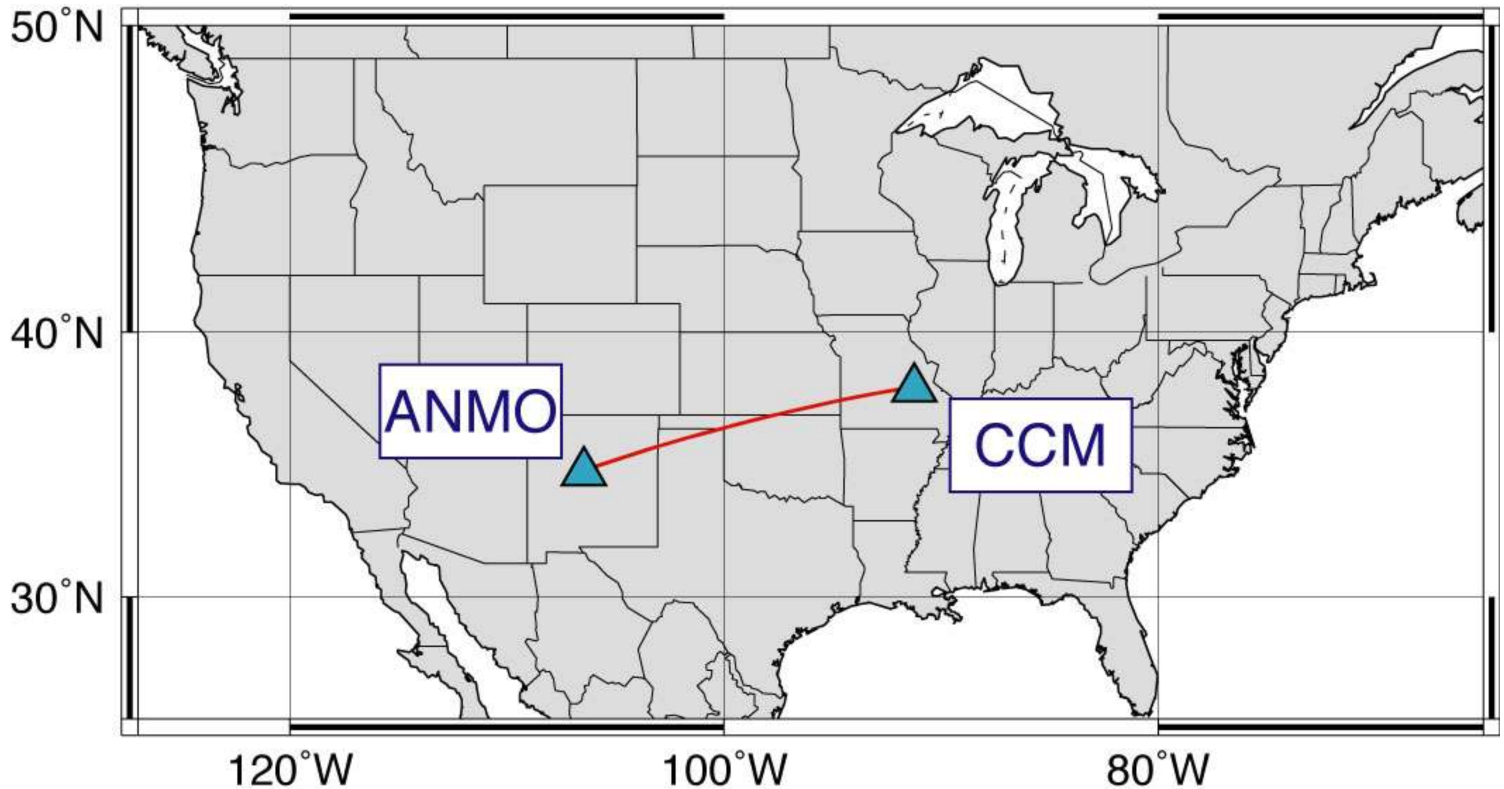
Effective density of sources is high in the vicinity of the line connecting two receivers

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

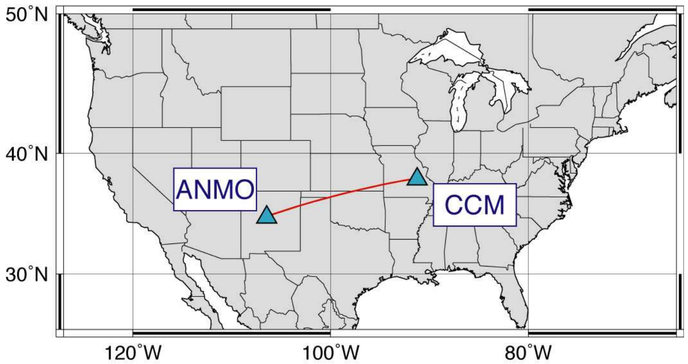
Cross-correlations of regional coda

From Campillo and Paul (2003)

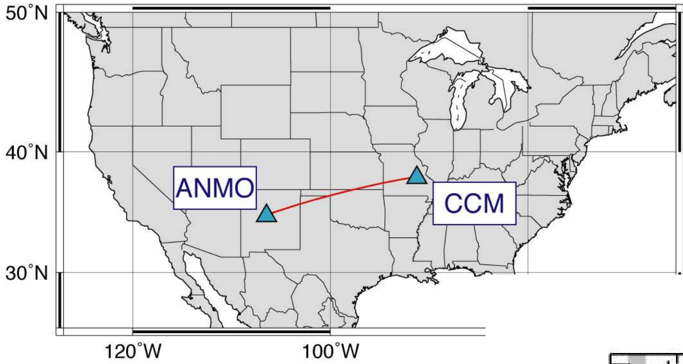




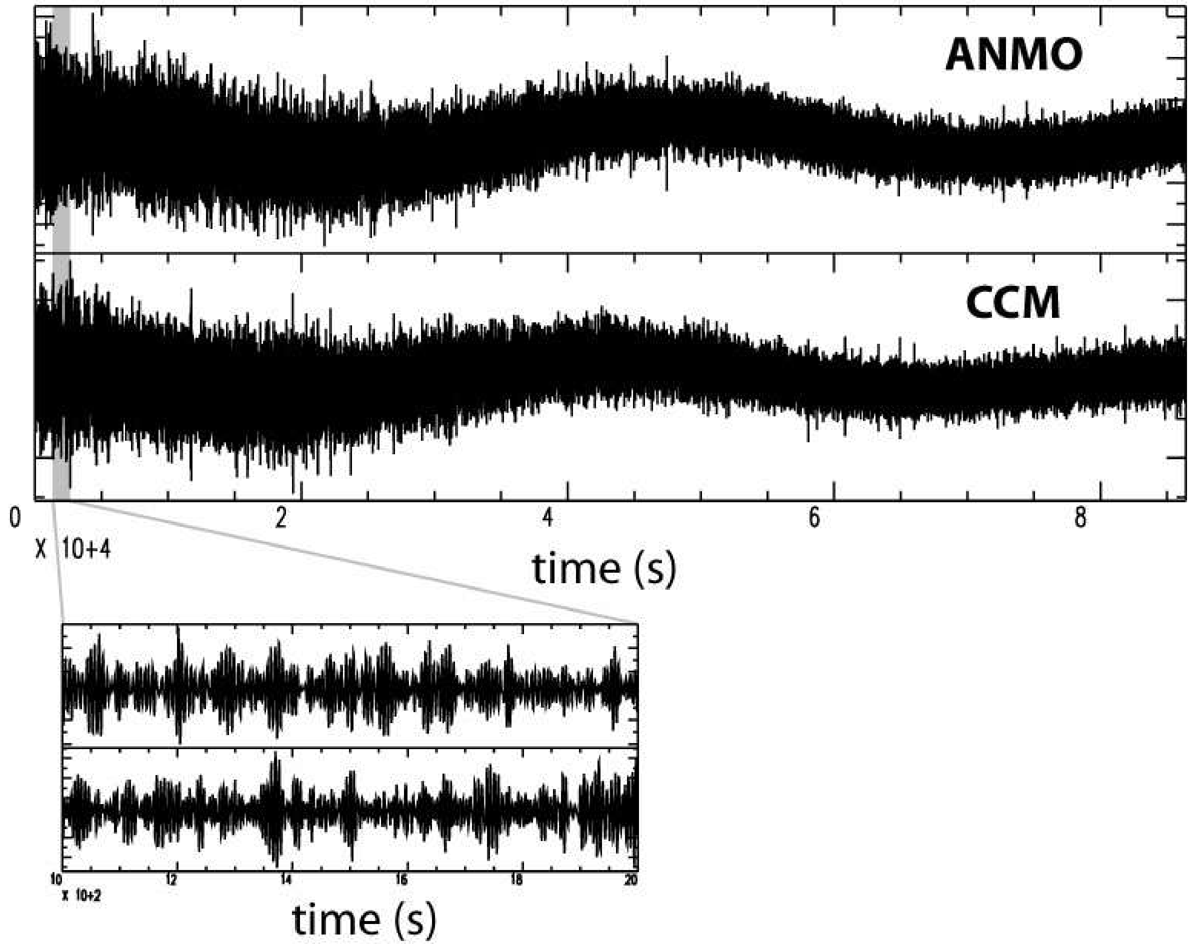
50°N
40°N
30°N
120°W
100°W
80°W
ANMO
CCM

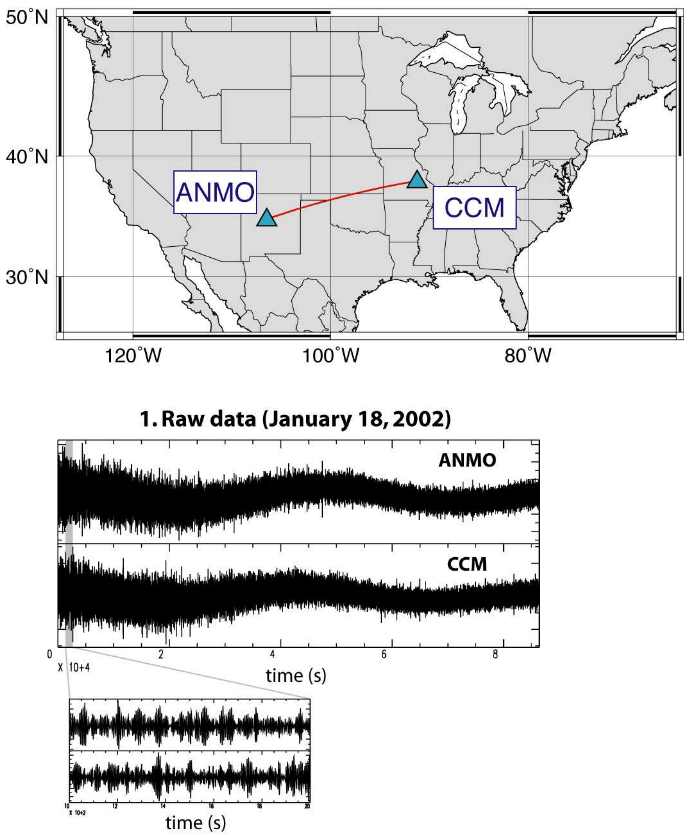


50˚N
40˚N
30˚N
120˚W
100˚W
80˚W
ANMO
CCM

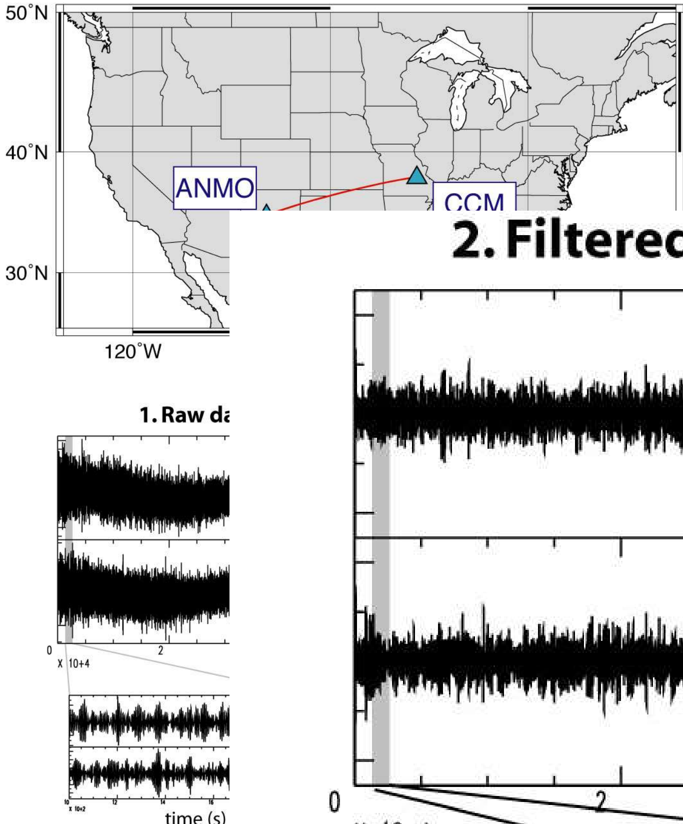


1. Raw data (January 18, 2002)

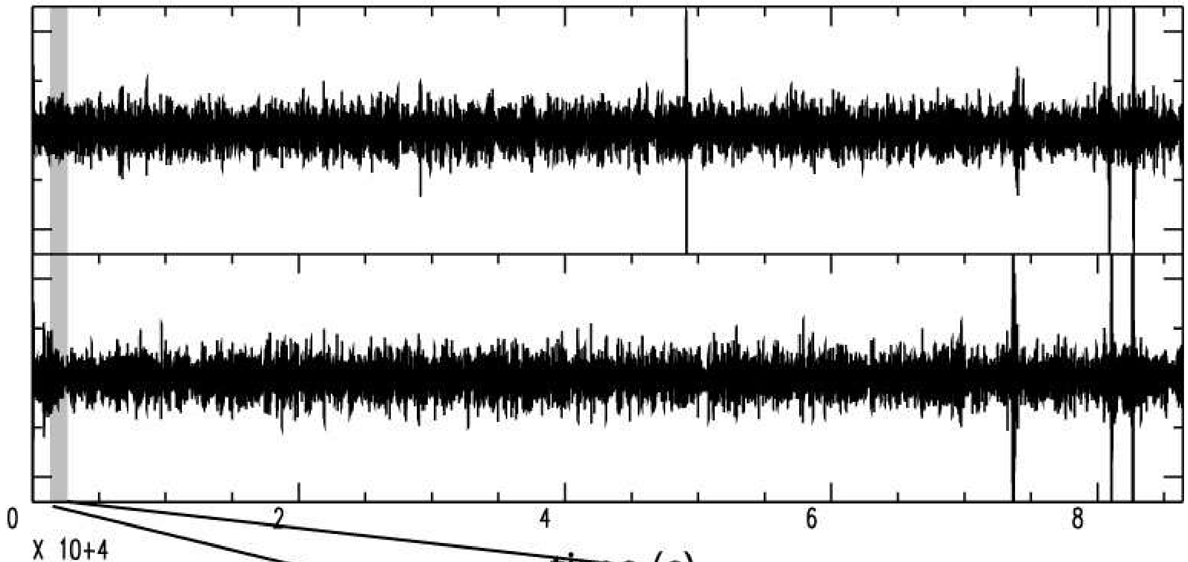


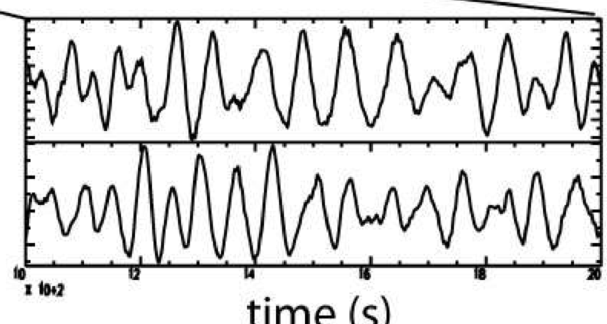


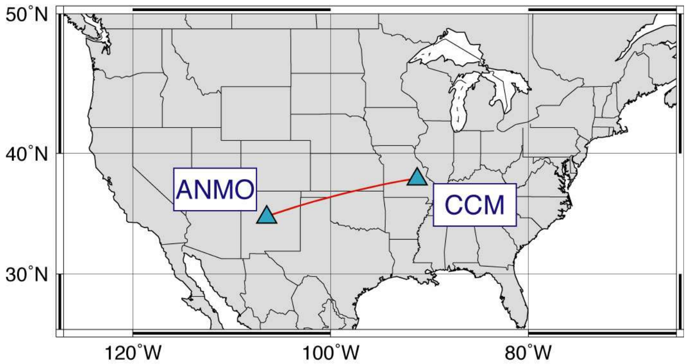
50˚N
40˚N
30˚N
120˚W
100˚W
80˚W
ANMO
CCM
1. Raw data (January 18, 2002)
ANMO
CCM
time (s)
time (s)



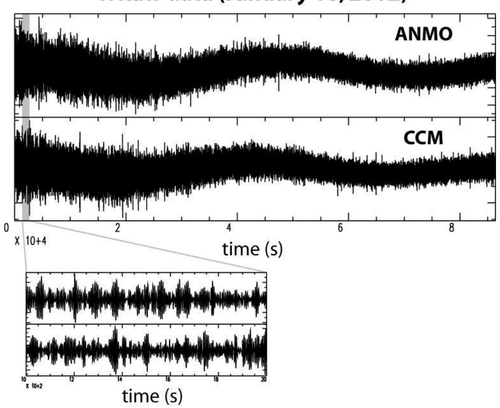
2. Filtered seismograms (0.01-0.025 Hz)



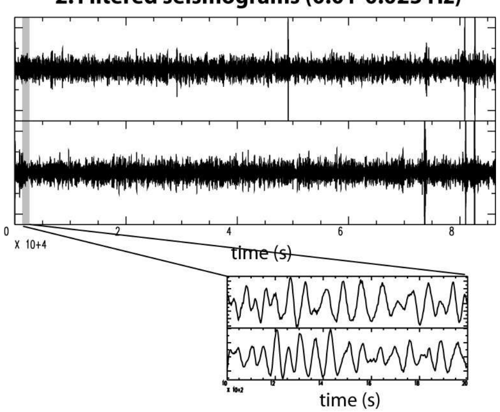


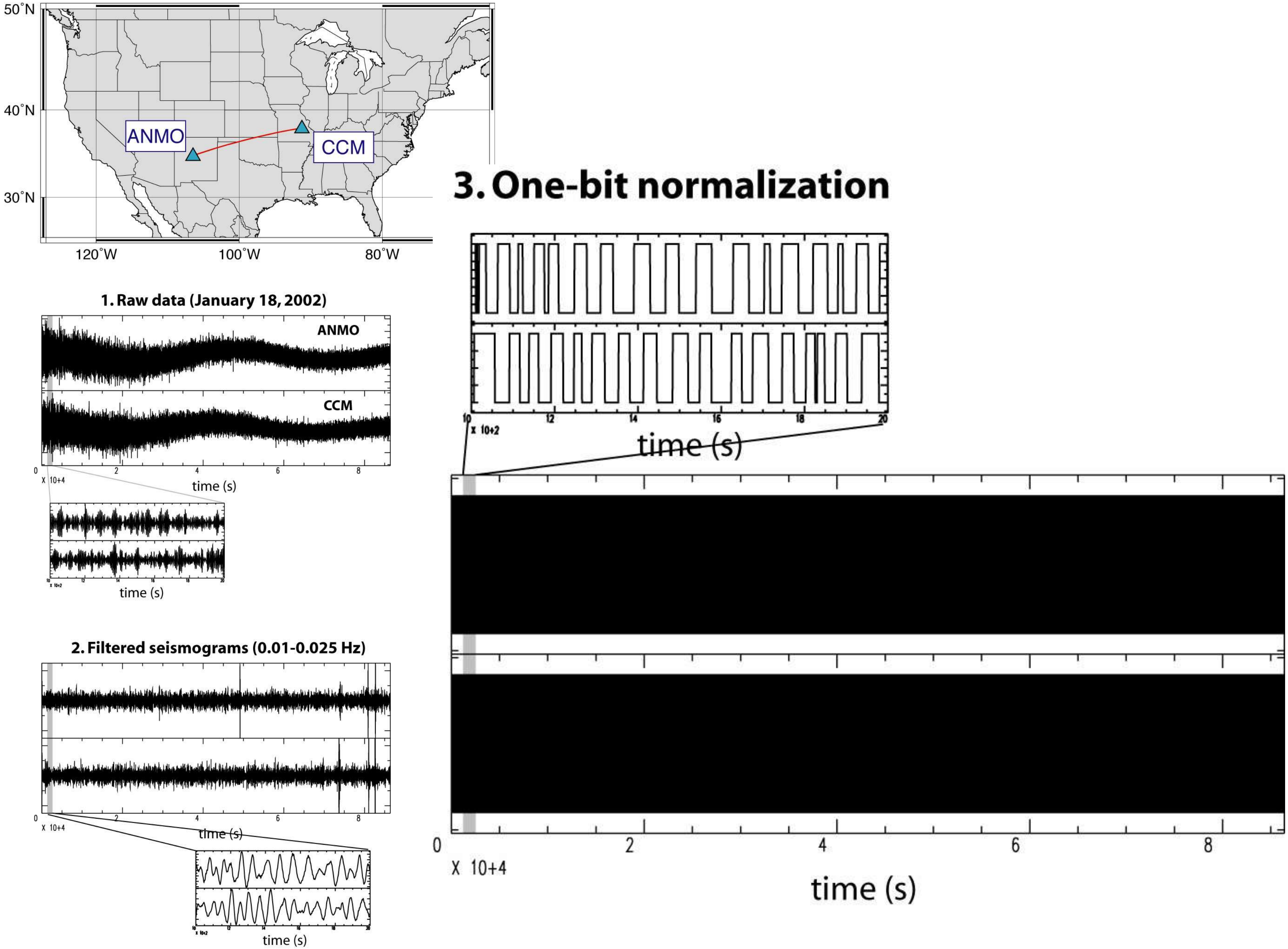


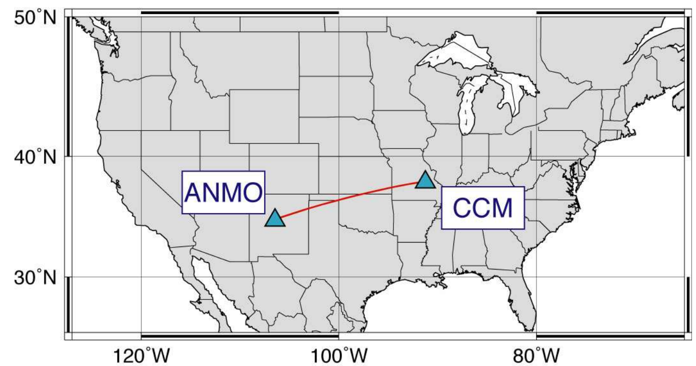
1. Raw data (January 18, 2002)



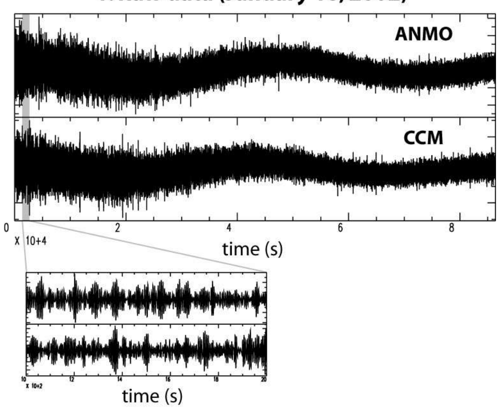
2. Filtered seismograms (0.01-0.025 Hz)



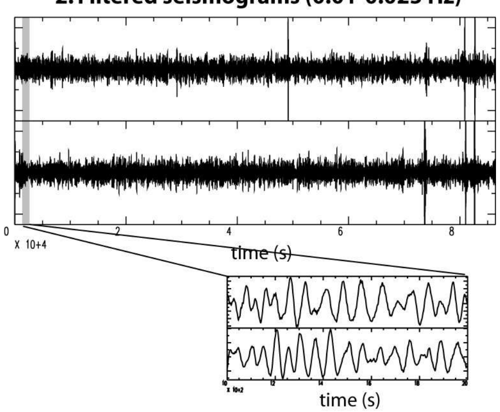

50˚N
40˚N
30˚N
120˚W
100˚W
80˚W
ANMO
CCM
1. Raw data (January 18, 2002)
ANMO
CCM
time (s)
time (s)
2. Filtered seismograms (0.01-0.025 Hz)
time (s)
time (s)
3. One-bit normalization
time (s)
0
2
4
6
8
X 10+4
time (s)



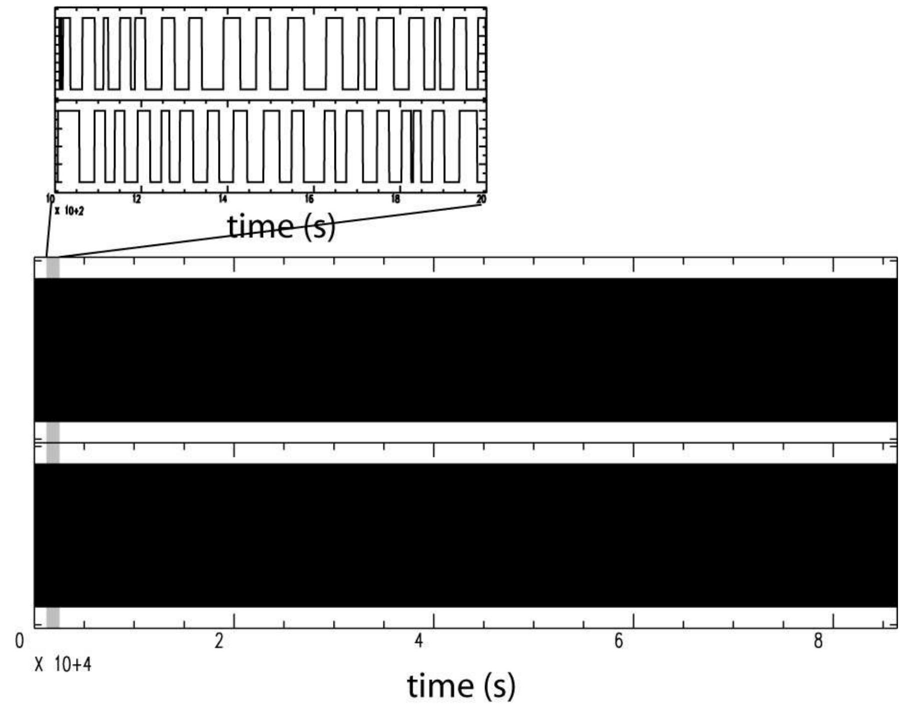
1. Raw data (January 18, 2002)

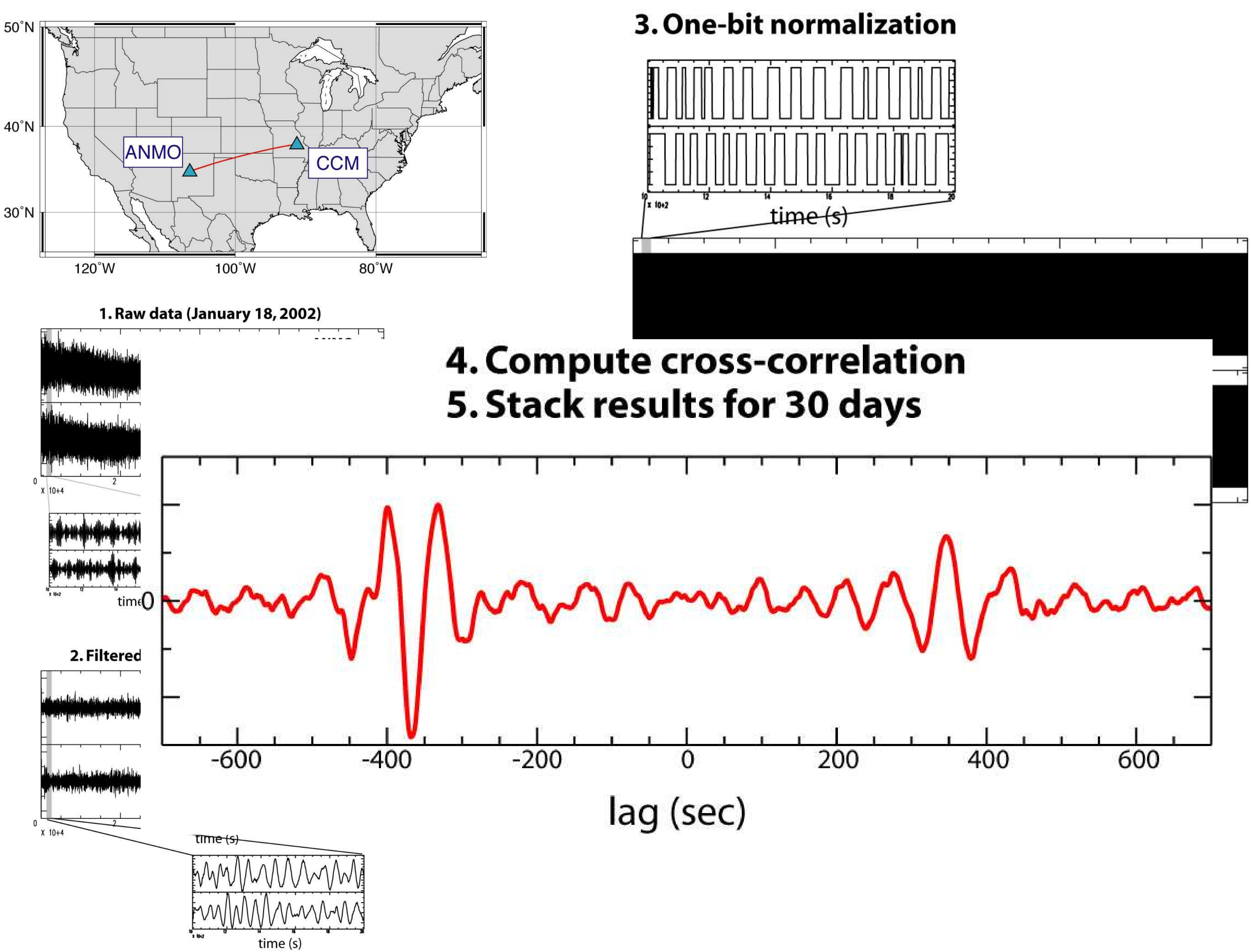


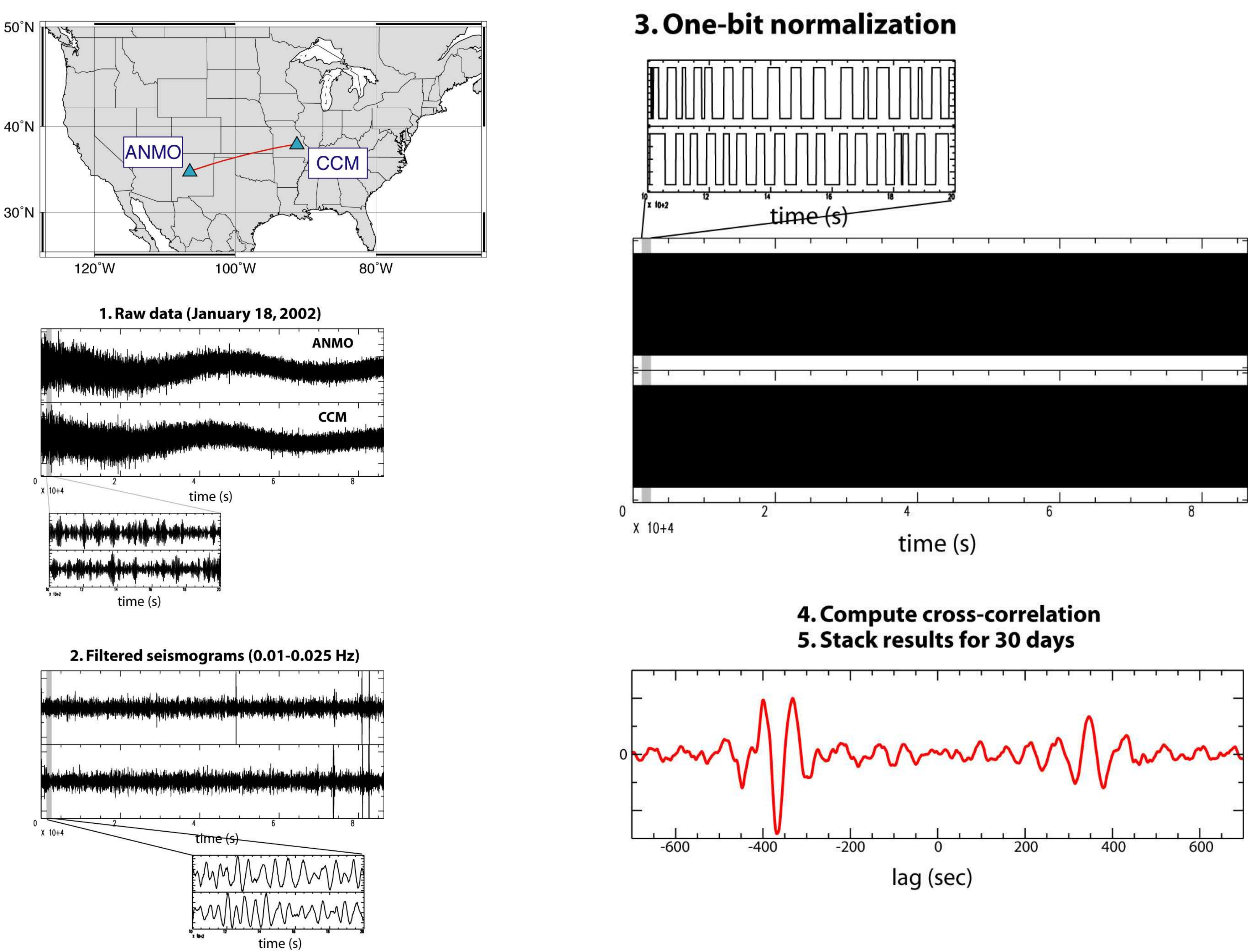
2. Filtered seismograms (0.01-0.025 Hz)



3. One-bit normalization

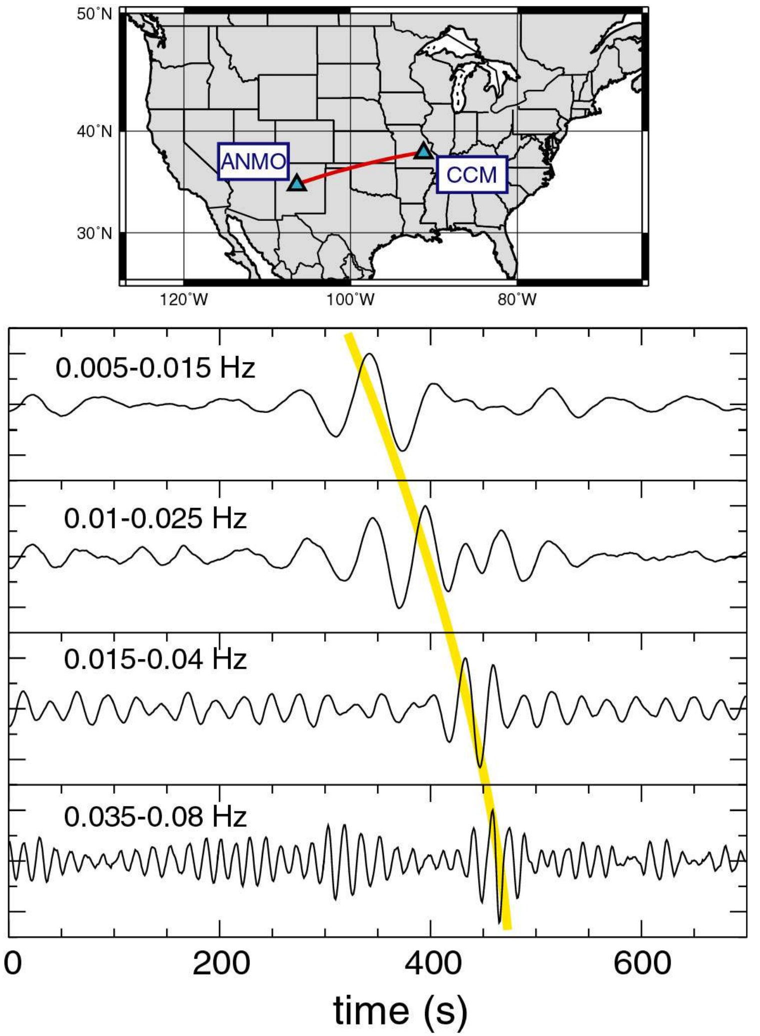



50˚N
40˚N
30˚N
120˚W
100˚W
80˚W
ANMO
CCM
1. Raw data (January 18, 2002)
2. Filtered
time (s)
3. One-bit normalization
time (s)
4. Compute cross-correlation
5. Stack results for 30 days
0
-600
-400
-200
0
200
400
600
lag (sec)

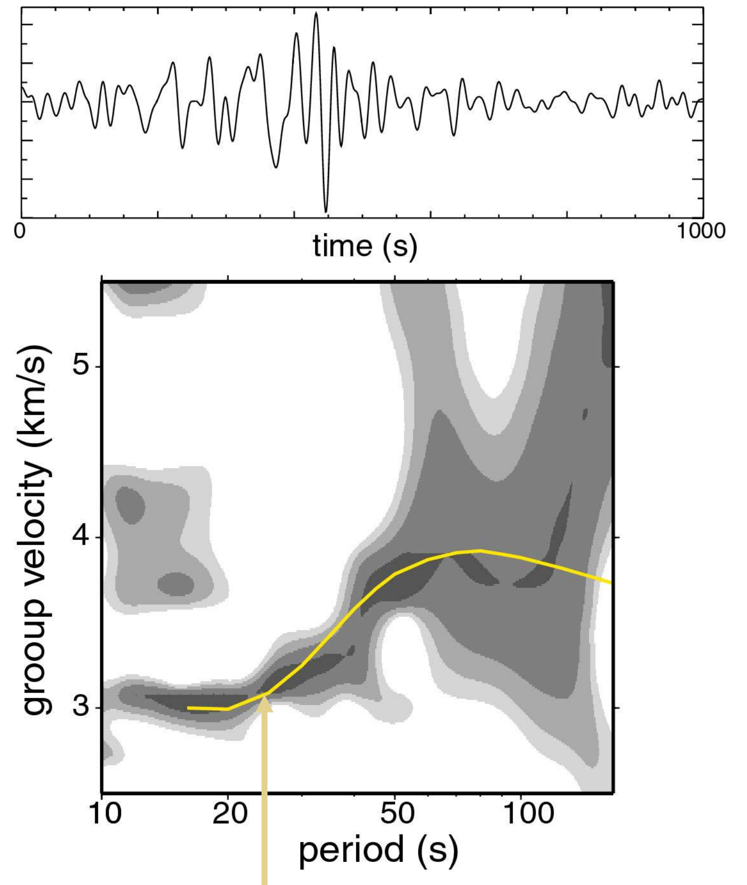

50˚N
40˚N
30˚N
120˚W
100˚W
80˚W
ANMO
CCM
1. Raw data (January 18, 2002)
ANMO
CCM
time (s)
time (s)
2. Filtered seismograms (0.01-0.025 Hz)
time (s)
time (s)
3. One-bit normalization
time (s)
time (s)
4. Compute cross-correlation
5. Stack results for 30 days
lag (sec)

Cross-correlations from ambient seismic noise: ANMO - CCM

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

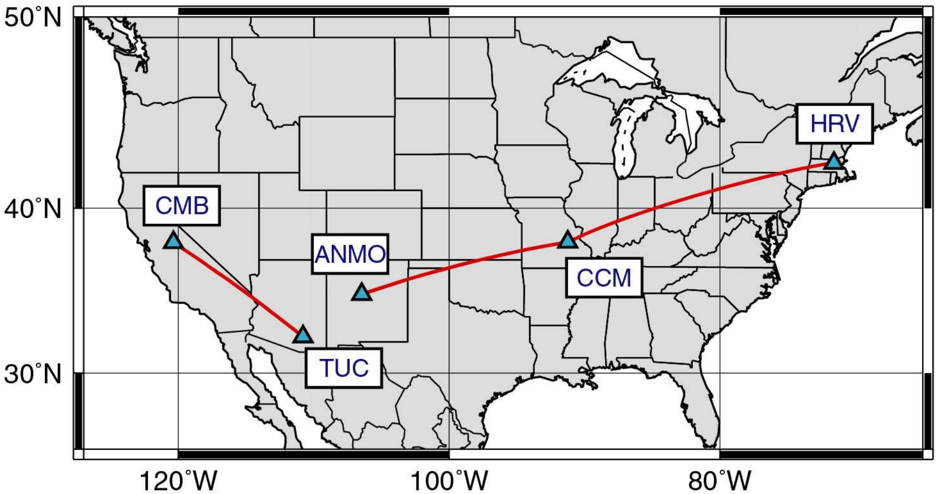


frequency-time analysis of the broadband cross-correlation

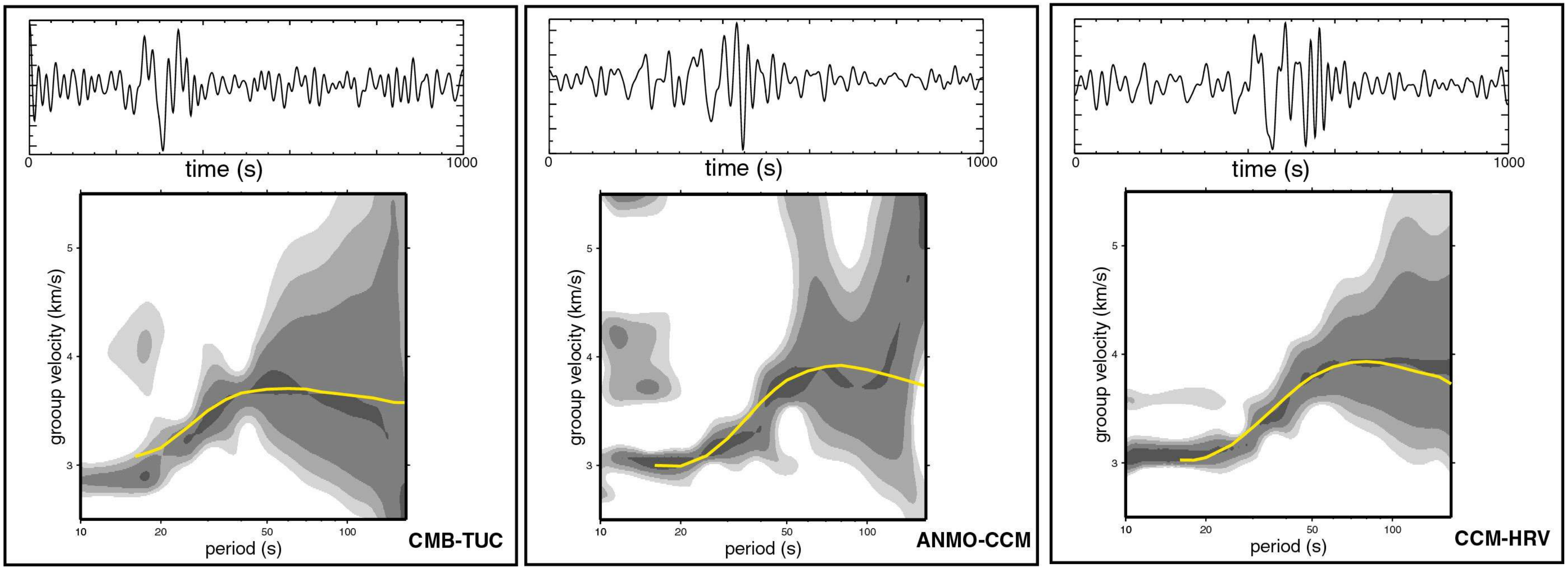


prediction from global group velocity maps of Ritzwoller et al. (2002)

Cross-correlations from ambient seismic noise at US stations

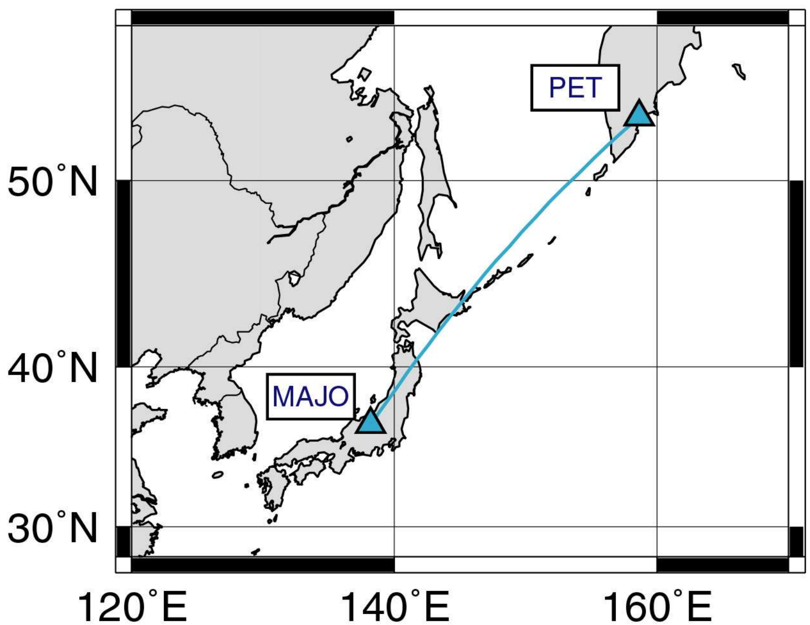


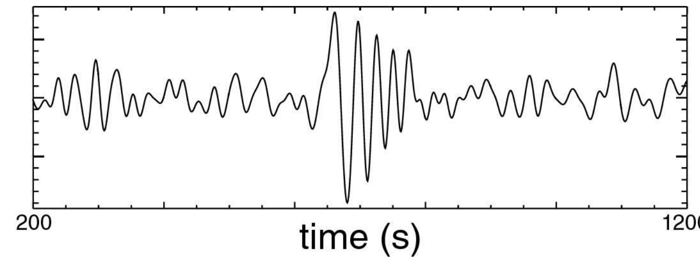
frequency-time analysis of broadband cross-correlations computed from 30 days of continuous vertical component records

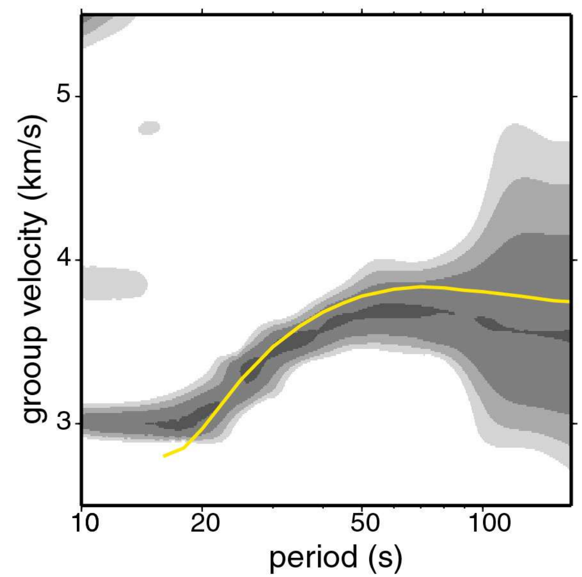


Cross-correlation from ambient seismic noise in North-Western Pacific

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

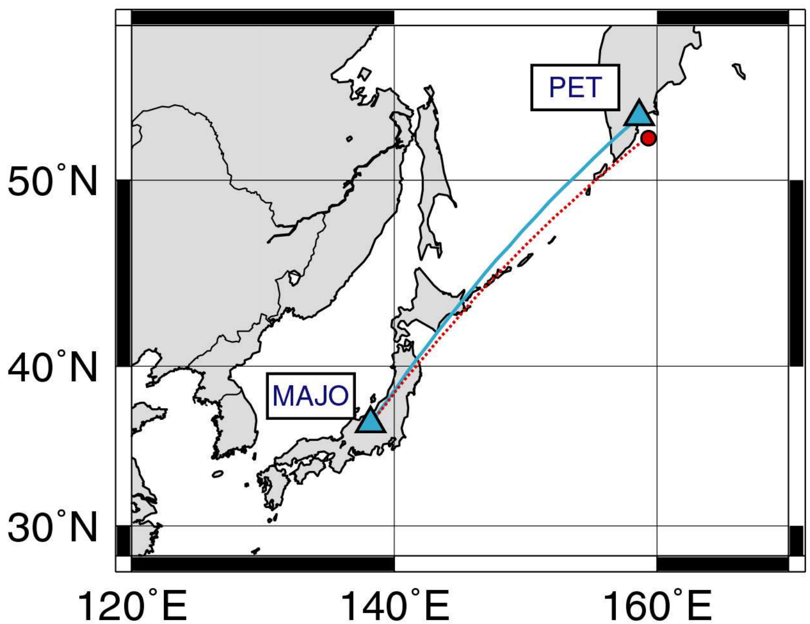


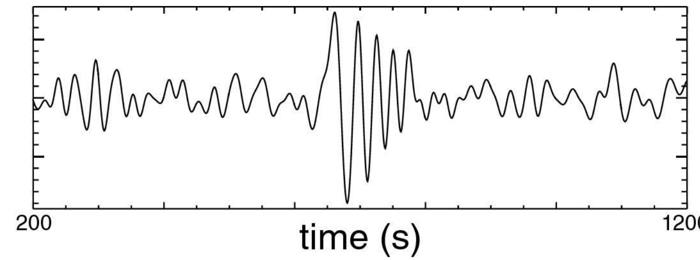


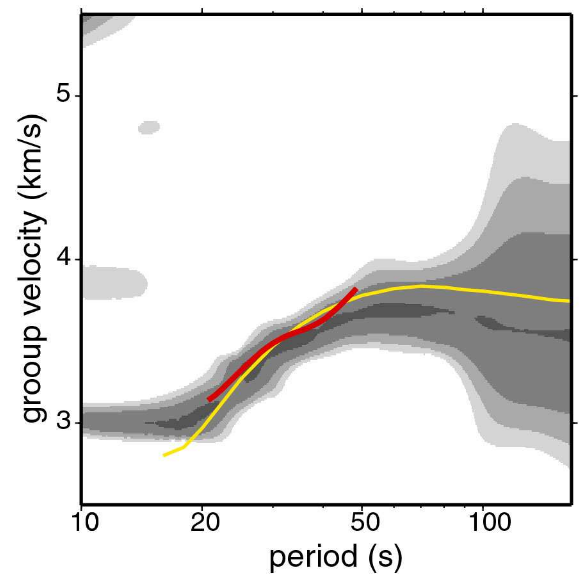


Cross-correlation from ambient seismic noise in North-Western Pacific

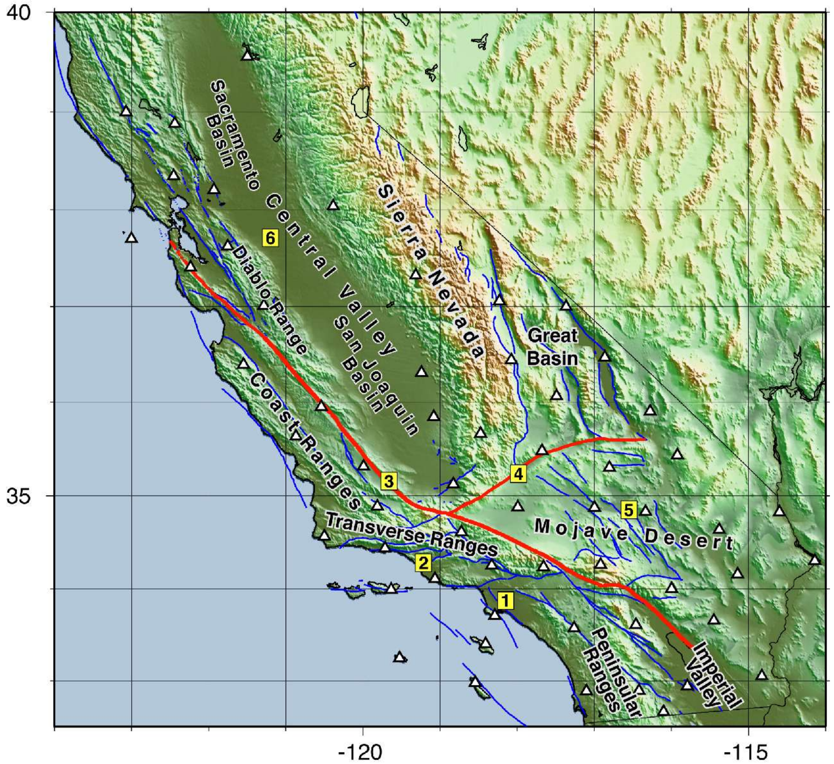
broadband cross-correlation computed from 30 days of continuous vertical component records



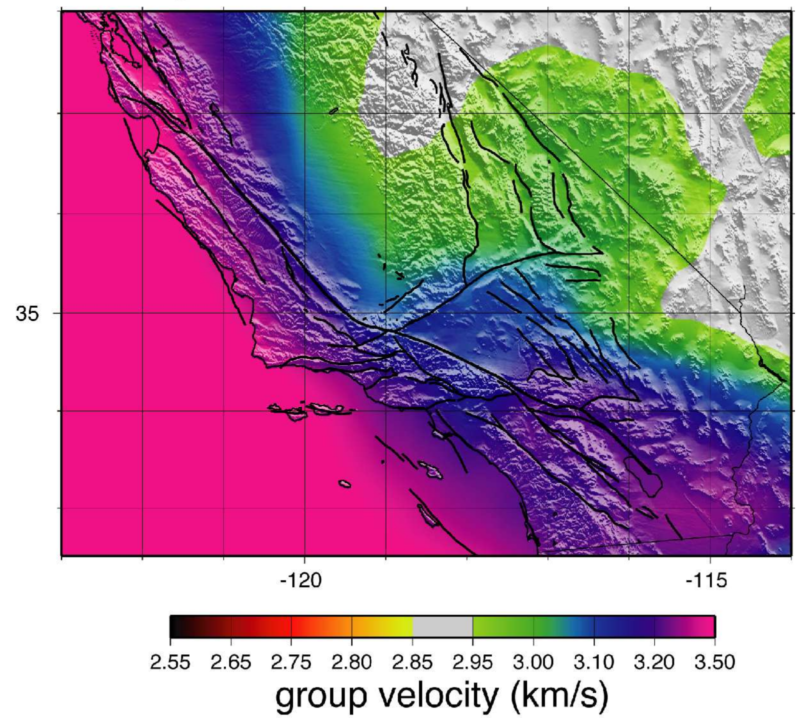




Cross-correlation of seismic noise in California

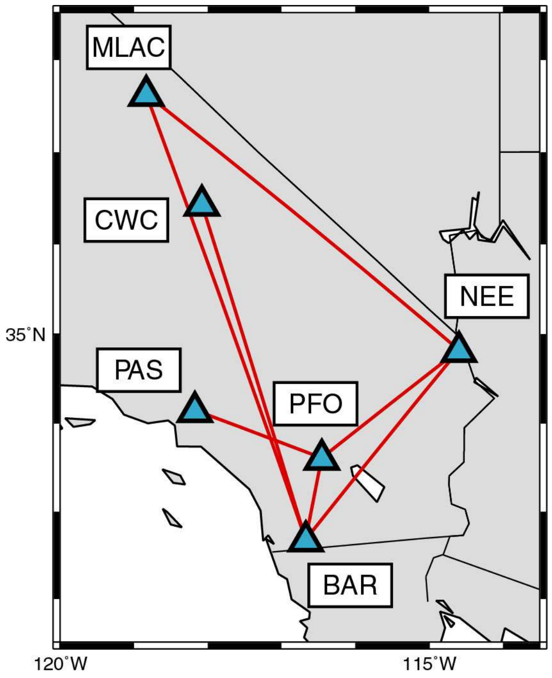


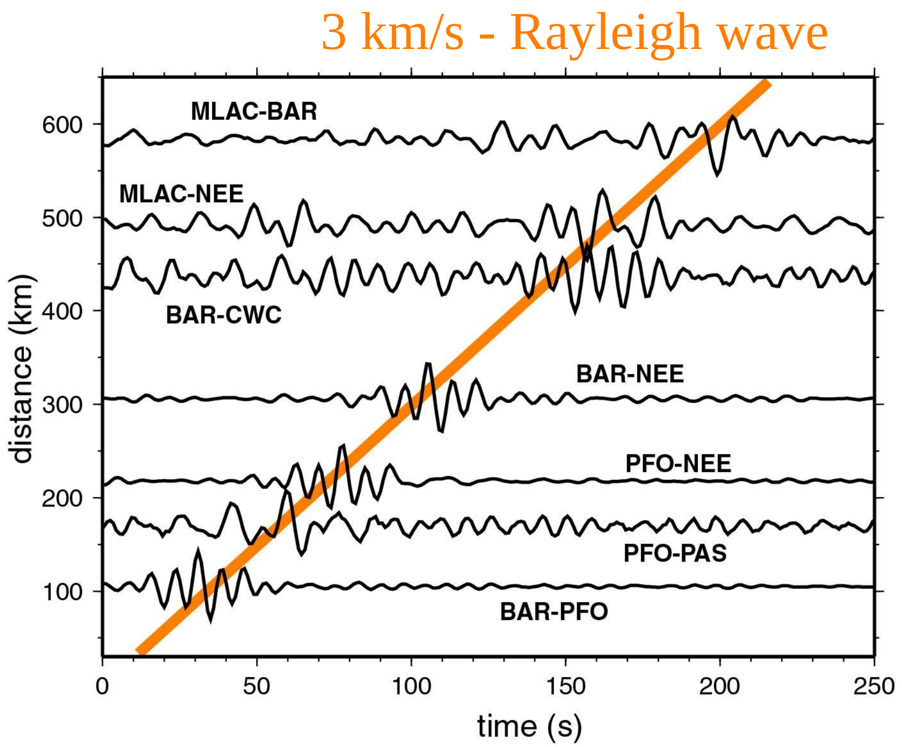
18 s global surface-wave measurements



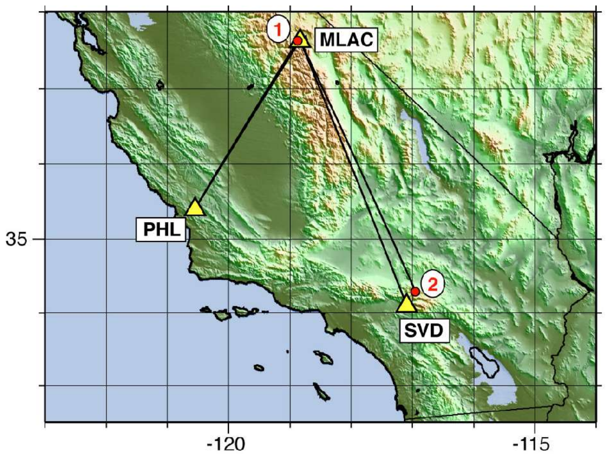
Cross-correlation of seismic noise in California

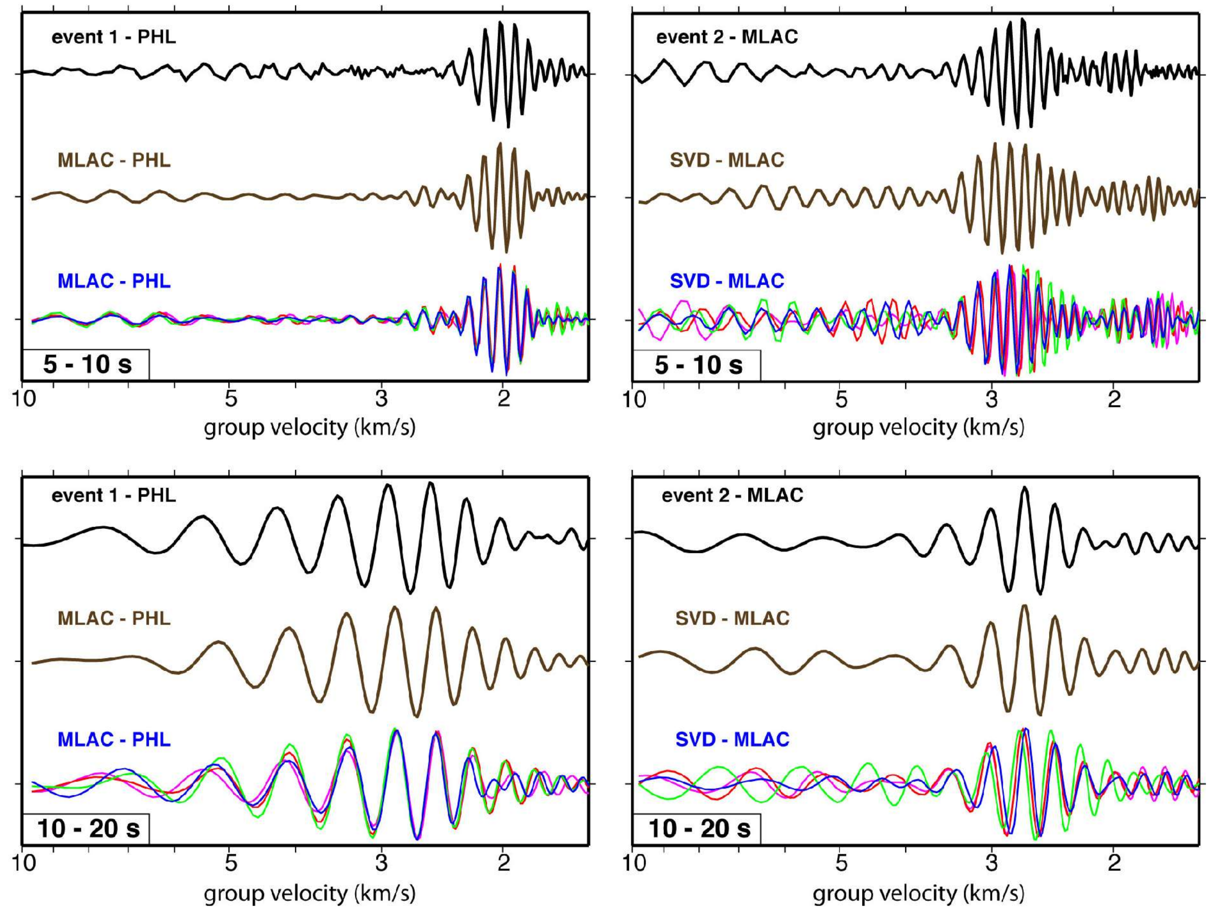
cross-correlations of vertical component continuous records (1996/02/11-1996/03/10)
0.03-0.2 Hz



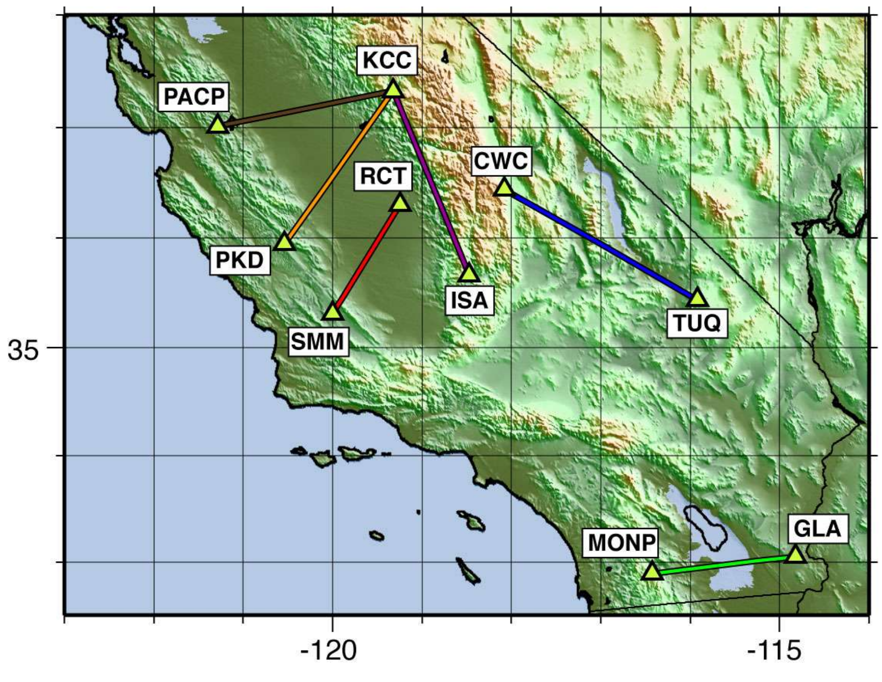


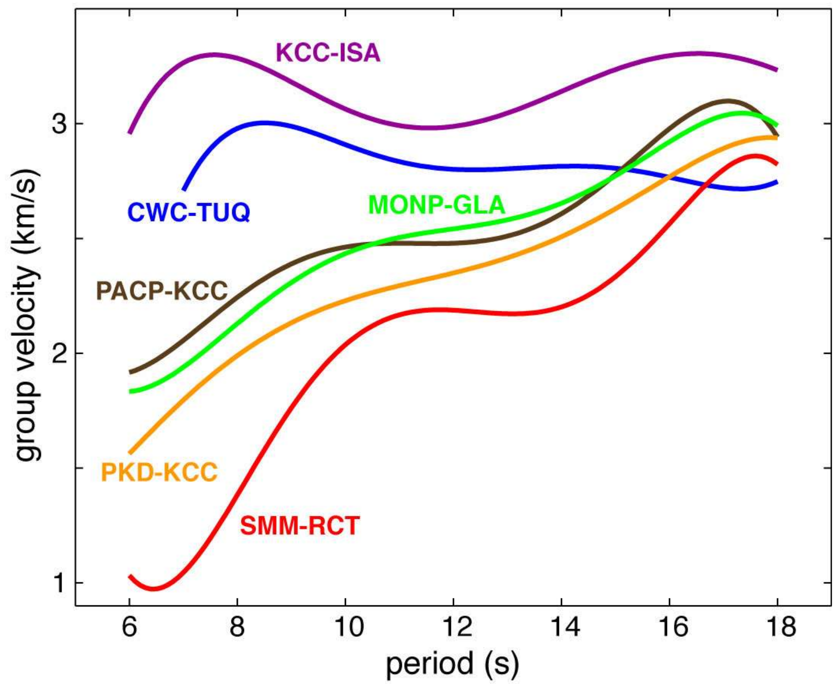
Comparison with signals from earthquakes



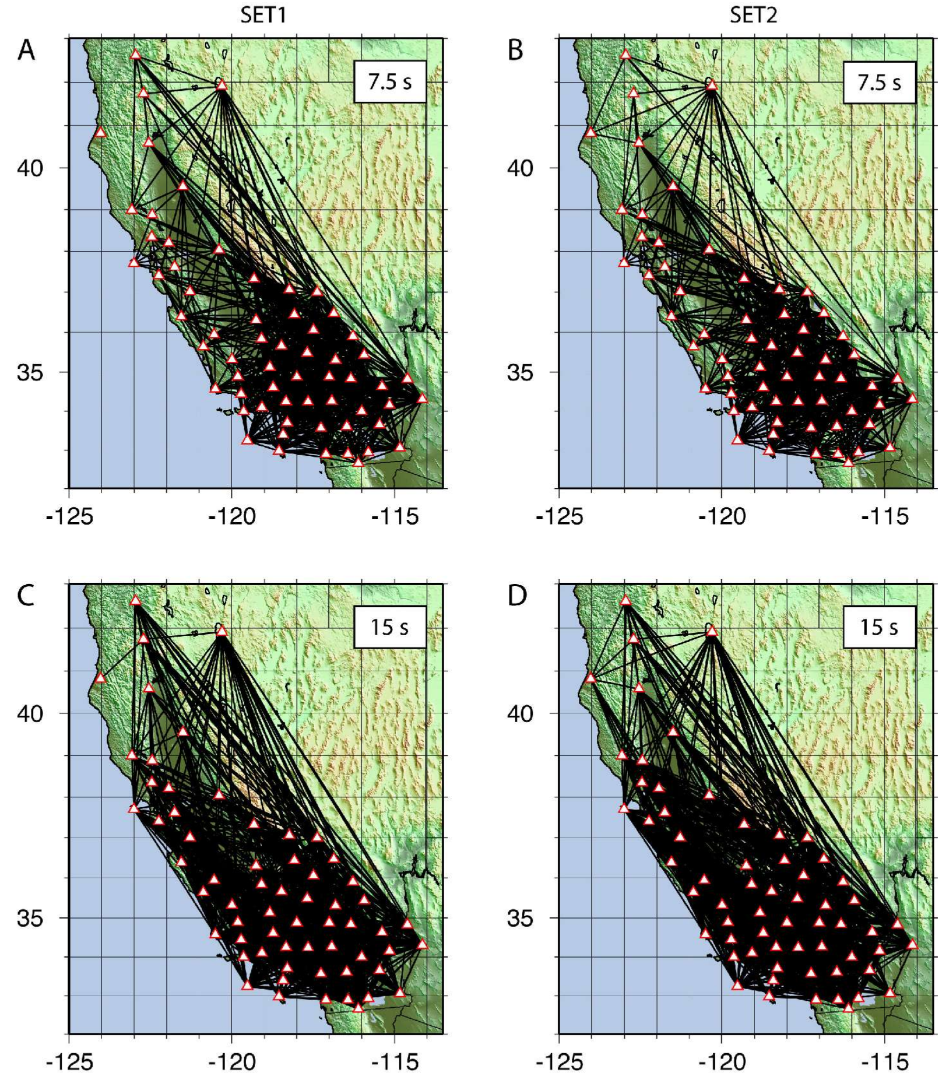


Examples of Rayleigh-wave dispersion curves

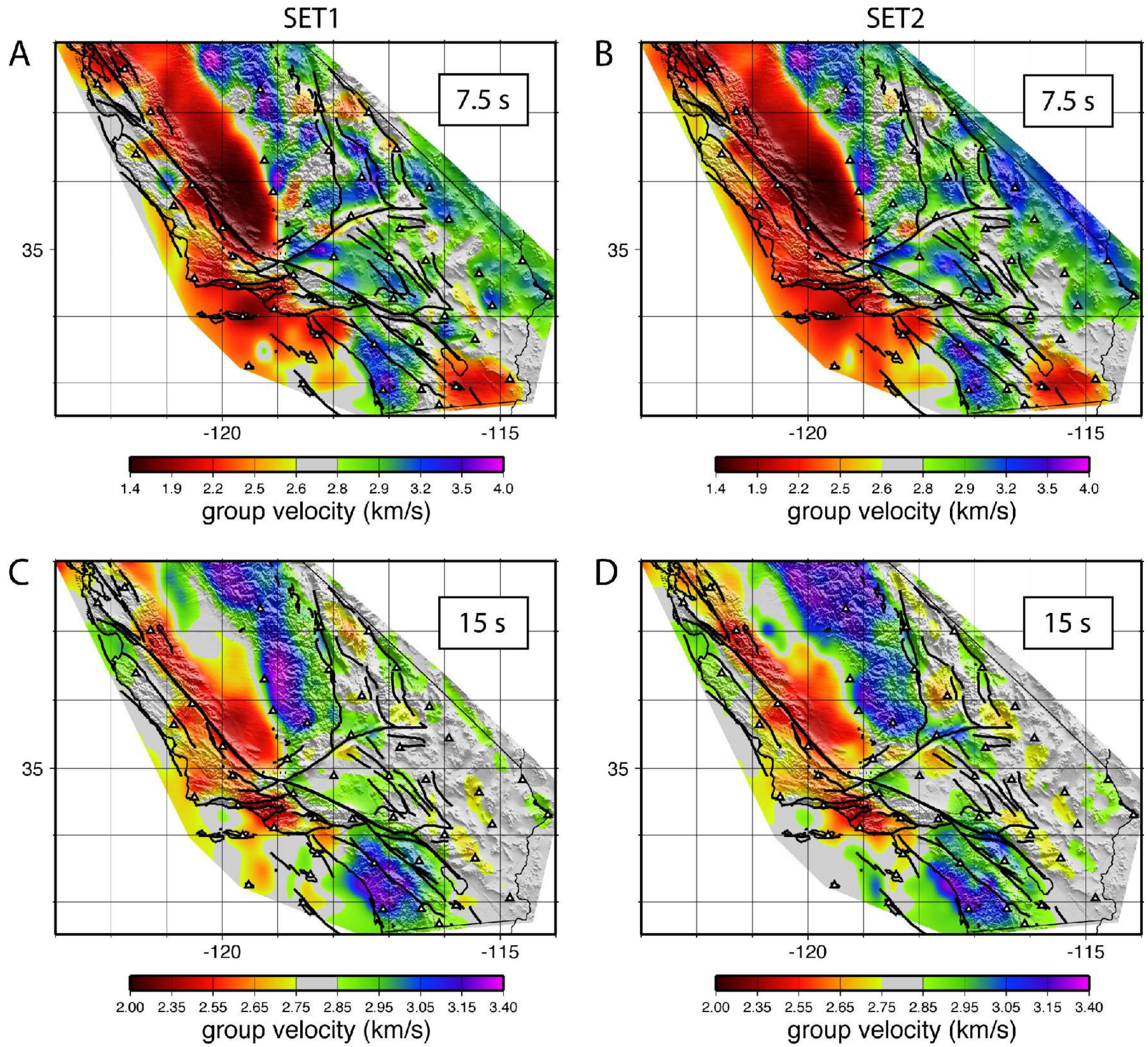




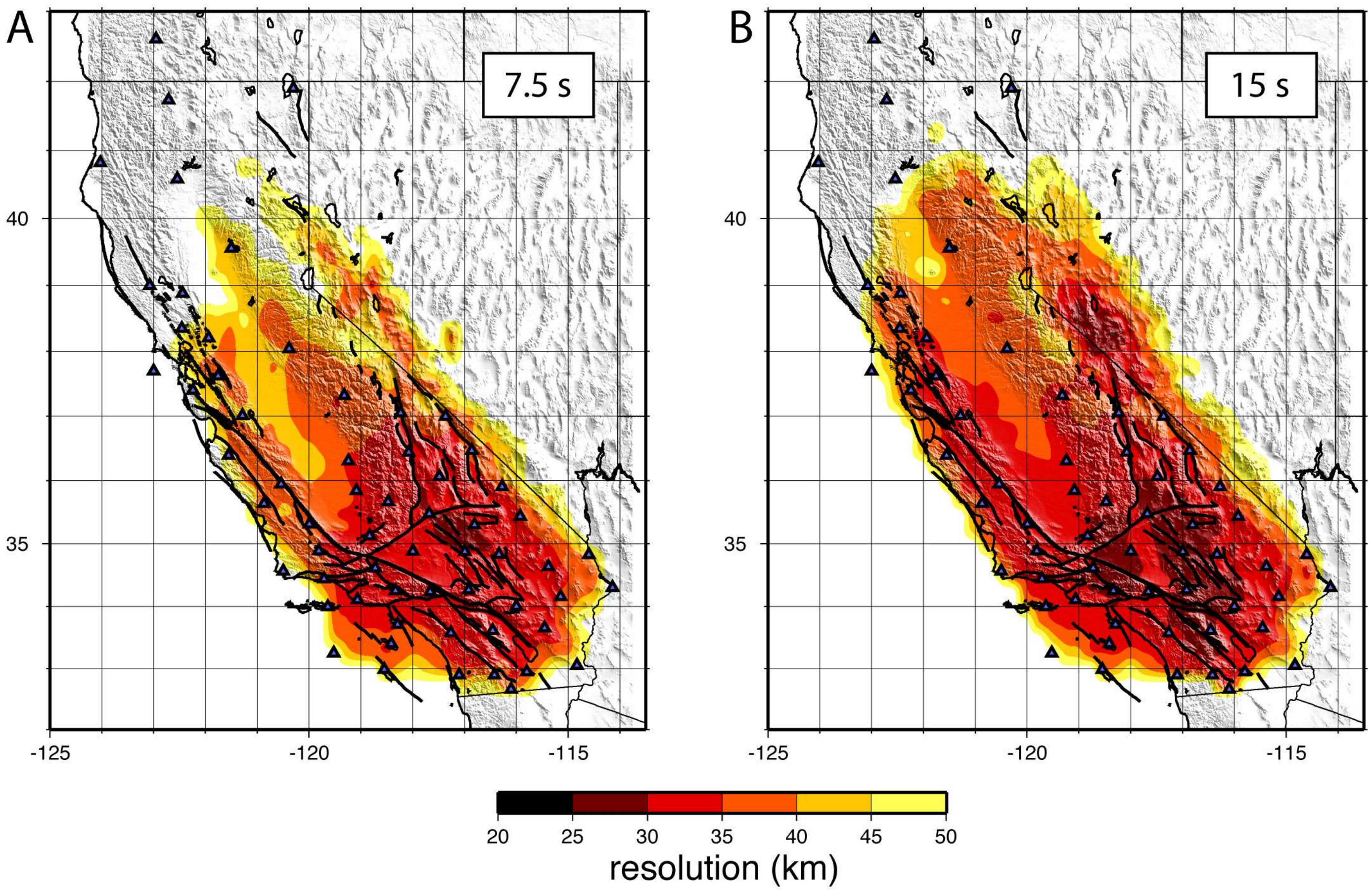
Measurements from two different months



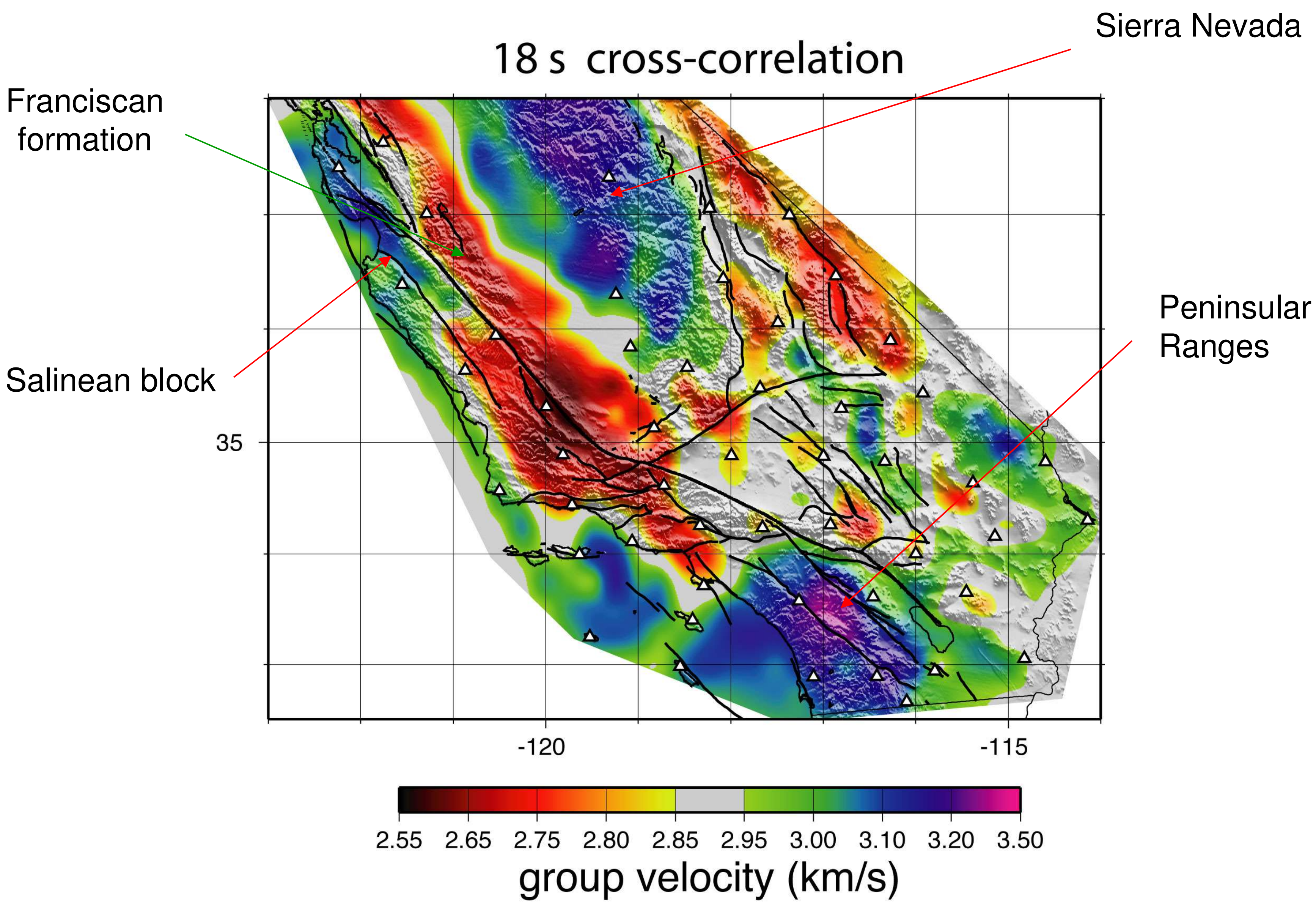
Repetitive tomography



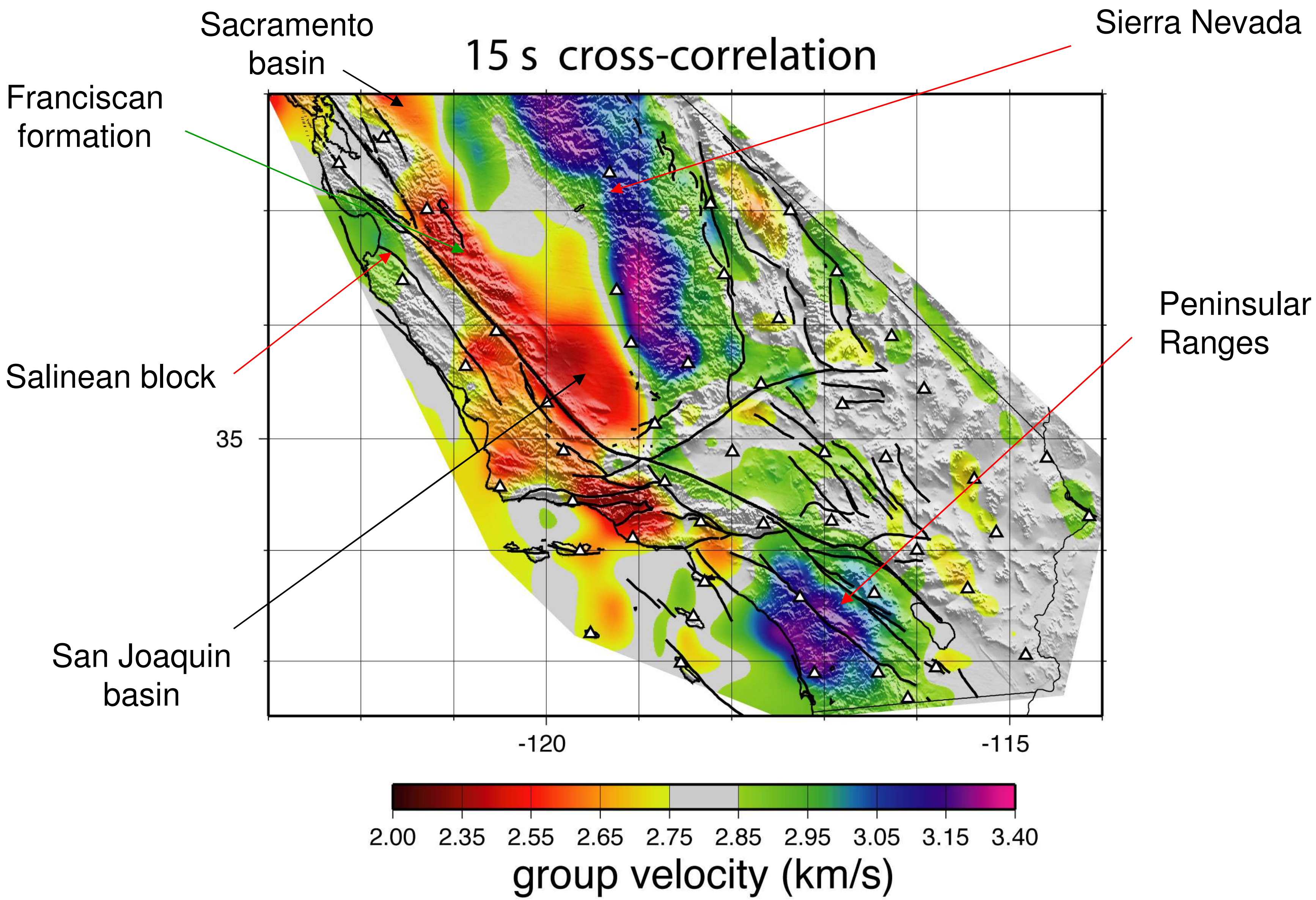
Resolution



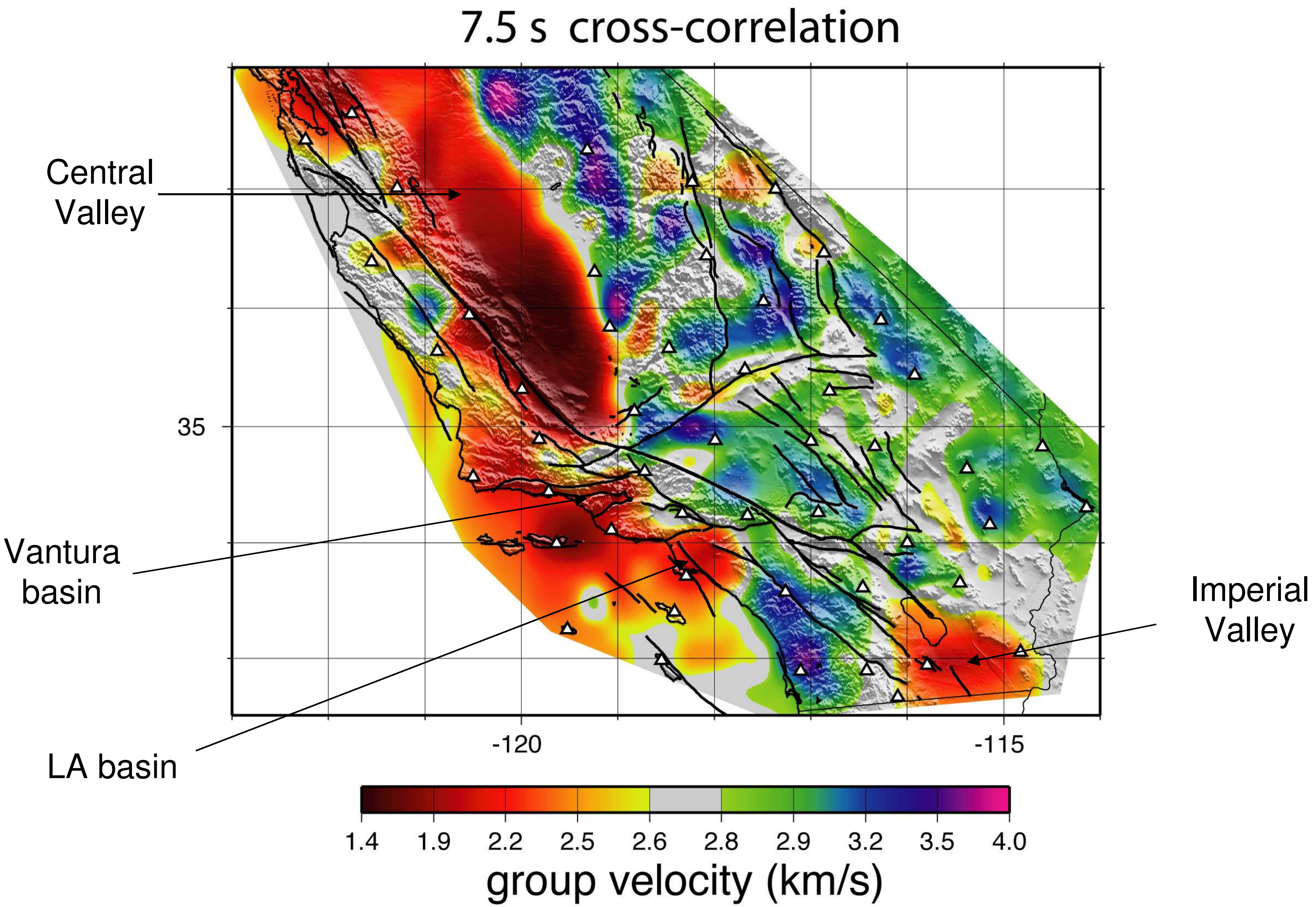
dispersion maps



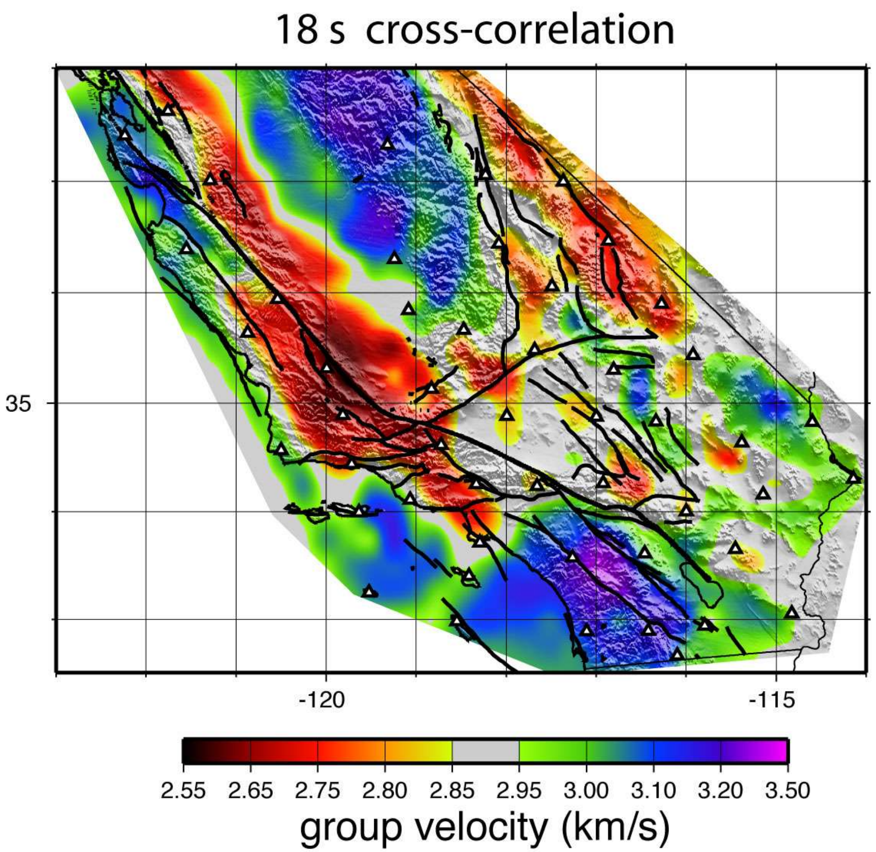
dispersion maps

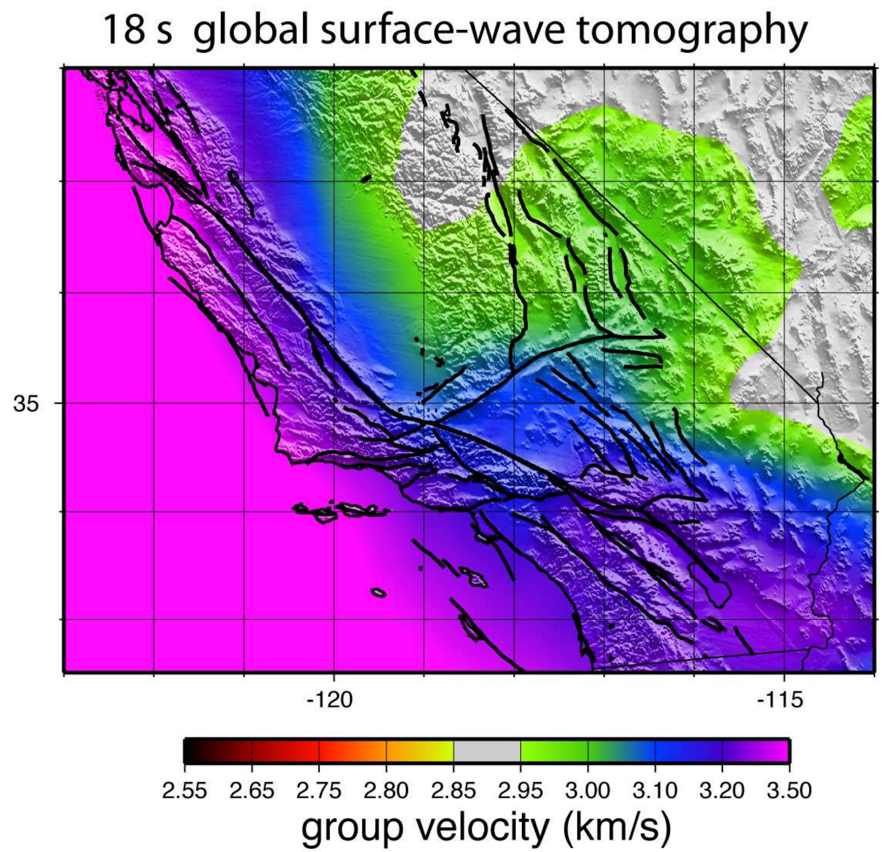


dispersion maps



Comparison between noise-based and earthquake-based tomographies





Extraction of surface waves from seismic noise

Measurements without earthquakes

Improved resolution

Possible applications:

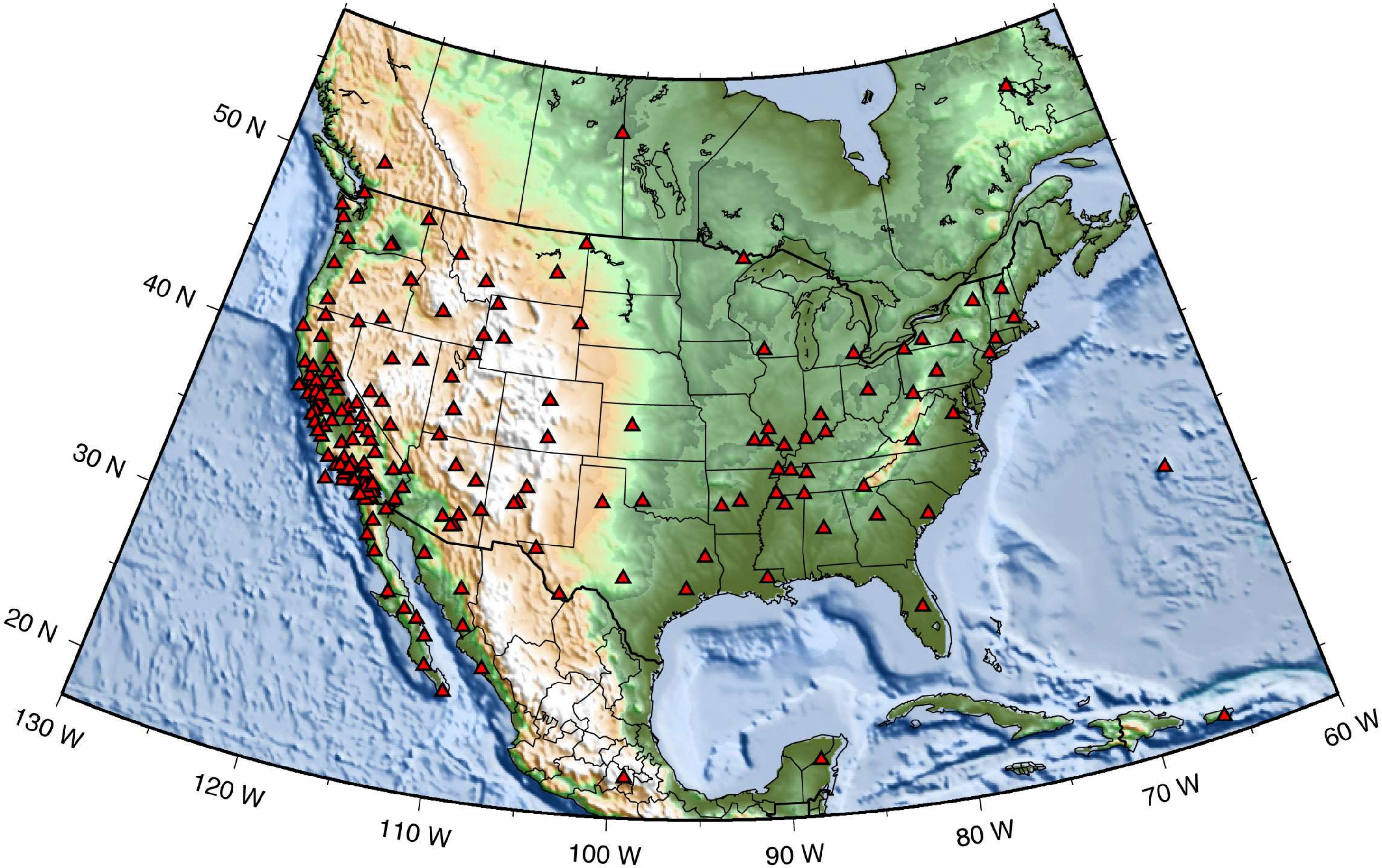
- imaging of the crust and the uppermost mantle
- structure of sedimentary basins for seismic hazard
- seismic calibration for nuclear monitoring
- monitoring of volcanoes and fault zones

Remaining questions:

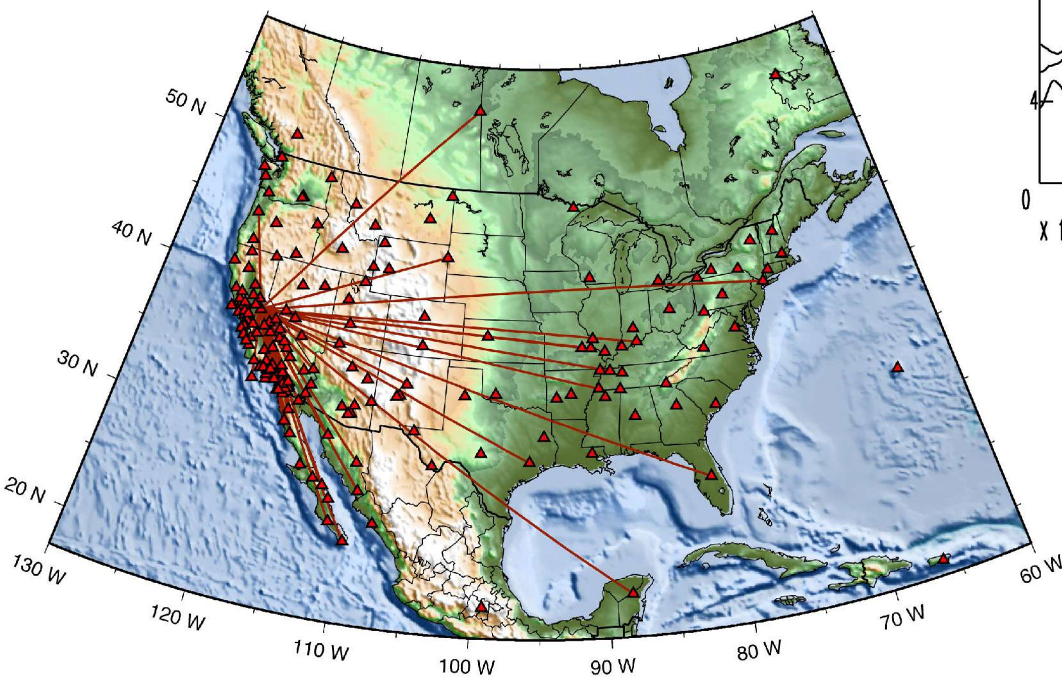
- optimal duration of noise sequences
- spectral range
- optimal inter-station distances
- optimal station orientation
- Other than Rayleigh waves (Love, body waves)

Perspectives of noise-based continental-scale imaging in USA

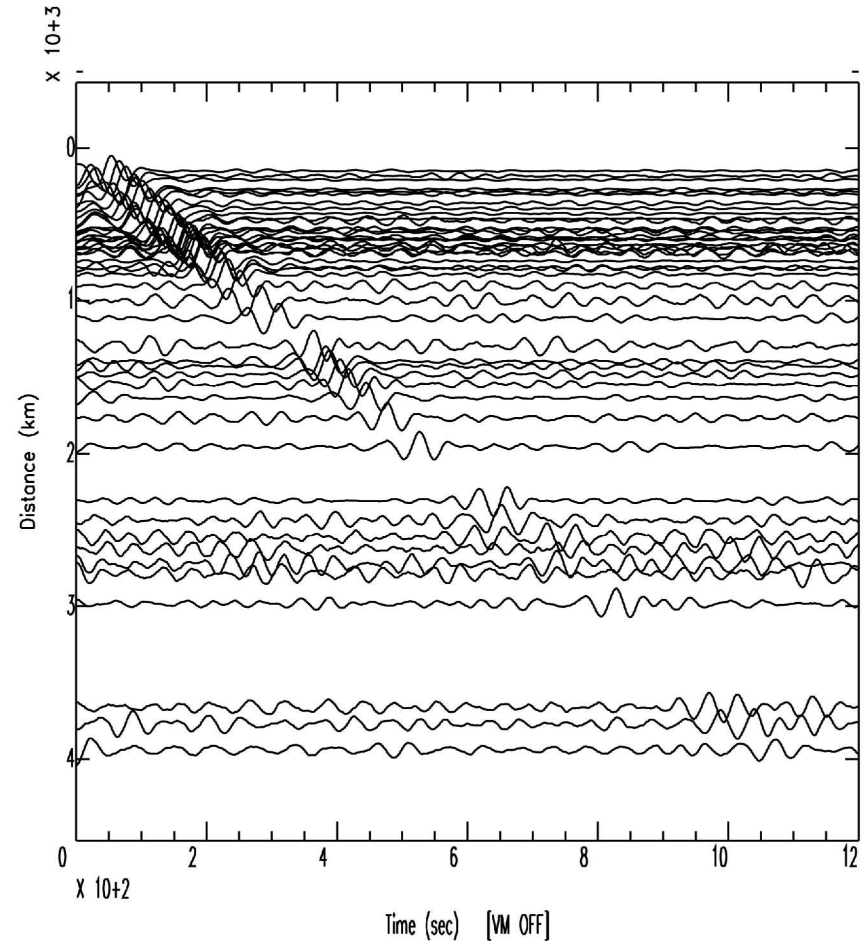
courtesy of Greg Bensen (CU Boulder)



CMB

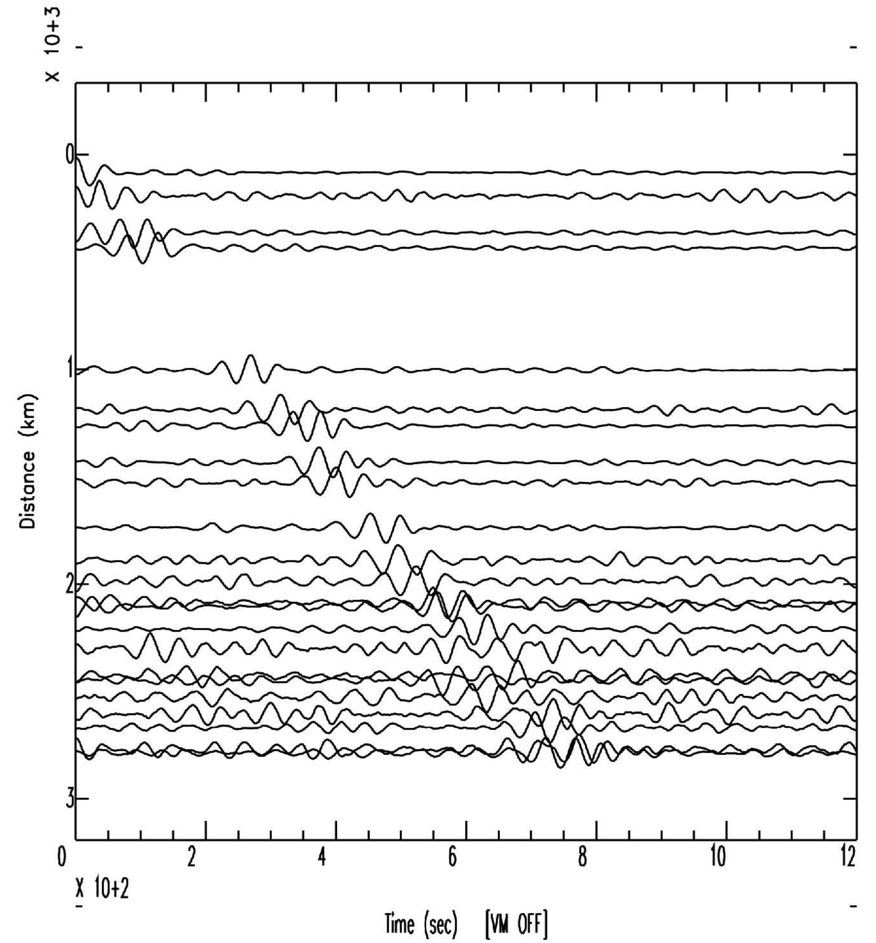


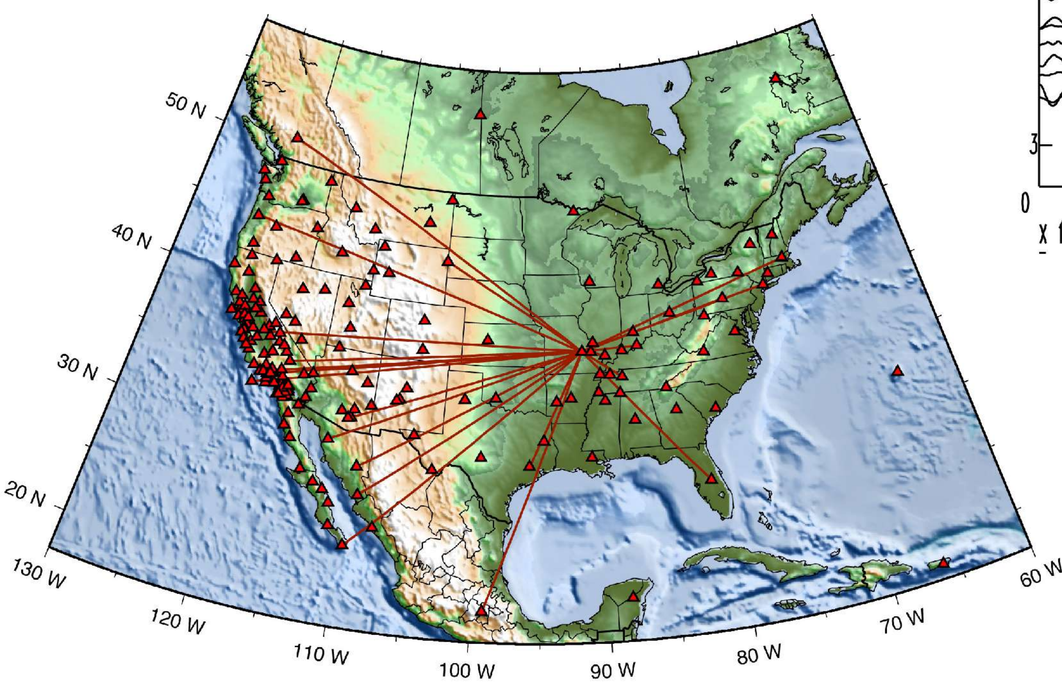
50 N
40 N
30 N
20 N
130 W
120 W
110 W
100 W
90 W
80 W
70 W
60 W



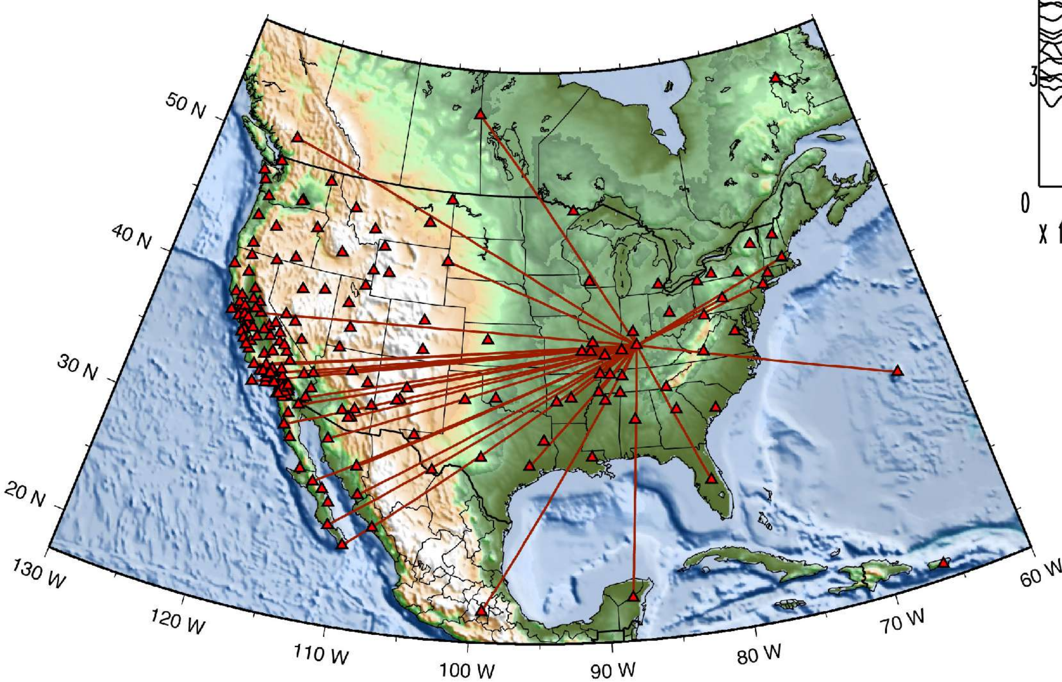
X 10+3
0
1
2
3
4
Distance (km)
0
2
4
6
8
10
12
X 10+2
Time (sec) [VM OFF]

CCM

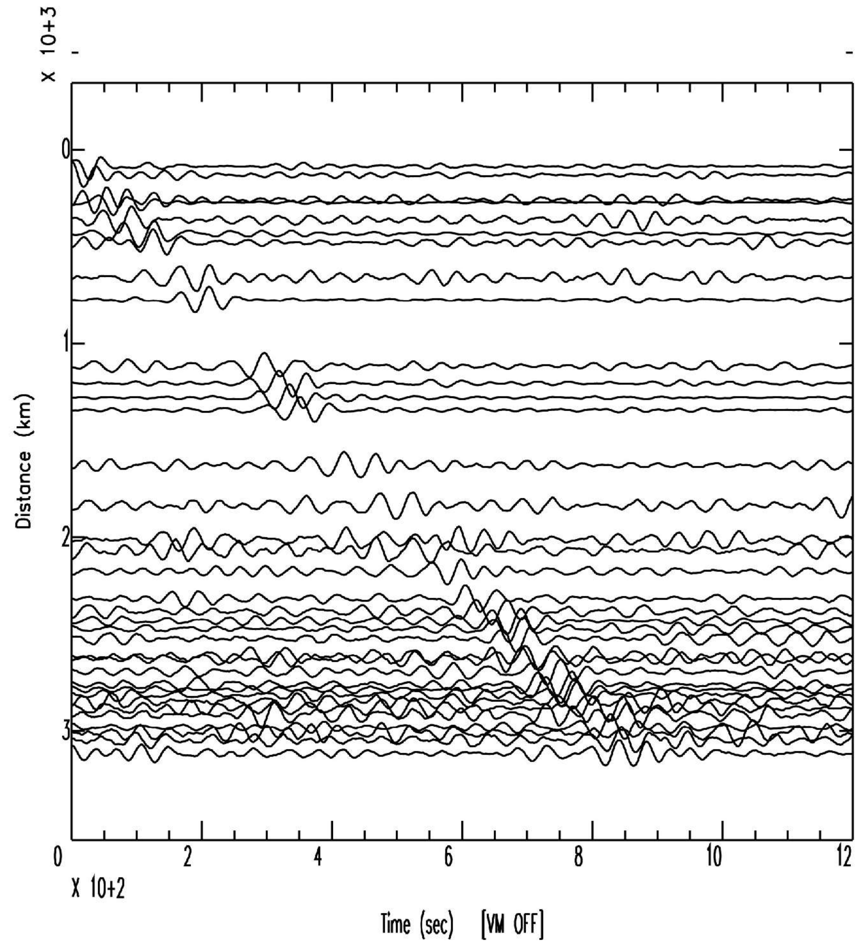

X 10+3
Distance (km)
X 10+2
Time (sec) [VM OFF]


50 N
40 N
30 N
20 N
130 W
120 W
110 W
100 W
90 W
80 W
70 W
60 W

WCI

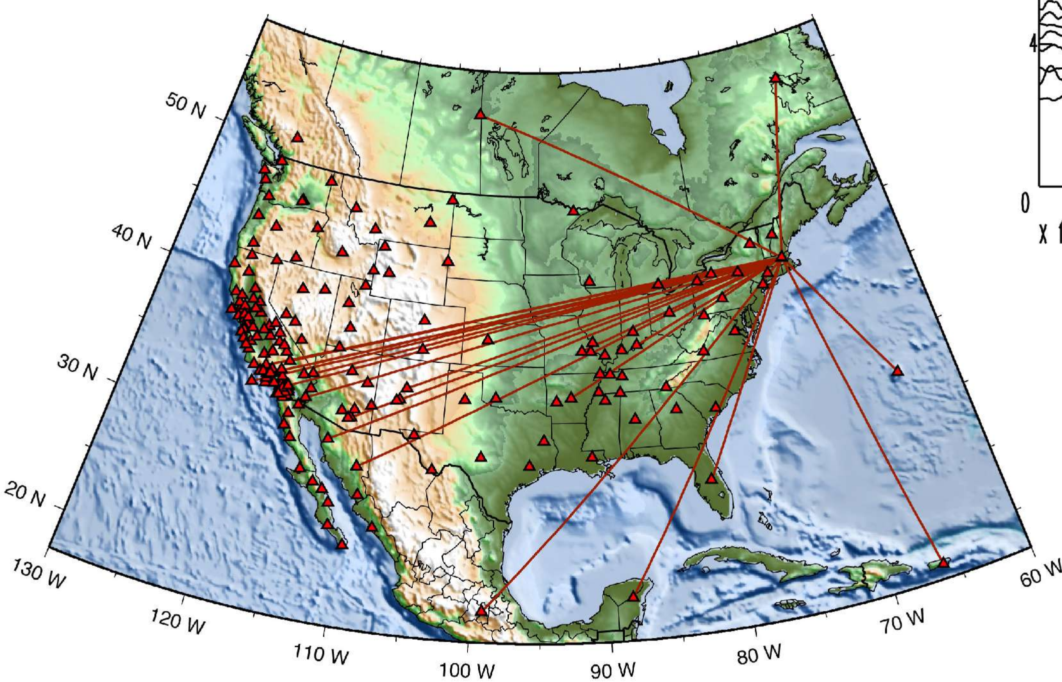


50 N
40 N
30 N
20 N
130 W
120 W
110 W
100 W
90 W
80 W
70 W
60 W

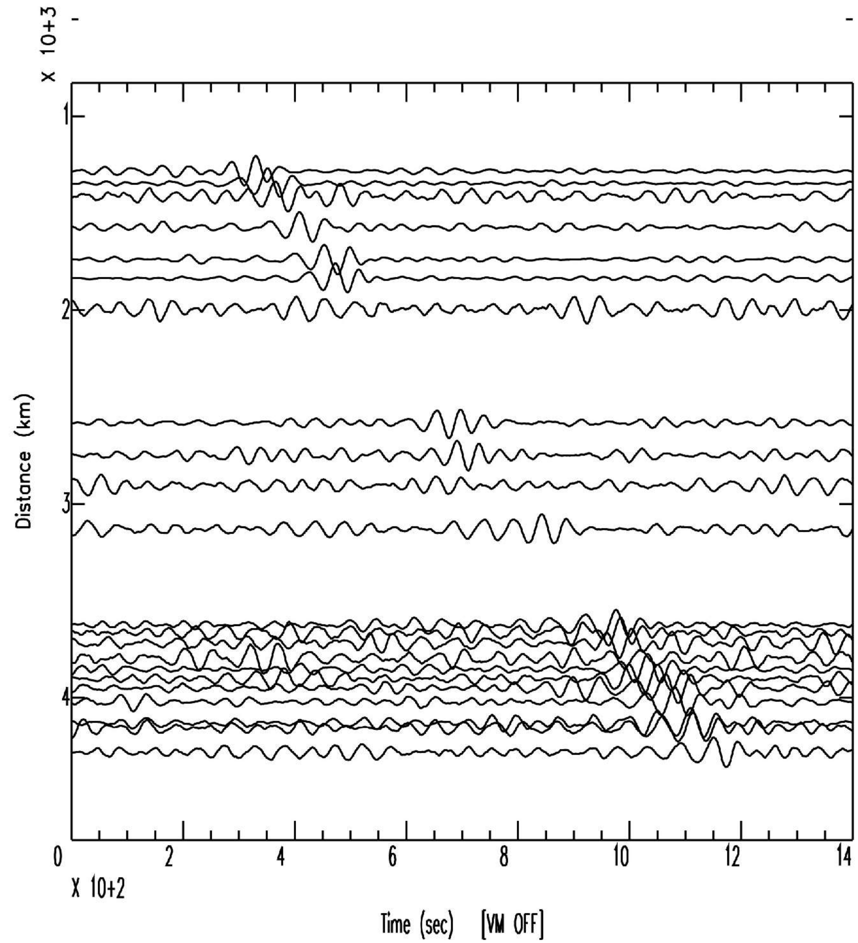


X 10+3
Distance (km)
X 10+2
Time (sec) [VM OFF]

HRV

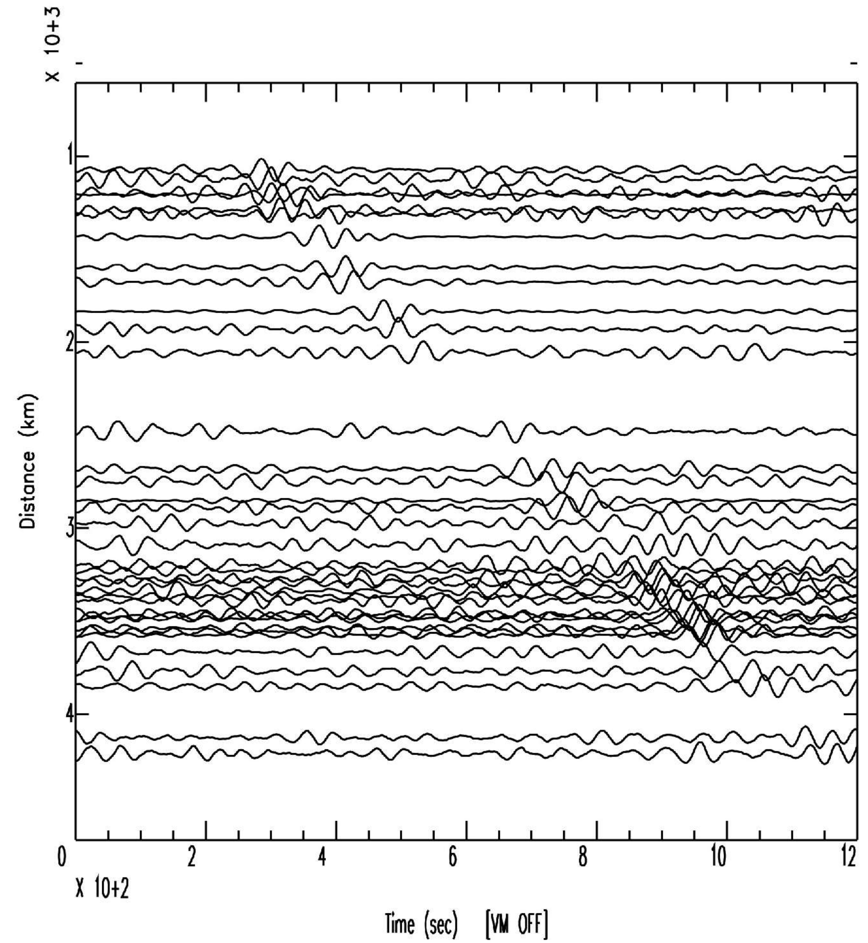


50 N
40 N
30 N
20 N
130 W
120 W
110 W
100 W
90 W
80 W
70 W
60 W

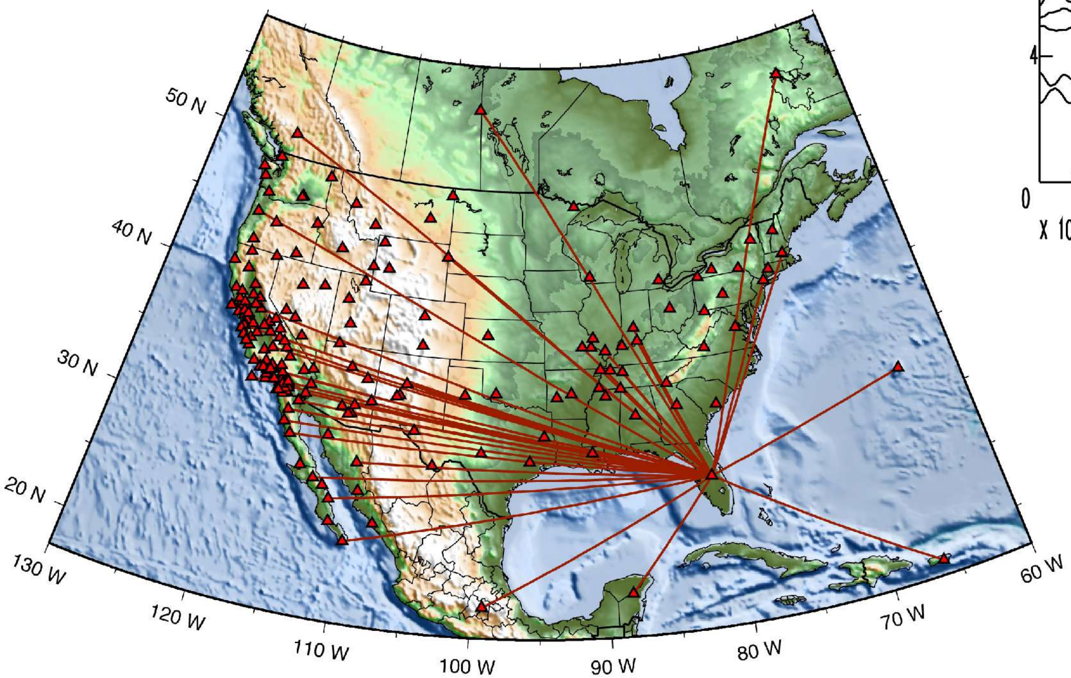


X 10+3
Distance (km)
1
2
3
4
0
2
4
6
8
10
12
14
X 10+2
Time (sec) [VM OFF]

DWPF

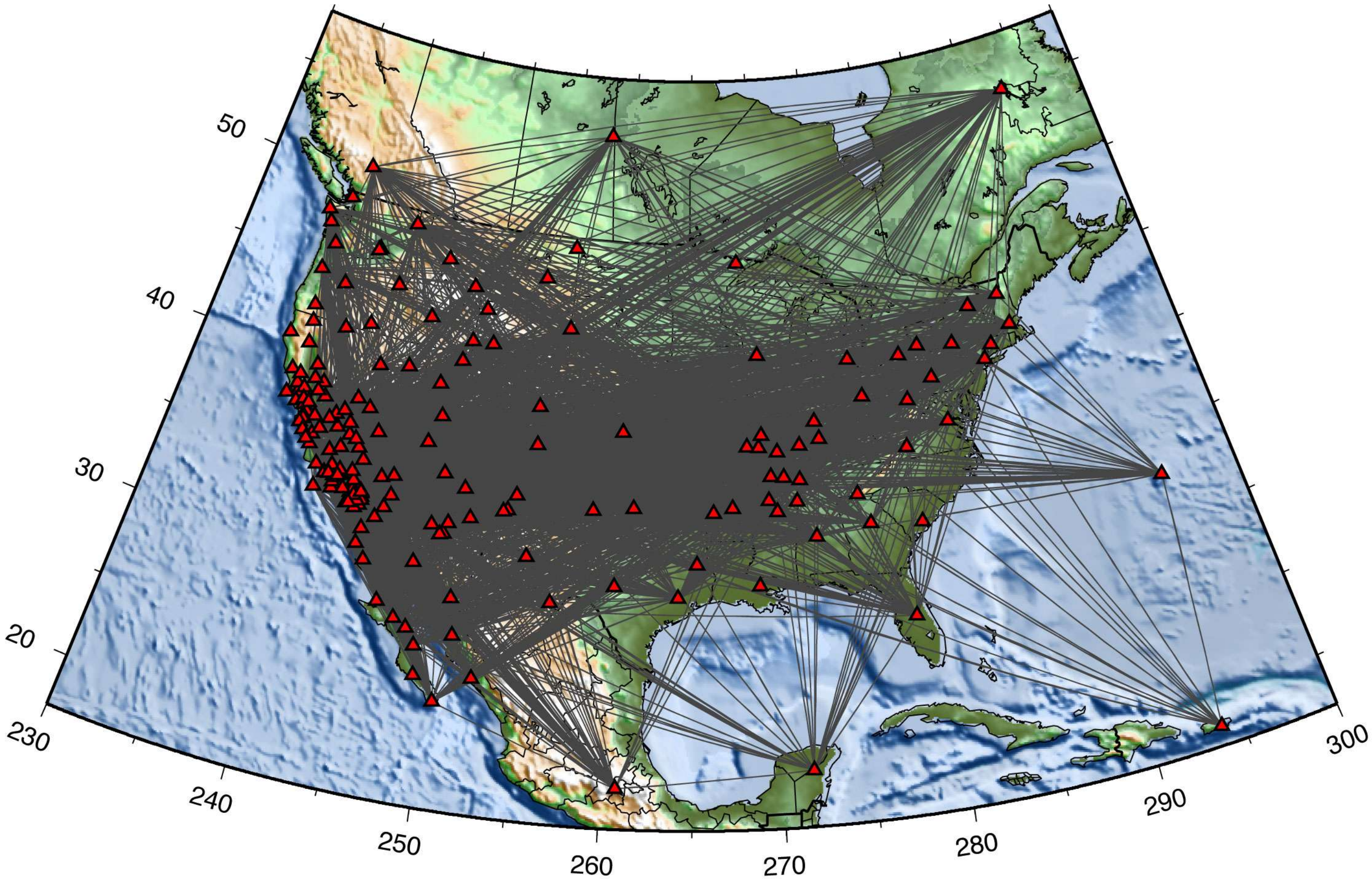


X 10+3
Distance (km)
Time (sec) [VM OFF]
X 10+2

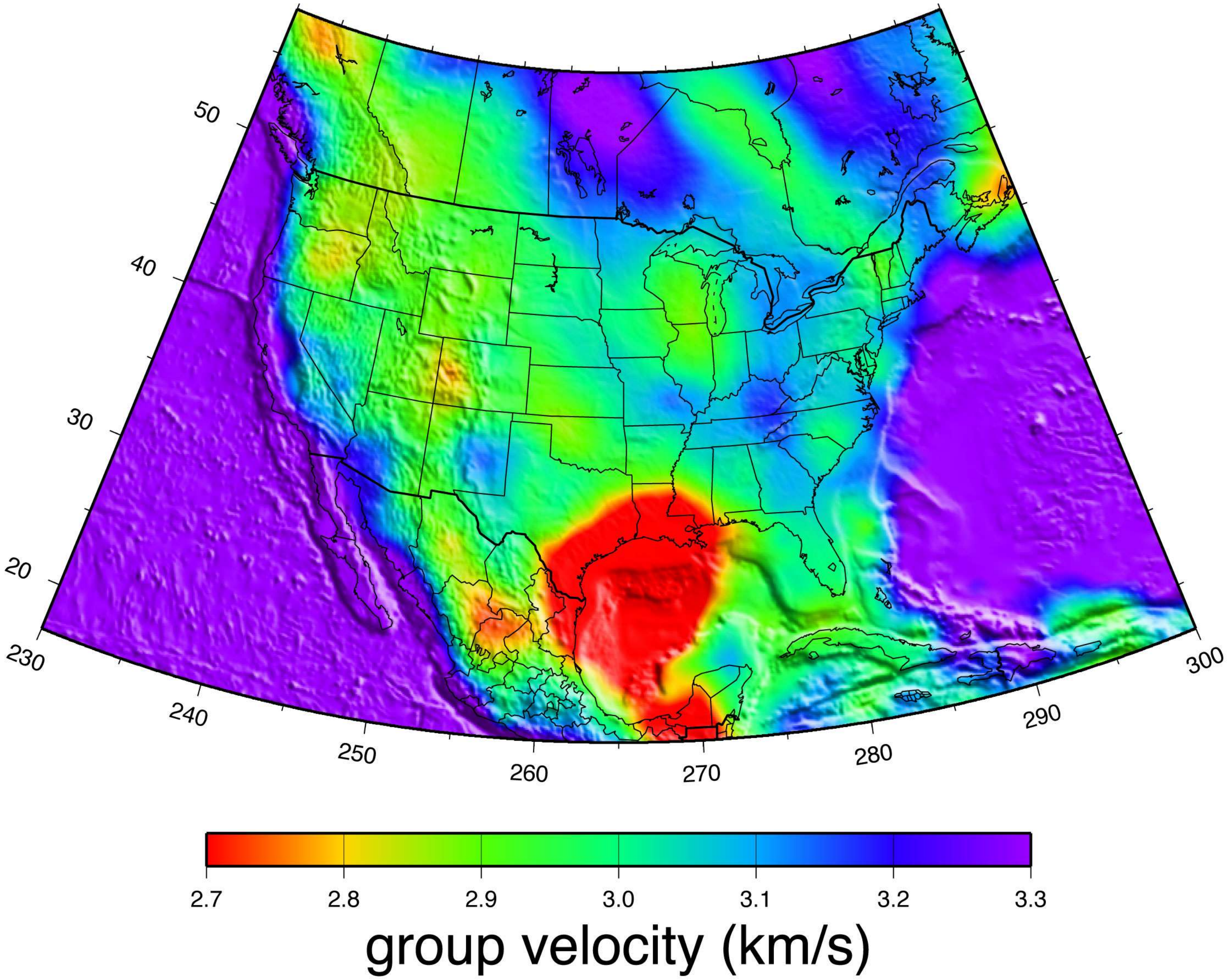


50 N
40 N
30 N
20 N
130 W
120 W
110 W
100 W
90 W
80 W
70 W
60 W

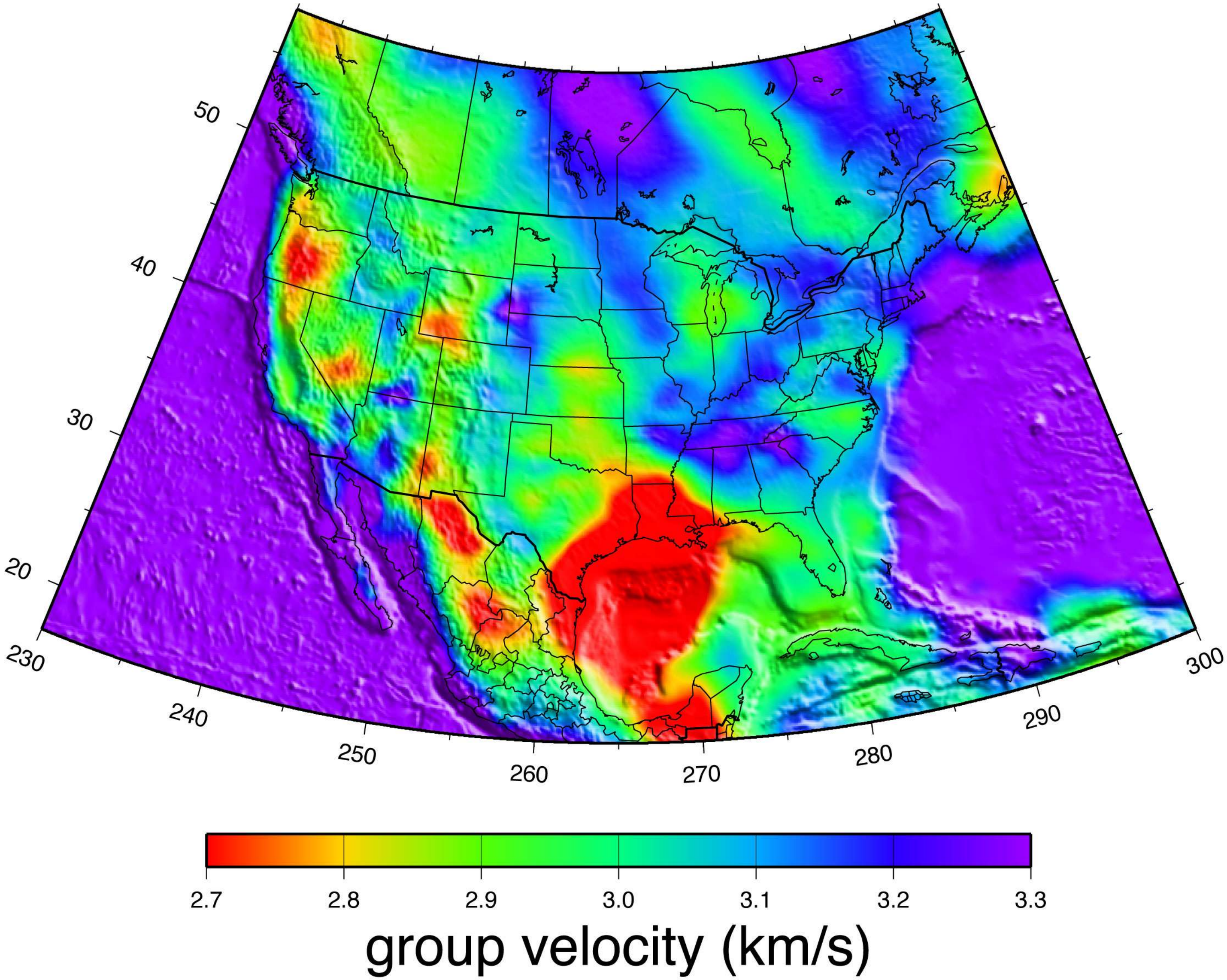
20 s Rayleigh wave group velocity measurements from ambient seismic noise (Nov., 2003-Feb., 2004; 4121 paths)



Reference dispersion map (CUB global tomographic model)

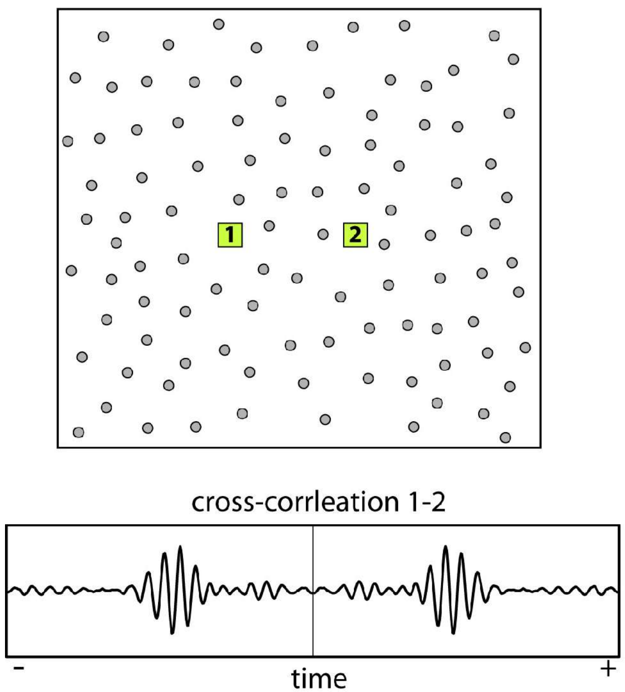


Inversion of noise-based measurements (Var. reduction 63%)

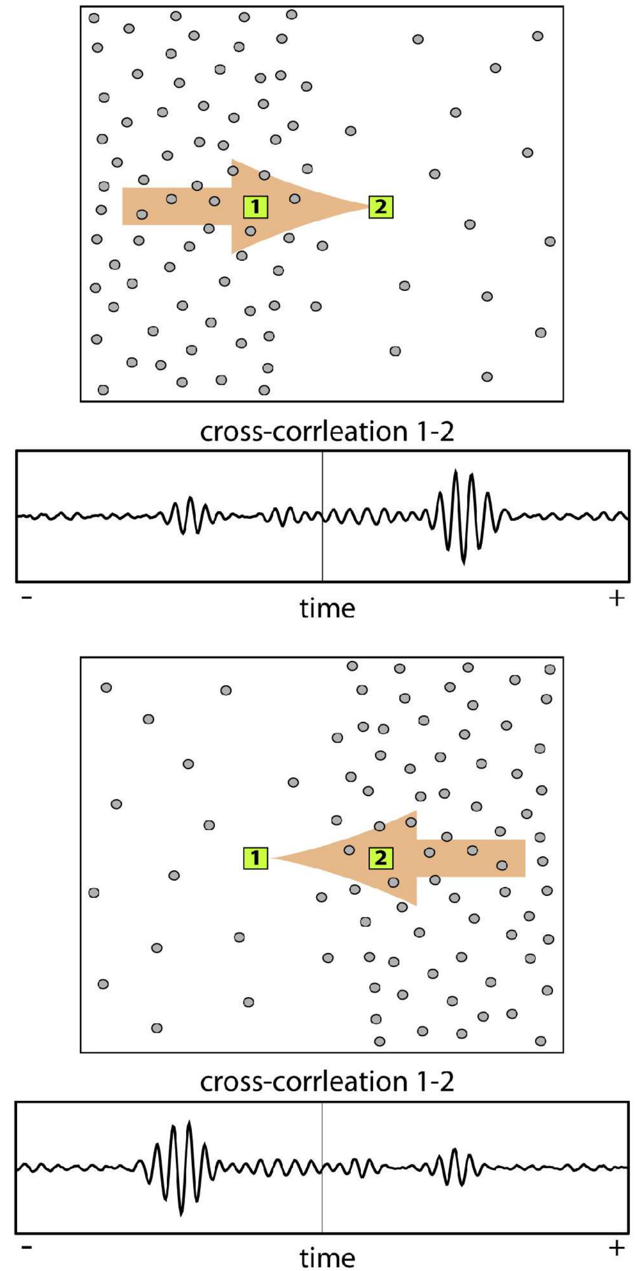


Tracing the origin of the seismic noise

Isotropic distribution of sources: symmetric cross-correlation

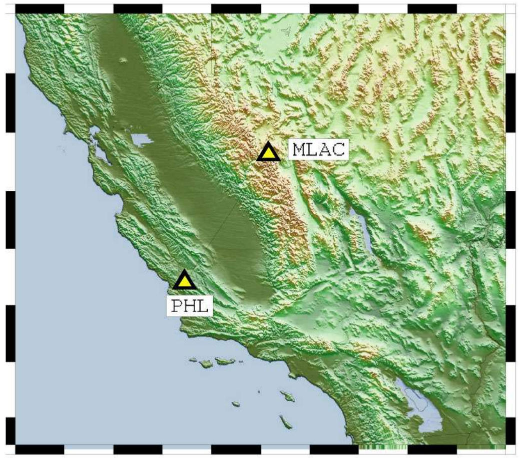


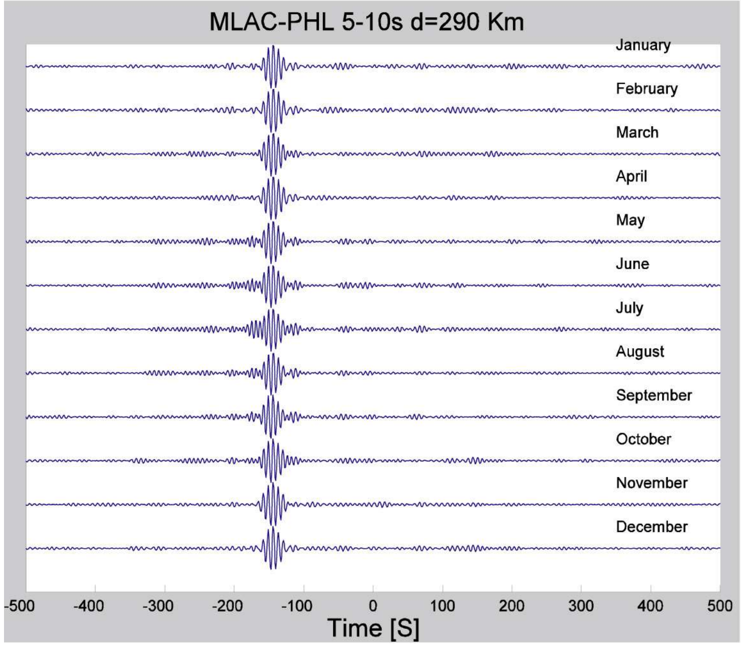
Anisotropic distribution of sources: asymmetric cross-correlation

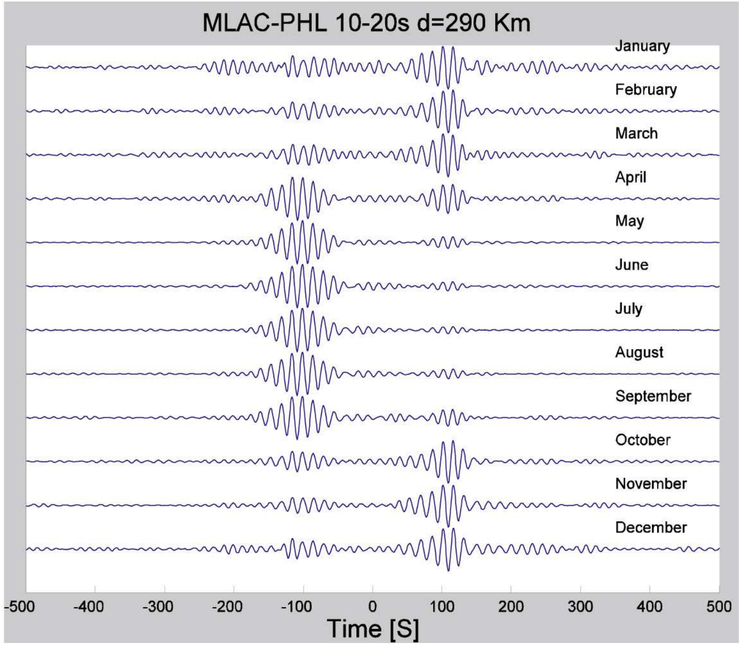


courtesy of Laurent Stehly (LGIT, Grenoble)

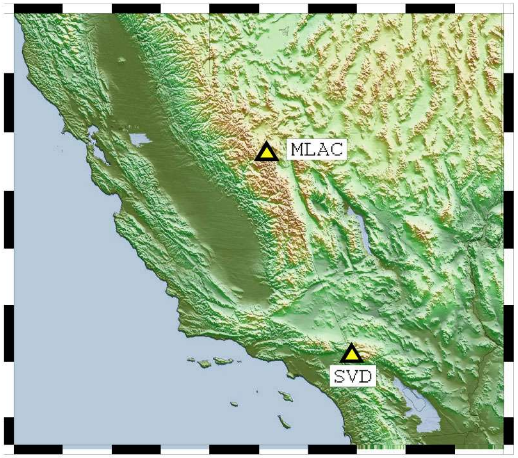
Tracing the origin of the seismic noise

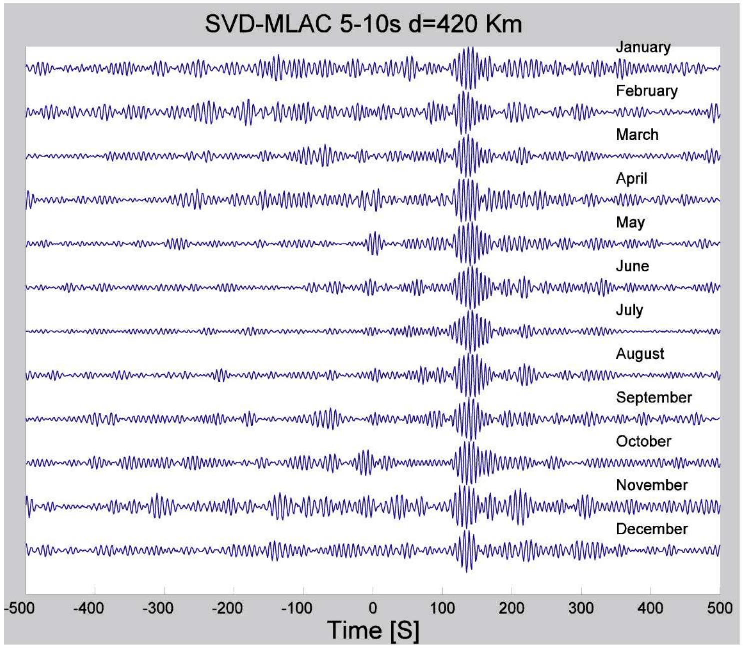


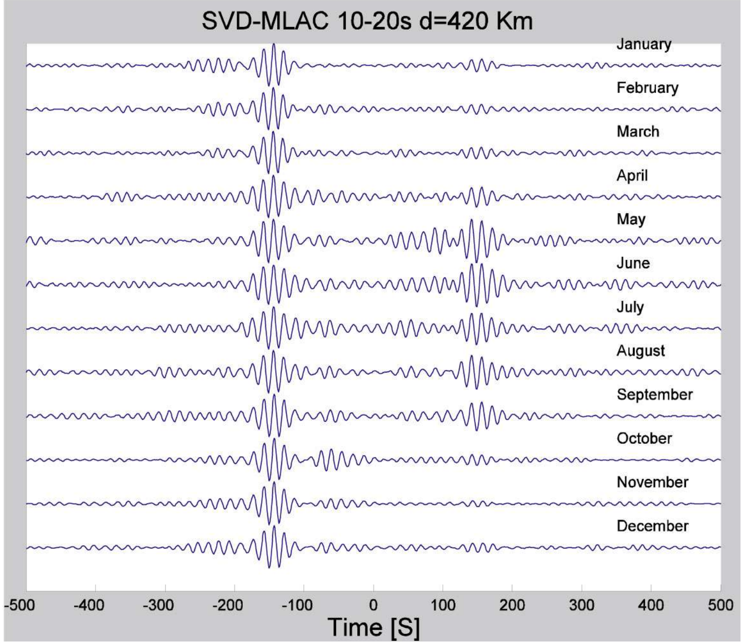


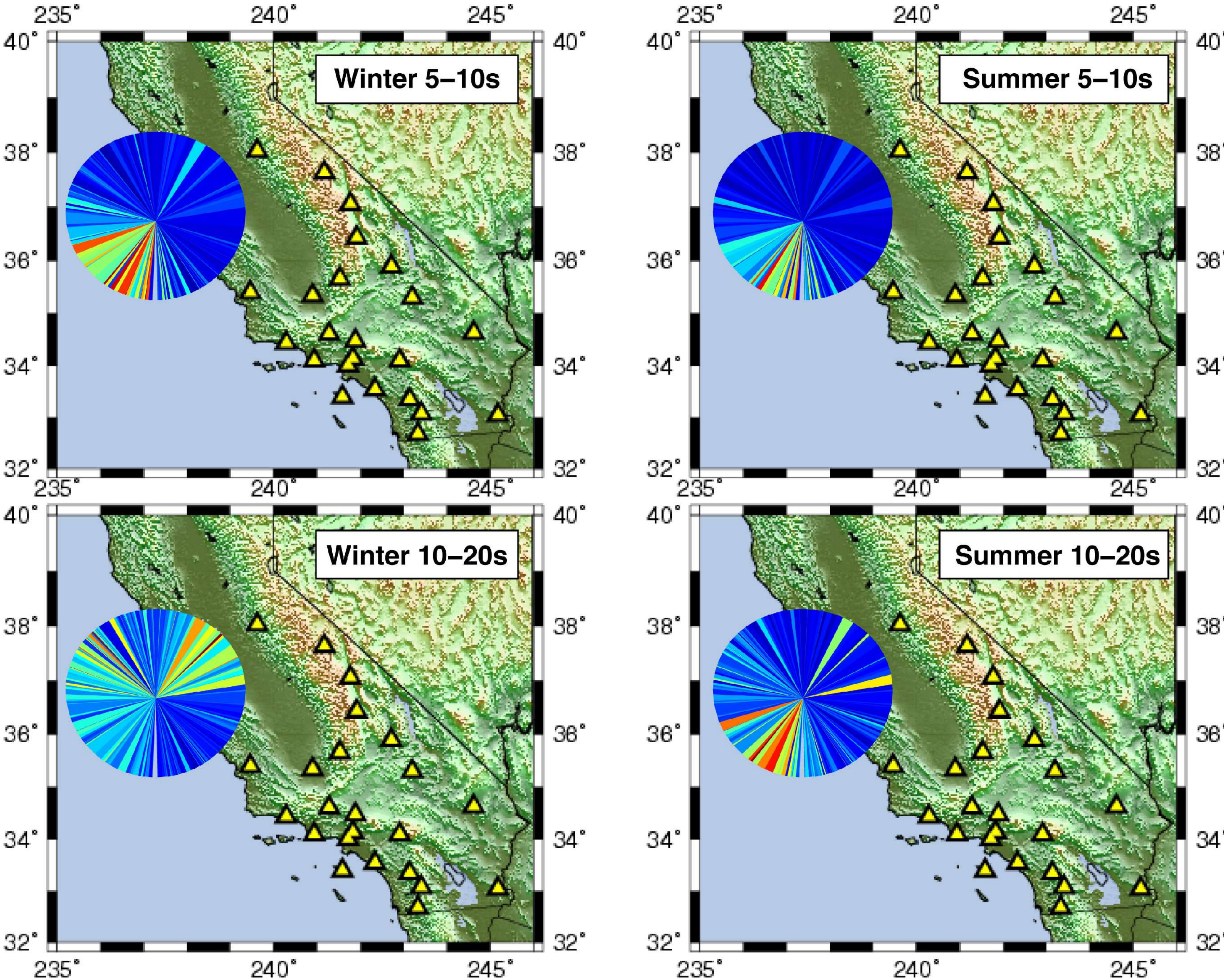


Tracing the origin of the seismic noise



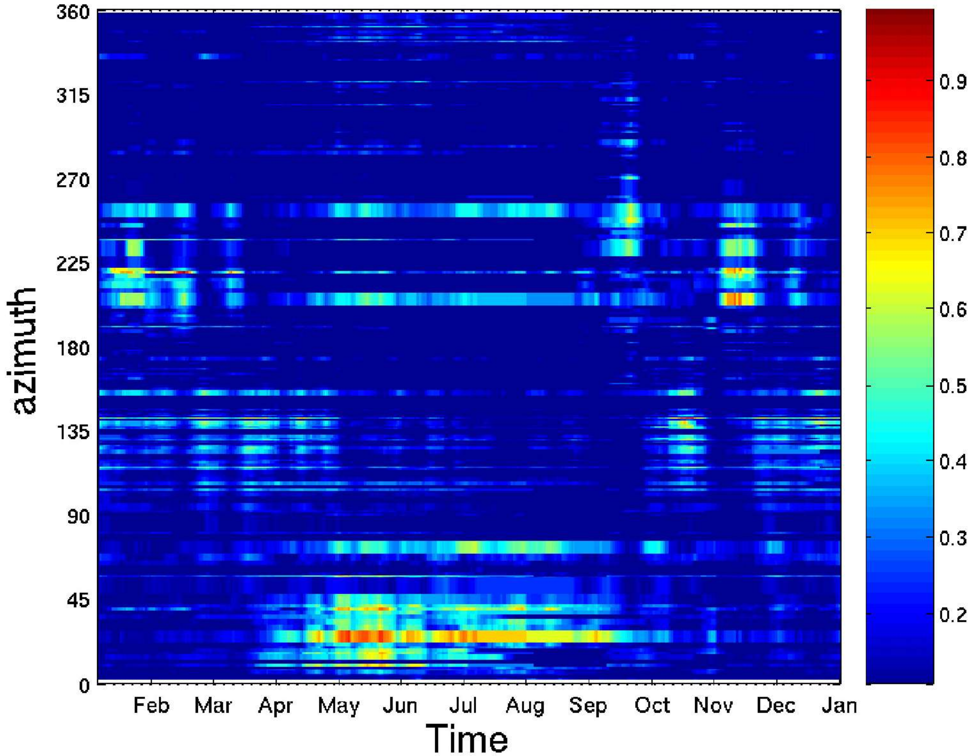


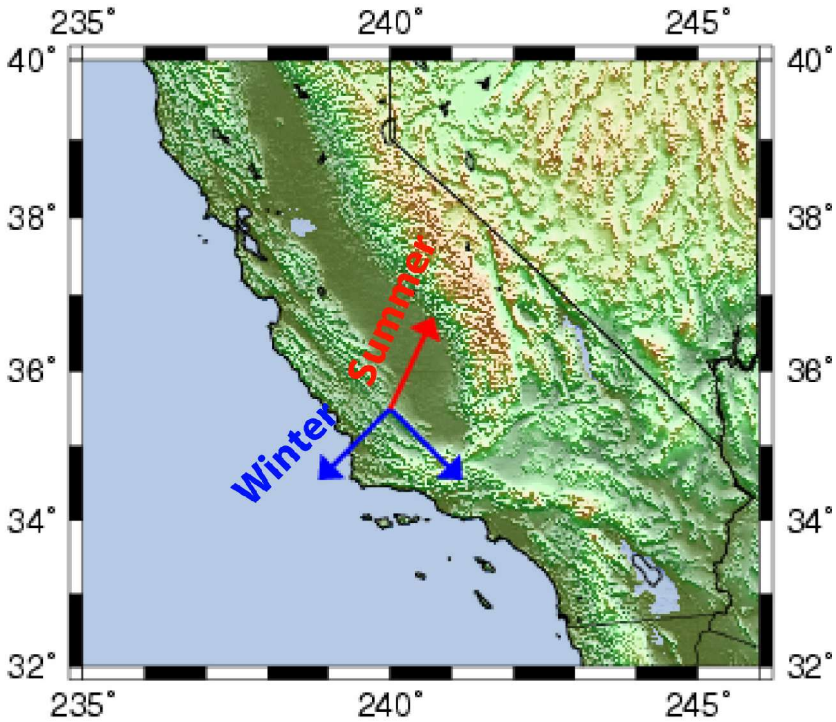



Winter 5–10s
Summer 5–10s
Winter 10–20s
Summer 10–20s
235°
240°
245°
40°
38°
36°
34°
32°

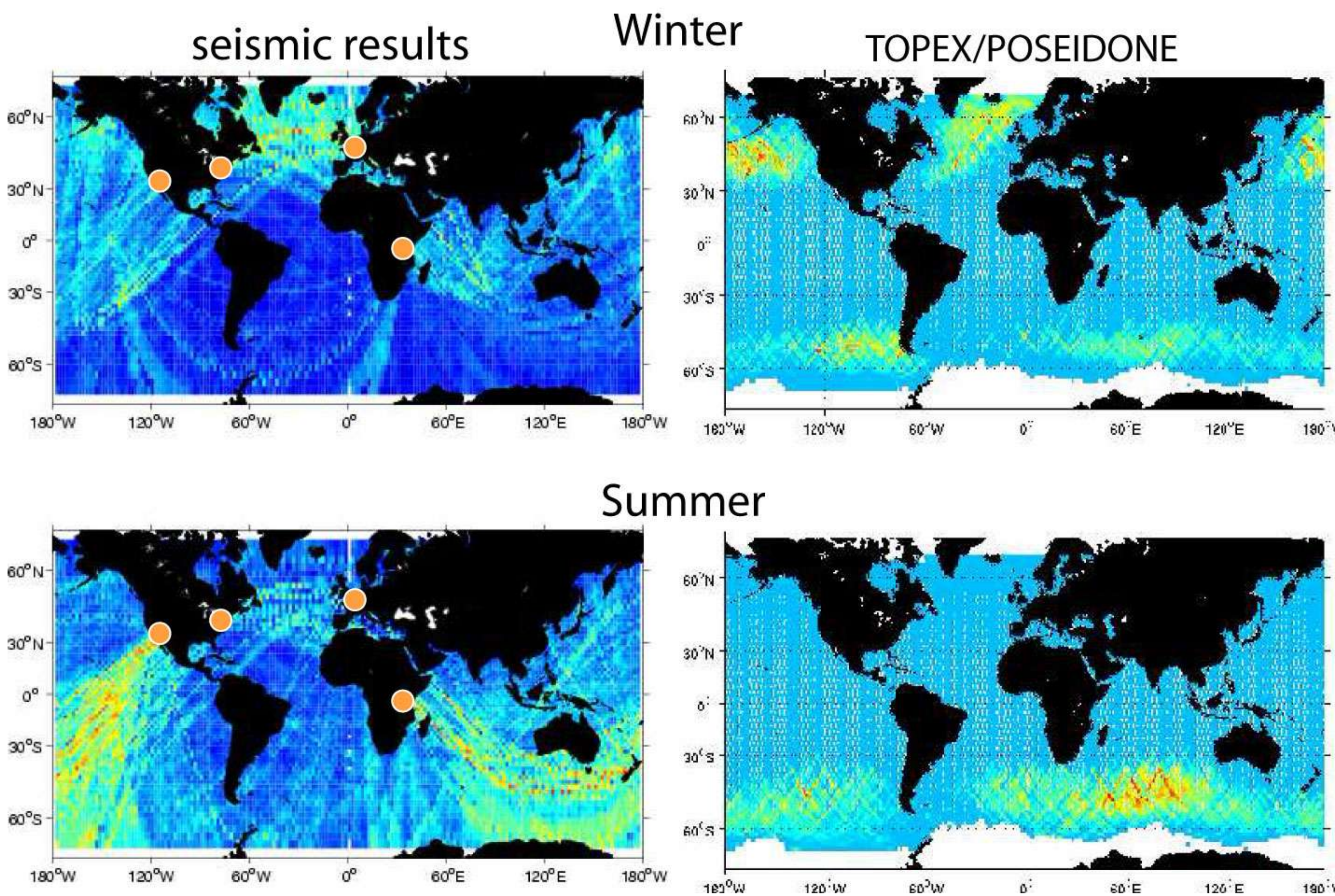
Tracing the origin of the seismic noise

10 - 20 s





Seismic noise sources (10-20 s)



the end

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:

- eigenfunctions

- eigenfrequencies

- modal excitations, uncorrelated random variables:

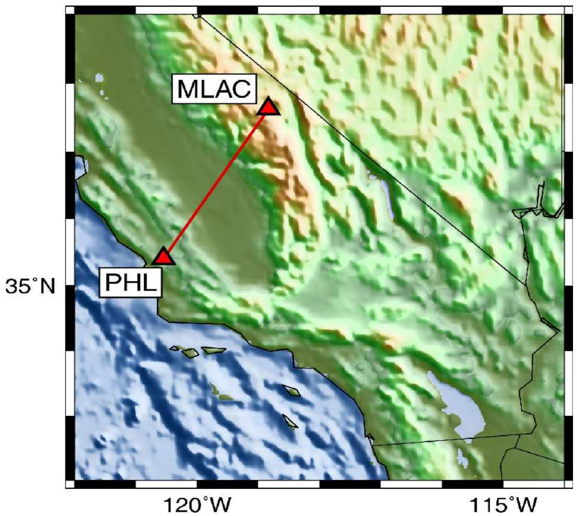
- spectral energy density

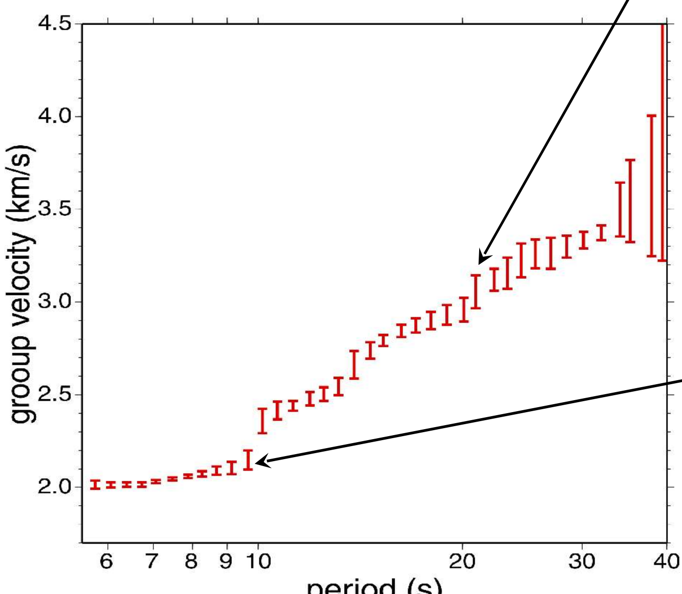
cross-correlation between points *x* and *y* :

differs only by an amplitude factor *F(ω)* from an actual Green function between *x* and *y*

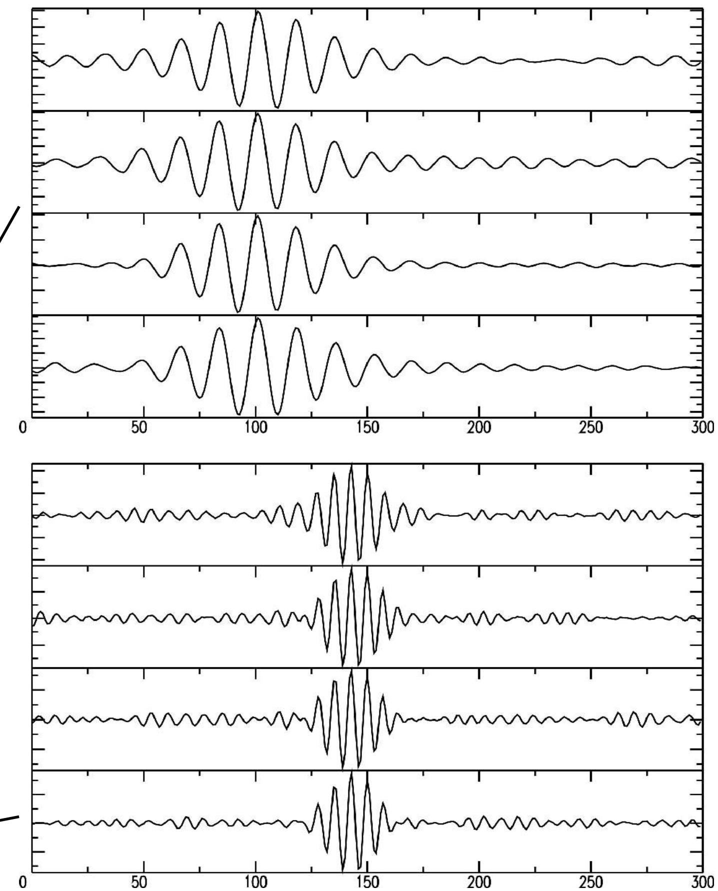
estimation of errors

PHL - MLAC 290 km





correlations computed over four different three-week periods



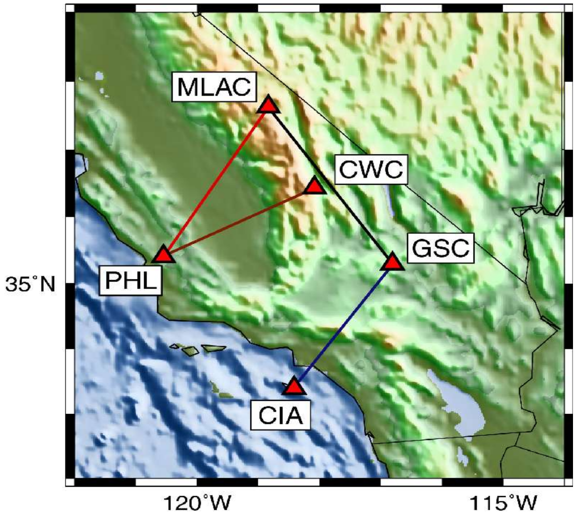
band-passed 15 - 30 s

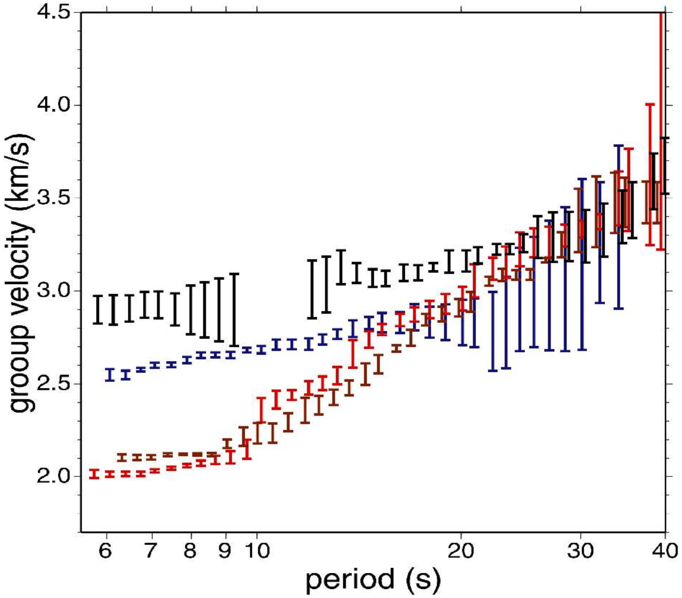
band-passed 5 - 10 s

repetitive measurements provide **uncertainty estimations**

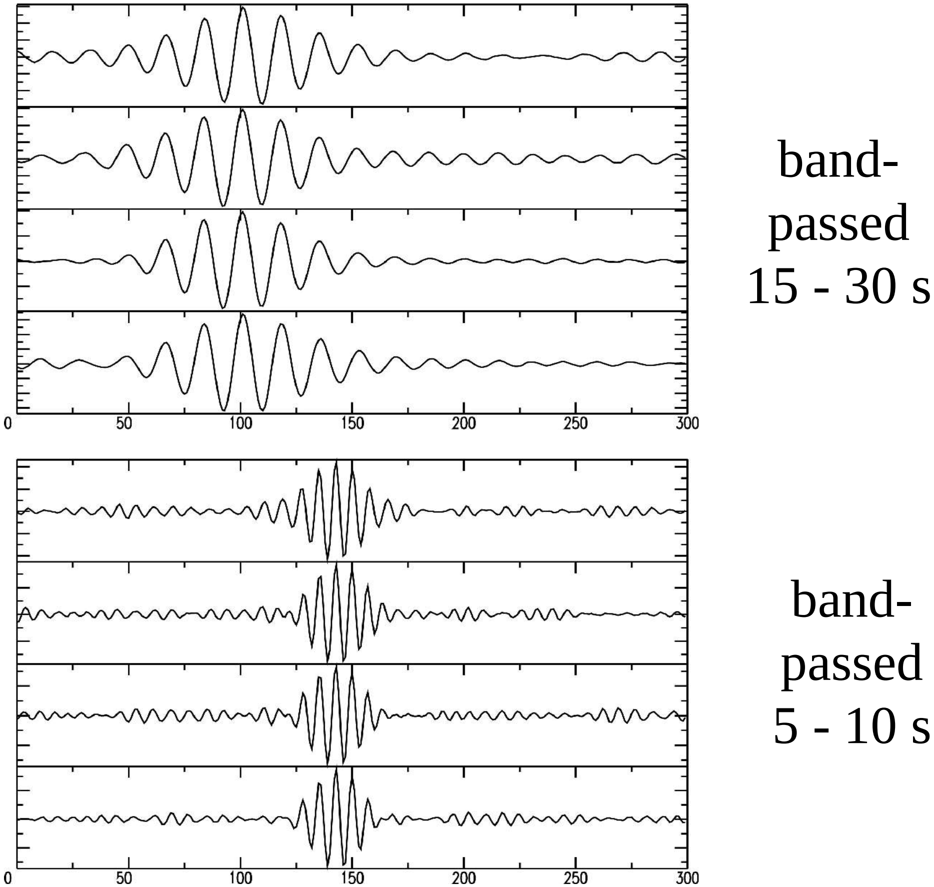
estimation of errors

PHL - MLAC 290 km





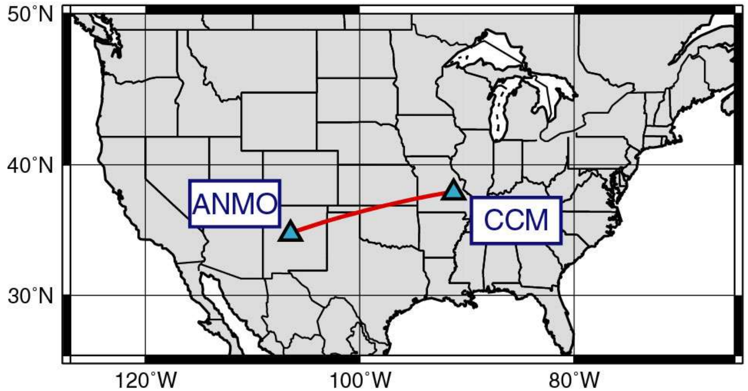
correlations computed over four different three-week periods



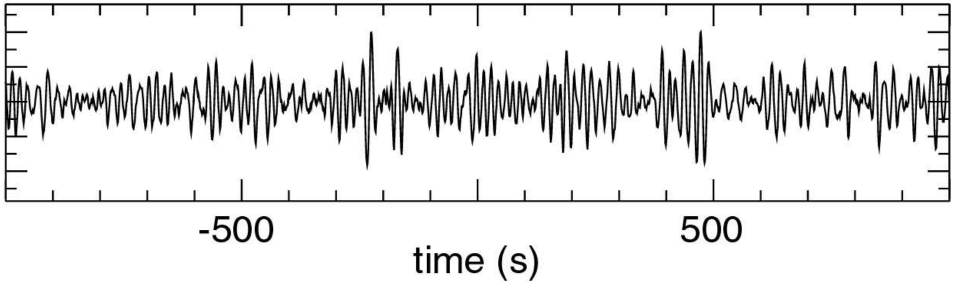
repetitive measurements provide **uncertainty estimations**

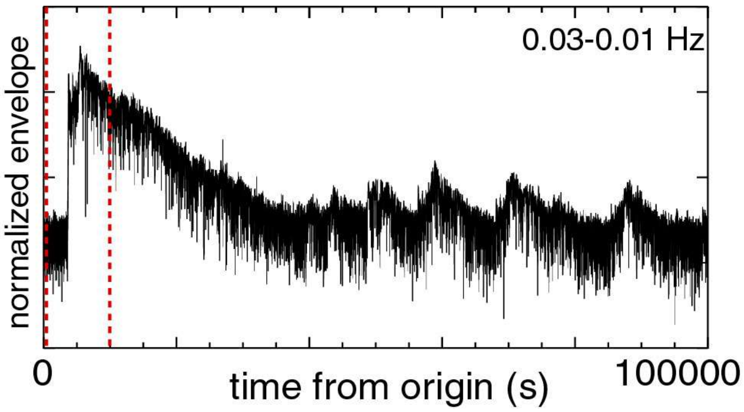
Cross-correlations from teleseismic codas: ANMO - CCM

distance 1405 km



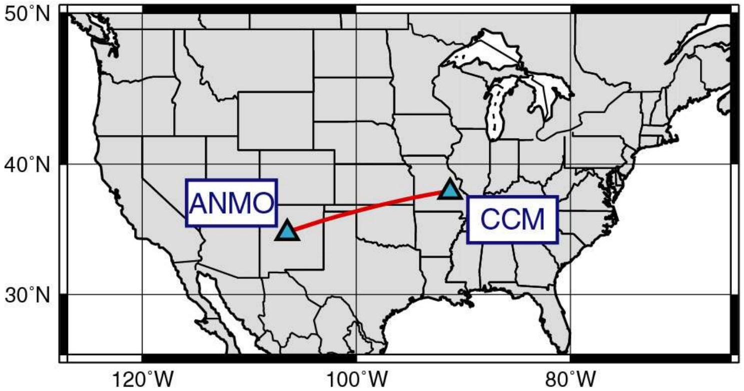
vertical component
stack from13 earthquakes

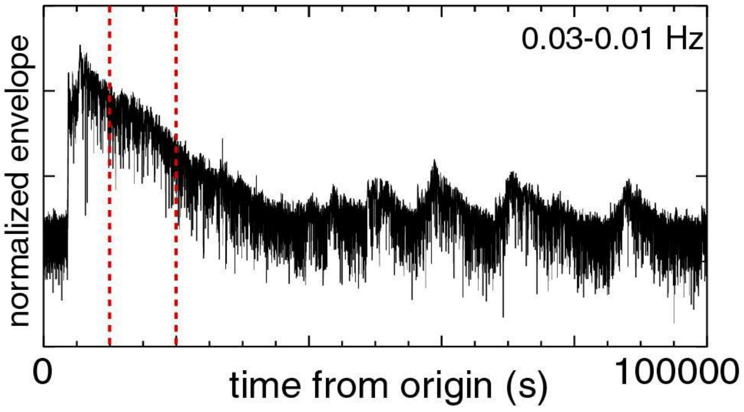




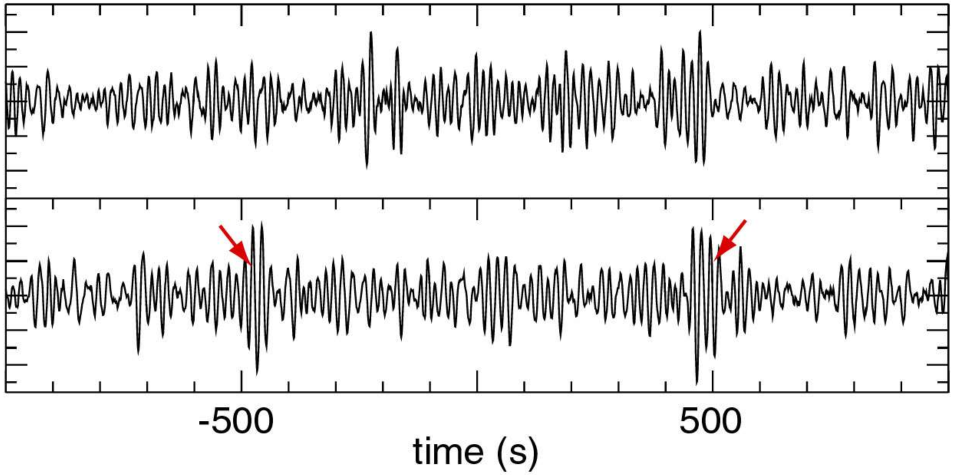
Cross-correlations from teleseismic codas: ANMO - CCM

distance 1405 km



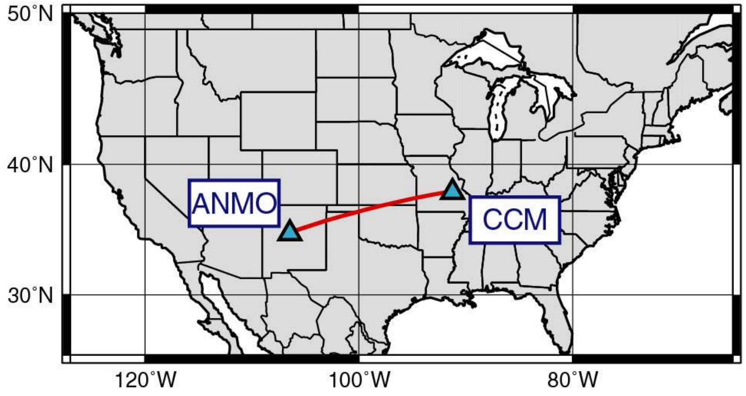


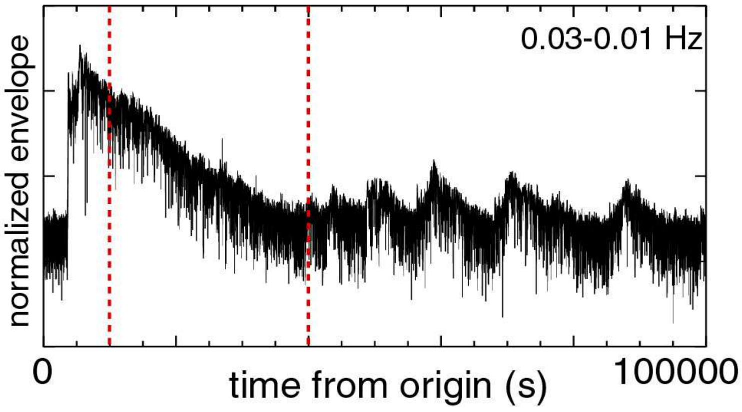
vertical component
stack from13 earthquakes



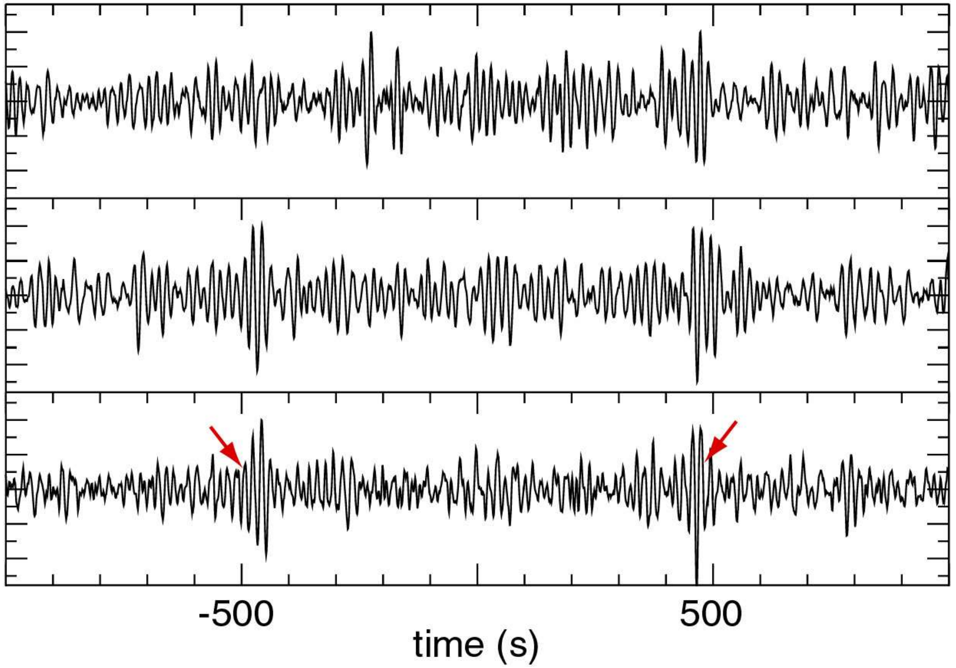
Cross-correlations from teleseismic codas: ANMO - CC

distance 1405 km



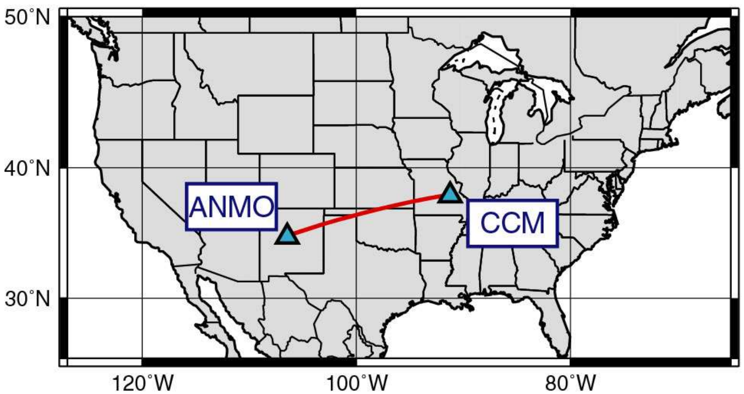


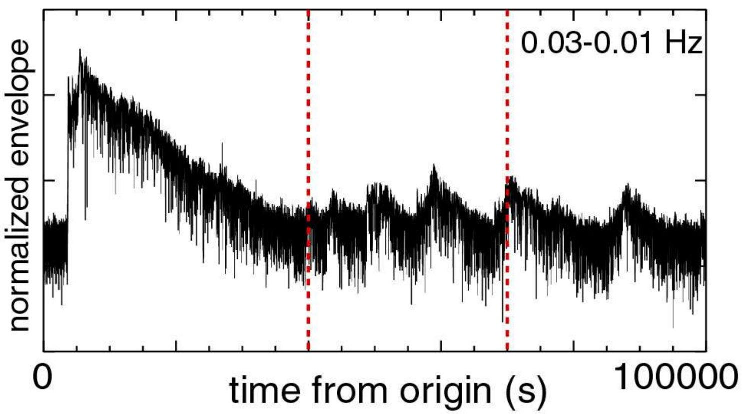
vertical component
stack from13 earthquakes



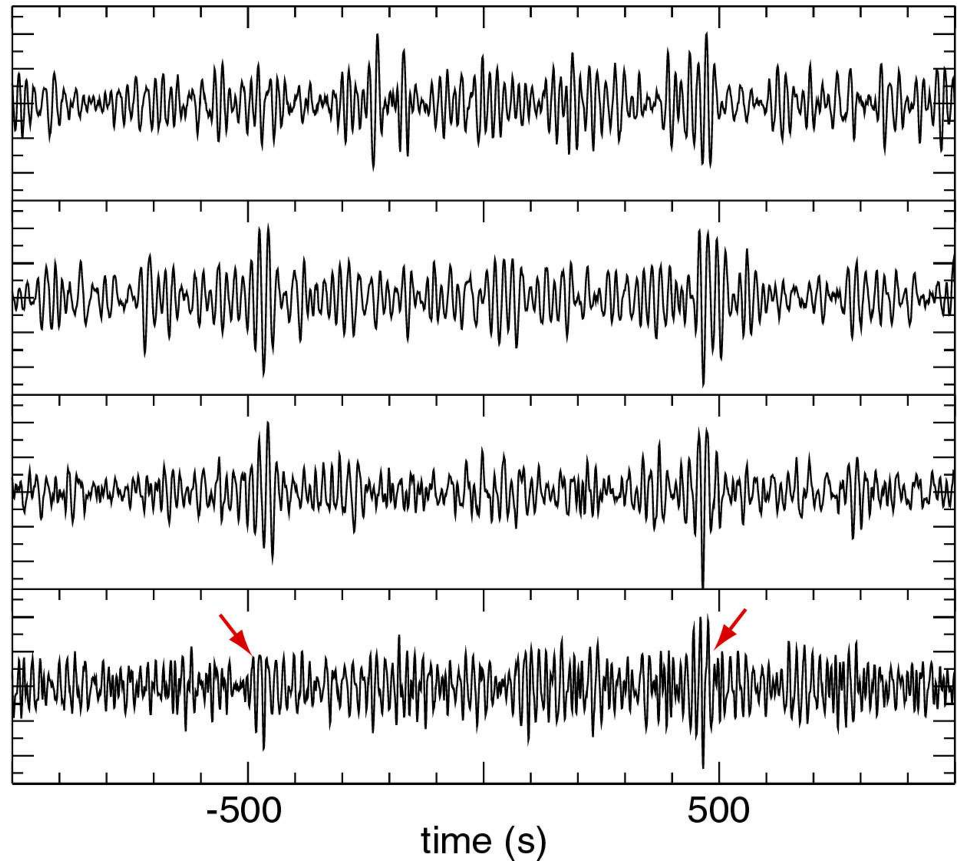
Cross-correlations from teleseismic codas: ANMO - CCM

distance 1405 km





vertical component
stack from13 earthquakes

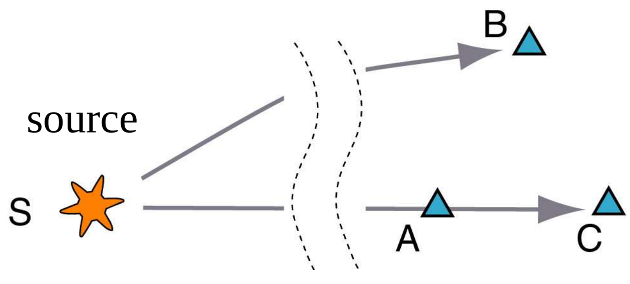


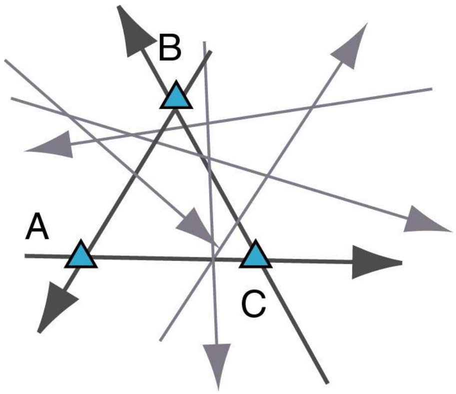
Measurement Procedure

- 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

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