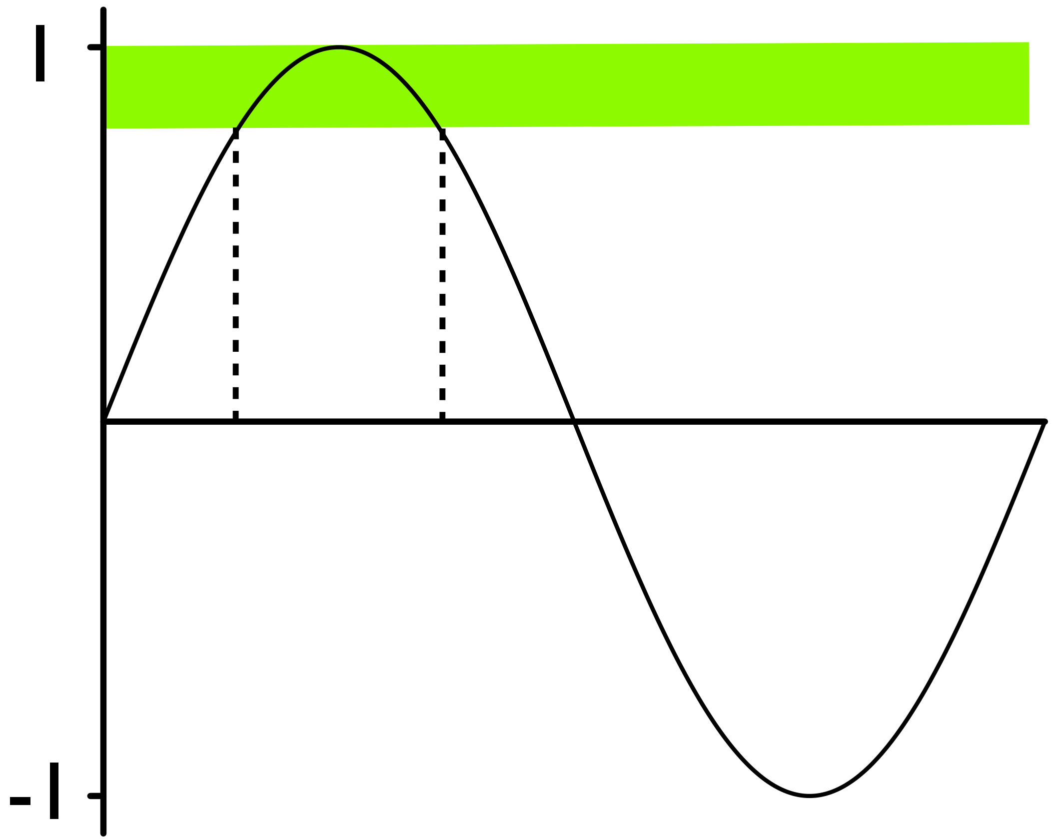
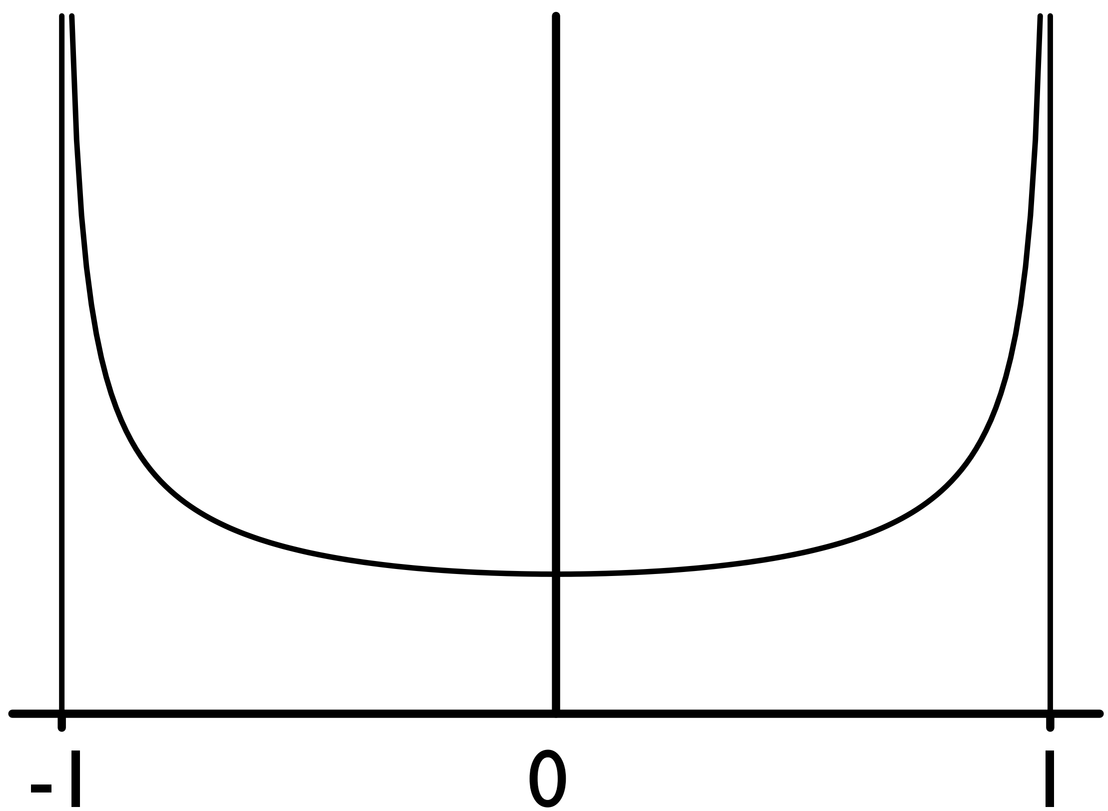
Using noise for tomography

Noise, cross correlation, phase velocities, and tomography

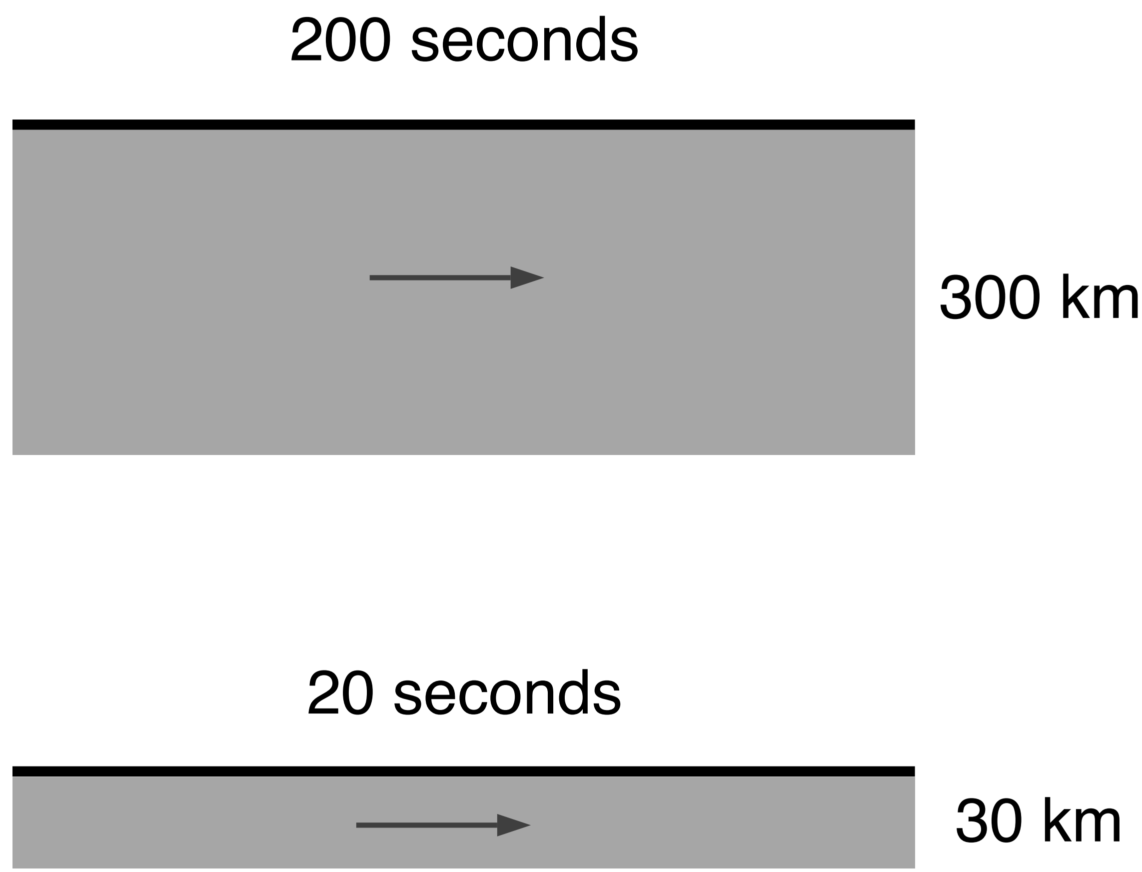
a sine wave

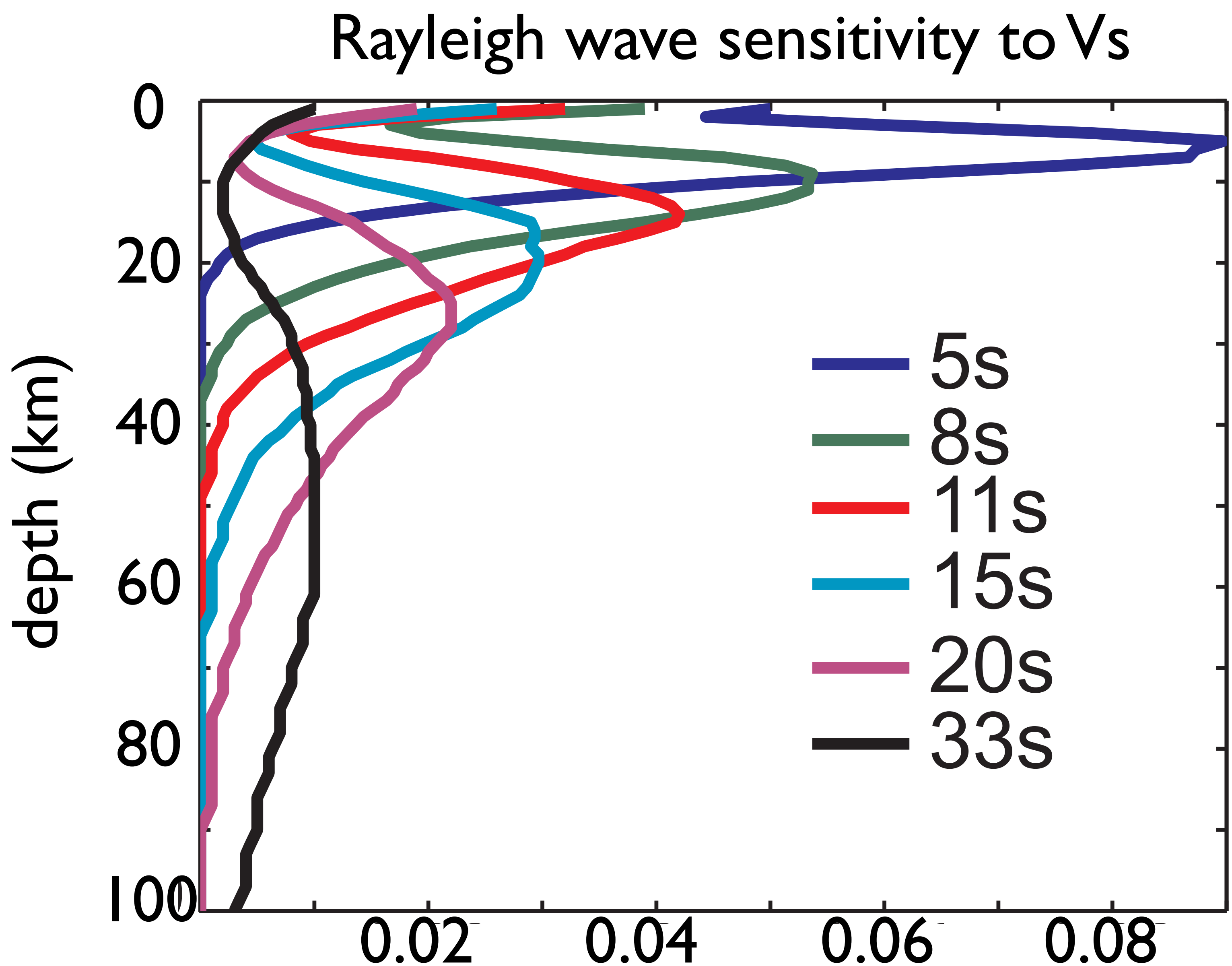


probability density function for a sine wave



Sensitivity of surface wave velocities to elastic stucture at depth





Rayleigh wave sensitivity to Vs
depth (km)
0
20
40
60
80
100
0.02
0.04
0.06
0.08
5s
8s
11s
15s
20s
33s

Requirements for high-resolution (~50 km) surface-wave tomography:

1. short paths to resolve small structures
2. short periods ($5 < T < 25$ sec) to resolve shallow (crustal) structure
3. evenly distributed sources (earthquakes) to create a tomographic image

These are not met by traditional earthquake-based techniques

Starting point:

Much of the "noise" recorded at a station is fundamental mode Rayleigh and Love waves arriving from different directions

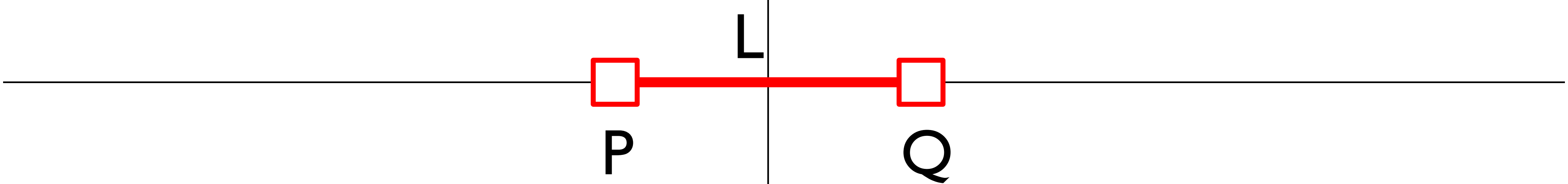
Proposition:

The cross correlation of background seismic noise recorded at two stations provides information about the propagation speed (the phase velocity) of surface waves between the two stations.

Explored by many, e.g., Aki, Campillo, Cox, Lobkis, Ritzwoller, Sabra, Shapiro, Snieder and many others, also in other fields

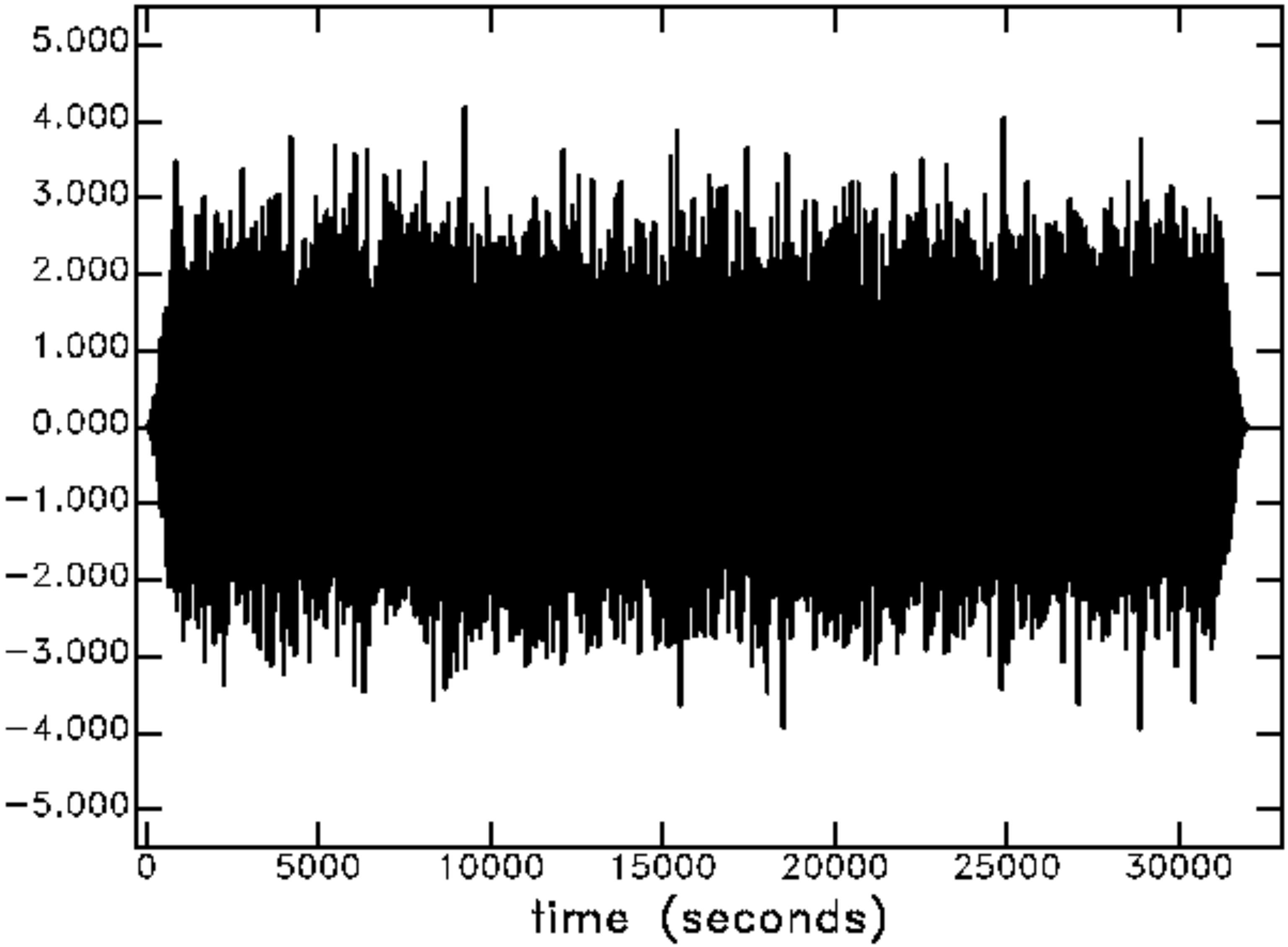
Two stations, P and Q, separated by L km

What is the cross correlation of noise signals recorded at P and Q?

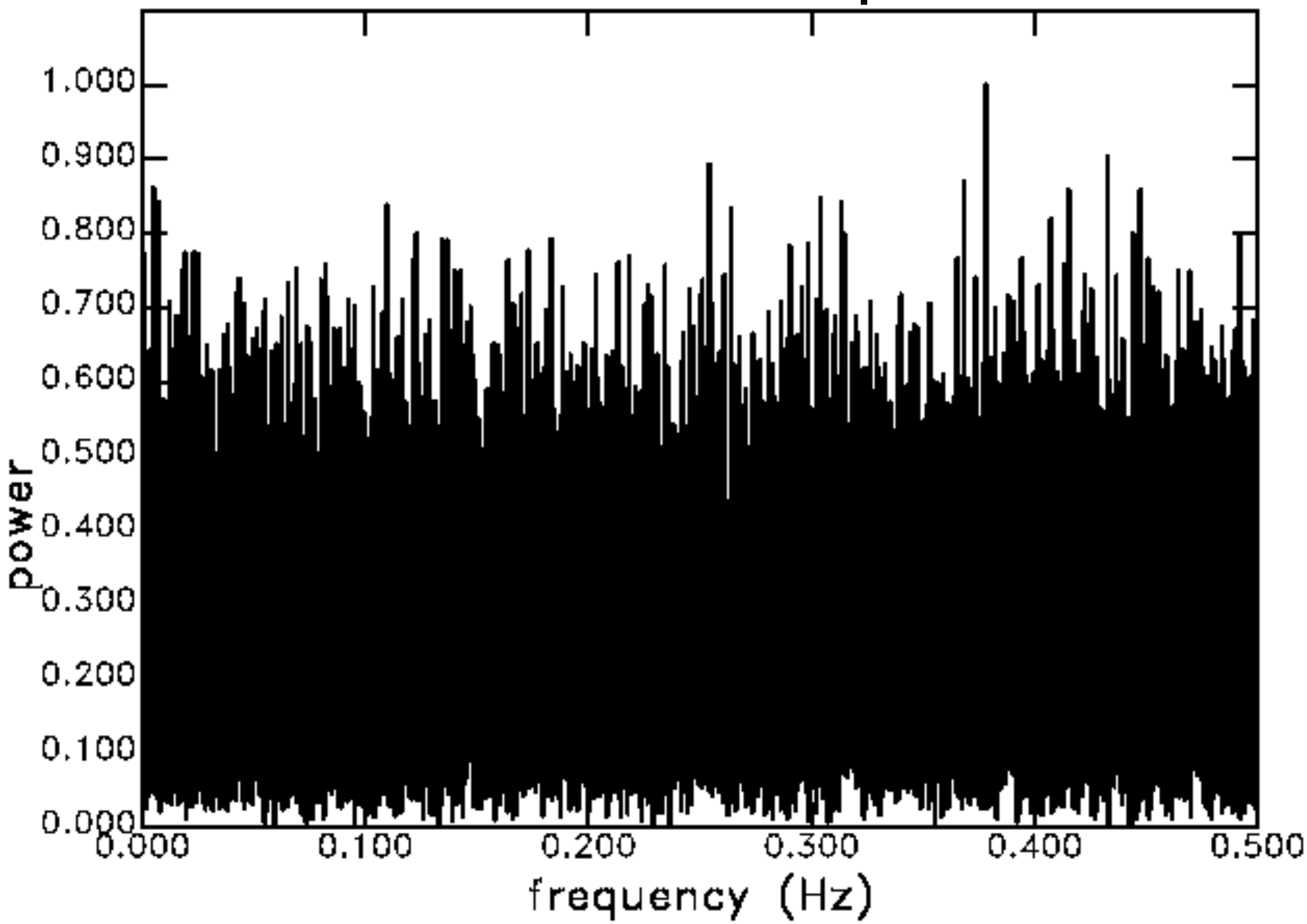


$$R_{PQ}(\tau) = \frac{1}{T}\int_0^T s_P(t)s_Q(t+\tau)dt$$

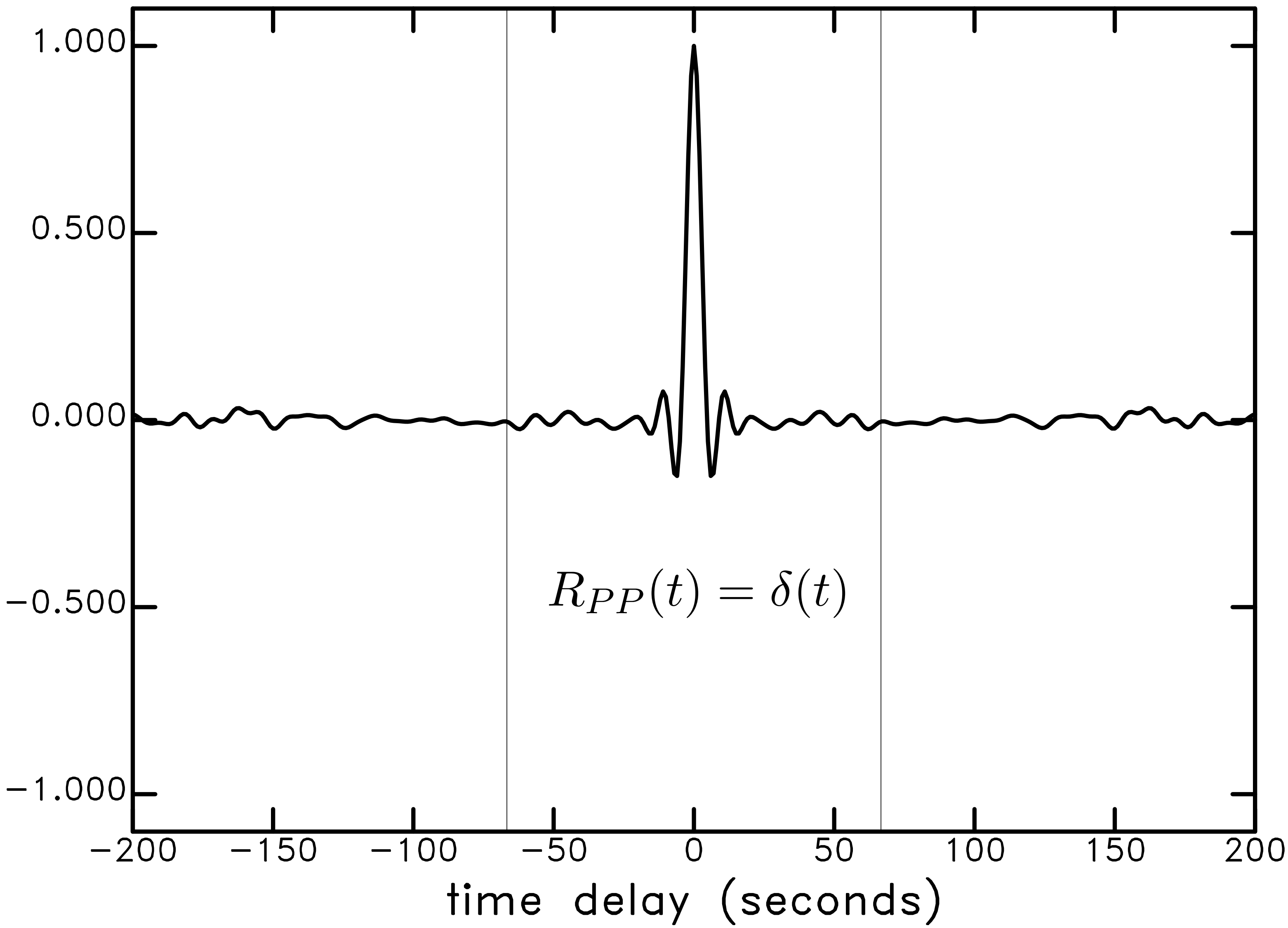
Gaussian white noise, 1 Hz sampling



Gaussian white noise spectrum

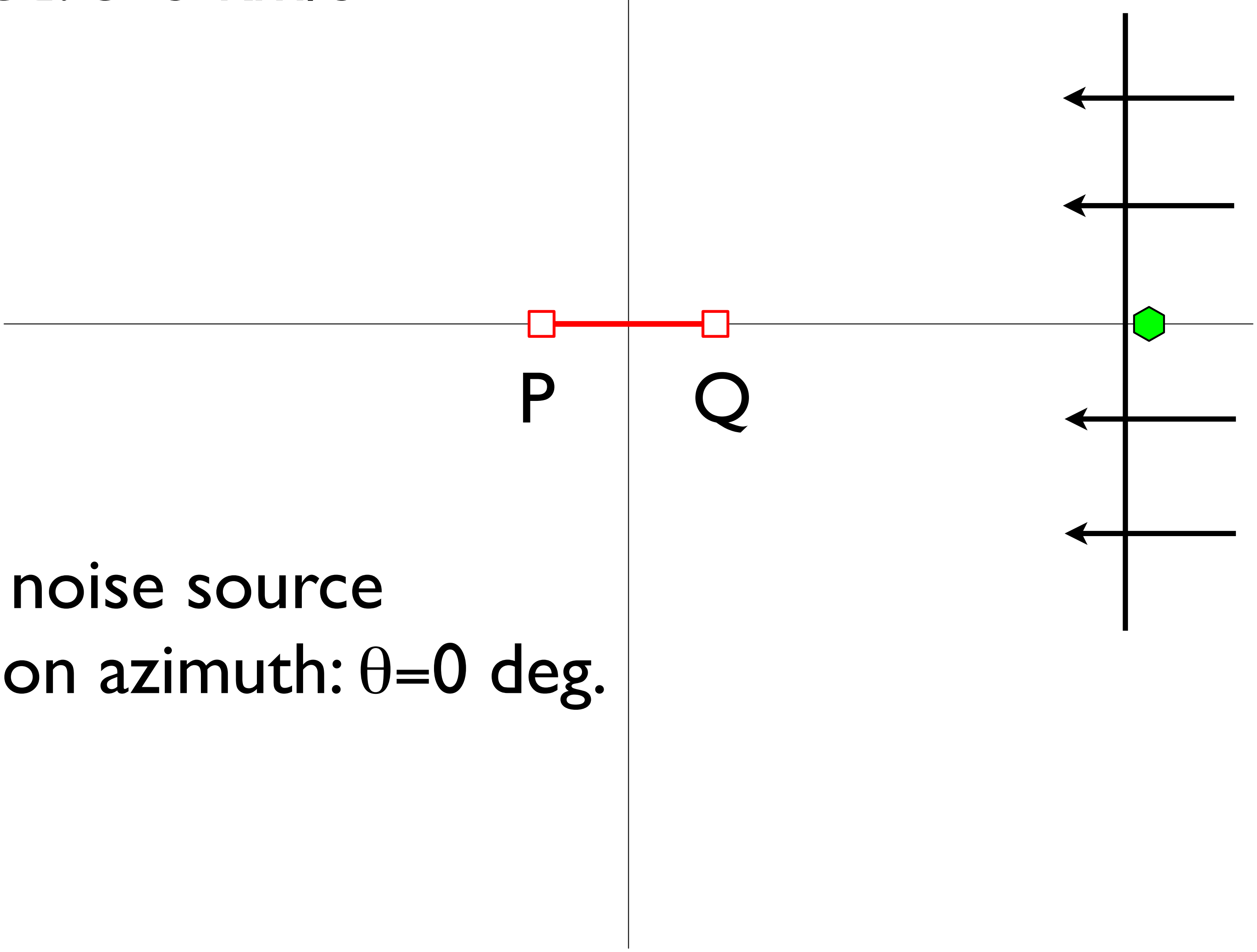


Auto-correlation function of noise



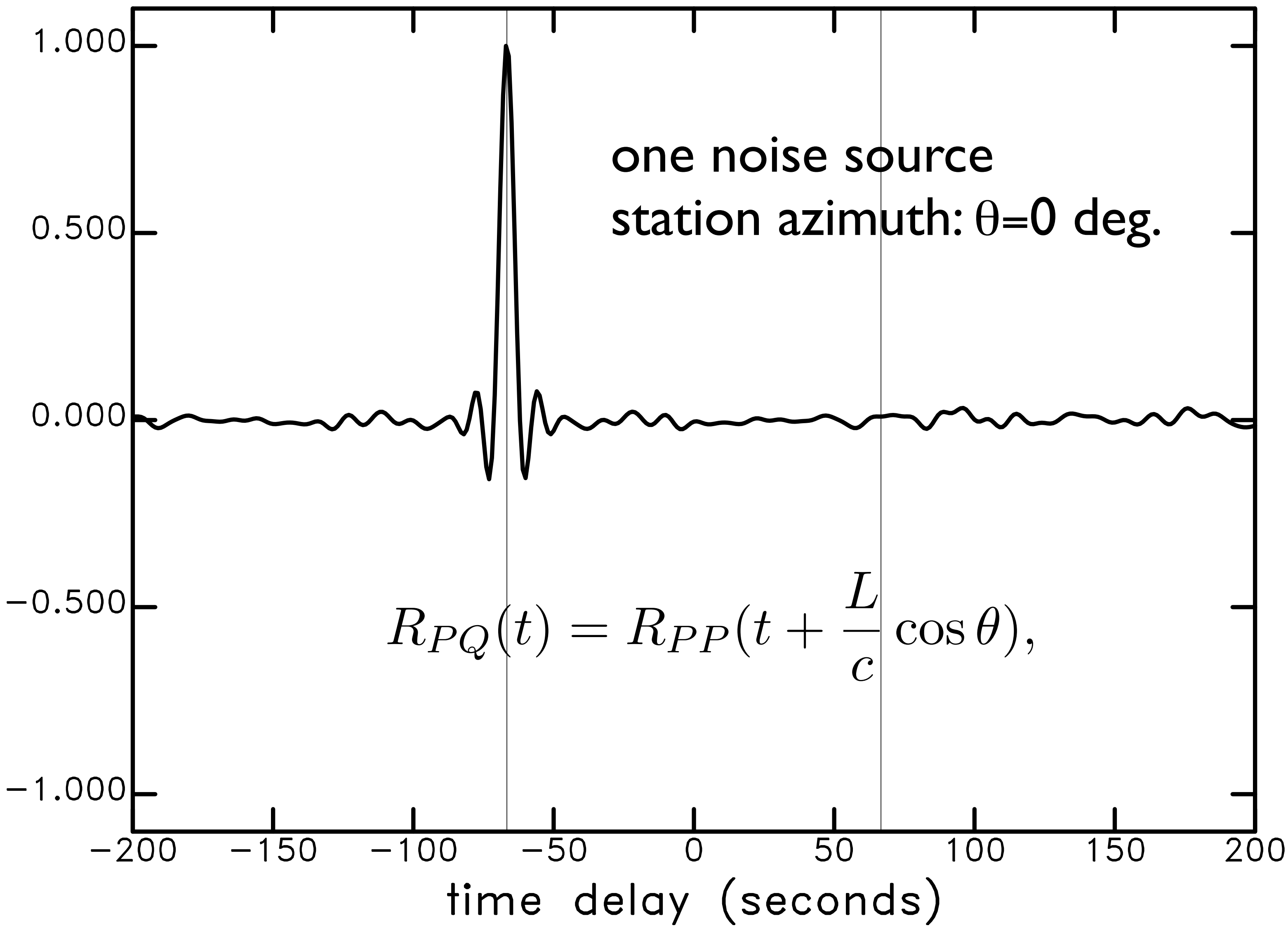
Plane wave incident on two stations, P and Q

distance: L=200 km
speed: c=3 km/s

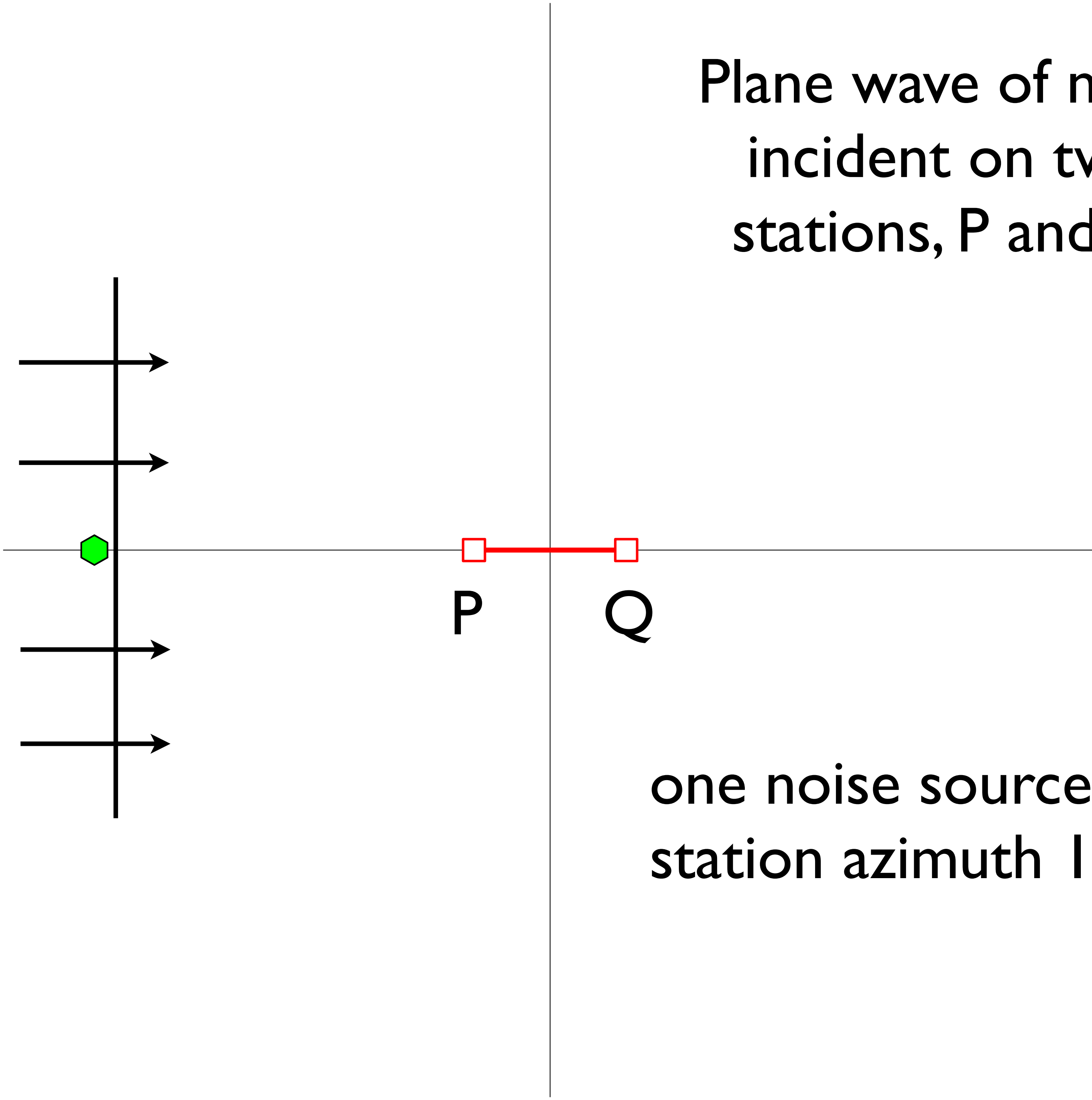


one noise source
station azimuth: θ=0 deg.

Cross-correlation function, P and Q

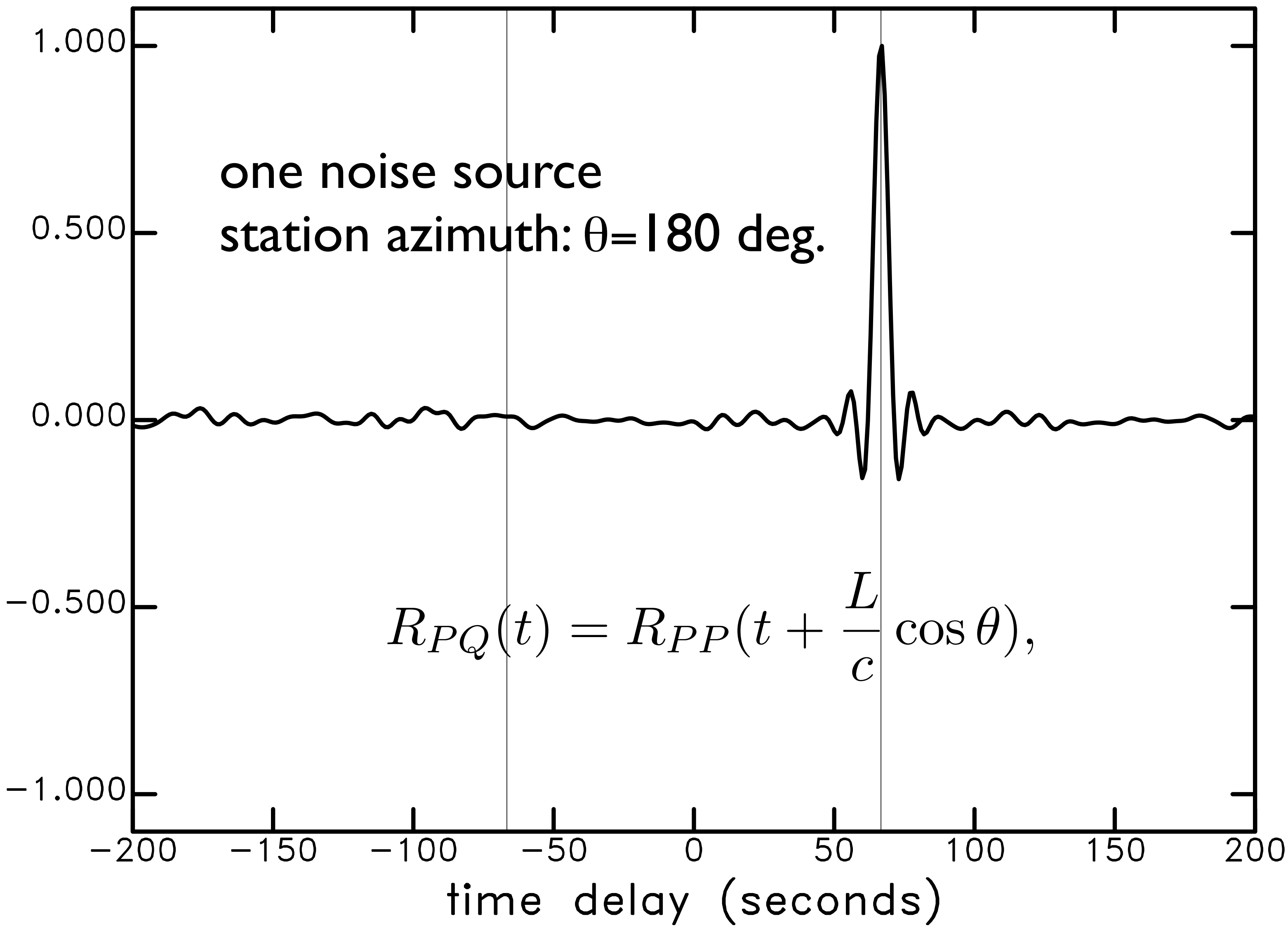


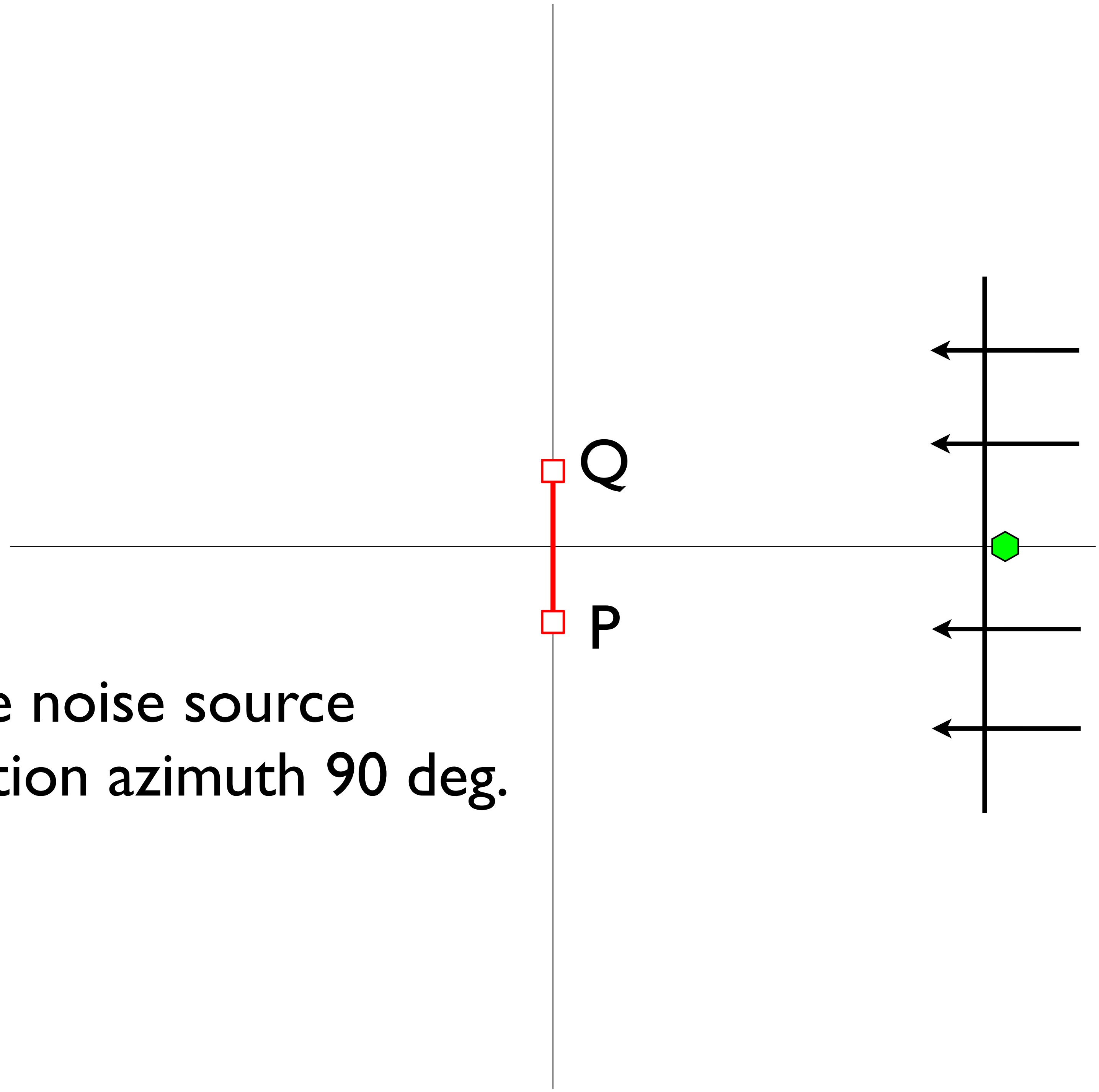
Plane wave of noise incident on two stations, P and Q



one noise source
station azimuth 180 deg.

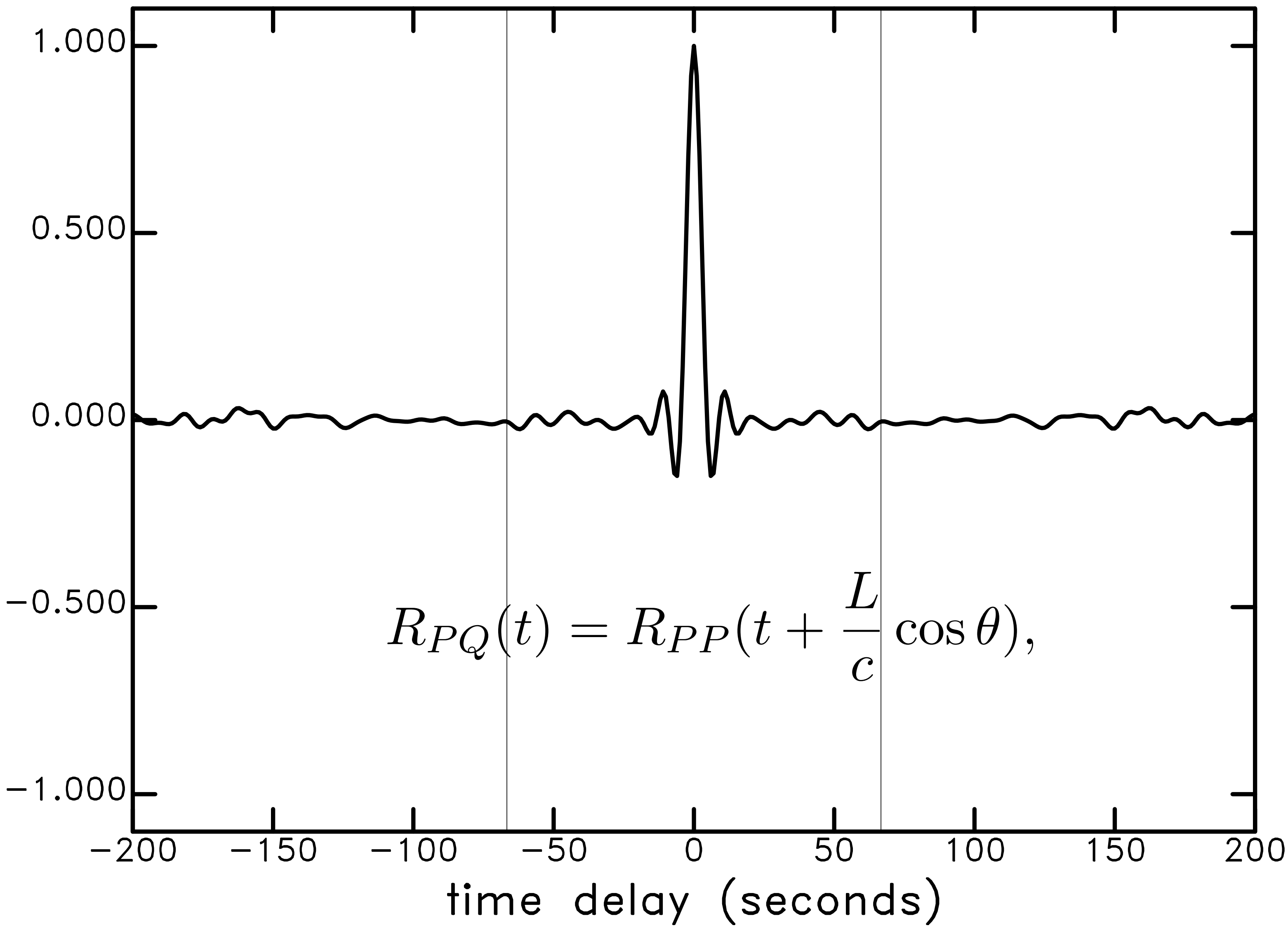
Cross-correlation function, P and Q

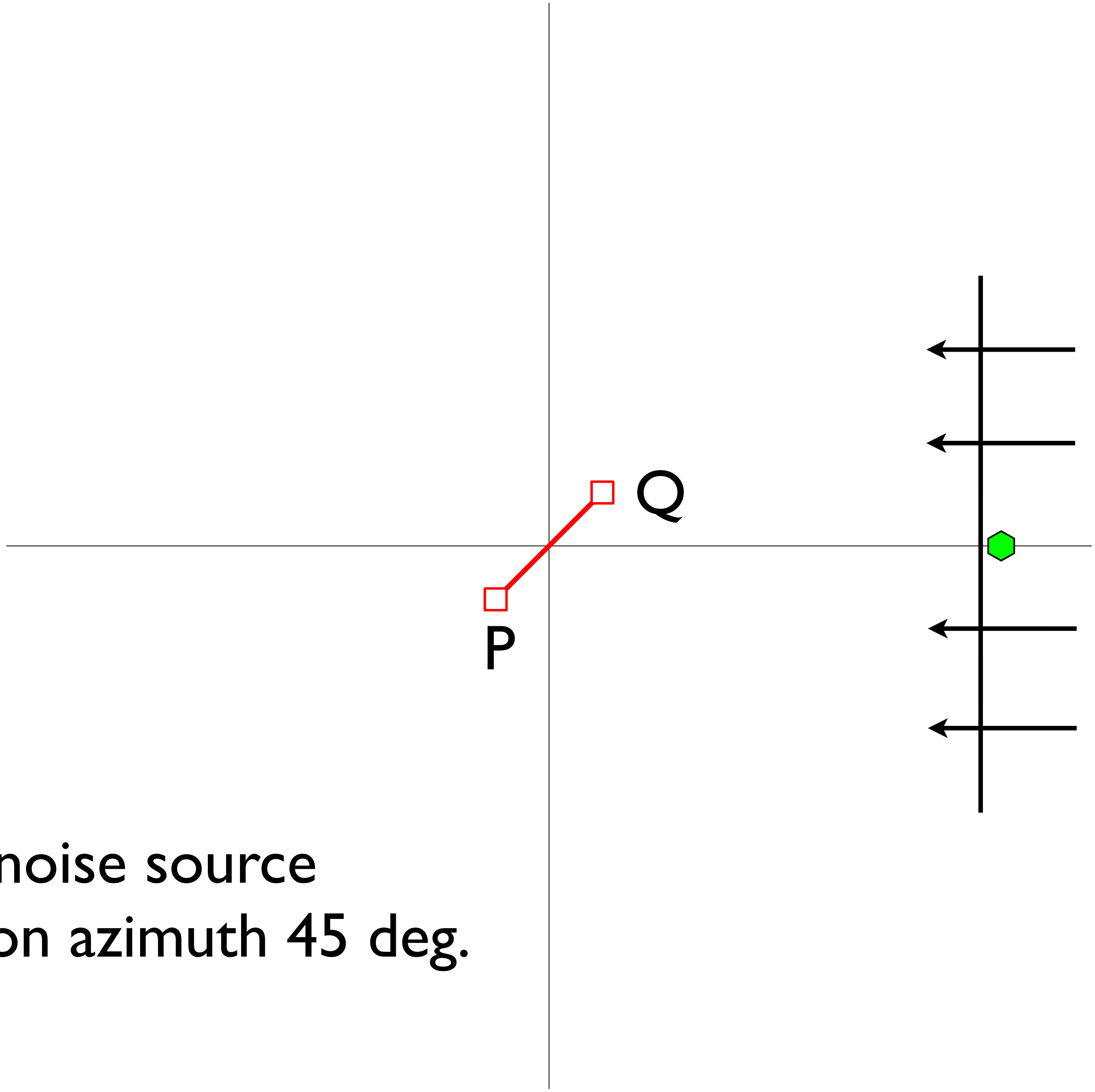




one noise source
station azimuth 90 deg.

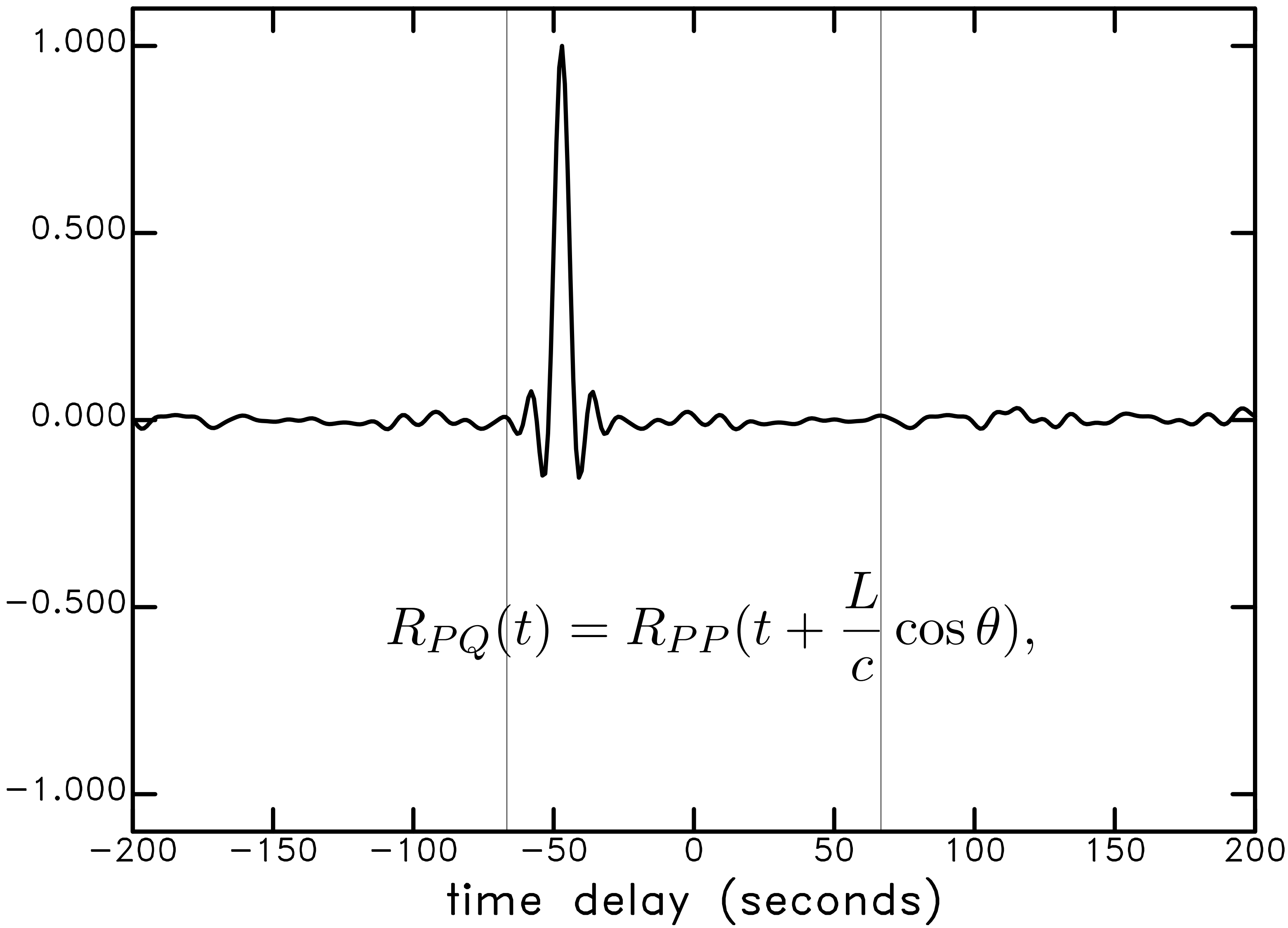
Cross-correlation function, P and Q

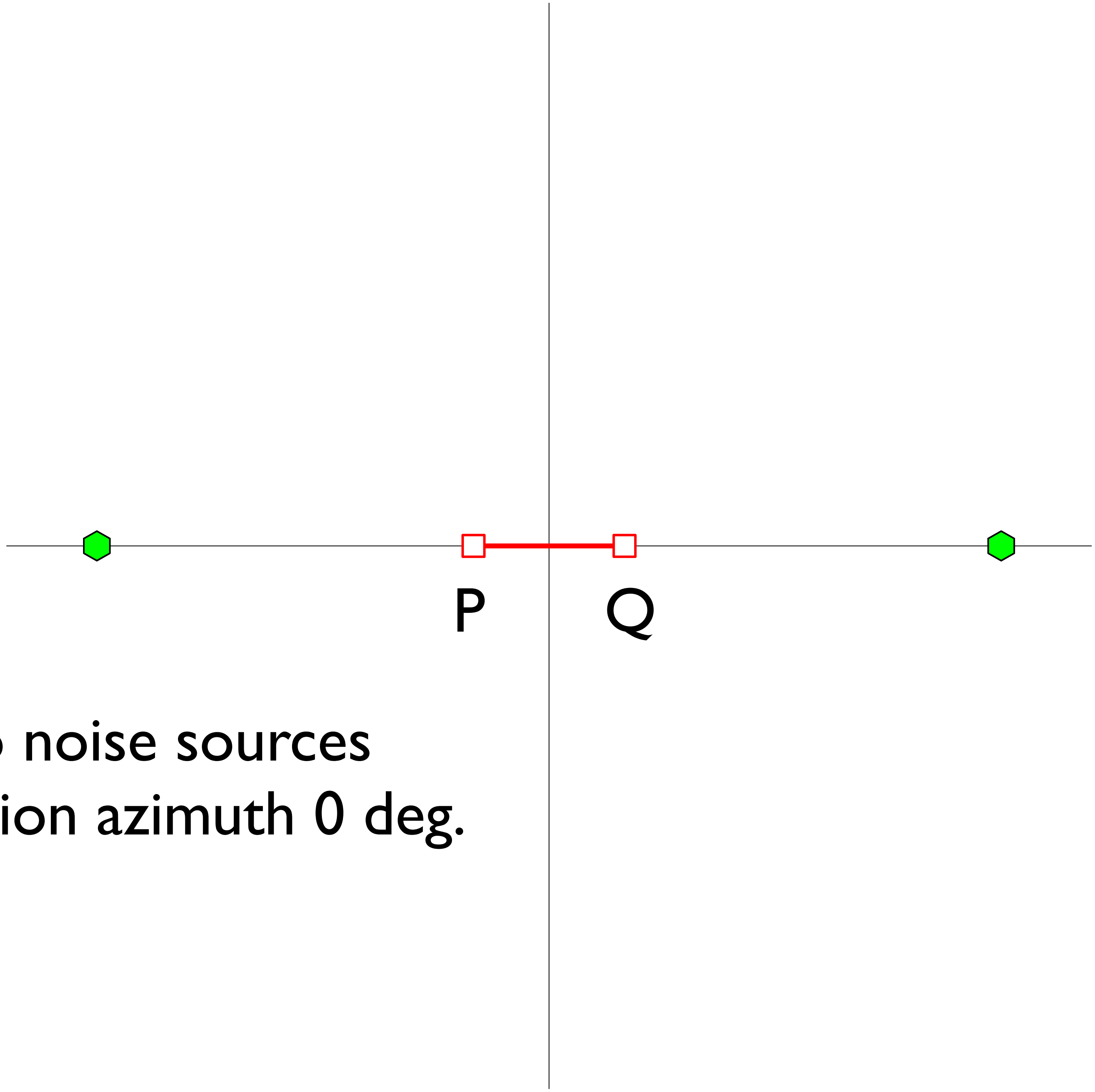




one noise source
station azimuth 45 deg.

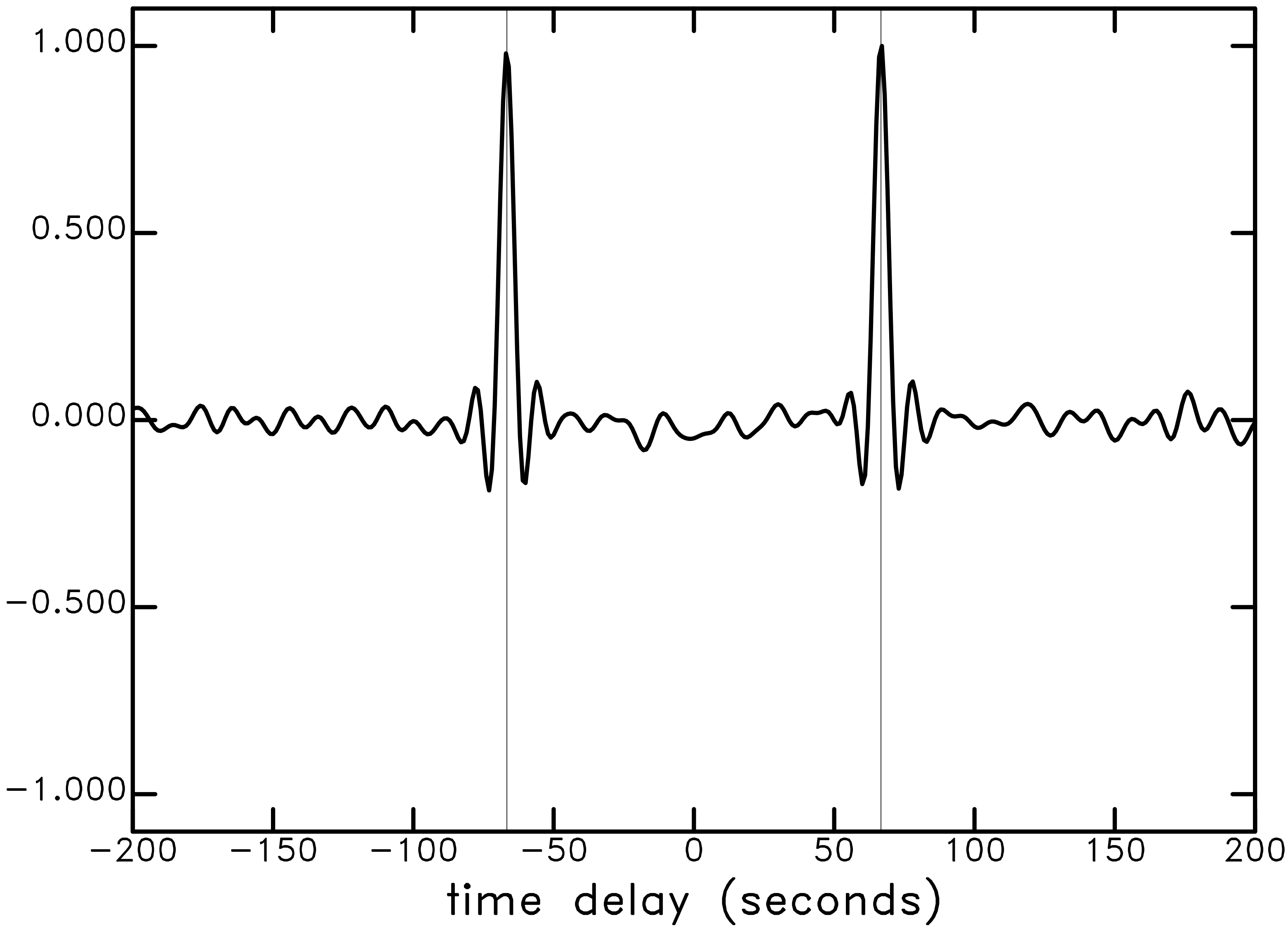
Cross-correlation function, P and Q

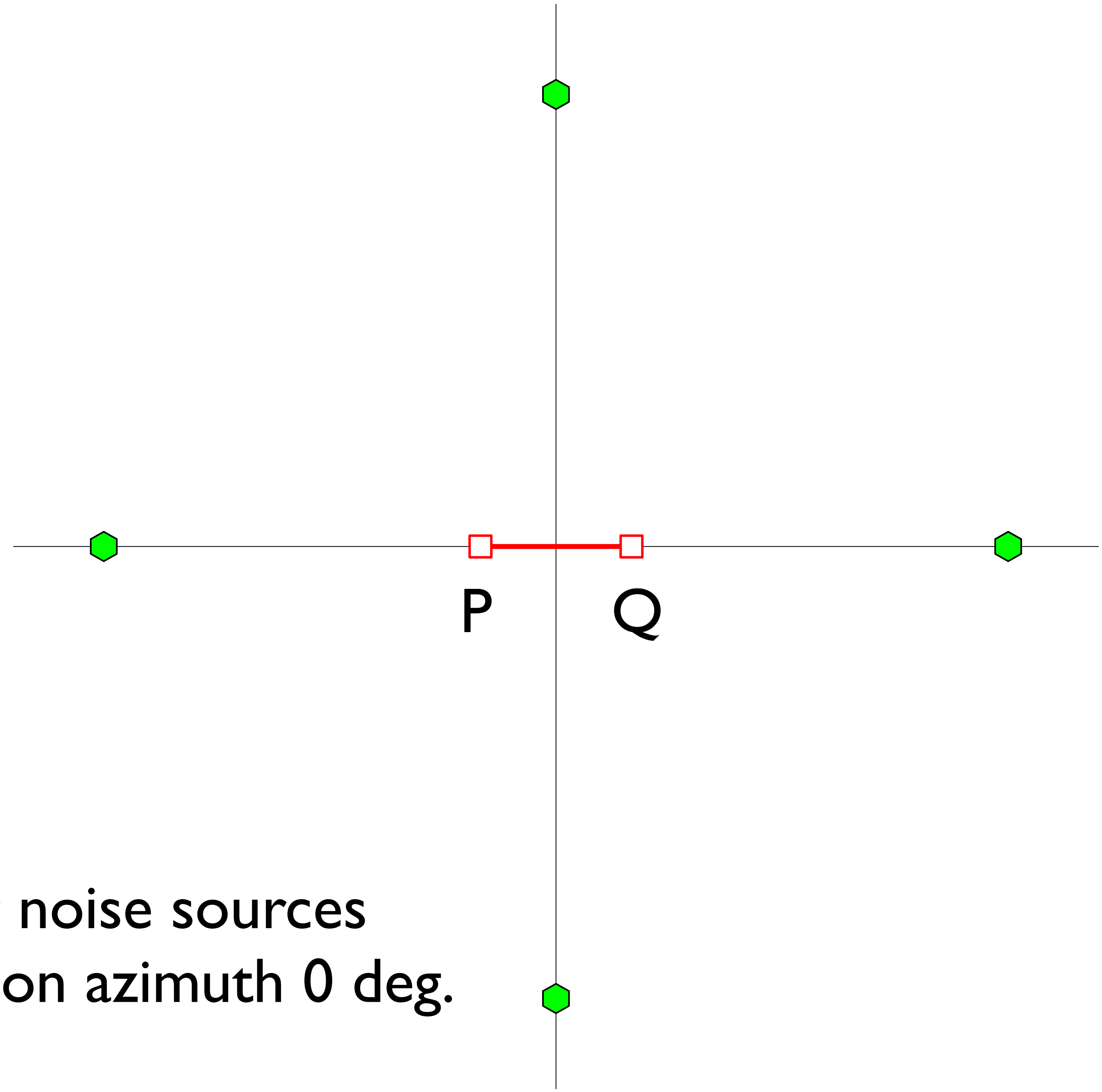




two noise sources
station azimuth 0 deg.

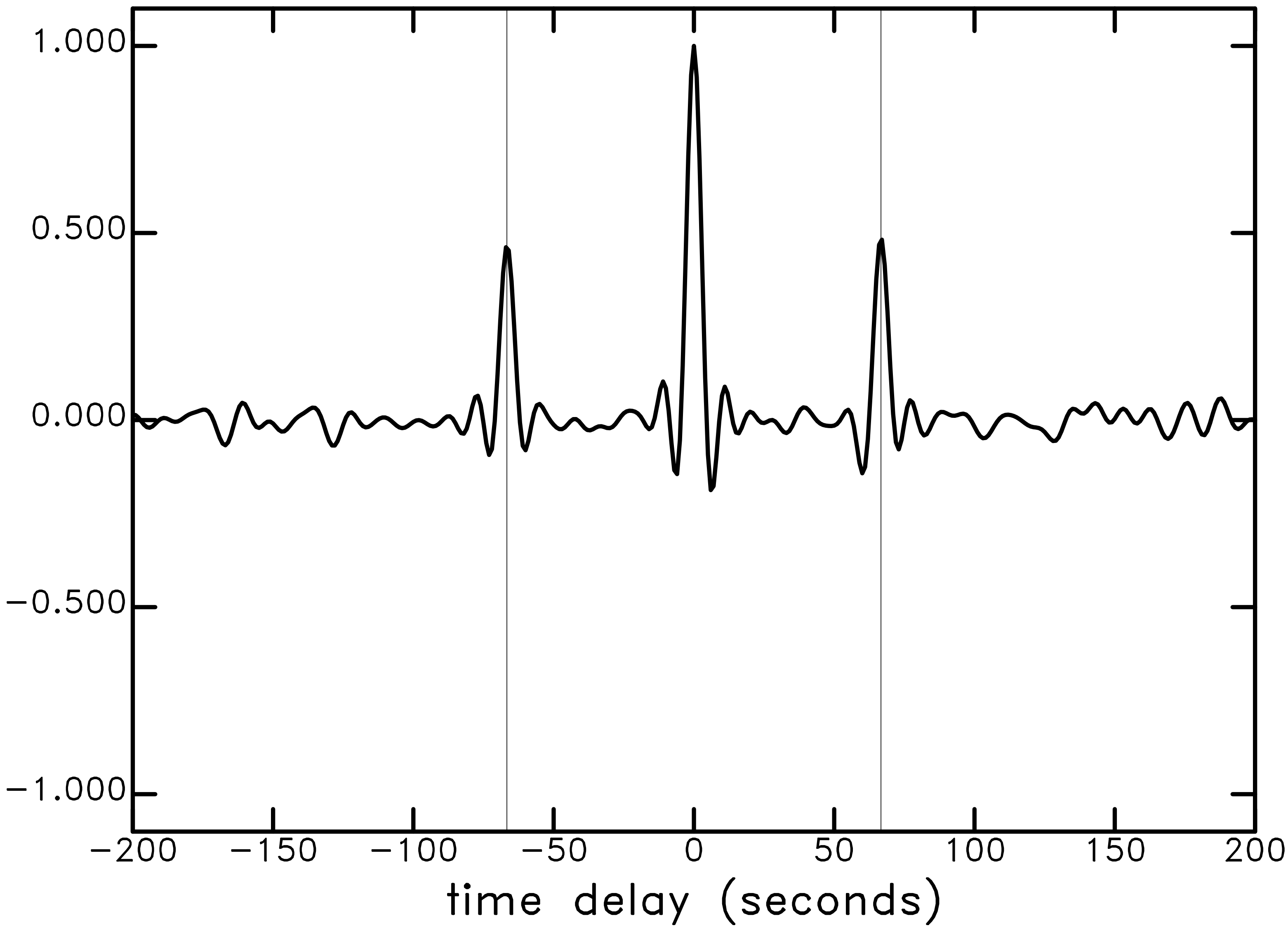
Cross-correlation function, P and Q



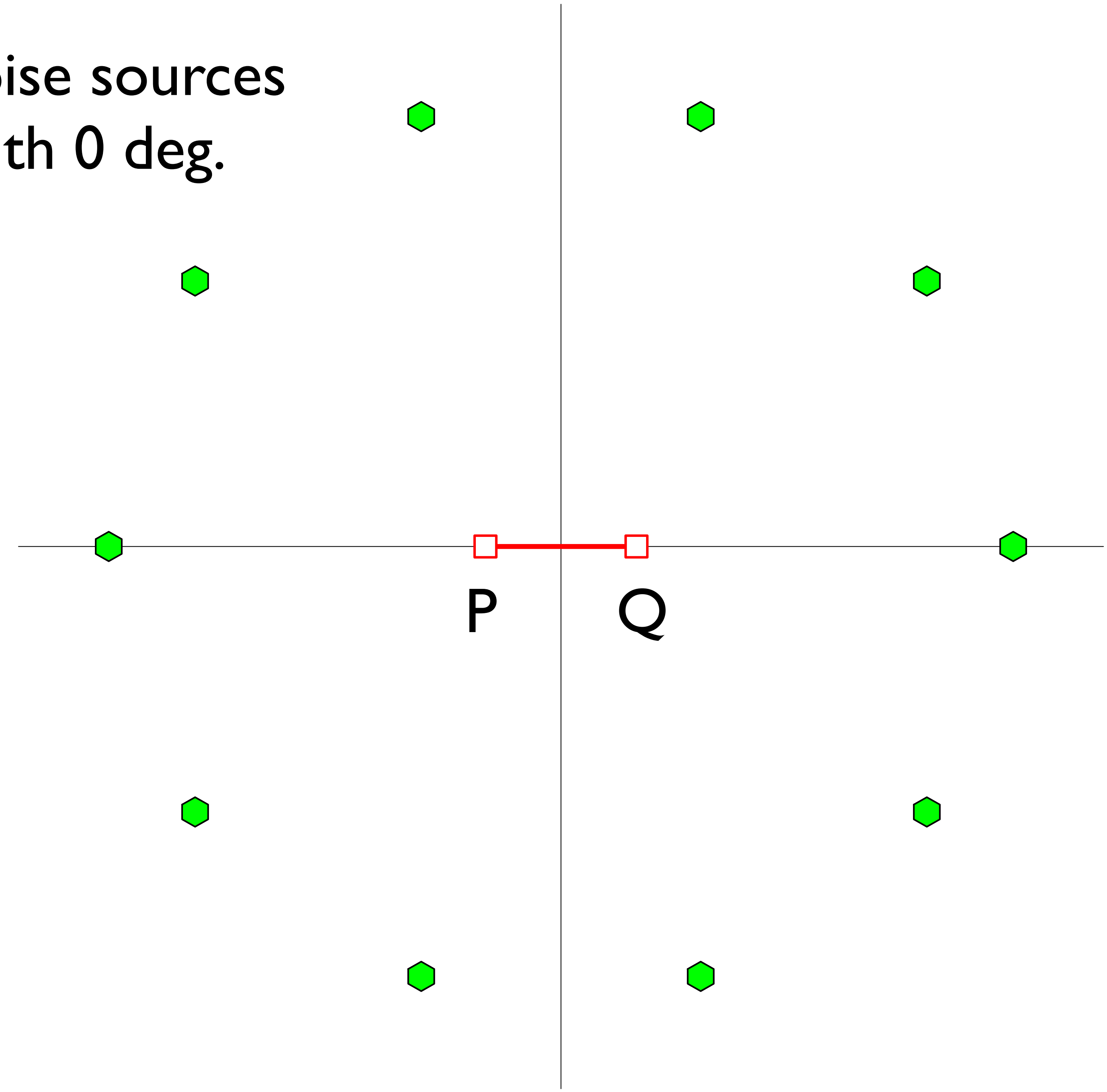


four noise sources
station azimuth 0 deg.

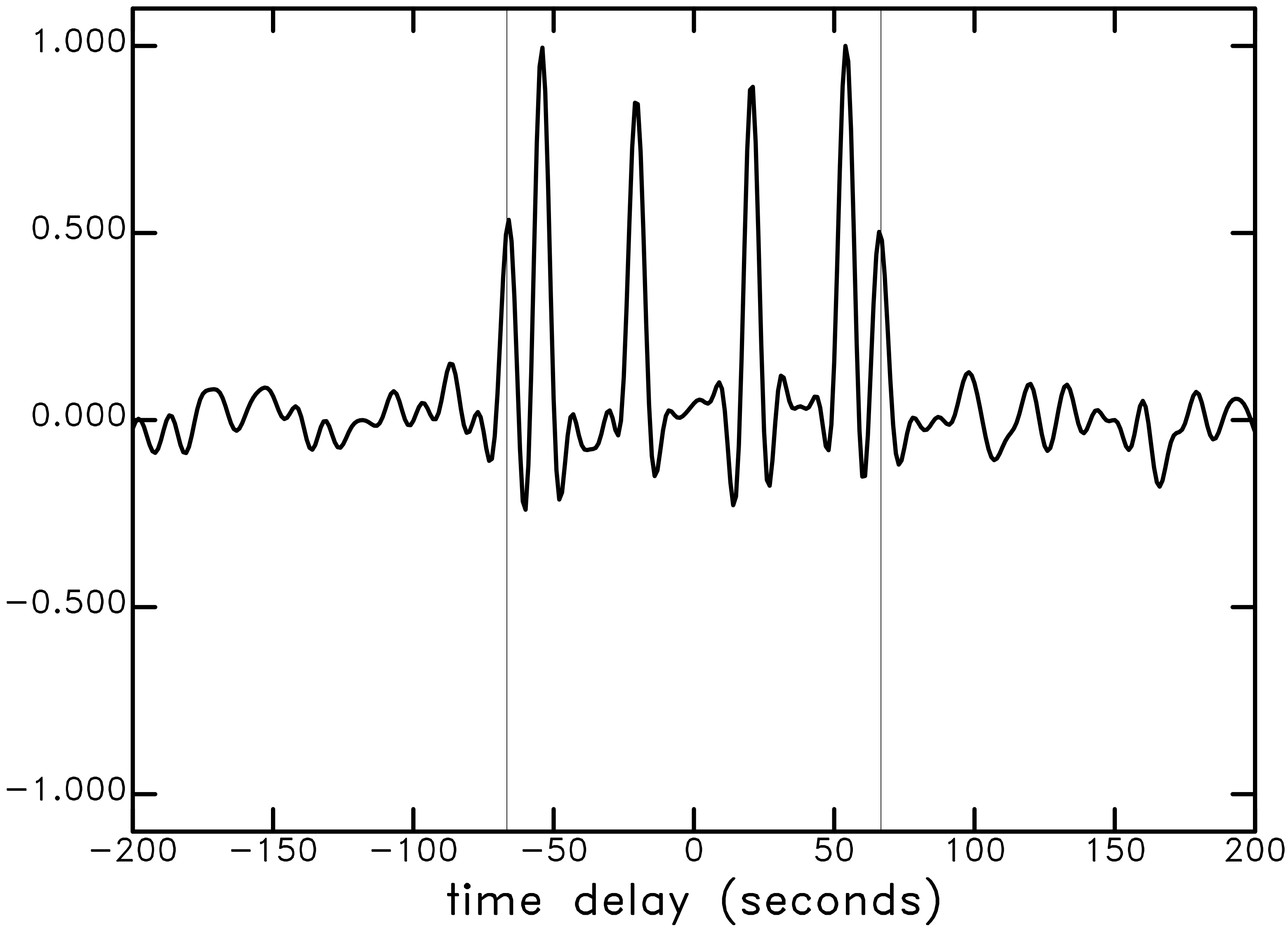
Cross-correlation function, P and Q



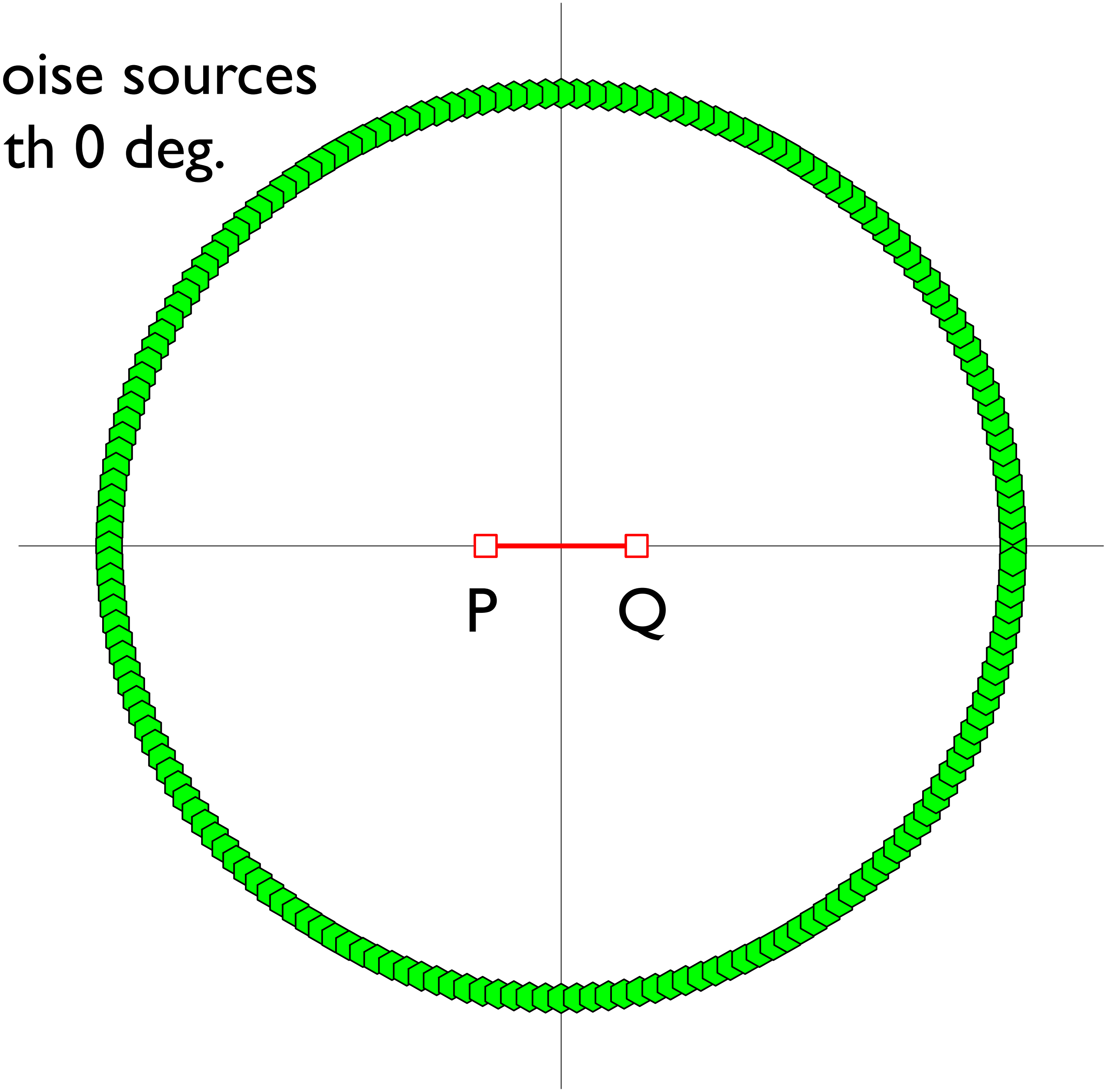
10 noise sources
azimuth 0 deg.



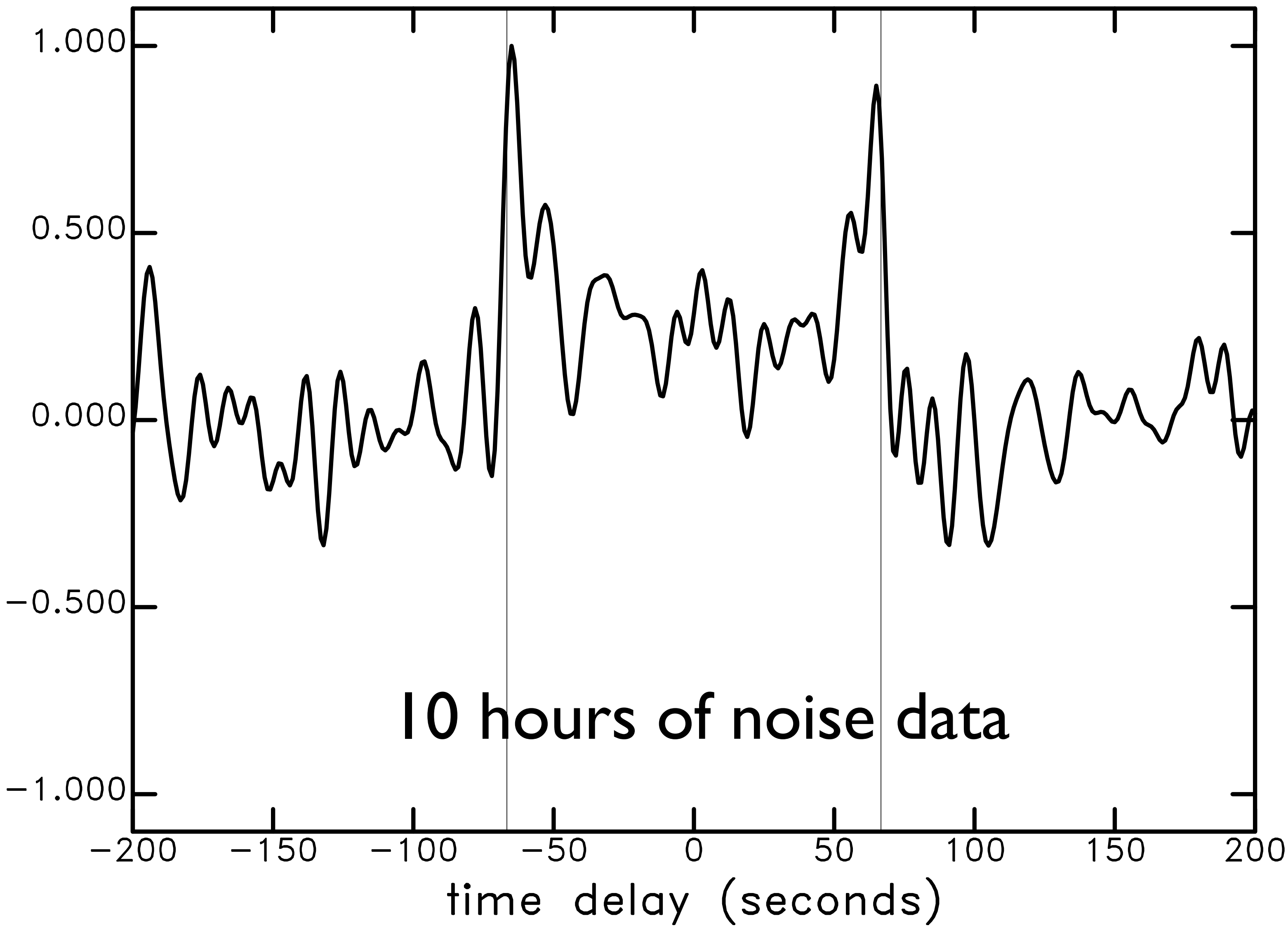
Cross-correlation function, P and Q



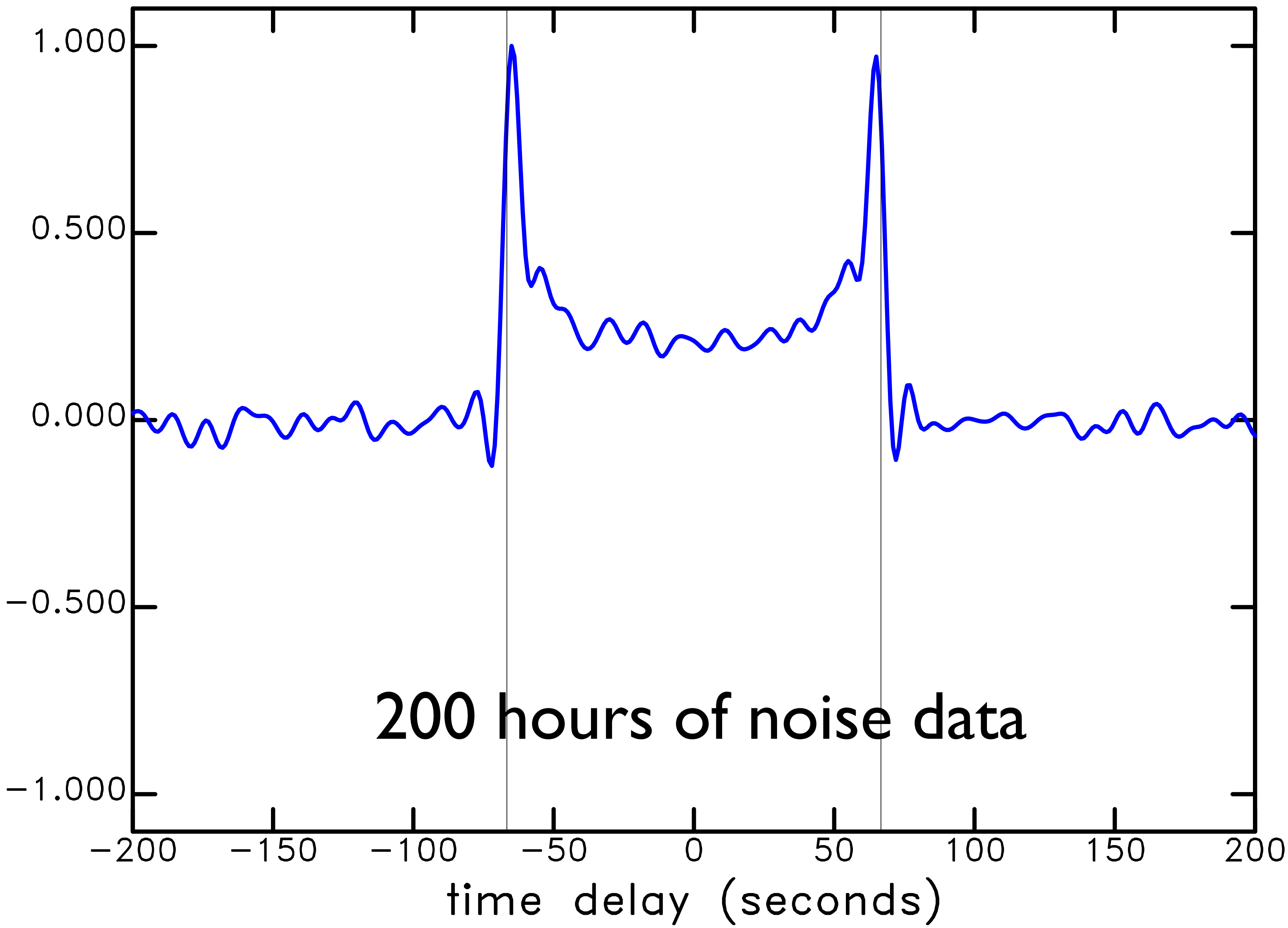
180 noise sources
azimuth 0 deg.

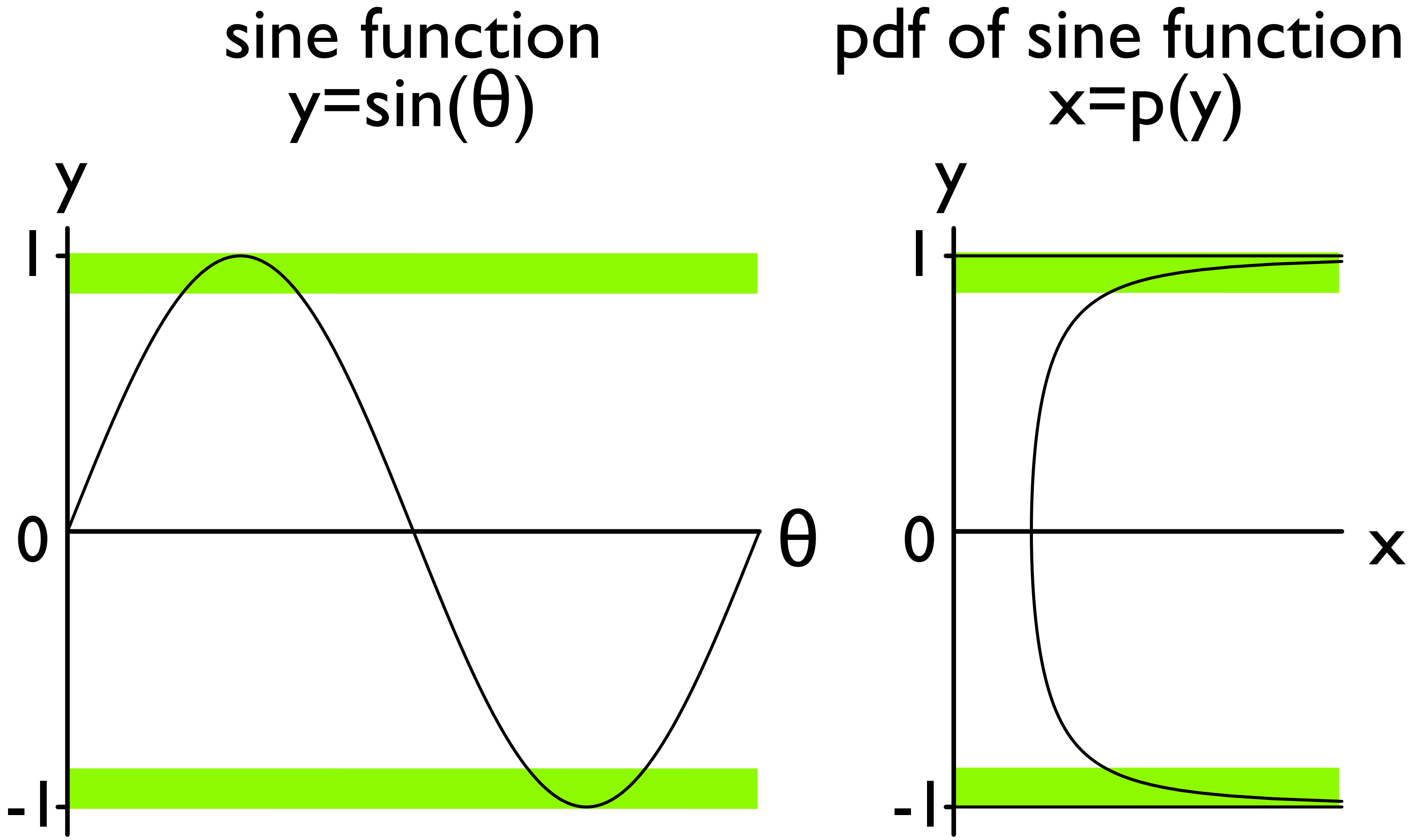


Cross-correlation function, P and Q

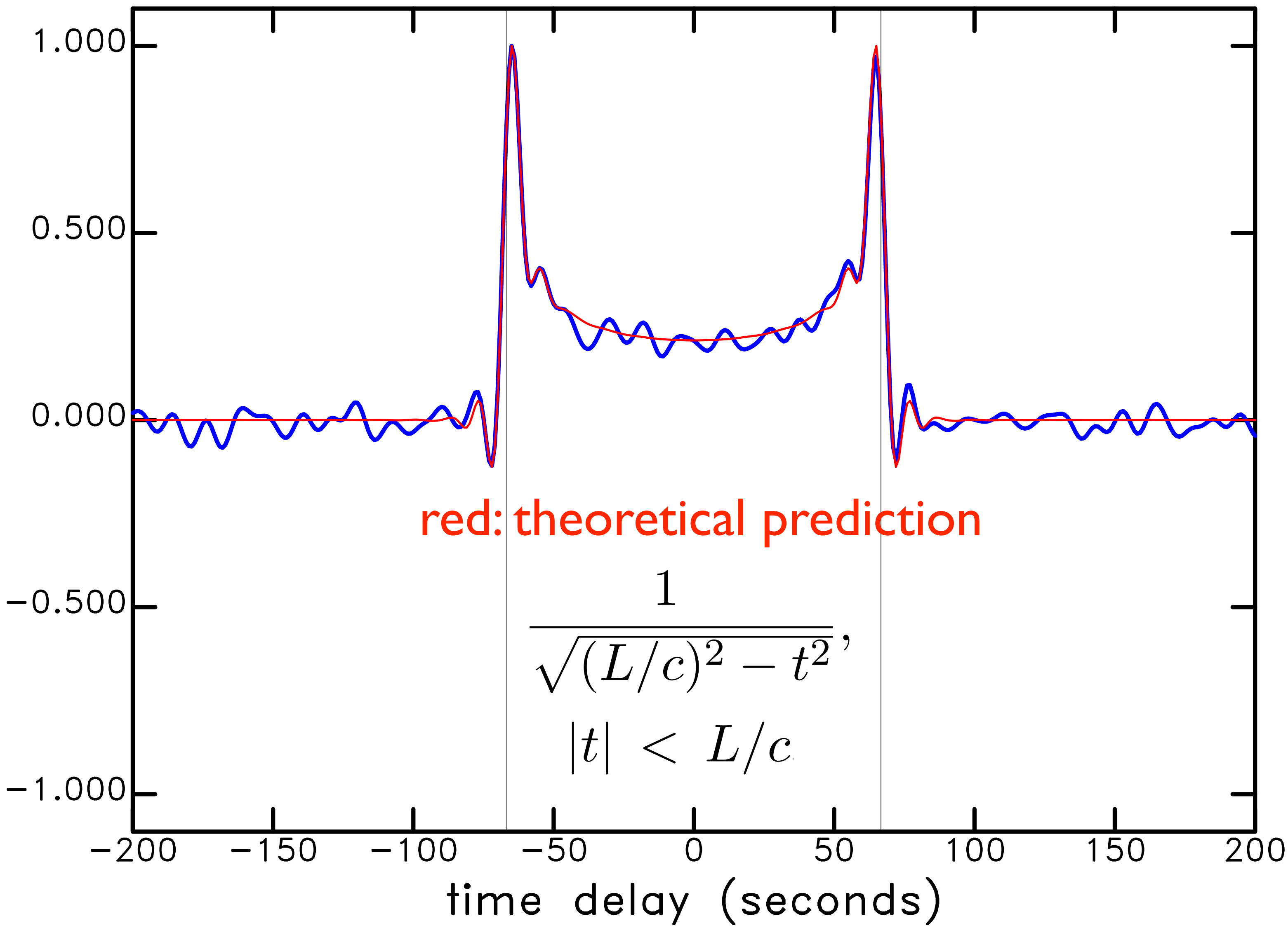


Cross-correlation function, P and Q




sine function
y=sin(θ)
pdf of sine function
x=p(y)
y
1
0
-1
θ
y
1
0
-1
x

Cross-correlation function, P and Q

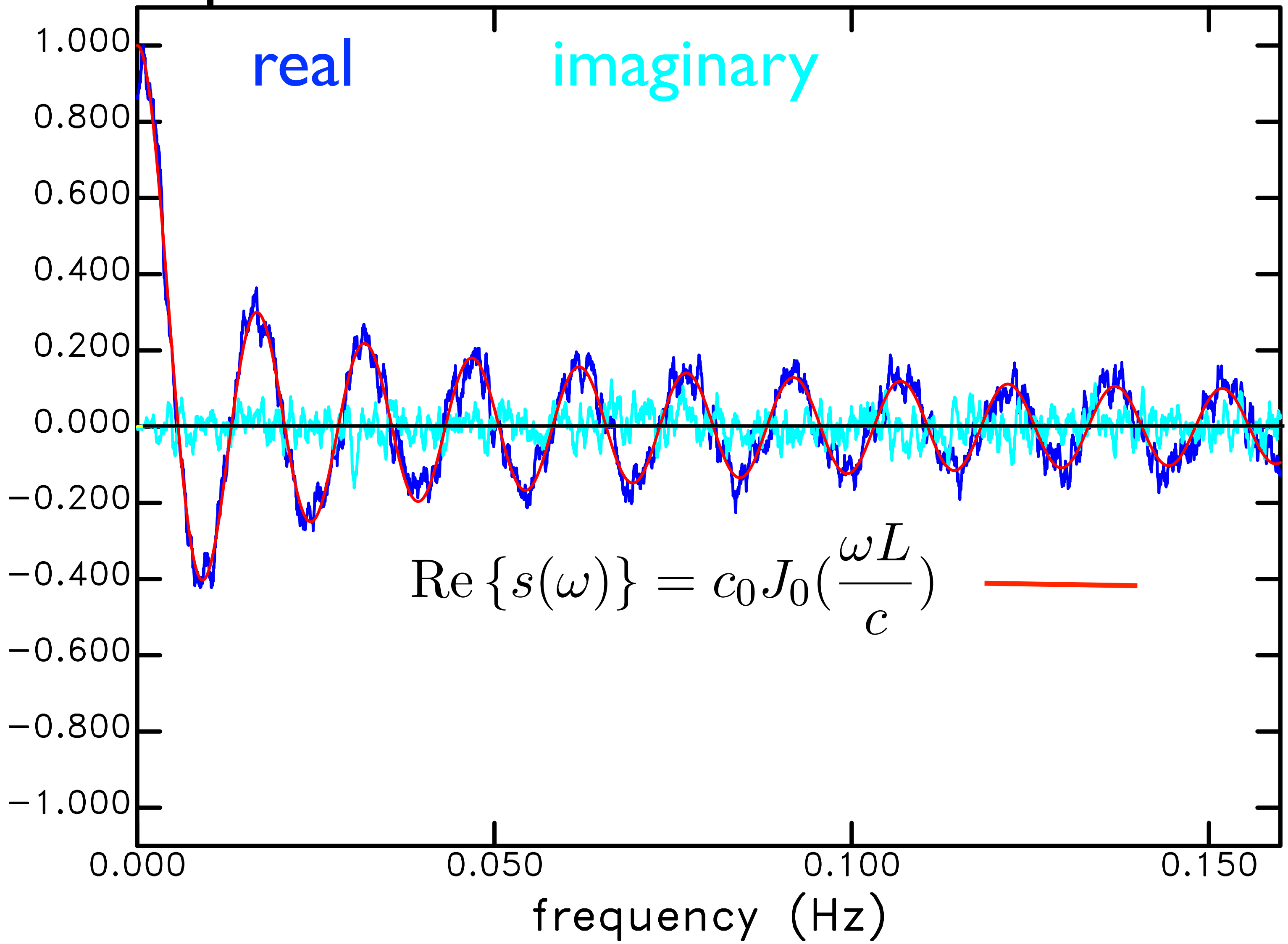


What about the Fourier transform?

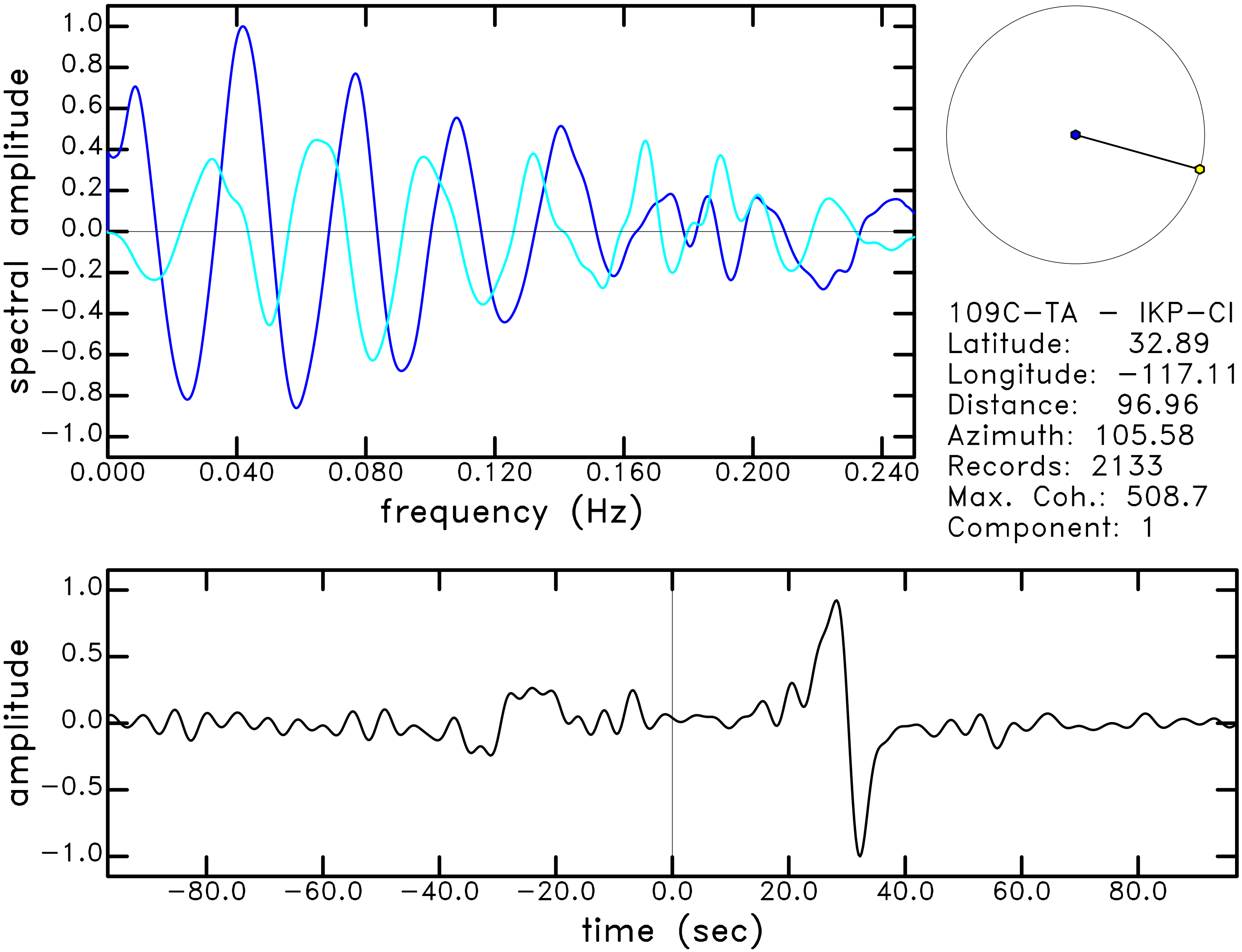
What about the Fourier transform?

$$\frac{1}{\sqrt{(L/c)^2 - t^2}} \quad \longrightarrow \quad J_0(\frac{\omega L}{c})$$

Spectrum of cross-correlation function

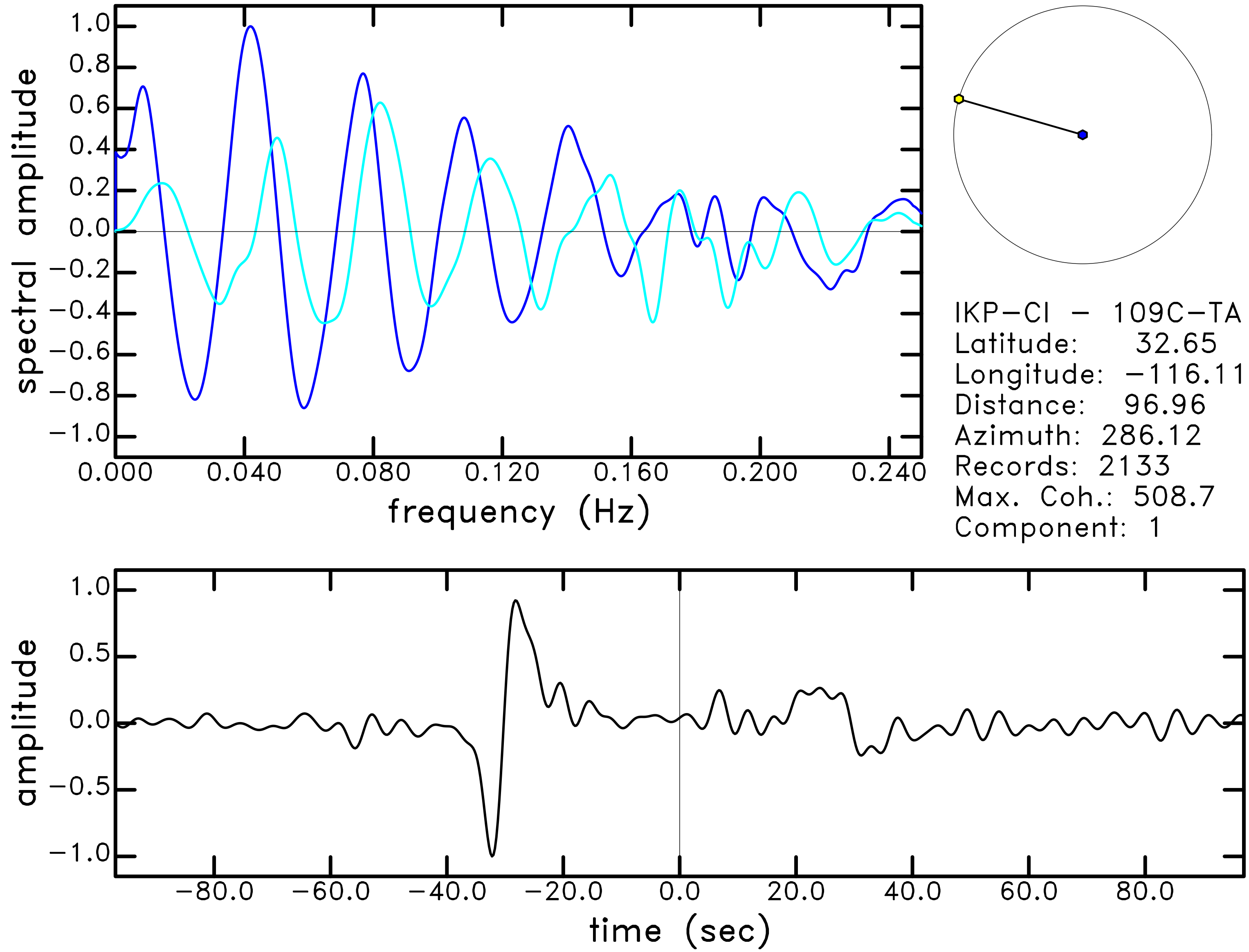


Real data

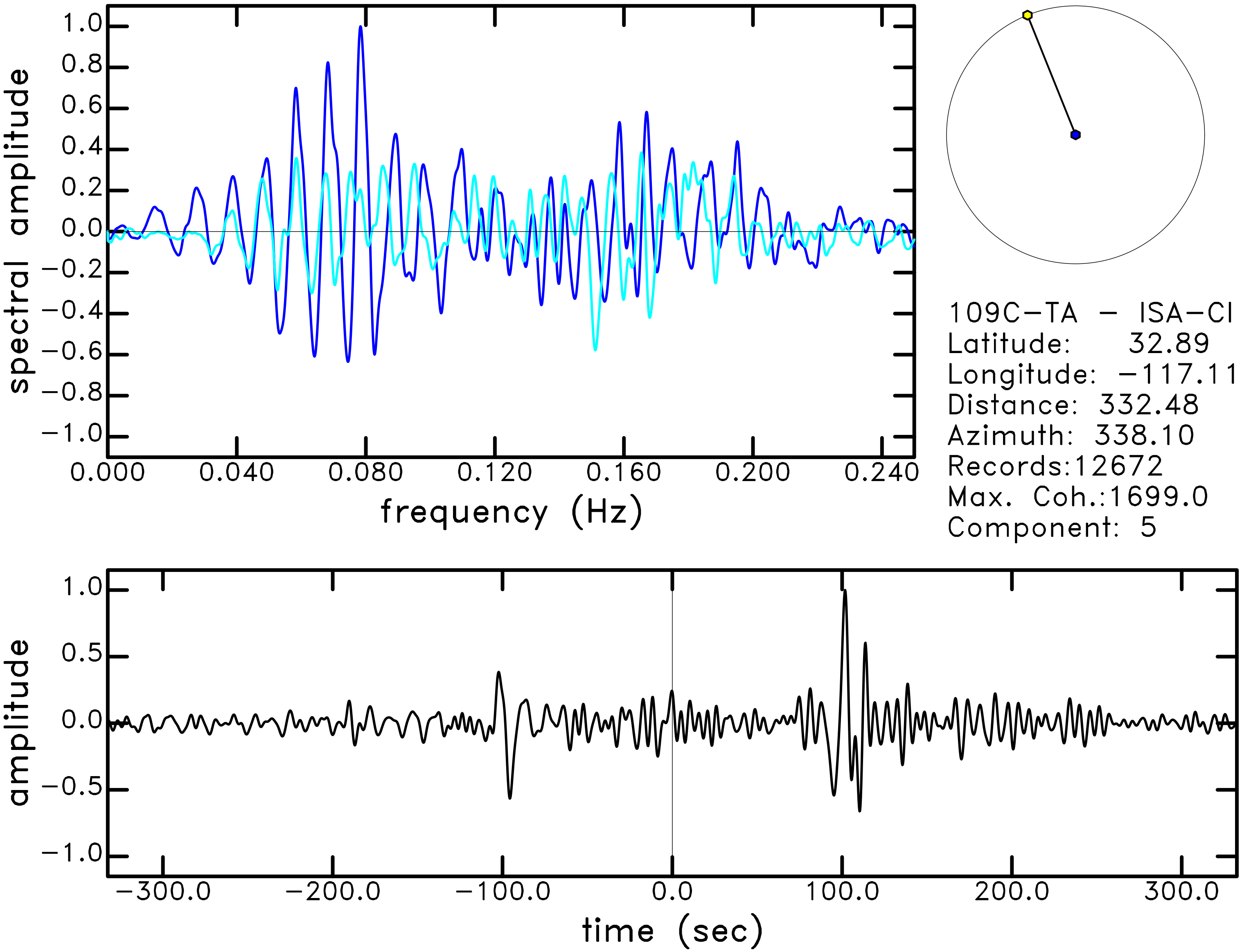


spectral amplitude
frequency (Hz)
109C−TA − IKP−CI
Latitude: 32.89
Longitude: −117.11
Distance: 96.96
Azimuth: 105.58
Records: 2133
Max. Coh.: 508.7
Component: 1
amplitude
time (sec)

Real data, reversed

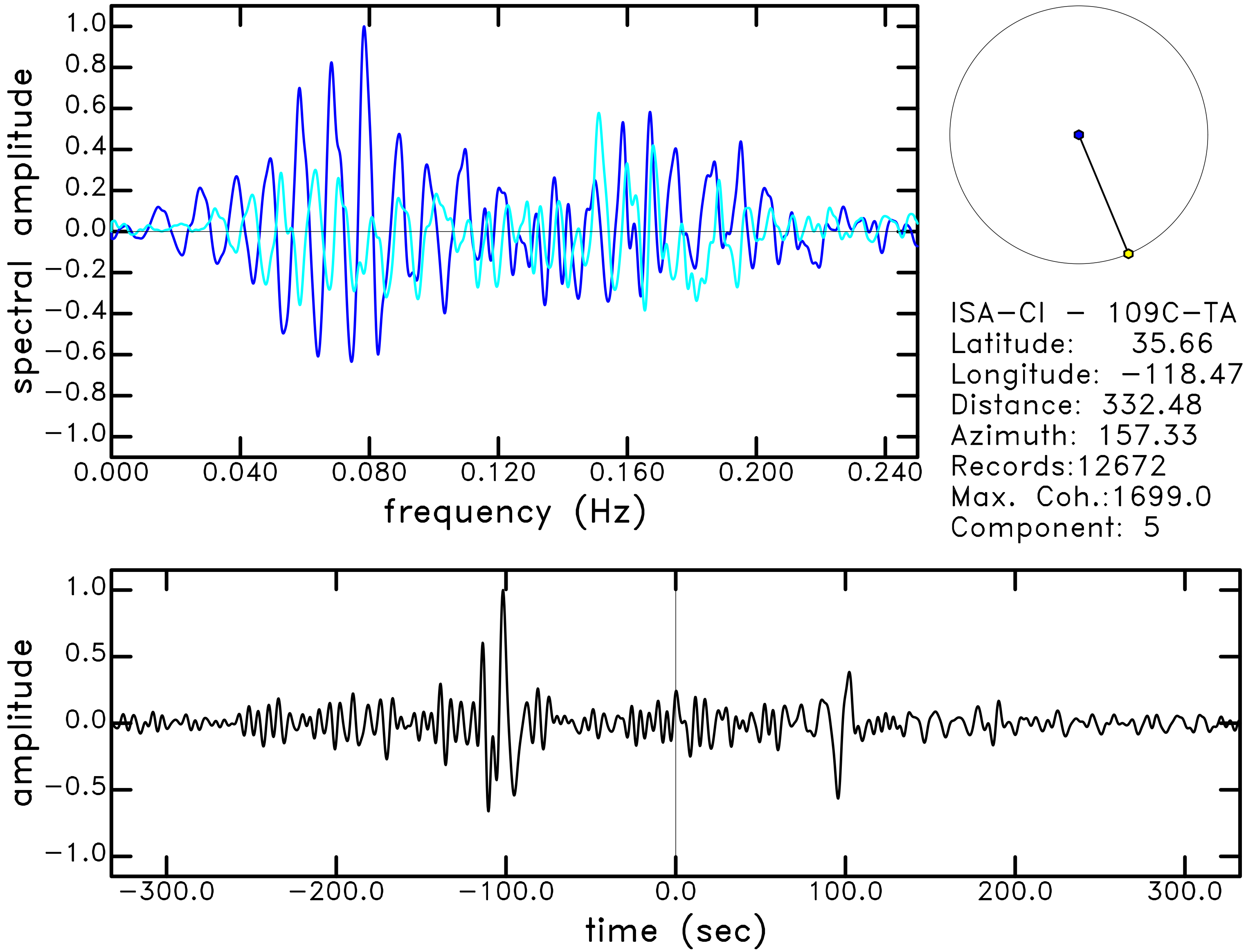


Love waves



spectral amplitude
1.0
0.8
0.6
0.4
0.2
0.0
−0.2
−0.4
−0.6
−0.8
−1.0
0.000
0.040
0.080
0.120
0.160
0.200
0.240
frequency (Hz)
109C−TA − ISA−CI
Latitude: 32.89
Longitude: −117.11
Distance: 332.48
Azimuth: 338.10
Records:12672
Max. Coh.:1699.0
Component: 5
amplitude
1.0
0.5
0.0
−0.5
−1.0
−300.0
−200.0
−100.0
0.0
100.0
200.0
300.0
time (sec)

Love waves, reversed



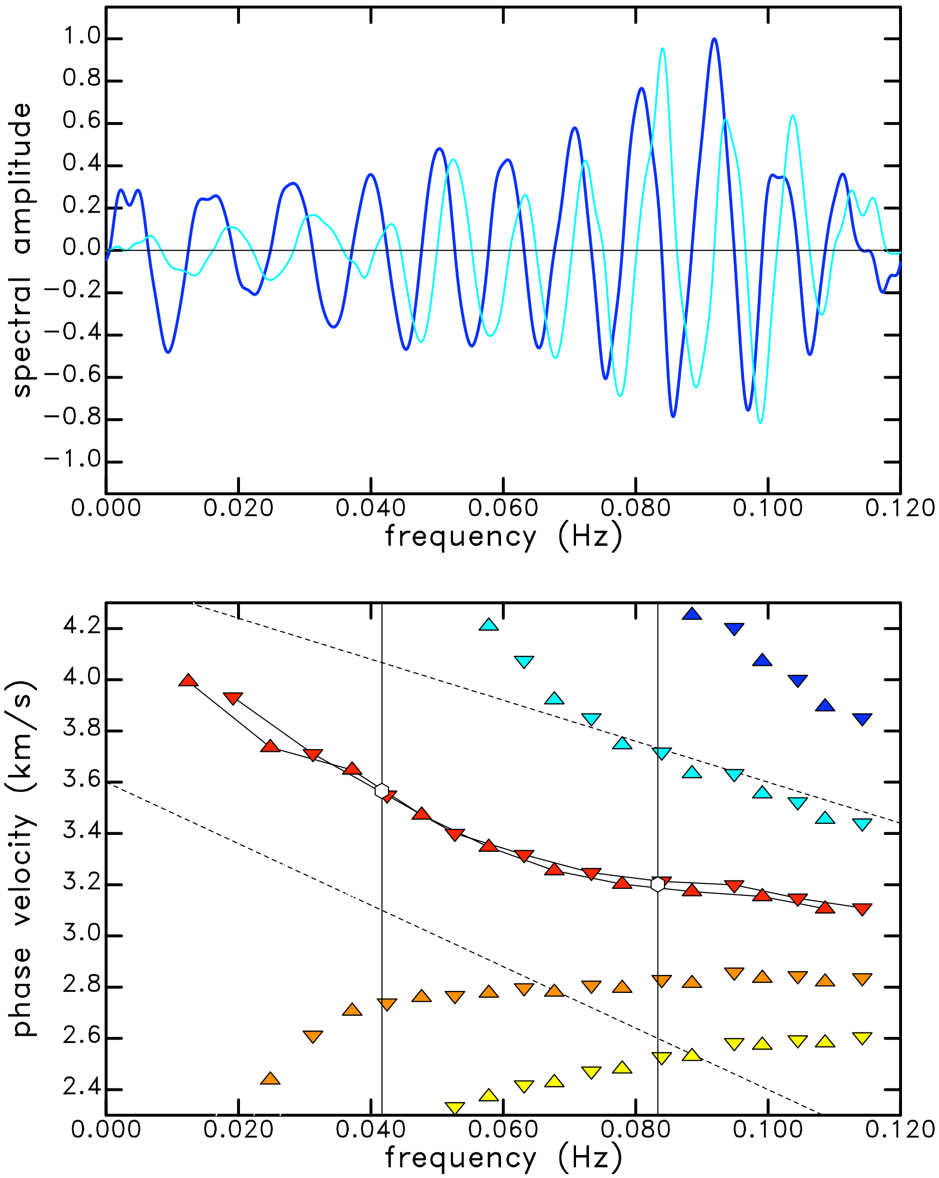
$$\overline{\rho}(r, \omega_0) = J_0\left(\frac{\omega_0}{c(\omega_0)} r\right)$$

"This formula clearly indicates that if one measures $\overline{\rho}(r, \omega_0)$ for a certain r and for various ω_0's, he can obtain the function $c(\omega_0)$, i.e., the dispersion curve of the wave for the corresponding range of frequency ω_0".

Aki, 1957

(made fashionable again by Ekström, Abers, and Webb, 2009)

Matching zero crossings for dispersion

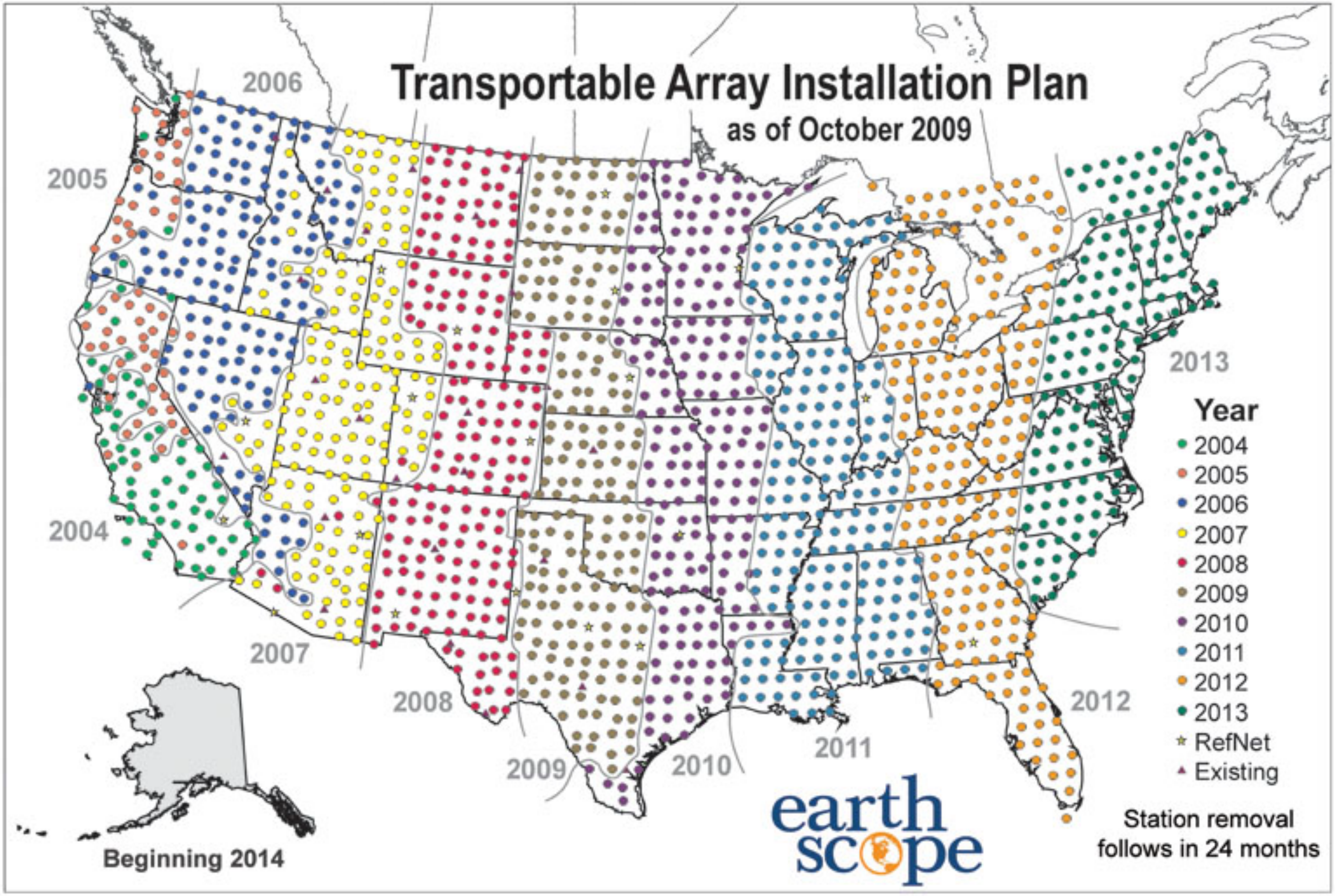


D07A-B04A

282 km

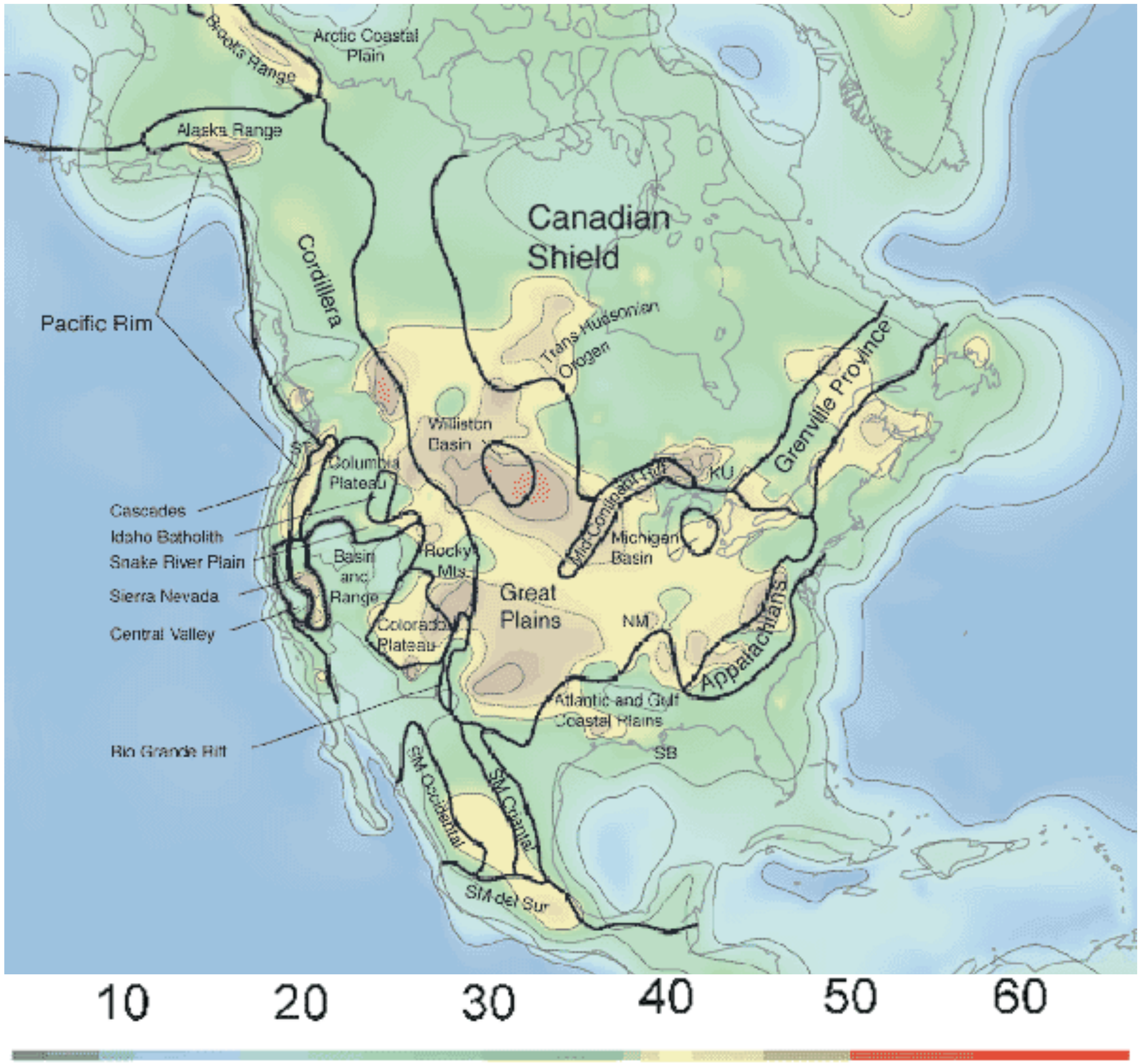
$$c(\omega_n) = \frac{\omega_n r}{z_n}$$

Some results from processing the USArray data 200601-201204



Transportable Array Installation Plan
as of October 2009
2006
2005
2004
2007
2008
2009
2010
2011
2012
2013
Year
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
RefNet
Existing
Beginning 2014
Station removal
follows in 24 months
earthscope

The crust of North America

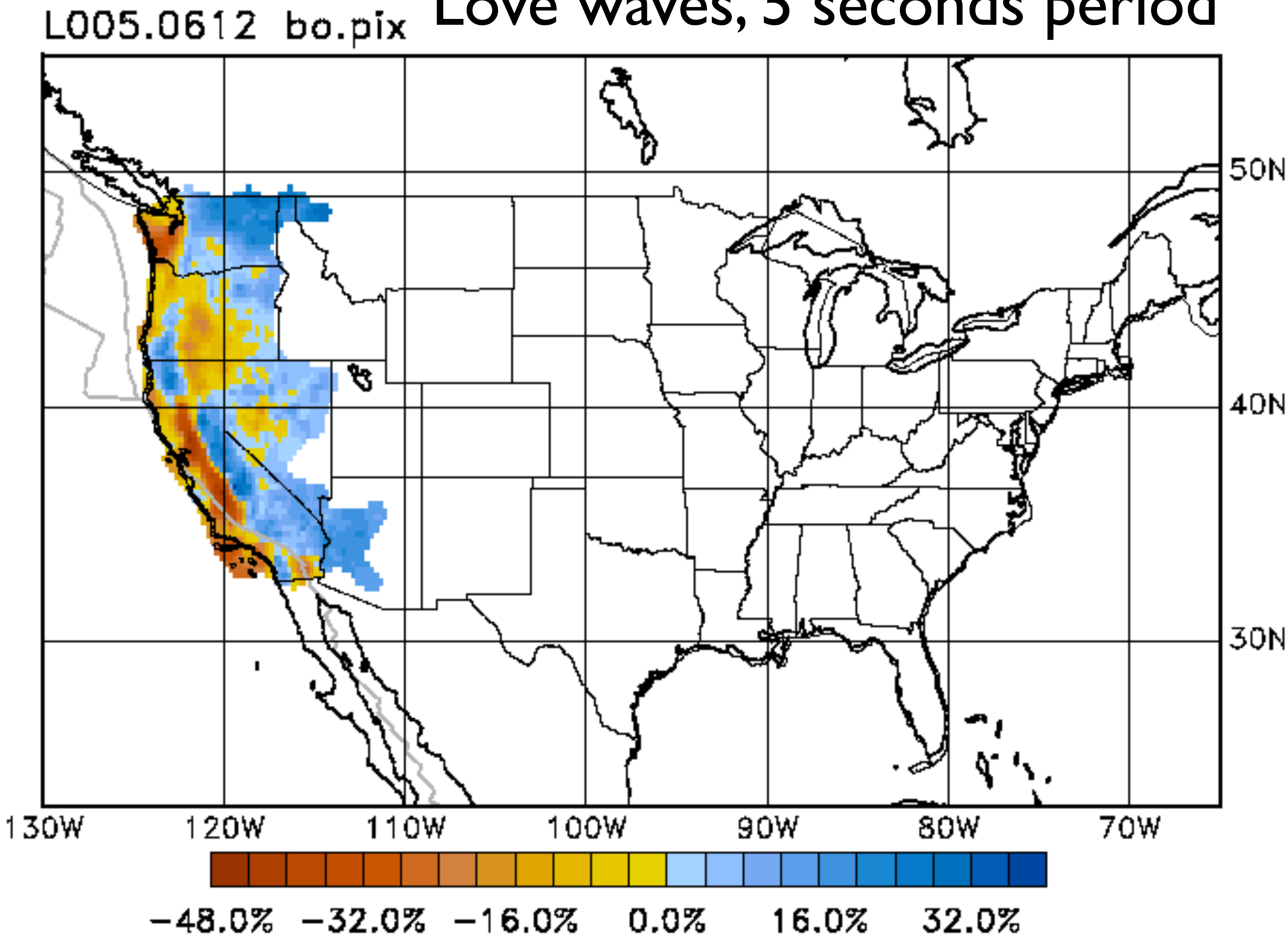


Chulick and Mooney, 2002

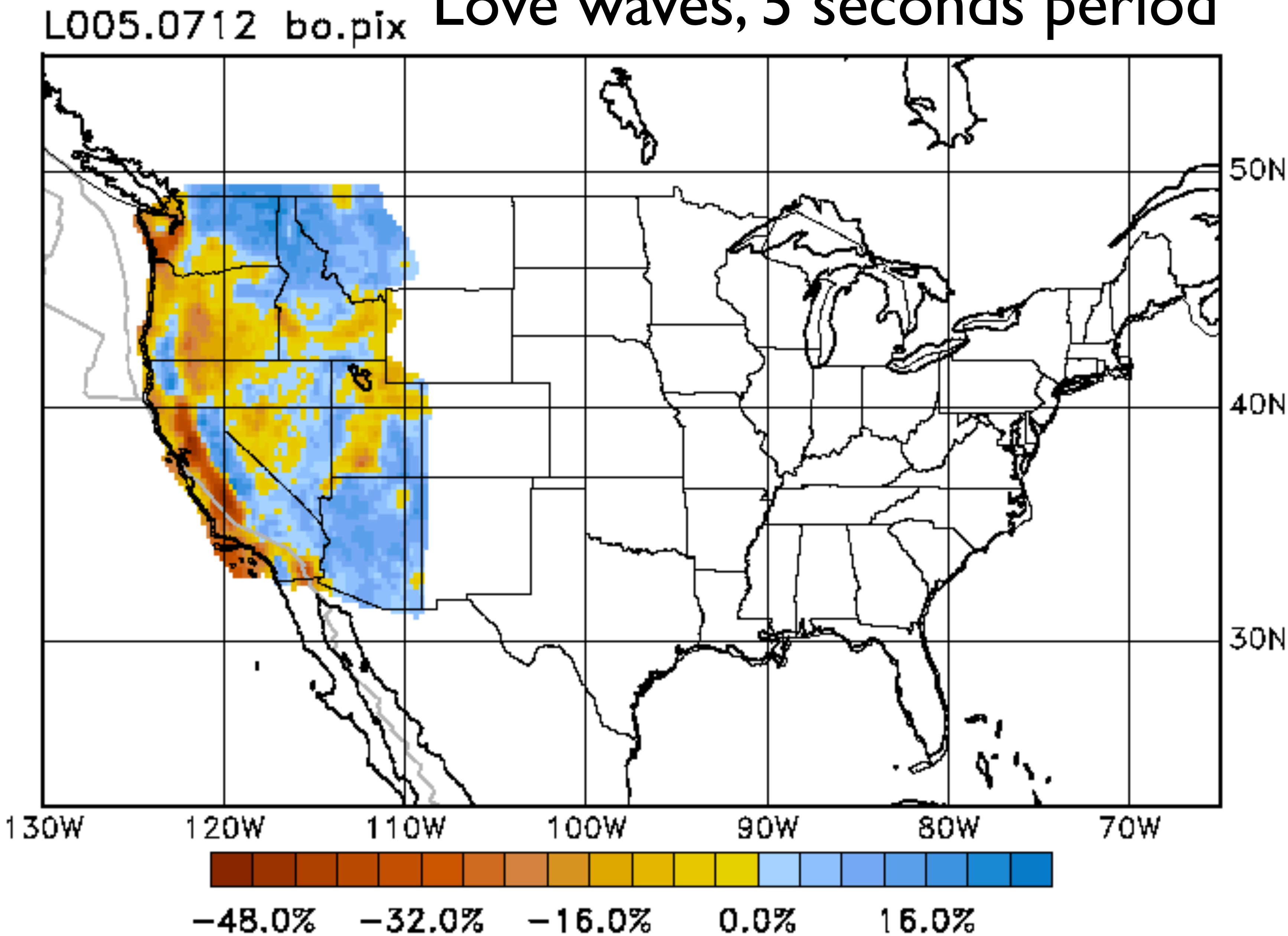
Recipe for success:

1. Correlate continuous recorded signals at all pairs of USArray stations in 4-h windows (note - this is a big calculation)
2. Stack all correlation functions for each pair
3. Determine zero crossings of stacked cross-correlation spectra
4. Determine phase velocities using Aki's formula
5. Invert phase-velocity observations to determine phase-velocity maps

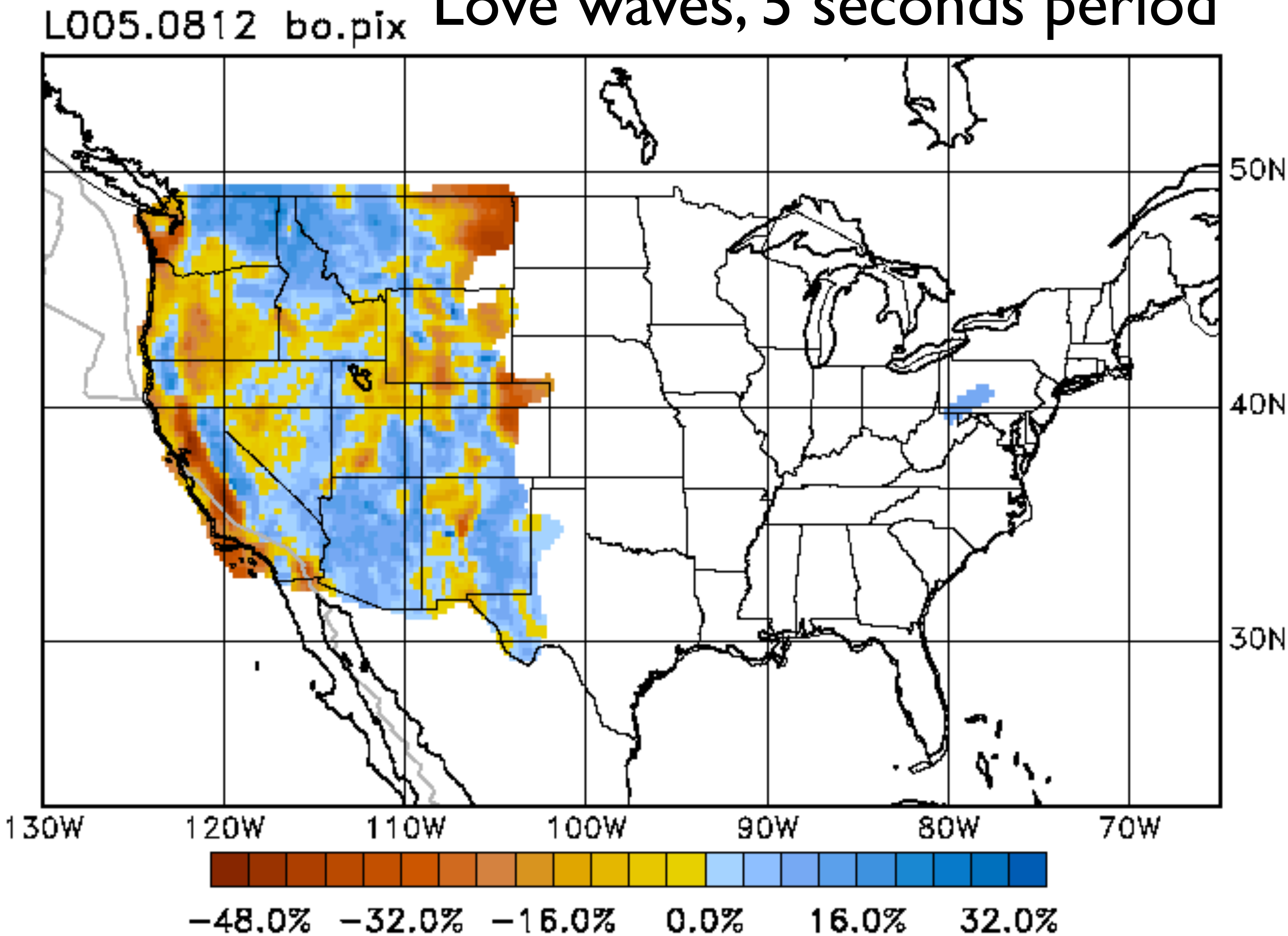
Love waves, 5 seconds period



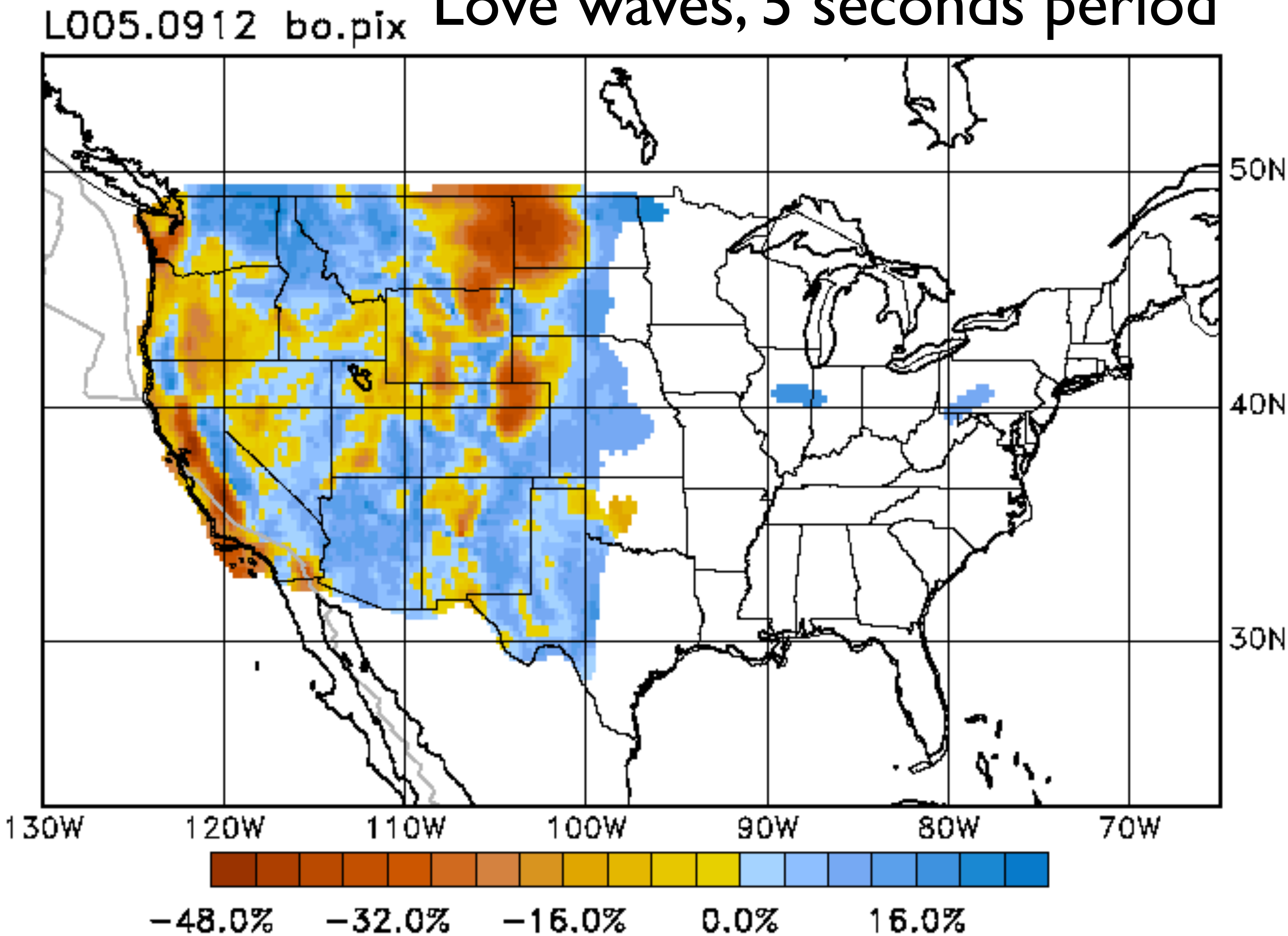
Love waves, 5 seconds period



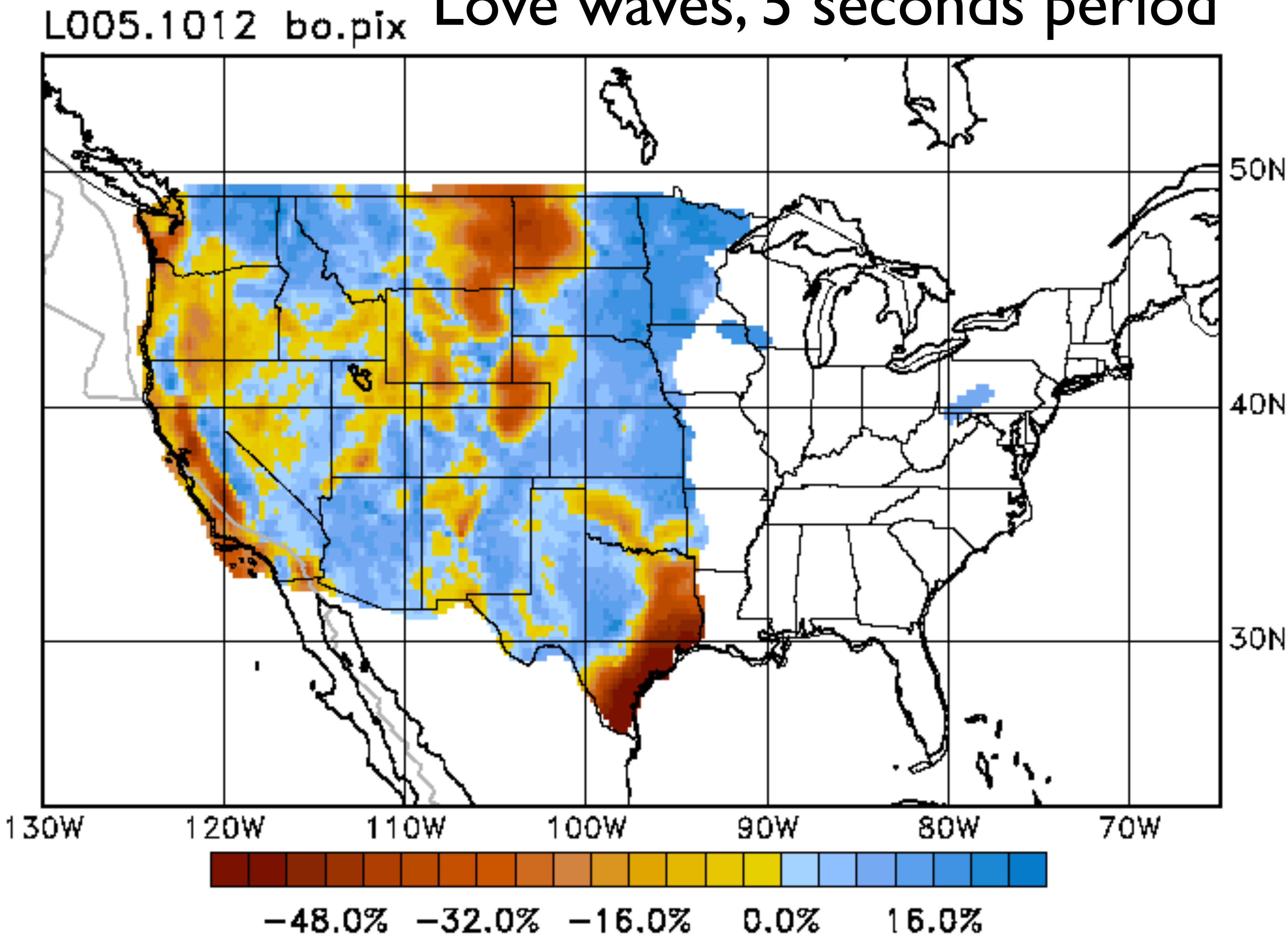
Love waves, 5 seconds period



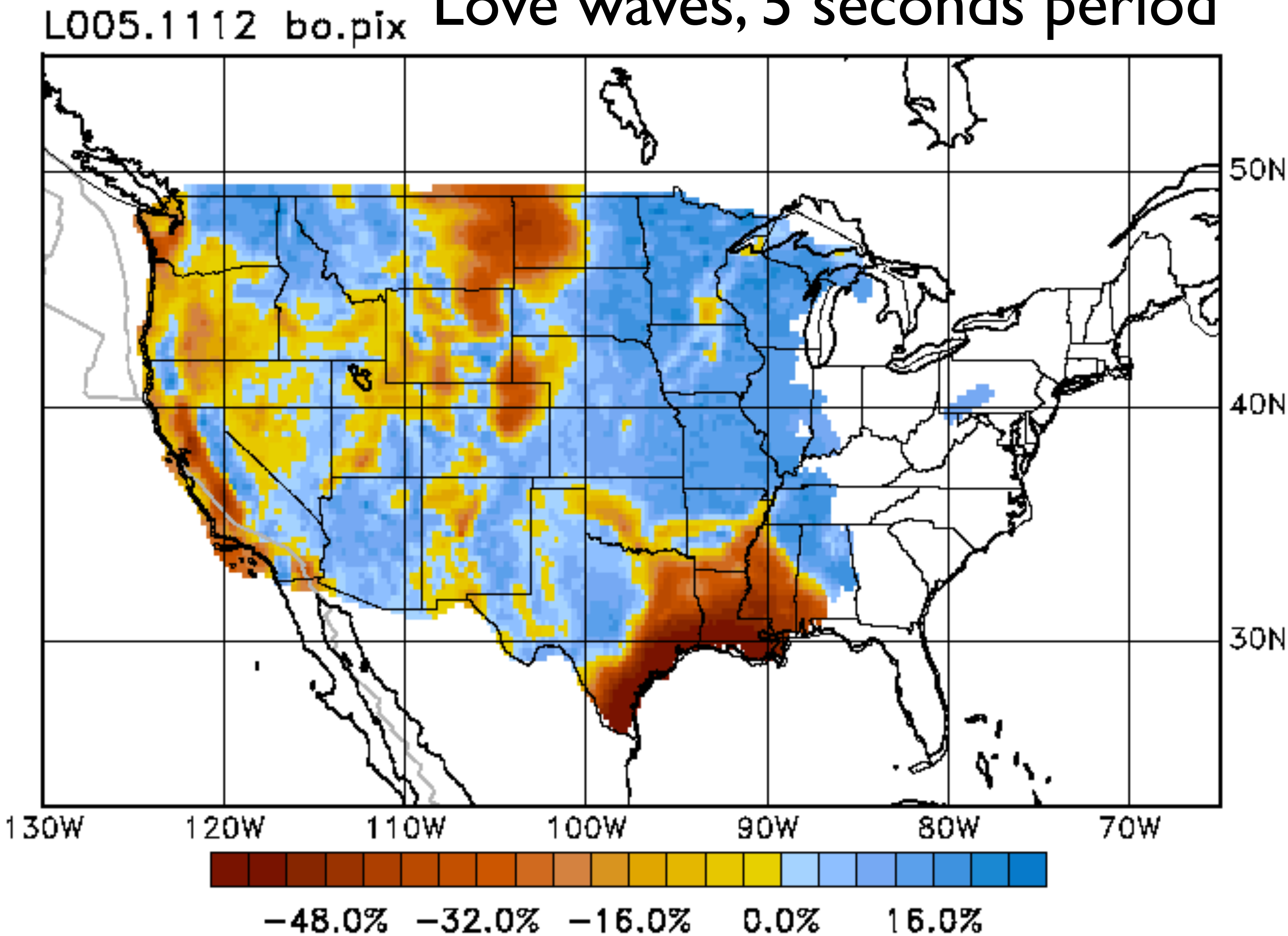
Love waves, 5 seconds period



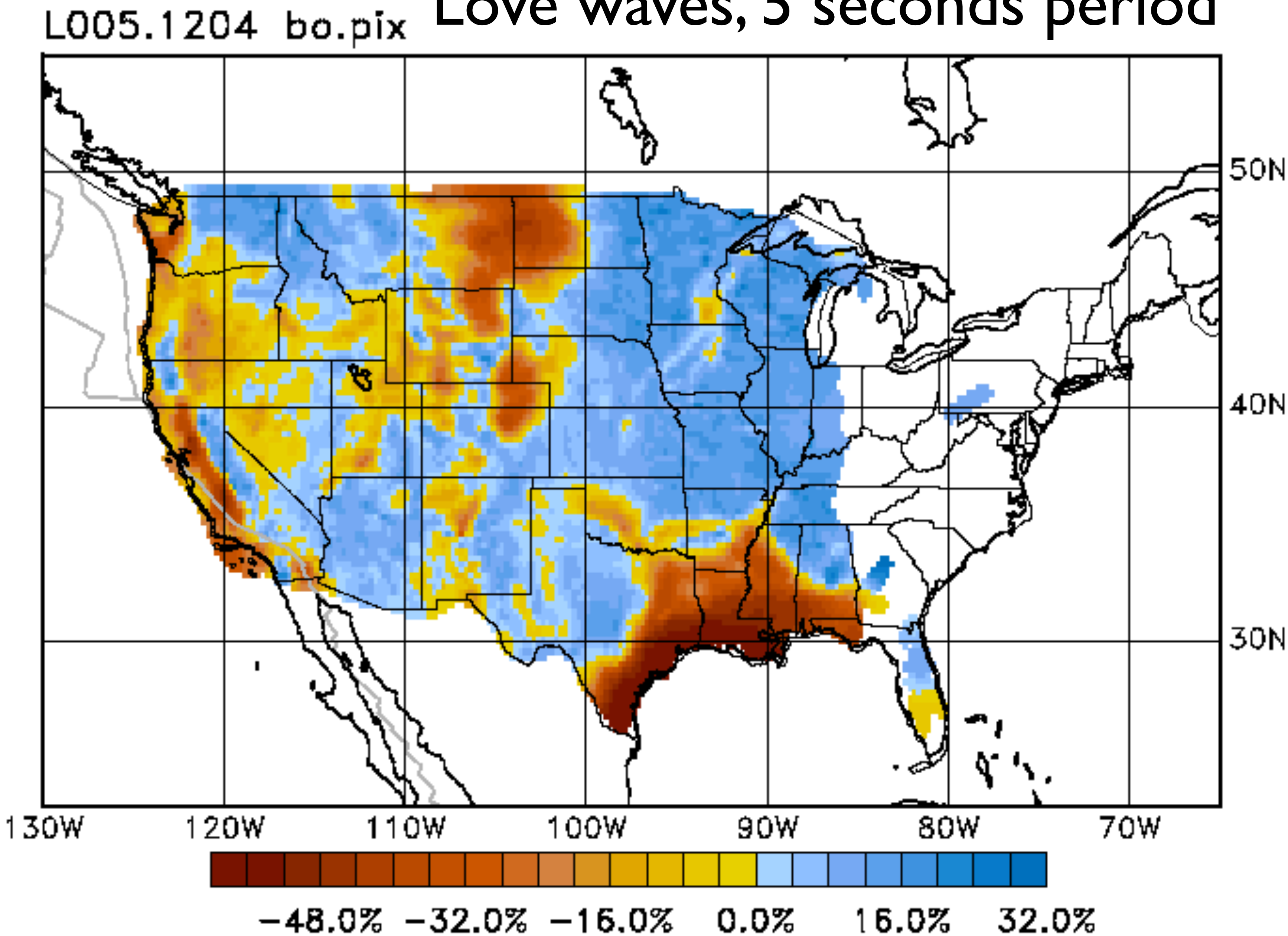
Love waves, 5 seconds period



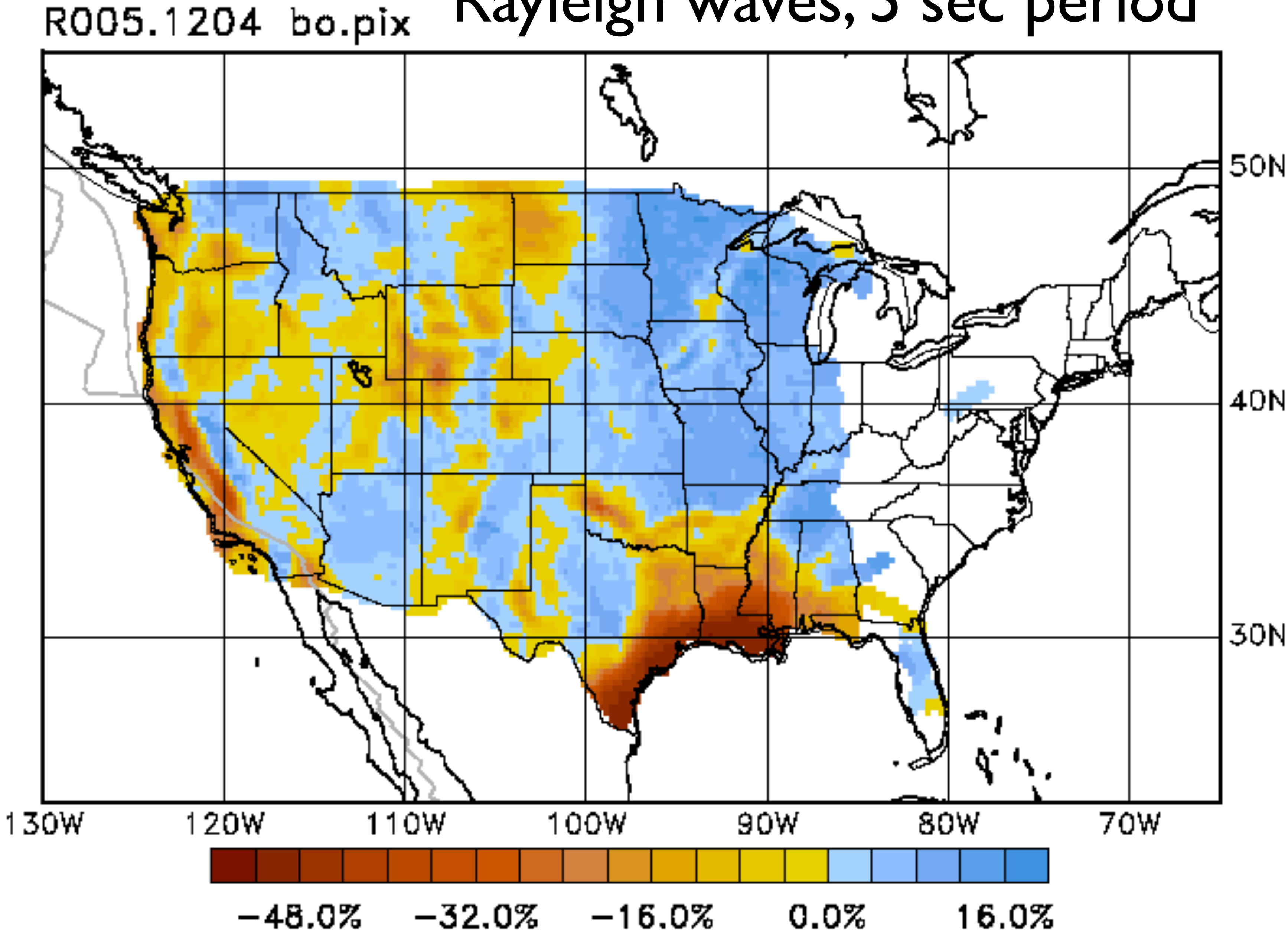
Love waves, 5 seconds period



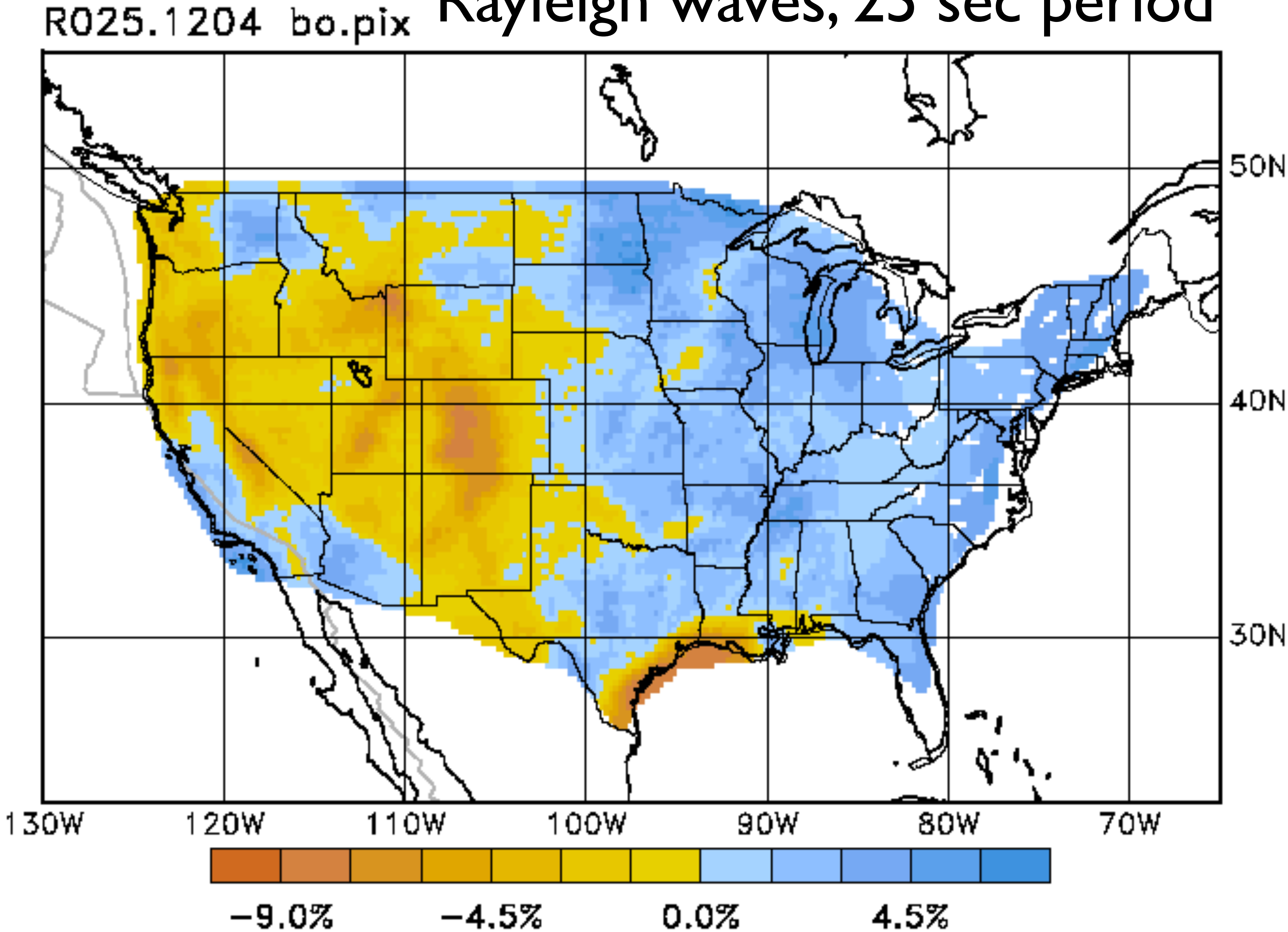
Love waves, 5 seconds period

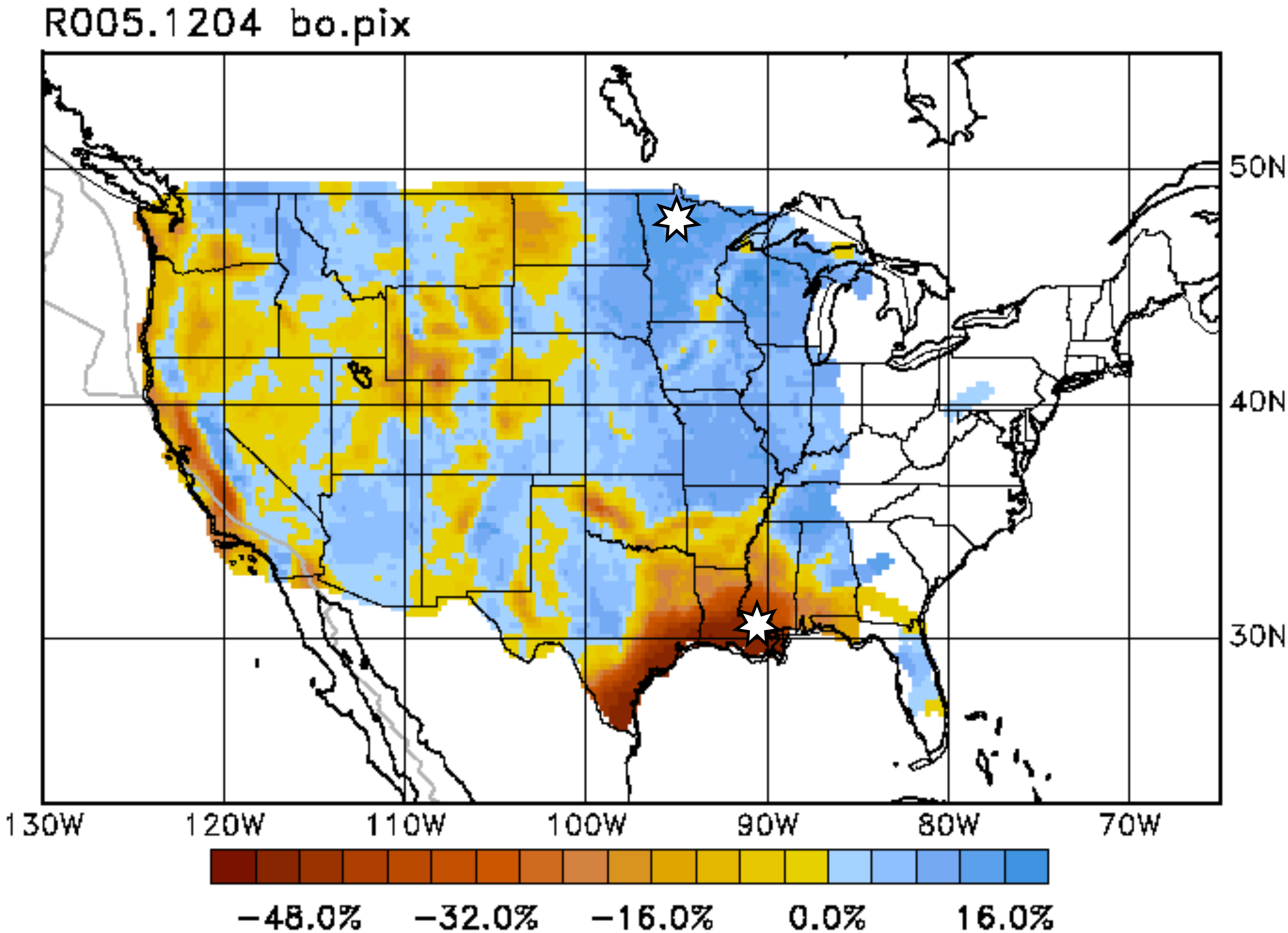


Rayleigh waves, 5 sec period

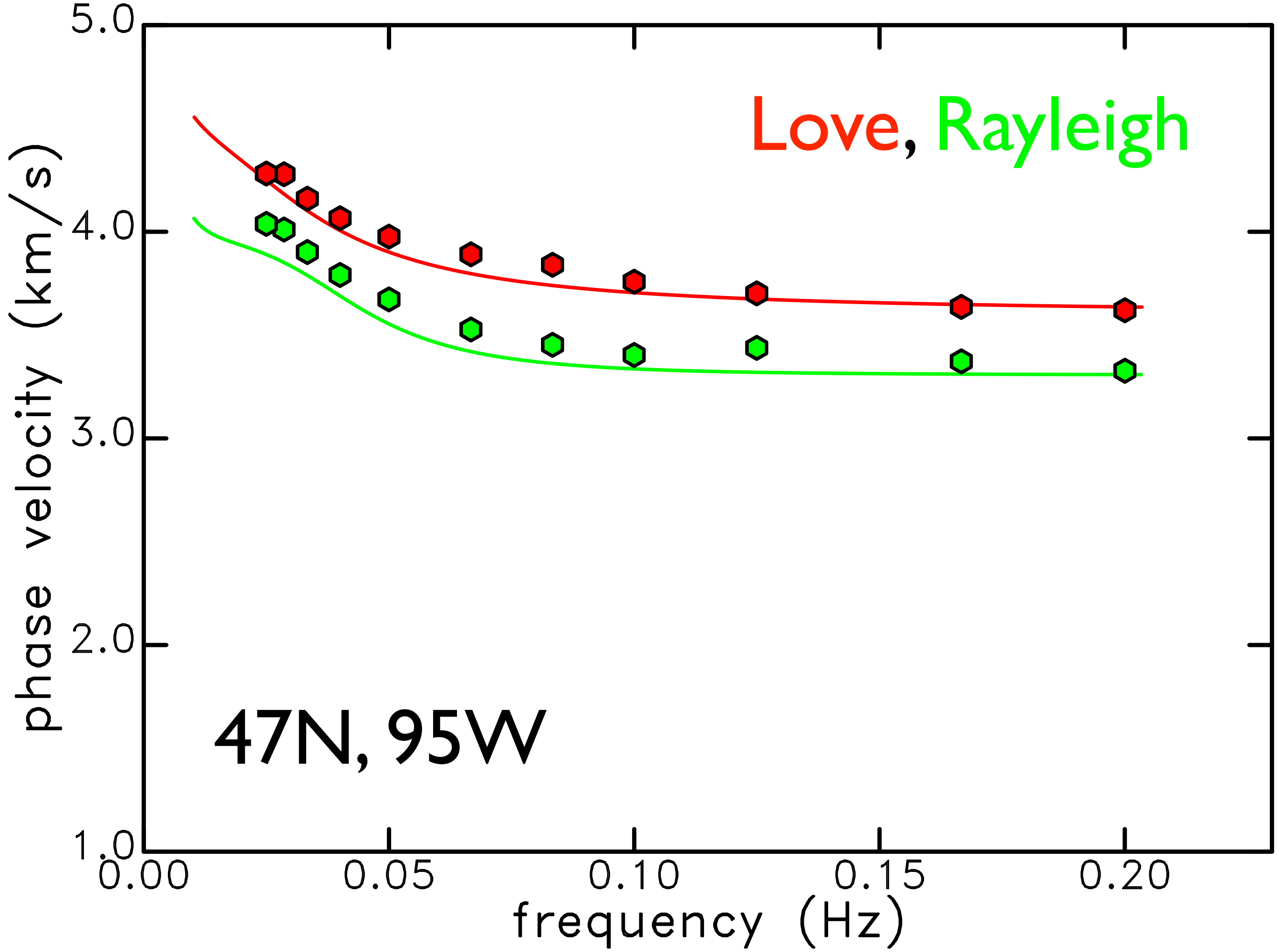


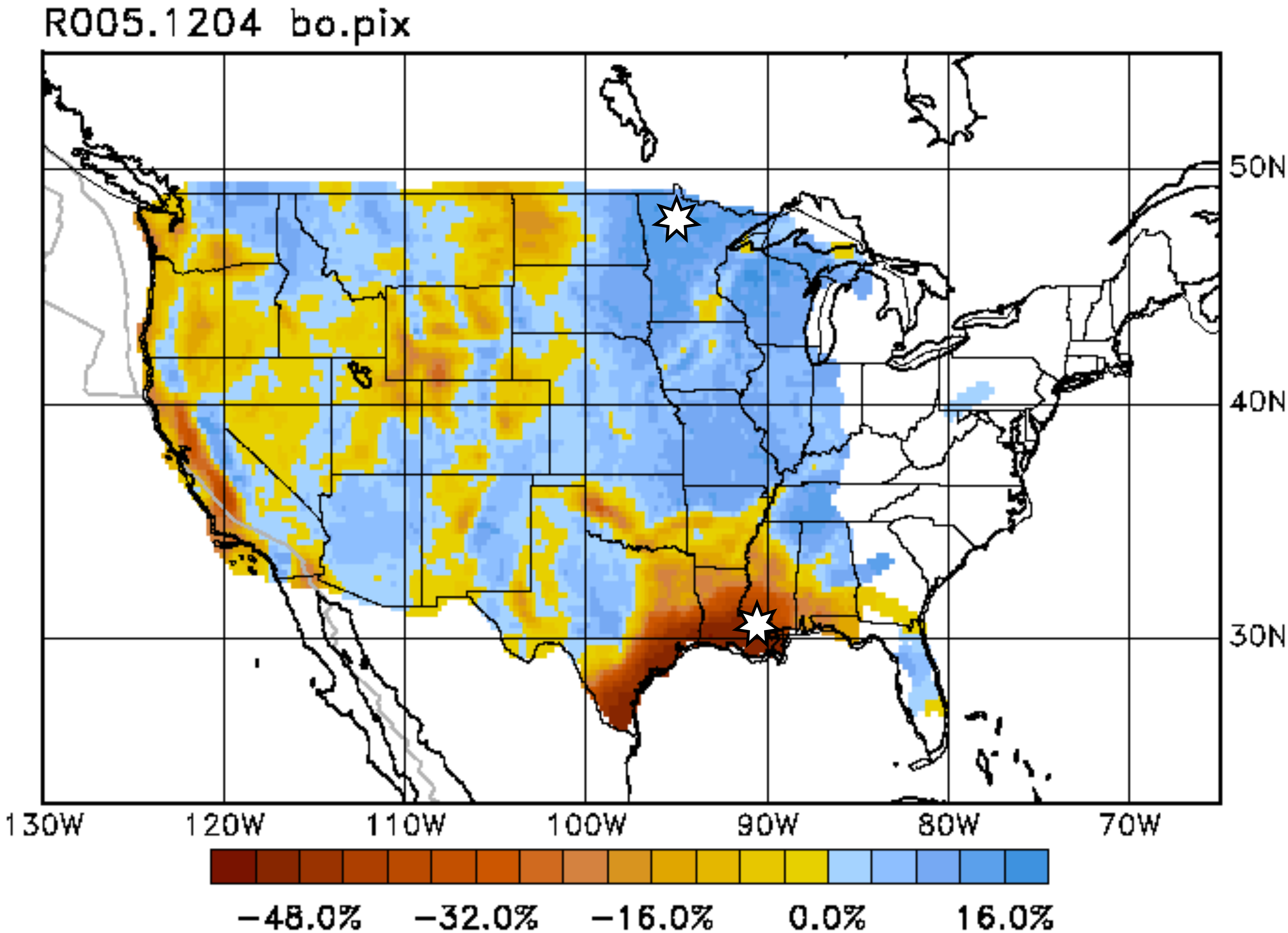
Rayleigh waves, 25 sec period



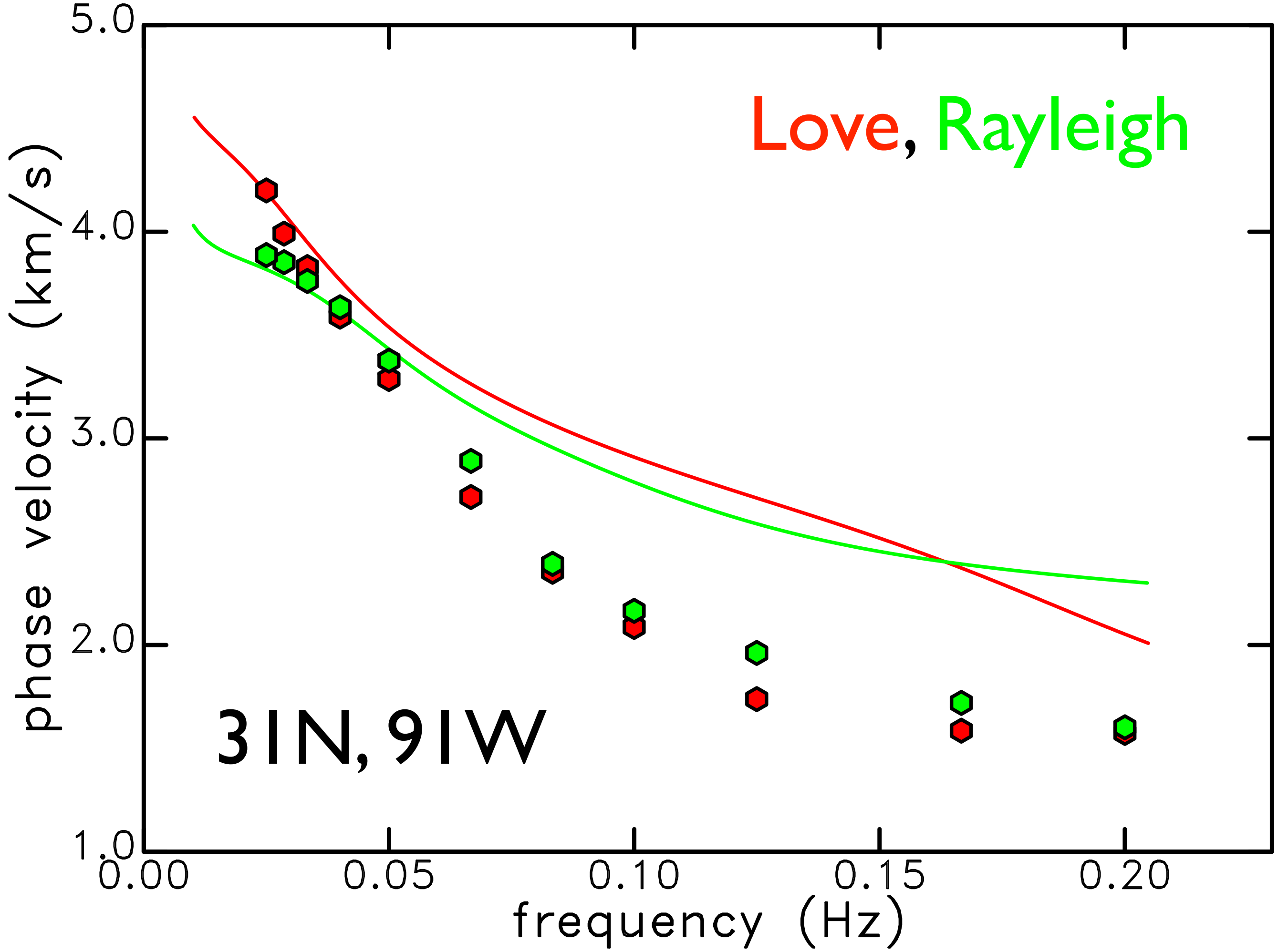

R005.1204 bo.pix
50N
40N
30N
130W
120W
110W
100W
90W
80W
70W
−48.0%
−32.0%
−16.0%
0.0%
16.0%

Observations and CRUST 2.0




R005.1204 bo.pix
50N
40N
30N
130W
120W
110W
100W
90W
80W
70W
-48.0%
-32.0%
-16.0%
0.0%
16.0%

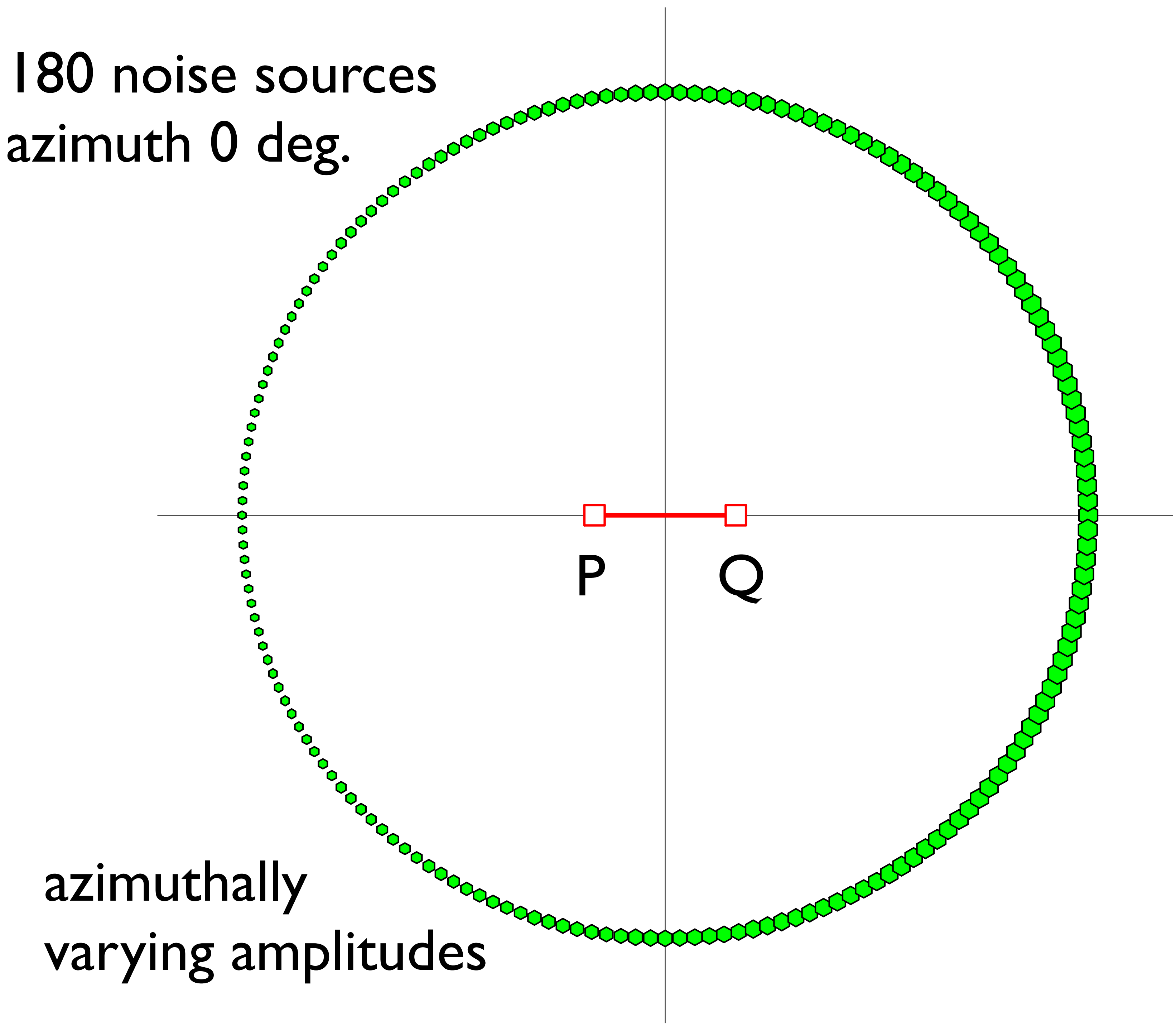
Observations and CRUST 2.0



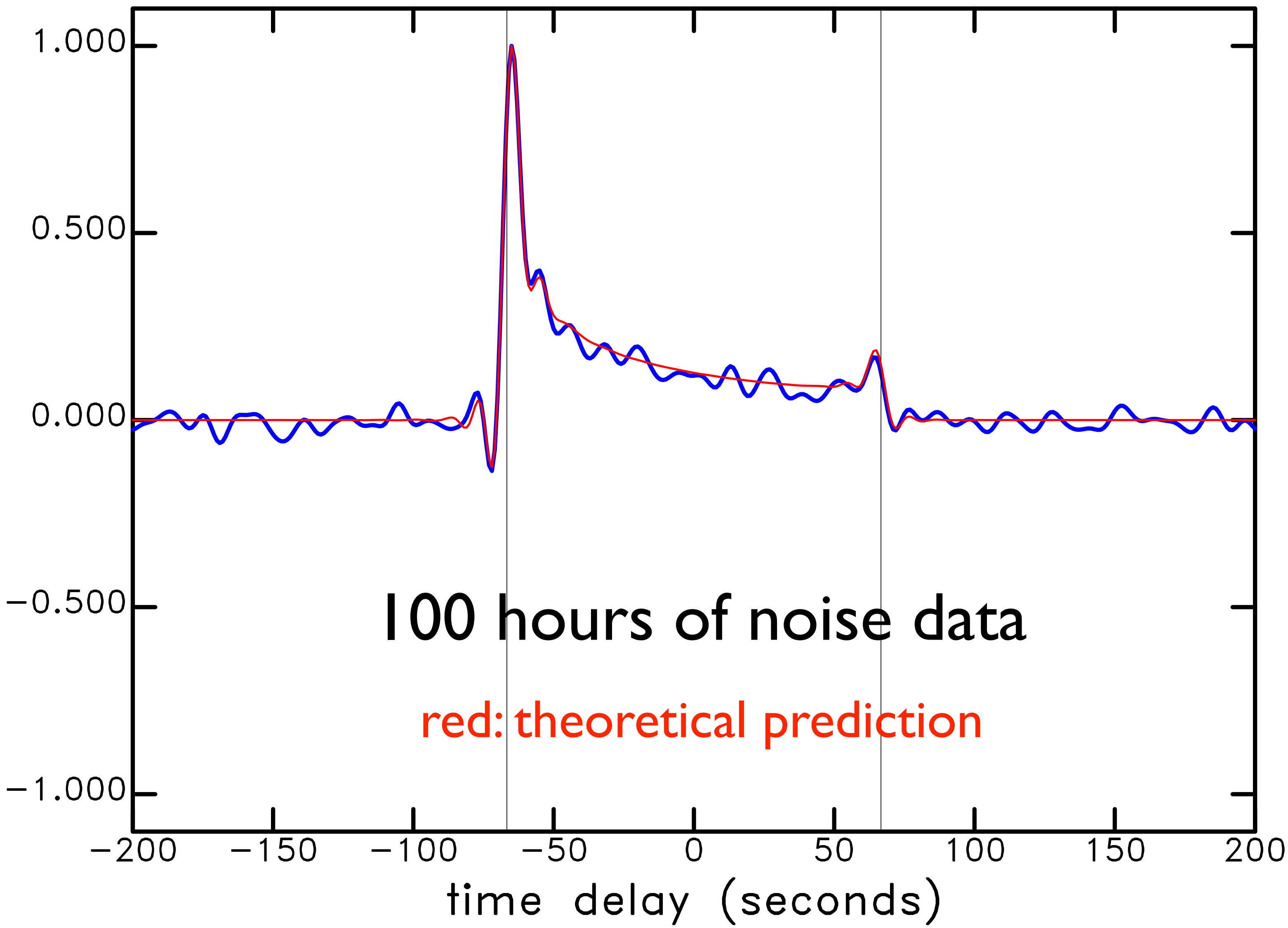
1. Noise tomography is a powerful tool to investigate shallow Earth structure using data from a regional network

2. There are different algorithms that are used -- Aki's method is perhaps the simplest

3. Noise tomography requires continuous data


180 noise sources
azimuth 0 deg.
P
Q
azimuthally
varying amplitudes

Cross-correlation function, P and Q



Spectrum of cross-correlation function