La sismica “ tra un po’ “

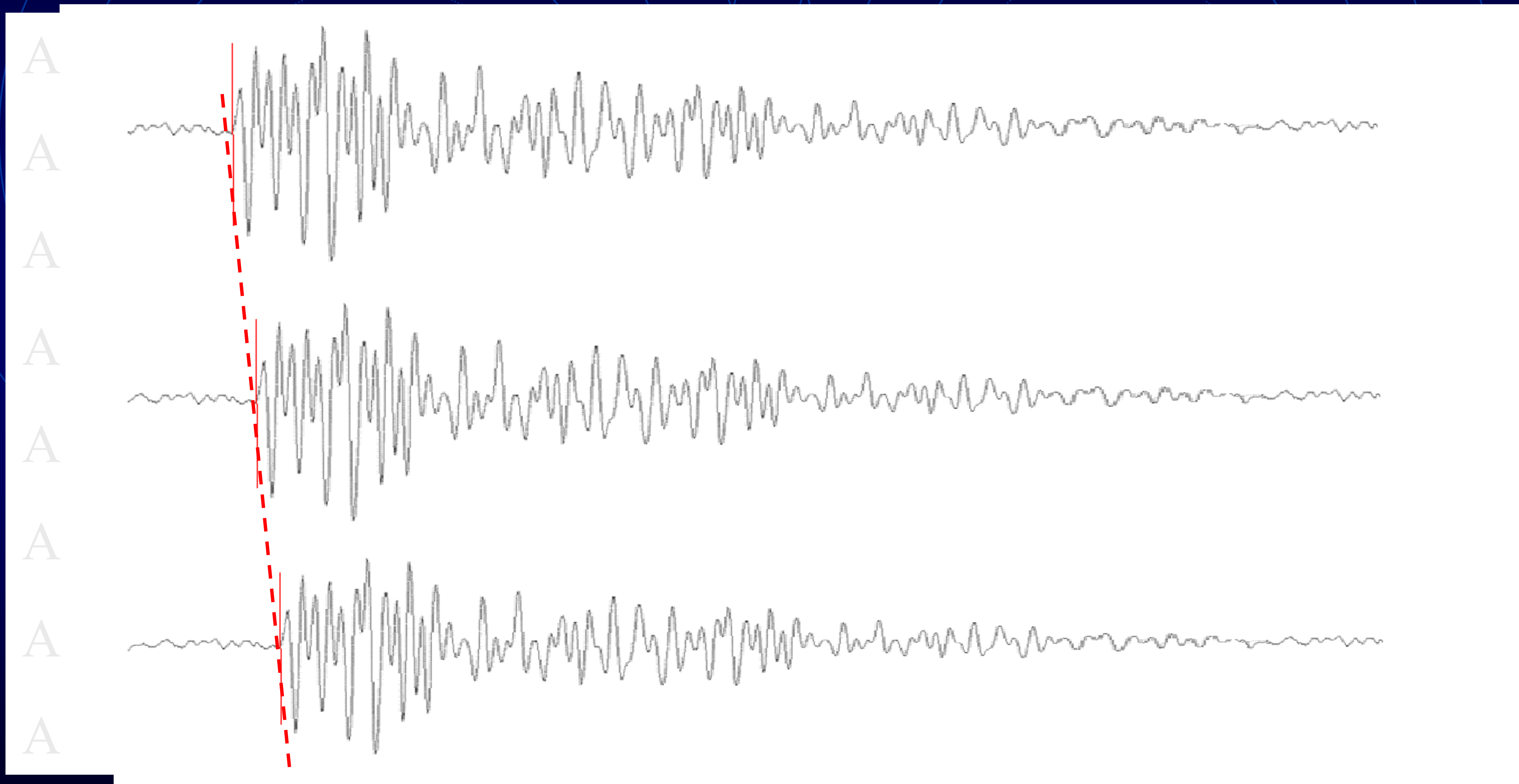
FRANCESCO MULARGIA

La sismica tradizionale

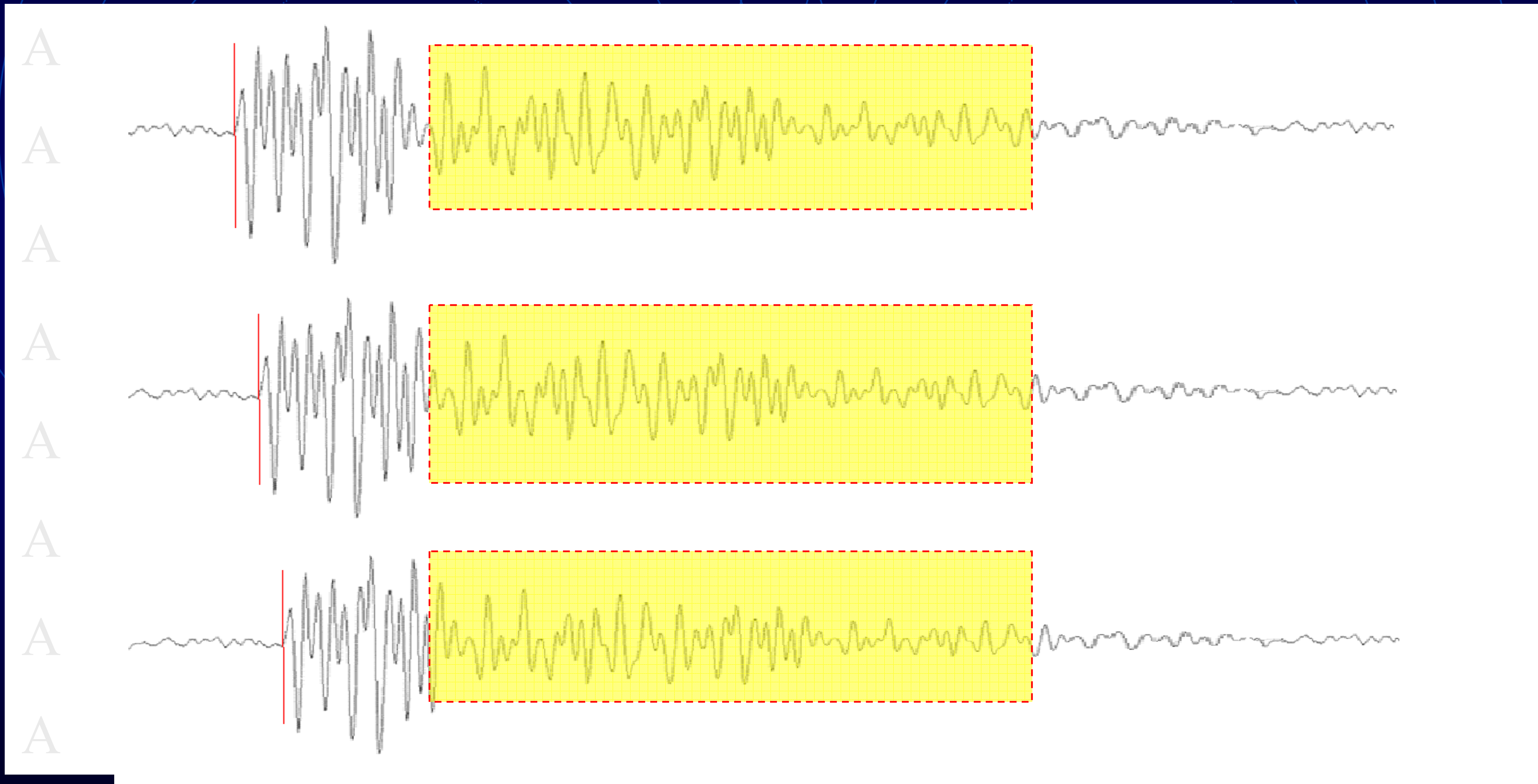
- Una sorgente di onde
- Molti geofoni
- Qualche foro

e soprattutto….

Un'informazione contenuta nei sismogrammi che viene quasi tutta "buttata"



Quanto meno in parte



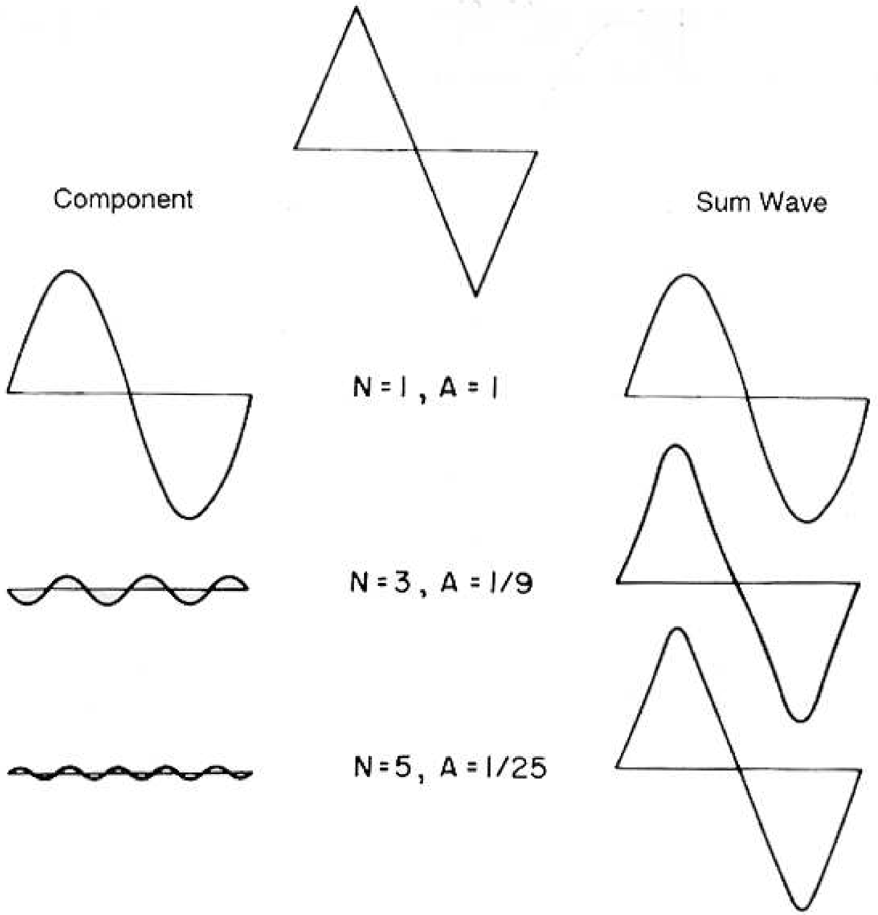


Figure 4–4 Fourier synthesis of a triangular wave. At the left are the successive harmonics; at the right are the sum waves including each successive harmonic. The graph at the top is the wave being synthesized.

Es 1: triangle wave with a sum of harmonics.

Adding in higher frequencies makes the triangle tips sharper and sharper.

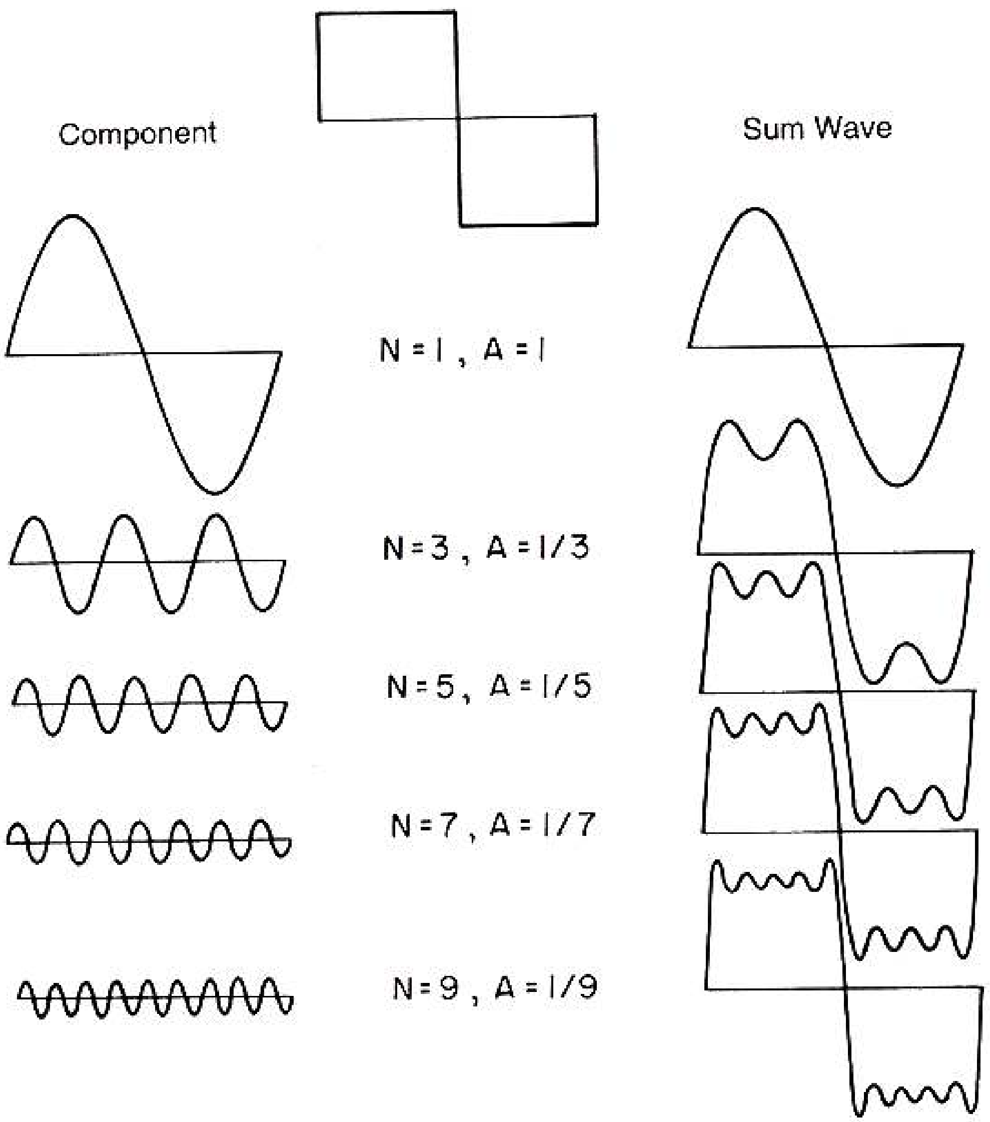


Figure 4–5 Fourier synthesis of a square wave. At the left are the successive harmonics; at the right are the sum waves including each successive harmonic. The graph at the top is the wave being synthesized.

Es. 2 Square wave

Same harmonics however the higher order harmonics are stronger.

Square wave sounds shriller than the triangle which sounds shriller than the sine wave

La sismica passiva

- Ovvero la sismica in cui non si butta via niente.

Apparent diffuse-like features of the seismic noise wavefield

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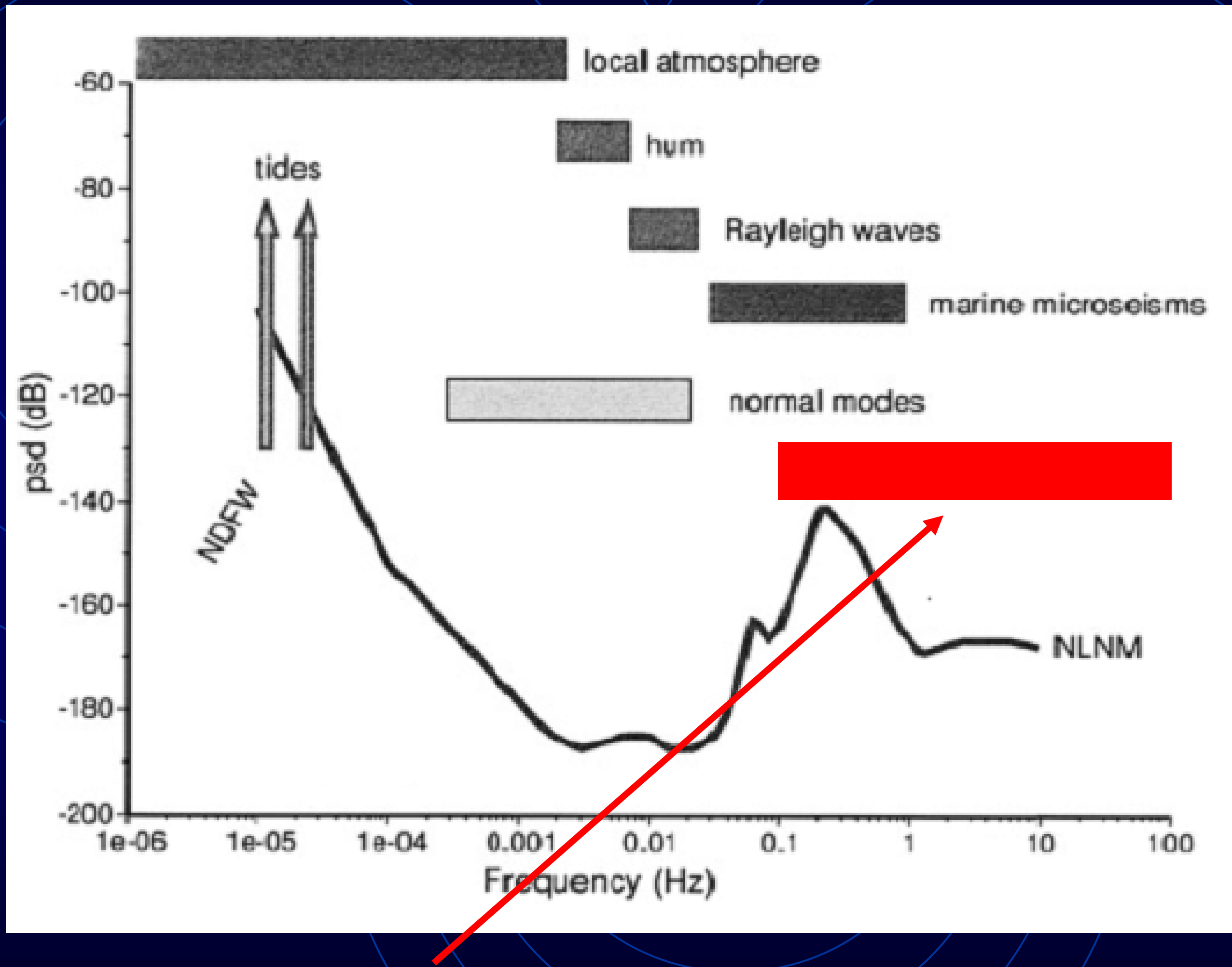
Which noise?

- <2mHz - Newtonian attraction of moving air masses above the seismic sensor (e.g., Zürn and Widmer, *GRL* 1995)
- 2–7 mHz - Fundamental Earth spheroidal modes, (e.g., Suda *et al.*, *Science* 1998)
- 7–30 mHz - Globe circling Rayleigh waves (e.g., Ekström, *JGR* 2001)

Which noise?

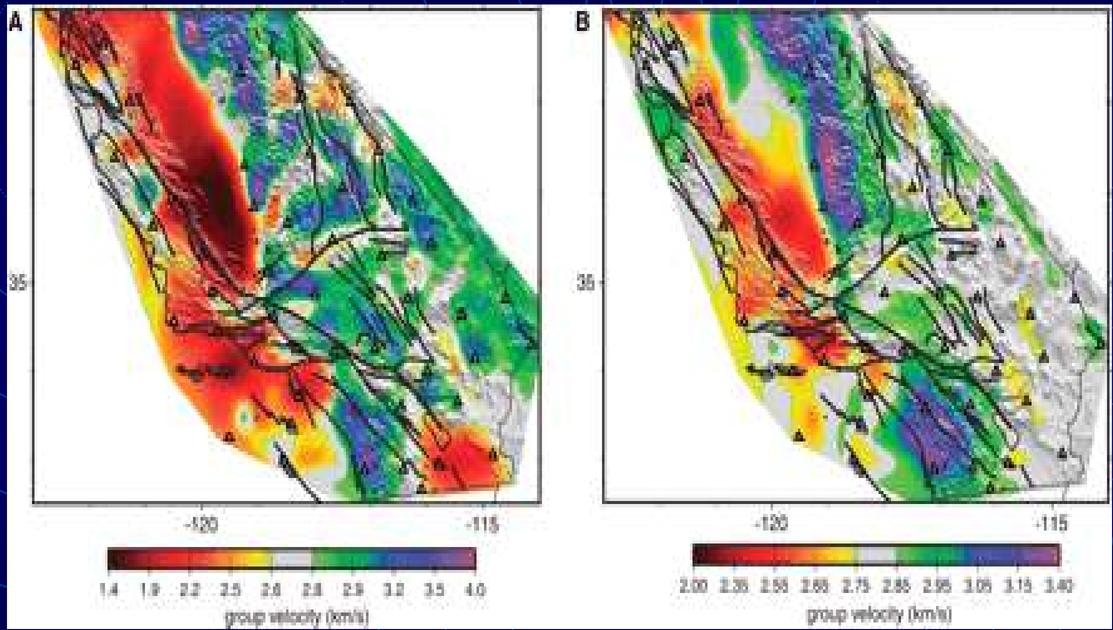
- 0.003–1 Hz - Marine microseisms (e.g. Douze, *JGR* 2001)
- 1 – 10 Hz - Marine microseisms, local meteo and anthropic origin (+ volcanoes, earthquake codas, tsunamis)
- 10 – 100 Hz - Local meteo and anthropic origin (+ volcanoes & nearby earthquakes)
- > 100 Hz – Anthropic origin

This noise



The HF noise, for its stratigraphic-engineering relevance

Passive seismic imaging already attempted with success



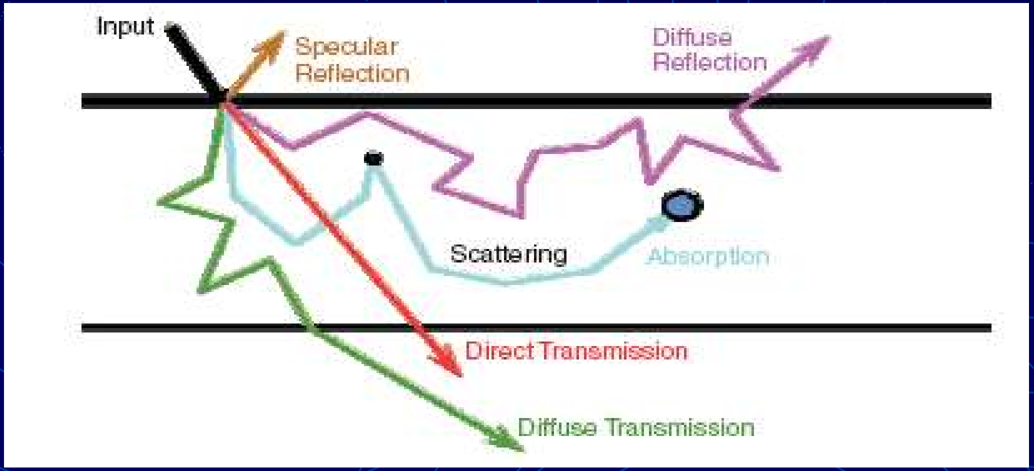
Shapiro et al, *Science* 2005, Sabra et al, *GRL* 2005, Lin et al. *GJI* 2008

However, so far restricted to

- station couples orthogonal to the coast
- surface waves

recent advances in nonlinear Optics and Acoustics still to be exploited

In a medium with distributed Huygens sources (*direct*=real sources or *indirect*=scatterers)

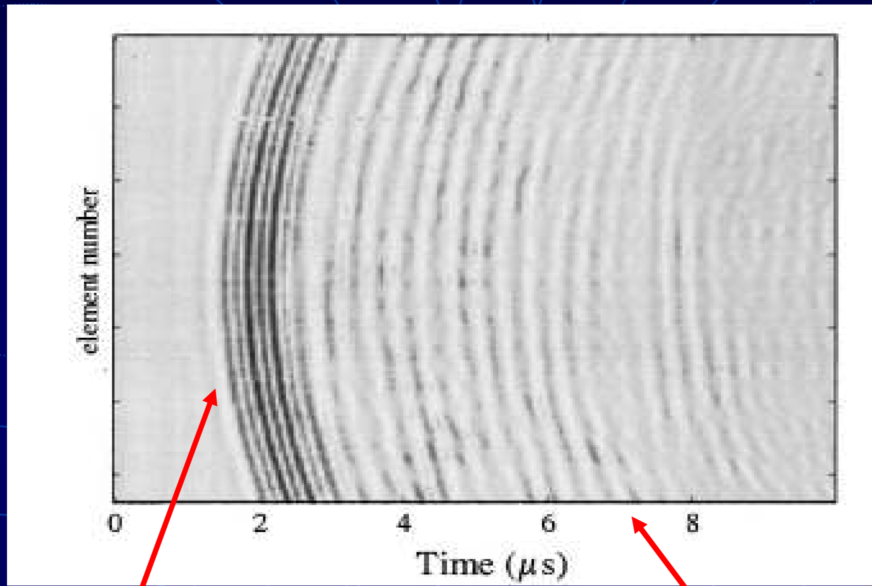


Two wavefields exist:

1) A *ballistic* wavefield (no scatter) exists at "short" distances

2) A *diffuse* multiple scattered wavefield exists at "long" distance

Ballistic & Diffuse wavefields



Ballistic waves

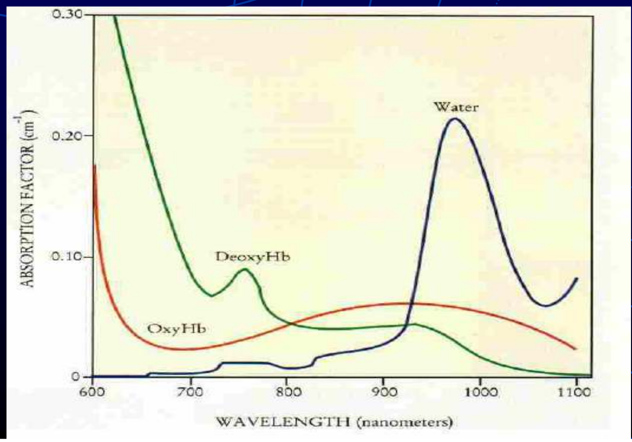
Diffuse waves

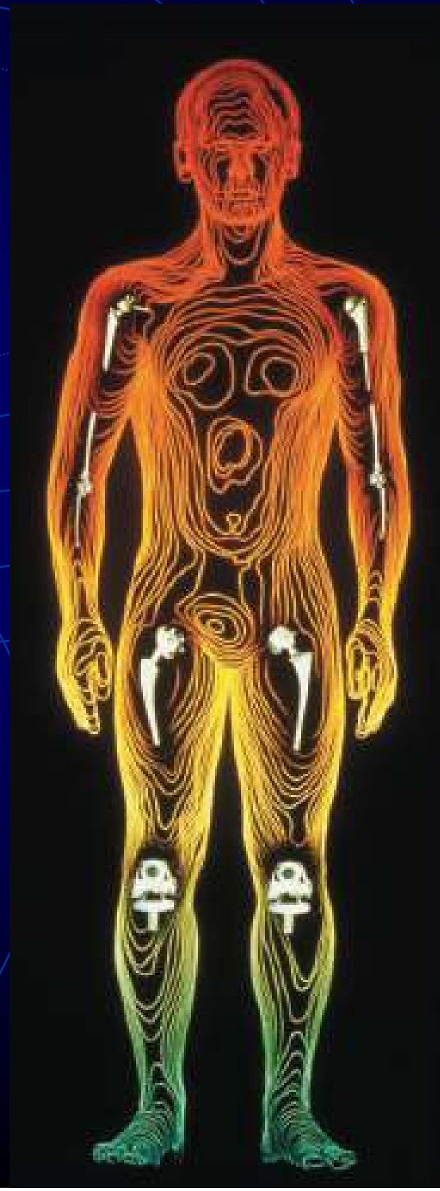
Both wavefields obey the laws of linear optics and allow imaging

Diffuse field optics

(e.g. Yodh & Chance, *Phys. Today* 1995)

- Allows to “see” through nontrasparent (turbid) media
- Diffusing near infrared light provided great advances in clinical diagnosis, much eased by tissue spectral features





Theoretical basis of diffuse wavefields

- Multiple scattered wavefields too complex to be analized directly
- *ensemble* described by the *diffusion equation*

$$S(r,t) = \nabla . D \nabla U(r,t) - c\,\mu_a U(r,t) - \partial U(r,t)/\partial t$$

where

S = *source*

U= *Energy density*

D= *Diffusion coeff.*

μ_a= *absorption coeff.*

The diffuse acoustic wavefield
(Weaver&Lobkis, *PRL* 2001)

Multiple scattering (N>10^2 scatters) induces:

- *spatially quasi-isotropic field and*
- *random superposition of plane waves*

$$<a_n|\, U \,|a_m>= \delta_{nm}$$

- *modal equipartition*

$$<a_n \,|\, a_m>= \sigma^2\delta_{nm}$$

Key property of diffuse wavefields for imaging

- Take *any* couple of points *a-b:* either one can be assumed to be the source and the other the receiver
- Both the retarded and advanced Green's

$$u(x) = \int_{-\infty}^{\infty} G(x;x')f(x')dx'$$

functions (hence the medium local properties) can be derived from simple x-correlation

The immature diffuse acoustic wavefield

(Mulargia&Castellaro, *Phys.Rev.Lett.* 2008)

Sparse multiple scattering (N>1 scatters) of Huygens sources induces:

- *spatially anisotropic but locally uniform wavefield*
- *random superposition of plane waves*

$$<a_n| U |a_m >= \delta_{nm}$$

- *no modal equipartition*

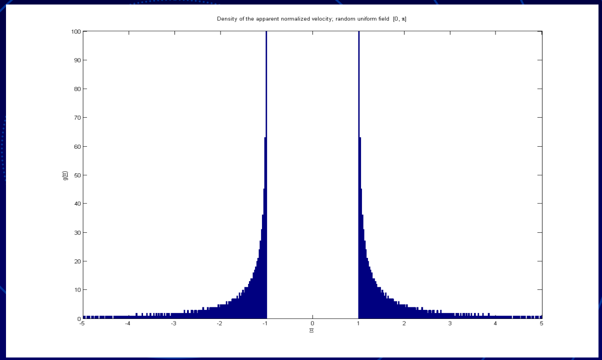
$$<a_n | a_m >= \sigma^2 \delta_{nm}$$

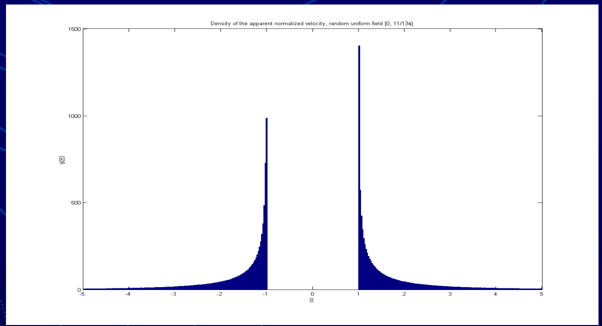
Key property of near diffuse wavefields for imaging

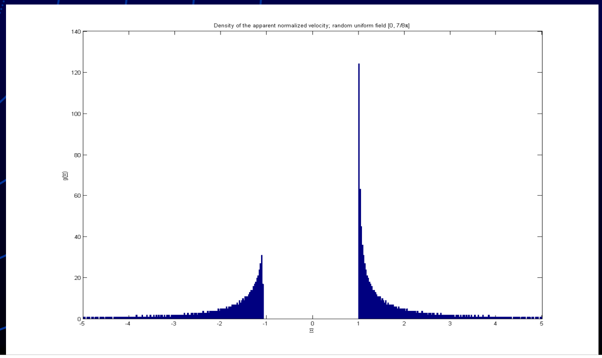
- Take *any* couple of points *a-b:* according to field azimuth and aperture one can be assumed to be the source and the other the receiver
- The retarded Green's function (hence the medium local properties) can be derived from simple X-correlation

Advanced and retarded Green's functions

- Distribution of the Normalized apparent velocity
  - peaked at –1 and 1 for diffuse fields
  - peaked only at 1 for the near diffuse fields

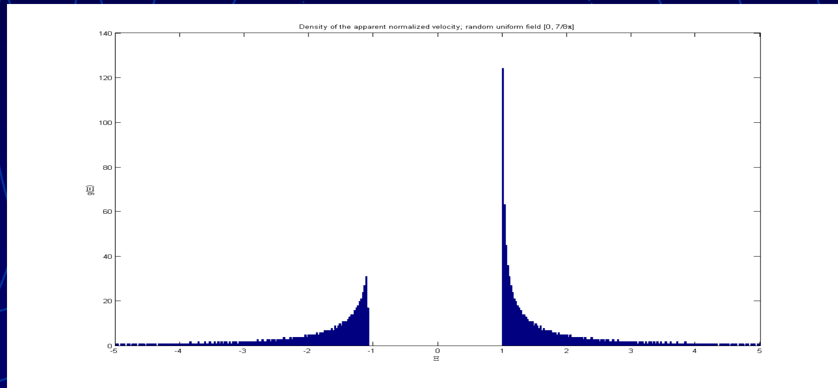


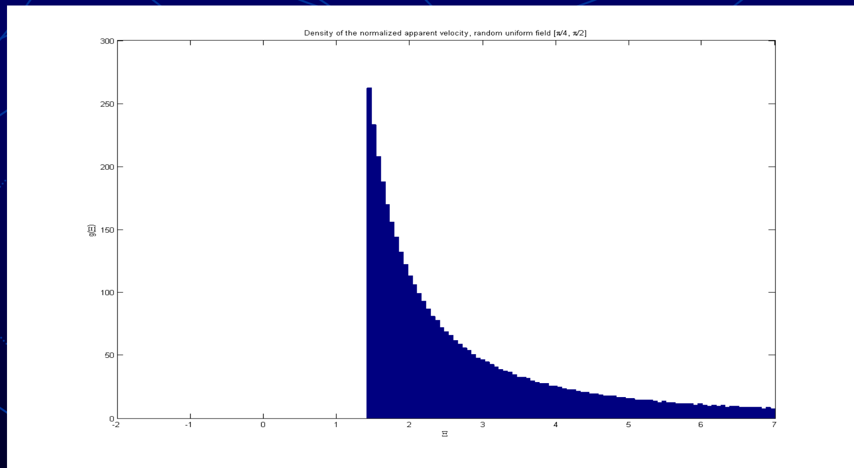




First practical consequence: the mode as a best estimator

- Minimally biased estimates of even near orthogonal fields





The same as ReMI, but statistically stable

Unfortunately, seismic noise is *not* diffuse

- The wavelengths of interest are comparable with local structure dimensions so that multiple scattering is *not* the basic mechanism
- The role of surface waves is very important
- Equipartition does *not* apply to surface waves

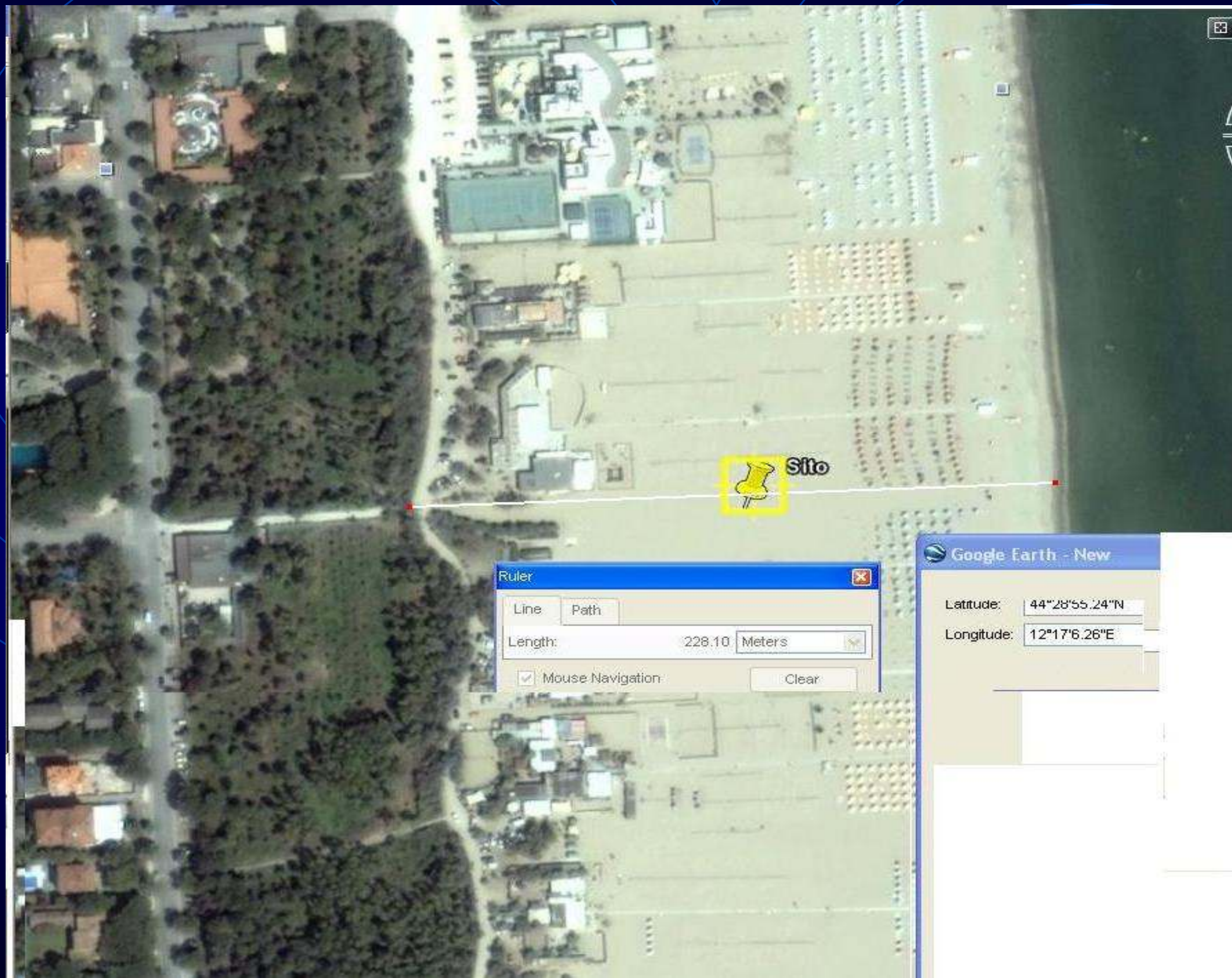
Is seismic noise *near diffuse?*

- This would allow - without time reversal, which practically irrelevant – an identical passive imaging capability to diffuse fields from simple noise x-correlation

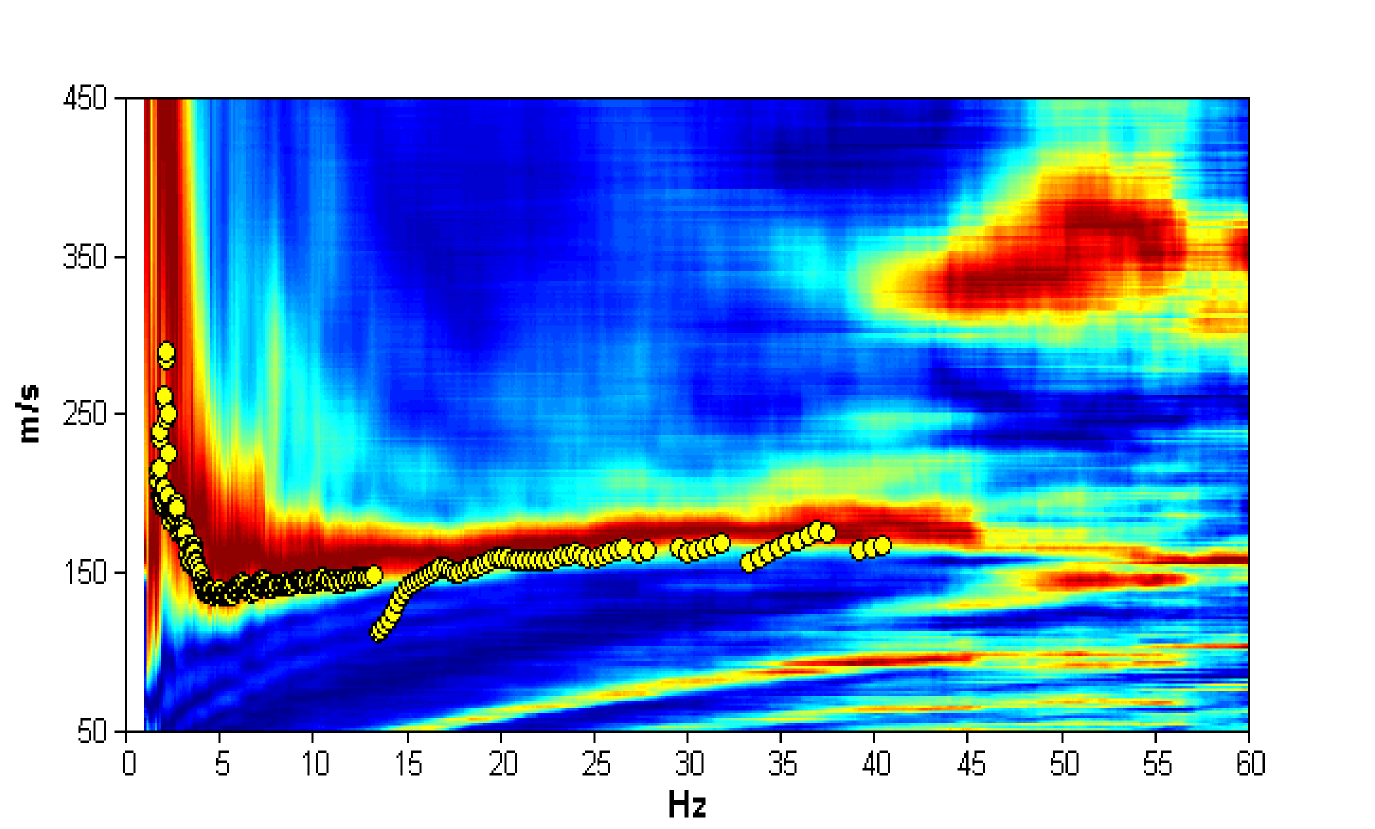
Is it?

- Design experiments to study the seismic noise wavefield in ϕ and t
- Experimental layout as simple as possible to avoid superimposing inputs
- Use R^2 minimization on a quadrant array

The Marina di Ravenna experiment

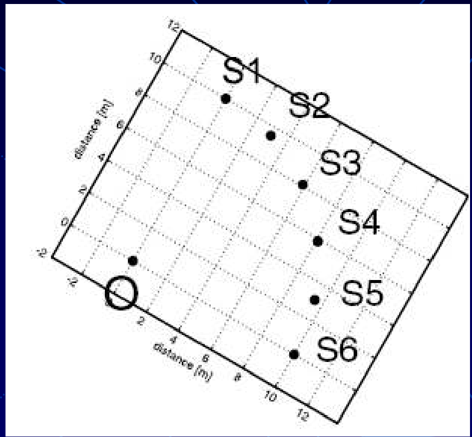

Sito
Ruler
Line
Path
Length: 228.10 Meters
Mouse Navigation
Clear
Google Earth - New
Latitude: 44°28'55.24"N
Longitude: 12°17'6.26"E

Homogeneous & isotropic first sand layer (no multiple scattering)



ReMi+ESAC show no dispersion on 4-60 Hz

Experiment



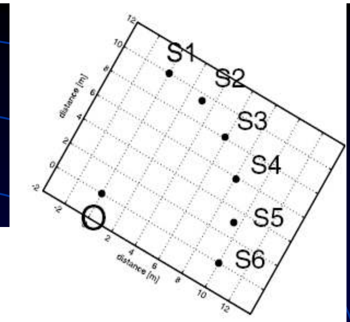
- X-correlation on synthetic (GPS synchronized) quadrant arrays

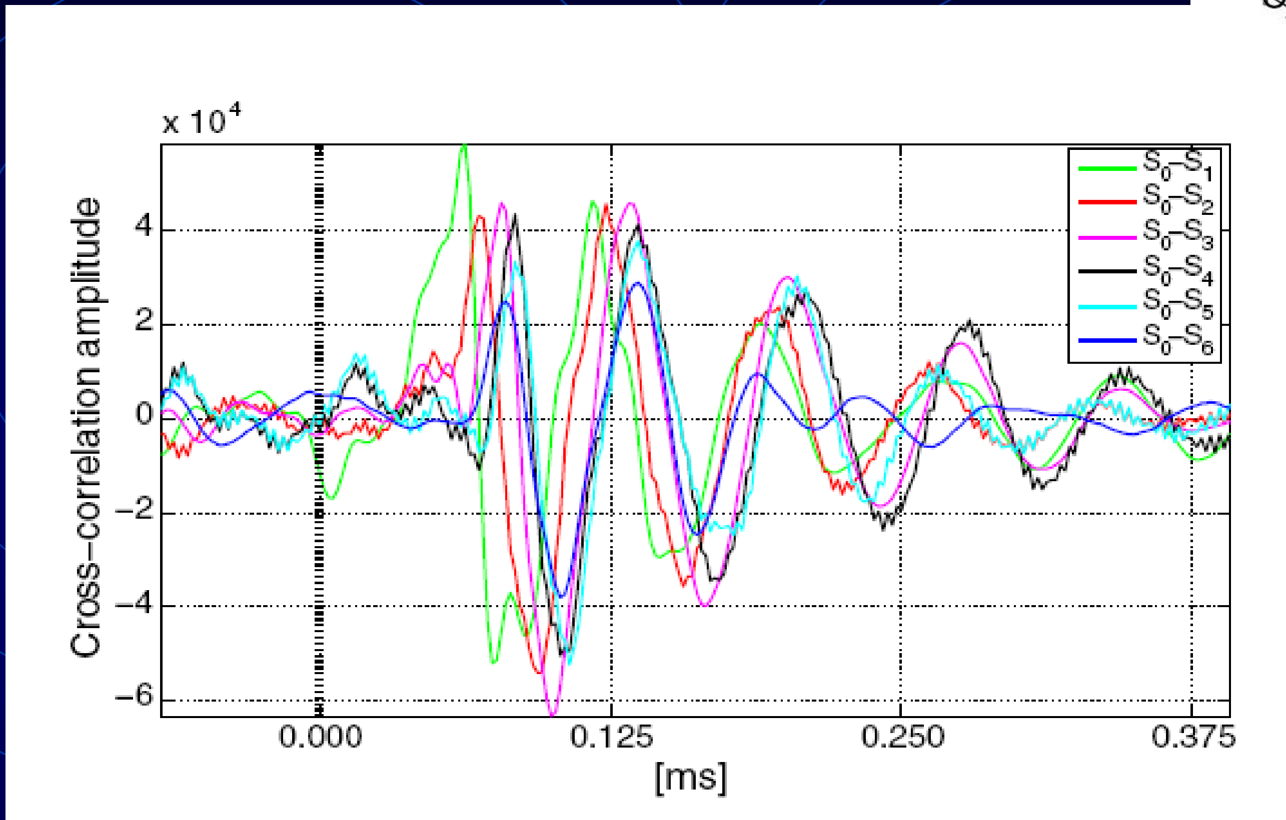
- Tromino (1 kg, 2200 v/m s, 24 bit, 0.1-250 Hz, 3vel.+3accel.) in each array element

Experiment

- sampling at 1024 Hz
- 1 s moving window
- very calm sea condition
- r=10 m
- full signal correlation (no 1bit)

Results

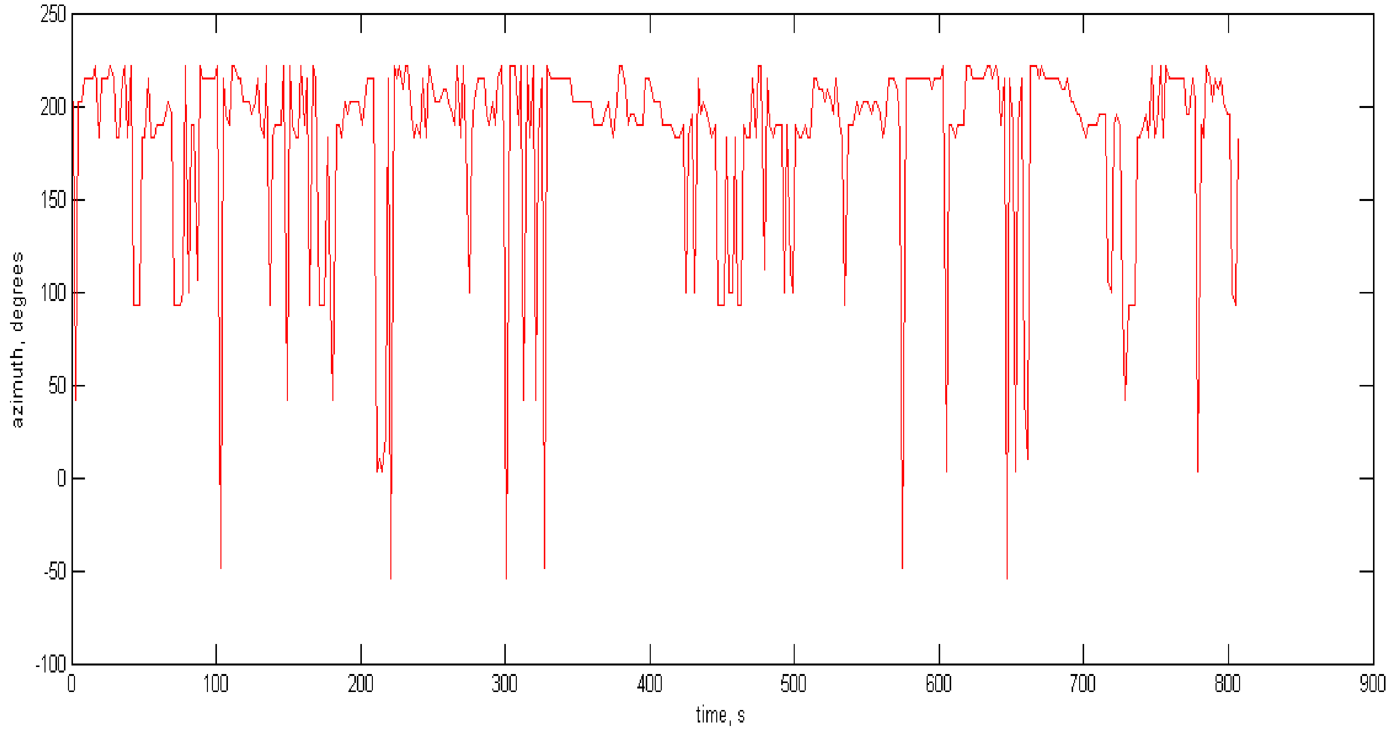




1) No time reversal

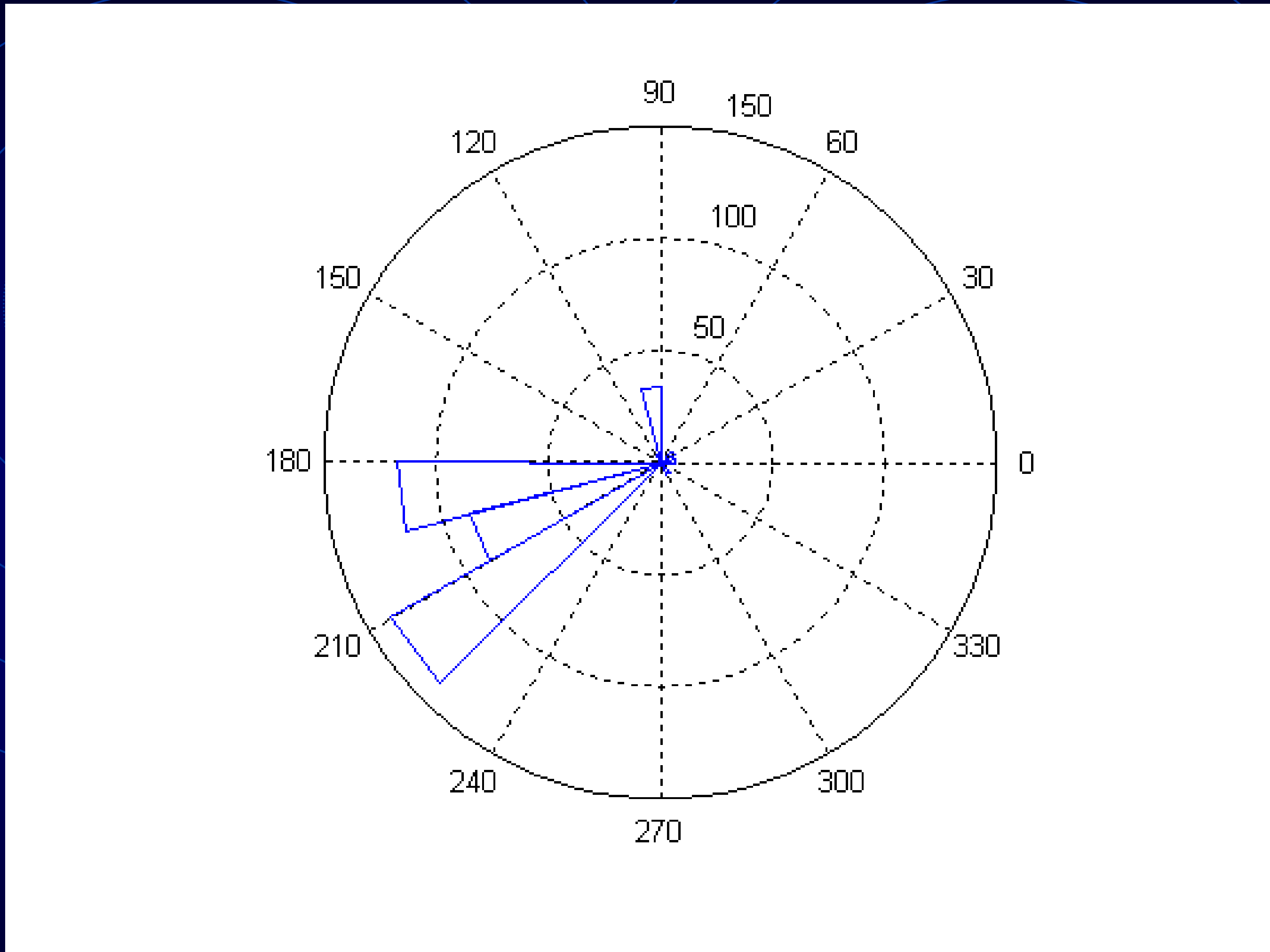
2) X-correlation near independent of station couple azimuth

Results



3) Huygens source random switch in time with 1-10 s latency

Results



4) Huygens source azimuthal distribution spatially anisotropic uniform

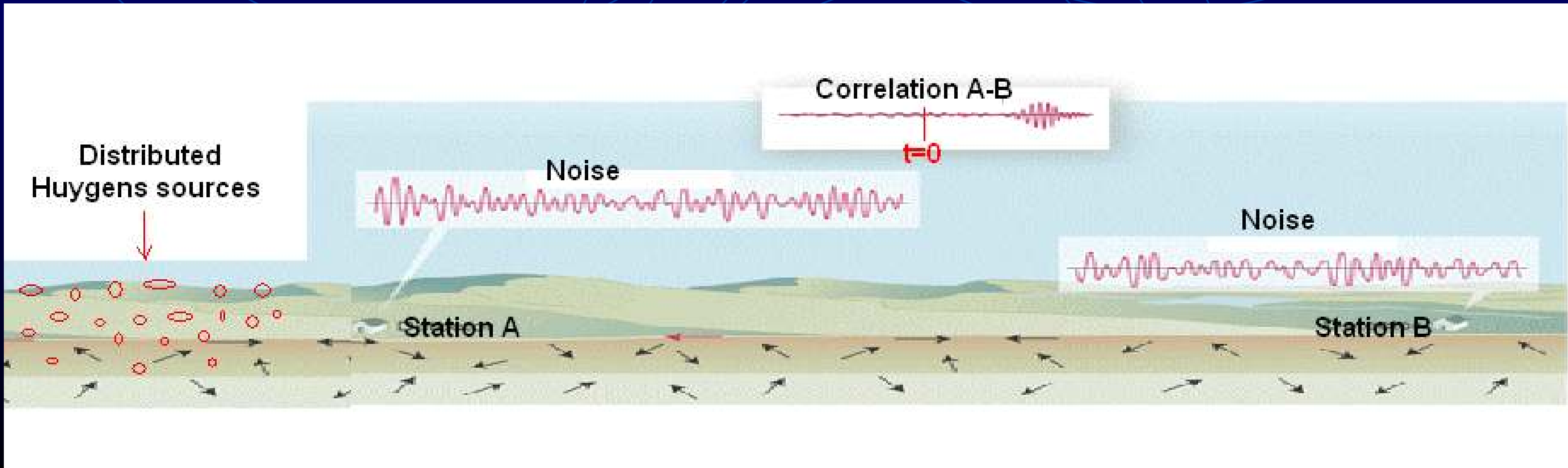
5) Huygens sources = real sources, traceable to Ravenna port activity

Conclusions

- Seismic noise fully compatible with a near diffuse wavefield
- Passive imaging on *any* couple of points seems therefore possible

Therefore, in practice

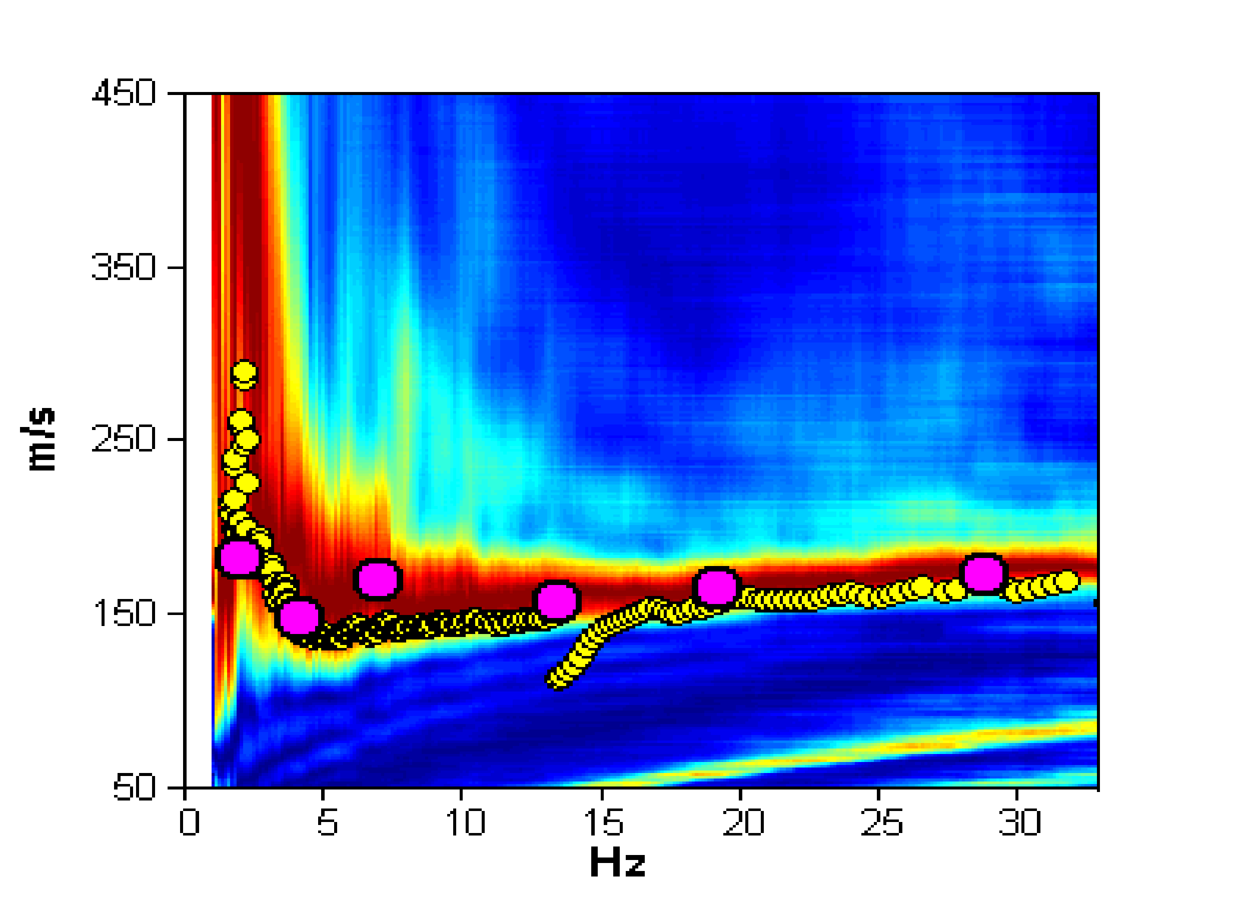
- Any couple of points A and B in a seismic noise wavefield can be respectively as source and station



Therefore, in practice

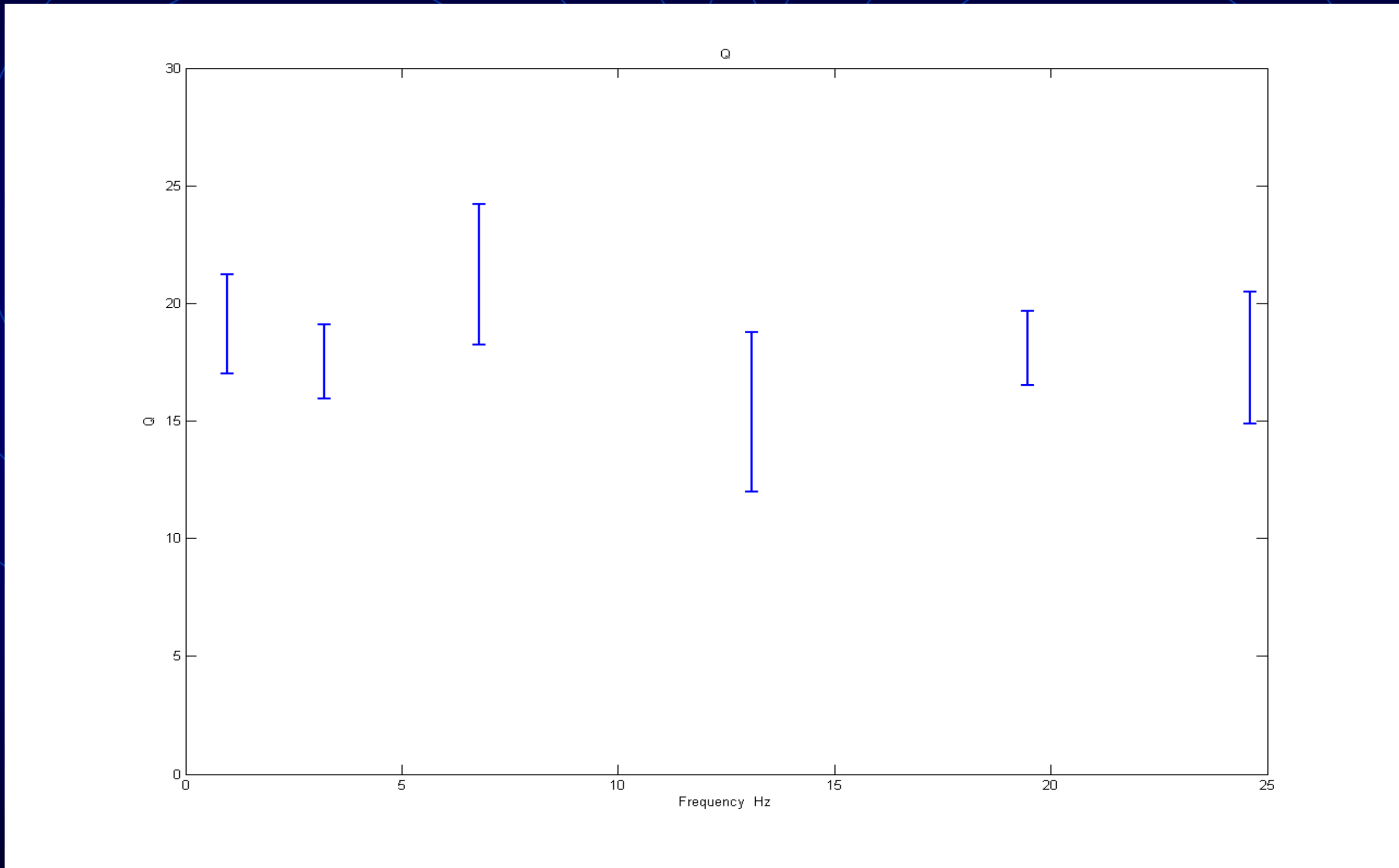
- This allows an immediate passive measure of elastic and anelastic local properties

Elastic properties



Wave velocity dispersion closely matching ReMi and ESAC

Anelastic properties



Q (ω)

A new view: time&frequency
(wavelet transform)