The ocean view of seismic interferometry

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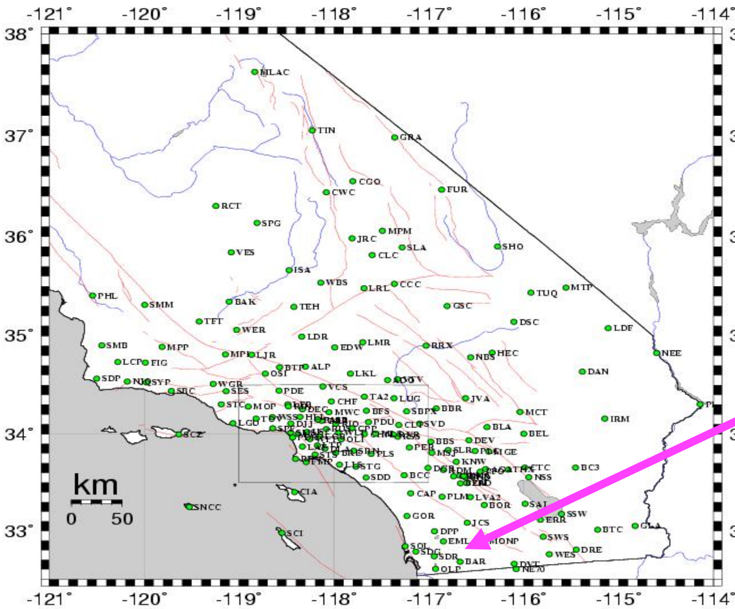
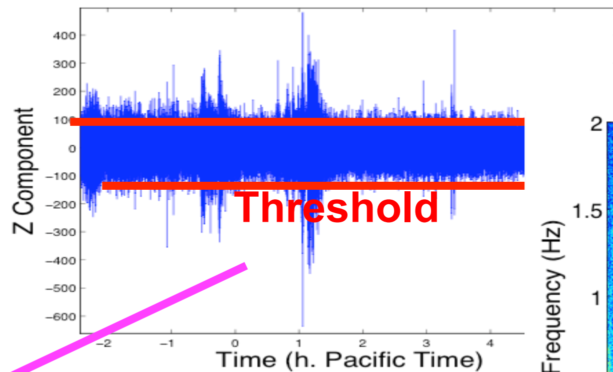
Plan:
- History/Introduction
- Passive fathometer
- P-wave microseisms
- Microseisms theory (summary)
- Attenuation
- Cars & airplane tracking

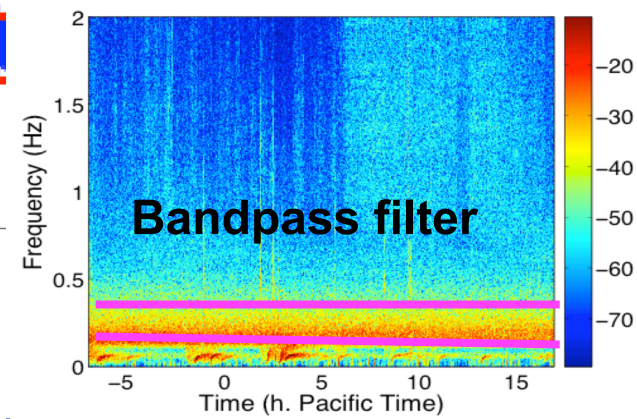
Main collaborators: Ravi Menon, James Traer, Nima Riahi, Peter Bromirski, Peter Shearer

Seismic interferometry in southern California

JULY 2004!

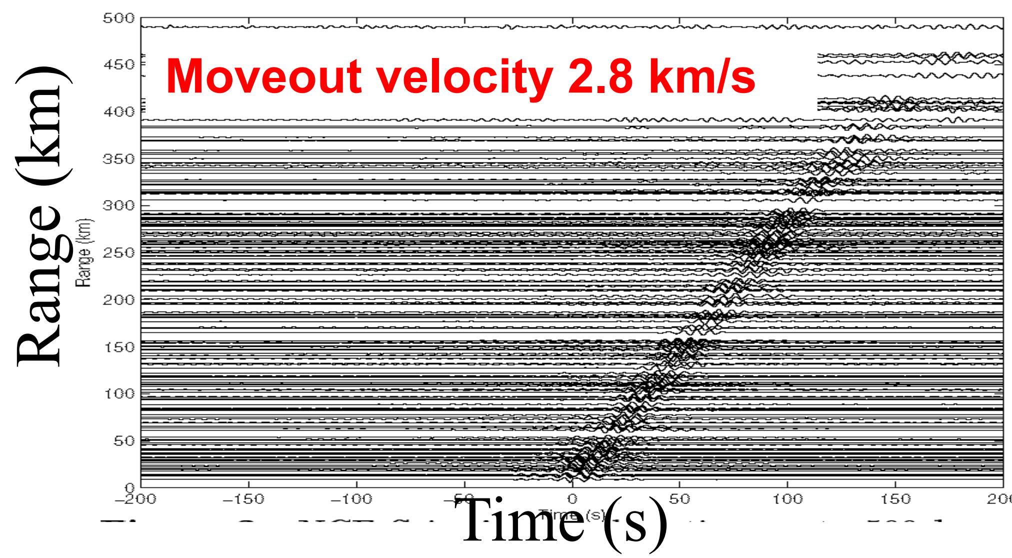






150 Stations
~11000 station pairs
30 Days of **continuous** data

Result of noise cross-correlations ordered with range

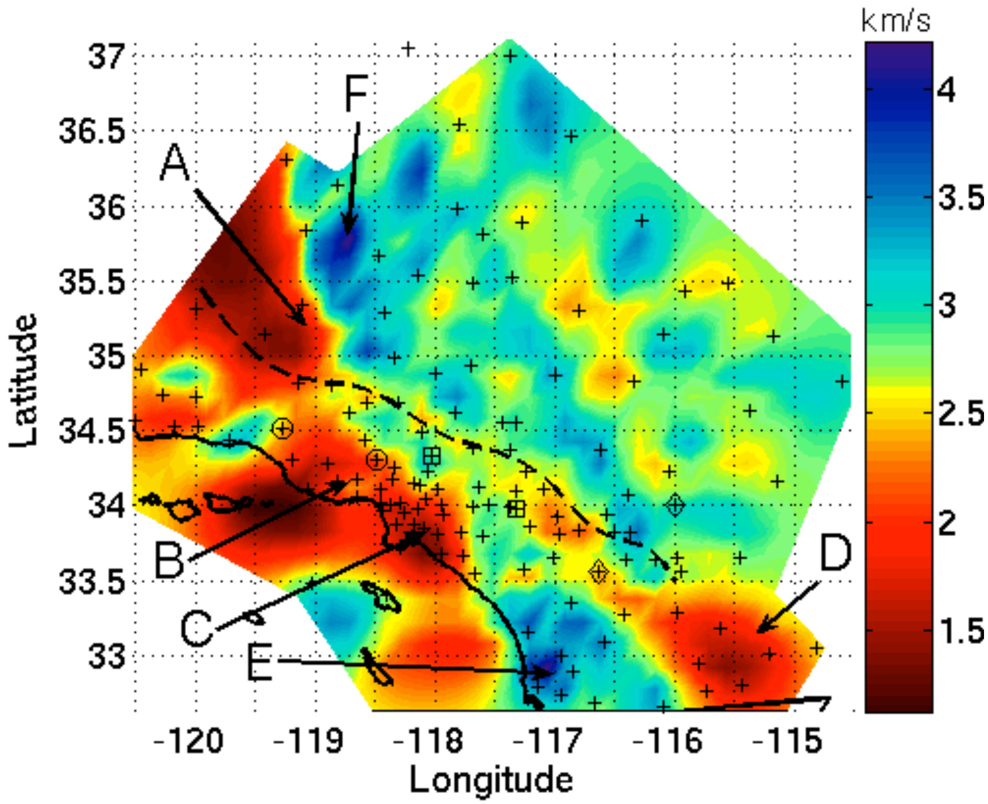


Individual paths have different travel time=> Tomograpghy

Sabra, GRL 2005; Gerstoft, Geophysics 2006

Ambient noise Surface wave Tomography

Tomographic map

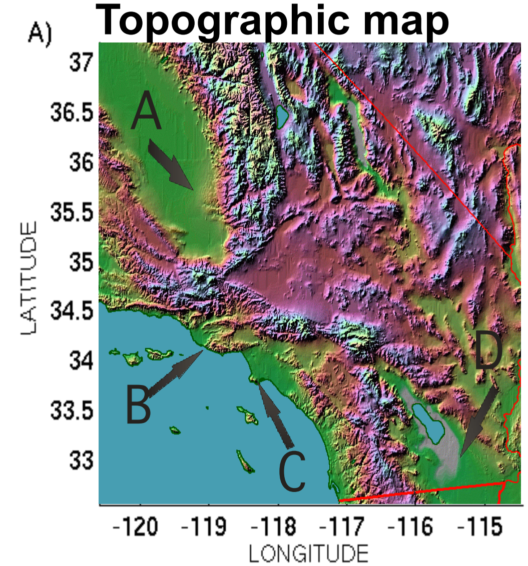


Low Velocity Region~Sedimentary basins A: San Joaquin, B: Ventura, C: L.A., D: Salton Sea

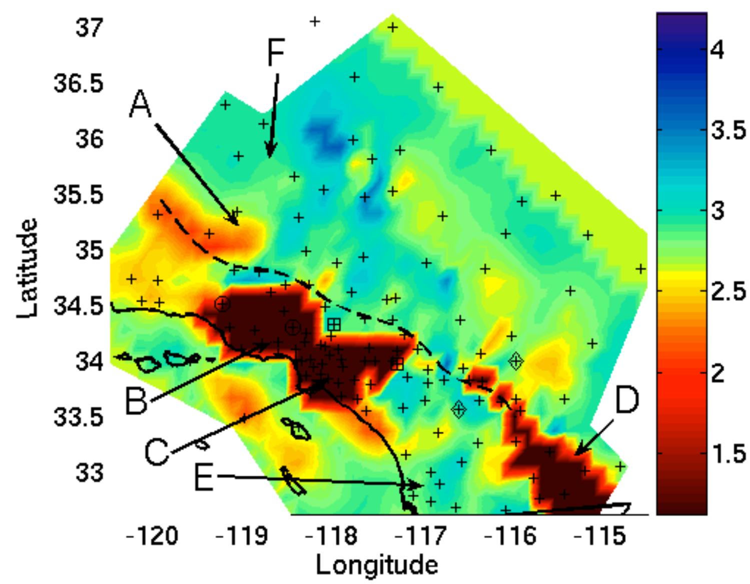
One month of ambient noise can replace 10 years of earthquake tomography!

Sabra, GRL 2005,
Gerstoft et al 2006

Topographic map



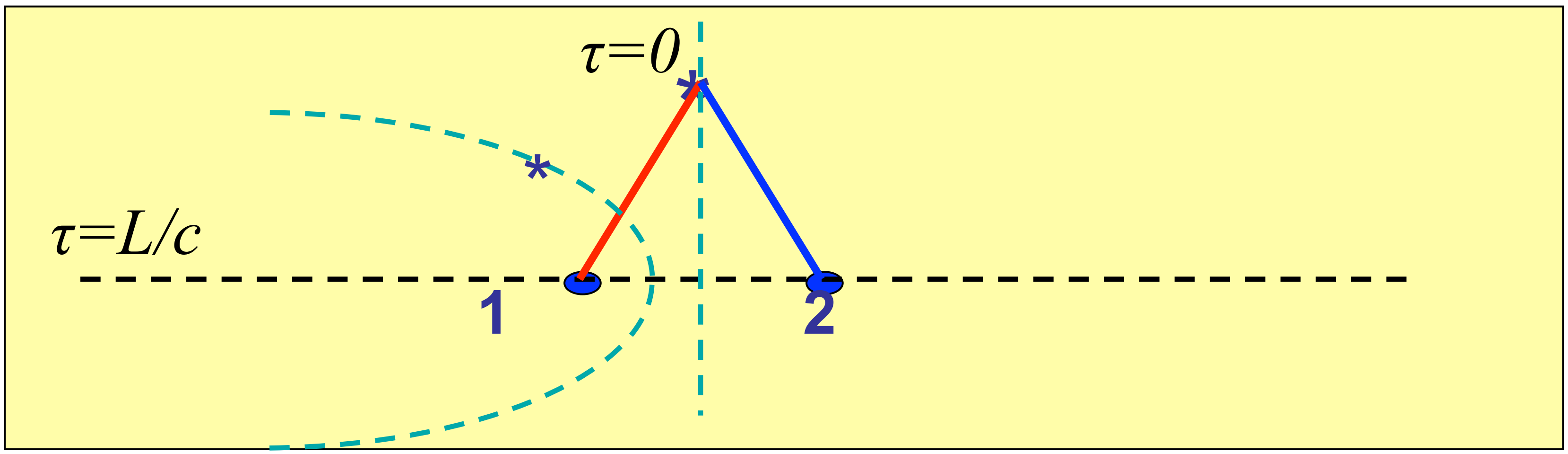
3D Earth model



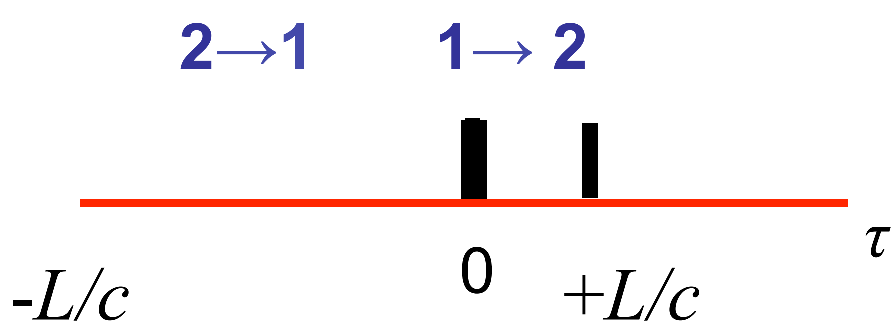
Free space noise correlation (3D)

$$C_{12}(\tau) = \int_{-\infty}^{\infty} P(\mathbf{r}_1, t) P(\mathbf{r}_2, t+\tau) \mathrm{d}\, t.$$

$$\frac{dC_{12}(\tau)}{d\tau} \propto -G(t) + G(-t)$$



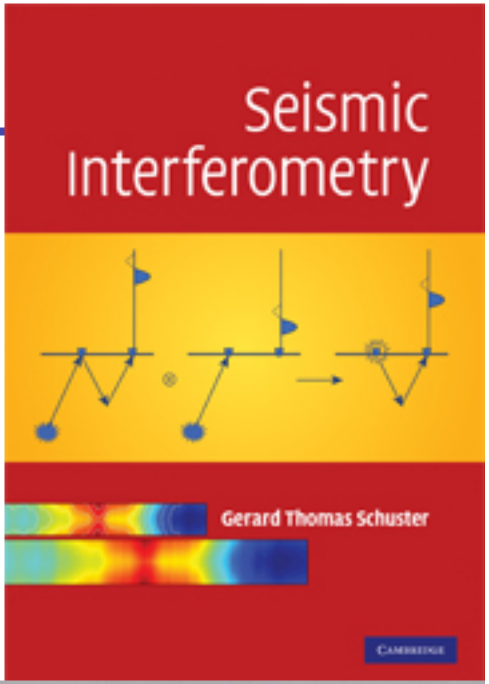
Sources yielding constant time-delay τ lay on same hyperbola

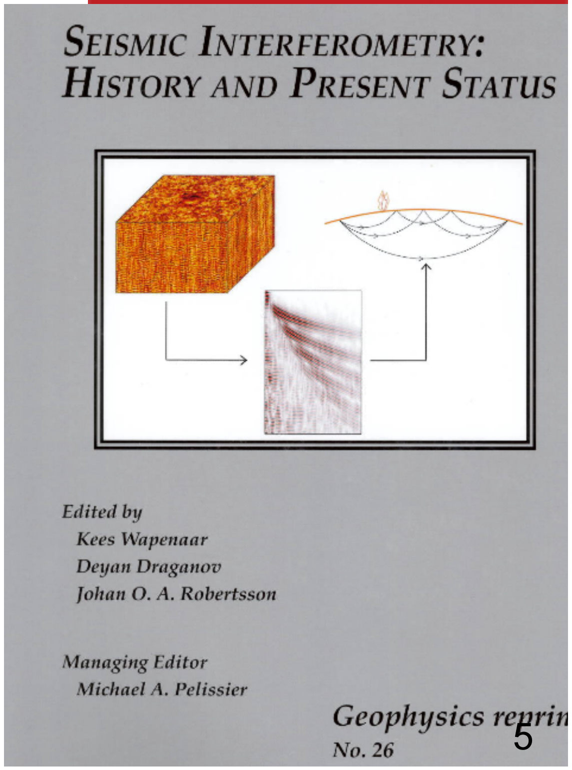


History of seismic/acoustic interferometry

- Multi-disciplinary effort in Theory, Ultrasound, Seismology, Geophysics, Ocean Acoustics, EM

- 1968 Claerbout
- 1980's experiment at Stanford
- 1990's helioseismology
- 2001 Weaver and Lobkis
- 2004 first papers in seismology, & ocean acoustics
- 2008 book "Seismic interferometry: History and present status"
- 2009 book "Seismic interferometry"
- 2009 ~100 papers/year; 2 in Science or Nature /year
- 2009 standard tool in seismology





Progress due to better computer resources, instrumentation and theory.

Still lots of low hanging fruits!

We have the ocean view

Extracting information from noise data is a multi-pronged effort. For the last 10 years my lab has been focused on this:

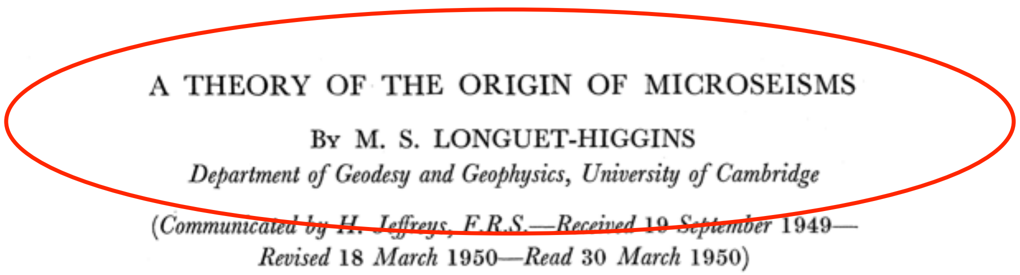
- Understanding microseism
  - Both ocean and seismic propagation
  - Mathematical model of microseism
  - Beamforming on microseisms
  - Observation of microseisms
- Development of signal processing:
  - Random matrix theory
  - Compressive sensing (sparse sampling)
  - Sequential estimation
  - Bayesian inverse methods
  - Big data approaches (tracking car and airplanes)
- Noise cross-correlation
  - For seismic structure
  - attenuation
  - Passive fathometer

Microseisms theory

Two interacting ocean waves give microseism:

$$S/(2a_1a_2) = \sin(\mathbf{q}_1^T\mathbf{x} - \sigma_1 t)\sin(\mathbf{q}_2^T\mathbf{x} - \sigma_2 t)$$
$$= \sin[(\mathbf{q}_1+\mathbf{q}_2)^T\mathbf{x} - (\sigma_1+\sigma_2)t] - \sin[(\mathbf{q}_1-\mathbf{q}_2)^T\mathbf{x} - (\sigma_1-\sigma_2)t]$$

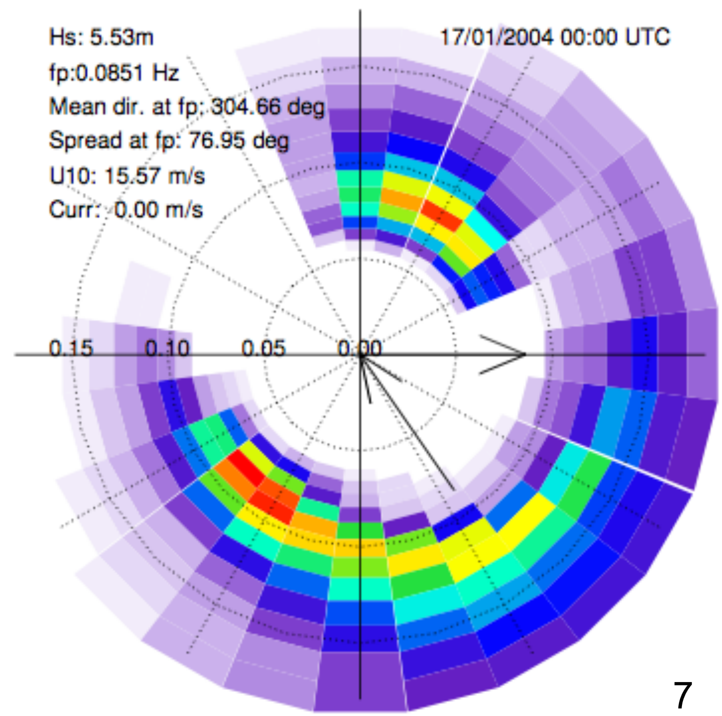
Sum ➔ Microseisms + Difference ➔ Hum (neglected by others)


A THEORY OF THE ORIGIN OF MICROSEISMS

BY M. S. LONGUET-HIGGINS

Department of Geodesy and Geophysics, University of Cambridge

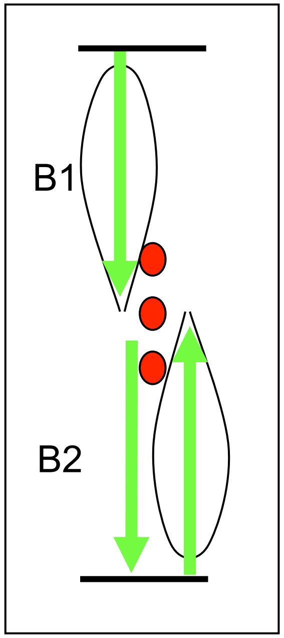
(*Communicated by H. Jeffreys, F.R.S.—Received* 19 *September* 1949—*Revised* 18 *March* 1950—*Read* 30 *March* 1950)

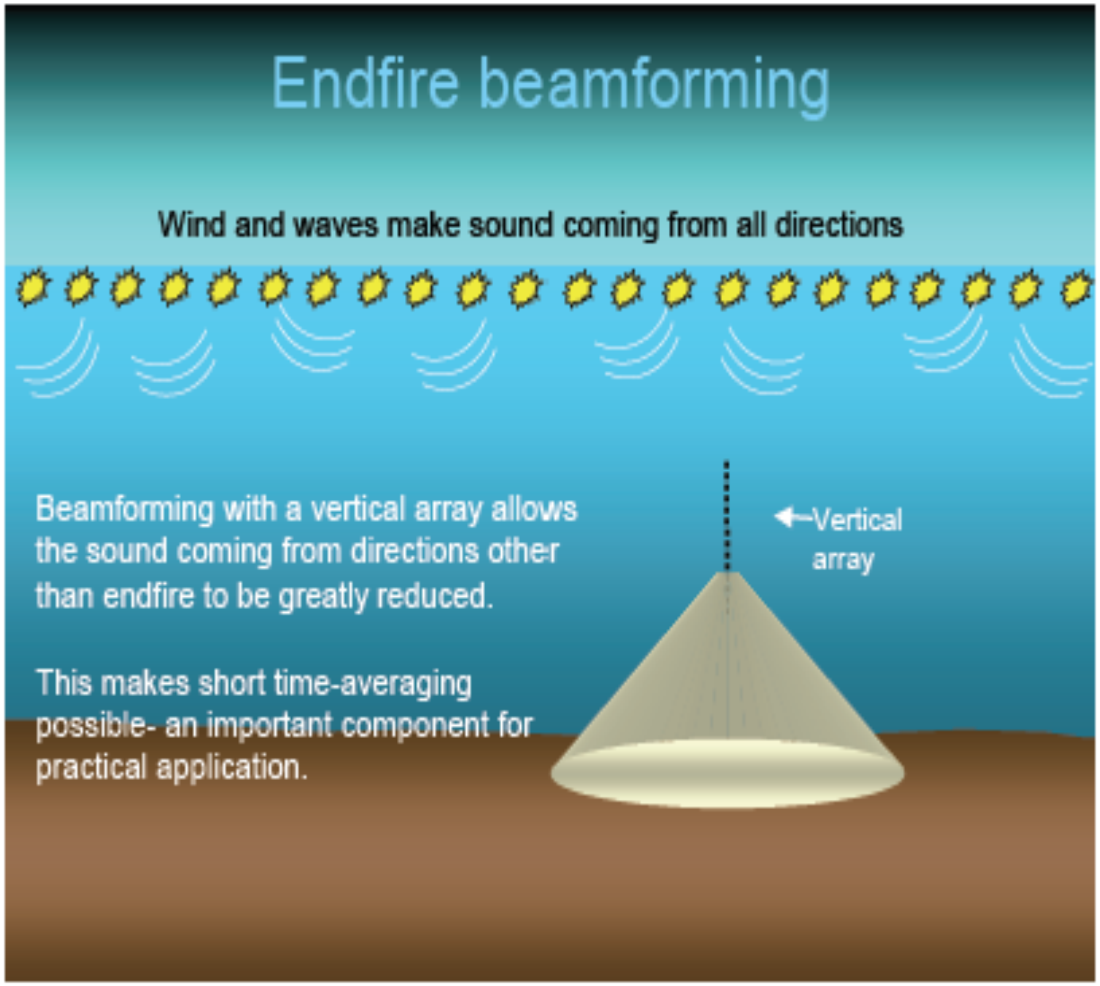


Traer and Gerstoft, GJR 2014

Passive fathometer

Using ambient noise on a drifting array we can map the bottom properties

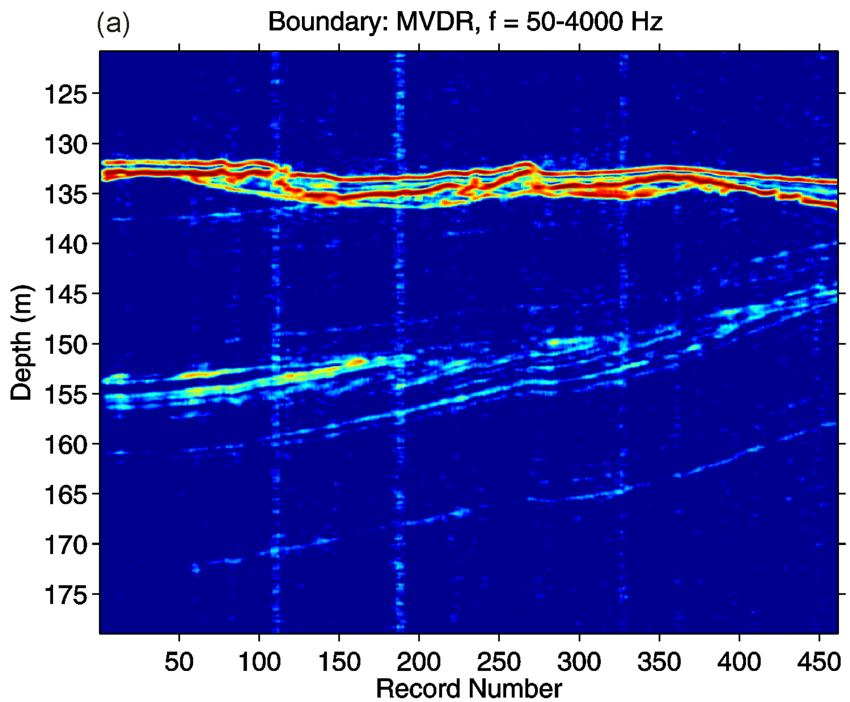




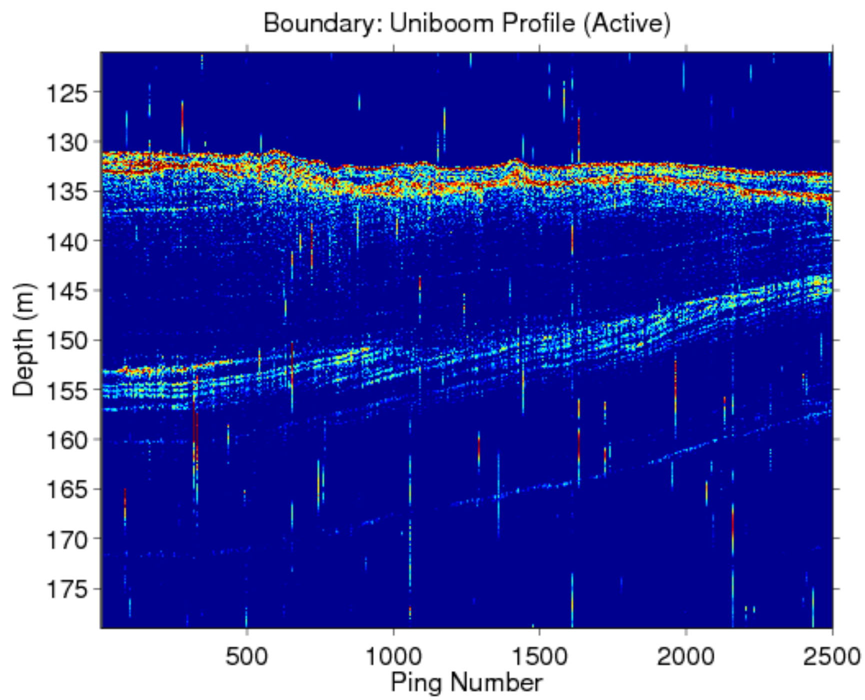
Siderius et al., JASA 2006,
Gerstoft et al., JASA 2008,
Harrison, JASA 2009,
Traer et al., JASA 2009, 2010, 2011
Siderius et al., JASA 2010

Passive fathometer

Ambient noise 50-4000 Hz



Active boomer

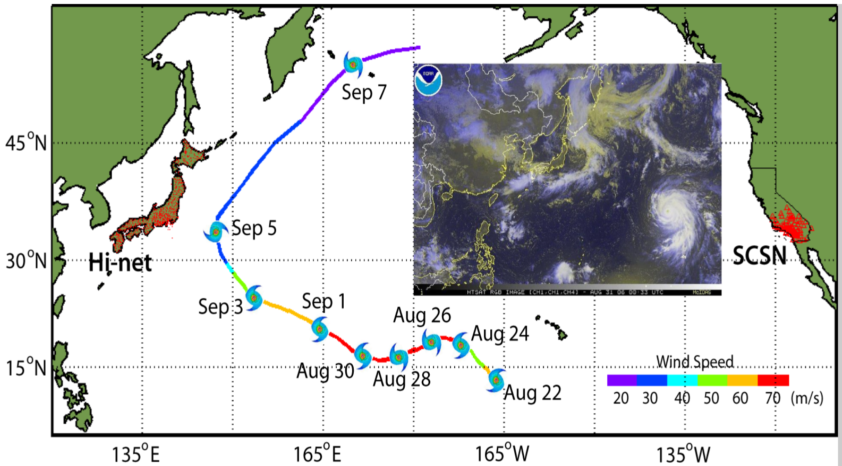


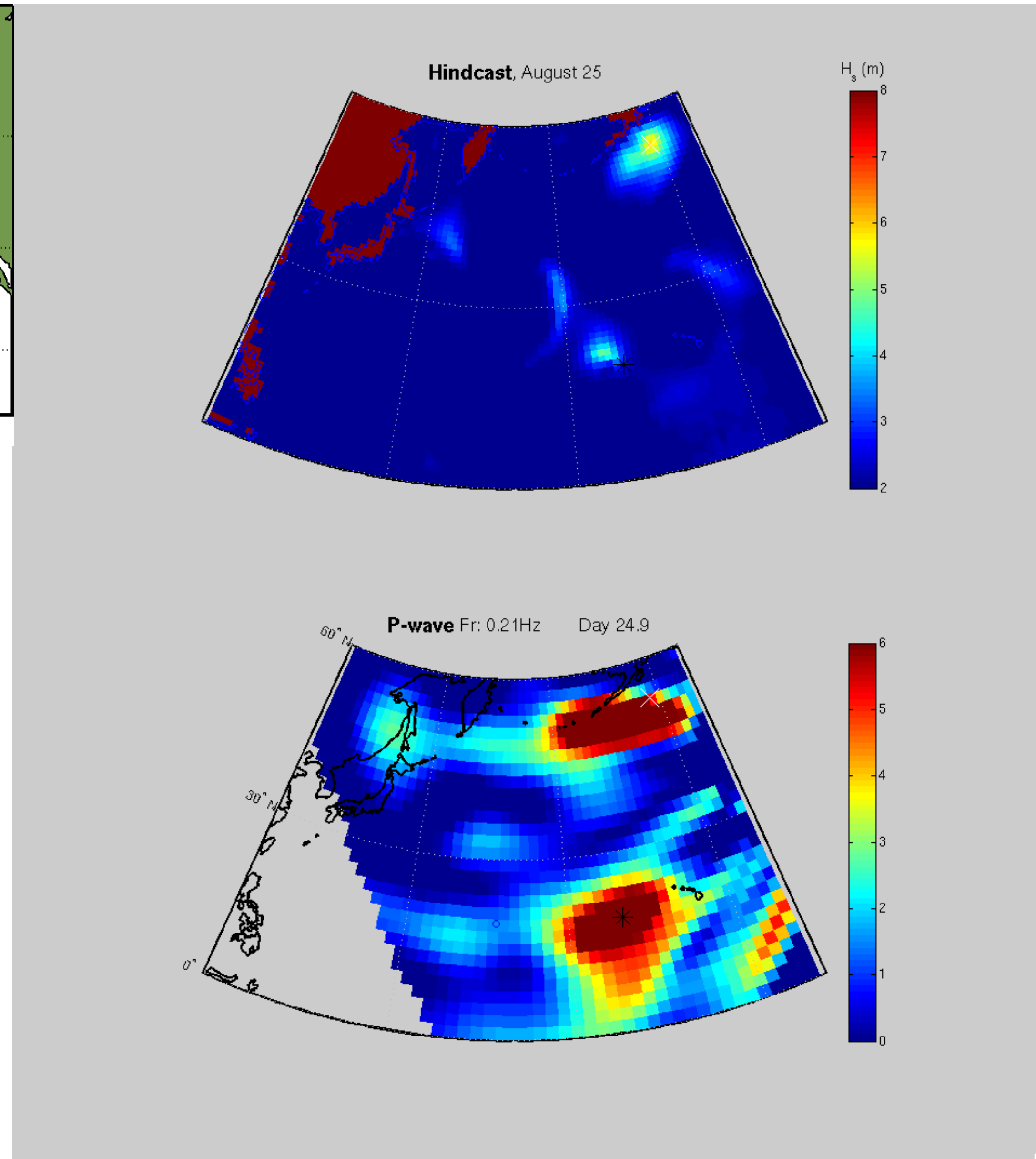
Adaptive processing gives better resolution of reflections

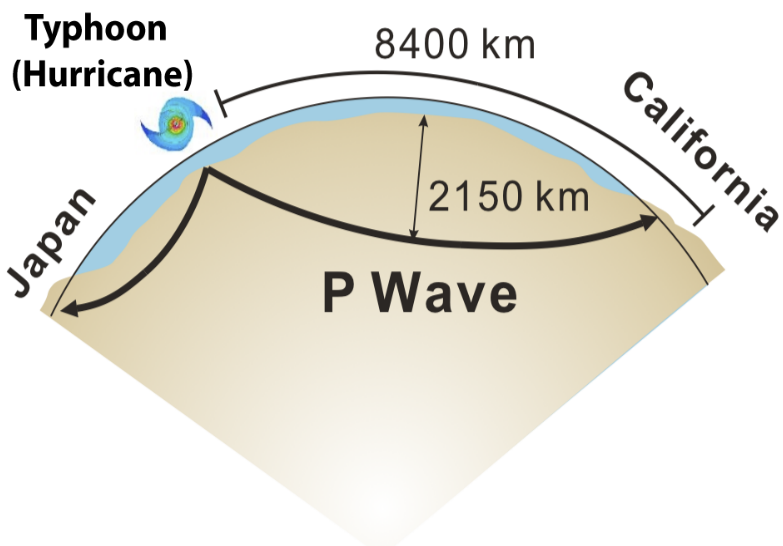
Try on VSP data?

Siderius et al., 2010

Imaging *P*-Wave Microseism Sources (due to storms)







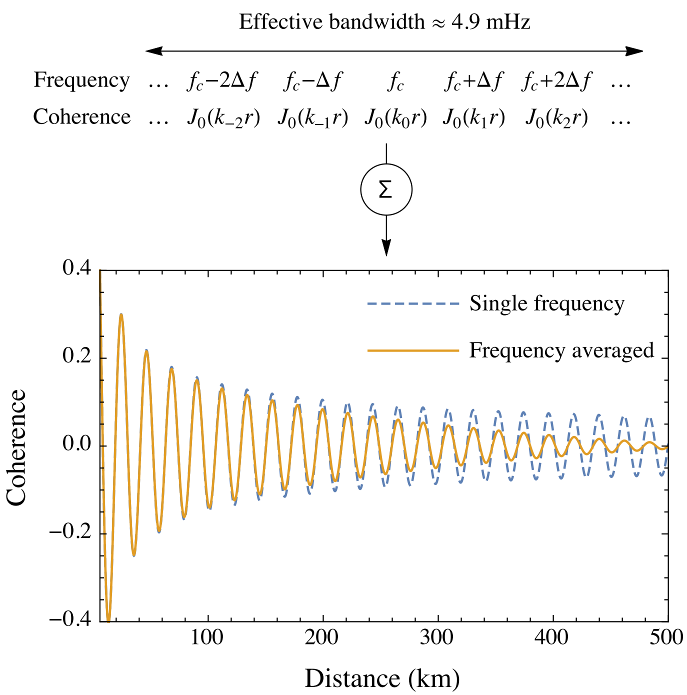
Noise attenuation is messy business!

Coherence:

$$\Gamma(r,\zeta) = \frac{P_{AB}(f)}{\sqrt{P_{AA}(f)P_{BB}(f)}}$$

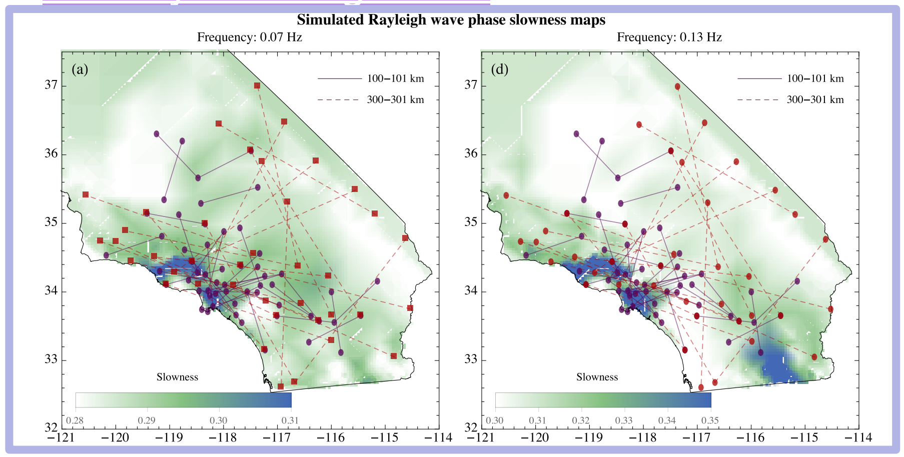
$$\Gamma_{2\text{-}D}(r) = J_0(2\pi frs)$$

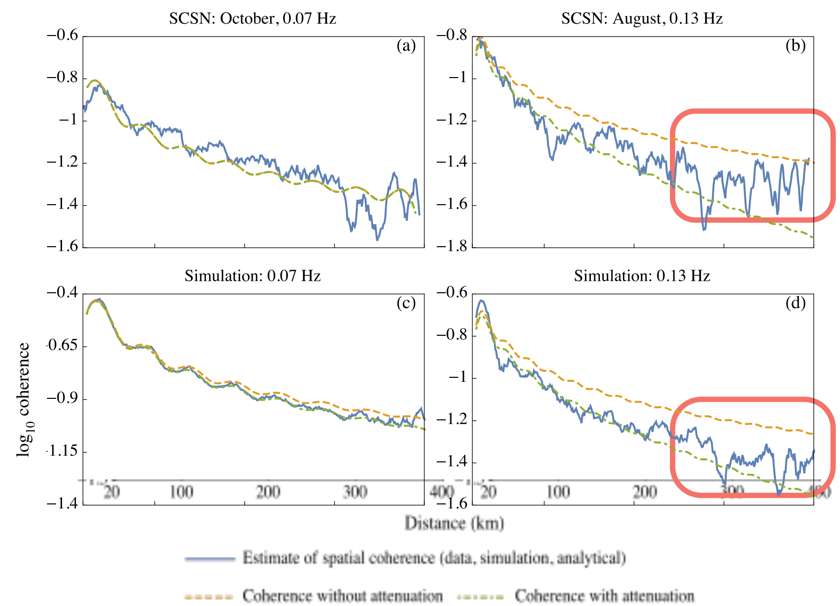
Frequency averaging



Interference of neighboring bins creates artificial attenuation

Velocity inhomogenities





The apparent "negative attenuation" is explained with velocity inhomogenity.

Menon et al. 2014

Noise attenuation is messy business!

So what is the actual (intrinsic+scattering) attenuation?

To reliably estimate attenuation you need:

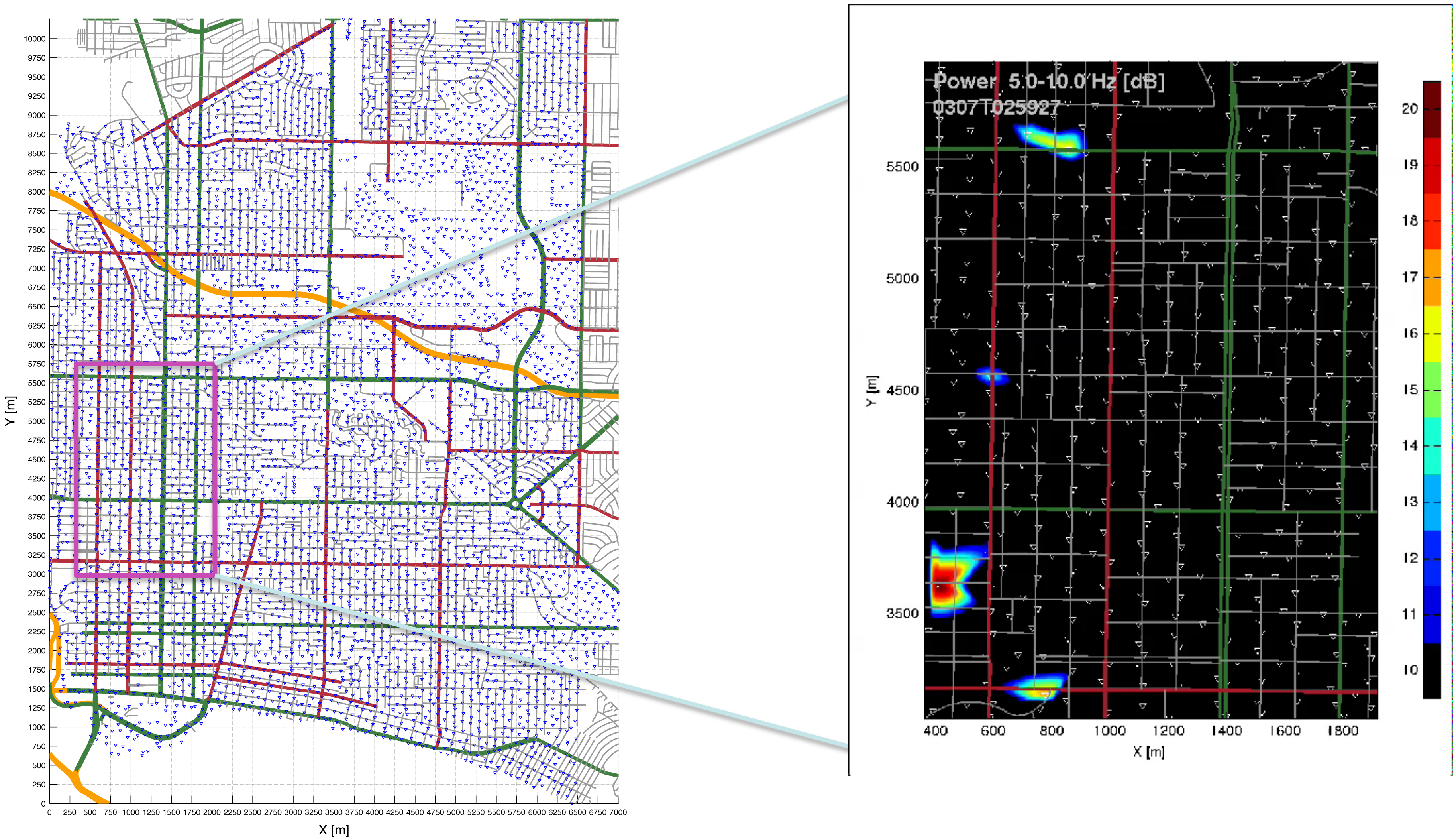
- Uniform source distribution (Harmon et al. 2010, Tsai 2011)
- No spectral whitening (Weemstra et al. 2014)
- No frequency averaging
- Account for body waves (from storms) and higher mode surface waves
- Correct for velocity inhomogenities and station distribution effects

These effects cannot be averaged out!
Need smarter processing approaches

Menon et al. 2014

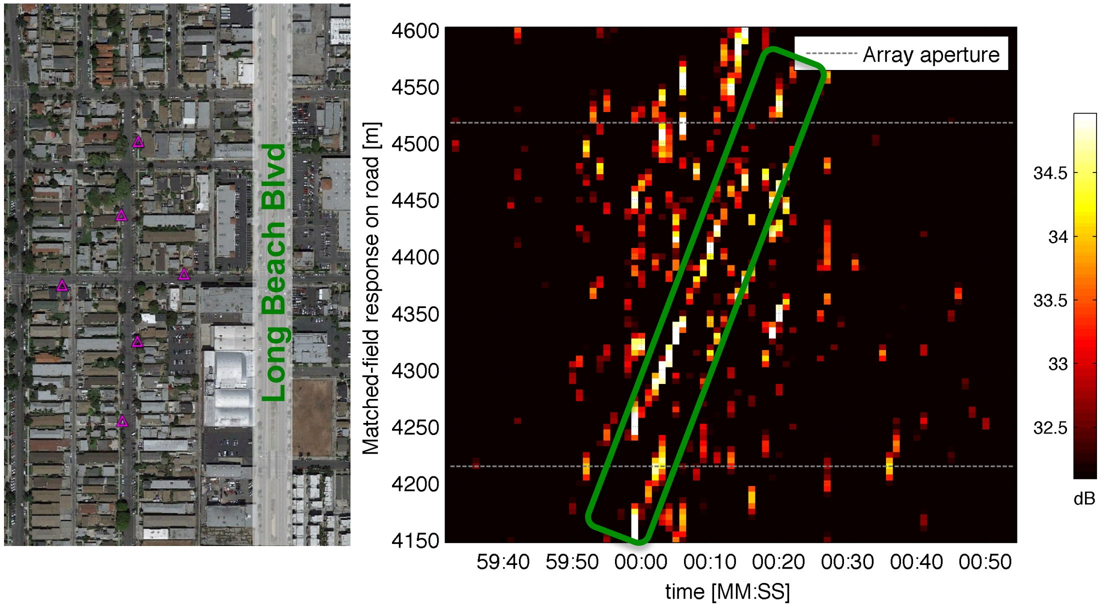
Noise Tracking of Cars

5200 element Long Beach array (Dan Hollis)



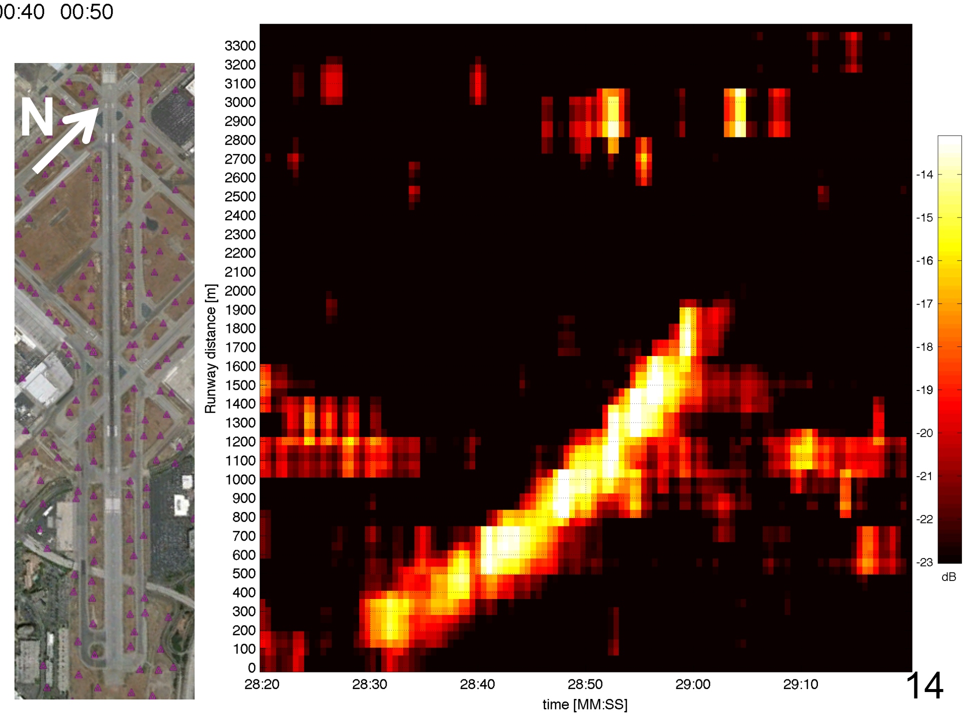
Nima Riahi 2014?

Noise Tracking of Cars/Airplanes



Car moving north on Long Beach Blvd at 35mi/h.

Accelerating airplane on Long Beach airport runway, moving northwest and taking off at about 120 mi/h.



Nima Riahi 2014?