Exploring the earth with seismic noise: Anthropogenic and exogenic noise sources

Peter Gerstoft, With help from Nima Riahi, Mike Bianco,

Slides are available from **http://noiselab.ucsd.edu**

- Noise is full of information.
- Think of characterizing a dark room
- My focus is on extracting information from noise (acoustic, seismic, EM) with the help of signal processing, compressive sensing, and **machine learning**.

Contents:

Long Beach array

Observing traffic

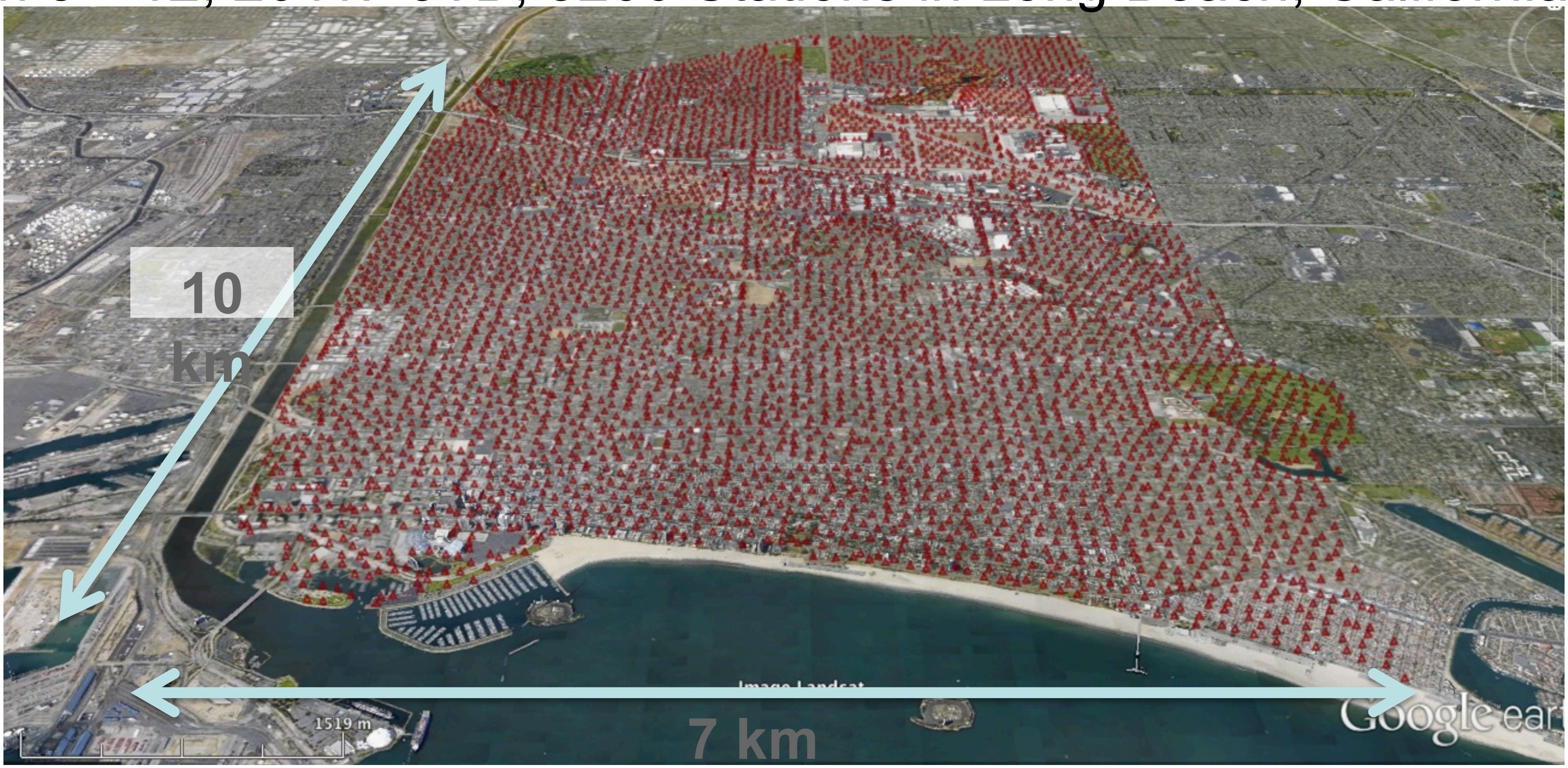
Localizing weak sources

Noise tomography

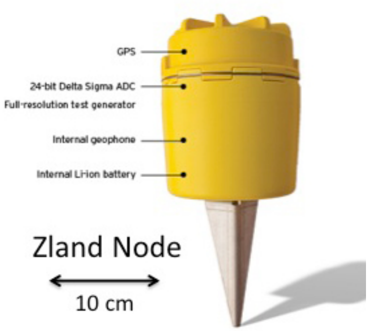
Antarctica Tsunami generated plate waves

Noise observation on seismic sensor array

March 5—12, 2011: 3TB, 5200 Stations in Long Beach, California



Geophones samples at 250 Hz for 6 months



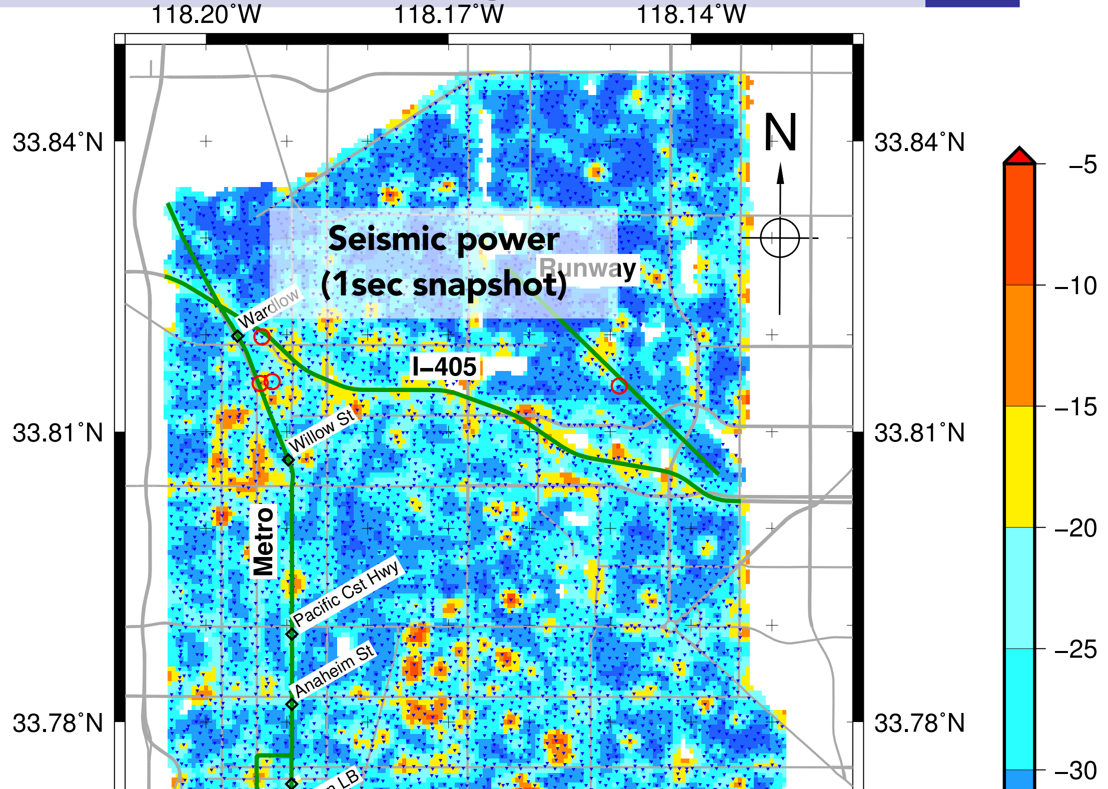
Our motivation: Long Beach (CA) array

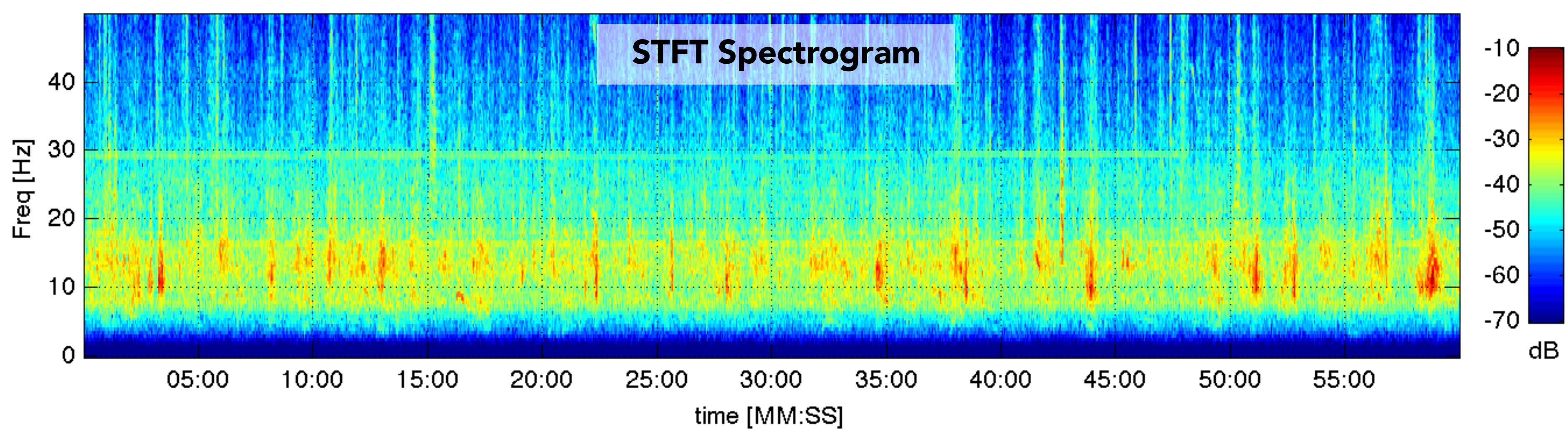
Oil industry dataset offers insight into urban noise sources:

- ✓ 5200+ sensors (GPS equipped nodes)
- ✓ Covers 70 km^2 of urban area
- ✓ Spacing ~100 m
- ✓ 1 week ambient vibrations

High attenuation in data.

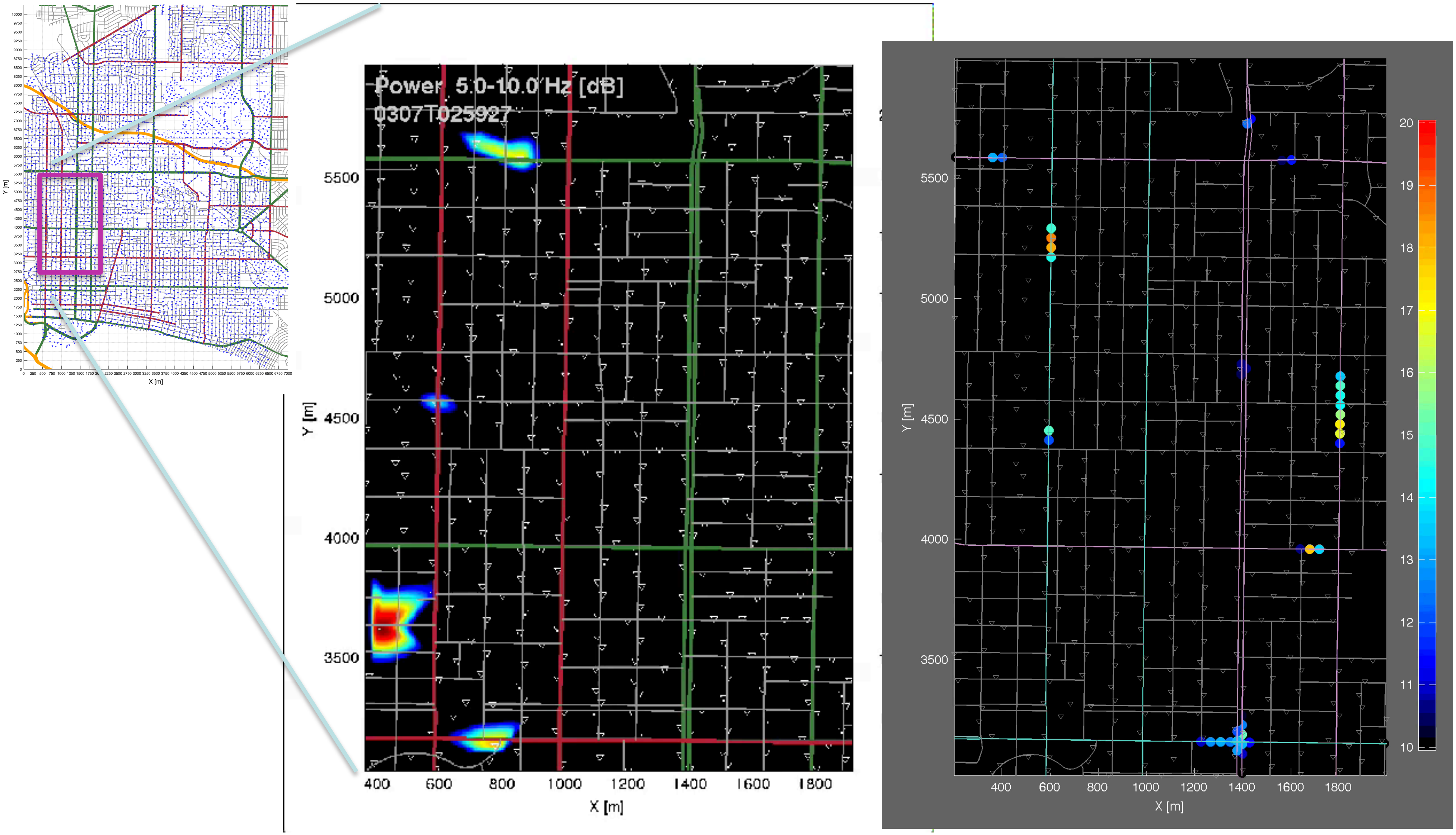
Very limited knowledge about near-surface seismic propagation parameters.





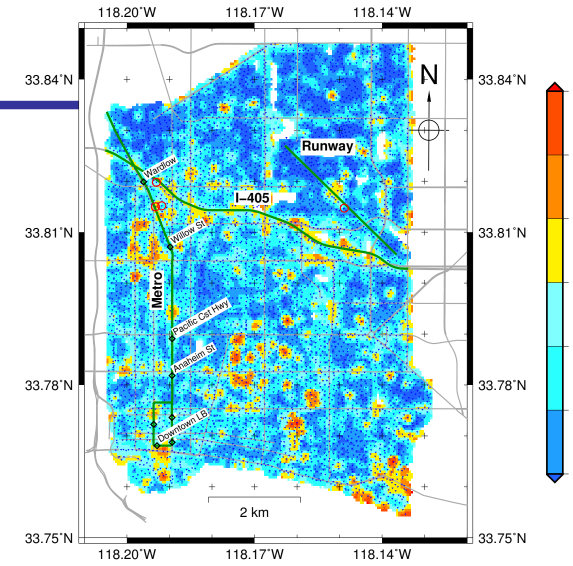
Noise Tracking of Cars/Trains/Airplanes

5200 element Long Beach array (Dan Hollis)



Riahi, Gerstoft, The seismic traffic footprint: Tracking trains, aircraft, and cars seismically, GRL 2015

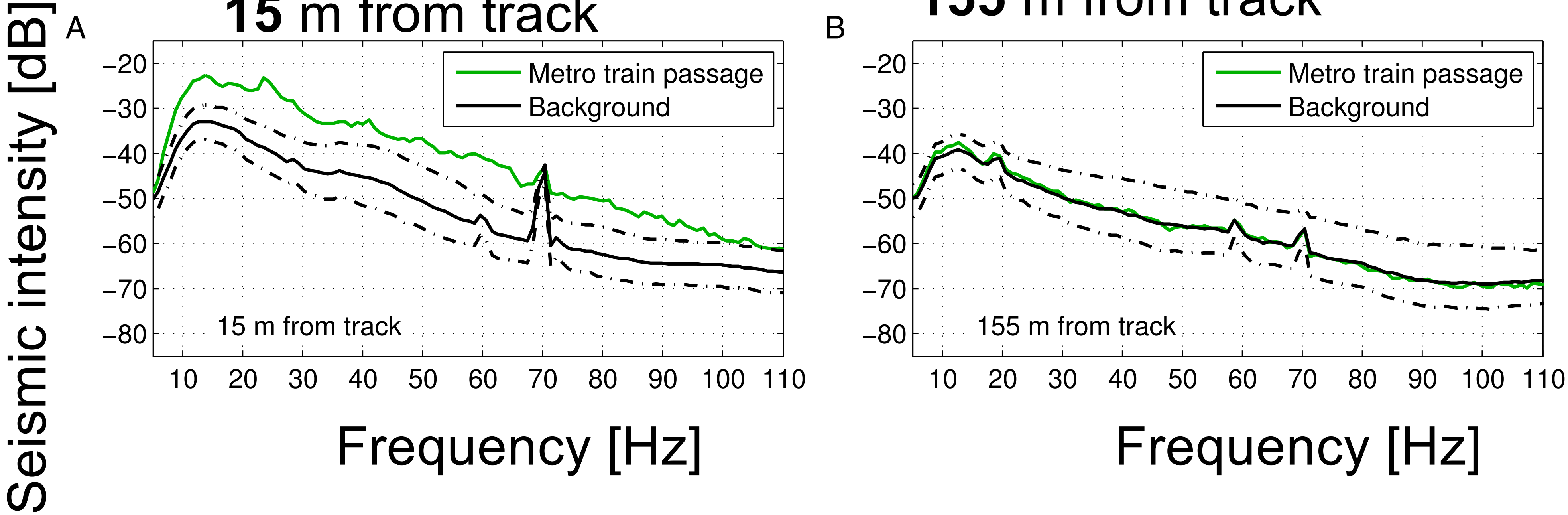
Power spectra



Seismic intensity can be used as source proximity indicator

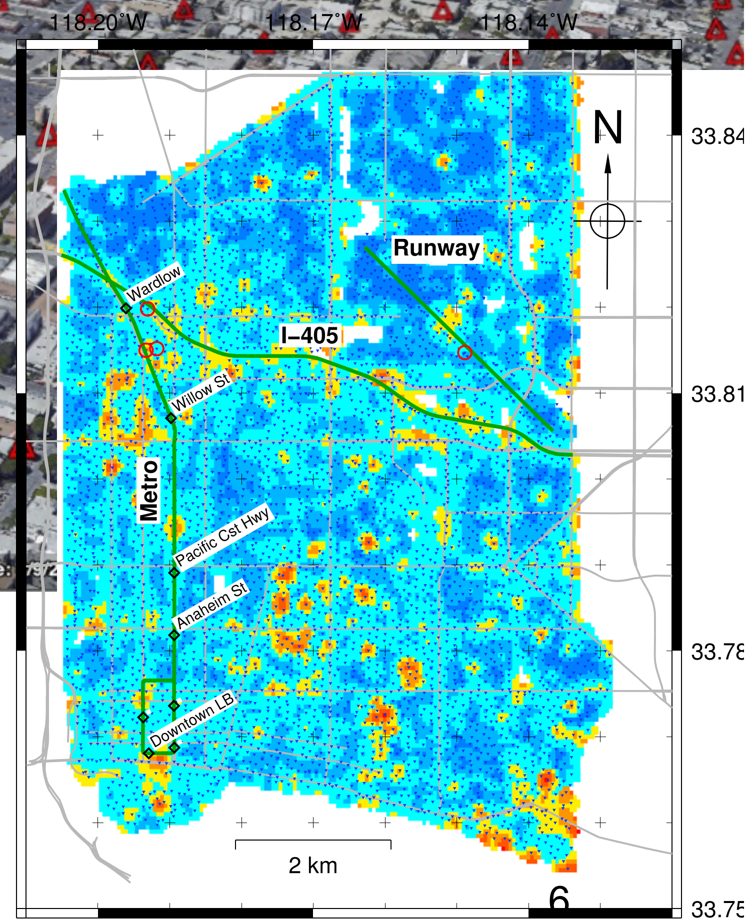
15 m from track

155 m from track



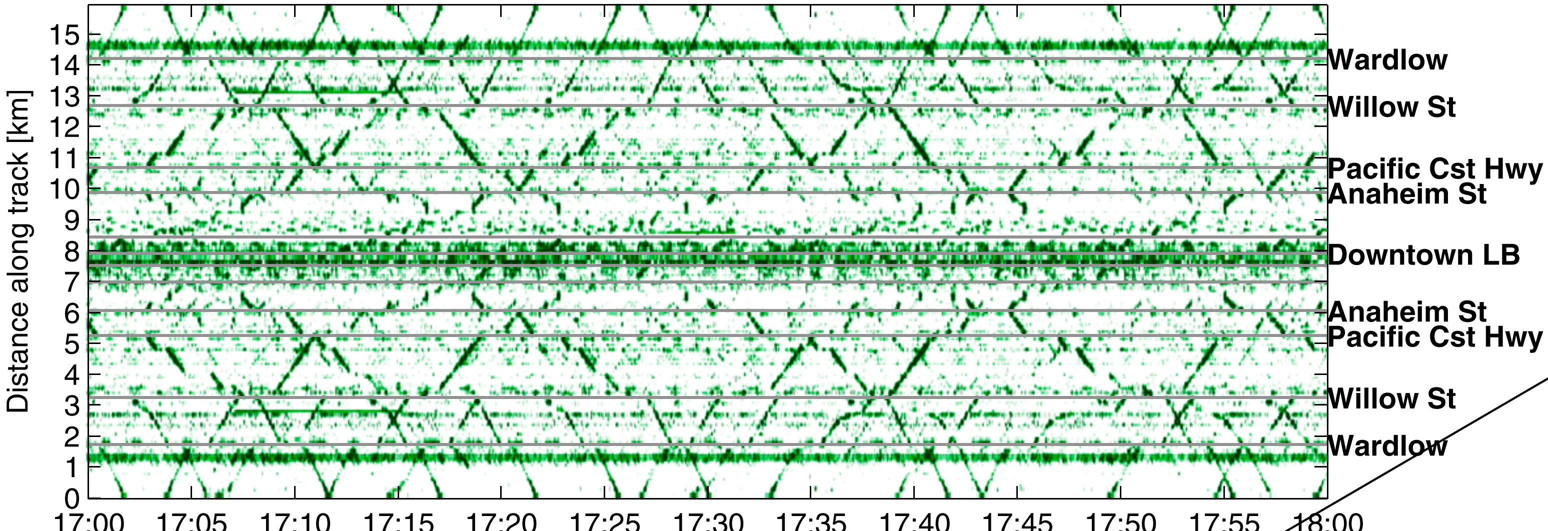
Riahi, 2015

Long Beach Blue Line Metro

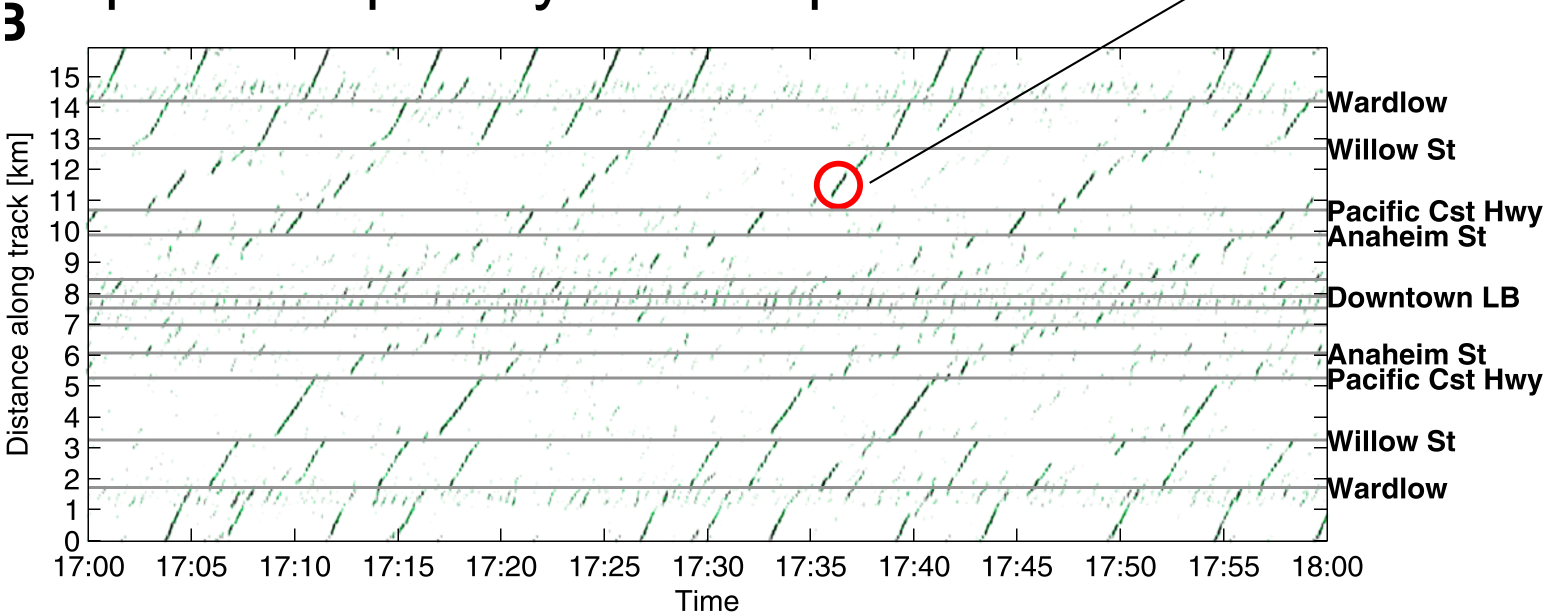


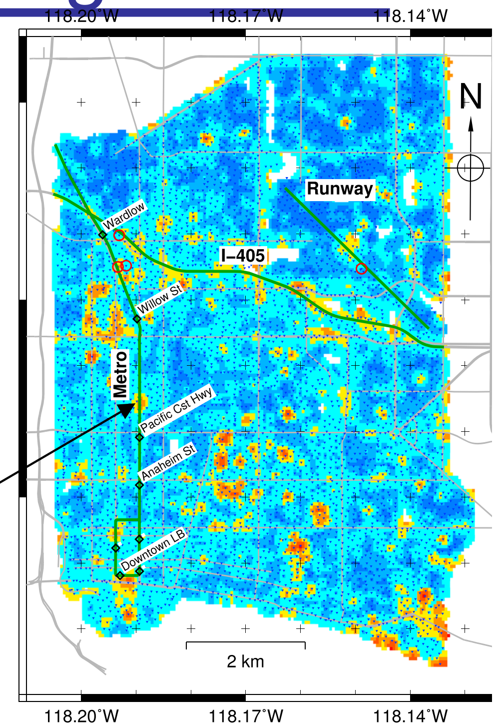
Seismic power along the metro track during rush hour

Raw seismic power

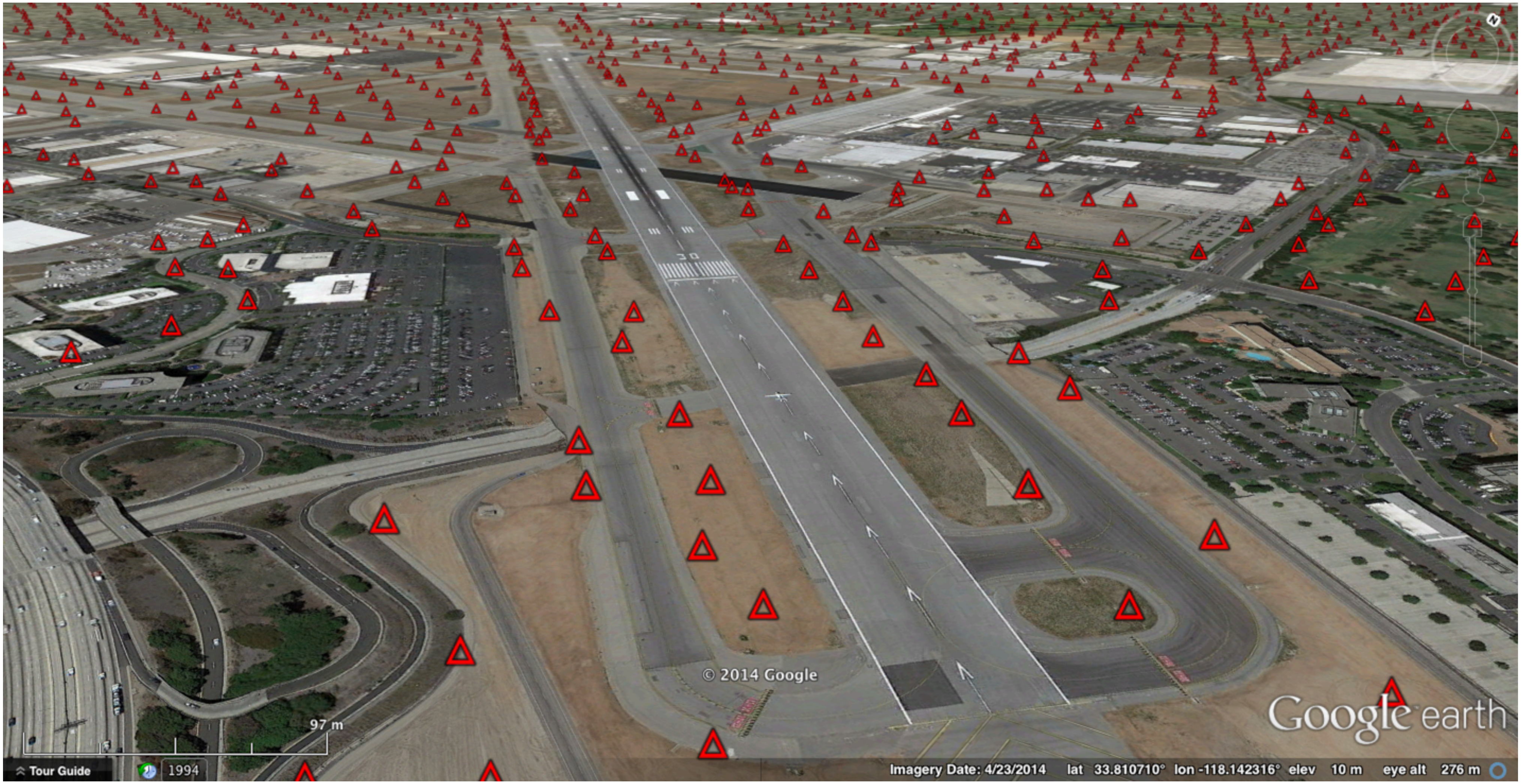


Spatiotemporally filtered power





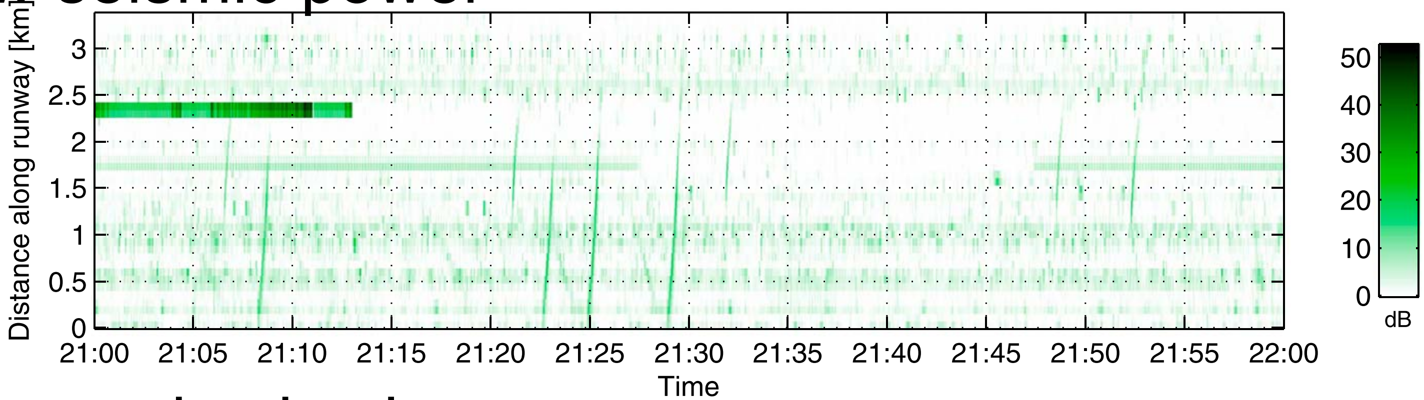
Riahi, 2015



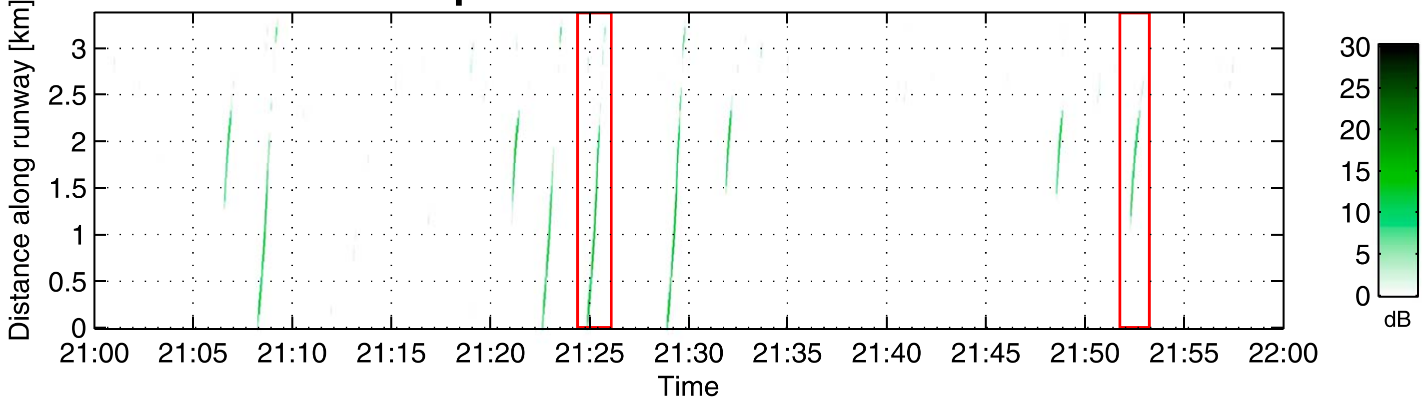
Watching airplanes with your feet (ears?)

Seismic power on runway

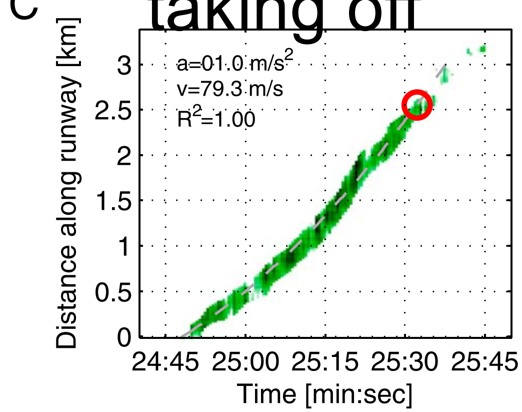
Raw seismic power



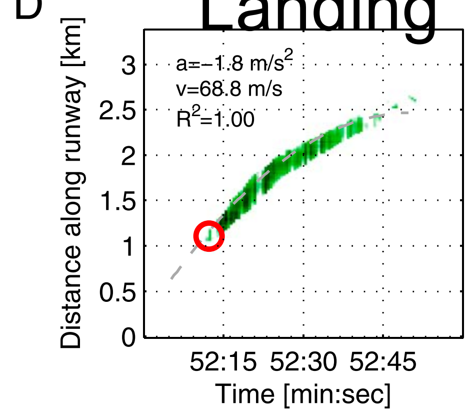
Processed seismic power.



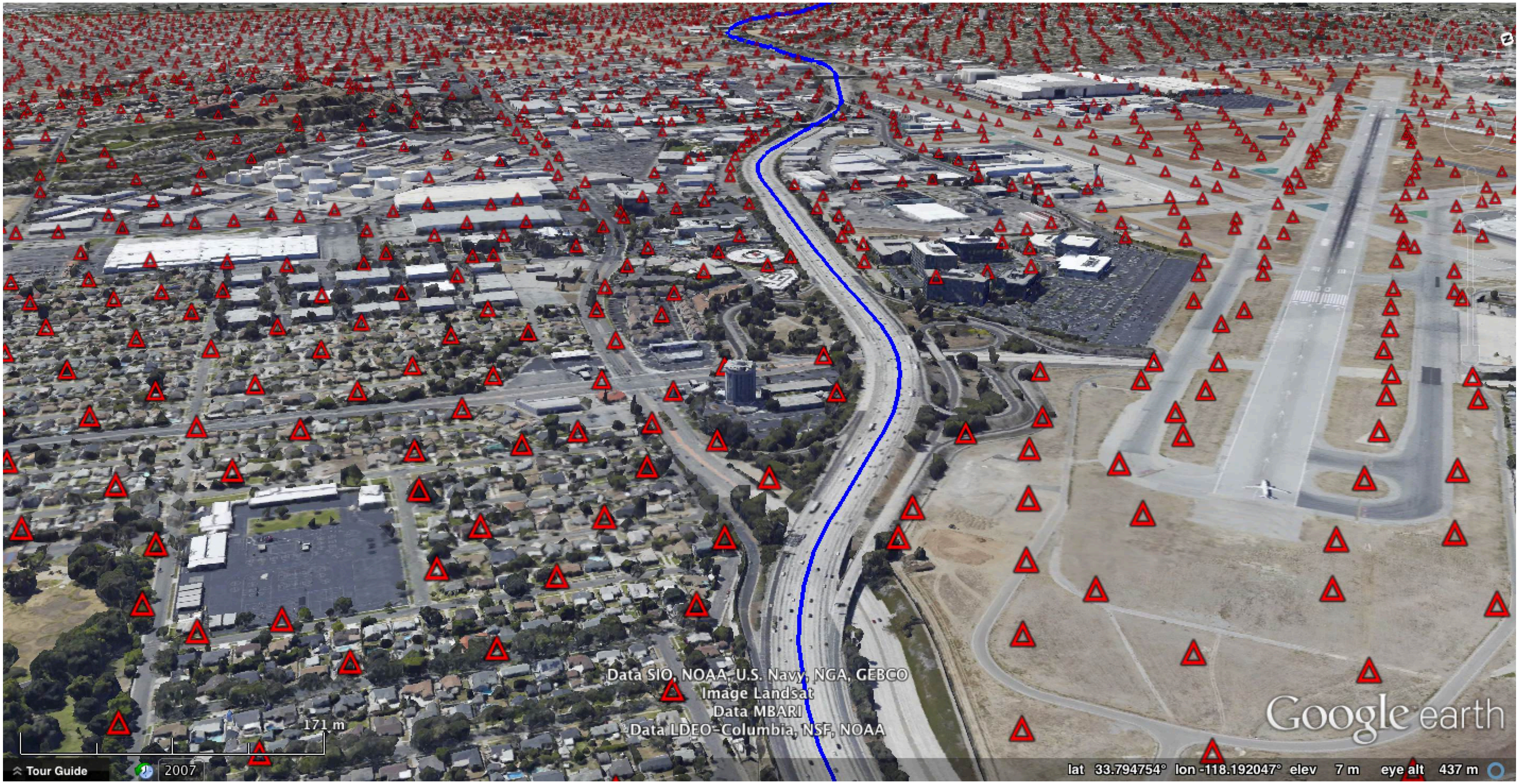
taking off



Landing



Riahi, 2015

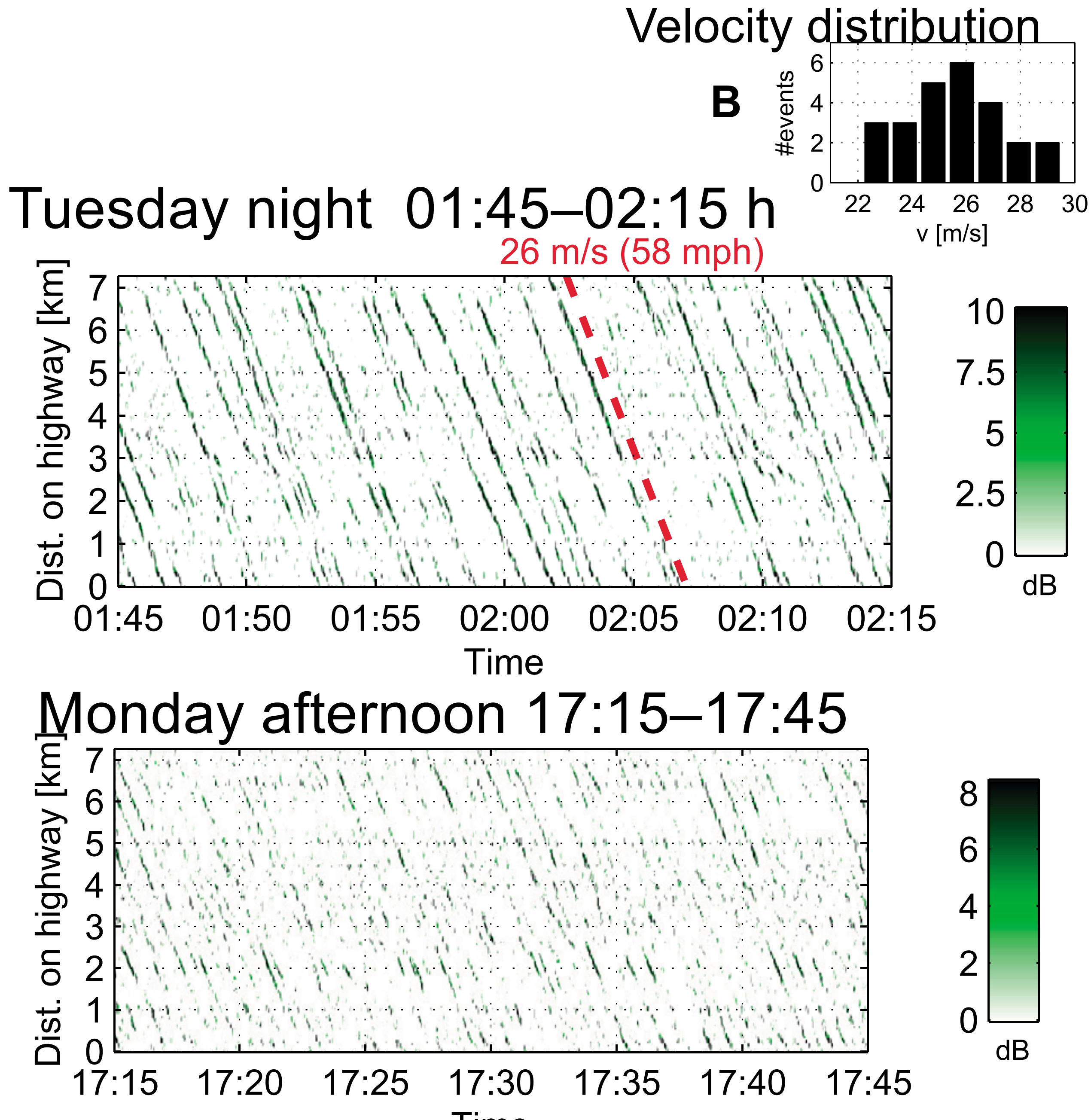


Observing the I-405

Seismic power for traffic monitoring

Processed seismic power along the I-405

Filtered for eastward moving sources



Currently other sensing techniques is favored.

Riahi, 2015

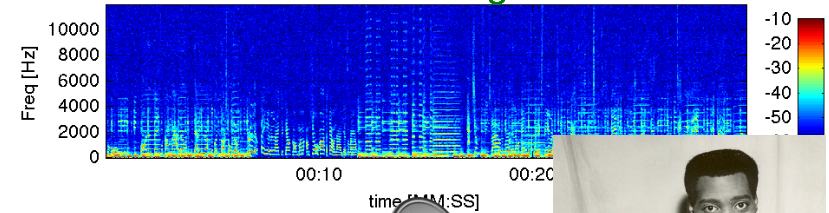
LOCATING WEAK SOURCES USING GRAPH SIGNAL PROCESSING

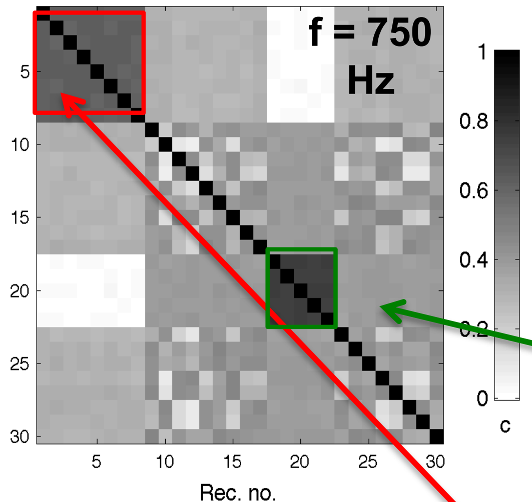
Riahi, Gerstoft (2017), Using Graph Clustering to Locate Sources within a Dense Sensor Array, Signal Processing 2017,

Graph Signal Processing for locating a source

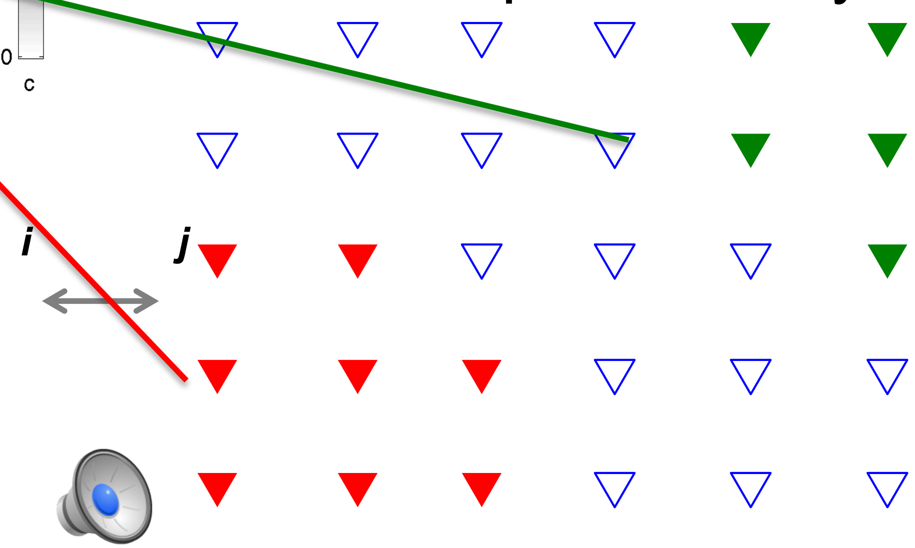
unsupervised

Location 2: Otis Redding - “Hard to handle”

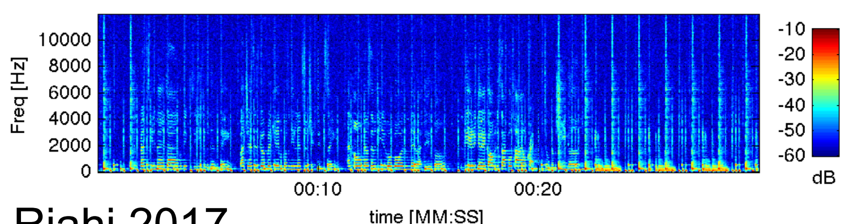




30-microphone array



Location 1: Prince - “Sign o’ the times”



Riahi 2017

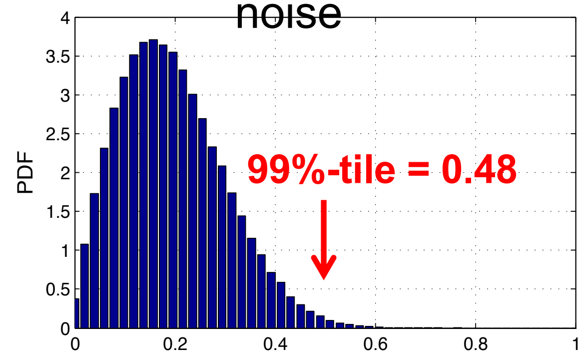
Spectral coherence

$$\hat{C}_{ij}(f) = \frac{1}{N}\sum_{t=1}^{N} X_i(f,t)\cdot \bar{X}_j(f,t)$$

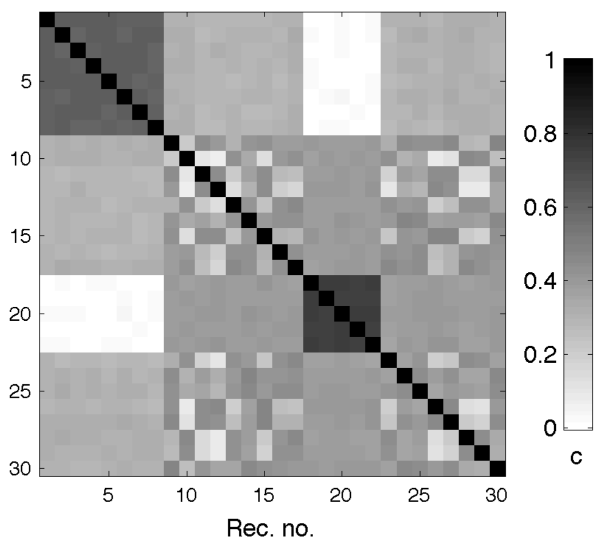
(Normalization: $|X(f,t)|^2=1$)

Each group is spatially coherent. But no temporal correlation between groups (i.e. different source)

Distribution of $|C_{ij}|$ for incoherent noise

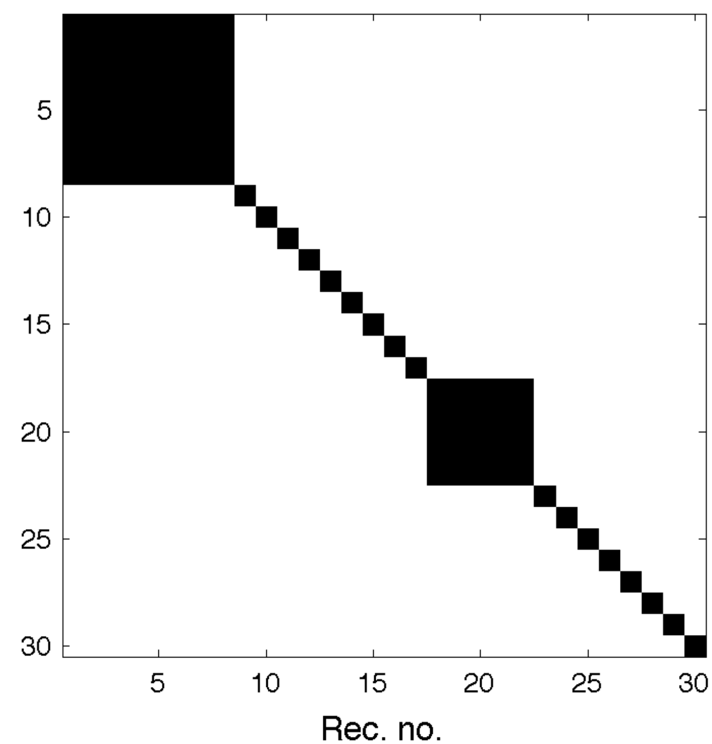


Magnitude of spectral **coherence** for 30 sensors



f = 750 Hz

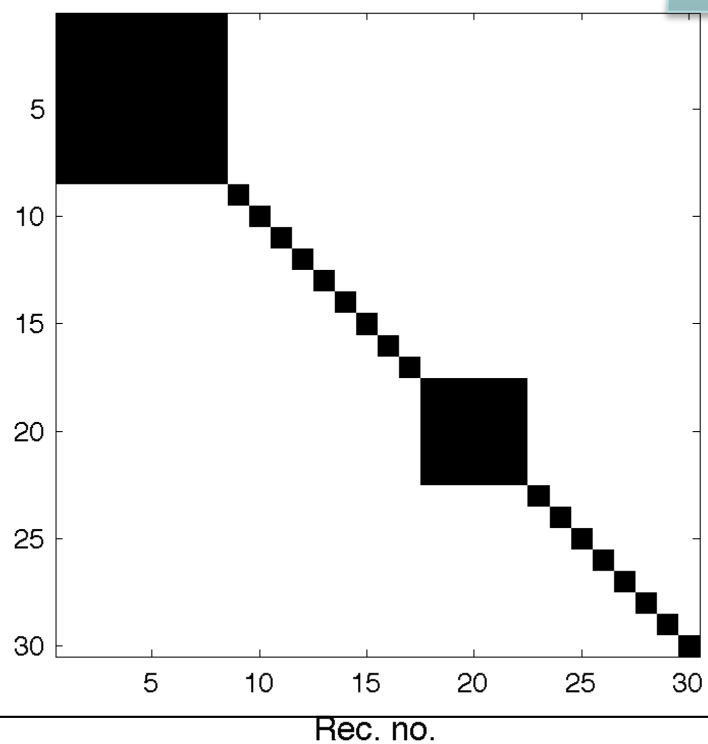
Statistically significant entries
=> Connectivity matrix



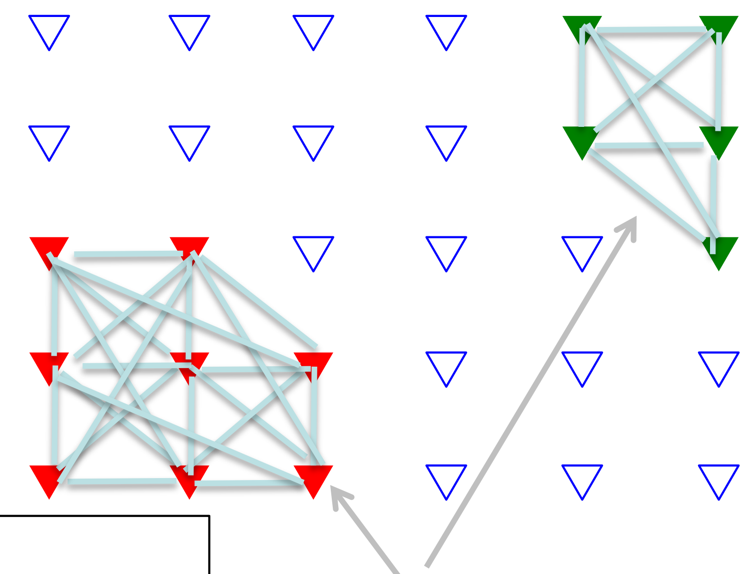
- Each sensor is a **node** in the graph. $|C_{ij}|$
- If **nodes** *i* and *j* are significantly correlated $|C_{ij}|>\xi$, then they share an ***edge***.

Two sources in the network

Statistically significant entries
=> Connectivity matrix



Graph with 30 nodes

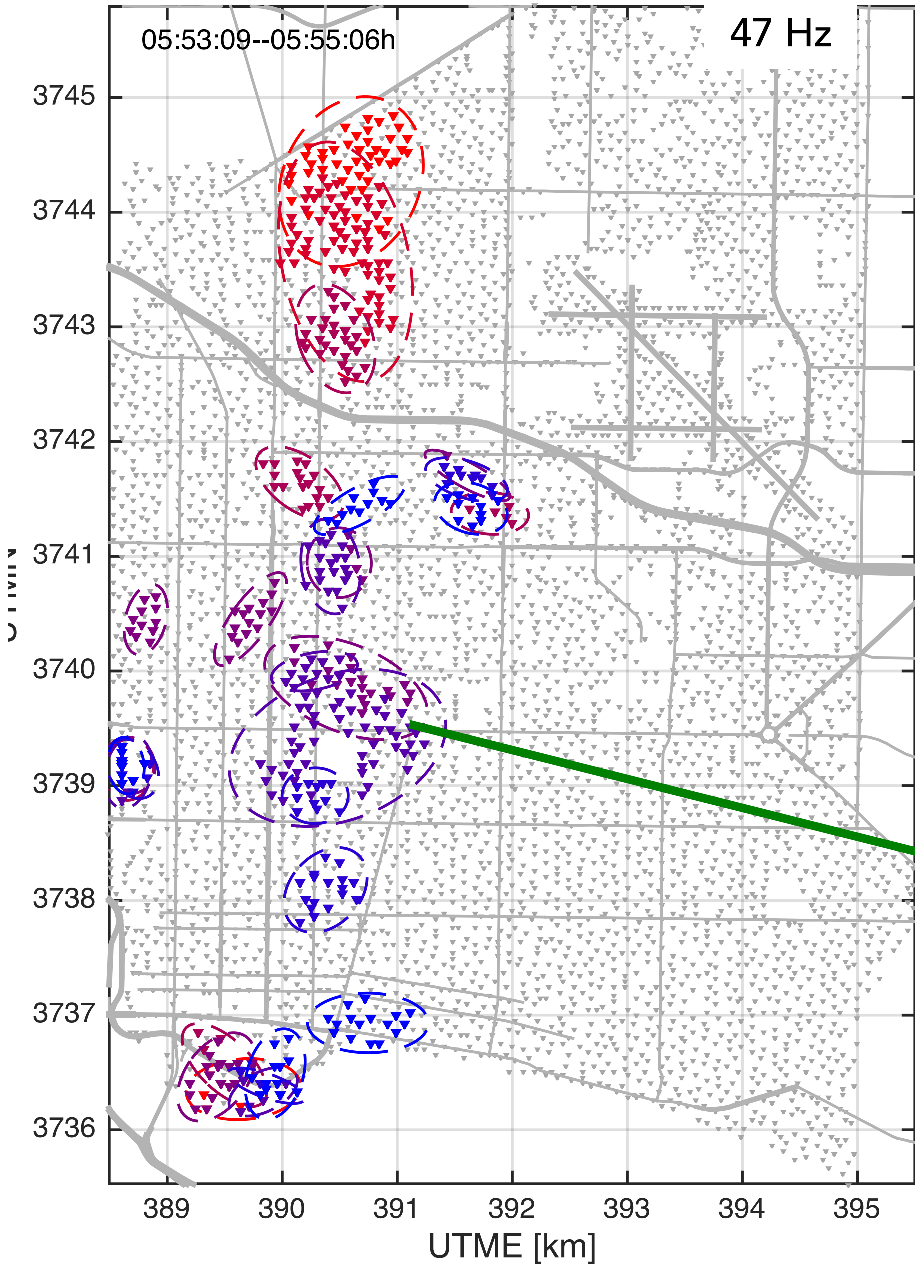


- Each sensor is a **node** in the graph.
- If **nodes** *i* and *j* are significantly correlated $|C_{ij}|>\xi$, then they share an ***edge***.
- A **subgraph** has high spatial coherence across a subarray (=> likely a source nearby).

Connected subgraphs:

5 nodes and 9 edges

8 nodes and 20 edges



Helicopter rotor noise (seismo-acoustic coupling)

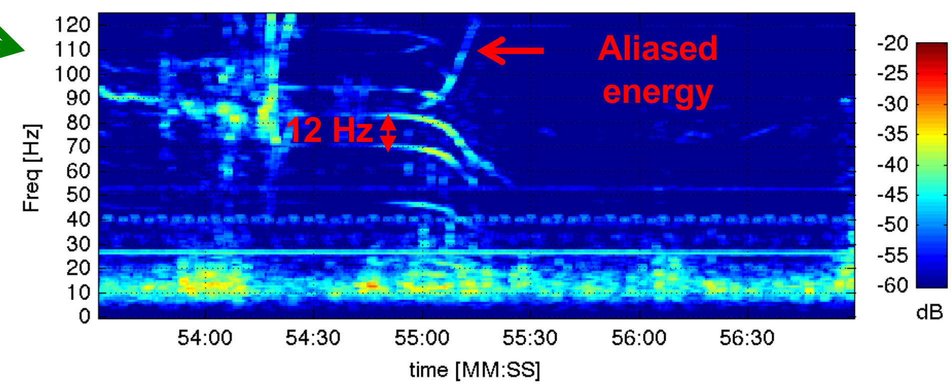
Several peaks consistent with helicopter rotor harmonics (20-100 Hz).

Doppler shift

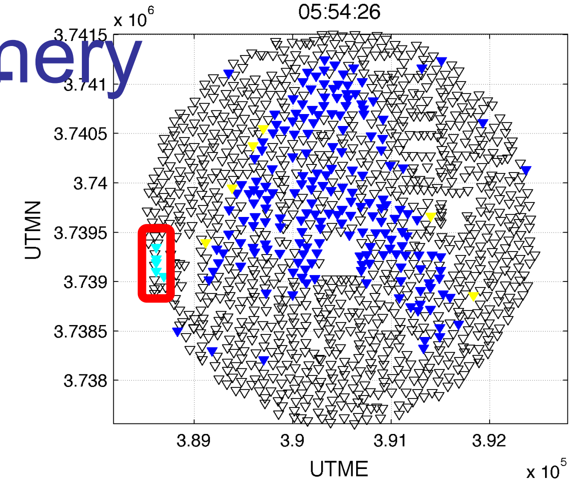
$f_{high}/f_{low}=(v_0+v)/(v_0-v)\approx1.4$ i.e. $v\approx250$ km/h

Speed over ground 7km/2min=210km/h

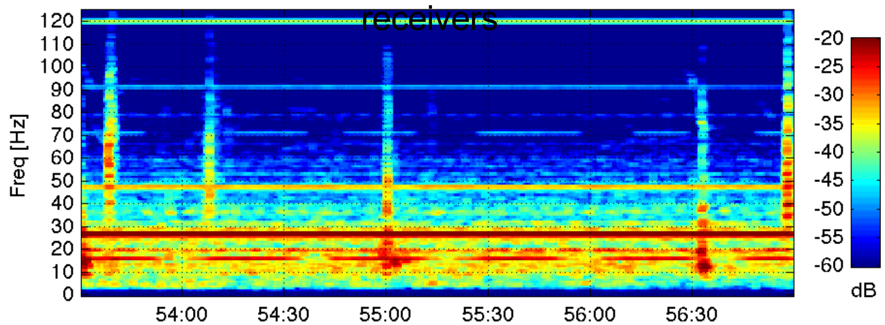
- √ Rotor frequencies
- √ Doppler frequency shift
- √ Movement in map



Example: Urban sounds…rotating machinery

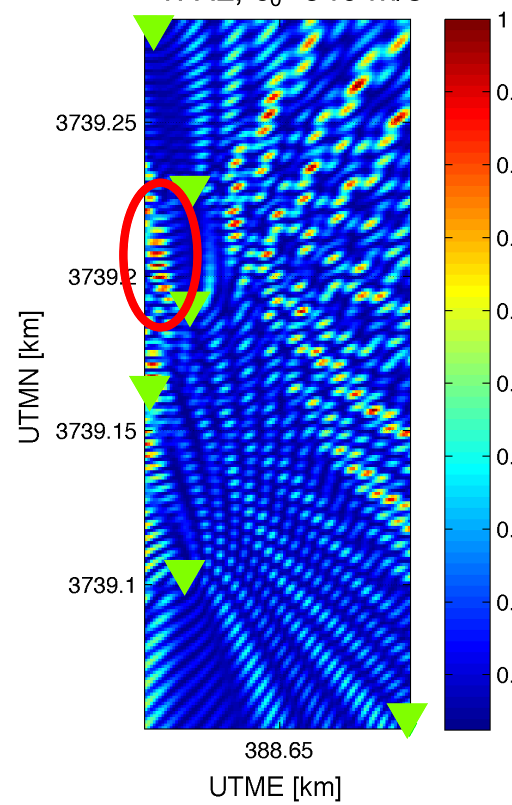


45-48 Hz machinery noise visible on several receivers



Location of mutually coherent receivers

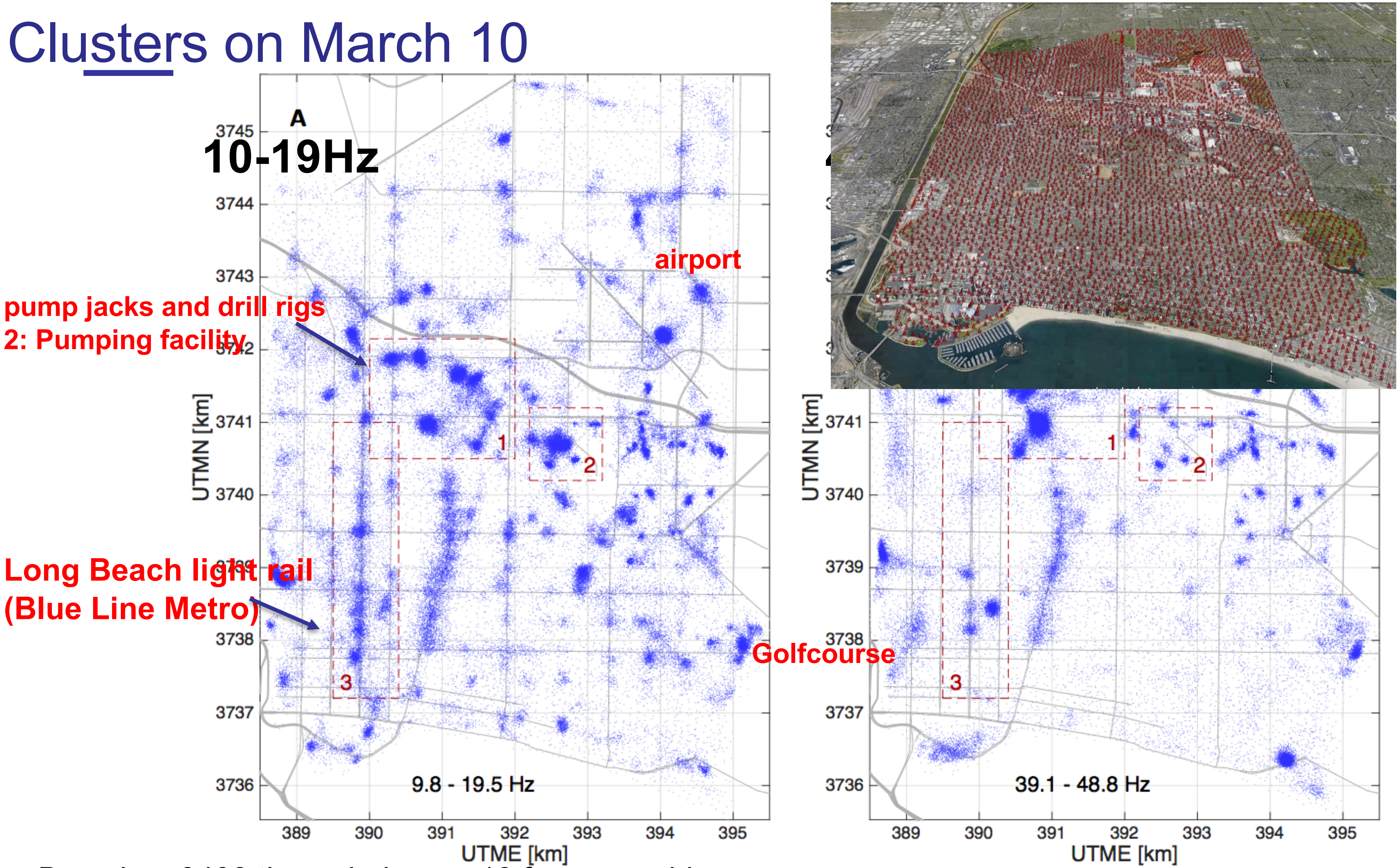
Matched-field processing 47Hz, c_0=340 m/s



Matched-field processing

- **Wavelength = 340/47 = 7 m**
- **Long Beach min. station spacing ≈70 m**
- **Seismic medium heterogeneities unknown.**

Clusters on March 10

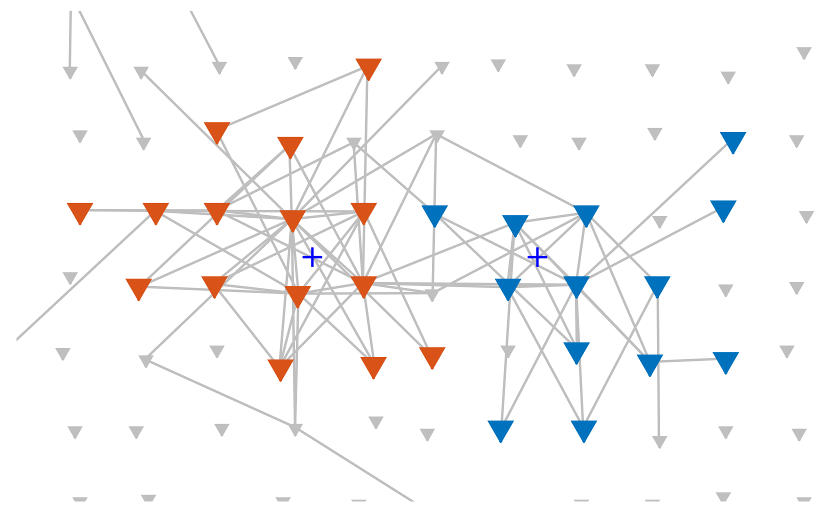


Based on 9400 time windows x 10 frequency bins.
Each dot is the center of a cluster. 90% of the clusters cover <1.5% of the area.
Few false detections **450’000 sensor clusters detected in total**

Riahi, Gerstoft, Signal Processing 2017

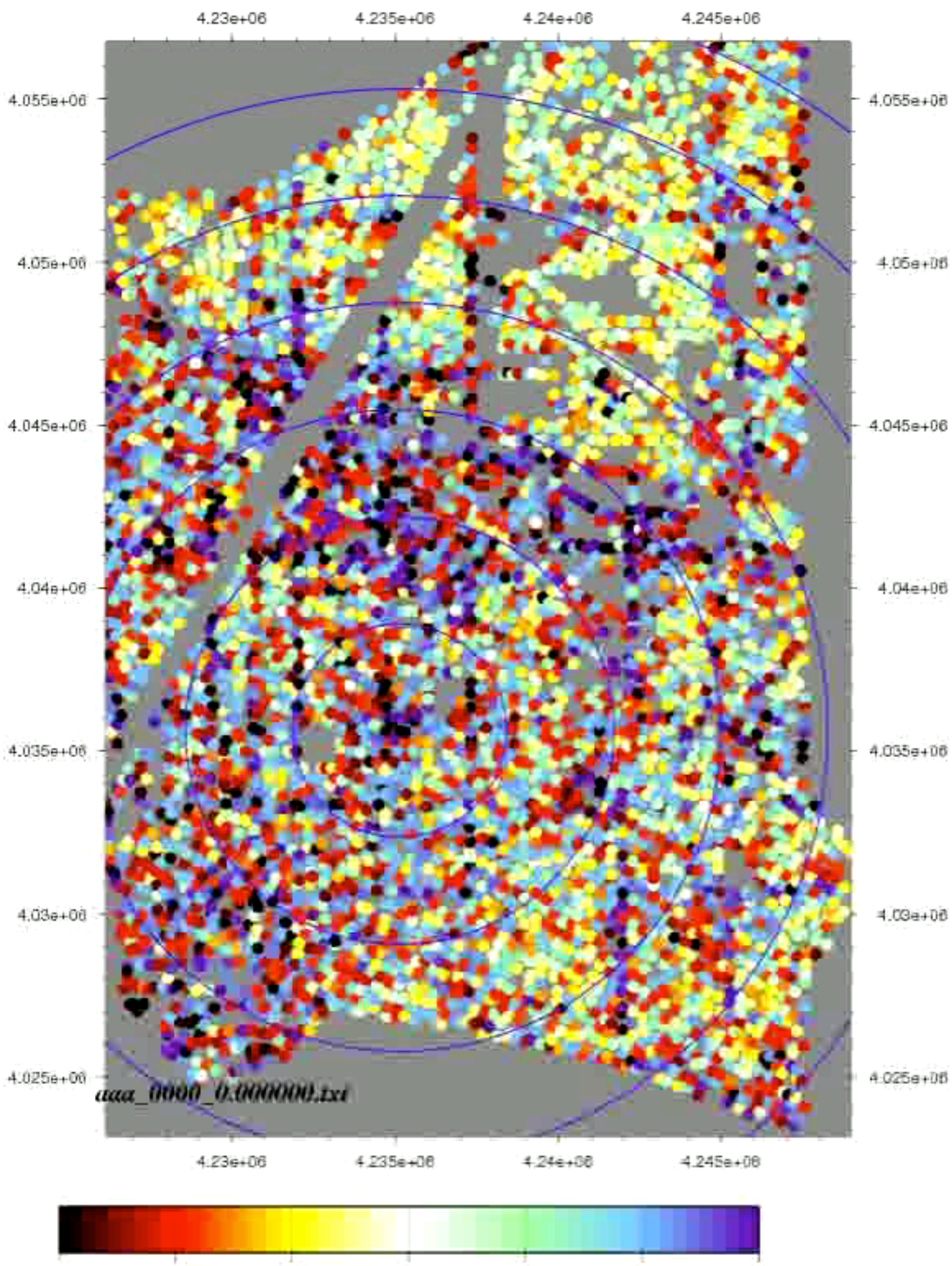
Conclusions

- ✓ Pair-wise coherence defines a network across array sensors.
- ✓ Weak within-array sources induce topology on that network. This topology is used to approximately localize weak sources.
- ✓ Model-free approach
- ✓ Tested on large-scale empirical geophone data

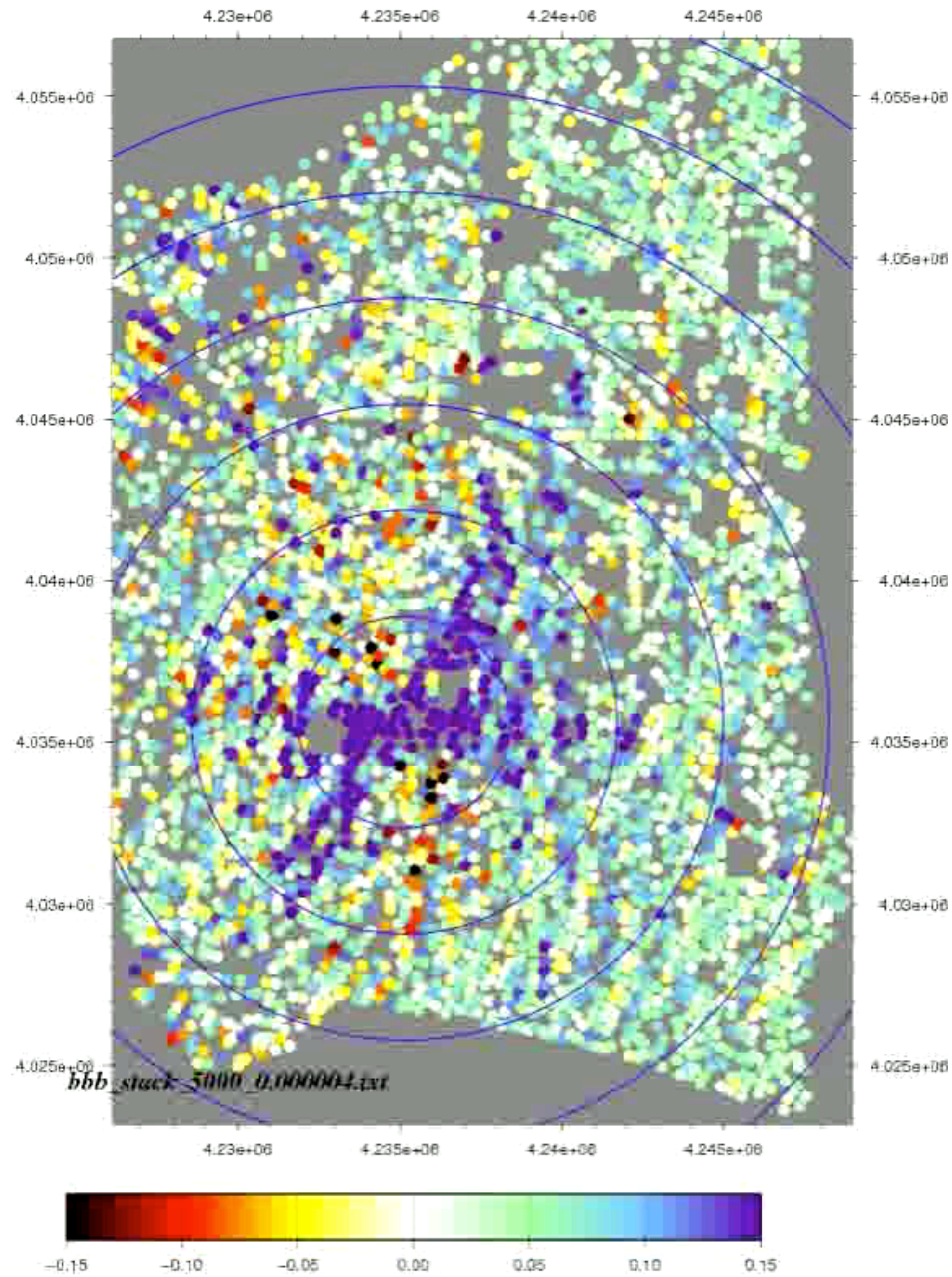


Constructing Greens Functions from noise

Vibro-source



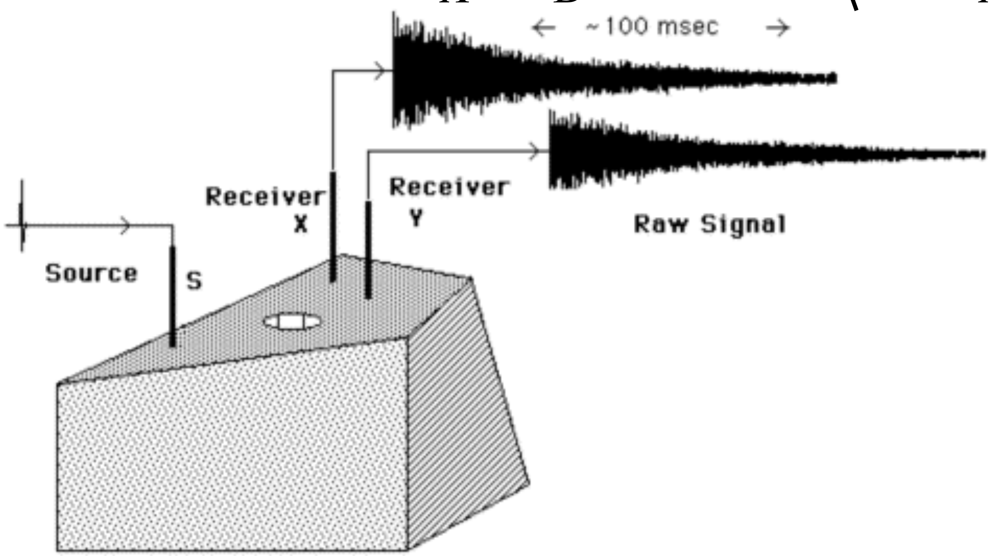
From ambient noise

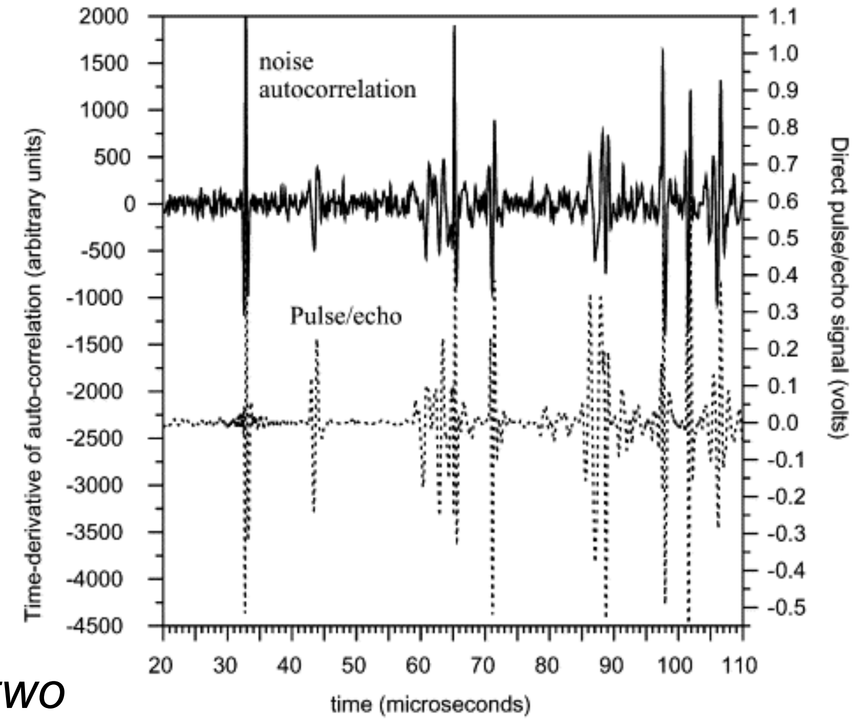


Coherent signals from noise data

The Green's function emerges from the cross-correlation of the diffuse wave field at two points of observation:

$$G(\mathbf{x}_A, \mathbf{x}_B, t) \propto \langle v(\mathbf{x}_A, -t) * v(\mathbf{x}_B, t) \rangle$$

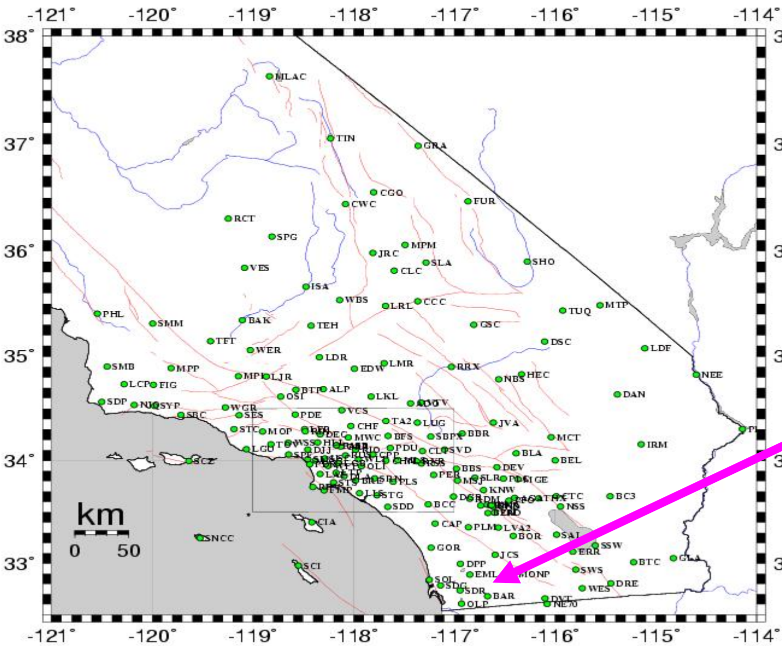


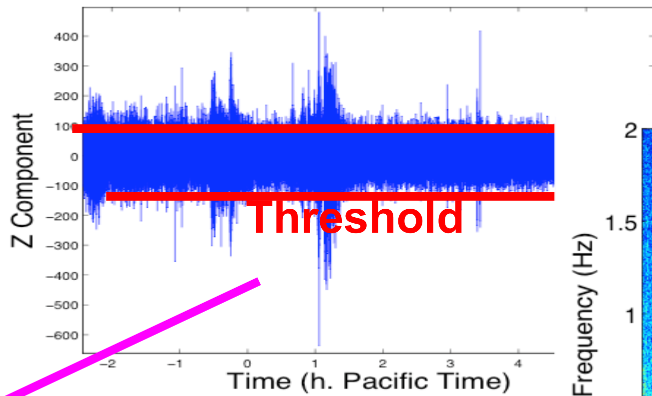


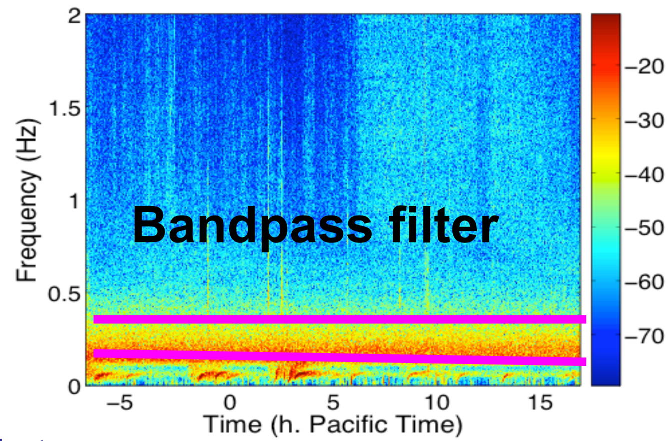
"By cross-correlating ambient noise recorded at two locations, the Green's function between these two locations can be reconstructed". (Claerbout 1999, Weaver 2001.)

Rickett and Clearbout 1999; Weaver and Lobkis, 2001

Seismic interferometry and in southern California

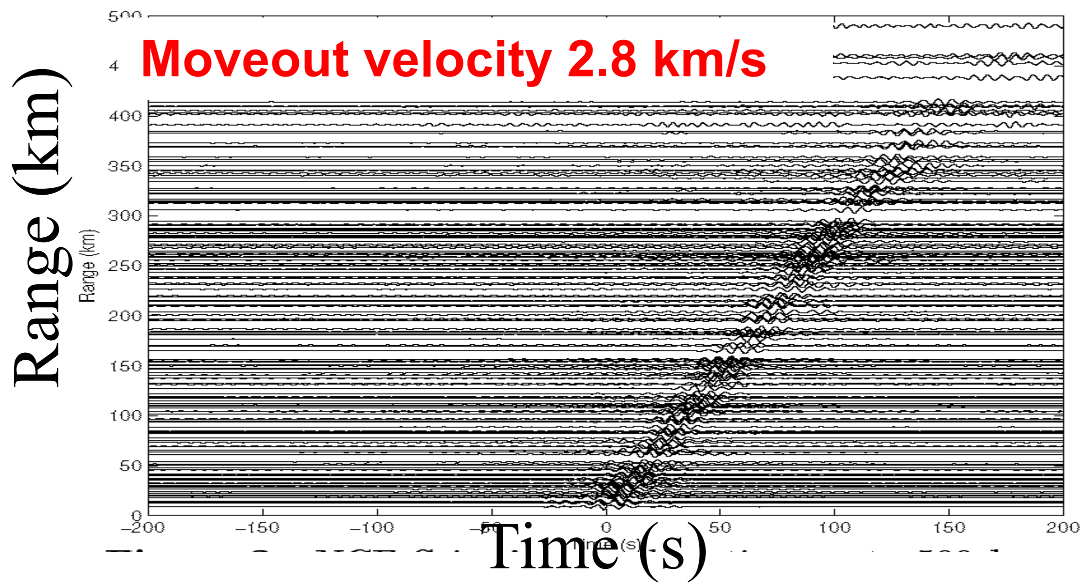






150 Stations
~11000 station pairs
30 Days of **continuous** data

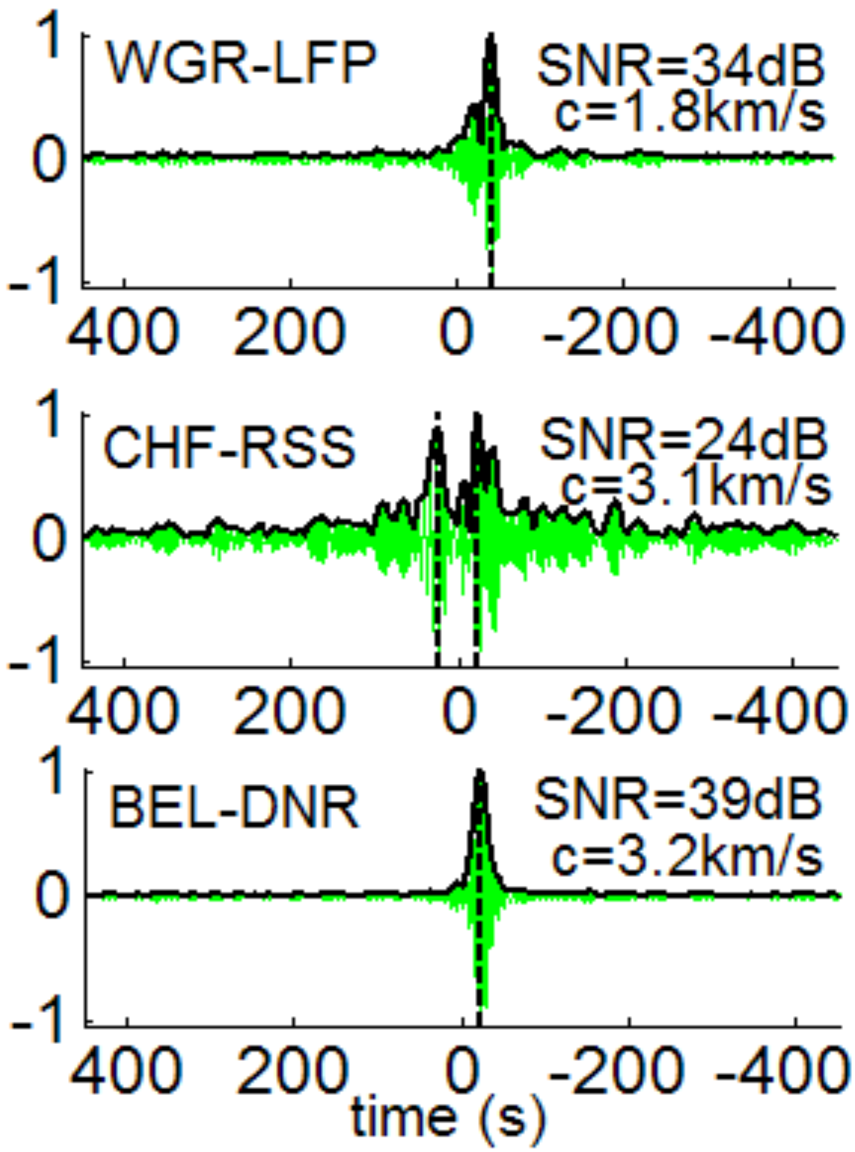
Result of noise cross correlation
order with range

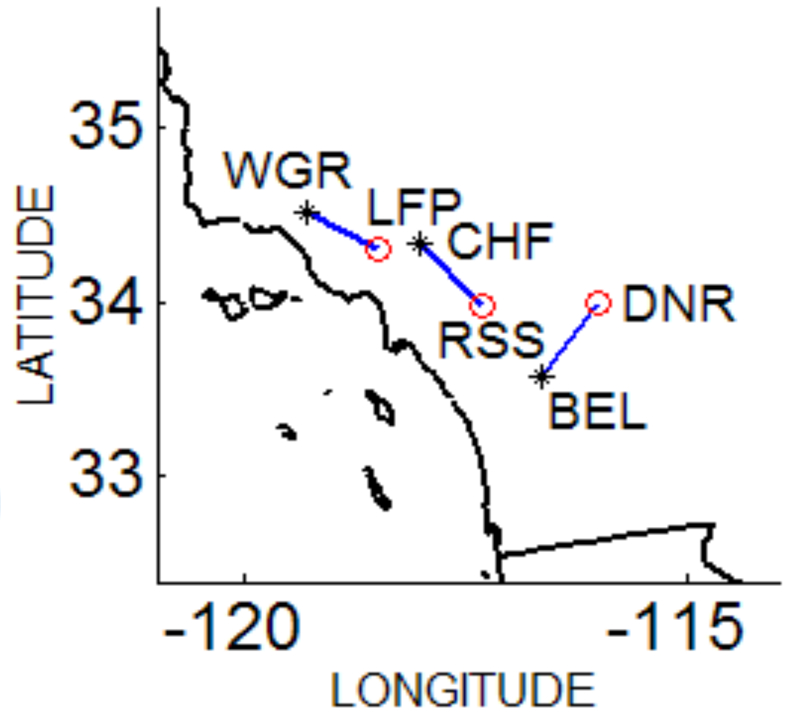


Individual paths have different travel time=> tomograpghy

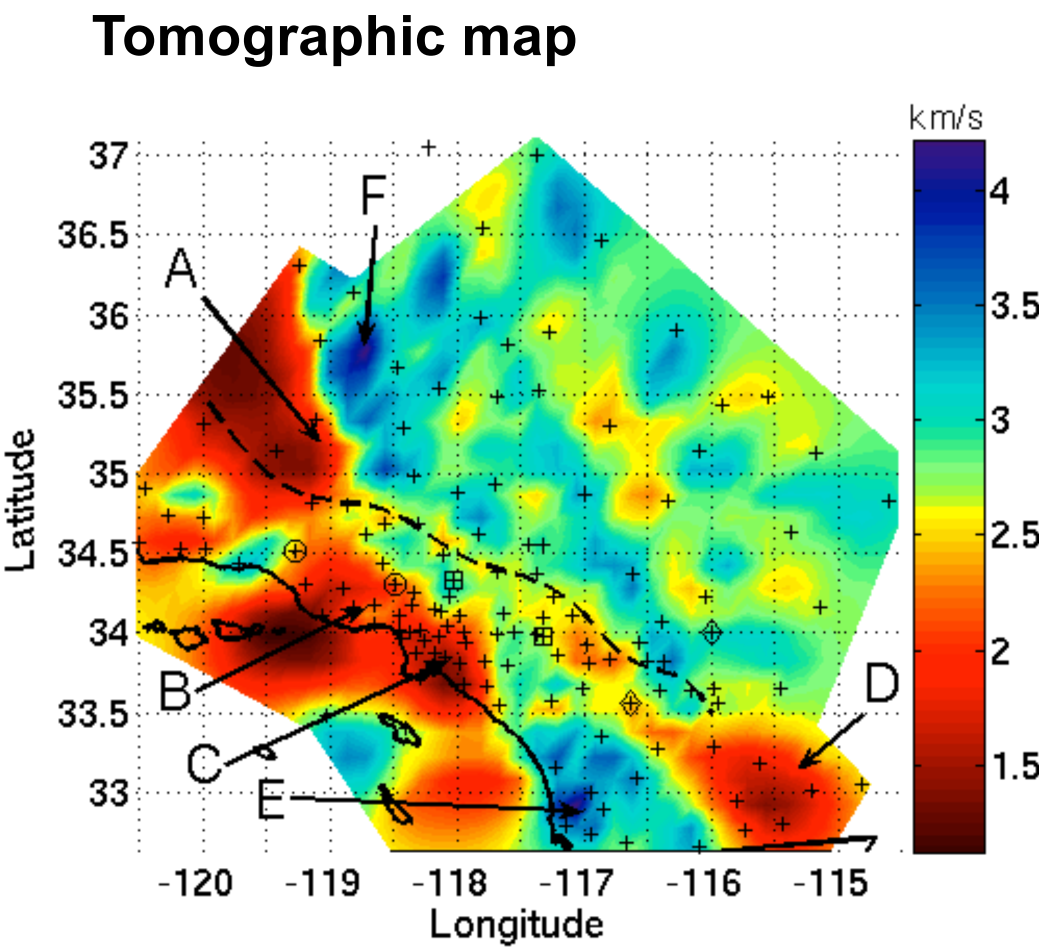
Sabra, GRL 2005; Gerstoft, Geophysics 2006

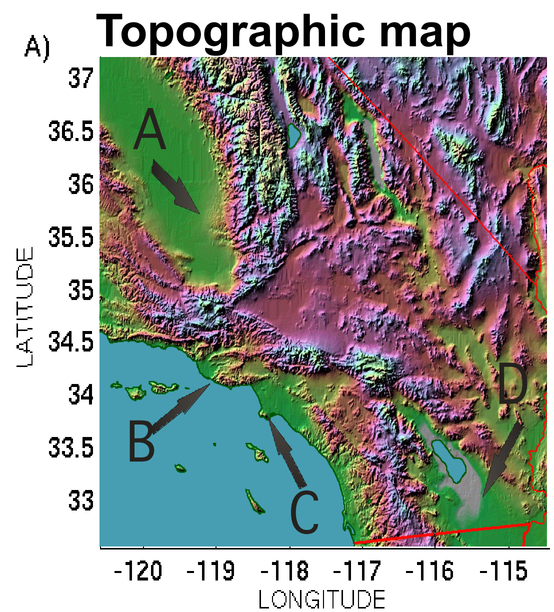
2D variations of the noise Rayleigh wave

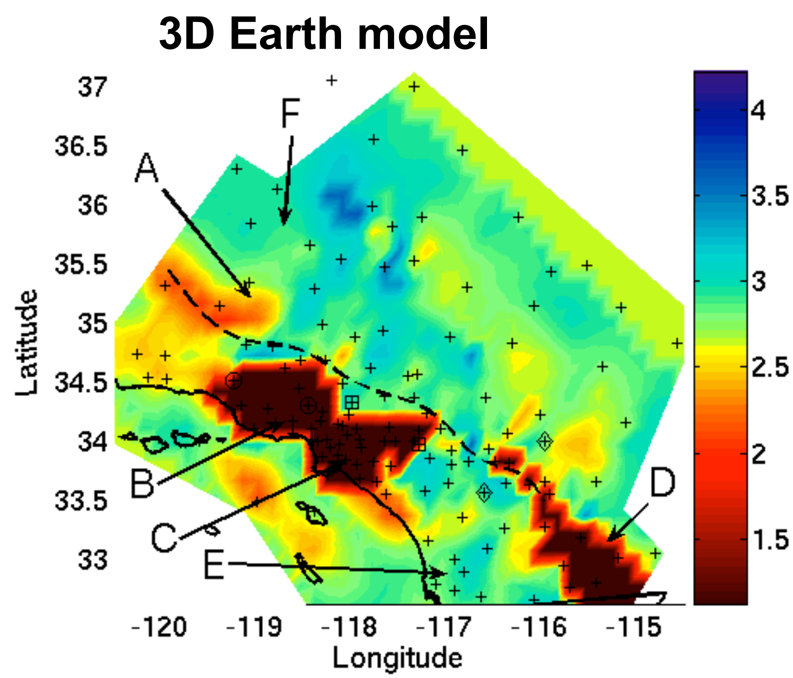




Ambient noise Surface wave Tomography







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

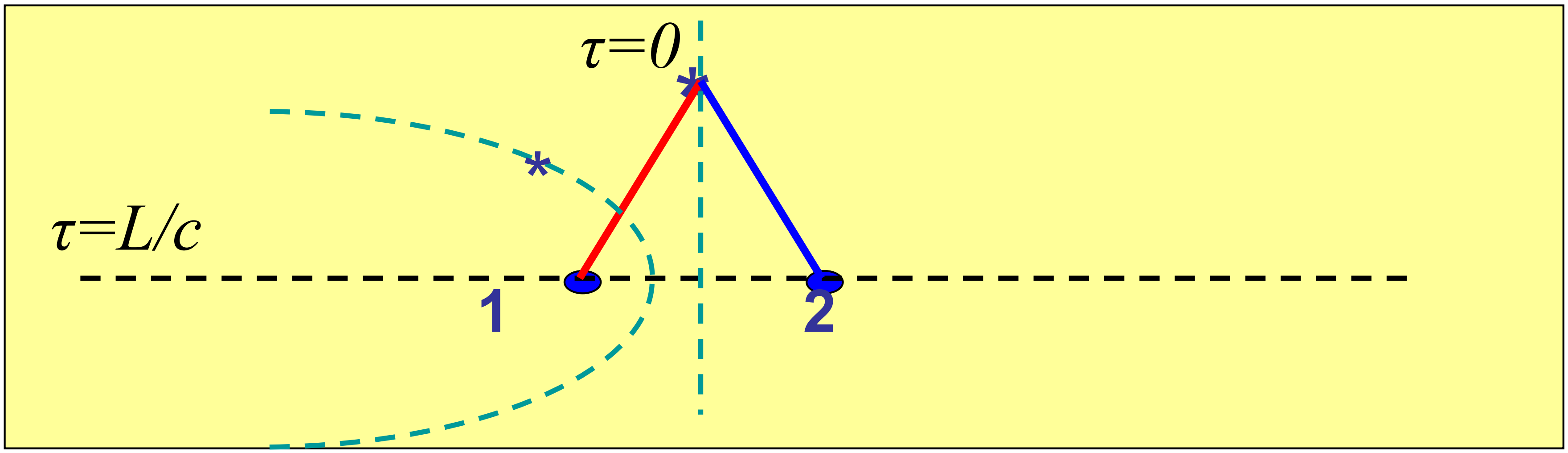
One month of ambient noise can replace 10 years of earthquake tomography!

Sabra, GRL 2005,
Gerstoft et al 2006

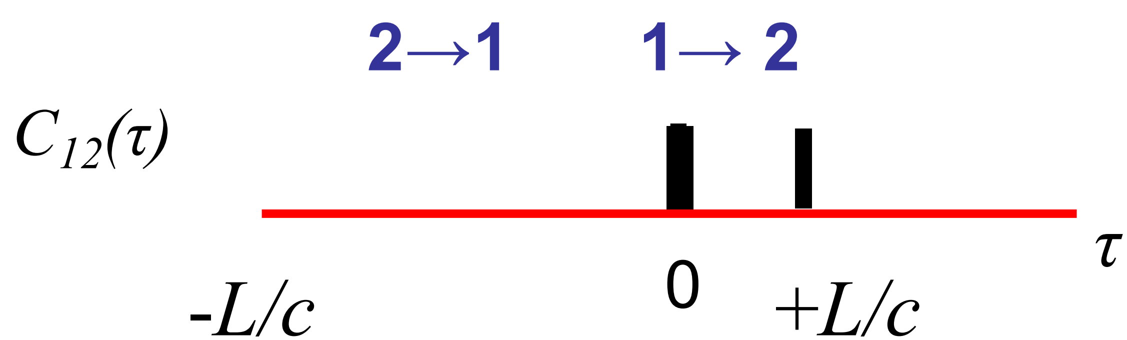
Free space noise correlation (3D)

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

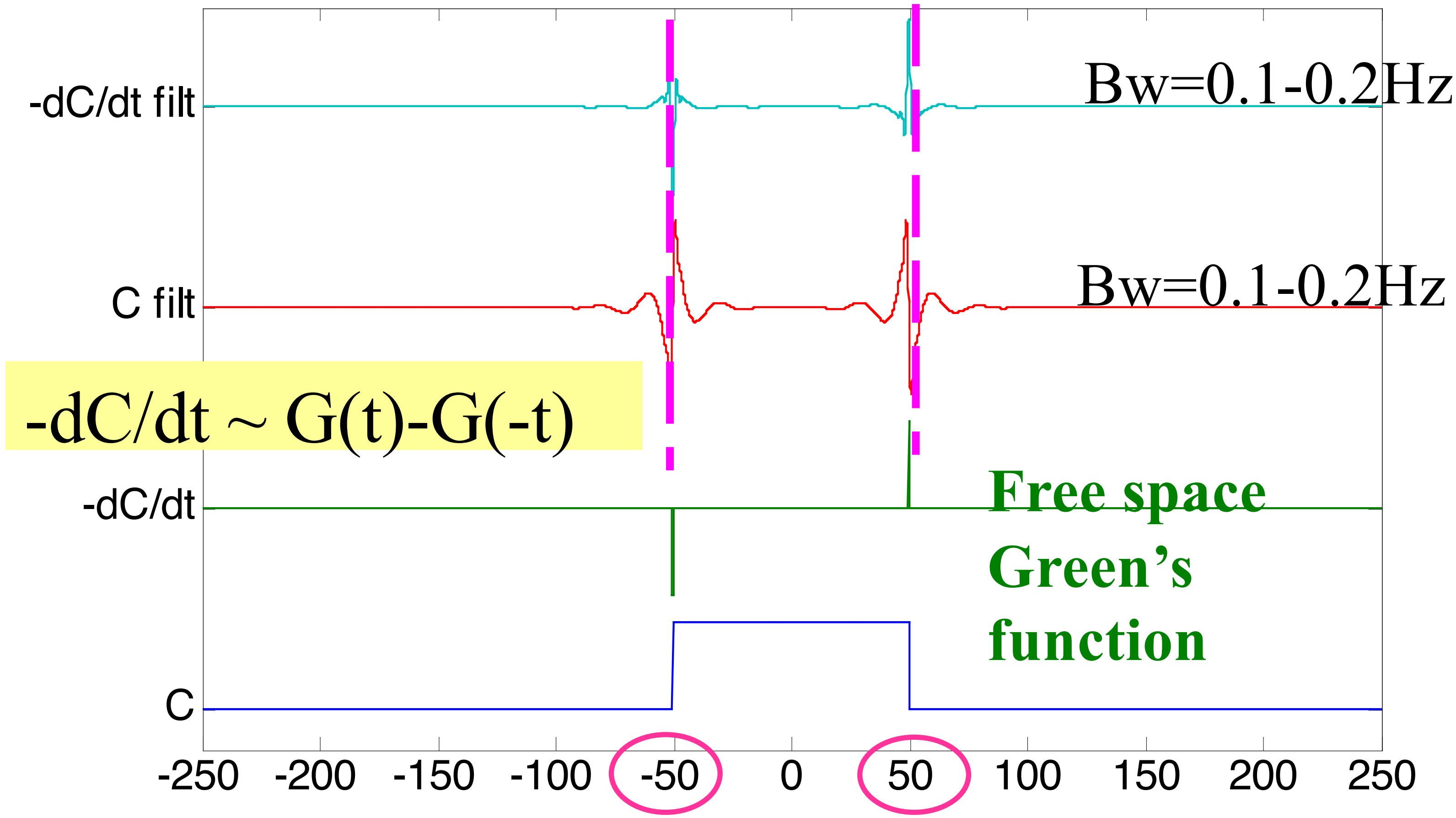
$$\frac{dC_{12}(\tau)}{d\tau} \propto -G(t) + G(-t)$$



Sources yielding constant time-delay τ lay on same hyperbola



C, dC/dt, band-limited signal

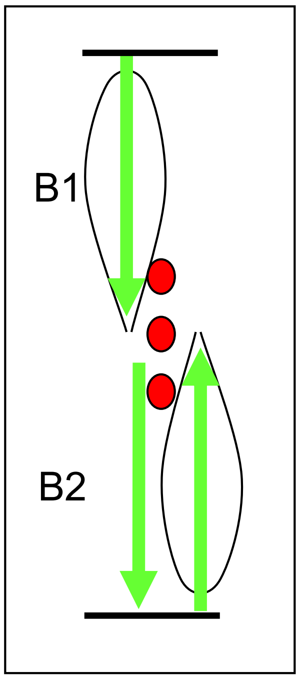


With cross-correlation process the phase of the source signal is removed,
→Arrival time is given by the center of the pulse (envelope maximum)

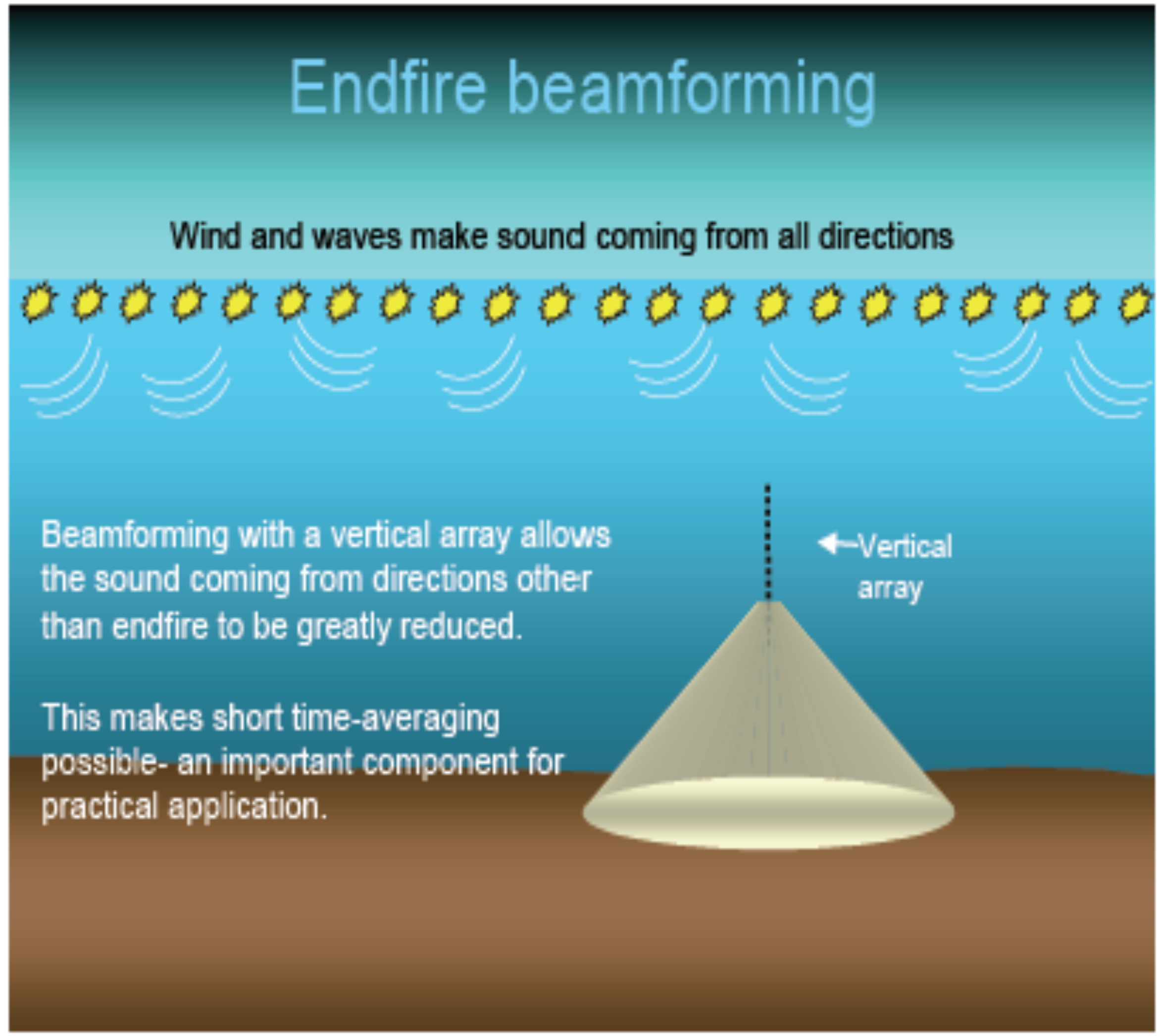
Isotropic noise distribution → Symmetric Correlation function.

Passive fathometer

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

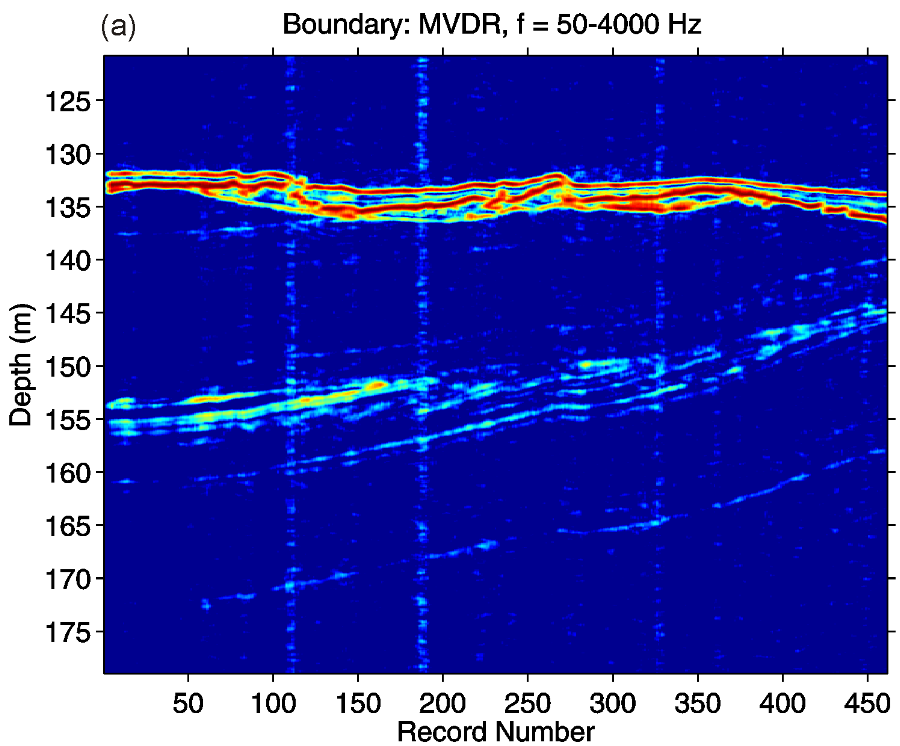


Siderius et al., JASA 2006,
Gerstoft et al., JASA 2008,
Harrison, JASA 2009,
Traer et al., JASA 2009, 2010, 2011
Siderius et al., JASA 2010

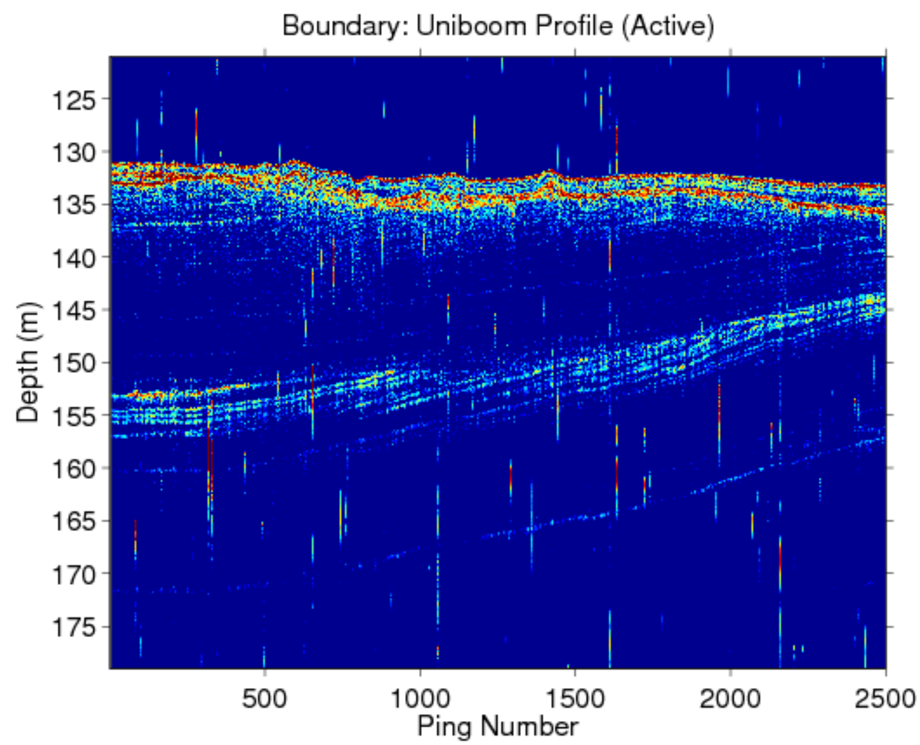


Passive fathometer

Ambient noise 50-4000 Hz



Boomer



Adaptive processing gives better resolution of reflections

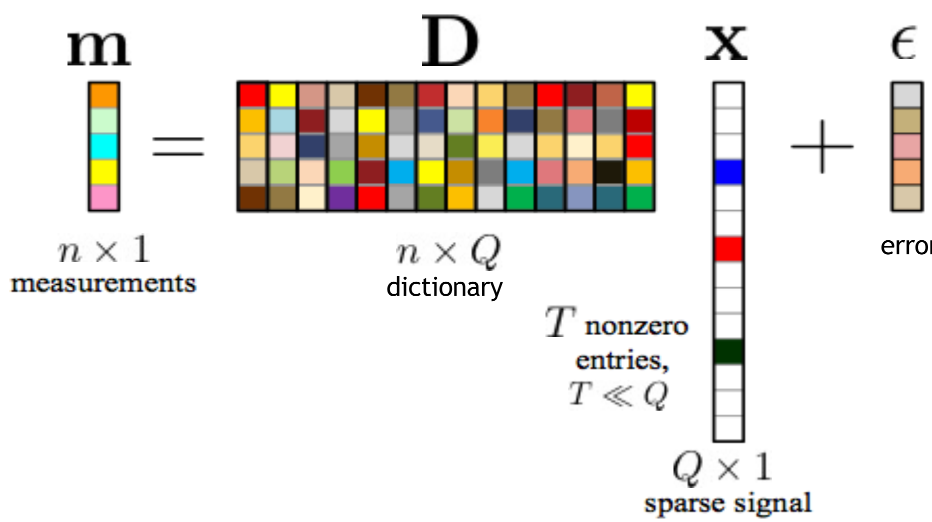
Siderius et al., 2009

Sparse models and dictionaries

- Sparse modeling assumes each signal model can be reconstructed from a few vectors from a large set of vectors, called a dictionary **D**
- Adds auxiliary sparse model to measurement model

$$\mathbf{d} = \mathbf{A}\mathbf{m} + \mathbf{n}, \ \ \mathbf{m} \approx \mathbf{D}\mathbf{x} \text{ and } |\mathbf{x}| \ll Q$$

- Optimization changes from estimating **m** to estimating sparse coefficients **x**

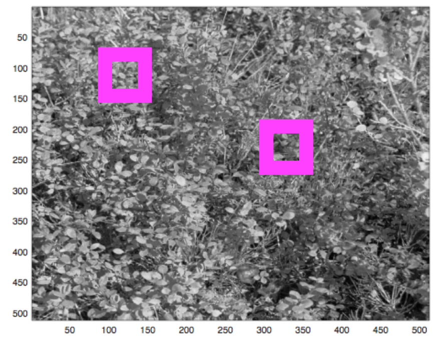


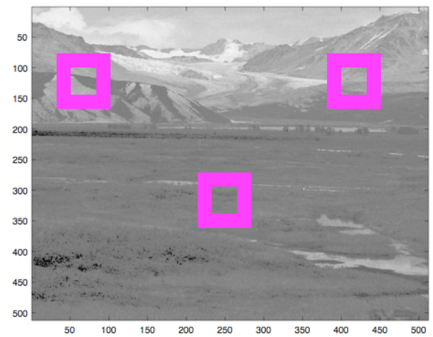
- Sparse objective: $\min_{\mathbf{x}} \|\mathbf{A}\mathbf{D}\mathbf{x} - \mathbf{d}\|_2 \text{ subject to } \|\mathbf{x}\|_0 \leq T$

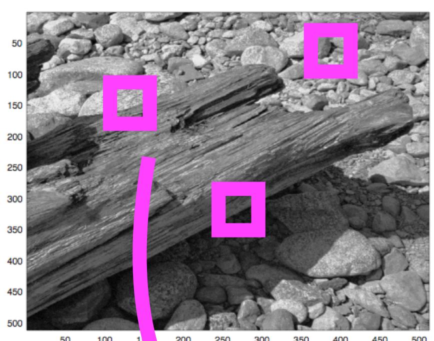
Dictionary learning and sparsity unsupervised

- Dictionary learning obtains "optimal" sparse modeling dictionaries directly from data
- Dictionary learning was developed in neuroscience (a.k.a. sparse coding) to help understand mammalian visual cortex structure
- Assumes (1) Redundancy in data: image patches are repetitions of a few elemental shapes; and (2) Sparsity: each patch is represented with few atoms from dictionary

"Natural" images, patches shown in **magenta**

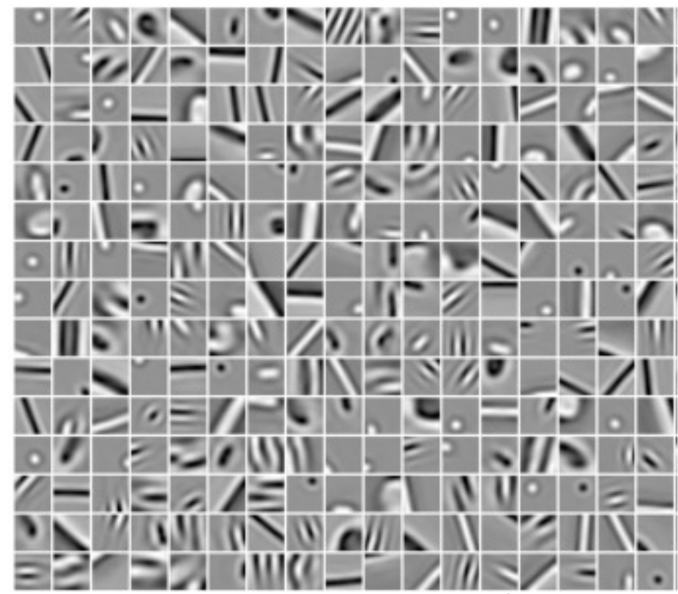






- Each patch is signal $\mathbf{y}_i$
- Set of all patches $\mathbf{Y} = [\mathbf{y}_1, ..., \mathbf{y}_I]$

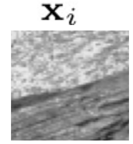
Learn dictionary **D** describing $\mathbf{Y} = [\mathbf{y}_1, ..., \mathbf{y}_I]$



Olshausen 2009

Sparse model for patch $\mathbf{y}_i$ composed of few atoms from **D**

$$\hat{\mathbf{x}}_i = \arg\min_{\mathbf{x}_i} \|\mathbf{y}_i - \mathbf{D}\mathbf{x}_i\|_2 \quad \text{subject to} \quad \|\mathbf{x}_i\|_0 \le T$$

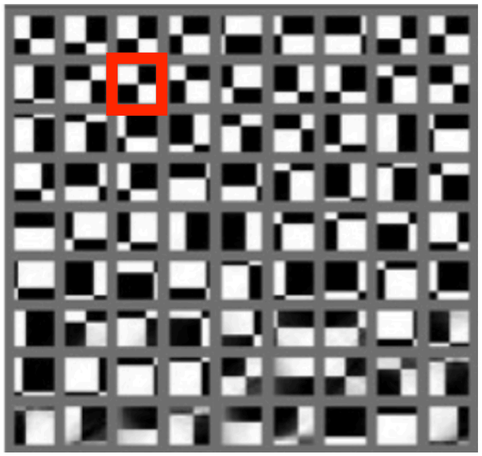
$\mathbf{y} =$  $=$  $x_1 +$  $x_2 + \ldots$

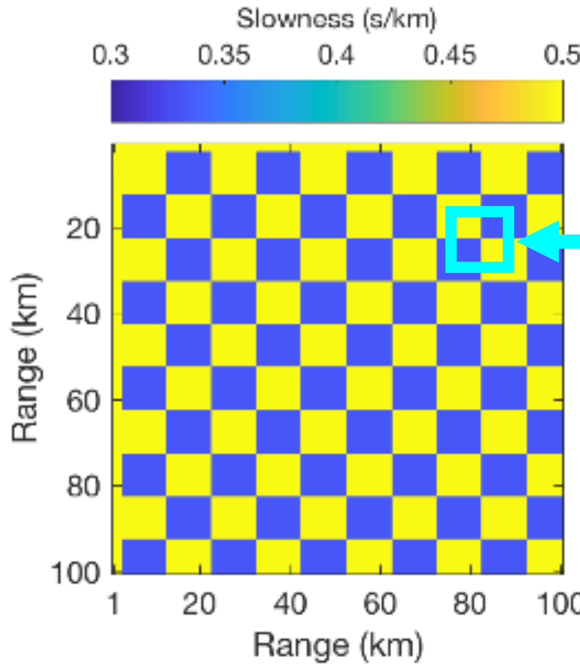
Bianco 2018, 2019

Checkerboard dictionary example

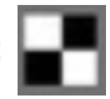
Dictionary $\mathbf{D}$

Slowness





$$\mathbf{y} = \mathbf{R}_i\mathbf{s} = \mathbf{D}\mathbf{x}_i$$

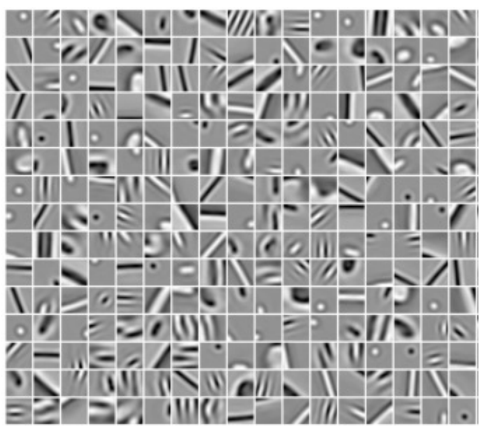
$\mathbf{R}_i\mathbf{s} =$  x_i

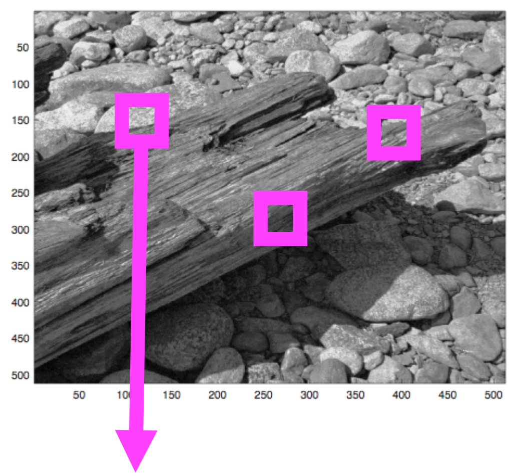
10x10 pixel patches

$$\mathbf{D} \in \mathbb{R}^{n\times Q}$$

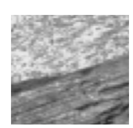
$$\mathbf{R}_i \in \{0,1\}^{n\times N}$$

Natural image



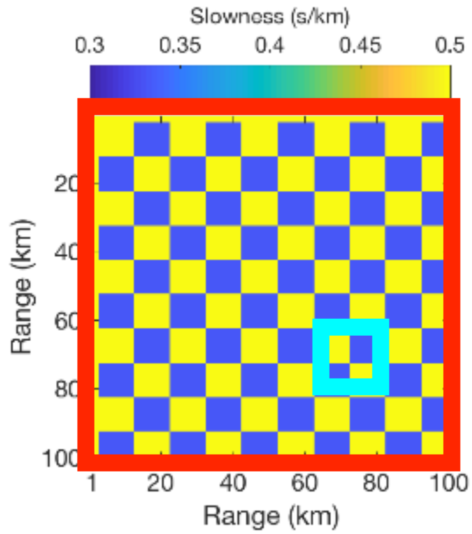


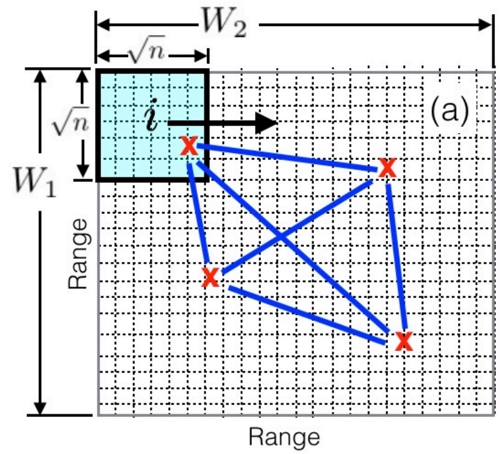
$$\widehat{\mathbf{x}}_i = \arg\min_{\mathbf{x}_i} \|\mathbf{y}_i - \mathbf{D}\mathbf{x}_i\|_2 \text{ subject to } \|\mathbf{x}_i\|_0 \le T$$

$\mathbf{y} =$  $=$  $x_1 +$  $x_2 + \ldots$

Bianco 2018, 2019

LST slowness image and sampling





Pixels and “patches”

Slowness map and measurements
- **stations in red**
- **rays in blue**

Slowness map and sampling:

- Discrete slowness map *N=W₁ x W₂* pixels
- I overlapping $\sqrt{n} \times \sqrt{n}$ pixel patches
- *M* straight-ray paths

Tomography matrix (straight ray) $\mathbf{A} \in \mathbb{R}^{M \times N}$

Slowness dictionary $\mathbf{D} \in \mathbb{R}^{n \times Q}$

$Q \ll I$

“Local” model $$\widehat{\mathbf{x}}_i = \arg\min_{\mathbf{x}_i} \|\mathbf{R}_i \mathbf{s}_\mathrm{s} - \mathbf{D}\mathbf{x}_i\|_2^2 \text{ subject to } \|\mathbf{x}_i\|_0 = T$$

“Global” model $$\mathbf{t} = \mathbf{A}\mathbf{s}_\mathrm{g} + \epsilon \qquad \widehat{\mathbf{s}}_\mathrm{g} = \arg\min_{\mathbf{s}_\mathrm{g}} \|\mathbf{t} - \mathbf{A}\mathbf{s}_\mathrm{g}\|_2^2 + \lambda_1 \|\mathbf{s}_\mathrm{g} - \mathbf{s}_\mathrm{s}\|_2^2,$$

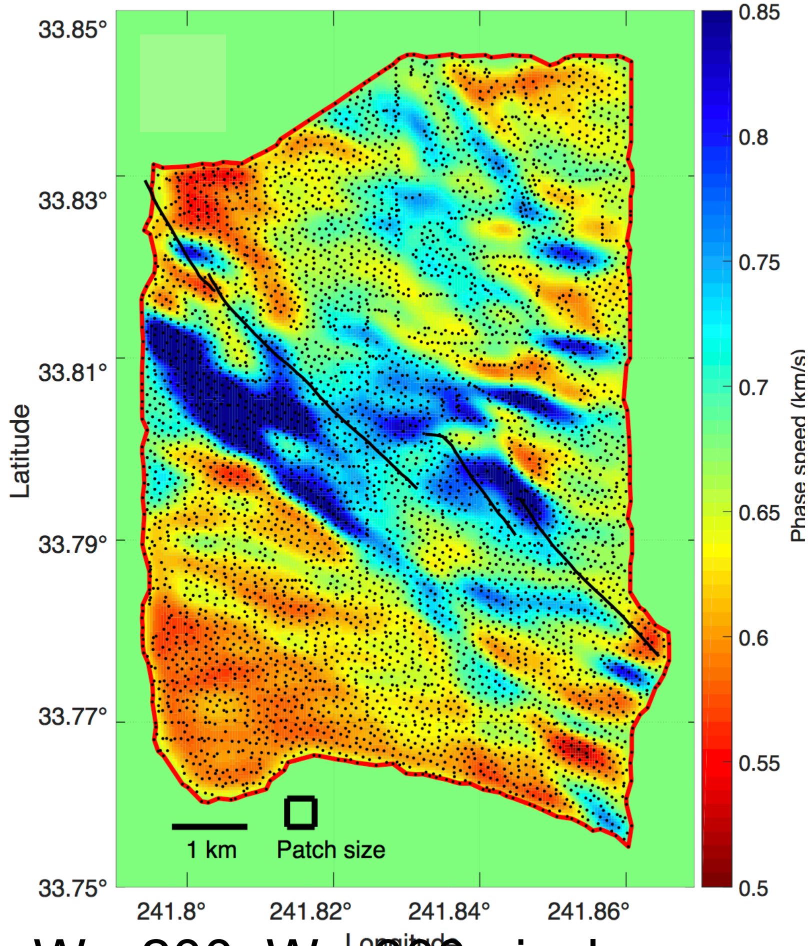
Bayesian formulation

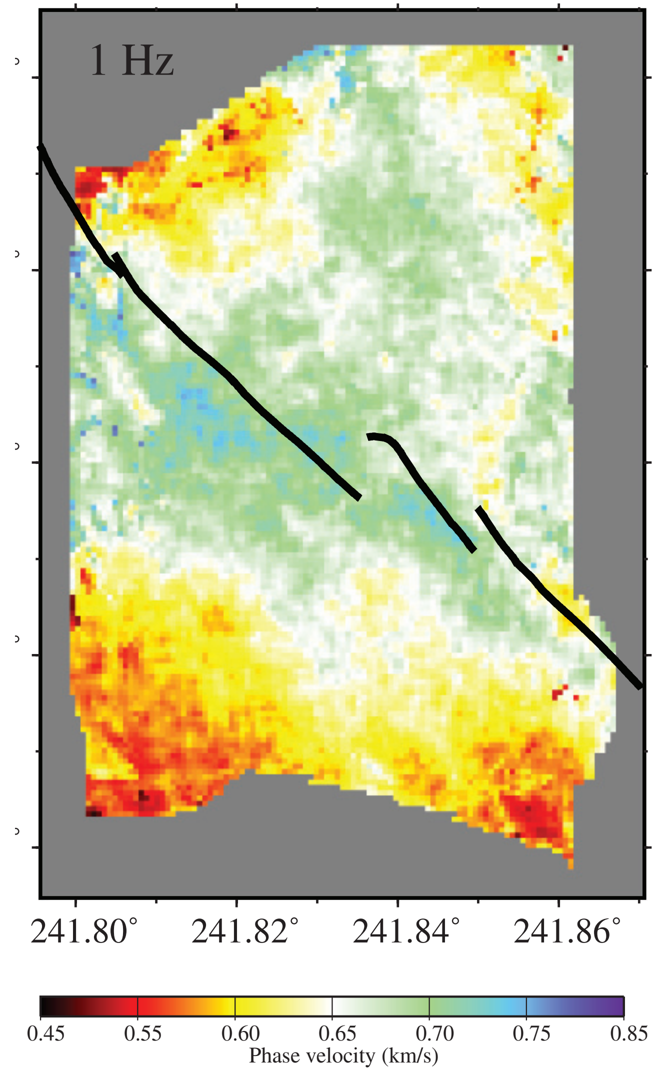
LST versus conventional tomography

Both use same travel times (from Fan-Chi Lin), unsupervised

LST 3 mill rays

Fan-Chi Lin, Geophysics, 8mill Rays

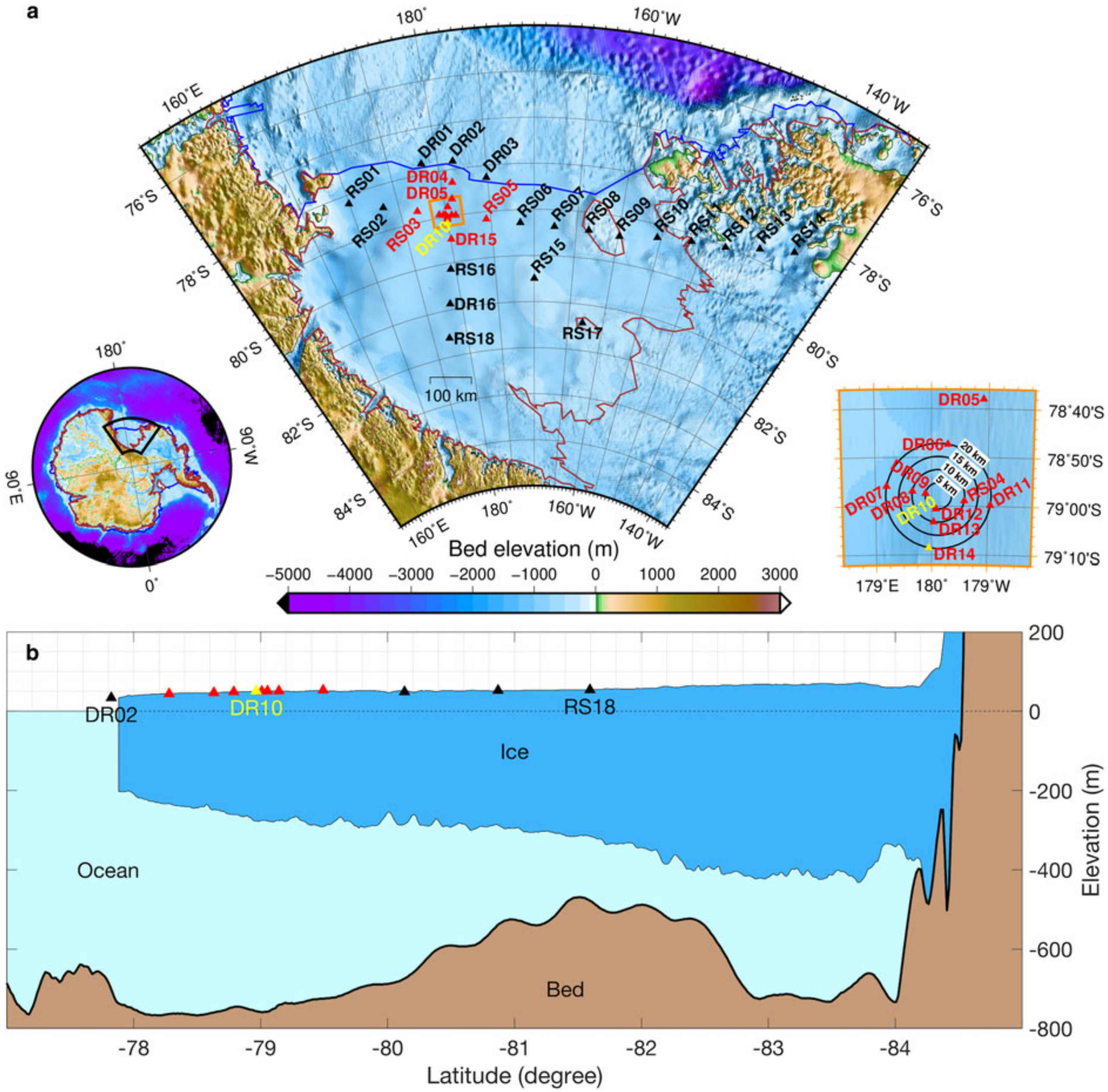




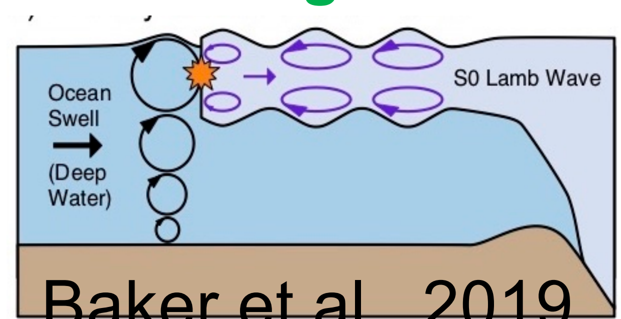
W_1=200, W_2=300 pixels
n=100, Q=200, T=1

Bianco 2018, 2019

Noise monitoring Ross Ice Shelf, Antarctica

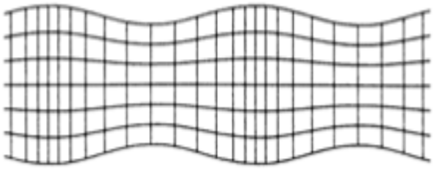


Gravitational restoring force

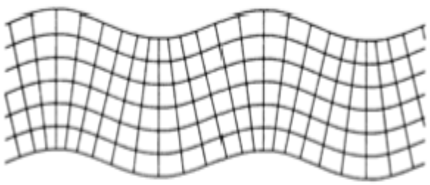


Baker et al., 2019

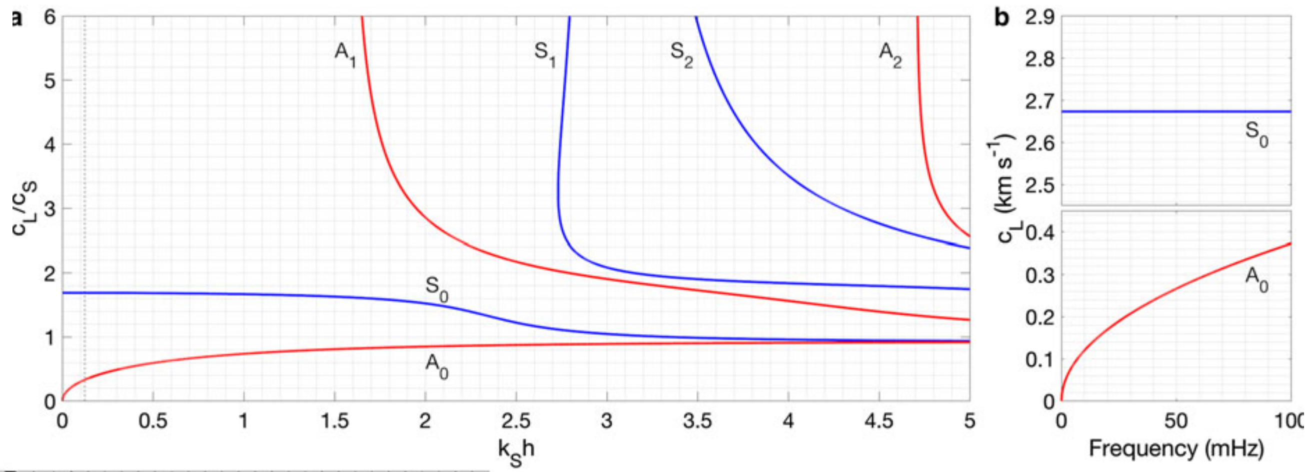
Plate waves simulated

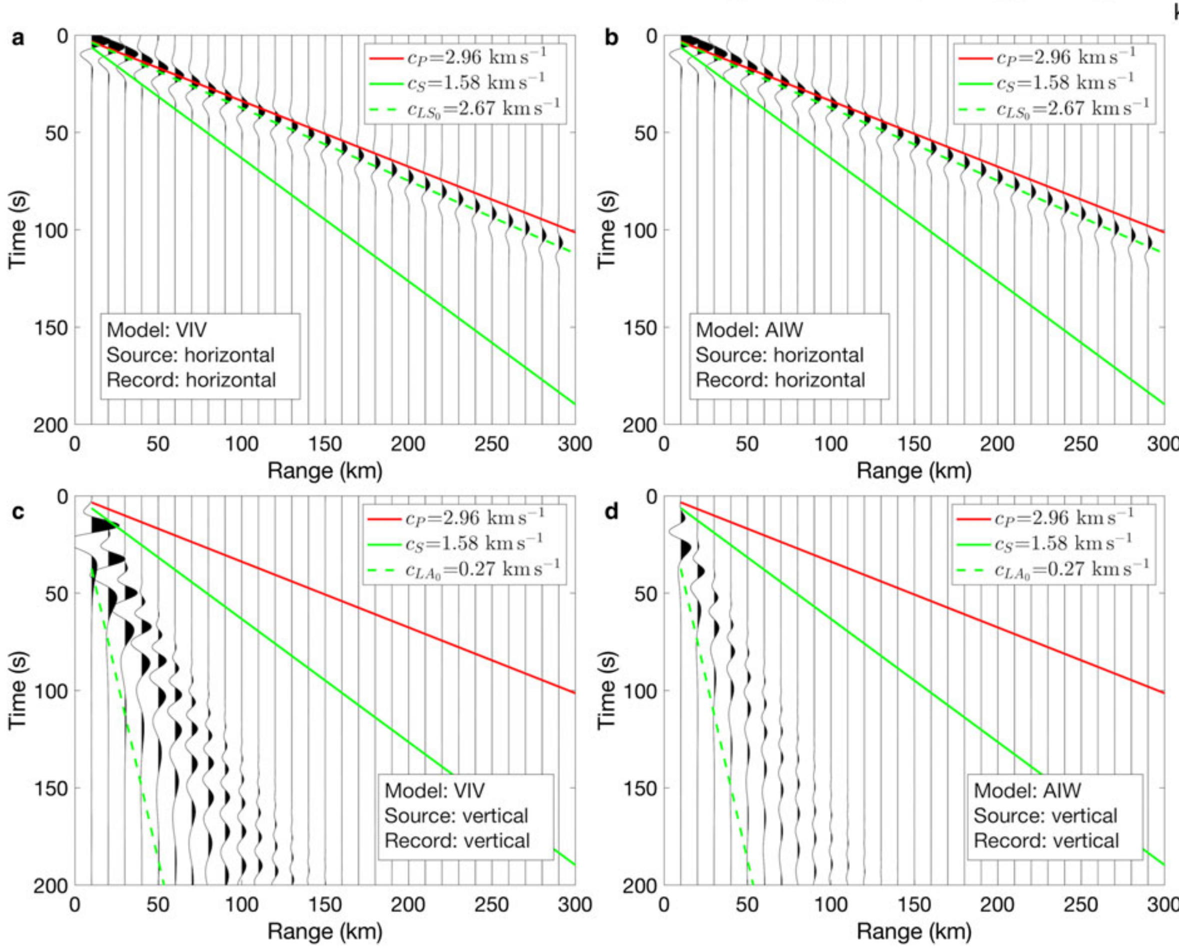


Symmetric Lamb Wave



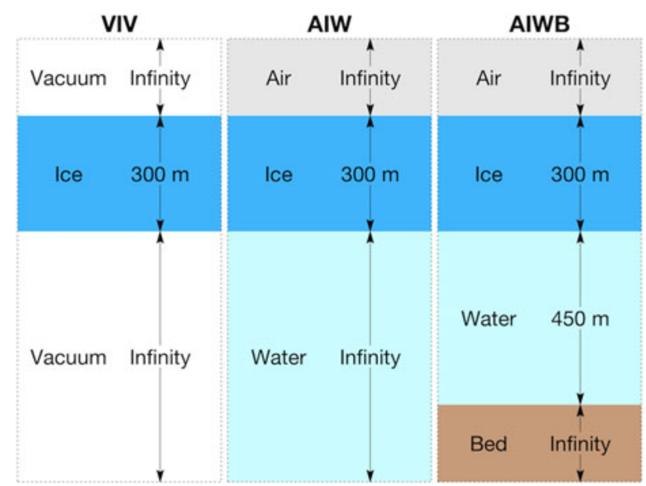
Anti-Symmetric Lamb Wave



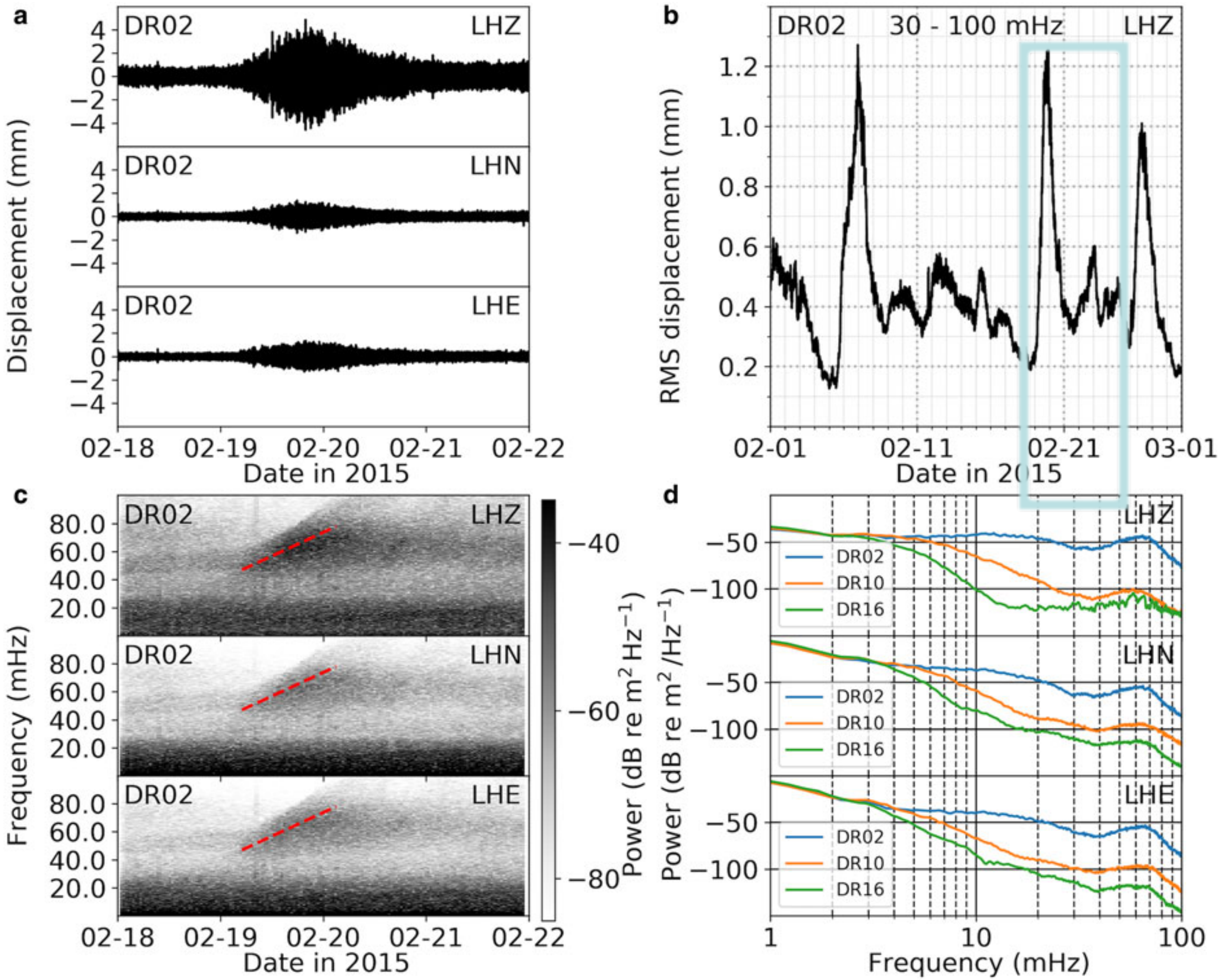


Iceplate 300m thick, Cs=1.6km/s

$$k_s h = \frac{2\pi f h}{c_L} = \frac{2\pi * 0.1 * 300}{1600} = 0.1$$

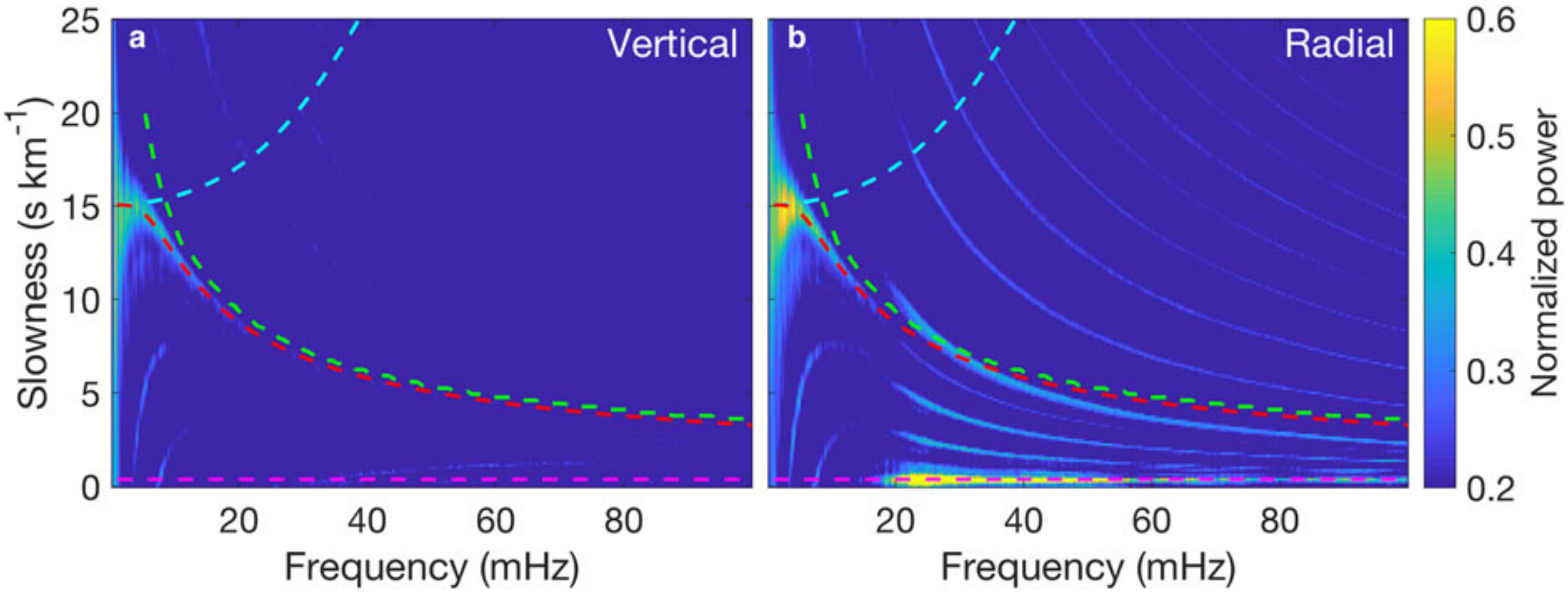


Strong IG event Feb 2015

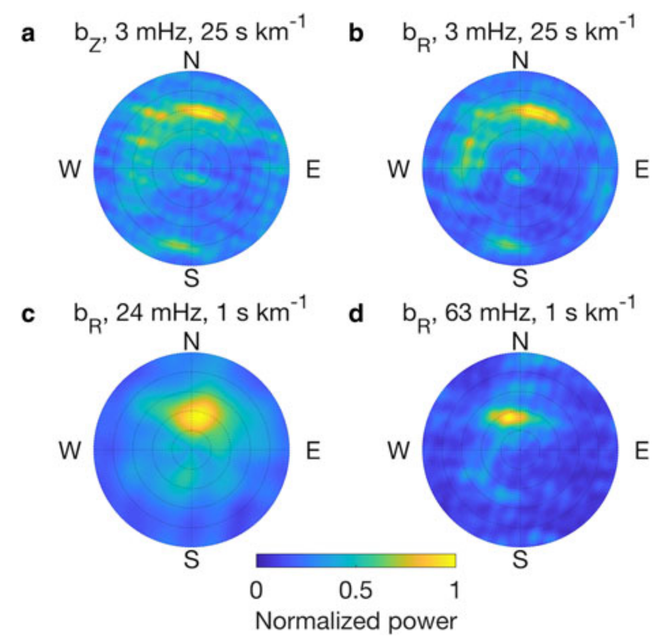


Range to storm 2000 km.

Slowness spectra 19-21 Feb 2015



Obtained by averaging the beamforming output over 0-20° azimuth. Phase speed dispersion curves of
ocean gravity waves,
flexural waves,
flexural-gravity waves
S_0 Symmetric AIWB model



Ambient seismic noise in the firn layer

AGU100 ADVANCING EARTH AND SPACE SCIENCE

Geophysical Research Letters

RESEARCH LETTER
10.1029/2018GL079665

Key Points:
- High-frequency (>5 Hz), narrow-band signals observed on an ice shelf are sensitive to changes in the near-surface firn layer
- Spectral peak frequency changes coincide with melt/freeze events on the ice shelf as well as with storm-driven redistribution snow
- Melt events have a unique spectral signature and can be modeled in terms of the penetration depth to which these thermal anomalies diffuse

Supporting Information:
- Supporting Information S1

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Citation:
Chaput, J., Aster, R. C., McGrath, D., Baker, M., Anthony, R. E., Gerstoft, P., et al. (2018). Near-surface environmentally forced changes

Near-Surface Environmentally Forced Changes in the Ross Ice Shelf Observed With Ambient Seismic Noise

J. Chaput[1,2], R. C. Aster[3], D. McGrath[3], M. Baker[3], R. E. Anthony[4], P. Gerstoft[5], P. Bromirski[5], A. Nyblade[6], R. A. Stephen[7], D. A. Wiens[8], S. B. Das[7], and L. A. Stevens[9]

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Abstract Continuous seismic observations across the Ross Ice Shelf reveal ubiquitous ambient resonances at frequencies >5 Hz. These firn-trapped surface wave signals arise through wind and snow bedform interactions coupled with very low velocity structures. Progressive and long-term spectral changes are associated with surface snow redistribution by wind and with a January 2016 regional melt event. Modeling demonstrates high spectral sensitivity to near-surface (top several meters) elastic parameters. We propose that spectral peak changes arise from surface snow redistribution in wind events and to velocity drops reflecting snow lattice weakening near 0°C for the melt event. Percolation-related refrozen layers and layer thinning may also contribute to long-term spectral changes after the melt event. Single-station observations are inverted for elastic structure for multiple stations across the ice shelf. High-frequency ambient noise seismology presents opportunities for continuous assessment of near-surface ice shelf or other firn environments.

EARTH SCIENCE

Scientists Discover a Weird Noise Coming From Antarctic Ice Shelf

Brian Kahn
10/16/18 4:52pm • Filed to: ICE ON THIN ICE

615.3K 84 6

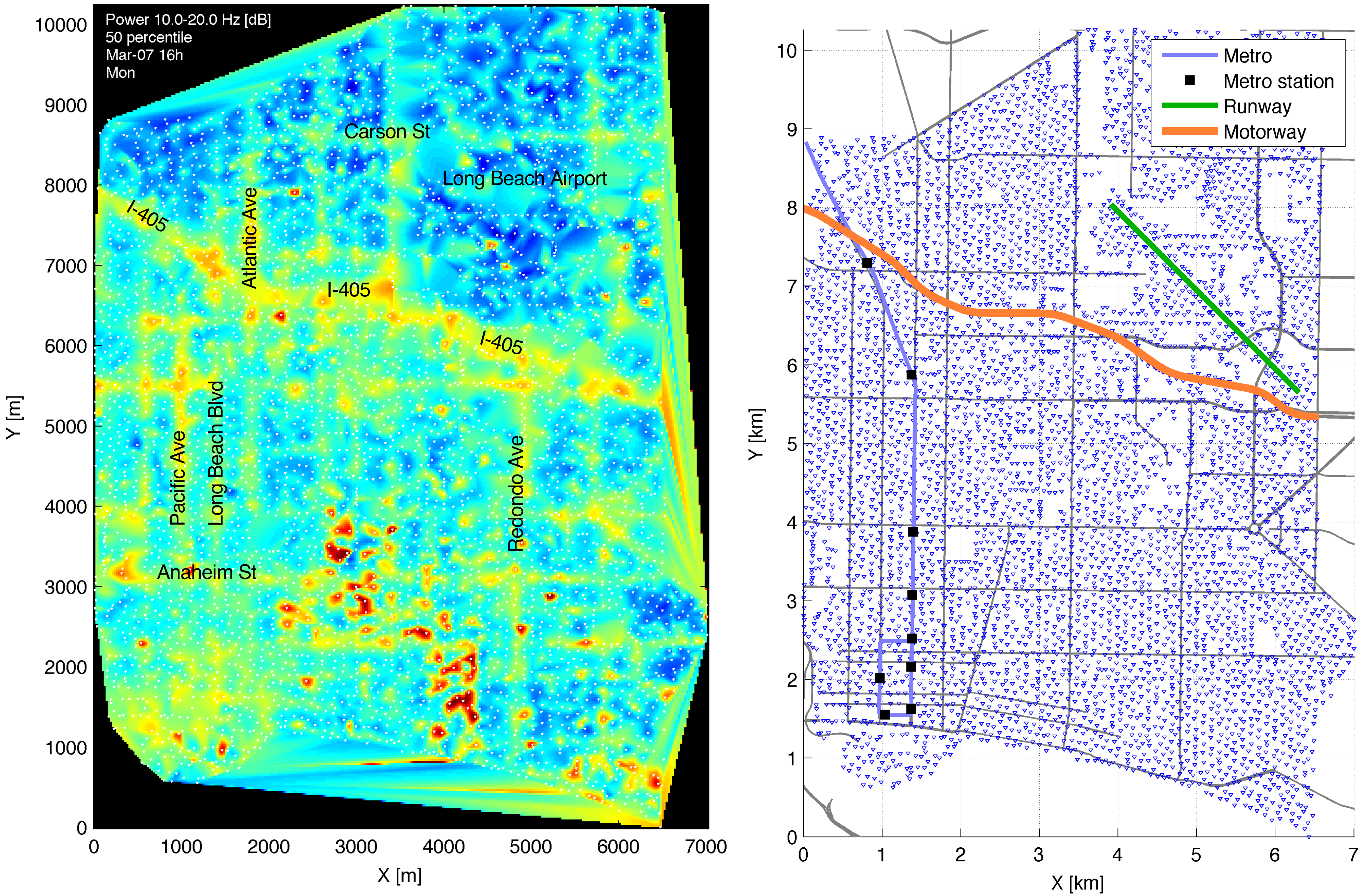
Photo: O.V.E.R.V.I.E.W. (Flickr)

The Antarctic is no stranger to weird sounds, from ancient trapped air bubbles popping to entire ice sheets disintegrating. Now we can add another freaky track to the ouevre of icy masterpieces.

And then, late night TV…

[redacted]

FINITO


Power 10.0-20.0 Hz [dB]
50 percentile
Mar-07 16h
Mon
Carson St
Long Beach Airport
I-405
Atlantic Ave
I-405
I-405
Pacific Ave
Long Beach Blvd
Redondo Ave
Anaheim St
Y [m]
X [m]
Metro
Metro station
Runway
Motorway
Y [km]
X [km]