Dense Arrays with Seismic and Acoustic Waves: Imaging, Monitoring and Source localization

Philippe Roux
ISTerre, Grenoble

ISTerre

Cargese 2015

Outline

1- Seismic / Geophysics Arrays at all Scales : fundamental Research & Industrial applications

2- Localization of Source buried in noise :

- Matched Field Processing in Underwater acoustics
- Time reversal
- Applications at the geophysics scale

3- Imaging with Ambient noise :

- Vs from Surface waves with Eikonal /Helmholtz tomography
- Vp from Body waves
- Anisotropy with Marine seismic data

4- Double beamforming : Identify / Separate different Wave types

- Active source array in Underwater acoustics
- Active source array in Geophysics
- Ambient noise on dense arrays in Geophysics / Seismology

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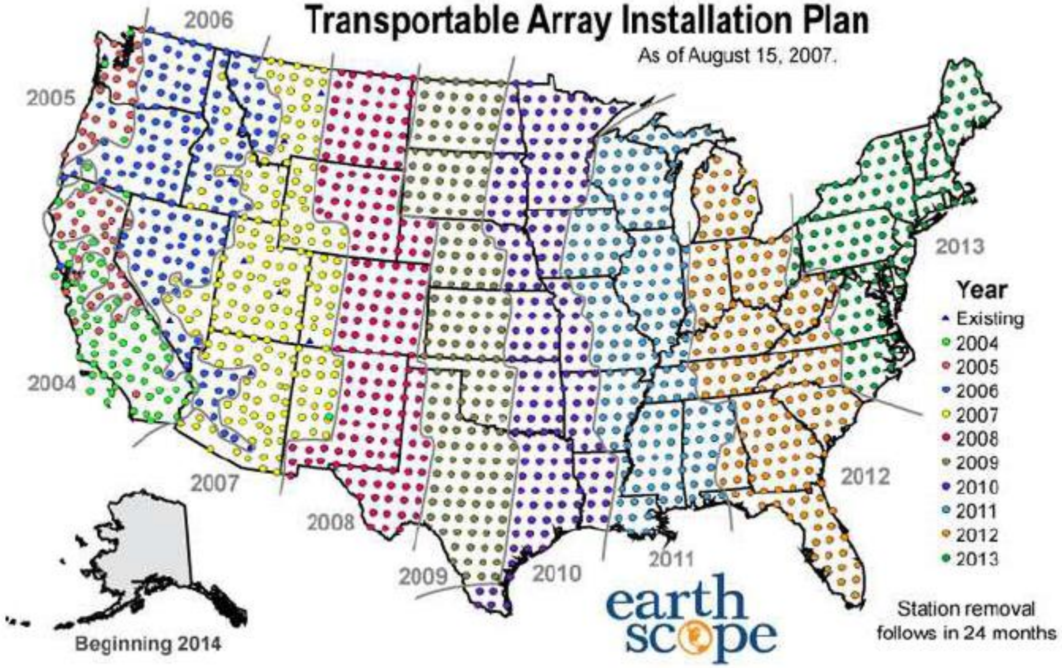
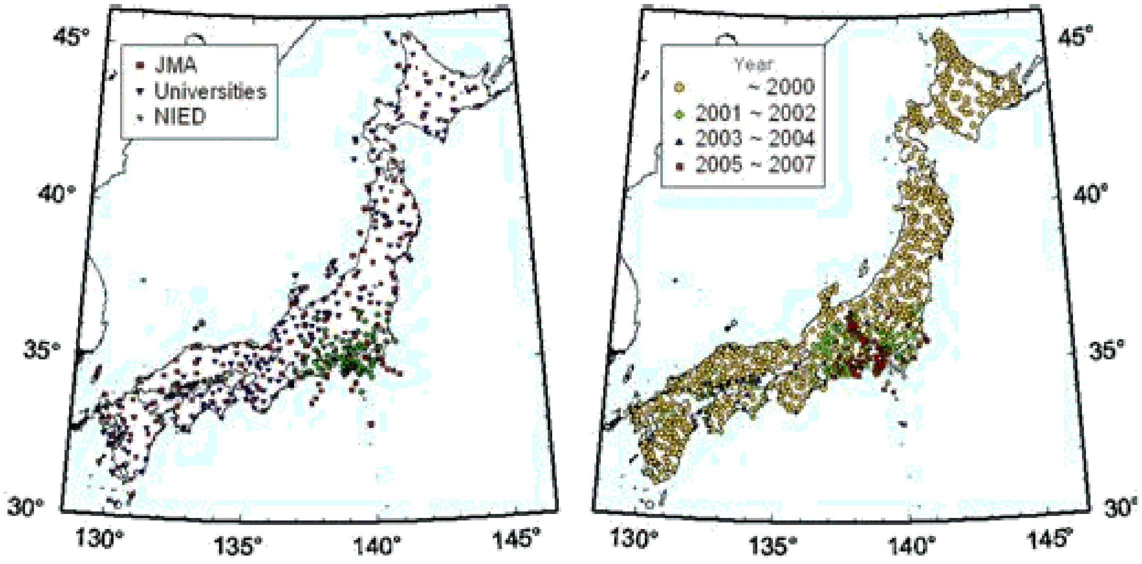
Dense Seismic arrays : Large scale

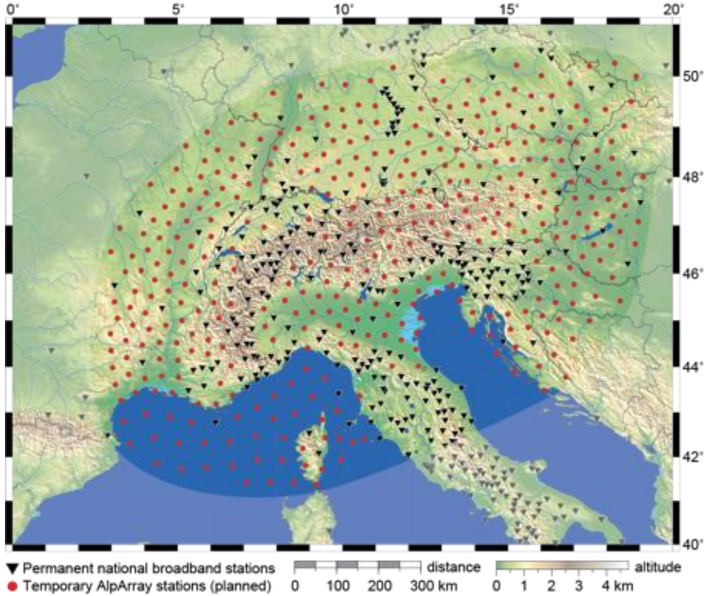
Hi-Net



Inter-station ~60 kms



Inter-station ~20 kms

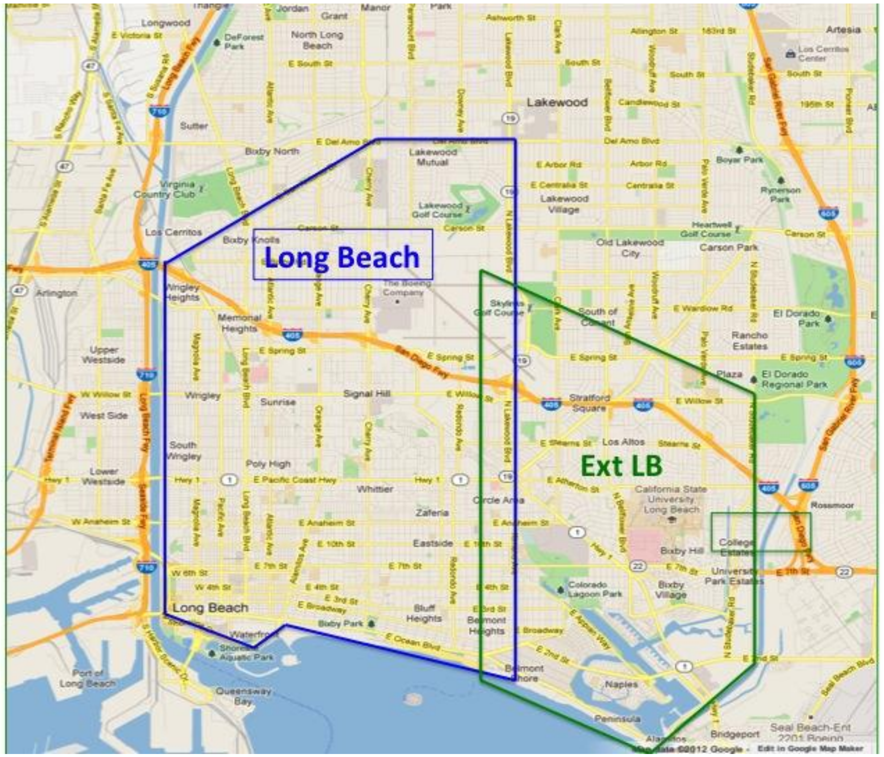


Alp' Array (2016)

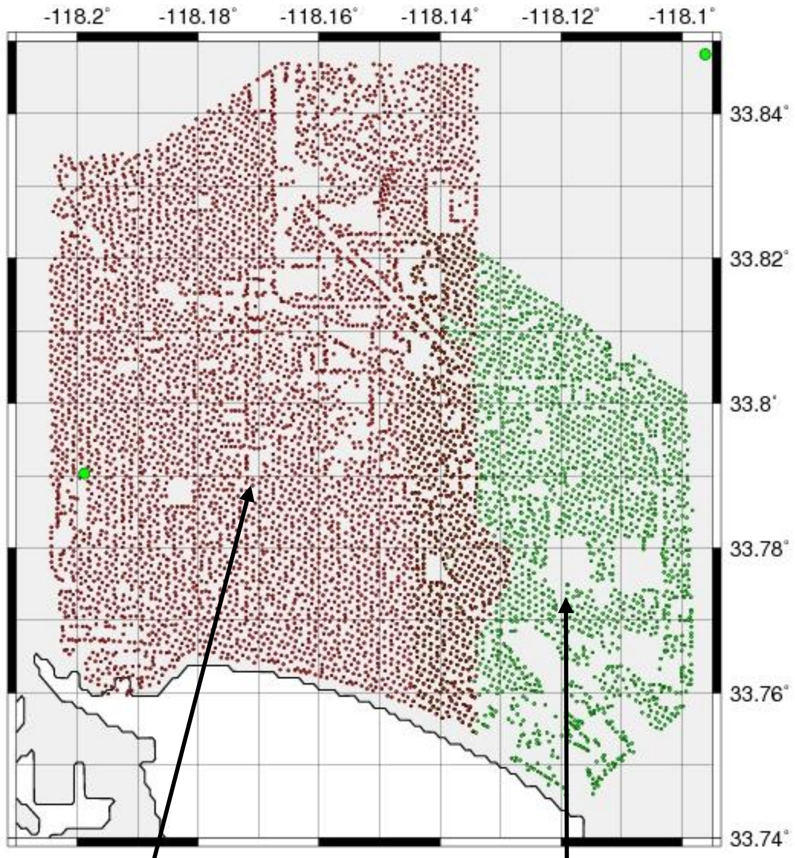
Inter-station ~40 kms

Dense seismic arrays : Small scale

Long Beach project in 2011-2012 (CA)



http://web.gps.caltech.edu/~clay/LB3D/LB3D.html



5300 sensors

2500 sensors

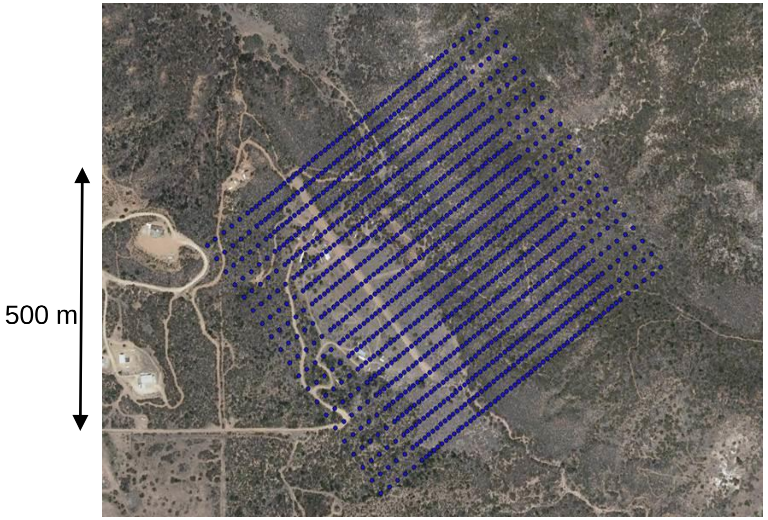
Density ~ 75 sensors per square-km

15 cm

- Continuous recording
- Autonomy ~11-14 days
- Crew can change 80 sensors/day

Dense Seismic arrays : Recent acquisitions

Dense seismic array (1108 sensors) accross the San Jacinto Fault (June 2014)

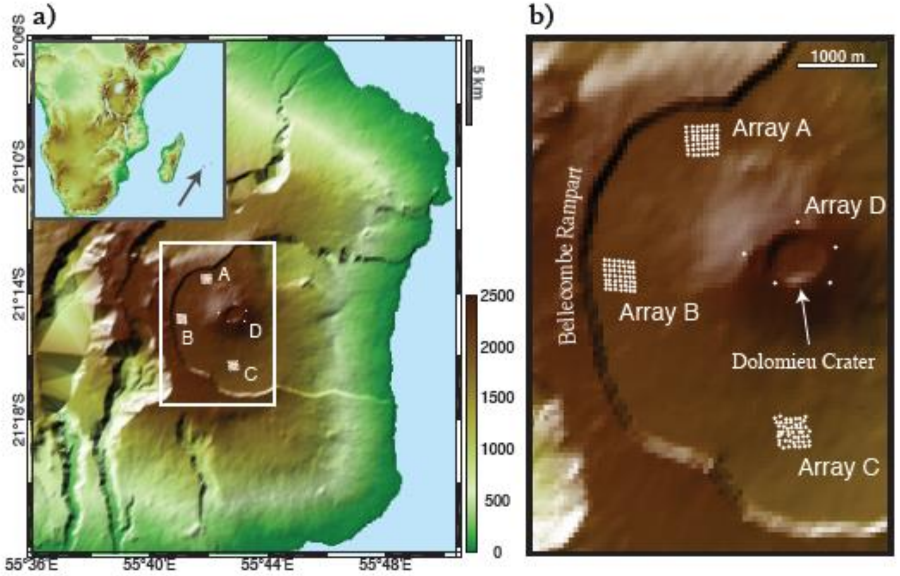


Yehuda Ben Zion, Univ. South. Cal., USA

Dense active/passive seismic experiment in La Solfatara (Puozzoli, Italy, 2013 & 2014)

MED-SUV European project (http://med-suv.eu/)

Design of 3 patch arrays (50 sensors each) on the Piton de la Fournaise Volcano (July 2014)



Florent Brenguier, Volc' Array, ISTerre

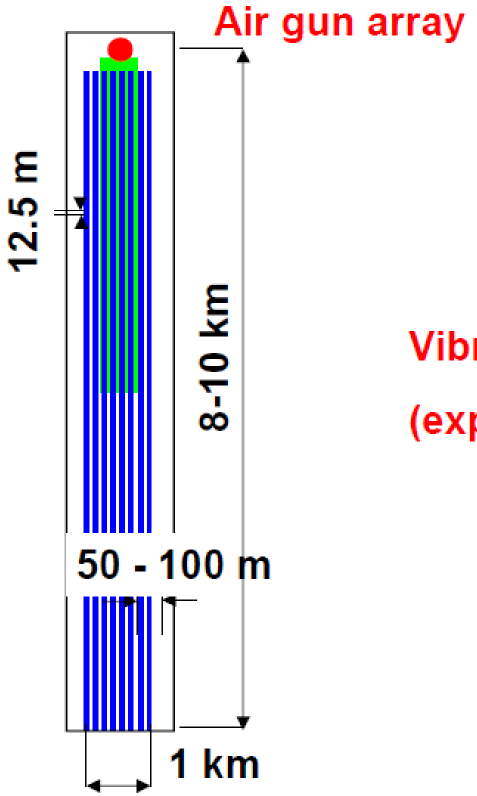
Oil/Gas Seismic Exploration (1)

Seismic Acquisition Geometries

More than 10,000 sensors for **Imaging purpose**

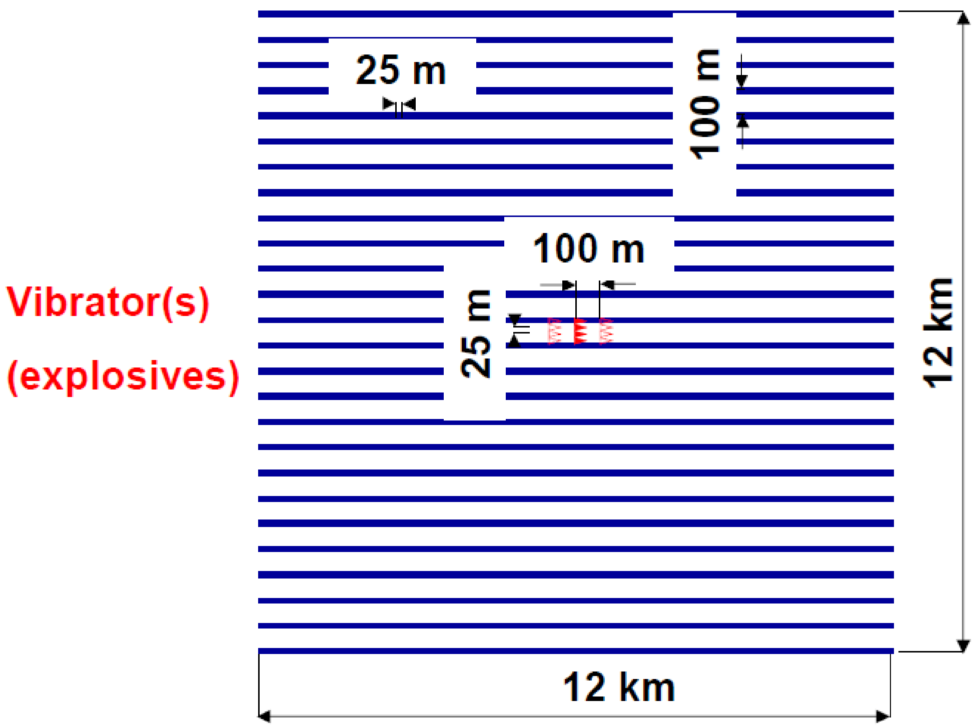
Marine

(60 km²/day)



Land

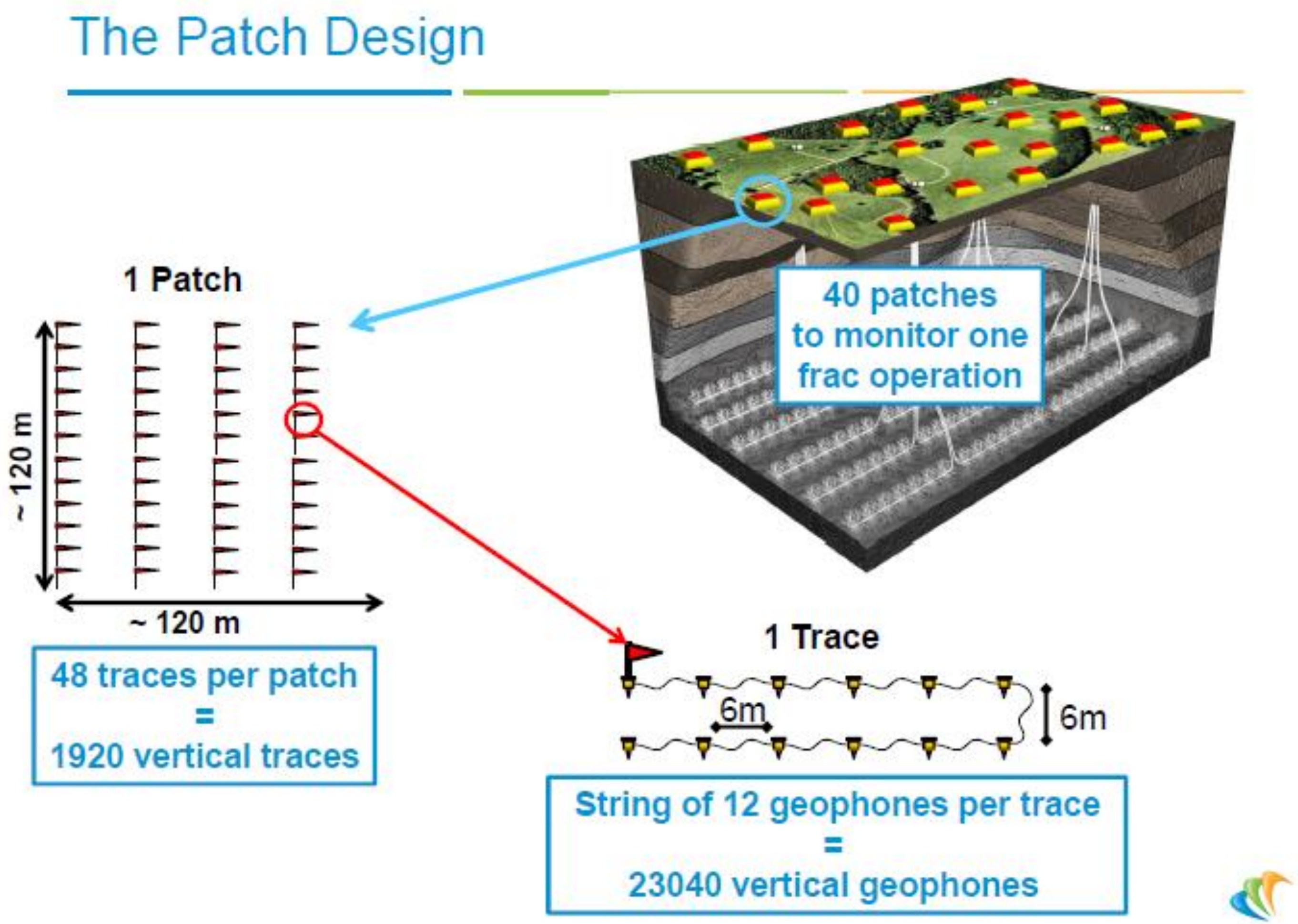
< 10 km²/day



Courtesy of Julien Meunier, CGG

Oil/Gas Seismic Exploration (2)

Detection/Localization of fracturation events or microseisms



Courtesy of Thomas Bardainne, CGG

Two goals for dense seismic arrays:

- Imaging / Monitoring with active / passive data
- Detection / Localization of local sources (at depth) buried in noise

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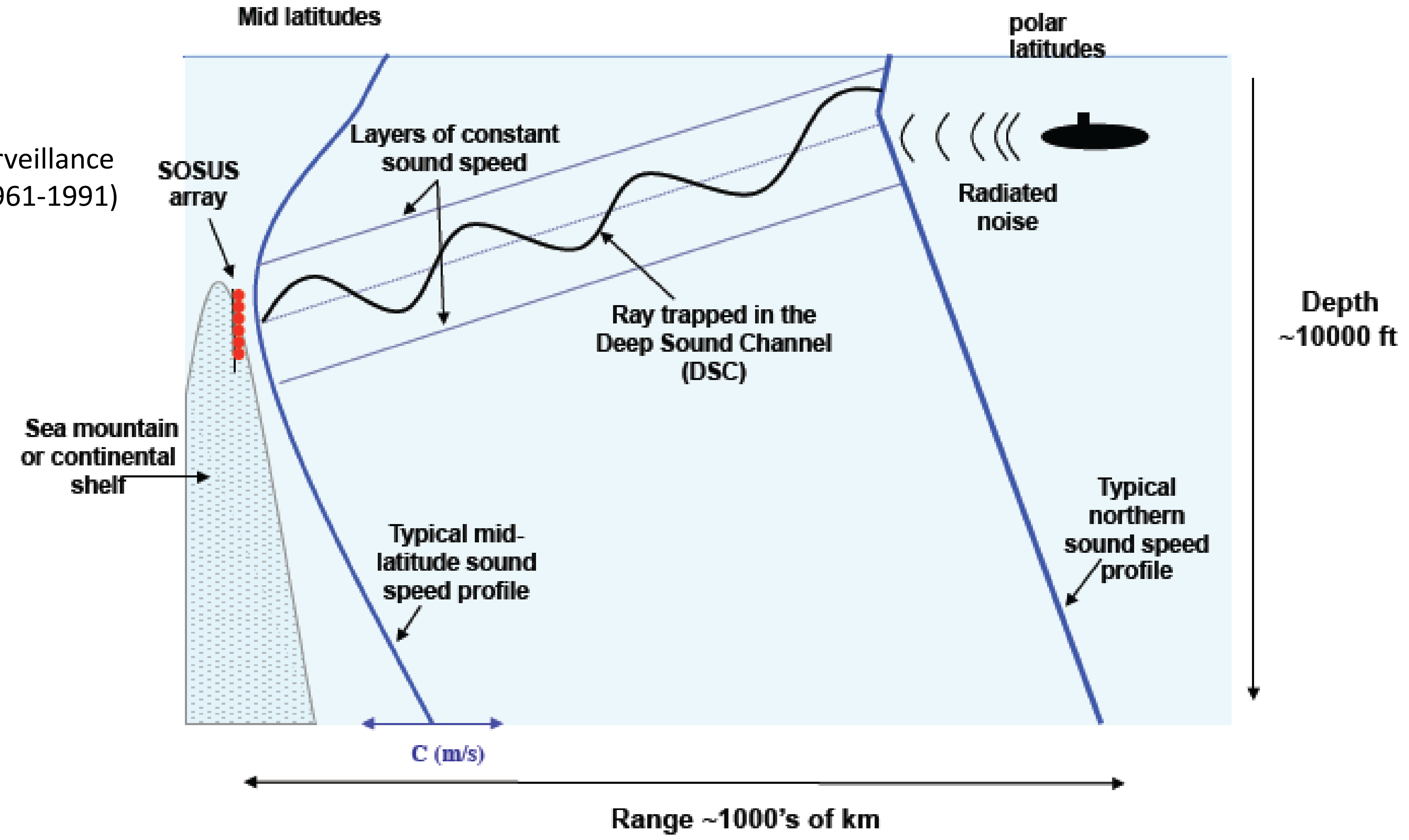
Detection / Localization of (acoustic) sources buried in noise

Matched Field Processing using Dense Hydrophone Arrays in Underwater acoustics

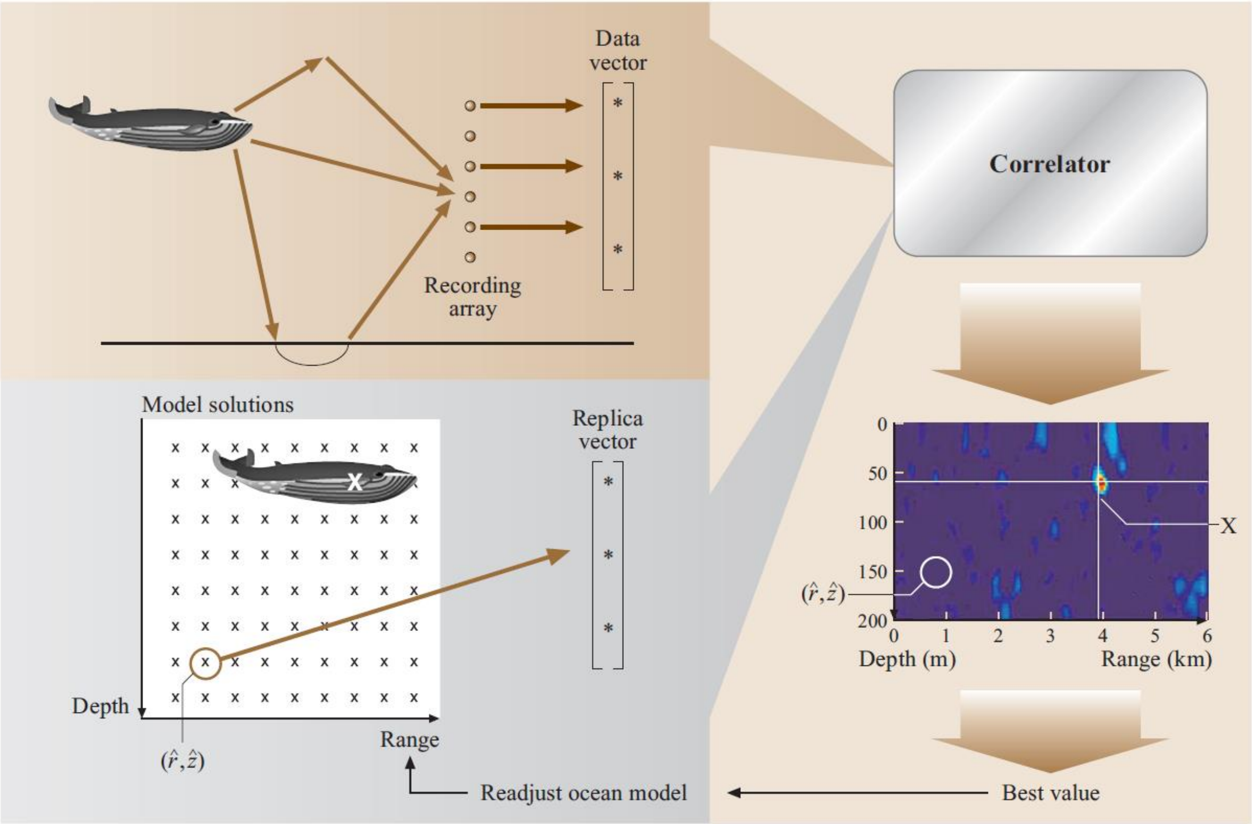
Historical Underwater Acoustics

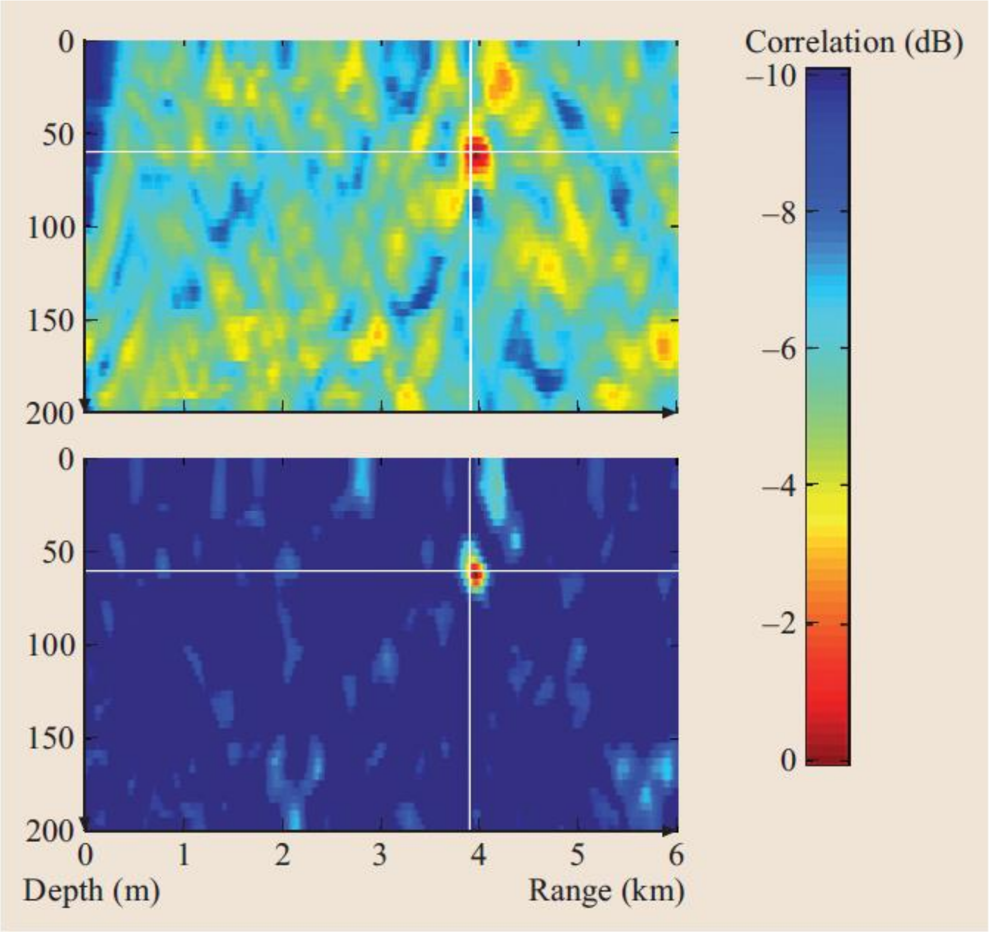
SOund SUrveillance System (1961-1991)



Courtesy of W.A. Kuperman, MPL

(1)Principles of Matched Field Processing



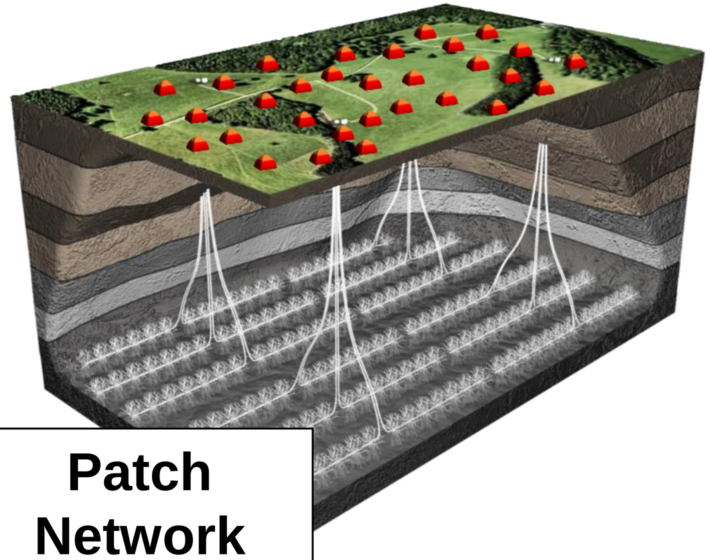


MFP works for (temporally incoherent) **CW signals** buried in **noise** in a **complex ocean** – No need for pulsed (coherent) signals

Good solution for (volcanic) tremors or cluster of acoustic/seismic micro-events (creeping in Fault zone, bubbling in geothermal areas)

Courtesy of W.A. Kuperman, MPL

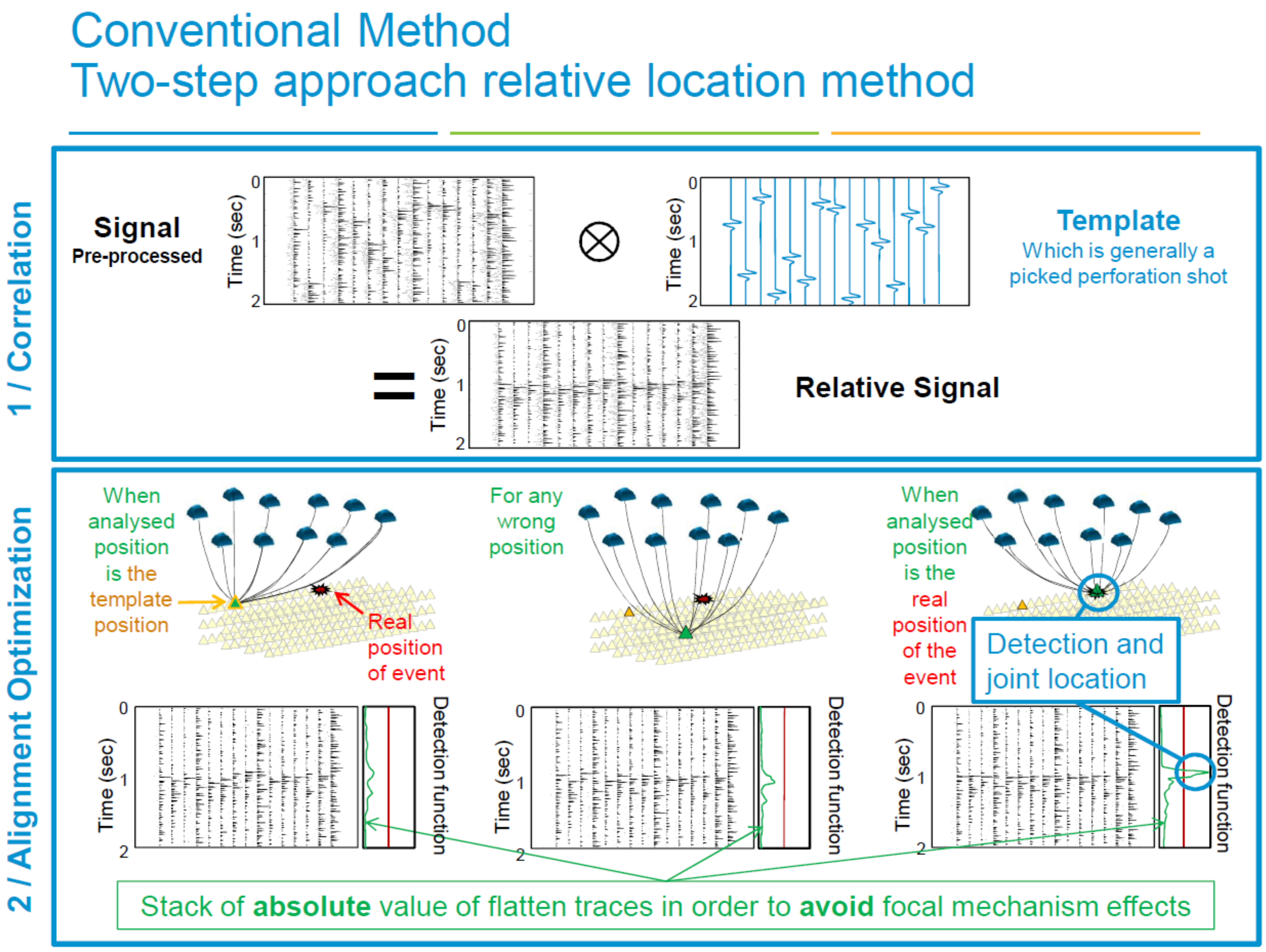
(2) Micro-Seismicity : Pulse Detection/Localization in Seismic Exploration Context



Patch Network

- High frequency ~ 30 Hz
- A template is required (data)
- Stack of absolute values

(no phase match as in MFP)



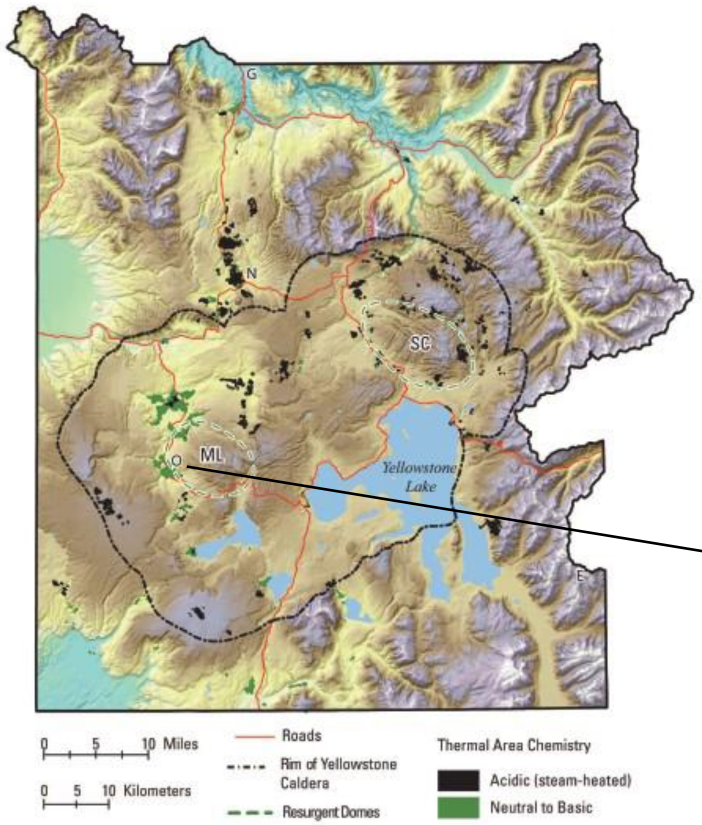
Courtesy of T. Bardainne, CGG

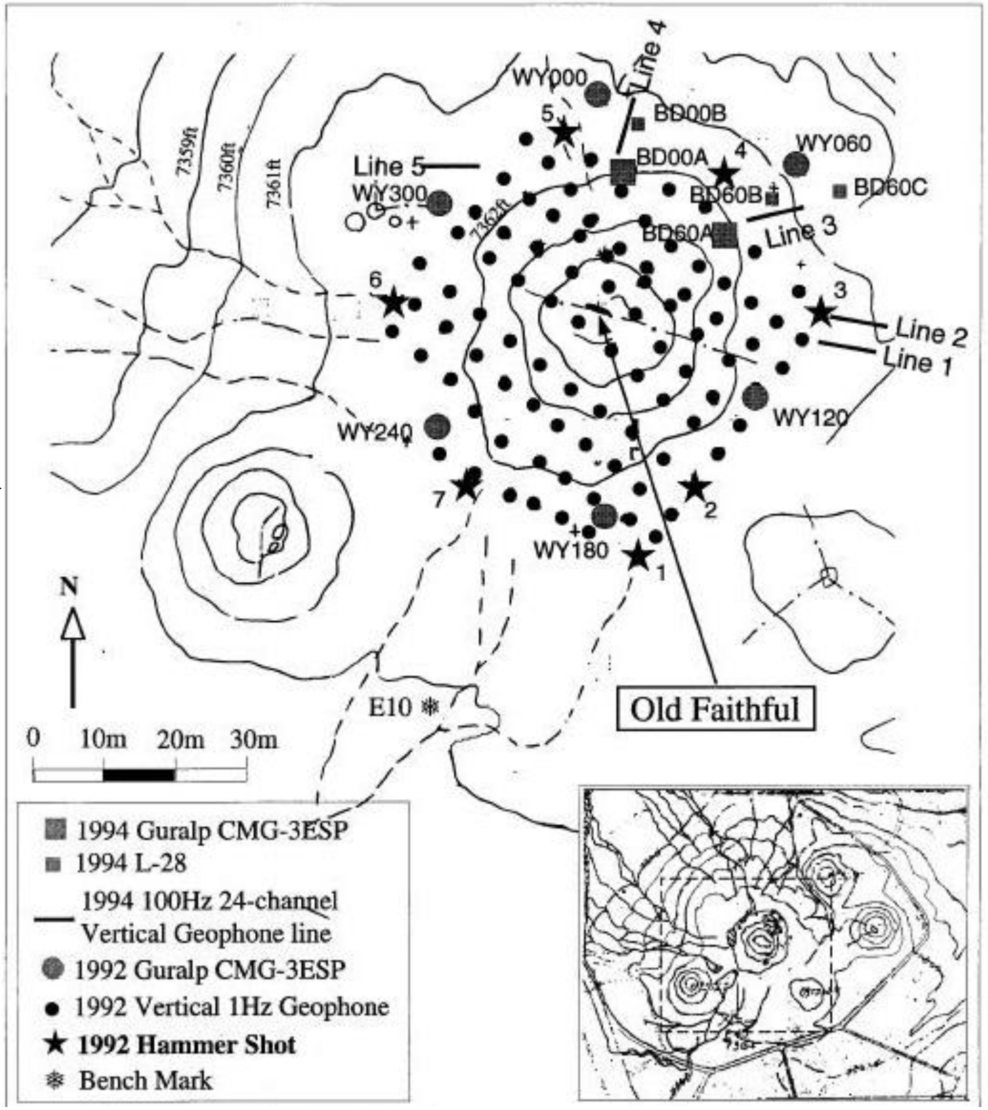
Examples of MFP in Geophysics

- Tracking of bubbling activity in Geothermal area

- Microseismicity monitoring in Exploration geophysics

Old Faithful Geyser, Yellowstone National Park





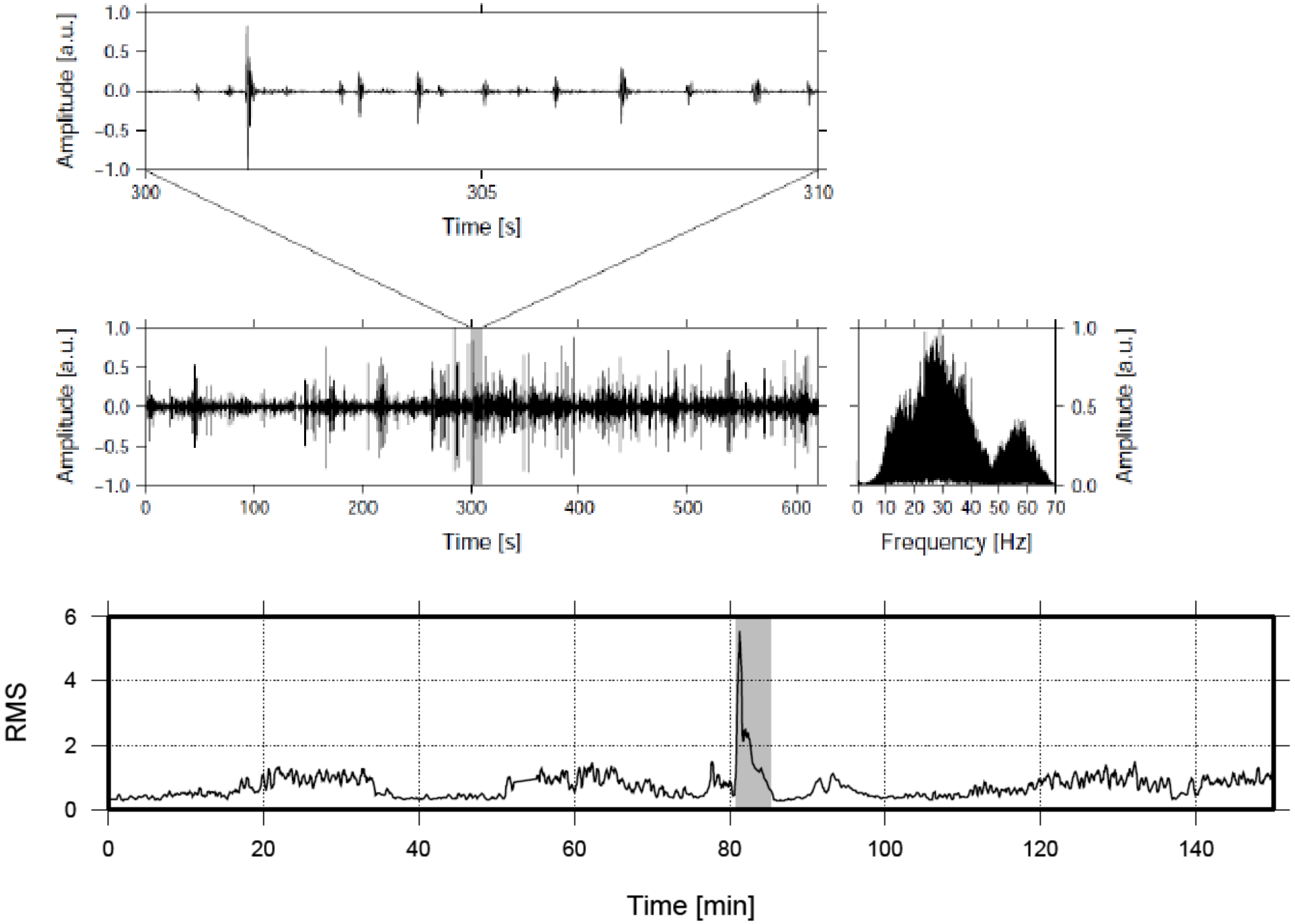
96 geophones

150 minutes of acoustic recordings spanding an eruption

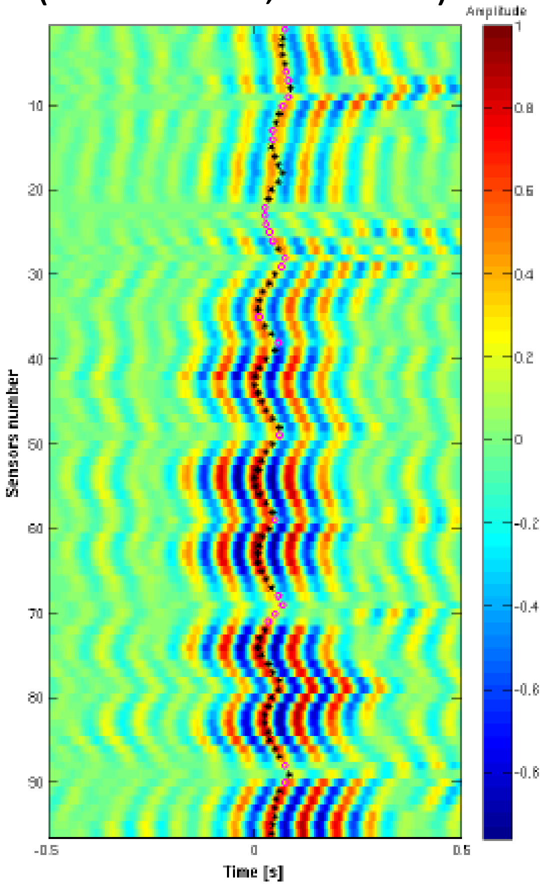
S. Kedar et al, Nature, 1996

Seismo-Acoustic Data

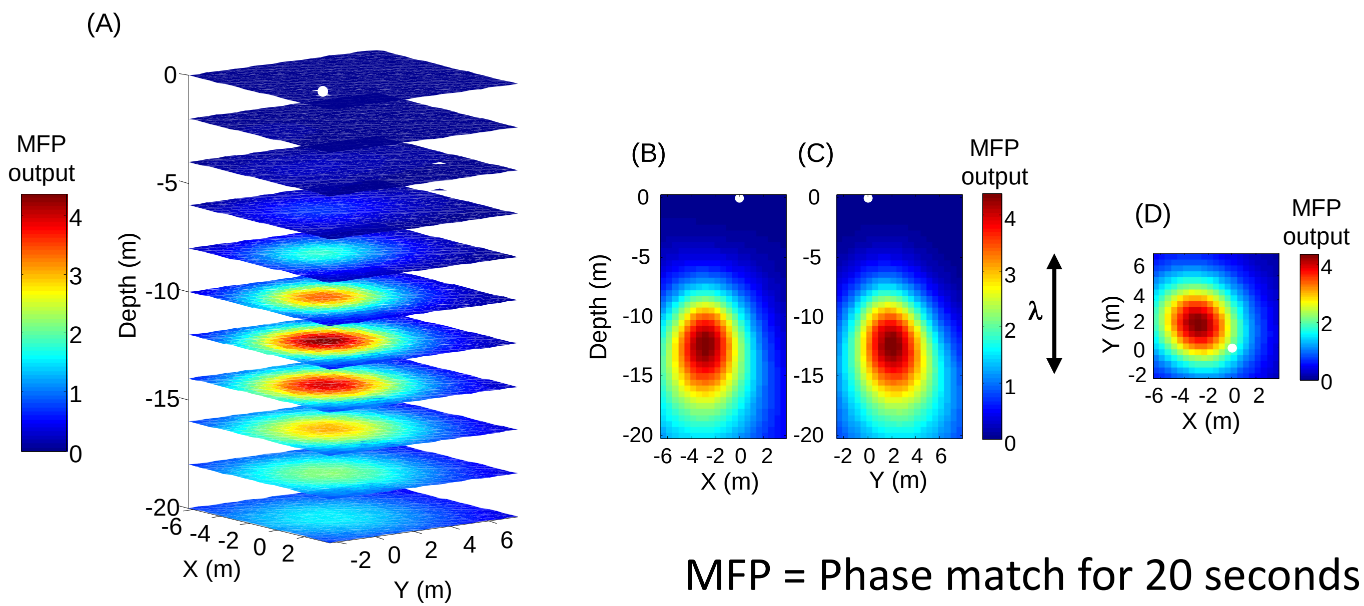
Raw data on one geophone



Noise correlation
(20s of data, 9-14 Hz)



Localization of cluster of bubbles with MFP



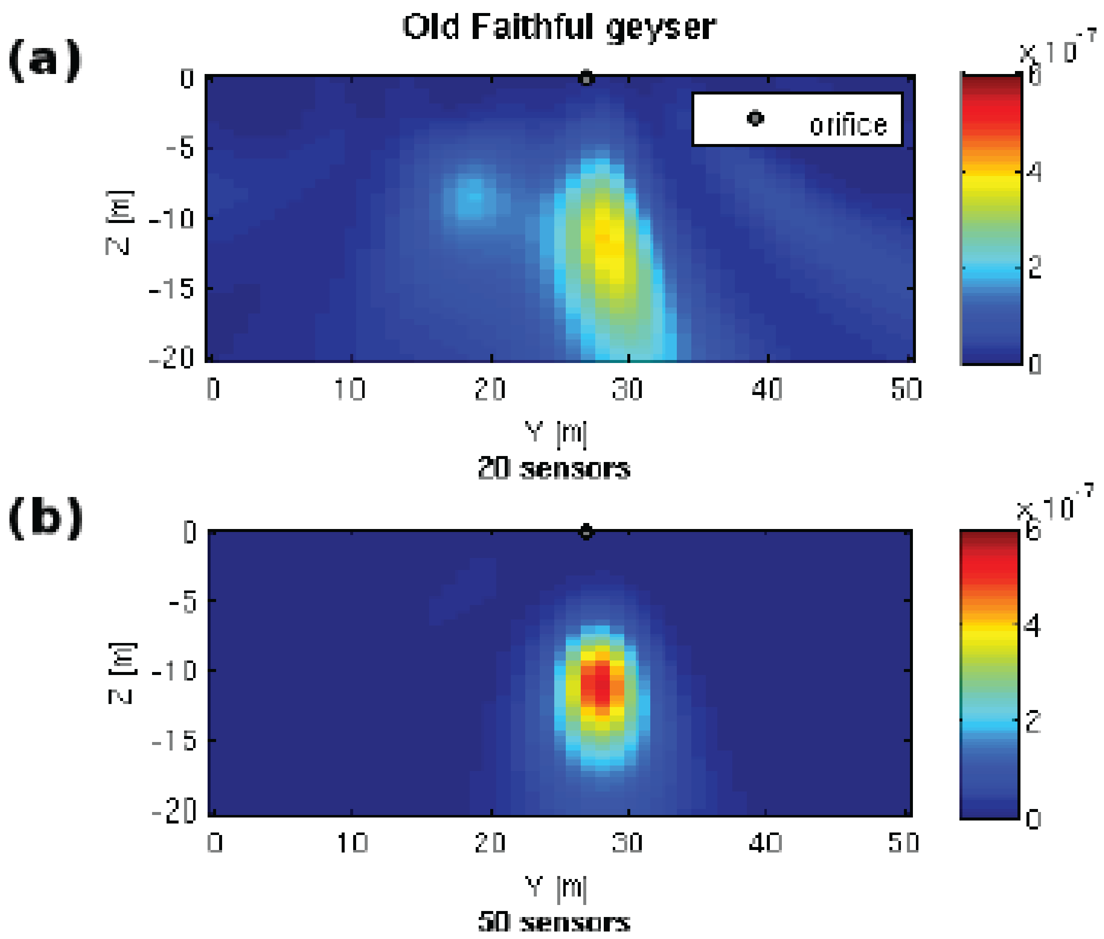
MFP = Phase match for 20 seconds of data

Cros et al, GJInt, 2011

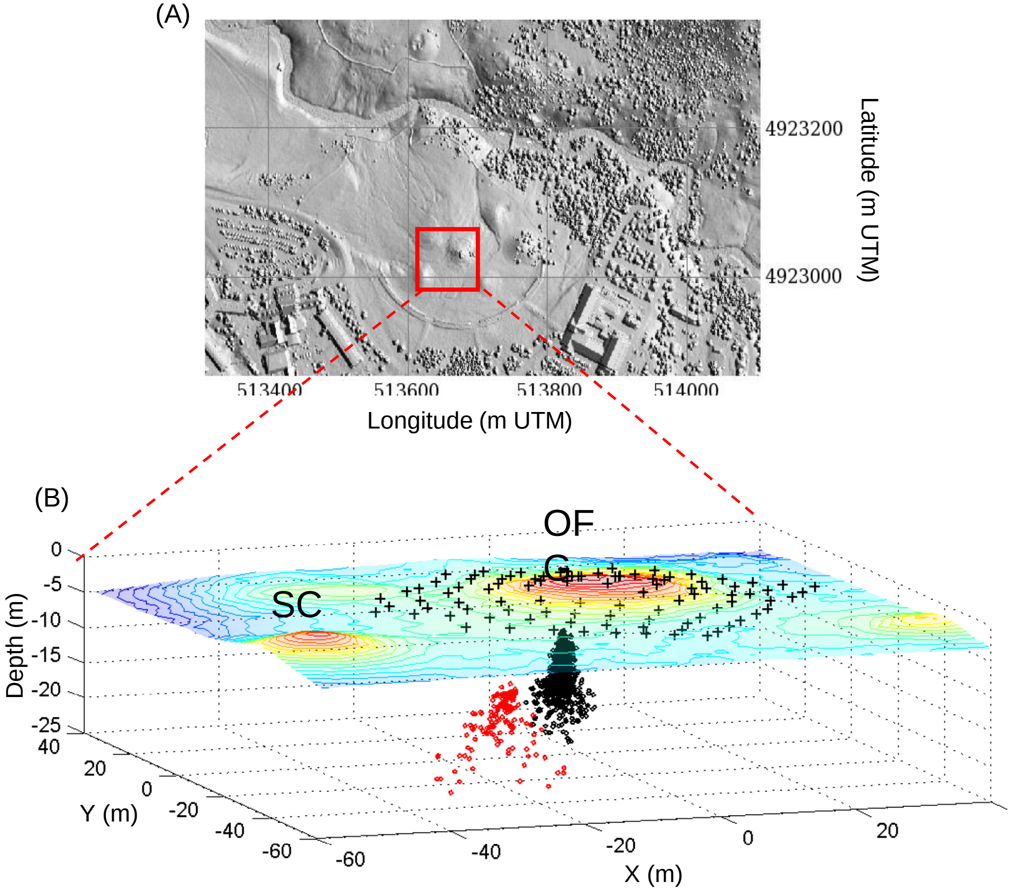
Spatial resolution with MFP

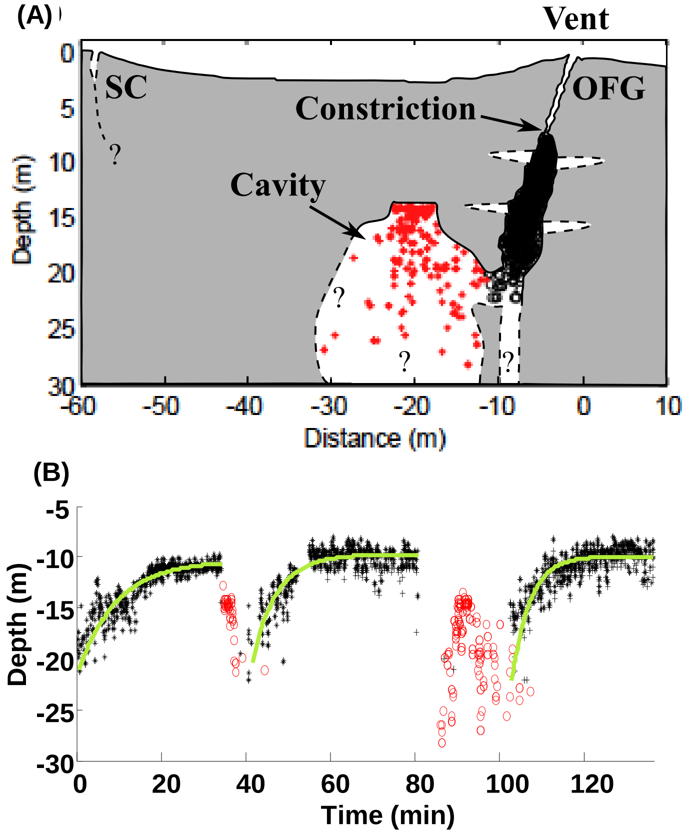
Small Array

Large Array



Spatial-Temporal Monitoring of Geyser activity



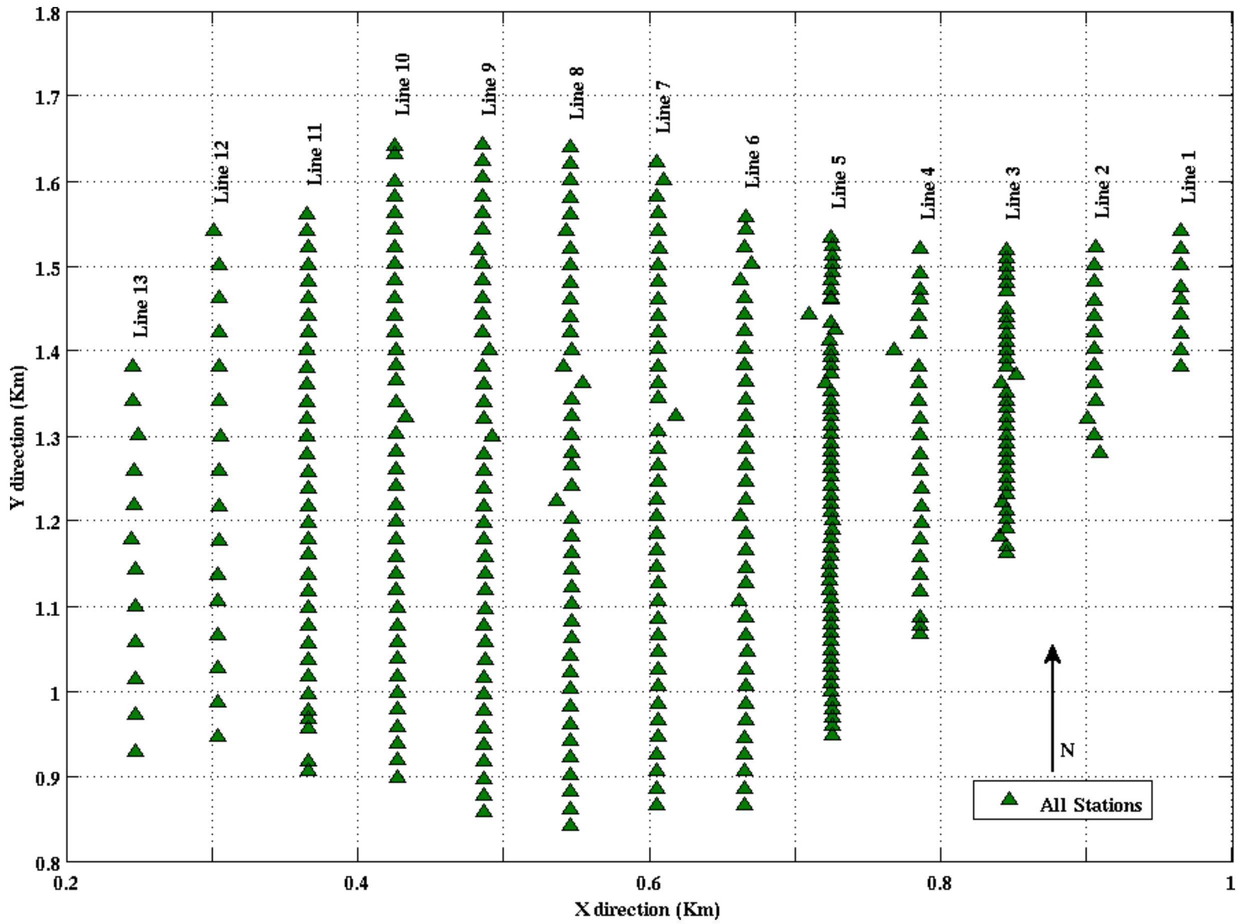


Vandemeulebrouck et al, GRL, 2013

Micro-seismicity Monitoring with MFP in Exploration Geophysics

ISTerre
Institut des Sciences de la Terre

Acquisition Geometry



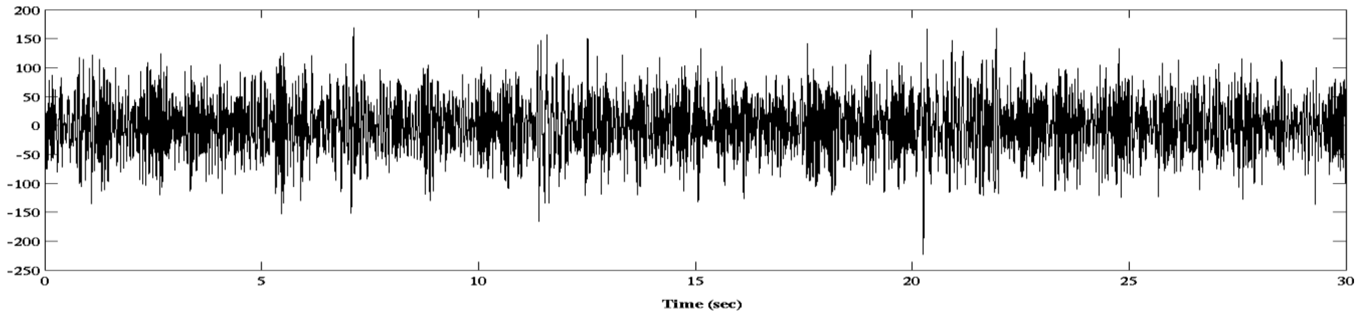
Nb. Stations => 397

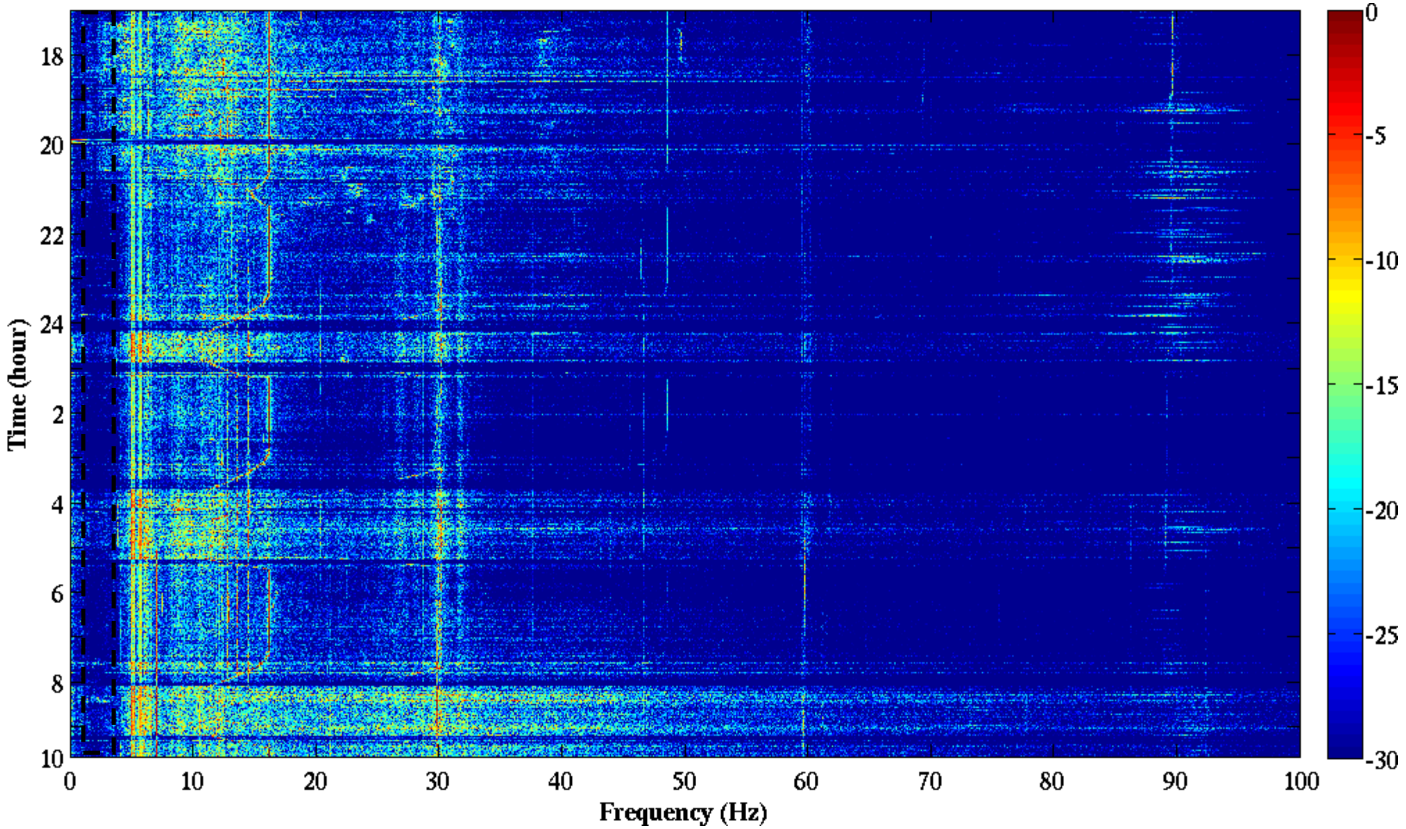
Network Size => 800X900 m

Samp. Freq => 1000 Hz

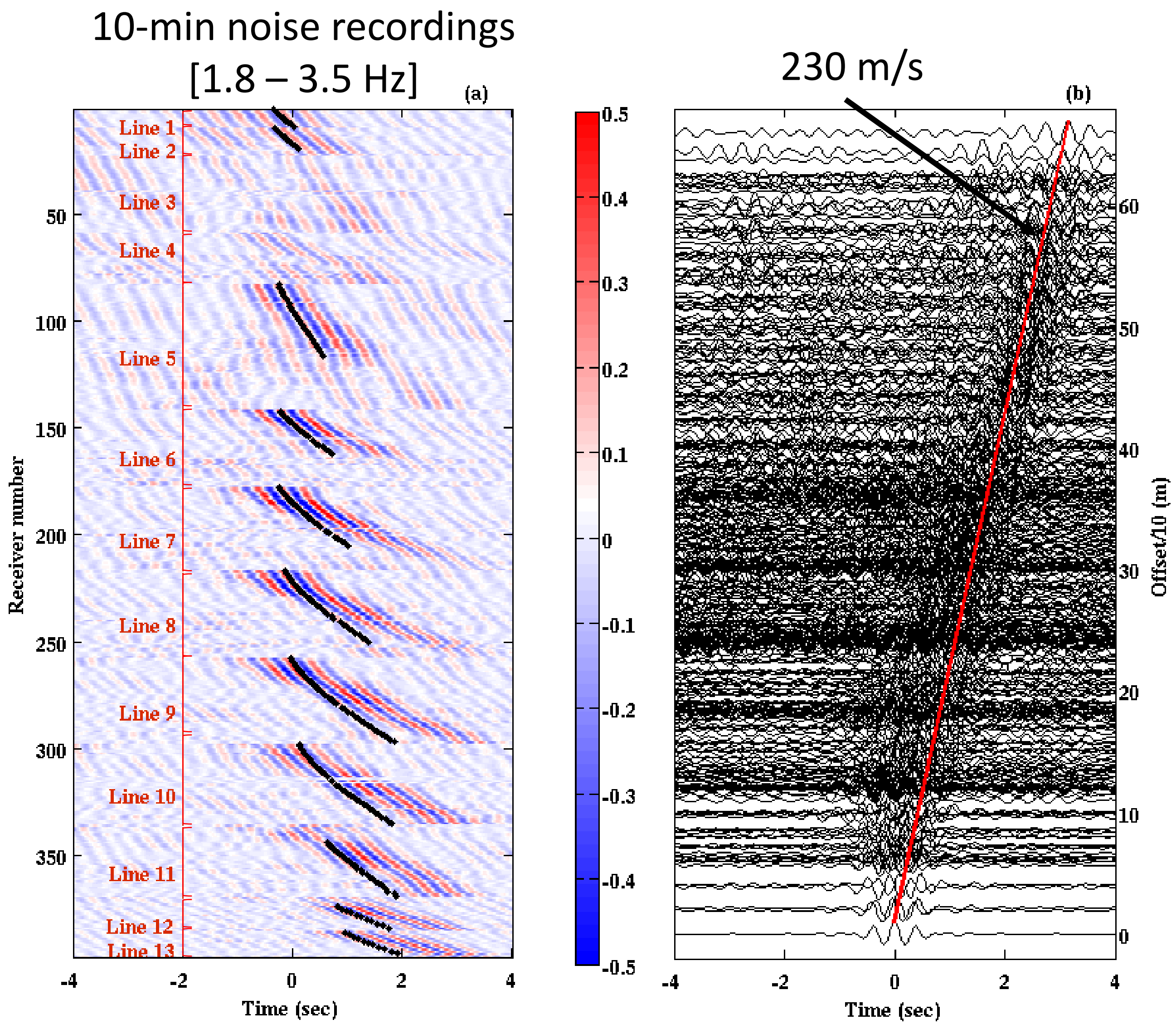
Acq. Duration => 5 days

Seismo-Acoustic Signals





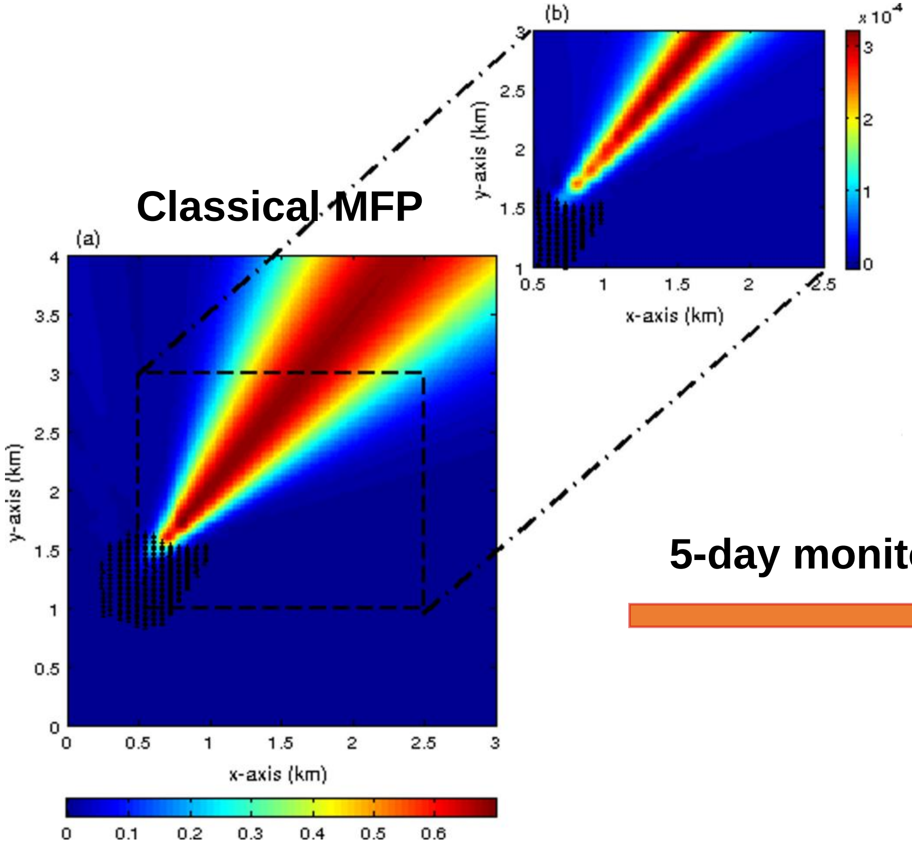
Noise Correlation



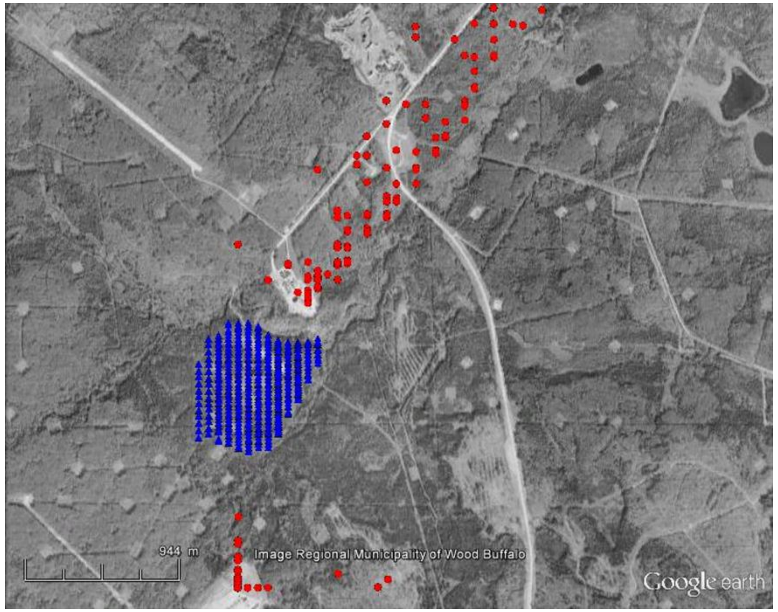
MFP Localization of the Dominant source

Adaptative MFP

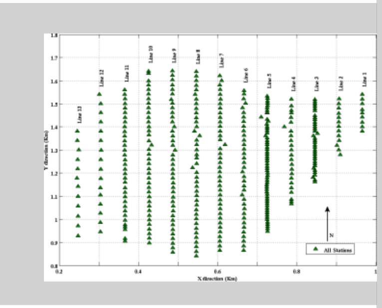
Classical MFP

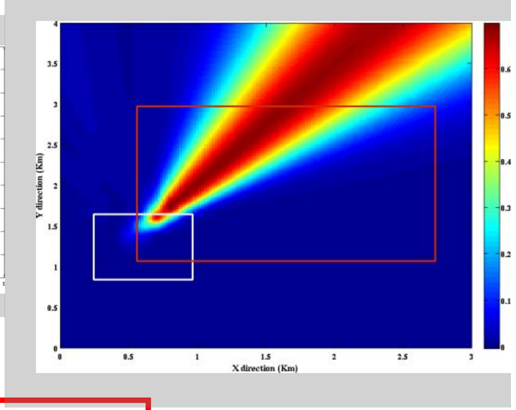


5-day monitoring



Multi-Rate Beamforming : Cancellation of the Dominant source





Singular Value decomposition

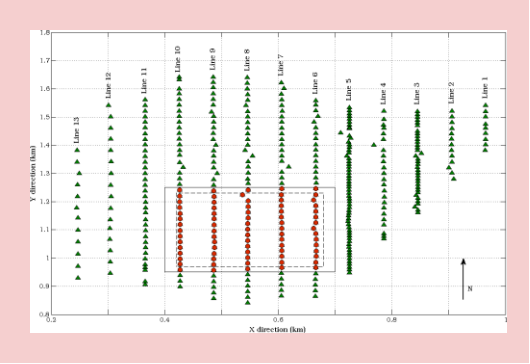
$$K_{ij}(\omega)=\langle d_i(\omega)d_j^*(\omega)\rangle = U\Lambda U^* + V\Omega V^*$$

Projector operator

$$z=\left[I-UU^*\right]d$$

« Clean » data set

$$P_{ij}(\omega)=\langle \tilde{z}_i(\omega)\tilde{z}_j^*(\omega)\rangle$$



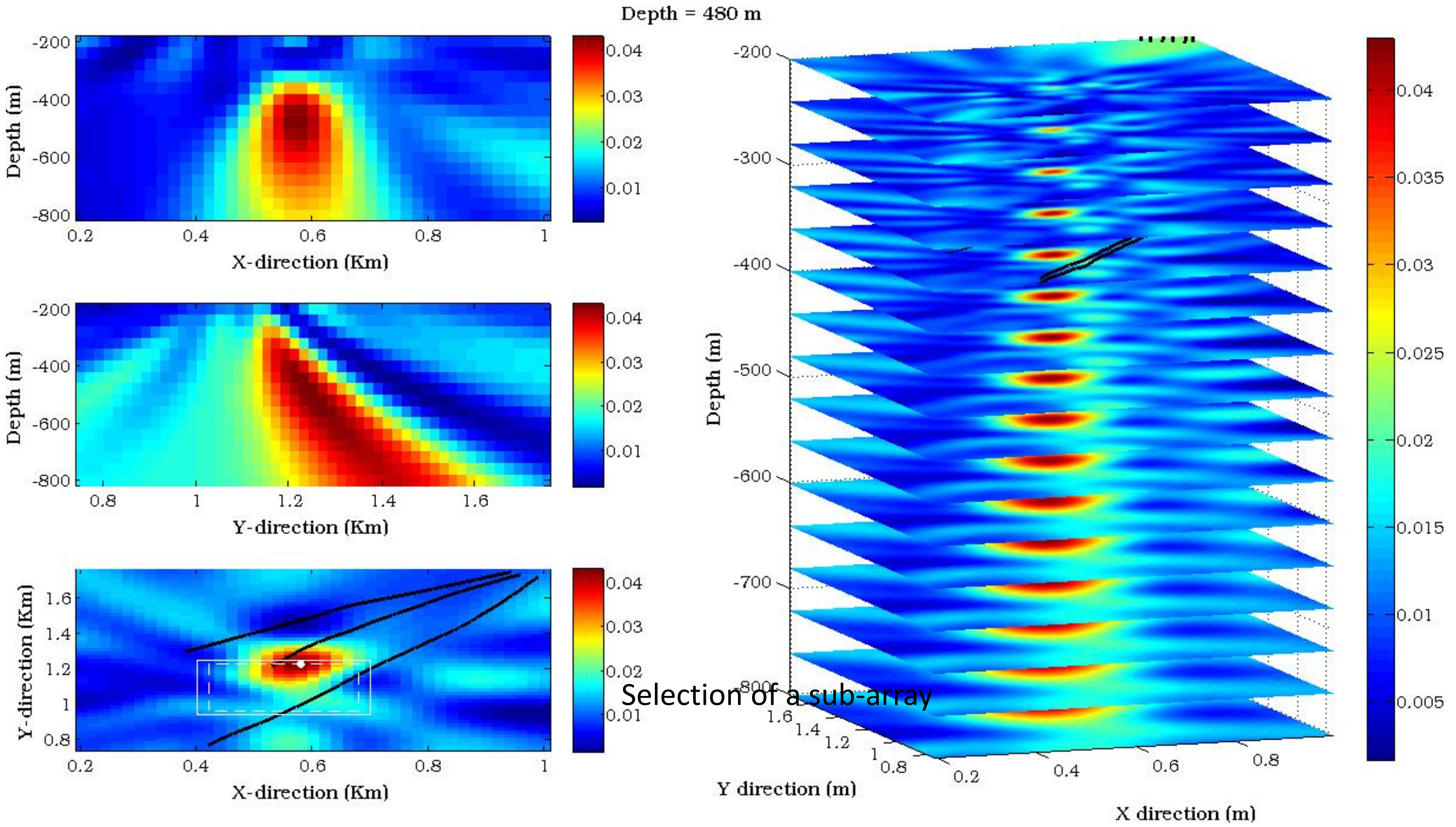
New MFP localization

Classical

Adaptative

Corciuolo et al, Geophysics, 2012

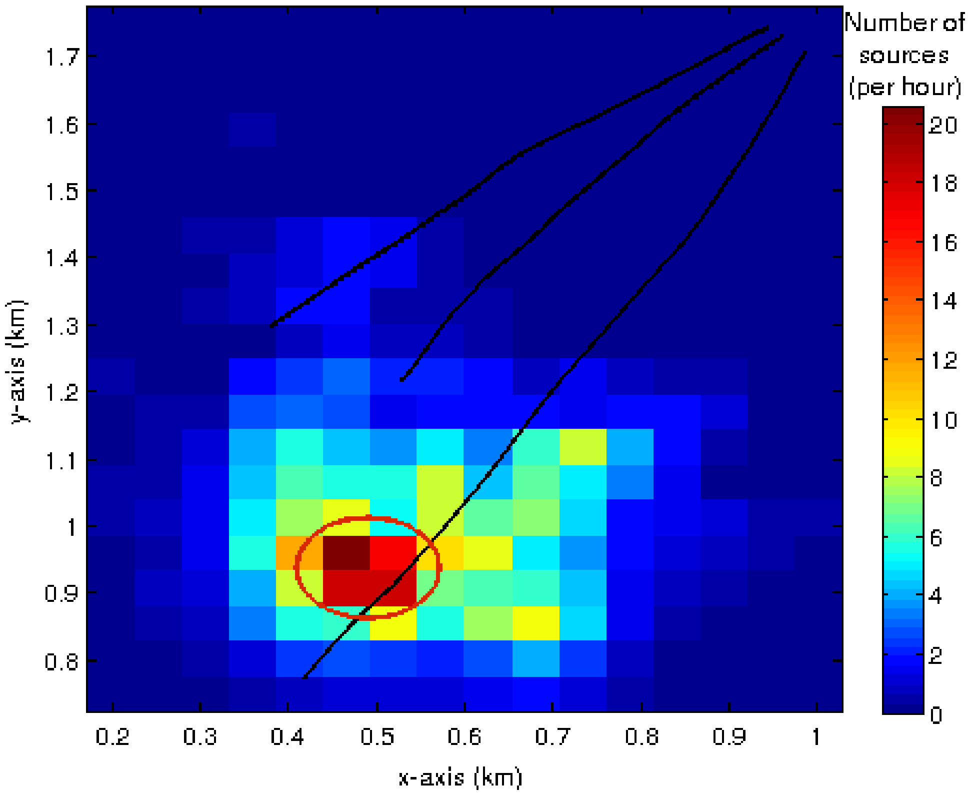
Micro-seismicity Localization with Multi-Rate Beamforming



Selection of a sub-array

Corciuolo et al, Geophysics, 2012

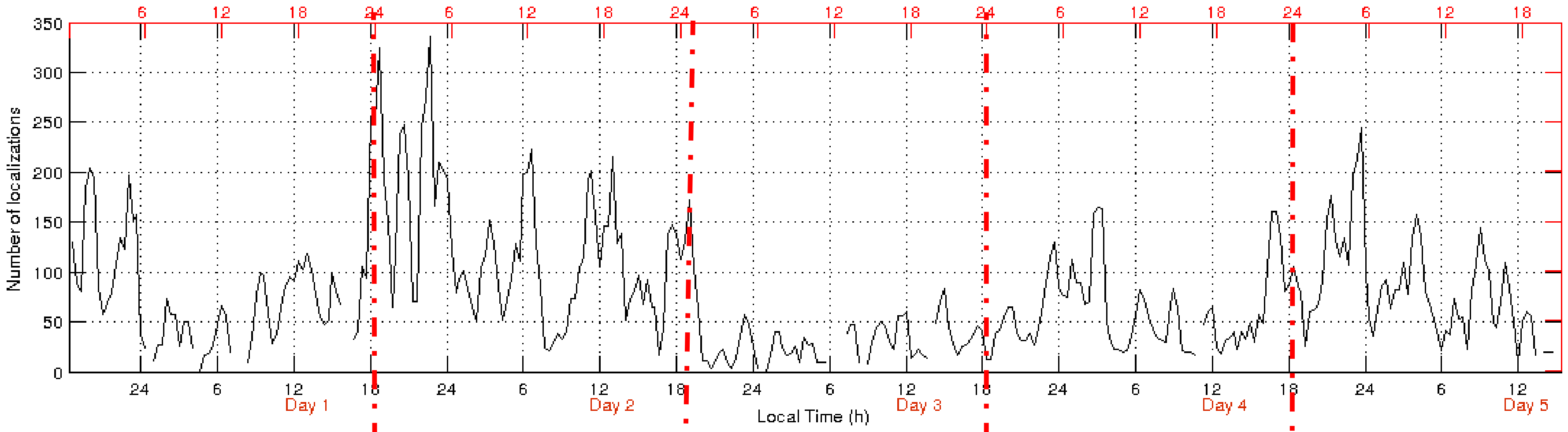
Automatic Detection of Micro-seisms over 5 days for ambient noise time windows of 2.5 min.

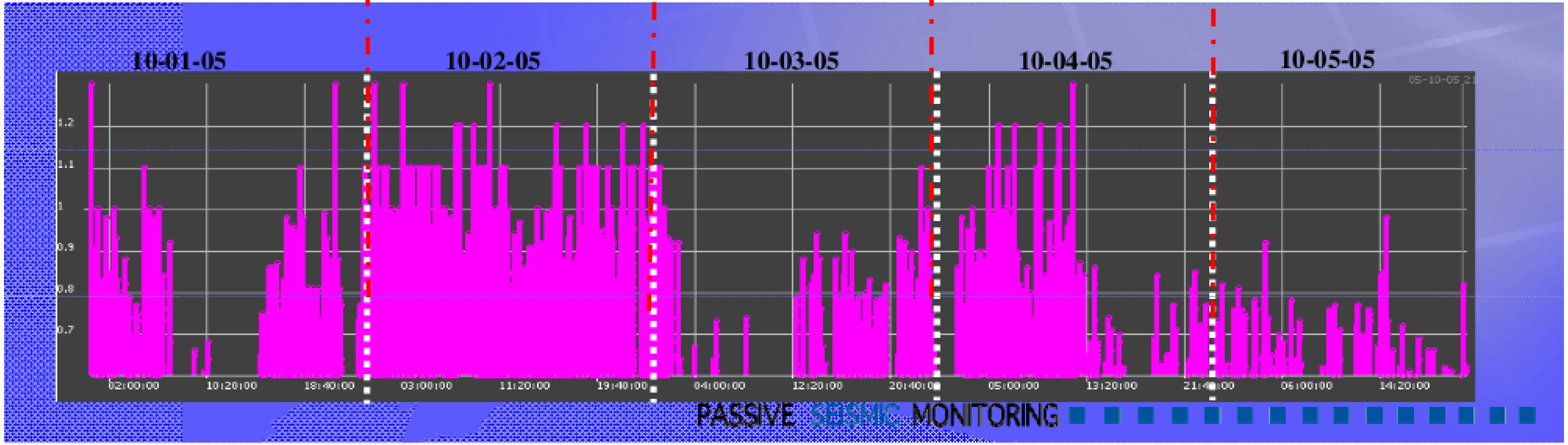


Horizontal localization of the rate of microseismicity (hour-by-hour).

Comparison Multi-Rate Beamforming vs Pulse Detection Technique

Multi-Rate Beamforming





Pulse detection

Courtesy of Magnitude

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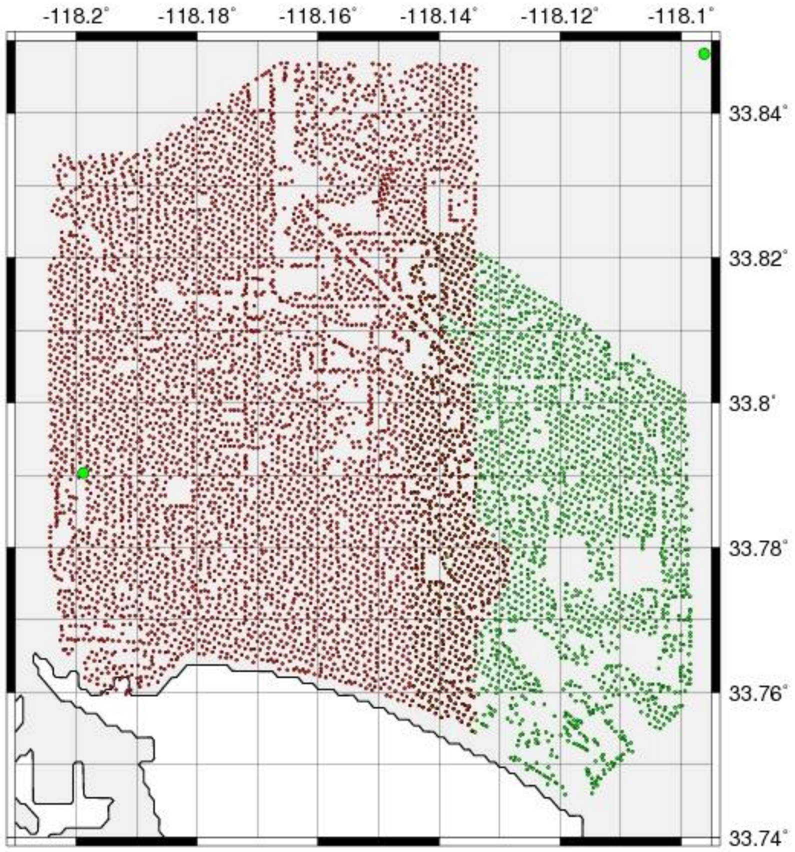
The Long Beach project (2011-2012, CA)



R. Clayton, V. Tsai, J-P. Ampuero, F-C. Lin, … CalTech

The Long Beach project (2011-2012, CA)

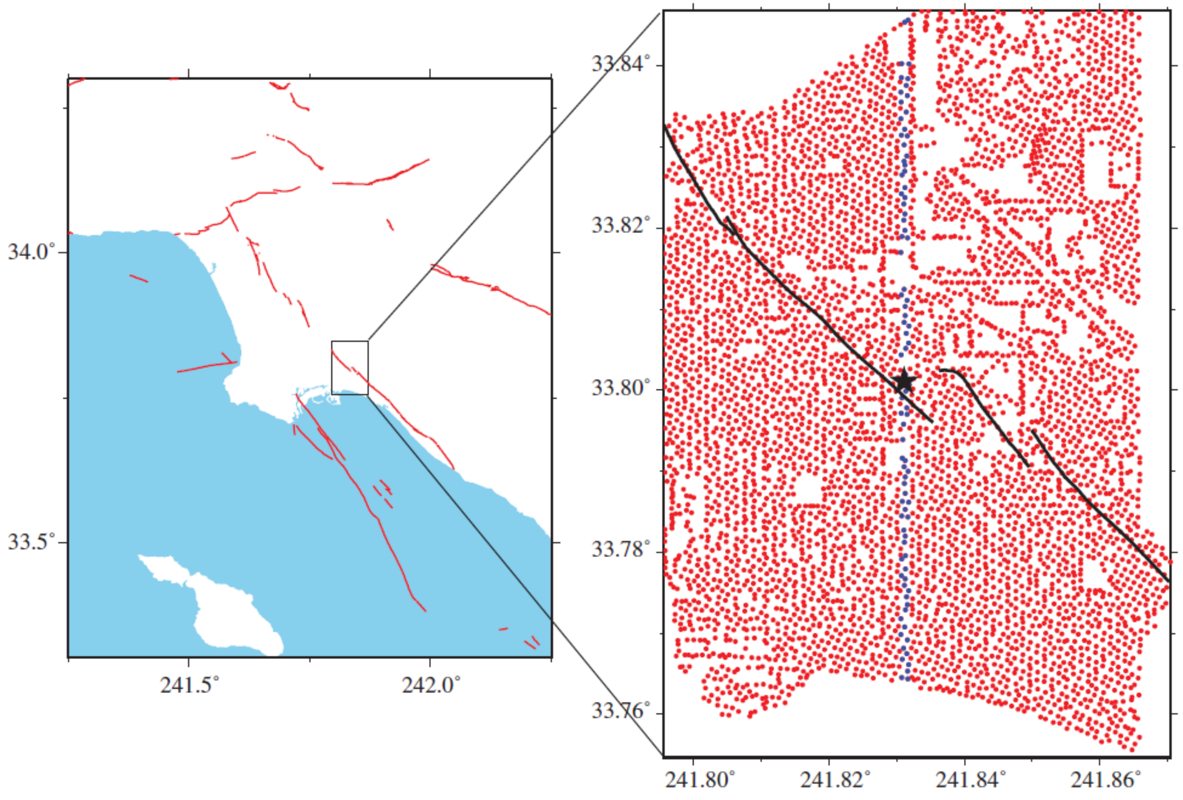
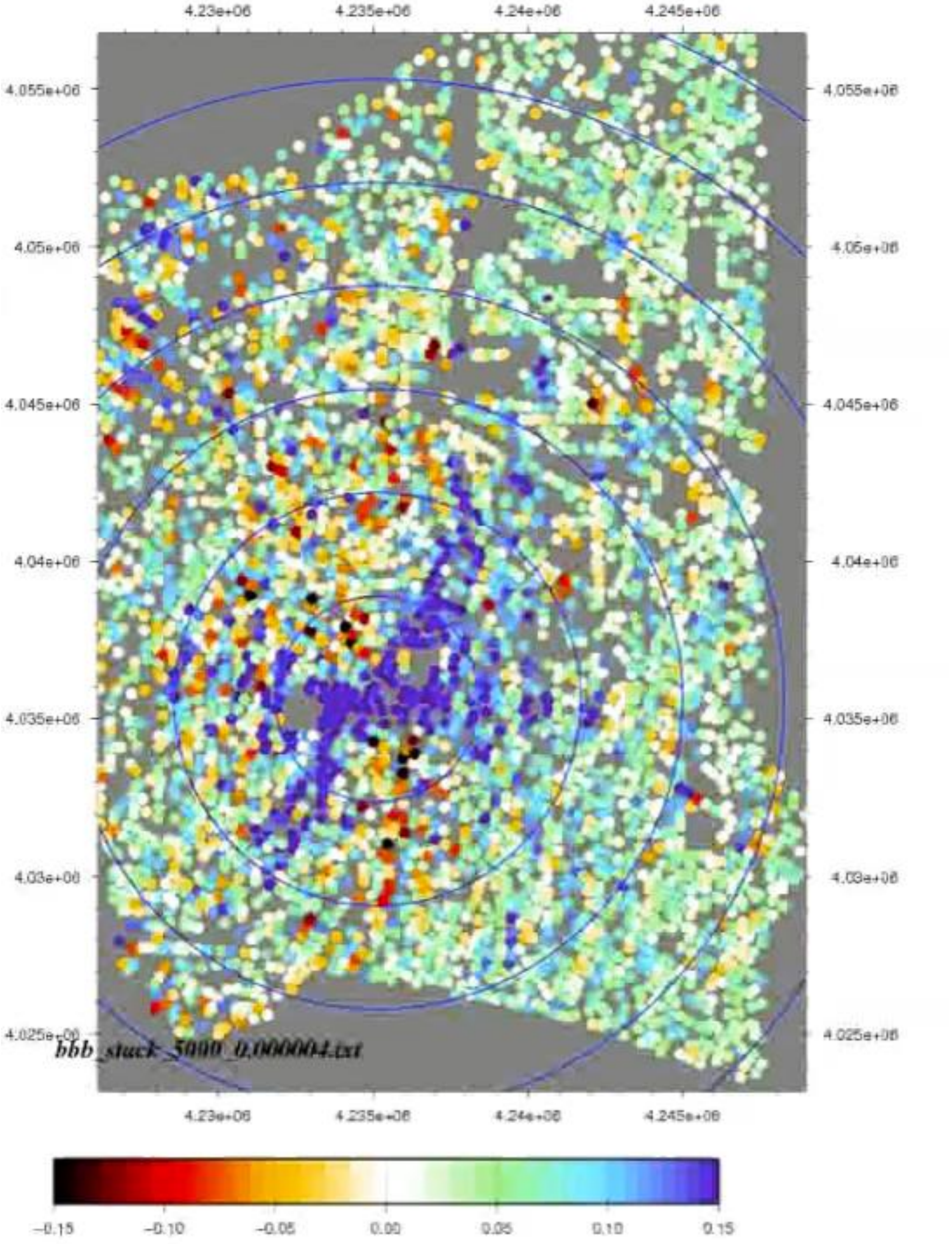


Figure 1. The array configuration and the regional fault lines in Southern California. The small circles show the 5204 stations used in this study. Several segments of the Newport-Inglewood fault system are denoted by black lines in the magnified plot.

http://web.gps.caltech.edu/~clay/LB3D/LB3D.html

Lin et al, Geophysics, 2013

Virtual source movie



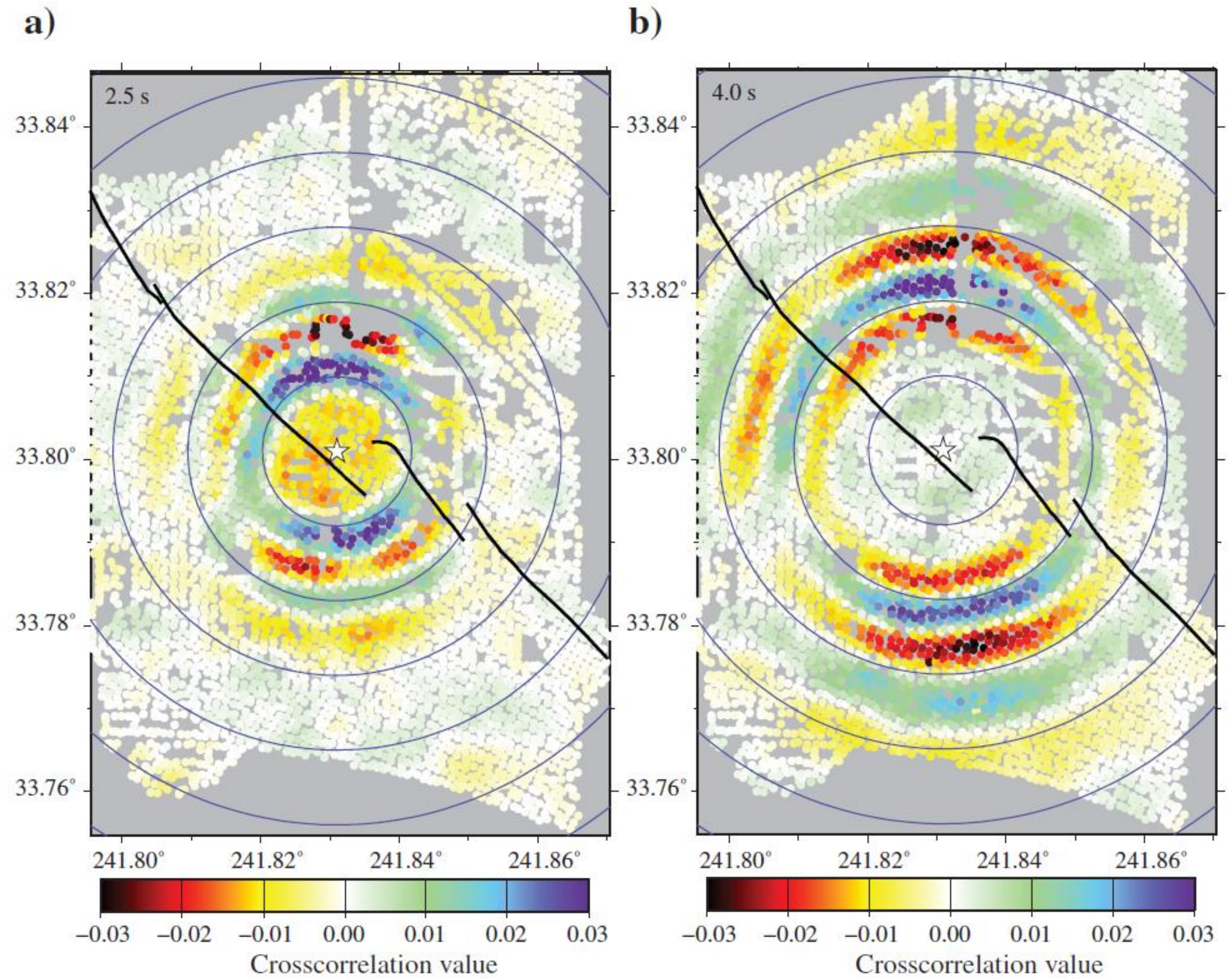


Figure 3. The wavefield emitted by a virtual source. The location of the virtual source is shown by the star near the center of the array. (a, b) Snapshots of the 0.5–1 Hz band-passed wavefield observed at each station location at 2.5- and 4.0-s lag times, respectively. The source distance contours are separated by 1-km intervals.

Eikonal Tomography applied to Surface Waves

$$\frac{1}{c(\mathbf{r})^2} = |\nabla \tau(\mathbf{r})|^2$$

Lin et al, Geophysics, 2013

Eikonal / Helmholtz Tomography

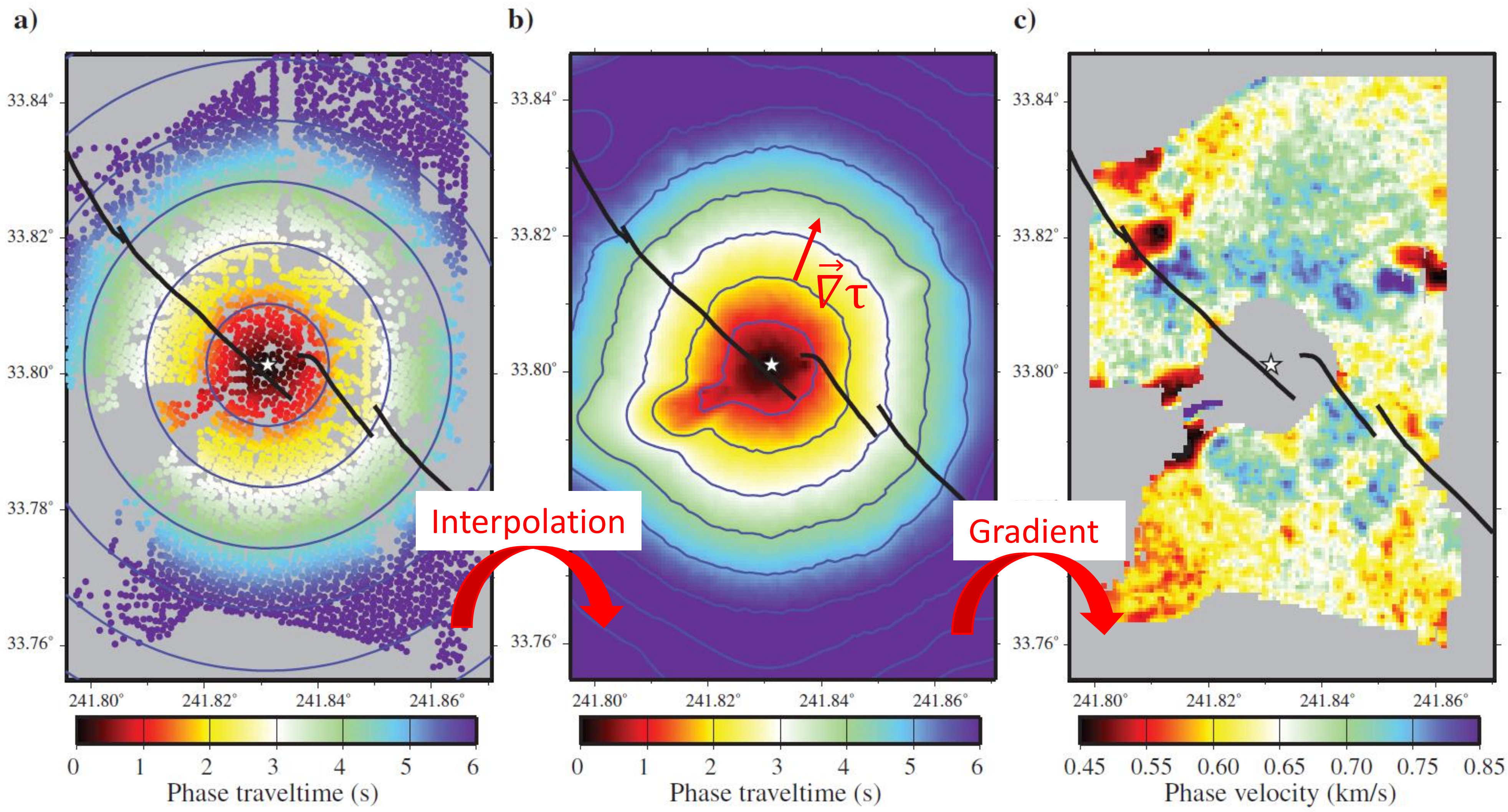


Figure 4. A demonstration of eikonal tomography. (a) The 1-Hz Rayleigh wave phase traveltime observed across the array for the wavefield shown in Figure 3. Only stations with S/N higher than our selection criterion are shown. The source distance contours are separated by 1-km interval. (b) The phase traveltime map derived from (a) using the minimum curvature fitting method. The traveltime contours are separated by a 1-s interval. (c) The phase velocity map derived from (b) based on the eikonal equation (equation 4). Only areas satisfying our one-period traveltime and three- out of four-quadrant selection criteria are shown.

Lin et al, Geophysics, 2013

Surface Wave Inversion with Eikonal tomography

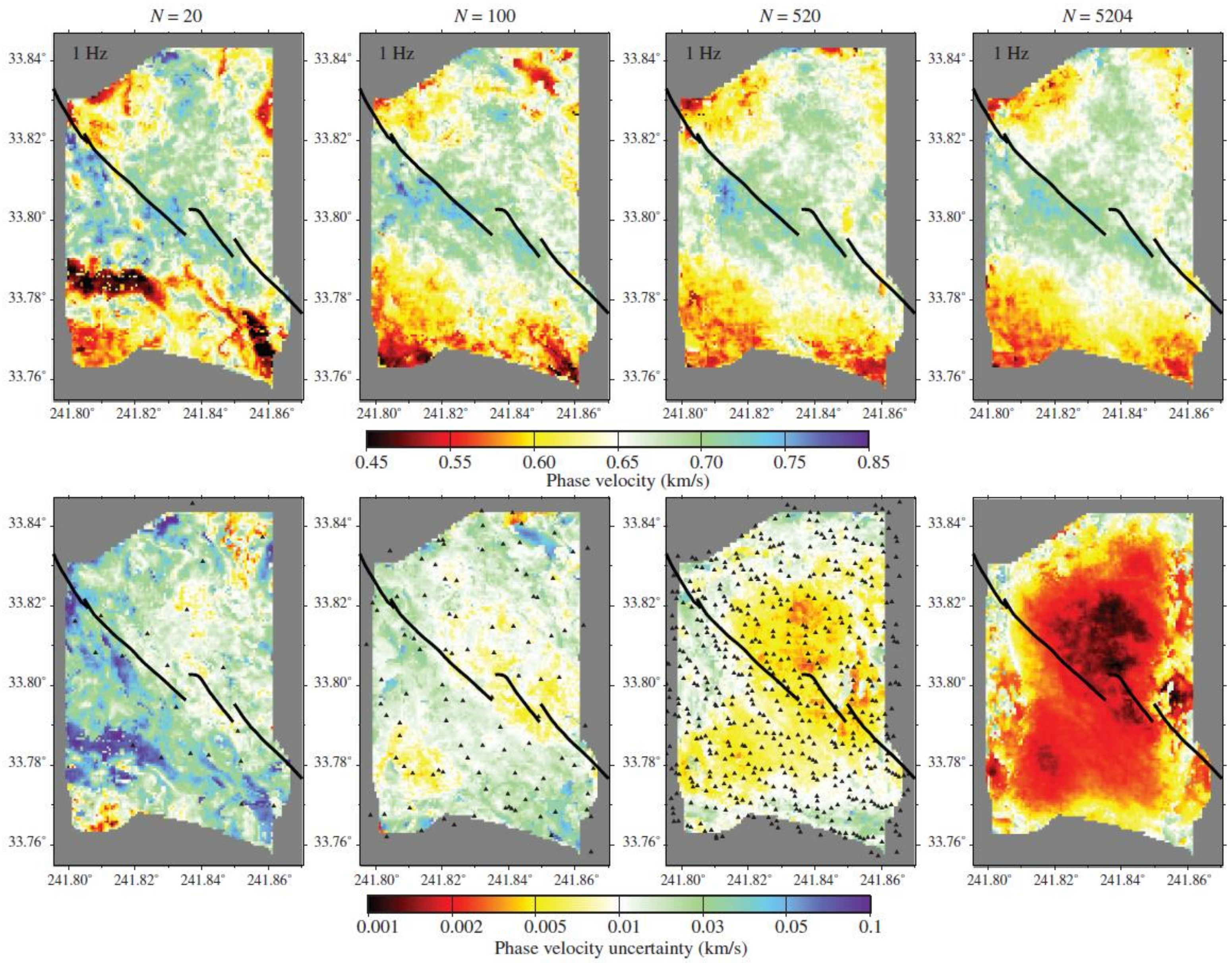
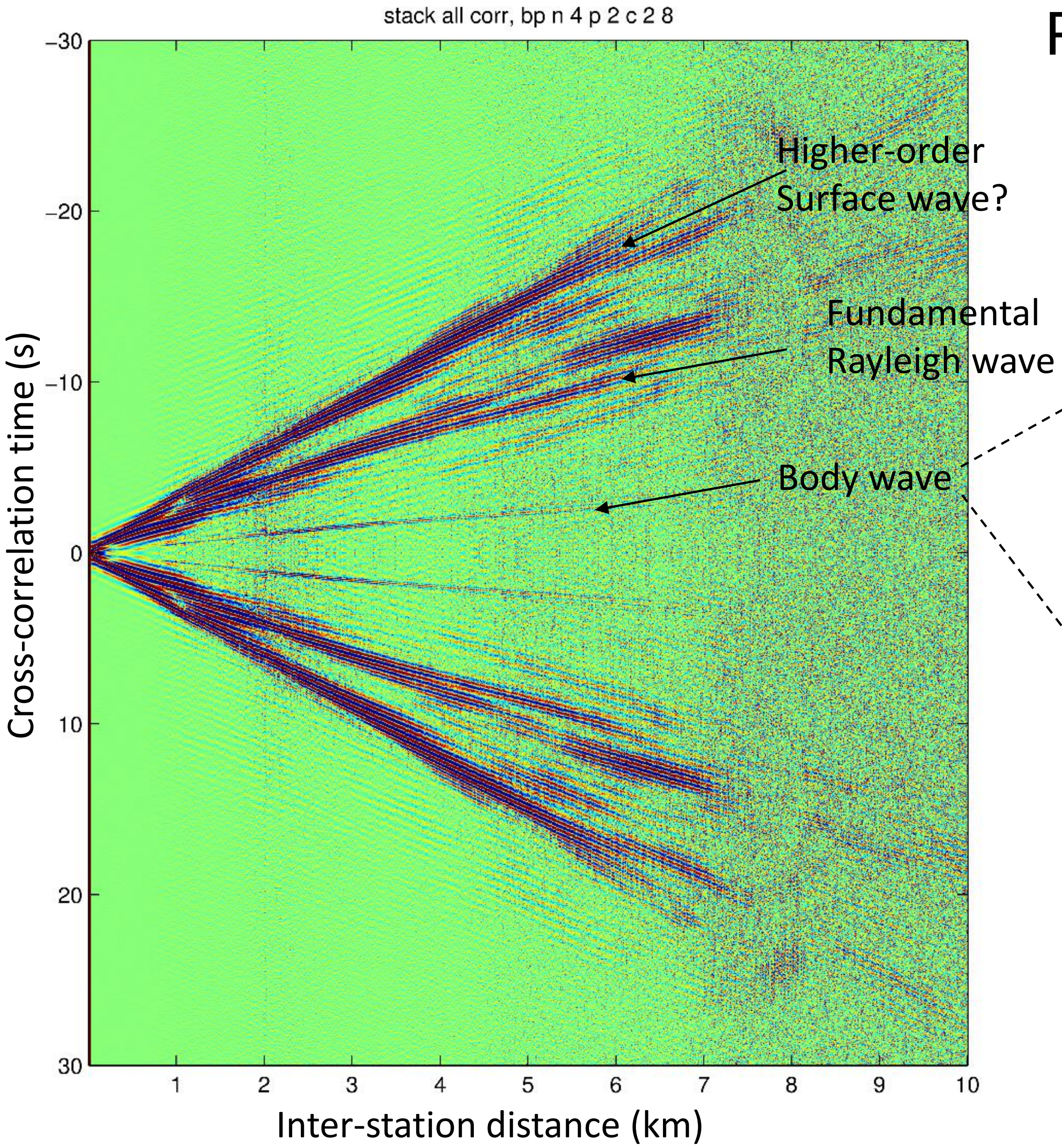
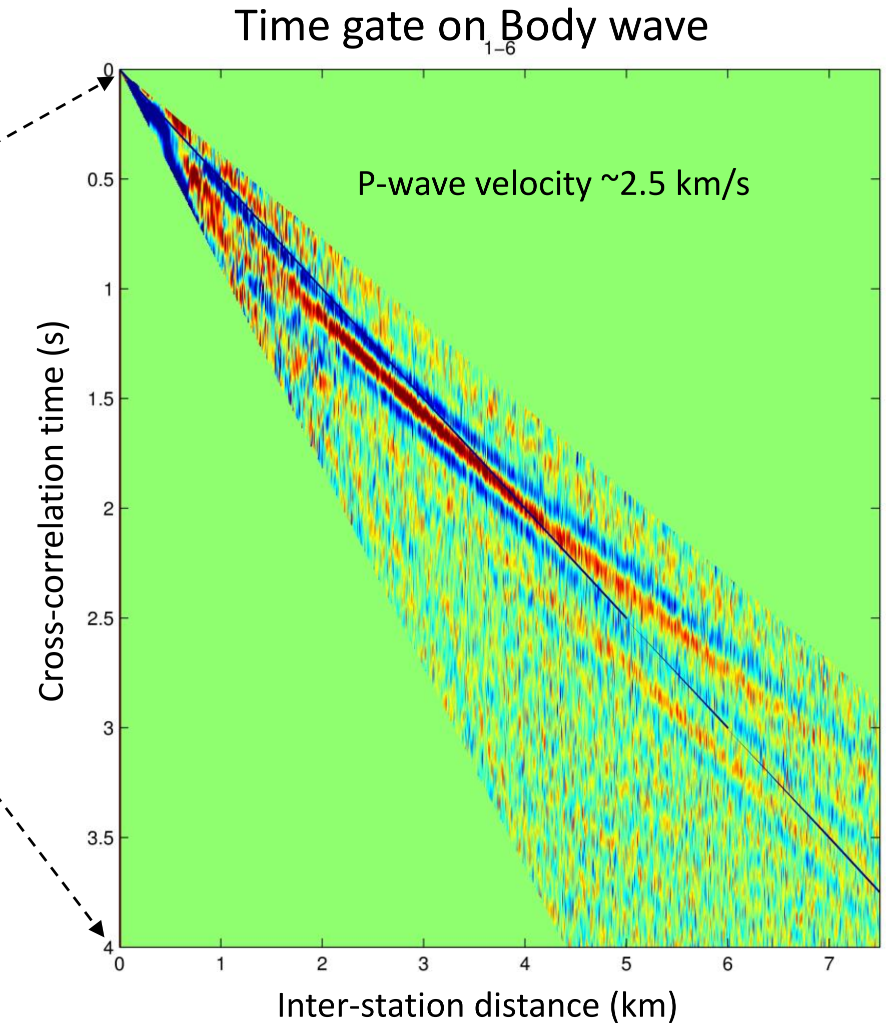


Figure 5. The 1-Hz Rayleigh wave phase velocity map (upper) and its associated uncertainty estimation (lower) based on different numbers of virtual sources. The number of virtual sources in each plot is shown on the top. Besides N equals to 5204, where all stations are used, the triangles in the lower plots show the virtual source locations used.

Lin et al, Geophysics, 2013

From Surface Waves to Body Waves





http://web.gps.caltech.edu/~clay/LB3D/LB3D.html

Body Wave Tomography from Ambient noise

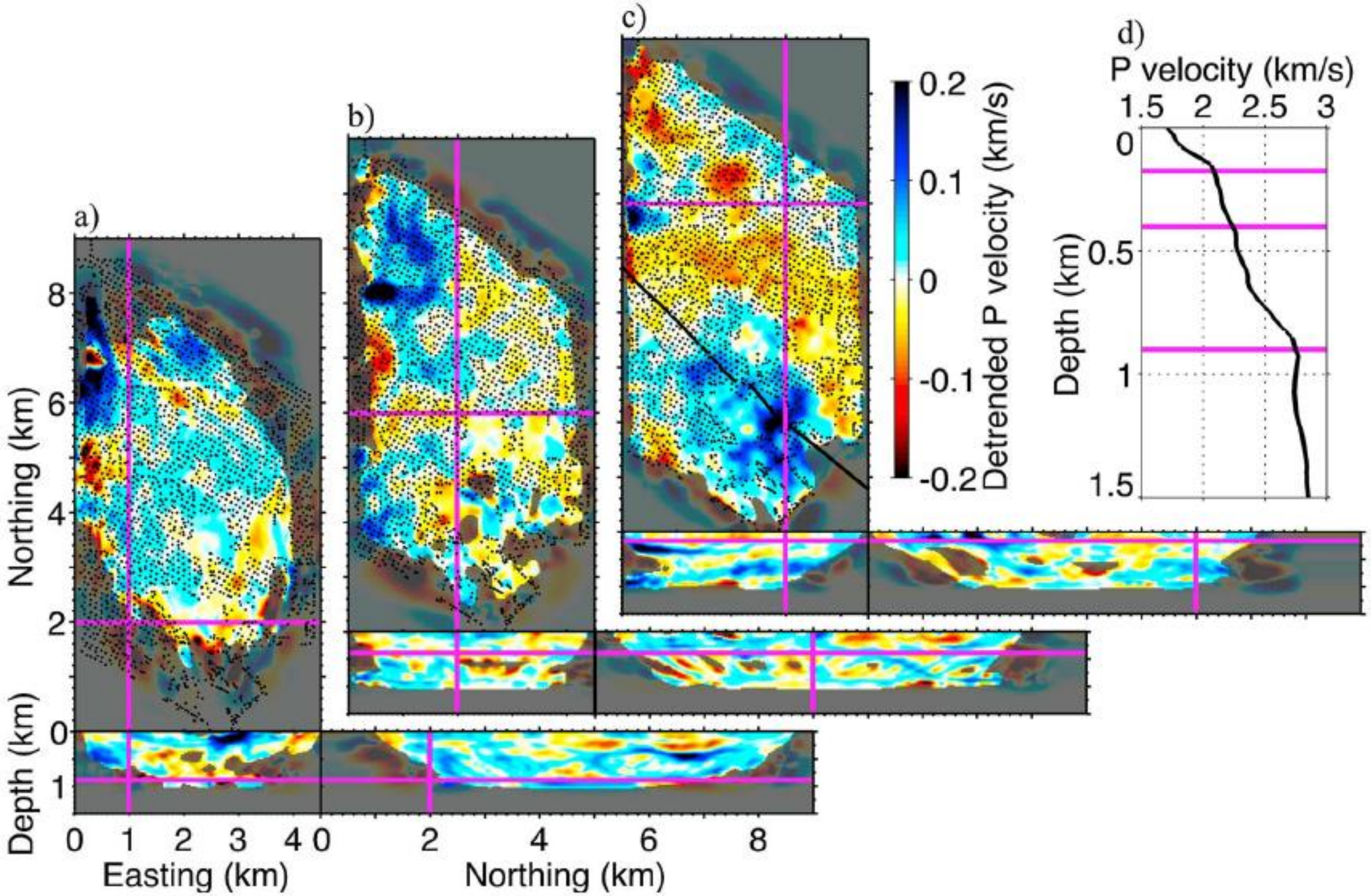
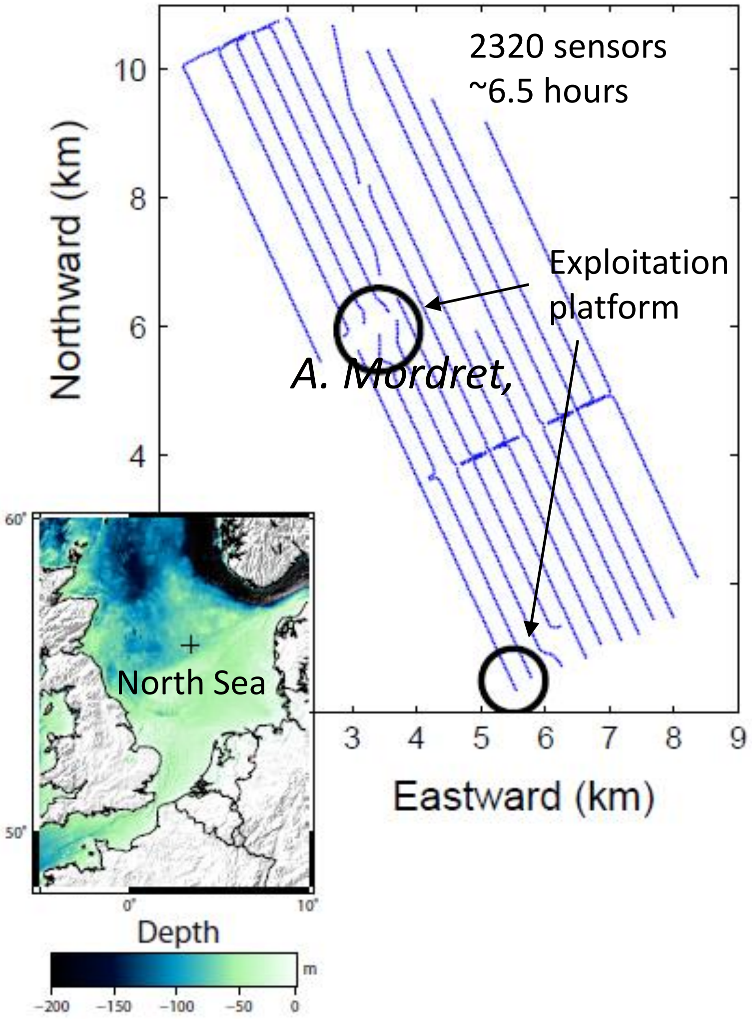


Figure 9. Vertical and horizontal slices of inverted *P* wave velocity cube. (a–c) Slices shift shallower, east, and north. The magenta lines show the location of slices, and the depths of horizontal slices are 0.17, 0.40, and 0.90 km. (d) Velocities are detrended by subtracting the horizontally averaged 1-D velocities. The color map is valid for Figures 9a–9c, where blue indicates velocities faster than the velocity at the corresponding depth in Figure 9d. The shaded areas in the velocity slices are poor ray coverage areas (see Figure C1). The black lines in Figure 9c show the portions of the surface location of the Newport-Inglewood fault [*U.S. Geological Survey and California Geological Survey*, 2006]. The origin of the local coordinate in this figure (Easting = 0 km and Northing = 0 km) is the southwest corner in Figure 1.

Nakata et al, JGR: Solid Earth, 2015

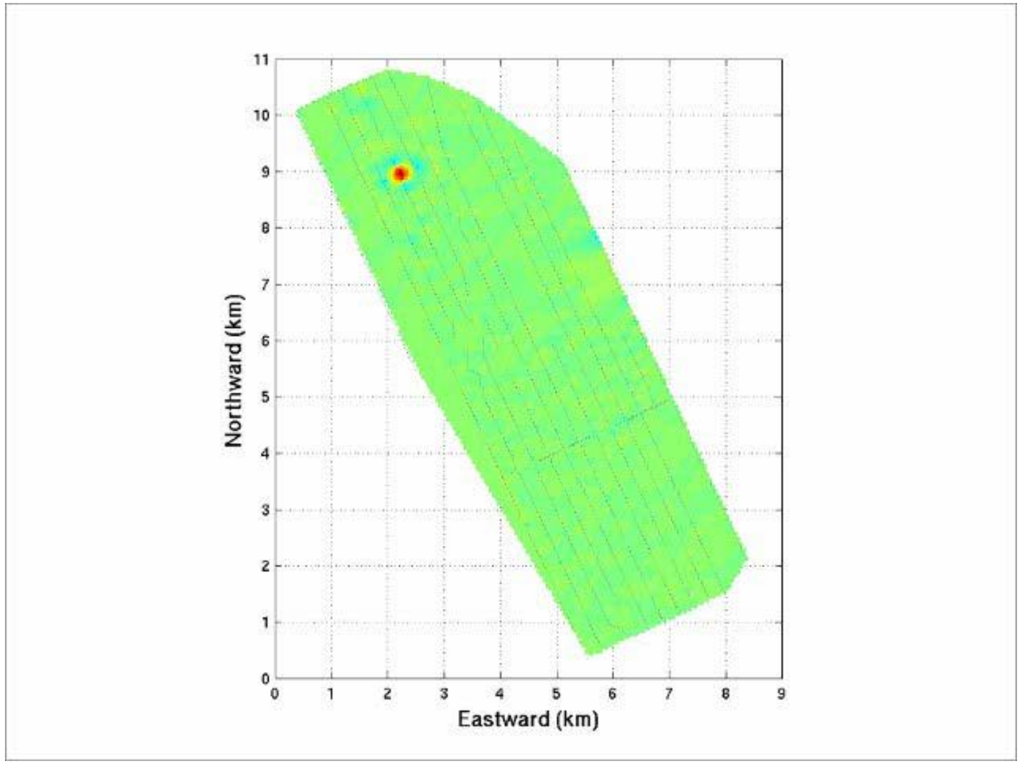
Ambient Noise on Marine Seismic Array in the context of Exploration Geophysics



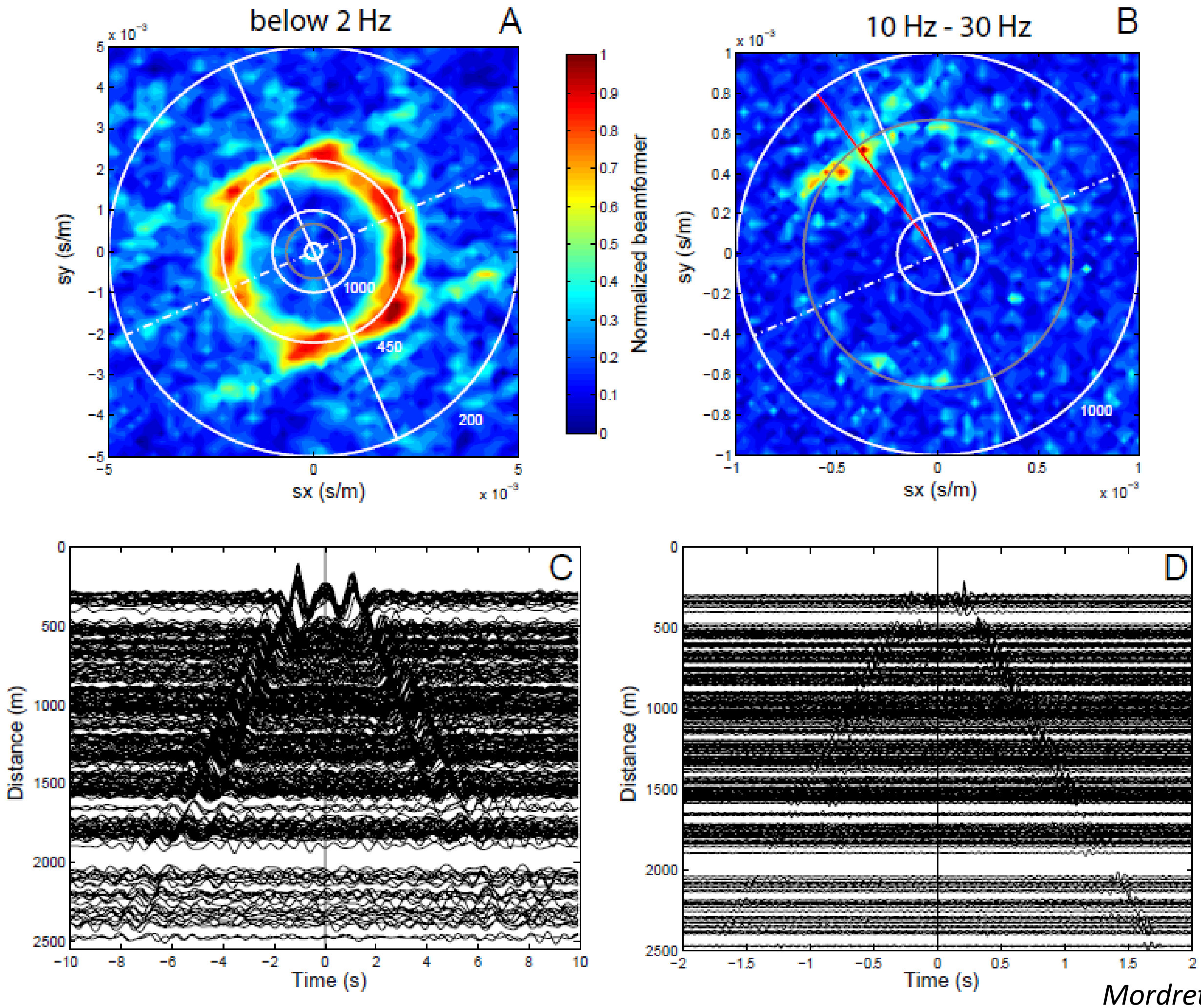
A. Mordret, N. Shapiro, S. Singh, P. Roux, … IPGP & ISTerre

Ambient Noise on Marine Seismic Array in the context of Exploration Geophysics

Virtual source

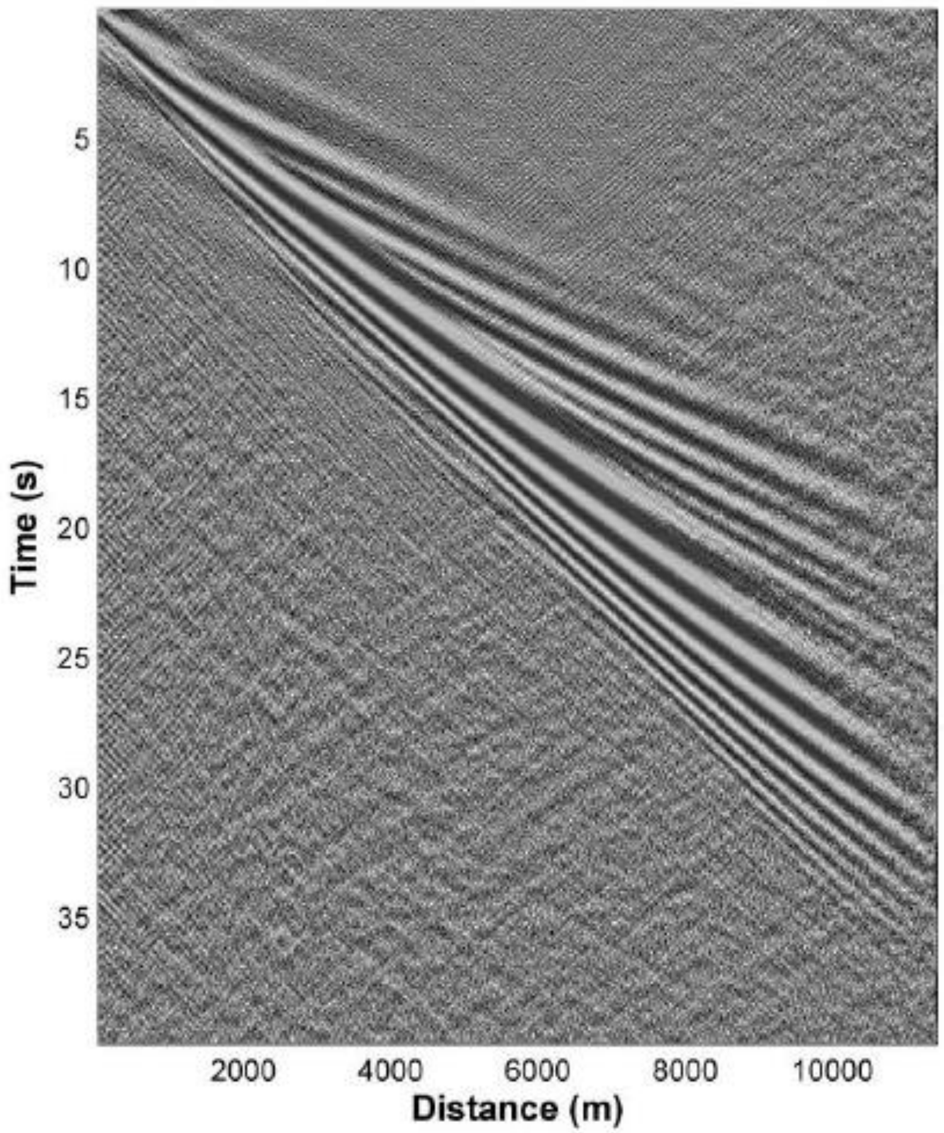


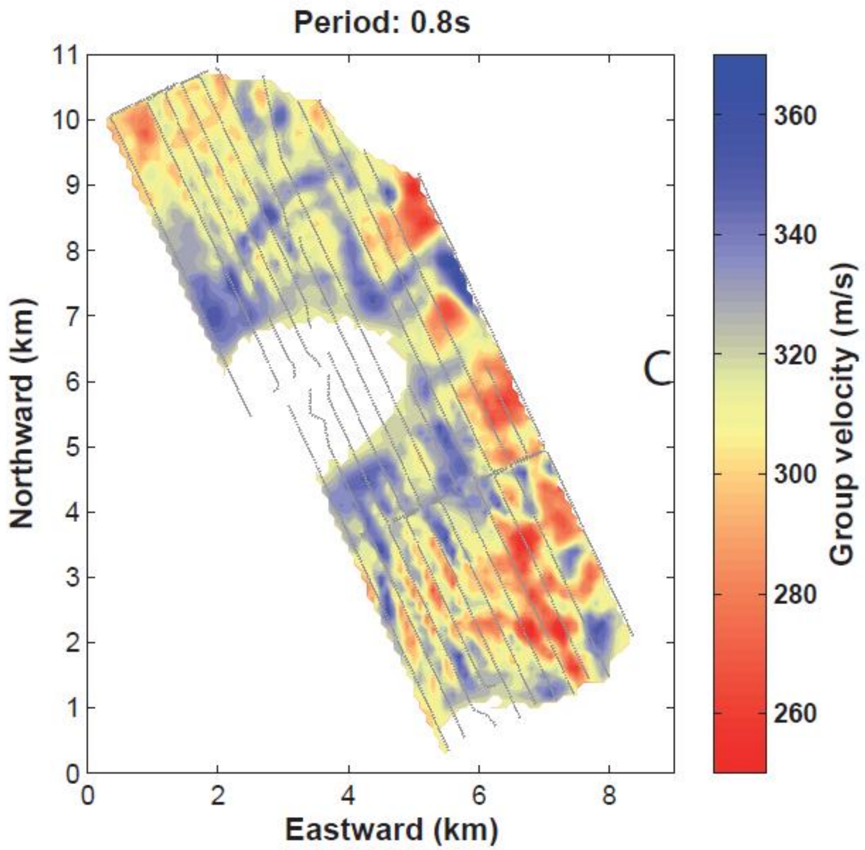
Beamforming and Correlation

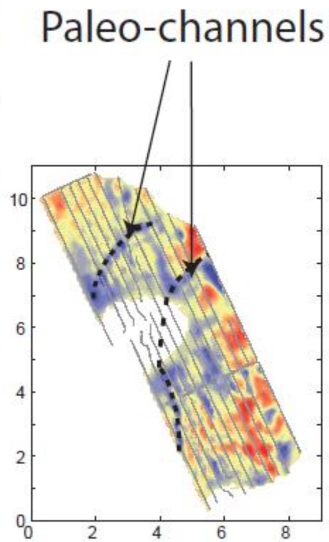


Mordret et al, GRL, 2013
Mordret et al, GJInt, 2014

Noise correlation and Surface Wave Inversion

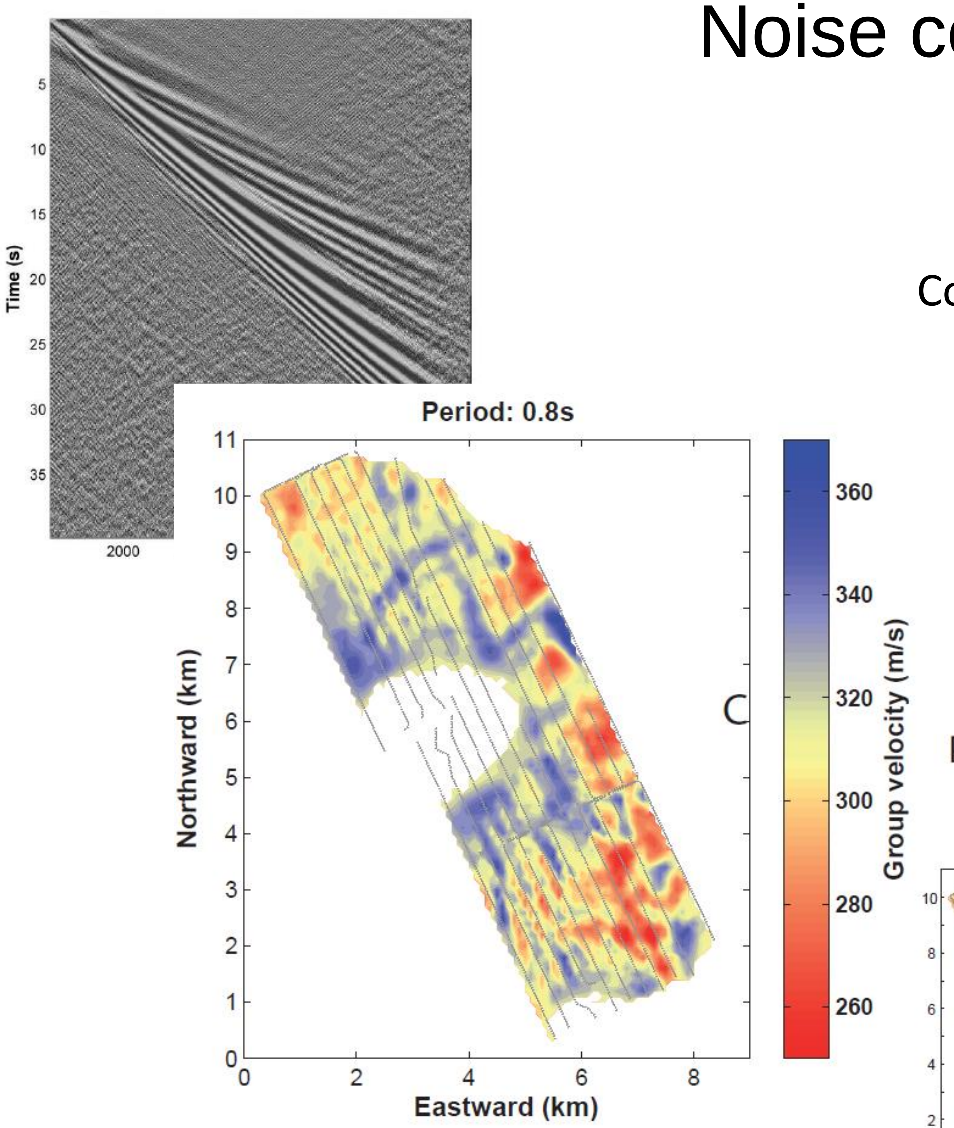




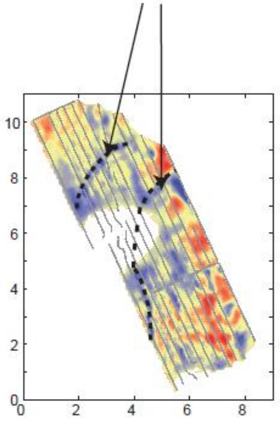


Mordret et al, GRL, 2013
Mordret et al, GJInt, 2014

Noise correlation and Surface wave Inversion



Paleo-channels



Comparison with Full Waveform Inversion result (active P-wave data)

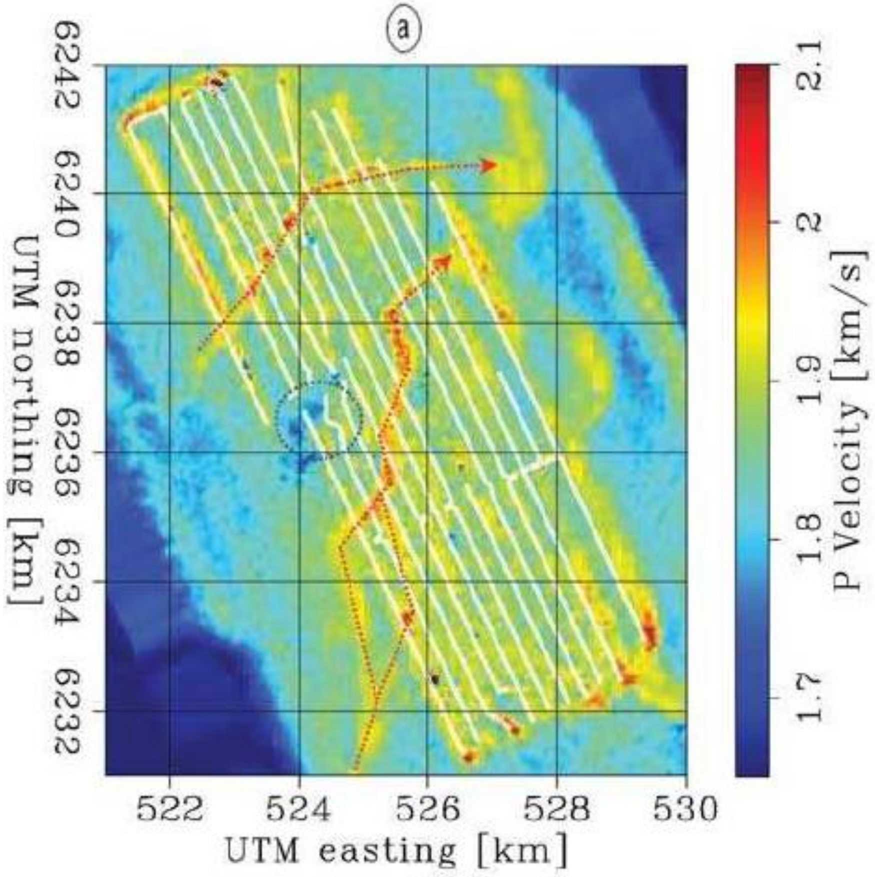
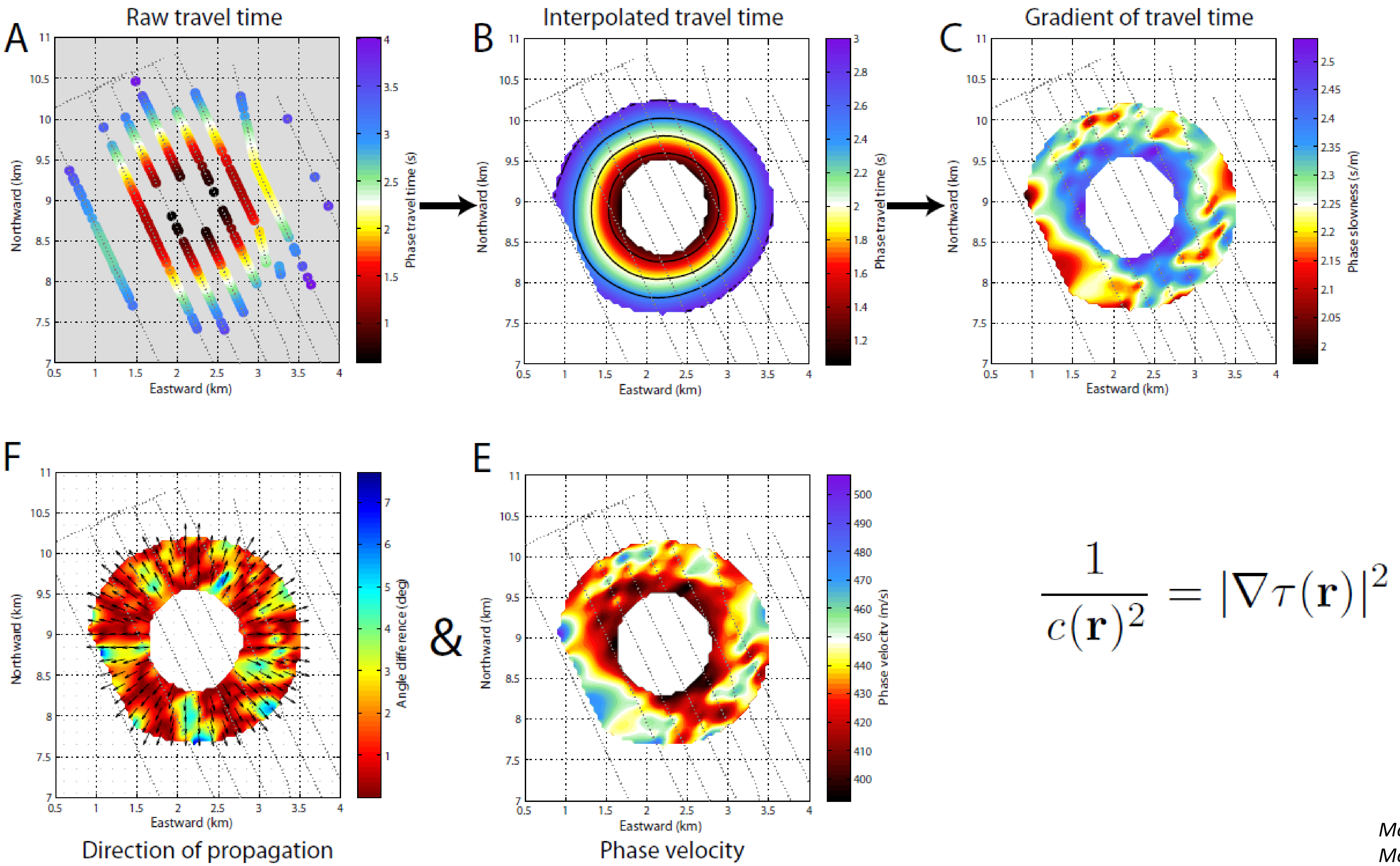


Figure 7. Images of average P-wave velocities obtained using waveform inversion (Sirgue et al., 2010) of active P-wave data: (a) between 60 and 105 m depth, (b) between 150 and 195 m depth. Dotted red lines indicate channel features; dotted blue lines indicate two distinct low-velocity zones.

Eikonal / Helmholtz Tomography

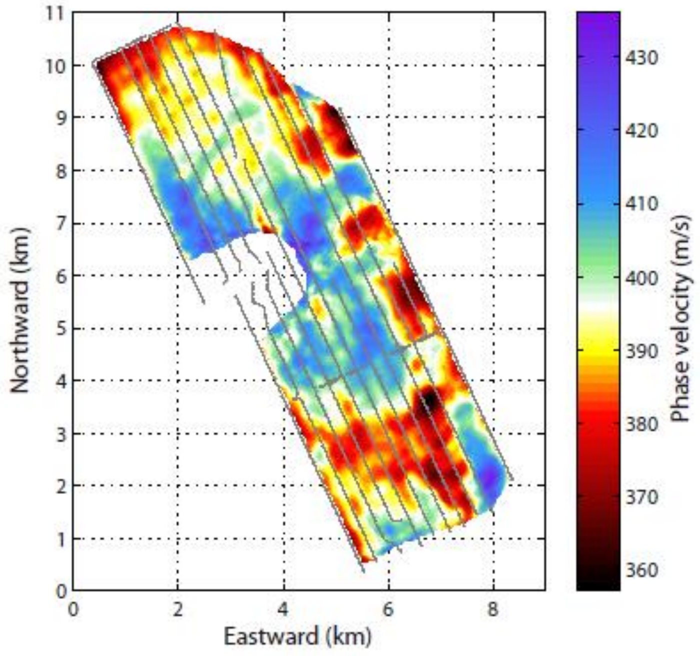


$$\frac{1}{c(\mathbf{r})^2} = |\nabla \tau(\mathbf{r})|^2$$

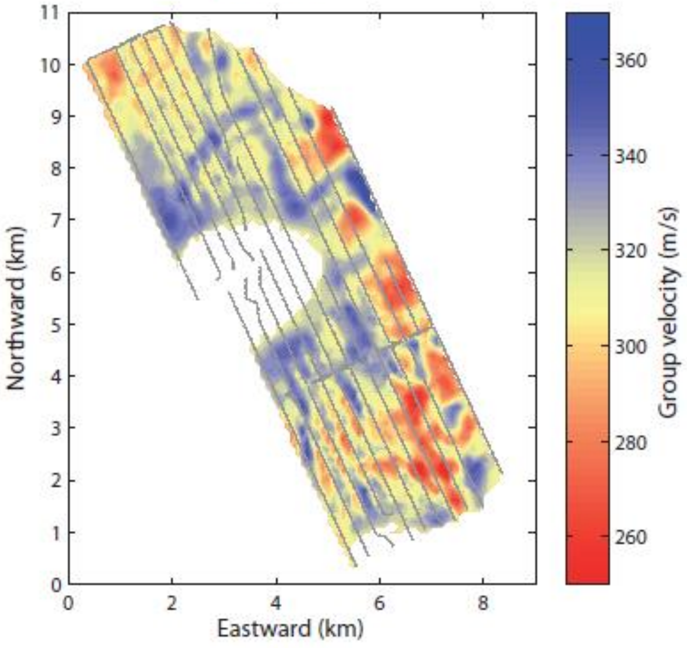
Mordret et al, GRL, 2013
Mordret et al, GJInt, 2014

Comparison Eikonal Tomography vs Surface Wave Inversion

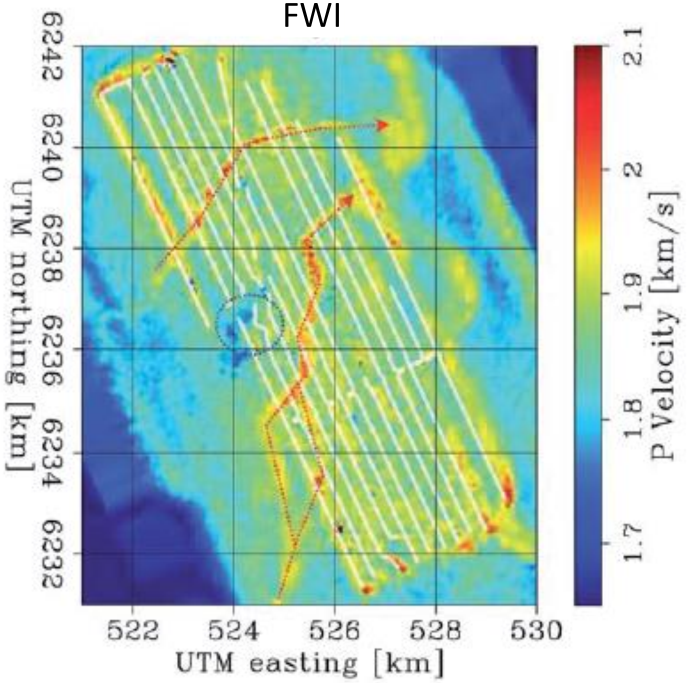
Eikonal Tomo (0.7 s)



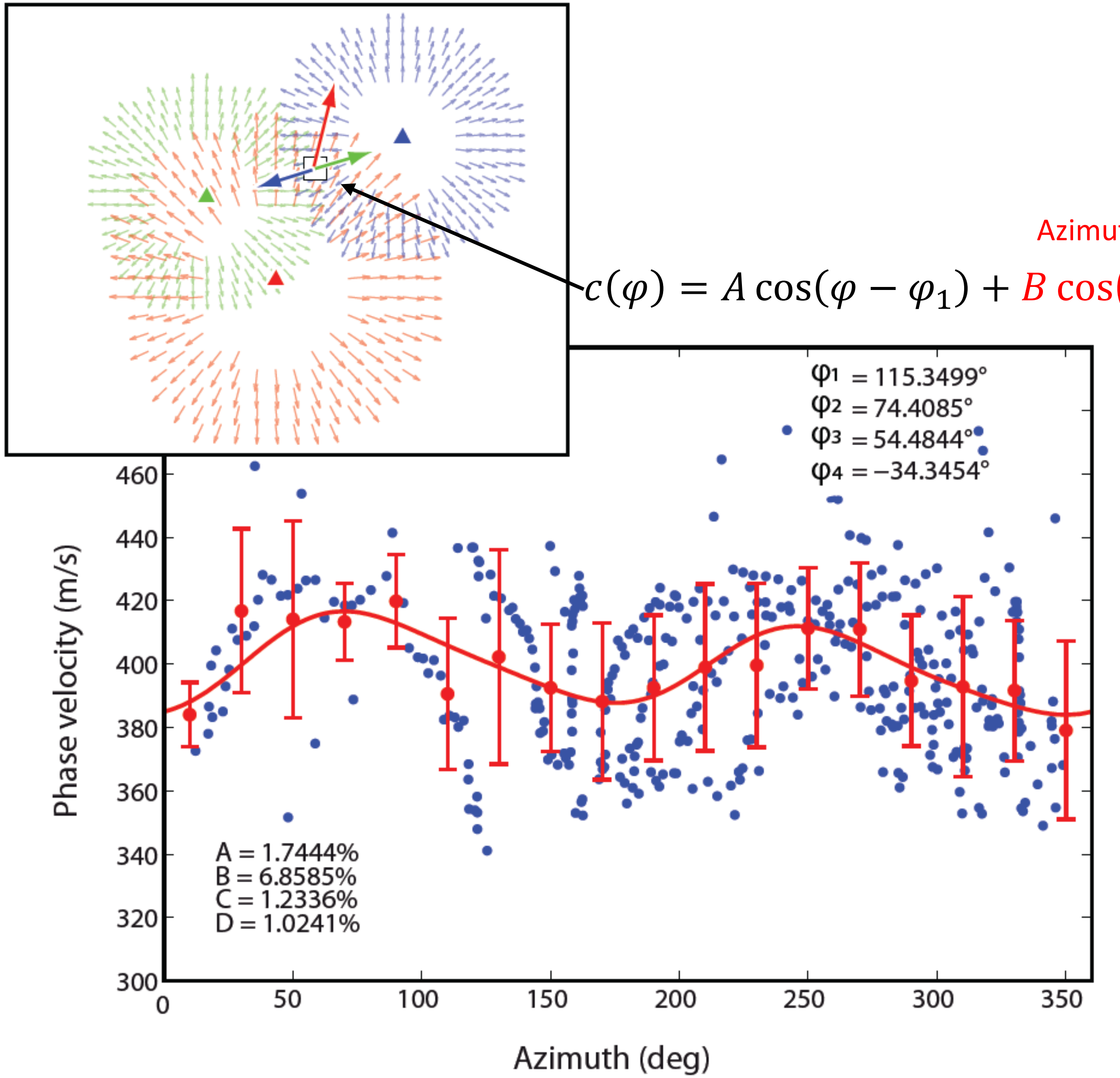
Surface Wave Inversion (0.8 s)



FWI



Azimuthal Anisotropy from Eikonal tomography

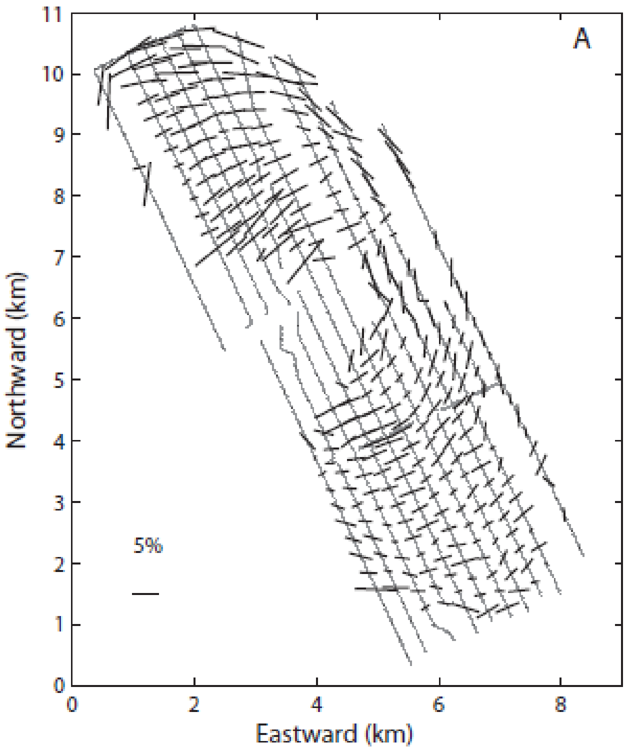


Azimuthal anisotropy

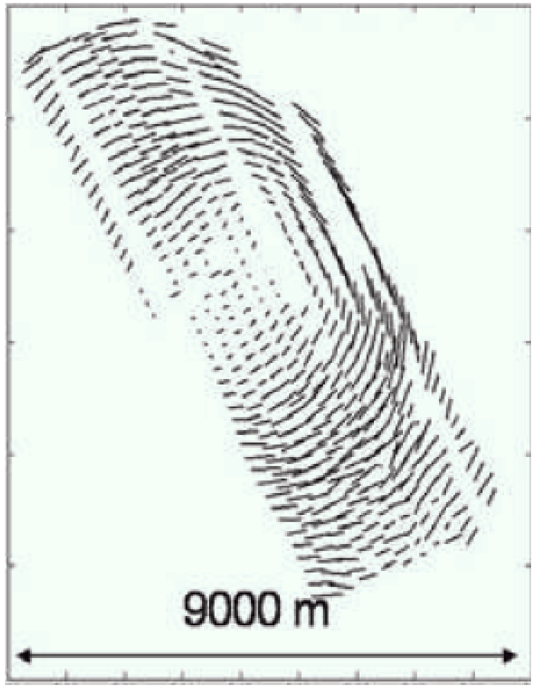
$$c(\varphi) = A\cos(\varphi-\varphi_1) + B\cos\big(2(\varphi-\varphi_2)\big) + C\cos\big(3(\varphi-\varphi_3)\big) + D\cos\big(4(\varphi-\varphi_4)\big)$$

Azimuthal Anisotropy from Eikonal tomography

Eikonal tomo (passive)



Shear wave splitting (active)
(Barkved & Kristiansen, 2005)



Outline

1- Seismic / Geophysics Arrays at all Scales : fundamental Research & Industrial applications

2- Localization of Source buried in noise :

- Matched Field Processing in Underwater acoustics
- Time reversal
- Applications at the geophysics scale

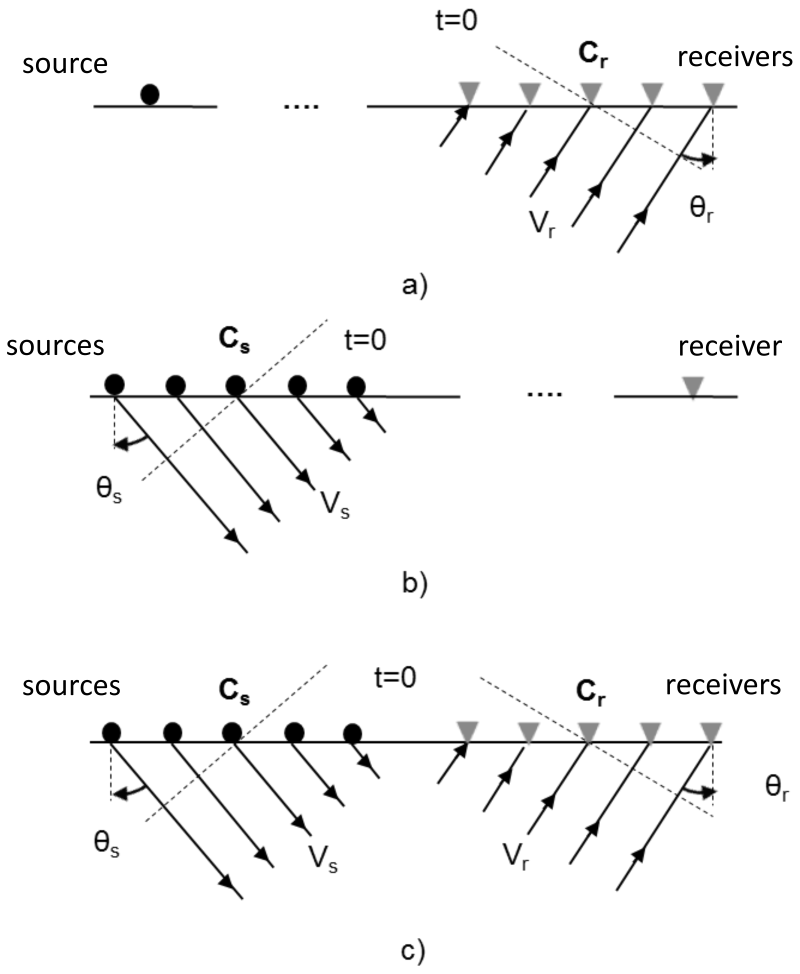
3- Imaging with Ambient noise :

- Vs from Surface waves with Eikonal /Helmholtz tomography
- Vp from Body waves
- Anisotropy with Marine seismic data

4- Double beamforming : Identify / Separate different Wave types

- **Active source array in Underwater acoustics : Application to imaging**
- **Active source array in Geophysics : Application to monitoring**
- **Ambient noise on dense arrays in Geophysics / Seismology**

Principles of Double BeamForming (DBF)



DBF in Seismology…

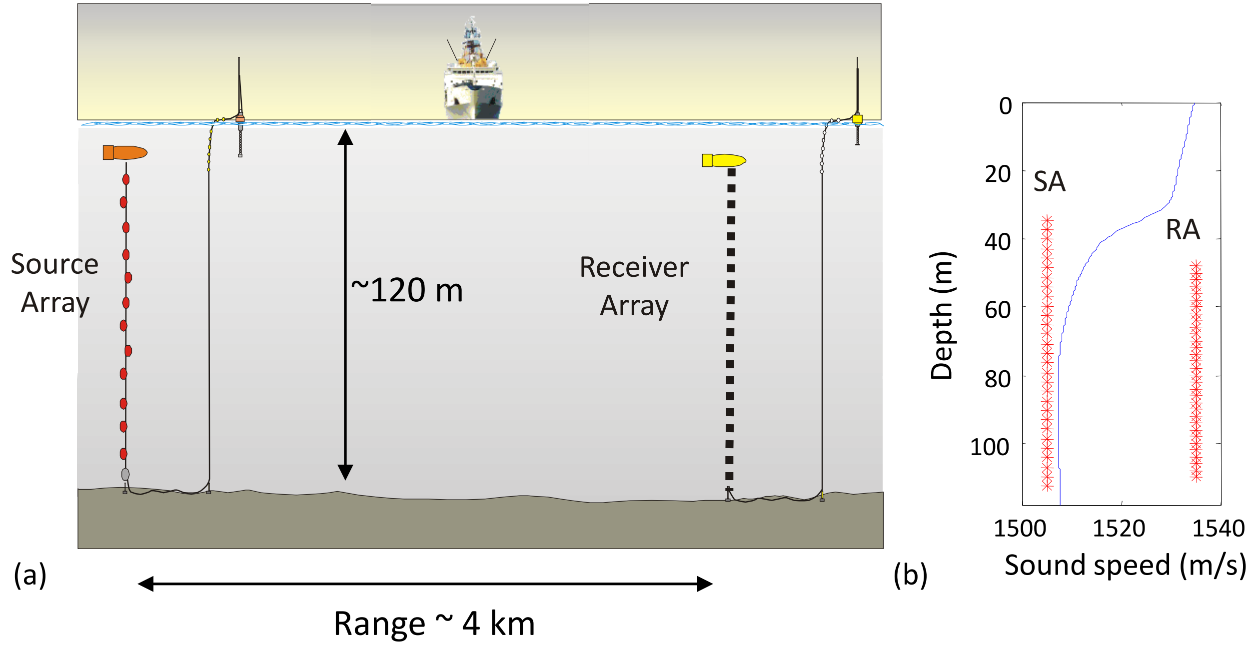
F. Krüger, M. Weber, F. Scherbaum and J. Sclittenhardt, Geophys. Res. Lett. 20, 1475-1478, 1993.

S. Rost and C. Thomas, Rev. Geophys. 40, 1008, 2002.

DBF in Underwater Acoustics…

Around Elba Island (Italy)

July 2005



Marine Physical Laboratory of the Scripps Institution of Oceanography University of California, San Diego

Source Array – 29 transducers

Receiver Array – 32 hydrophones

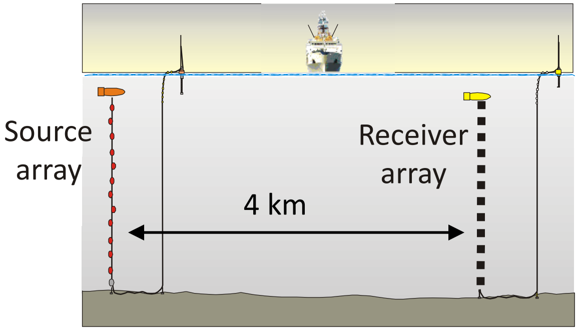
Fc ~ 3.5 kHz

Δf ~ 1 kHz

NATO SACLANT UNDERSEA RESEARCH CENTRE

W.A. Kuperman, W.S. Hodgkiss, M. Stevenson, H.C. Song, P. Roux, … 2003-2004-2005-2006

Double Beamforming on Source/Receiver Arrays

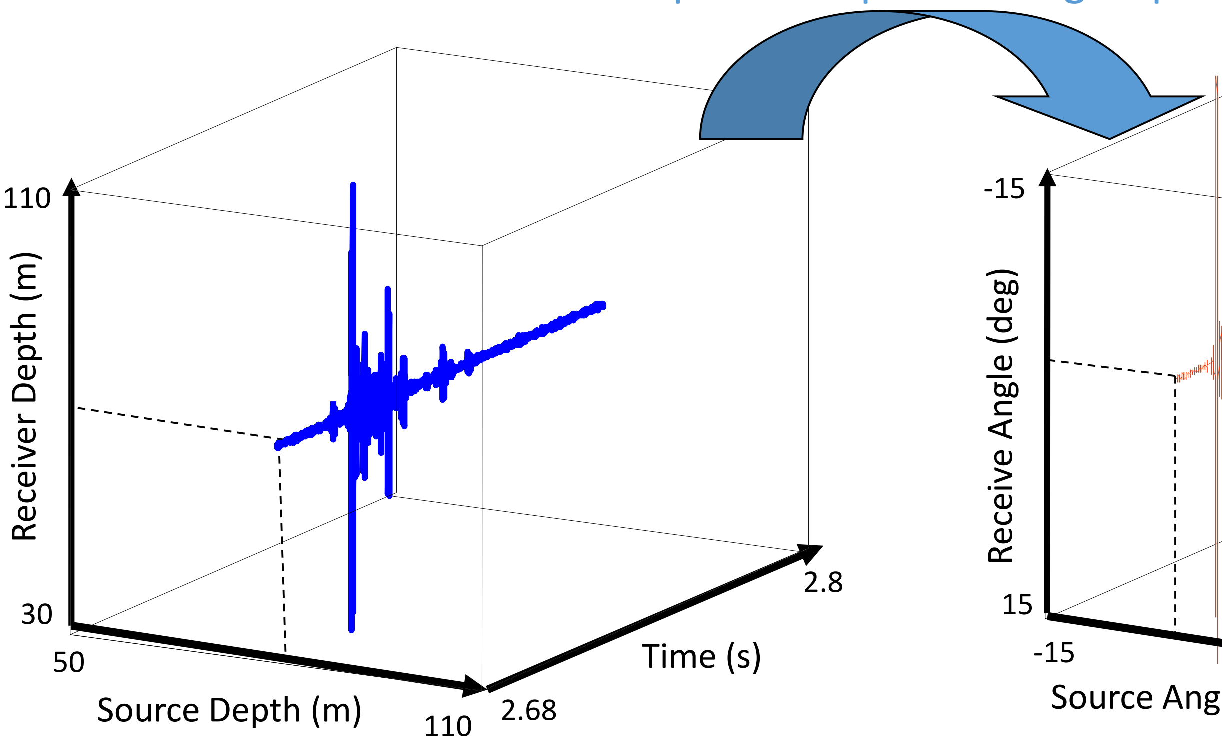


$$P(\theta_s,\theta_r,t) = \sum_{sources}\sum_{receivers} P\left(z_s, z_r, t - \Delta\tau_s(\theta_s) - \Delta\tau_r(\theta_r)\right)$$

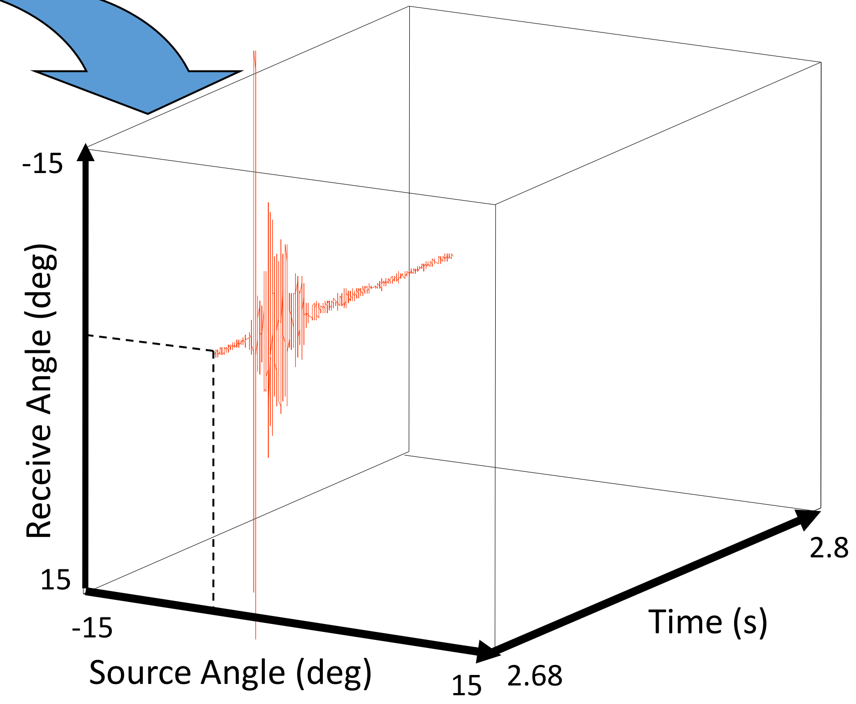
$$\Delta\tau_i(\theta) = \int_{z_0}^{z_i} \sqrt{\frac{1}{c^2(z)} - \frac{\cos^2\theta}{c_0^2}}\,dz \approx (z_i - z_0)\frac{\sin\theta}{c}$$

Dzieciuch et al, JASA, 2001

From position space to angle space



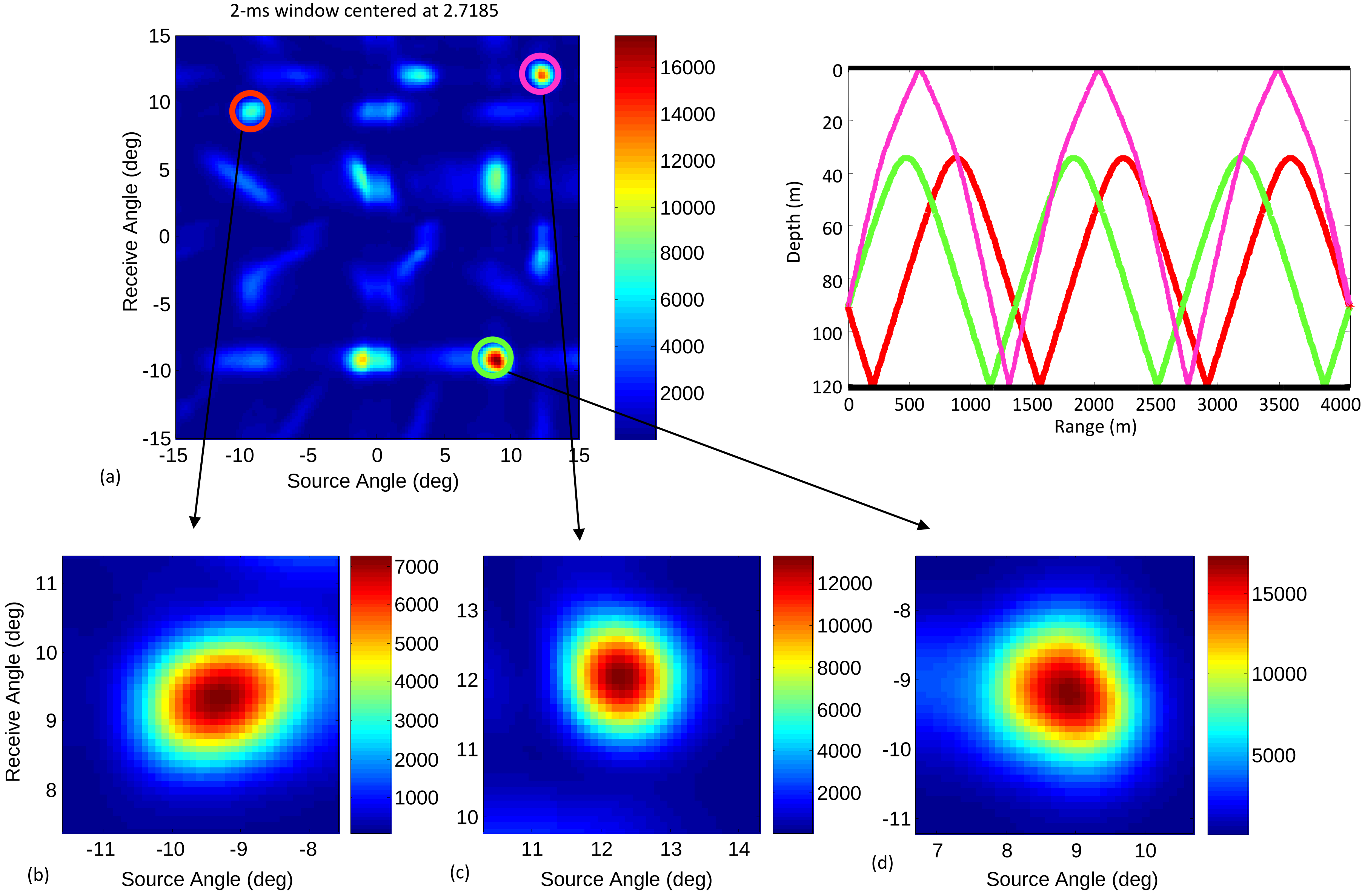
DATA=(Source, Receiver, time)



DATA=(Source Angle, Receive Angle, time)

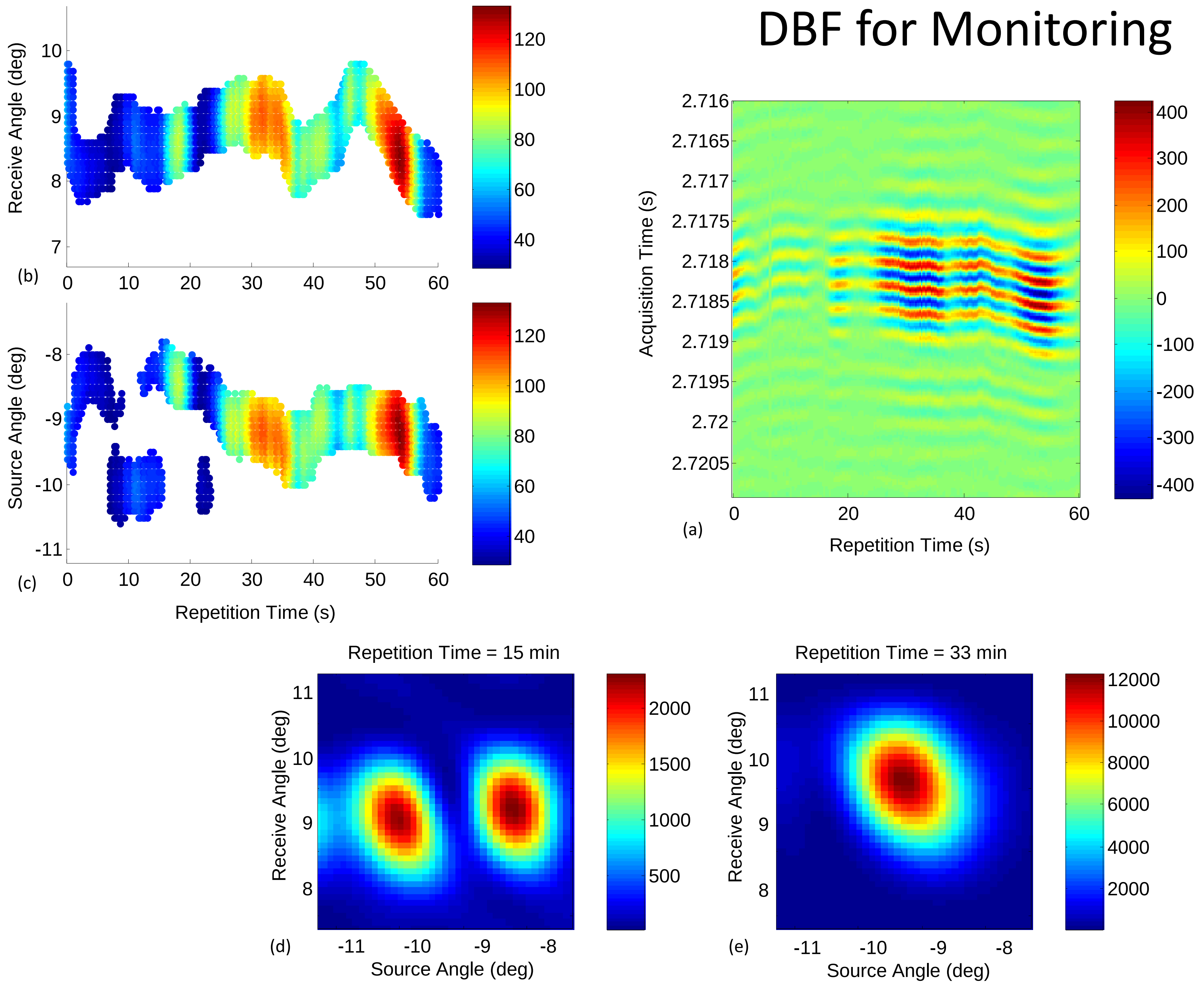
Roux et al, JASA, 2004

DBF for Wave Separation & Identification

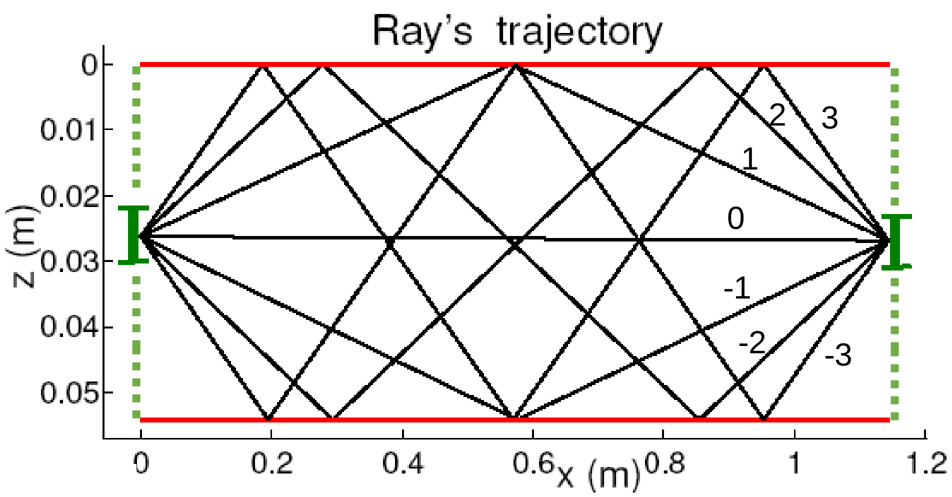


Roux et al, JASA, 2008

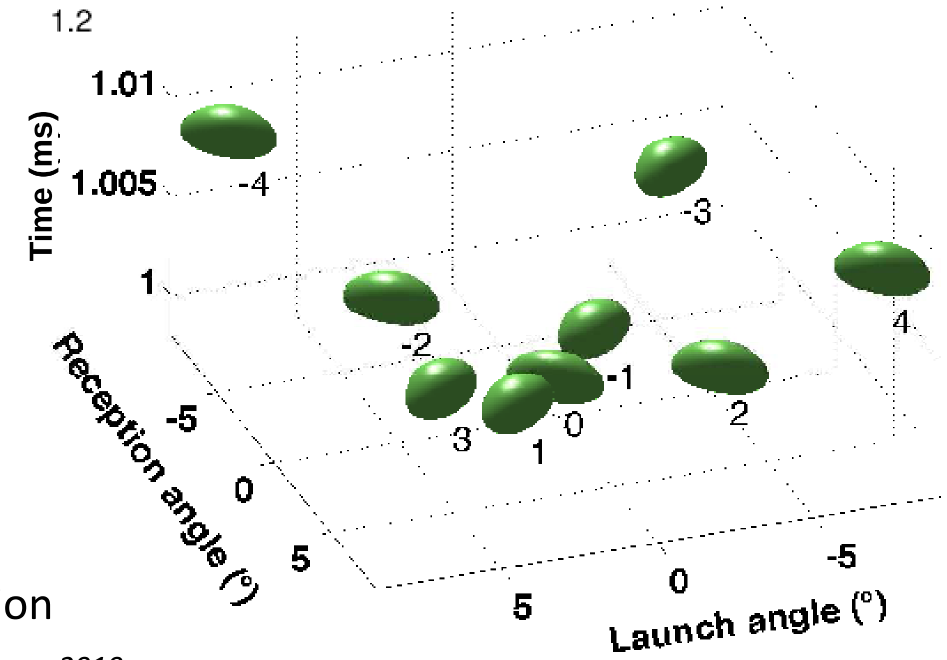
DBF for Monitoring



Tomography Application at the Lab scale



DBF Result



Spot size limited by:

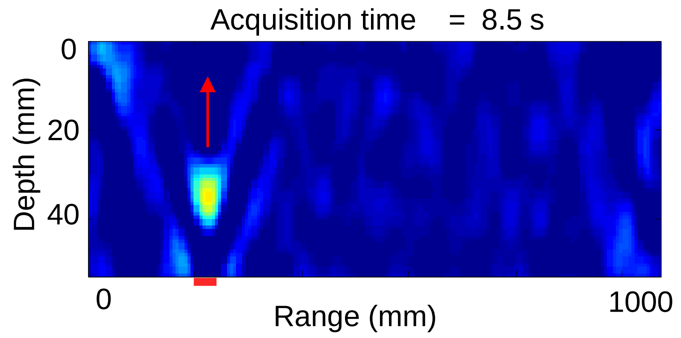
- Array aperture

- Frequency + Bandwidth

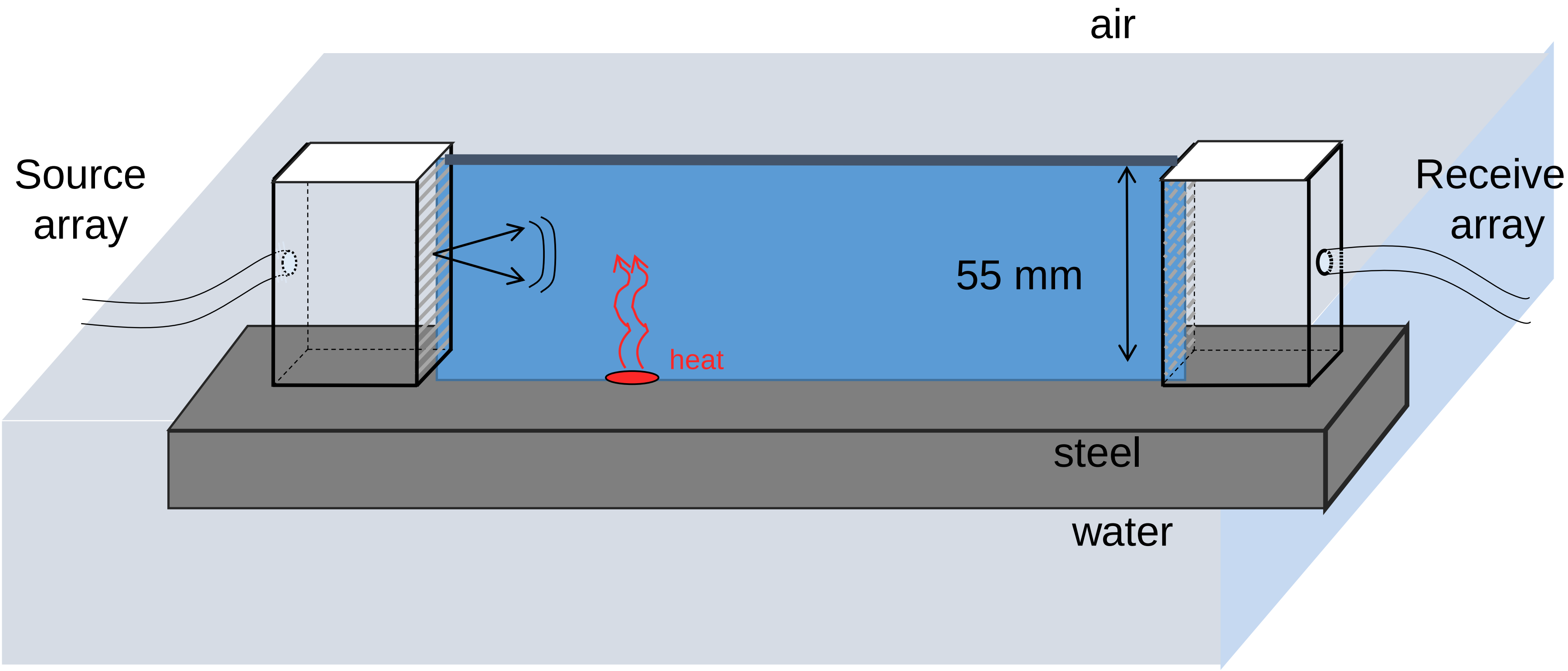
Capon + DBF = better resolution

Letouze et al, Signal Proc., 2010

Shallow water Tomography



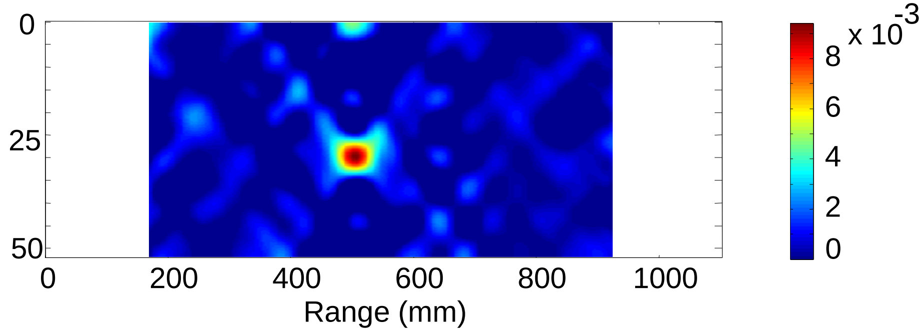
Ultrasonic waveguide (L=1100 mm, H=55 mm)
Two source-receiver arrays (64 elements)
Perturbation : Heat plume



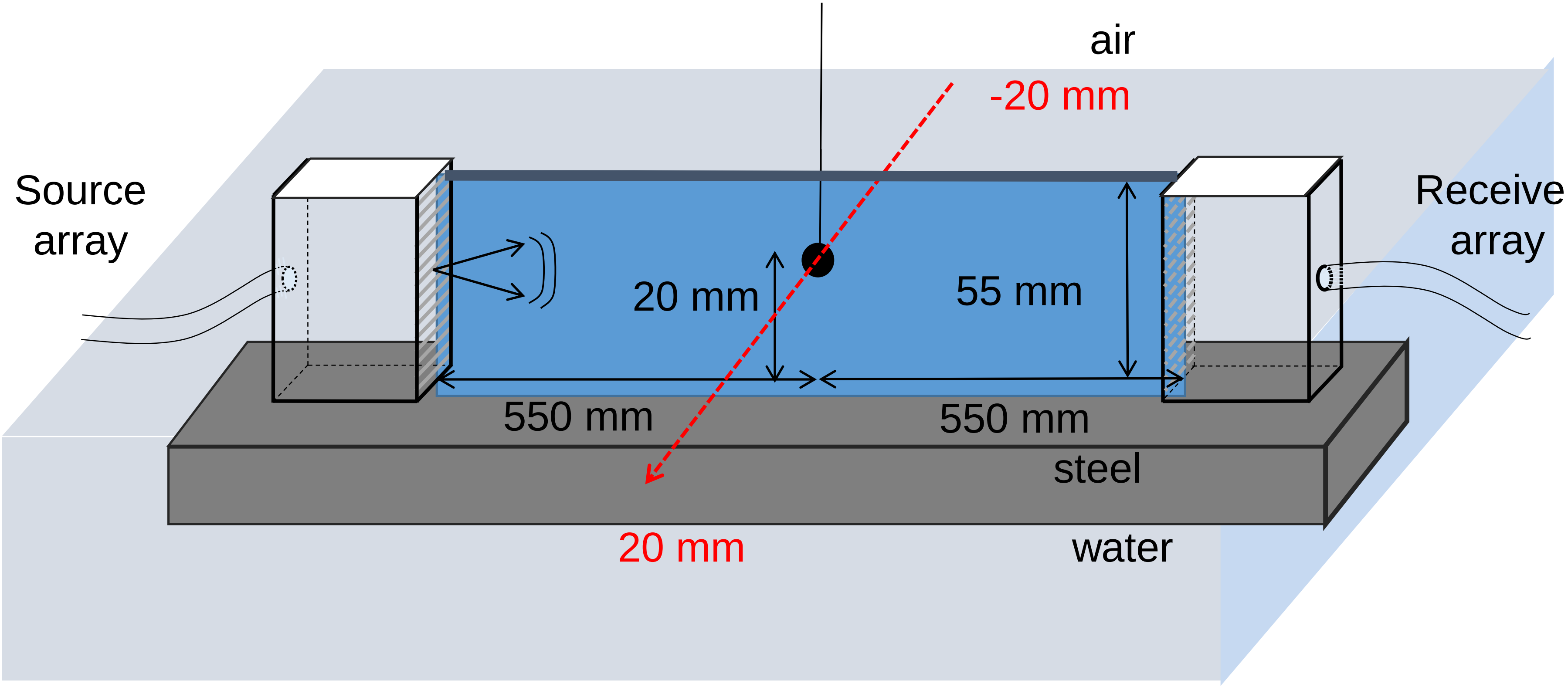
Acquisition of the waveguide transfer matrix every 0.1 s

Iturbe et al, IEEE J. Ocean. Eng. , 2009
Roux et al, JASA, 2011

Target Localization in Shallow water



Ultrasonic waveguide (L=1100 mm, H=55 mm)
Two source-receiver arrays (64 elements)
Perturbation : target crossing

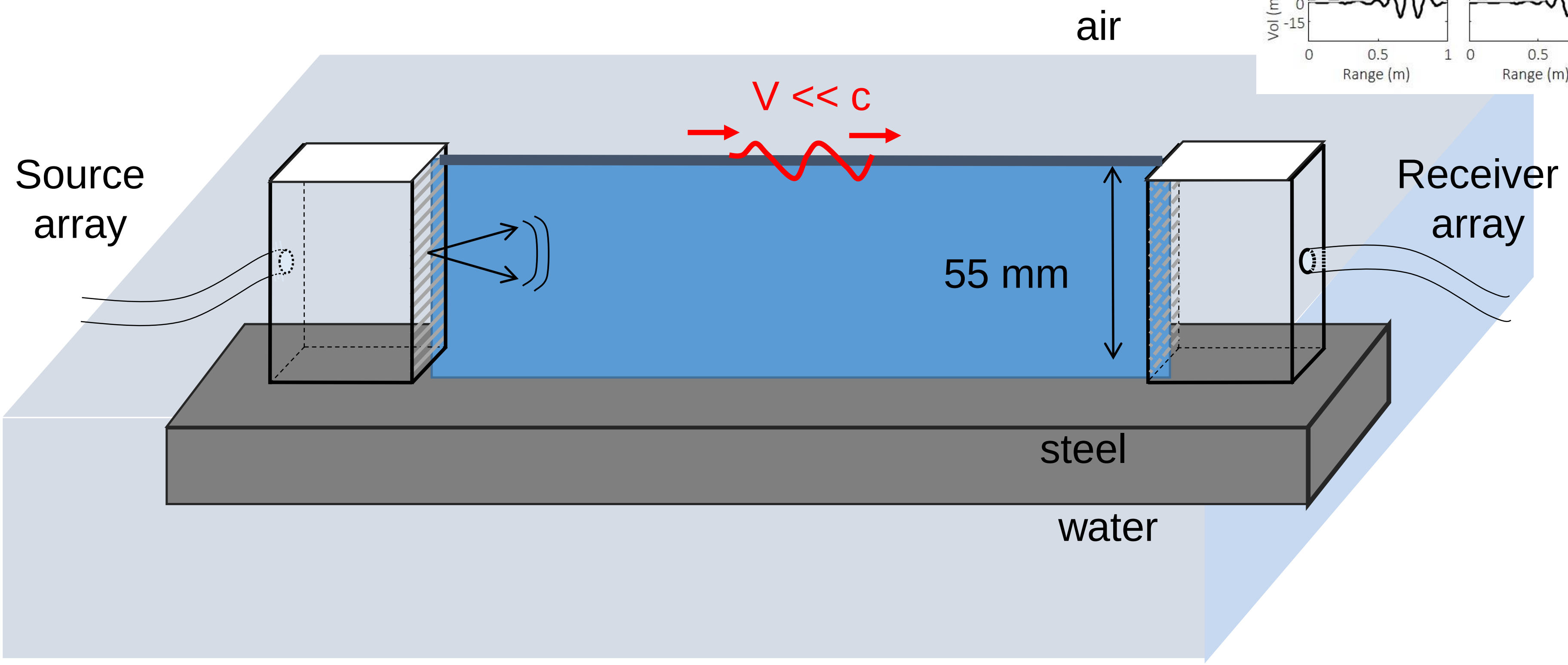


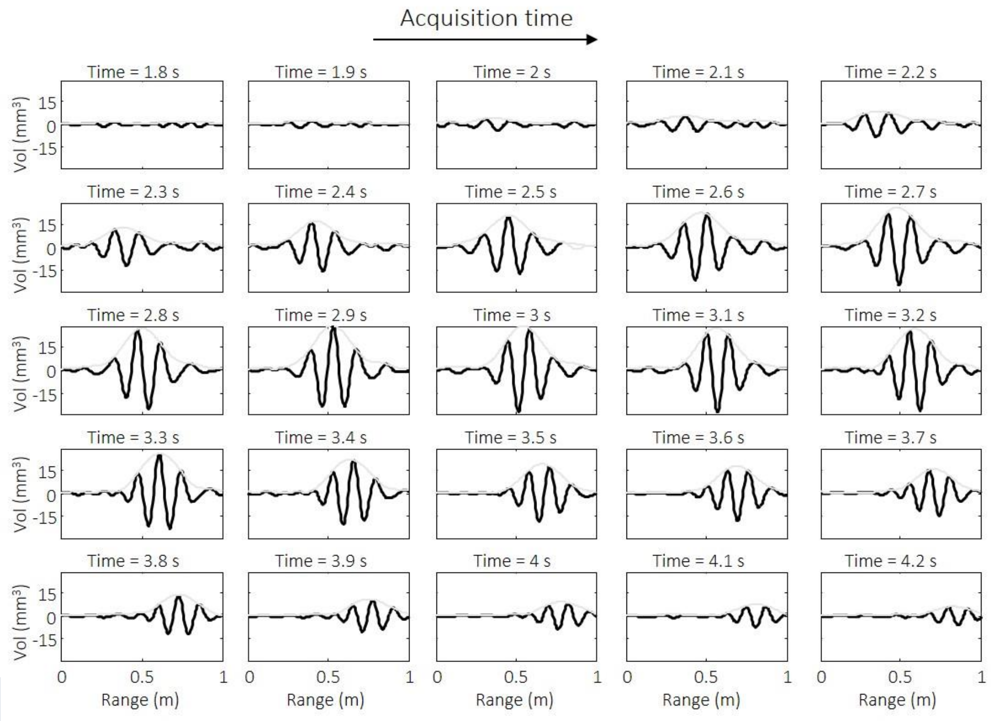
Acquisition of the waveguide transfer matrix for each target position

Marandet et al, JASA, 2011

Surface/Gravity Wave Inversion

Ultrasonic waveguide (L=1100 mm, H=55 mm)
Two source-receiver arrays (64 elements)
Perturbation : Gravity wave at the air / water interface





Sarkar et al, JASA, 2012
Roux et al, JASA, 2013

DBF in Geophysics :
Gel-based phantom at the Lab scale

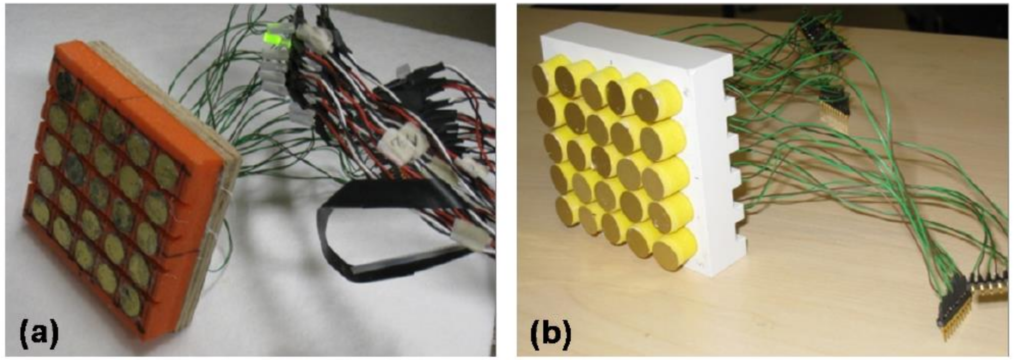
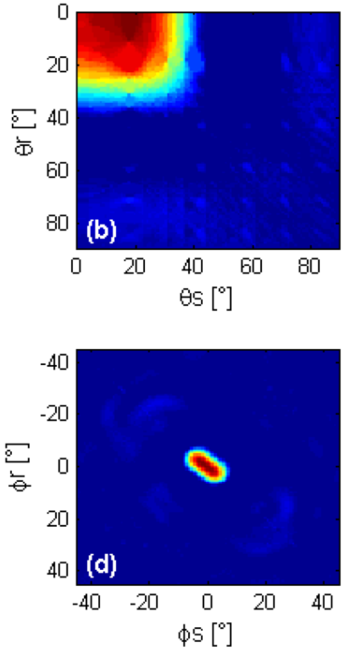
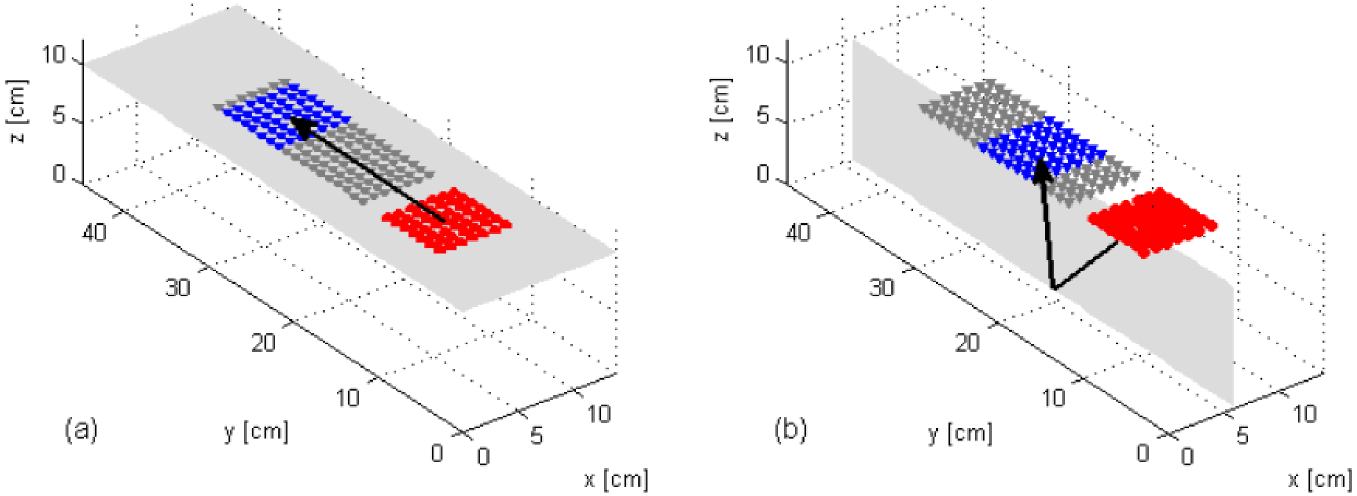
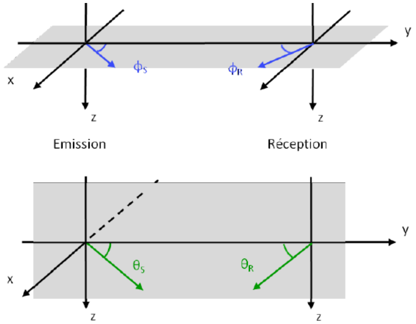


FIGURE 19: Antennes 5x5 (a) Isolation acoustique en mousse et rainures creusées entre les lignes de sources (b) Isolation acoustique par bouchon d'oreille.

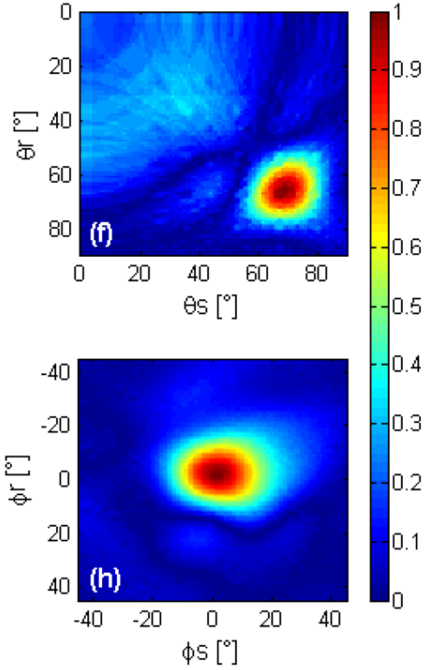
Angle-Angle representation





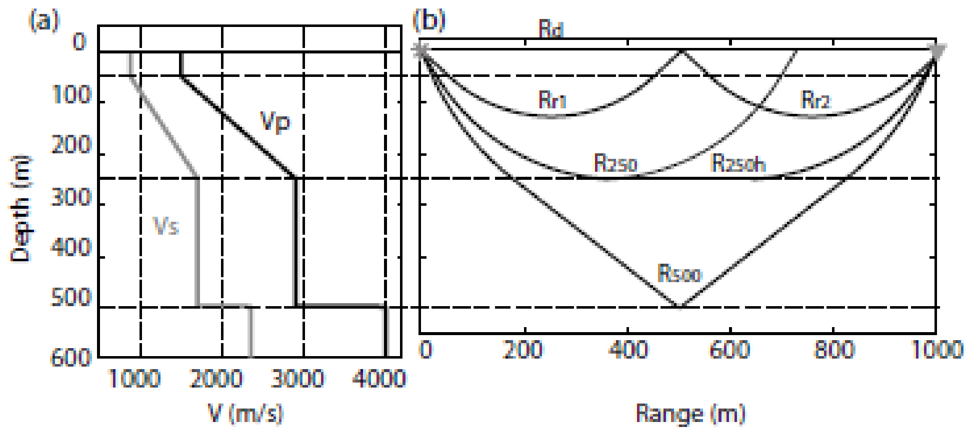


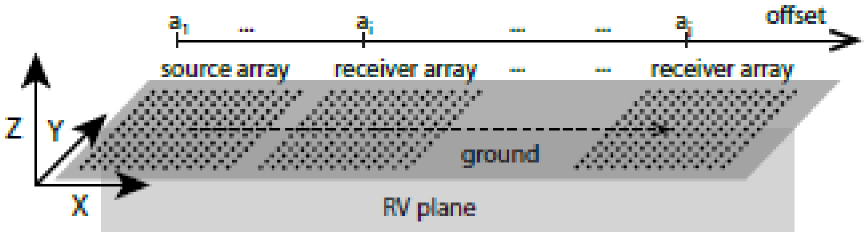
Angle-Angle representation

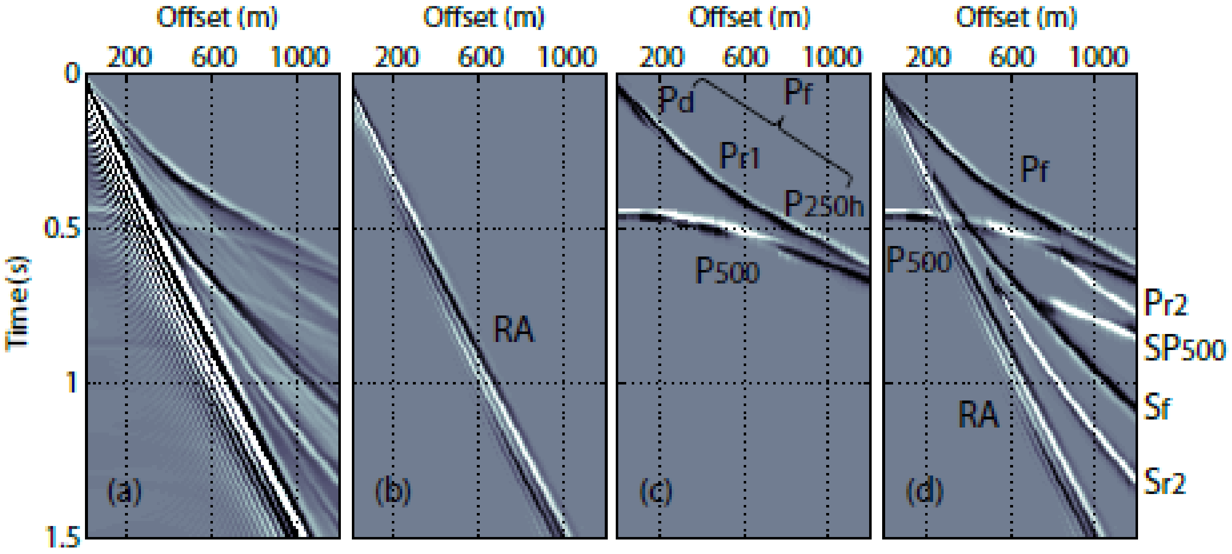


De Cacqueray et al, Geophysics, 2013

DBF in Geophysics : Numerical simulation



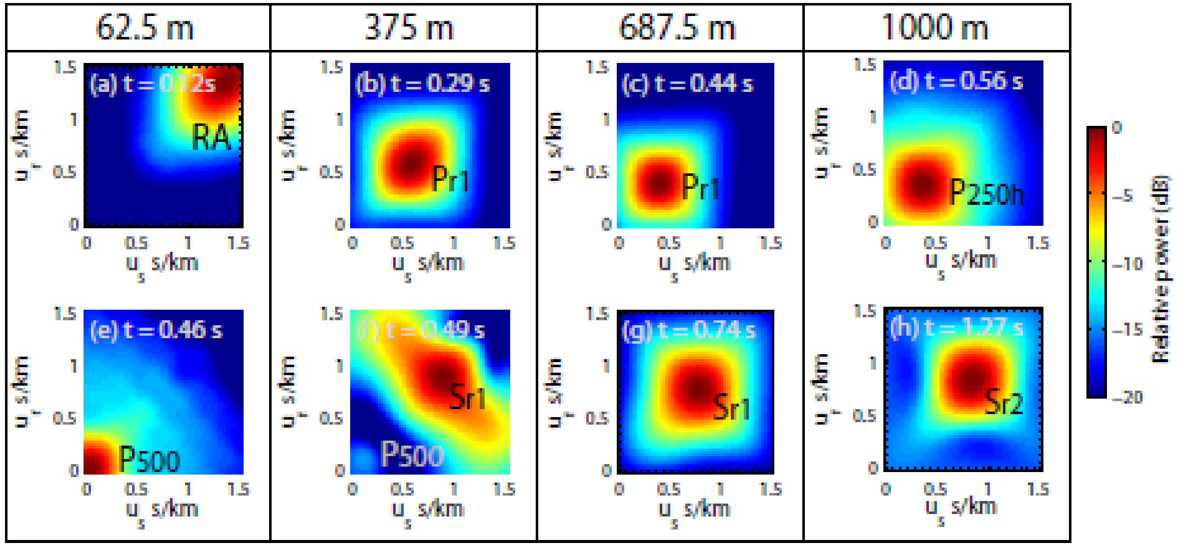




Raw data

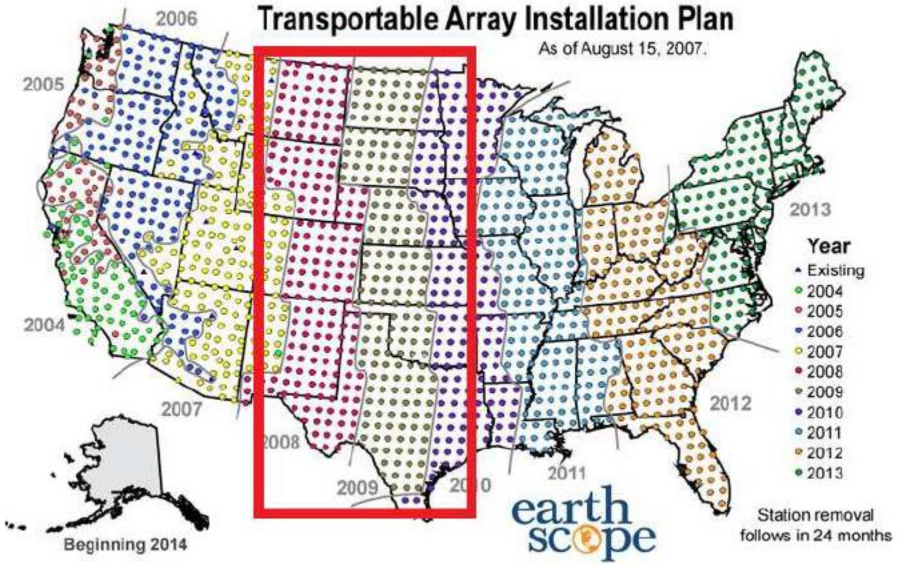
DBF-extracted data

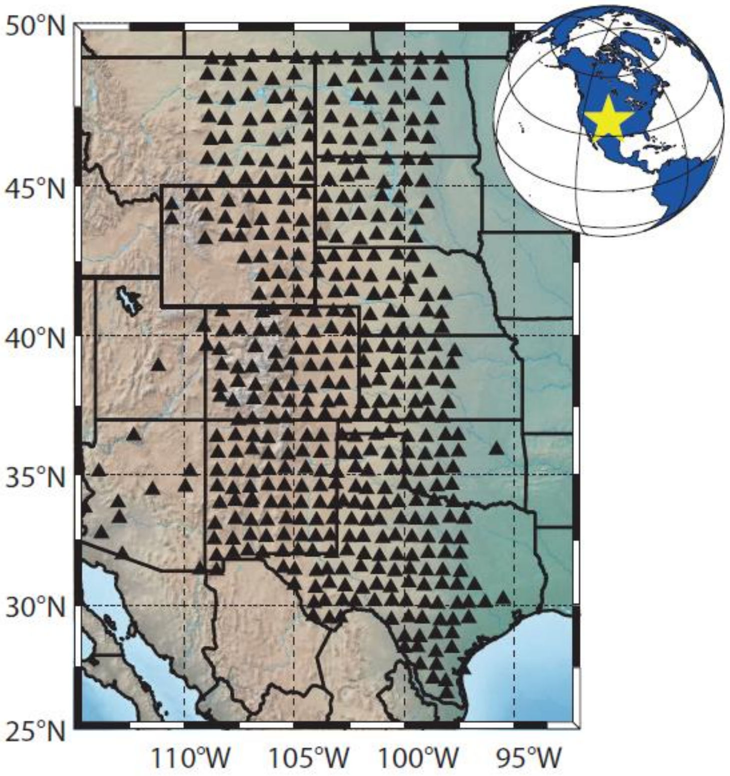
Slowness-Slowness DBF representation
vs source-receiver distance



Boue et al, Geophysics, 2013

DBF + Ambient noise data in seismology



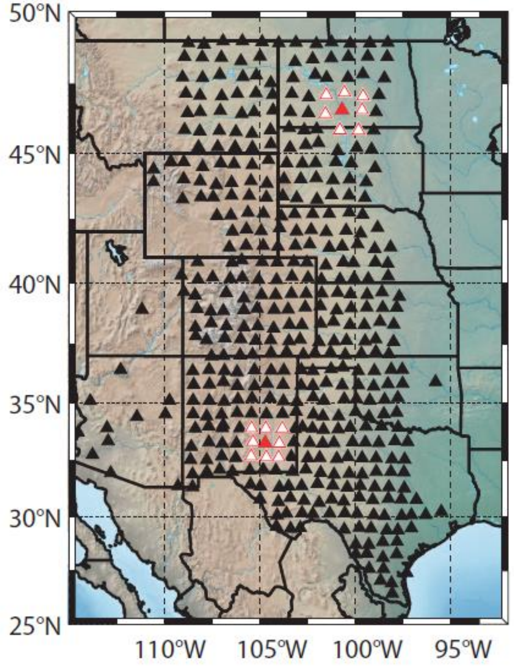


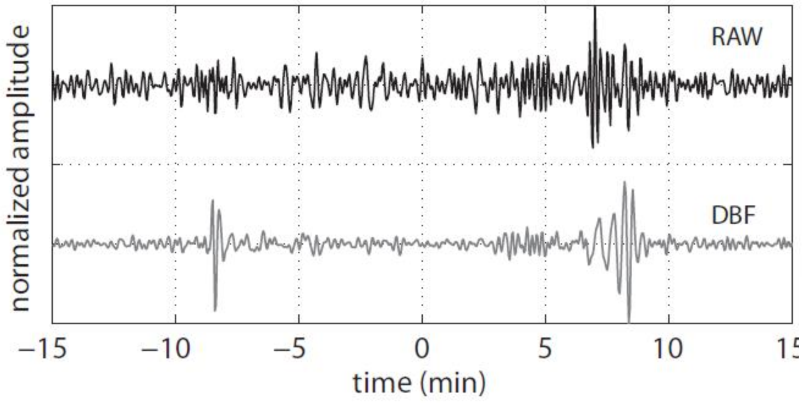
Data Selection

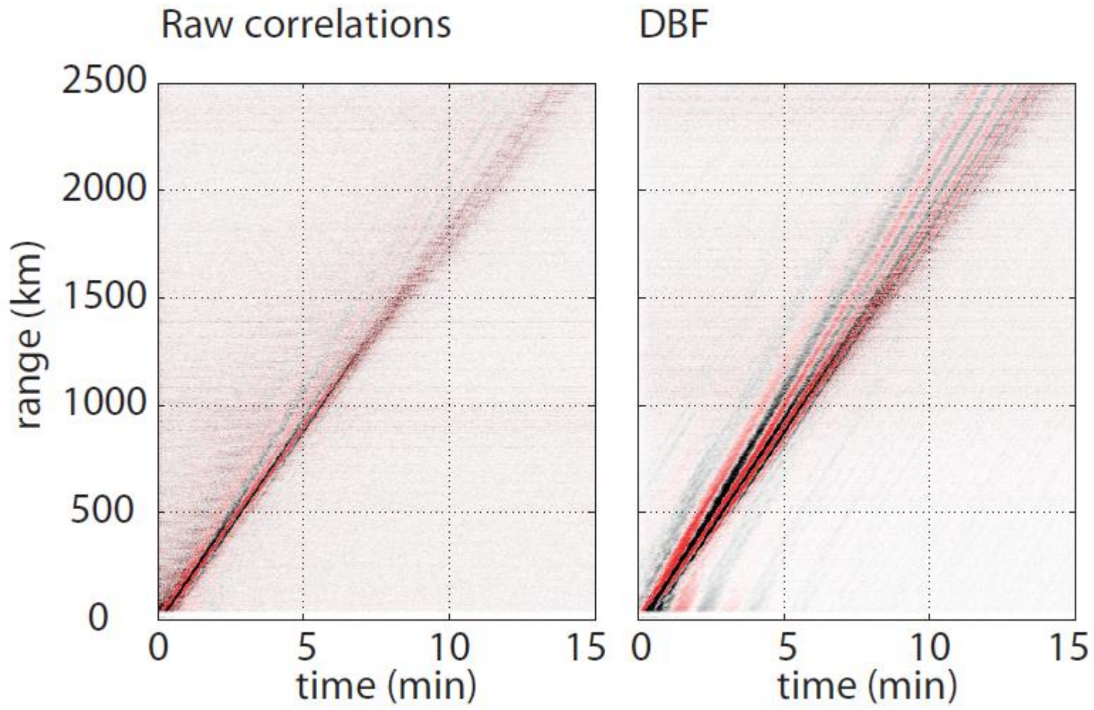
- Transportable array (USArray)
- 3 months (winter): Nov. 2009 to Jan. 2010
- 465 broadband stations

P. Boue, M. Campillo, P. Roux, … ISTerre

DBF + Ambient noise :
Cross-correlations instead of active Sources



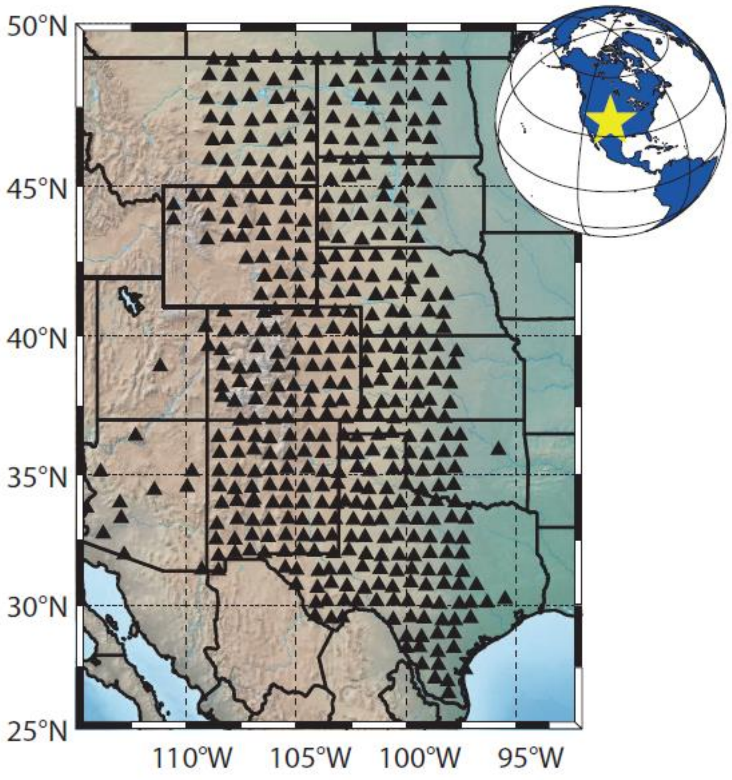


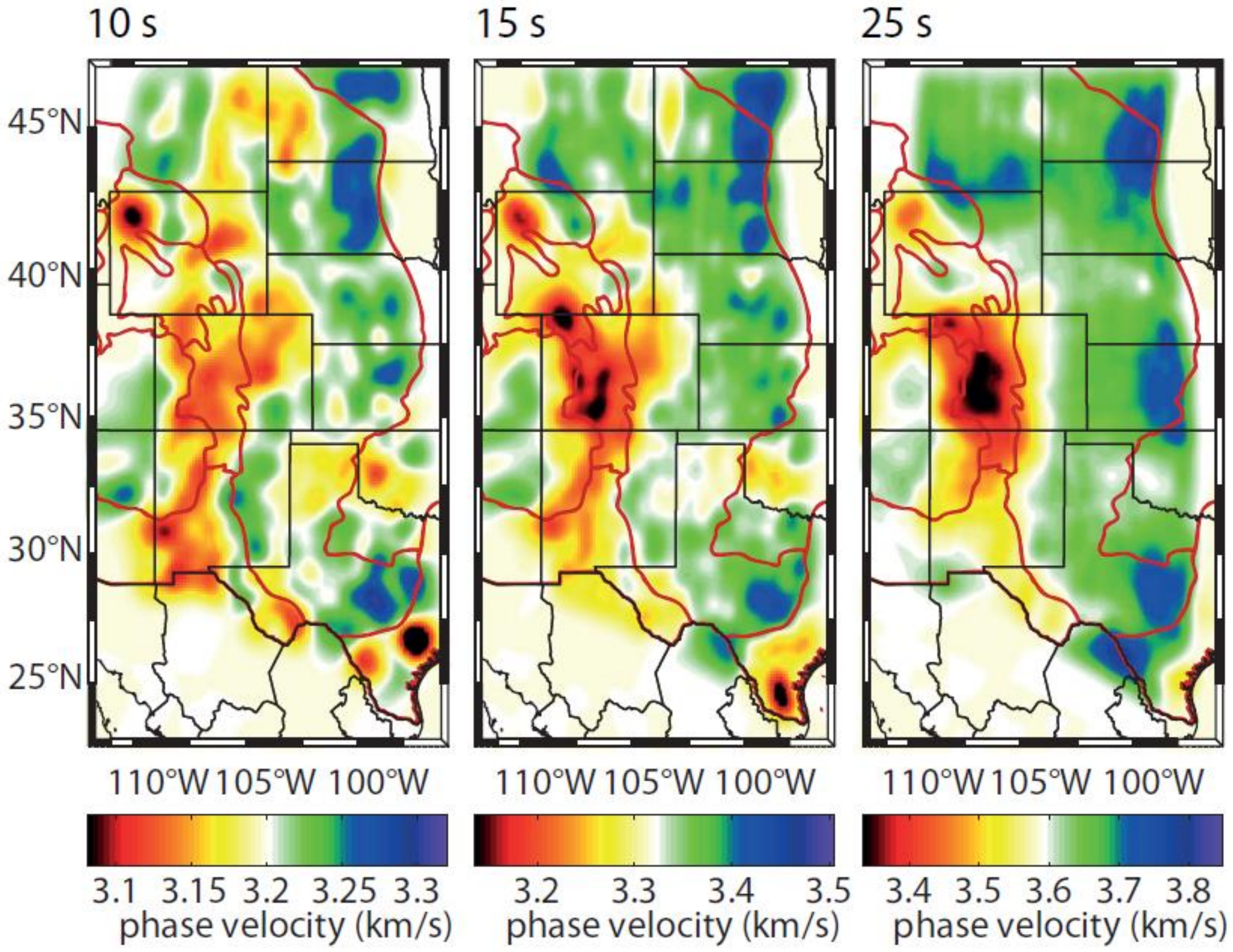


Increase of SNR

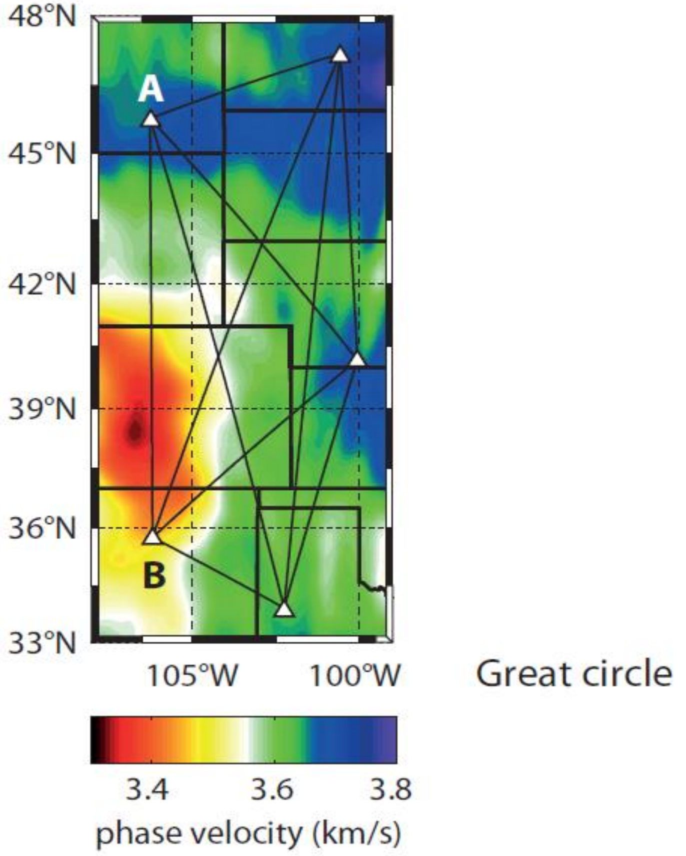
Boue et al, JGR, 2014

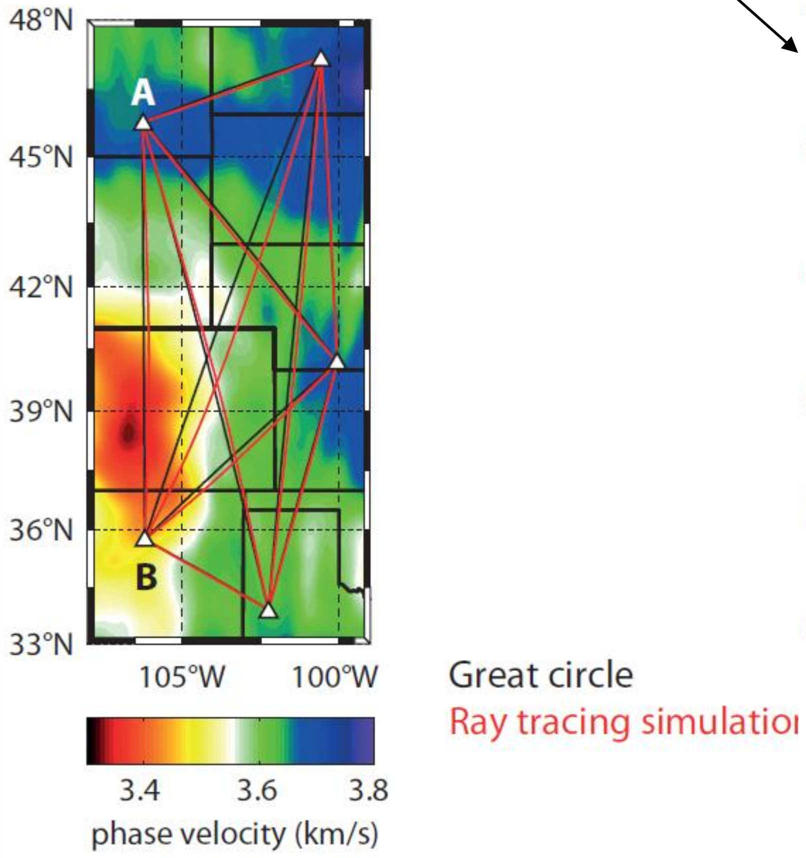
DBF with Ambient noise : Surface wave Inversion on a large Bandwidth

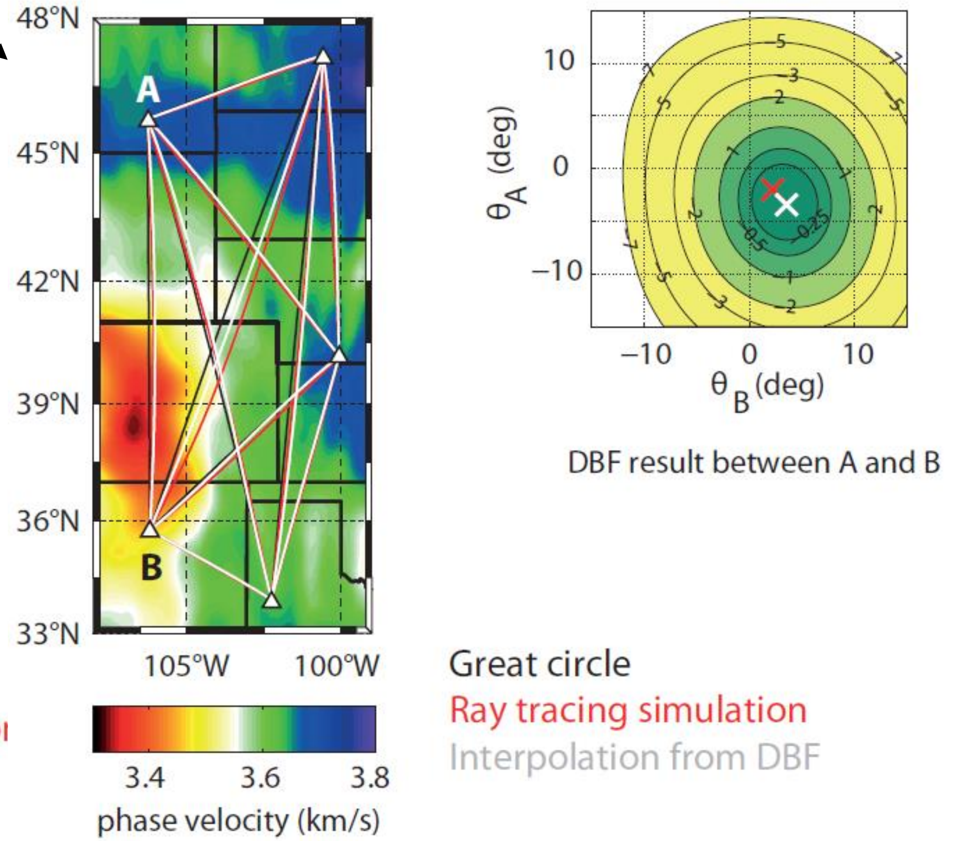




DBF + Ambient noise :
The Azimuthal angles are relevant!

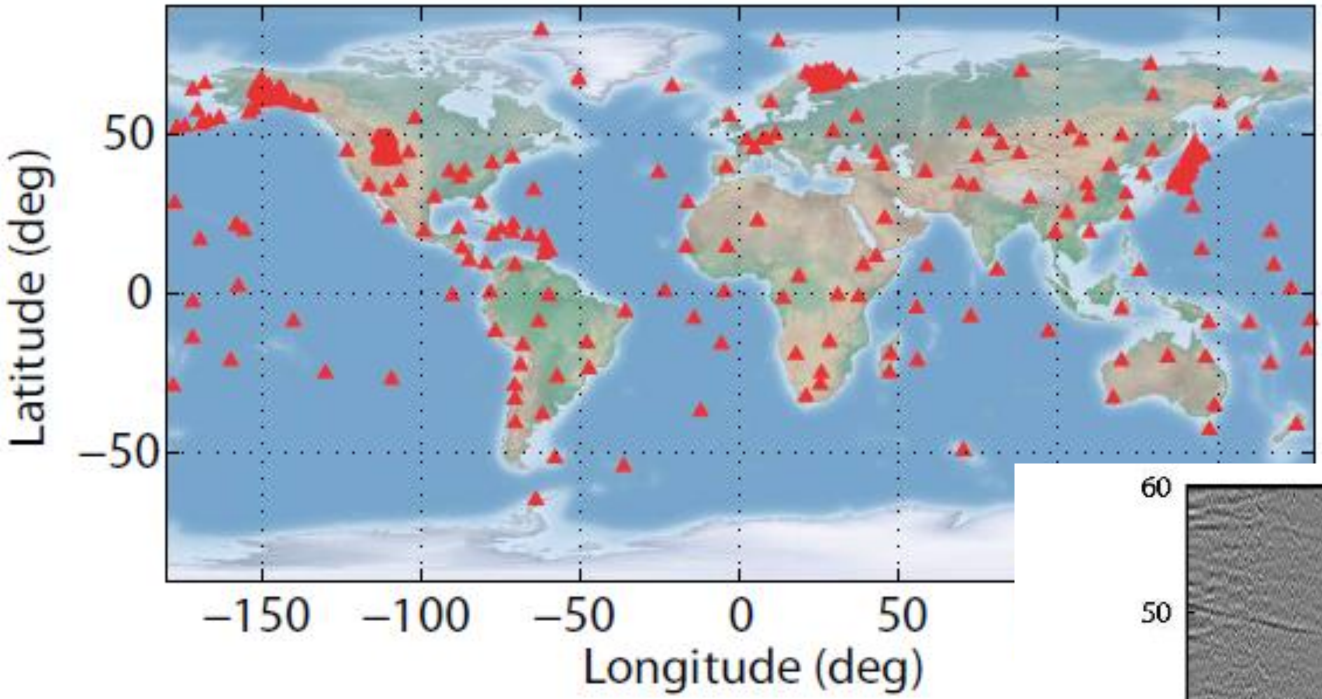


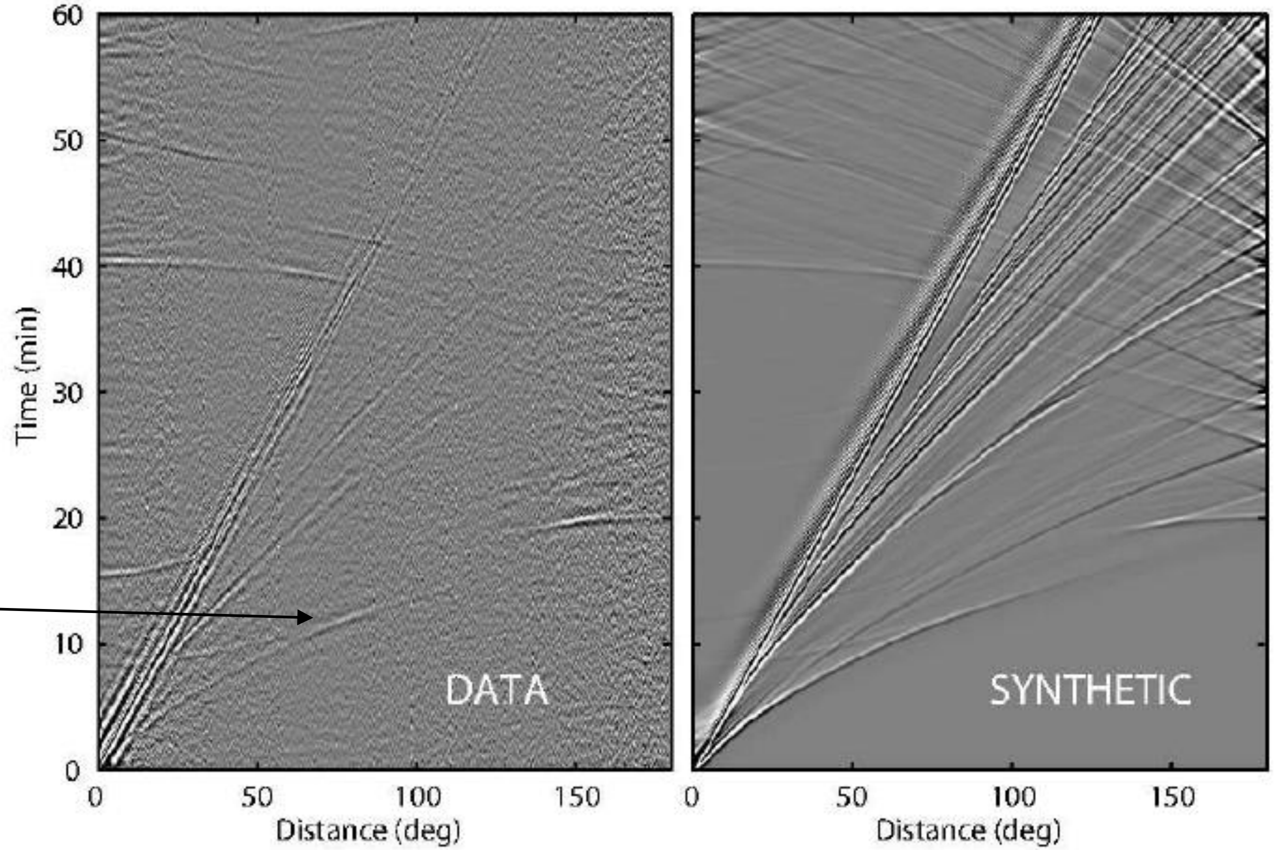




Boue et al, JGR, 2014

And finally DBF + Ambient noise for Global seismology…

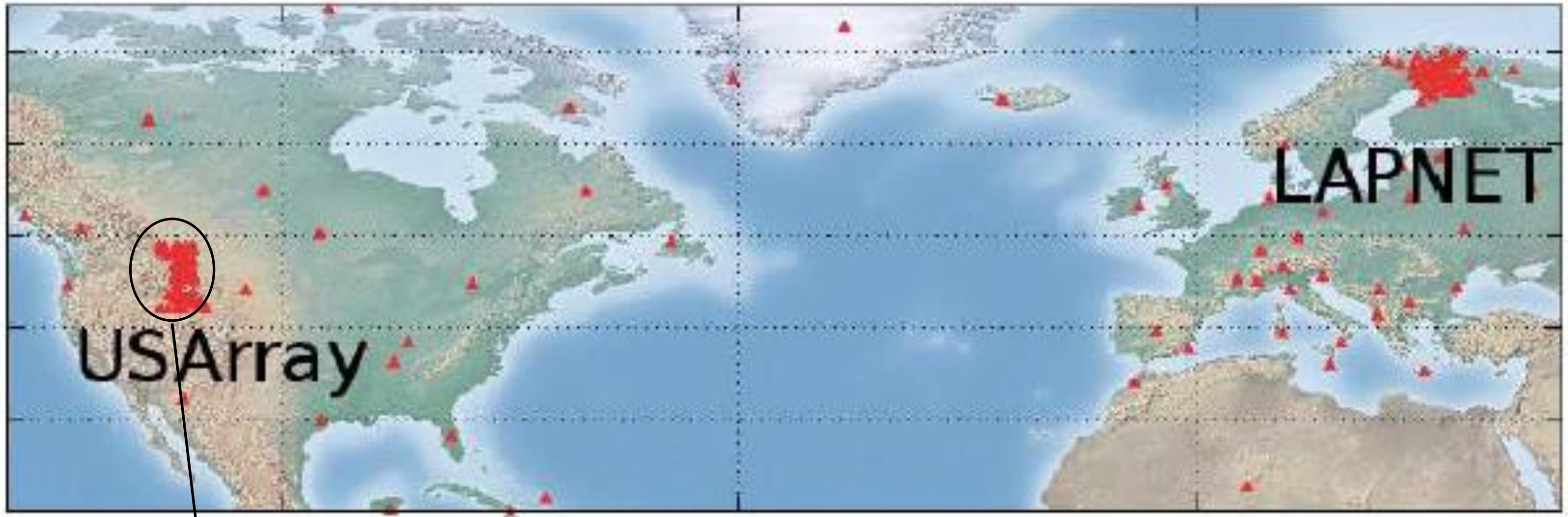


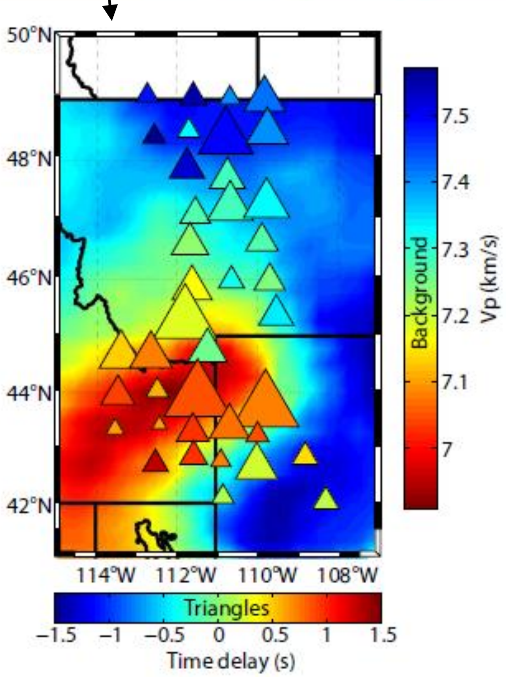


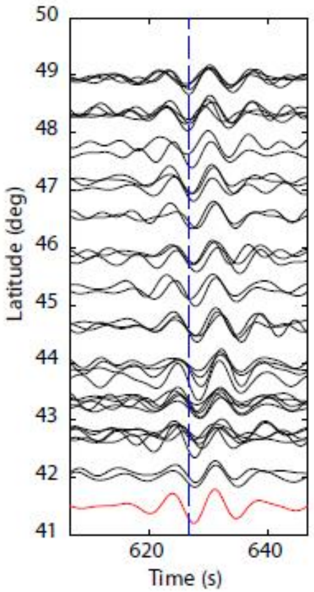
Stack on a lot of station pairs

Poli et al, Science, 2012
Boue et al, GJInt, 2013

DBF + Ambient noise + Body Waves on dense Networks







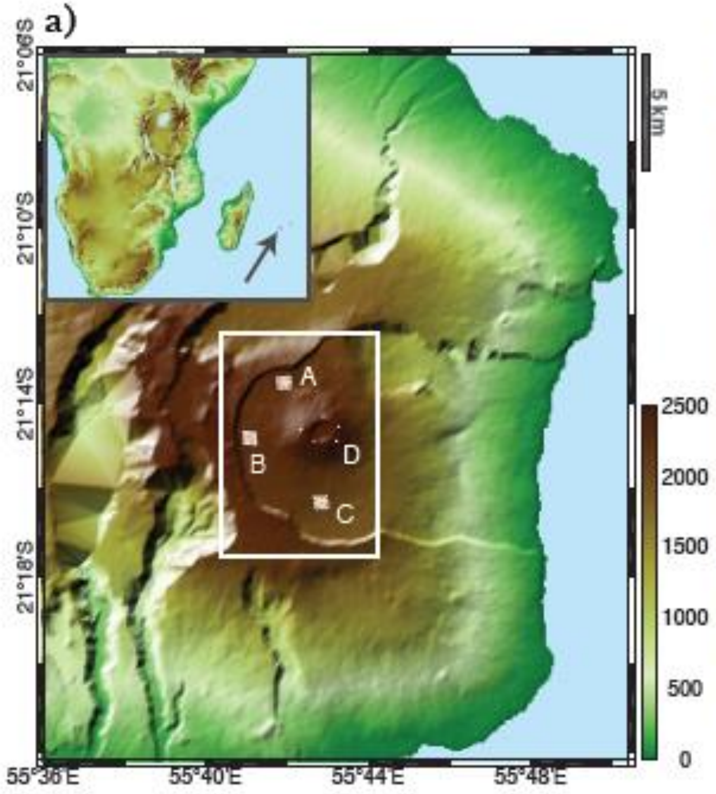
Travel Time Anomalies between LAPNET and a Part of USArray

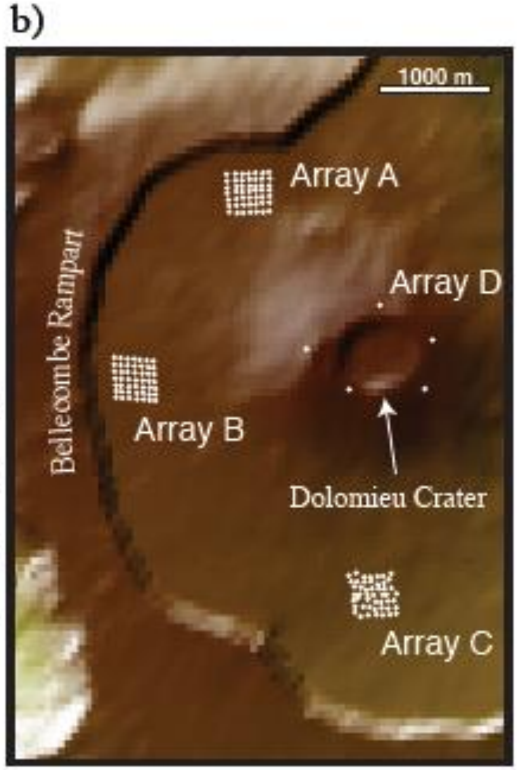
- Small array aperture and weak heterogeneities under LAPNET (Poli et al., 2013) → **Average seismograms in Finland**
- **Comparison** with Vp tomography from Shen et al. (2013)

Boue et al, GJInt, 2013

Future / Present work : Experimental Design for DBF processing (1)

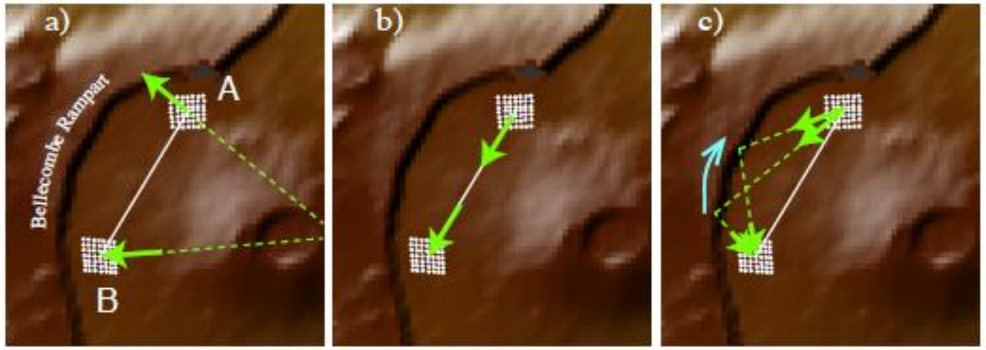
Piton de la Fournaise Volcano - July 2014





Three arrays made of 7 x 7 geophones
4 weeks continuous recording

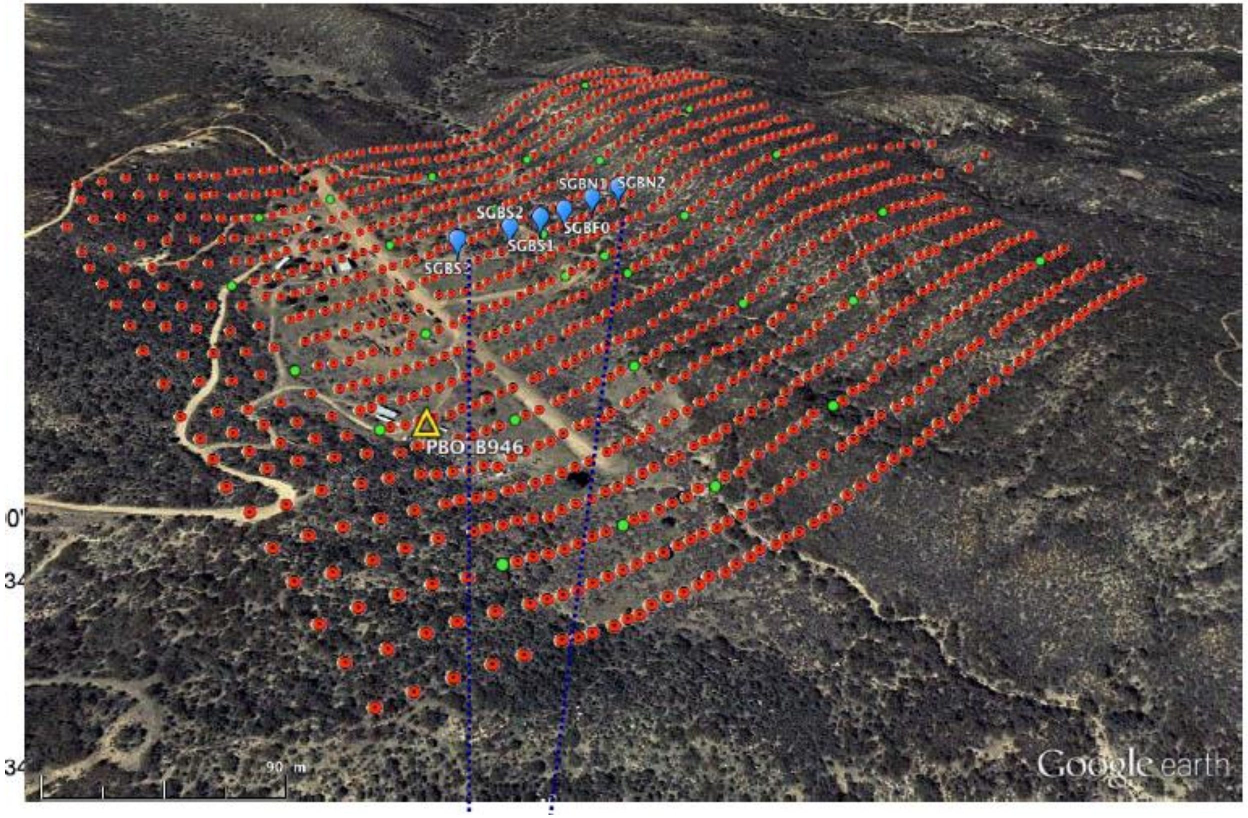
Wave extraction from DBF



Boue, Nakata et al, in preparation

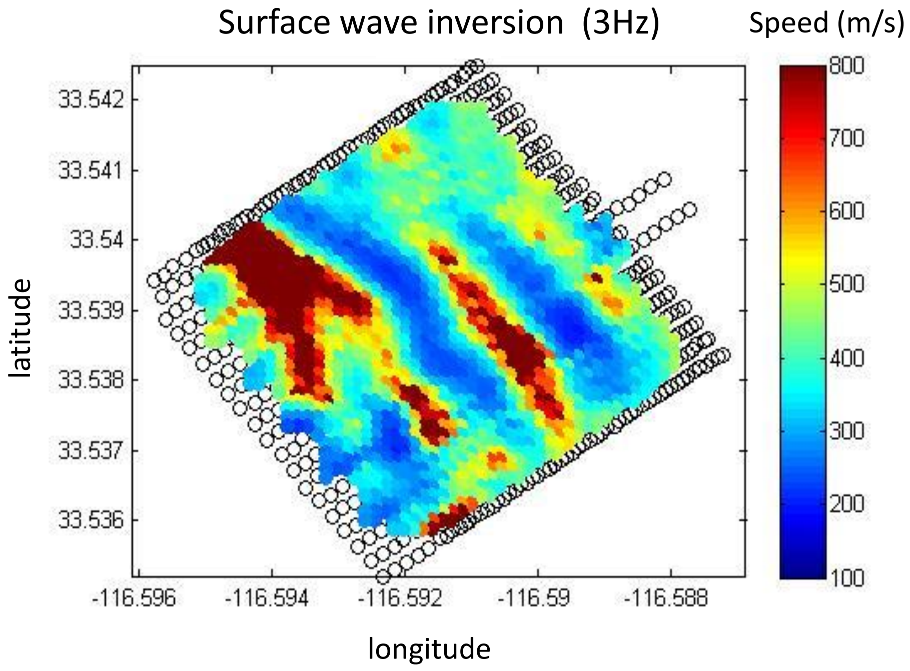
Future / Present work : Experimental Design for DBF processing (2)

San Jacinto Fault (CA) – Dense array data –June 2014



600 m x 600 m – 1108 geophones – 4 weeks continuous recording

Surface wave inversion (3Hz)



Ben Zion et al, GJInt, 2015

Conclusion

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