# VIRGO, SEISMIC NOISE, ENVIRONMENTAL SEISMOLOGY AND TIME REVERSAL IMAGING

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**Carène Larmat**, LANL, New Mexico, U.S.A.

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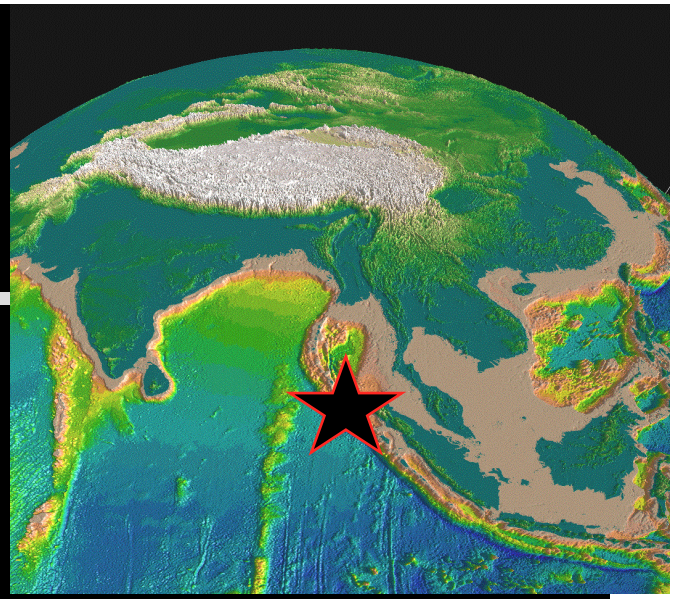
# Background



-**New Data: Seismic noise:**

**Microseismic** (1-20s), **Hum** (T>150s)

-**Time reversal Mirrors (Fink's group)**

⇒**focusing; source imaging**

⇒Cross-correlation techniques **(Sun, Earth)**

-Development of **numerical techniques**:SEM (spectral element method)

-Motivation: ***Big Sumatra-Andaman earthquake 12/04***

***Haiti, 01/10; Chile, 02/10; Japan-Tohoku, 03/11***

# OUTLINE

- Data: Earthquake, Seismic noise (seismic Hum; microseismic noise; cross-correlation techniques)
- Time-reversal technique (Numerical Techniques SEM)
- **Scientific Issues**:

- Seismic tectonic sources: Sumatra-Andaman earthquake…
- Time reversal concept applied to seismic source imaging
- "Exotic sources": Glacial earthquakes

- Similarities: Time reversal-cross correlations techniques

- Structure of the Earth from Seismic Hum
- Temporal changes of anisotropy in seismogenic zones (Parkfield earthquake)
- Interest in Virgo Interferometer data

# OUTLINE

- **Data (Seismic source) + Instrument (Seismometer) => Observations (seismograms)**
- Seismic noise (microseismic noise 1<T<20s; seismic Hum,T>150s; 1998)
- Time-reversal technique (Normal Mode theory, Numerical Techniques SEM, C-SEM)
- **Scientific Issues**:

- Seismic tectonic sources: Sumatra-Andaman earthquake…
- Time reversal concept applied to seismic source imaging
- "Exotic sources": Glacial earthquakes

- Similarities: Time reversal-cross correlations techniques

- Structure of the Earth from Seismic Hum
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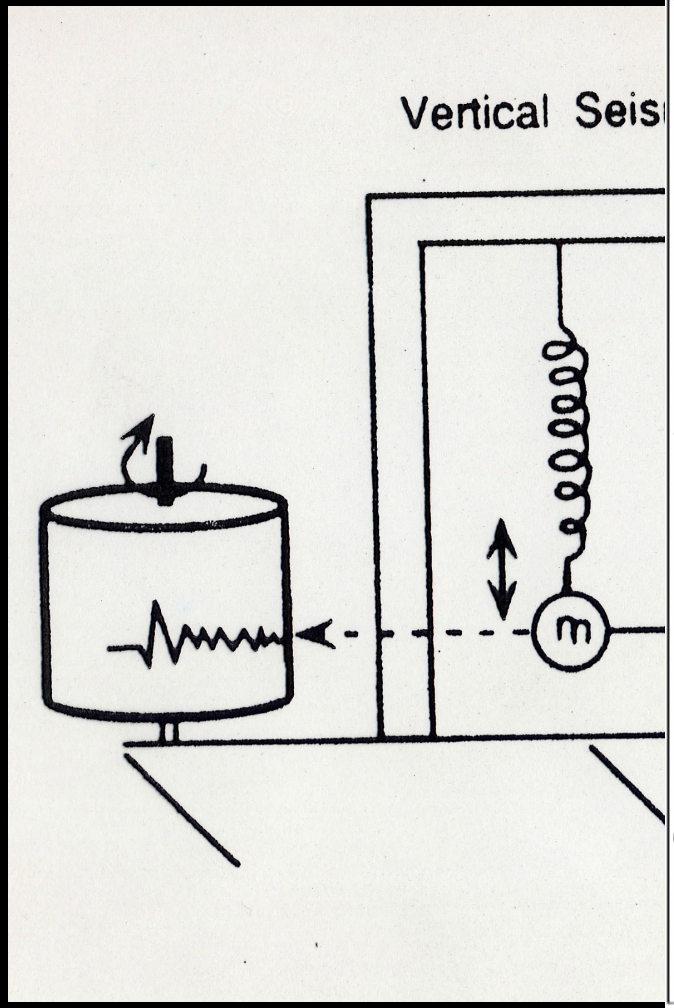
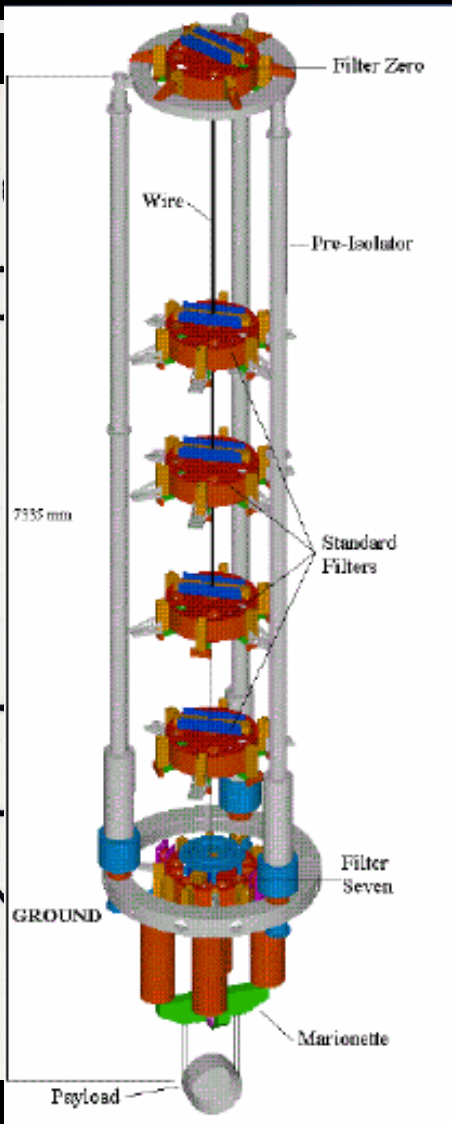
- Interest in Virgo Interferometer data

# Seismometers

- Seismoscope (China -100BC)



# Seismometers

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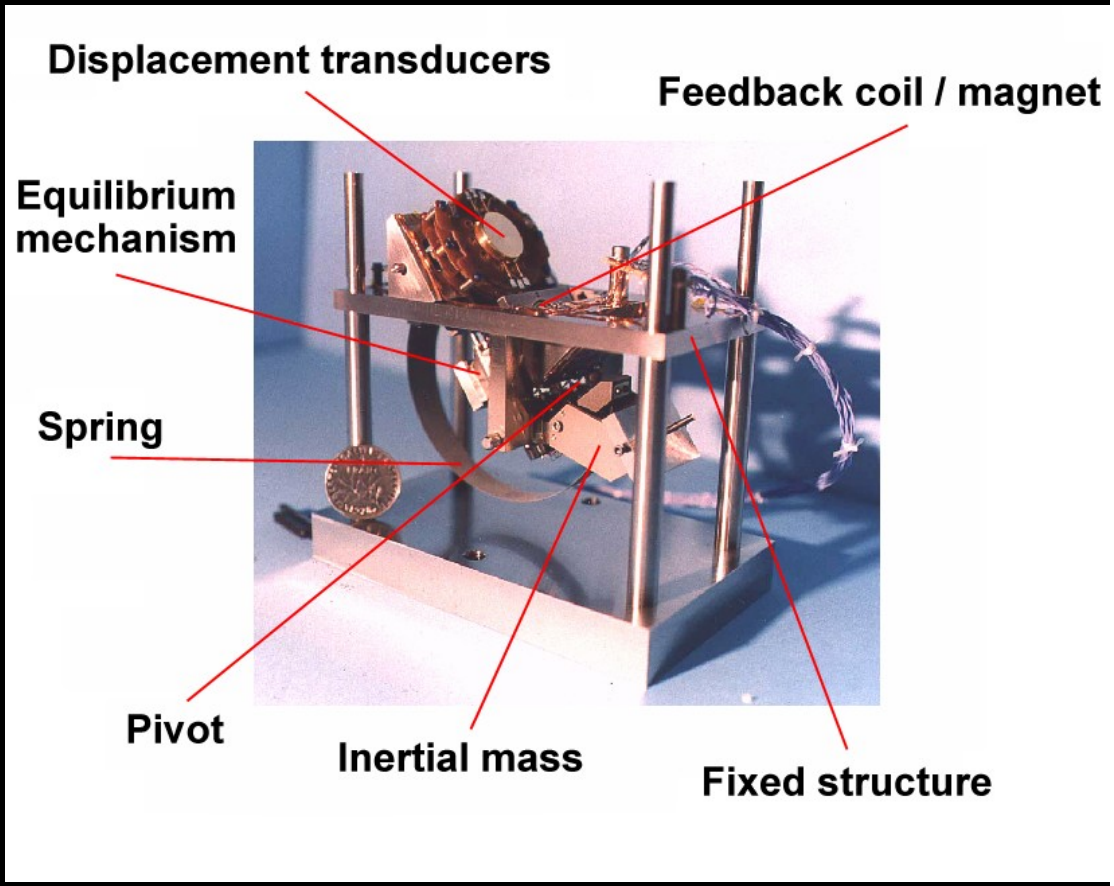


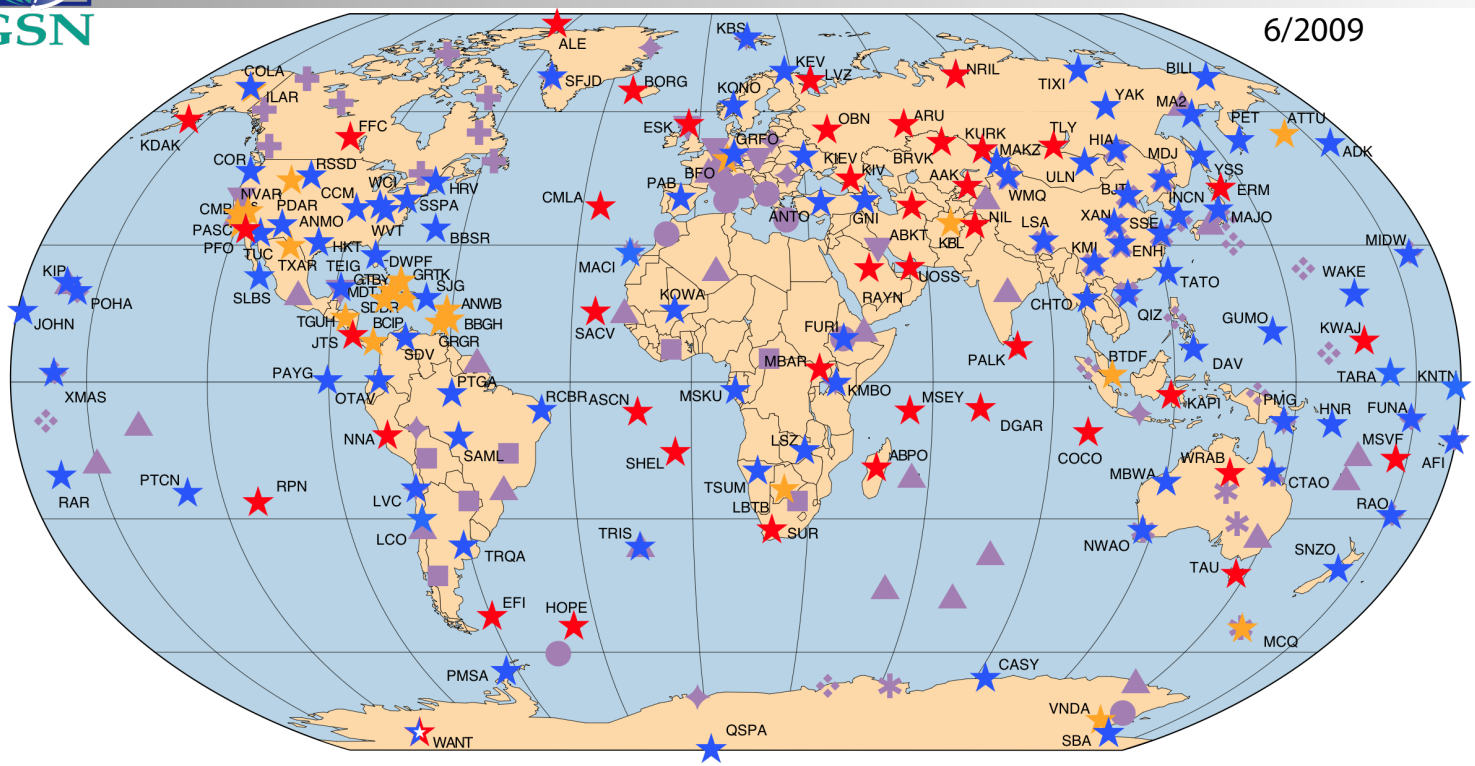

Broadband seismometer (1mHz-10Hz) (Cacho, 1998)

# GLOBAL SEISMOGRAPHIC NETWORK

## FEDERATION OF BROADBAND DIGITAL SEISMIC NETWORKS (FDSN)

GSN

6/2009



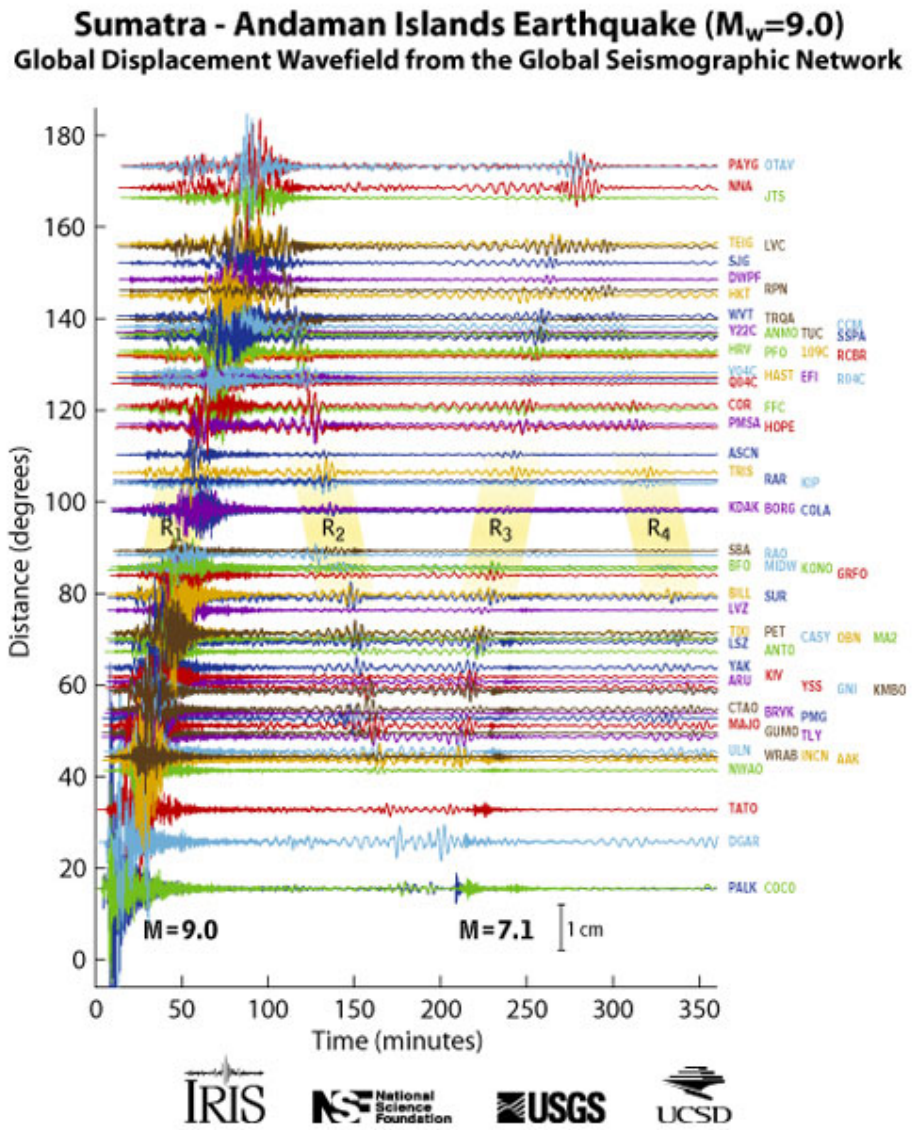

★ IRIS / IDA Stations ★ IRIS / USGS Stations ★ Affiliate Stations

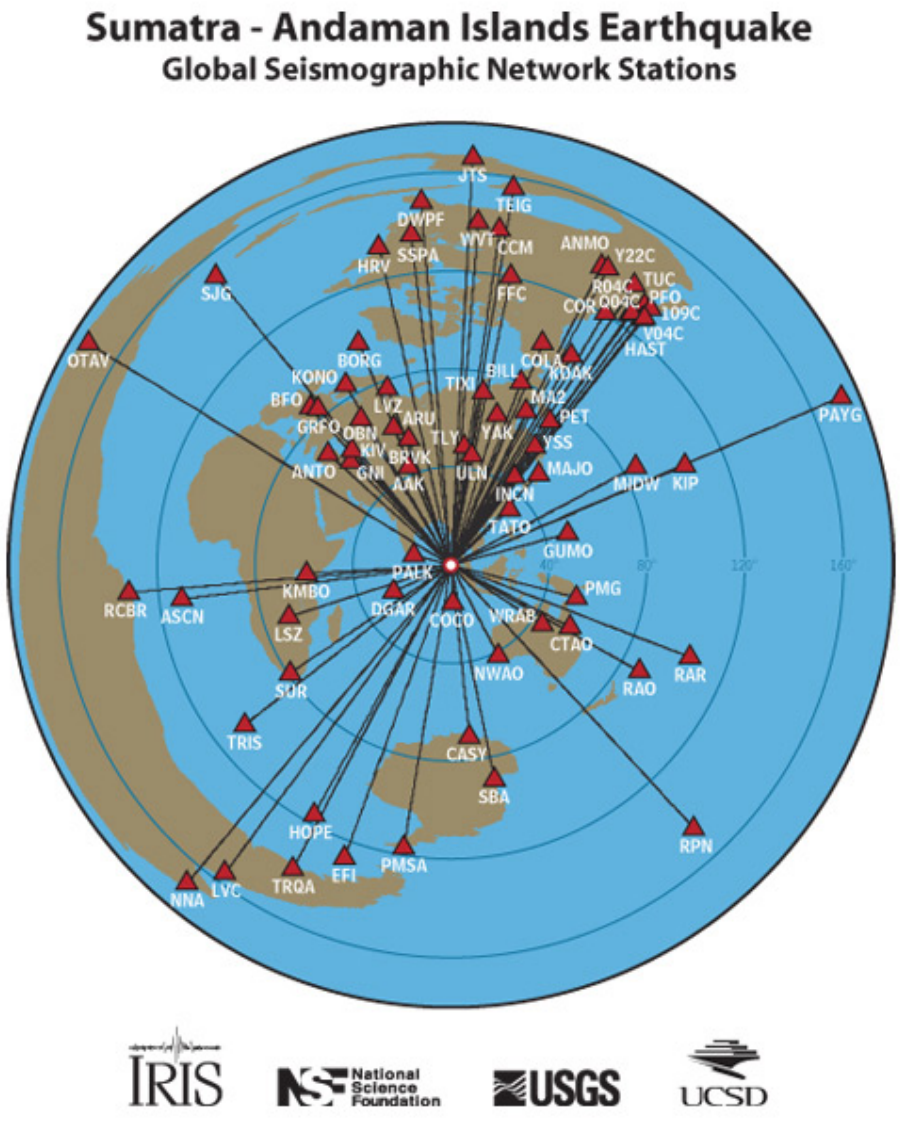
☆ Planned Stations

Australia Canada France Germany Italy Japan U.S. China Spain Other

# *Experimental field*

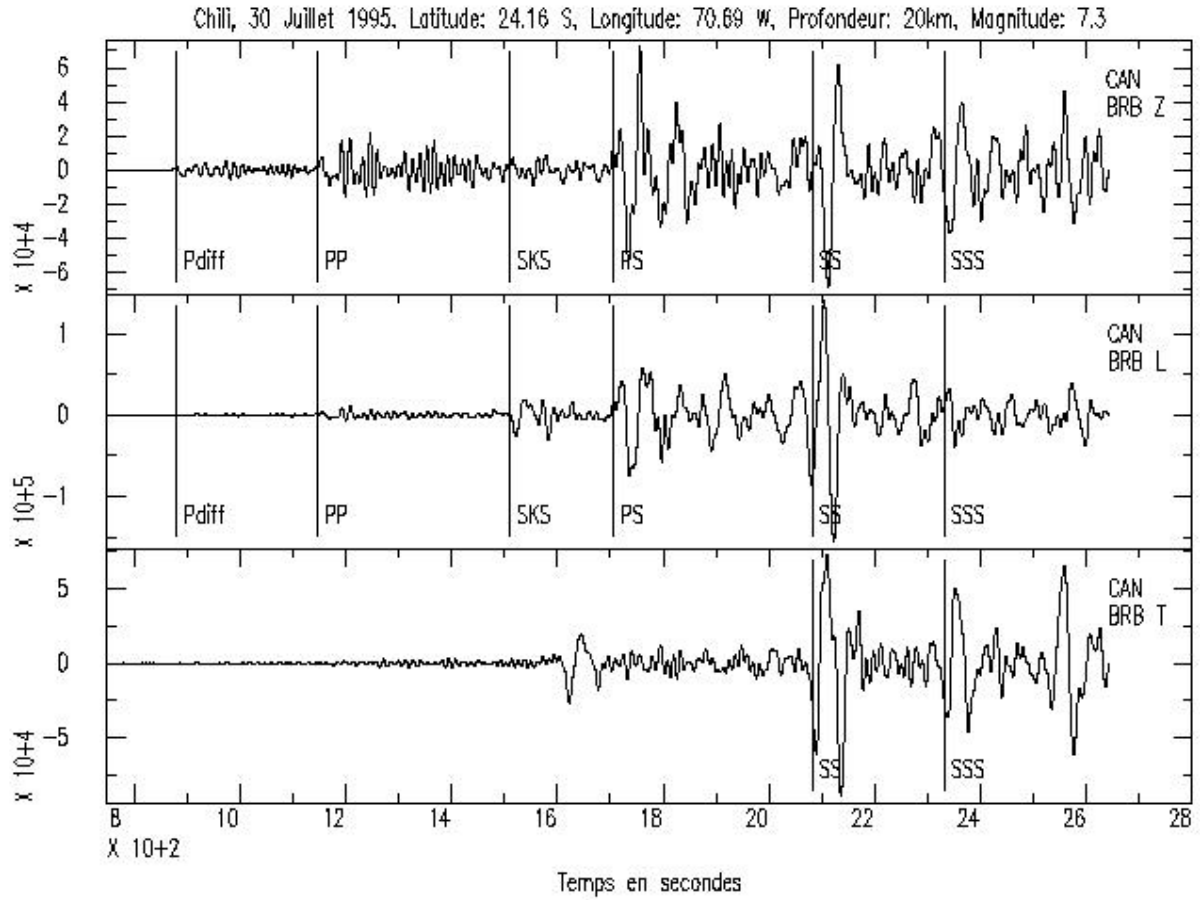
# *Data: seismograms*



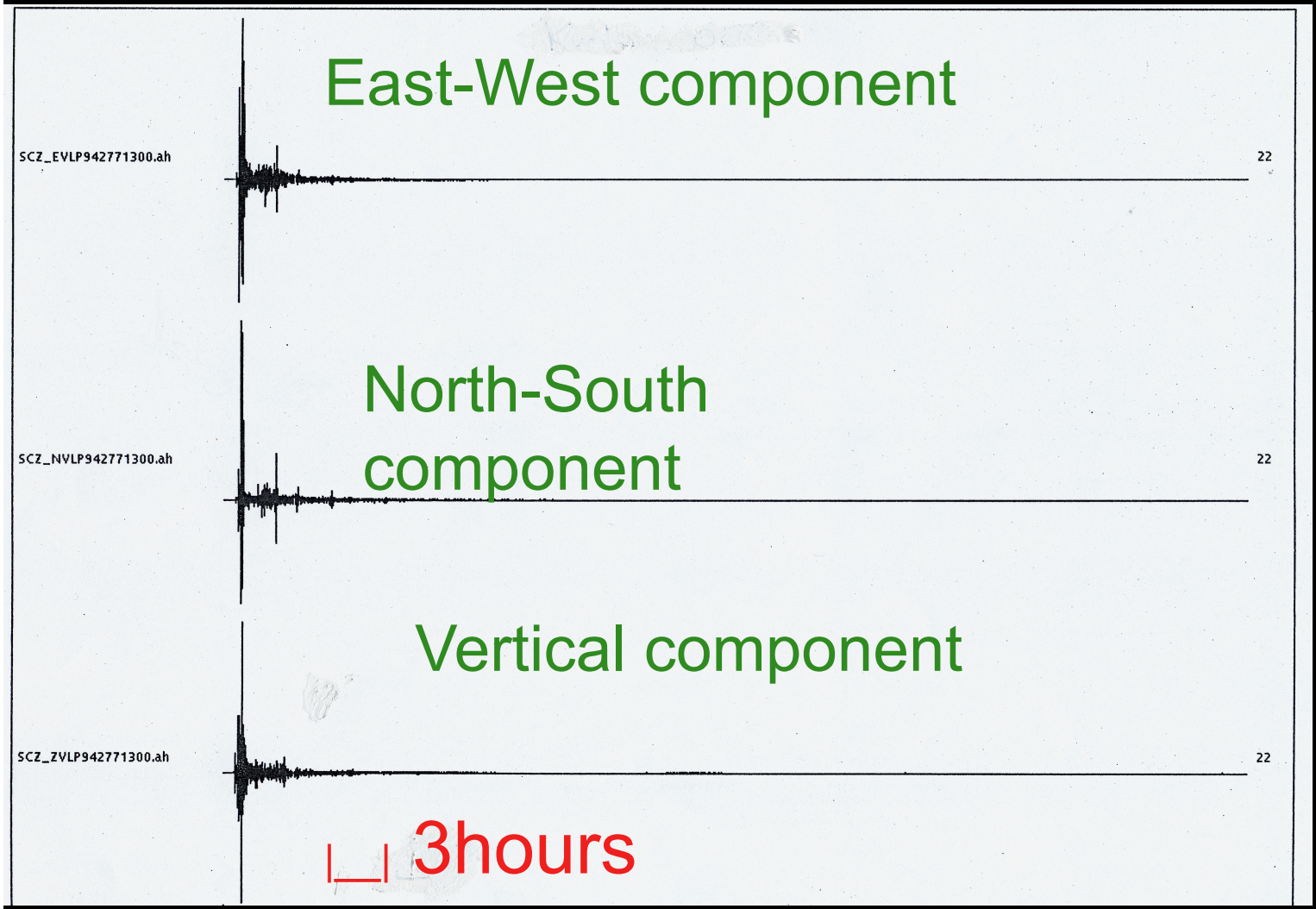



# 3 components
# Frequency range: 1mHz-10Hz
# Period range: 0.1-1000s

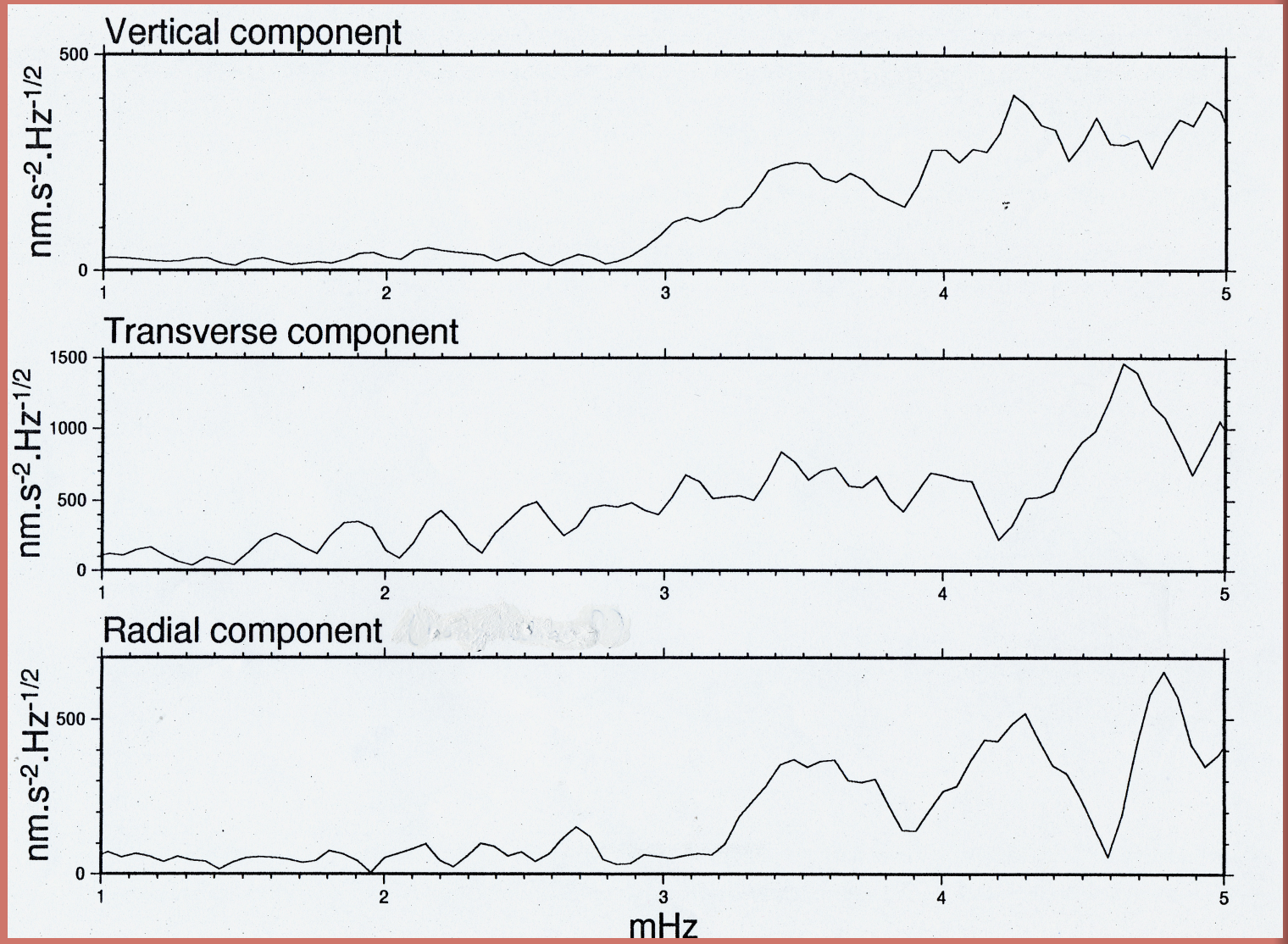
Chile July 30, 1995, Ms=7.3



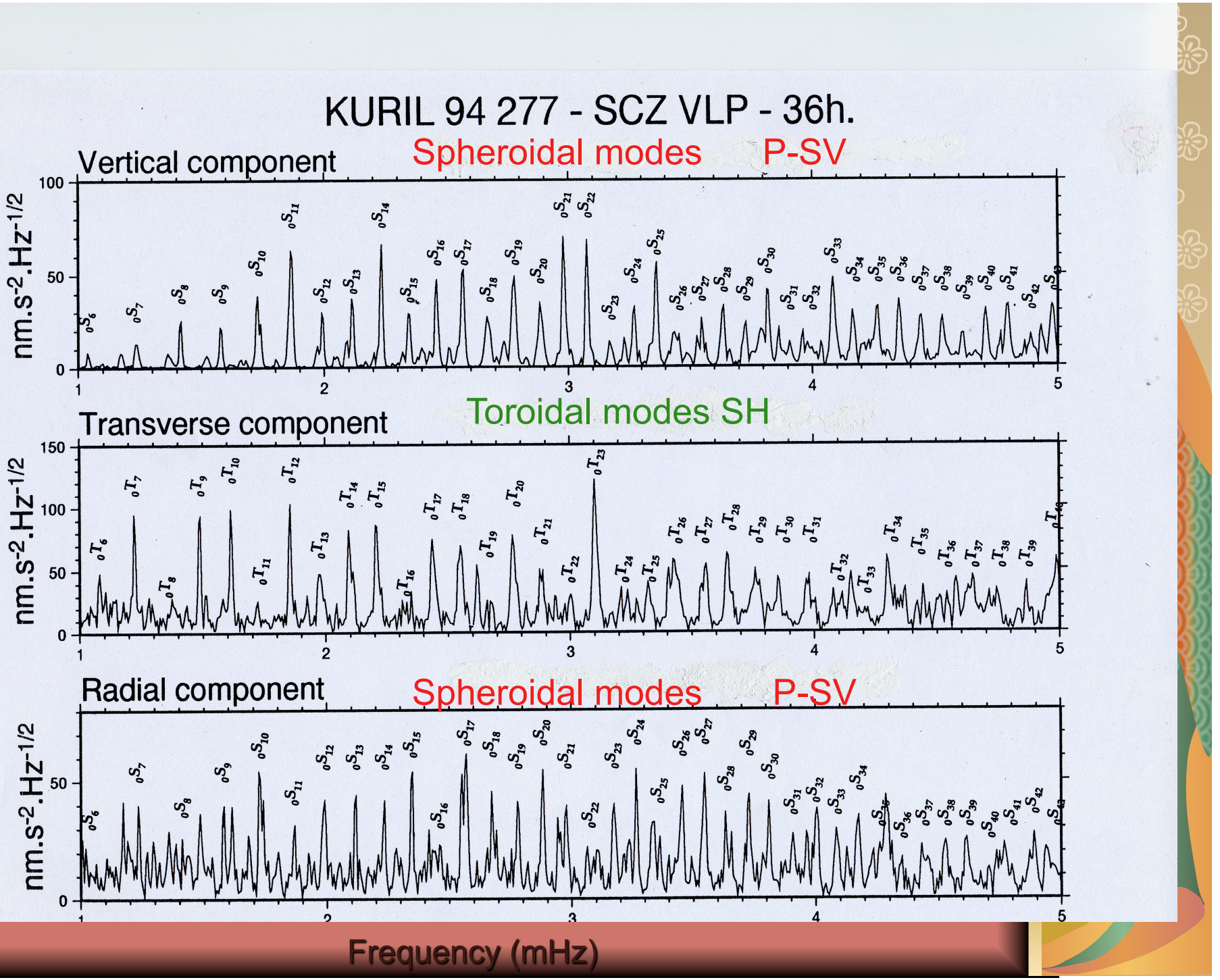
# Kurils islands 1994-277 Ms=8.3



# Kurils islands 1994-277 SCZ-VLP Spectra 3 hours



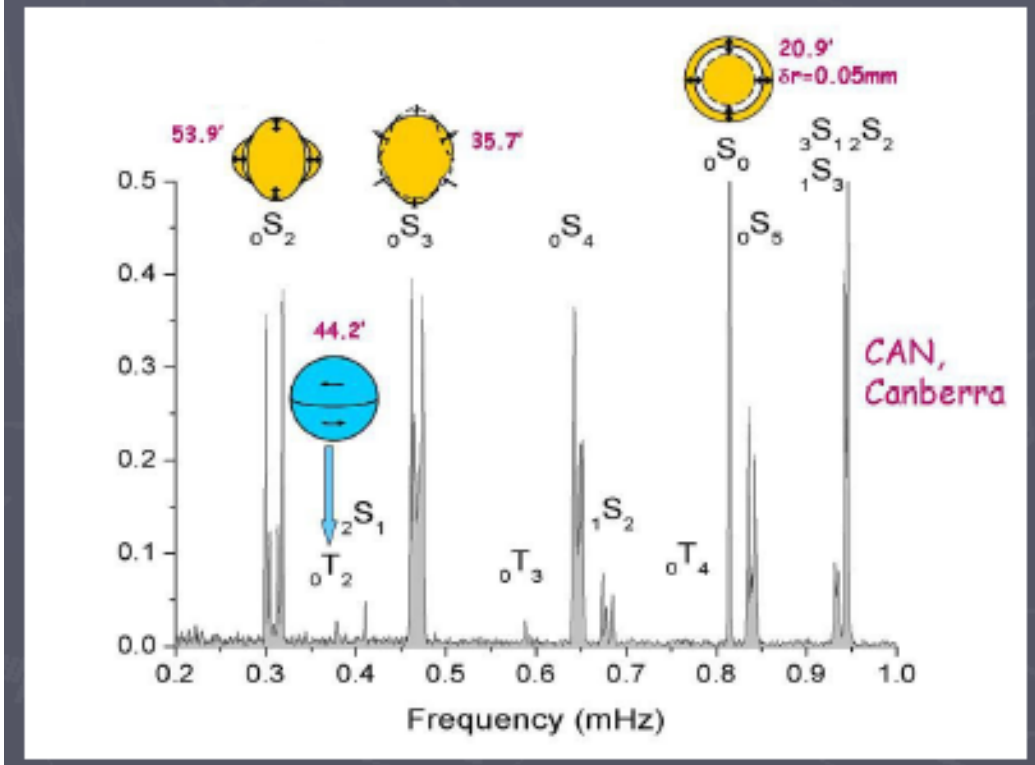

Frequency (mHz)

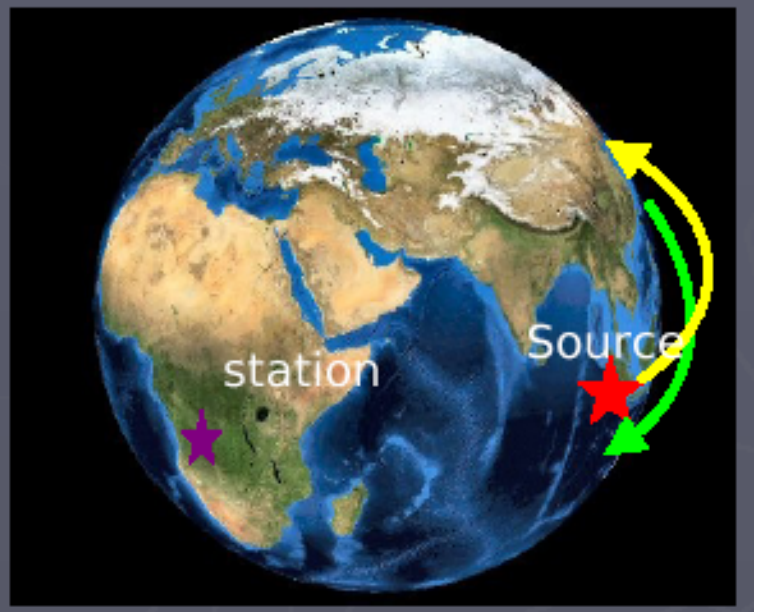

KURIL 94 277 - SCZ VLP - 36h.
Vertical component
Spheroidal modes P-SV
Transverse component
Toroidal modes SH
Radial component
Spheroidal modes P-SV
nm.s-2.Hz-1/2
Frequency (mHz)

# What are normal modes ?

constructive and destructive interferences between surface waves

Standing waves




P-Sv Rayleigh waves waves

spheroidal

Sh Love

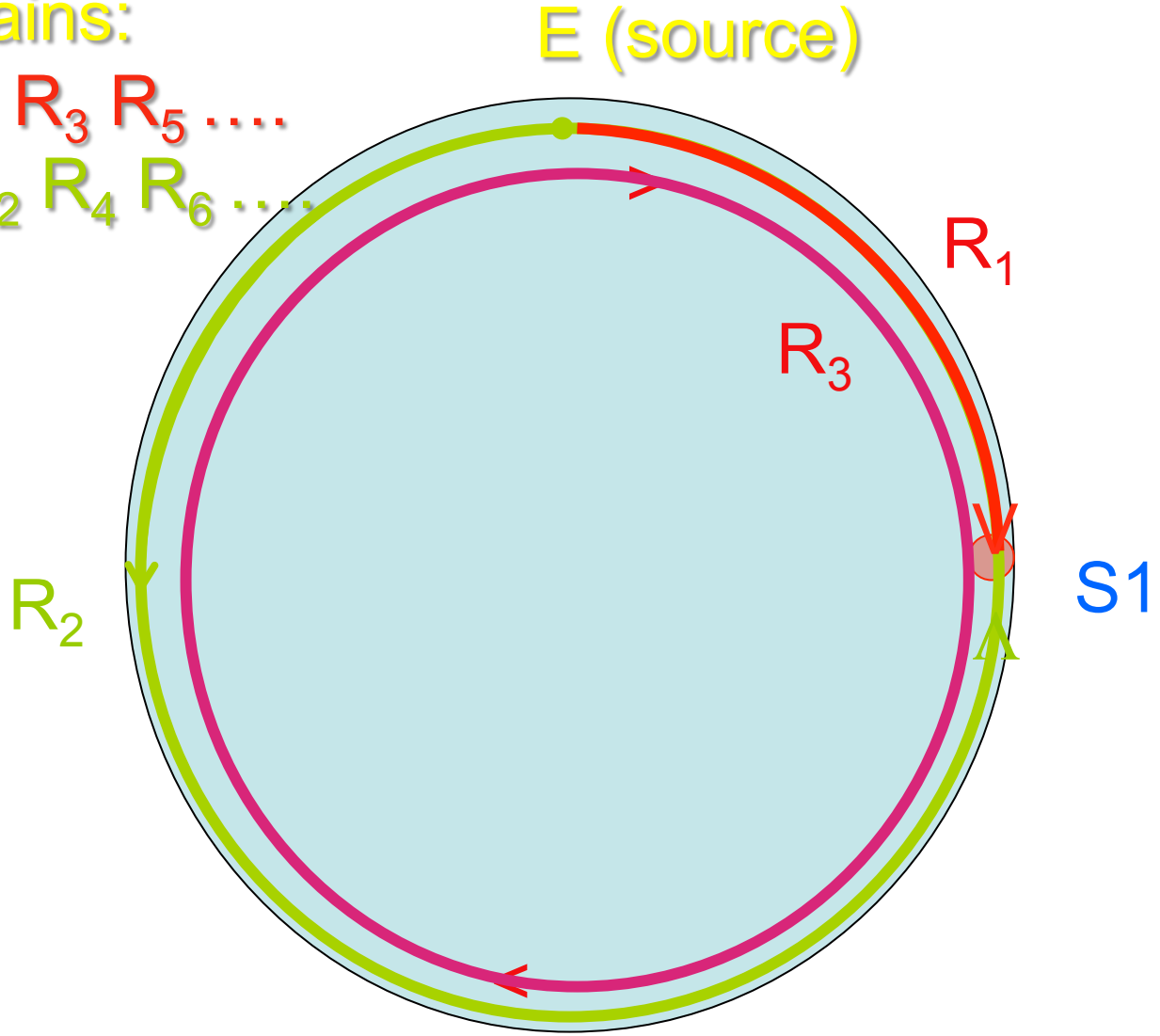
toroidal

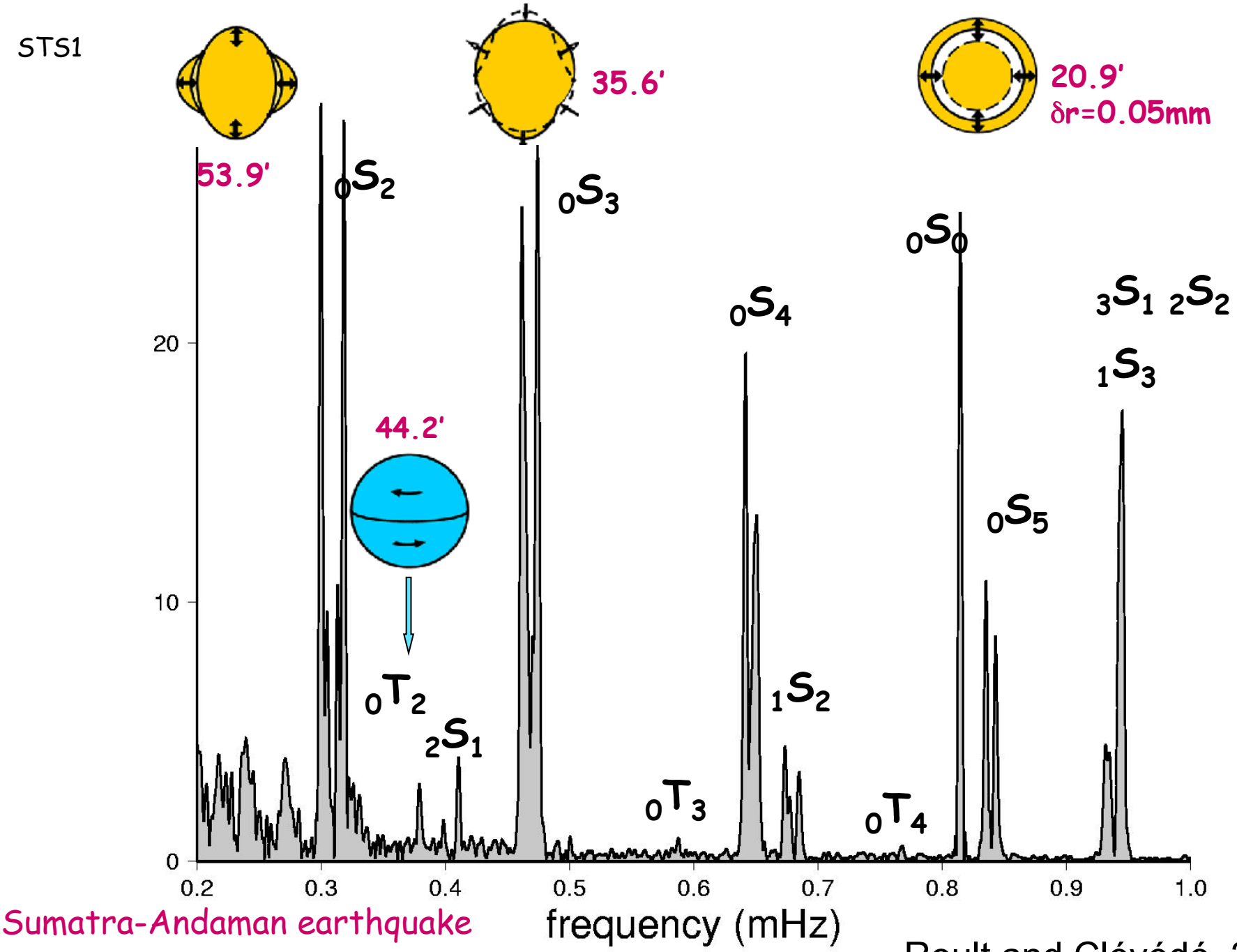
(Roult & Clévédé, 2005)

Wavetrains:

Odd $R_1$ $R_3$ $R_5$ ….

Even $R_2$ $R_4$ $R_6$ ….

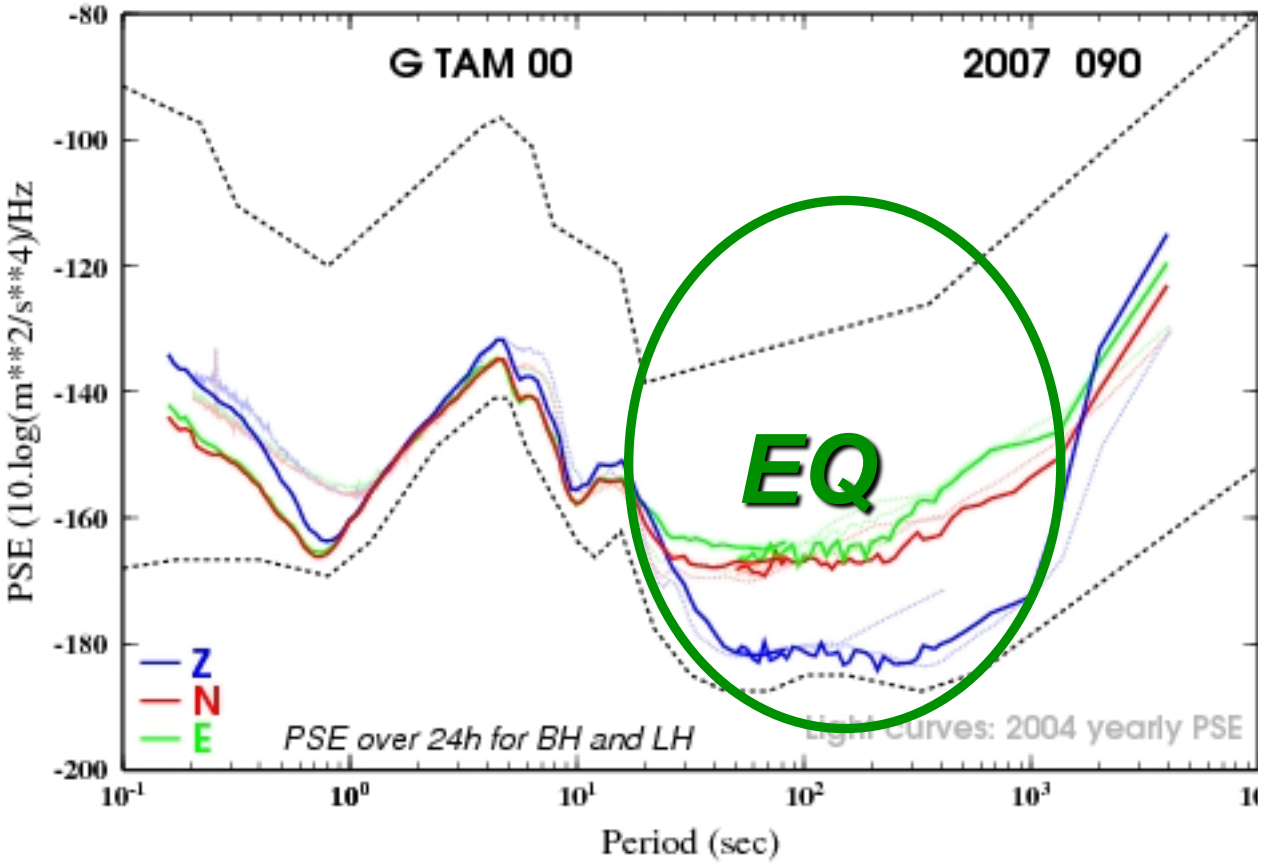





Sumatra-Andaman earthquake
26 December 2004

Roult and Clévédé, 2005

# BROADBAND SEISMOLOGY



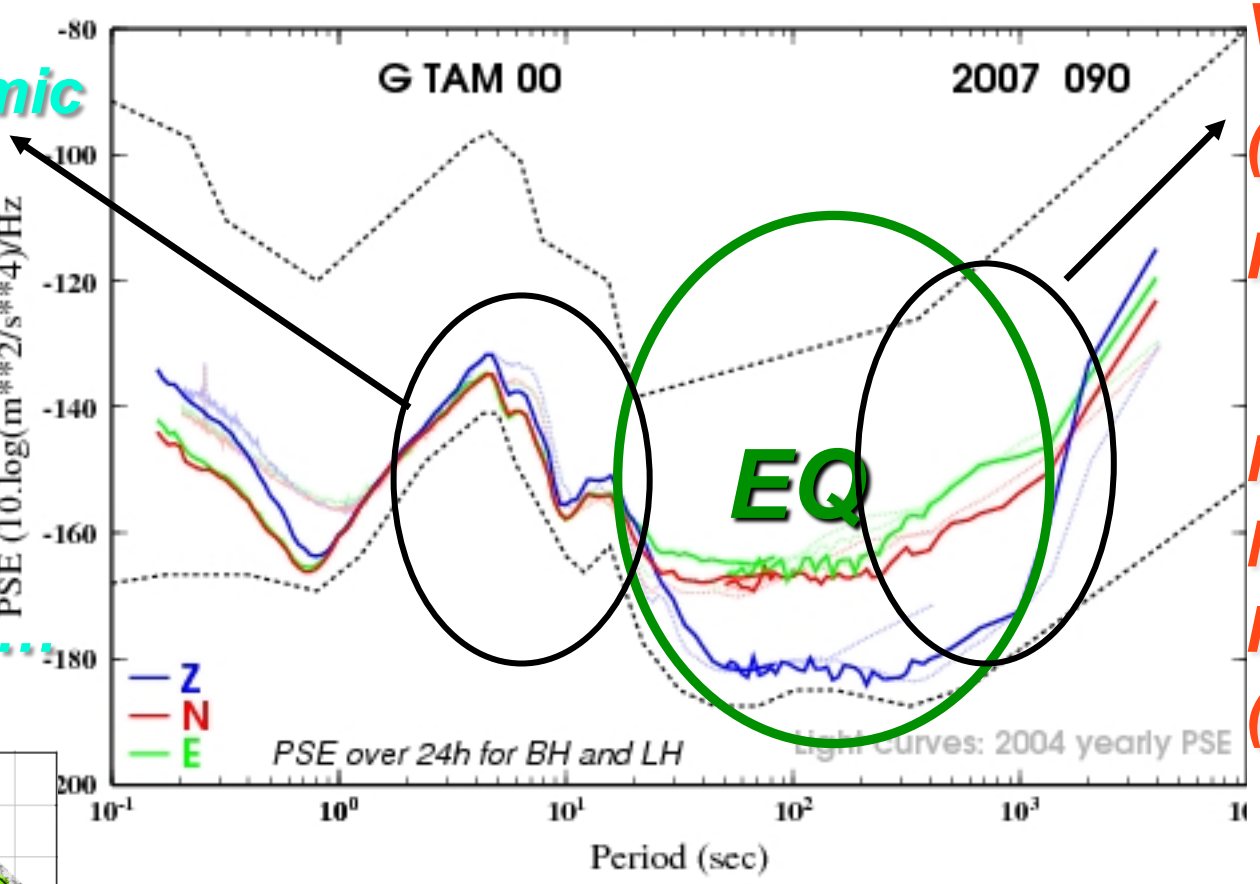

TAM (Tamanrasset, Algeria)

http://geoscope.ipgp.fr

# GEOSCOPE and Noise

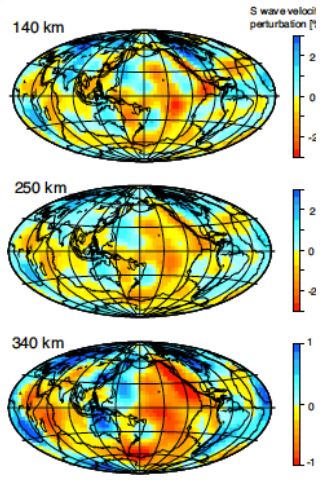
***Microseismic Noise***

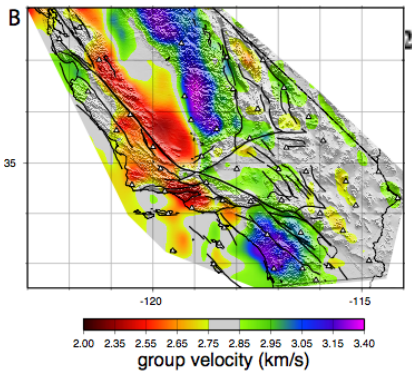
***Shapiro, Campillo, Roux, Brenguier,…***




***VLP Noise (transient, Hum, …)***

***Nishida, Montagner, Kawakatsu (2009)***




TAM (Tamanrasset, Algeria)

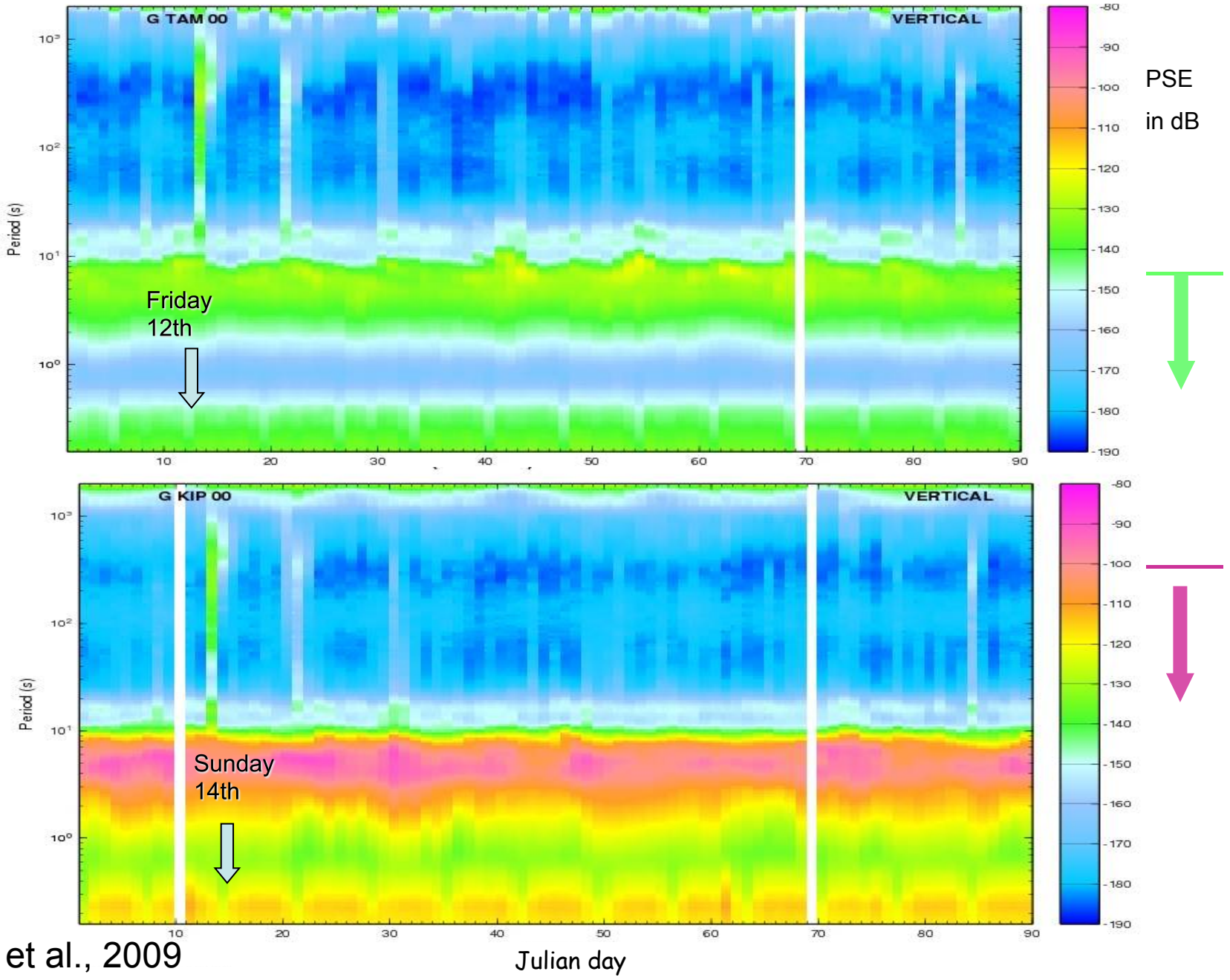
# Seismic Signal Daily variations (PSE in DB) in 2007 at 2 stations

TAM

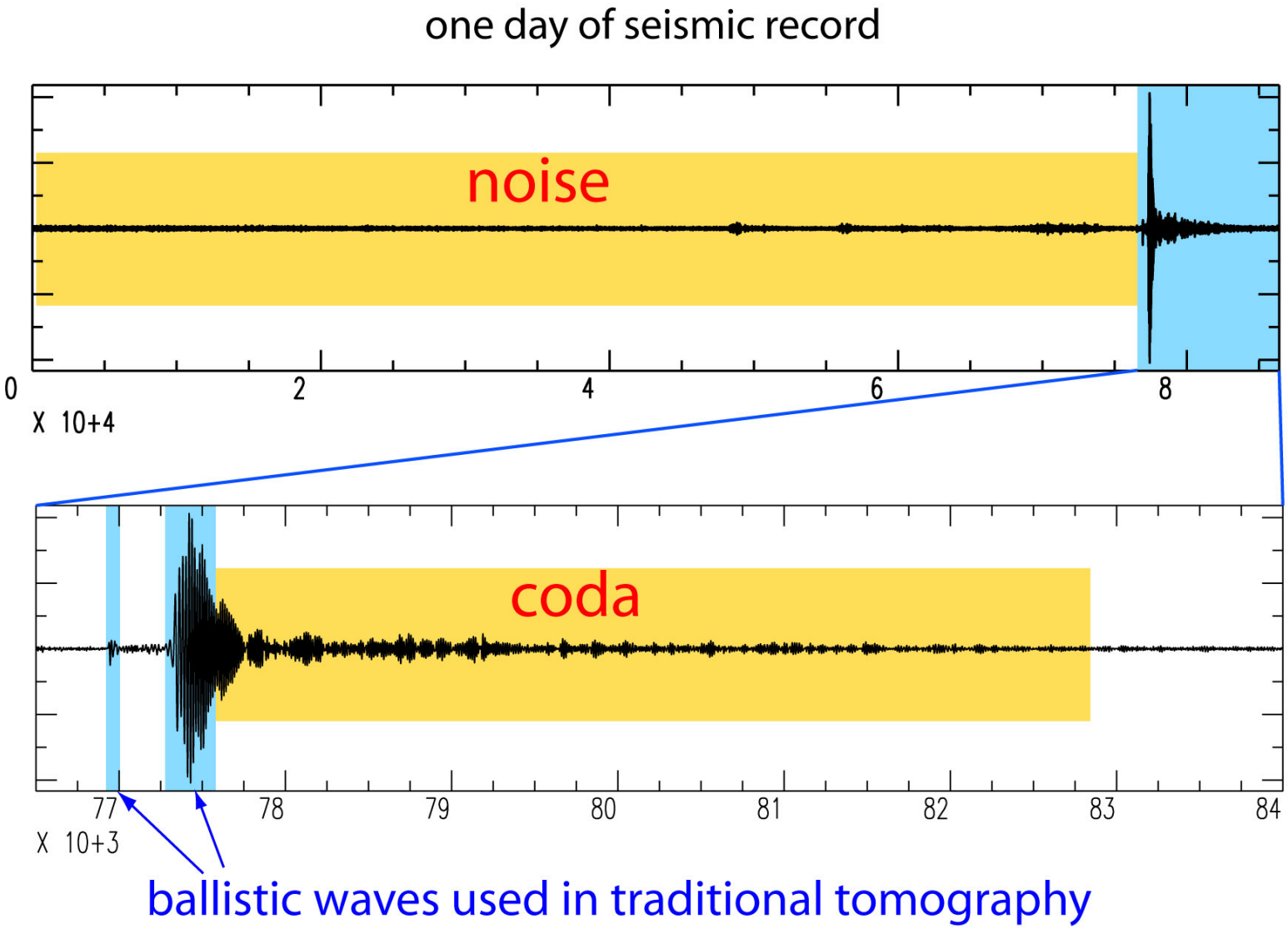
Algeria

KIP

Hawaï

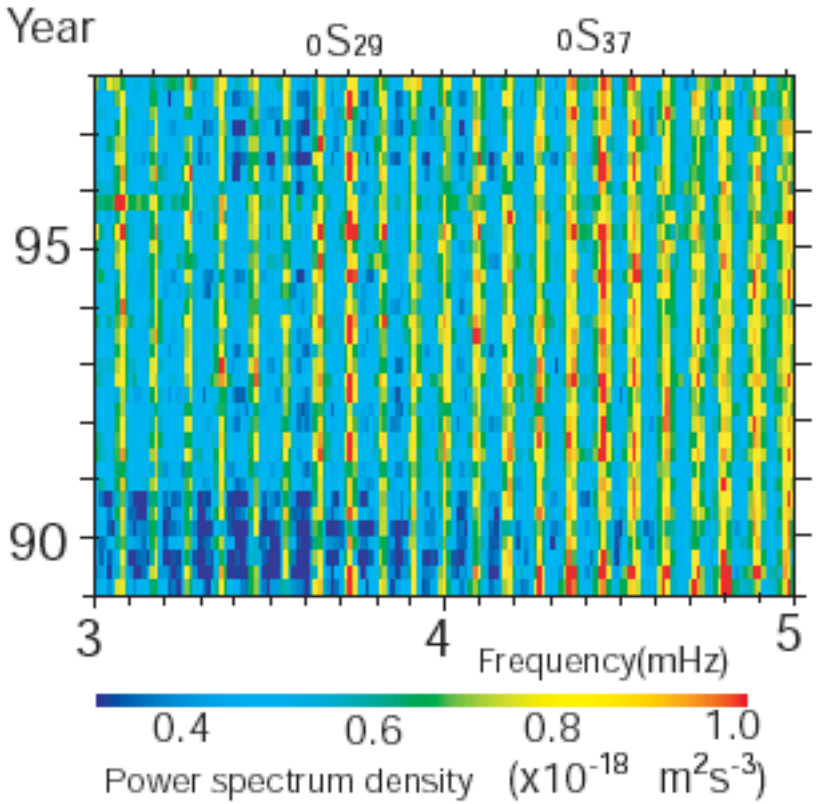



Stutzmann et al., 2009

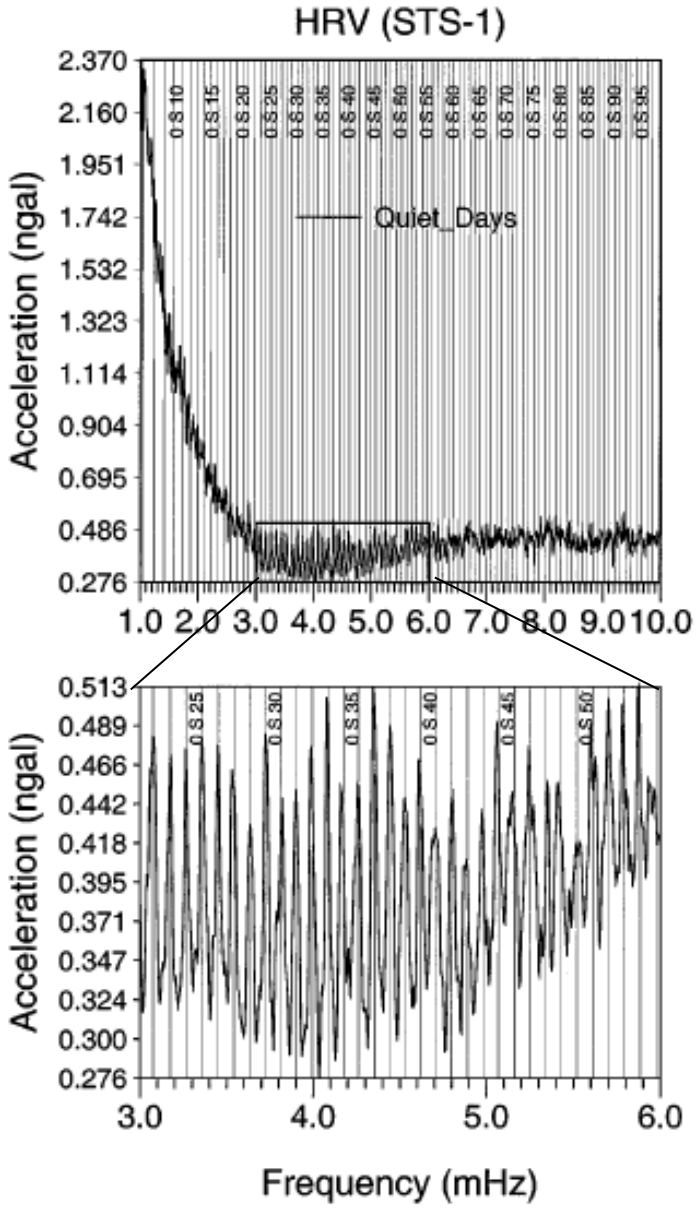



**=> N. Shapiro et al., 2005: cross-correlation technique**

# *Global Investigations*
# *New data: seismic hum, T>150s*



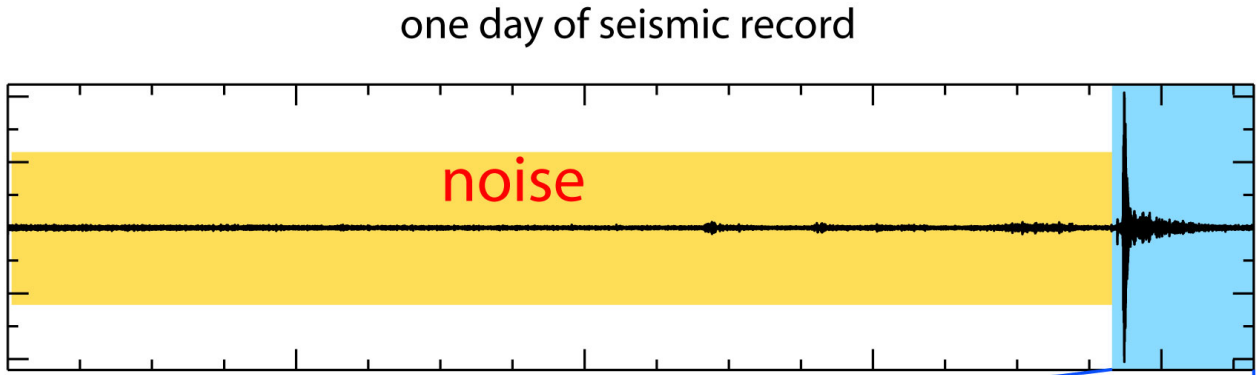

Nishida et al., 2000
Normal modes
OHP document



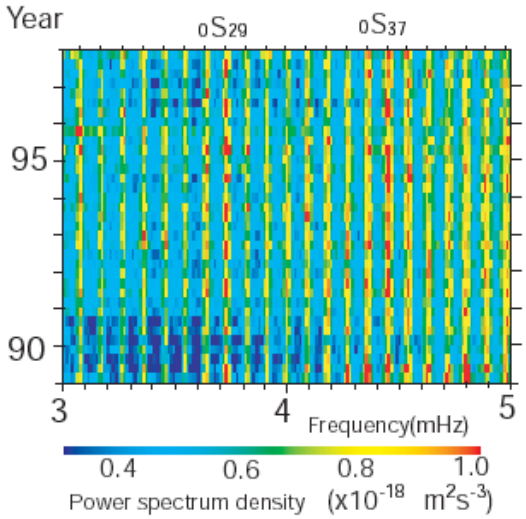

Tanimoto, 2001

# NEW APPROACHES

## - *New data*




Noise data
Microseismic noise
(Shapiro et al., 2005)
Seismic Hum
(ERI, Japanese groups,
UC Santa Barbara, UC Berkeley, …)



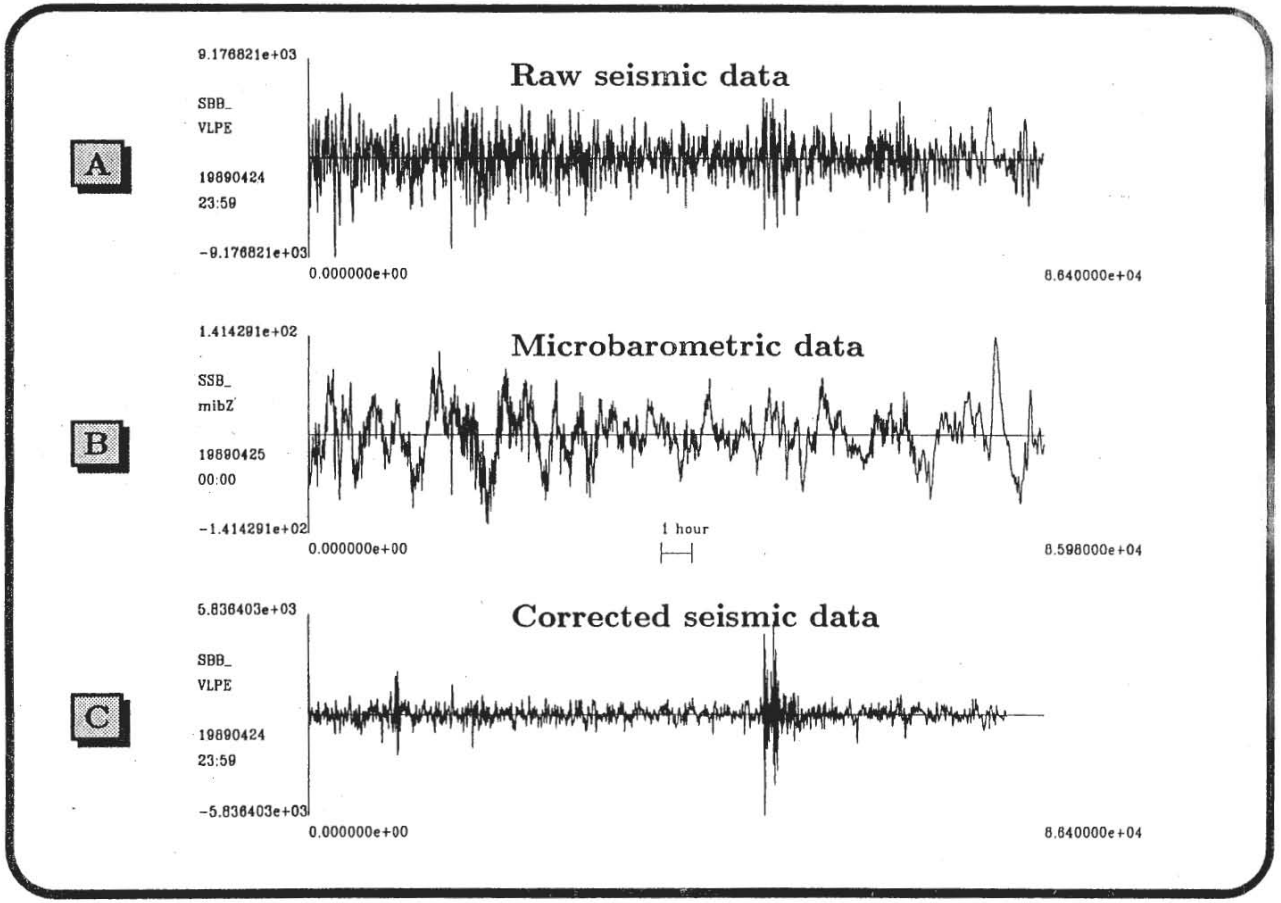

## *New Methods*

**-*More sophisticated methods***

*Time reversal method, massive cross-correlations*

*-New instruments: Multiparameter stations, VIRGO BBOBS, Dense Arrays*

# Multiparameter Station
# Deconvolution of the seismic signal from the pressure influence

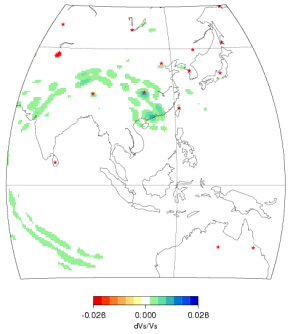



*Beauduin et al.,1996*

- **Data: Seismic noise** (seismic Hum; microseismic noise; cross-correlation techniques) NEW DATA
- ***"Exotic sources": Glacial earthquakes***
- ***Time-reversal technique (Numerical Techniques SEM)***
- **Scientific Issues**:

- Seismic tectonic sources: Sumatra-Andaman, Haiti, Chile, Japan earthquakes
- Similarities: Time reversal-cross-correlations techniques

- Structure of the Earth from seismic hum
- Temporal changes of anisotropy in seismogenic zones
- Interest in Virgo Interferometer data




# Broadband Seismology

- « Environmental » Seismology: ***New sources***

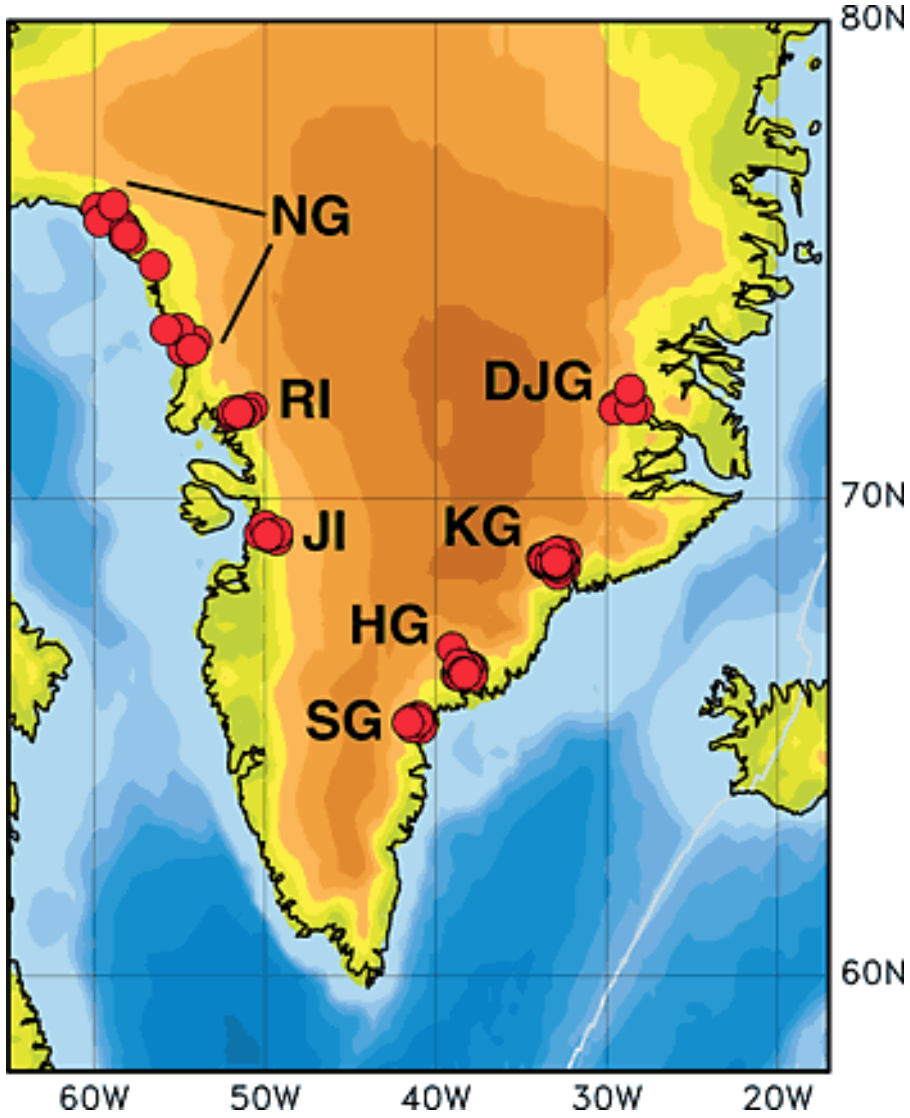
Glacial EQ, seismic Hum, tremors, hurricanes, Microseismic noise, …

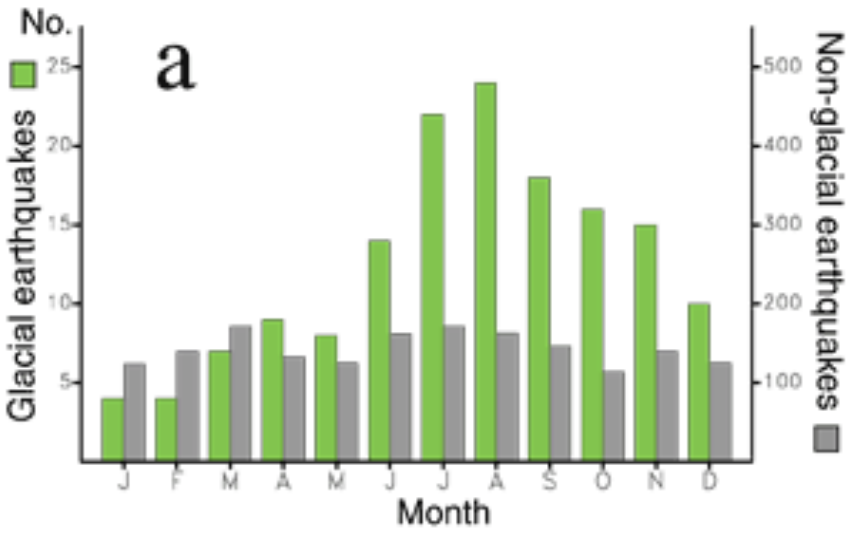
- Similarities between time reversal imaging and cross-correlation techniques

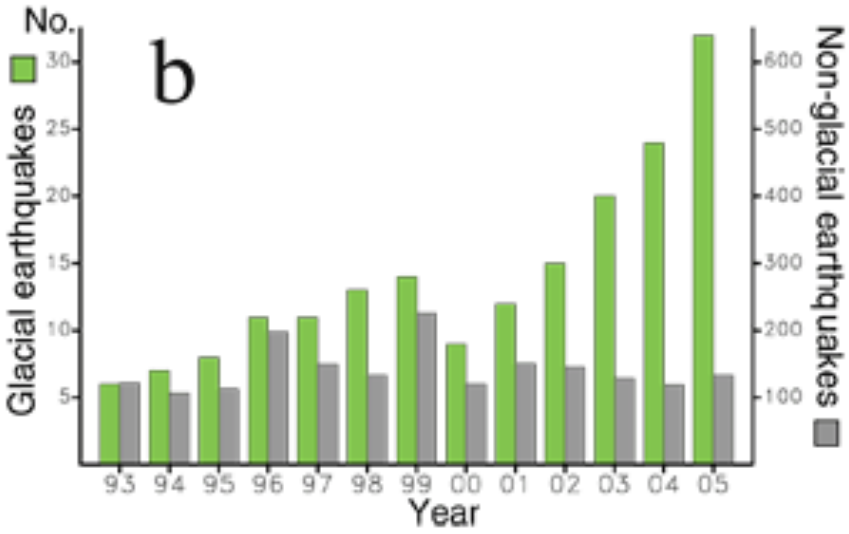
- Temporal variations of physical parameters

Seismic noise and Anisotropy

# “Exotic” sources: Glacial Earthquakes

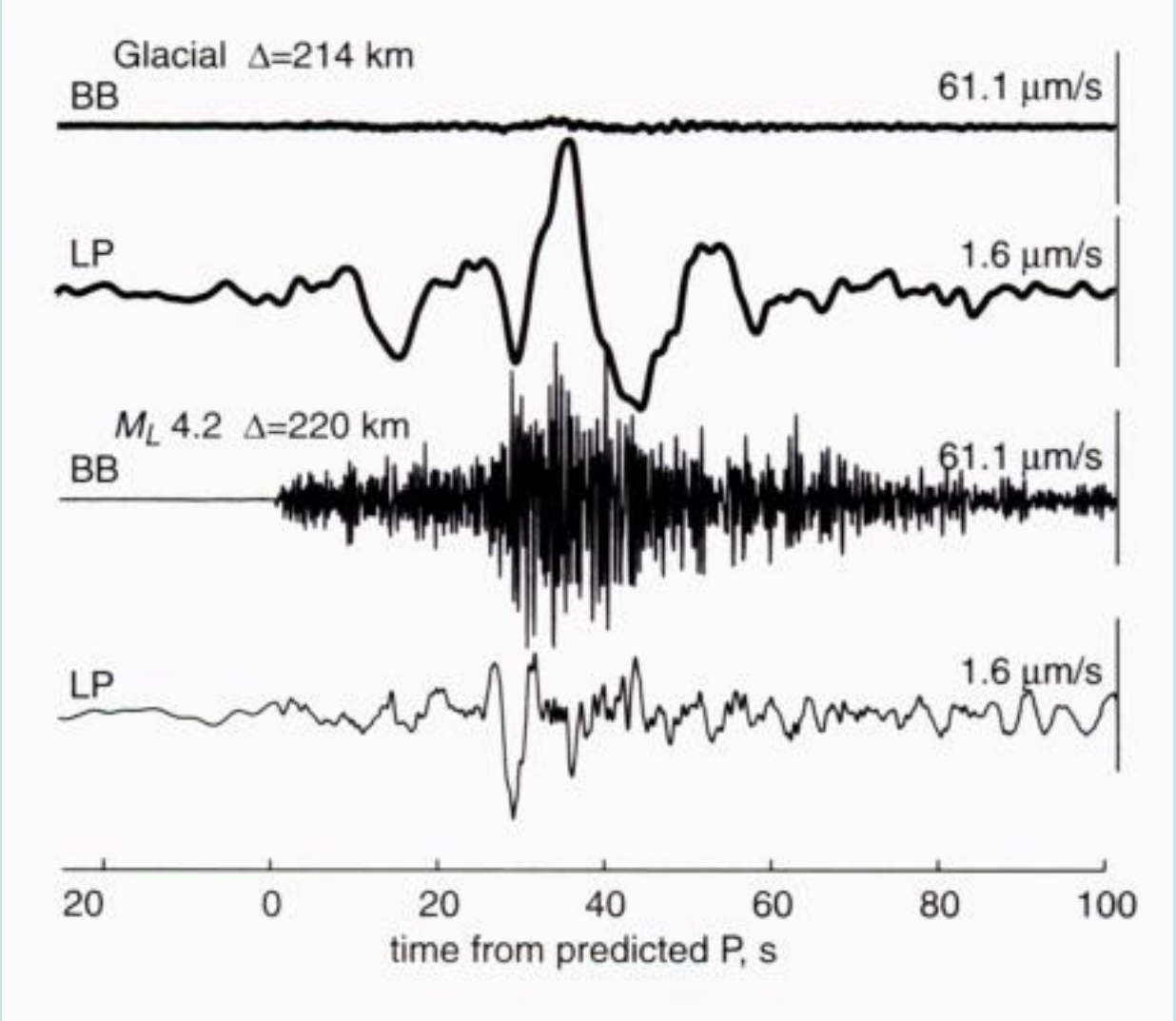



(Ekström et al., 2003, 2006)

# Glacial Earthquakes (Ms ≈ 5)



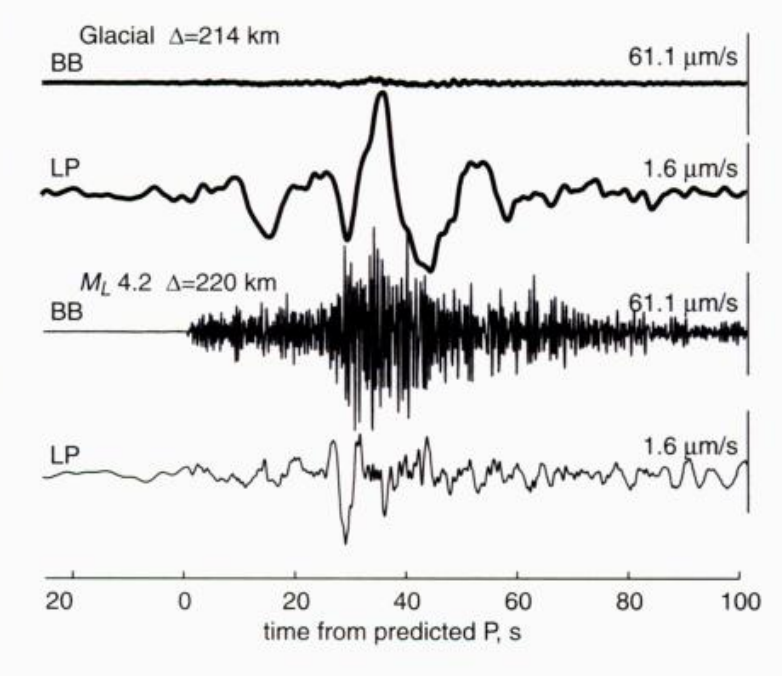

Glacial Earthquake

Tectonic Earthquake

Ekstrom et al., 2003

# Glacial Earthquakes

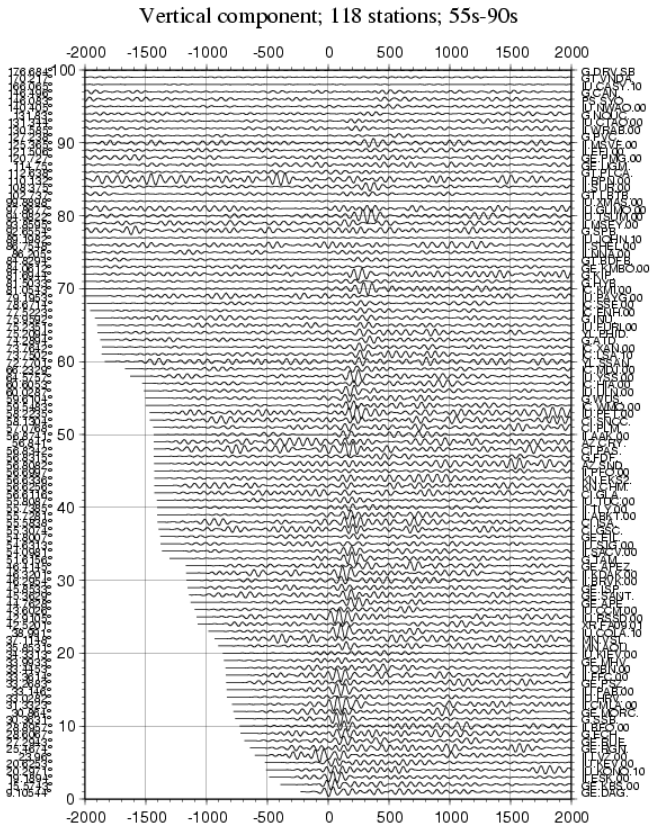
- Carene Larmat (LANL), Jeroen Tromp (Caltech), Qinya Liu (IGPP)
- Very long period excitation
- Can we locate glacial earthquakes by time reversal?

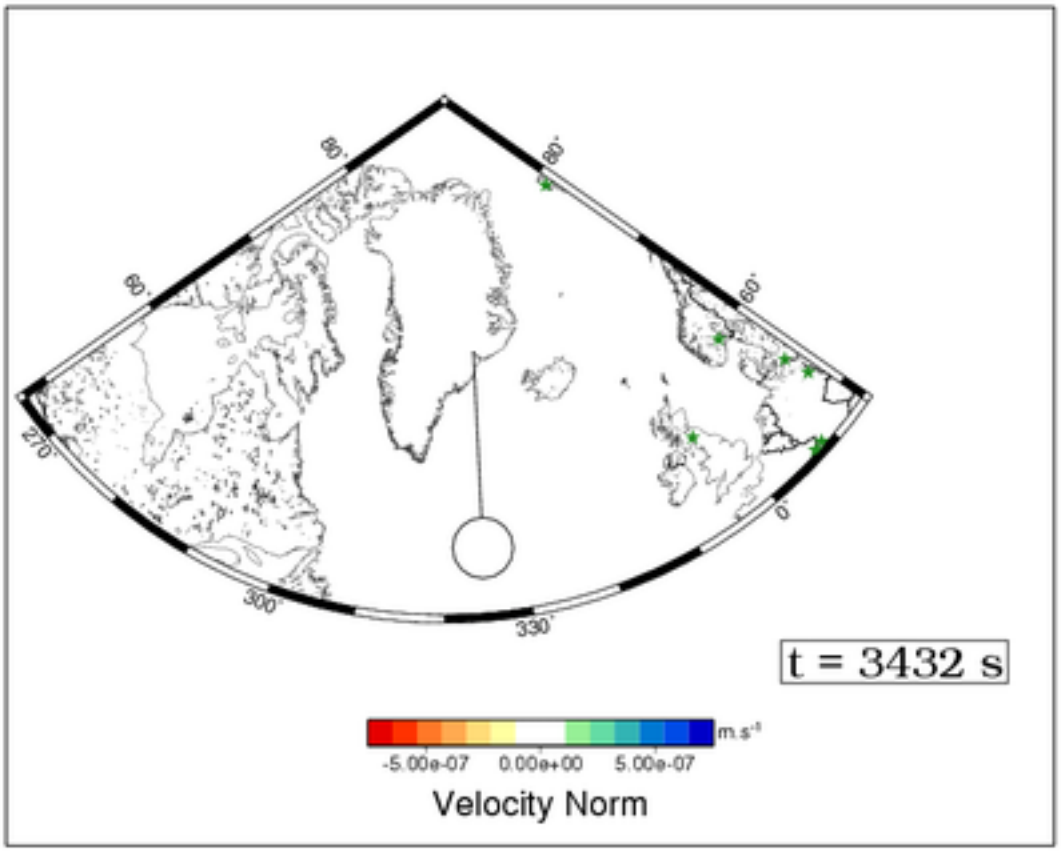


# Greenland - 28 dec 2001- M=5.0

## Time-Reversal Method

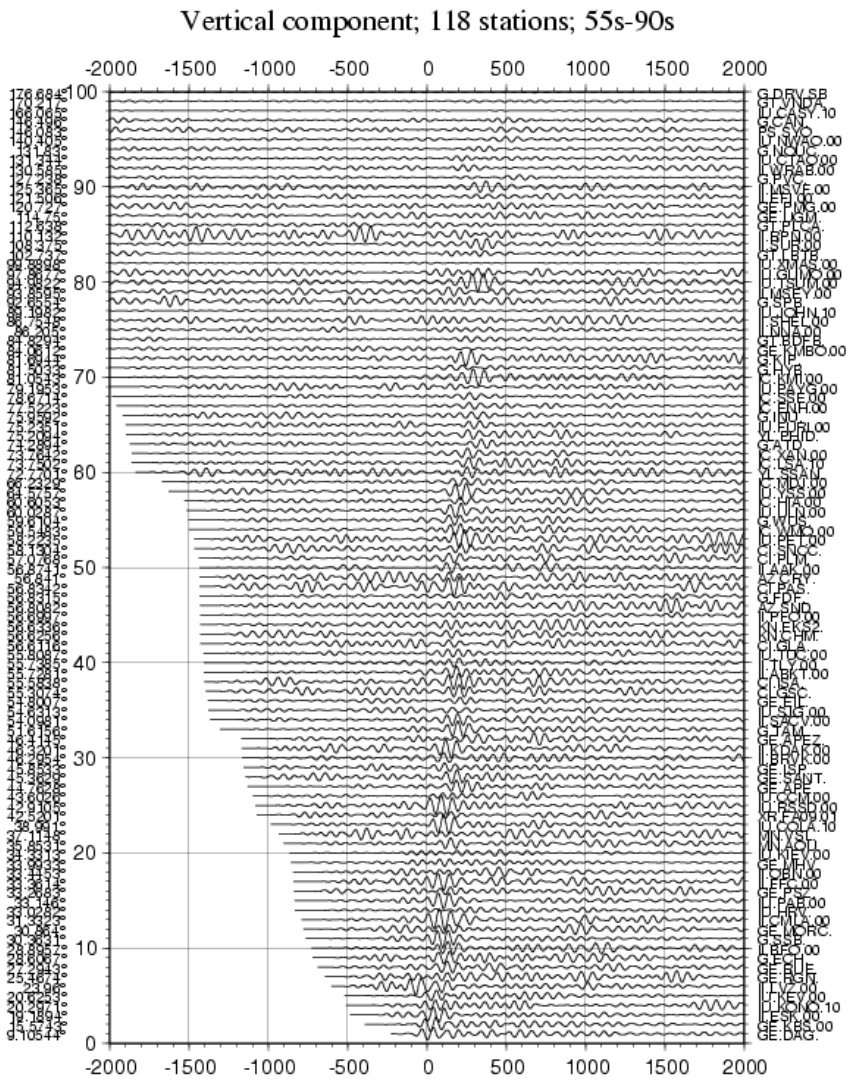
## SEM (spectral element method) + S20RTS (Ritsema et al., 2001)



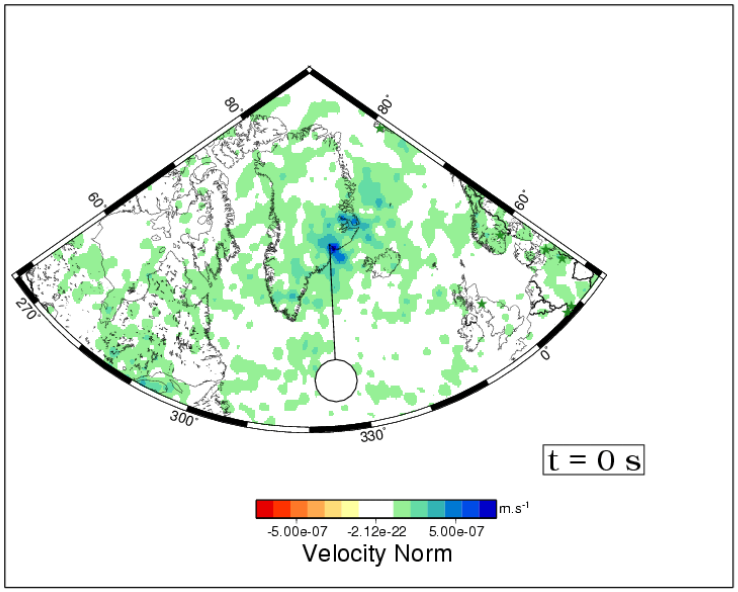



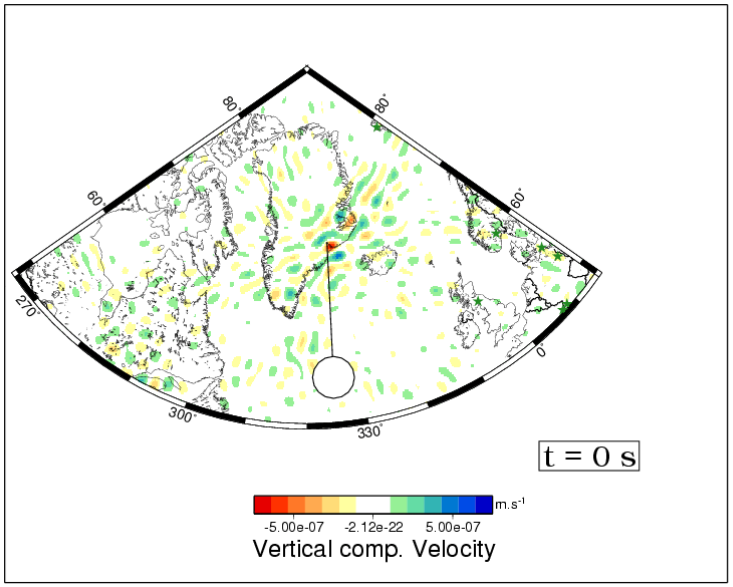

(Larmat et al., 2008)

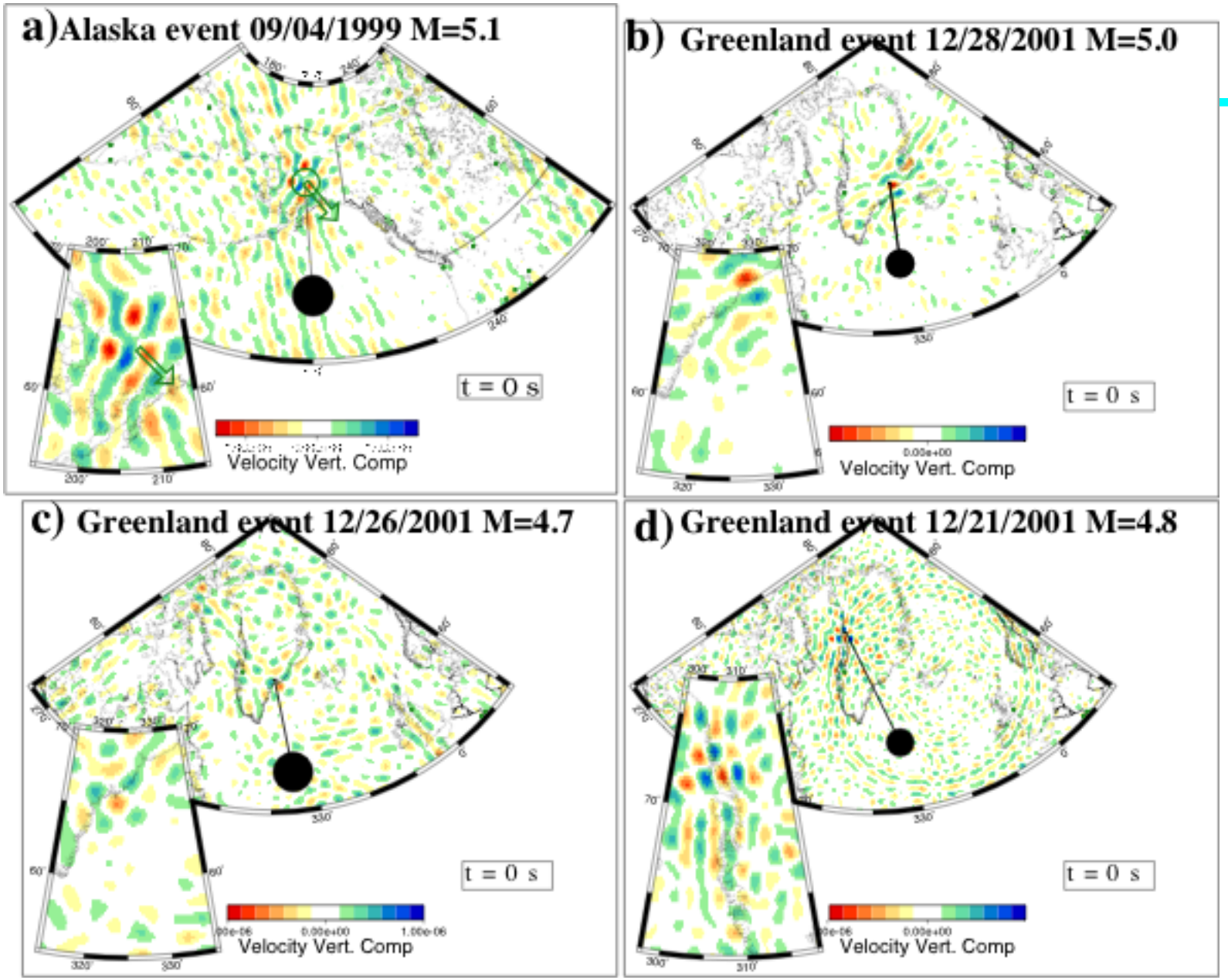
# Greenland - 28 dec 2001- M=5.0




(Larmat et al., 2008)






Monitoring of Glacial Earthquakes

Larmat et al., 2008

# OUTLINE

- **Data: Seismic noise** (seismic Hum; microseismic noise; cross-correlation techniques)
- **Scientific Issues**:

- Seismic tectonic sources: Sumatra-Andaman earthquake…
- "Exotic sources": Glacial earthquakes
- Structure of the Earth from Seismic Hum

-Temporal changes of anisotropy in seismogenic zones

- Similarities: Time reversal-cross correlations techniques
- Time-reversal technique (Normal Mode theory, Numerical Techniques SEM, C-SEM)
- Time reversal concept applied to seismic source imaging

# *Global Investigations: Imaging from CC*
# *New dataset: seismic hum*

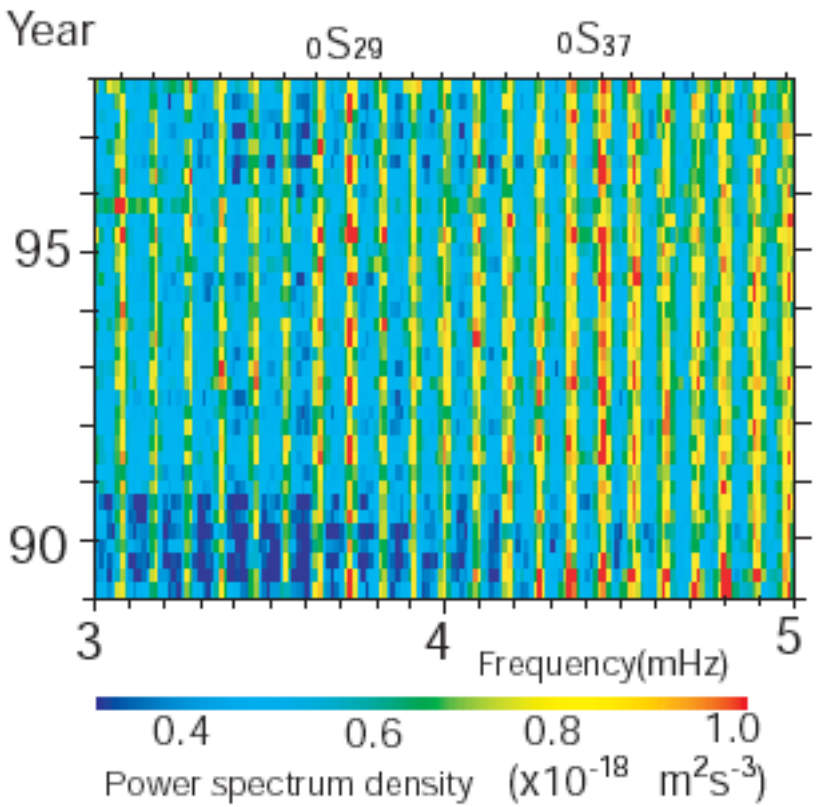


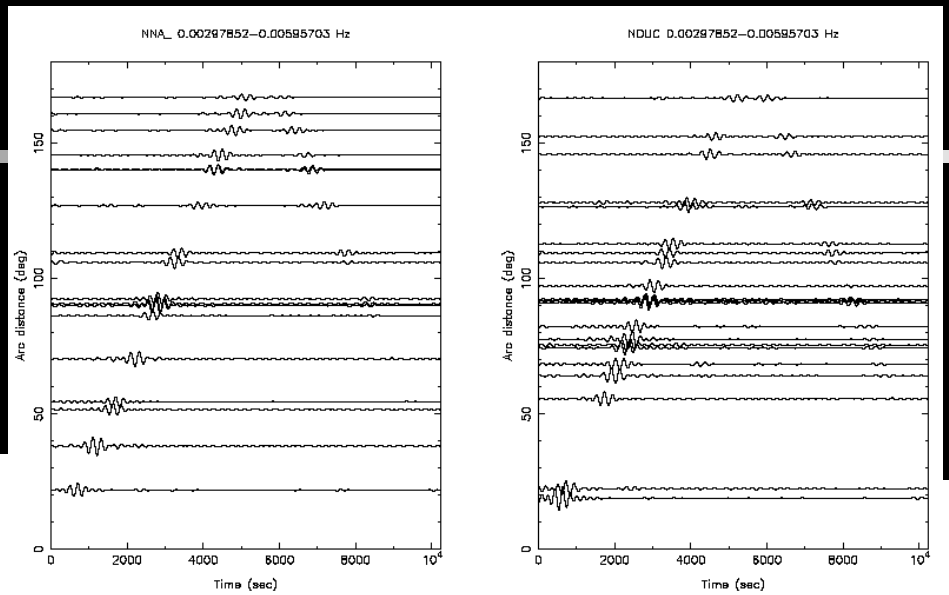

Fig. 2. Ground motion spectrum of seismically quiet days. Days are represented in the ordinate and frequencies in the abscissa. The vertical yellowish lines indicate the incessant free oscillations of the Earth.

Continuous Excitation of Normal modes even when there is no Earthquake: Source unknown

Nishida et al., 2000
OHP document

# Seismic Hum: Cross-correlations of noise between stations

NNA



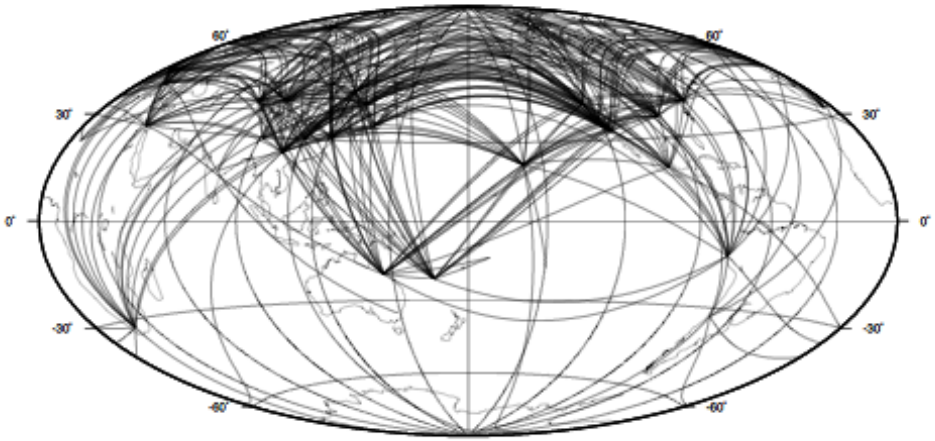




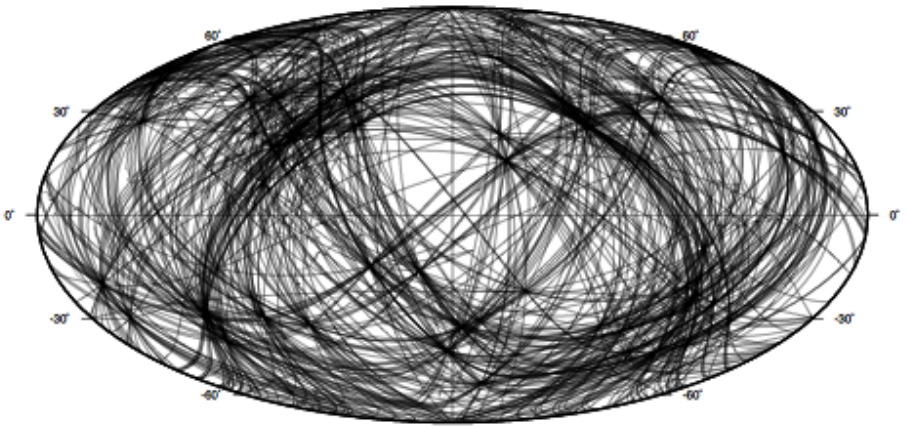
NOUC

55 stations

R1



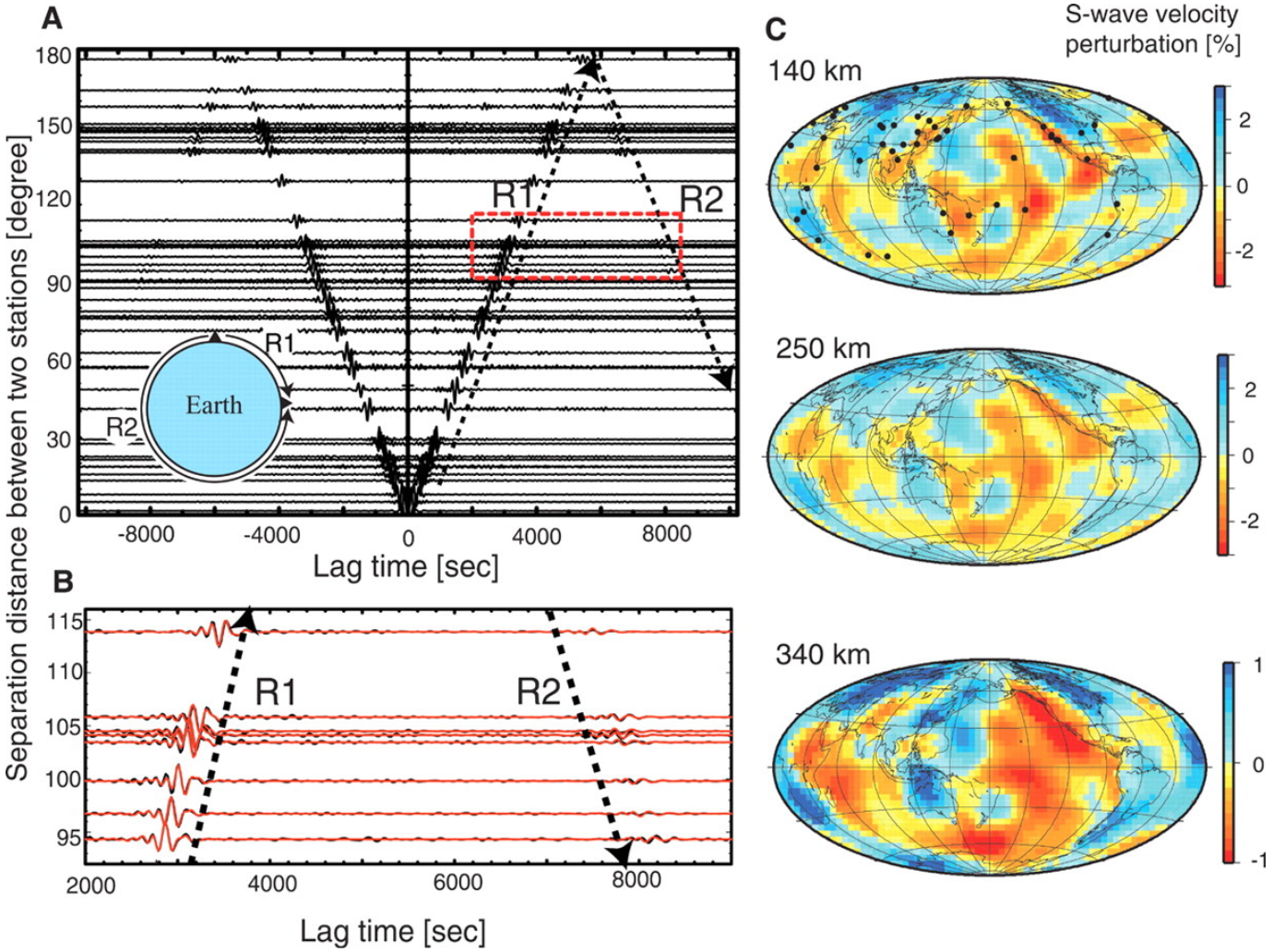
R2



Nishida, Montagner, Kawakatsu, science, 2009

**Observed CC functions plotted against separation distance between a pair of stations**

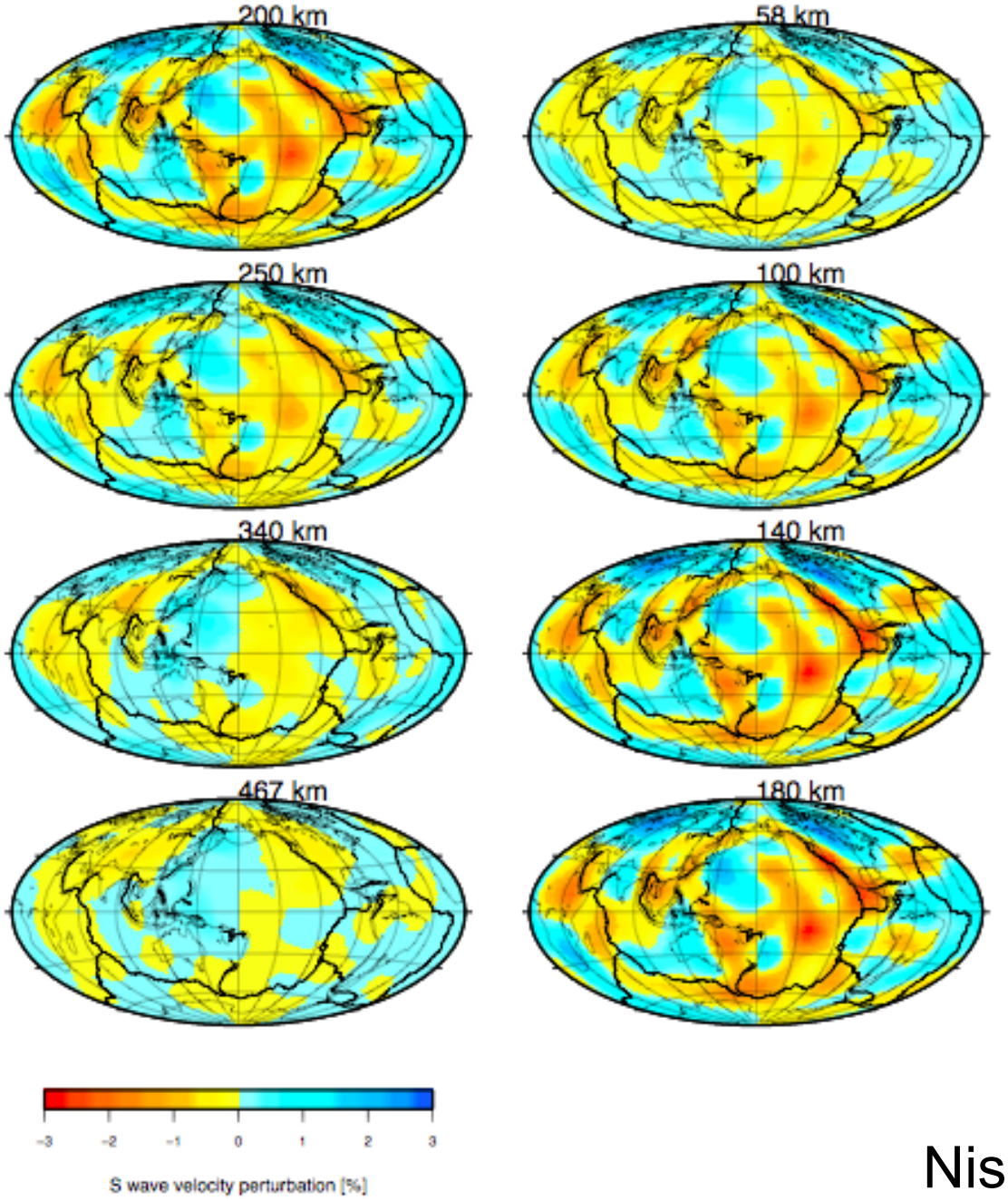
**Resolution of the tomographical model related to the density of station coverage**




Published by AAAS

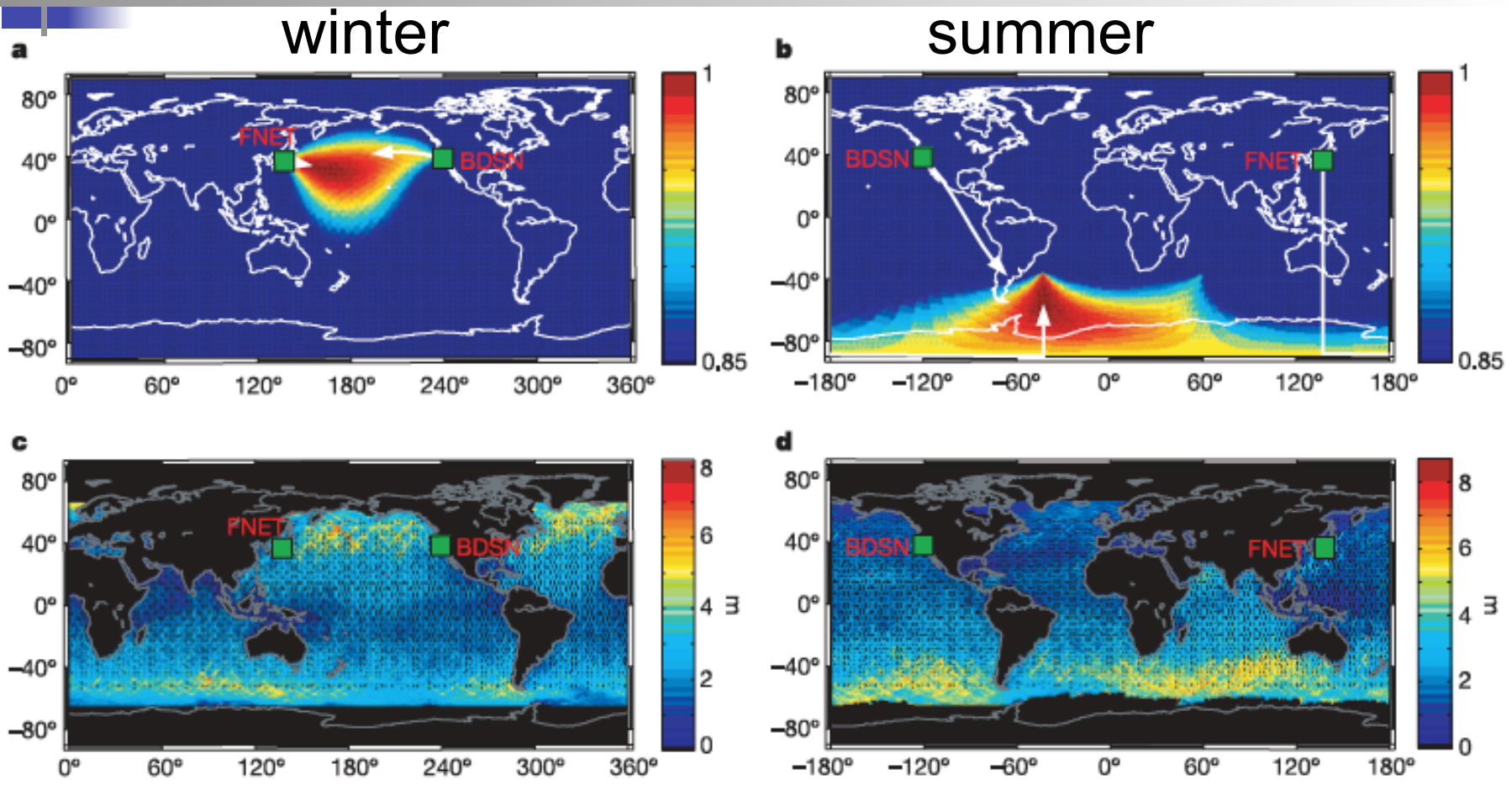
**Nishida et al., Science (2009)**

Science AAAS




Nishida et al., 2009

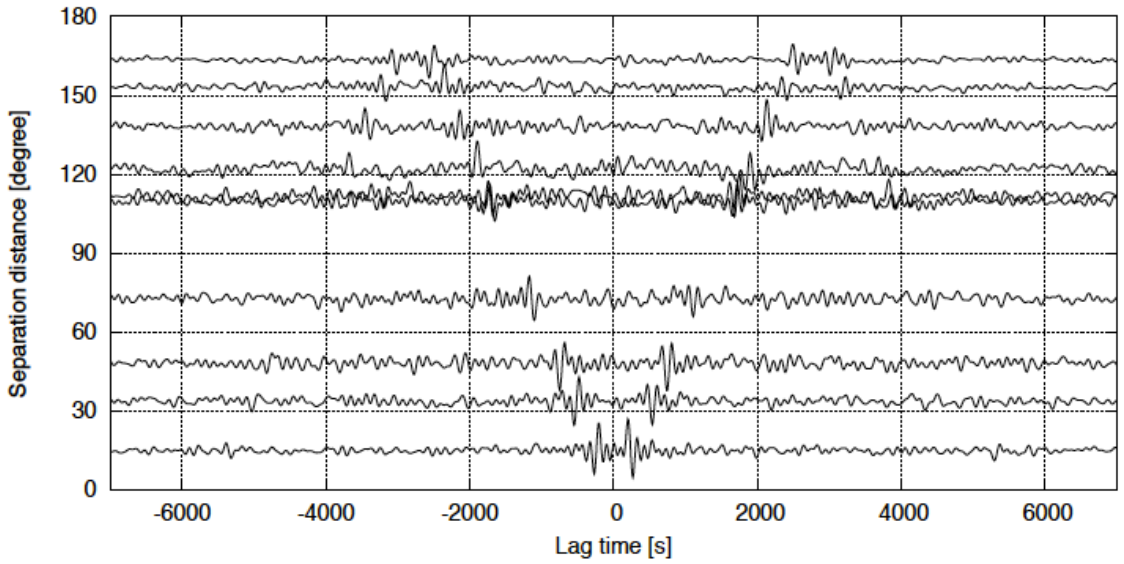
# ORIGIN OF THE SEISMIC HUM



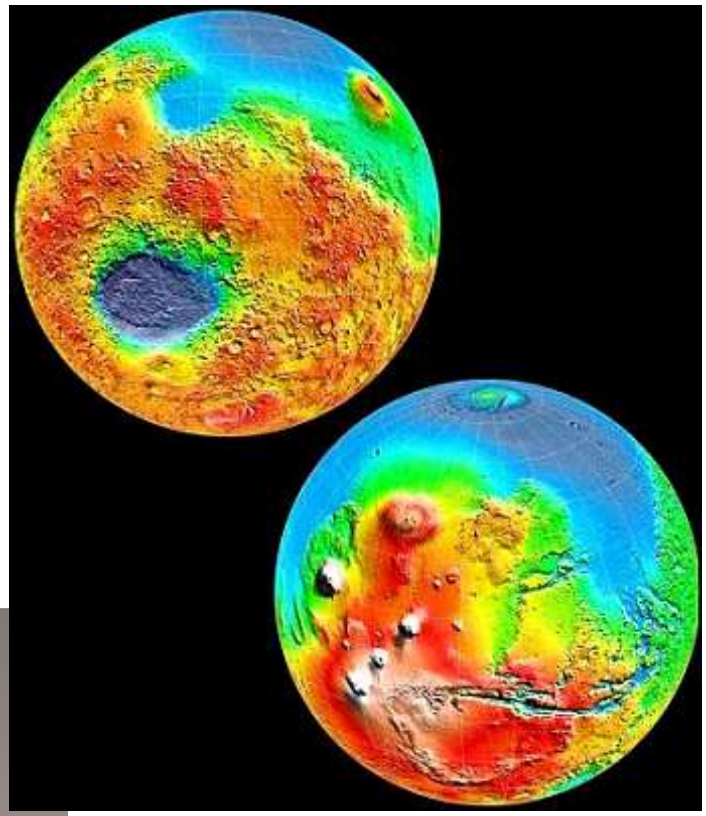

Wave height

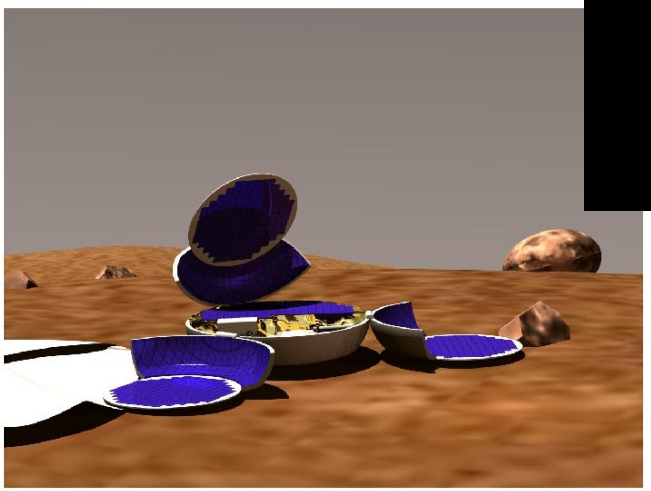
Rhie and Romanowicz, 2004

# APPLICATION TO TERRESTRIAL PLANETS NETWORK OF AT LEAST 5 STATIONS



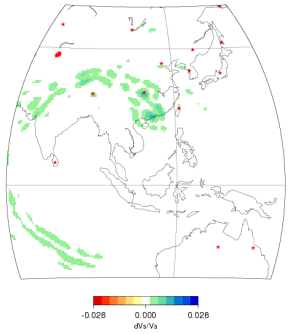

Cross-correlations of Synthetic Mars Hum (Nishida et al., 2009)





NETLANDER: MARS…

(Lognonné et al. 2004)




# Broadband Seismology

- « Environmental » Seismology: ***New sources***

Microseismic noise, seismic Hum, glacial EQ…

-Similarities between time reversal imaging and cross-correlation techniques (normal mode theory)

- Temporal variations of physical parameters

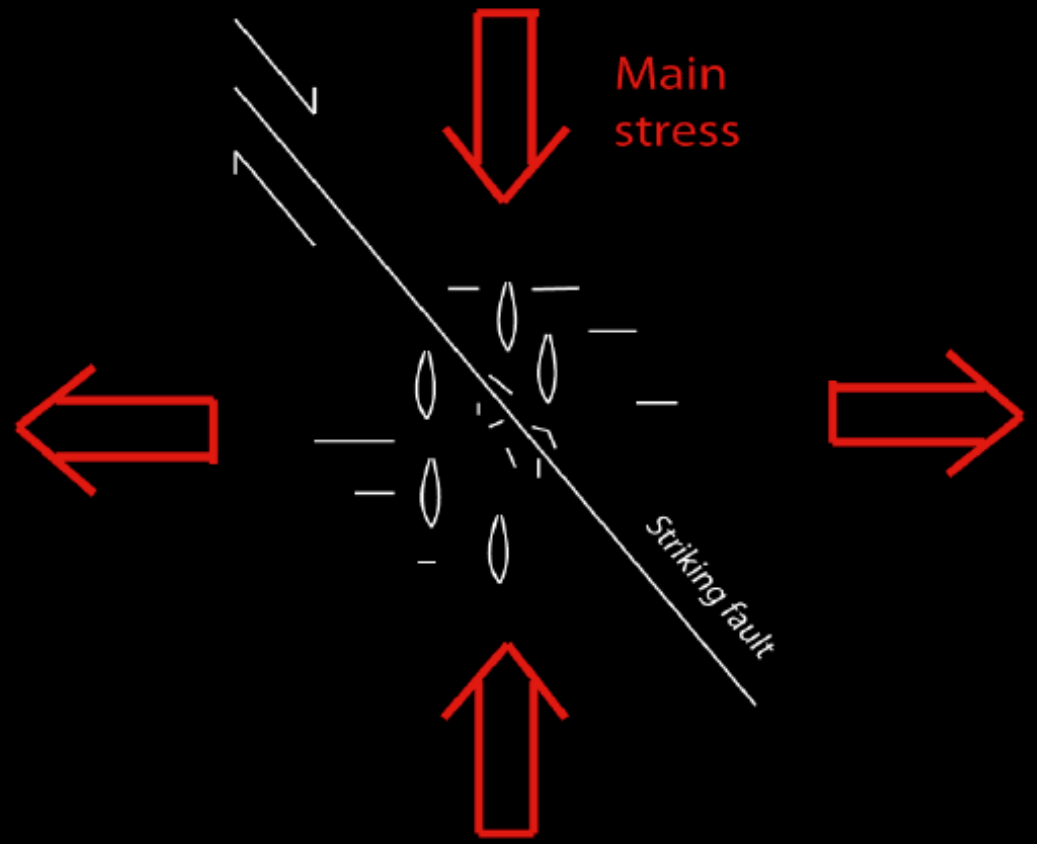
**Seismic noise and Anisotropy**

# TEMPORAL VARIATIONS OF SEISMIC ANISOTROPY RELATED TO THE PARKFIELD EARTHQUAKE (28/09/04)

*Stéphanie Durand, Jean-Paul Montagner, Philippe Roux, Florent Brenguier, Robert Nadeau…*

*IPG-Paris, LGIT-Grenoble, ENS-Lyon, U.C. Berkeley*

# Seismic Anisotropy: Cracks, fluid inclusions (strain-meter or stress-meter) stress field rotations in the crust ⇒temporal variations of velocity and anisotropy during seismic cycle?



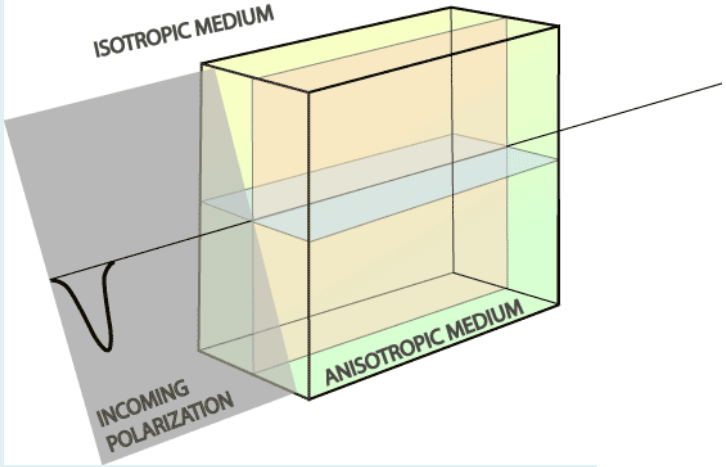
# Different kinds of anisotropy effects on seismic waves

•Body waves: Shear wave splitting (birefringence)

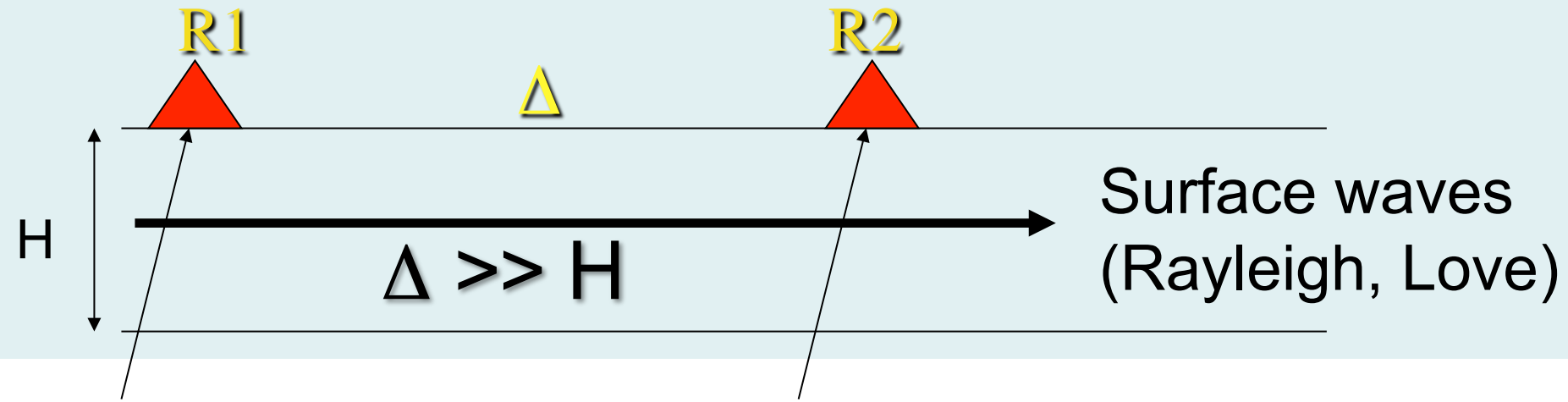
•Surface waves:

-Azimuthal variations of phase (or group) velocities, radial anisotropy

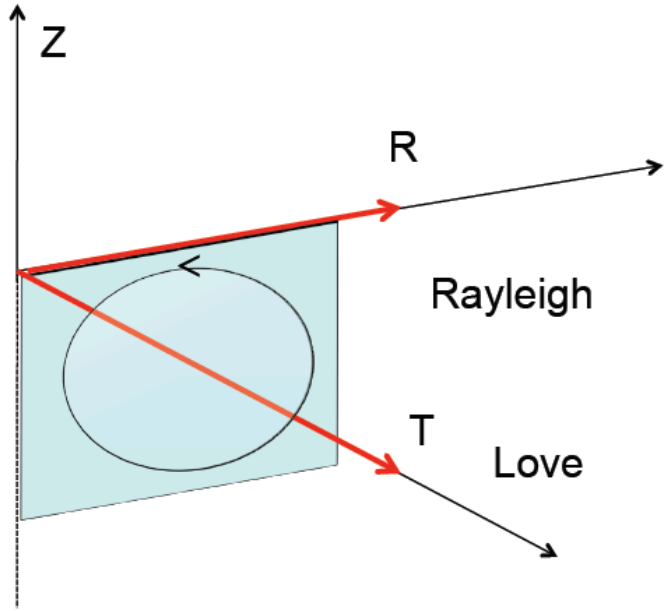
-Quasi-Rayleigh, Quasi- Love polarization anomalies



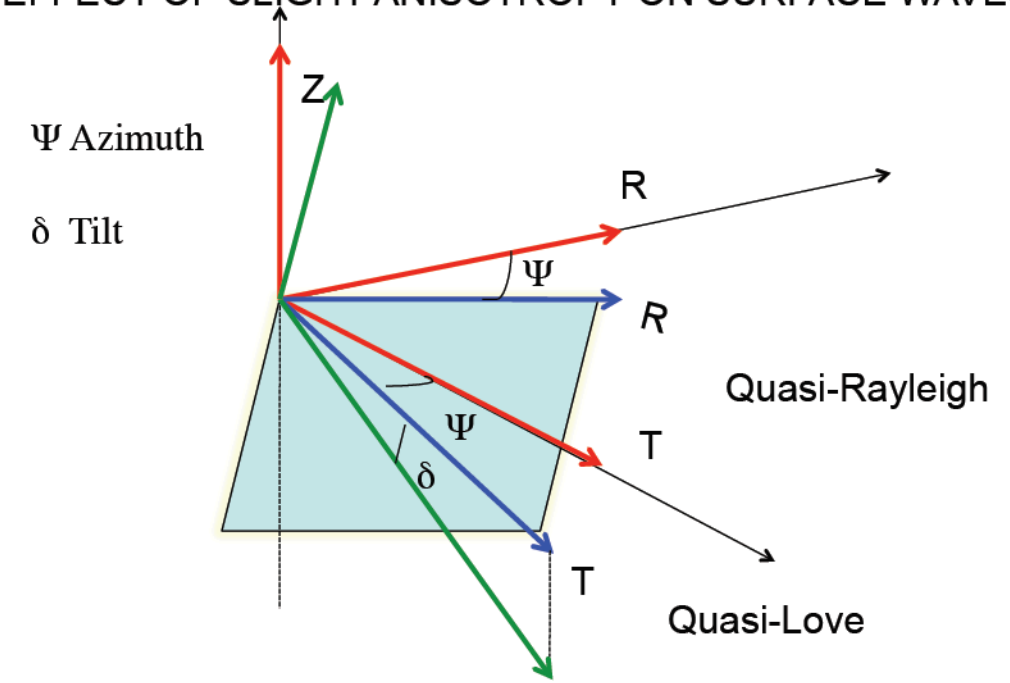

Courtesy of Ed. Garnero



ISOTROPIC MEDIUM




EFFECT OF SLIGHT ANISOTROPY ON SURFACE WAVES

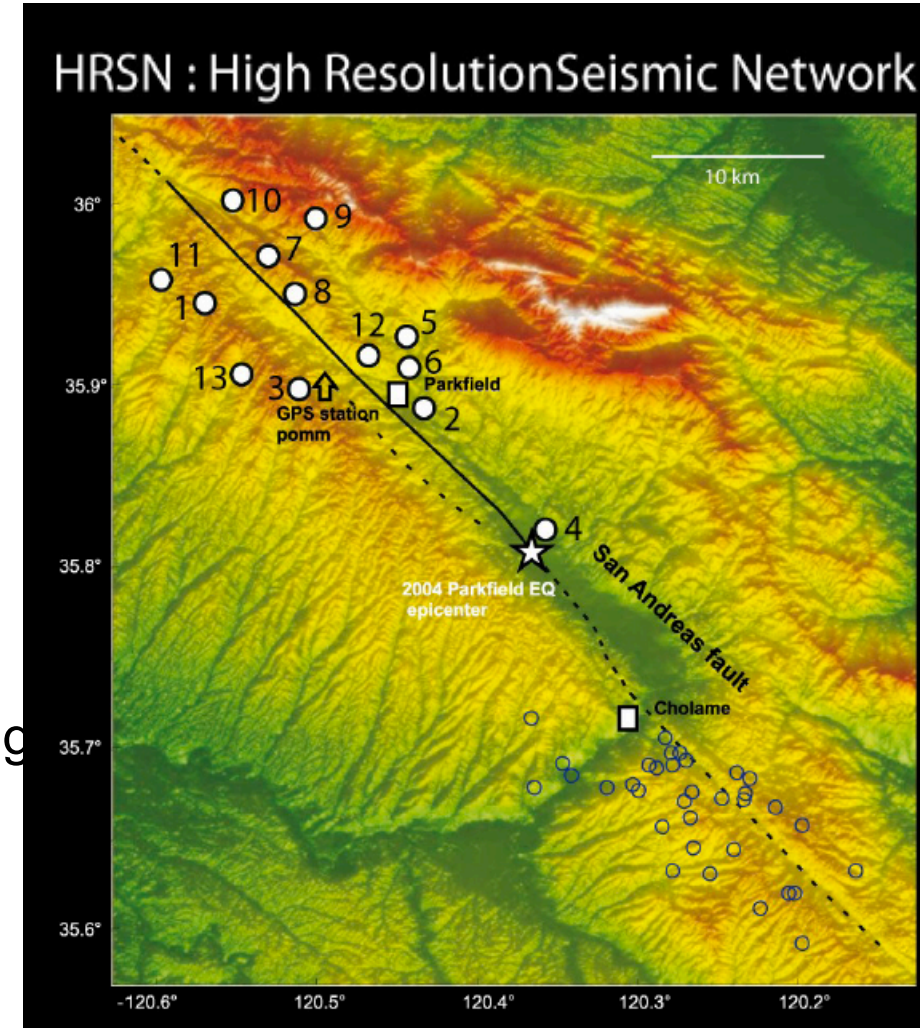


# Monitoring of seismogenic zones by ambient noise

Surface waves recovered by ambient noise cross-correlation

ADVANTAGES

- Surface waves instead of body waves
- Independent of seismicity
- Continuous noise = continuous monitoring




- Application to the Parkfield area
- 3Component HRSN
- Sept. 2004: Parkfield event, Mw=6.0
- 2005: No significant local earthquake (>4)

# THEORY

Cross-correlation for 2 stations i, j and 3 components k, l

$$[C_{ij}(t)]_{kl} = \frac{\int_0^T S_{ik}(\tau)\, S_{jl}(t+\tau)\, d\tau}{\sqrt{\int_0^T S_{ik}^2(\tau) d\tau \int_0^T S_{jl}^2(\tau) d\tau}}$$

→ Random sources:
Green's Function i,j
Medium response

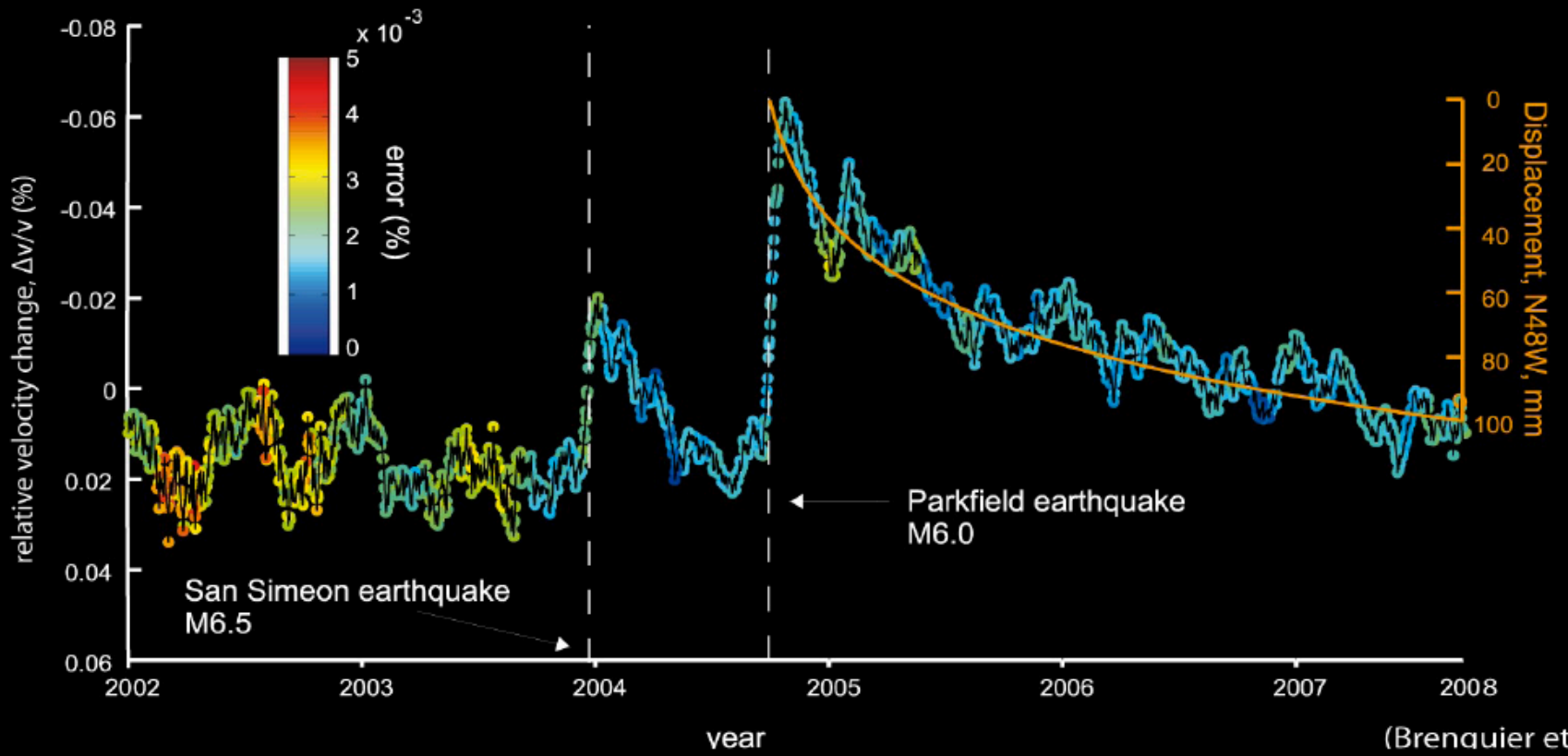
Cross-Correlation Tensor

Brenguier et al., 2008

| | | |
|---|---|---|
| ZZ | ZR | ZT |
| RZ | RR | RT |
| TZ | TR | TT |

Brenguier et al, 2008 : Noise correlation

=> Co-seismic and post-seismic relative velocity change




(Brenguier et al, 2008)

Temporal variations of anisotropy at Parkfield

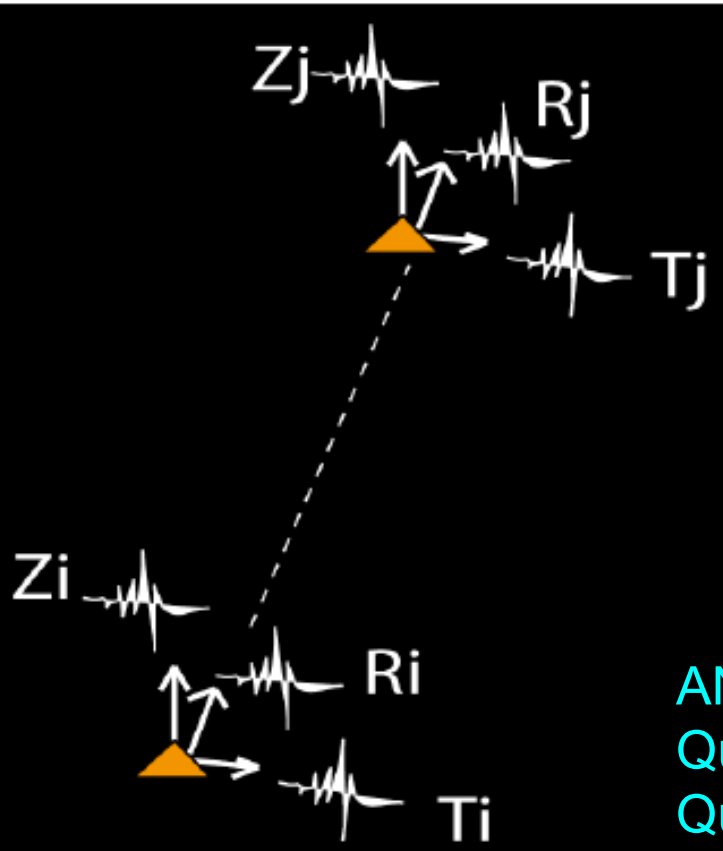
Liu et al, 2008 : SWS

=> No precursory, co-seismic or post-seismic signals of anisotropy changes

$$[C_{ij}(t)]_{kl} = \frac{\int_0^T S_{ik}(\tau)\, S_{jl}(t+\tau)\, d\tau}{\sqrt{\int_0^T S_{ik}^2(\tau) d\tau \int_0^T S_{jl}^2(\tau) d\tau}},$$

| | | |
|---|---|---|
| ZZ | ZR | ~0 |
| RZ | RR | ~0 |
| ~0 | ~0 | TT |

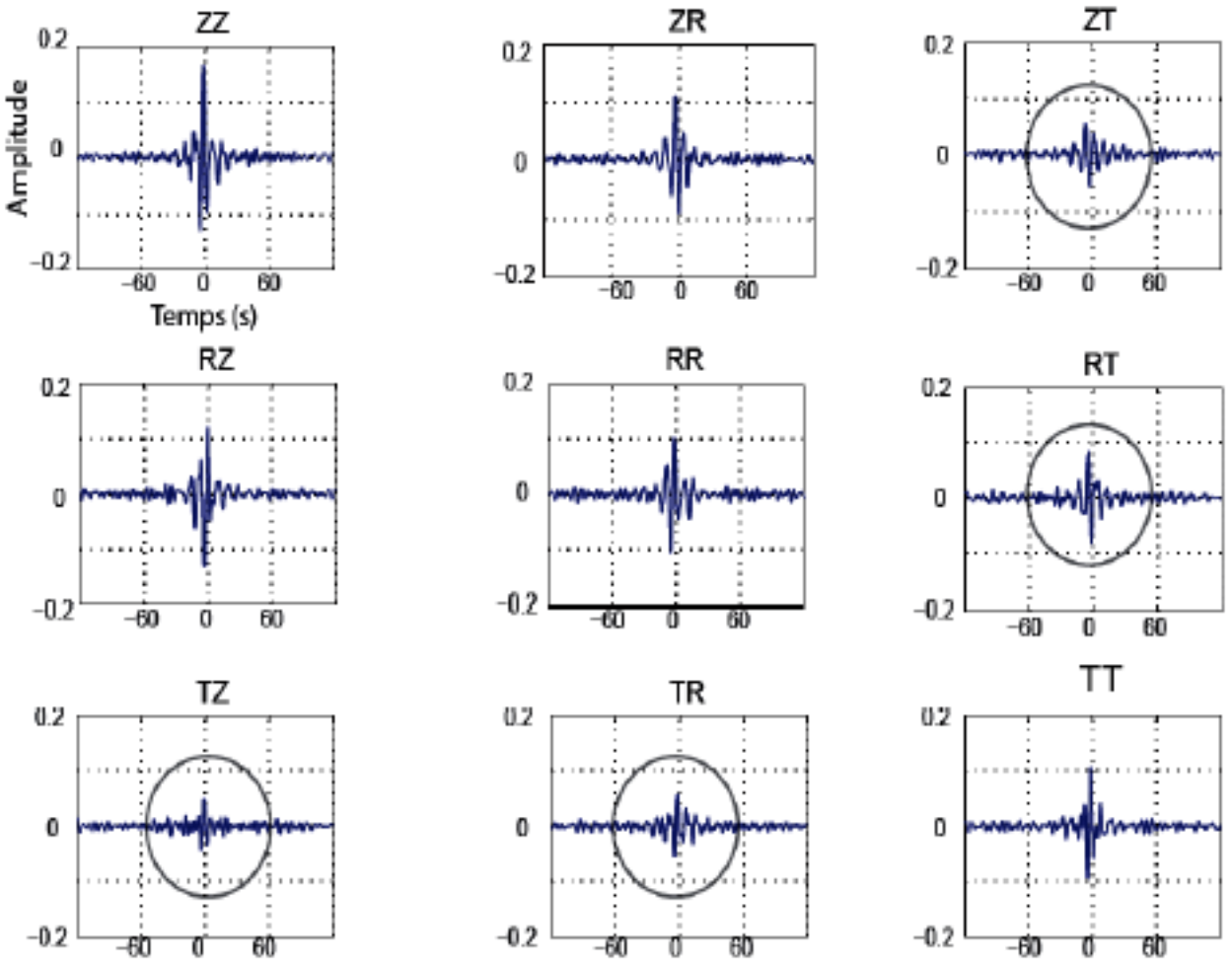
ISOTROPIC MEDIUM
Rayleigh wave
Love wave




| | | |
|---|---|---|
| ZZ | ZR | ZT |
| RZ | RR | RT |
| TZ | TR | TT |

ANISOTROPIC MEDIUM
Quasi-Rayleigh wave
Quasi-Love wave

# Example of cross-correlation tensor

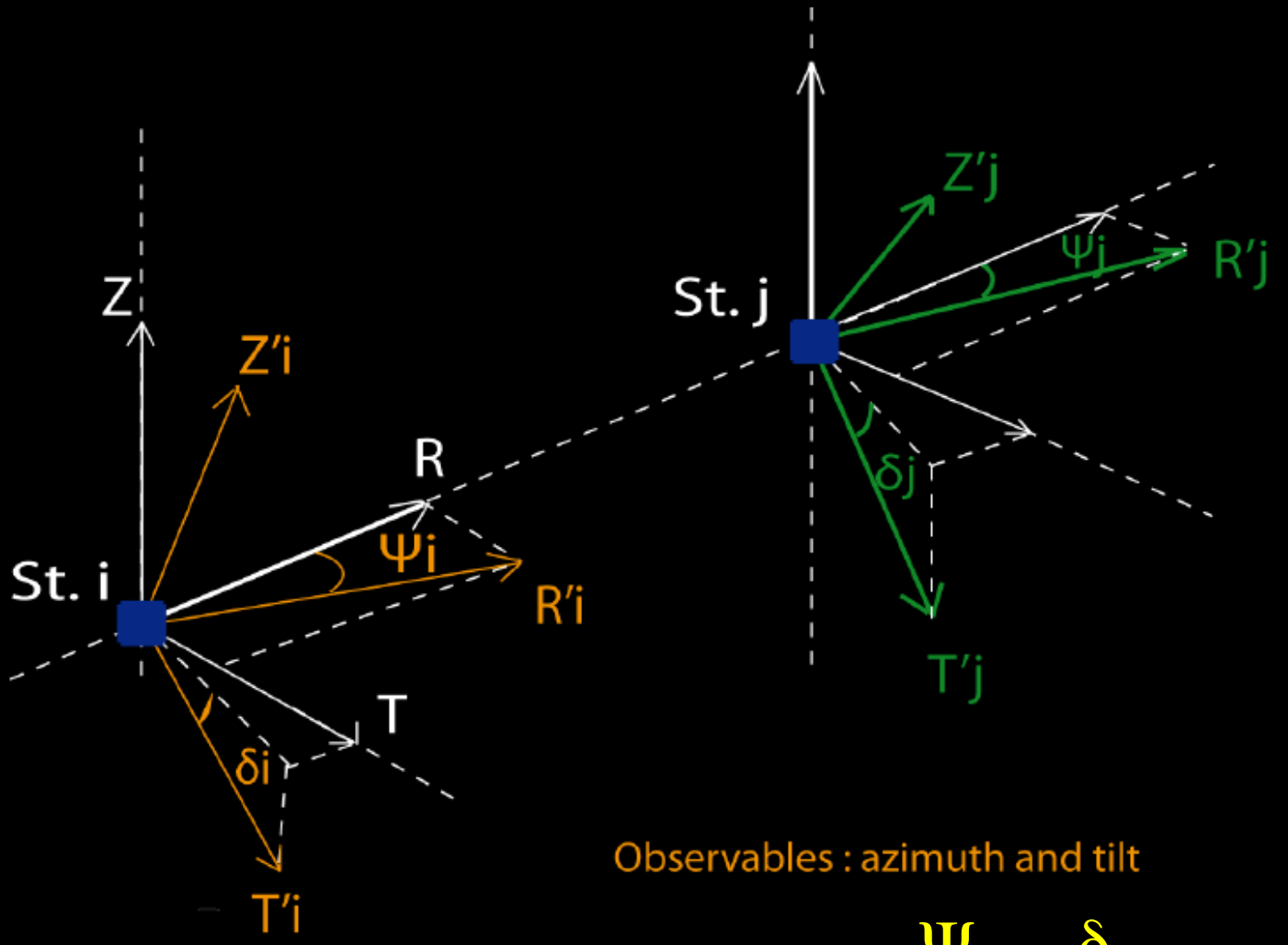



TZ, TR, ZT, RT ≠ 0

# ORA: Optimal Rotation Algorithm (Roux, GJI, 2009)

Minimization of the RT, TR, ZT and TZ components

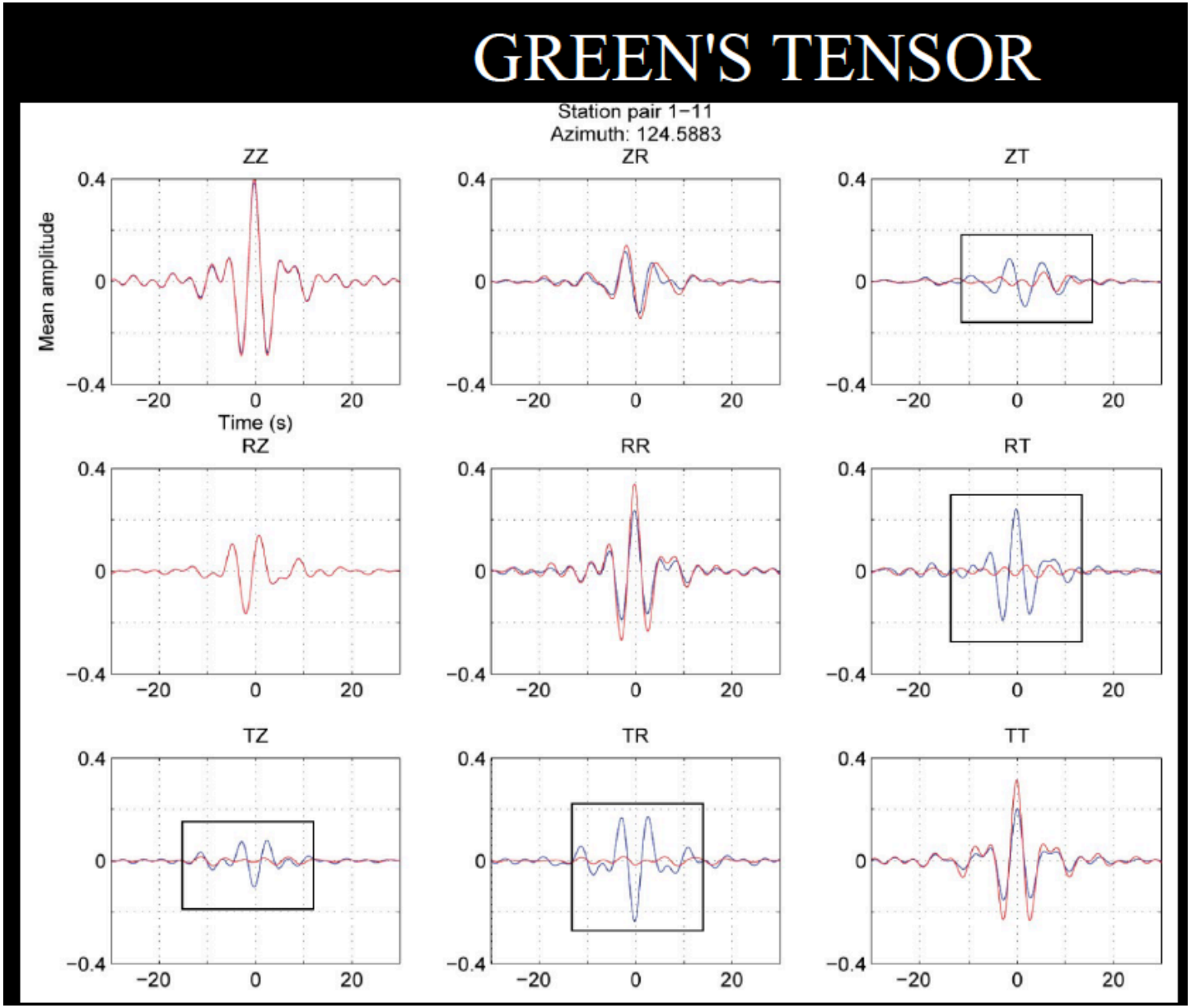
| | | |
|---|---|---|
| ZZ | ZR | ~~ZT~~ |
| RZ | RR | ~~RT~~ |
| ~~TZ~~ | ~~TR~~ | TT |




Observables : azimuth and tilt

Ψ δ

# GREEN'S TENSOR




Before ORA

After ORA

Not a Rayleigh Tensor

=>

Quasi-Rayleigh

Temporal Changes of $\Psi$ and $\delta$ ?

## *Temporal changes of Cross-correlations:*

2 effects:

- Non-random distribution of seismic sources

→ seasonal variations
(beamforming analysis)

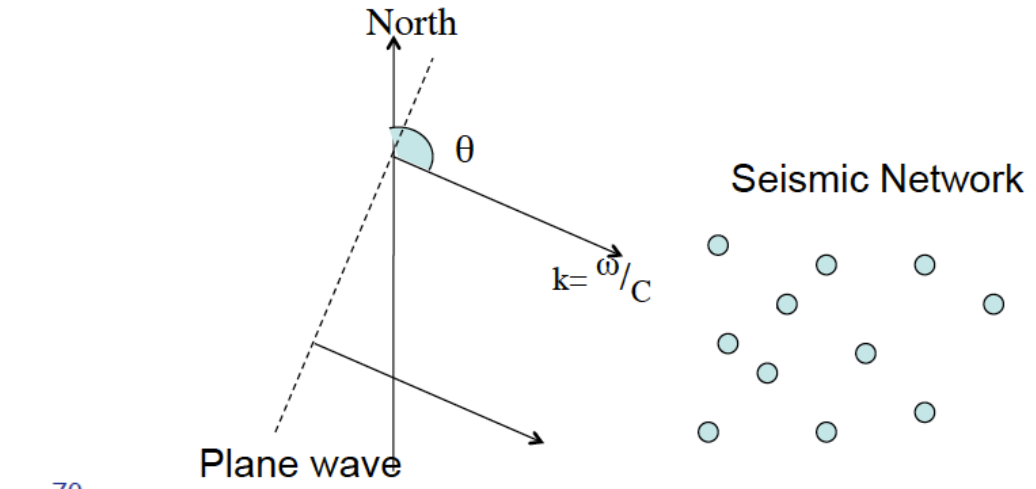
- Stress field temporal variations

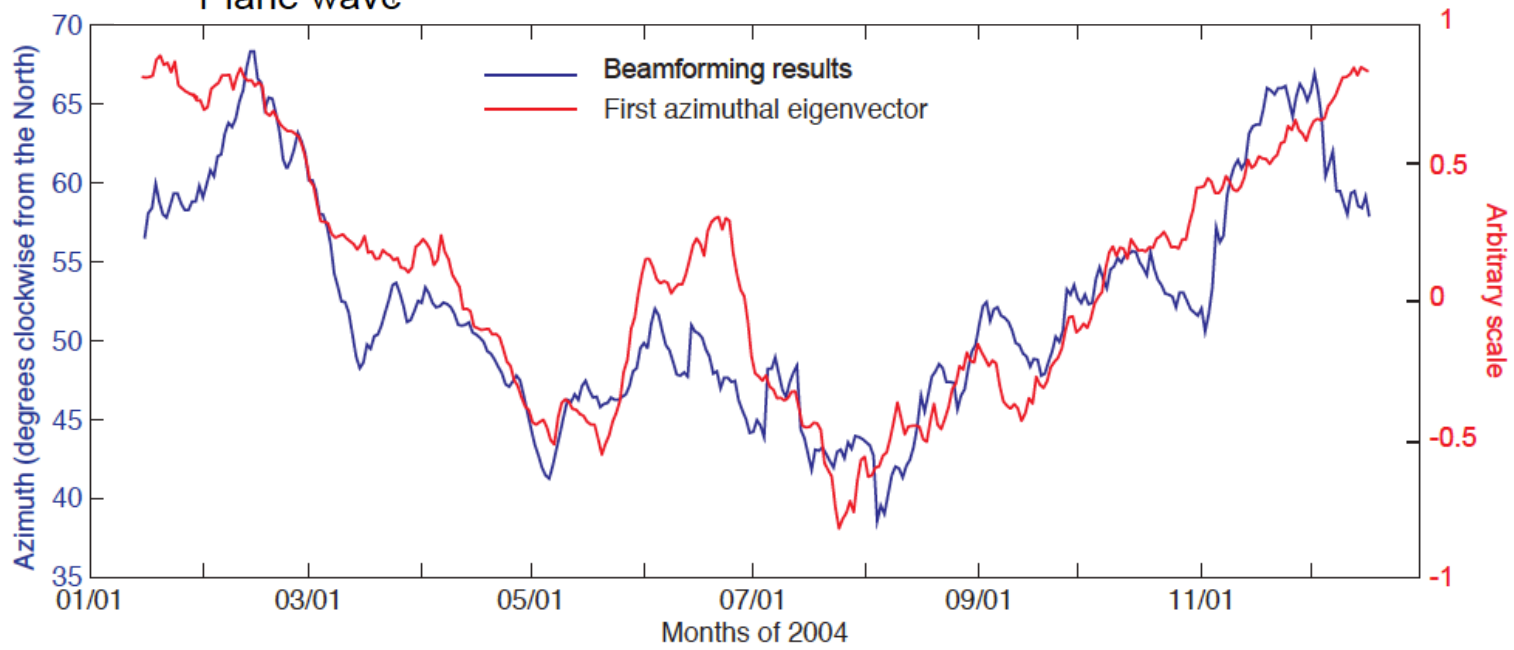
→ anisotropy changes

# Seasonal Changes

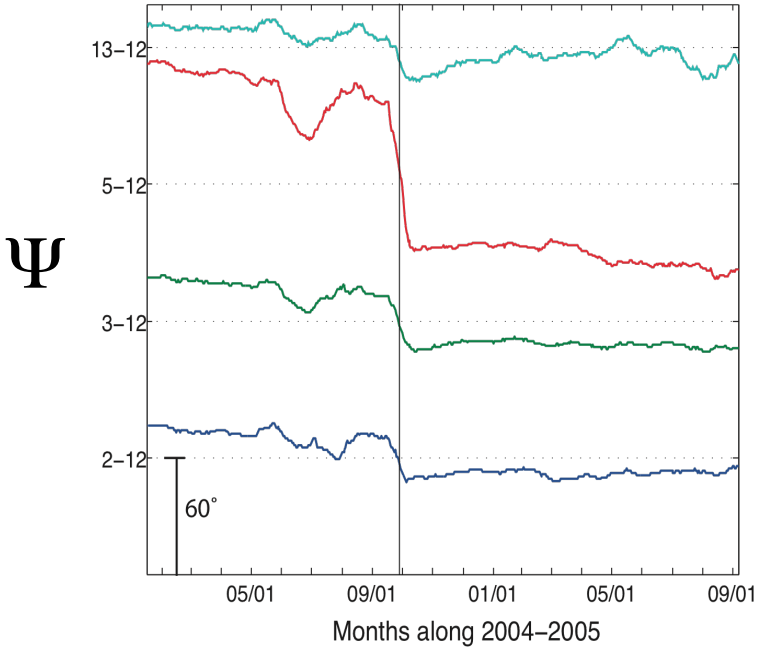
Origin of seismic sources: Beamforming (Roux, 2009)

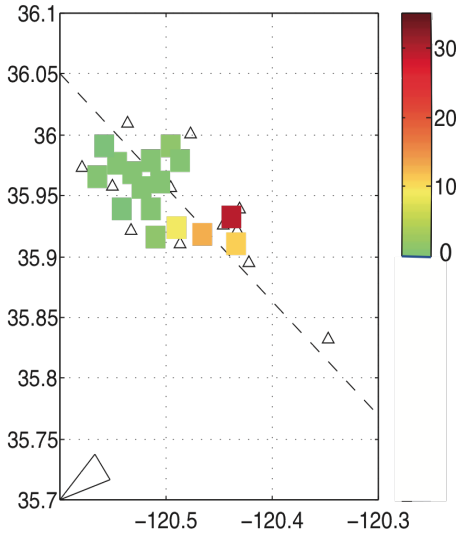
$$B(\theta, c) = \frac{1}{\Delta\omega} \int_{\omega_c - \Delta\omega/2}^{\omega_c + \Delta\omega/2} \left| \sum_{i=1}^{N} \tilde{S}_i(\omega) \exp\left[ i \frac{\omega}{c} (x_i \sin\theta + y_i \cos\theta) \right] \right|^2 d\omega$$



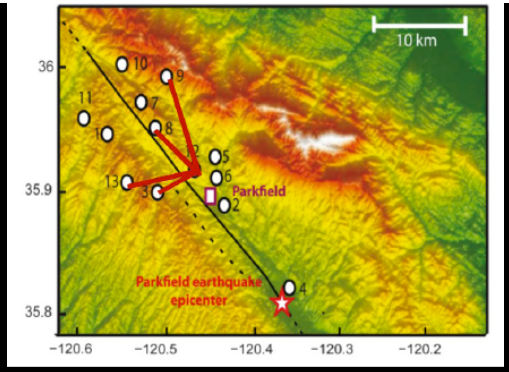



# Time variations of Ψ angle after noise removal



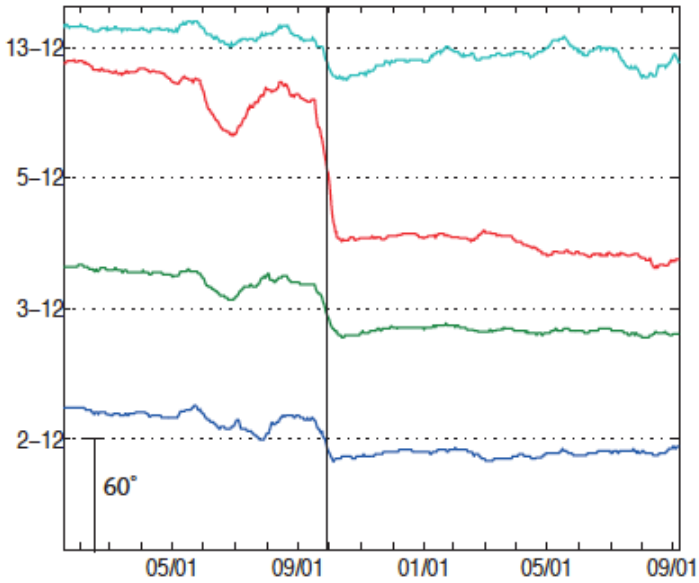

Significant co-seismic jumps for station pairs containing station 12

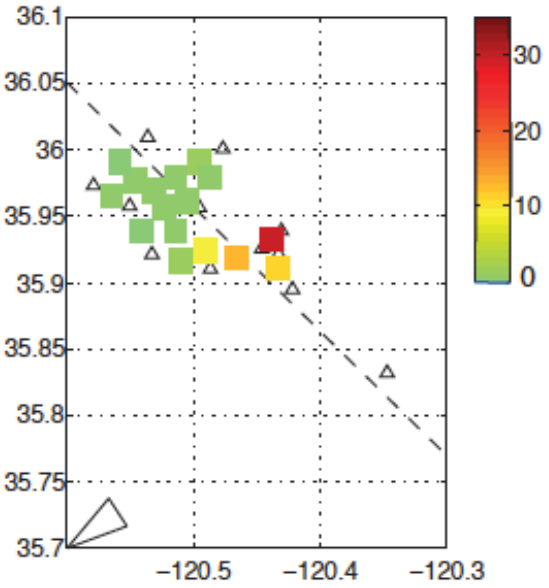



Tentative interpretation:
stress rotation => rotation of the crack distribution

# Conclusion 1

•New Method for continuous monitoring of stress field
•Noise correlations sensitive to:
-1) Noise source location
-2) Anisotropy (stressmeter)
•Separation of 1) and 2) by SVD
•Significant co-seismic signal observed at station 12

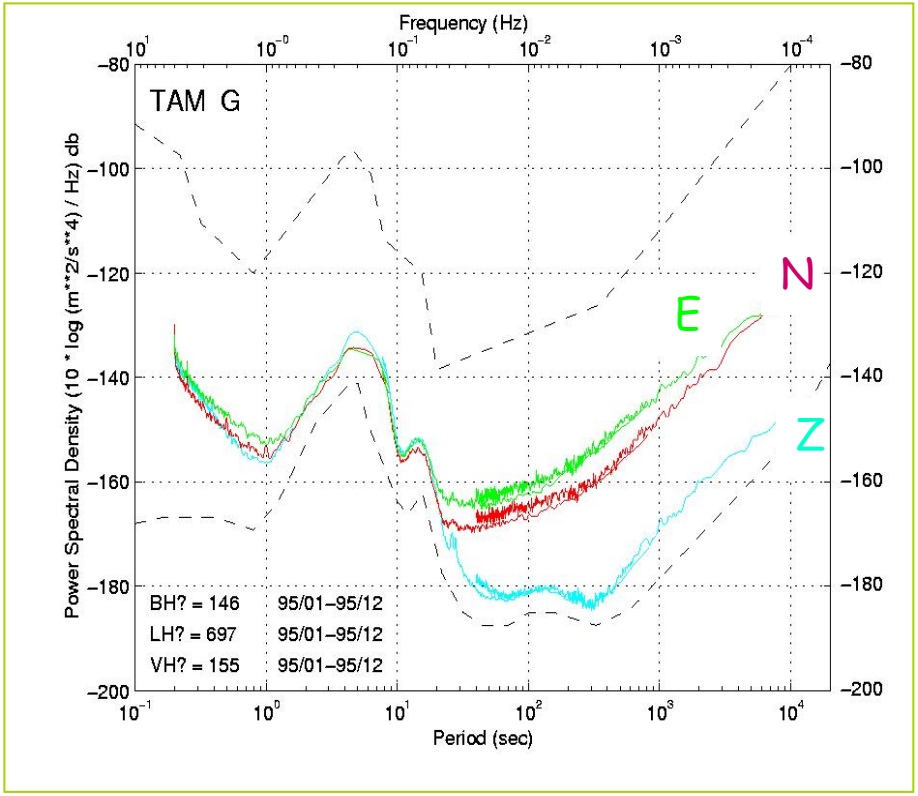



## Future

•Strain measurements
•Application to other tectonic contexts and volcanoes
•New Instruments

# New instrumentation




TAM (Tamanrasset, Algeria)

The PRESENT and the FUTURE?

**Multiparameter stations**

(microbarometer, thermometer, GPS)

Other sensors:

Supraconducting gravimeter

Electromagnetic sensors?

Long base tiltmeters?

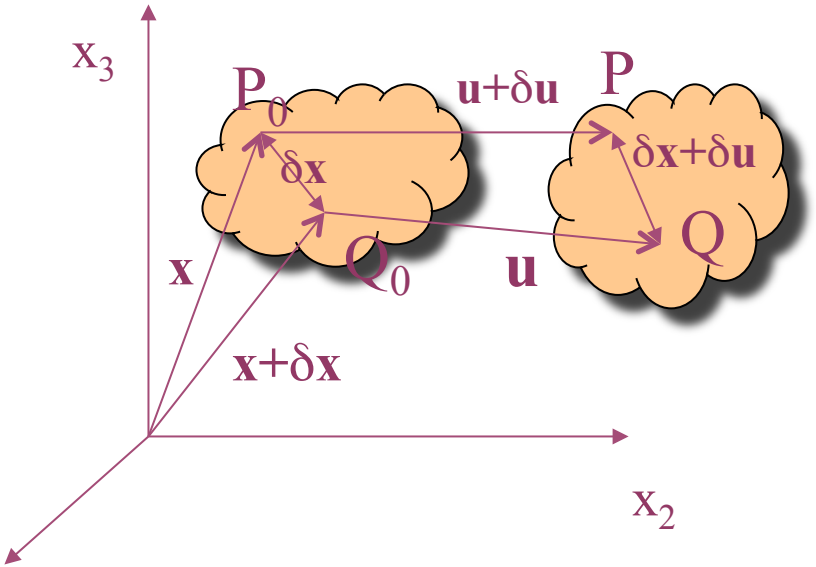
Rotational seismometer?

Seismometer Array

} **VIRGO**

**New signals =>New findings**

## Deformation of a continuum




$P_0$, $Q_0$ … undeformed medium

P, Q ….. deformed medium

$$u_i(x+\delta x) = u_i(x) + \frac{\partial u_i(x)}{\partial x_j}\delta x_j + O(\frac{\partial u}{\partial x})^2$$

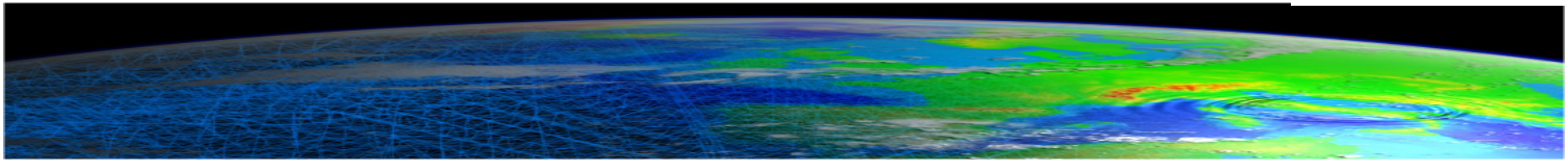
Displacement derivatives represent a second-rank tensor which can be resolved into a **symmetric** and **anti-symmetric** parts:

$$\delta u_i = \frac{\partial u_i(x)}{\partial x_j}\delta x_j = \frac{1}{2}(\frac{\partial u_i}{\partial x_j}+\frac{\partial u_j}{\partial x_i})\delta x_j + \frac{1}{2}(\frac{\partial u_i}{\partial x_j}-\frac{\partial u_j}{\partial x_i})\delta x_j = e_{ij}\delta x_j + \omega_{ij}\delta x_j$$

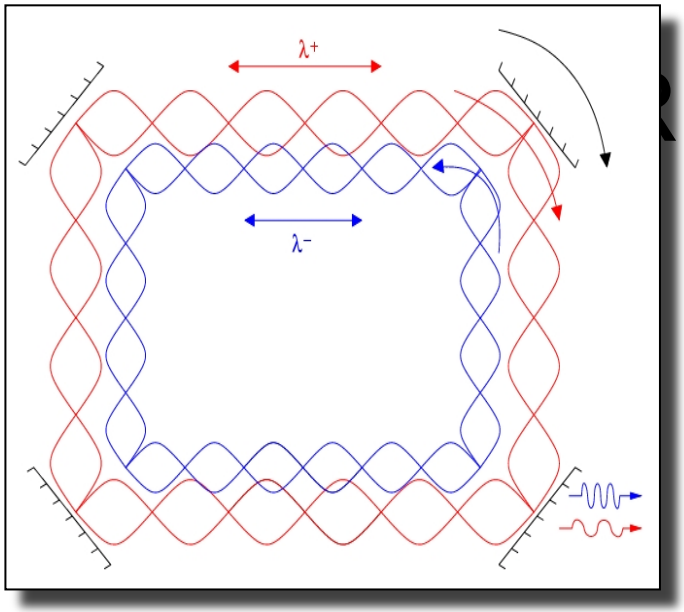
strain tensor

rotation tensor

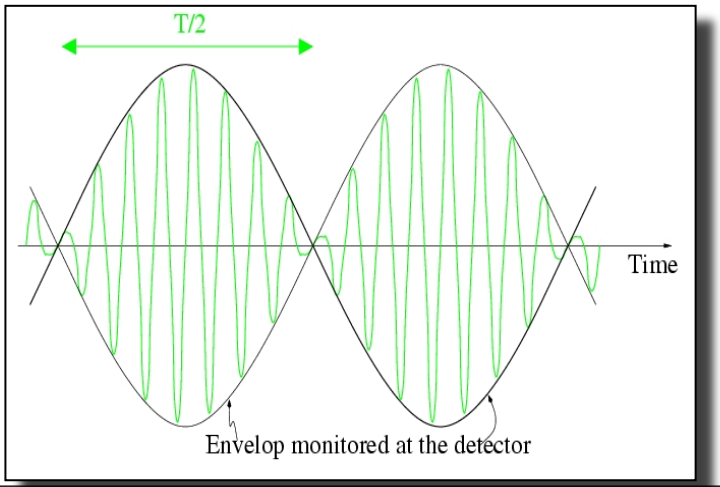
$$\frac{1}{2}(\mathrm{curl}\ \mathbf{u} \times \delta\mathbf{x})_i$$

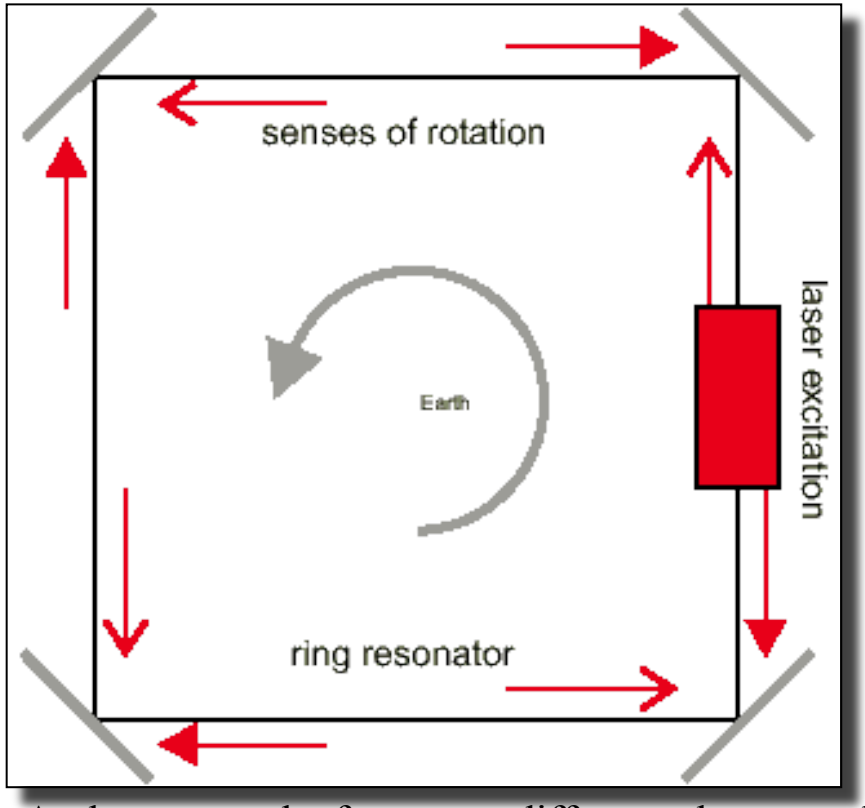


# Ring laser interferometer

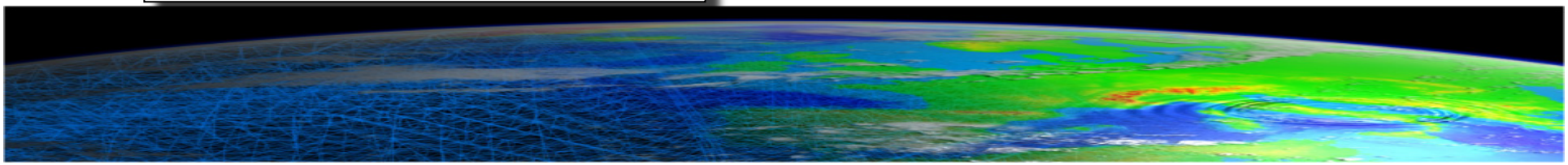



Superposition of co- and counter-rotating laser beams

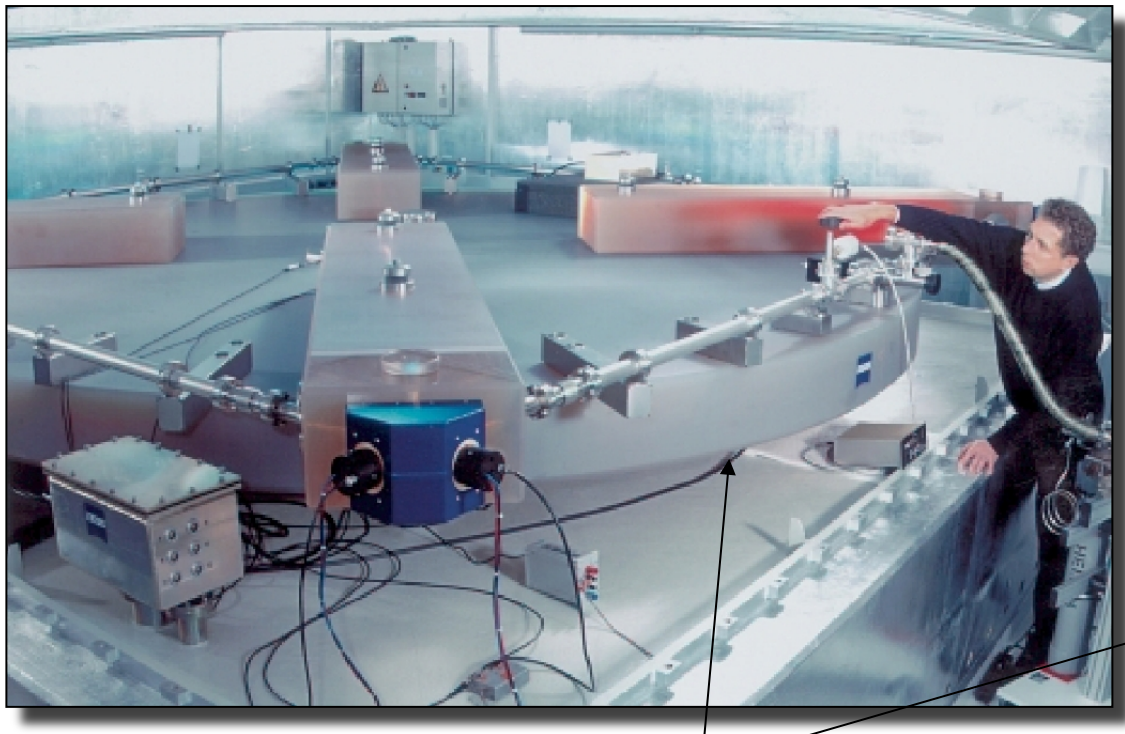


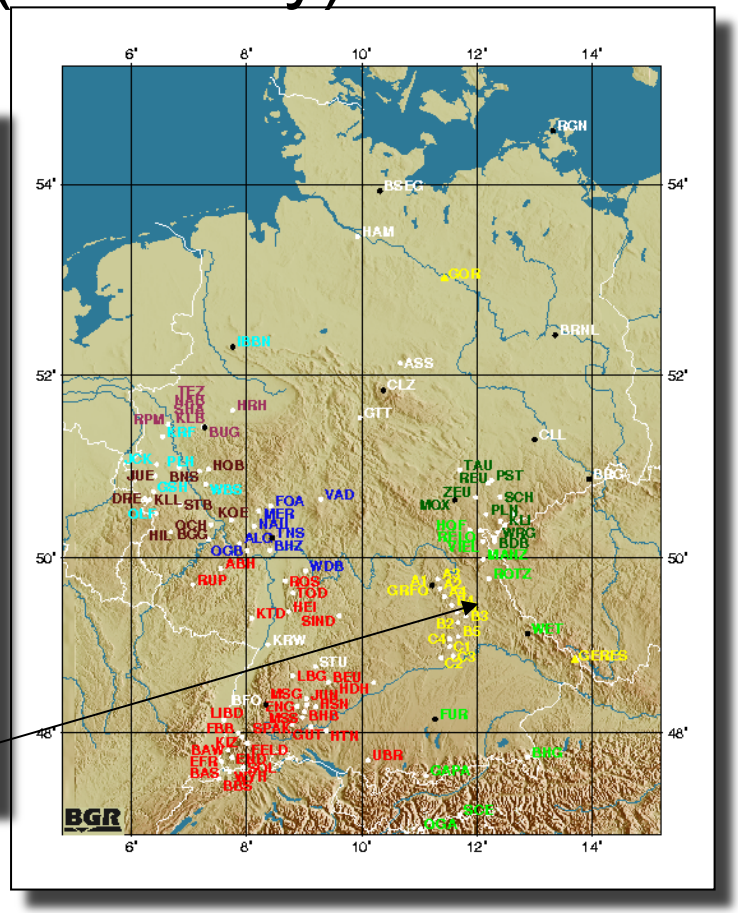




At the output, the frequency difference between the beams carries the information about the rotation rate.



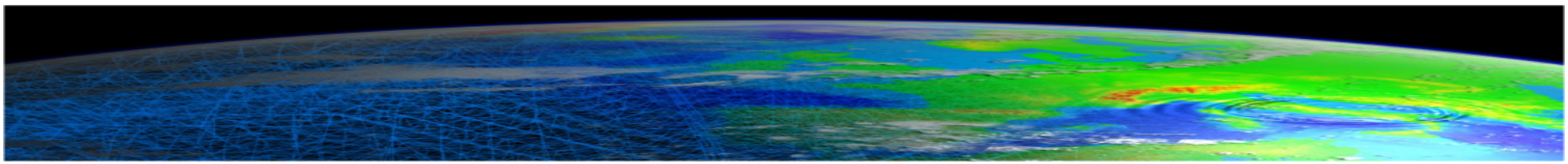
# The ring laser at Wettzell (Germany)






4 x 4 m ring laser

(resolution $10^{-12}$ rad/s)



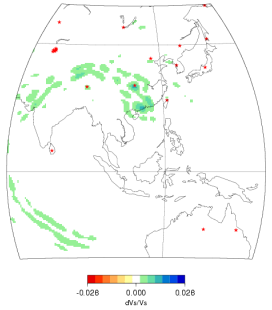
# Exploratory Project

## Geophysics and Gravitational Wave Interferometers
## APC – IPGP
## (M. Barsuglia & J.-P. Montagner)

Sensitivity of GW interferometers limited by seismic noise (tectonic, Environmental, human activity)

Geology and environment influences the GW detectors, then GW detectors can be used for geophysical Applications (strainmeter, tiltmeter)

# General Conclusions



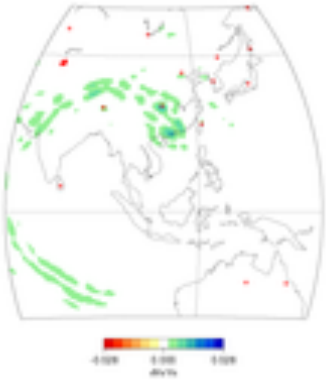
- Earthquake Seismology

- ***New sources*** « Environmental » Seismology: Microseismic noise, seismic Hum, glacial EQ, tremors,…

-***New Instruments «Gravitational wave interferometer »***

-***New Data (noise => signal)***

# General Conclusions



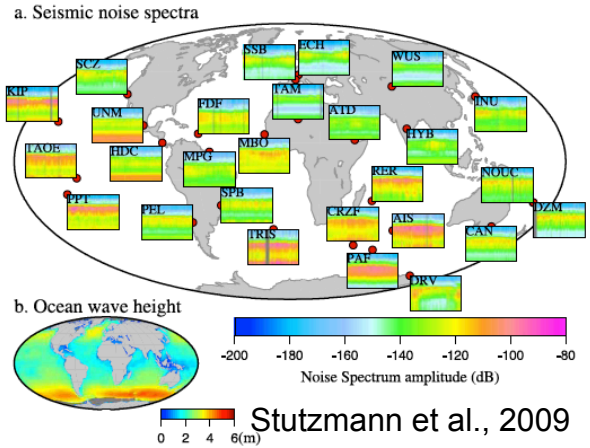
- « Environmental » Seismology: Hum,

Glacial Earthquakes (time-reversal imaging), …

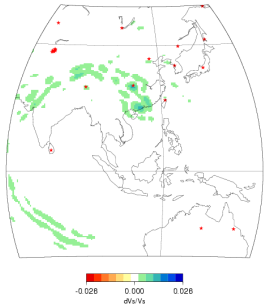
- Noise => Signal

-Similarities time-reversal and cross-correlation techniques: tomography

- MONITORING: Long-term temporal variations of physical parameters from Noise (anisotropy, temperature, glacial earthquake frequency …)




Stutzmann et al., 2009




# General Conclusions

- Earthquake Seismology

- ***New sources*** « Environmental » Seismology: Microseismic noise, seismic Hum, glacial EQ, tremors,…

-***New Instruments « Gravitational wave interferometer »***

MONITORING:

•Seismic activity by Time-Reversal Methods

•Temporal variations of physical parameters from Noise (velocity, anisotropy, pressure, temperature, glacial earthquake frequency…) using similarities between TR imaging and CC-techniques