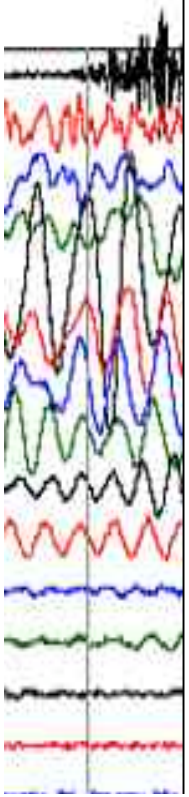
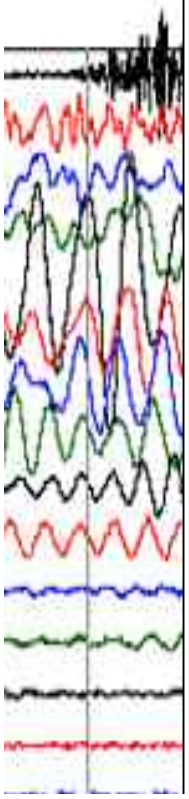


Low-Frequency Rotational Seismology: Observations with Ring Laser Technology

H. Igel[1], A. Cochard[1], A. Fichtner[1], A. Flaws[1,2], U. Schreiber[3] , B. Schuberth[1], W. Suryanto[1], D.N. Pham[1], A. Velikoseltsev[3], F. Vernon[4], J. Wassermann[1], M. Bernauer[1], F. Bernauer[1], D. Kurrle[1]

[1]Department of Earth and Environmental Sciences, LMU Munich
[2]Department of Physics and Astronomy, Christchurch, New Zealand
[3]Fundamentalstation Wettzell, Kötzting
[4]IGPP, La Jolla, USA

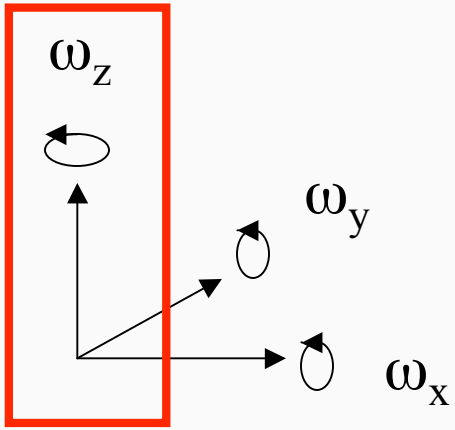
- What is *rotation* in seismology? (Why bother?)
- The ring laser instrument
- Observations: What to do with rotations?
  - Waveform comparison with translations
  - Tomography without travel times
  - **Free oscillations of the Earth!!!**
- Array-derived vs. directly measured rotations
- Conclusions and Outlook



Rotation is the curl of the wavefield

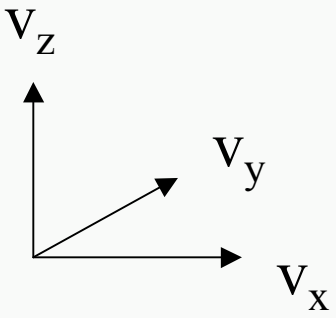
... it separates P- and S-waves in isotropic media

$$\begin{pmatrix} \omega_x \\ \omega_y \\ \omega_z \end{pmatrix} = \frac{1}{2}\nabla \times \underline{\mathbf{v}} = \frac{1}{2}\begin{pmatrix} \partial_y v_z - \partial_z v_y \\ \partial_z v_x - \partial_x v_z \\ \partial_x v_y - \partial_y v_x \end{pmatrix}$$



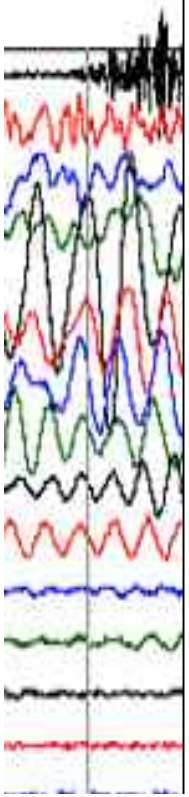
Rotation rate

Rotation sensor



Ground velocity

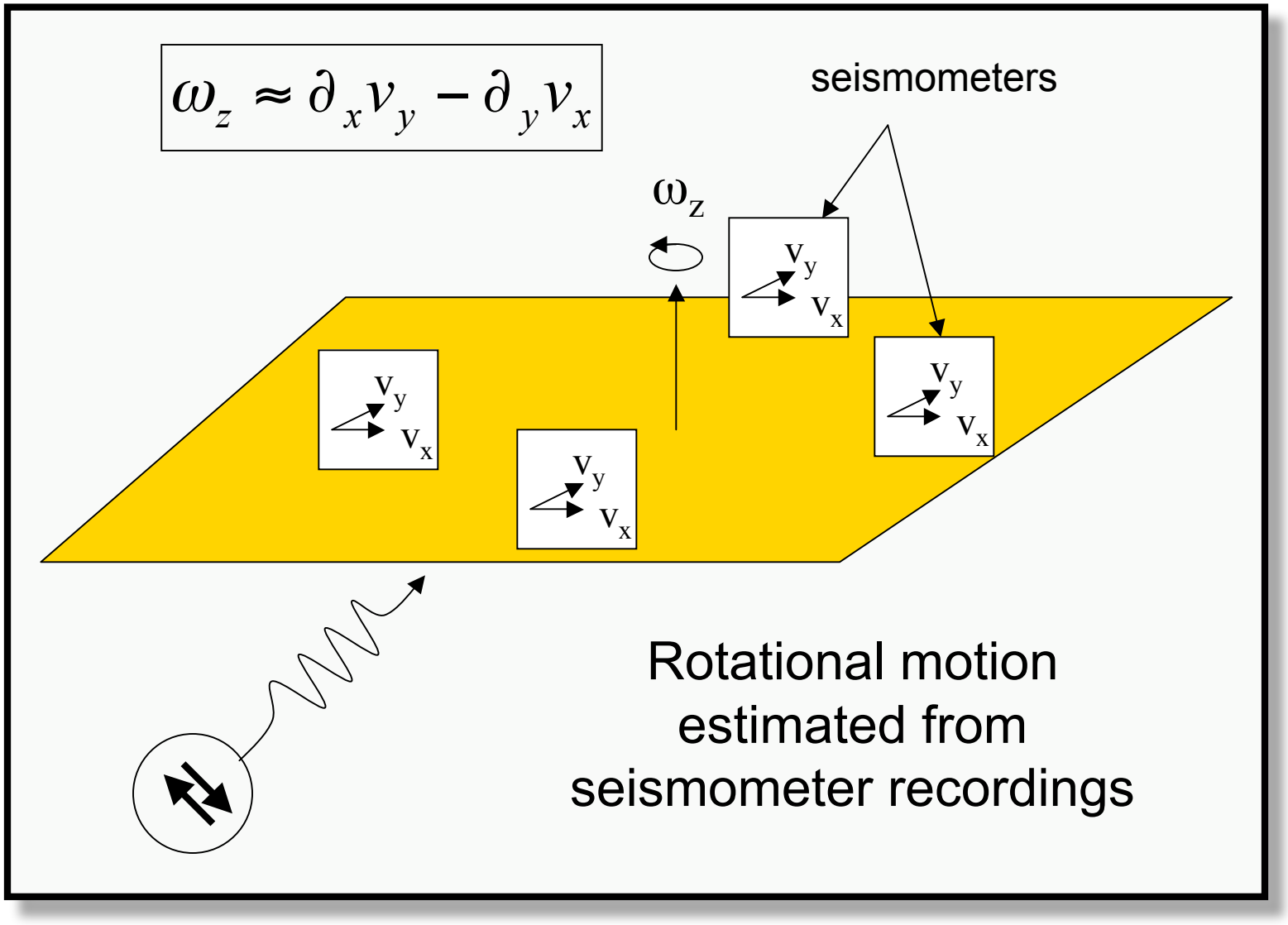
Seismometer

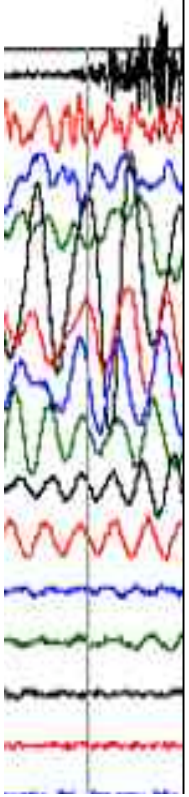


Rotation from seismic arrays?

... by finite differencing ...

$$\omega_z \approx \partial_x v_y - \partial_y v_x$$





Rotations – why bother?

- Standard seismological observations are contaminated by rotations (e.g. OBS, strong motions, free oscillations)
- Tiltmeters (rotation around horizontal axes) are contaminated by translations
- 6C sensor may allow integration to displacements

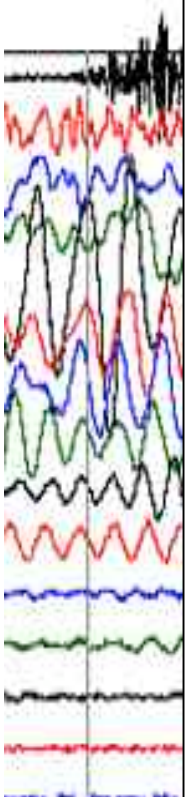
Instruments

- Rotations may contribute to co-seismic structural damage

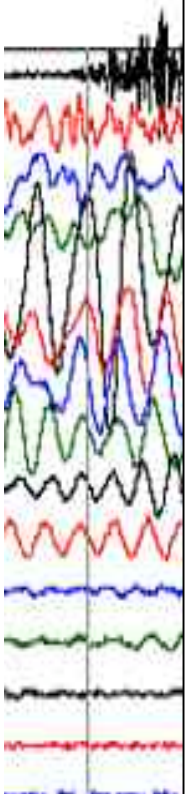
Earthquake engineering

- Rotational measurements provides additional wavefield information (phase velocities, structure, propagation direction, anisotropy, etc)
- ... and may allow putting further constraints on rupture processes ...

Tomography and sources



THEORY



Radiation from a point source

Ground displacement

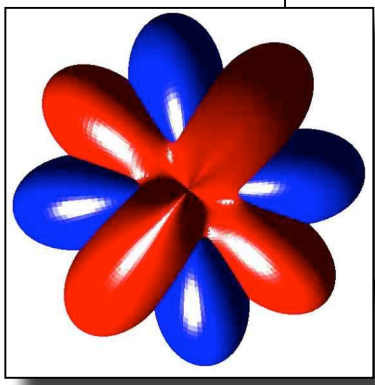
$$u(x,t) = \frac{1}{4\pi\rho} A^N \frac{1}{r^4} \int_{r/v_P}^{r/v_S} \tau M_0(t-\tau)\, d\tau$$

$$+ \frac{1}{4\pi\rho v_P^2} A^{IP} \frac{1}{r^2} M_0(t - r/v_P)$$

$$+ \frac{1}{4\pi\rho v_S^2} A^{IS} \frac{1}{r^2} M_0(t - r/v_S)$$

$$+ \frac{1}{4\pi\rho v_P^3} A^{FP} \frac{1}{r} \dot{M}_0(t - r/v_P)$$

$$+ \frac{1}{4\pi\rho v_S^3} A^{FS} \frac{1}{r} \dot{M}_0(t - r/v_S).$$

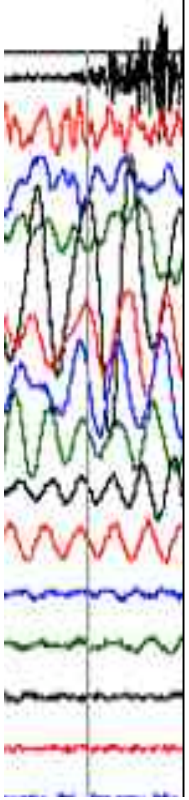


Near field term contains the static displacement

Intermediate terms

Far field terms: the main ingredient for source inversion, ray theory, etc.

Aki and Richards (2002)



The rotational part

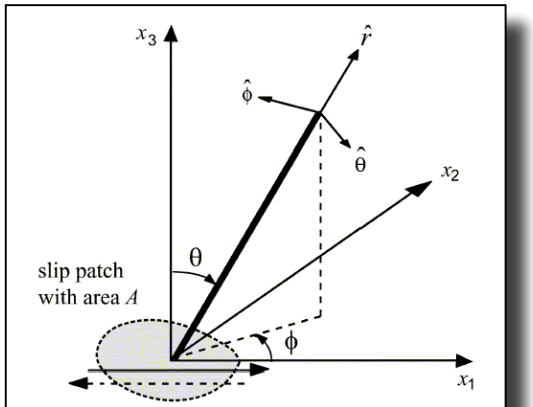


FIGURE 5 Cartesian and polar coordinate systems for analysis of radiation by a slip patch with area A and average slip $\langle \Delta u(t) \rangle$.

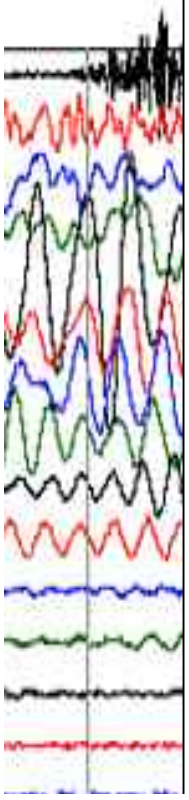
$$\omega(\mathbf{x},t) = \frac{1}{2}\nabla \times \mathbf{u}(\mathbf{x},t)$$

$$= \frac{-\mathbf{A}^R}{8\pi\rho}\left[\frac{3}{\beta^2 r^3}M_0\left(t-\frac{r}{\beta}\right) + \frac{3}{\beta^3 r^2}\dot{M}_0\left(t-\frac{r}{\beta}\right) + \frac{1}{\beta^4 r}\ddot{M}_0\left(t-\frac{r}{\beta}\right)\right]$$

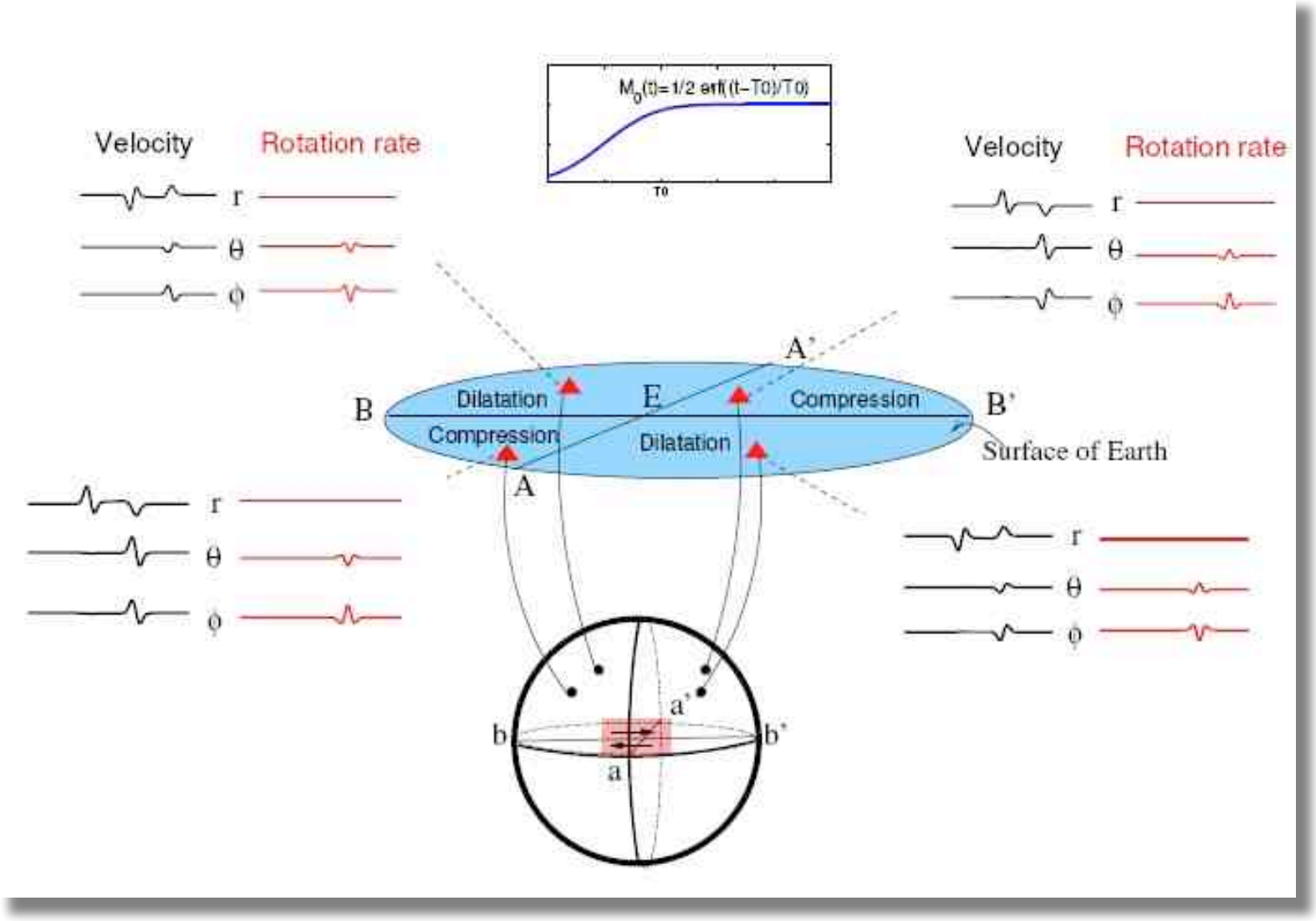
$$\mathbf{A}^R = \cos\theta\,\sin\phi\,\hat{\boldsymbol{\theta}} + \cos\phi\,\cos 2\theta\,\hat{\boldsymbol{\phi}}$$

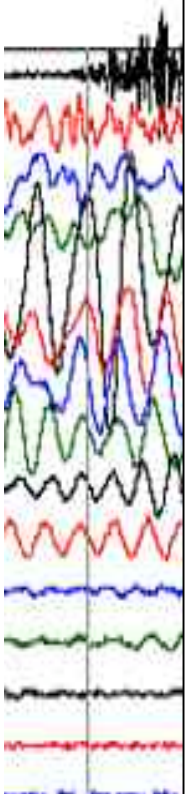
- Rotations are zero before S arrival
- Far-field P-rotation is not zero! Only the sum of all contributions cancel!

Cochard et al. (2006)



Basic seismograms, full space





Rotation rate and transverse acceleration

plane-wave propagation

Plane transversely polarized wave propagating in x-direction with phase velocity c

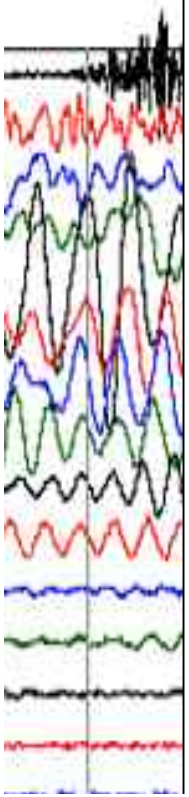
$$u_y(x,t) = f(kx - \omega t) \qquad c = \omega / k$$

Acceleration $$a_y(x,t) = \ddot{u}_y(x,t) = \omega^2 f''(kx - \omega t)$$

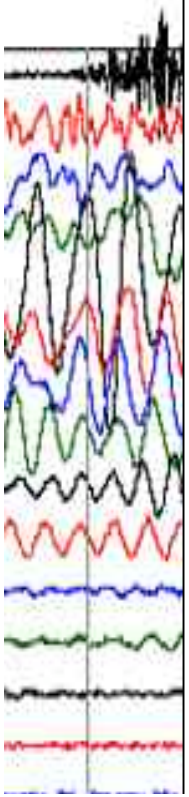
Rotation rate $$\dot{\Omega}(x,t) = \frac{1}{2}\nabla \times \left[0, \dot{u}_y, 0\right] = \left[0, 0, -\frac{1}{2} k\omega f''(kx - \omega t)\right]$$

$$a(x,t) / \dot{\Omega}(x,t) = -2c$$

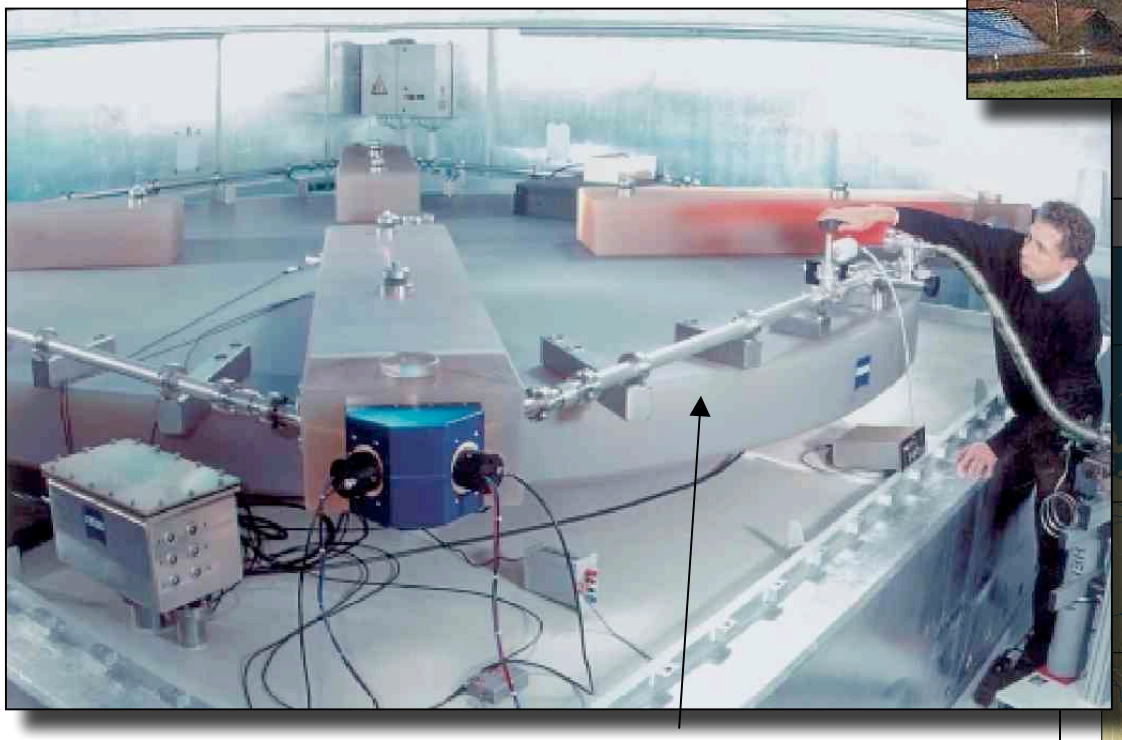
Rotation rate and acceleration should be in phase and the amplitudes scaled by two times the horizontal phase velocity



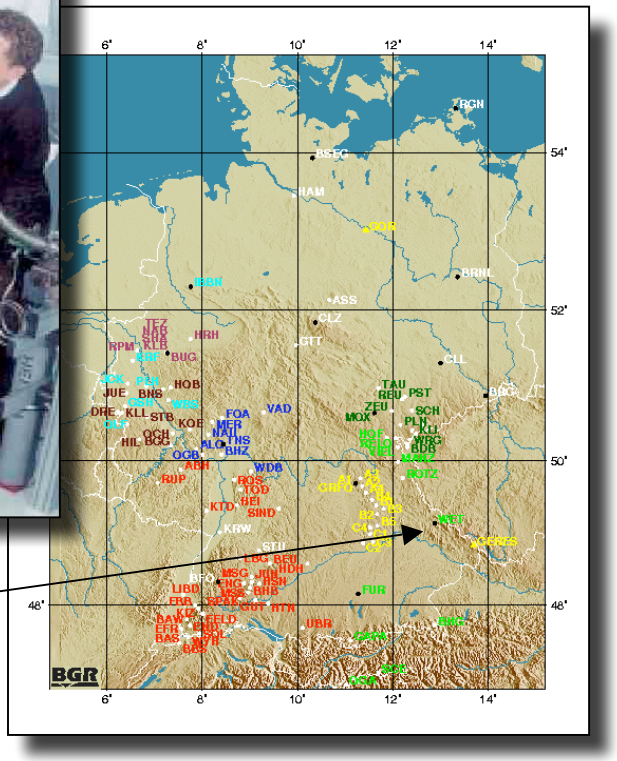
Instrumentation



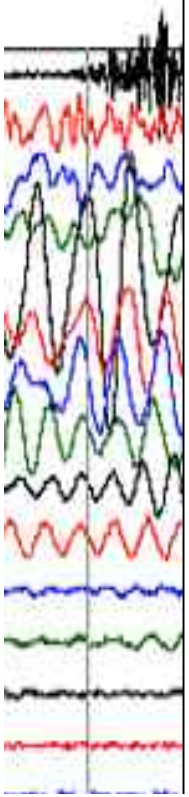
The ring laser at Wettzell



ring laser

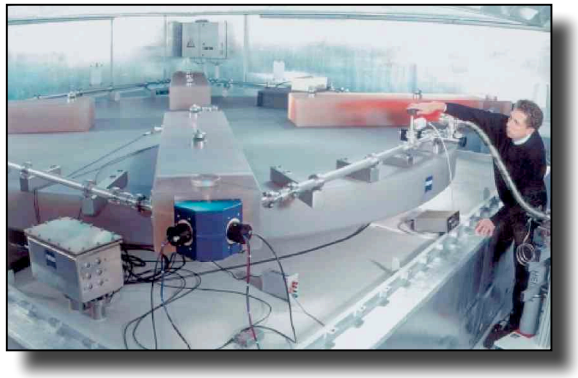


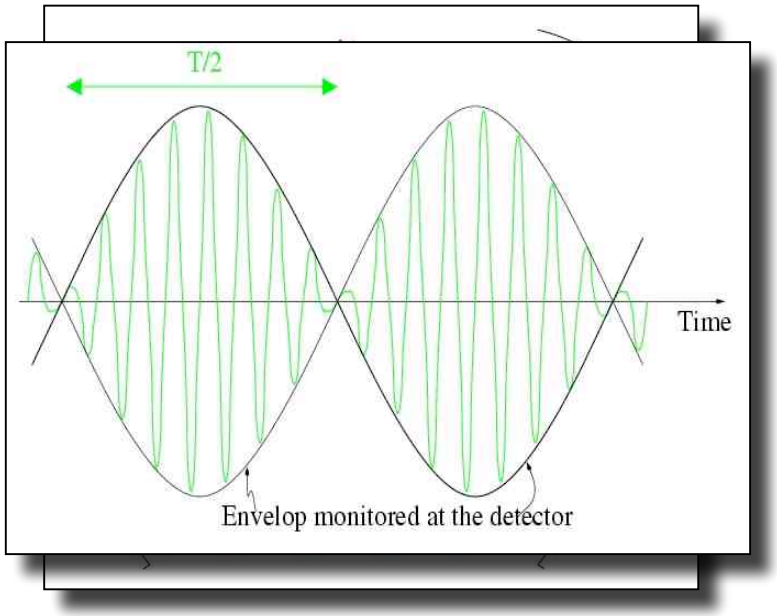
Data accessible at www.rotational-seismology.org

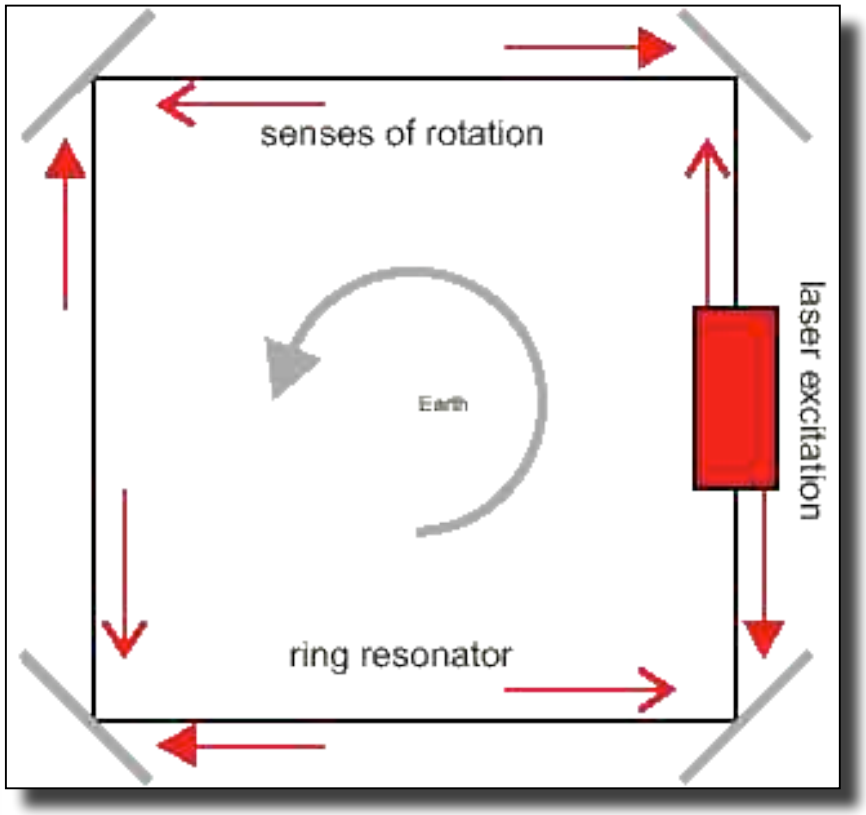


How can we observe rotations?

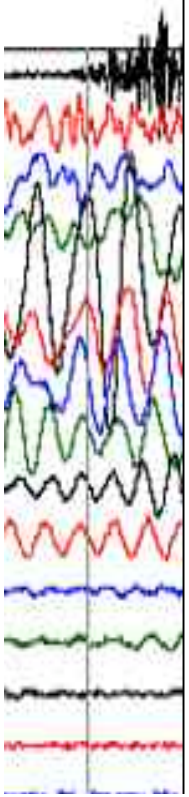
-> ring laser



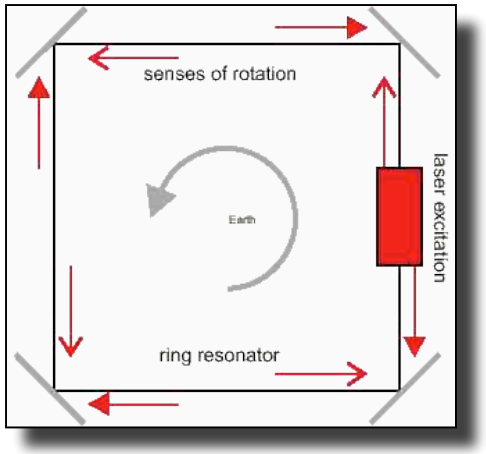




Ring laser technology developed by the groups at the Technical University Munich and the University of Christchurch, NZ



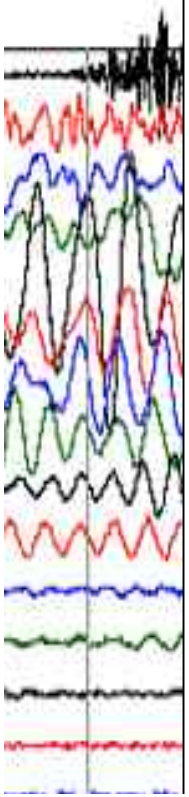
Ring laser – the principle



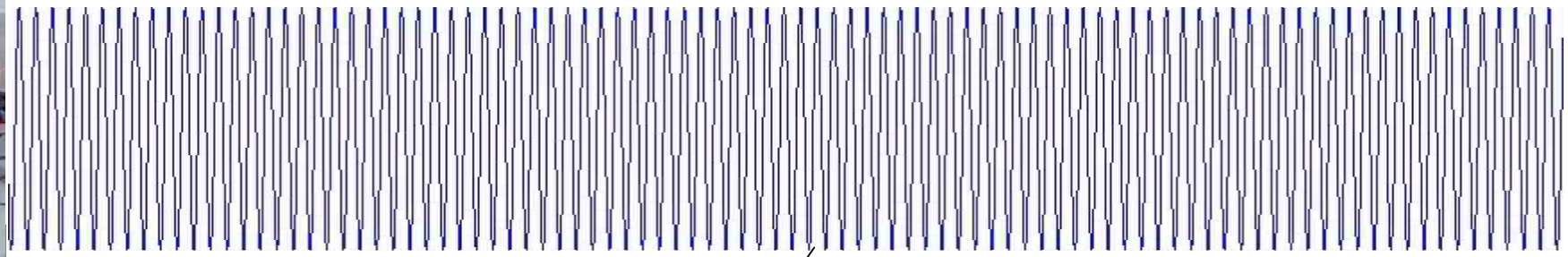
$$\Delta f_{Sagnac} = \frac{4\Omega \cdot A}{\lambda P}$$

A	surface of the ring laser (vector)
Ω	imposed rotation rate (Earth's rotation + earthquake +...)
λ	laser wavelength (e.g. 633 nm)
P	perimeter (e.g. 4-16m)
Δf	Sagnac frequency (e.g. 348,6 Hz sampled at 1000Hz)

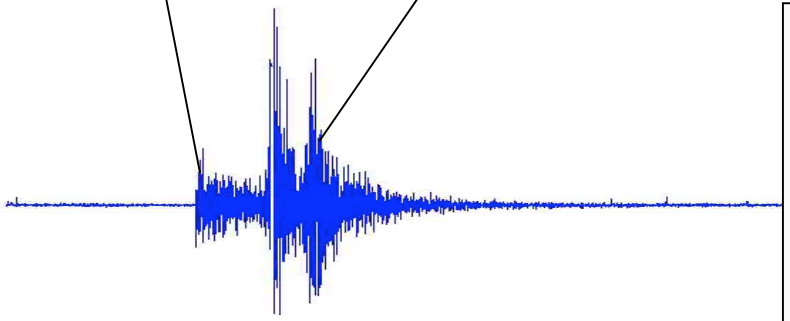
Resolution down to $O(10^{-11})$ rad/s



The Sagnac Frequency
(schematically)

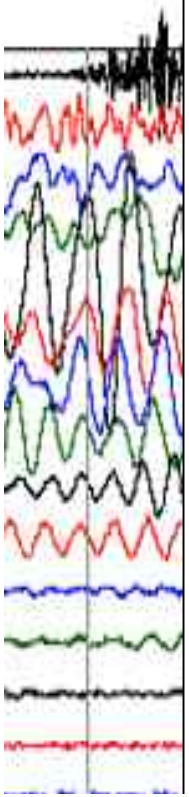


Sagnac frequency sampled with 1000Hz (Reftek)
-> instantaneous freq. using Hilbert transform



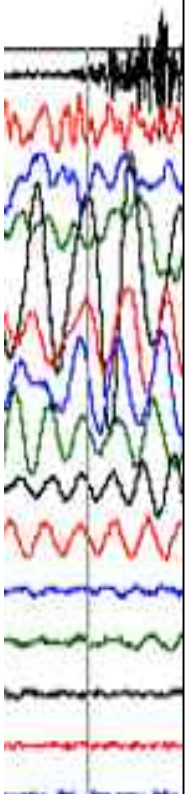
Tiny changes in the Sagnac frequencies are extracted to obtain the time series with rotation rate
$\Delta f \rightarrow \Theta$

Rotation rate sampled with 20Hz

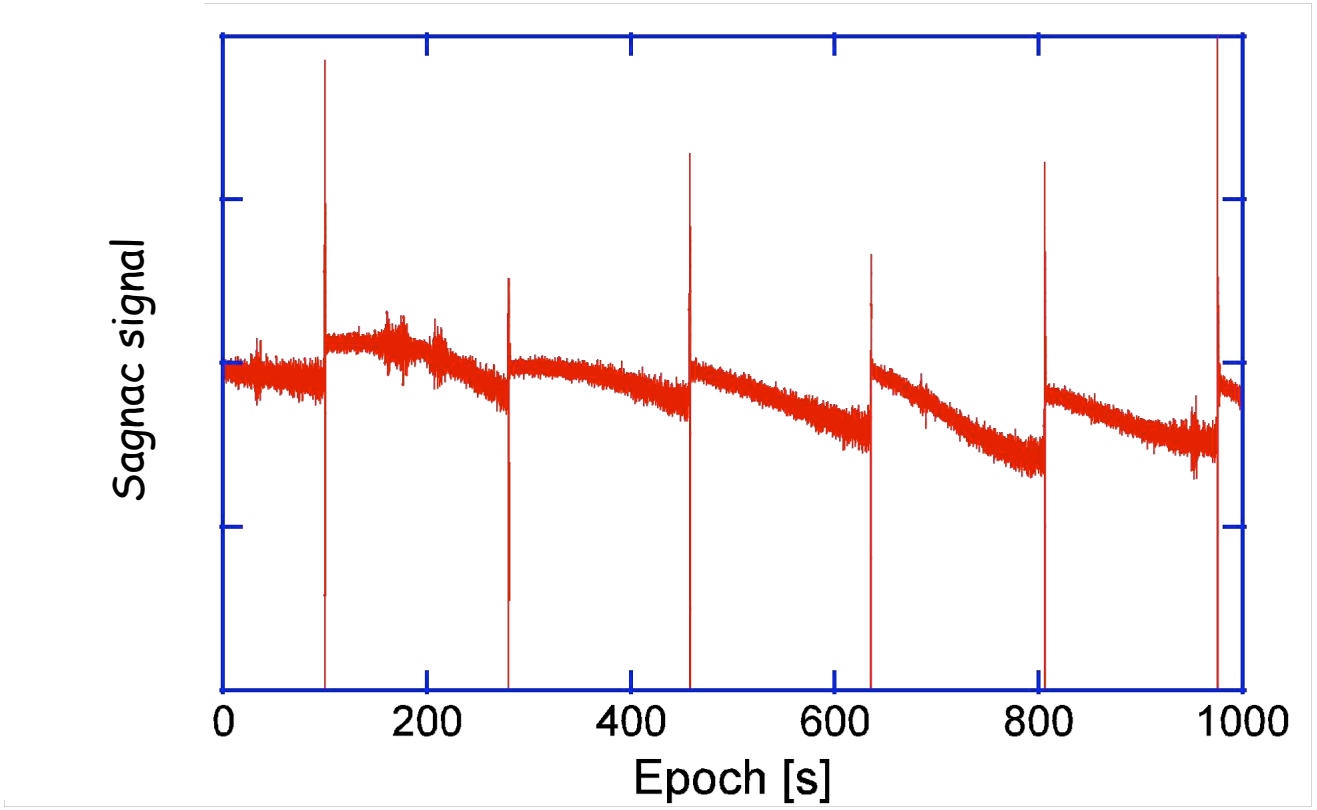


The PFO sensor

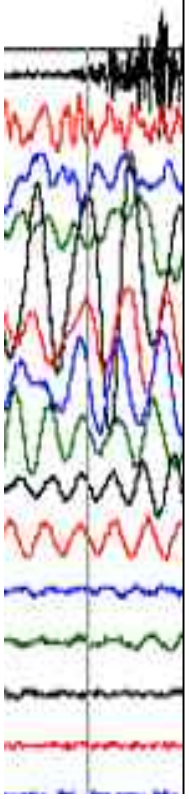
... built for seismology



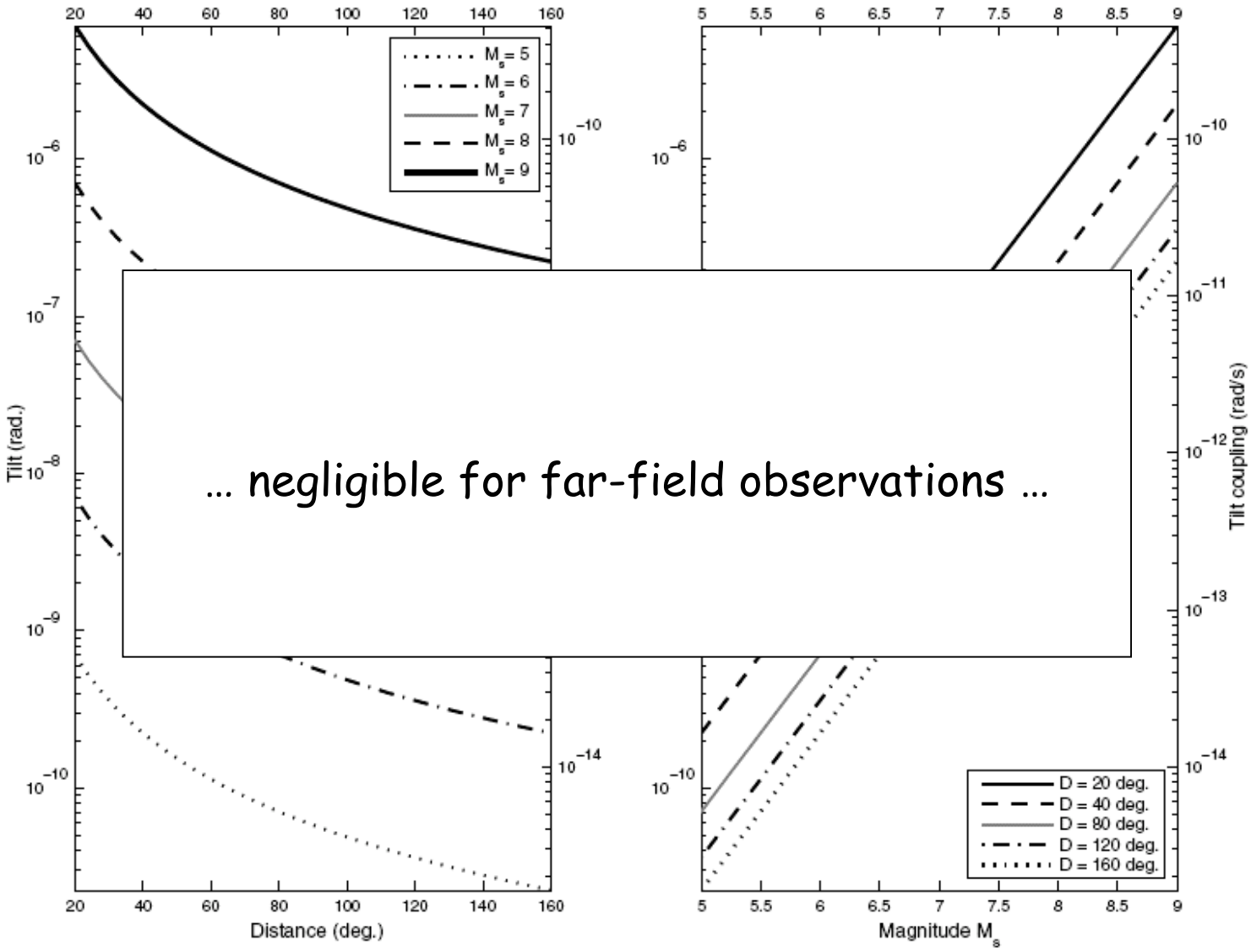
The PFO sensor
mode hopping



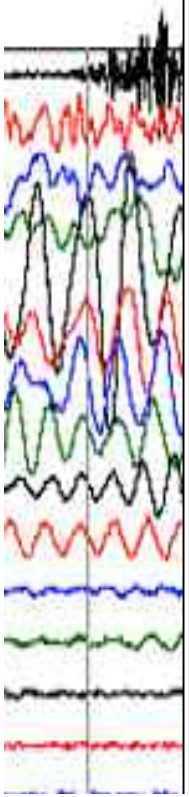
... mode hops can be avoided by cleaning through *getter function* (reducing outgassing)



Cross-axis sensitivity: tilt-Ringlaser coupling



… negligible for far-field observations …

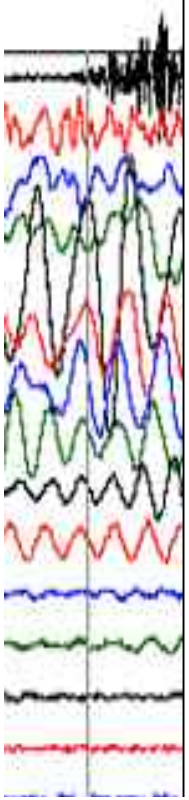


Horizontal axes?

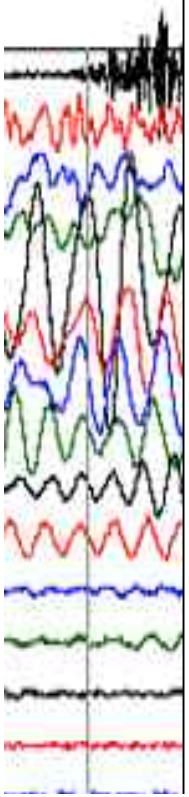
- First application in VIRGO project (gravitational wave detection, Pisa, Italy)
- 3C planned for PFO
- Options to get around „lock-in" problem:
  - 45 degree arrangement, projections
  - Running RL with „dithering" out of lock-in

RL1

RL2

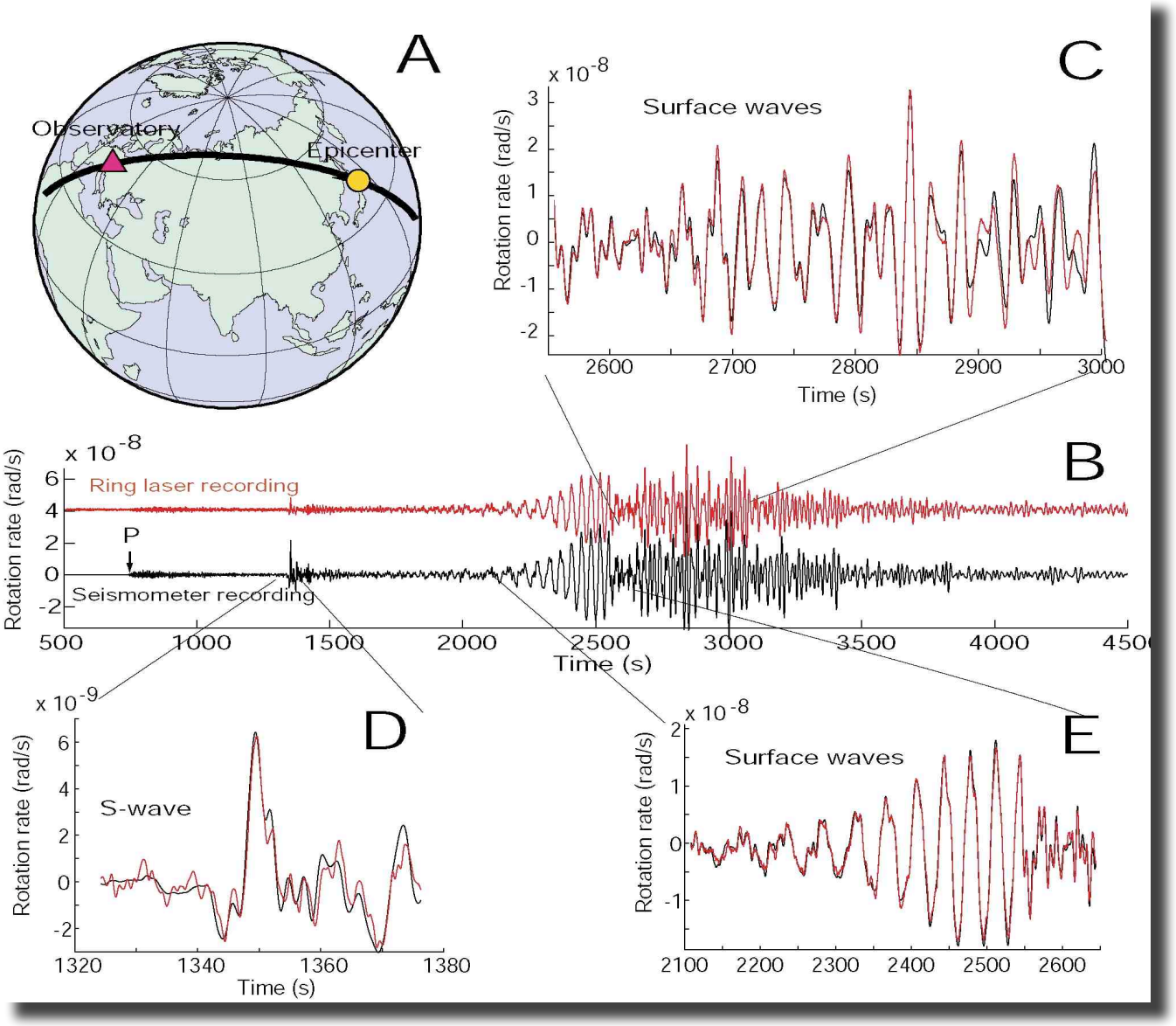


Data, Data, Data

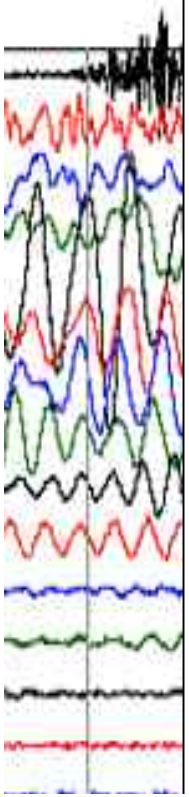


Mw = 8.3 Tokachi-oki 25.09.2003

transverse acceleration – rotation rate

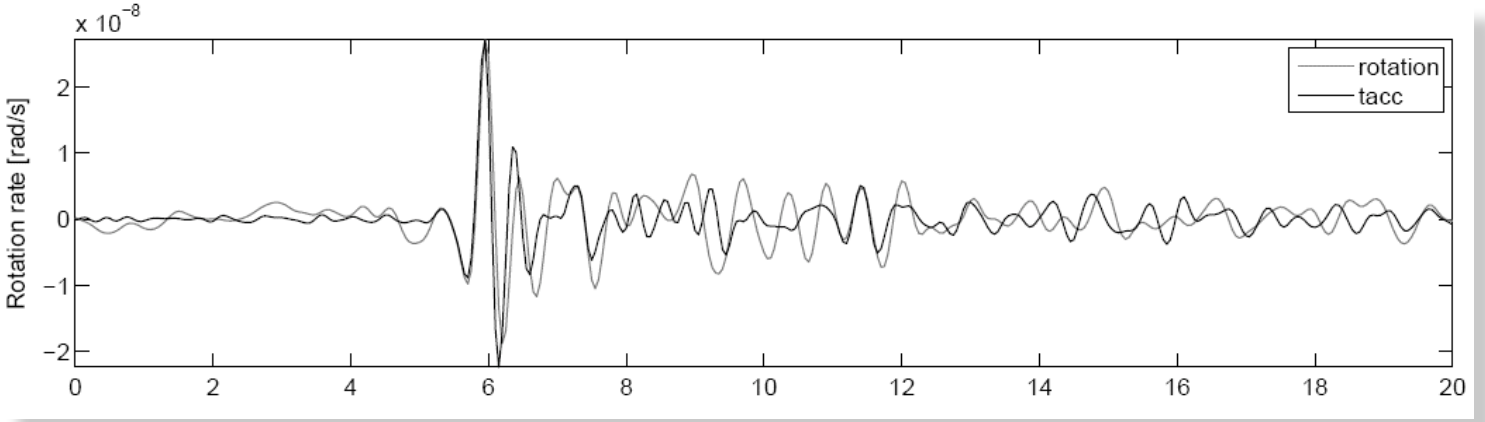


From Igel et al., GRL, 2005

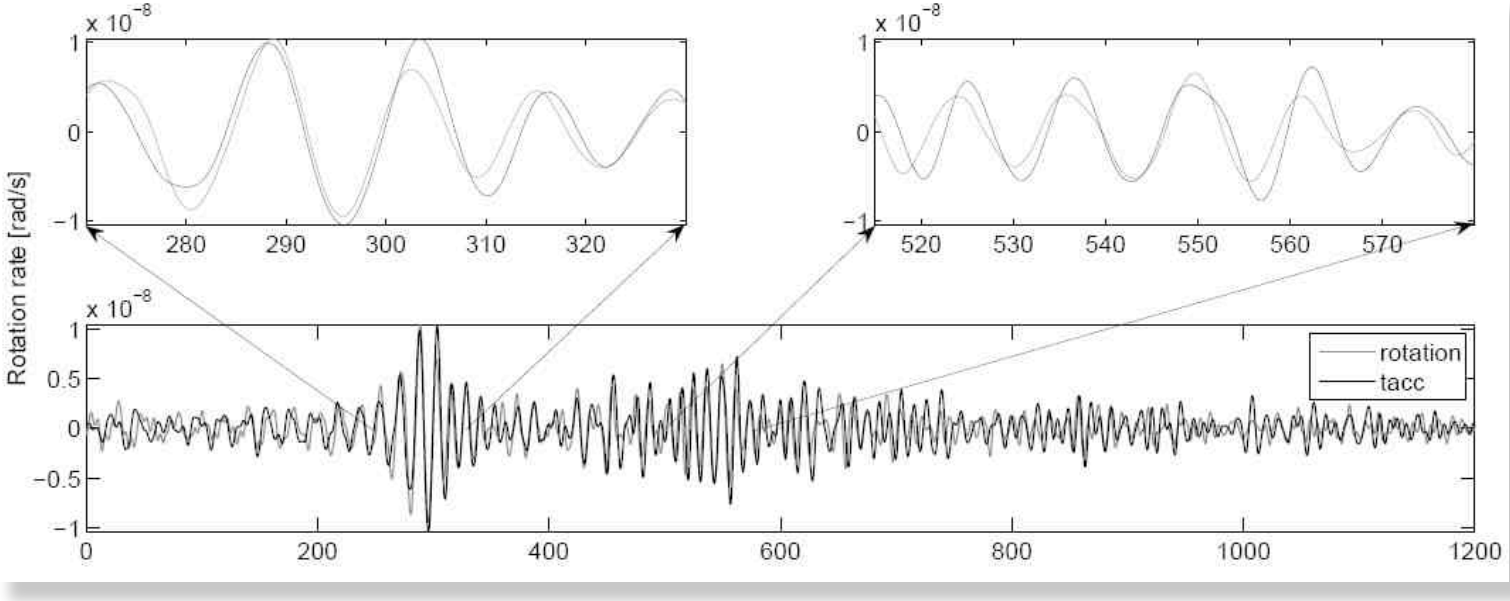


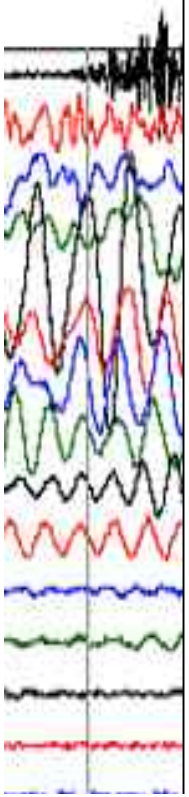
PFO Observations

California M3.9



Kamtchatka M7.6

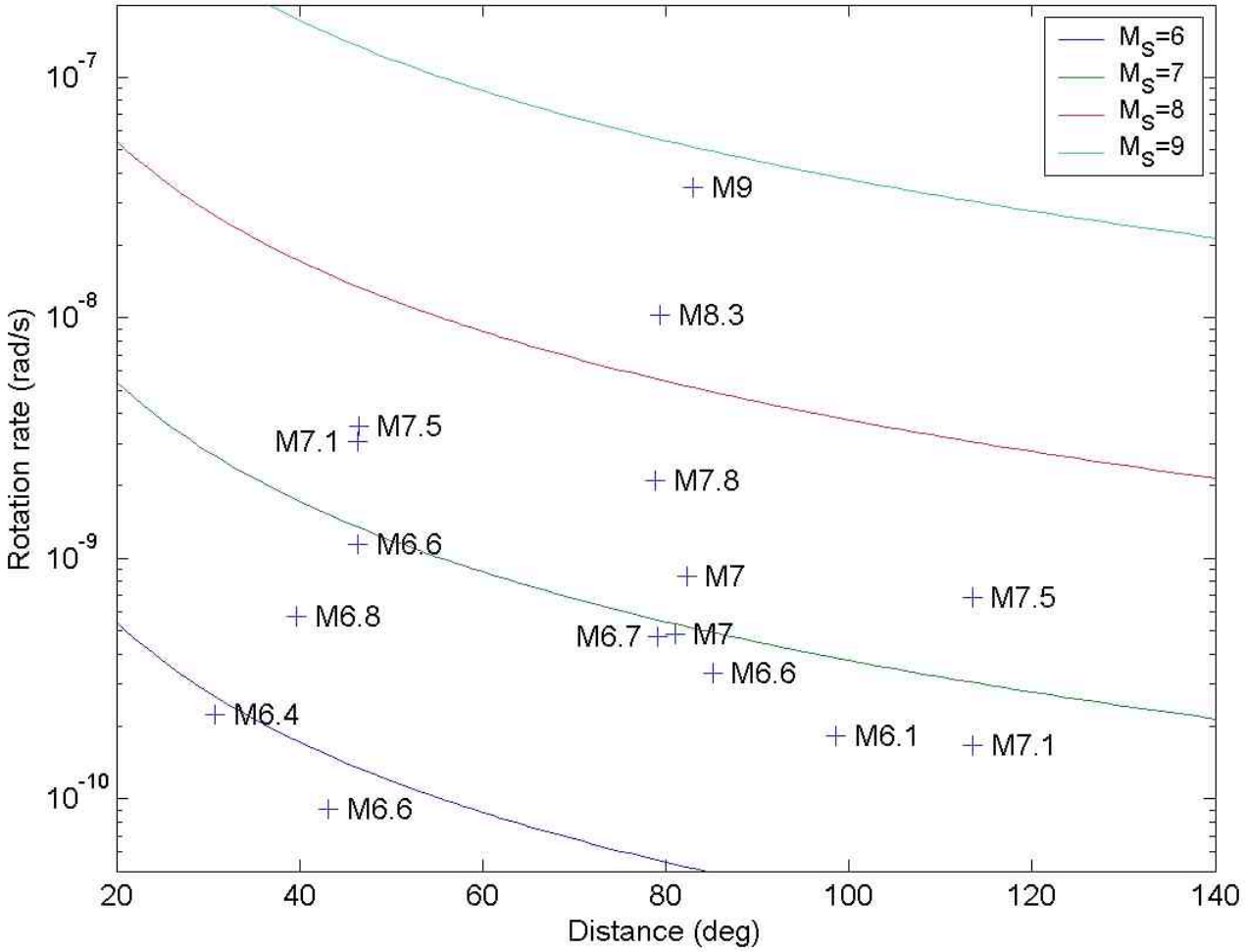


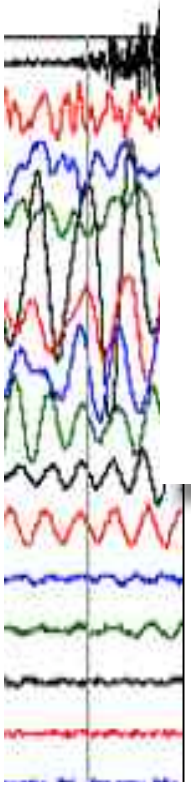


Compatibility with MS (surface wave magnitude) T=30s, c=4300m/s

$$M_S = \log_{10}\frac{A}{T} + 1.66\log_{10} D + 3.3$$

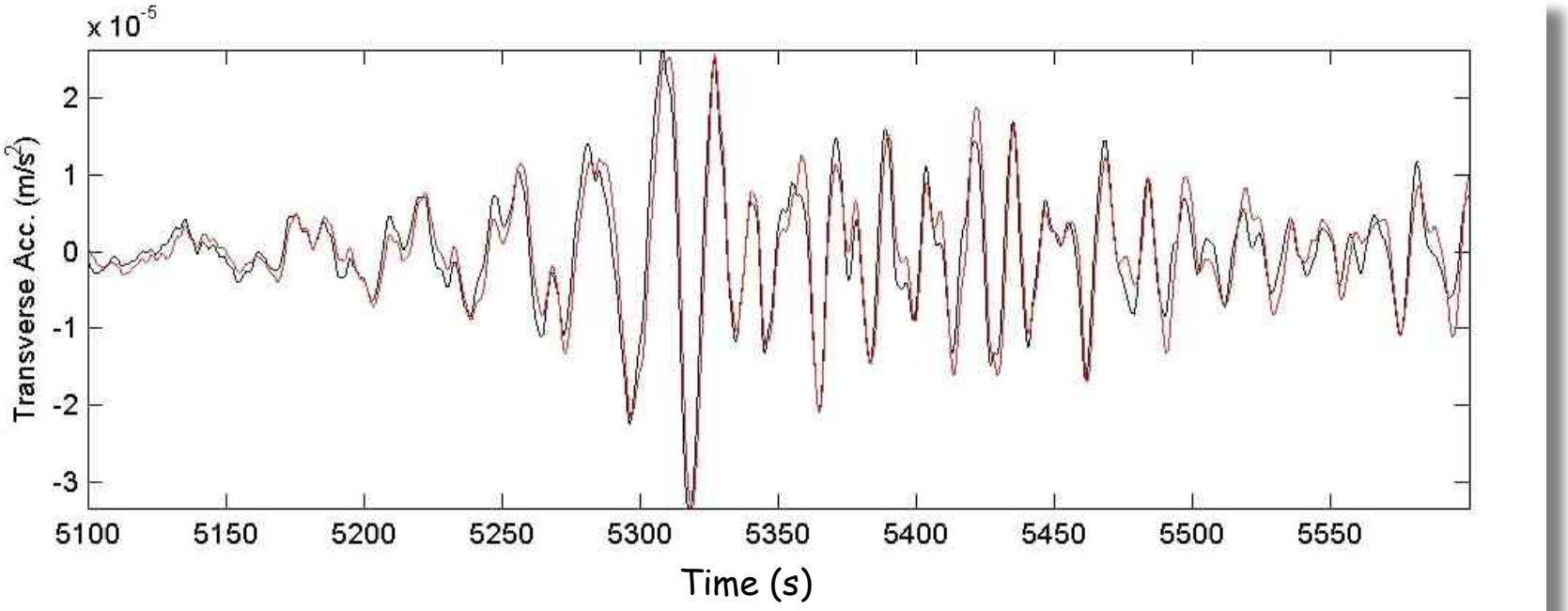
$$\Omega_z = 2\frac{\pi^2}{cT^2} A(M_S, D) = 2\frac{\pi^2}{cT} 10^{M_S - 1.66\log_{10} D - 9.3}$$

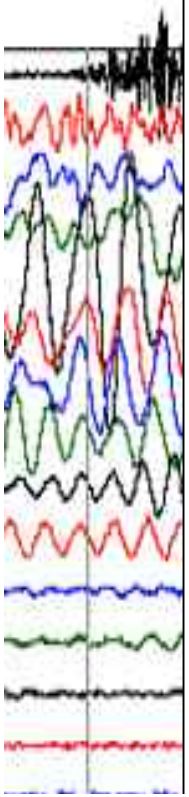




Instrument correction!
transverse acceleration – rotation rate

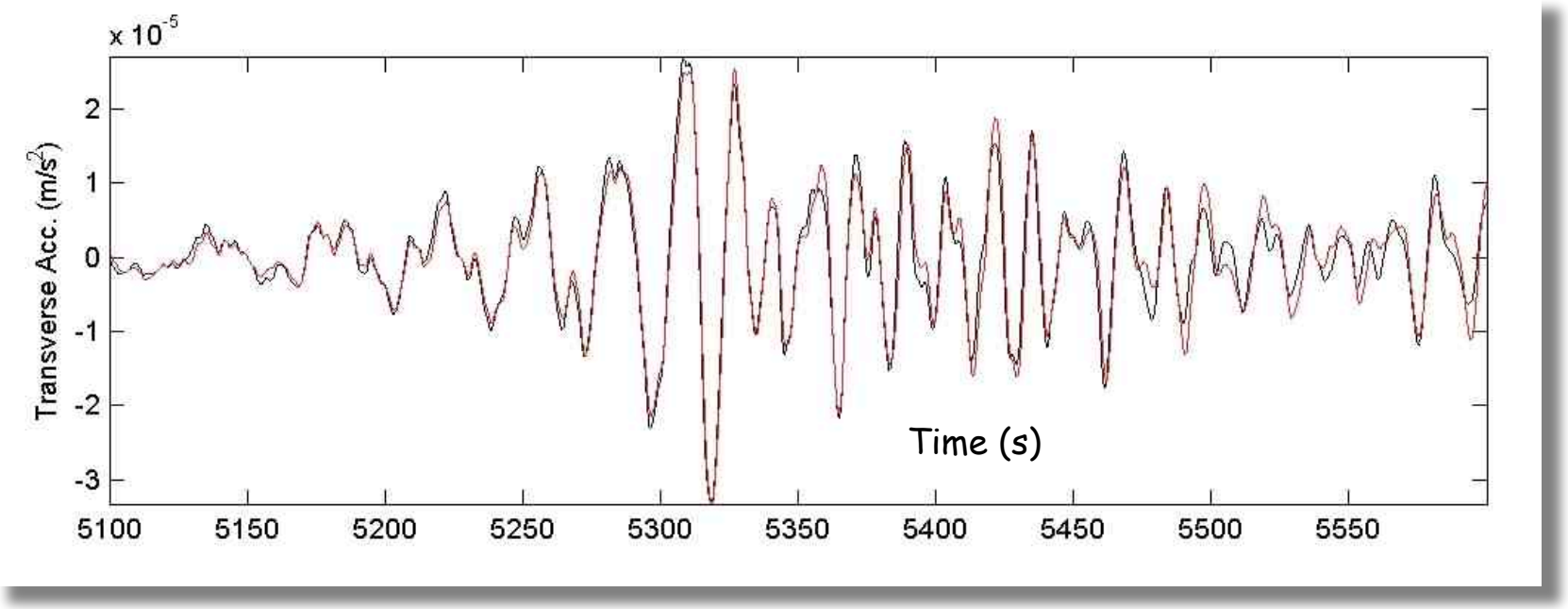
Before correction



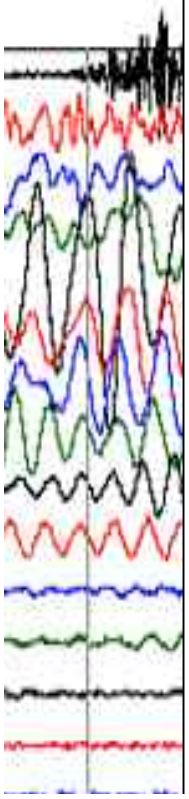


Instrument correction!
transverse acceleration – rotation rate

After correction

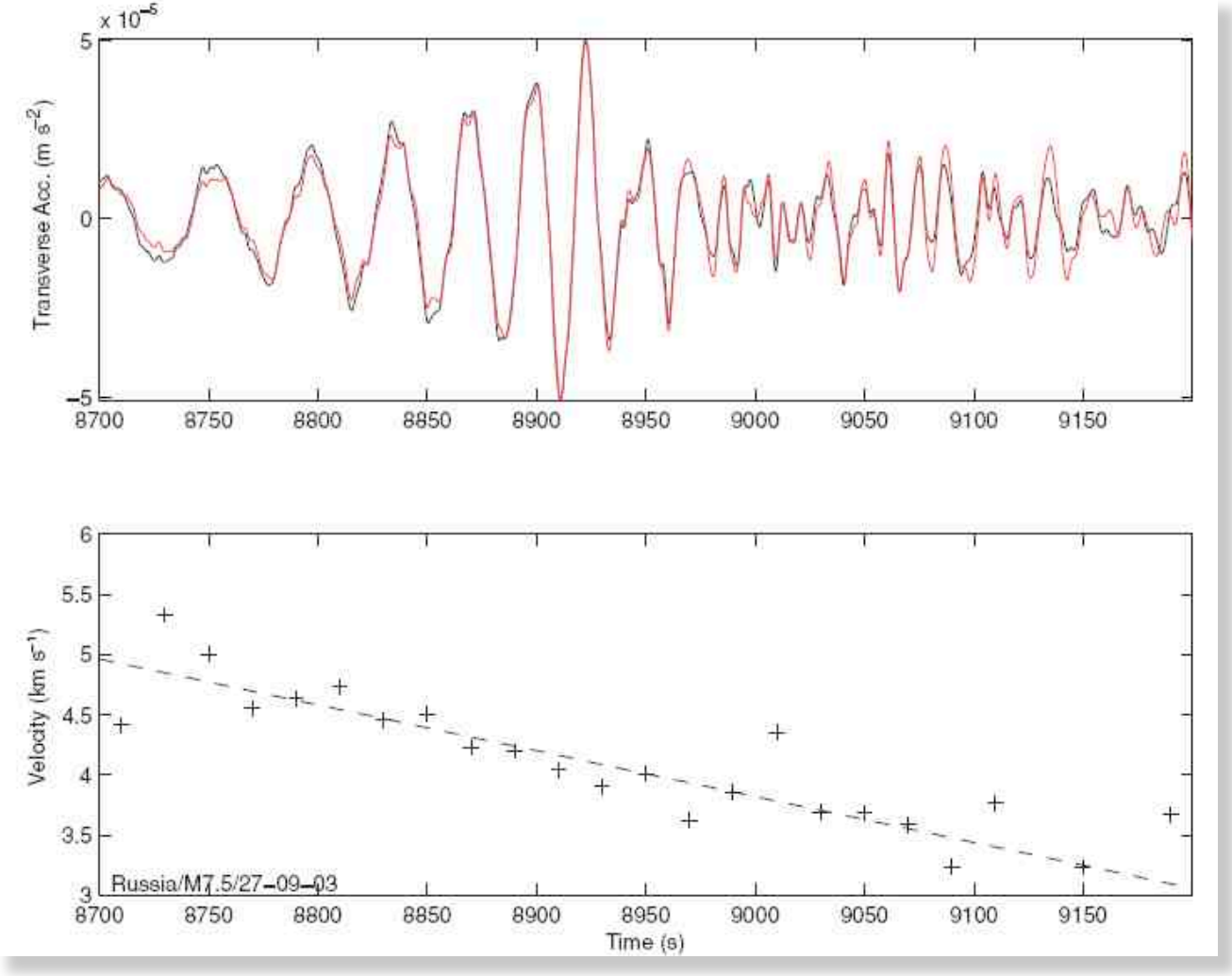


... an independent confirmation of the quality of the instrument correction ...

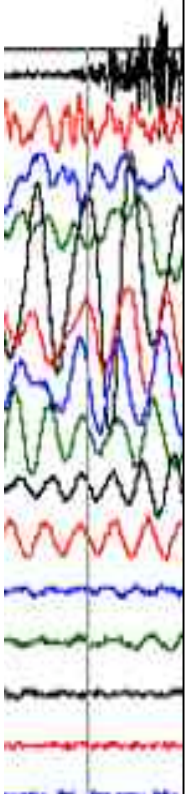


Love wave dispersion

transverse acceleration – rotation rate

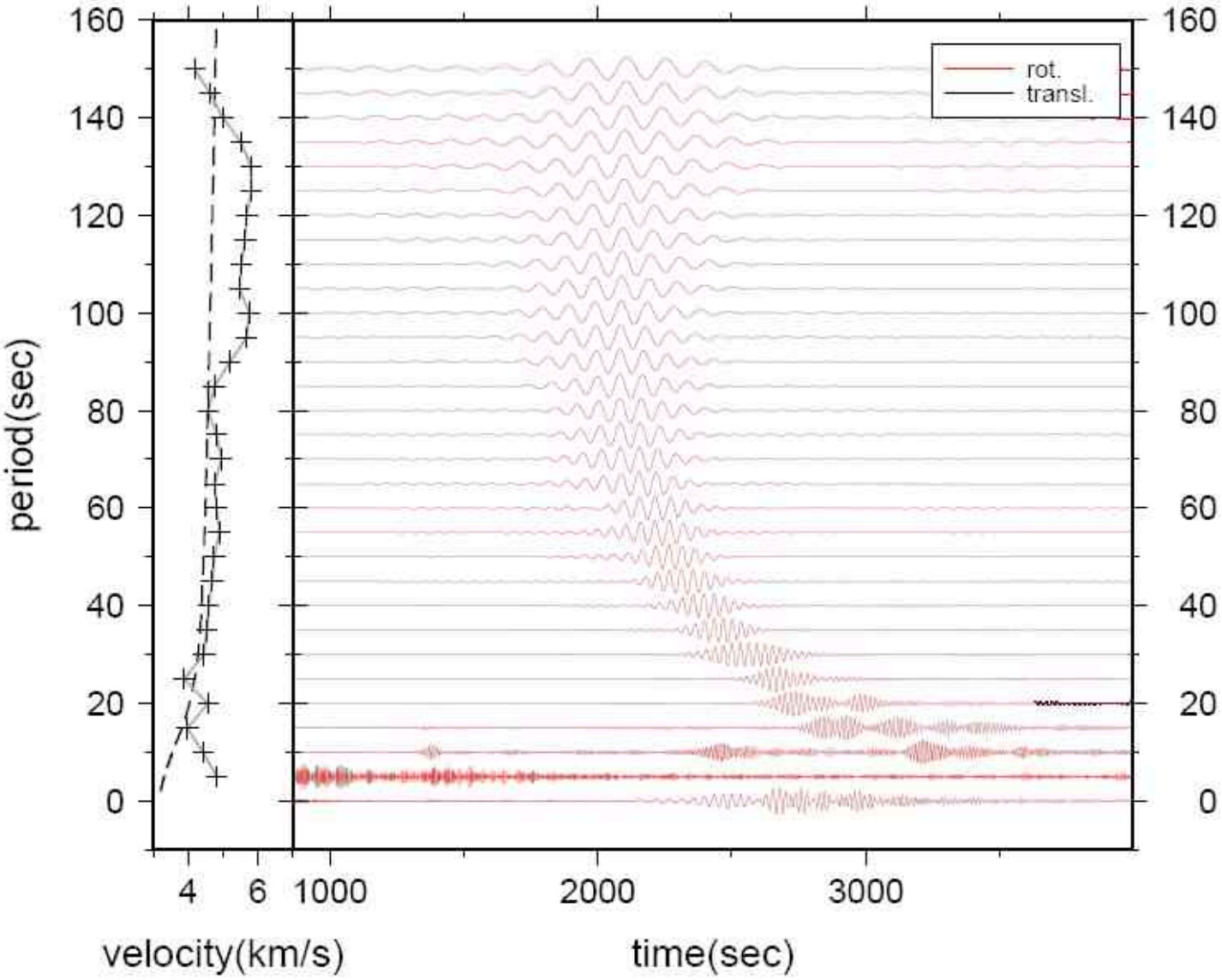


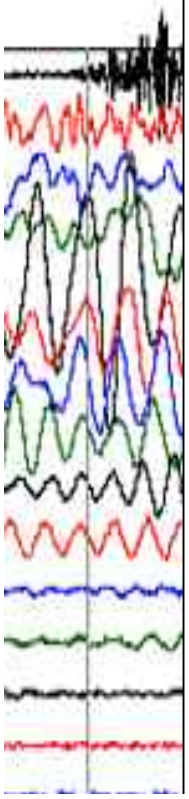
From Igel et al. (GJI, 2007)



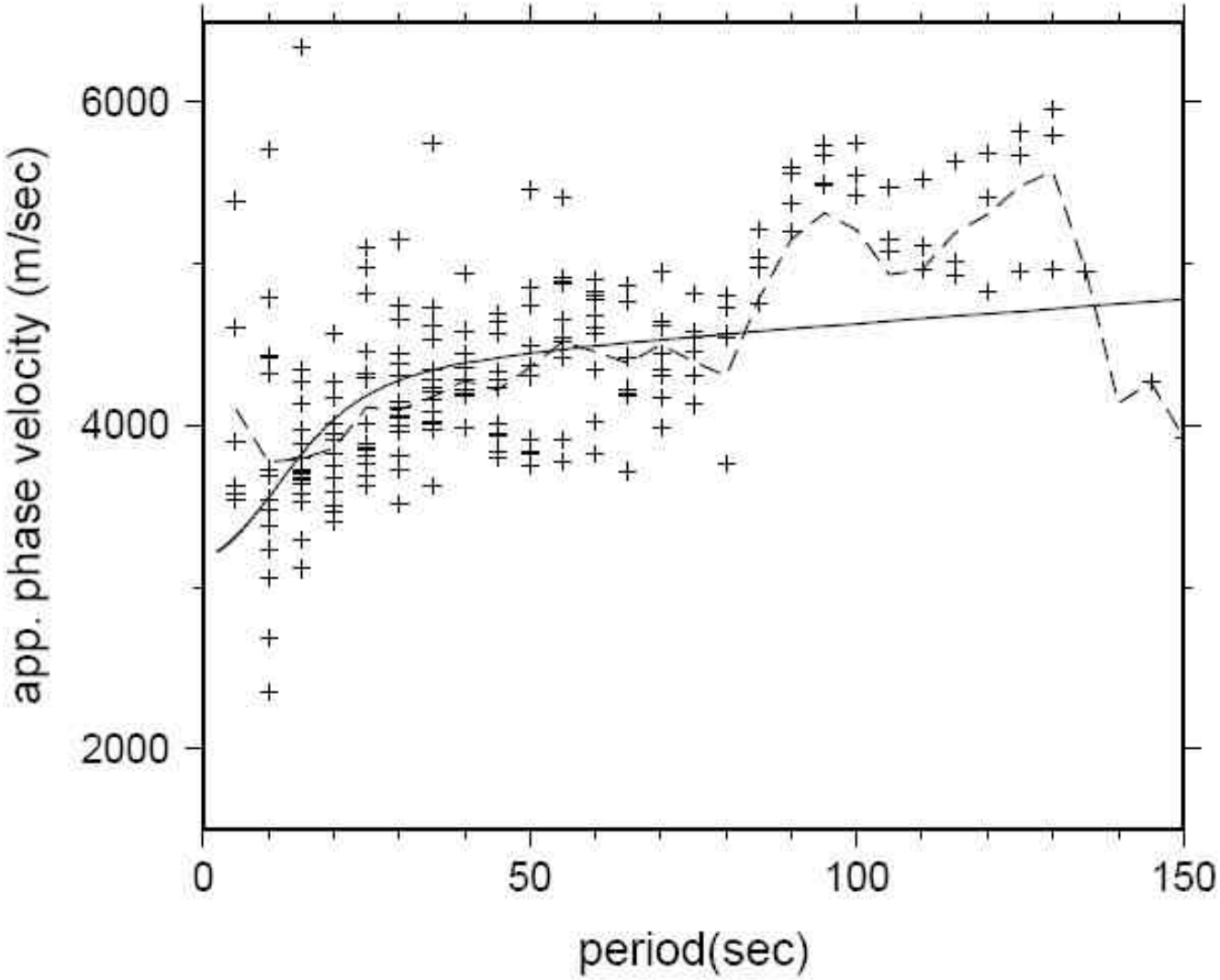
… dispersion …

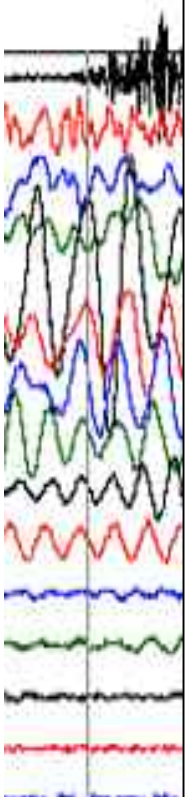
M7.4 Kuril islands, 15/1/09



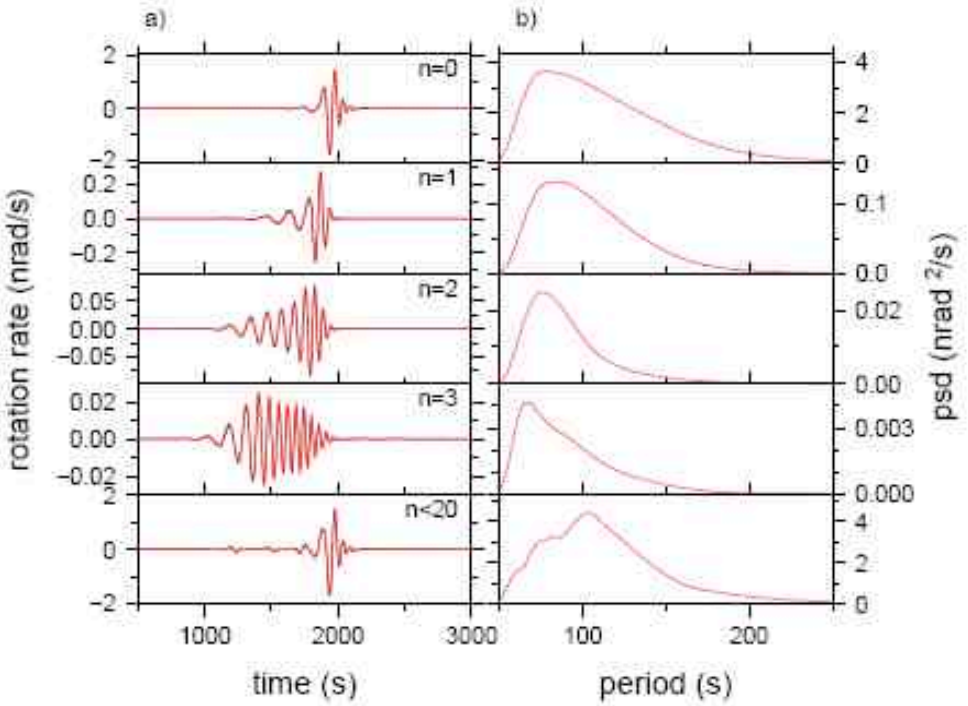


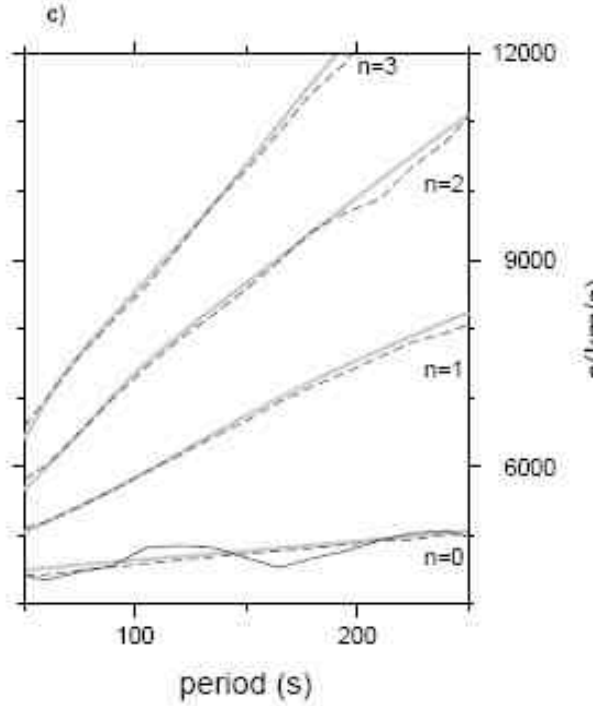
Love wave dispersion from 28 events





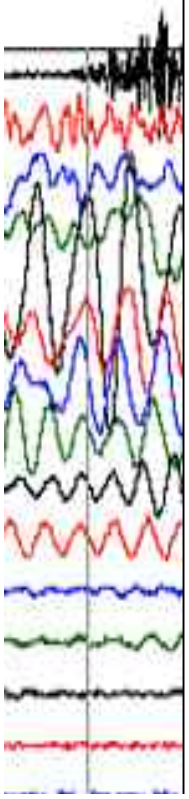
… why the large variations?



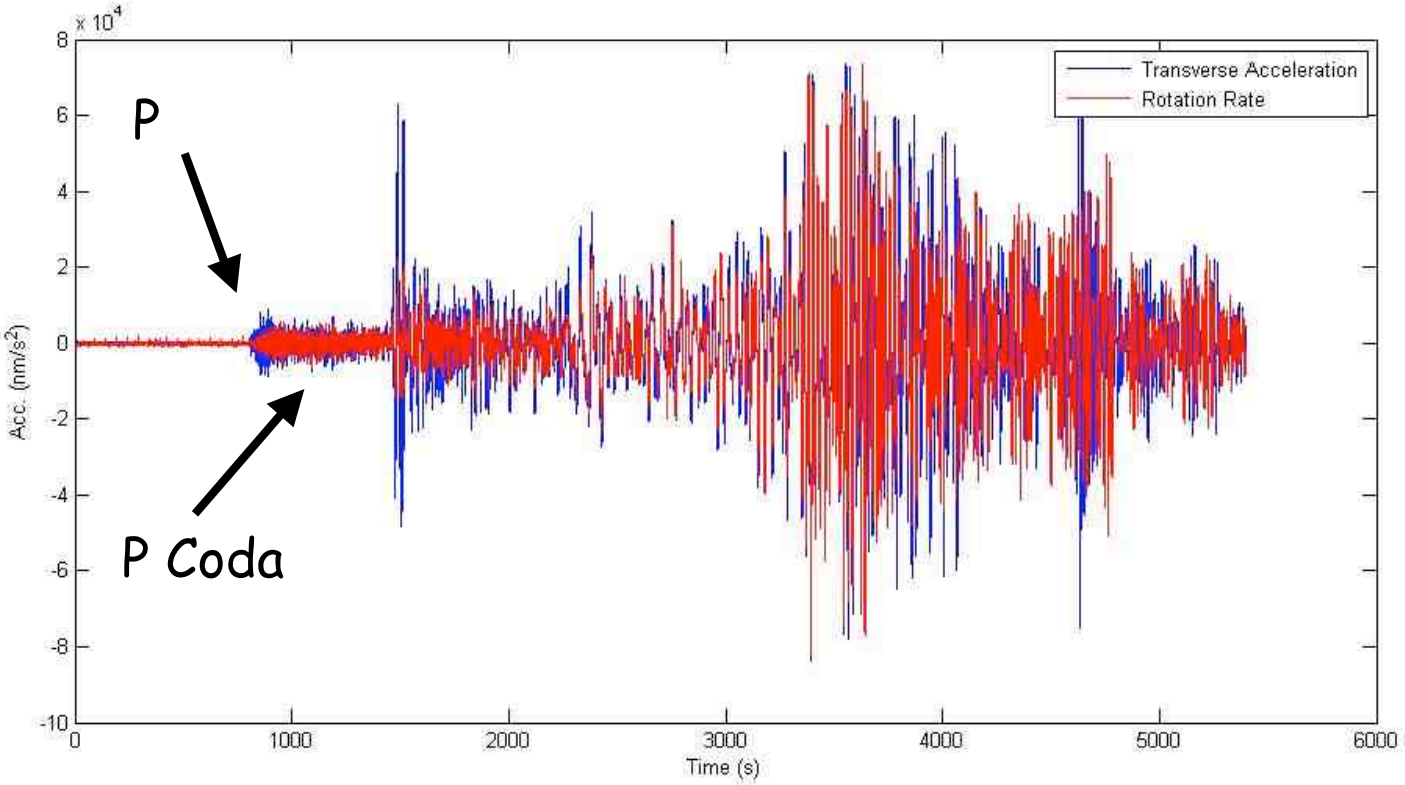


… overtones alone can do it …

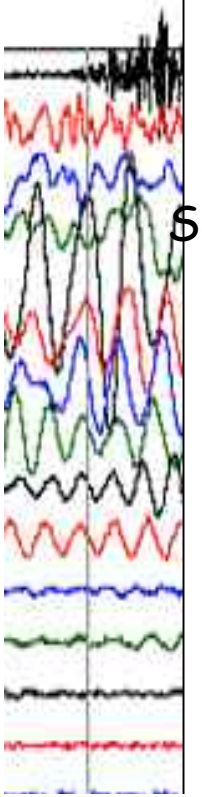
(Kurrle et al., in preparation)



Sumatra M8.3 12.9.2007



Modelling the ratio of Energy in P-Rotations and Translations allows putting constraints on crustal scattering (Pham et al., BSSA, 2009)



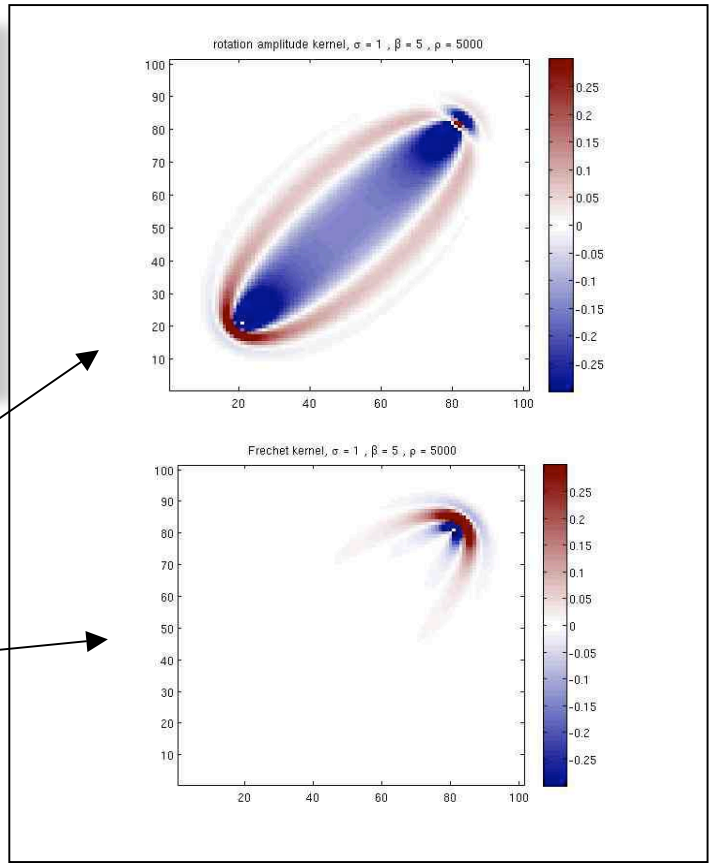
Adjoint method and rotations
sensitivity kernels

$$\beta_a(\mathbf{x}^r) := \frac{1}{2}\frac{A_v(\mathbf{x}^r)}{A_\omega(\mathbf{x}^r)},$$

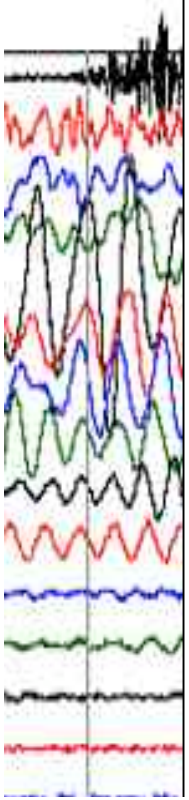
$$A_v := \sqrt{\int_{\mathbb{R}} [F * (W\mathbf{v})]^2\, dt}, \quad A_\omega := \sqrt{\int_{\mathbb{R}} [F * (W\boldsymbol{\omega})]^2\, dt}$$

Sensitivity of travel times (or rotation amplitudes alone)

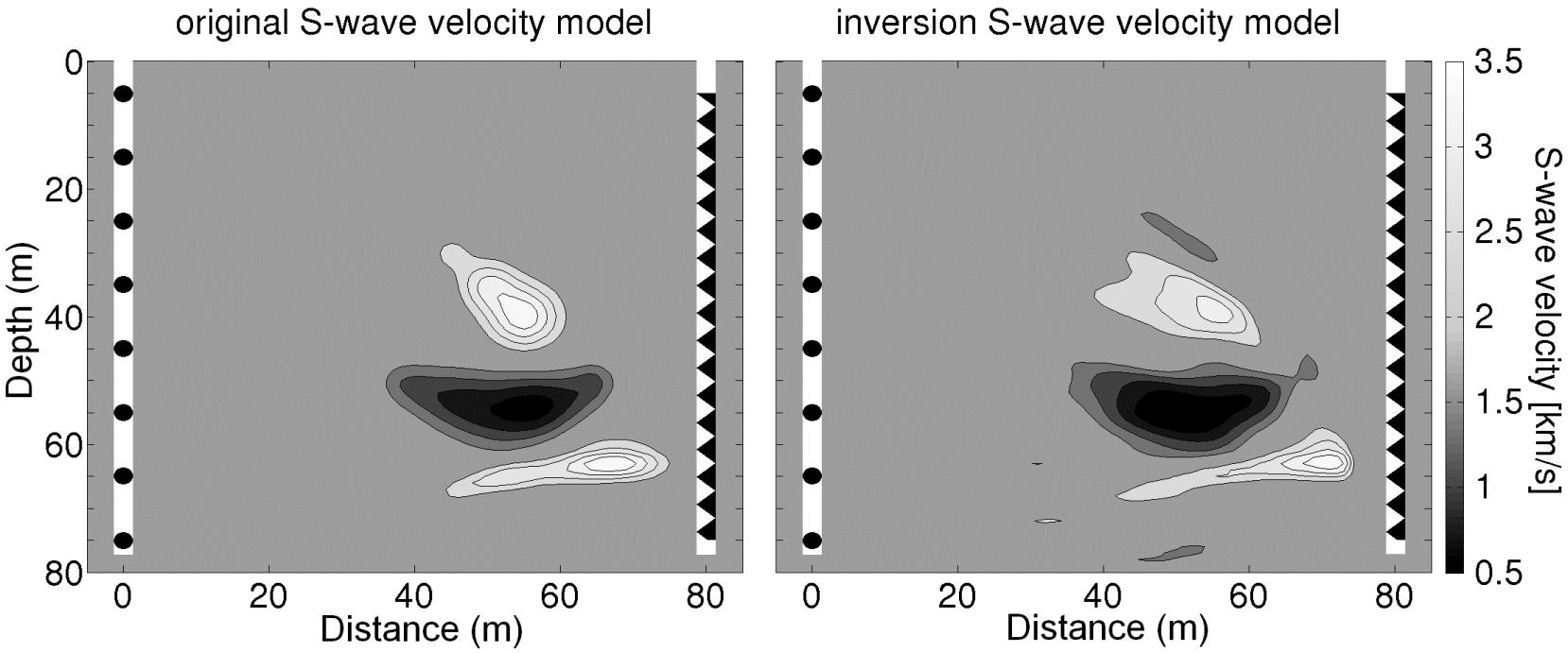
Sensitivity of acceleration/rotation (apparent shear wave speed)



Fichtner and Igel, 2009, BSSA.

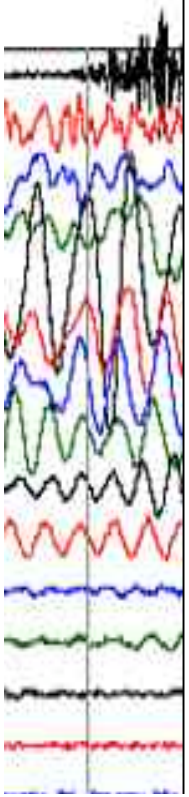


… tomography without travel times!

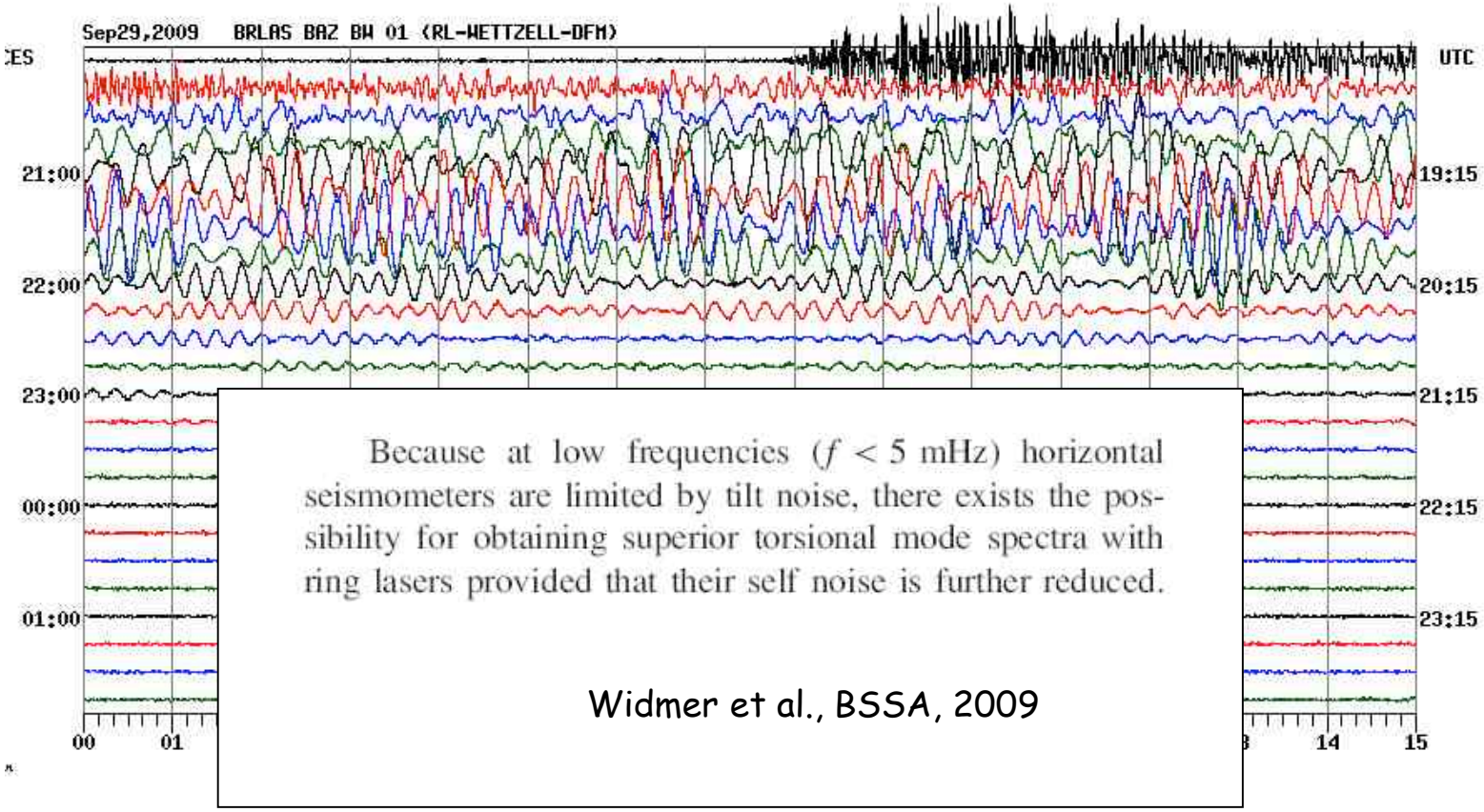


… the observables are frequency dependent amplitude ratios of rotations and translations …

Bernauer et al, Geophysics, in print



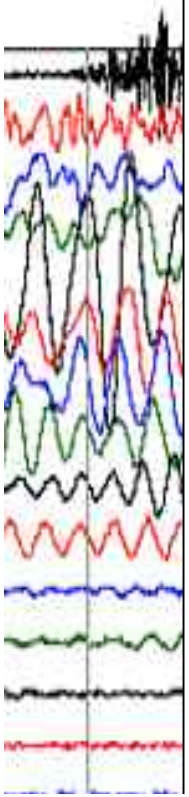
EARTHQUAKE on 29/09/2009 at 17:48 (UTC) SAMOA ISLANDS REGION 164 km S Siumu MAGNITUDE: Mw 7.9



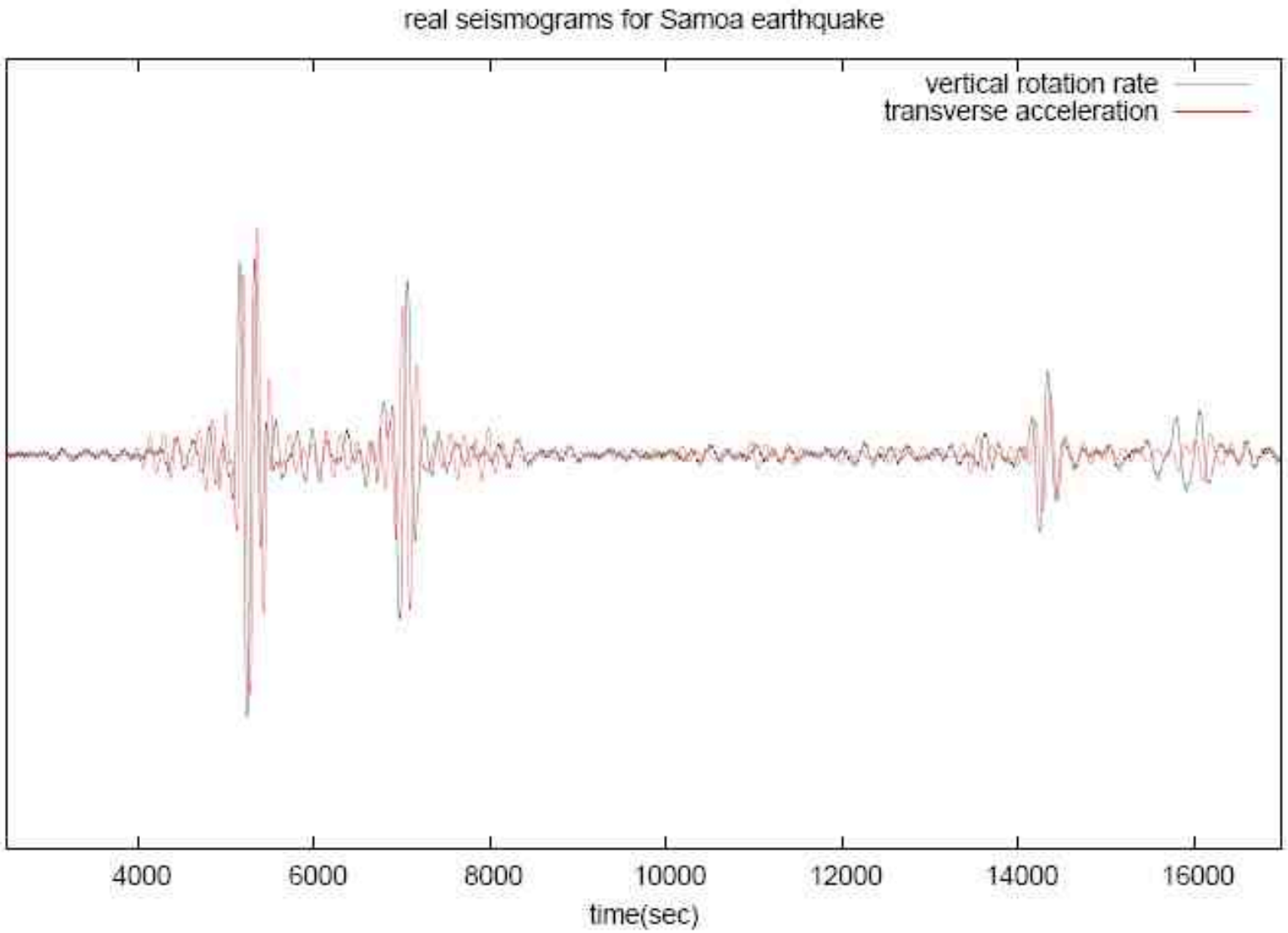
Because at low frequencies ($f < 5$ mHz) horizontal seismometers are limited by tilt noise, there exists the possibility for obtaining superior torsional mode spectra with ring lasers provided that their self noise is further reduced.

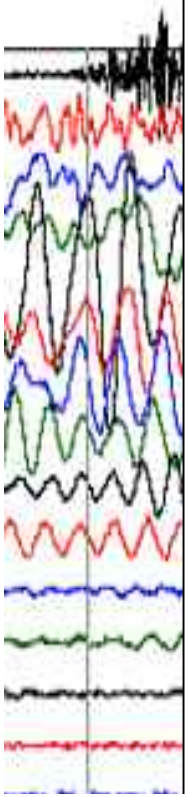
Widmer et al., BSSA, 2009

Ring laser record, Wettzell, Germany



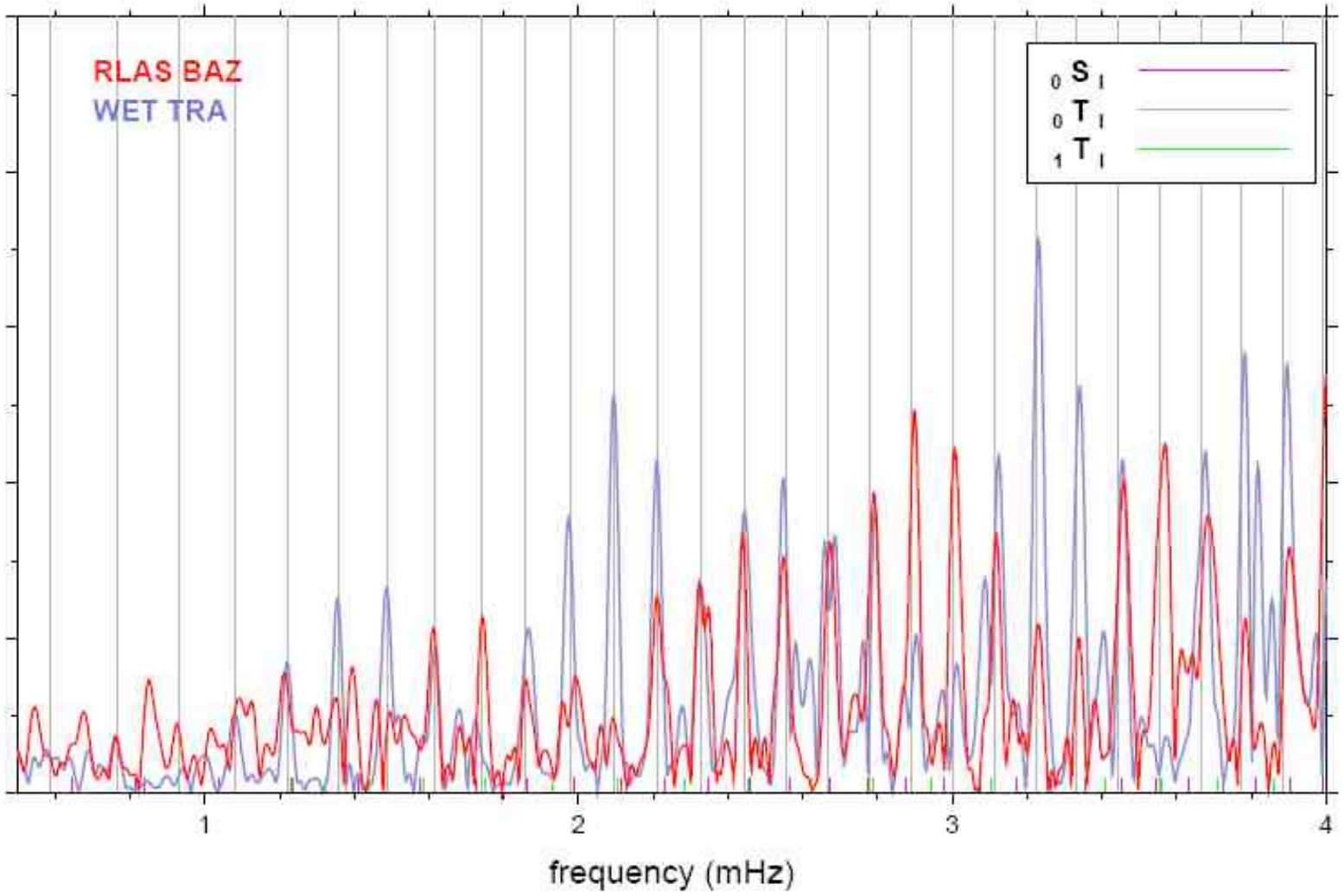
… long periods ….

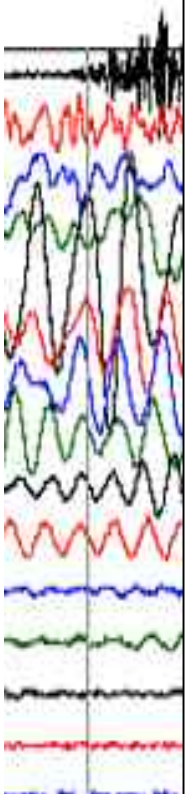




First observations of eigenmodes with ring laser!

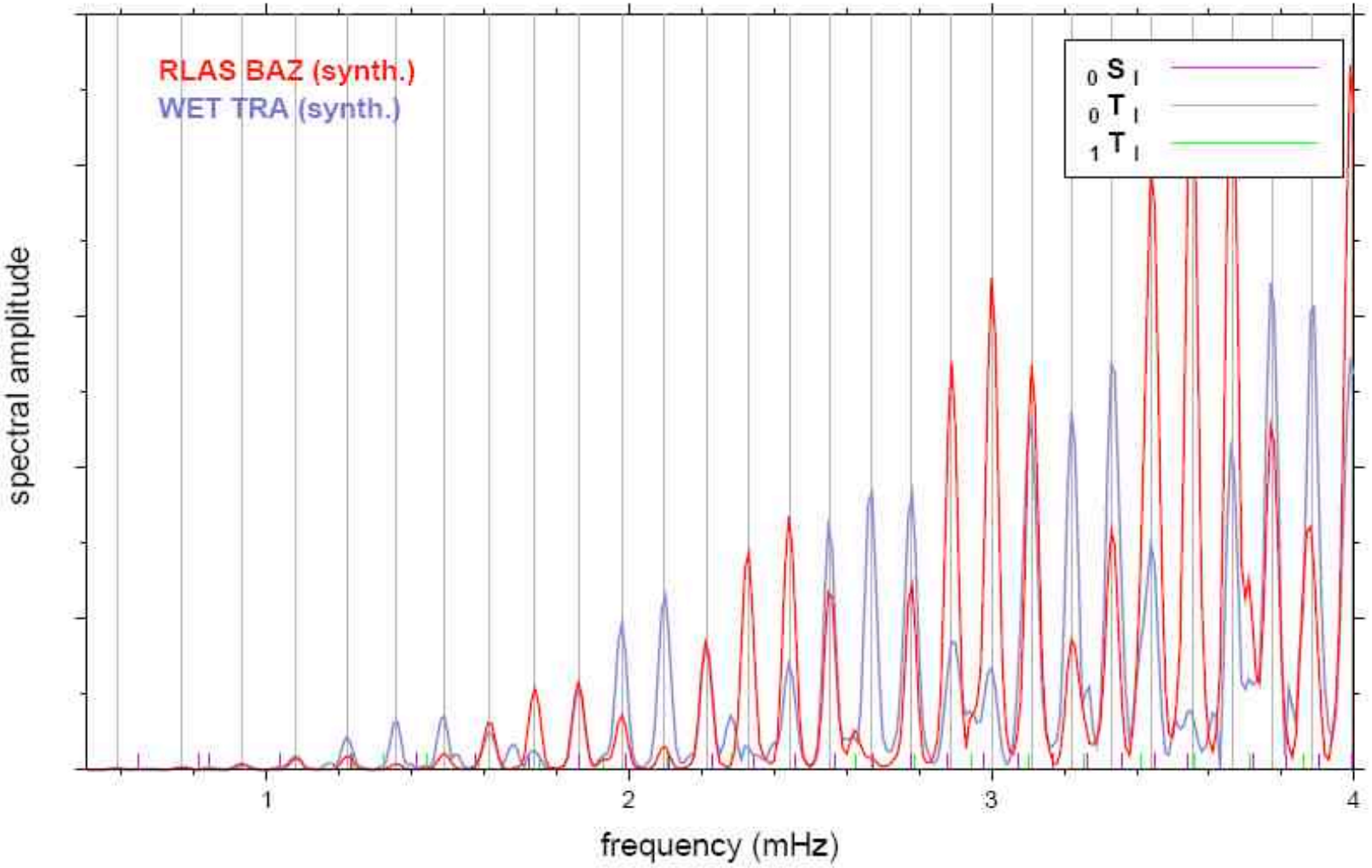
16 hours after 2009/09/29 Samoa earthquake

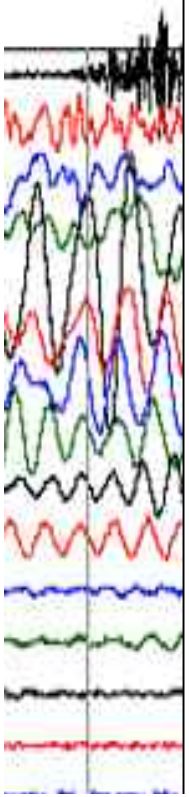




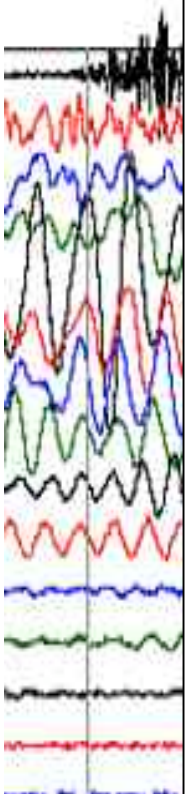
Synthetics ….

16 hours after 2009/09/29 Samoa earthquake





Rotations using Seismic Arrays



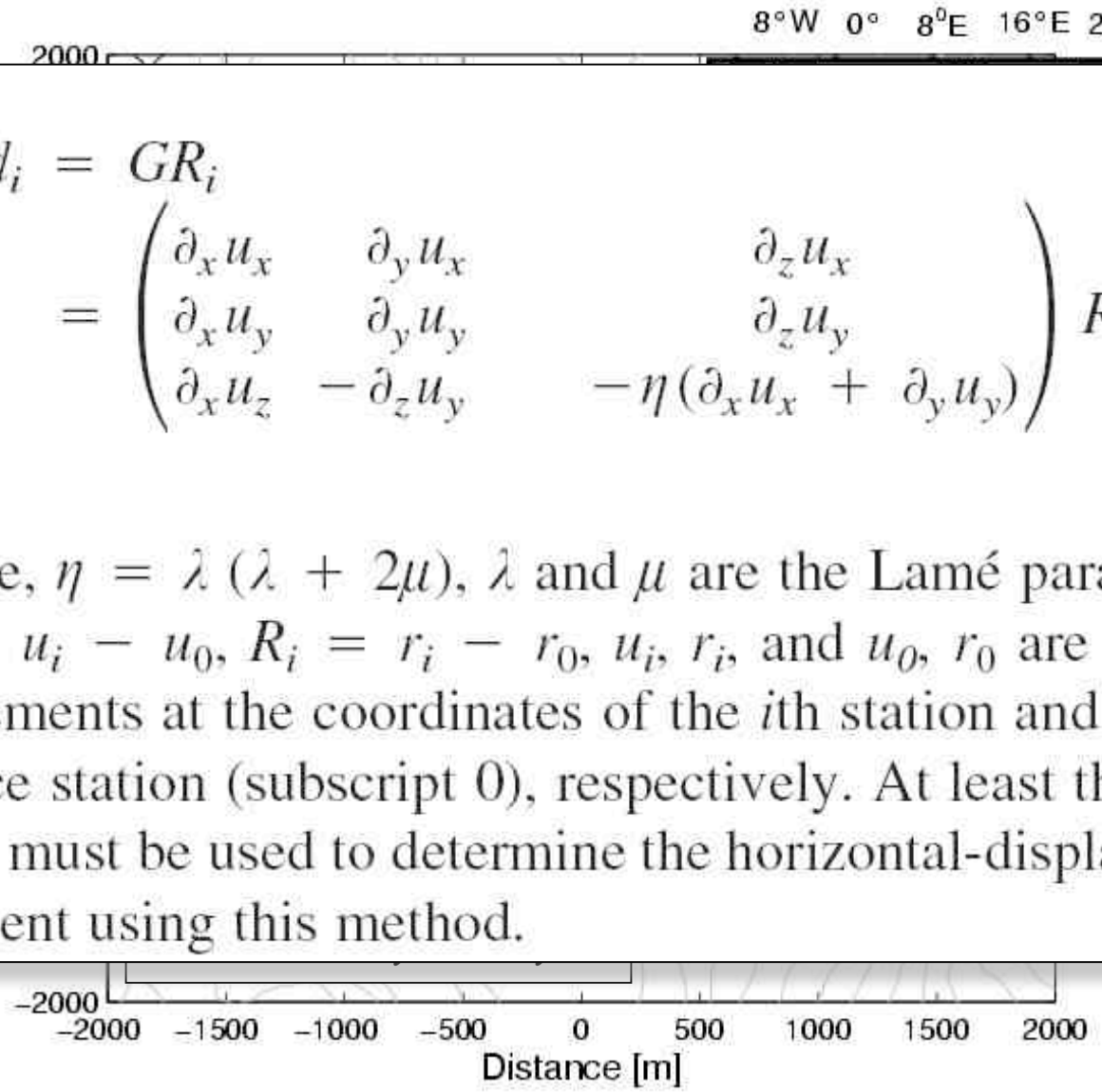
Array measurements

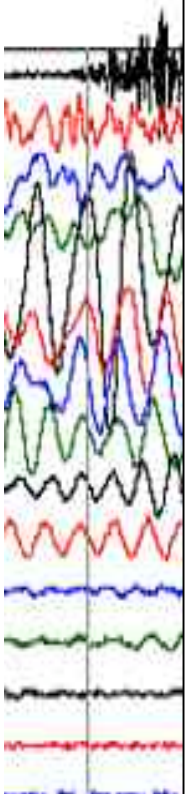
Dec 2003-Mar 2004

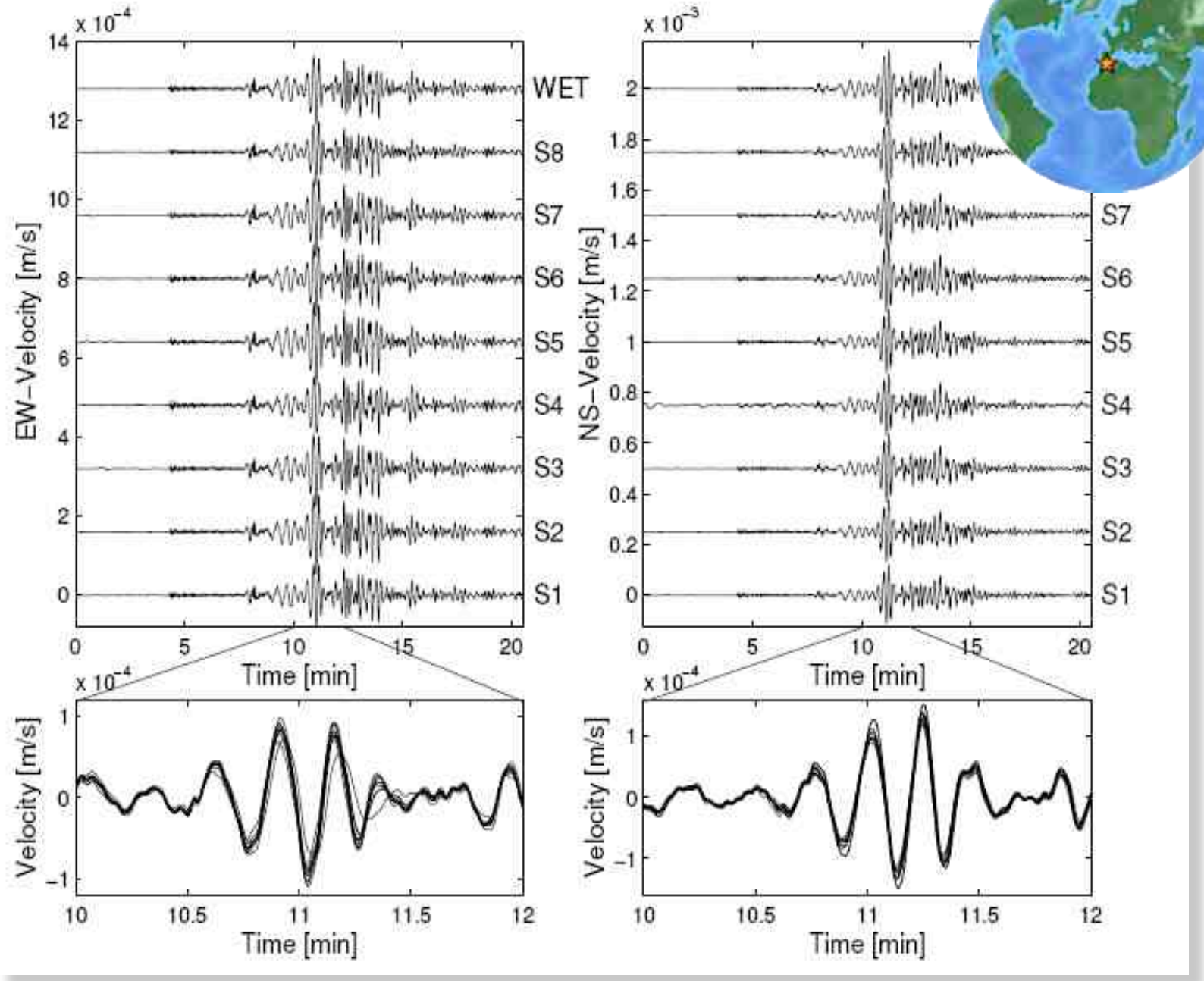
$$d_i = GR_i \qquad (2)$$

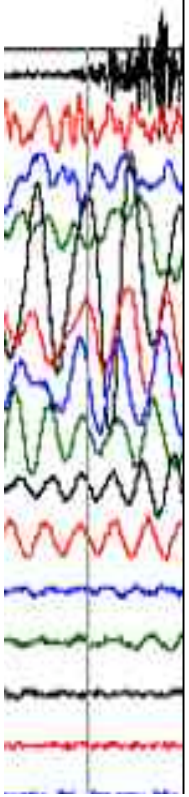
$$= \begin{pmatrix} \partial_x u_x & \partial_y u_x & \partial_z u_x \\ \partial_x u_y & \partial_y u_y & \partial_z u_y \\ \partial_x u_z & -\partial_z u_y & -\eta\,(\partial_x u_x + \partial_y u_y) \end{pmatrix} R_i,$$

where, $\eta = \lambda\,(\lambda + 2\mu)$, λ and μ are the Lamé parameters, $d_i = u_i - u_0$, $R_i = r_i - r_0$, u_i, r_i, and u_0, r_0 are the displacements at the coordinates of the ith station and the reference station (subscript 0), respectively. At least three stations must be used to determine the horizontal-displacement gradient using this method.

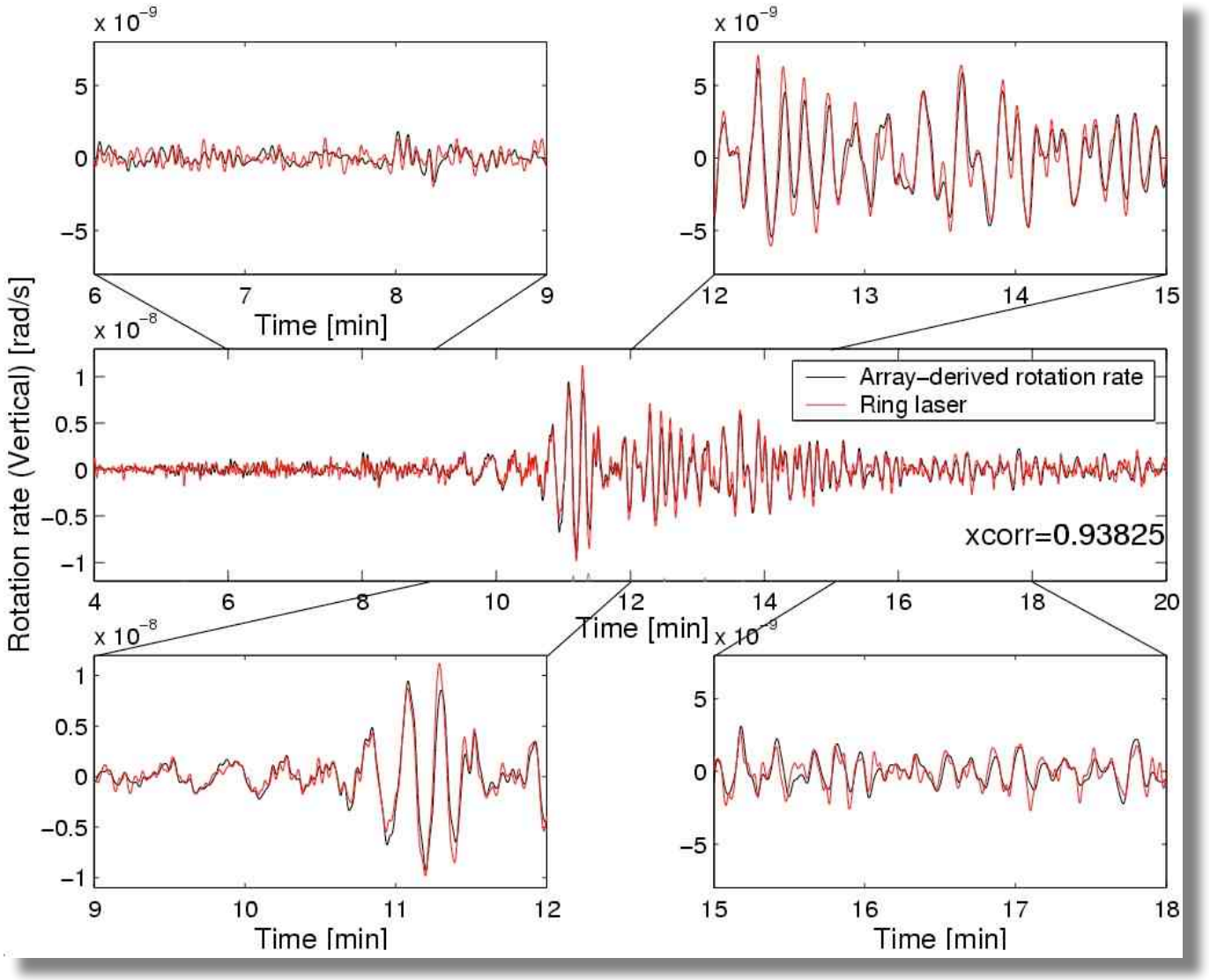





x 10^-4
EW–Velocity [m/s]
WET
S8
S7
S6
S5
S4
S3
S2
S1
Time [min]
x 10^-3
NS–Velocity [m/s]
Velocity [m/s]

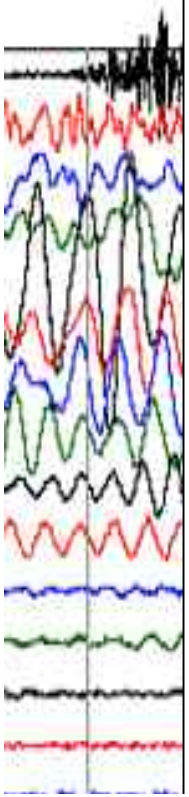


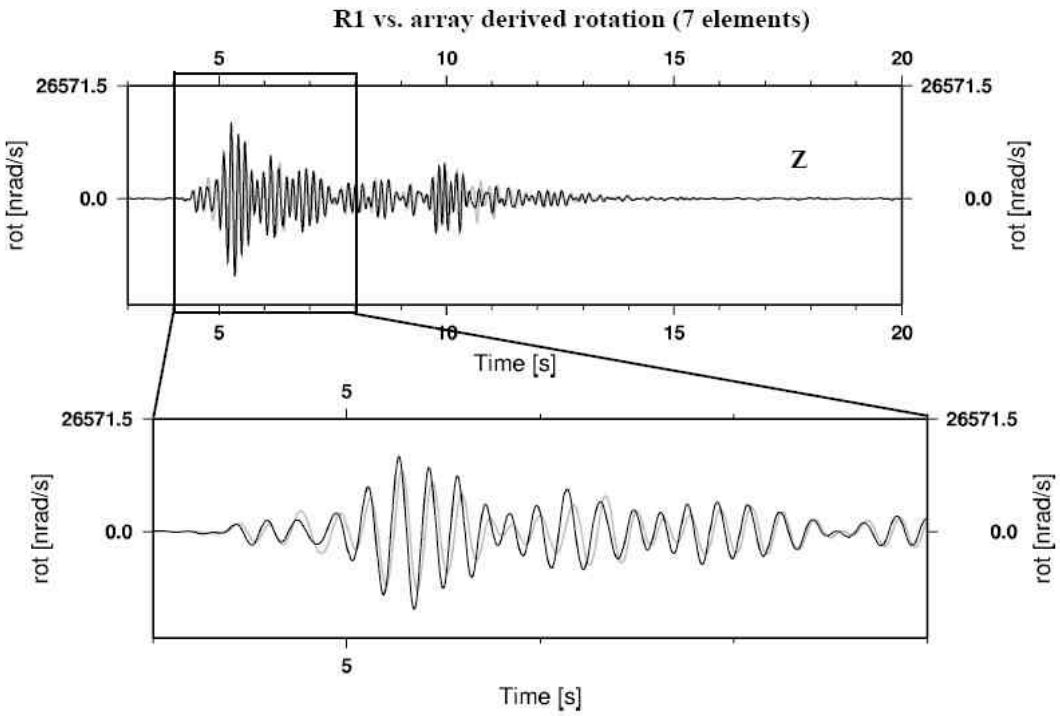
First comparison of array-derived rotations (**black**) and direct ring laser measurements (**red**)

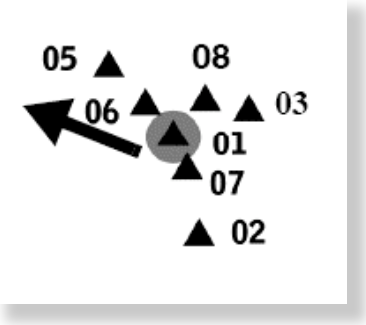


From Suryanto et al (2006, BSSA)

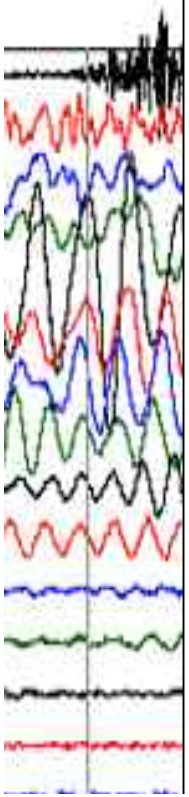
Array vs. direct



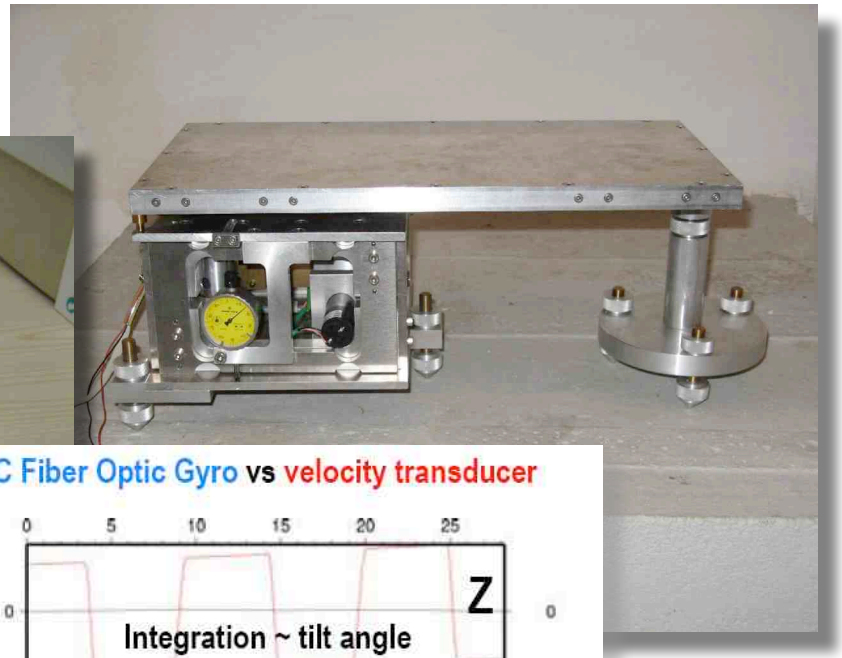


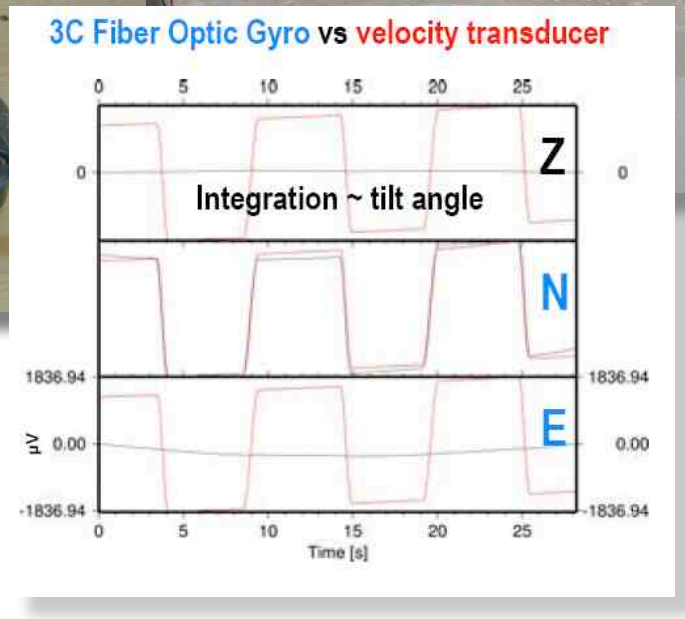


Wassermann et al., 2009, BSSA.

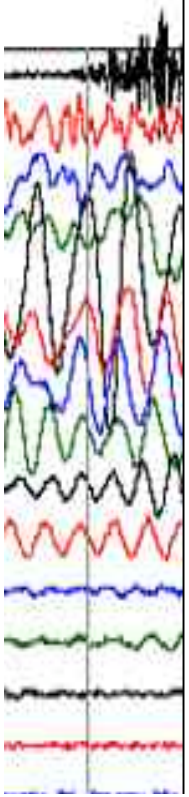


Step table tests with low-resolution sensors



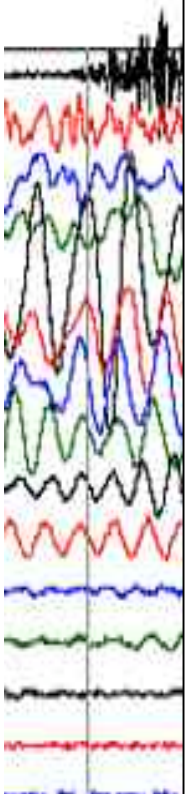


See poster by Wassermann et al!



Conclusions

- Ring laser technology is the most promising technology for broadband far-field observations (Hz – mHz range, 10^{-11}-10^{-6} rad/s)
- Measuring tilts (horizontal component of rotation) in broadband seismology is a fundamental research question!
- Collocated observations of rotations and translations are providing additional structural information!
- Our current state of knowledge:
  - Broadband, far field: ring lasers
  - Seismological applications, portable: fiber-optic gyros
  - Strong motion: fluid-based sensors (e.g., R1)

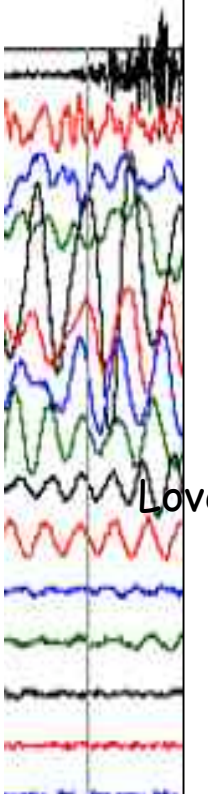


Future

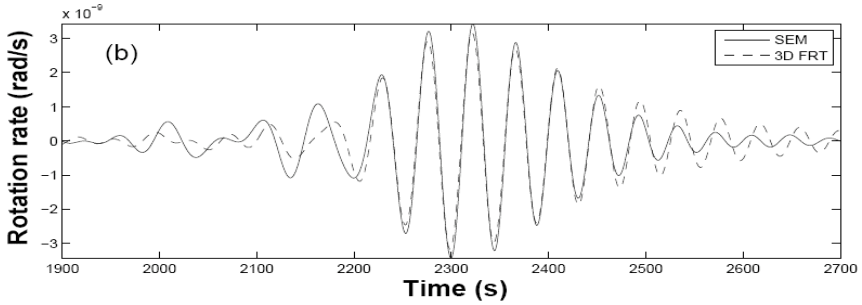
- A 6C permanent observatory (with surrounding BB array) at PFO
- Cooperation with Gravitational Wave Experiments (e.g., LIGO, VIRGO)
- Applications in earthquake engineering, source problems, reservoir seismics, strong motion seismology, ocean bottom seismology, planetology
- Tilts, tilts, tilts!

-> www.rotational-seismology.org (IWGoRS)

-> IWGoRS Meeting in Europe, provisional schedule for 2nd Meeting in Prague 12-15 October, 2010



Using Surface Wave Ray Theory



$$\dot{\Omega}_r = \omega \frac{(l+1/2)}{2a} W Y_l^m = \omega \frac{k}{2} W Y_l^m$$

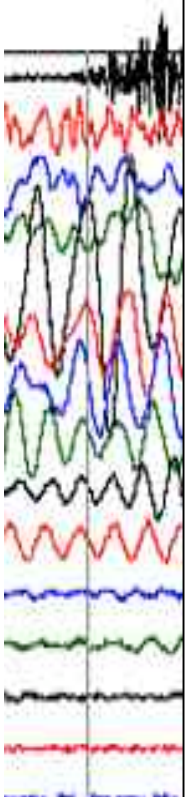
$$\ddot{s}_T = \omega^2 W Y_l^m$$

$l \gg 1$

$$\frac{\dot{\Omega}_r(\omega)}{\ddot{s}_T(\omega)} = \frac{k}{2\omega} = \frac{1}{2c_T(\omega)}$$

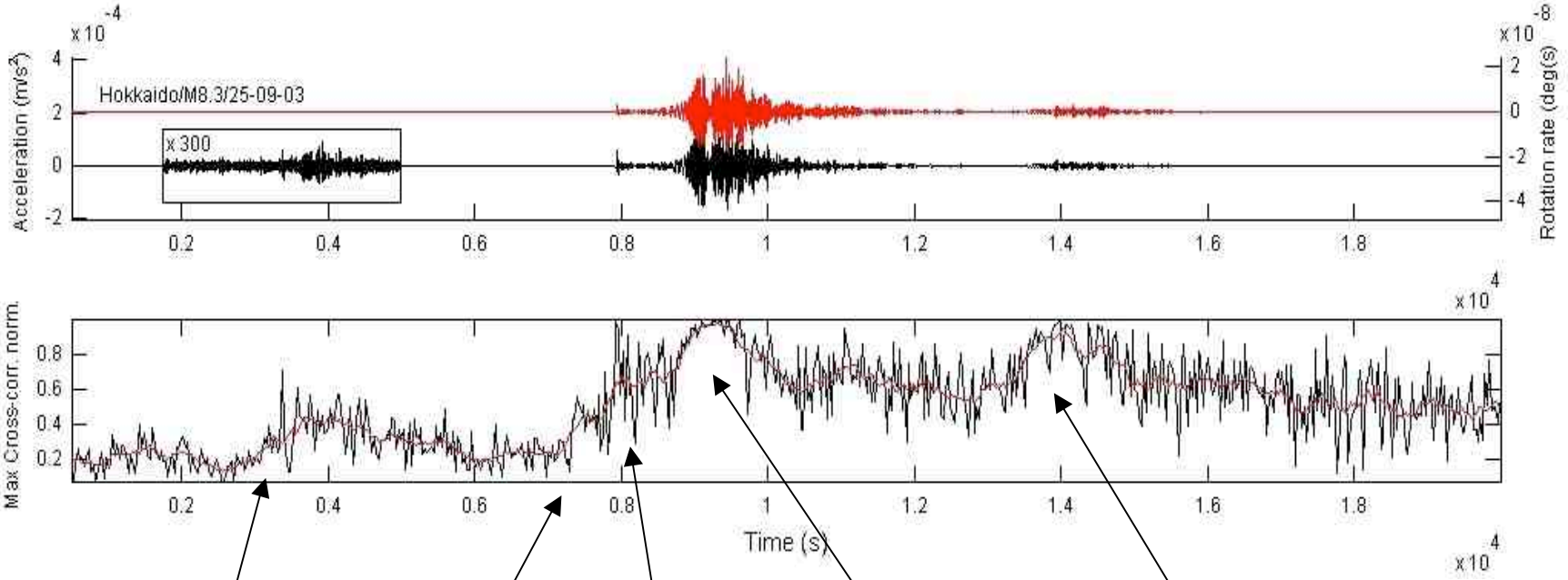
Love wave dispersion from **point measurement**!

Ferreira and Igel, 2009, BSSA.



Max. cross-corr. coefficient in sliding time window

transverse acceleration – rotation rate



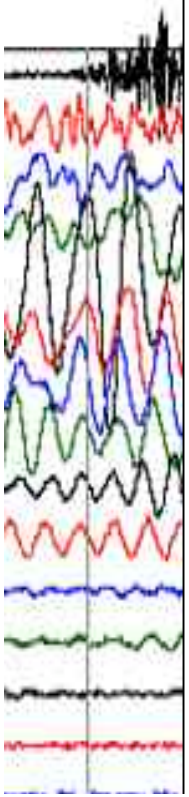
P-onset

S-wave

Love waves

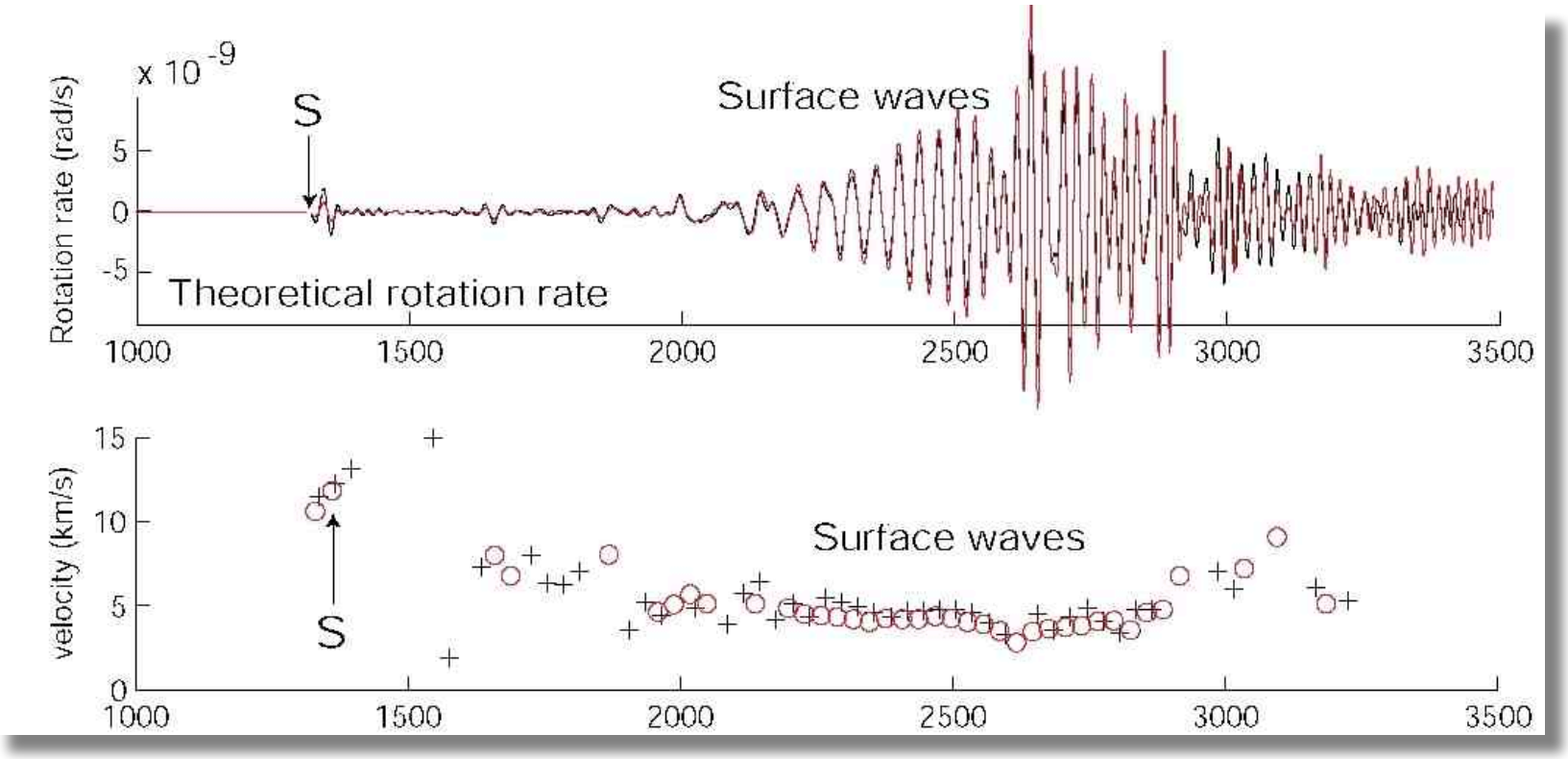
Aftershock

Small tele-seismic event



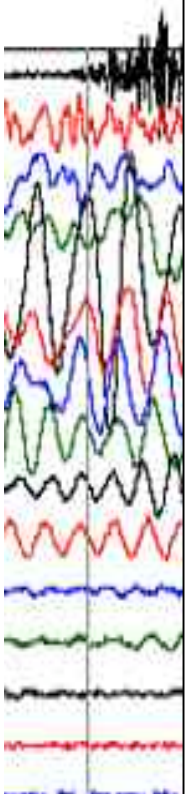
M8.3 Tokachi-oki, 25 September 2003

phase velocities (+ observations, o theory)

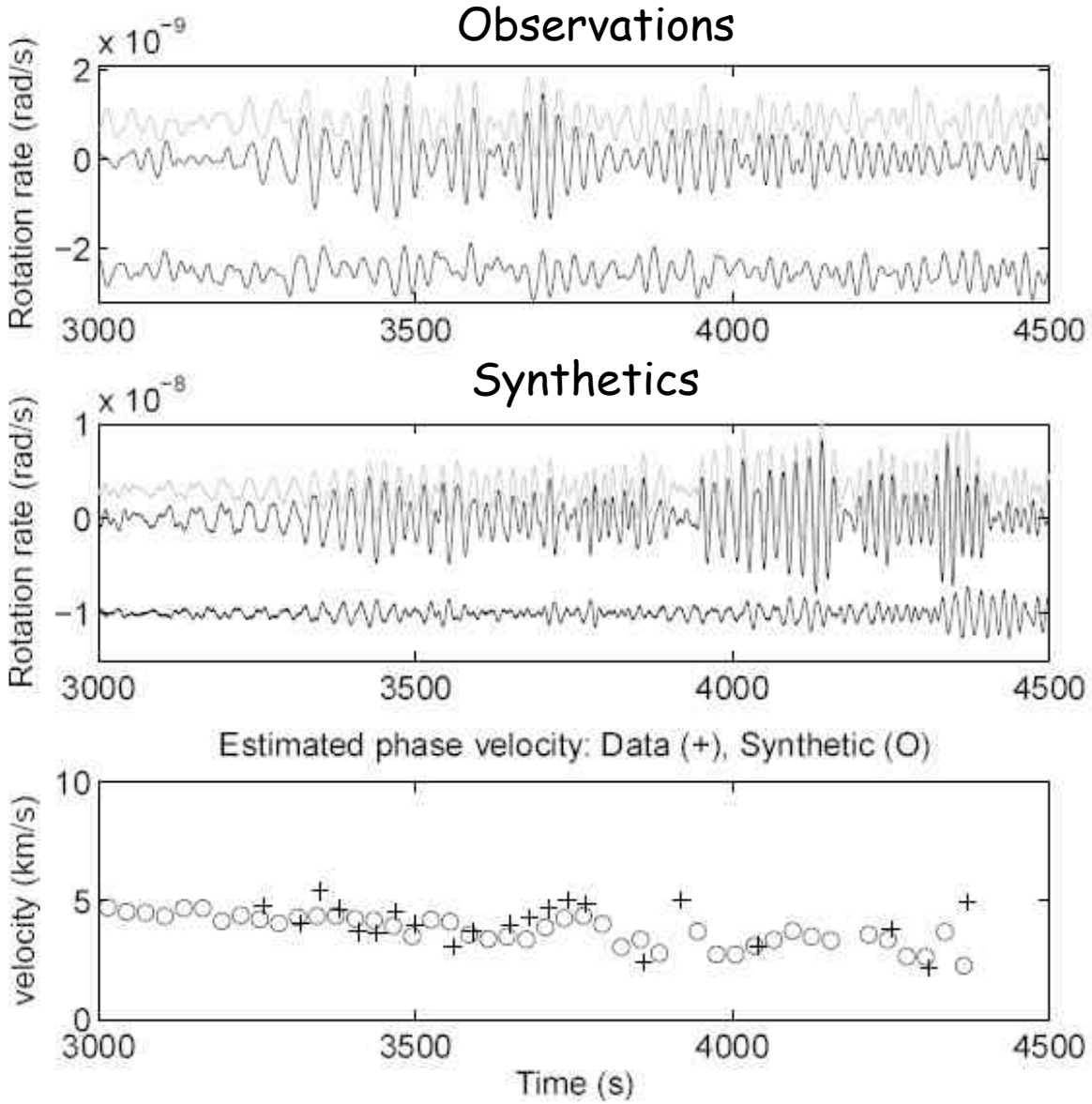


Horizontal phase velocity in sliding time window

From Igel et al. (GRL, 2005)

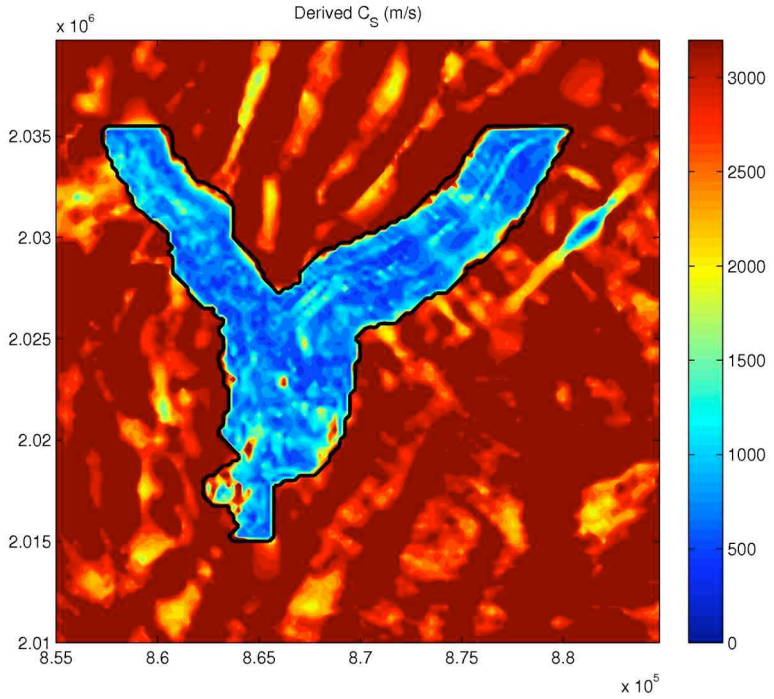


Real vs. Synthetics : Papua event

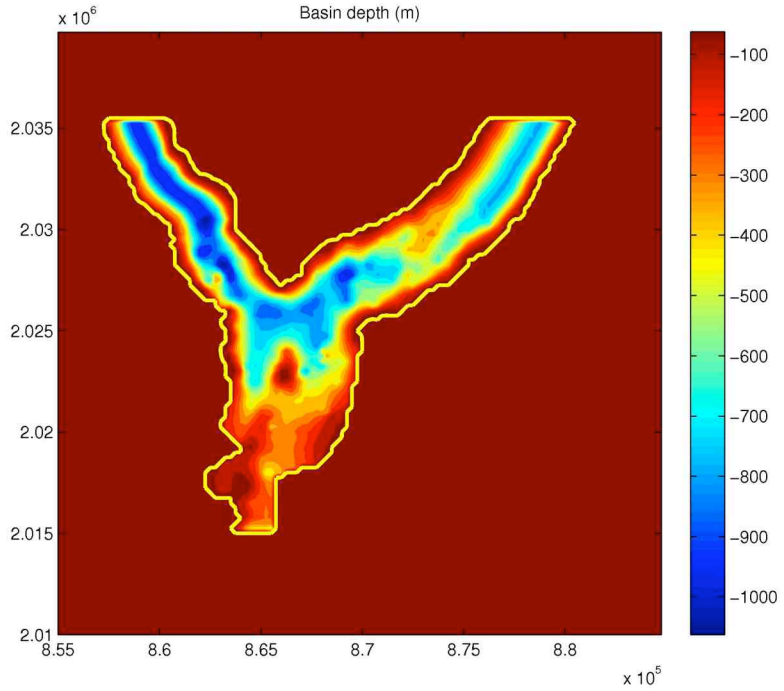


Cochard et al., 2006

Collocated measurements of translations and rotations Grenoble Basin (synthetics) and the LA basin

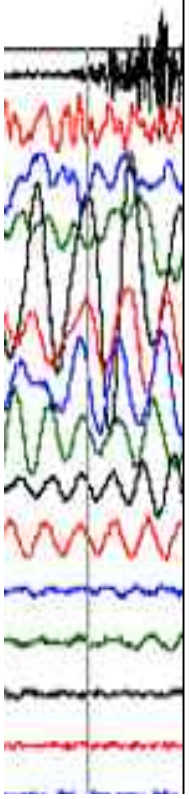


Apparent shear velocity from ratio acceleration/rotation



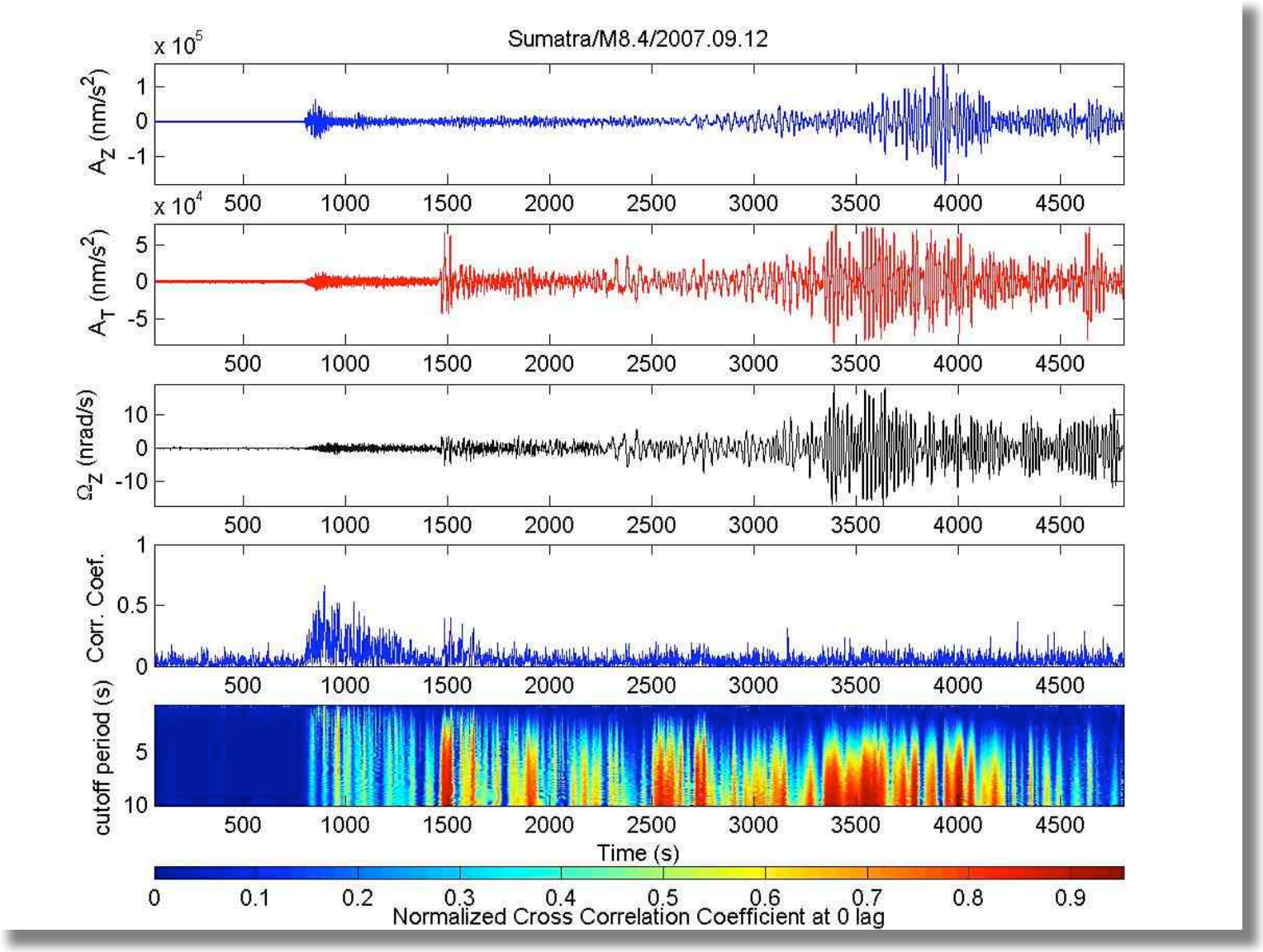
Basin model

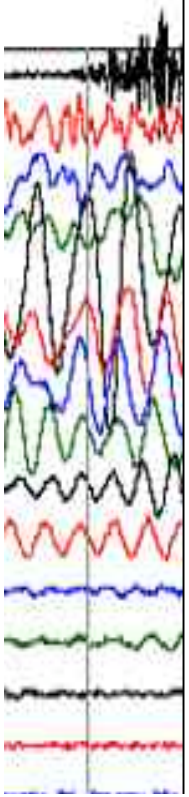
Stupazzini et al., 2009, BSSA, and Wang et al. BSSA, 2009



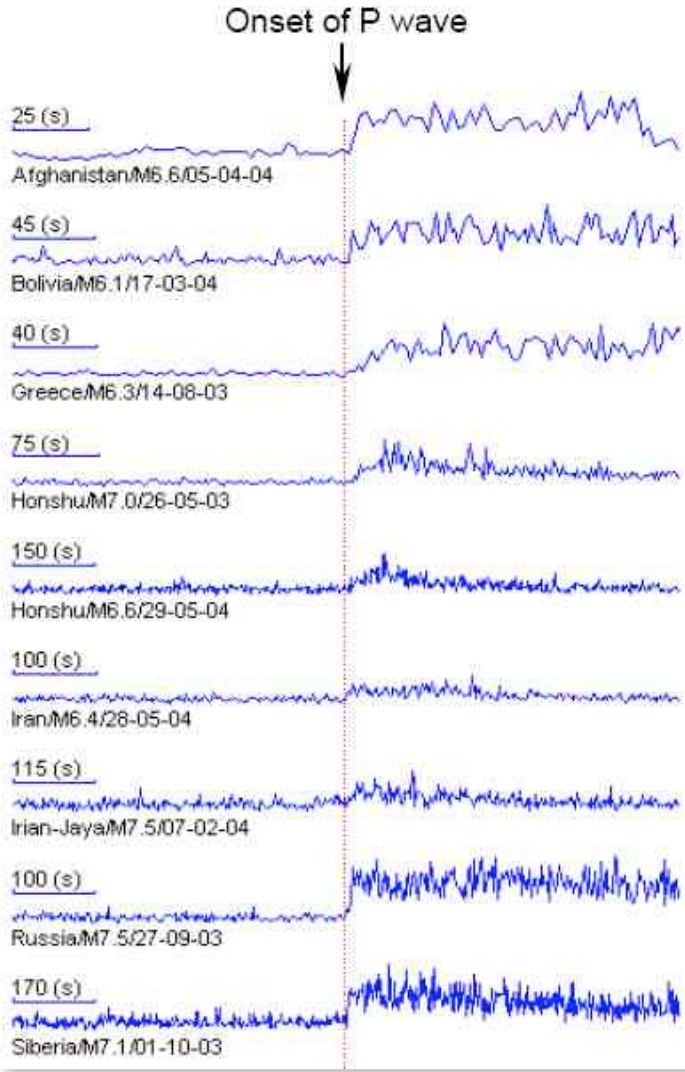
Rotational signals in the P-coda?

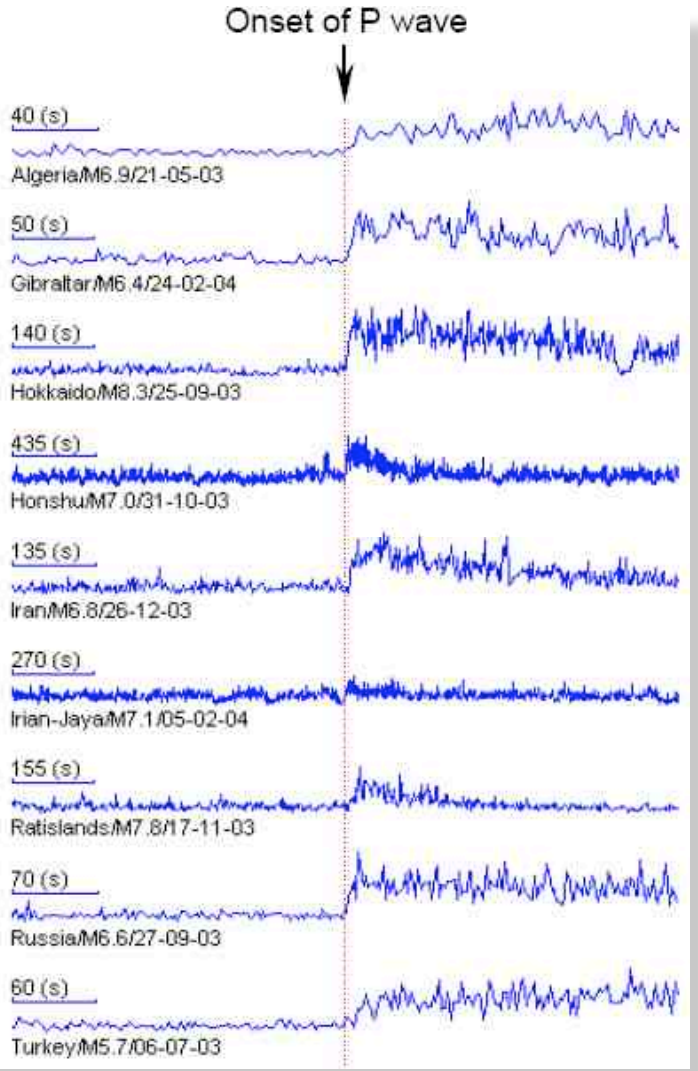
frequency dependence

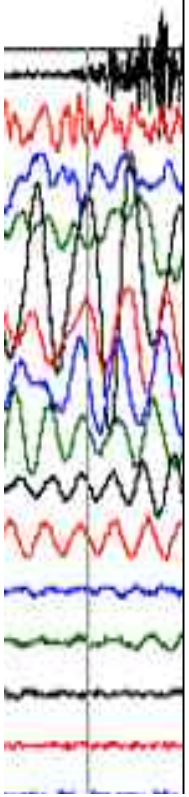




… observable for all events!

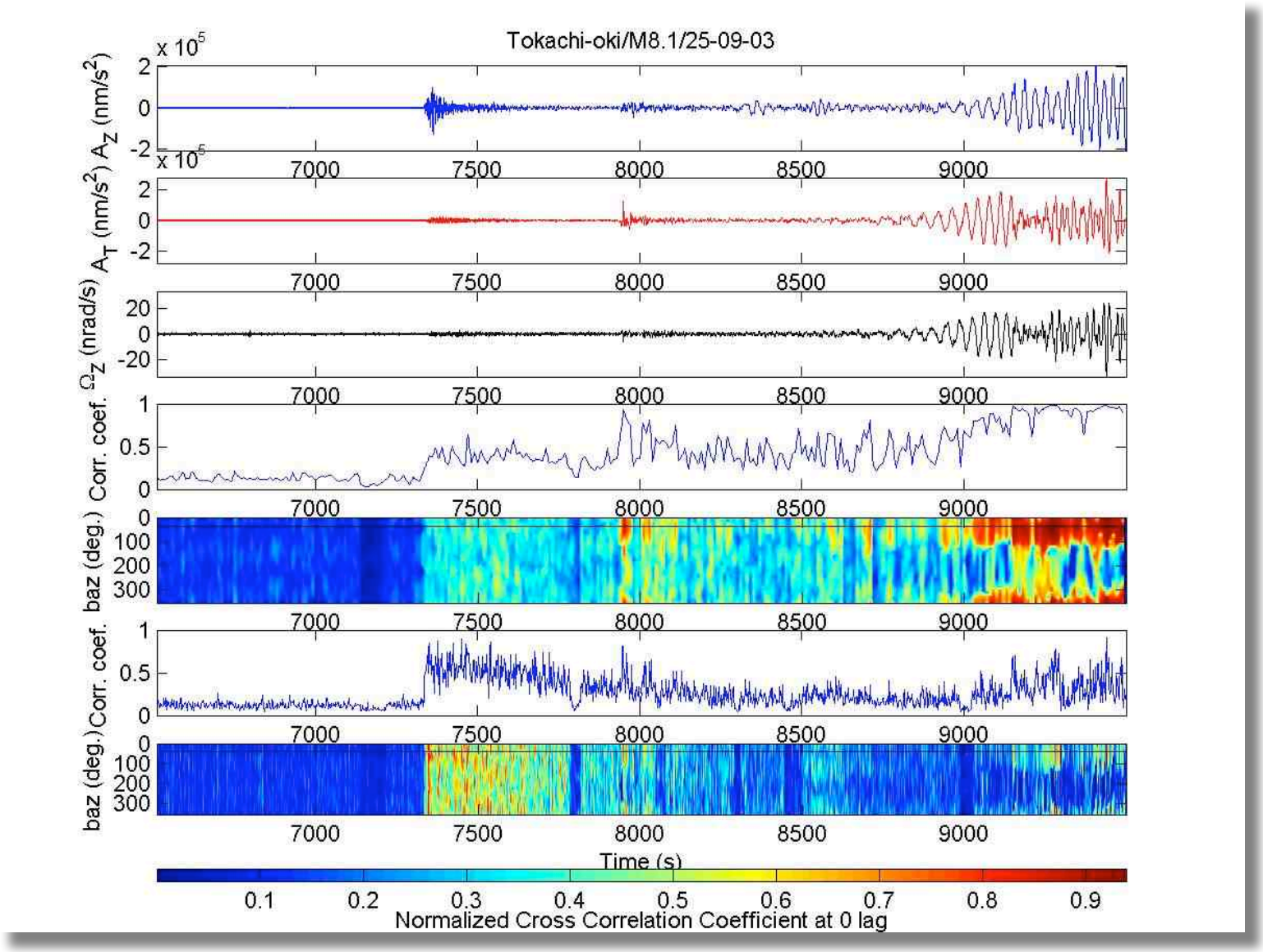


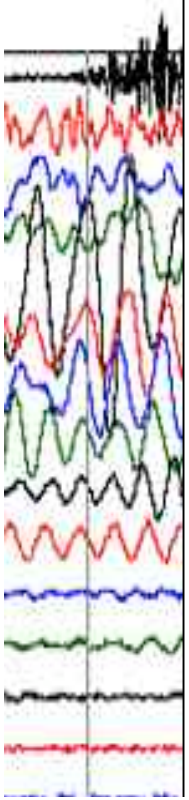




Rotational signals in the P-coda?

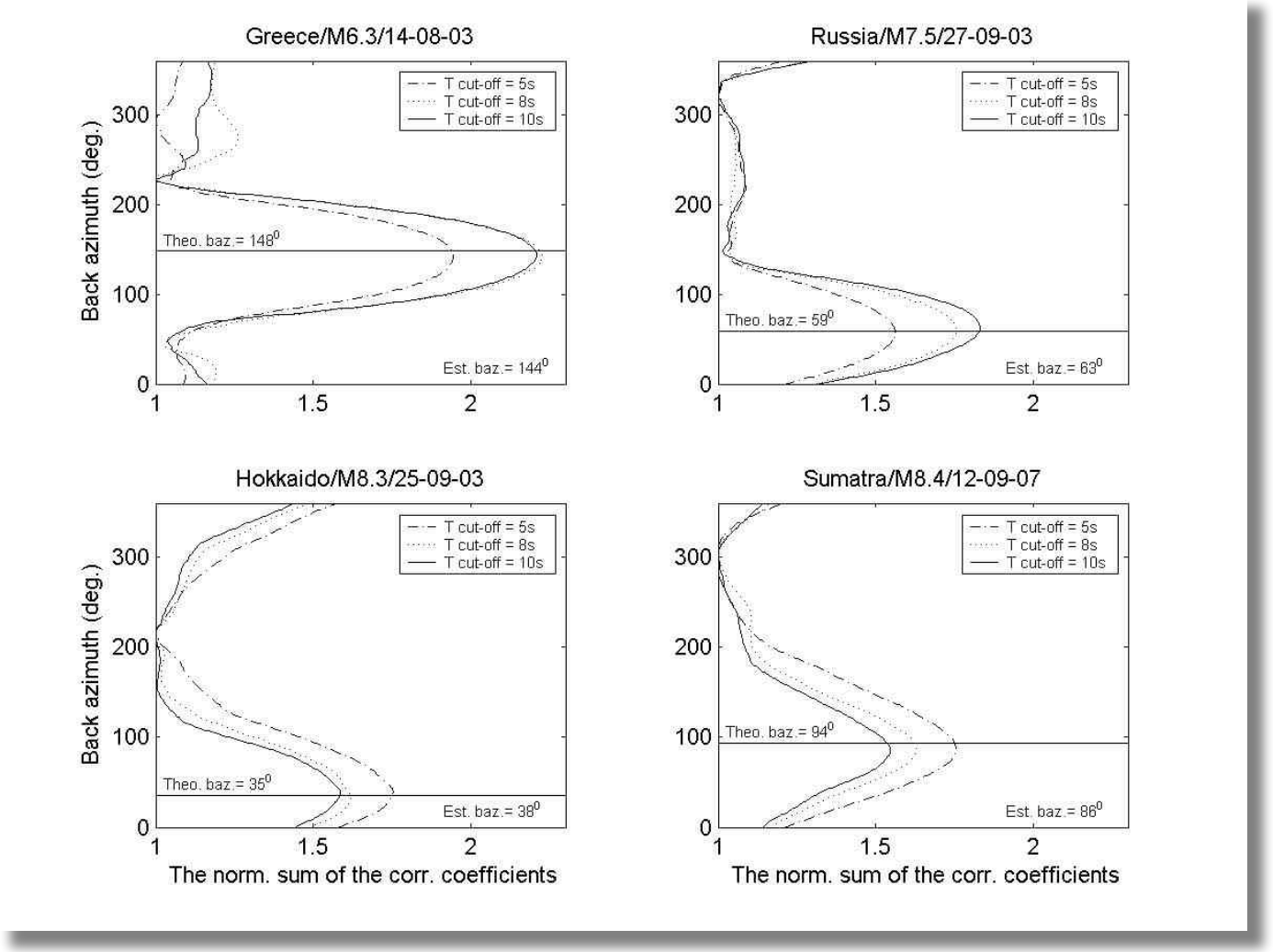
azimuth dependence



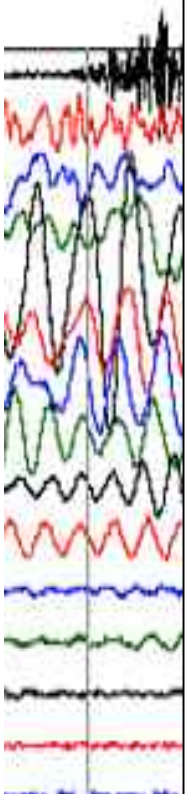


Love waves – direction of energy

… from rotations and translations measured at one point …

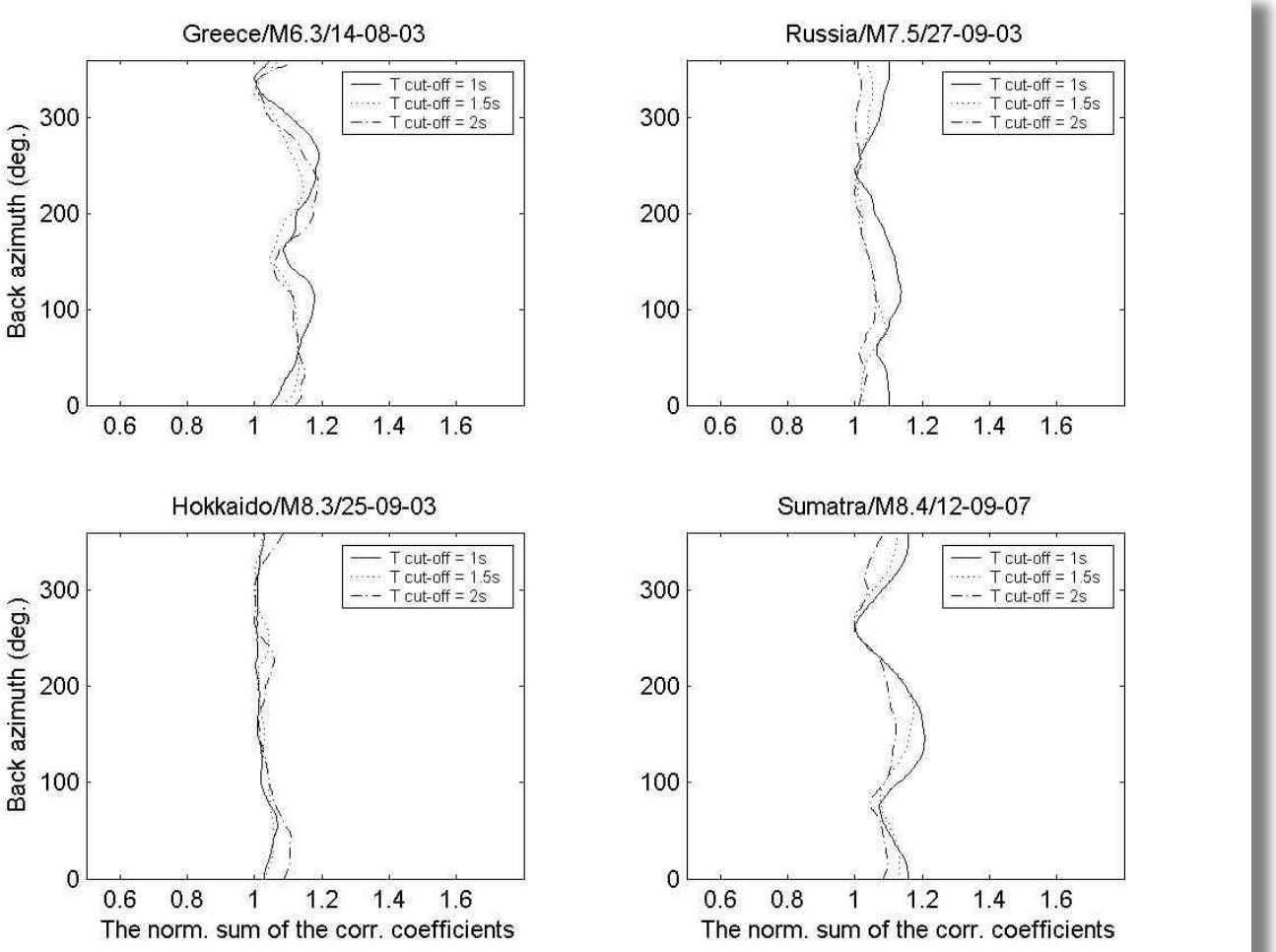


correlations in Love wave window

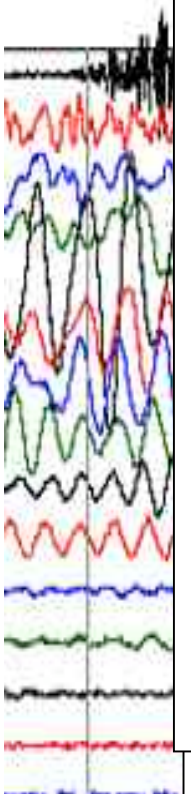


P-Coda energy direction

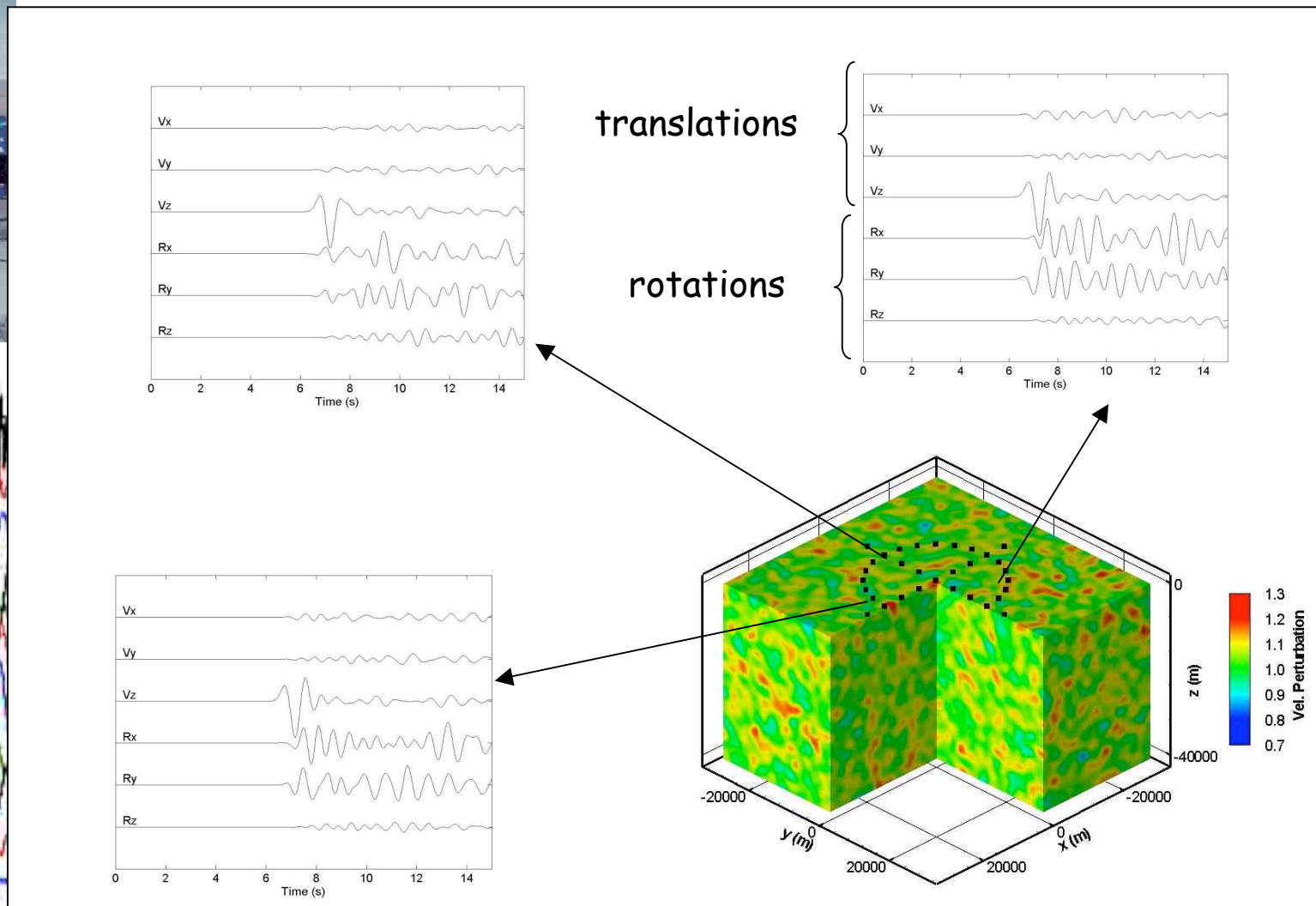
… comes from all directions …

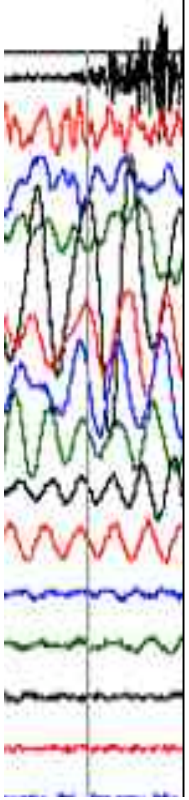


correlations in P-coda window



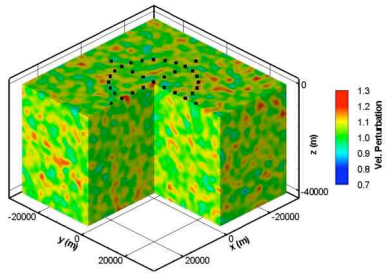
P-SH scattering
simulations with ADER-DG

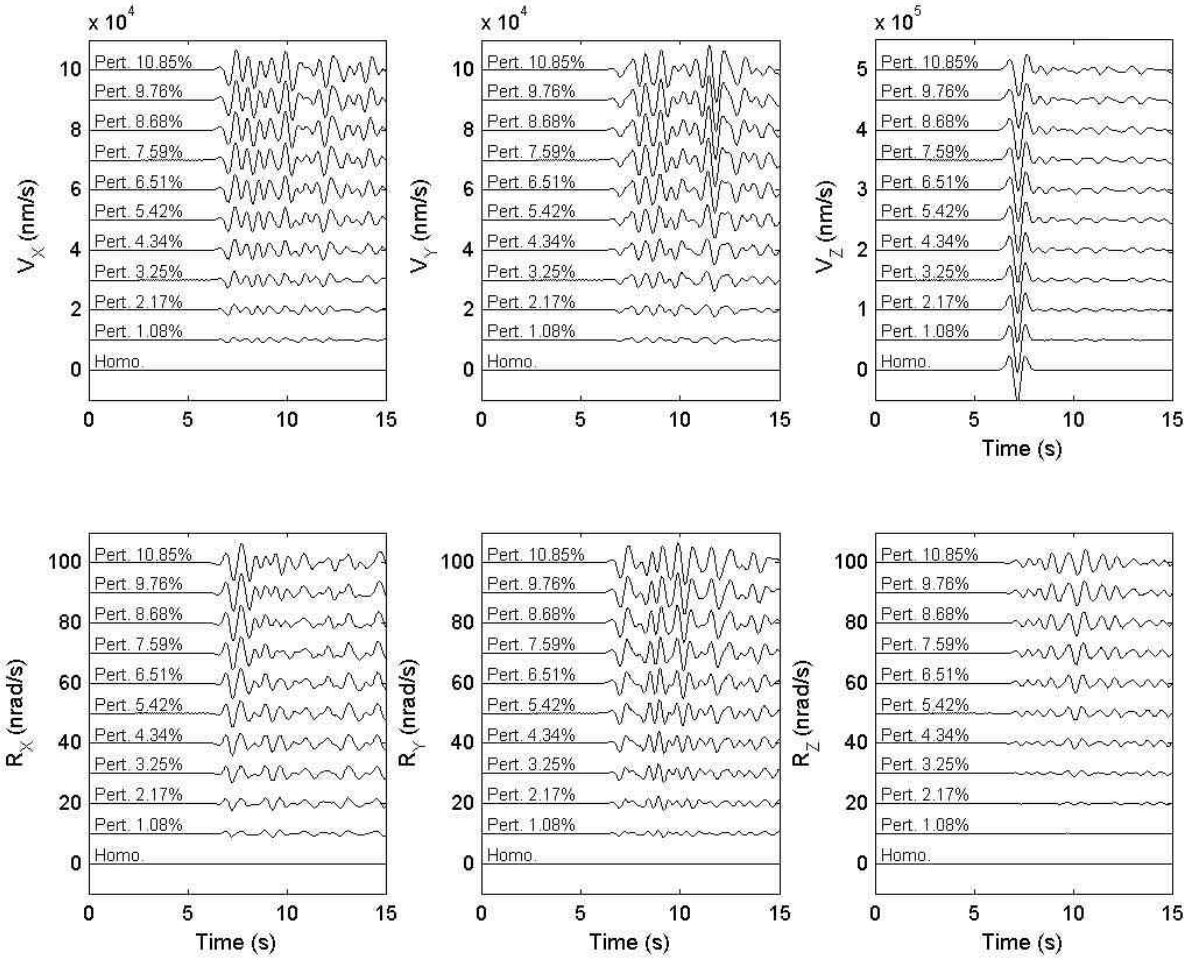


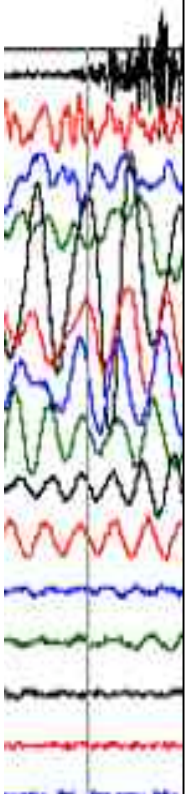


P-SH scattering

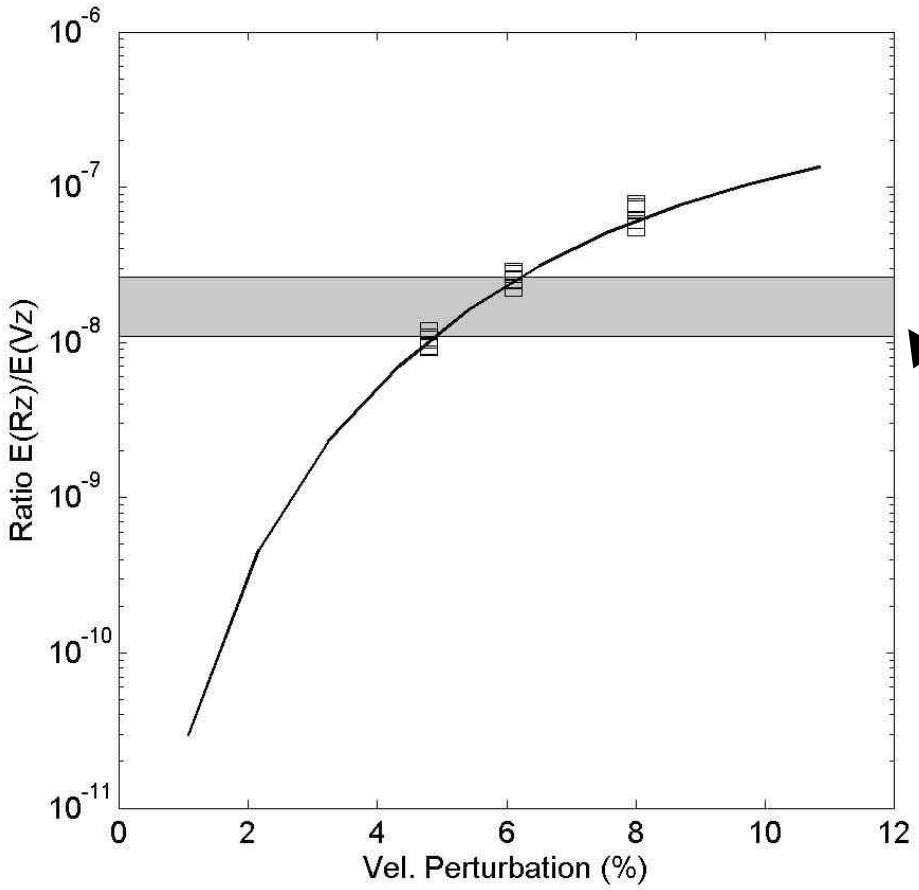
simulations with ADER-DG





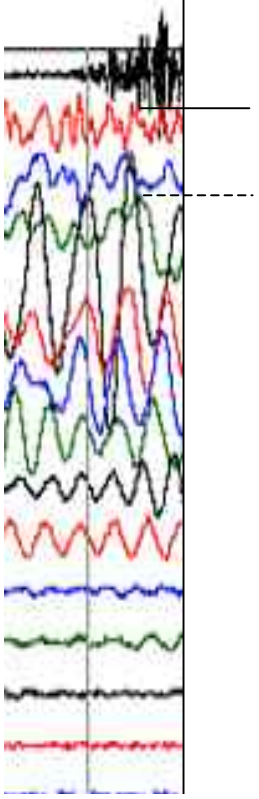


Ratio of Rotational energy vs. Translational energy



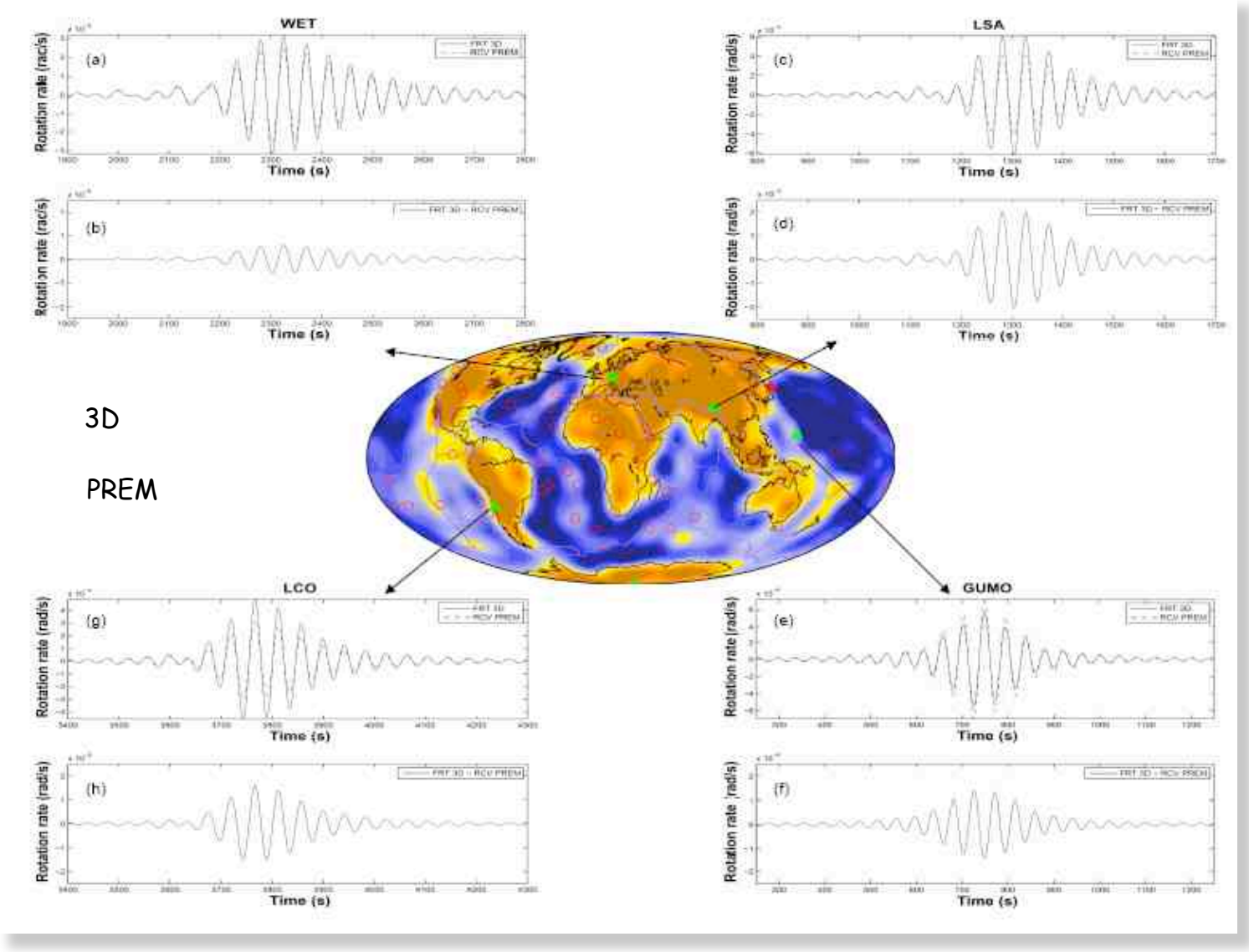
Observed range of energy ratios

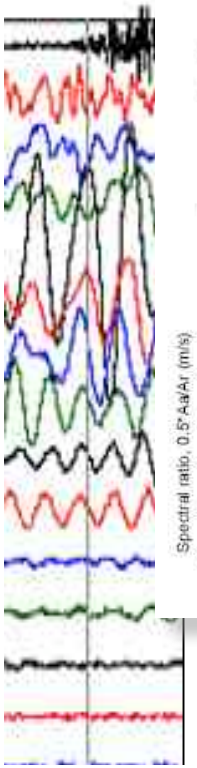
Pham et al., 2008, BSSA, subm.



Love wave wave rotations

JWKB synthetics

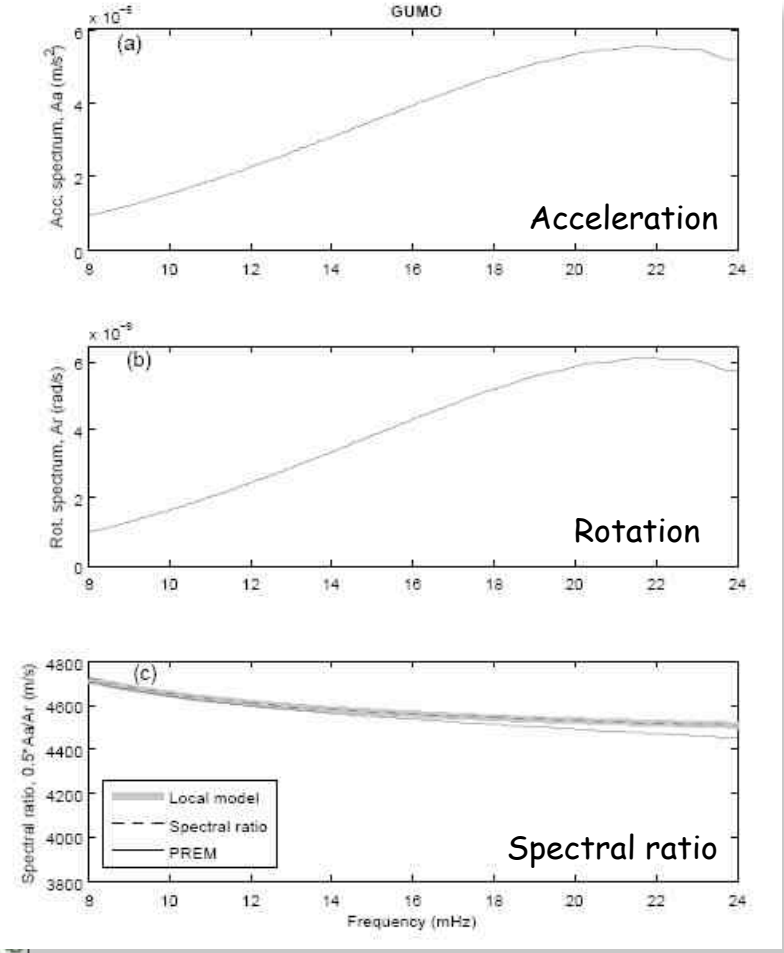




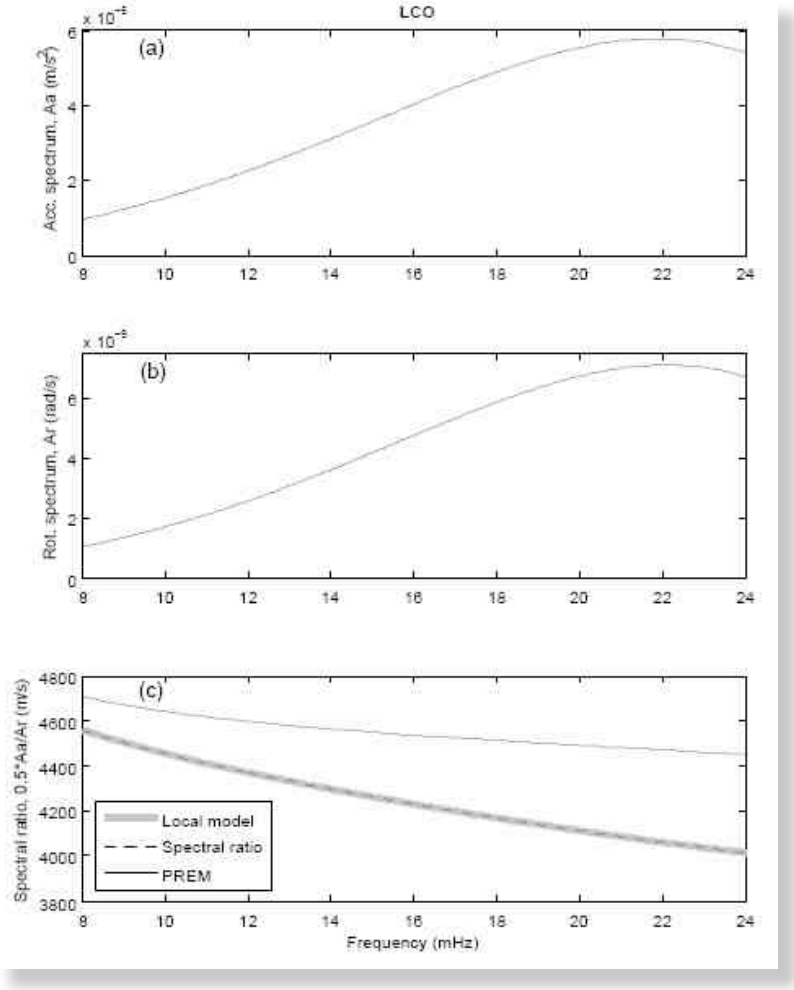
Love wave dispersion

-> S-wave tomography

Oceanic Crust



Continental Crust



Ferreira and Igel., 2009, BSSA.