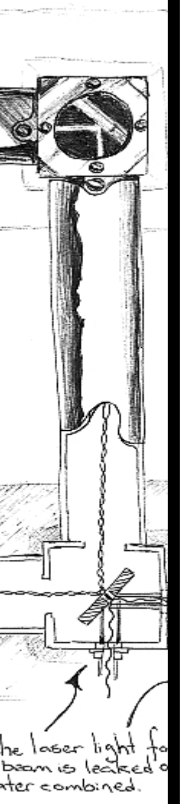


Broadband Observations of Rotational Ground Motions: Observations and Modelling

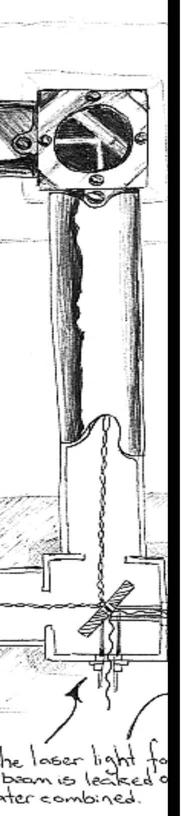
H. Igel[1], A. Cochard[1,4], A. Flaws[1,2], W. Suryanto[1], B. Schuberth[1], U. Schreiber[3] , D.N. Pham[1], A. Velikoseltsev[3]

[1]Department of Earth Sciences, LMU Munich, Germany
[2]Department of Physics and Astronomy, Christchurch, New Zealand
[3]Fundamentalstation Wettzell, Germany
[4]University of Strasbourg, France

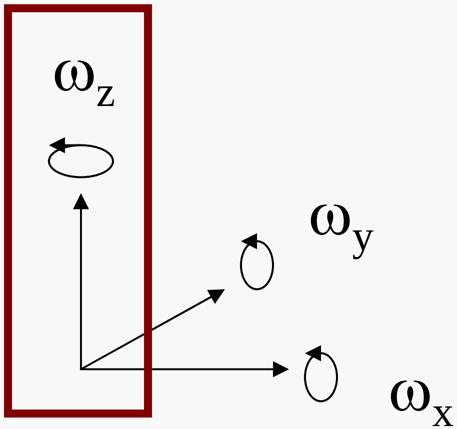
- **Array-derived vs. directly measured rotations**
- **Broadband observations of rotations vs. transverse accelerations**
  - Peak rotation rates
  - Waveform comparison with translations
  - Horizontal phase velocities
  - Love wave dispersion
  - P-coda signals
- **Conclusions and future**

Rotation is the curl of the wavefield

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

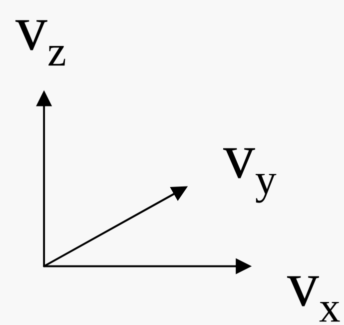


$$\begin{pmatrix}\omega_x\\ \omega_y\\ \omega_z\end{pmatrix} = \frac{1}{2}\nabla\times\underline{\mathbf{v}} = \frac{1}{2}\begin{pmatrix}\partial_y v_z - \partial_z v_y\\ \partial_z v_x - \partial_x v_z\\ \partial_x v_y - \partial_y v_x\end{pmatrix}$$



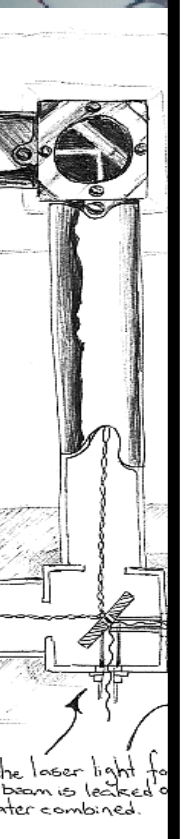
Rotation rate

Rotation sensor



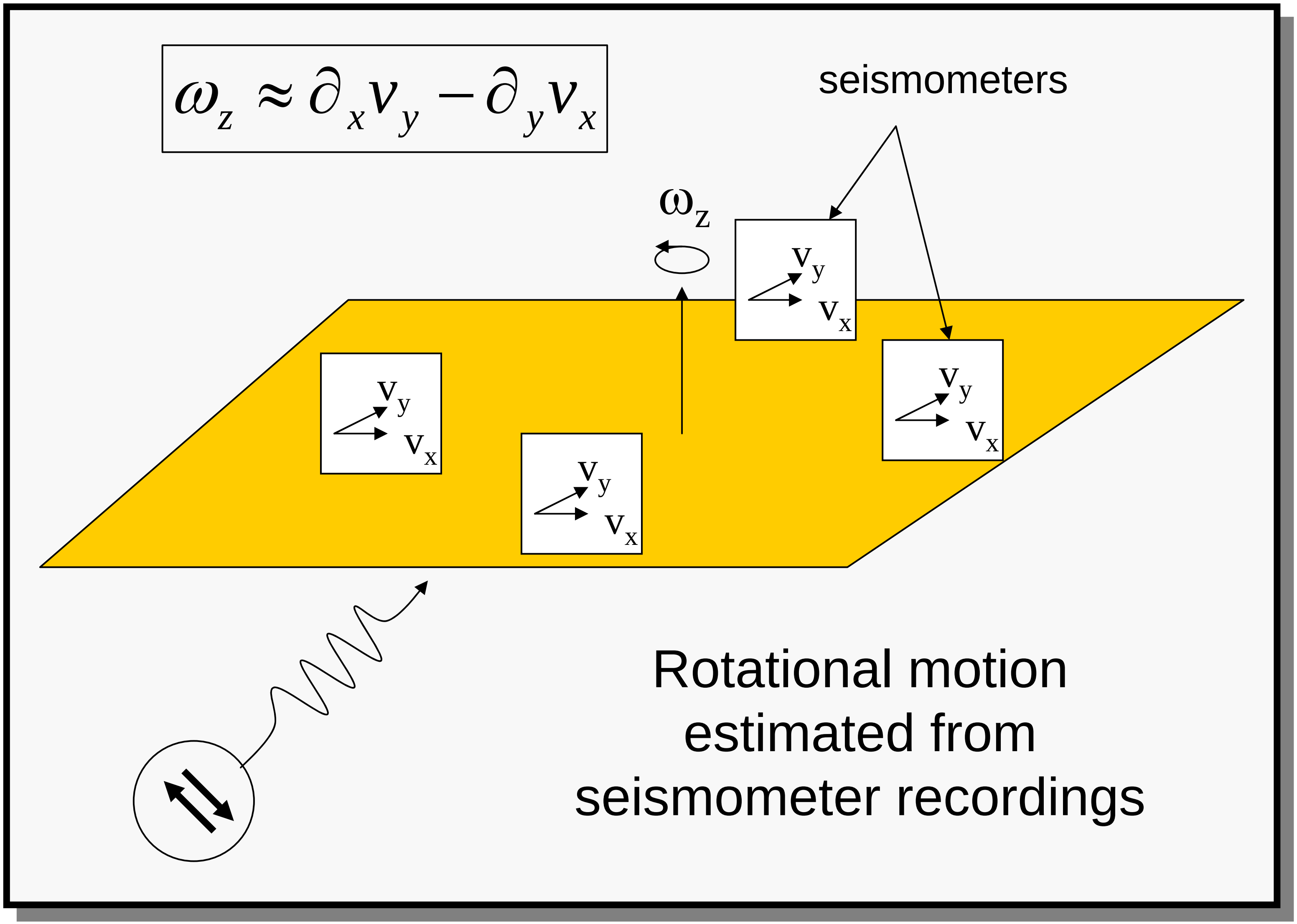
Ground velocity

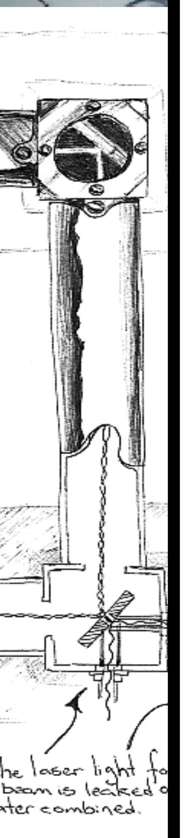
Seismometer



Rotation from seismic arrays?

... by finite differencing ...



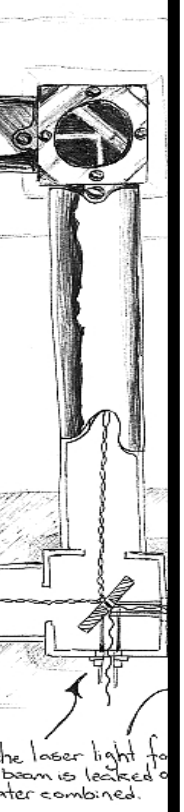


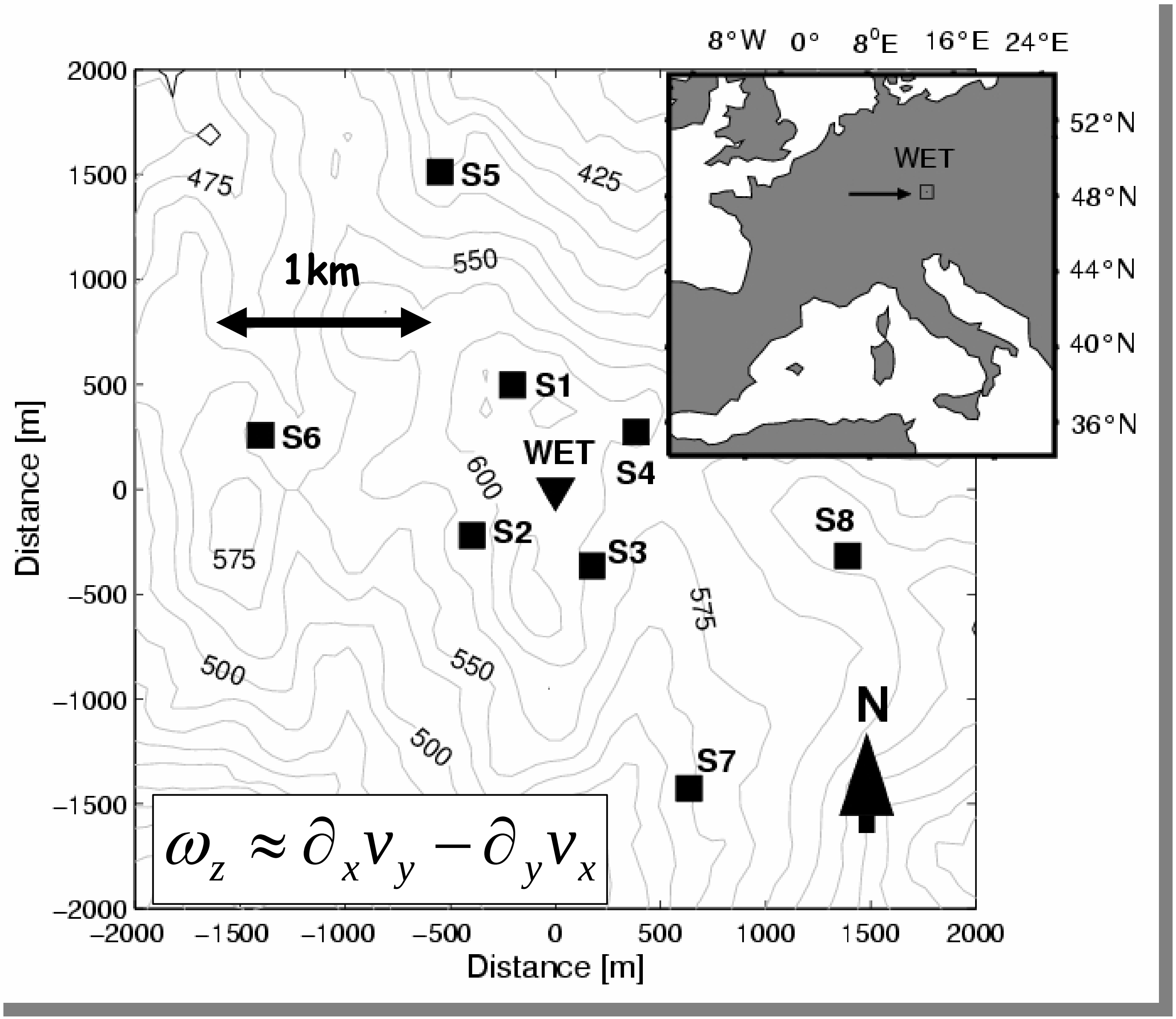
Initial Questions

- How do direct observations compare with array-derived rotations?
- Are the direct observations consistent with broadband translations?
- Can we extract any useful information from collocated recordings of translations and rotations?

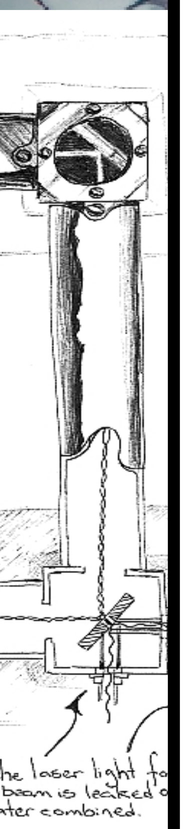
Array Experiment

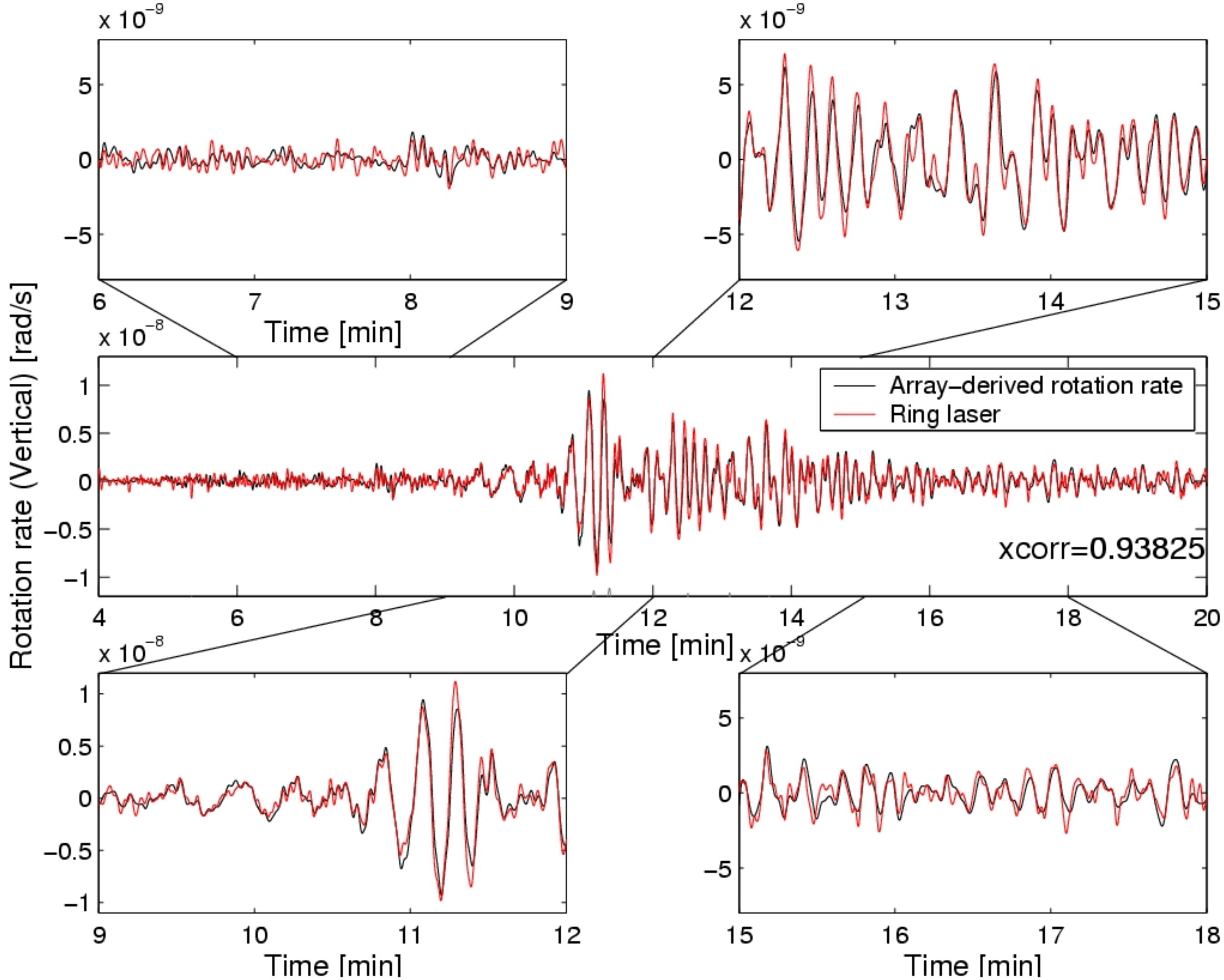
Dec 2003-Mar 2004



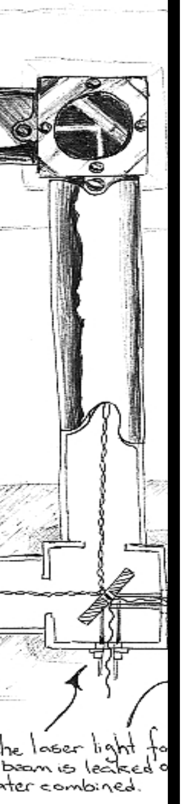


First comparison of array-derived rotations (**black**) and direct ring laser measurements (red)





From Suryanto et al (2006, BSSA, in print)



Theoretical relation

rotation rate and transverse acceleration
plane-wave propagation

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

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

Acceleration

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

Rotation rate

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

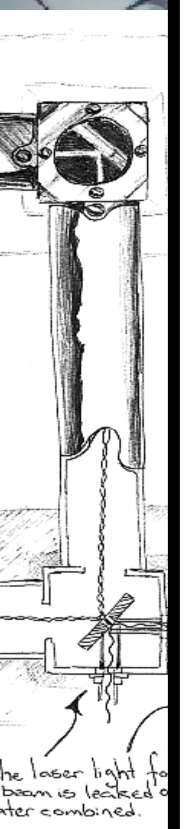
$$a(x,t) / \Omega(x,t) = -2c$$

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

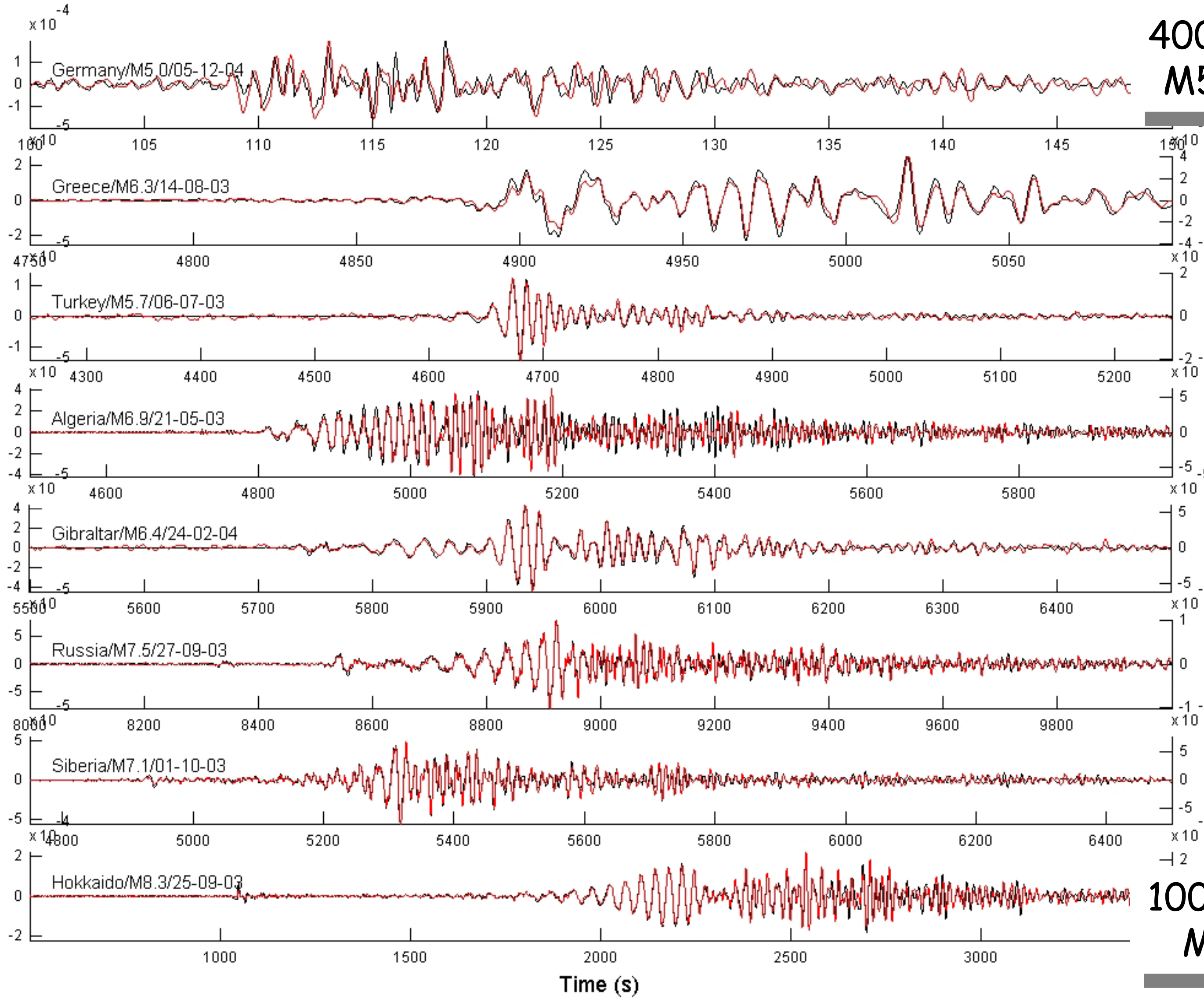
Rotational data base

events with varying distance

transverse acceleration – rotation rate



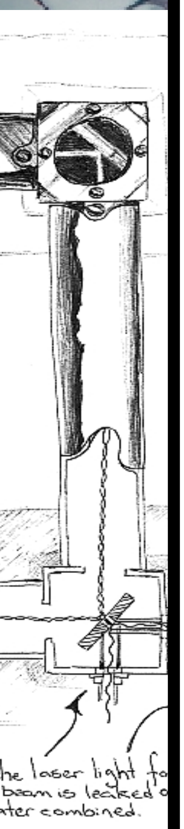
increasing epicentral distance



400km
M5.0

10000km
M8.3

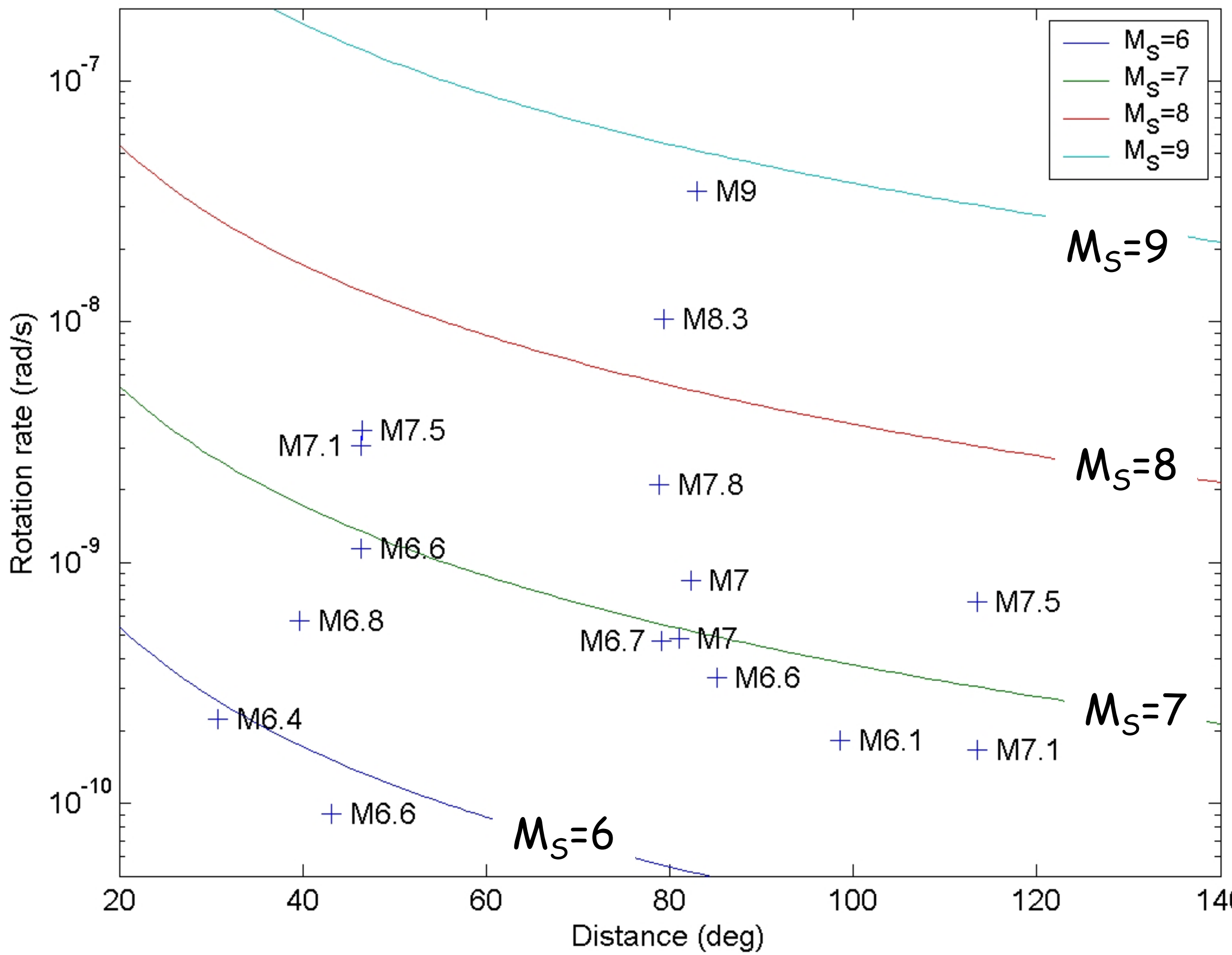
From Igel et al., GJI, 2007

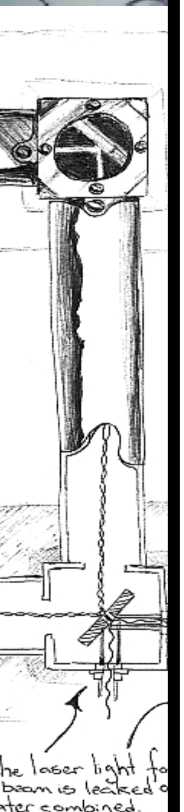


Compatibility with MS (surface wave magnitude) T=30s, c=4300m/s

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

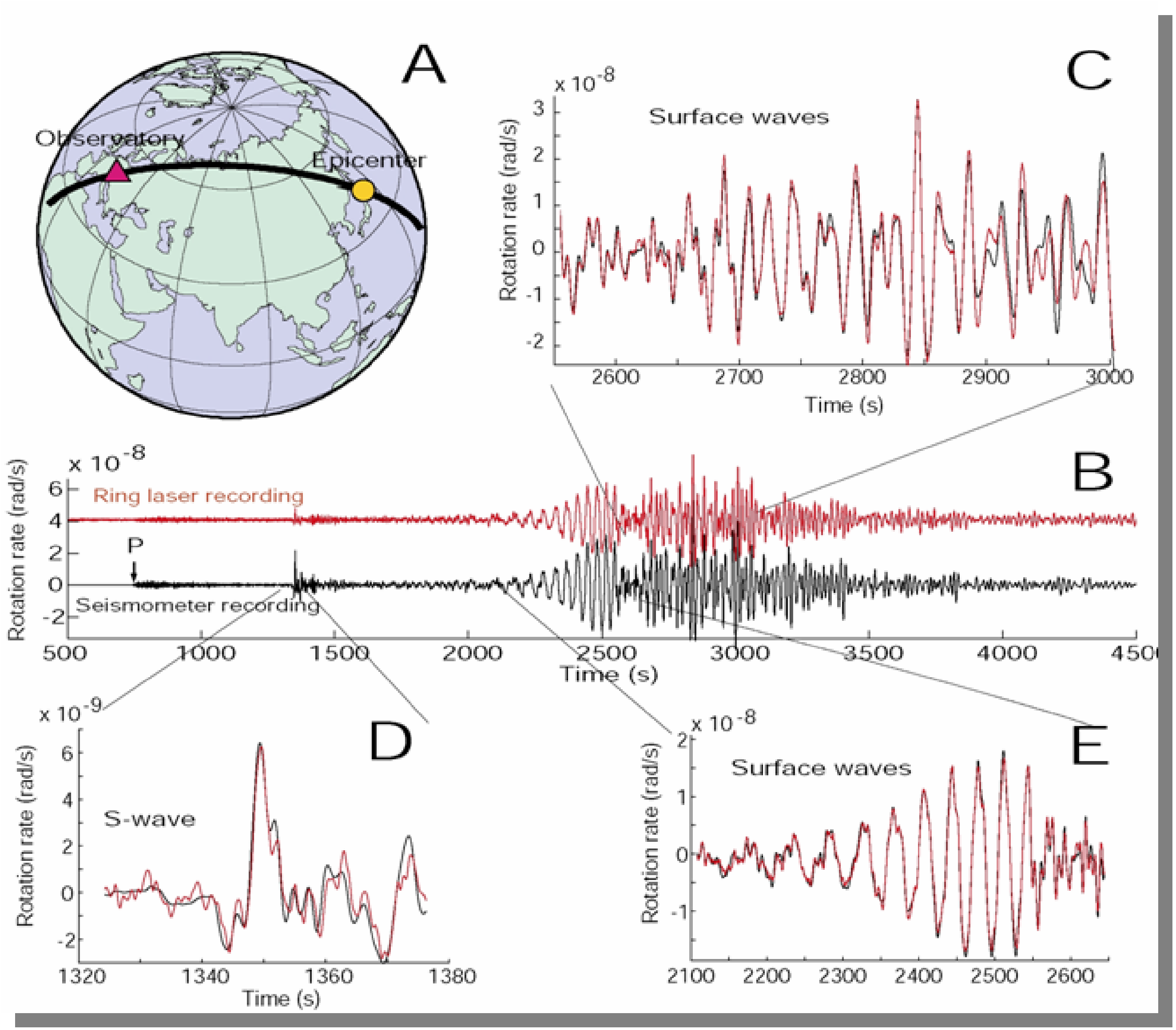
$$\Omega_z = 2\frac{\pi^2}{cT^2}A(M_S, D) = 2\frac{\pi^2}{cT}10^{M_S - 1.66\log_{10} D - 9.3}$$



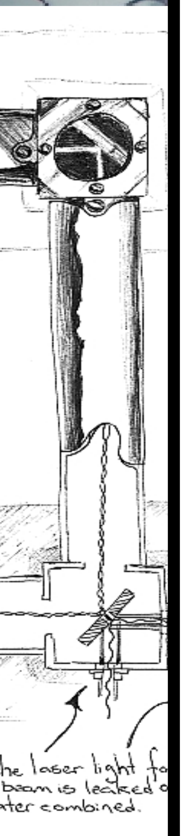


Mw = 8.3 Tokachi-oki 25.09.2003

transverse acceleration – rotation rate

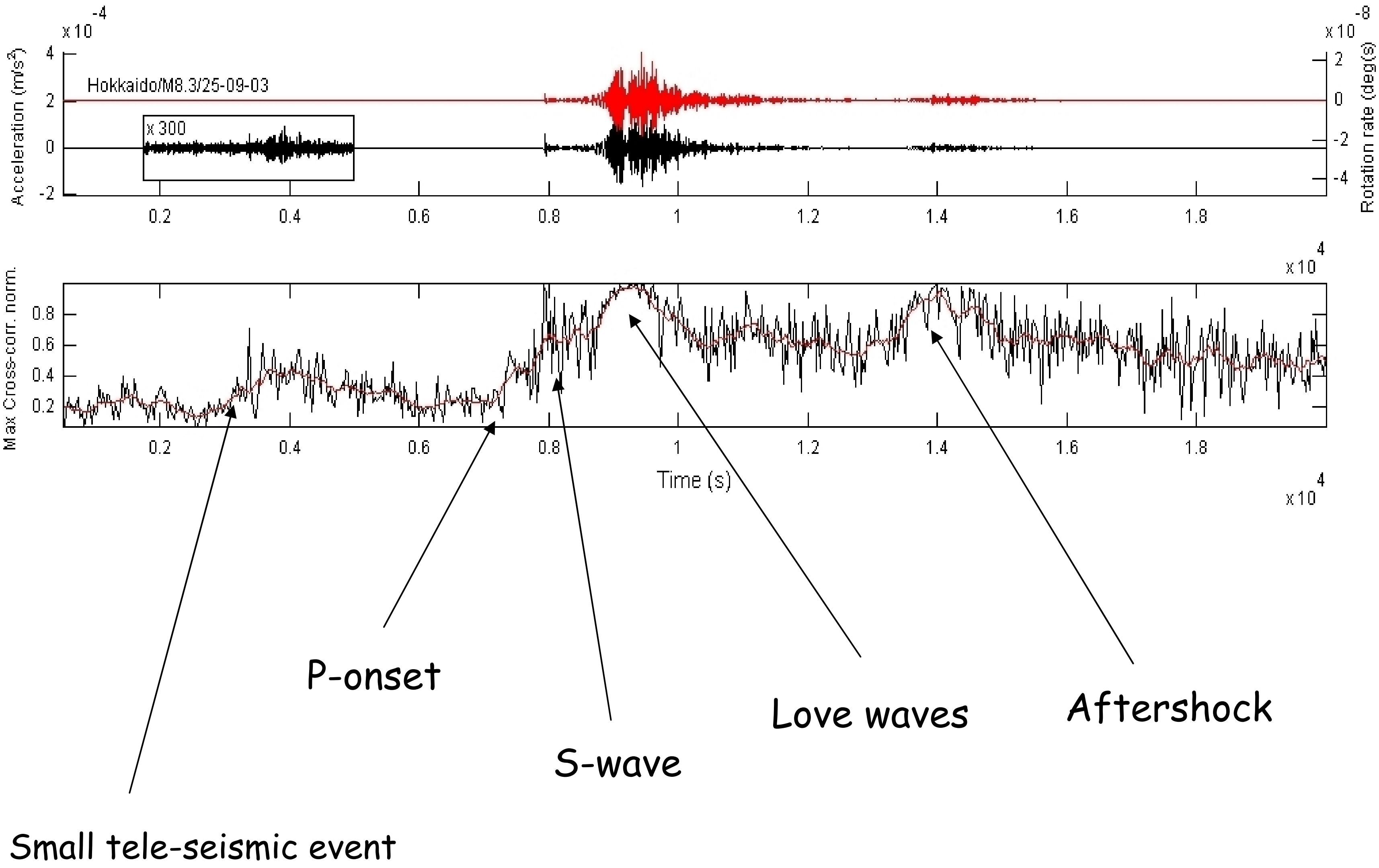


From Igel et al., GRL, 2005



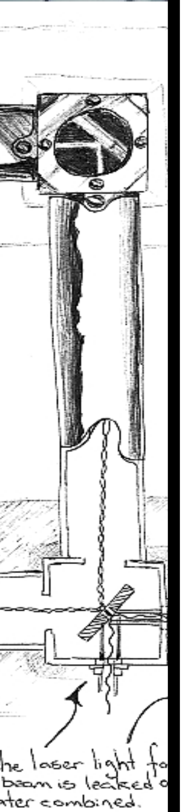
Max. cross-corr. coefficient in sliding time window

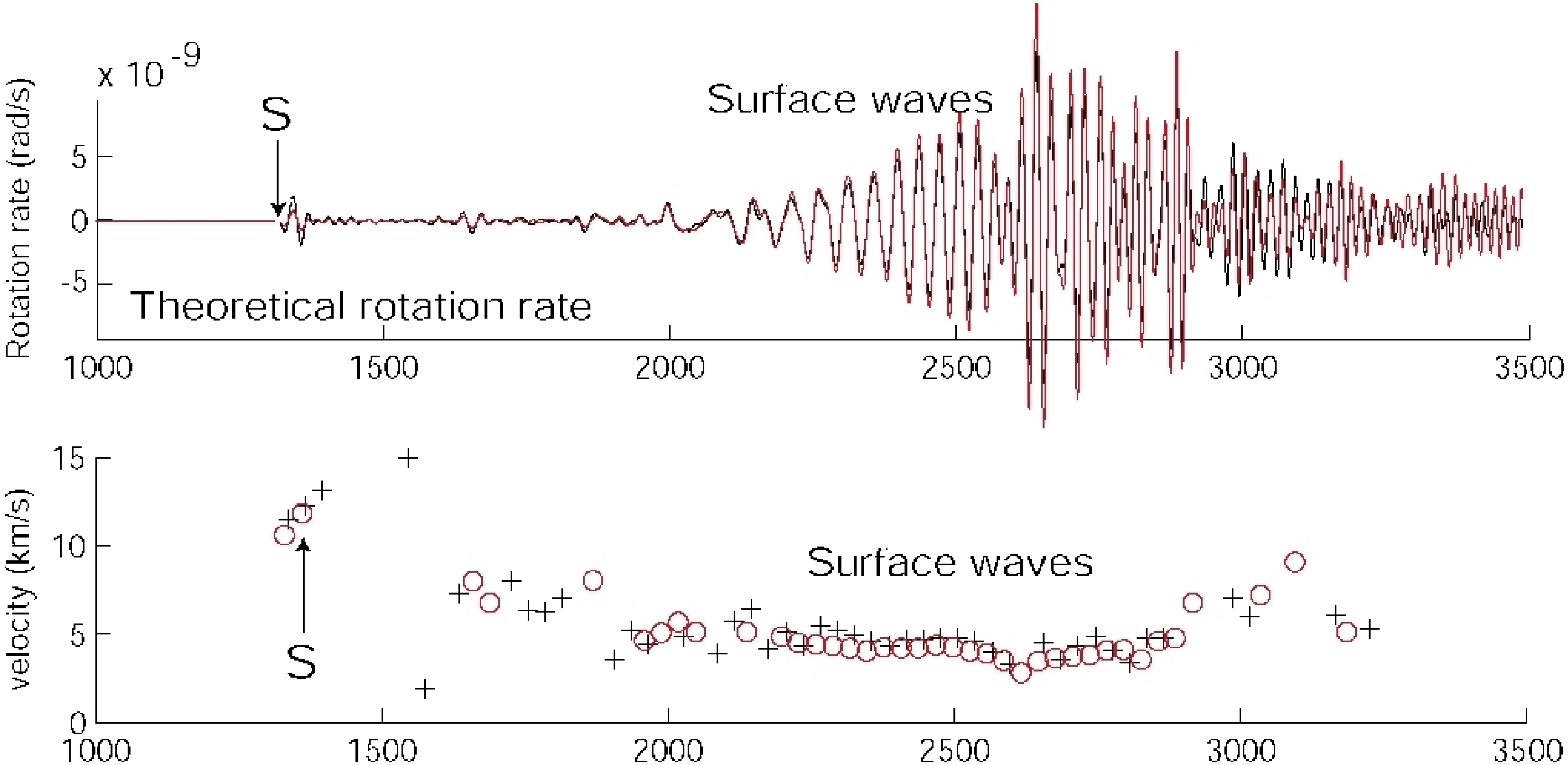
transverse acceleration – rotation rate



M8.3 Tokachi-oki, 25 September 2003

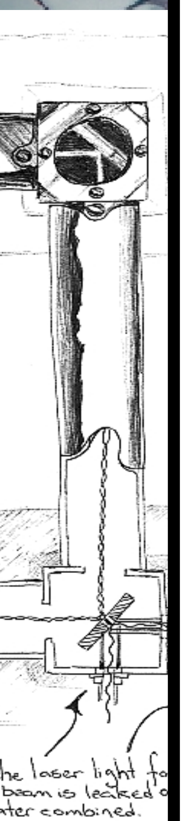
phase velocities (+ observations, o theory)





Horizontal phase velocity in sliding time window

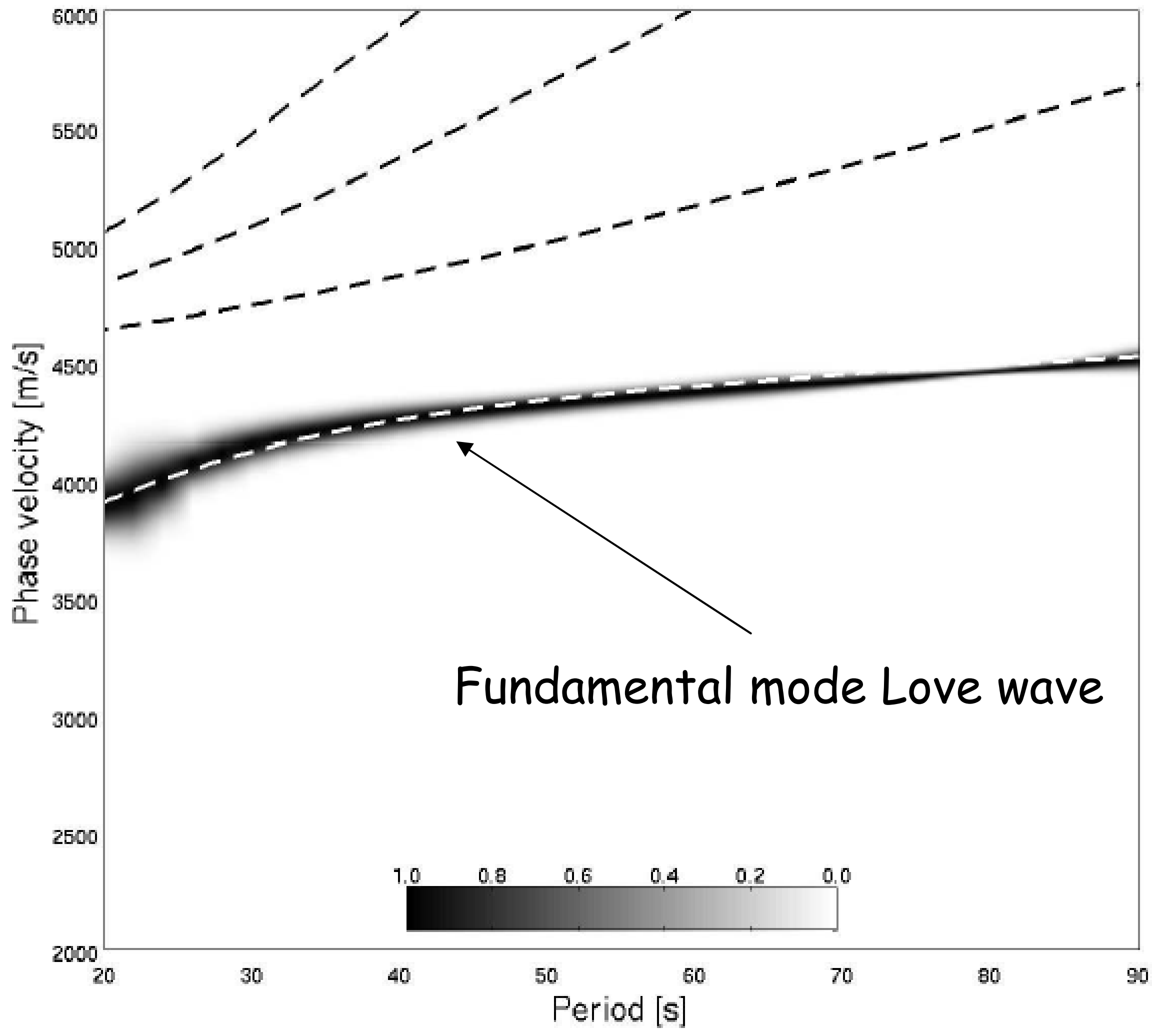
From Igel et al. (GRL, 2005)

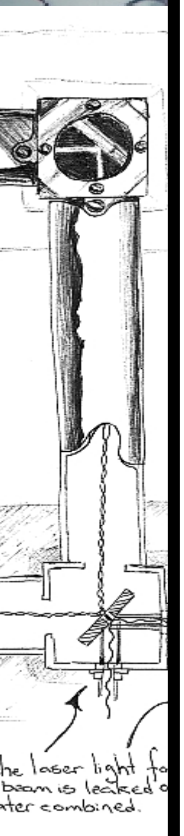


Stacked spectral ratios …

Synthetic example

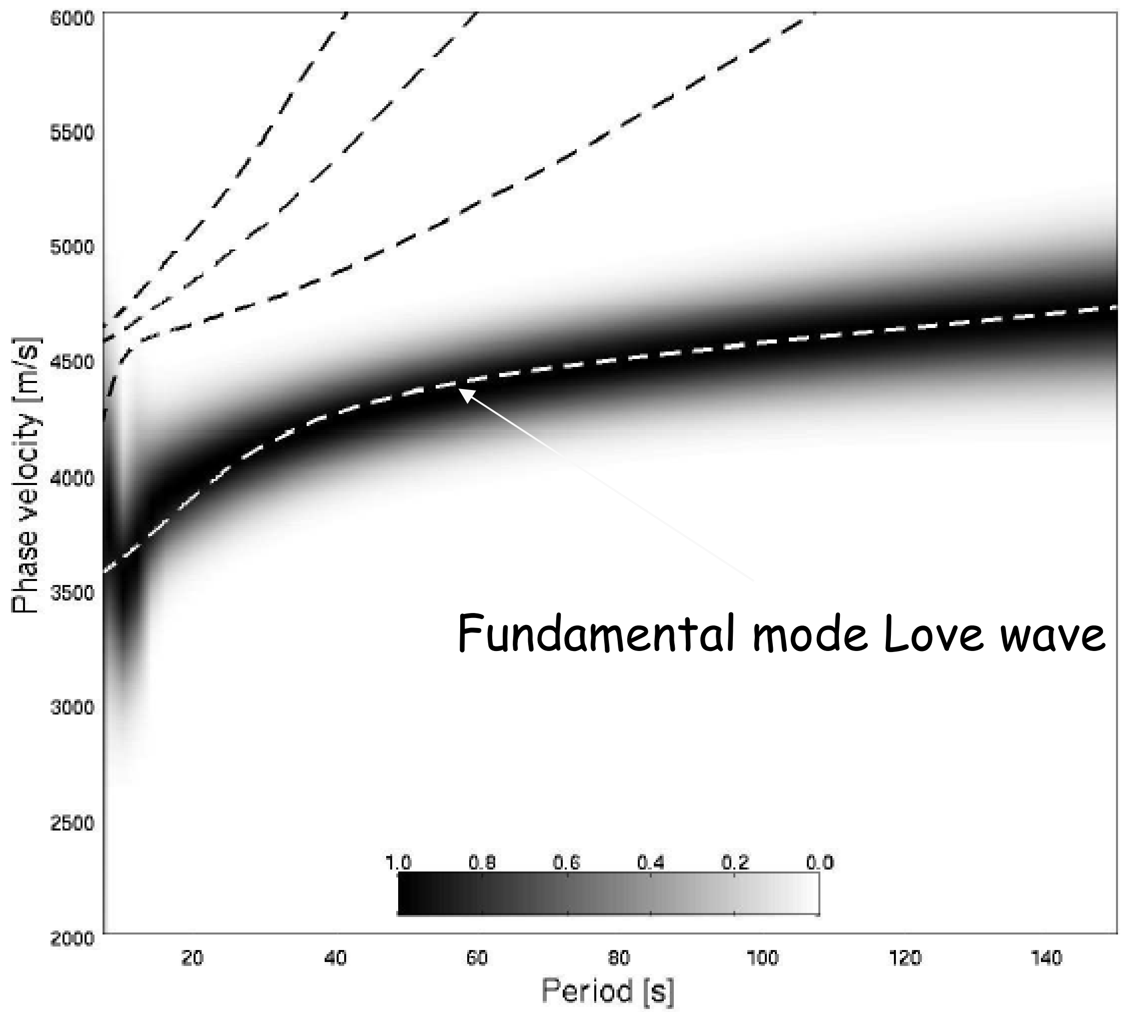
Four spectral ratios averaged – theoretical dispersion for ak135

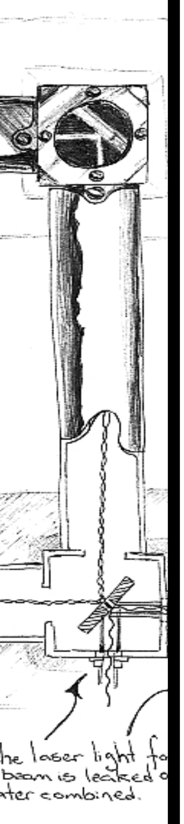




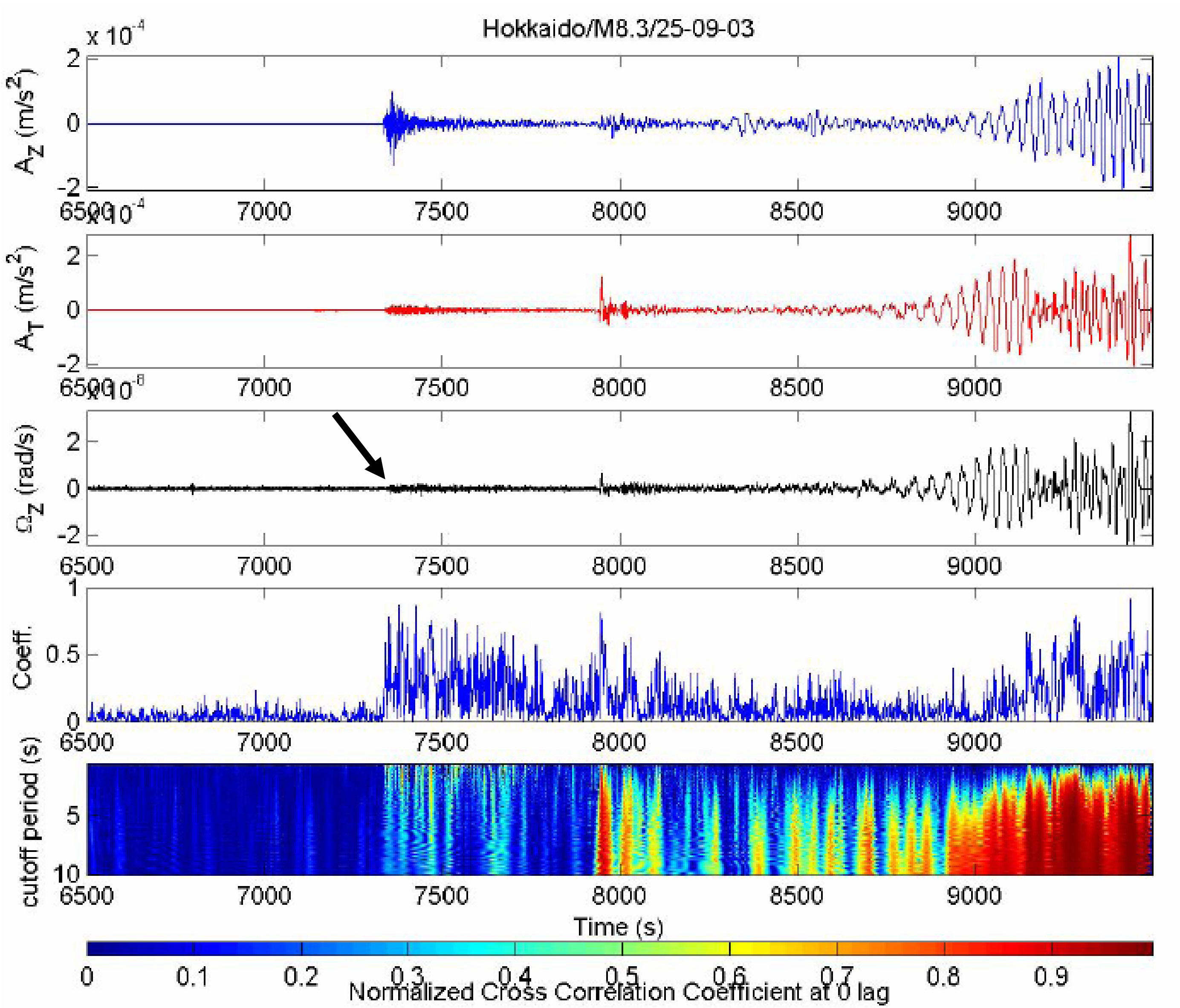
Stacked spectral ratios …

observations – nine teleseismic events

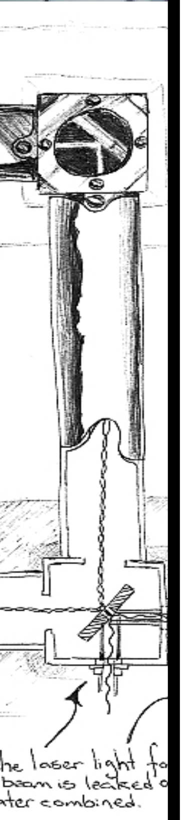


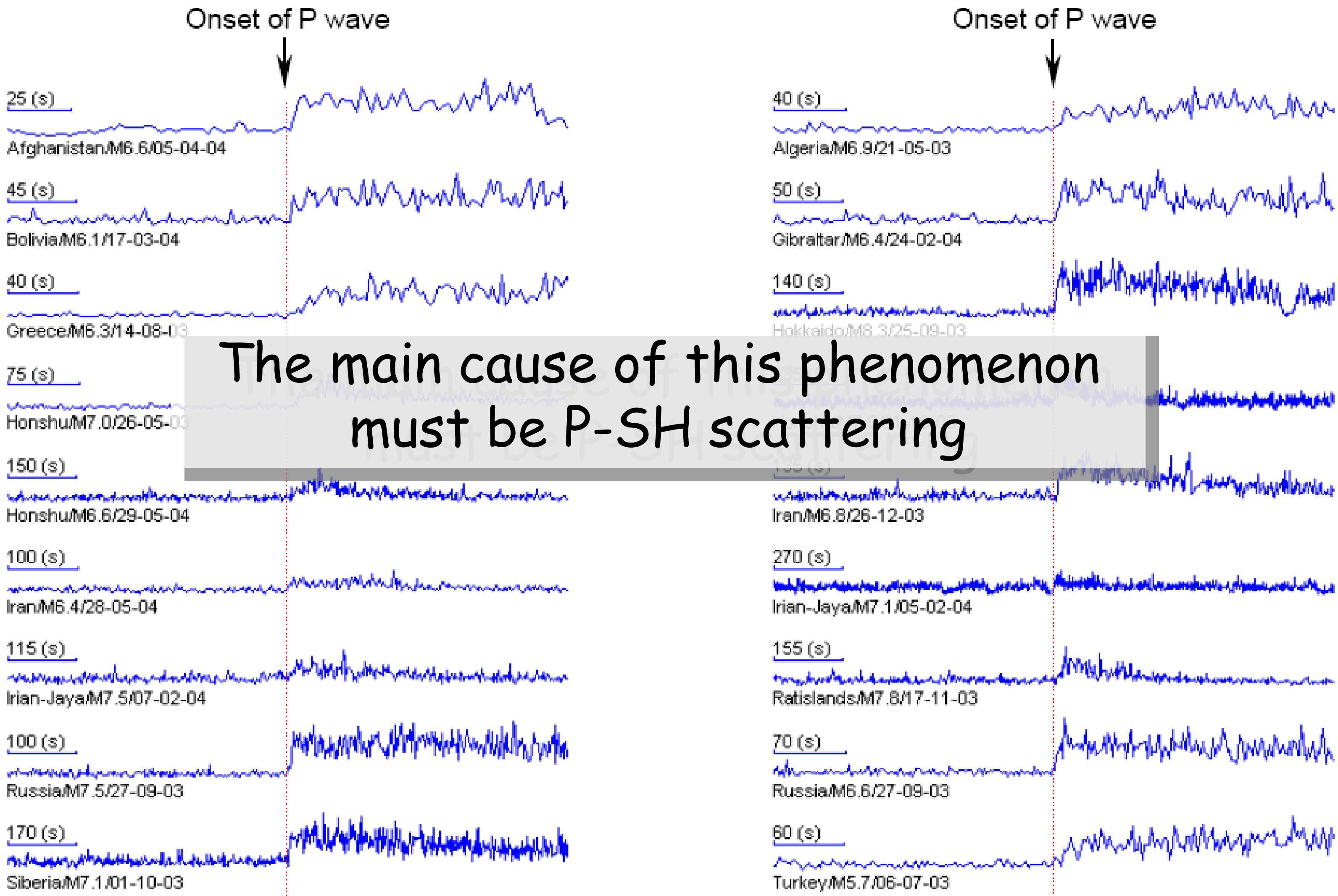


Rotational signals in the P-coda???

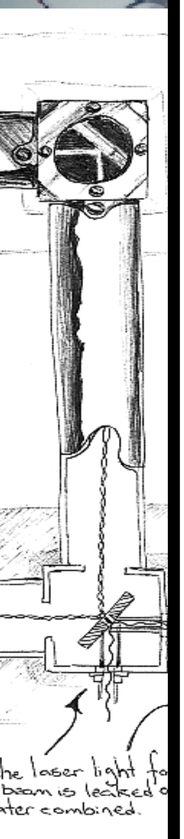


Increase in correlation (rotation rate vs. transverse aceleration) at P-onset … observable for all events!





The main cause of this phenomenon must be P-SH scattering



Rotations – why bother?

- Standard seismological observations are polluted by rotations
- Tiltmeters (rotation around horizontal axes) are polluted by translations
- 6C sensor may allow integration to displacements

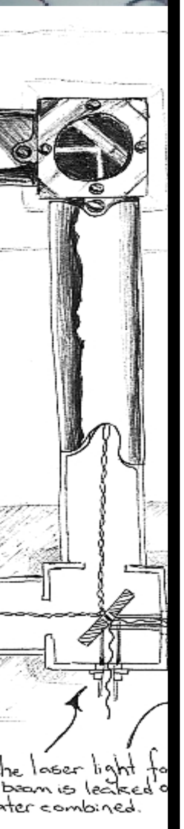
Instruments

- Rotations may contribute to co-seismic structural damage

Earthquake engineering

- Rotational measurements may provide additional wavefield information (phase velocities, etc)
- ... and may allow further constraints on rupture processes ...

Waves and rupture



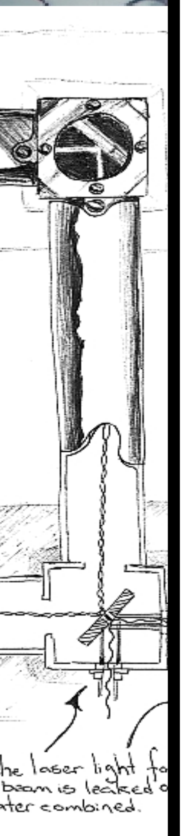
Summary

seismic ground rotations

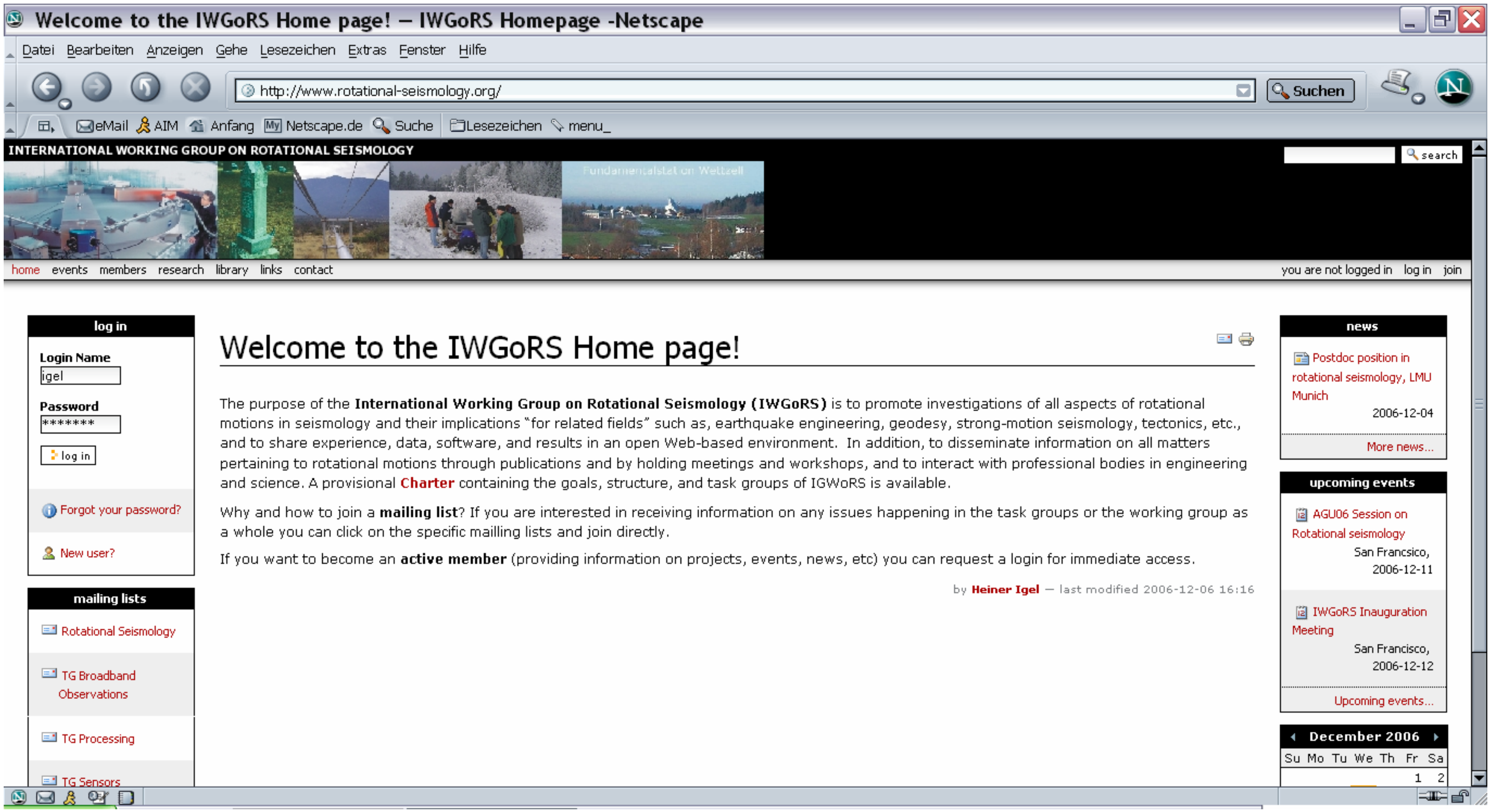
- We do have a new observable for broadband seismology, that is consistent in phase and amplitude with collocated recordings of translations
- The joint observations allow seismic array-type (but array-free!) processing steps
- A prototype sensor designed for seismology has been installed at Piñon Flat Observatory, CA

Open questions:

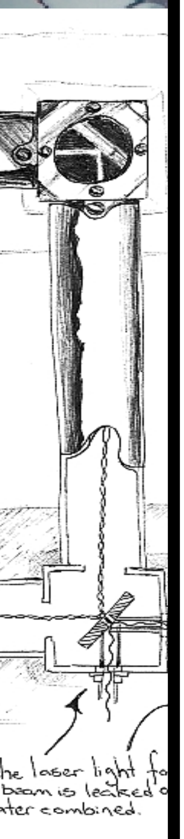
- Love-wave dispersion, how accurate? -> Tomography? -> What volume does it represent?
- Understanding observations in data base in terms of structure, anisotropy, scattering, source, etc.
- How to improve S/N ratio of ring laser records?
- What technology is best for strong motions?
- Would observations of rotations allow tighter constraints on finite source parameters?



International Working Group on Rotational Seismology

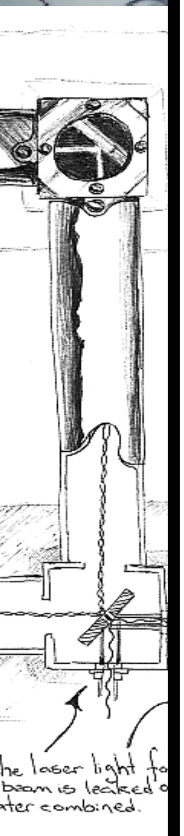


www.rotational-seismology.org



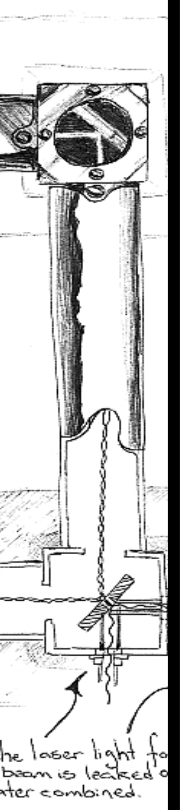
International Working Group on Rotational Seismology aims at

- promoting investigations of all aspects of rotational motions in seismology and their implications for „related fields" such as, earthquake engineering, geodesy, strong-motion seismology, tectonics, etc.
- sharing experience, data, software, and results in an open Web-based environment.
- disseminating information on all matters pertaining to rotational motions through publications and by holding meetings and workshops
- interacting with professional bodies in engineering and science.
- seeking funding for research projects



Provisional Sub-Groups

- Processing of rotational motions
- Strong motion
- Theory
- Sensors
- Broadband observations



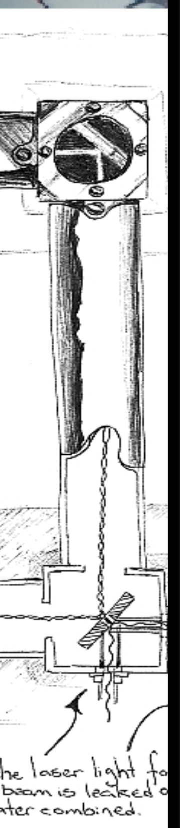
Sub-Group: Processing of rotational motions

Chair: Joachim Wassermann, LMU Munich.

Goals: Development and provision of processing and modelling tools for rotational motions

Current project:

- Developing a new Web-based methodology to archive and process multi-component data with six-degree-of-freedom (6DOF) data (specifically, but not exclusively, included).
- 3-year project, funded by German Research Foundation, Project scientist: Robert Barsch

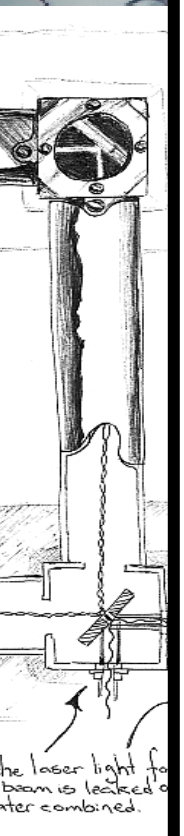


Sub-Group: Strong Motions

Chair: Misha Trifunac and Maria Todorovska, USC, Los Angeles.

Goals:

- Guidelines and recommendations for how and where to record rotational strong motions.
- Promoting establishment of several full-scale laboratories for measurement of rotational strong motions in buildings and on bridges, dams, and lifelines, as well as in the free field (near and far).
- Developing data processing methods for processing 6DOF strong-motion records.
- Developing software for synthetic generation of realistic rotational accelerograms, to facilitate engineering studies of the associated structural response.

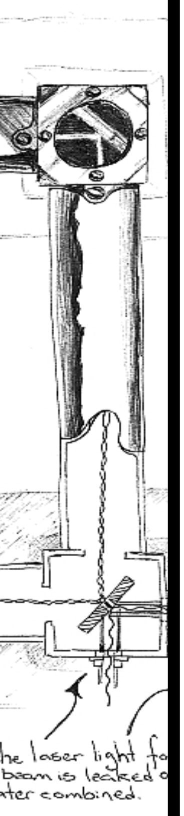


Sub-Group: Theory

Chairs: Alain Cochard, Strasbourg, and Eugeneiusz "Eugene" Majewski, Poland.

Goals:

- The relevance of rotational motions for source inversion.
- Rotational motions in various rheologies (anisotropic, viscoelastic, viscoplastic).
- Understanding the difference between direct rotation and acceleration-derived rotation
- Physics of rotations in rock-forming minerals: dislocations and disclinations.
- Generation, propagation, and attenuation of seismic rotational waves.
- Dispersion of seismic rotational waves.
- Solitary rotational waves as a fracture mechanism.



Sub-Group: Sensors

This task group will be divided into **strong** and **weak** motion sensors.

Chairs: Robert Nigbor, UCLA, John R. Evans, USGS, and Robert Hutt, USGS.

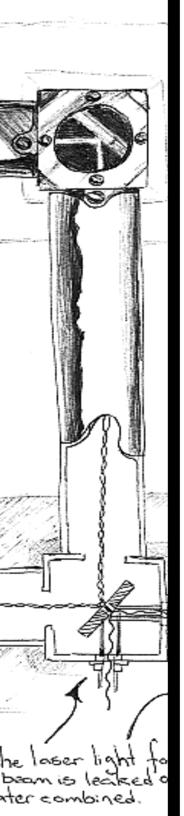
Strong-motion rotational sensors

- **Test sensitivity**, linearity, 6DOF cross-axis sensitivity, and self noise of various strong-motion rotational sensors.
- Work with the USGS Albuquerque Seismological Laboratory to procure and validate improved testing aparatus and to perform precision tests of at least strong-motion rotational sensors.

Chairs: Ulrich Schreiber, Wettzell, and B. Hurst, Christchurch.

Weak-motion rotational sensors

- **Improving the performance** of large ring lasers for seismic studies
- Verification of rotational sensor data by collocation of alternative techniques
- Improve existing detection concepts
- Explore and evaluate **alternative sensor concepts** (FOG, IMU, Superfluid helium, electro-chemical) for teleseismic and strong motion application
- Develop a full **highly sensitive 6-degrees of freedom sensor** to be tested at Pinon Flat Observatory and verify the performance (investigate implications of alignment errors)
- Develop and evaluate sensor concepts to **monitor rotations in civil eng. structures**
- Enhance productivity by interacting with other development groups



Sub-Group: Broadband Observations

Chairs: Heiner Igel, Munich, and Frank Vernon, SCRIPPS.

Goals:

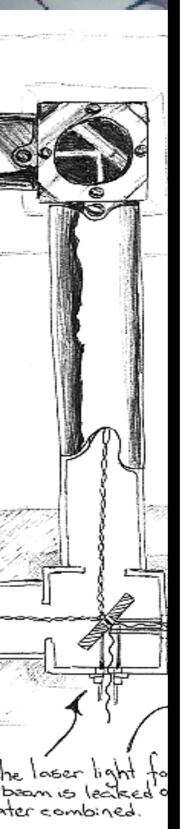
- Develop infrastructure for data transfer and availability of high-resolution broadband sensors (Wettzell, Germany; Christchurch, New Zealand; Pinon Flat Observatory, California).
- Defining formats for storage and transfer of multi-component ground motion data (e.g., translations, rotations, tilt, strain, etc.).
- Data analysis, interpretation and modeling of observations.

Current projects:

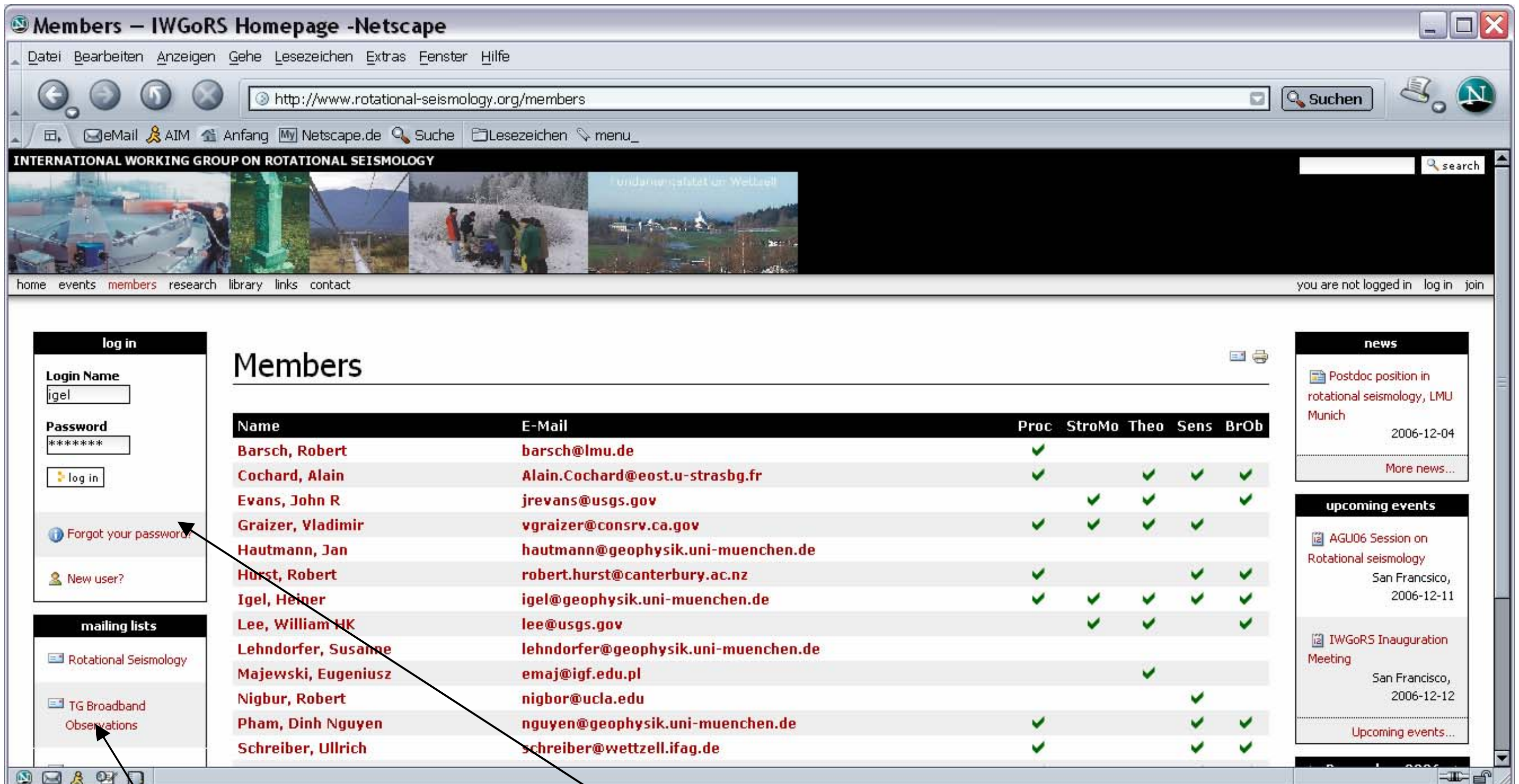
Array-derived rotations and tilt (PhD project Wiwit Suryanto, finished in a few weeks).

Analysis of broadband data (N.D. Pham, PhD project, currently working on P-coda).

2 year postdoctoral position in broadband rotational motions (open and advertised)

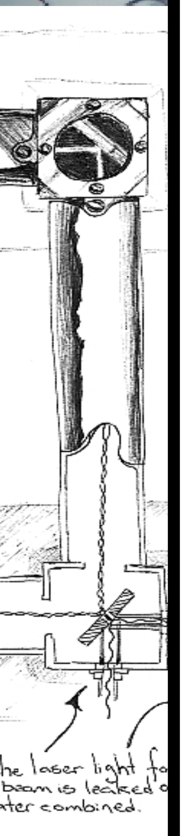


The web-interface



Get login for active membershop

Join mailing lists (global or subgroup)



Inauguration Lunch

The Garden Terrace Restaurant on the Second Floor of the **San Francisco Marriott Hotel**, 55 Fourth Street

Today 12:30