Ground rotations: what do they tell us, that we did not know before?

H. Igel, D. Kurrle, J. Wassermann, LMU Munich, U. Schreiber, TU Munich, F. Vernon, UCSD La Jolla, A. Ferreira, Univ. East Anglia.

Currently there are two types of measurements that are routinely used to monitor global and regional seismic wave fields. Standard inertial seismometers measure three components of translational ground displacement (velocity, acceleration) and form the basis for monitoring seismic activity and ground motion. The second type aims at measuring the deformation of the Earth (strains). It has been noted for decades (Aki and Richards, 2002, and previous edition) that there is a third type of measurement that is needed in seismology and geodesy in order to fully describe the motion at a given point, namely the measurement of ground rotation. The three components of seismically induced rotation have been extremely difficult to measure, primarily because previous devices did not provide the required sensitivity to observe rotations in a wide frequency band and distance range.

The rotational motion amplitudes were expected to be small even in the vicinity of faults (Bouchon and Aki, 1982) whereas there is growing evidence that these amplitudes have been underestimated. Following the pioneering observations with ring laser rotation sensor in Christchurch, New Zealand (Pancha et al., 2000, McLeod et al., 1998) a ring laser for the observations of the Earth's rotation rate located at Wettzell, Germany (Schreiber et al., 2006, 2009) was adapted to the sampling rate requirements in seismology allowing the observations of earthquake-induced rotational ground motions over a wide magnitude and epicentral distance range (Igel et al., 2005, 2007, Cochard et al., 2006). Analysis of these observations in combination with collocated recordings by a standard broadband seismometer showed the possibility of extracting additional information on subsurface structure compared to translational measurements alone (e.g., Suryanto, 2007; Pham et al., 2009a; Ferreira and Igel, 2009; Fichtner and Igel, 2009, Bernauer et al., 2009), otherwise accessible with seismic array measurements only. The interest of various communities (e.g., instrumentation, earthquake engineering, earthquake physics, seismic decoupling, ocean-bottom seismology, long-period seismology) in measuring rotations has been documented in the special issue of the Bulleting of the Seismological Society of America published in May 2009. For a review article we refer to Lee et al. (2009).

These studies and earlier considerations motivated the development of a ring laser sensor specifically designed for seismological purposes given an observatory infrastructure. Ring lasers are active optical interferometers, where the beat frequency between the two counter-propagating beams in a square or triangular cavity is observed. This beat frequency is proportional to the rate of rotation, which the entire apparatus is experiencing. Because beams of light are used, the sensitivity for rotational motion is as high as 10^{-10} rad/s/sqrt(Hz) for a square ring with 4m length of one side. This sensitivity is sufficient to even record rotational signals from teleseismic events (Igel et al. 2005). Passive optical fiber gyroscopes are less sensitive ($\approx 10^{-5}$ rad/s/sqrt(Hz)) and much smaller. They are useful for strong motion measurements and civil engineering applications (Schreiber et al. 2009).

It is important to note that – particularly in the near field – seismic sensors are contaminated by rotations, one of the main reasons why it is so difficult to integrate strong motion recordings to displacements (e.g., Trifunac and Todorovska, 1993).

Cross-validation of rotational ground motions with seismic array-measurements

Rotation is the curl of the wavefield and thus a linear combination of the derivatives of the displacement wavefield w.r.t. space coordinates. This implies that rotations can be estimated from seismic array data (e.g., Spudich et al., 1995; Huang, 2003; Spudich et al., 2008) with all problems associated with such experiments: (1) taking space derivatives makes the results extremely sensitive to errors concerning differences in instrument response, amplitudes either from instrument noise or site effects, or effects due to the fact that the gradients are not constant across the array. (2) The estimation of the horizontal components of rotations (tilts) is not unique as assumptions on subsurface properties have to be employed. Examples of comparisons between ring laser recordings of rotations with surface seismic array measurements were presented by Suryanto et al. (2007) and Wassermann et al. (2009). Both studies show good agreement for the vertical component of rotation (directly measured vs. array-derived). However, the studies also indicate the problems with deriving rotations from arrays.

Rotational motions: What can we get out of them?

In the following we will discuss the processing possibilities that collocated observations of rotations and translations offer.

Phase Velocities and propagation directions. A simple calculation for elastic plane waves with transverse polarization shows that the ratio of transverse acceleration and rotation rate is proportional to phase velocity. This is a remarkable fact as it implies that information on the subsurface velocity structure (otherwise only accessible through seismic array measurements and combined analysis) is contained in a point measurement. It could be shown that the derived phase velocities match well the ones predicted by synthetic calculations (Igel et al., 2005). In a recent theoretical study based on full ray theory for Love waves using normal mode summation, it could be demonstrated that the Love wave dispersion relation can be directly obtained by taking the spectral ratio of transverse acceleration and rotation rate (vertical axis, Ferreira and Igel, 2009, Kurrle et al., 2010a with an analysis on data). In addition to phase velocities it is important to note that information on the direction of propagation is contained in the azimuth dependent phase fit (quantified by time-windowed correlation coefficients) between rotation and translations. The fit is best in the direction of propagation and back azimuths can be estimated to within a few degrees (Igel et al., 2007, Pham et al., 2009a).

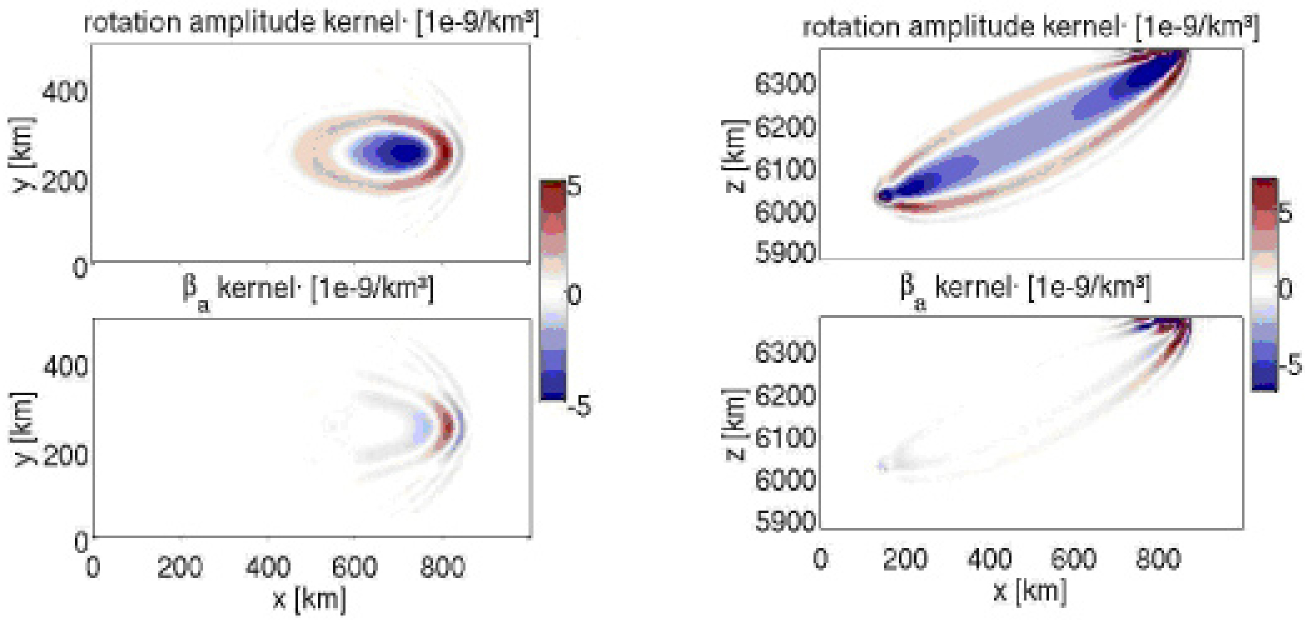

Figure 1. Comparions of sensitivity kernel for rotations alone (top) and the apparent shear velocity, i.e., the ration between velocity and rotation angle (bottom). The latter has sensitivity localized around the receiver position, an attractive feature for near-surface velocity inversion (Fichtner and Igel, 2009).

Tomography without travel times. The possibility of the derivation of local dispersion relations leads to the question which subsurface volume one actually "sees" and down to what depth velocity perturbations could be recovered. The method of choice to answer these types of questions is the adjoint method, with which sensitivity kernels can be calculated that indicate the volume in which the observable (mostly travel times) is sensitive to structural perturbations (Fig. 1). Fichtner and Igel (2009) introduced a new observable quantity – apparent shear wave velocity –, which is a time-windowed ratio of the moduli of velocity and rotation angle. It turns out that the sensitivity near the source vanishes leading to a new type of kernel that shows high sensitivity in the vicinity of the receiver only. This implies that a tomographic inversion scheme for near-receiver structures based on rotation and translations is conceivable and further highlights the potential of additional rotation measurements. This was realized in a follow-up study by Bernauer et al. (2009) recovering a velocity structure without the use of travel-time information (but with amplitude measurements only).

Scattering properties of the crust: Partitioning of P and S waves. The partitioning of P and S energy and the stabilization of the ratio between the two is an important constraint on the scattering properties of the medium. It was a surprise to discover considerable rotational energy in a time window containing the P-code in the seismometer recordings (Igel et al., 2007, Pham et al., 2009a). The ring laser is sensitive to SH-type motion only. Other causes (e.g., tilt-ring laser coupling, topography, anisotropy) are estimated to be small (Pham et al., 2009b). Detailed analysis of the signals and modeling of wave propagation through 3-D random media demonstrated that the observed signals can be explained with P-SH scattering in the crust with scatterers of 5km correlation length (not well constrained) and rms perturbation amplitude of 5% (well constrained).

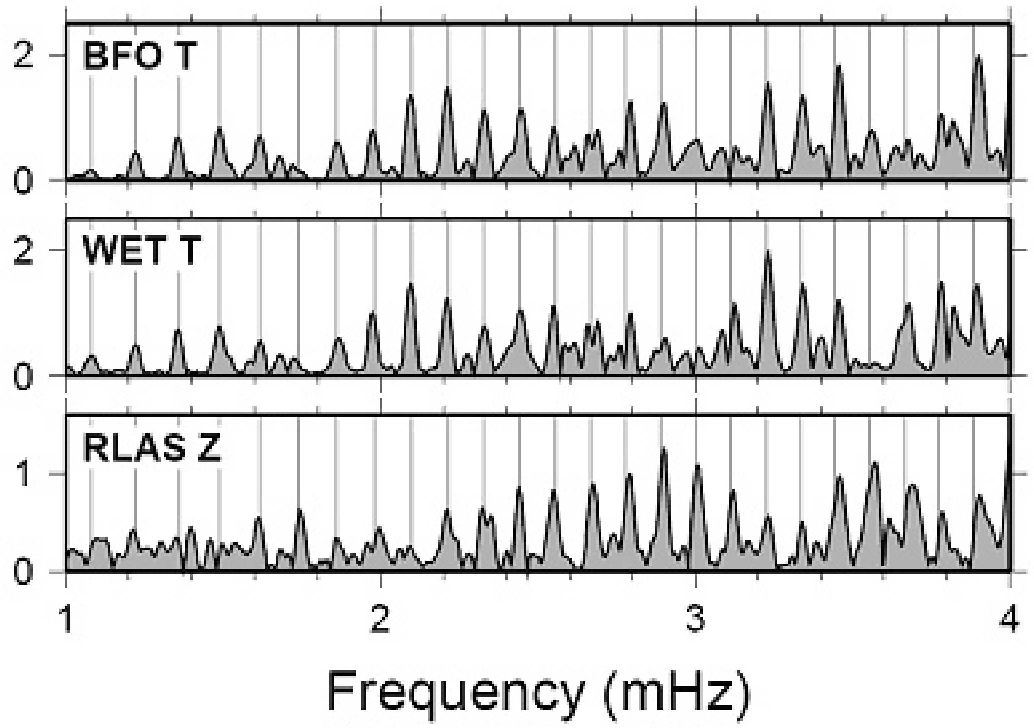

Figure 2: First observations of toroidal free oscillations with the ring laser at Wettzell, Germany (Kurrle et al., 2010b). Ring laser observations (RLAS Z) are compared with spectra of transverse acceleration (collocated WET T and at BFO, 200km away).

Long period seismology: Earth's free oscillations (see Fig. 2).: In September 2009 an M8 earthquake close to the Samoa islands excited Earth's free oscillations. Following a technical change to the ring laser at Wettzell the signal-to-noise ratio could be improved by a factor of three. This led to the first ever measurements of the toroidal eigenmodes of the Earth by a rotation sensor. Widmer and Zürn (2009) indicated that "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". Thus our recent observations opens up a new domain of applications for ring laser measurements (Kurrle et al., 2010b). Measurements of pure tilts might help decontaminating long-period seismometer records from tilt signals and thereby improve the use in free oscillations studies.

In summary, ring laser technology has opened an entirely new opportunity in seismology allowing for the first time consistent high resolution measurements of rotational ground motions. So far this could only be demonstrated with one component measuring the vertical axis of rotation. Understanding the horizontal components of motion, i.e. measuring it correctly and exploring the processing options in combination with other motion components, will fill one of the major remaining gaps in instrumental and theoretical seismology.

References

Aki, K. & Richards, P. G. Quantitative Seismology, 2nd Edition, University Science Books (2002).

Bernauer, Moritz, Andreas Fichtner, and Heiner Igel (2009), Inferring Earth structure from combined measurements of rotational and translational ground motions, Geophysics, in press.

Bouchon, M. & Aki, K. Strain, tilt, and rotation associated with strong ground motion in the vicinity of earthquake faults. Bull. Seism. Soc. Amer. 72, 1717-1738 (1982).

Cochard, A., Igel, H., Schuberth, B., Suryanto, W., Velikoseltsev, A., Schreiber, U., Wassermann, J., Scherbaum, F., Vollmer, D. Rotational motions in seismology: theory, observations, simulation, in "Earthquake source asymmetry, structural media and rotation effects" eds. Teisseyre et al., Springer Verlag (2006).

Ferreira A. M. G., and H. Igel, Rotational Motions of Seismic Surface Waves in a Laterally Heterogeneous Earth, Bull. Seism. Soc. Amer., 99: 1429-1436.

Fichtner A., and H. Igel Sensitivity Densities for Rotational Ground-Motion Measurements, Bull. Seism. Soc. Amer., 2009 99: 1302-1314.

Huang, B.-S. Ground rotational motions of the 1999 Chi-Chi, Taiwan earthquake as inferred from dense array observations, Geophys. Res. Lett., 30, doi:10.1029/2002GL015157 (2003).

Igel, H., Schreiber, K.U., Flaws, A., Schuberth, B., Velikoseltsev, A., Cochard, A., Rotational motions induced by the M8.1 Tokachi-oki earthquake, September 25, 2003, Geophys. Res. Lett., 32, L08309, doi:10.1029/2004GL022336 (2005).

Igel, H., A. Cochard, J. Wassermann, A. Flaws, U. Schreiber, A. Velikoseltsev, and N. P. Dinh (2007), Broad-band observations of earthquake-induced rotational ground motions, Geophysical Journal International, 168(1), 182-197, doi:10.1111/j.1365-246X.2006.03146.x.

Kurrle, D., Igel, H., Ferreira, A., Wassermann, J., Schreiber, U., Can we estimate local Love-wave dispersion properties from col-

located measurements of translations and rotations ?, Geophys. Res. Lett., in press (2010a).
Kurrle, D., Igel, H., Ferreira, A., Wassermann, J., Schreiber, U., First observations of Earth's free oscillations with a rotation sensor, in preparation (2010b).
Lee W. H. K, M. Çelebi, M. I. Todorovska, and H. Igel, Introduction to the Special Issue on Rotational Seismology and Engineering Applications, Bull. Seism. Soc. Amer., (2009) 99: 945-957.
McLeod, D.P., Stedman, G.E., Webb, T.H. & Schreiber, U. Comparison of standard and ring laser rotational seismograms. Bull. Seism. Soc. Amer., 88, 1495-1503 (1998).
Nigbor, R. Six-degree-of-freedom ground-motion measurement. Bull. Seism. Soc. Amer. 84, 1665-1669 (1994).
Pancha, A., Webb, T.H., Stedman, G.E., McLeod, D.P. & Schreiber, U. Ring laser detection of rotations from teleseismic waves. Geophys. Res. Lett. 27, 3553-3556 (2000).
Pham N. D., H. Igel, J. Wassermann, A. Cochard, and U. Schreiber, The Effects of Tilt on Interferometric Rotation Sensors, Bull. Seis. Soc. Amer., 2009a 99: 1352-1365.
Pham N. D., H. Igel, J. Wassermann, M. Käser, J. de la Puente, and U. Schreiber, Observations and Modeling of Rotational Signals in the P Coda: Constraints on Crustal Scattering, Bull. Seis. Soc. Amer., 2009b 99: 1315-1332.
Schreiber K. U., J. N. Hautmann, A. Velikoseltsev, J. Wassermann, H. Igel, J. Otero, F. Vernon, and J.-P. R. Wells Ring Laser Measurements of Ground Rotations for Seismology, Bull. Seis. Soc. Amer., (2009) 99: 1190-1198.
Schreiber, U., Stedman, G.E., Igel, H., Flaws, A. Ring laser gyroscopes as rotation sensors for seismic wave studies. In "Earthquake source asymmetry, structural media and rotation effects" eds. Teisseyre et al., Springer Verlag (2006).
Spudich, P, and J. B. Fletcher, (2008). Observation and prediction of dynamic ground strains, tilts, and torsions caused by the M6.0 2004 Parkfield, California, earthquake and aftershocks derived from UPSAR array observations, Bull. Seis. Soc. Amer., 98 (4): 1898-1914, AUG 2008.
Spudich, P., Steck, L.K., Hellweg, M., Fletcher, J.B., Baker, L.M. Transient stresses at Parkfield, California, produced by the M7.4 Landers earthquake of June 28, 1992: Observations from the UPSAR dense seismograph array. J. Geophys. Res., 100 675-690 (1995).
Stedman, G.E. Ring laser tests of fundamental physics and geophysics. Reports Progr. Phys. 60, 615-688 (1997).
Stedman, G.E., Li, Z. & Bilger, H.R. Sideband analysis and seismic detection in large ring lasers. Appl. Opt. 34, 7390-7396 (1995).
Suryanto, W., J. Wassermann, H. Igel, A. Cochard, D. Vollmer, F. Scherbaum, A. Velikoseltsev, and U. Schreiber (2006), First comparison of seismic array derived rotations with direct ring laser measurements of rotational ground motion, Bull. Seism. Soc. Am., 96(6), 2059-2071, doi:10.1785/0120060004.
Takeo, M. Ground rotational motions recorded in near-source region of earthquakes. Geophys. Res. Lett. 25, 789-792 (1998).
Trifunac, M.D. & Todorovska, M.I. A note on the usable dynamic range of accelerographs recording translation. Soil Dyn. and Earth. Eng. 21(4), 275-286 (2001).
Widmer-Schnidrig, R. & Zürn, W.: Perspectives of ring laser gyroscopes in low-frequency seismology, Bull. Seis. Soc. Amer.; May 2009; v. 99; no. 2B; p. 1199-1206; DOI: 10.1785/0120080267.
Wassermann, J., S. Lehndorfer, H. Igel, and U. Schreiber (2009), Performance Test of a Commercial Rotational Motions Sensor, Bull. Seis. Soc. America, 99(2B), 1449-1456, doi:10.1785/0120080157.