Rotational motions induced by the M8.1 Tokachi-oki earthquake, September 25, 2003

Heiner Igel,[1] Ulrich Schreiber,[2] Asher Flaws,[3,4] Bernhard Schuberth,[1] Alex Velikoseltsev,[2] and Alain Cochard[1]

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[1] We report the first consistent observations of rotational motions around a vertical axis induced by distant large earthquakes. It is standard in seismology to observe three components (up-down, N-S, E-W) of earthquake-induced translational ground motions using inertial seismometers. However, only recently ring laser technology has provided the required sensitivity for observations of the theoretically predicted rotational part of ground motion generated by seismic waves in a wide distance range and frequency band. Here we show that the rotations observed are consistent in waveform and amplitude with collocated recordings of transverse accelerations recorded by a standard seismometer. This suggests that rotations may become a new observable for seismology and related fields with the potential of providing complementary information on earthquake source processes, structural properties, and ground shaking.
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1. Introduction

[2] At present, there are two types of measurements that are routinely used to monitor global and regional seismic wave fields. First, 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*, 1980, 2002] 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 (a vectorial quantity). Specifically, if $\mathbf{u}(\mathbf{x})$ is the displacement at position $\mathbf{x}$, the displacement at an arbitrarily close position is given by $\mathbf{u}(\mathbf{x} + \delta\mathbf{x}) = \mathbf{u}(\mathbf{x}) + \mathrm{D}\,\delta\mathbf{x} = \mathbf{u}(\mathbf{x}) + \varepsilon\delta\mathbf{x} + \omega \times \delta\mathbf{x}$, where D is the deformation gradient, ε is the – symmetric – strain tensor and $\omega = (1/2)\nabla \times \mathbf{u}$ is the rotation (also sometimes called spin or vorticity). 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 two horizontal components, equal to tilt at the free surface, are generally recorded at low frequencies). Indeed, *Aki and Richards* [2002, p. 608] note that "seismology still awaits a suitable instrument for making such measurements". Furthermore, the 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 [*Castellani and Zembaty*, 1996].

[3] In the past years, ring laser gyroscopes were developed primarily to observe variations in Earth's absolute rotation rate with high precision [*Stedman et al.*, 1995; *Stedman*, 1997]. One of these instruments – located near Christchurch, New Zealand – recorded seismically induced signals of ground rotation rate for several large earthquakes [*McLeod et al.*, 1998; *Pancha et al.*, 2000]. These observations gave evidence that the optical sensors provide sufficient accuracy to record seismic rotations. However, these observations were not fully consistent in phase and amplitude with translational motions recorded with collocated seismometers and were compared only in a narrow frequency band. Attempts to observe ground rotations with other devices (e.g., solid state rotational velocity sensor, fibre-optical gyros) were limited to large signals close to artificial or earthquake sources [*Nigbor*, 1994; *Takeo*, 1998] and did not lead so far to an instrument type with the required sensitivity useful for broadband seismology.

[4] The recording of the (complete) rotational motion is expected to be useful particularly for (1) further constraining earthquake source processes when observed close to the active faults [*Takeo and Ito*, 1997]; (2) estimating permanent displacement from seismic recordings [*Trifunac and Todorovska*, 2001]; (3) estimating local (horizontal) phase velocities from collocated observations of translations and rotations as described later. Here we show consistent broadband ring-laser observations of the vertical component of rotation rate observed for a distant large earthquake and model the observations with numerical simulations of the complete rotational wave field in a 3-D heterogeneous global Earth model.

2. Measurement Principle

[5] A ring laser detects the Sagnac beat frequency of two counter-propagating beams [*Stedman*, 1997] (see Figure 1). This beat frequency δf is directly proportional to the rotation rate $\boldsymbol{\Omega}$ around the surface normal $\mathbf{n}$ of the ring laser system as given by the Sagnac equation

$$\delta f = \frac{4A}{\lambda P}\mathbf{n} \cdot \boldsymbol{\Omega}$$

[1]Department of Earth and Environmental Sciences, Ludwig-Maximilians-University of Munich, Munich, Germany.
[2]Forschungseinrichtung Satellitengeodäsie, Technical University of Munich, Fundamentalstation Wettzell, Kötzting, Germany.
[3]Department of Physics and Astronomy, University of Canterbury, Christchurch, New Zealand.
[4]Now at Department of Earth and Environmental Sciences, Ludwig-Maximilians-University of Munich, Munich, Germany.

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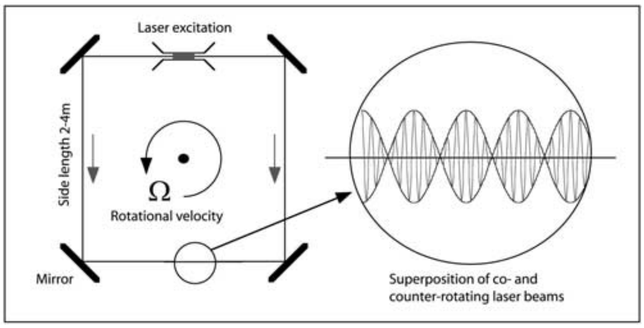

Figure 1. Ring laser measurement principle. The instrument is mounted horizontally and rigidly attached to the ground. Two counter-rotating single-mode laser beams interfere to generate a beating in case the system rotates with respect to the surface normal. The beating frequency is directly proportional to rotational velocity.

where P is the perimeter of the instrument, A the area, and λ the laser wavelength. Inherently, this equation has three contributions that influence the beat frequency δf. (1) Variations of the scale factor ($4A/\lambda P$) have to be avoided by making the instrument mechanically as rigid and stable as possible. (2) Changes in orientation $\mathbf{n}$ enter the beat frequency via the inner product. Finally, (3) variations in $\mathbf{\Omega}$ (e.g., due to changes in Earth's rotation rate, or seismically induced rotations) are representing the most dominant contribution to δf. Note that translations do not generate a contribution to the Sagnac frequency. Ring lasers are sensitive to rotations only, given stable ring geometry and lasing.

[6] The ring laser used in this study (named G) is a He-Ne-gas laser with a high Q cavity and a surface area of 16 m^2. It operates on a laser wavelength of 633 nm and – being mounted horizontally at a latitude of 49.15° north – the Sagnac frequency induced by Earth's rotation amounts to 348.6 Hz, sampled at 1000 Hz. This signal is frequency modulated by any additional rotational motions (e.g., due to a passing seismic wave field). The instrumental resolution of ring lasers is limited by the scale factor and quantum noise processes. For the G ring laser rotation rates as small as 10^{-10} rad/s/$\sqrt{\text{Hz}}$ can be observed [*Schreiber et al.*, 2003b]. Ring lasers rigidly attached to bedrock allowed the detection of very small changes of the orientation of the surface normal caused by solid Earth tides, ocean loading [*Schreiber et al.*, 2003a] and in particular diurnal polar motion [*Schreiber et al.*, 2004].

3. Observations and Modelling

[7] On September 26, 2003 at 19:50 GMT a large thrust earthquake occurred off Tokachi-oki, Hokkaido, Northern

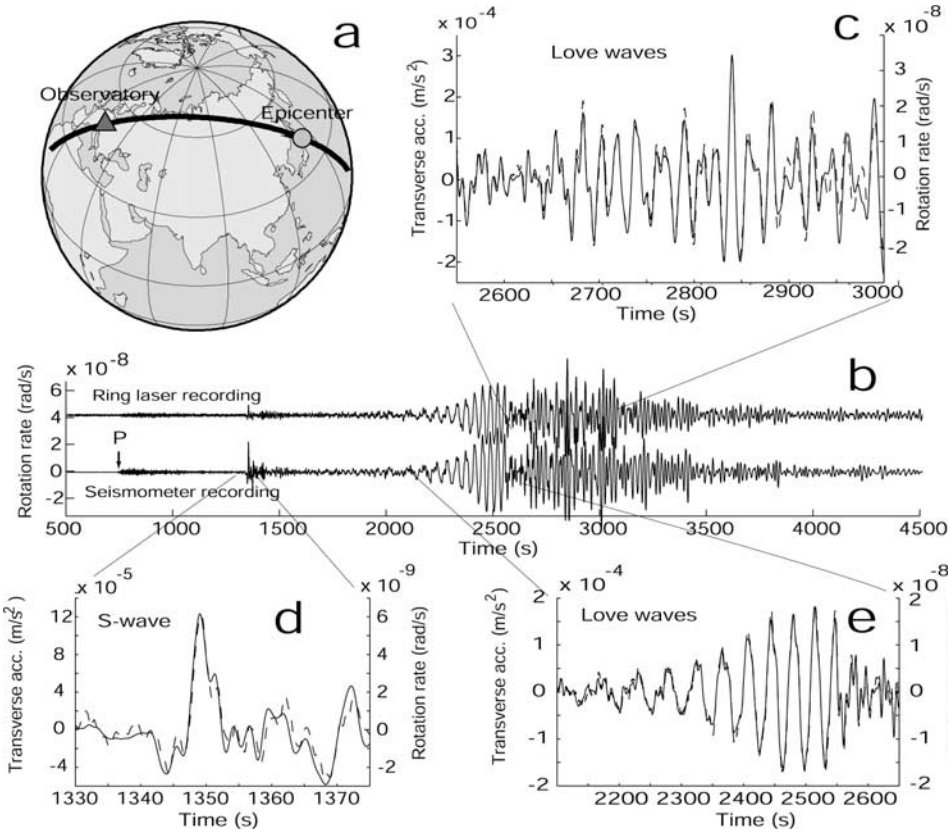

Figure 2. Observed ground motion. Comparison of direct measurements of ground rotational motions around a vertical axis with transverse accelerations for the M8.1 Tokachi-oki earthquake, September 25, 2003. (a) Schematic view of the great-circle-path through the epicentre in Hokkaido, Japan, and the observatory in Wettzell, SE-Germany. (b)–(e) Superposition of rotation rate and transverse acceleration for different time windows. B, Complete signal, transverse acceleration was divided by 2c, c being 5 km/s. (c), (d), (e) Transverse acceleration (solid, left axis), rotation rate (dashed, right axis). (c) Latter part of the surface wave train. (d) Direct S-wave arrival. (e) Initial part of the surface wave train.

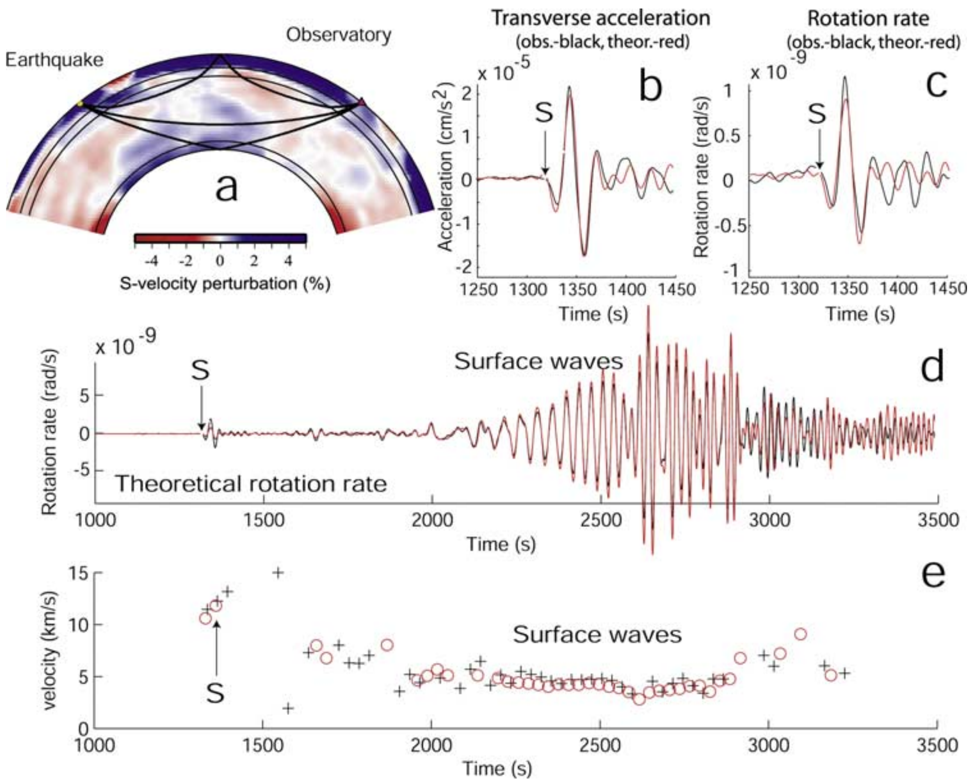

Figure 3. Modelling of rotational ground motions. Complete theoretical seismograms are calculated for a 3-D isotropic, attenuating global Earth model using the spectral-element method [*Komatitsch and Tromp*, 2002a, 2002b]. The cut-off period is 20 s. (a) Schematic view of some ray paths (S, ScS, SS) in a cross section through a 3-D global velocity model. (b) Observed (black) and theoretical (red) transverse acceleration of the direct S-wave. (c) Observed (black) and theoretical (red) rotation rate of the direct S-wave. (d) Theoretical rotation rate (red) and converted rotation rate from theoretical transverse accelerations (black). (e) Superposition of estimated horizontal phase velocities from observations (black crosses) and theory (red circles), see text for details.

Japan. In this region, the pacific plate subducts towards N60°W under Hokkaido from the Kuril trench at a rate of about 80 mm/year [*DeMets et al.*, 1990]. The total seismic moment was estimated to be $M_0 = 1.7 \times 10^{21}$ Nm (Mw = 8.1) with a total source duration of 50 s. The propagating seismic wave field was recorded by the STS-2 broadband seismic station WET (Lat = 49.15°, Lon = 12.88°) near Wettzell, Germany, where the G-Ring is located at a distance of approximately 300 m from the seismometer. The epicentral distance is 79.4° (8830 km) with a back-azimuth of 34.9° (required to rotate the horizontal components into transverse motion, see Figure 2a). Translations were recorded with a sampling rate of 20 Hz, the vertical component of rotation rate at 4 Hz.

[8] In order to compare translations with the vertical component of the vector of rotation – which is what the G-ring is measuring – the horizontal components were rotated into radial and transverse directions. Note that Rayleigh waves should not generate such a vertical component, while Love waves are horizontally polarized hence generate rotations around a vertical axis only. To obtain transverse acceleration the transverse velocity traces were differentiated with respect to time. Let us now assume a transversely polarized plane wave with displacement $\mathbf{u} = (0, u_y(t - x/c), 0)$, c being the horizontal phase velocity. The vector of rotation (curl) is thus given as $\frac{1}{2}\nabla \times \mathbf{u} = (0, 0, -\frac{1}{2c}\dot{u}_y\,(t - x/c))$ with the corresponding z-component of rotation rate $\Omega_z\,(x, t) = -\frac{1}{2c}\ddot{u}_y(t - x/c)$. This implies that – under the given assumptions – at any time rotation rate and transverse acceleration are in phase and the amplitudes are related by $\ddot{u}_y(x, t)/\Omega_z(x, t) = -2c$. In practice (e.g., Figure 3e), the phase velocities can be estimated by best-fitting waveforms in sliding a time-window of appropriate length along the seismic signal. The equivalent derivation can be carried out in the frequency domain. The spectral ratio between transverse accelerations and rotation rate leads to phase velocity estimates as a function of frequency. In this study the estimation in the time domain was preferred as the frequency dependent estimation requires stacking of several events and windowing of specific seismic phases. Thus, under this assumption both signals should be equal in phase and amplitude [*McLeod et al.*, 1998; *Pancha et al.*, 2000]. This assumption is expected to hold for a considerable part of the observed ground motion due to the large epicentral distance compared to the considered wavelengths and source dimensions. This property is exploited here to verify the consistency of the observations. Close to the seismic source this assumption no longer holds and may form the basis for further constraining rupture processes [*Takeo*, 1998; *Takeo and Ito*, 1997].

[9] The broadband observations of transverse acceleration and rotation rate (both unfiltered) are presented in

Figures 2b–2e. The transverse acceleration, divided by twice a constant phase velocity (5 km/s, approx. the local Love wave phase velocity) is compared with the direct observation of rotation rate in Figure 2b. The observations show that the expected phase correlation between accelerations and rotations are matched in a substantial part of the seismogram. The superposition of the time-window containing the direct S-wave (Figure 2d, local horizontal phase velocity 13 km/s) shows that the ring laser seems to capture well the rotational signal of the near-plane S-arrival with parts of the wave forms matched down to a period of 5 s. The overall match is best for the passing fundamental mode Love-type surface waves (Figures 2c and 2e; the maximum of the normalized cross-correlation function for both time windows is approx. 0.96). Note that rotational energy is also observable right after the P-wave onset, suggesting P-SH converted energy (in theory, P-waves would not lead to a signal on the vertical component of rotation). We conclude that the ring-laser measures broadband rotational signals that are consistently in phase with the expected translational motions.

[10] In order to test the consistency of the observed amplitudes of the rotational motions, we model the observations by calculating complete theoretical seismograms. To be as realistic as possible we calculate seismograms for a recent 3-D global tomographic model [*Ritsema and Van Heijst*, 2000] (see Figure 3a), incorporating a crust-model [*Bassin et al.*, 2000] and a finite-source model of the Hokkaido event (J. Chen, personal communication). Seismograms are calculated using the spectral-element method [*Komatitsch and Tromp*, 2002a, 2002b] that was extended to allow outputting the curl of the velocity-wave field. The large-scale numerical simulation was carried out with a spatial and temporal resolution allowing theoretical seismograms accurate down to periods of 20 s.

[11] To be able to compare directly observations and theoretical simulations (Figure 3), the observed transverse accelerations and rotations were low-pass filtered with a cut-off period of 20 s. In Figures 3b and 3c the theoretical and observed transverse accelerations and rotation rates are superimposed, respectively, in a time window containing the direct S-wave arrival. Note the excellent fit in waveform and absolute amplitude for both transverse acceleration and rotation rate, with a slightly better fit of the accelerations. The complete theoretical seismograms are shown in Figure 3d (to allow direct comparison, the transverse accelerations were converted to rotation rate with a constant phase velocity of 5 km/s). As motivated above, collocated observations of translations and rotation rate allow the estimation of local transverse phase velocities given the direction of propagation (e.g., along the great circle path). To estimate the horizontal phase velocity we slide a 30 s time window over the observed time-series and find the best-fitting phase velocity for those windows, for which there is sufficient phase correlation (maximum of cross-correlation function > 0.95).

[12] The estimated horizontal phase velocities are shown for both observations (+) and theoretical seismograms (o) in Figure 3e. Note that these estimations are obtained through a point measurement. Estimates of horizontal seismic phase velocities can otherwise only be obtained through analysis of seismic array data. The theoretical predictions of phase velocities match well the observed values. The initial large horizontal phase velocity for the direct S wave (approx. 13 km/s) is compatible with the expected incidence angle of approximately 18°. The observed surface wave phase velocities are slightly higher than the theoretical predictions. This may be compatible with the fact that the receiver location is situated in a province of igneous rocks with higher-than average seismic velocities that might not be captured by the crust model used, or the slight discrepancy may be within the error bars, that need to be estimated by processing several earthquakes. These simulations suggest that in – addition to the phase compatibility – also the absolute amplitudes of the rotational motions – analysed through the estimation of apparent phase velocities – are consistent.

4. Conclusions

[13] We show here that ring-laser technology provides the required resolution for consistent broadband observations of rotational motions induced by distant earthquakes. With appropriate adaptations to the needs of seismology it is likely that global networks of rotation sensors may be feasible in the future, with applications in global and regional seismology, earthquake source studies, earthquake engineering and geodesy. As a first step in this direction, the construction of a simpler low-cost ring laser with equivalent sensitivity called GEOsensor [*Schreiber et al.*, 2003b] was successfully completed. This instrument is now available for field testing and has been deployed in a seismically active region (the Pinon Flat Observatory PFO in Southern California) in order to capture signals not only from teleseismic but also from local events.

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A. Cochard, A. Flaws, H. Igel, and B. Schuberth, Department of Earth and Environmental Sciences, Ludwig-Maximilians-University of Munich, Theresienstrasse 41, D-80333 Munich, Germany. (heiner.igel@lmu.de)

U. Schreiber and A. Velikoseltsev, Forschungseinrichtung Satellitengeodäsie, Technical University of Munich, Fundamentalstation Wettzell, Sackenriederstrasse 25, D-93444 Kötzting, Germany.