Recent Advances in Rotational Seismology

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INTRODUCTION

Rotational seismology is an emerging field of study concerned with all aspects of rotational motions induced by earthquakes, explosions, and ambient vibrations. Two recent monographs (Teisseyre *et al.* 2006; Teisseyre *et al.* 2008) and a *Bulletin of the Seismological Society of America* special issue on Rotational Seismology and Engineering Applications (Lee, Celebi *et al.* 2009) are useful starting points. Rotational seismology is of interest to a wide range of disciplines, including various branches of seismology, earthquake engineering, and geodesy, as well as to physicists using Earth-based observatories for detecting gravitational waves generated by astronomical sources, as predicted by Einstein in 1916.

Traditionally, only *translational* ground motions are observed in seismology. However, we should also measure the three components of *rotational* motion and the six or more components of strain (Lee, Celebi *et al.* 2009). We will improve our understanding of the earthquake process (and the complex ground motions it generates) by developing new processing and inversion schemes including the new observables in rotations and strains. In this article we provide a summary of recent activities, some background information, and selected highlights of advances in rotational seismology and engineering applications.

INTERNATIONAL WORKING GROUP ON ROTATIONAL SEISMOLOGY

Following Hudnut (2005) on integrating real-time GPS with inertial sensors (including both translation and rotational), W. H. K. Lee (with K. W. Hudnut and J. R. Evans as coordinators) organized a mini-workshop on rotational seismology on February 16, 2006 (Evans *et al.* 2007). After the workshop, Evans and Lee contacted other groups active in rotational motions in several countries. An international working group on rotational seismology (IWGoRS) was then organized to promote investigations of rotational motions and their implications and to share experience, data, software, and results in an open Web-based environment (Todorovska *et al.* 2008). Anyone can join IWGoRS at http://www.rotational-seismology.org, subscribe to the mailing list, and contribute to the content (publications, data, links, etc.).

The IWGoRS organized a special session on rotational motions in seismology, convened by H. Igel, W. H. K. Lee, and M. Todorovska during the 2006 AGU Fall Meeting (Lee, Igel *et al.* 2007). The goal was to discuss rotational sensors, observations, modeling, theoretical issues, and potential applications of rotational ground motions. It became apparent that there is a need for a workshop dedicated specifically to rotational seismology so investigators from different countries and different fields can discuss their many issues of mutual interest and draft a research plan.

FIRST INTERNATIONAL WORKSHOP

The First International Workshop on Rotational Seismology and Engineering Applications was hosted by the U.S. Geological Survey (USGS) in Menlo Park, California, on September 18–19, 2007. The technical program consisted of three sessions: plenary and oral presentations on the first day, posters on the second day, and discussions. A post-workshop session was held on September 20 in which scientists of the Laser Interferometer Gravitational-Wave Observatory (LIGO) presented their work on seismic isolation of their ultra-high-precision facility, which requires very accurate recording of translational and rotational components of ground motions (Lantz 2009).

In the plenary session, three lectures were presented for a general audience and the workshop participants. Five oral presentations were given in the afternoon on major areas of research on rotational seismology and engineering issues. The next morning's session was devoted to 30 posters covering a wide range of topics, including large block rotations in geological-scale time; rotations of monuments after earthquakes; and theories, instruments, observations, and analyses of rotational motions. That afternoon participants divided into five panels for in-depth discussions on theory, far-field observations, near-field monitoring, engineering applications, and instrument design and testing. These discussions were followed by general discussion in which the panel chairs summarized the group discussions, listing key issues and future research directions. The assembled workshop concluded that collaborative work is essen-

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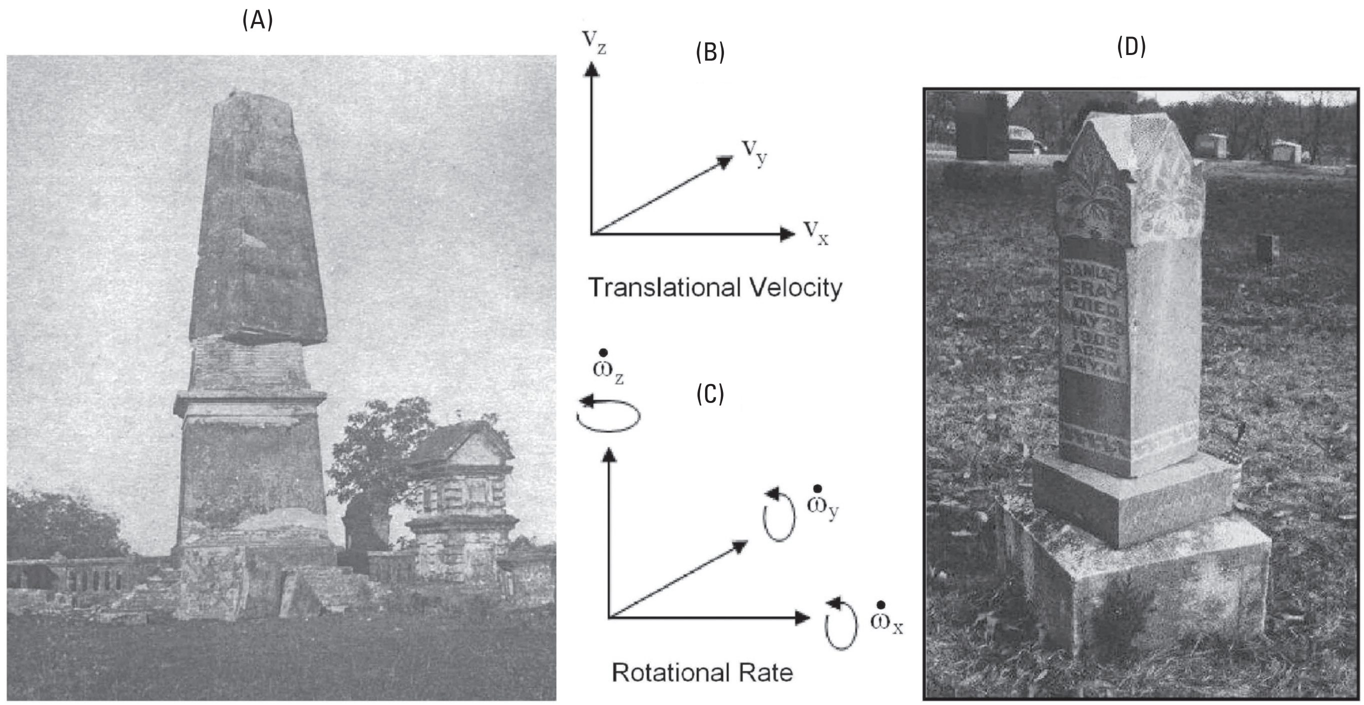


▲ **Figure 1.** (A) Rotation of the monument to George Inglis (erected in 1850 at Chatak, India) as observed by Oldham (1899) after the 1897 Great Shillong earthquake. (B) Coordinate system for translational velocity. (C) Coordinate system for rotational rate. (D) rotated monument. See text for explanation.

tial for nurturing this new field of inquiry. The panel reports and proposed future directions and research plans are described in detail by Lee, Celebi *et al.* (2007); the DVD in that report contains all presentation files and supporting materials.

ROTATIONAL EFFECTS DUE TO EARTHQUAKES

Rotational effects of earthquake waves together with rotations caused by soil-structure interaction have been observed for centuries (*e.g.*, rotated chimneys, monuments, and tombstones relative to their supports). Figure 1(A) shows the rotation of the monument to George Inglis (erected in 1850 at Chatak, India) as observed by Oldham (1899) after the 1897 Great Shillong earthquake. This monument had the form of an obelisk rising over 60 feet high from a base 12 feet on each side. During the earthquake, the topmost six-foot section was broken off and fell to the south, and the next nine-foot section was thrown to the east. The remnant is about 20 feet high and is rotated ~ 15° relative to the base. Rotation angles are generally given in units of radians (1 rad = 57.3°). Since the instrumentally observed rotations are very small, the units are often given in milli-radians (mrad), or micro-radians (μrad).

A few early authors proposed rotational waves or at least some "vortical" motions. Many different terms were used for the rotational motion components at this early stage of the field's development. For example, "rocking" is rotation around a horizontal axis, sometimes also referred to as tilt. Ferrari (2006) summarized two models of an electrical seismograph with sliding smoked paper, developed by P. Filippo Cecchi in 1876 to record three-component *translation* motions and also the *torsion* movements from earthquakes. Although these instruments operated for several years, no rotational motion could be recorded because of low transducer sensitivity. Mallet (1862) proposed that rotations of a body on the Earth's surface are due to a sequence of different seismic phases emerging at different angles. Reid (1910, 43–47.) studied rotational effects from the 1906 San Francisco earthquake and pointed out that the large observed angles of rotation could not be due to propagation of the rotational components of the seismic waves in the classical elasticity theory. A modern analysis of such rotational effects is presented in Todorovska and Trifunac (1990).

ROTATIONS CAUSED BY RESPONSE OF STRUCTURES

Man-made structures reach several tens to several hundreds of meters above the ground. Supported at their base, with their center of gravity near mid-height, structures undergo rocking motions when excited by earthquakes, strong winds, and man-made transient and steady excitations. Through the rocking compliance, the soil-structure interaction converts the incident wave energy into rotational motions of the foundation and the surrounding soil. In this way a building acts as a source of rotational waves. In densely populated metropolitan areas where separation of adjacent buildings is small, building-soil-building interactions occur. In such instances, and where long bridges have multiple supports resting on soil, detailed two- and three-dimensional analyses are required to describe the complex generation of rotational response and of rotations in the ground (Trifunac 2008).

Full-scale experiments of soil-structure interaction have provided data to measure and to quantify the nature of the rotational motions at the interface between the soil and the building foundations, but in the absence of recorded rotational strong motion in the near field and in the buildings, engineering studies had to use numerical modeling to assess and estimate the contribution of the rotational motions to the response of structures. For example, Jalali and Trifunac (2009) have shown that the pseudo-relative velocity (PSV) spectral amplitudes for excitation by horizontal, vertical, and rocking strong ground motion can be represented by superposition of three mathematical terms. This new result emphasizes the significance of rotational ground excitation and why it is necessary to incorporate it into the response estimates in the design of very tall buildings (Zembaty 2009). In another numerical simulation study, Gičev and Trifunac (2009) showed how large seismic waves propagate through the structure and deform its members beyond the linear range of response, and how the creation of nonlinear response zones and their localization (plastic hinges) will give rise to the zones of large local rotations. By placing small-aperture arrays of rotational transducers on beams and columns, they showed how it will be possible to achieve the next level in the resolution of point deformations, because from closely spaced rotational sensors it will be possible to also record the point curvature (Trifunac 1990). Thus, future array measurements of rotational motions in important structures will make it possible to reliably monitor the state of structural health in real time.

TRANSLATIONAL AND ROTATIONAL MOTIONS

The general motion of the particles or a small volume in a solid body can be divided into three parts: *translation* (along the *x, y,* and *z* axes), *rotation* (about the *x, y,* and *z* axes), and *strain*. Figure 1(B) shows the axes in a Cartesian coordinate system for *translational velocity* measured by seismometers typically used in seismology, and Figure 1(C) shows the corresponding axes of *rotation rate* measured by rotational sensors. Figure 1(D) shows earthquake-induced rotation of an almost perfectly symmetrical structure that is difficult to explain without at least some local rotational acceleration.

Since the recurrence interval of a large earthquake at a given active fault can be ~ 100 to ~ 10,000 years, seismologists have been optimizing their observations for either 1) studying large earthquakes at great distances or 2) studying small local earthquakes nearby (Lee 2002). Consequently, traditional seismographs are designed to have high sensitivity at the expense of being able to record large motions on scale. Until recent decades, monitoring strong motion from damaging earthquakes has been left to earthquake engineers and their colleagues, generally using accelerometers (Trifunac 2009). In addition, observational seismology is based mainly on measuring *translational* motions because of a widespread belief that *rotational* motions are insignificant. For example, Richter (1958, 213, footnote) states that "theory indicates, and observation confirms, that such rotations are negligible." Richter did not provide any references, and there were no instruments sensitive enough to measure rotation motions at the level of microradians (μrad) at that time.

EARLY ATTEMPTS TO STUDY ROTATIONAL MOTIONS

Rotational ground motions can be measured directly by gyroscopic sensors or inferred indirectly from an array of translational sensors. According to Cochard *et al.* (2006), displacement $\mathbf{u}$ of a point $\mathbf{x}$ is related to a neighboring point $\mathbf{x} + \delta\mathbf{x}$ by

$$\mathbf{u}(\mathbf{x} + \delta\mathbf{x}) = \mathbf{u}(\mathbf{x}) + \boldsymbol{\varepsilon}\,\delta\mathbf{x} + \boldsymbol{\omega} \times \delta\mathbf{x} \tag{1}$$

where $\boldsymbol{\varepsilon}$ is the strain tensor and

$$\boldsymbol{\omega} = \tfrac{1}{2}\nabla \times \mathbf{u}(\mathbf{x}) \tag{2}$$

is a pseudo vector representing the infinitesimal angle of rigid rotation generated by the disturbance. The three components of rotation about the *x* axis, *y* axis, and *z* axis are given by the following equations for such infinitesimal motions:

$$\begin{aligned} \omega_x &= \tfrac{1}{2}(\partial u_z/\partial y - \partial u_y/\partial z), \\ \omega_y &= \tfrac{1}{2}(\partial u_x/\partial z - \partial u_z/\partial x), \\ \omega_z &= \tfrac{1}{2}(\partial u_y/\partial x - \partial u_x/\partial y) \end{aligned} \tag{3}$$

Therefore, rigid rotations can be observed: 1) indirectly by an array of translational seismometers for "cord" rotations (Equation 2) associated with long wavelengths by assuming that contamination of translational signals by rotational motions is small, and that classical elasticity theory is valid (*e.g.*, Spudich and Fletcher 2008); or 2) by rotational sensors directly for "point" rotations (*e.g.*, Lee, Huang *et al.* 2009).

Pioneers in several countries attempted to measure rotational motions induced by earthquakes. Nearly a century ago, Galitzin (1912) suggested using two identical pendulums installed on different sides of the same axis of rotation for separate measurement of rotational and translational motion. This was later implemented, for example, by Kharin and Simonov (1969) in an instrument designed to record strong ground motion. Using an azimuthal array of seismographs, Droste and Teisseyre (1976) derived rotational seismograms for rock bursts in a nearby mine. Inspired by Walter Munk, Farrell (1969) constructed a gyroscopic seismometer and obtained a static displacement of < 1 cm and a tilt of < 0.5 μrad at La Jolla, California, during the Borrego Mountain earthquake of 9 April 1968 (magnitude 6.5) at an epicentral distance of 115 km.

Early efforts also included studies of explosions. For example, Graizer (1991) recorded tilts and translational motions in the near field of two nuclear explosions, using seismological observatory sensors to measure point rotations directly. Nigbor (1994) measured rotational and translational point ground motions directly with a commercial rotational MEMS sensor and found significant near-field rotational motions (660 µrad at 1 km distance) from a one-kiloton explosion.

Rotations and strains in the ground (Trifunac 1979, 1982) have been deduced indirectly from accelerometer arrays using methods valid for seismic waves with long wavelengths compared to the distances between sensors (*e.g.*, Spudich and Fletcher 2008). The rotational components of ground motion have also been estimated theoretically, using kinematic source models (Bouchon and Aki 1982) and the linear elastodynamic theory of wave propagation in elastic solids (Lee and Trifunac 1985, 1987).

In the past decade, rotational motions—from small local earthquakes to large teleseisms—were successfully recorded by sensitive rotational sensors in several countries (*e.g.*, Takeo 1998; McLeod *et al.* 1998; Igel *et al.* 2005; Suryanto *et al.* 2006). In particular, the application of Sagnac interferometry provided greatly improved sensitivity to rotation. Observations in Japan and Taiwan showed that the amplitudes of rotations can be one to two orders of magnitude greater than expected from the classical elasticity theory, as first noted by Takeo (1998). Theoretical work suggests that in granular materials or cracked continua, asymmetries of the stress and strain fields can create rotations separate from those predicted by classical elastodynamic theory (*e.g.*, Teisseyre and Boratyński 2003). These rotations naturally generate rotational seismic waves and seismic spin and twist solitons (Majewski 2006).

LARGE RING LASER GYROS

An unexpected advance in studying rotational ground motions came from a different field. Recent developments of highly sensitive ring laser gyroscopes to monitor the Earth's rotation also yield interesting data on rotational motions from large teleseismic events. The two most important properties that make a rotation sensor useful for seismology are its noise floor for rotational motions around the intended axes and its insensitivity to translational and cross-rotational motions. The rotation rates to be expected in seismology range from 10^{-1} rad/s (*e.g.*, Nigbor 1994; Trifunac, forthcoming) close to seismic sources to 10^{-11} rad/s observed for large earthquakes at teleseismic distances (*e.g.*, Igel *et al.* 2005, 2007). This range spans at least 10 orders of magnitude, and it is unlikely that one instrument or one instrumental technology will be capable of providing accurate measurements over such a large range of amplitudes. Ring laser technology is currently the most promising approach to recording the small rotational motions induced by earthquakes. The primary drawback is its high cost, about $1 million for a three-component ring laser gyro, and also the need for a well-insulated site.

Ring lasers detect the Sagnac beat frequency of two counter-propagating laser beams (Stedman 1997; and see Figure 2C). These active interferometers are realized by triangular or square closed evacuated cavities in which the light beams interfere. If this instrument is rotating on a platform with respect to inertial space, the effective cavity length between the co-rotating and the counter-rotating laser cavity differs, and one observes frequency splitting, thus a beat frequency. This beat frequency δf is directly proportional to the rotation rate $\mathbf{\Omega}$ around the surface normal $\mathbf{n}$ of the ring laser system, as given by the Sagnac equation:

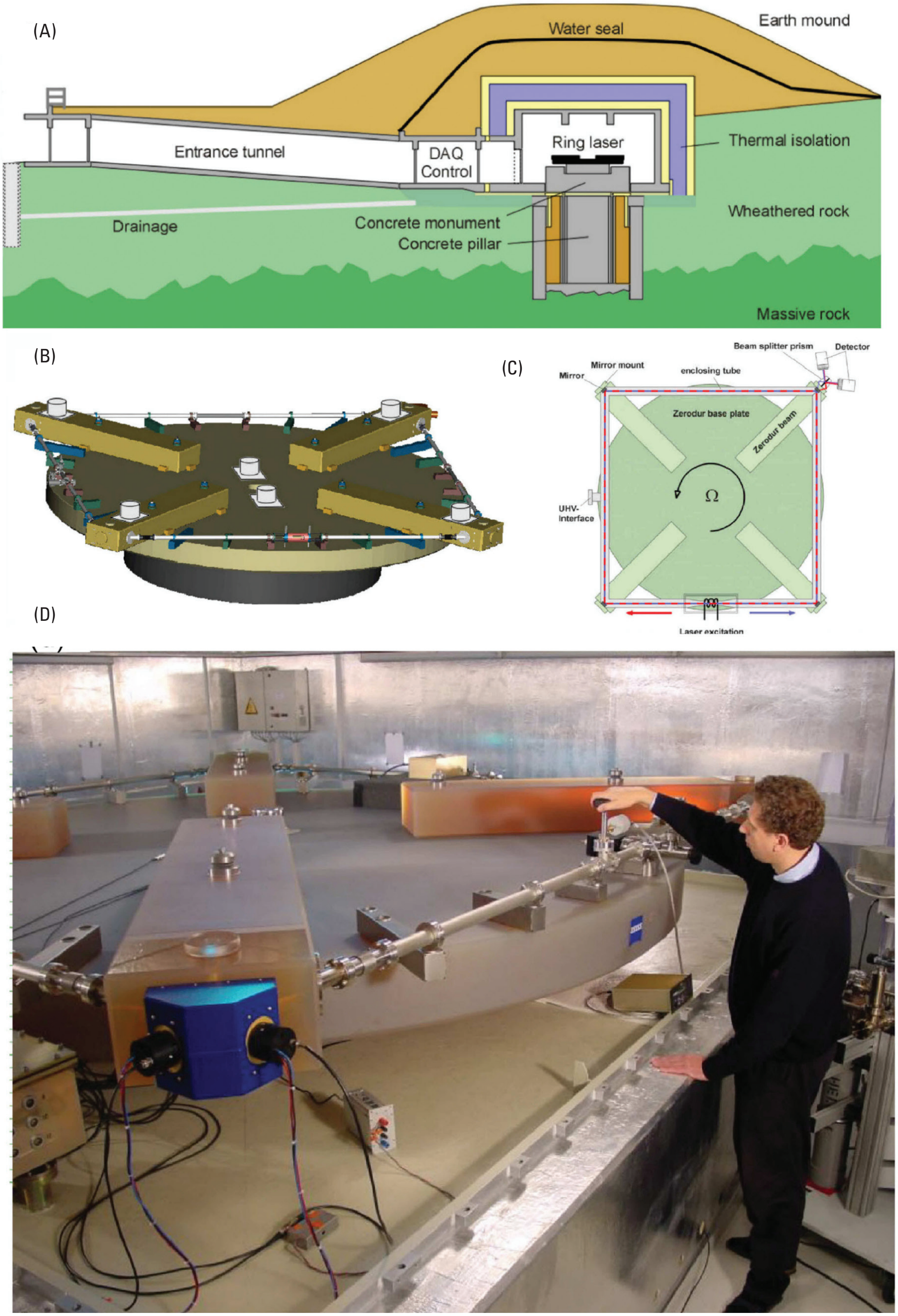
$$\delta f = \frac{4A}{\lambda P}\, \mathbf{n} \cdot \mathbf{\Omega}, \tag{4}$$

where P is the perimeter of the instrument, A its area, and λ the laser wavelength. This equation has three contributions that influence the beat frequency δf: 1) variations in 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; and 3) variations in $\mathbf{\Omega}$ (*e.g.*, due to changes in Earth's rotation rate or seismically induced rotations), the most dominant contribution to δf. Note that translations do not contribute to the Sagnac frequency unless they affect P or A in some indirect manner. Ring lasers are sensitive to rotations only, assuming stable ring geometry and lasing. The second effect implies that for coseismic observations at the Earth's surface the horizontal components of rotation (*i.e.*, tilts) will contribute to the vertical component of rotation rate. As recently shown by Pham *et al.* (2009), this tilt-coupling effect is several orders of magnitude below the level of the actual rotational signal unless one is very close to the source (where sensitive ring lasers would not be the right technology).

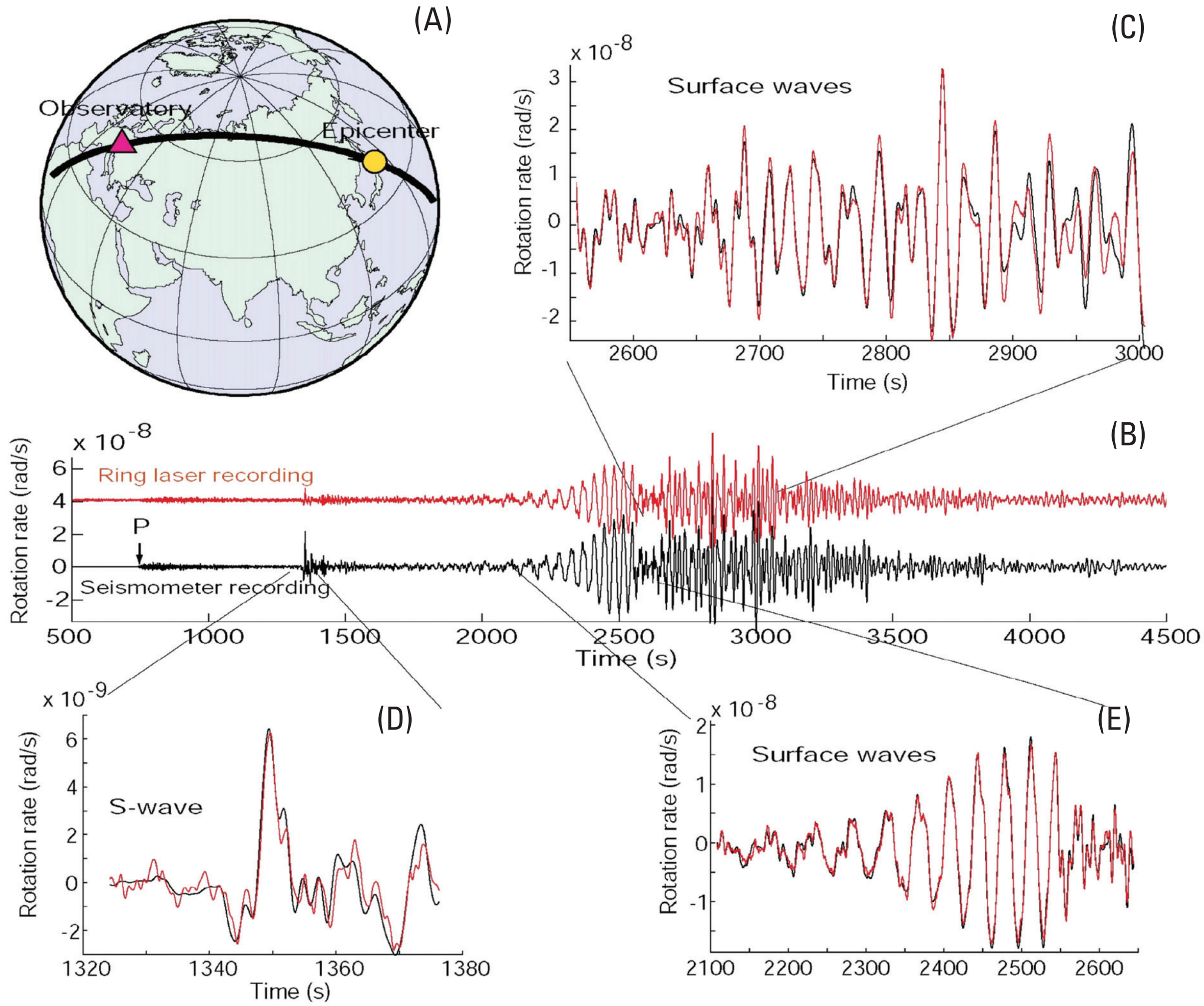
At present, there are ring laser gyros capable of measuring rotation (induced by small local earthquakes or distant large teleseisms) at four sites: 1) Cashmere Caverns, Christchurch, New Zealand (McLeod *et al.* 1998); 2) Wettzell, Germany (Schreiber *et al.* 2006); 3) Conway, Arkansas (Dunn *et al.* 2009); and 4) Piñon Flat, California (Schreiber, Hautmann *et al.* 2009).

THE G RING LASER AT WETTZELL

Since October 2001, The G ring laser has been operating at the Fundamentalstation Wettzell, in Bavaria, Germany (http://www.fs.wettzell.de/). A cross-section view of the site of the G ring laser is shown in Figure 2(A). The instrument is resting on a polished granite table (Figure 2B) being embedded in a 90-ton concrete monument. As shown in Figure 2(A), the monument is attached to a massive 2.7-m-diameter concrete pillar, which is founded on crystalline bedrock 10 m below. A system of concrete rings and isolation material shields the monument and pillar from lateral weathered-rock deformations and heat flow. The G ring laser is protected from external influences by a subsurface installation with passive thermal stability provided by a 2-m layer alternating between Styrofoam and wet clay, this beneath a 4-m soil mound. A lateral entrance tunnel with five isolating doors and a separate control room minimize thermal perturbations during maintenance. After two years of thermal adaptation, the average temperature reached 12.2° C with seasonal variations of less than 0.6° C. Figure 2(C) shows the schematic drawing of the instrument, and Figure 2(D) is a photo of the G ring laser with its designer, Ulli Schreiber, standing to the right.



▲ **Figure 2.** G ring laser gyro at the Wettzell Superstation, Germany. (A) Cross-section view of the instrument site. (B) Instrument resting on a granite table. (C) Schematic drawing. (D) Photo of G ring laser gyro with its designer, Ulli Schreiber. See text for explanation.



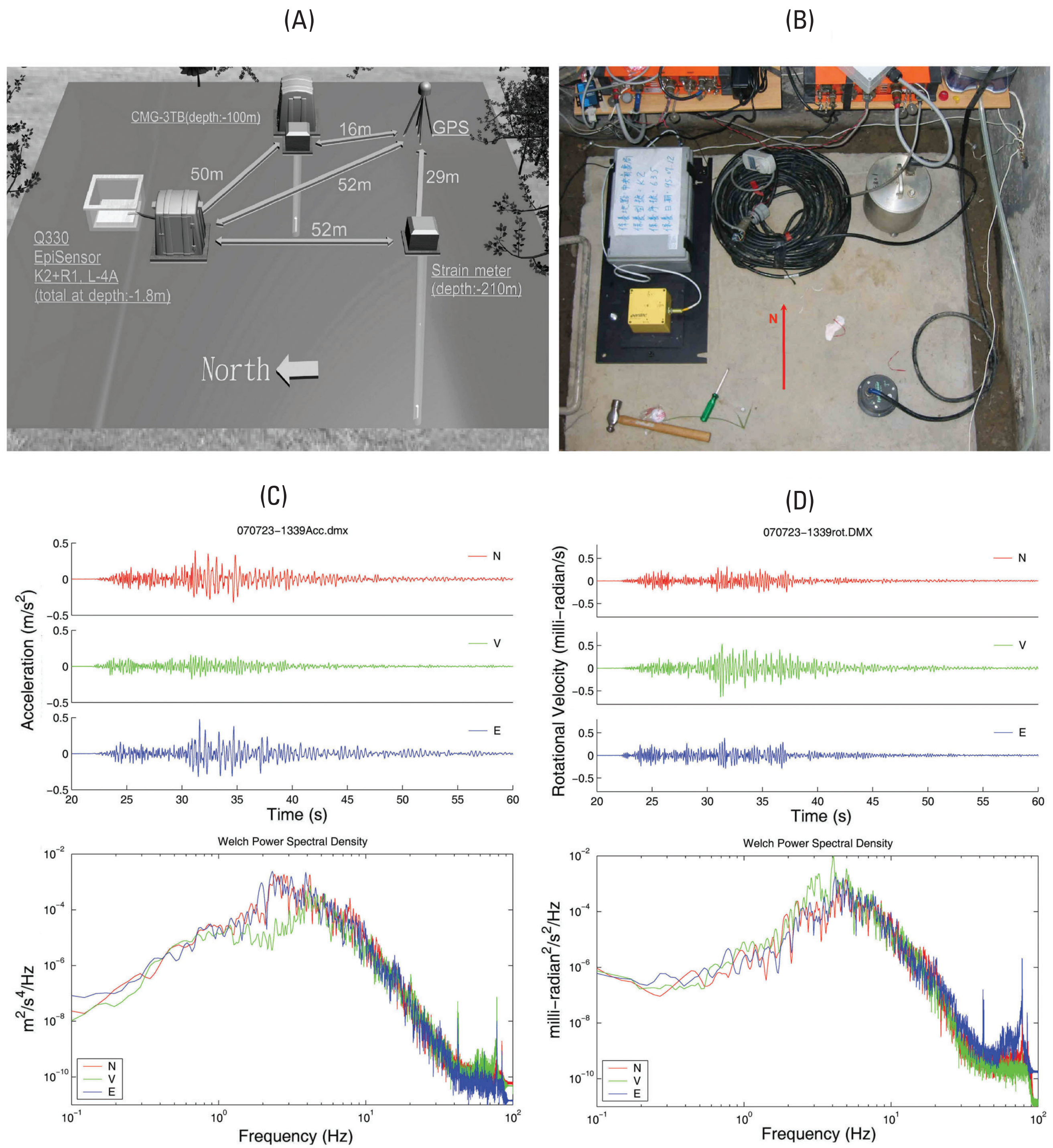
▲ **Figure 3.** Comparison of direct measurements of ground rotational motions around a vertical axis (red lines) with transverse accelerations (black lines, converted to rotation rate for each time window) for the **M** 8.1 Tokachi-oki earthquake, 25 September 2003. See text for explanation.

Figure 3 shows a comparison of direct point measurements of ground rotations around a vertical axis (red lines) to transverse accelerations (black lines, converted to rotation rate for each time window) for the **M** 8.1 Tokachi-oki earthquake, 25 September 2003 (Igel *et al.* 2005). Figure 3(A) is a schematic view of the great-circle-path through the epicenter in Hokkaido, Japan, and the observatory in Wettzell, Germany. Figure 3(B–E) shows the superposition of the rotation rate derived from transverse translations (black) and measured directly (red) for different time windows: (B) for the complete signal, (C) for the latter part of the surface wave train, (D) for the direct *S*-wave arrival, and (E) for the initial part of the surface wave train.

SMALL INERTIAL ANGULAR SENSORS

In aerospace, automotive, and mechanical engineering, small rotational motion sensors are common and generically known as gyroscopic or inertial angular sensors. Nigbor (1994) used a micro-electro-mechanical-systems-based (MEMS-based) Coriolis sensor to measure the rotational components of strong ground motions of a large chemical explosion, as mentioned above. Similar sensors were used by Takeo (1998) to measure rotational motions from an earthquake swarm ~3 km away. However, such sensors do not have the sensitivity to record rotations from small (M ~ 4) local earthquakes at distances of tens of kilometers.

The eentec model R-1 rotational seismometer is the first modestly priced sensor capable of recording small M ~ 4 earthquakes at distances up to several tens of kilometers. It uses electrochemical technology in which the motion of an electrolytic fluid inside a torus is sensed electronically, yielding a voltage signal proportional to rotational velocity. Nigbor *et al.* (2009) carried out extensive tests of commercial rotational sensors and concluded that the R-1 sensor generally meets the specifications given by the manufacturer, but that clip level and frequency response vary from those specifications and between



▲ **Figure 4.** (A) Instruments deployed at the HGSD station. (B) Photo showing the instrument vault for a K-2 accelerograph, an R-1 rotational seismometer (yellow), an EpiSensor accelerometer, and a L4A velocity seismometer. (C) Recorded translational acceleration (top) and its spectra (bottom) from an M_W5.1 earthquake. (D) Recorded rotational rate (top) and its spectra (bottom) from the same earthquake. See text for explanation

individual channels enough that more detailed calibrations are warranted for each unit. A typical transfer function for the R-1 sensor can be found at the manufacturer's website (http://www.eentec.com/). The instrument response is roughly "flat" from 0.1 to 20 Hz, and its self noise is < 10 μrad/s rms over the same frequency band.

The R-1 rotational seismometers successfully recorded several hundred local earthquakes and two explosions in Taiwan (Lee, Huang *et al.* 2009). Figure 4(A) shows the instruments deployed at station HGSD in eastern Taiwan. The top frame is a schematic drawing of the various seismic, geodetic, and strain instruments. The bottom frame shows the instruments deployed in the vault at the left-hand side of the upper drawing, including a datalogger (Quanterra Q330), an accelerometer (Kinemetrics Episensor), a six-channel digital accelerograph (Kinemetrics K2 with an external rotational seismometer, R-1 by eentec), and a short-period seismometer (Mark Products L-4A). The K2+R-1 instrument is at the left-hand side, and the yellow-colored box is the R-1 rotational seismometer.

The largest peak rotational rate recorded in Taiwan to date is from an M_W 5.1 earthquake at a hypocentral distance of 51 km; it occurred at 13:40 UTC on 23 July 2007. Figure 4(C) shows the amplitudes and spectra of translational acceleration recorded by the K2's internal accelerometer for this earthquake. The peak ground acceleration recorded is 0.47 m/s^2, and the two horizontal components have much higher amplitude than the vertical. Figure 4(D) shows the amplitudes and spectra of rotational rate from its external R-1 rotational seismometer for the same earthquake. The peak rotational rate recorded is 0.63 mrad/s for the vertical component, much more than for the horizontal components. The spectra in Figure 4(C) show that the dominant frequency band in ground acceleration is about 2–5 Hz for the two horizontal components; the spectra in Figure 4(D) show that the dominant frequency band in ground rotational rate is about 2.5–5.5 Hz for the vertical.

Other studies report observations with the R-1 sensor and compare the direct, point measurements of rotations with array-derived area rotations (*e.g.*, Wassermann *et al.* 2009). It is important to note that further studies are needed to fully understand the instrument response of rotational sensors and their broadband accuracy in phase and amplitude in comparison to standard seismometers.

BSSA SPECIAL ISSUE

In recognition of this emerging field of study, on 31 August 2007 the Seismological Society of America approved the publication of a special issue. More than 50 manuscripts were received after an open call for papers. The *BSSA* special issue (Lee, Celebi *et al.* 2009) contains an introduction, four reviews, 27 research articles, 11 short notes, six tutorials, and three supplements. The six tutorials and three supplements are intended to help readers who are not familiar with rotational seismology. For example, Grekova and Lee (2009) compiled suggested readings that may be useful in providing mathematical and physical bases for rotational seismology. They also included some suggested readings in earthquake seismology for scientists who are not seismologists. Because standard dictionaries may not include new technical terms, Lee (2009) compiled a list of glossary terms for rotational seismology from contributions of some of the authors of the special issue and also included some glossary terms on earthquakes. Readers are encouraged to read this *BSSA* special issue; its table of contents is highlighted in this issue of *SRL* on page 508.

DISCUSSION

Many authors have already emphasized the benefits of studying rotational motions (*e.g.*, Twiss *et al.* 1993; Spudich *et al.* 1995; Takeo and Ito 1997; Teisseyre *et al.* 2006; Trifunac 2006, forthcoming; Igel *et al.* 2007; and Fichtner *et al.* 2009). We will discuss briefly some basic issues.

Classical Elasticity versus Other Theories

Real materials of the Earth are heterogeneous, anisotropic, and nonlinear, especially in the damage zone surrounding faults and in poorly consolidated sediments and soil just beneath seismic instruments. In the presence of large nonlinearities, we are forced to consider the mechanics of chaos (Trifunac, forthcoming), and to interpret such complexities we must record the rotational components of strong motion in addition to the translational components.

Seismology is primarily based on the linear elasticity theory of simple homogeneous materials under infinitesimal strain. This theory was mostly developed in the early nineteenth century. Since then, linear elasticity theory has been embedded in seismology. "Cord" rotation is defined as the curl of the displacement field in Equation 2, and in linear elasticity theory, the rotational components of motion are contained in the *S* waves. Meanwhile, modern continuum mechanics in the past century has advanced far beyond the classical linear elastic theory. In particular, the elasticity theory of the Cosserat brothers (Cosserat and Cosserat 1909) incorporates 1) a local rotation of continuum particles as well as the translational motion assumed in classical theory, and 2) a couple stress (a torque per unit area) as well as the force stress (force per unit area). In the constitutive equation of classical elasticity theory there are two independent elastic constants; in Cosserat elastic theory there are six or more elastic constants. Pujol (2009) provides a tutorial on rotations in the theories of finite deformation and micropolar (Cosserat) elasticity. Twiss (2009) derives an objective asymmetric micropolar moment tensor from a discrete-block model for a deforming granular material. He also investigates seismogenic deformation associated with volumes of distributed seismicity in three different areas and finds support of the micropolar model for the effects of a granular substructure on the characteristics of seismic focal mechanisms.

Near-Field Seismology

Seismology has been very successful in the *far field* because large earthquakes occur every week somewhere on Earth and because classical elasticity theory works very well for interpreting the recorded *translational* motions at large distances. Because of this success and limited instrumentation options, most funding for earthquake monitoring historically has gone into global and regional seismic networks using only translational seismometers. However, to improve our understanding of damaging earthquakes we must also deploy appropriate instruments in the *near field* of active faults where large earthquakes (M > 6.5) occur infrequently. As is true for all strong-motion seismology and engineering, this is a risky business because a large earthquake on any given fault may not take place for hundreds of years—many times longer than the carrier span of any scientist. Therefore, seismologists and earthquake engineers must accumulate data over centuries and must be willing to invest substantial resources in order to observe earthquakes in the near field.

Recording ground motions in the near field would require extensive seismic instrumentation along some well-chosen active faults—and luck. Several seismologists have been advocating such instrumentation. A current deployment in southwestern Taiwan by that nation's Central Weather Bureau is designed to "capture" a repeat of the 1906 Meishan earthquake (M 7.1) with both translational and rotational instruments (Wu *et al*. 2009).

Processing Collocated Measurements of Translations and Rotations

Processing collocated observations of rotation and translation is routinely performed in the inertial navigation units of aircraft and space vehicles. A similar analysis should be possible for various combinations of strain components, rotations, and translations. With the exception of velocity-strain combinations (*e.g.*, Gomberg and Agnew 1996) this terrain is largely unexplored.

Phase velocities and propagation directions.
A simple calculation for linear-elastic plane (not dispersed) waves with transverse polarization shows that the ratio of transverse acceleration to rotation rate is proportional to phase velocity. This implies that information on subsurface velocity structure (otherwise only accessible through seismic array measurements and combined analyses) is contained in a single point measurement. It has been shown that the ratio-derived phase velocities agree with the velocities predicted by calculation (Igel *et al*. 2005). In a recent theoretical study based on full ray theory for Love waves, using normal mode summation, it has been demonstrated that the Love wave dispersion relation can be obtained simply by taking the spectral ratio of transverse acceleration to rotation rate (vertical axis; Ferreira and Igel 2009). This result implies that seismic shear wave tomography can be possible without relating seismic observations from different stations, that is, without averaging over subarrays used to compute local mean phase velocities. Information on the direction of propagation also is contained in the azimuth-dependent phase fit between rotations and translations. This fit is optimal in the direction of propagation, from which back azimuths can be estimated to within a few degrees (Igel *et al.* 2007). Linking observational translations, strains, and rotations together can yield a snapshot of the wavefield where wave direction, slownesses, and radial/azimuthal amplitude gradients can be directly inferred from the data; Langston (2007) has also advocated this approach.

Toward a new kind of tomography.
The possibility of deriving local dispersion relations from single stations leads to the question of which subsurface volume one actually "sees" and down to what depth velocity perturbations can be recovered. The method of choice to answer this type of question is the adjoint method, with which sensitivity kernels can be calculated to indicate the volume in which the observable (mostly travel times) is sensitive to structural perturbations. 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 result implies that a tomographic inversion scheme for near-receiver structures based on rotations and translations is possible and further highlights the potential of rotation measurements. Preliminary synthetic tomographic inversions are given in Bernauer *et al.* (2008).

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 a medium. It was a surprise to discover considerable rotational energy in a time window containing the *P* coda in the teleseismic seismometer records of Igel *et al.* (2007). Detailed analysis of the signals and modeling of wave propagation through three-dimensional random media demonstrated that the observed signals can be explained with *P–SH* scattering in the crust with scatterers of roughly 5-km correlation length (not well-constrained) and rms perturbation amplitude of 5% (well-constrained). This result further illustrates the efficacy of rotation measurements, for example, as a filter for *SH*-type motion. Similar processing steps will be possible for the horizontal components of rotation and the corresponding components of translation. It is conceivable that the combination of these various components might lead to tight constraints on near-receiver structure, results otherwise only available from array measurements.

CONCLUSION

Seismology and earthquake engineering are based primarily on the observation and modeling of three-component *translational* ground and structural motions. Although rotational effects from earthquakes have been observed for centuries, *rotational* ground motion has been ignored due to a widespread belief that rotation is insignificant, and because there were practical difficulties in measuring rotation. Seismology has been very successful in the far field using linear elasticity theory, where it is appropriate to assume *infinitesimal stress and strain* for interpreting the recorded *translational* motions. However, to improve our understanding of damaging earthquakes we must also deploy appropriate instruments in the near field of active faults where large earthquakes (M > 6.5) occur infrequently. Furthermore, by deploying both translational and rotational sensors, we can learn a lot more about earthquakes, as discussed in the previous section.

Theoretical work in modern rotational seismology began in the 1970s, and attempts to deduce rotational motion from accelerometer arrays began in the 1980s. However, modern *direct* measurements of rotational ground motions began only about a decade ago when affordable commercial angular inertial sensors became sensitive enough to detect microradian rotations while large ring laser gyros (intended for studying the Earth's rotation) became capable of detecting nanoradian rotations.

Ring laser observations at Wettzell, Germany, and Piñon Flat, California, demonstrated consistent measurements of rotational ground motions in the far field. So far this success can only be demonstrated with one component of rotation. The high cost of present high-precision ring laser gyros makes widespread deployment unlikely. Less expensive and/or less sensitive alternatives are now being pursued by five academic groups (Cowsik *et al.* 2009; Dunn *et al.* 2009; Jedlička *et al.* 2009; Schreiber, Velikoseltsev *et al.* 2009; Takamori *et al.* 2009). At present, only Taiwan has a modest program to monitor both translational and rotational ground motions from local and regional earthquakes at several free-field sites, as well as two arrays equipped with both accelerometers and rotational seismometers in a building and a nearby site (Wu *et al.* 2009). The goal is to record both translational and rotational ground motions in the near field of damaging earthquakes.

Based on the developments described in the *BSSA* special issue, we believe that observation, analysis, and interpretations of both rotational and translational ground motions will soon play a significant role in seismology and earthquake engineering.

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